On the disputed $\pi_1(1600)$ resonance

Frank Nerling
Institut für Kernphysik, Univ. Mainz
on behalf of the COMPASS Collaboration

DSPIN2013, Dubna, Russia, 07th – 12th October

Outline:

- **Introduction**
  - Spin-exotic mesons – some history
  - COMPASS experiment & PWA method
- **Results on the diffractive 3π production**
  - 3π final states neutral vs. charged mode
  - PWA results on main & small waves
- **Summary & outlook**

bmb+f - Förderschwerpunkt
COMPASS
Großgeräte der physikalischen Grundlagenforschung

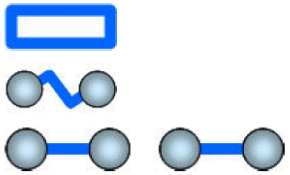
Mesons and Spin Exotic States

Constituent quark model

- color neutral $q\bar{q}$ systems
- quantum numbers $I^G J^{PC}$
- $P = (-1)^{L+1}$ $C = (-1)^{L+S}$ $G = (-1)^{I+L+1}$
- J^{PC} *multiplets:* $0^{++}, 0^{-+}, 1^{--}, 1^{+-}, 1^{++}, 2^{++}, \ldots$
- *Forbidden:* $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$

QCD: meson states beyond

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



Hybrid candidates (1.3 - 2.2 GeV/c²):

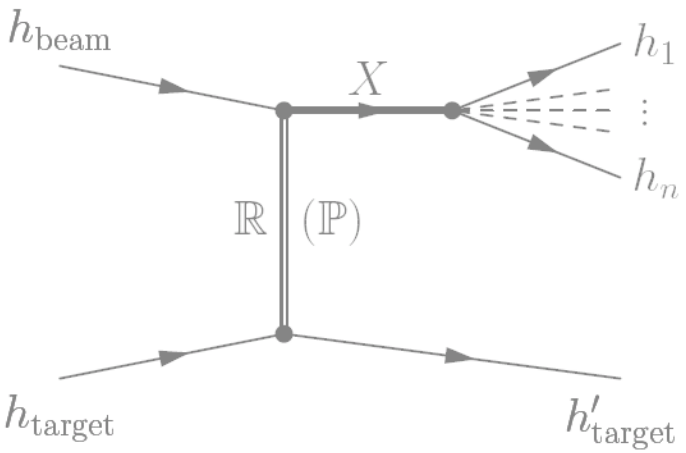
lightest hybrid predicted: exotic $J^{PC} = 1^{-+}$

- $\pi_1(1400)$: VES, E852, Crystal Barrel −> $\eta\pi$
- $\pi_1(1600)$: E852, VES −> $\rho\pi, \eta'\pi, f_1\pi, b_1\pi$
- $\pi_1(2000)$: E852 −> $f_1(1285)\pi$, $b_1(1235)\pi$

.... still controversial → COMPASS

Diffractive scattering

- study of J^{PC} exotic mesons
- t-channel Reggeon exchange
- forward kinematics, target stays intact
- small momentum transfer



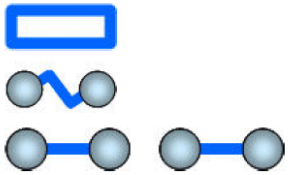
Mesons and Spin Exotic States

Constituent quark model

- color neutral $q\bar{q}$ systems
- quantum numbers $I^G J^{PC}$
- $P = (-1)^{L+1}$ $C = (-1)^{L+S}$ $G = (-1)^{I+L+1}$
- J^{PC} *multiplets:* $0^{++}, 0^{-+}, 1^{--}, 1^{+-}, 1^{++}, 2^{++}, \ldots$
- *Forbidden:* $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$

QCD: meson states beyond

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



Hybrid candidates (1.3 - 2.2 GeV/c²):

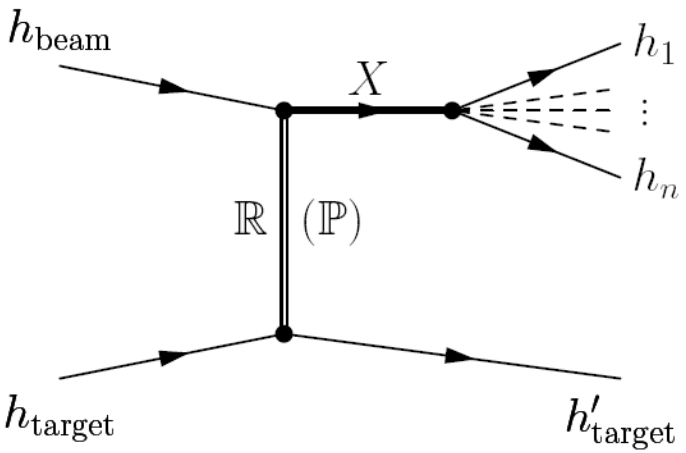
lightest hybrid predicted: exotic $J^{PC} = 1^{-+}$

- $\pi_1(1400)$: VES, E852, Crystal Barrel –> $\eta\pi$
- $\pi_1(1600)$: E852, VES –> $\rho\pi, \eta`\pi, f_1\pi, b_1\pi$
- $\pi_1(2000)$: E852 –> $f_1(1285)\pi$, $b_1(1235)\pi$

…. still controversial → COMPASS

Diffractive scattering

- study of J^{PC} exotic mesons
- t-channel Reggeon exchange
- forward kinematics, target stays intact
- small momentum transfer



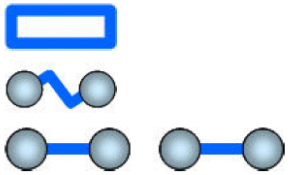
Mesons and Spin Exotic States

Constituent quark model

- color neutral $q\bar{q}$ systems
- quantum numbers $I^G J^{PC}$
- $P = (-1)^{L+1}$ $C = (-1)^{L+S}$ $G = (-1)^{I+L+1}$
- J^{PC} *multiplets:* $0^{++}, 0^{-+}, 1^{--}, 1^{+-}, 1^{++}, 2^{++}, \ldots$
- *Forbidden:* $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$

QCD: meson states beyond

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



Hybrid candidates (1.3 - 2.2 GeV/c²):

lightest hybrid predicted: exotic $J^{PC} = 1^{-+}$

- $\pi_1(1400)$: VES, E852, Crystal Barrel –> $\eta\pi$
- $\pi_1(1600)$: E852, VES –> $\rho\pi, \eta'\pi, f_1\pi, b_1\pi$
- $\pi_1(2000)$: E852 –> $f_1(1285)\pi, b_1(1235)\pi$

…. still controversial → COMPASS

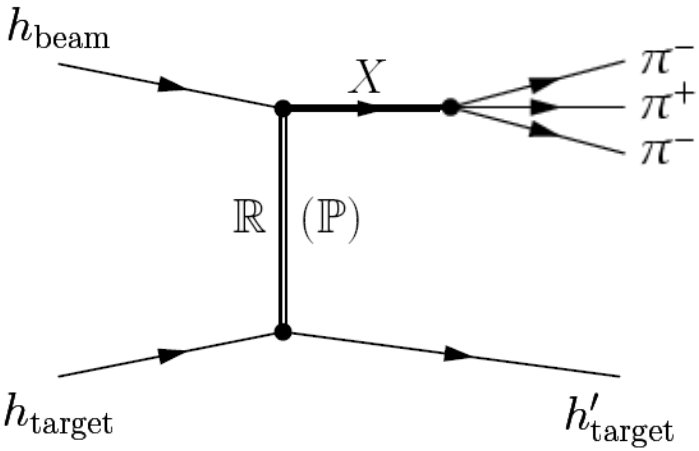
COMPASS (2004 pilot run)

- 190 GeV π^- beam *(Pb target)*
- studied $\rho\pi$ decay channel via

  π^- Pb –> $\pi^-\pi^+\pi^-$ Pb

Diffractive pion dissociation

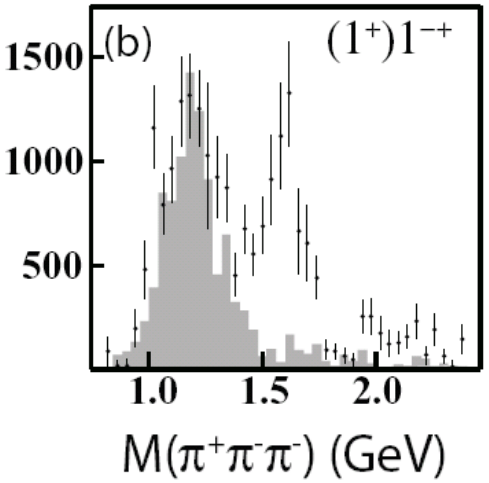
- incoming π^- excited to resonance ***X***$^-$
- ***X***$^-$ decays into final state, e.g. $(3\pi)^-$:



The $\pi_1(1600)$ in the 1^{-+} partial-wave
controversy -- some history

$\pi_1(1600)$: E852, VES –> $\rho\pi$, $\eta'\pi$, $f_1\pi$, $b_1\pi$
…. still controversial → **COMPASS**

BNL/E852:
- 250k events (charged), 18 GeV/c, 21 waves

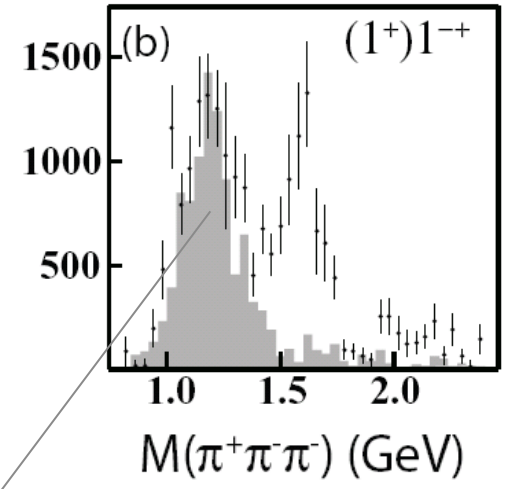


[G.S. Adams et al., E852, PRL 81, 5760 (1998)]

The $\pi_1(1600)$ in the 1^{-+} partial-wave
controversy -- some history

$\pi_1(1600)$: E852, VES –> $\rho\pi$, $\eta'\pi$, $f_1\pi$, $b_1\pi$
…. still controversial → **COMPASS**

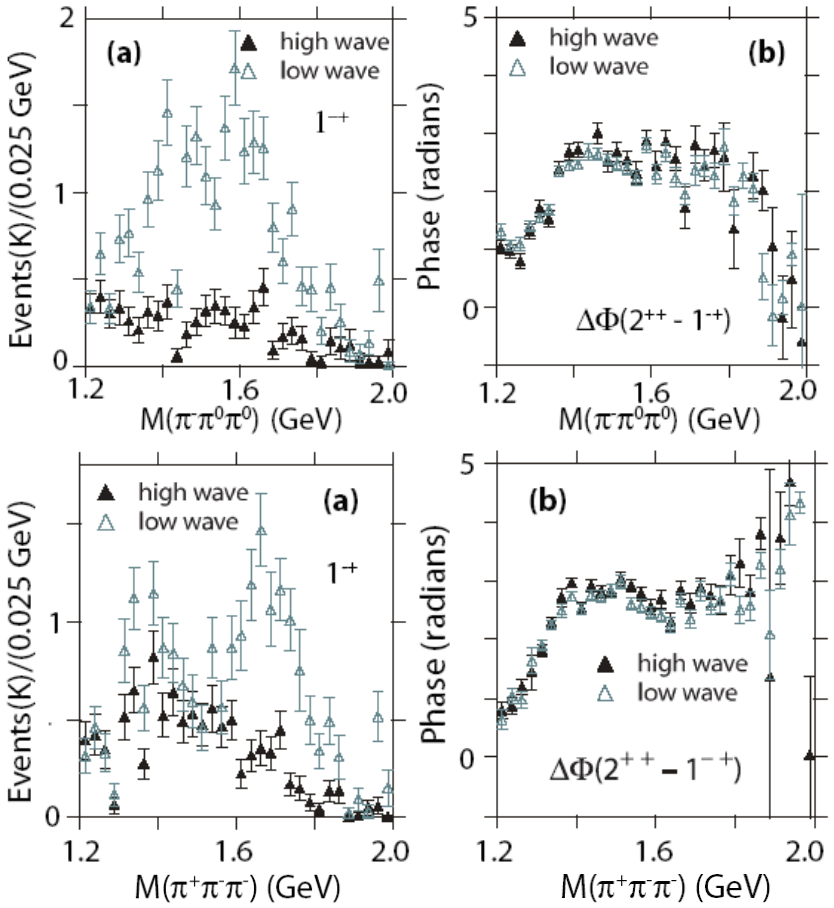
BNL/E852:
- 250k events (charged), 18 GeV/c, 21 waves



validated to be leakage from $a_2(1320)$

[G.S. Adams et al., E852, PRL 81, 5760 (1998)]

