Hadron Spectroscopy with COMPASS

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PANIC11
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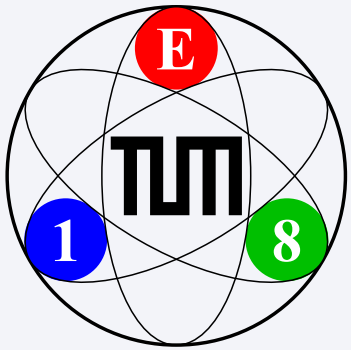

The COMPASS Physics Program

COmmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy

Goal

- Study non-perturbative regime of QCD
- Probe structure and dynamics of hadrons

Very low Q^2: chiral dynamics

- π and K polarizabilities
- Chiral anomaly $F_{3\pi}$

Intermediate Q^2: spectroscopy

- Mass spectrum of hadrons
- Gluonic excitations

Large Q^2: nucleon structure

- Helicity, transversity PDFs
- Generalized PDFs

$\longrightarrow$ 3B-4 and 4B-1

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Outline

1. The experimental setup

2. Search for spin-exotic mesons
   - Introduction
   - Partial-wave analysis of $(3\pi)^-$ final state from π^- diffraction
   - Partial-wave analysis of $\pi^- p \to \eta' \pi^- p$

3. Kaon diffraction into $K^-\pi^+\pi^-$ final state

Outline

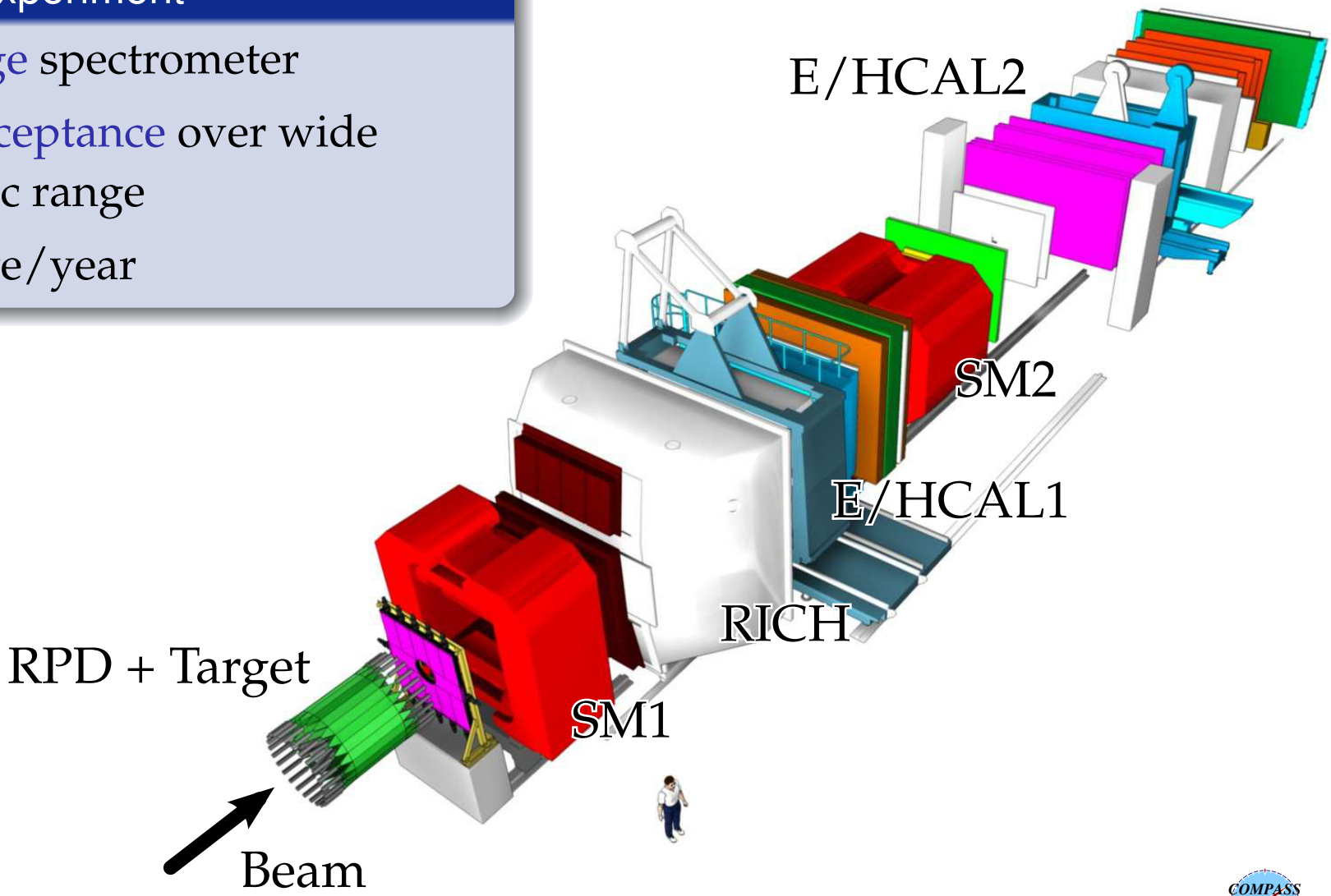
The COMPASS Experiment at the CERN SPS

Experimental Setup

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

Fixed-target experiment

- Two-stage spectrometer
- Large acceptance over wide kinematic range
- > 1 PByte/year



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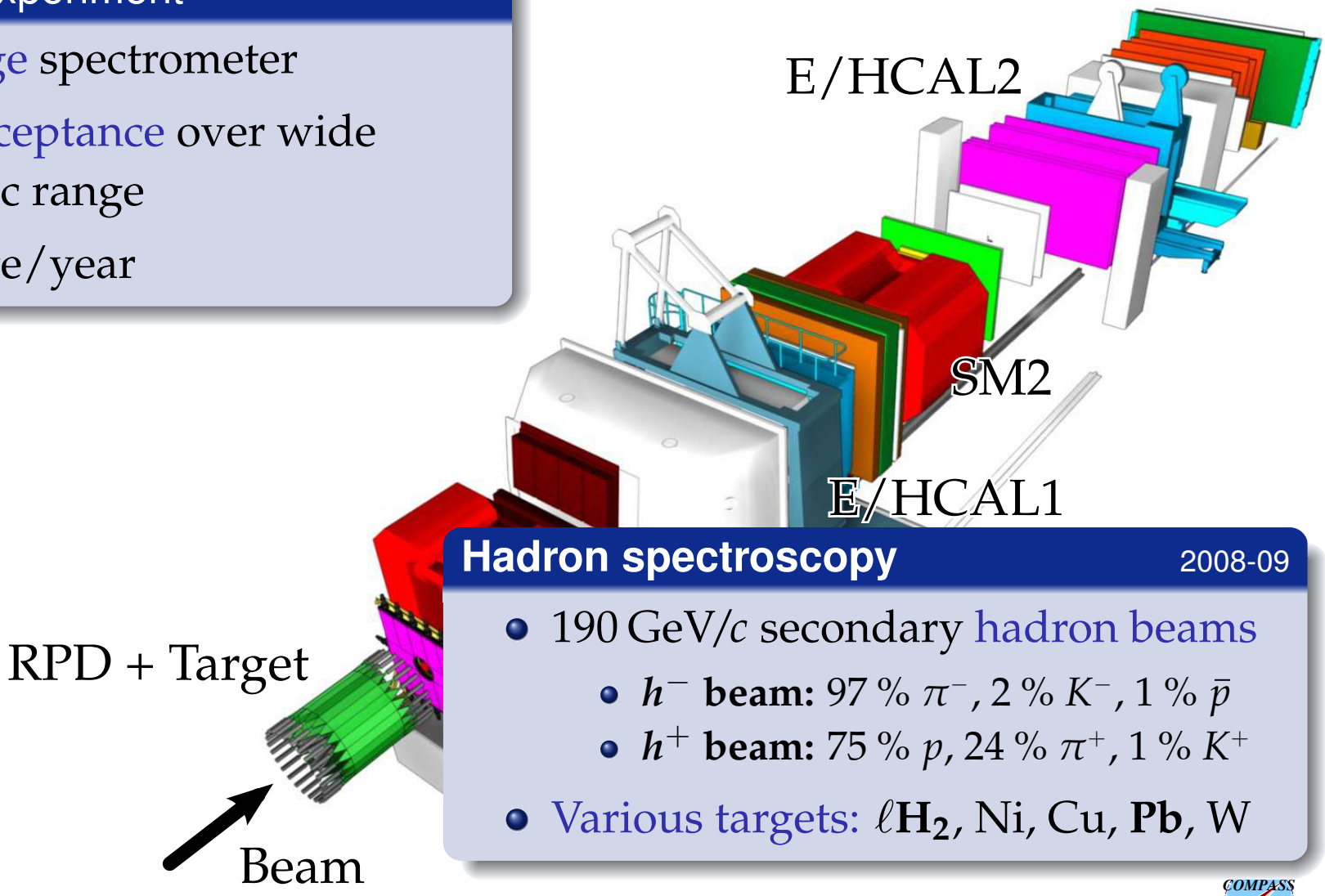


Hadron spectroscopy 2008-09

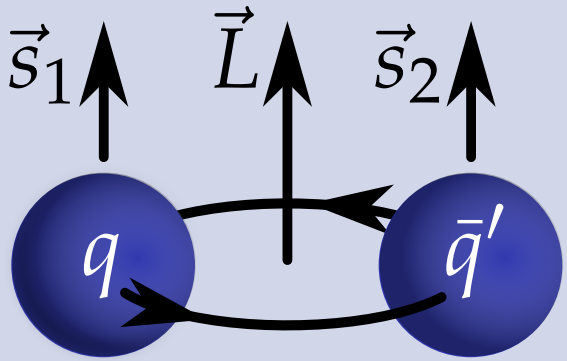
- 190 GeV/c secondary hadron beams
  - h^- **beam:** 97 % π^-, 2 % K^-, 1 % $\bar{p}$
  - h^+ **beam:** 75 % p, 24 % π^+, 1 % K^+
- Various targets: $\ell\mathbf{H_2}$, Ni, Cu, **Pb**, W

Outline

Mesons in the Constituent Quark Model

Spin-parity rules for bound $q\bar{q}'$ system

- Quark spins couple to total intrinsic spin $S = 0$ (singlet) or 1 (triplet)
- Relative orbital angular Momentum $\vec{L}$ and total spin $\vec{S}$ couple to meson spin $\vec{J} = \vec{L} + \vec{S}$
- Parity $P = (-1)^{L+1}$
- Charge conjugation $C = (-1)^{L+S}$
- **Forbidden J^{PC} combinations: $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$**



QCD allows for states beyond the CQM

- Hybrids $|q\bar{q}g\rangle$, glueballs $|gg\rangle$, multi-quark states $|q^2\bar{q}^2\rangle, \ldots$
- Physical mesons: linear superposition of all allowed basis states
- "Exotic" mesons have quantum numbers forbidden for $|q\bar{q}\rangle$
  - Particularly interesting: J^{PC}-exotic states

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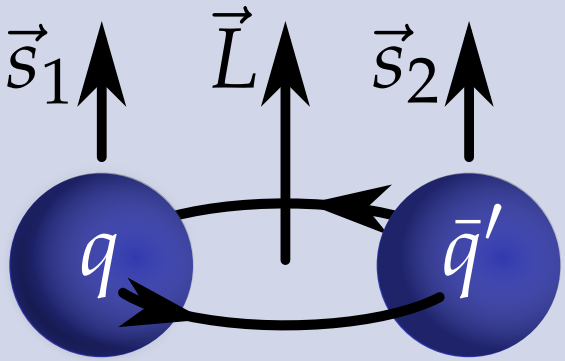

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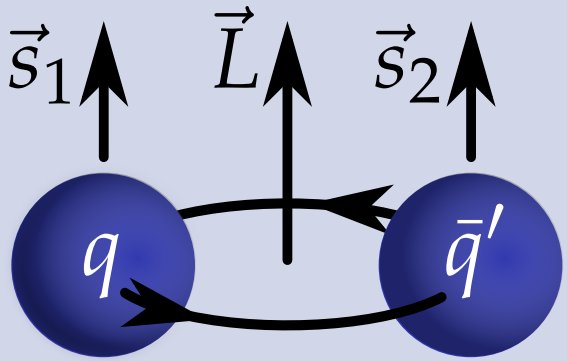

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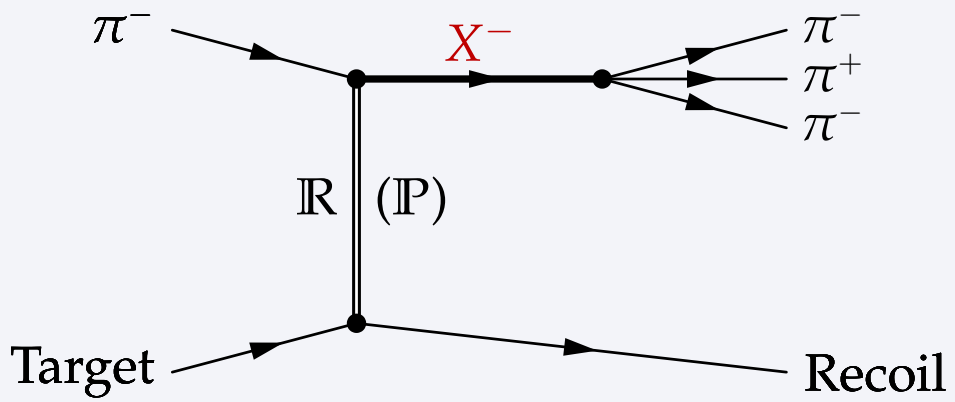
Production of Hadrons in Diffractive Dissociation



- Soft scattering of beam hadron off nuclear target (remains intact)
  - Beam particle is excited into some resonance X
  - X decays into n-body final state
- At high energies Pomeron exchange dominates
- Rich spectrum of intermediate states X
- **Goal:** use kinematic distribution of the final-state particles
  - Disentangle all resonances X
  - Determine their mass, width, and quantum numbers
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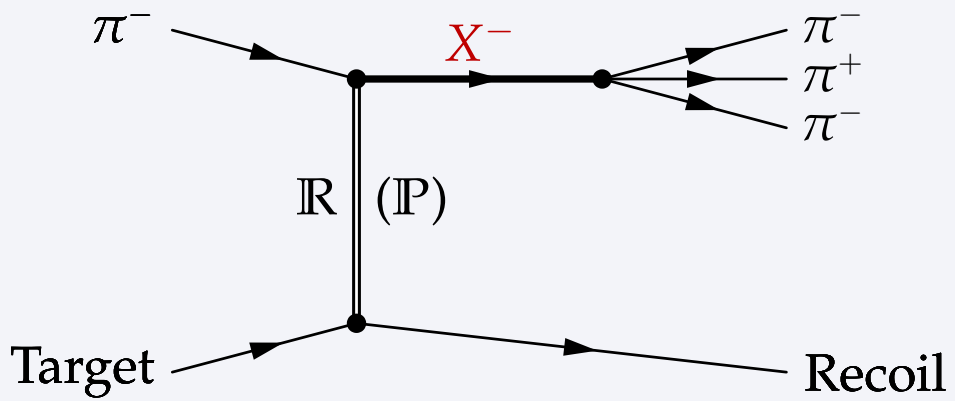

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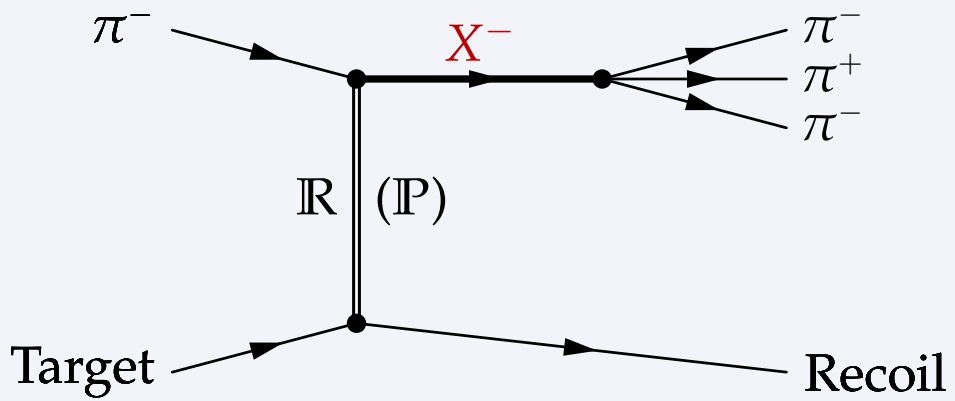

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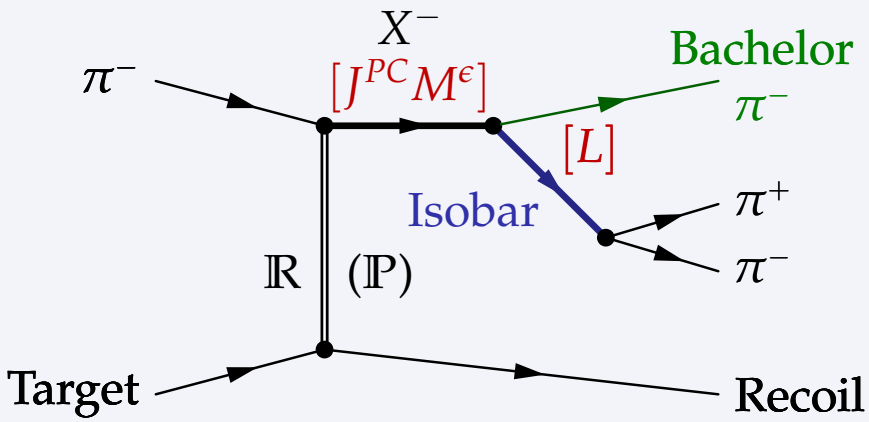
Diffractive Dissociation of π^- into $\pi^-\pi^+\pi^-$ Final State



Isobar model: X^- decay is chain of successive two-body decays

- Isobar has spin S and relative orbital angular momentum L w.r.t. bachelor π^-; L and S couple to spin J of X^-
- **"Wave":** unique combination of isobar and quantum numbers
  - Full wave specification (in reflectivity basis): $J^{PC}M^{\epsilon}[\text{isobar}]L$

Fit model: $\sigma(m_X,\tau) = \sigma_0 \left|\sum_{\text{waves}} T_{\text{wave}}(m_X)\, A_{\text{wave}}(m_X,\tau)\right|^2$

- Transition amplitudes T_{wave} determined from fit to full kinematic distributions taking into account interference effects

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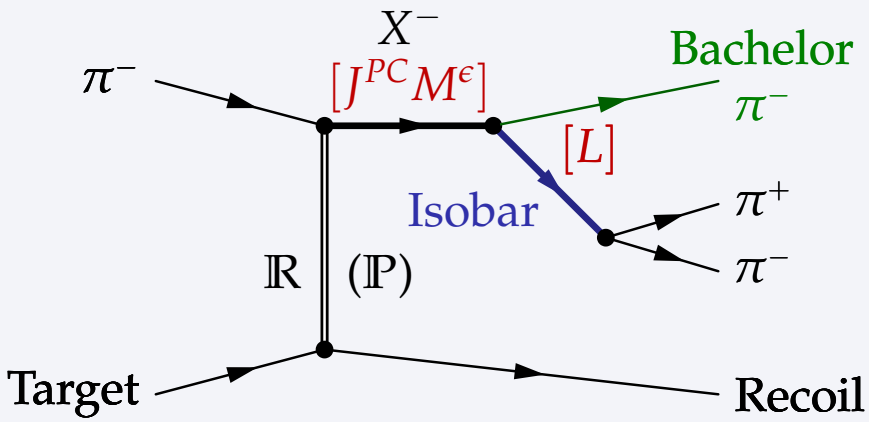

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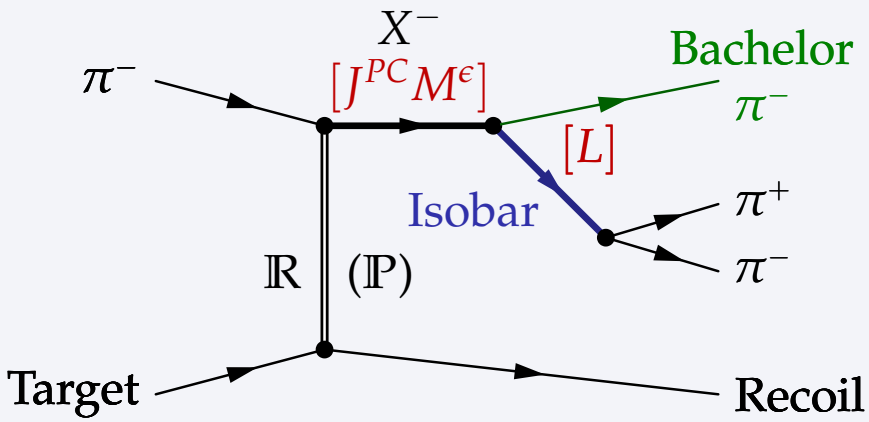

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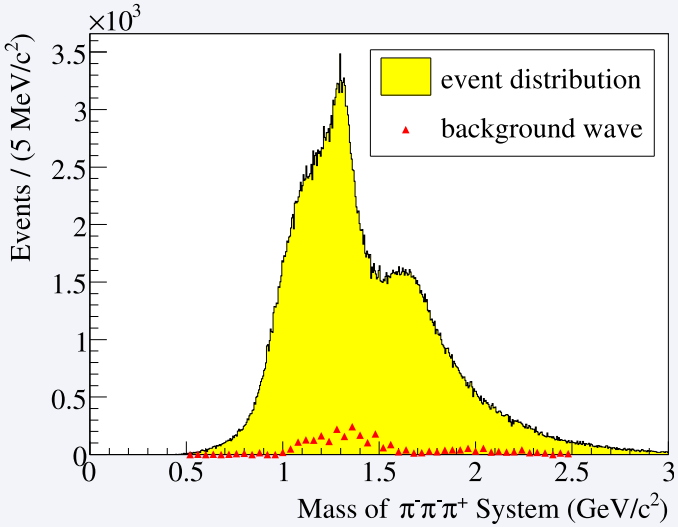
PWA of π^- Pb $\to \pi^-\pi^+\pi^-$ Pb (2004 Data)

PRL 104 (2010) 241803

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



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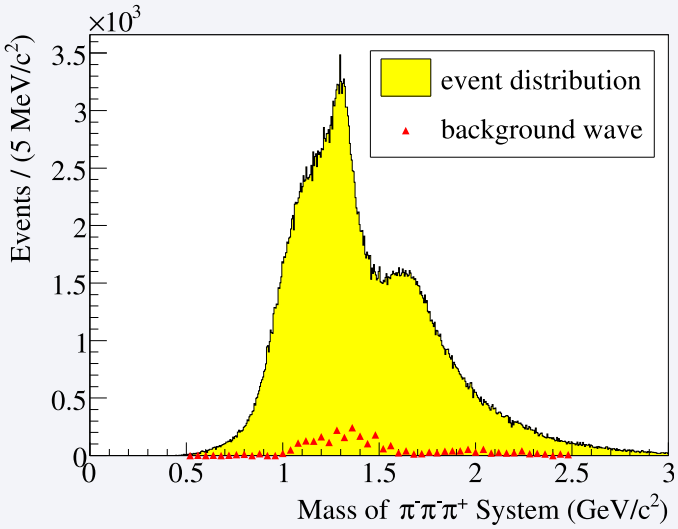
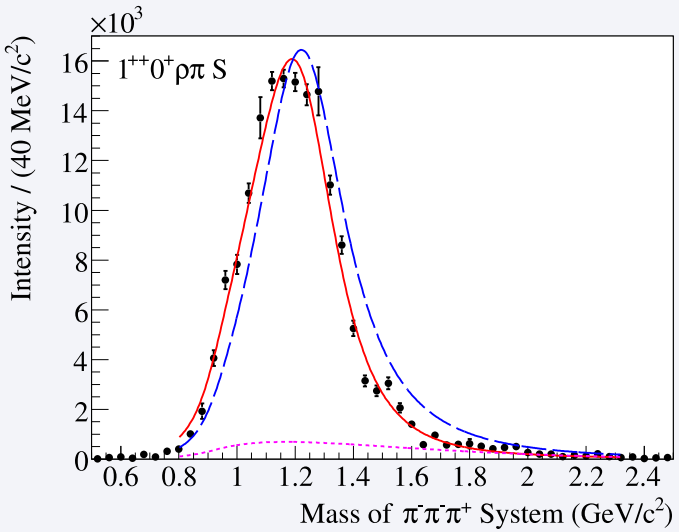


$1^{++}\,0^+\,[\rho\pi]\mathrm{S} : a_1(1260)$



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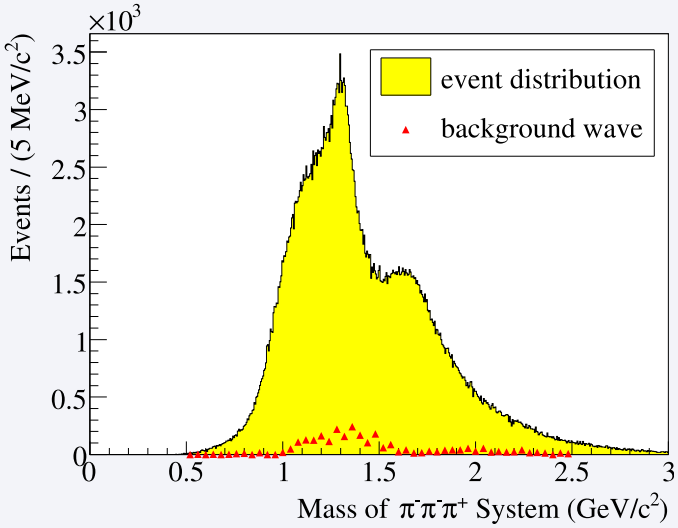

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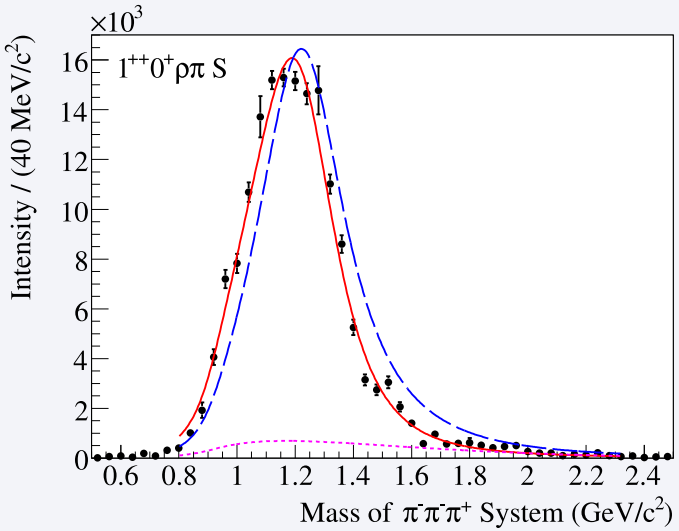
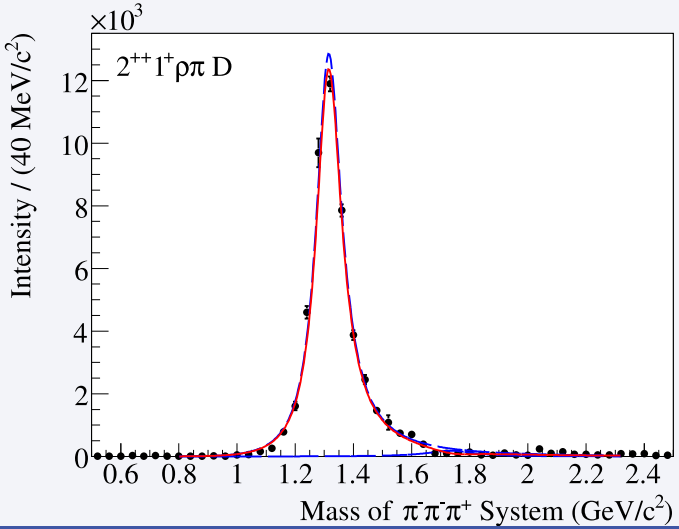


