Recent Results on Spectroscopy from COMPASS

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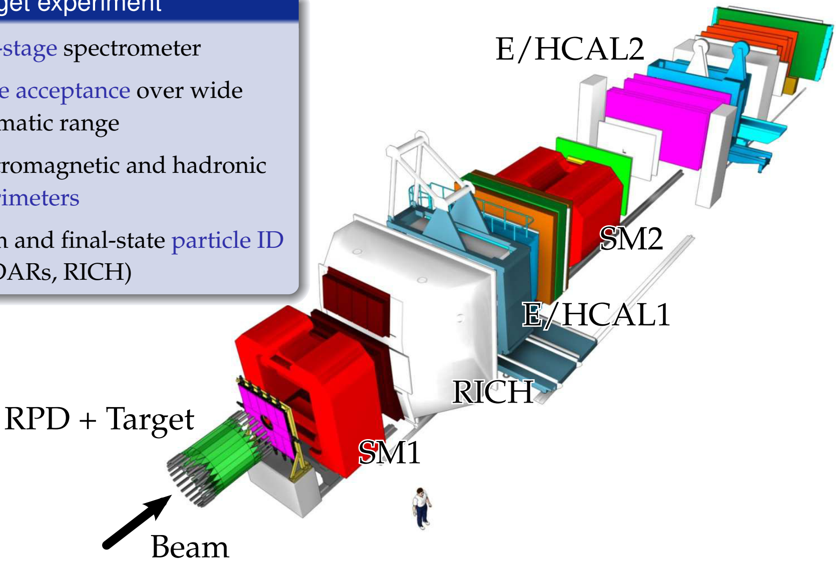
NIMA **779** (2015) 69

Fixed-target experiment

- Two-stage spectrometer
- Large acceptance over wide kinematic range
- Electromagnetic and hadronic calorimeters
- Beam and final-state particle ID (CEDARs, RICH)



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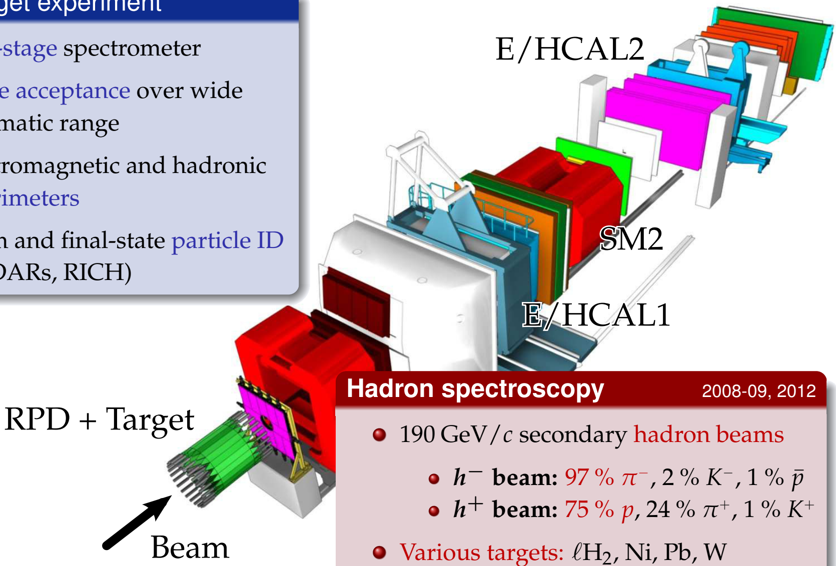

Hadron spectroscopy 2008-09, 2012

- 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: ℓH_2, Ni, Pb, W

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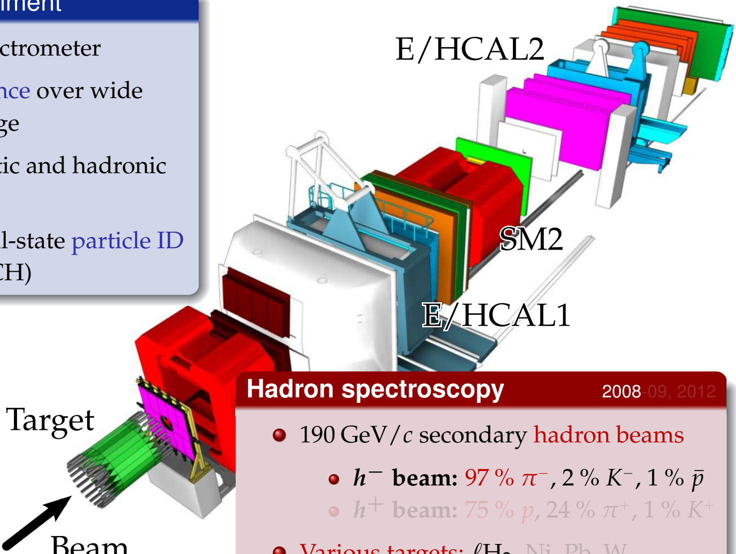