E852-IU re-analysis:
- higher statistics: 3M & 2.6M (neutral & charged)
- extended wave-set (35 waves) => 1^{-+} object vanished

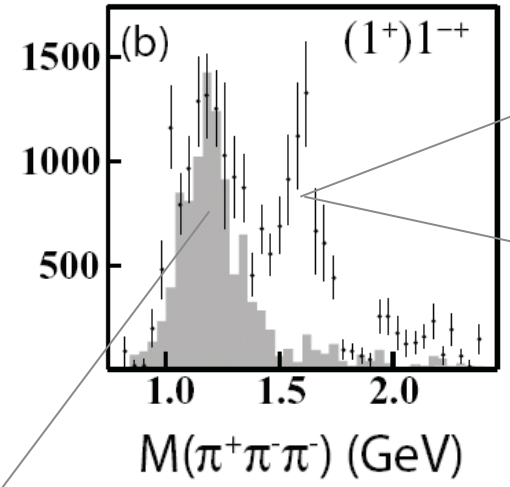


[A.R. Dzierba et al., E852-IU, PRD 73, 072001 (2006)]

The $\pi_1(1600)$ in the 1^{-+} partial-wave
controversy -- some history

$\pi_1(1600)$: E852, VES –> $\rho\pi$, $\eta'\pi$, $f_1\pi$, $b_1\pi$
…. still controversial → **COMPASS**

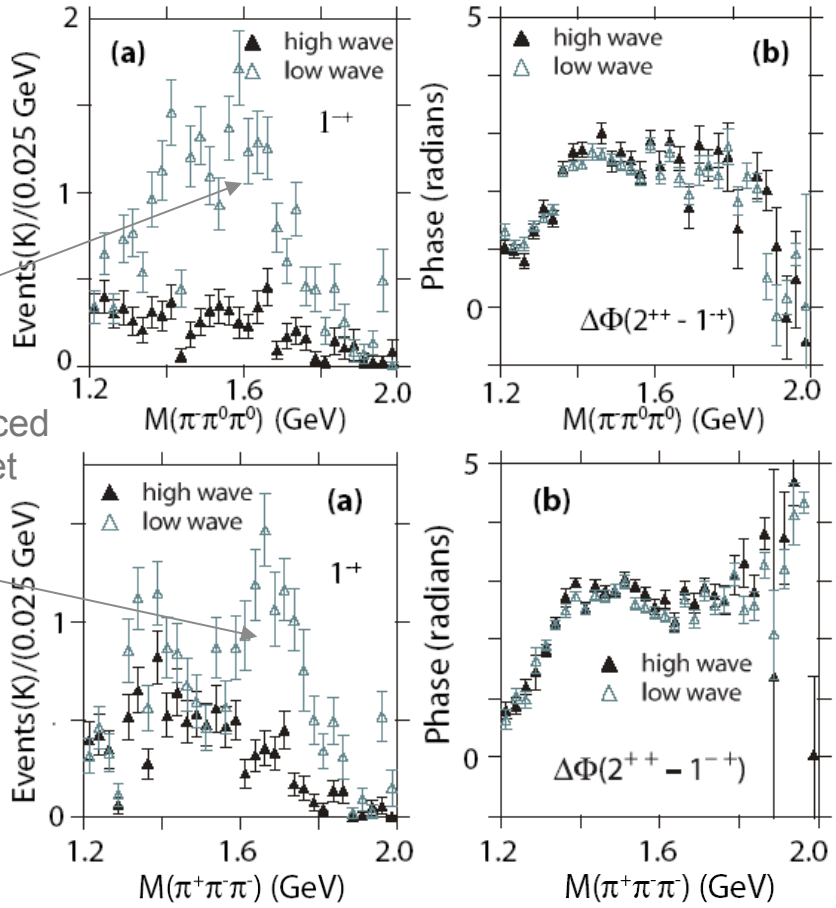
BNL/E852:
- 250k events (charged), 18 GeV/c, 21 waves



validated to be leakage from $a_2(1320)$

1^{-+} object reproduced using low wave-set

E852-IU re-analysis:
- higher statistics: 3M & 2.6M (neutral & charged)
- extended wave-set (35 waves) => 1^{-+} object vanished

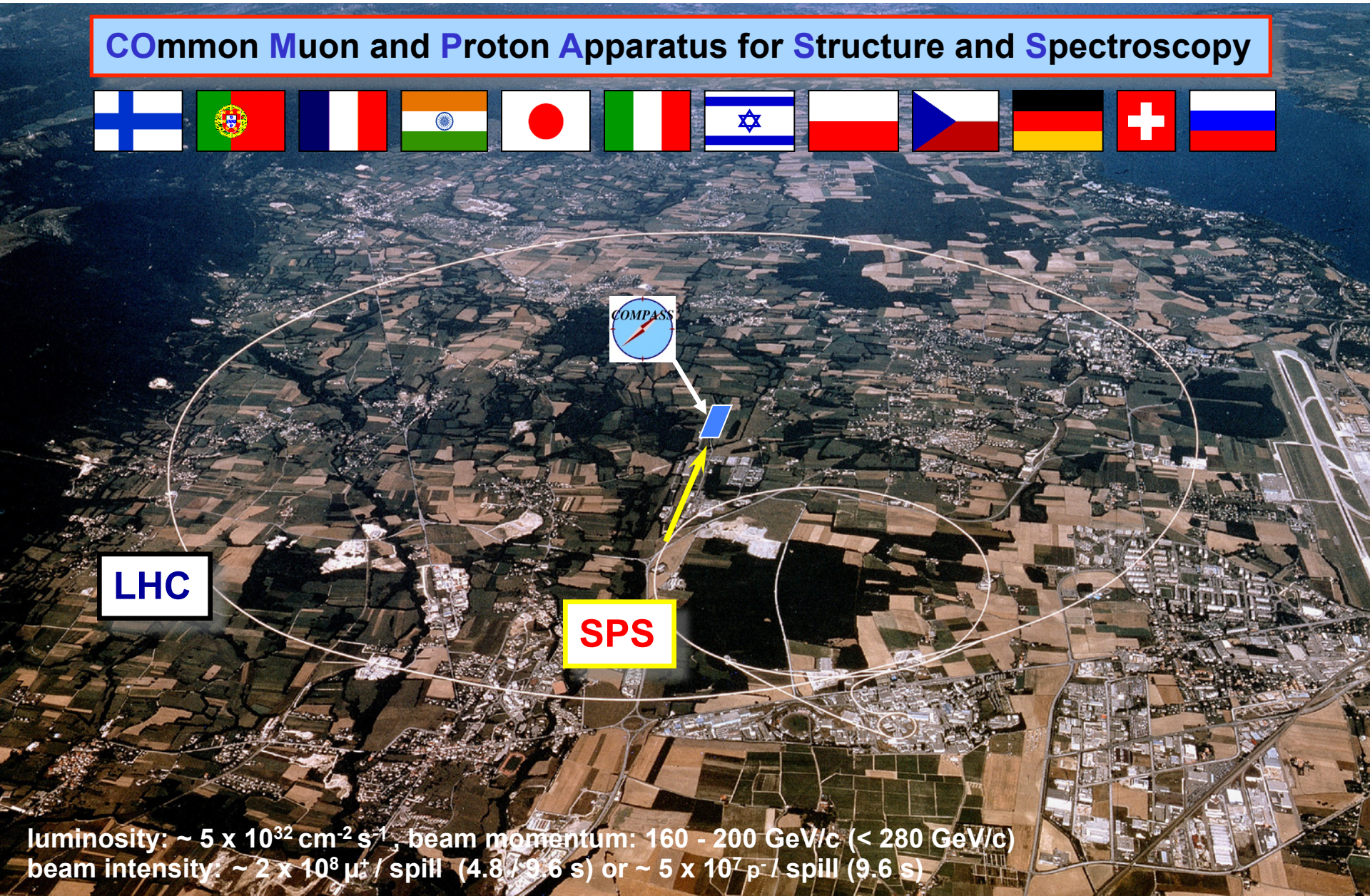


[G.S. Adams et al., E852, PRL 81, 5760 (1998)]

[A.R. Dzierba et al., E852-IU, PRD 73, 072001 (2006)]

The COMPASS Experiment at CERN

COmmon Muon and Proton Apparatus for Structure and Spectroscopy



luminosity: ~ 5 x 10^{32} cm^{-2} s^{-1} , beam momentum: 160 - 200 GeV/c (< 280 GeV/c)
beam intensity: ~ 2 x 10^{8} μ^{+} / spill (4.8 / 9.6 s) or ~ 5 x 10^{7} p^{-} / spill (9.6 s)

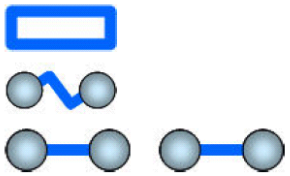
Mesons and Spin Exotic States

Constituent quark model

- color neutral $q\bar{q}$ systems
- Quantum numbers $I^G J^{PC}$
- $P = (-1)^{L+1}$ $C = (-1)^{L+S}$ $G = (-1)^{I+L+1}$
- J^{PC} *multiplets:* $0^{++}, 0^{-+}, 1^{--}, 1^{+-}, 1^{++}, 2^{++}, \ldots$
- *Forbidden:* $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$

QCD: meson states beyond

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



Hybrid candidates (1.3 - 2.2 GeV/c²):

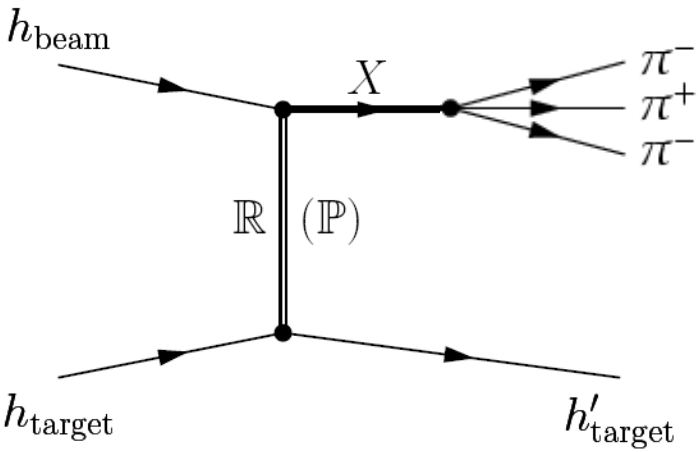
lightest hybrid predicted: exotic $J^{PC} = 1^{-+}$

- $\pi_1(1400)$: VES, E852, Crystal Barrel –> $\eta\pi$
- $\pi_1(1600)$: E852, VES –> $\rho\pi, \eta'\pi, f_1\pi, b_1\pi$
- $\pi_1(2000)$: E852 –> $f_1(1285)\pi, b_1(1235)\pi$

…. still controversial → COMPASS

Diffractive pion dissociation

- incoming π^- excited to resonance ***X***$^-$
- ***X***$^-$ decays into final state, e.g. $(3\pi)^-$:



COMPASS (2004 pilot run)