$2^{++}\,1^+\,[\rho\pi]\mathrm{D} : a_2(1320)$



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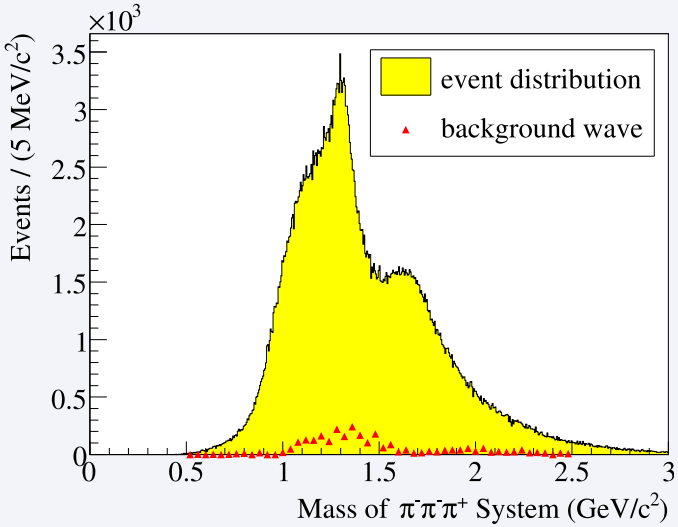

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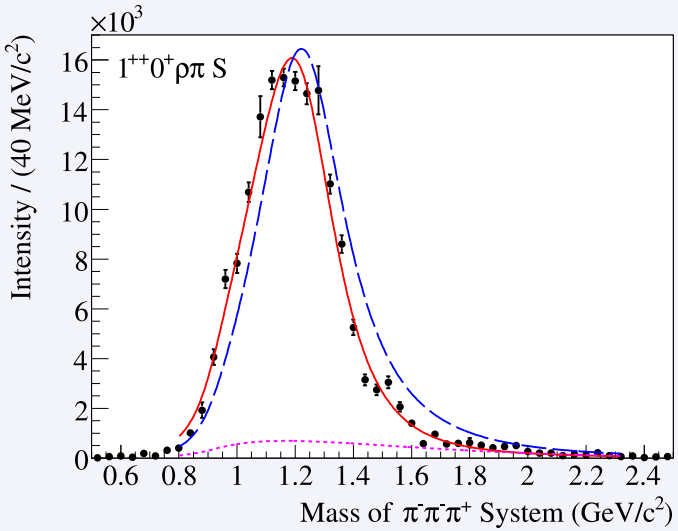
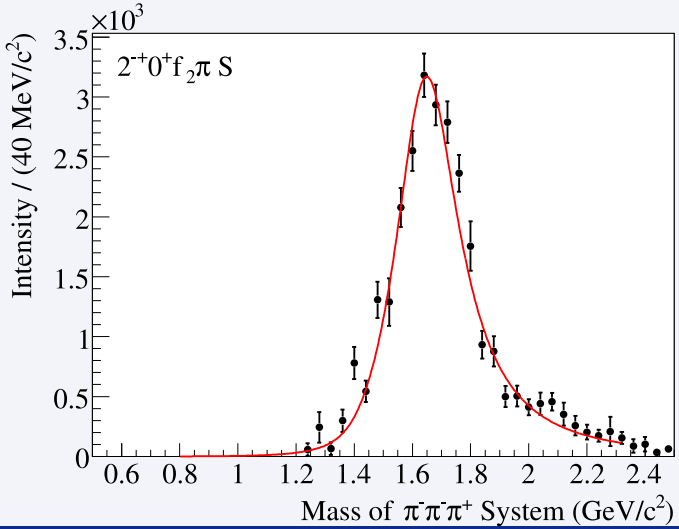


$2^{-+}\,0^+\,[f_2\pi]\mathrm{S} : \pi_2(1670)$



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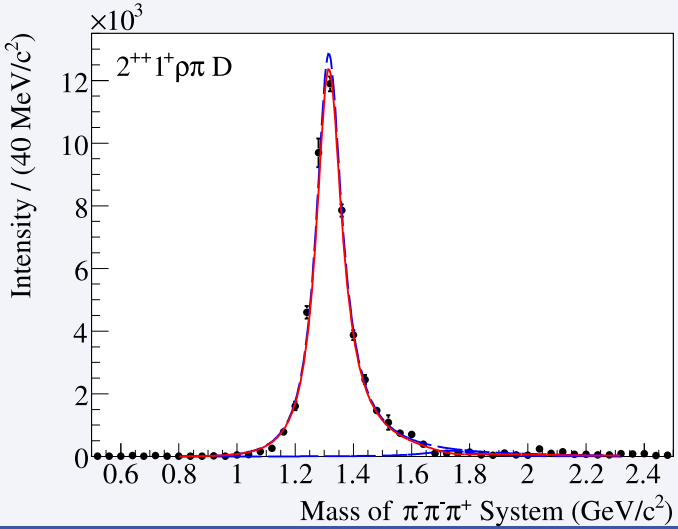

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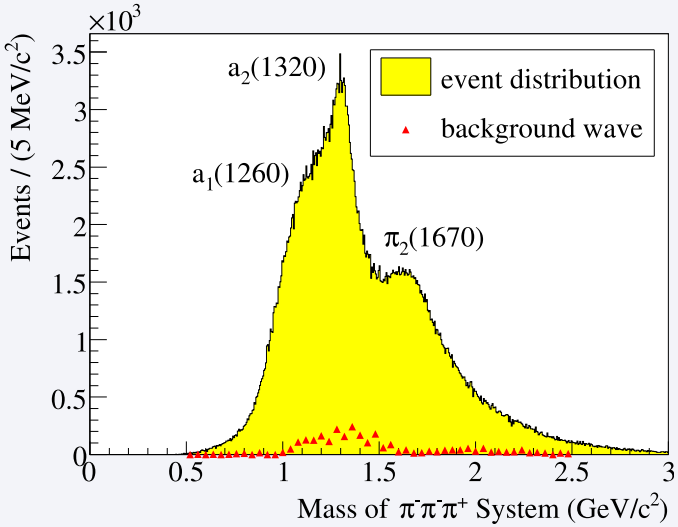

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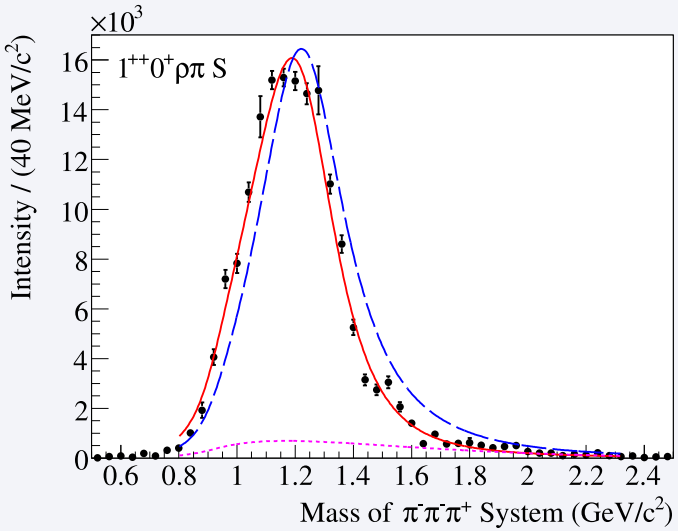

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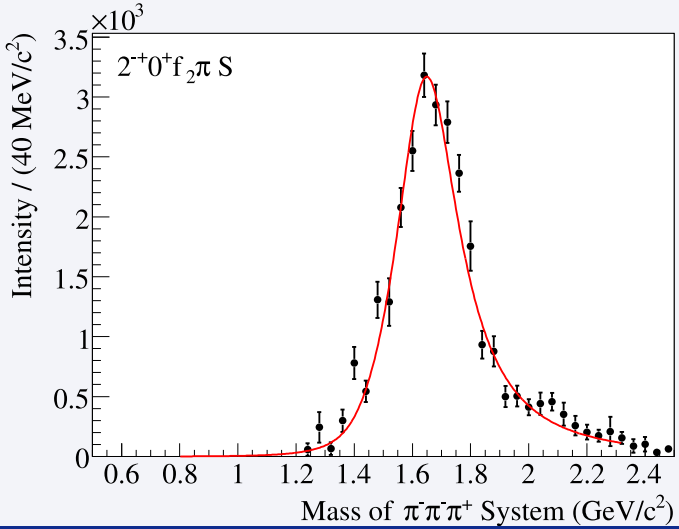

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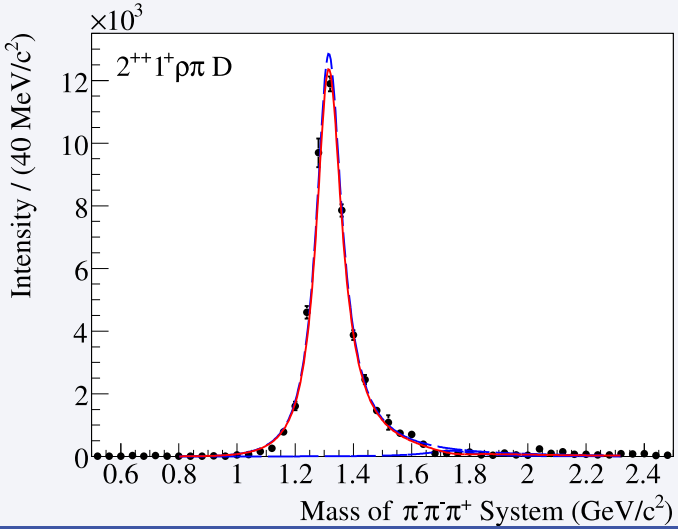

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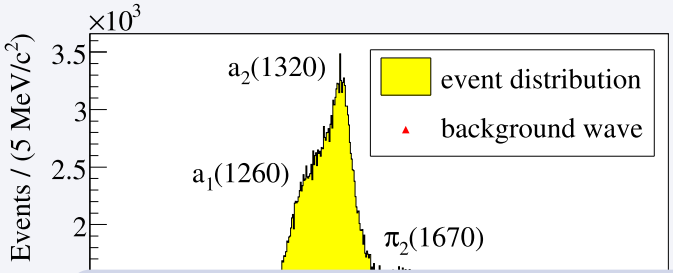

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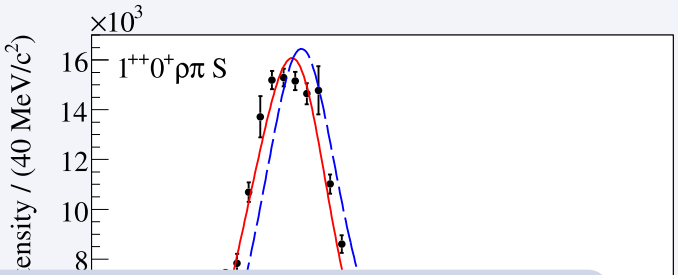
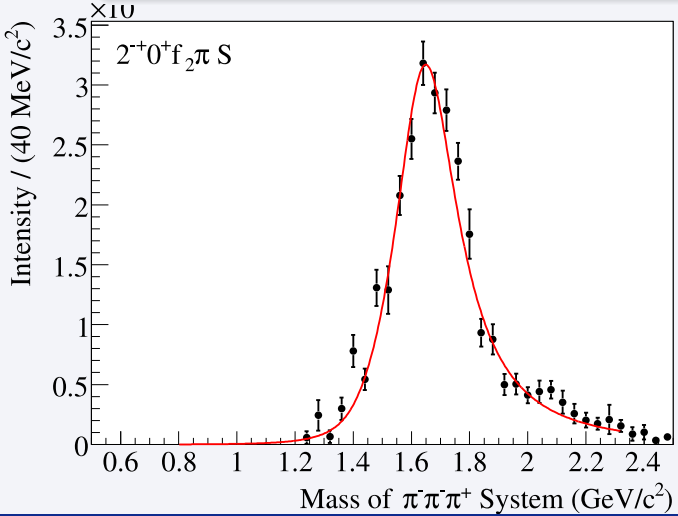
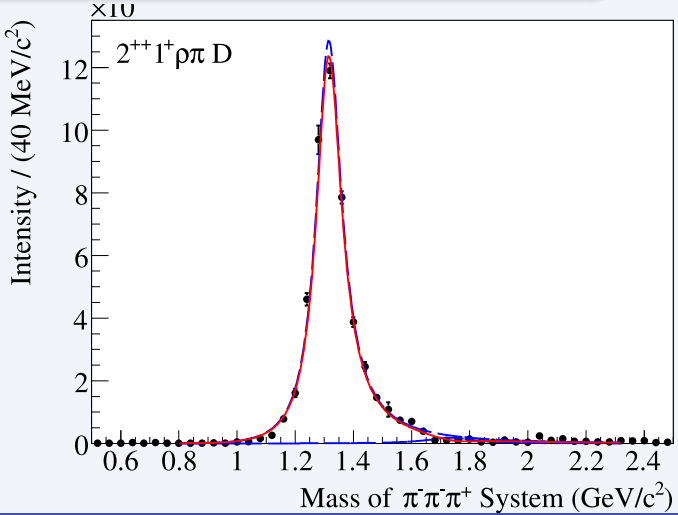


- Momentum transfer: $0.1 < t' < 1.0\ (\mathrm{GeV}/c)^2$
- Data described by model consisting of 41 waves + incoherent isotropic background
  - Isobars: $(\pi\pi)_S$, $f_0(980)$, $\rho(770)$, $f_2(1270)$, and $\rho_3(1690)$





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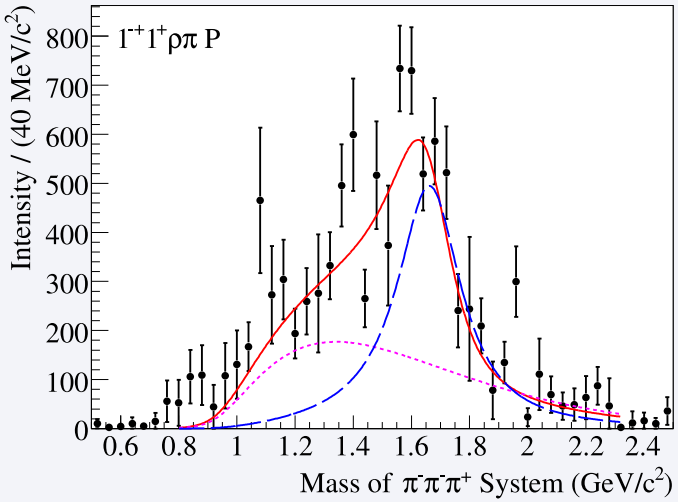
Spin-exotic $1^{-+}\,1^+\,[\rho\pi]\mathrm{P}$



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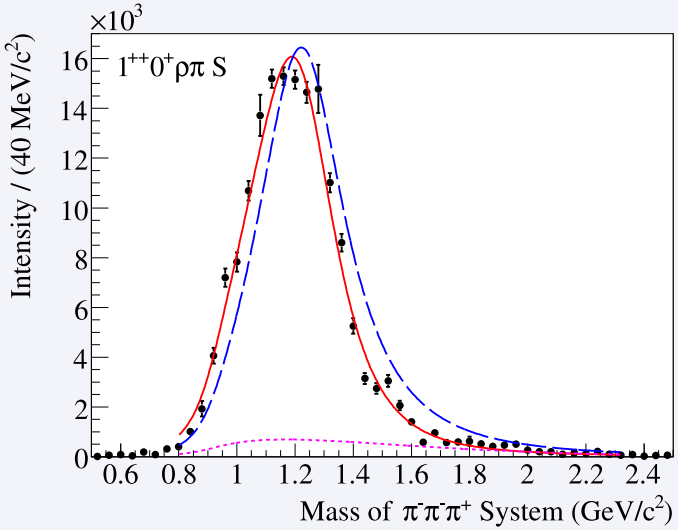
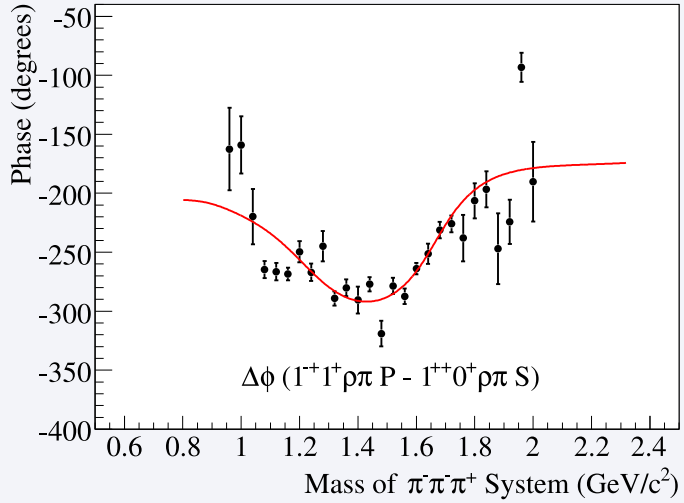


$1^{-+}\,1^+\,[\rho\pi]\mathrm{P} - 1^{++}\,0^+\,[\rho\pi]\mathrm{S}$



- 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

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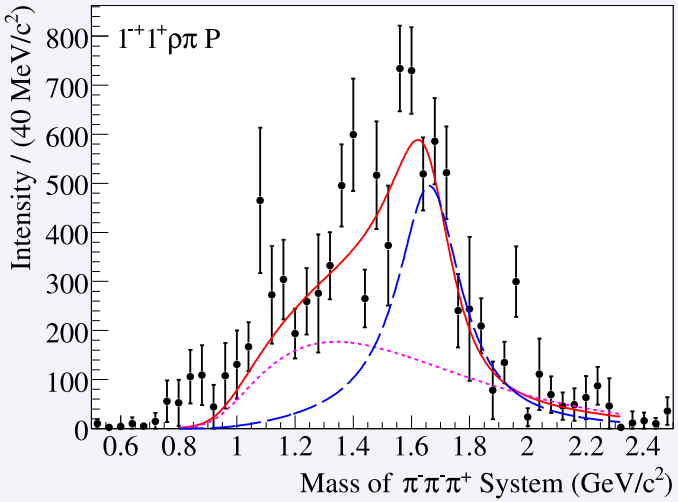
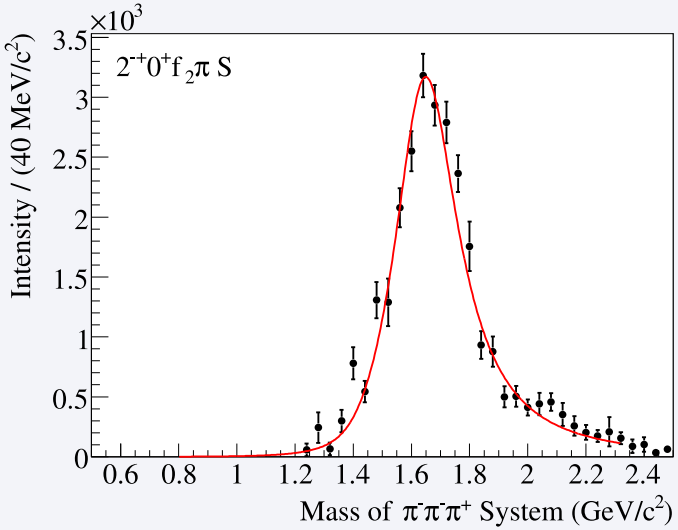
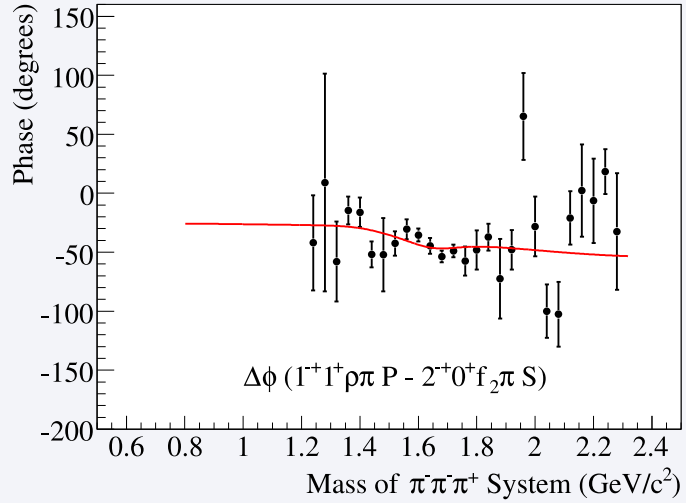


$2^{-+}\,0^+\,[f_2\pi]\mathrm{S} : \pi_2(1670)$



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



- 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

PWA of $\pi^- p \to \pi^- \pi^+ \pi^- p$ (2008 Data)

- Liquid hydrogen target
- **Spectrometer upgrade:** recoil proton detector, beam PID, calorimetry, and tracking
- 190 GeV/c negative hadron beam: 97 % π^-, 2 % K^-, 1 % $\bar{p}$
- 200× 2004 statistics: 96 M events $\Longrightarrow$ challenging analysis

PWA of $\pi^- p \to \pi^-\pi^+\pi^- p$ (2008 Data)

- Liquid hydrogen target
- **Spectrometer upgrade:** recoil proton detector, beam PID, calorimetry, and tracking
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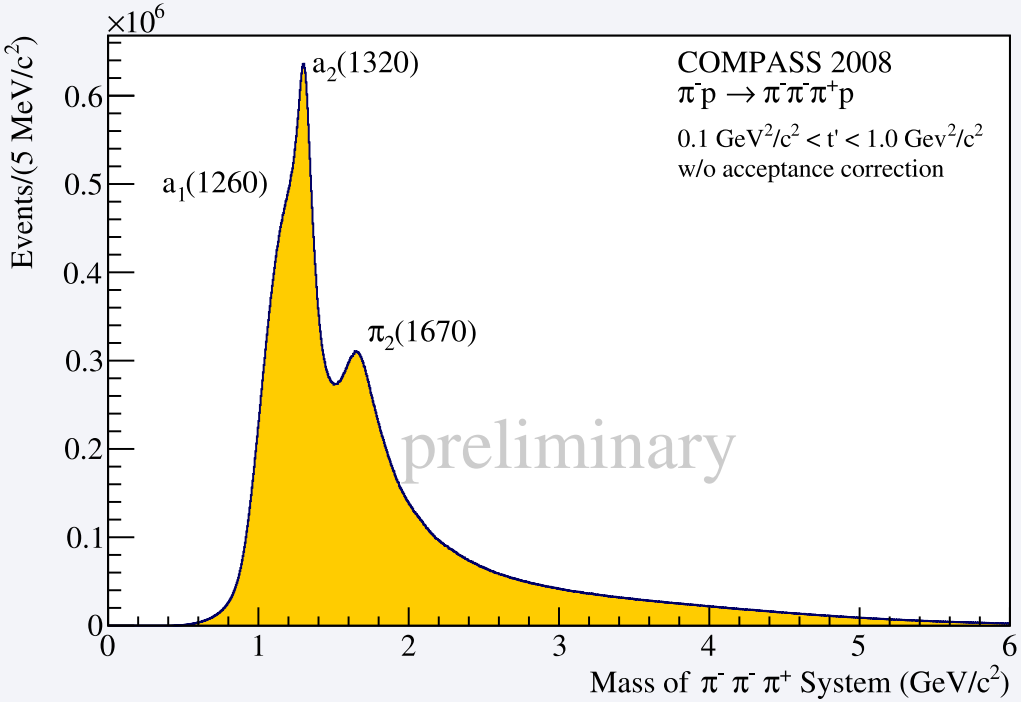
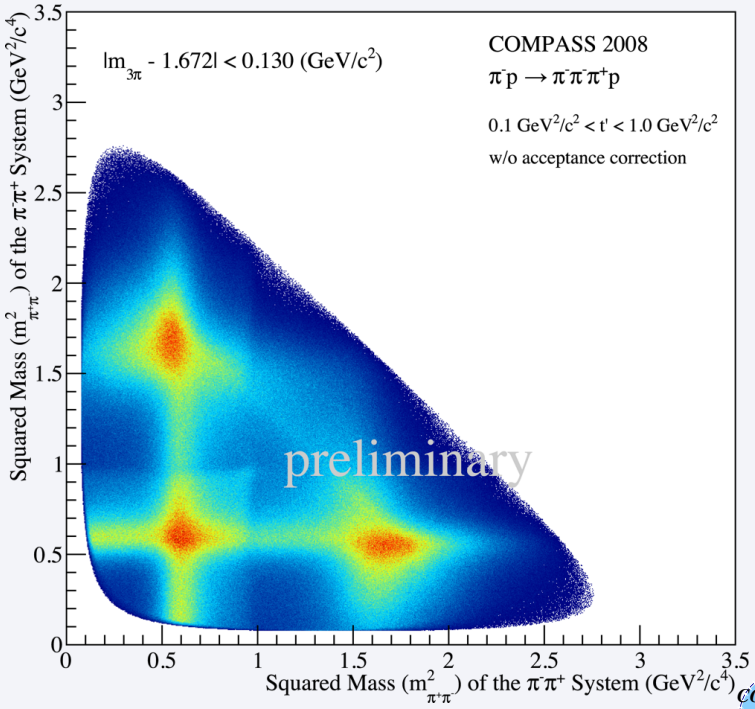
- 200× 2004 statistics: 96 M events $\Longrightarrow$ challenging analysis

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

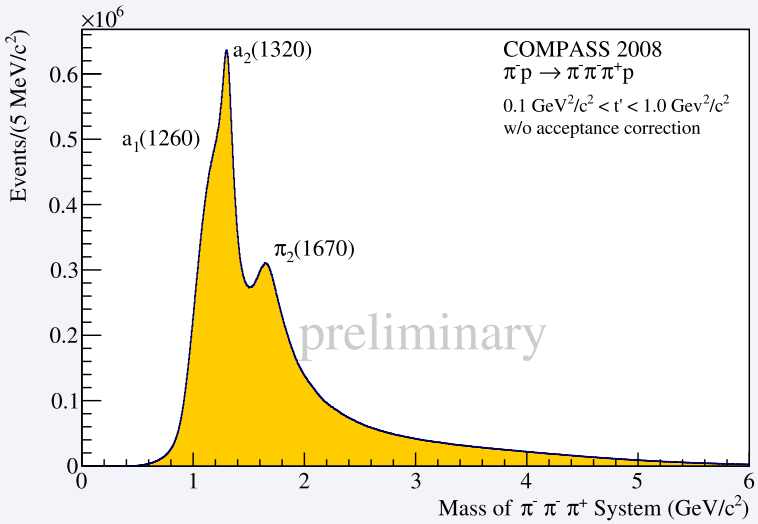


Dalitz plot for $\pi_2(1670)$ region



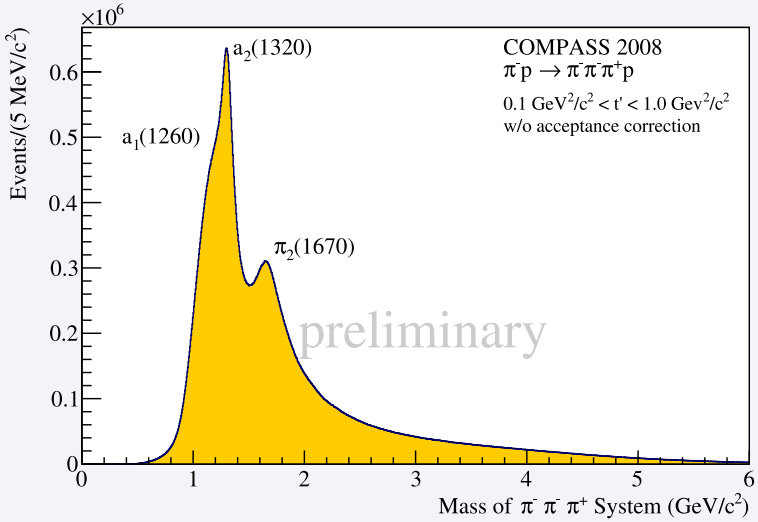
PWA of $\pi^- p \to \pi^- \pi^+ \pi^- p$ (2008 Data)