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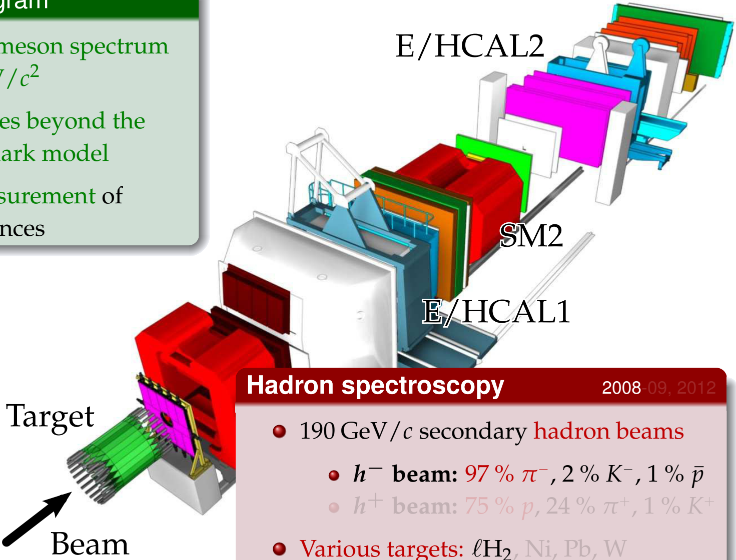
Spectroscopy program

- Explore light-meson spectrum for $m \gtrsim 2\ \mathrm{GeV}/c^2$
- Search for states beyond the constituent quark model
- Precision measurement of known resonances



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Outline

1. Introduction
   - Meson production in diffractive dissociation
   - Partial-wave analysis method

2. PWA of diffractively produced $\pi^-\eta$ and $\pi^-\eta'$ final states

3. PWA of diffractively produced 3π final states
   - Observation of a new narrow axial-vector meson $a_1(1420)$
   - $J^{PC} = 1^{-+}$ spin-exotic partial wave

4. Conclusions and outlook

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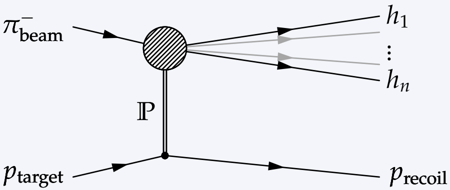
Meson Production in Diffractive Dissociation



- Soft scattering of beam particle off target
  - Production of n forward-going hadrons
  - Target particle stays intact
- At 190 GeV/c, interaction dominated by space-like pomeron exchange
- All final-state particles are measured

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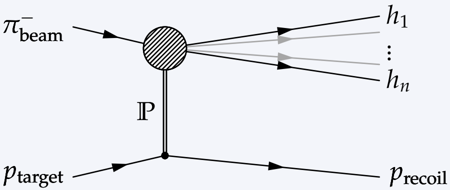
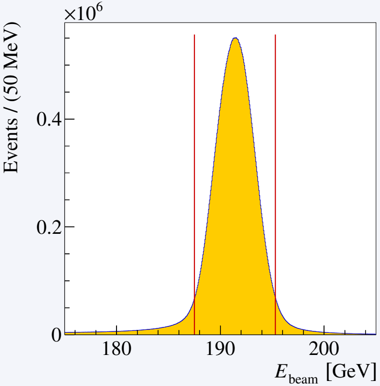


- Exclusive measurement
  - Clean data sample
- Reduced four-momentum transfer squared $t' \equiv |t| - |t|_{\text{min}}$
  - Analyzed range: $0.1 < t' < 1.0\,(\text{GeV}/c)^2$

Example: $\pi^-\pi^+\pi^-$ final state



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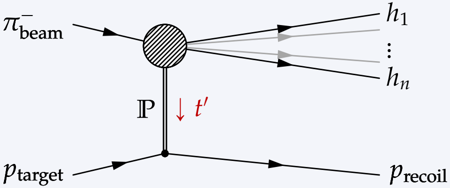