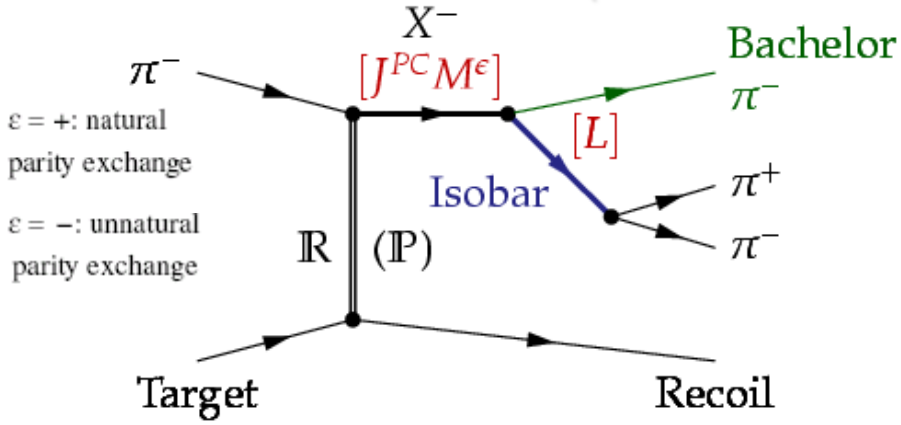
- 190 GeV π^- beam *(Pb target)*
- studied $\rho\pi$ decay channel via

  $\pi^- Pb \rightarrow \pi^-\pi^+\pi^- Pb$

=> confirmation of a 1^{-+} resonance at 1.66 GeV

[PRL 104 (2010) 241803]

COMPASS PWA method
(meanwhile extended, cf. later)



X^- decay described using isobar model:

- Intermediate di-pion resonance (isobar)
  - *Spin S and rel. orbital angular momentum L w.r.t bachelor π^-*
  - *L+S couple to J*
- Partial waves (reflectivity basis): $J^{PC}\, M^{\varepsilon}\, [\text{isobar}]\, L$

Partial wave analysis:

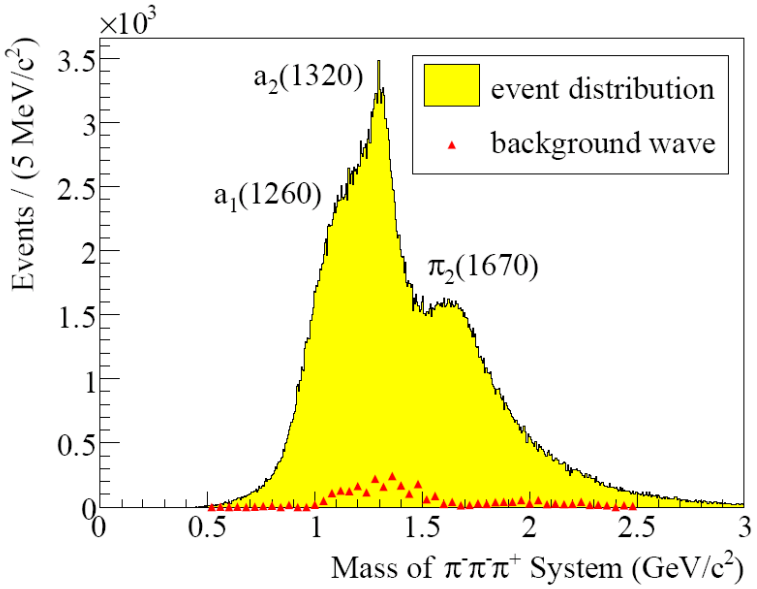
- **Isobars:** All possible, needed isobars
- **Acceptance:** corrections included (normalisation integrals)

Step 1) Mass independent PWA (loglikelihood fit)

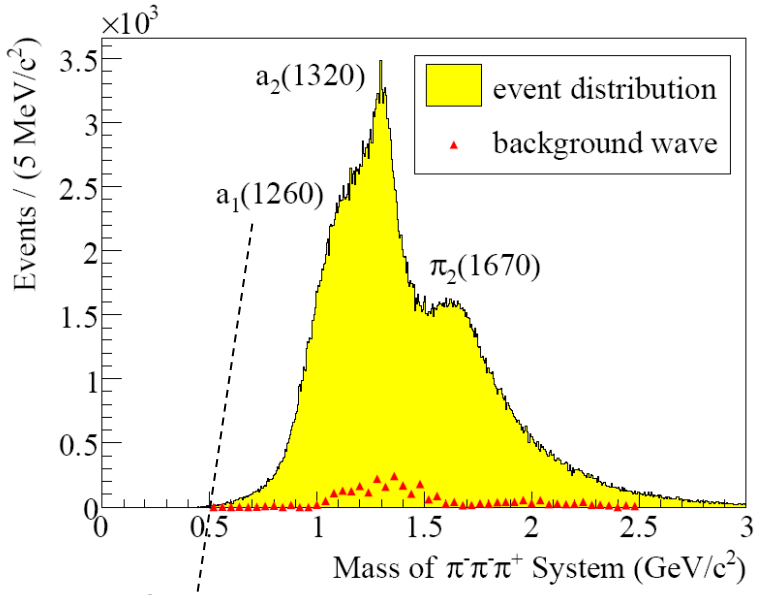
Step 2) Mass dependent χ^2 fit: (to mass independent result)

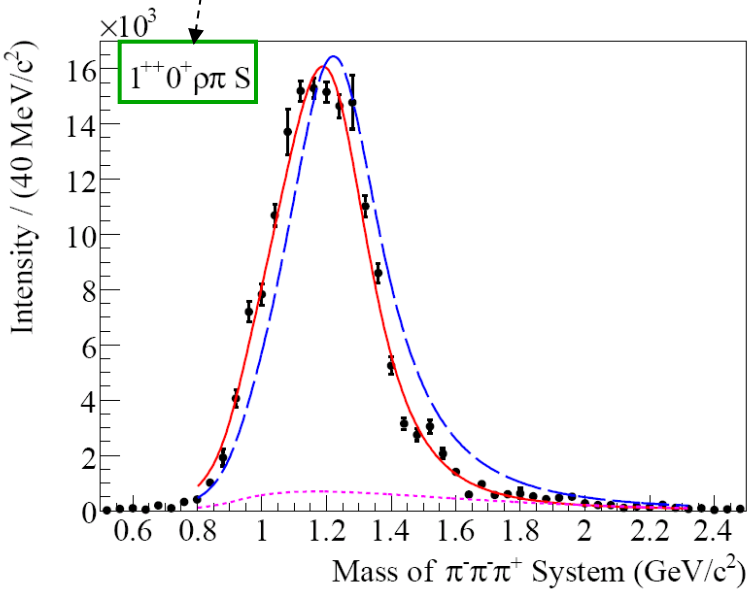
- Main partial waves chosen, parameterised by Breit-Wigner
- Non-resonant background for some waves

Diffractive dissociation into 3π final states
(2004 data, Pb target) [PRL 104 (2010) 241803]

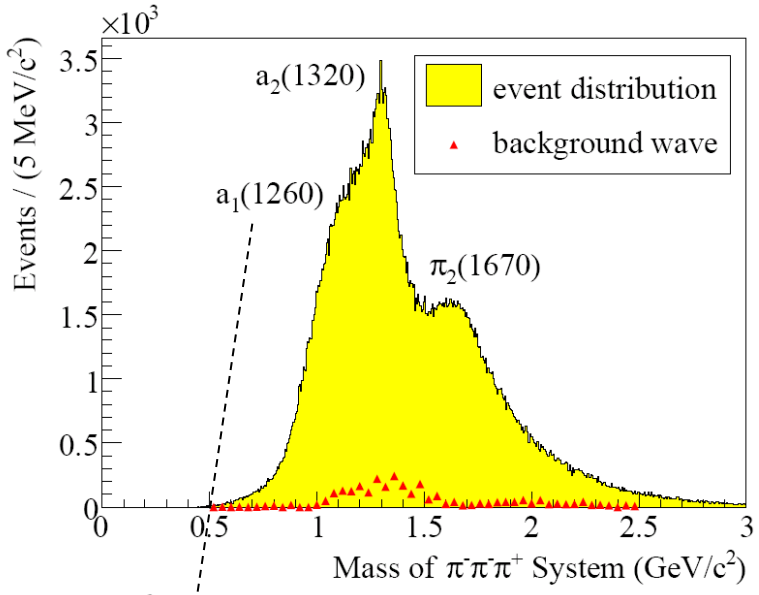


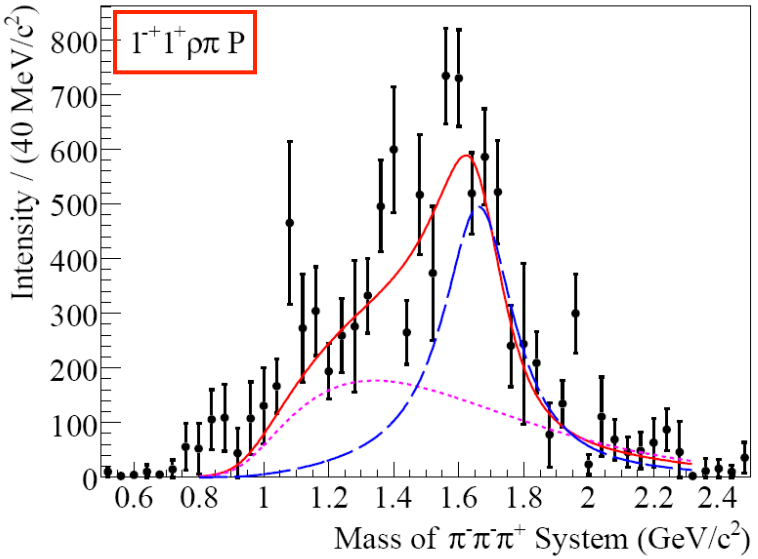
Diffractive dissociation into 3π final states
(2004 data, Pb target) [PRL 104 (2010) 241803]

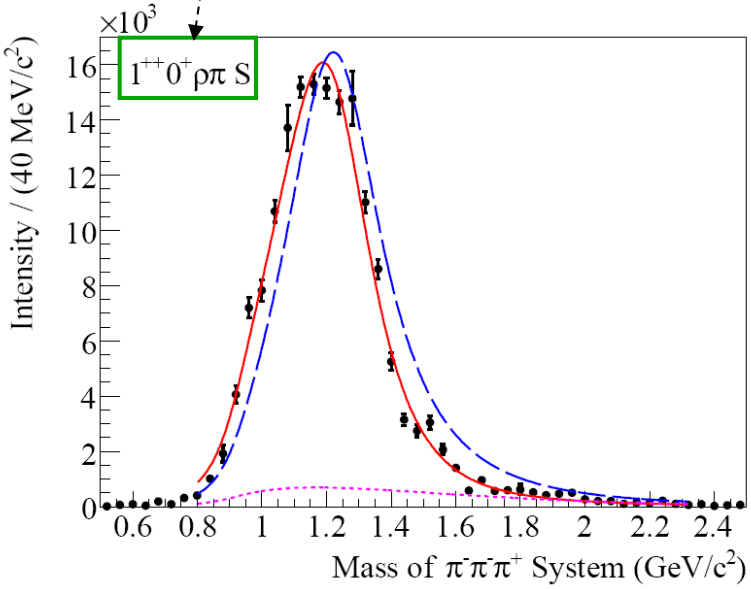




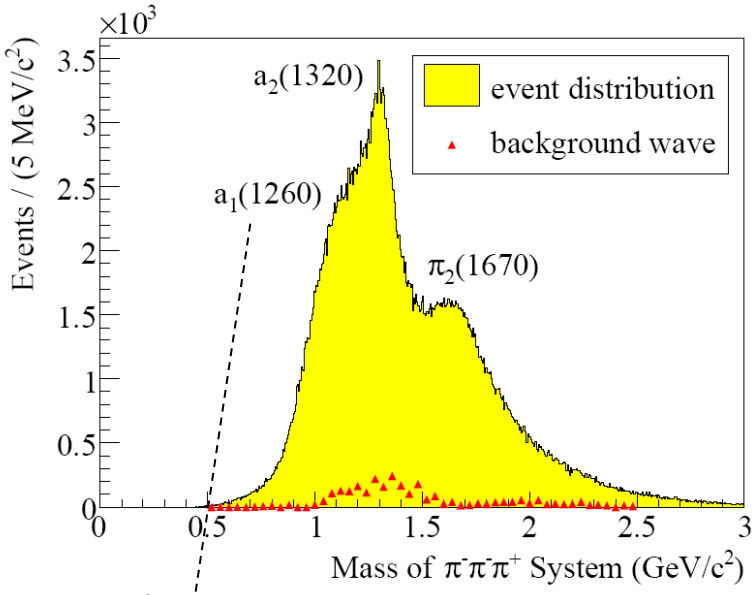
Diffractive dissociation into 3π final states
(2004 data, Pb target) [PRL 104 (2010) 241803]