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

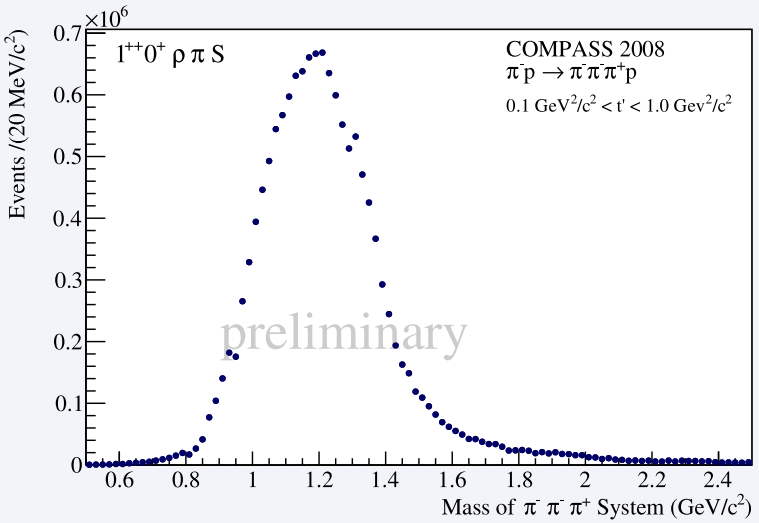


PWA of $\pi^- p \to \pi^- \pi^+ \pi^- p$ (2008 Data)

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

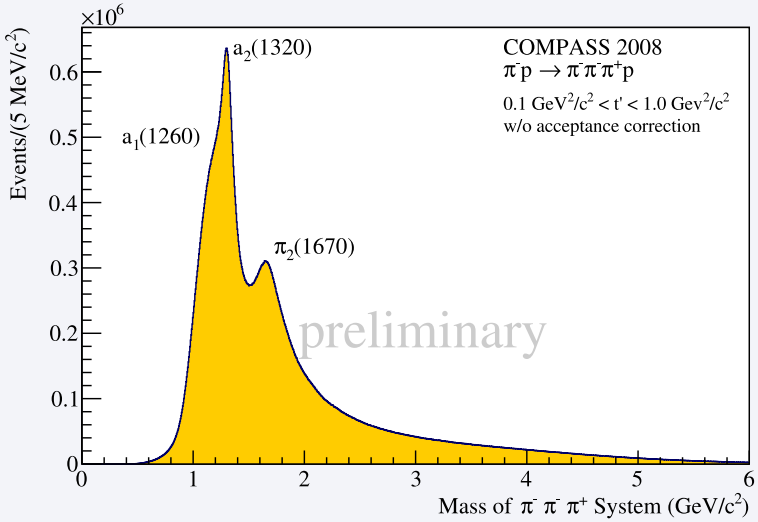


$1^{++}\,0^+\,[\rho\pi]\mathrm{S} : a_1(1260)$

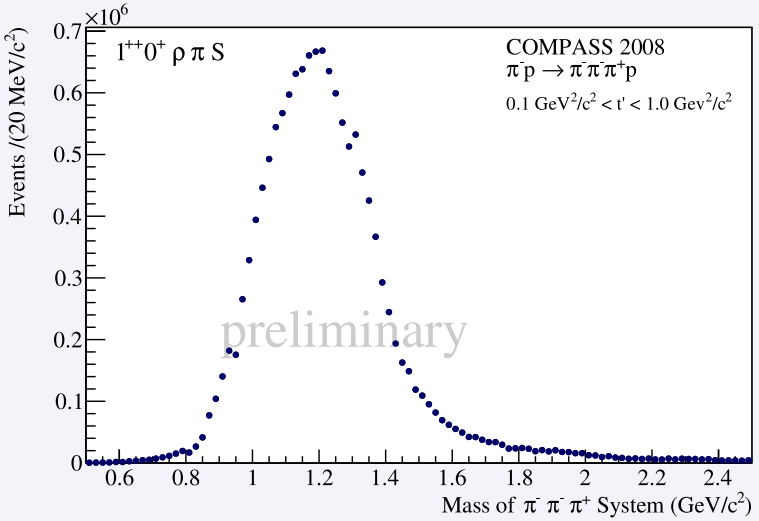


PWA of $\pi^- p \to \pi^- \pi^+ \pi^- p$ (2008 Data)

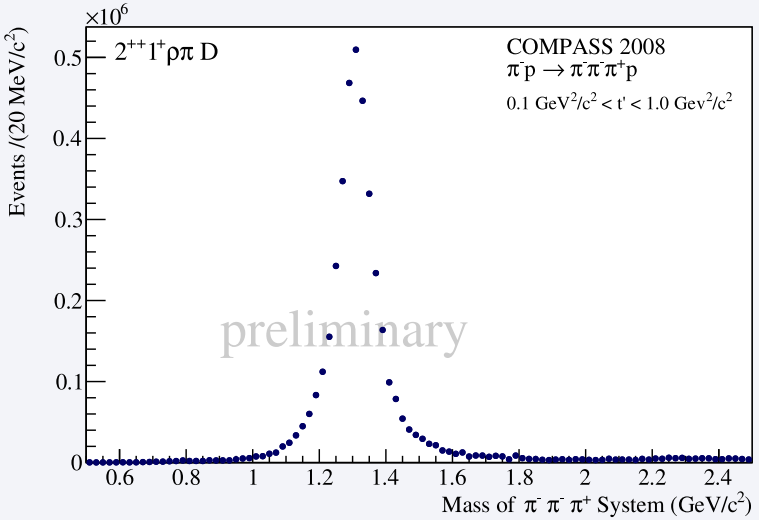
$\pi^- \pi^+ \pi^-$ mass spectrum



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

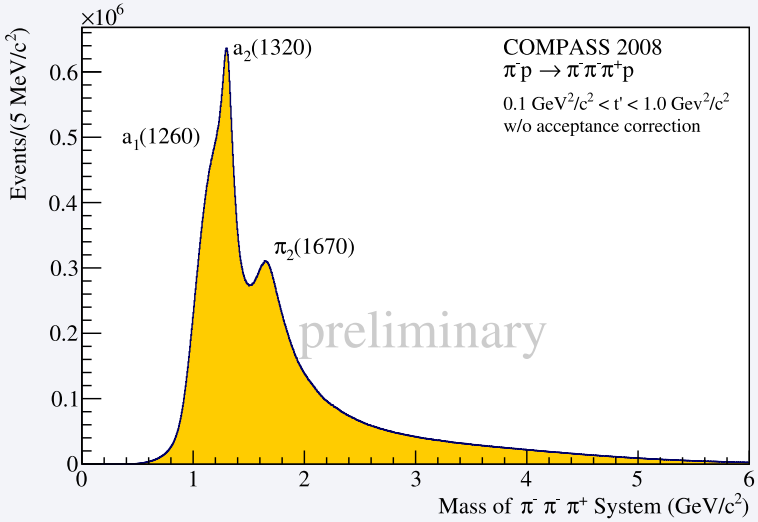


$2^{++}\,1^+\,[\rho\pi]\mathrm{D} : a_2(1320)$

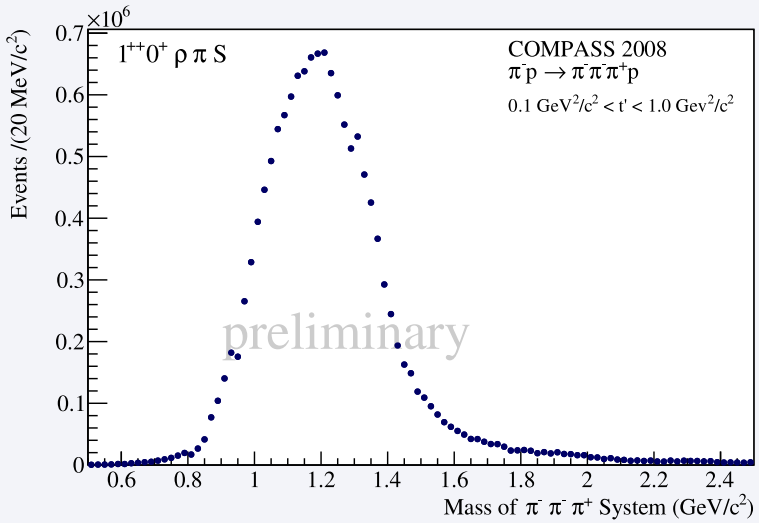


PWA of $\pi^- p \to \pi^- \pi^+ \pi^- p$ (2008 Data)

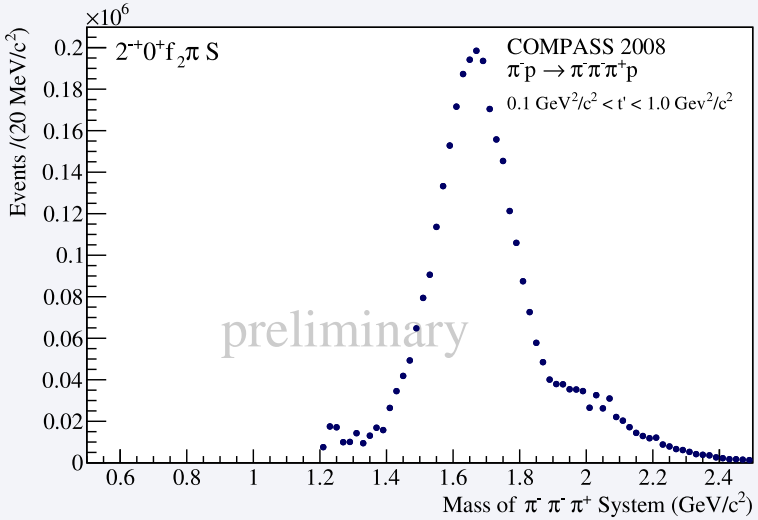
$\pi^- \pi^+ \pi^-$ mass spectrum



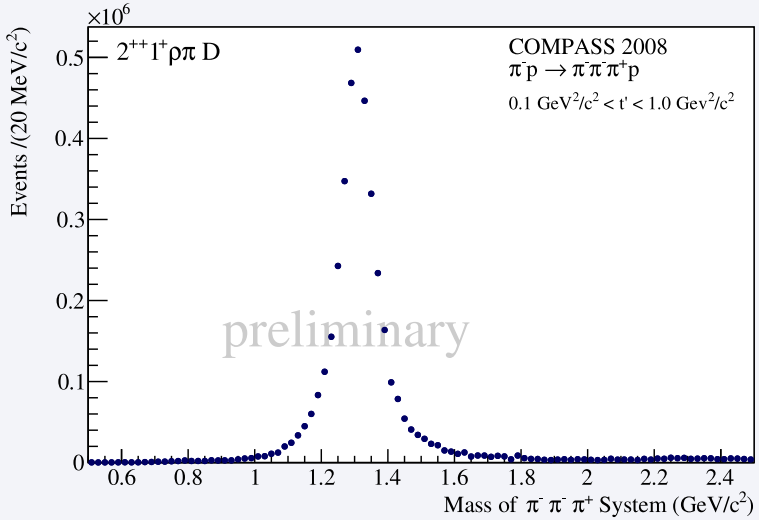
$1^{++}\,0^+\,[\rho\pi]\mathrm{S} : a_1(1260)$



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

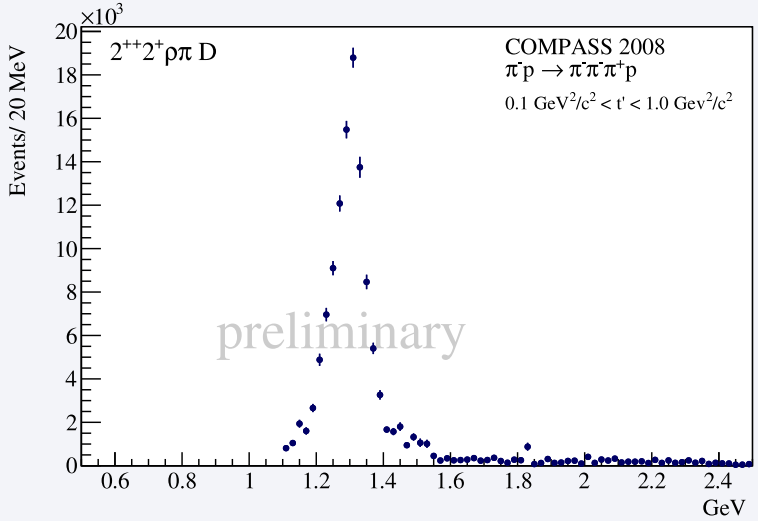


$2^{++}\,1^+\,[\rho\pi]\mathrm{D} : a_2(1320)$



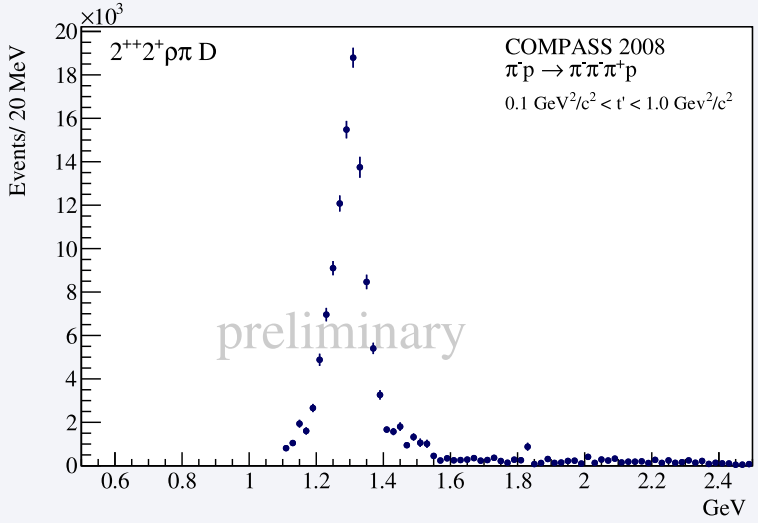
PWA of $\pi^- p \to \pi^- \pi^+ \pi^- p$ (2008 Data)

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

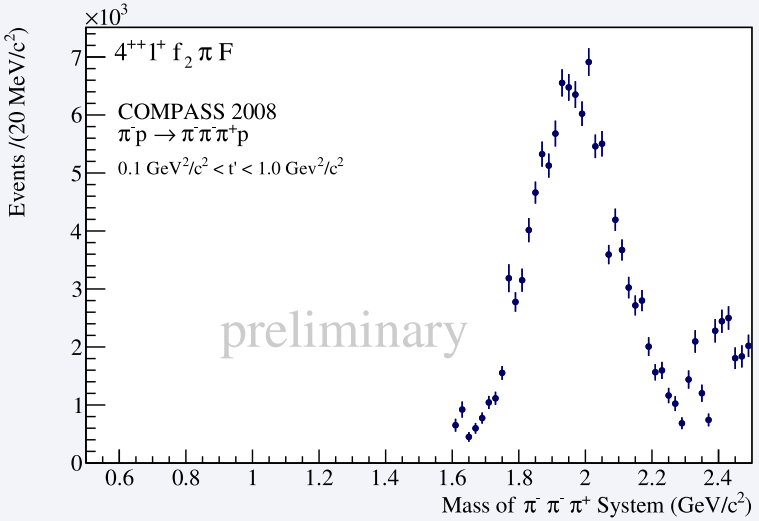


PWA of $\pi^- p \to \pi^-\pi^+\pi^- p$ (2008 Data)

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

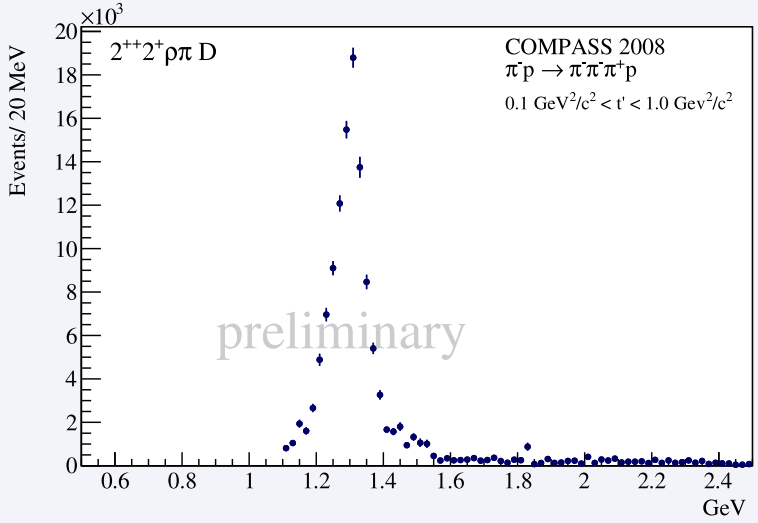


$4^{++}\,1^+\,[f_2\pi]\mathrm{F} : a_4(2040)$

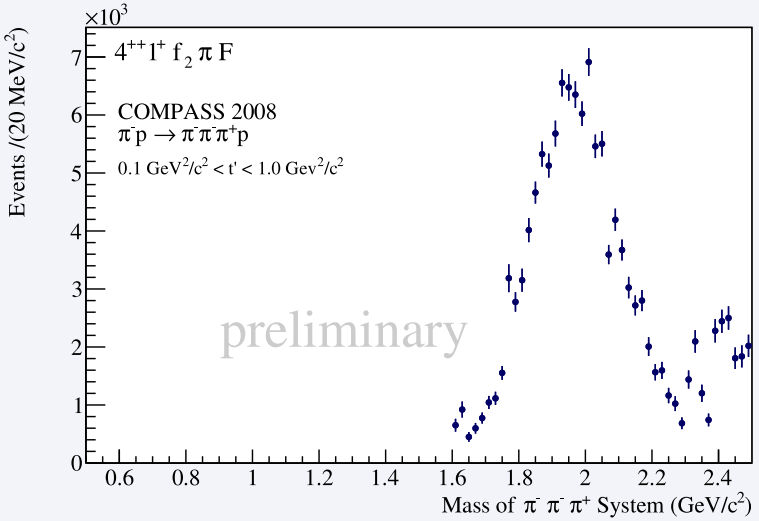


PWA of $\pi^- p \to \pi^- \pi^+ \pi^- p$ (2008 Data)

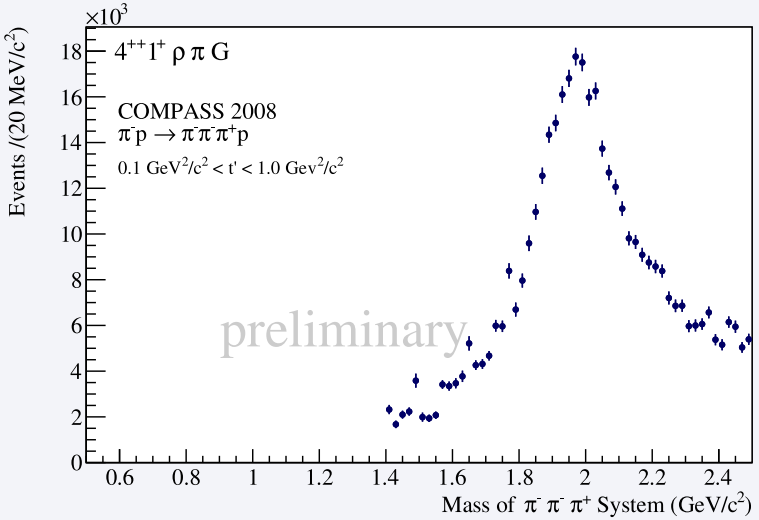
$2^{++}\,2^+\,[\rho\pi]\mathrm{D} : a_2(1320)$



$4^{++}\,1^+\,[f_2\pi]\mathrm{F} : a_4(2040)$

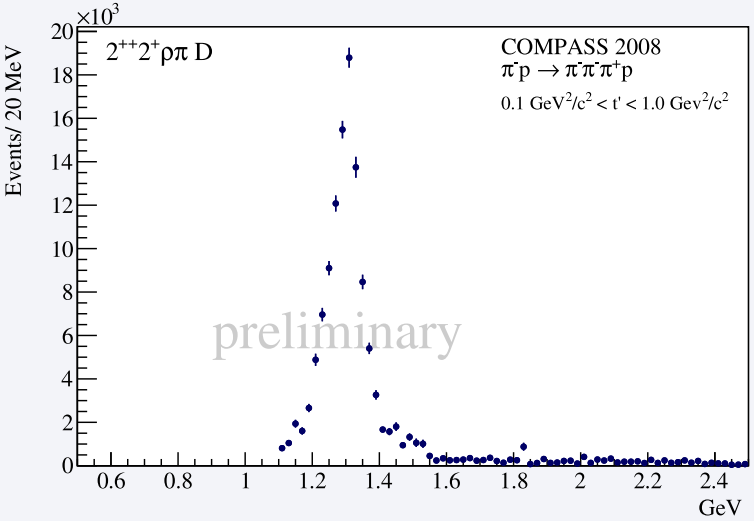


$4^{++}\,1^+\,[\rho\pi]\mathrm{G} : a_4(2040)$

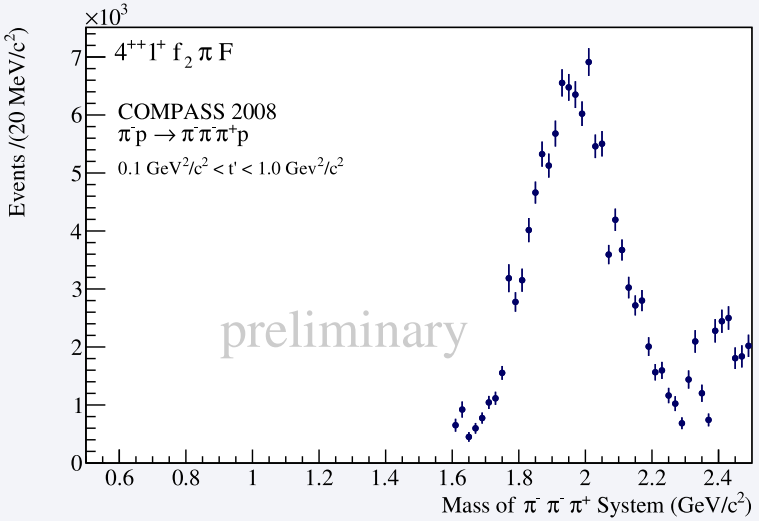


PWA of $\pi^- p \to \pi^- \pi^+ \pi^- p$ (2008 Data)

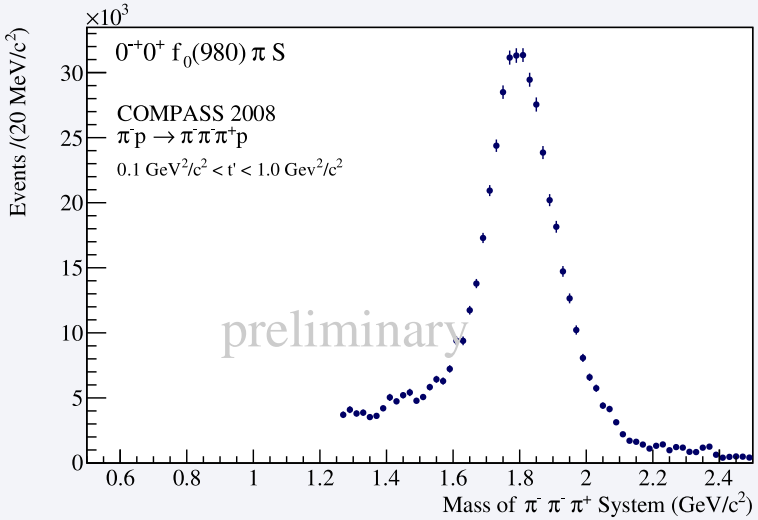
$2^{++}\,2^{+}\,[\rho\pi]\mathrm{D} : a_2(1320)$



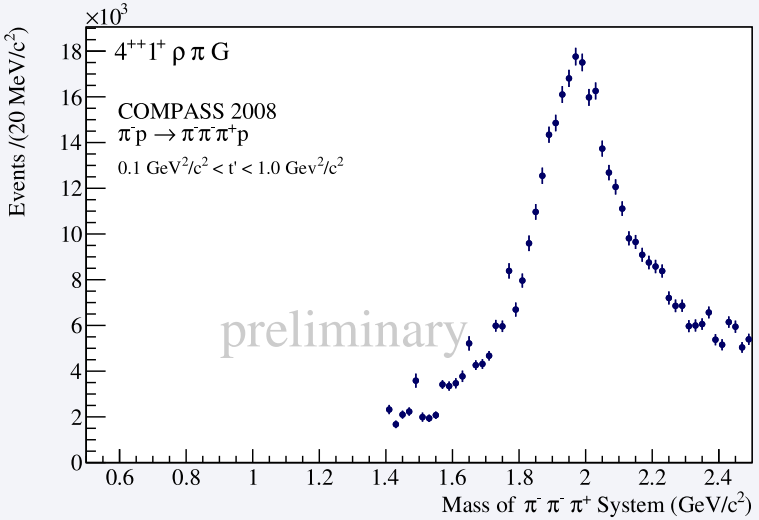
$4^{++}\,1^{+}\,[f_2\pi]\mathrm{F} : a_4(2040)$



$0^{-+}\,0^{+}\,[f_0(980)\pi]\mathrm{S} : \pi(1800)$

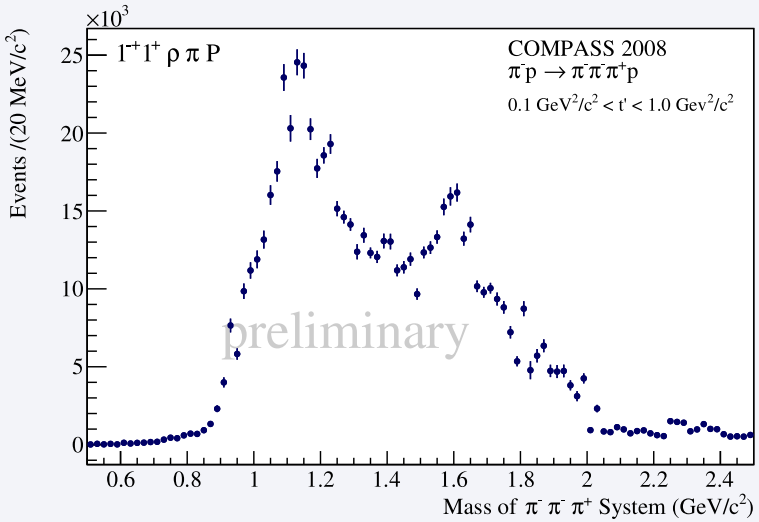


$4^{++}\,1^{+}\,[\rho\pi]\mathrm{G} : a_4(2040)$



PWA of $\pi^- p \to \pi^- \pi^+ \pi^- p$ (2008 Data)