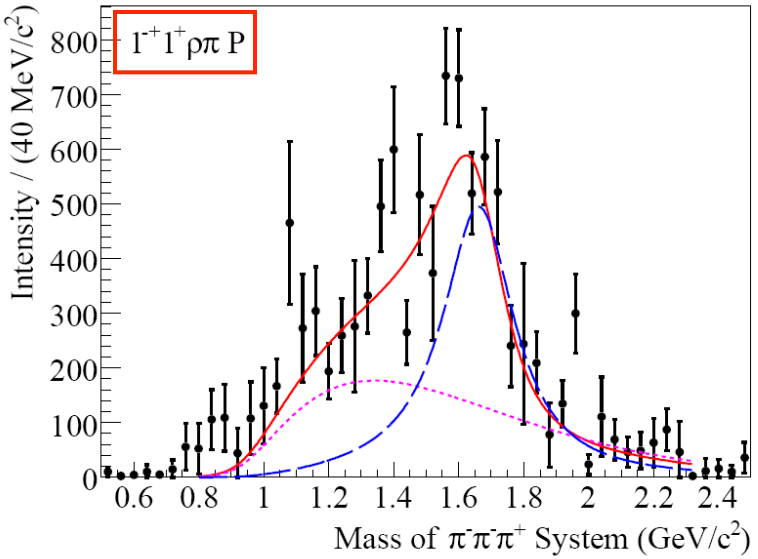


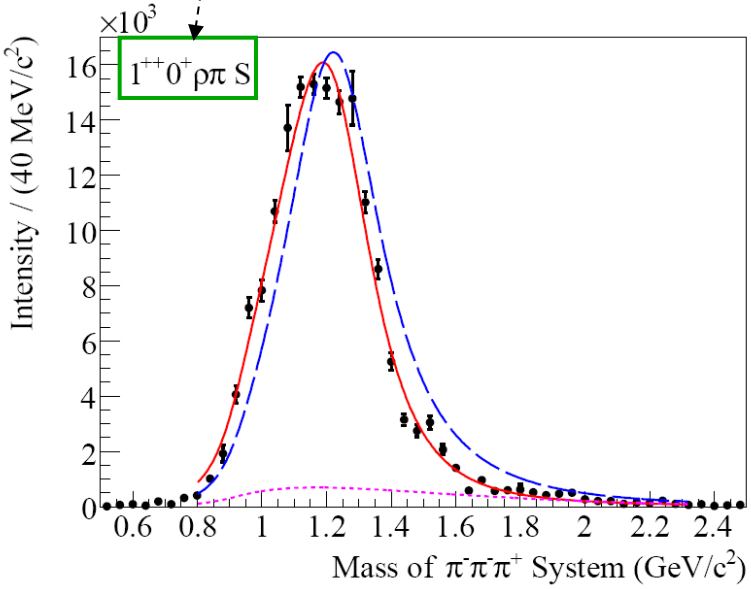


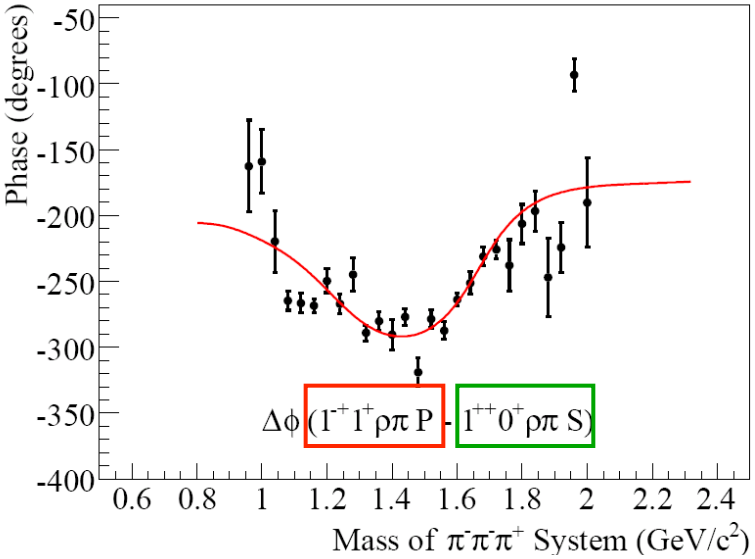


Diffractive dissociation into 3π final states
(2004 data, Pb target) [PRL 104 (2010) 241803]



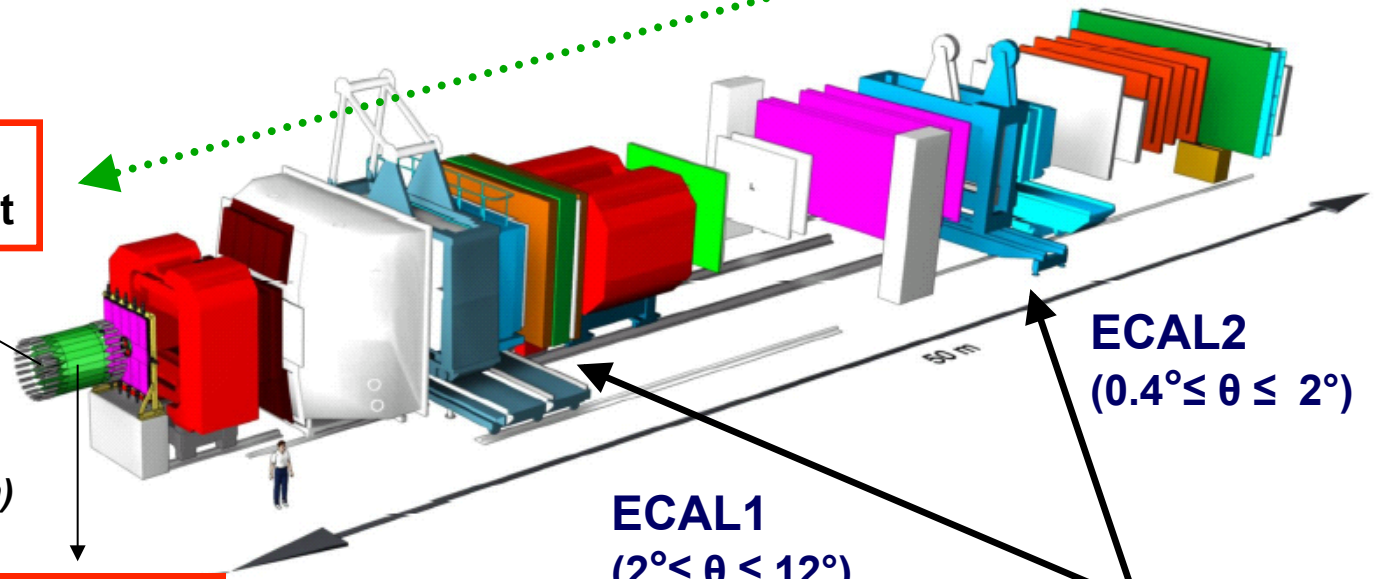






COMPASS spectrometer: Hadron setup
(2008/09) -- main changes w.r.t. muon setup

All COMPASS trackers (upgraded close to beam):
SciFi, Si, MM, GEM, DC, Straw, MWPC



0.4m
liquid H_2 target

Beam

(muon or hadron)

Recoil detector (RPD)
to trigger on reactions
inside target

ECAL2
($0.4° \leq \theta \leq 2°$)

ECAL1
($2° \leq \theta \leq 12°$)

Electromagnetic calorimeters

PID using
RICH & CEDARs

(final states involving neutrals,
e.g. π^0, η, or η')

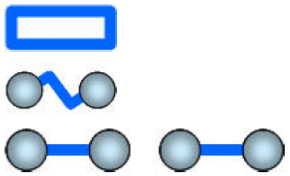
Mesons and Spin Exotic States

Constituent quark model

- color neutral $q\bar{q}$ systems
- quantum numbers $I^G J^{PC}$
- $P = (-1)^{L+1}$ $C = (-1)^{L+S}$ $G = (-1)^{I+L+1}$
- J^{PC} *multiplets:* $0^{++}, 0^{-+}, 1^{--}, 1^{+-}, 1^{++}, 2^{++}, \ldots$
- *Forbidden:* $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$

QCD: meson states beyond

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



Hybrid candidates (1.3 - 2.2 GeV/c²):

lightest hybrid predicted: exotic $J^{PC} = 1^{-+}$

- $\pi_1(1400)$: VES, E852, Crystal Barrel –> $\eta\pi$
- $\pi_1(1600)$: E852, VES –> $\rho\pi, \eta'\pi, f_1\pi, b_1\pi$
- $\pi_1(2000)$: E852 –> $f_1(1285)\pi, b_1(1235)\pi$

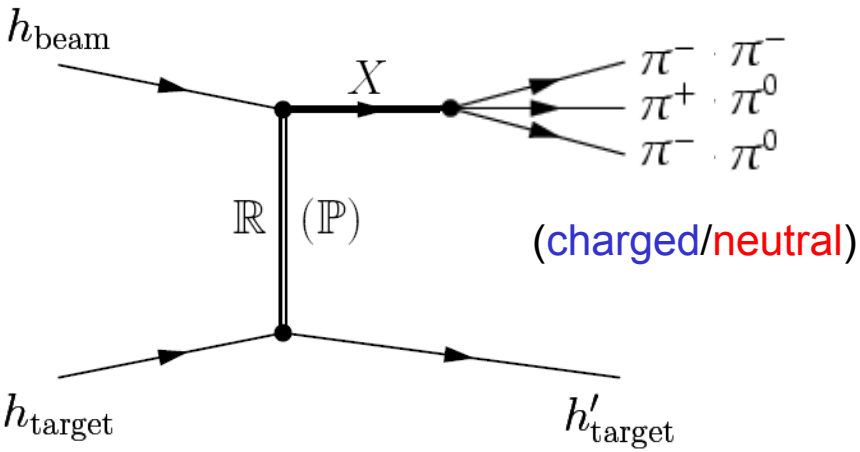
…. still controversial → COMPASS

COMPASS (2008/09 data)

- 190 GeV π^- beam *(proton target)*
- study of $\rho\pi$ decay channel via:
  - a) $\pi^- p \rightarrow \pi^-\pi^+\pi^- p$ (charged mode)
  - b) $\pi^- p \rightarrow \pi^-\pi^0\pi^0 p$ (neutral mode)

Diffractive pion dissociation

- incoming π^- excited to resonance X^-
- X^- decays into final state, e.g. $(3\pi)^-$:

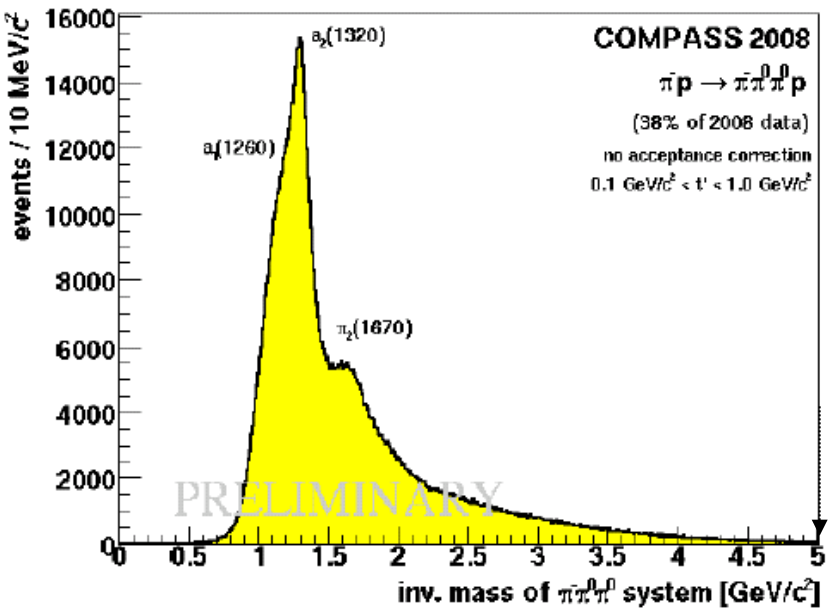


(charged/neutral)

Diffractive dissociation into 3π final states
(2008 data, proton target)

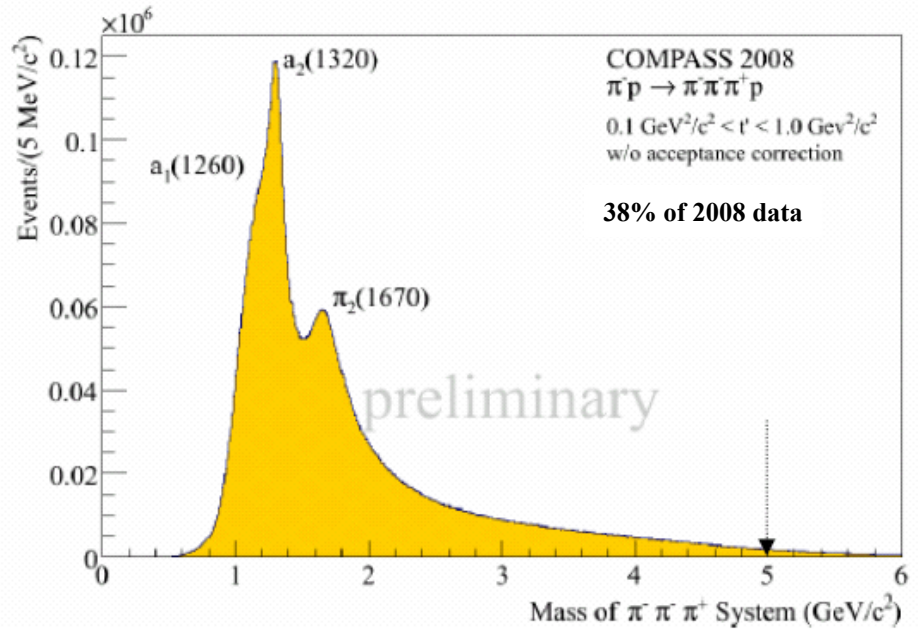
search for $\pi_1(1600)$

Mass of outgoing 3π system – neutral mode: $\pi^- p \rightarrow \pi^-\pi^0\pi^0 p$



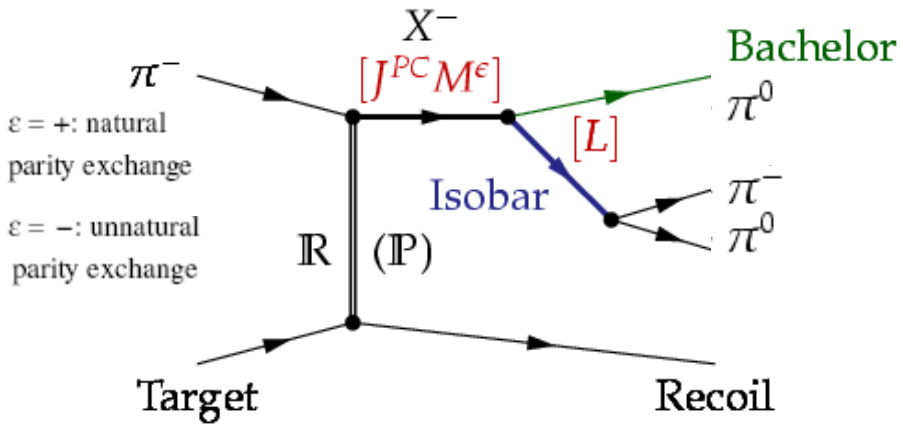
PWA: ~ 1M events

Mass of outgoing 3π system – charged mode: $\pi^- p \rightarrow \pi^-\pi^+\pi^- p$



PWA: ~ 24M events

PWA using isobar model



X^- decay described using isobar model:

- Intermediate di-pion resonance (isobar)
  - *Spin S and rel. orbital angular momentum L w.r.t bachelor π^-*
  - *L+S couple to J*
- Partial waves (reflectivity basis): $J^{PC}\, M^{\varepsilon}\, [\text{isobar}]\, L$

Partial wave analysis:

- **Program:** Illinois/Protvino/Munich (D.Ryabchikov) software (IHEP/VES, TUM/COMPASS)
- **Isobars:** *$(\pi\pi)_S$ [broad $f_0(600)$+$f_0(1370)$], $f_0(980)$, $\rho(770)$, $f_2(1270)$, $\rho_3(1690)$*
- **Acceptance:** corrections included (via normalisation integrals)

Step 1) Mass independent PWA: (40MeV/c² bins, 53 partial waves) **= following results**

Step 2) Mass dependent c^2 fit: (to mass independent result)

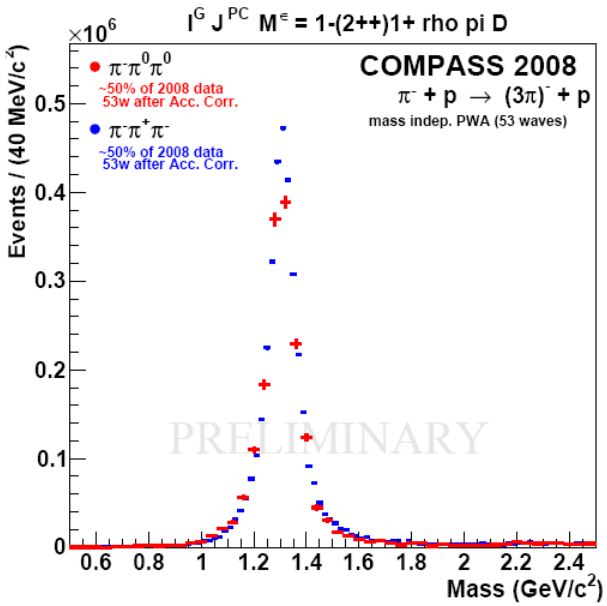
- Main partial waves chosen, parameterised by Breit-Wigner
- Coherent background for some waves

Comparison: Neutral vs. charged mode

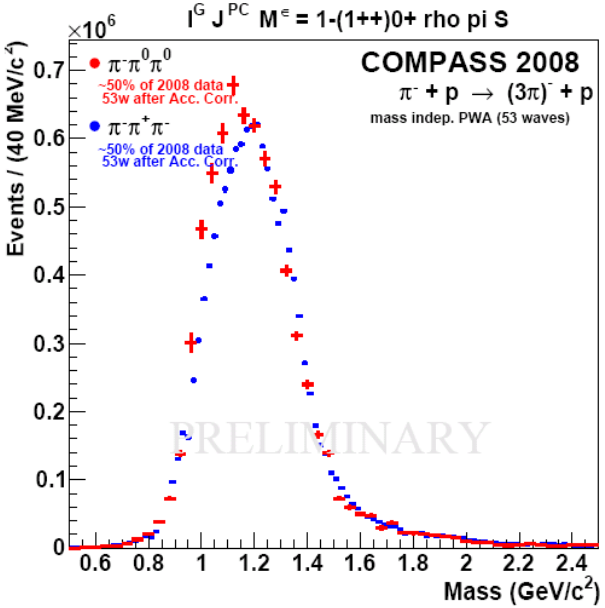
The 3 prominent resonances -- Consistency of isospin partners (Acceptance Corrections applied)

search for $\pi_1(1600)$

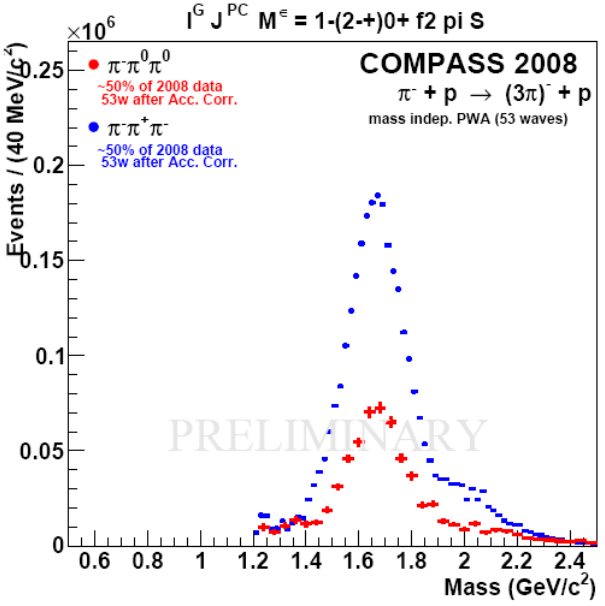
$a_2(1320) \rightarrow \rho\pi$



$a_1(1260) \rightarrow \rho\pi$



$\pi_2(1670) \rightarrow f_2\pi$



Isospin symmetry: neutral / charge mode

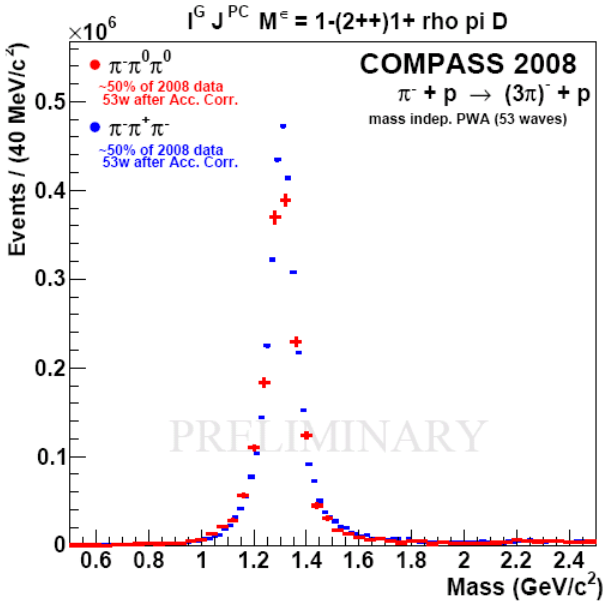
- X^- decaying into $\rho\pi$: 1/1 intensity expected *(isovector)*
- X^- decaying into $f_2\pi$: 1/2 intensity expected *(isoscalar)*