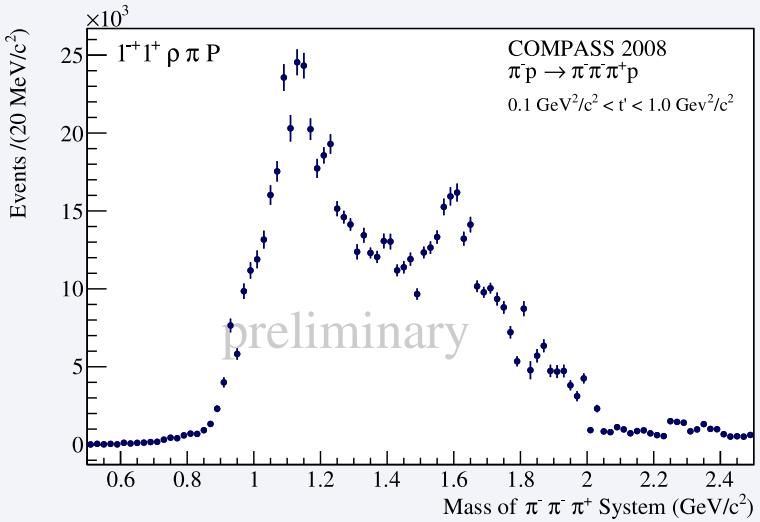
Spin-exotic $1^{-+}\,1^+\,[\rho\pi]\mathrm{P}$



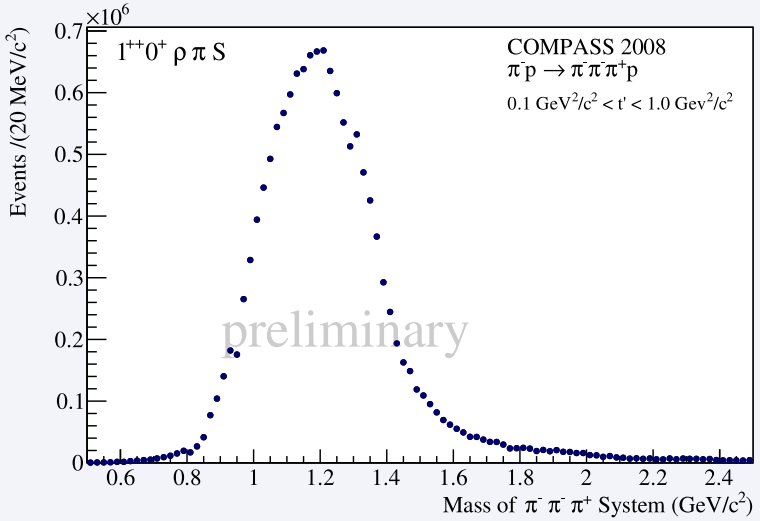
- Structure around 1.1 GeV/c^2 unstable w.r.t. fit model
- Stable enhancement around 1.6 GeV/c^2
- Phase motion w.r.t. to tail of $a_1(1260)$
- Phase locked w.r.t. $\pi_2(1670)$
- Ongoing analysis

PWA of $\pi^- p \to \pi^- \pi^+ \pi^- p$ (2008 Data)

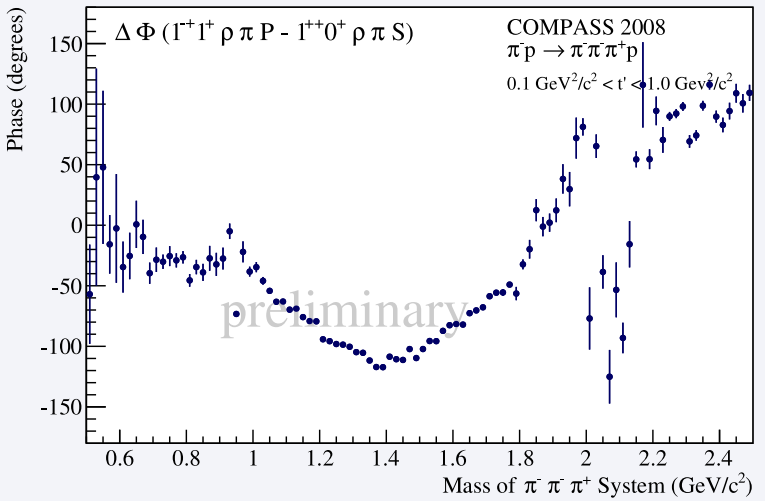
Spin-exotic $1^{-+}\,1^+\,[\rho\pi]\mathrm{P}$



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



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



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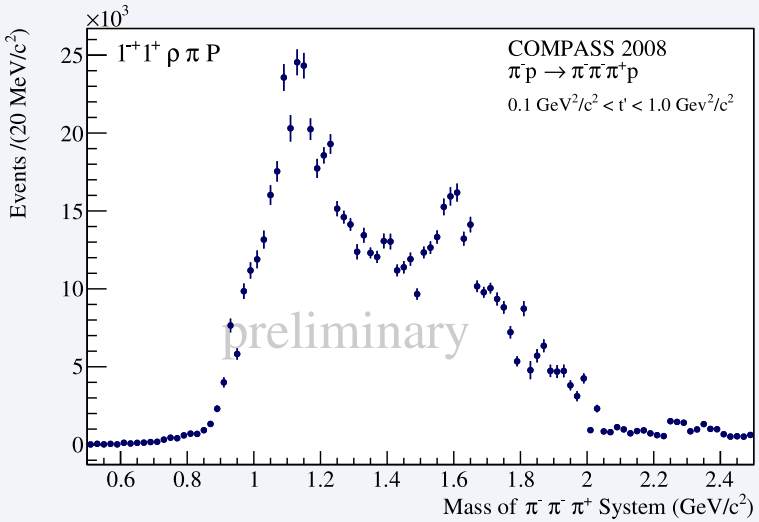
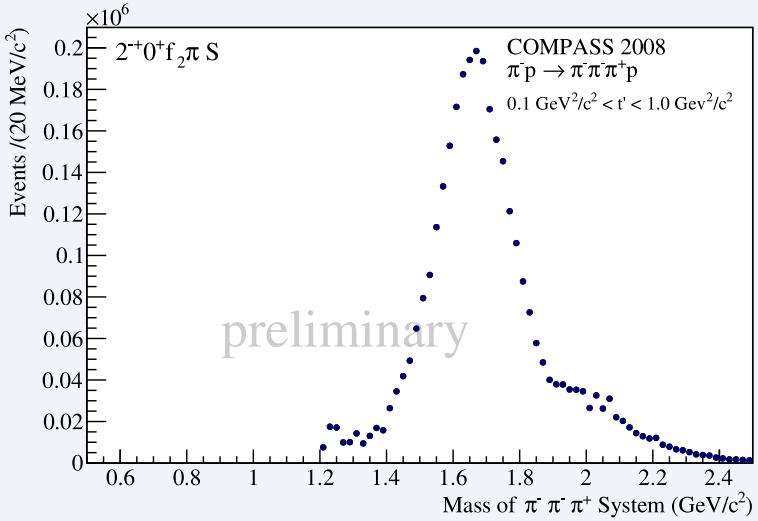
PWA of $\pi^- p \to \pi^- \pi^+ \pi^- p$ (2008 Data)

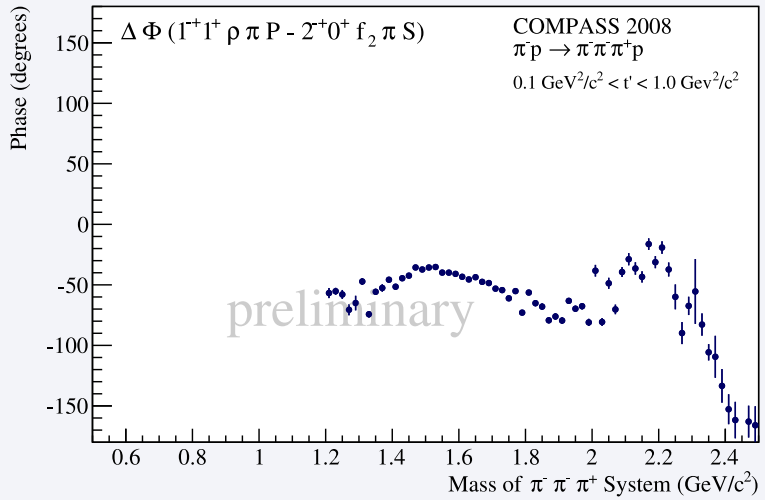
Spin-exotic $1^{-+}\,1^+\,[\rho\pi]\mathrm{P}$



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



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



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- Ongoing analysis

Nuclear Effect in Diffractive $\pi^-\pi^+\pi^-$ Production

Comparison of PWA results using different target materials

- 2008: H_2 target (≈ 23 M events)
- 2009: Pb target (≈ 1.2 M events)
- Normalized to $a_2(1320)$ region $[1.1, 1.6]$ GeV/c^2

Nuclear Effect in Diffractive $\pi^-\pi^+\pi^-$ Production

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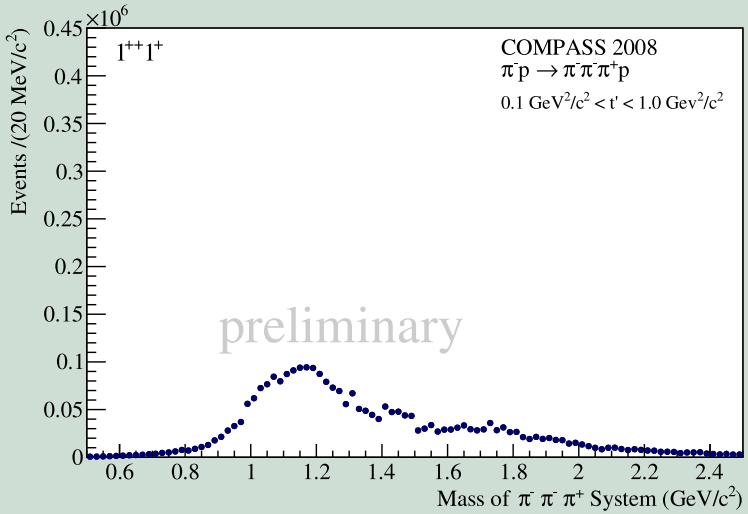
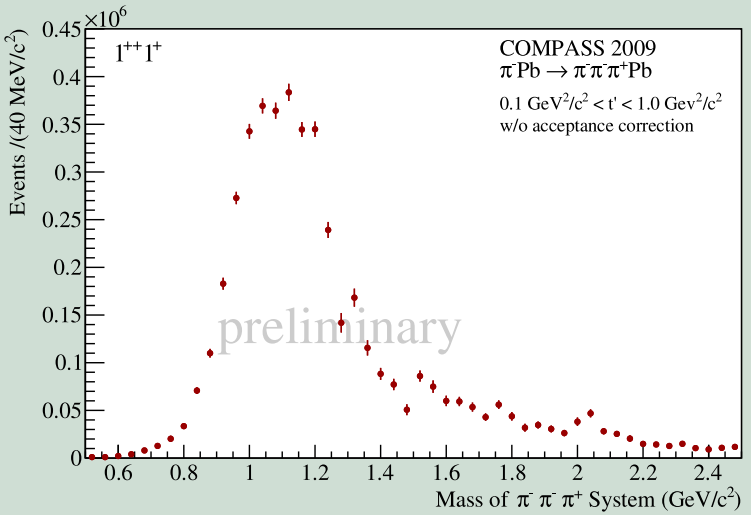
- Normalized to $a_2(1320)$ region $[1.1, 1.6]$ GeV/c^2

Enhancement of $M = 1$ states on Pb target

Total intensity of $J^{PC} = 1^{++}$ waves with $M^\epsilon = 1^+$



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



$\pi^- \mathrm{Pb} \to \pi^-\pi^+\pi^- \mathrm{Pb}$

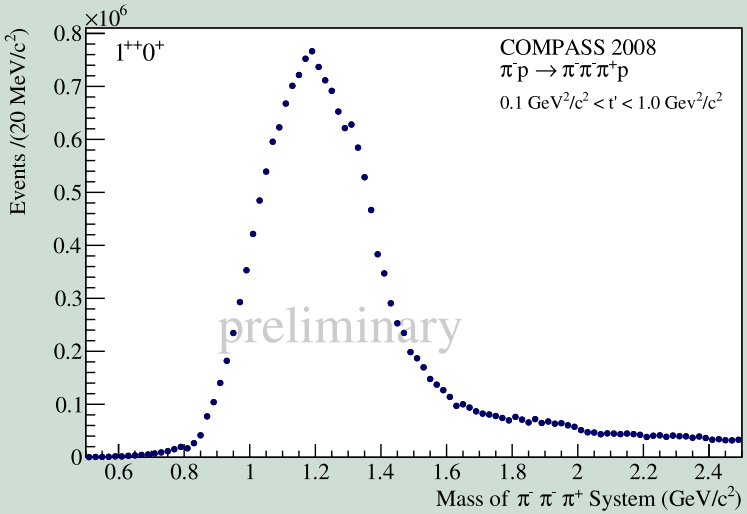
Nuclear Effect in Diffractive $\pi^-\pi^+\pi^-$ Production

Comparison of PWA results using different target materials

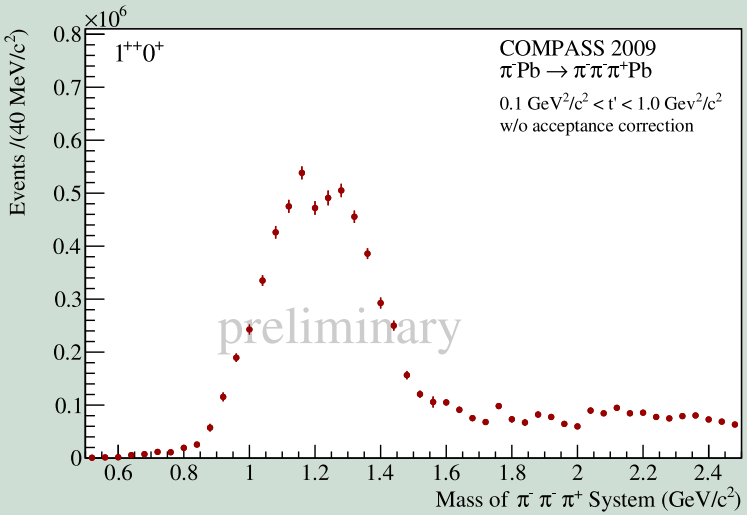
- 2008: H_2 target (≈ 23 M events)
- 2009: Pb target (≈ 1.2 M events)
- Normalized to $a_2(1320)$ region $[1.1, 1.6]$ GeV/c^2

Suppression of $M = 0$ states on Pb target

Total intensity of $J^{PC} = 1^{++}$ waves with $M^{\epsilon} = 0^+$



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



π^- Pb $\to \pi^-\pi^+\pi^-$ Pb

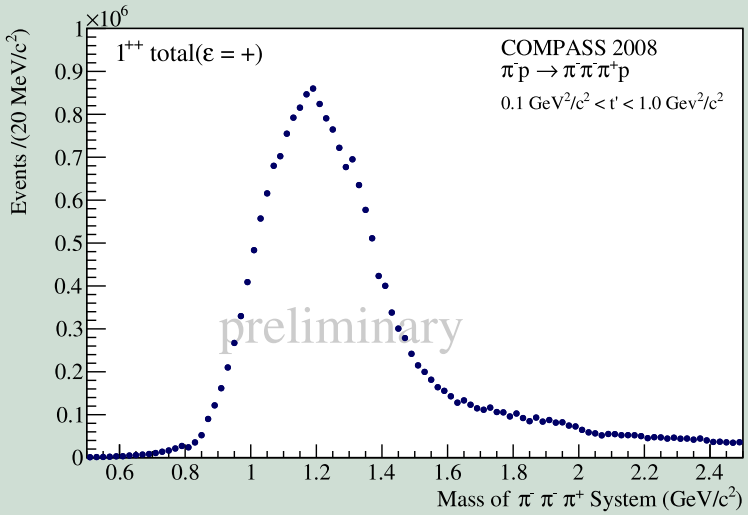
Nuclear Effect in Diffractive $\pi^-\pi^+\pi^-$ Production

Comparison of PWA results using different target materials

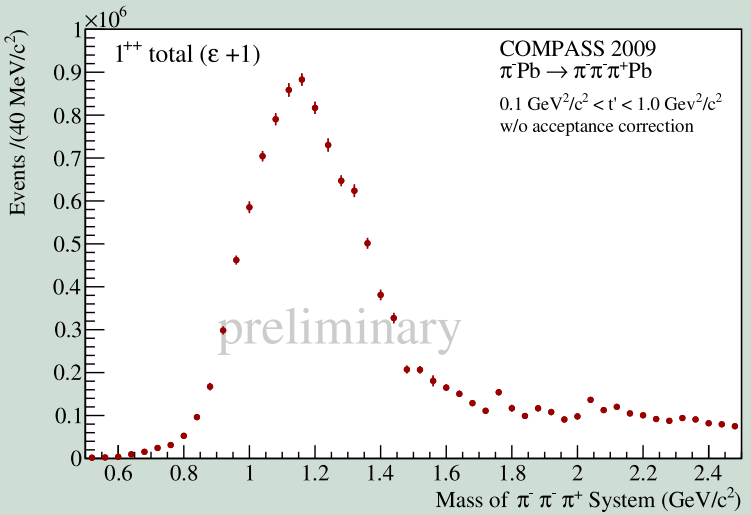
- 2008: H_2 target (≈ 23 M events)
- 2009: Pb target (≈ 1.2 M events)
- Normalized to $a_2(1320)$ region $[1.1, 1.6]$ GeV/c^2

Total intensity of sum over all M states comparable

Total intensity of $J^{PC} = 1^{++}$ waves (all M)



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



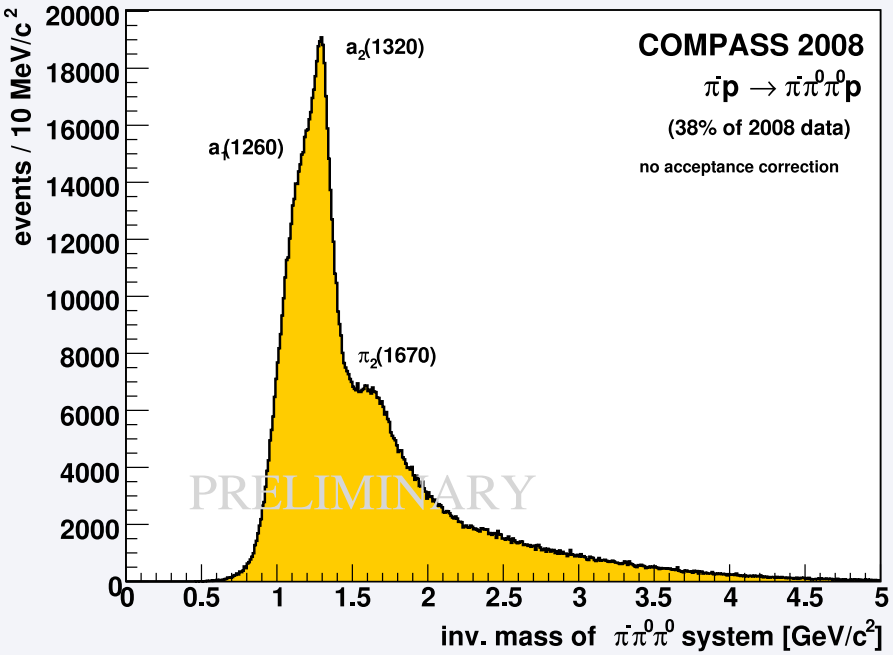
π^- Pb $\to \pi^-\pi^+\pi^-$ Pb

Comparison to PWA of $\pi^- p \to \pi^- \pi^0 \pi^0 p$ (2008 Data)

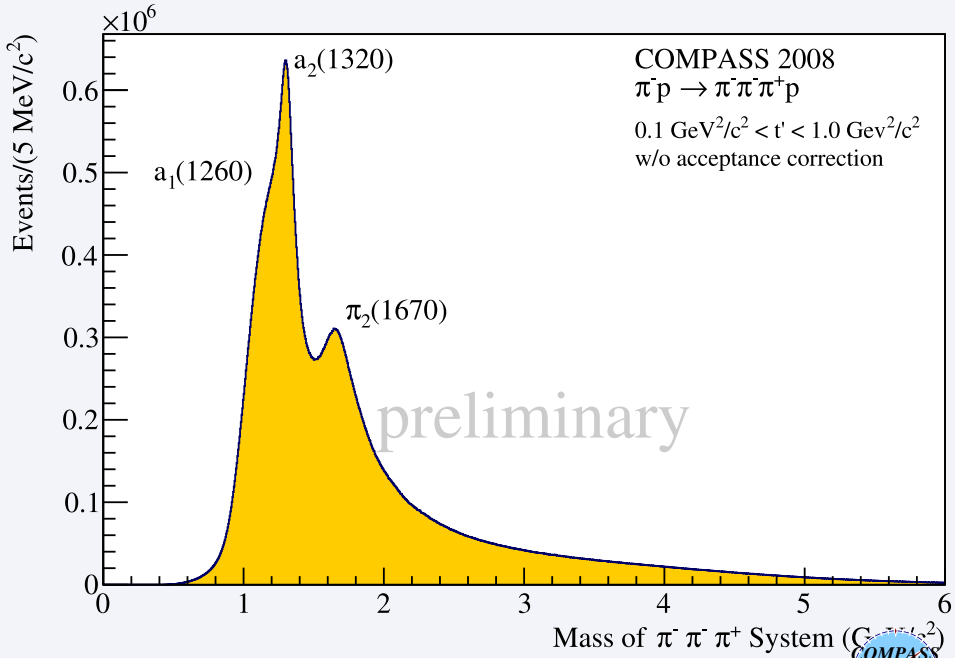
Isospin partner to $\pi^- p \to \pi^- \pi^+ \pi^- p$

- Important consistency check
- Comparison with $\pi^- \pi^+ \pi^-$ data set: normalization to $a_2(1320)$
- Isospin symmetry: $I = 1$ isobar $\Longrightarrow$ same intensity
  $I = 0$ isobar $\Longrightarrow$ half intensity

$\pi^- \pi^0 \pi^0$ mass distribution



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



Comparison to PWA of $\pi^- p \to \pi^- \pi^0 \pi^0 p$ (2008 Data)

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

- Important consistency check
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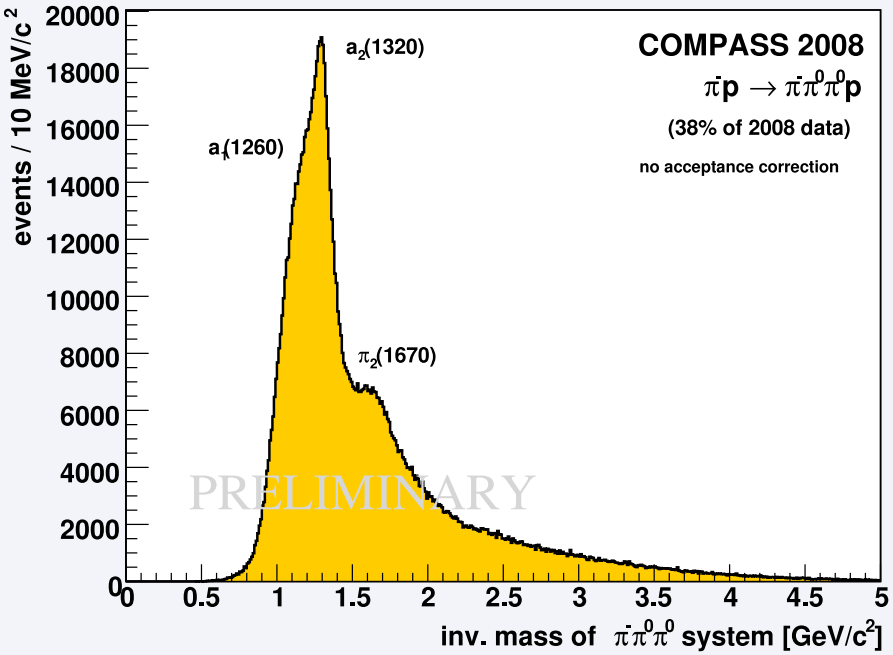
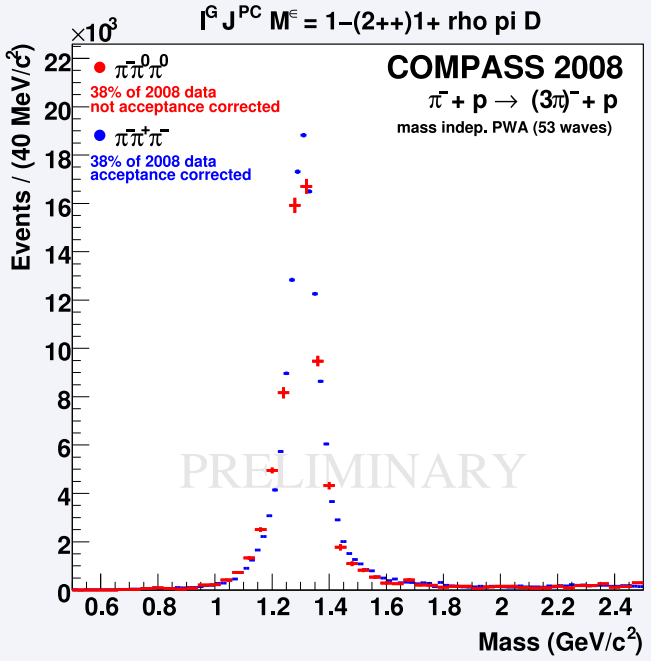
$\pi^- \pi^0 \pi^0$ mass distribution



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

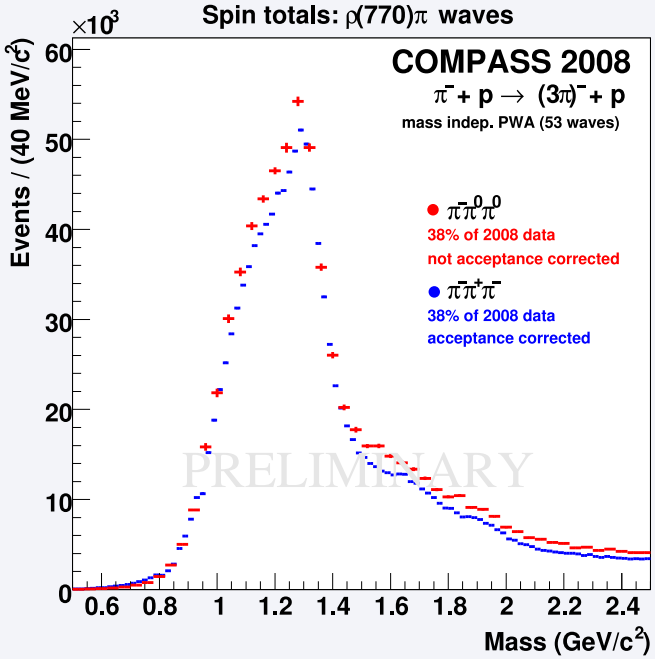


Comparison to PWA of $\pi^- p \to \pi^-\pi^0\pi^0 p$ (2008 Data)

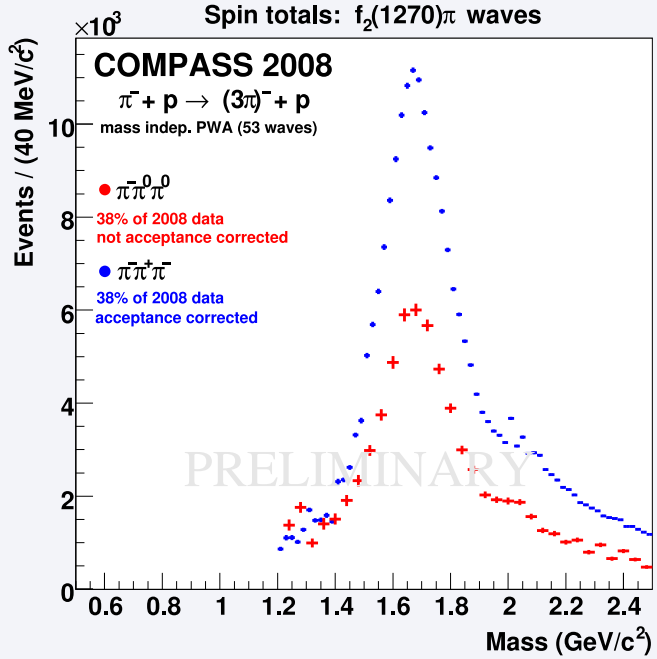
Isospin partner to $\pi^- p \to \pi^-\pi^+\pi^- p$

- Important consistency check
- Comparison with $\pi^-\pi^+\pi^-$ data set: normalization to $a_2(1320)$
- Isospin symmetry: $I = 1$ isobar $\implies$ same intensity
  $I = 0$ isobar $\implies$ half intensity

All $\rho\pi$ waves



All $f_2\pi$ waves

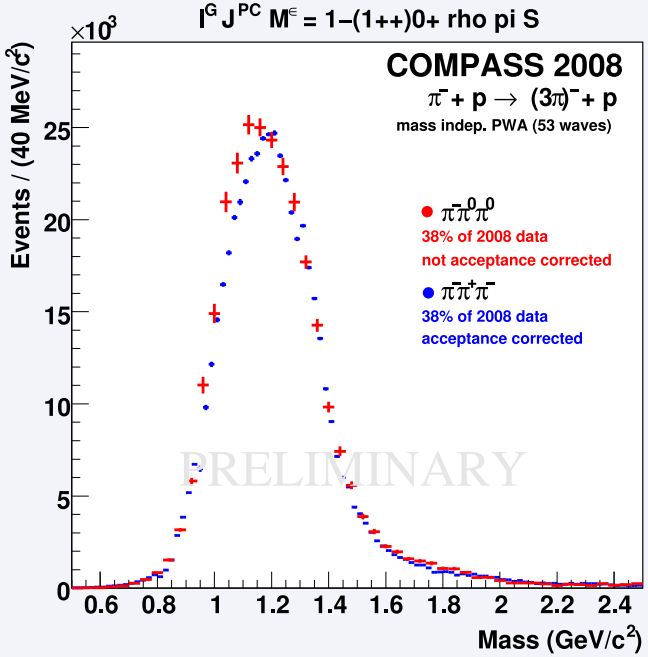


Comparison to PWA of $\pi^- p \to \pi^-\pi^0\pi^0 p$ (2008 Data)

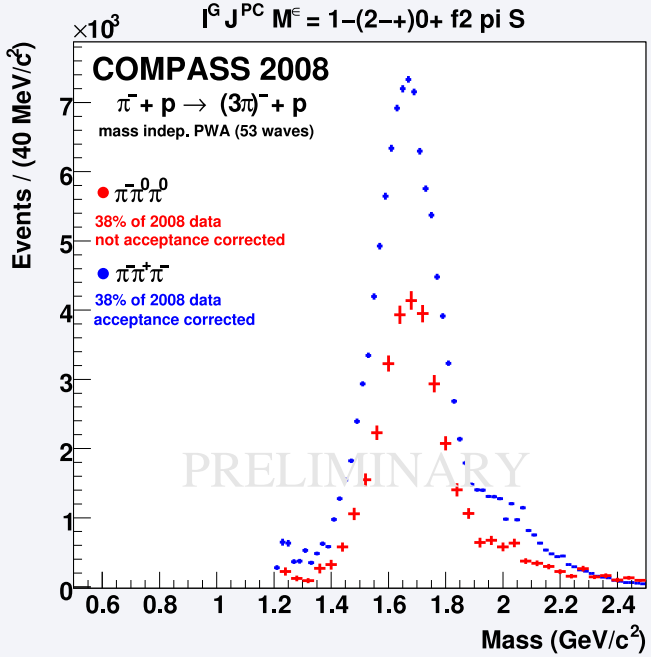
Isospin partner to $\pi^- p \to \pi^-\pi^+\pi^- p$

- Important consistency check
- Comparison with $\pi^-\pi^+\pi^-$ data set: normalization to $a_2(1320)$
- Isospin symmetry: $I = 1$ isobar $\implies$ same intensity
  $I = 0$ isobar $\implies$ half intensity

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



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



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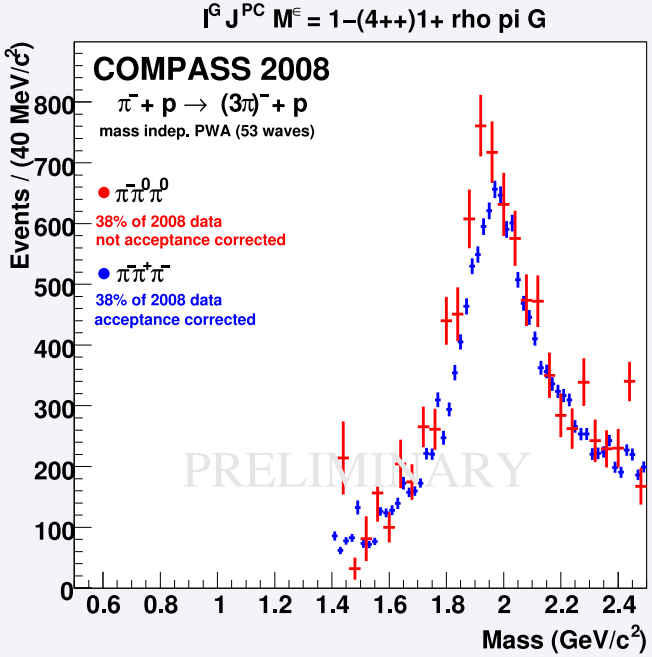
$4^{++}\, 1^+\, [\rho\pi]\mathrm{G} : a_4(2040)$



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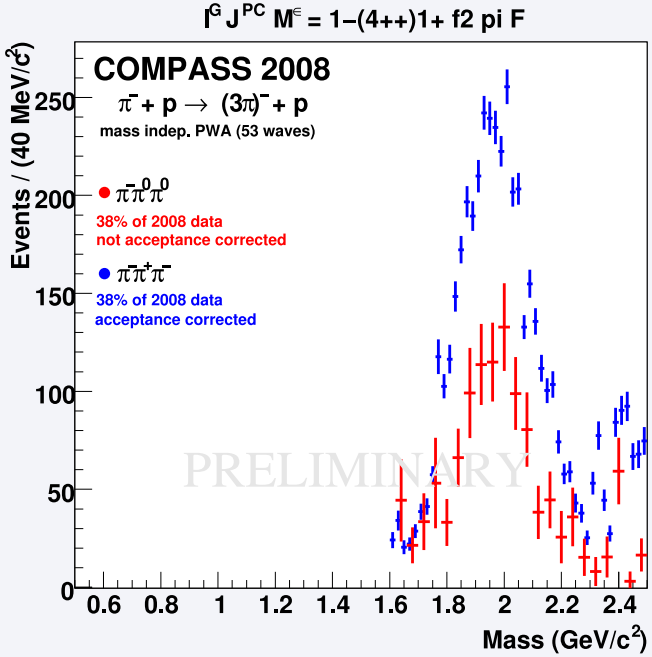
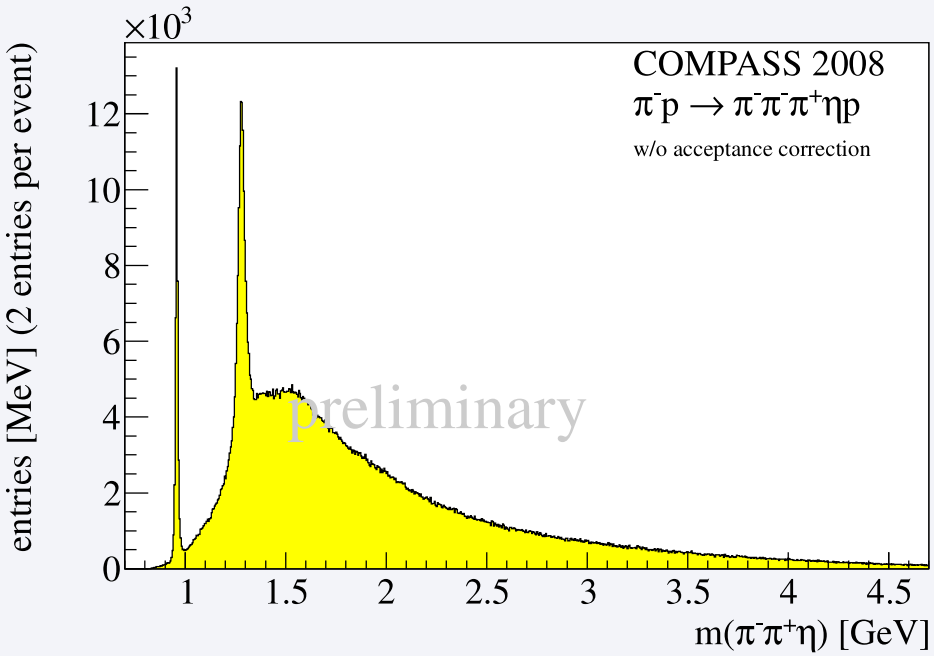


PWA of $\pi^- p \to \eta' \pi^- p$ (2008 Data)

Selection of exclusive 3 charged tracks + 2 photons events

- η' reconstructed via $\pi^+ \pi^- \eta$ decay
- η reconstructed from $\eta \to \gamma\gamma$
- 35 000 events after selection

$\pi^+ \pi^- \eta$ mass distribution



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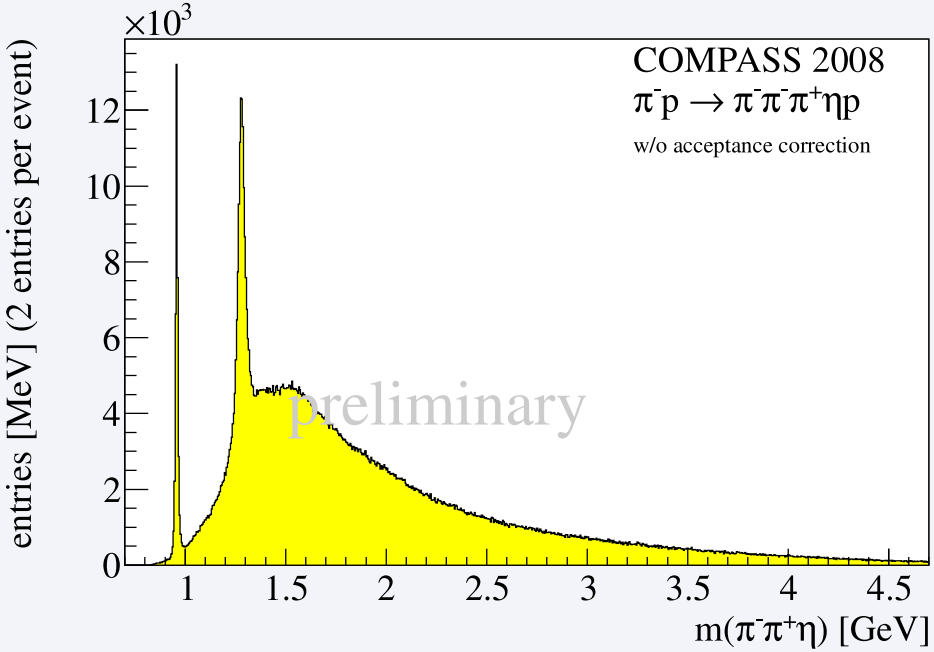
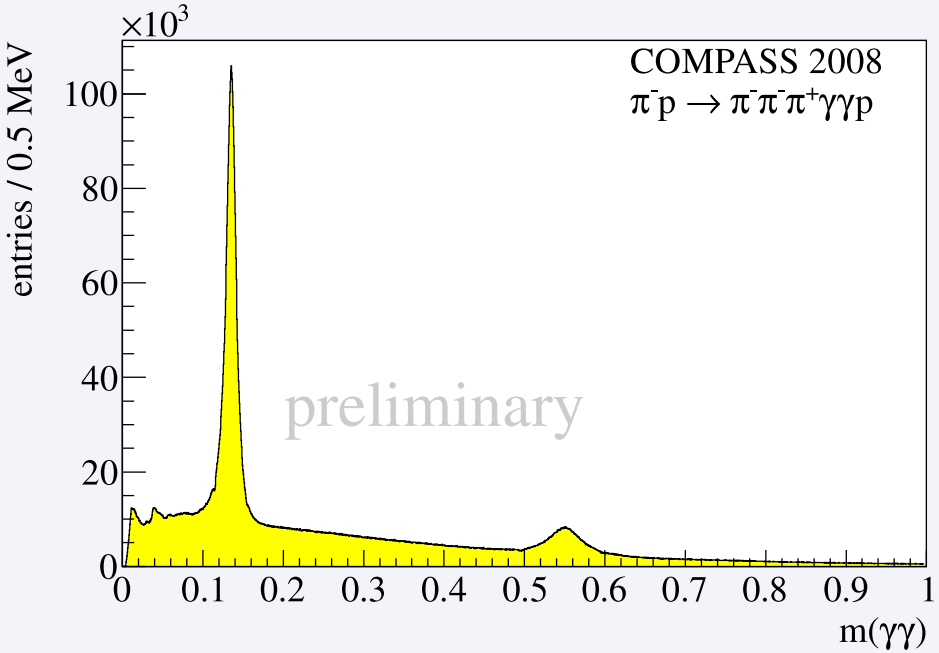


$\gamma\gamma$ mass distribution



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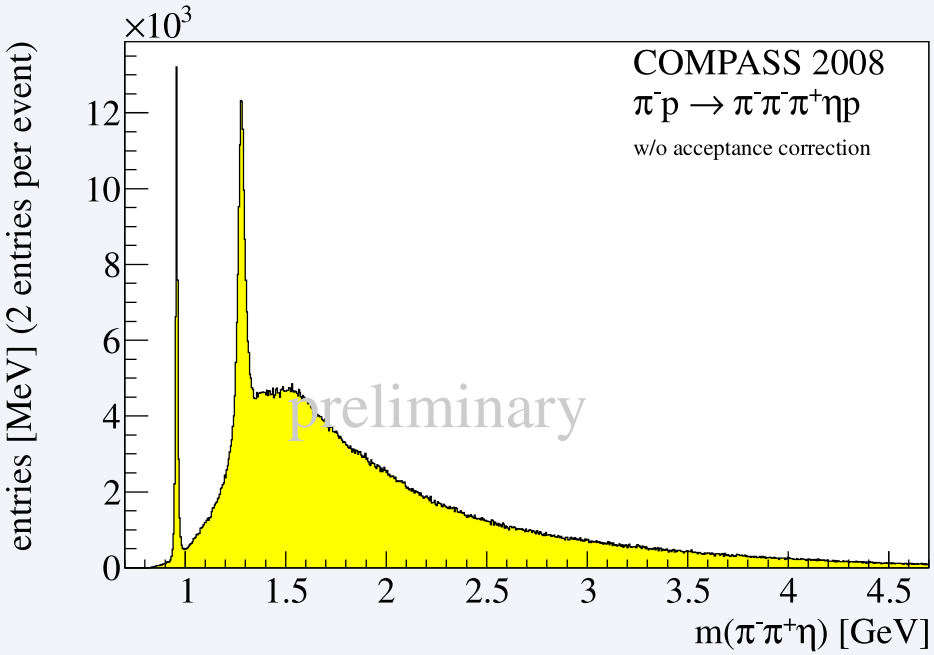

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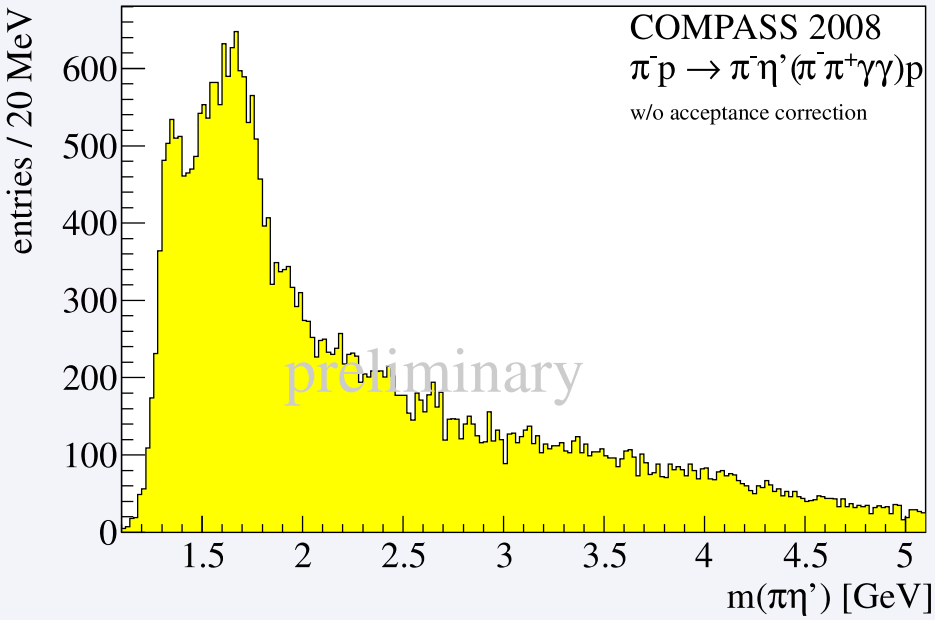
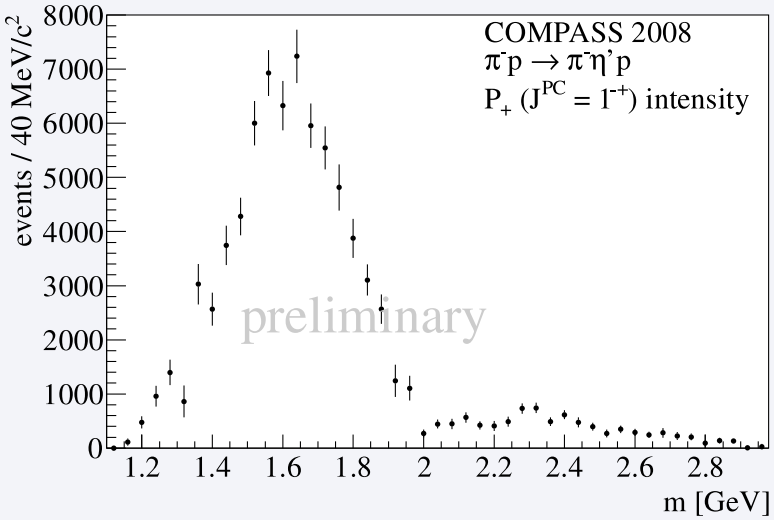


PWA of $\pi^- p \to \eta' \pi^- p$ (2008 Data)

Spin-exotic $1^{-+}\,1^+$



- $1^{-+}\,1^+$ is dominant wave
- Phase motion w.r.t. $2^{++}\,1^+$
- No phase motion in the $2\,\mathrm{GeV}/c^2$ region
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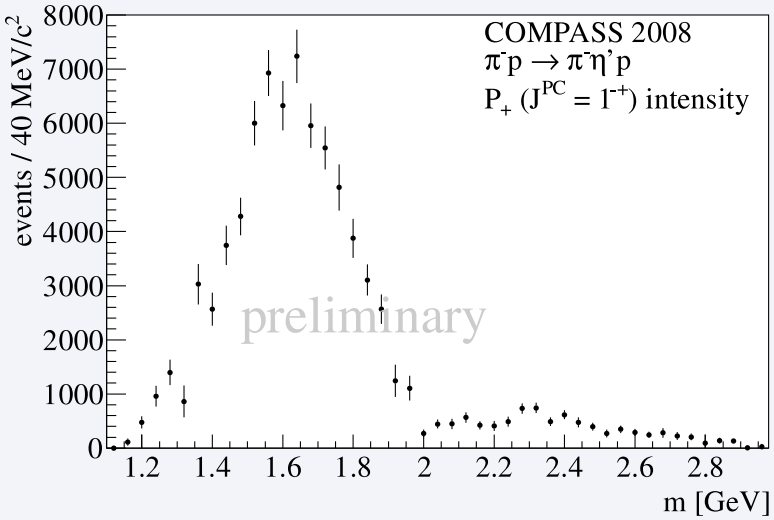
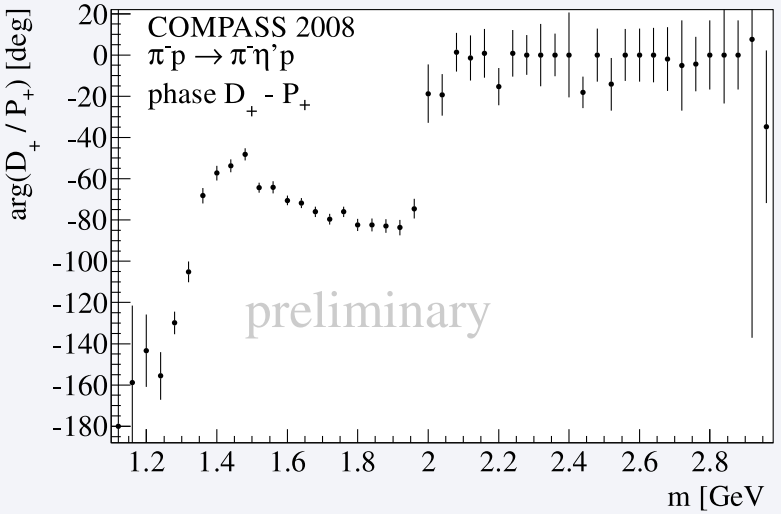
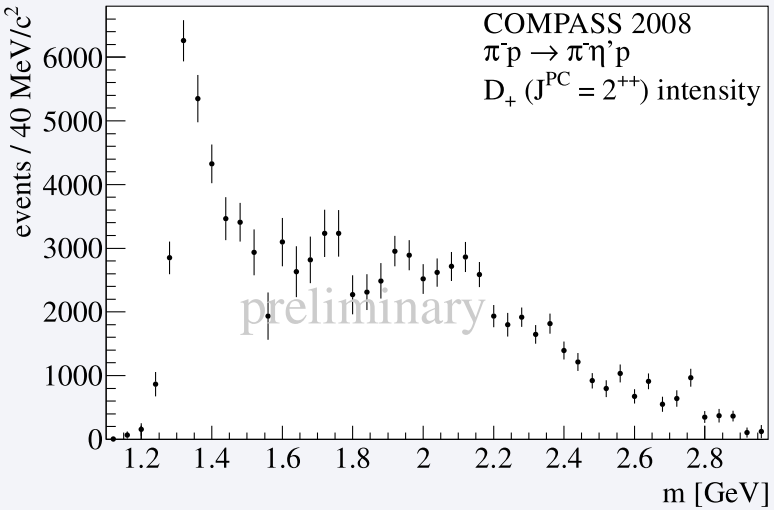


$2^{++}\,1^+ - 1^{-+}\,1^+$



$2^{++}\,1^+ : a_2(1320)$



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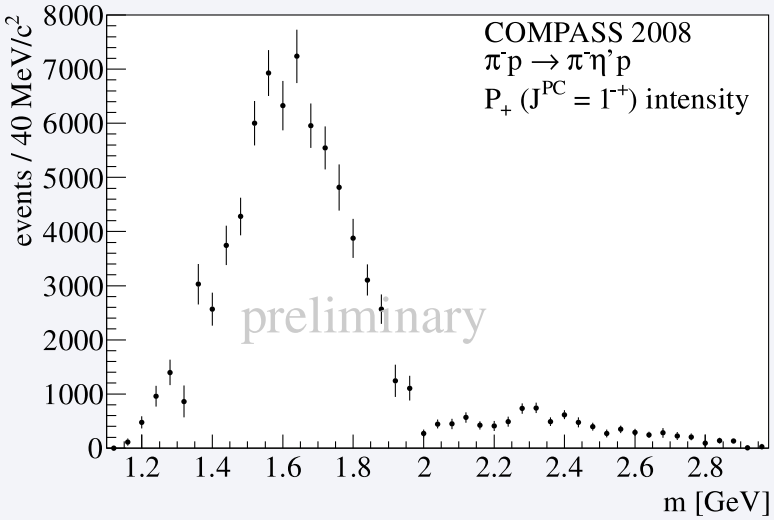
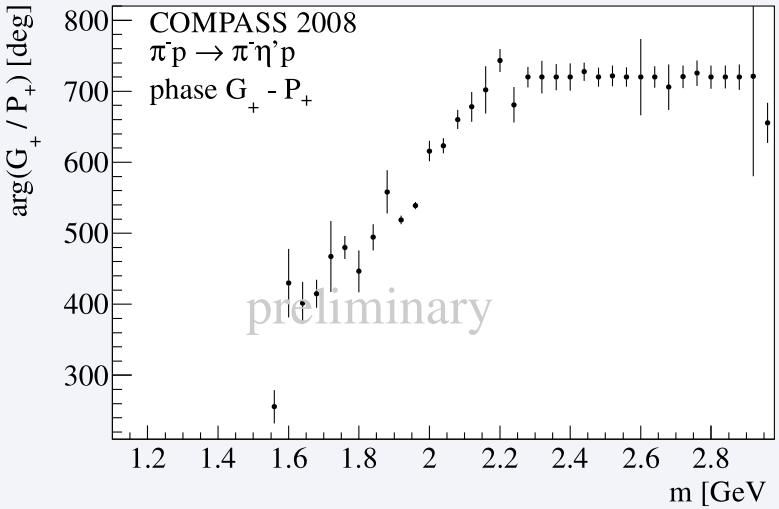
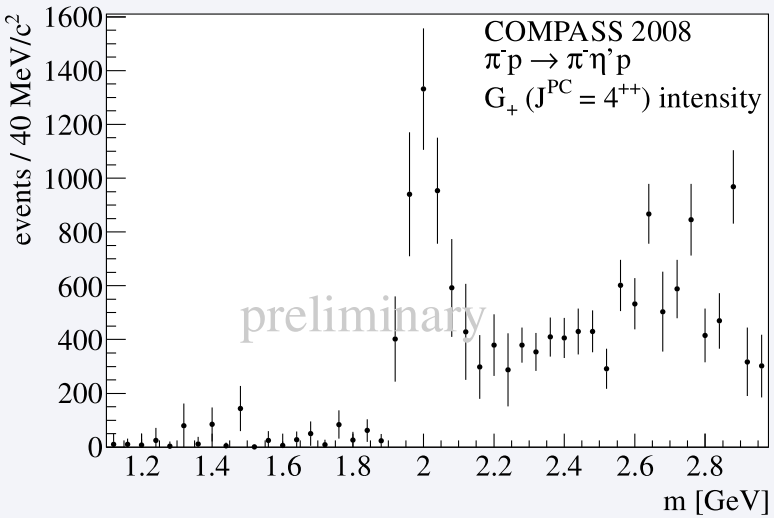