Comparison: Neutral vs. charged mode

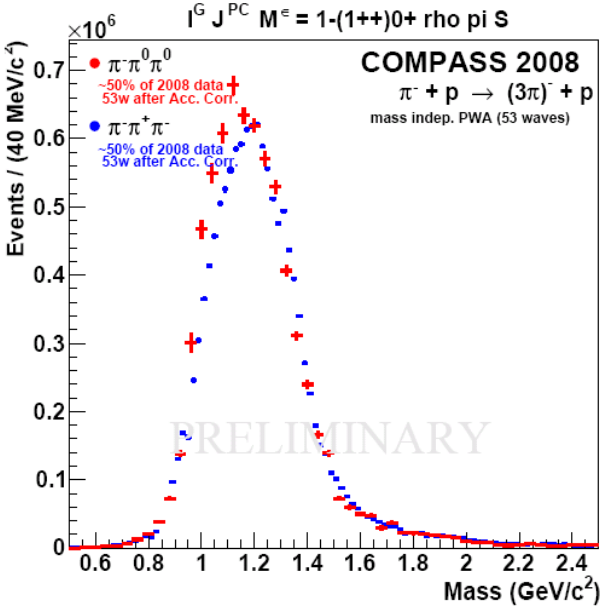
The 3 prominent resonances -- Consistency of isospin partners (Acceptance Corrections applied)

search for $\pi_1(1600)$

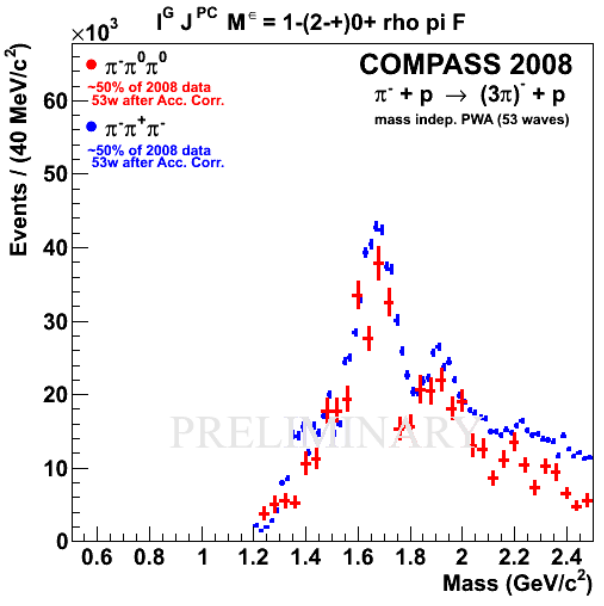
$a_2(1320) \rightarrow \rho\pi$



$a_1(1260) \rightarrow \rho\pi$



$\pi_2(1670) \rightarrow \rho\pi$

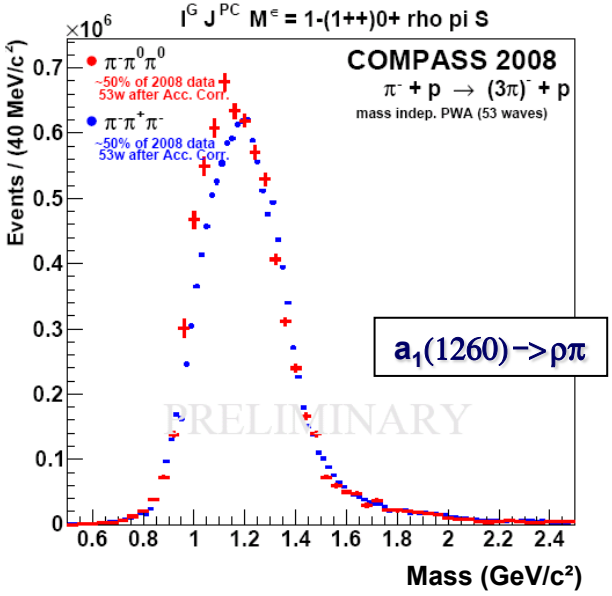


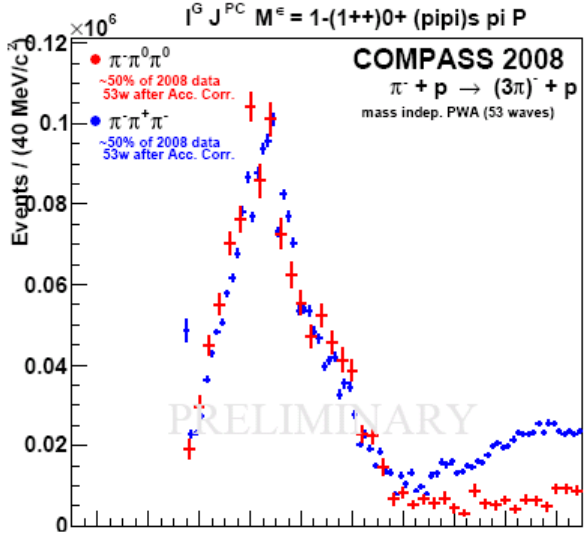
Isospin symmetry: neutral / charge mode

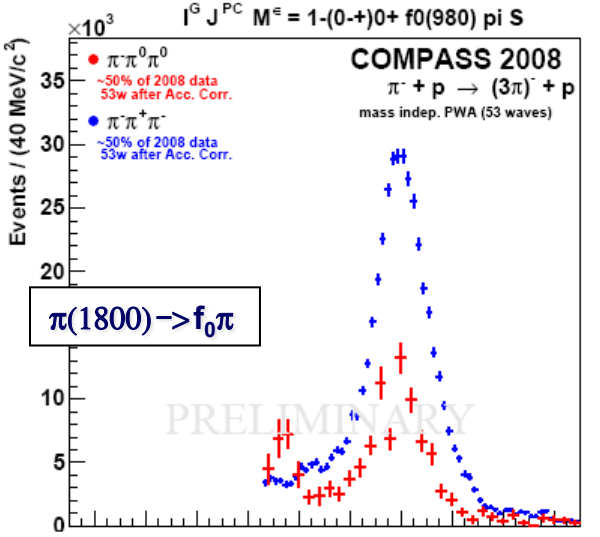
- X^- decaying into $\rho\pi$: 1/1 intensity expected *(isovector)*
- X^- decaying into $f_2\pi$: 1/2 intensity expected *(isoscalar)*

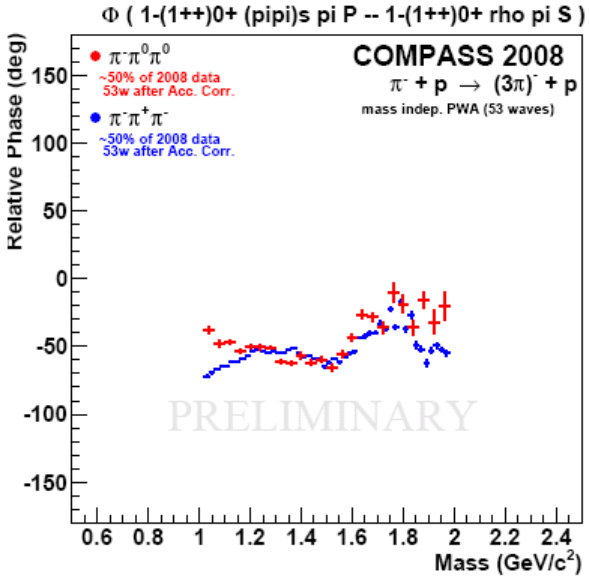
Selected partial waves & phases

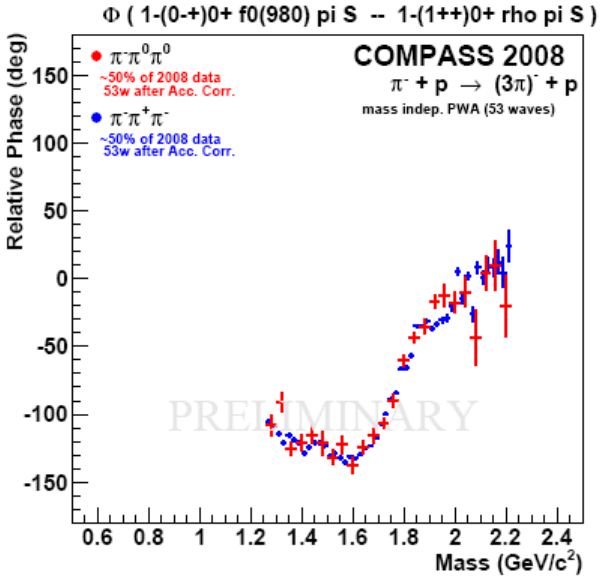
3π diffractive -- Neutral vs. Charged mode: 53 waves





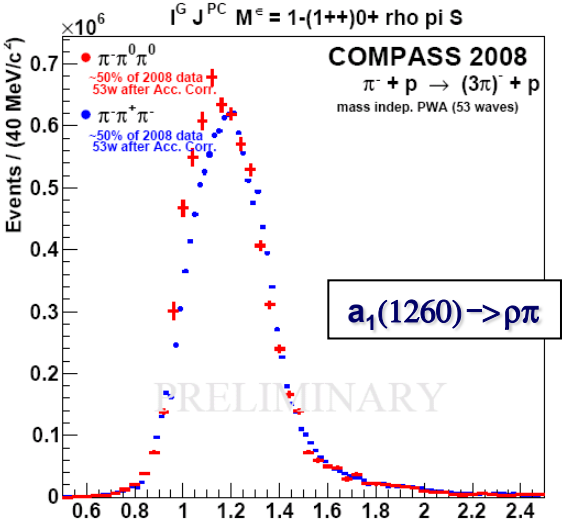


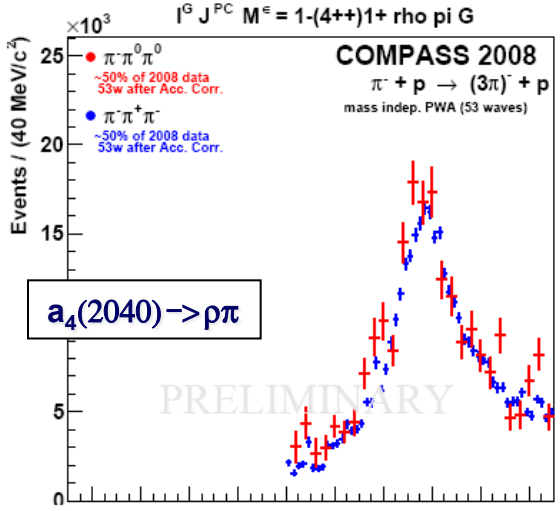


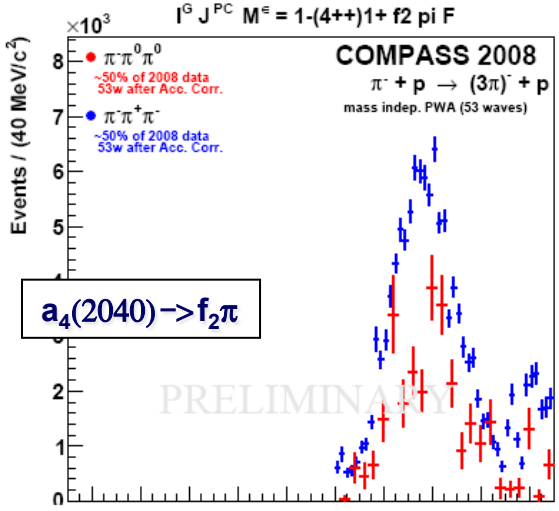


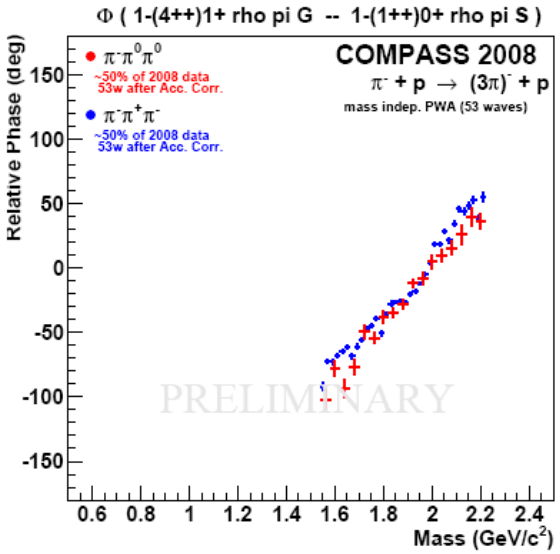
Selected partial waves & phases

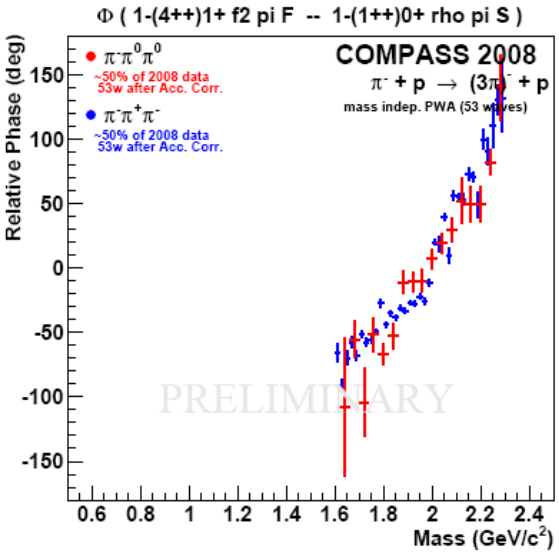
3π diffractive -- Neutral vs. Charged mode: 53 waves





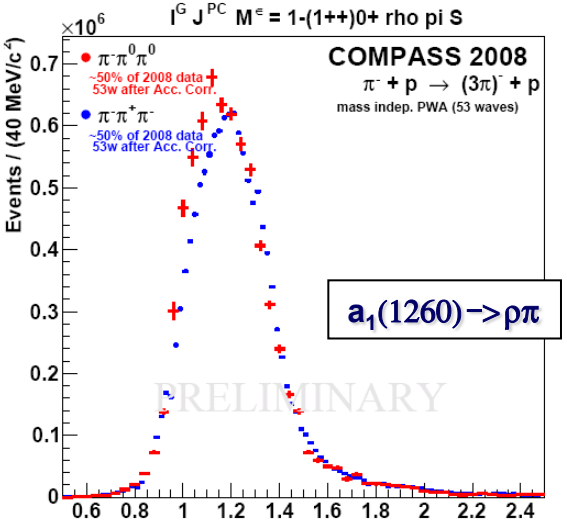


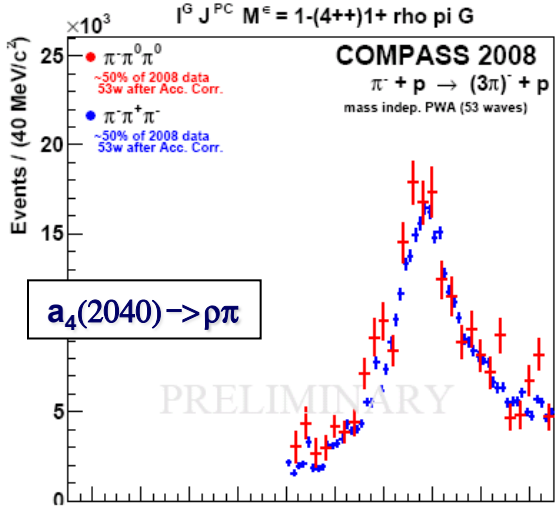


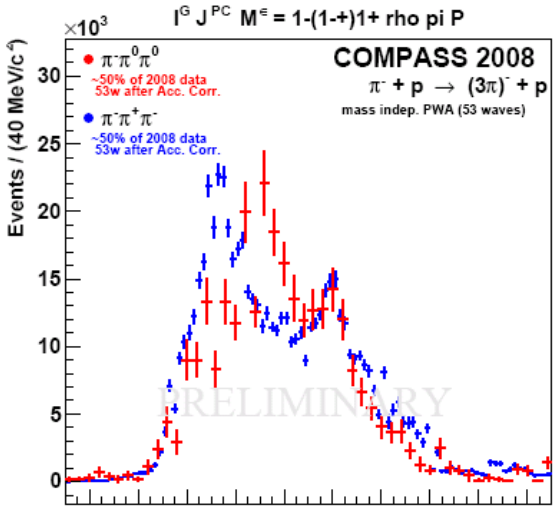


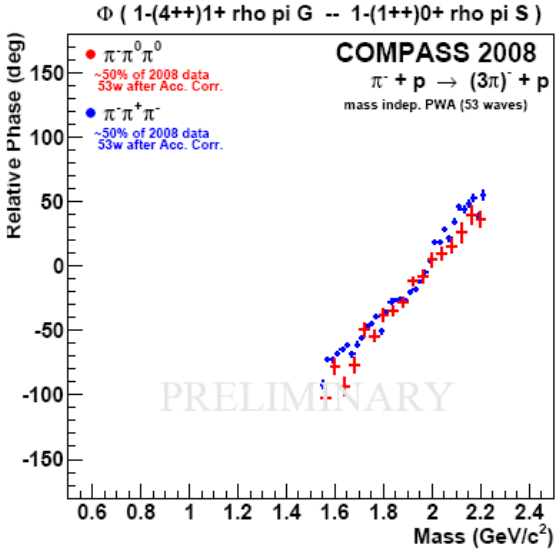
Selected partial waves & phases

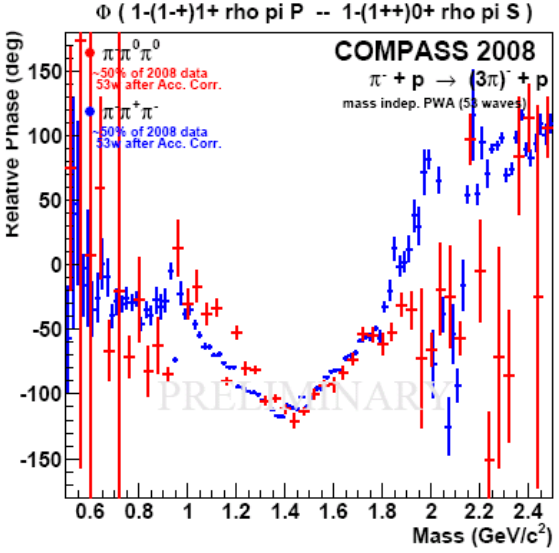
3π diffractive -- Neutral vs. Charged mode: 53 waves