$4^{++}\,1^+ - 1^{-+}\,1^+$



$4^{++}\,1^+ : a_4(2040)$



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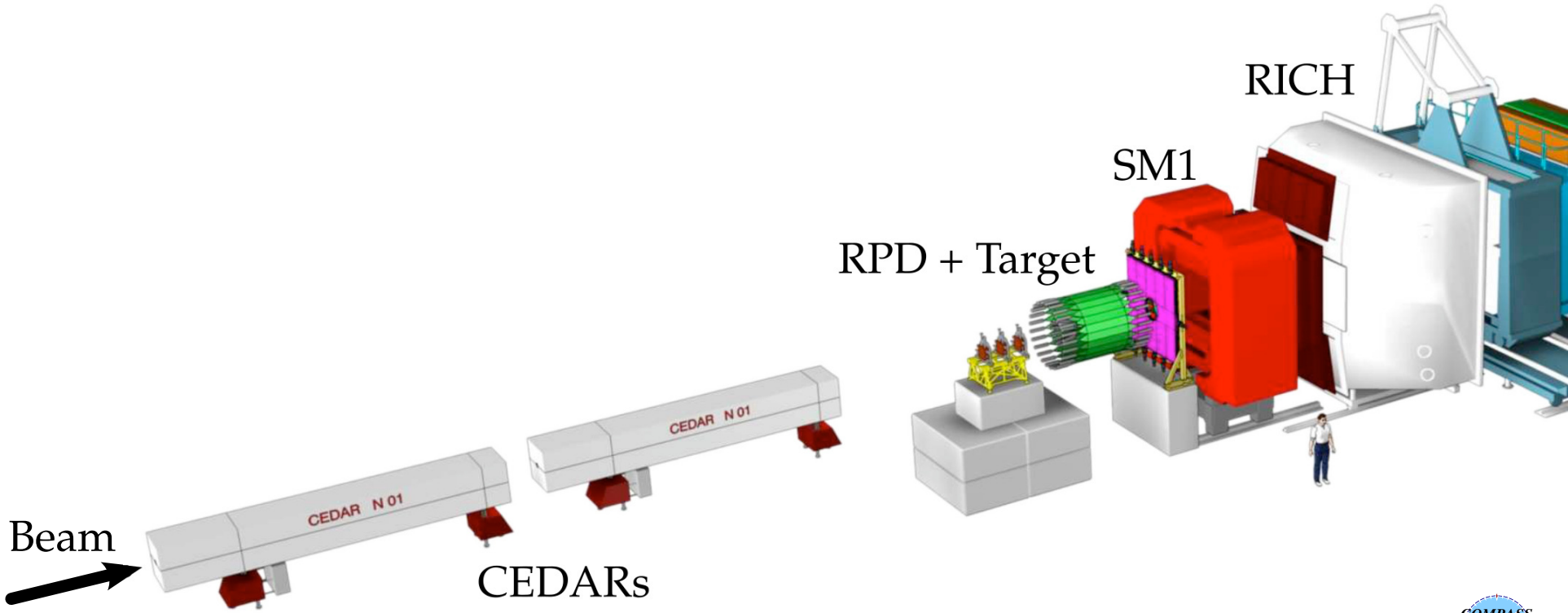
Outline

Kaon Diffraction into $K^-\pi^+\pi^-$ Final State

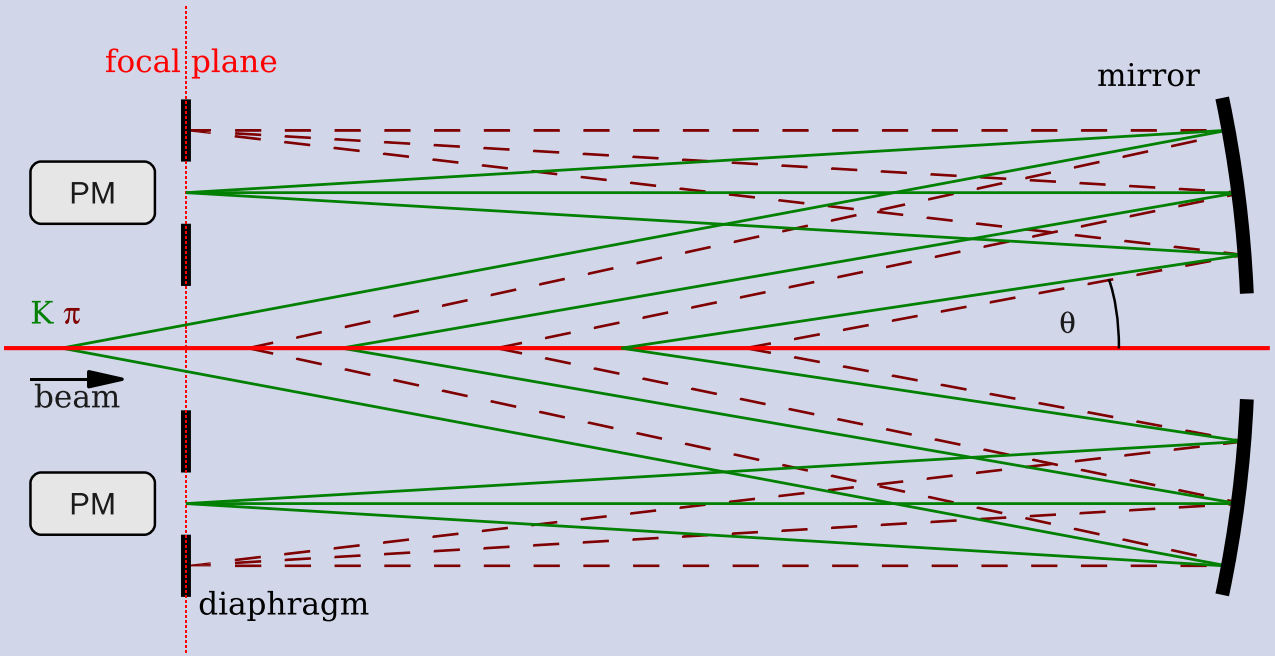
Experimental Setup

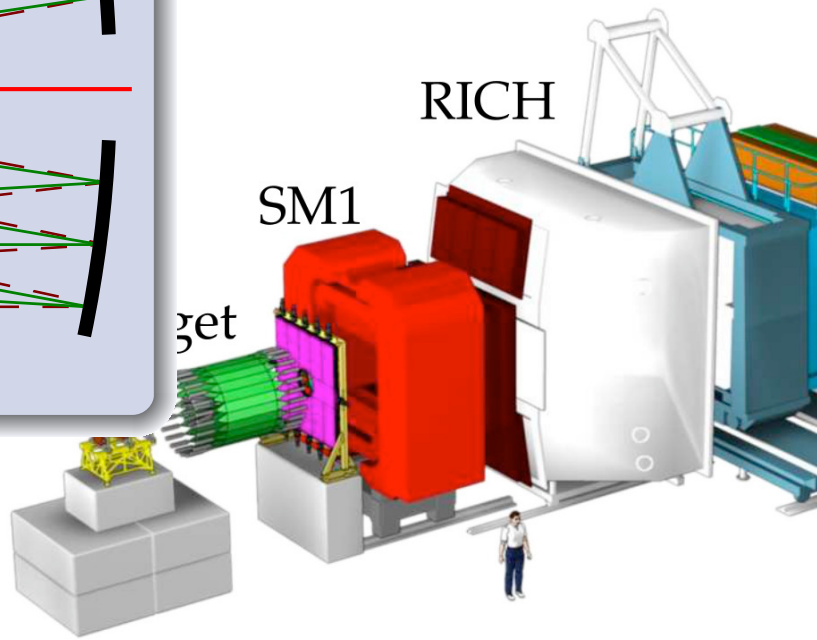


Kaon Diffraction into $K^-\pi^+\pi^-$ Final State

Experimental Setup

2 % K^- beam content tagged by CEDARs

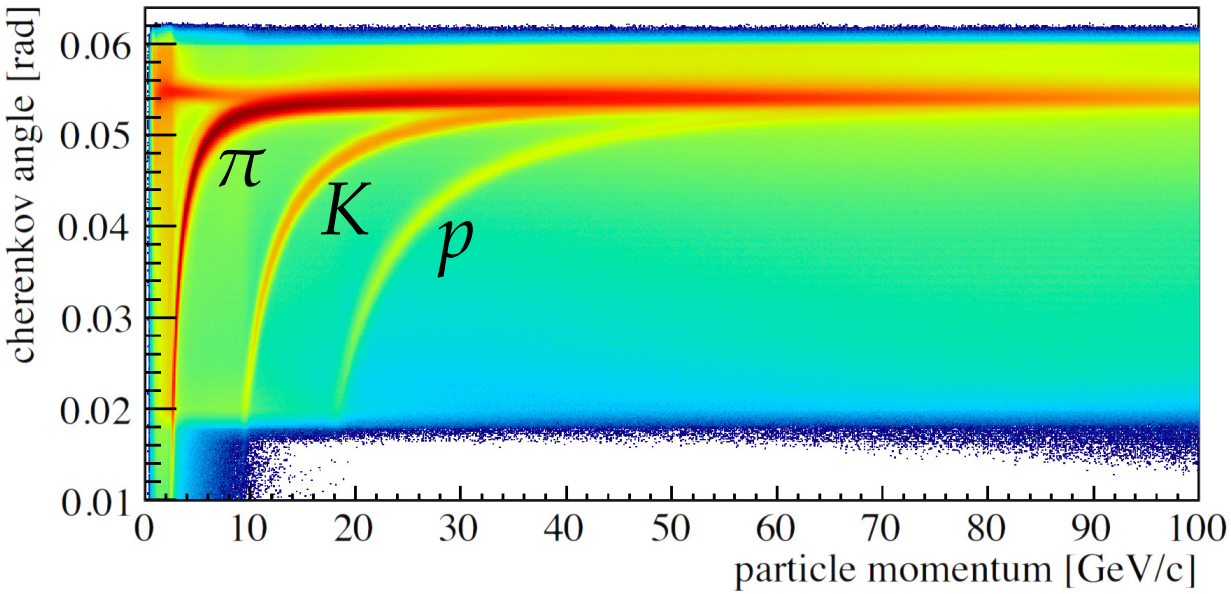


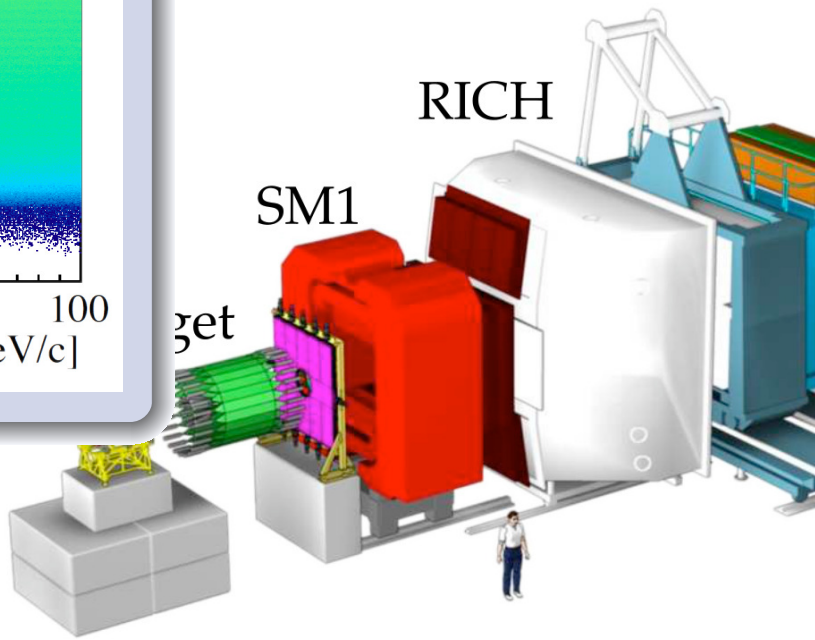


Kaon Diffraction into $K^-\pi^+\pi^-$ Final State

Experimental Setup

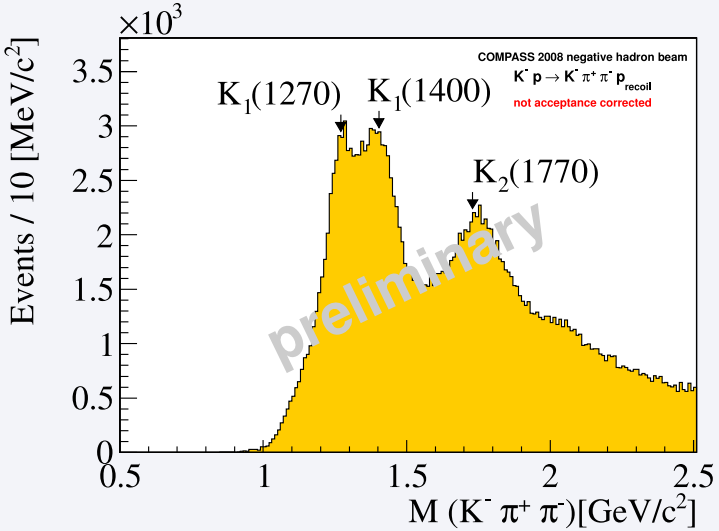
Final-state K^- identified by RICH





PWA of $K^- p \to K^- \pi^+ \pi^- p$ (2008 Data)

$K^-\pi^+\pi^-$ mass spectrum



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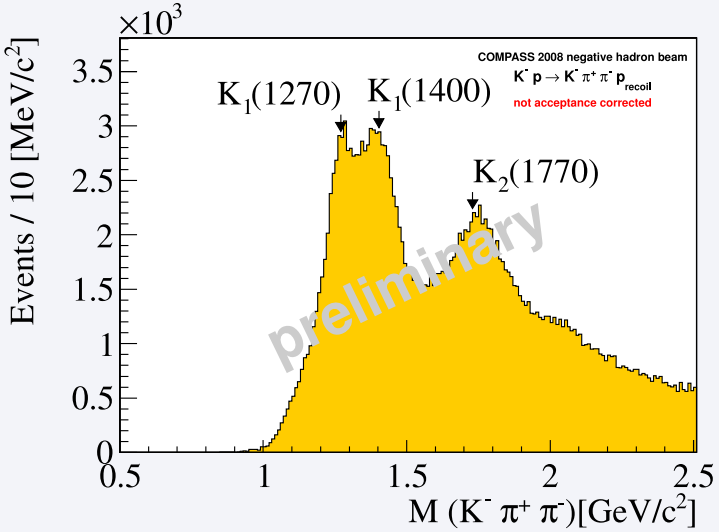
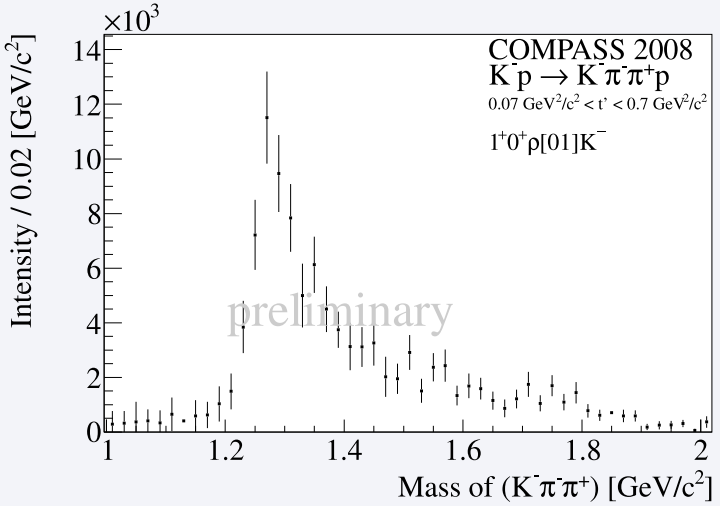


$1^+ 0^+ [\rho K^-]S : K_1(1270)$



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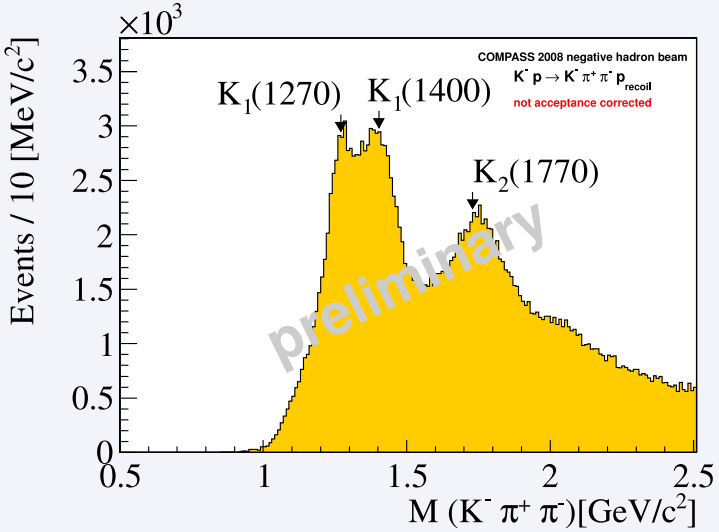
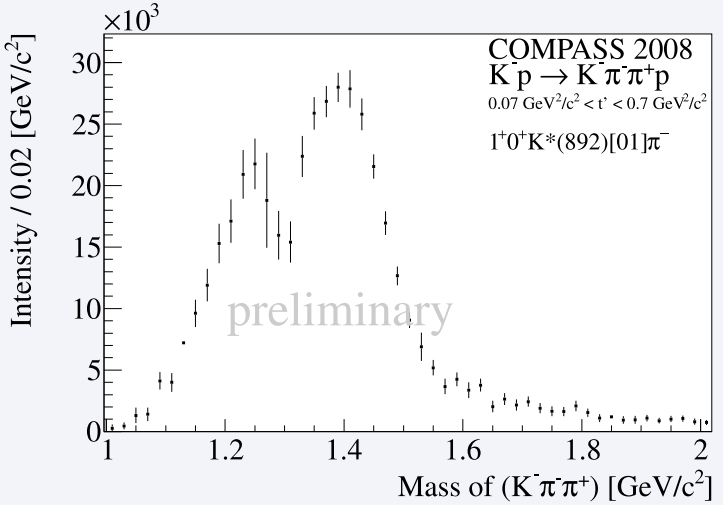


$1^+ 0^+ [K^*(892)\pi^-]S : K_1(1270, 1400)$



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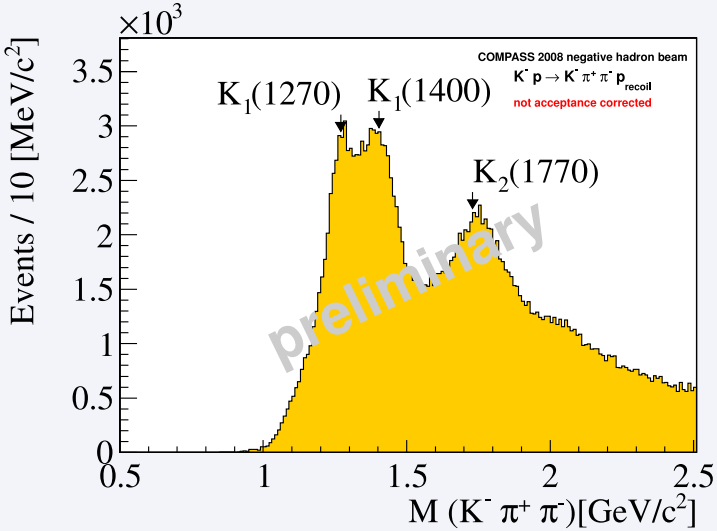

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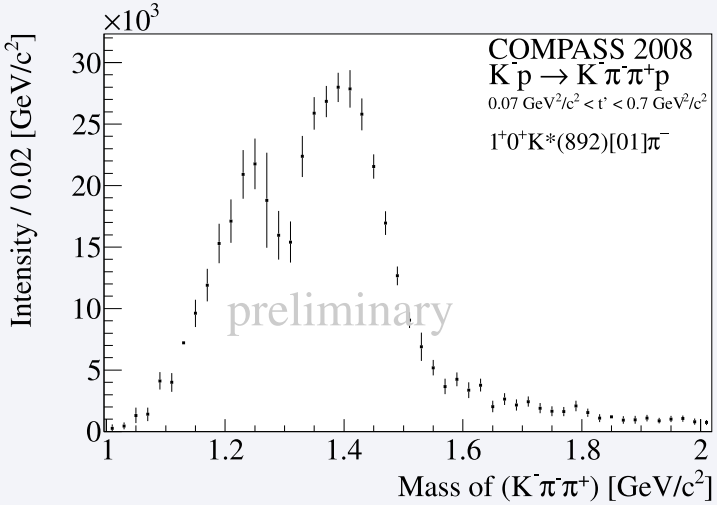
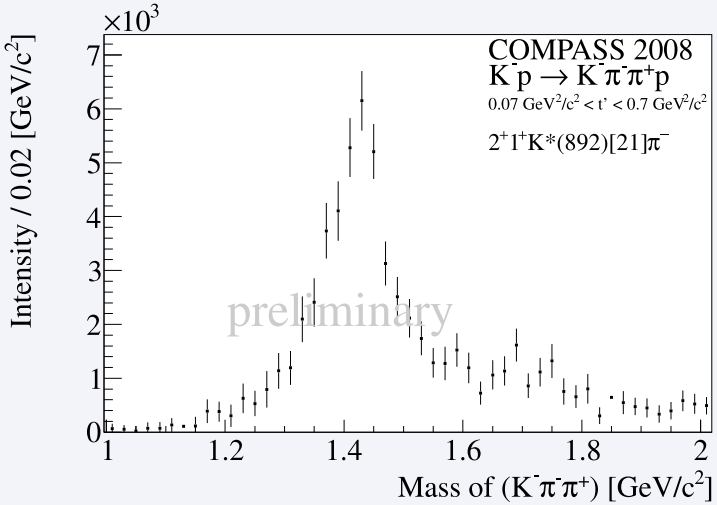


$2^+\,1^+\,[K^*(892)\pi^-]D : K^*_2(1430)$



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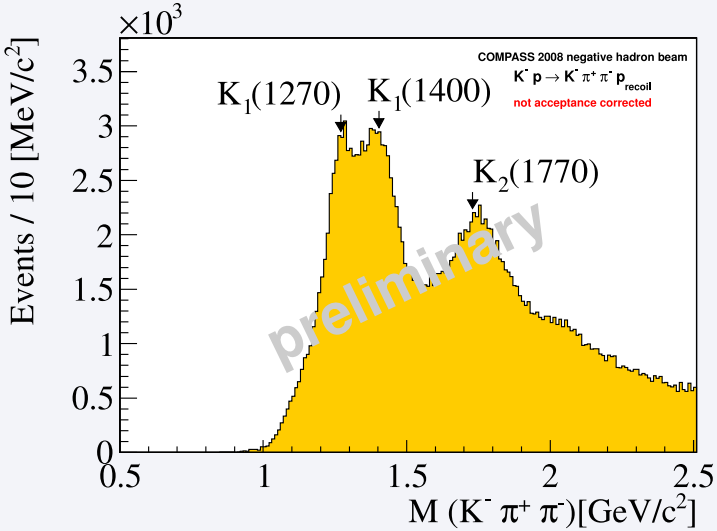

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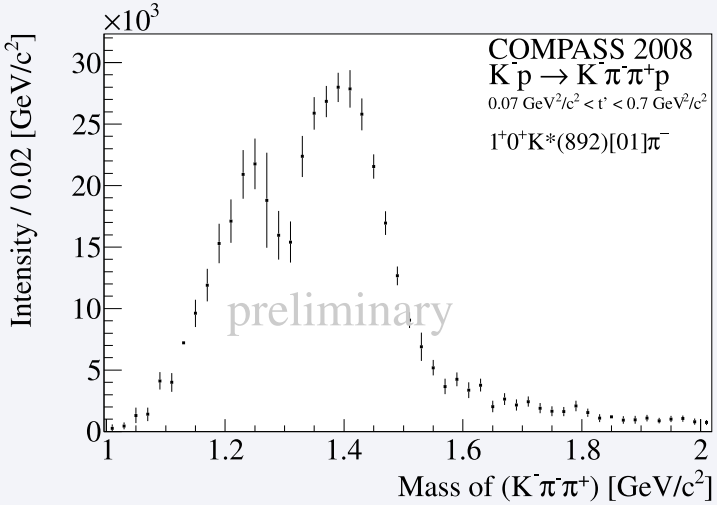
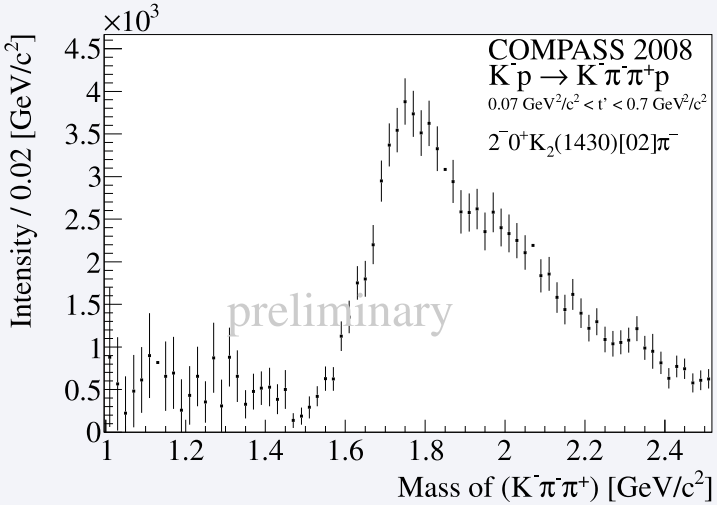


$2^-\,0^+\,[K_2(1430)\pi^-]S : K_2(1770, 1820)$



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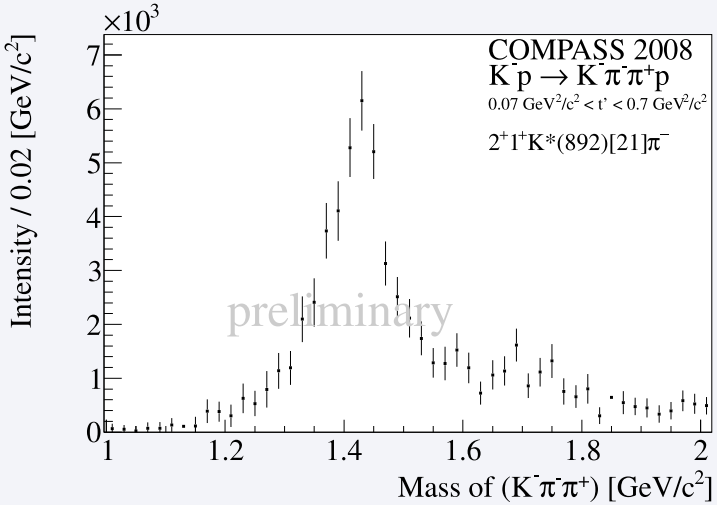

Conclusions and Outlook

Huge amount of data from 2008-09 runs

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- Main focus on search for J^{PC}-exotic mesons
  - Pilot run: significant $J^{PC} = 1^{-+}$ signal consistent with $\pi_1(1600)$ seen in $\pi^-\pi^+\pi^-$ data on Pb target
  - Detailed study of $\pi^-\pi^+\pi^-$ final state
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Poster session

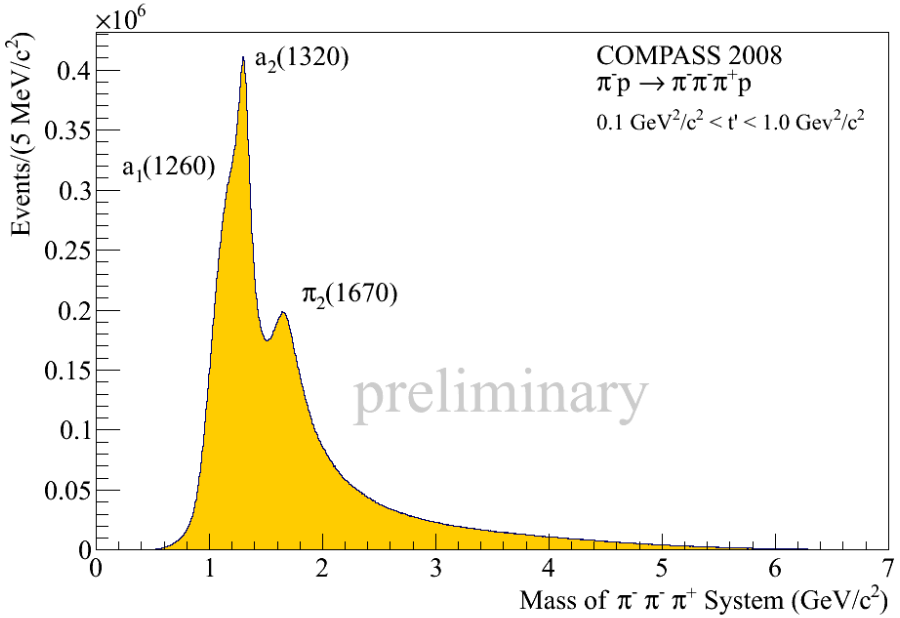
- **#25:** Study of the π^- Pb $\to \pi^-\pi^+\pi^-$ Pb Primakoff Reaction at COMPASS
- **#16:** OZI Test and Spin Alignment of Vector Mesons with the COMPASS Experiment

Outline

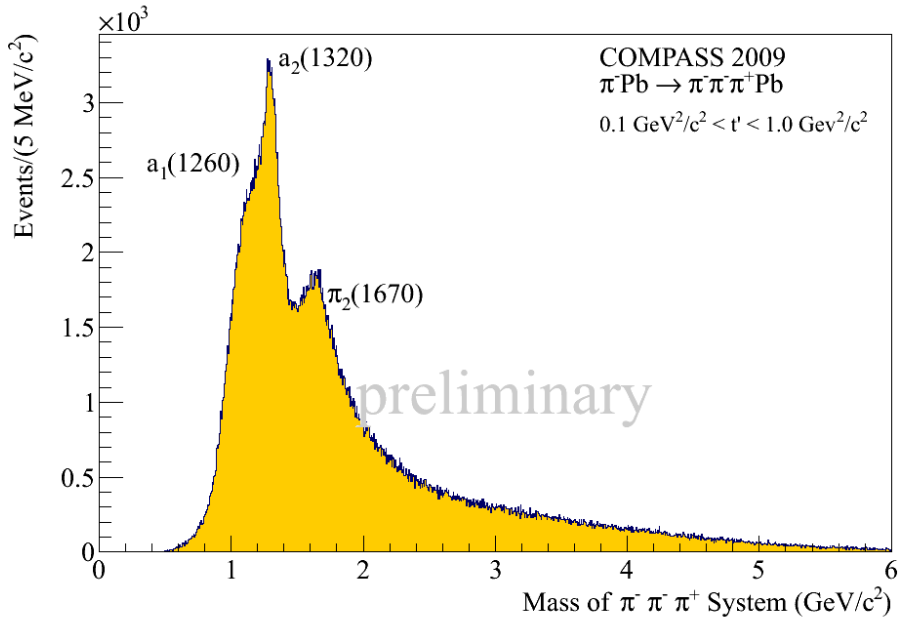
$\pi^-\pi^+\pi^-$ Final State

$\pi^-\pi^+\pi^-$ Invariant Mass Distribution

p target



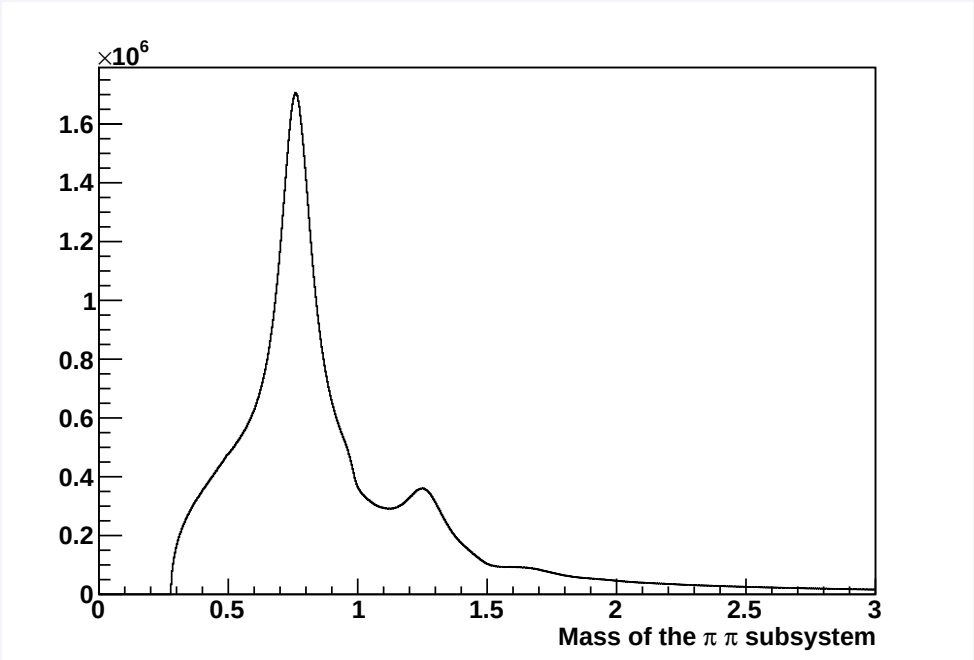
Pb target



$\pi^-\pi^+\pi^-$ Final State

$\pi^+\pi^-$ Invariant Mass Distribution

p target



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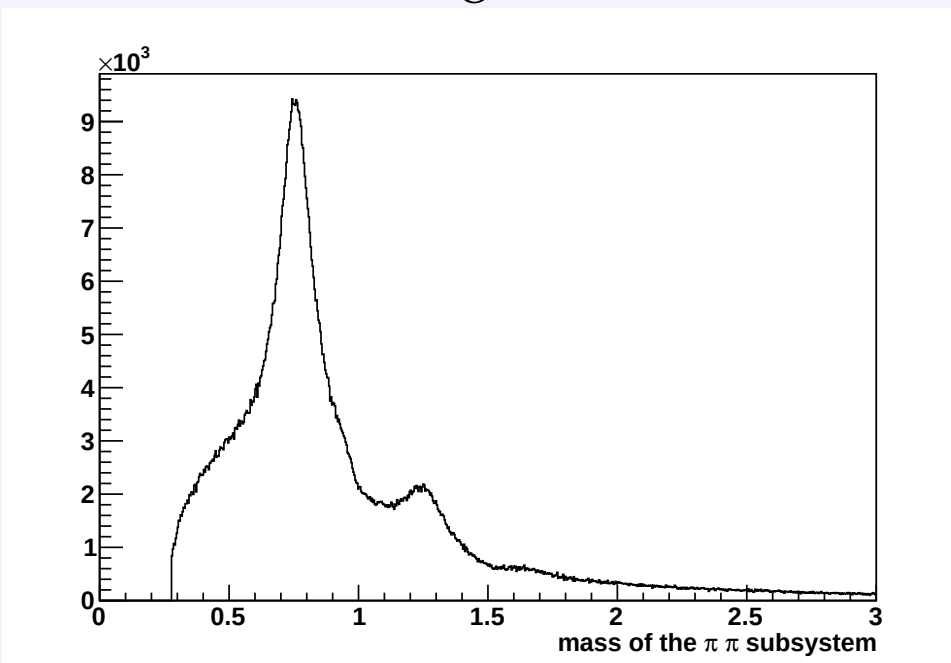
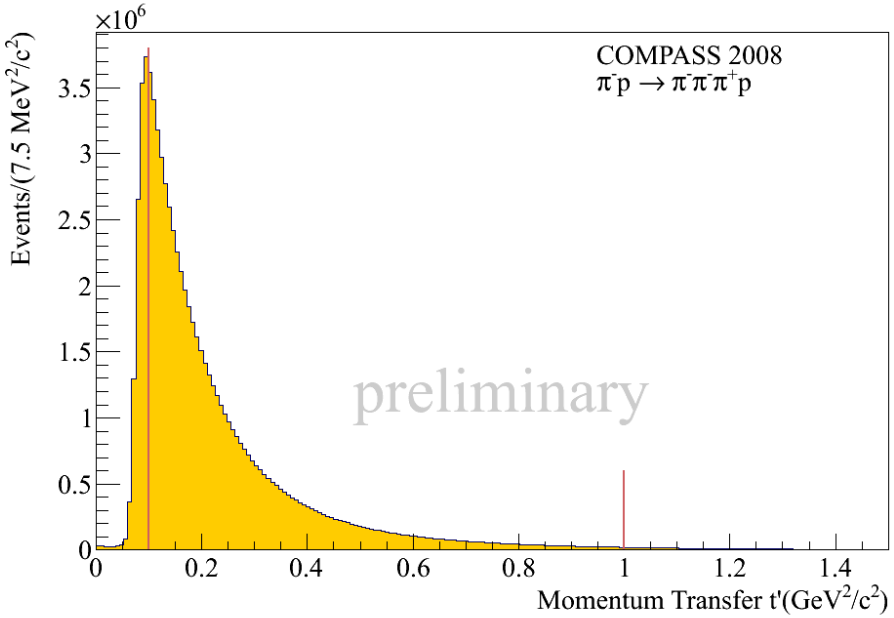


$\pi^-\pi^+\pi^-$ Final State

Momentum Transfer Distribution

p target



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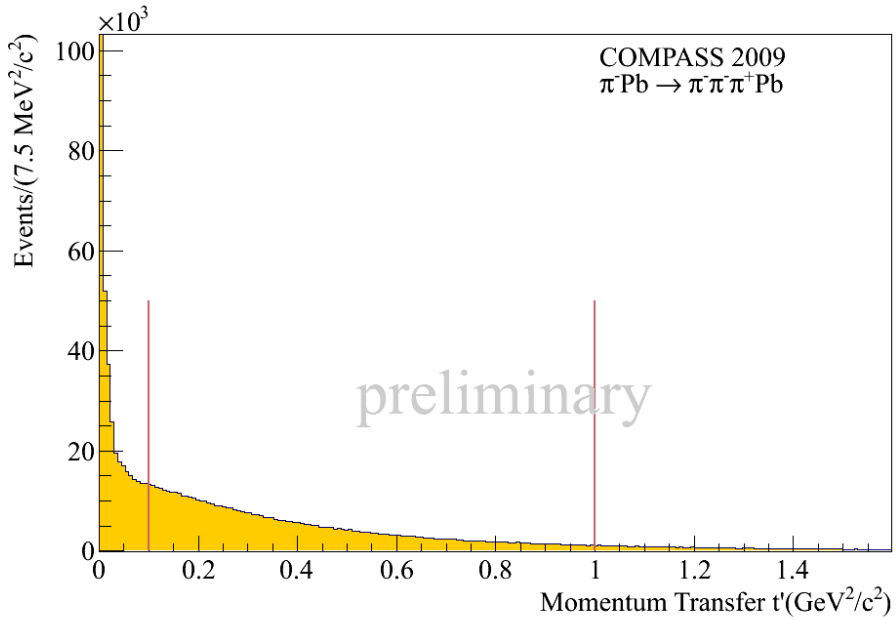
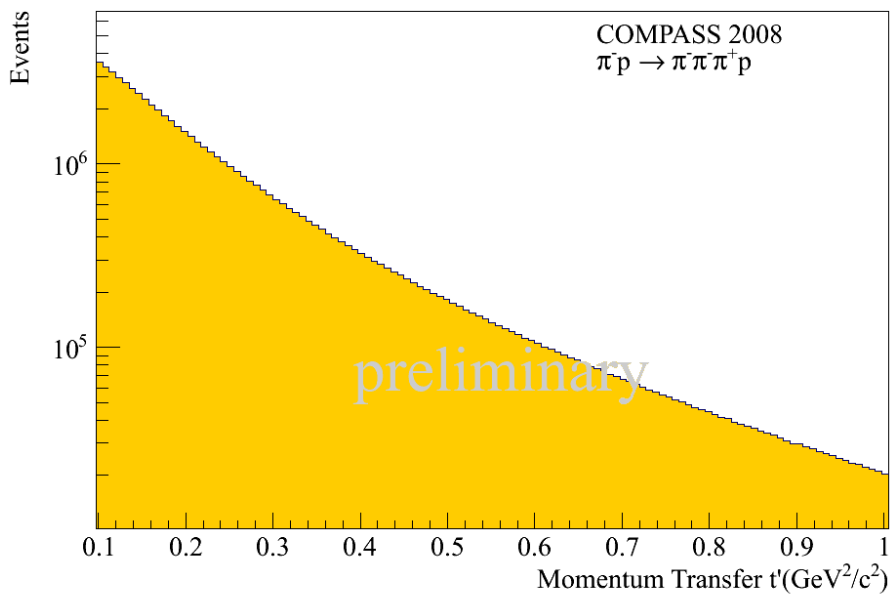


$\pi^-\pi^+\pi^-$ Final State

Momentum Transfer Distribution

p target



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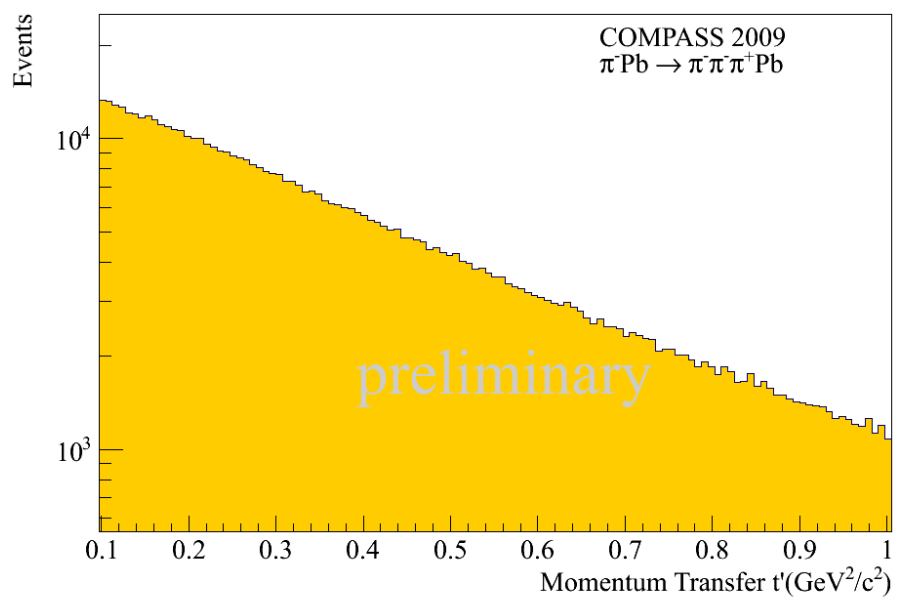
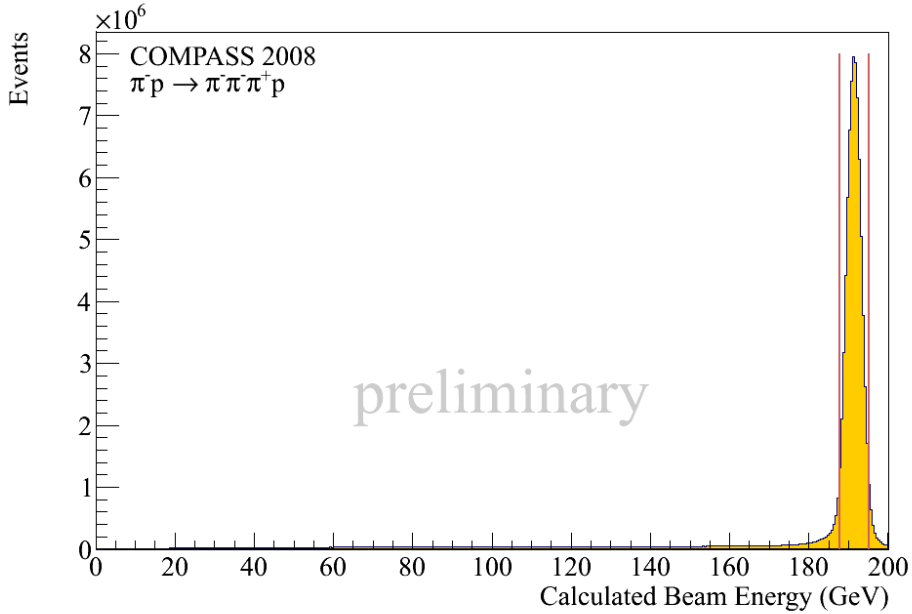


$\pi^-\pi^+\pi^-$ Final State

$\pi^-\pi^+\pi^-$ Exclusivity

p target



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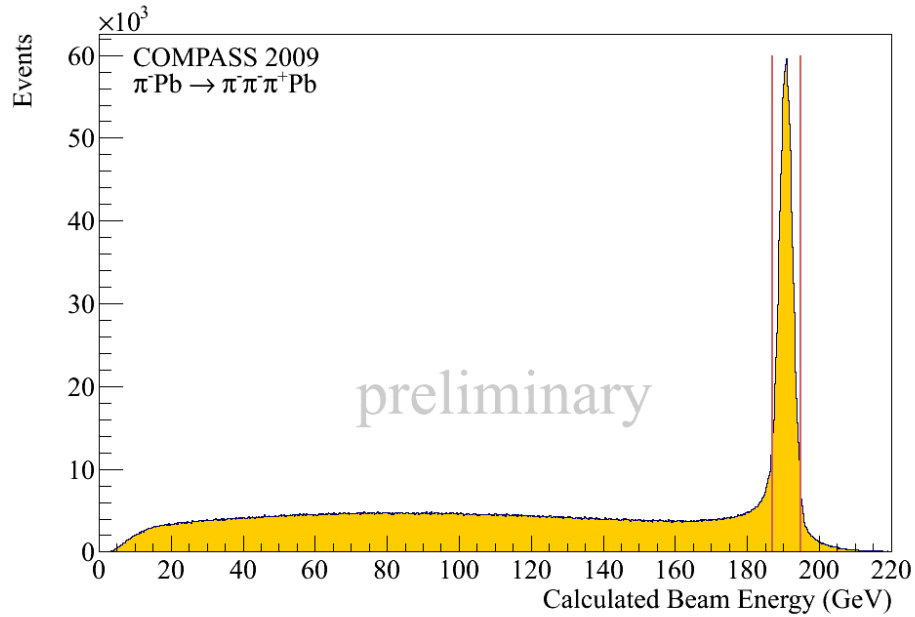
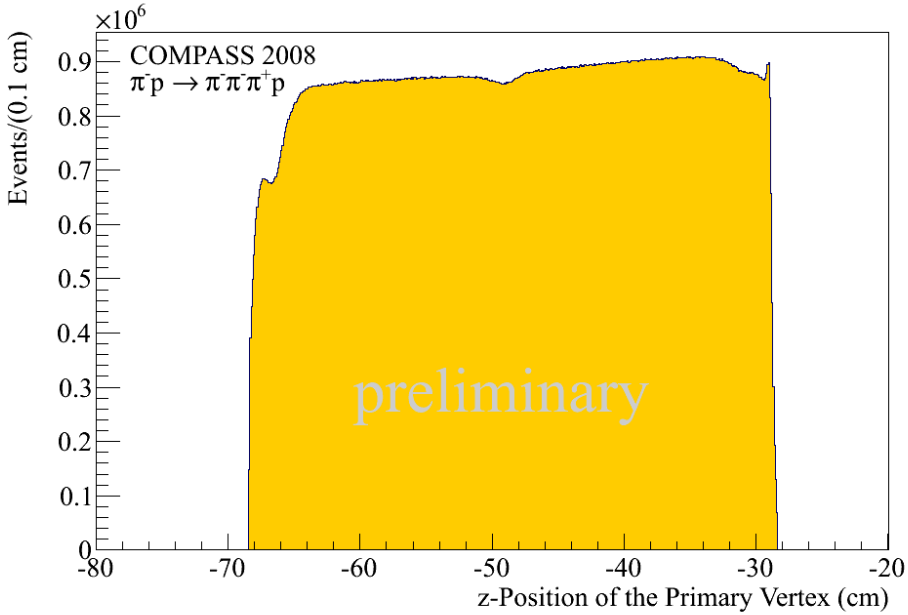


$\pi^-\pi^+\pi^-$ Final State

Primary Vertex Distribution

p target



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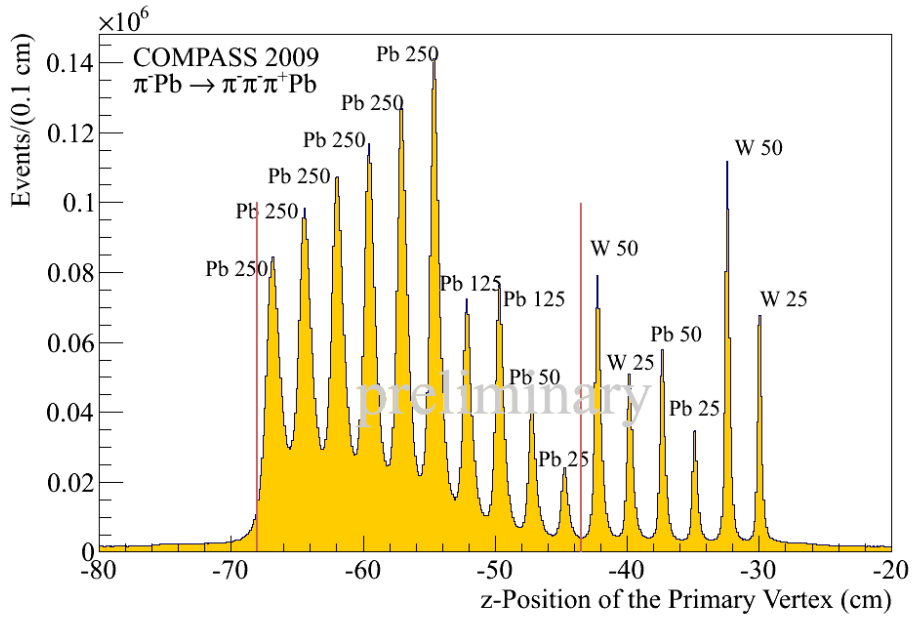
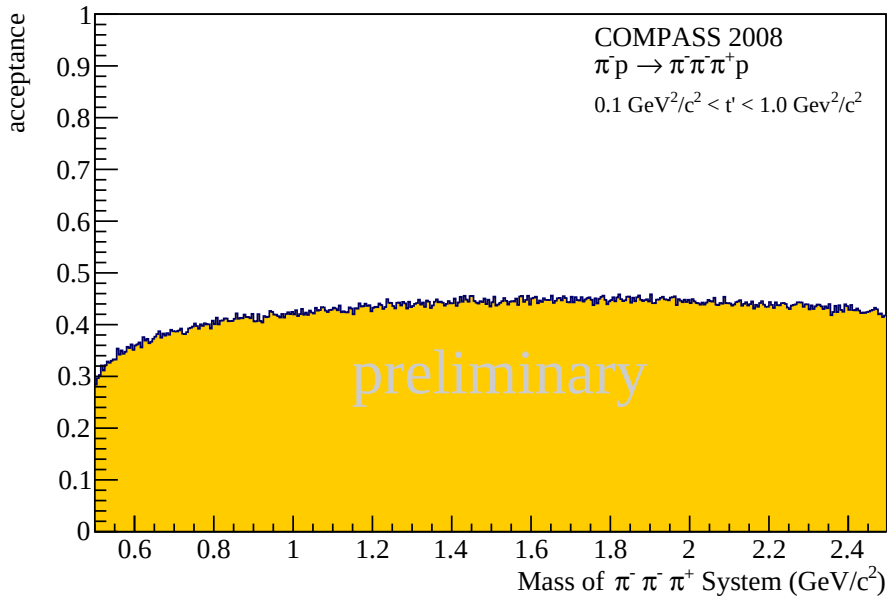


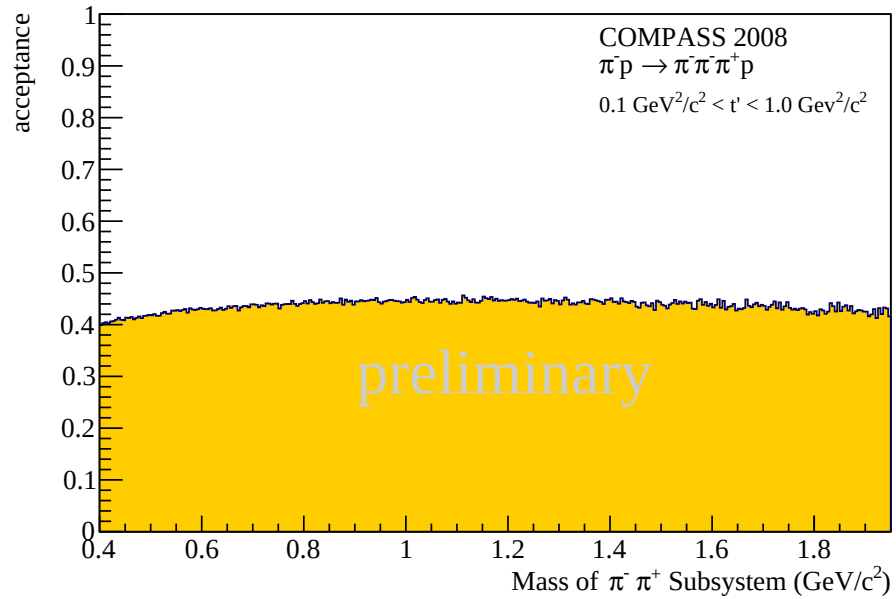
$\pi^-\pi^+\pi^-$ Final State

Acceptance (p Target)

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



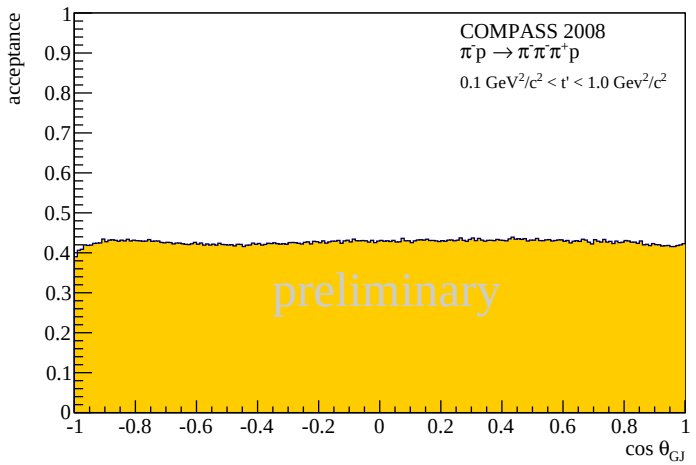
$\pi^+\pi^-$ mass



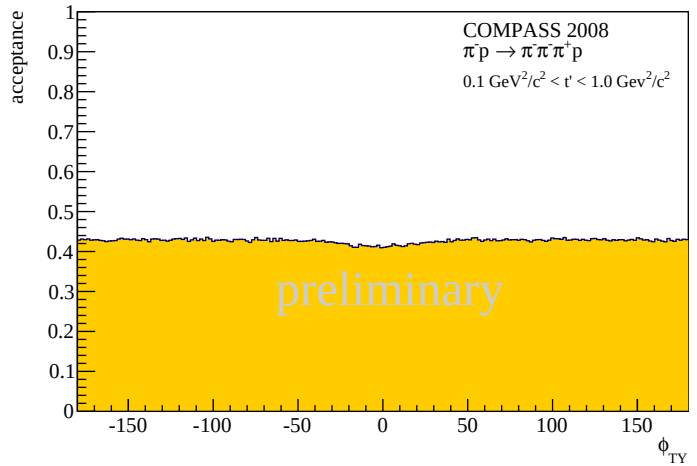
$\pi^-\pi^+\pi^-$ Final State

Acceptance (p Target)

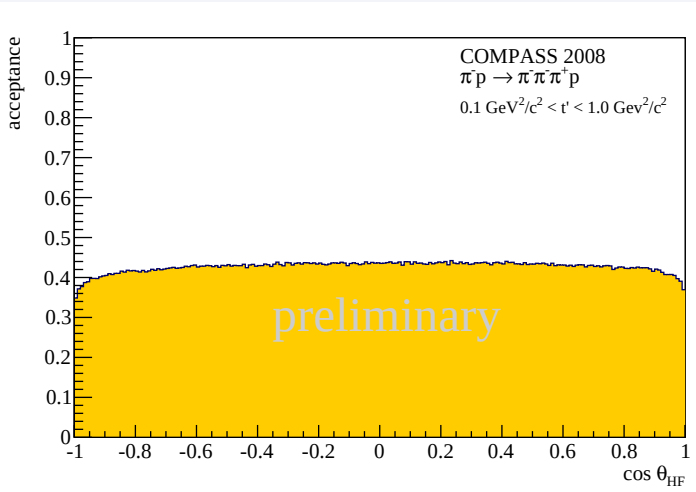
Gottfried-Jackson frame: $\cos\theta_{GJ}$