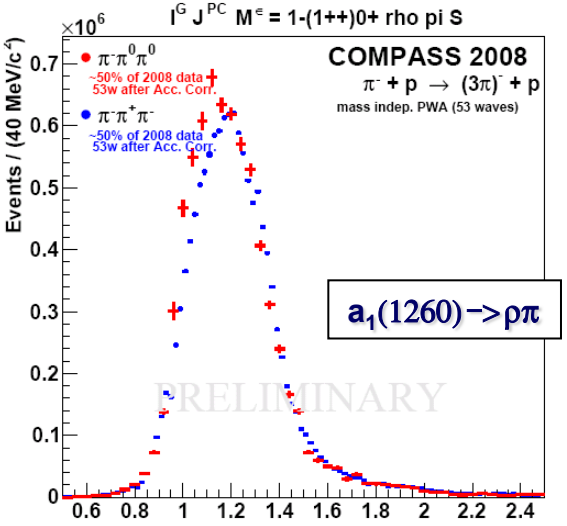


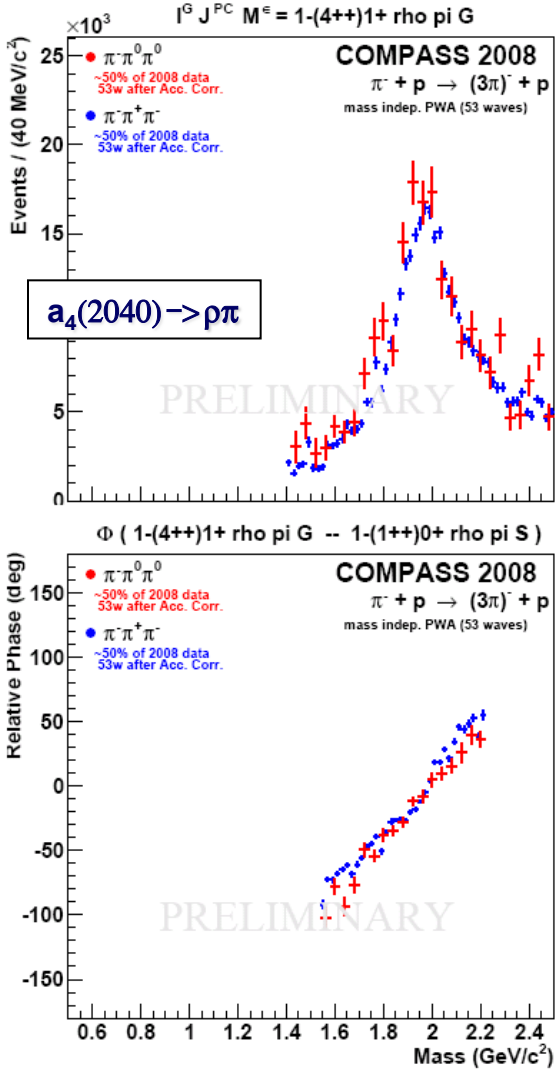


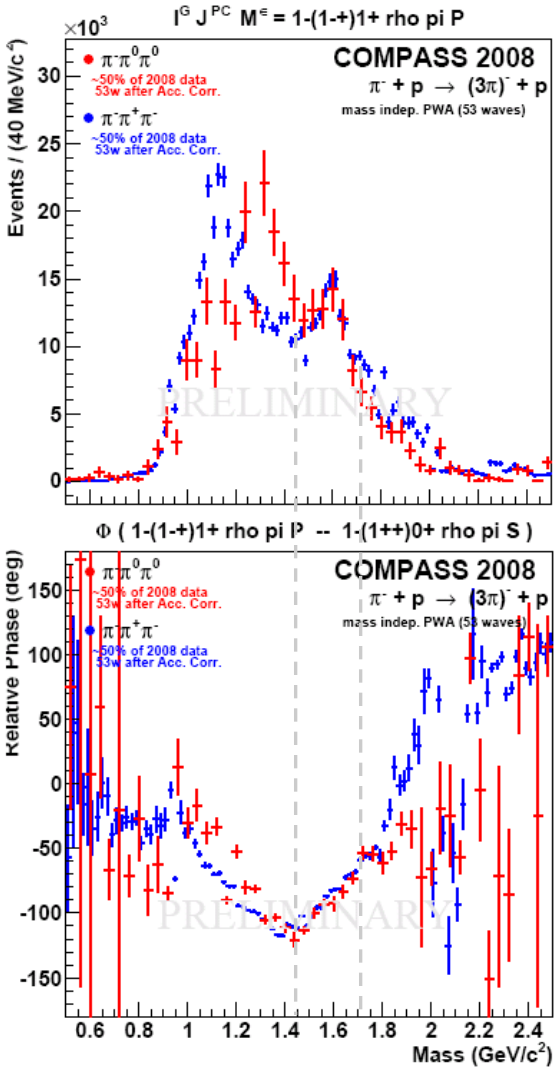


Selected partial waves & phases

3π diffractive -- Neutral vs. Charged mode: 53 waves

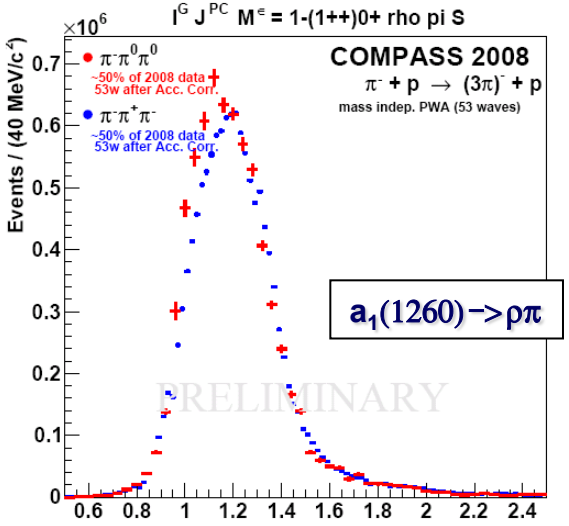


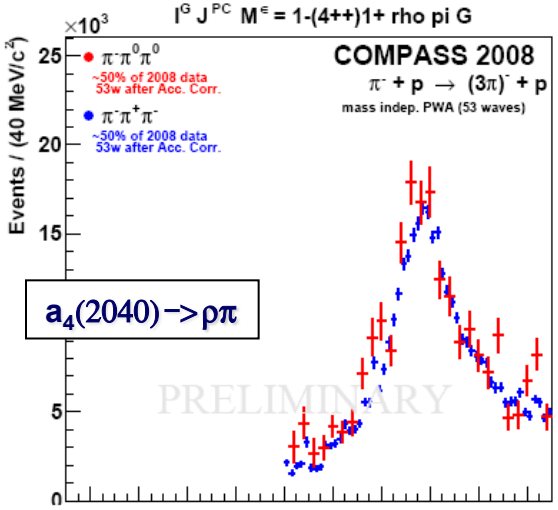


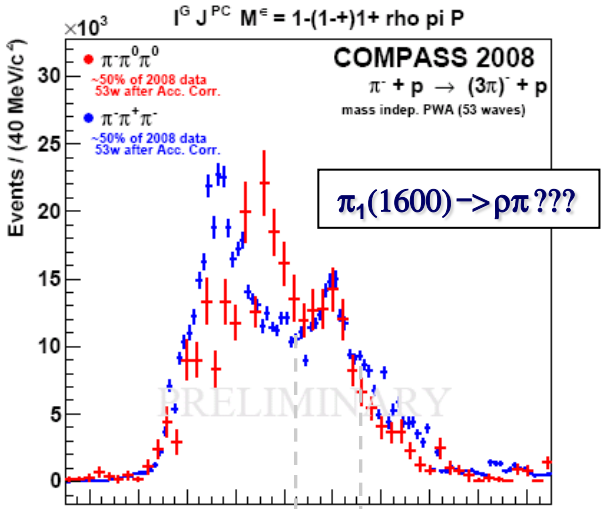


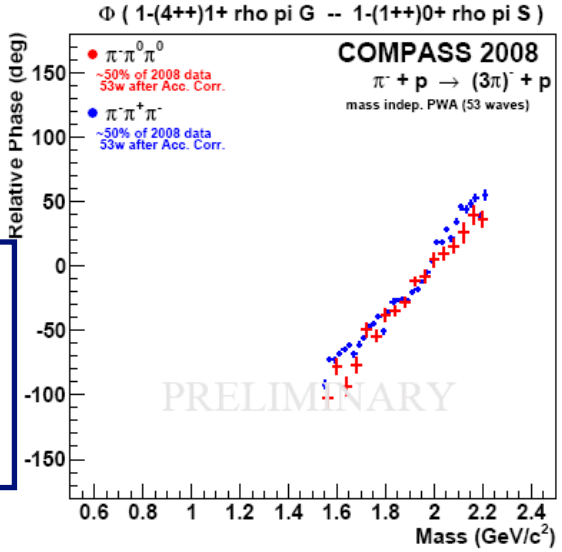
Selected partial waves & phases

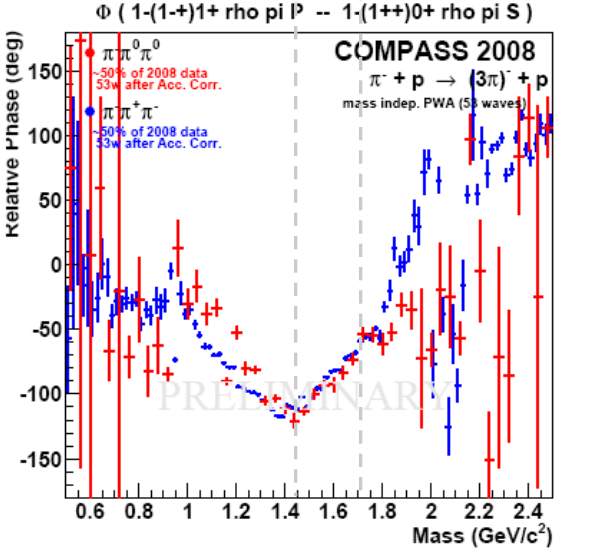
3π diffractive -- Neutral vs. Charged mode: 53 waves











$\pi_1(1600) \rightarrow \rho\pi$???

More systematic studies needed
(e.g. Non-resonant contributions, bkgrds)
and of course mass-dependent fit!
→ *new, extended PWA method,*
→ *before any strong conclusion!*

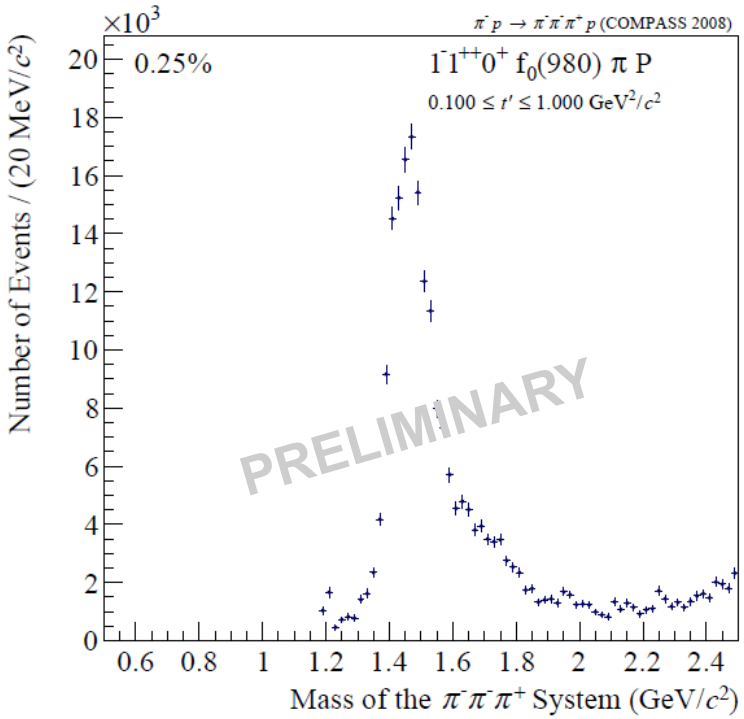
Comparison with VES data removed on request of VES

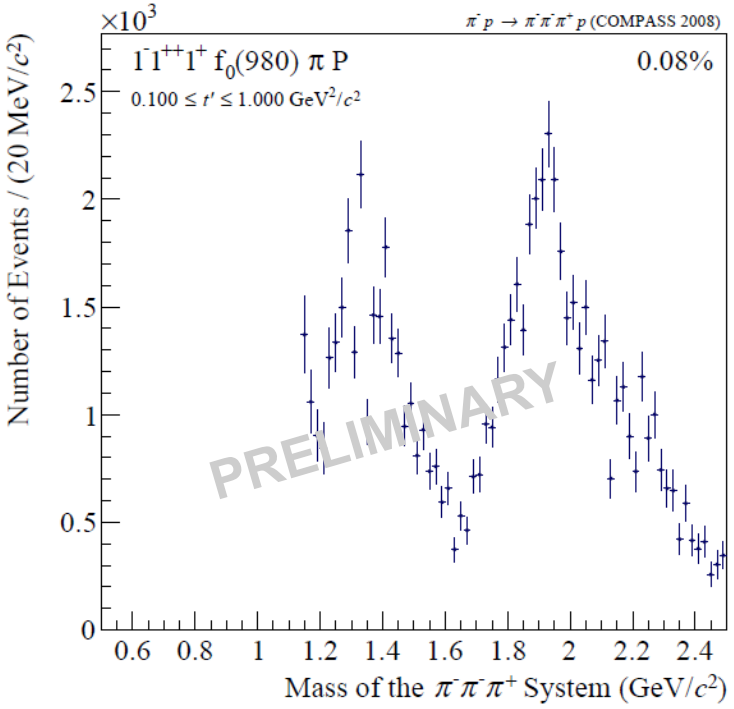
Extended PWA method -- recent finding: $a_1(1420)$

Meanwhile new, extended PWA method applied: Mass bins & ranges in t`
=> Separation of non-resonant and resonant (Pomeron) production

π^- p –> $\pi^-\pi^+\pi^-$ p, full 2008 data: Wave-set extended to 88 partial-waves,
100 bins in 3π mass & 11 slices of t`

Incoherent sum of mass-independent results in t`slices:

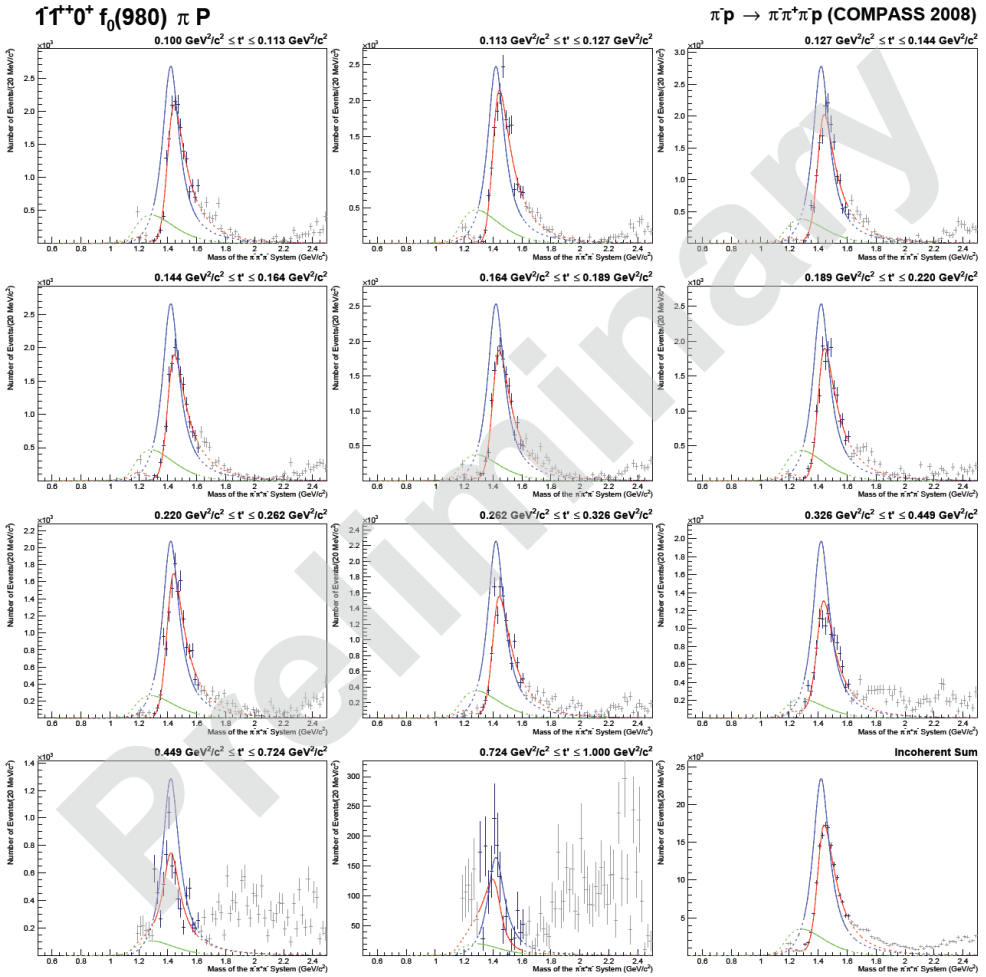




Method applied to neutral mode, incl. exotic wave → not yet released

Extended PWA method -- recent finding: $a_1(1420)$

Meanwhile new, extended PWA method applied: Mass bins & ranges in t`
=> Separation of non-resonant and resonant (Pomeron) production



Rather narrow object:
Width: ~130-150 MeV
Mass: ~1412-1422 MeV/c²

Method applied to neutral mode, incl. exotic wave → not yet released

Summary & outlook

- **COMPASS: high potential for search for exotic and new states**
  - **Very high statistics of 2008/09 hadron run data**
    → *allows and demands for improved PWA method*
  - **COMPASS measures Neutral & Charged channels**
    → *Independent confirmation of new states within same experiment*
  - **Present results basically consistent with published 2004 data result**
    → *all relevant channels for spin-exotic search feasible*
  - **Further interesting, exotic objects, especially huge charged mode data**
    → *new axial vector state*

Outlook:

- **More systematic studies, PWA model, Mass-dependent PWA under way**
  → *Full 2008 stats, also improved data production (done, not yet released),*
  → *PWA in mass and t' bins (done, not yet released for neutral)*
  → *New mass-dependent BW fit: Simultaneously for different t' (done, not yet released)*
- **New $(\pi\pi)_s$ wave approach (extracted from data) to be applied also for neutral mode**
- **Further extended wave-set (88 waves, driven by charged) to be applied for neutral mode**
  => more work ahead, before final COMPASS conclusions on $\pi_1(1600)$