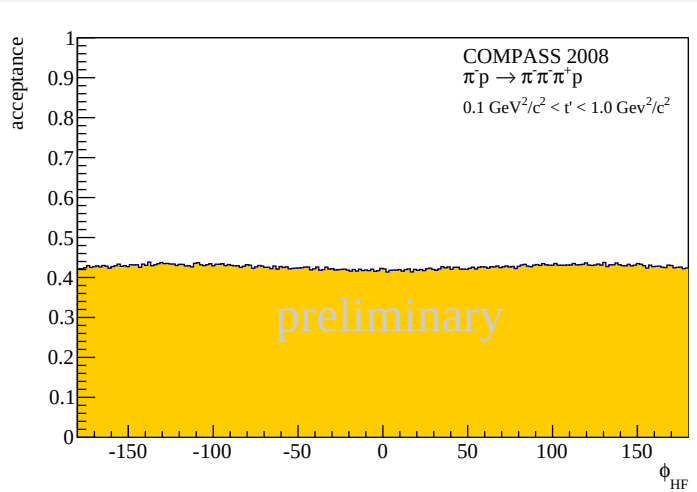
Gottfried-Jackson frame: φ_{TY}



Helicity frame: $\cos\theta_{HF}$

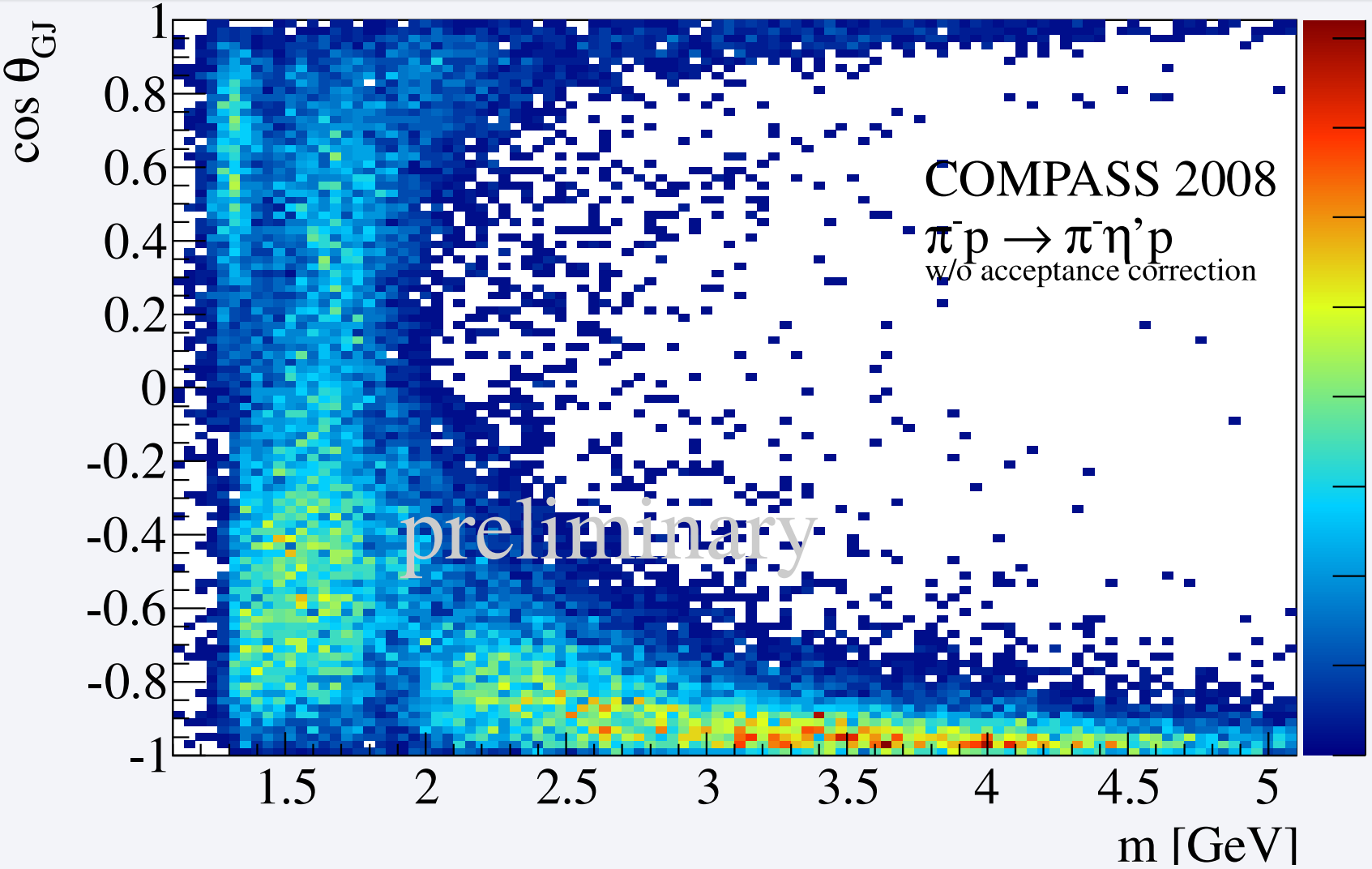


Helicity frame: φ_{HF}



$\eta'\pi^-$ Final State

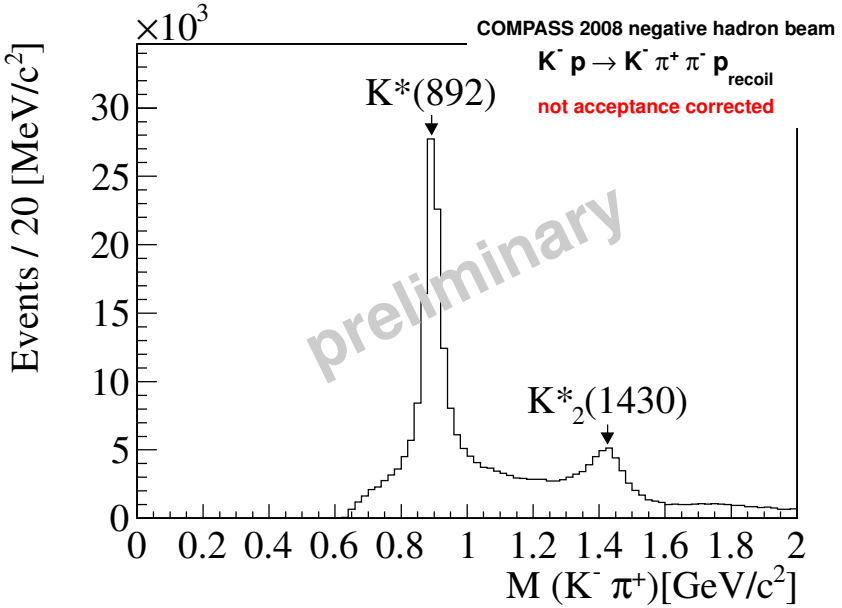
$\cos\theta_{GJ}$ vs. $\eta'\pi^-$ Invariant Mass



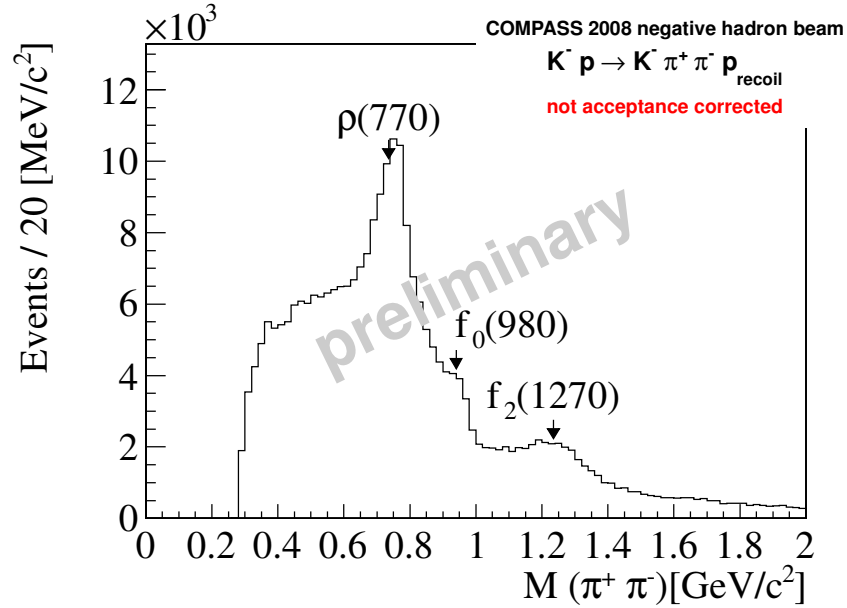
$K^-\pi^+\pi^-$ Final State

Subsystem Invariant Mass

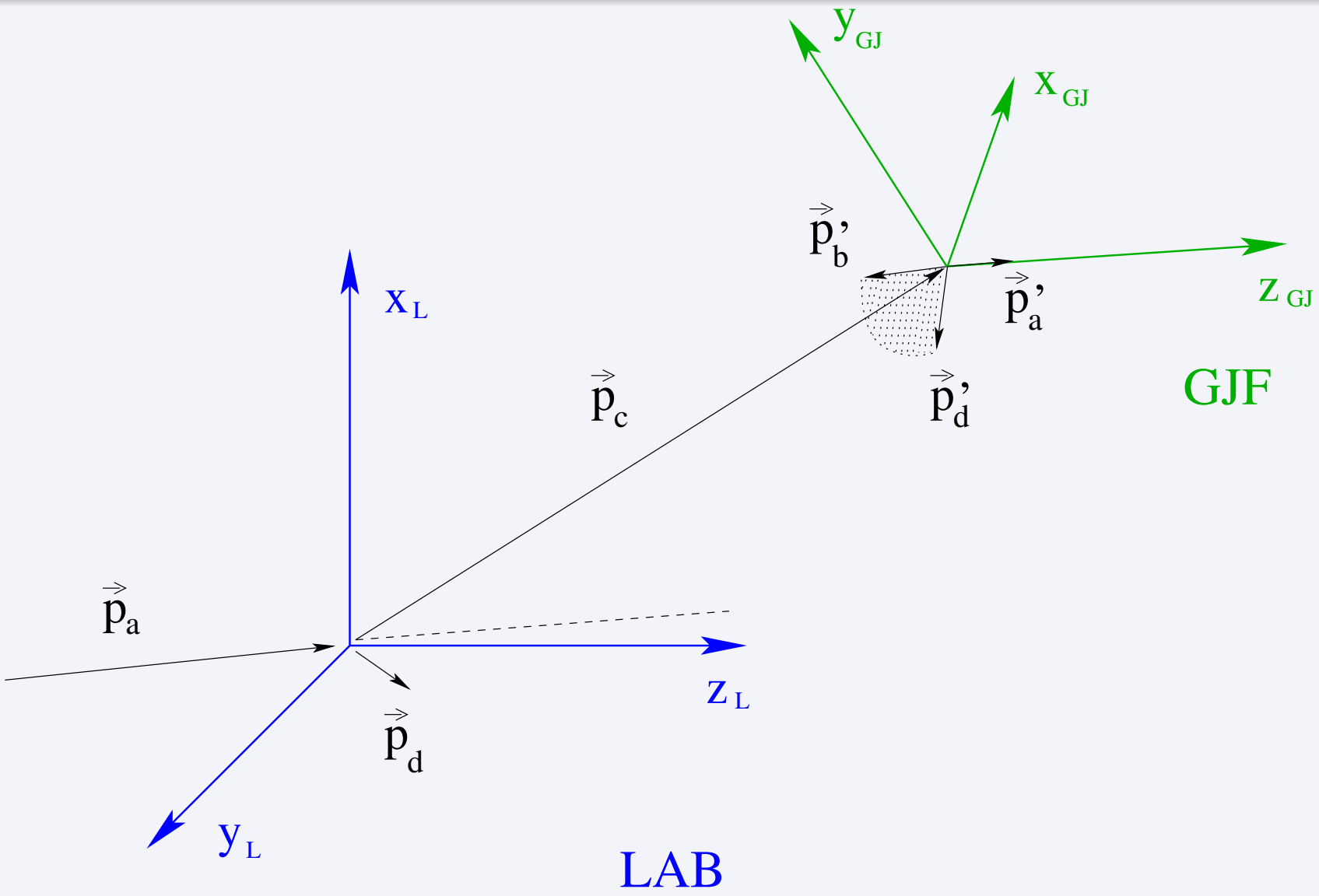
$K^-\pi^+$ mass



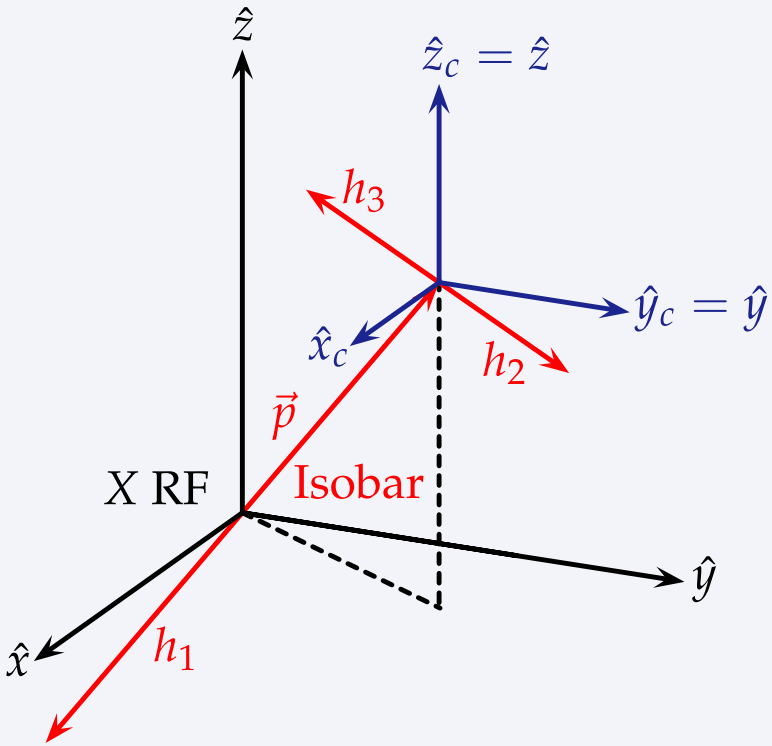
$\pi^+\pi^-$ mass

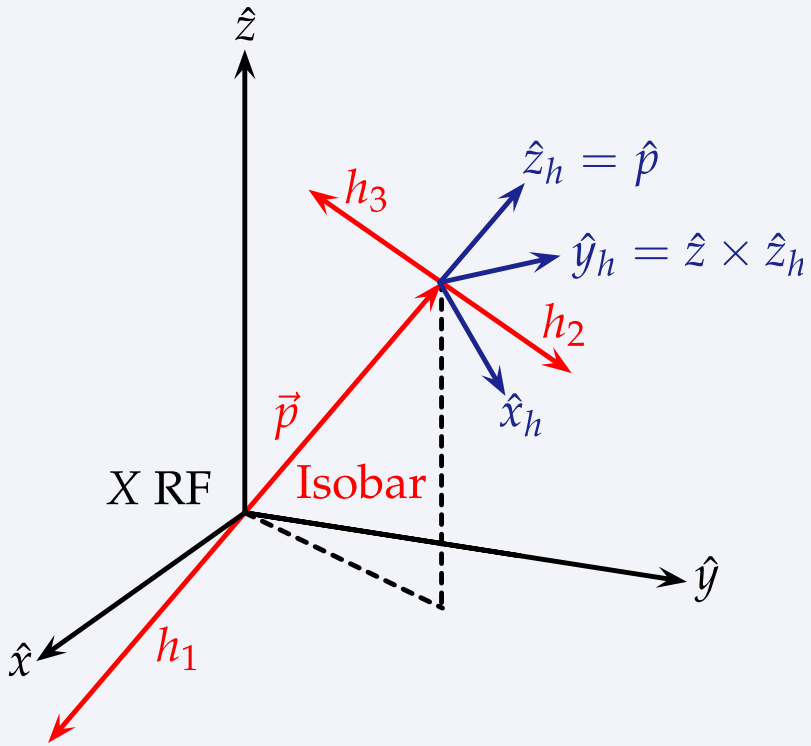


Gottfried-Jackson Coordinate System



Canonical vs. Helicity Coordinate System





Partial-Wave Analysis Formalism

Cross section parameterization in mass-independent PWA

$$\sigma(\tau; m_X) = \sum_{\epsilon=\pm1} \sum_{r=1}^{N_r} \left| \sum_{i}^{\text{waves}} T^{\epsilon}_{ir}(m_X)\, A^{\epsilon}_{i}(\tau) \right|^2$$

- ϵ, i: quantum numbers of partial wave ($J^{PC} M^{\epsilon}[\text{isobar}] L$)
- T^{ϵ}_{ir}: complex production amplitudes; fit parameters
- A^{ϵ}_{i}: complex decay amplitudes
- τ: phase space coordinates

Spin-density matrix

$$\rho^{\epsilon}_{ij} = \sum_{r=1}^{N_r} T^{\epsilon}_{ir}\, T^{\epsilon *}_{jr} \qquad \sigma(\tau; m_X) = \sum_{\epsilon=\pm1} \sum_{i,j}^{\text{waves}} \rho^{\epsilon}_{ij}(m_X)\, A^{\epsilon}_{i}(\tau)\, A^{\epsilon *}_{j}(\tau)$$

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

Partial-Wave Analysis Formalism

Two-body decay amplitude in helicity formalism

- Decay $X(w, J, \lambda) \to 1(J_1, \lambda_1)\ [L, S]\ 2(J_2, \lambda_2)$

$$A_X^{\text{hel}} = \sqrt{2L+1} \sum_{\lambda_1, \lambda_2} (J_1\, \lambda_1\ J_2\, -\lambda_2 | S\, \delta)\ (L\, 0\ S\, \delta | J\, \delta)$$
$$D^{J*}_{\lambda\delta}(\theta, \phi, 0)\ F_L(q)\ \Delta(w)\ A_1\ A_2$$

- $\delta = \lambda_1 - \lambda_2$
- $D^{J*}_{\lambda\delta}(\theta, \phi, 0)$ — Wigner D-function describes rotational properties of helicity states
- θ, ϕ — polar angles of decay daughter 1 in X rest frame (GJ or helicity frame)
- $F_L(q)$ — Blatt-Weisskopf barrier factor
- $\Delta(w)$ — amplitude that describes resonance shape of X
- $A_{1,2}$ — decay amplitudes of (unstable) daughter particles 1 and 2

Partial-Wave Analysis Formalism

Two-body decay amplitude in canonical formalism

- Decay $X(w, J, M) \to 1(J_1, M_1)\ [L, S]\ 2(J_2, M_2)$

$$A_X^{\text{can}} = \sqrt{2J+1} \sum_{M_1, M_2} (J_1\, M_1\ J_2\, M_2 | S\, M_S) \sum_{M_L} (L\, M_L\ S\, M_S | J\, M)$$
$$\sqrt{\frac{4\pi}{2L+1}} Y_{M_L}^L(\theta, \phi)\, F_L(q)\, \Delta(w)\, A_1\, A_2$$

- $Y_{M_L}^L(\theta, \phi)$ — Spherical harmonic describes rotational property of $|L\, M_L\rangle$ state
- θ, ϕ — polar angles of decay daughter 1 in X rest frame (reached by simple boost, no rotations)
- $F_L(q)$ — Blatt-Weisskopf barrier factor
- $\Delta(w)$ — amplitude that describes resonance shape of X
- $A_{1,2}$ — decay amplitudes of (unstable) daughter particles 1 and 2

Partial-Wave Analysis Formalism

Extended maximum-likelihood method

- Likelihood $\mathcal{L}$ to observe N events distributed according to $\sigma(\tau; m_X)$ and acceptance $\mathrm{Acc}(\tau; m_X)$

$$\mathcal{L} = \underbrace{\left[\frac{\overline{N}^N}{N!}\, e^{-\overline{N}}\right]}_{\text{Poisson likelihood}} \prod_{n=1}^{N} \underbrace{\left[\frac{\sigma(\tau_n; m_X)}{\int \mathrm{d}\tau\ \sigma(\tau; m_X)\, \mathrm{Acc}(\tau; m_X)}\right]}_{\text{Likelihood of event } n}$$

$$\text{with} \qquad \overline{N} \propto \int \mathrm{d}\tau\ \sigma(\tau; m_X)\, \mathrm{Acc}(\tau; m_X)$$

$$\mathcal{L} \propto \left[\frac{\overline{N}^N}{N!}\, e^{-\overline{N}}\right] \left[\frac{1}{\overline{N}^N} \prod_{n=1}^{N} \sigma(\tau_n; m_X)\right]$$

$$\mathcal{L} \propto e^{-\int \mathrm{d}\tau\ \sigma(\tau; m_X)\, \mathrm{Acc}(\tau; m_X)} \prod_{n=1}^{N} \sigma(\tau_n; m_X)$$

Partial-Wave Analysis Formalism

Extended maximum-likelihood method (cont.)

- Insert parameterization of cross section for $\sigma(\tau_n; m_X)$

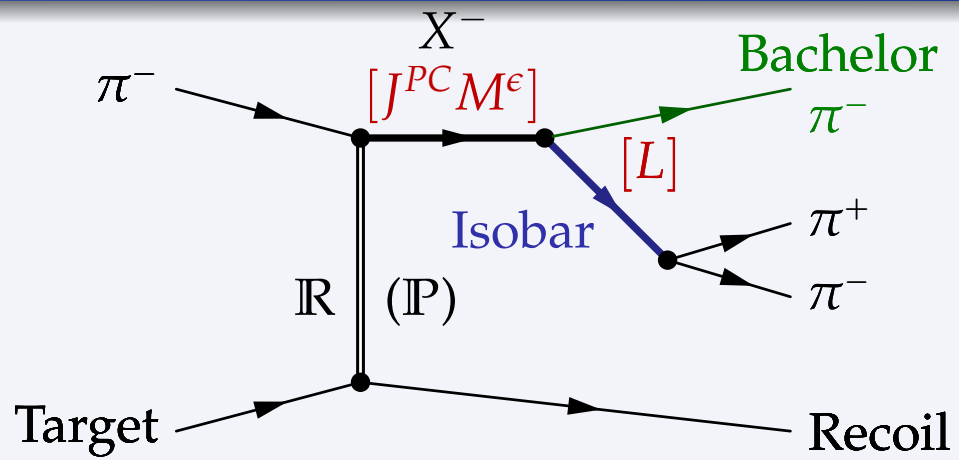
$$\mathcal{L} \propto e^{-\int \mathrm{d}\tau\, \sigma(\tau;m_X)\,\mathrm{Acc}(\tau;m_X)} \prod_{n=1}^{N} \sum_{r=1}^{N_r} \left| \sum_{\text{waves}} T_{r,\text{wave}}(m_X)\, A_{\text{wave}}(\tau_n; m_X) \right|^2$$

- Make expression less unwieldy by taking logarithm

$$\ln \mathcal{L} = \sum_{n=1}^{N} \ln \left[\sum_{r=1}^{N_r} \left| \sum_{\text{waves}} T_{r,\text{wave}}(m_X)\, A_{\text{wave}}(\tau_n; m_X) \right|^2 \right] - \underbrace{\int \mathrm{d}\tau\, \sigma(\tau; m_X)\,\mathrm{Acc}(\tau; m_X)}_{\text{Normalization integral}}$$

- Normalization integral estimated using phase space Monte Carlo

Diffractive Dissociation of π^- into $\pi^-\pi^+\pi^-$ Final State



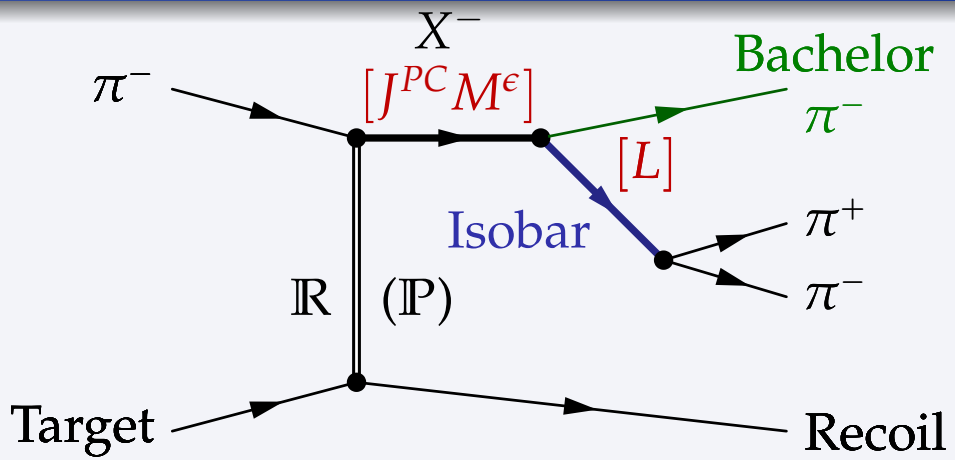
Partial-wave analysis (PWA)

- Cross section parameterization

$$\sigma(\tau; m_X) \propto \left| \sum_{\text{waves}} T_{\text{wave}}(m_X)\, A_{\text{wave}}(\tau; m_X) \right|^2$$

- Determination of transition amplitudes $T_{\text{wave}}(m_X)$
  1. Bin data in m_X (neglect m_X dependence within mass bin)
  2. Calculate decay amplitudes $A_{\text{wave}}(\tau; m_X)$ for every event
  3. Extended maximum likelihood fit of τ distribution in each mass bin taking into account detector acceptance $\Longrightarrow$ $T_{\text{wave}}(m_X)$
- Resonance parameters from χ^2-fit of $T_{\text{wave}}(m_X)$

Diffractive Dissociation of π^- into $\pi^-\pi^+\pi^-$ Final State



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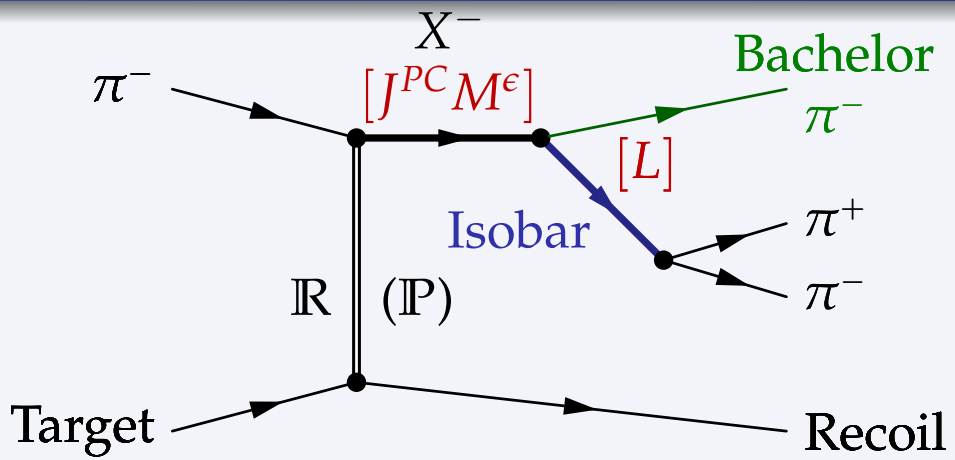

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