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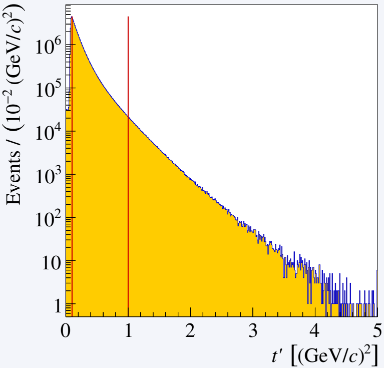

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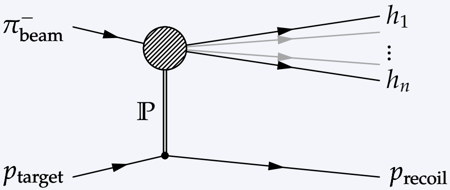

- Beam particle gets excited into intermediate resonances X
- X dissociate into n-body final state
- Rich spectrum of intermediate states X

Disentanglement of all contributing X by **partial-wave analysis** (PWA)

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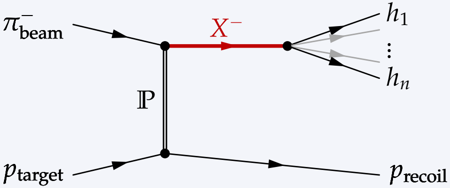

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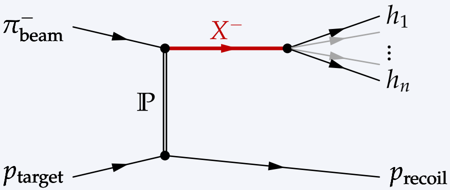

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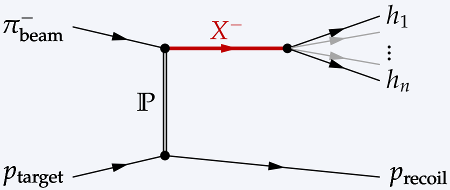
Partial-Wave Analysis Method



Ansatz: Factorization of production and decay

$$\sigma(\tau; m_X) \propto \sum_{\epsilon=\pm1} \left| \sum_i^{\text{waves}} T_i^\epsilon(m_X)\, A_i^\epsilon(\tau; m_X) \right|^2$$

- Transition amplitudes $T_i^\epsilon(m_X)$ contain interesting physics
- Decay amplitudes $A_i^\epsilon(\tau; m_X)$
  - Describe kinematic τ distribution of partial waves
  - Calculable using isobar model (for $n > 2$) and helicity formalism (Wigner D-functions)
- $\epsilon = \pm1$: naturalities of exchange particle
  - 190 GeV/c beam momentum $\implies$ pomeron ($\epsilon = +1$) dominates

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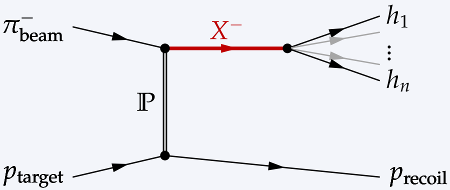

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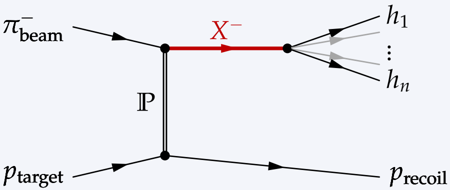

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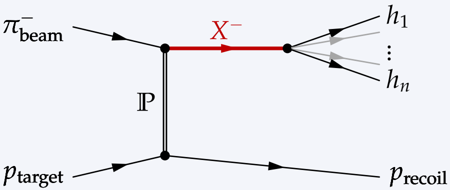

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   - Independent maximum likelihood fits to τ distributions in narrow m_X bins
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   - No assumptions about resonance content of X
2. **Extraction of resonances**
   - χ^2 fit of resonance model to spin-density (sub)matrix

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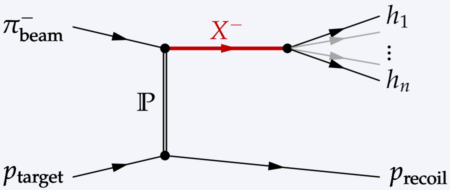

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PWA of $\pi^- p \to \pi^- \eta^{(\prime)} p_{\text{recoil}}$

- Odd-spin waves: spin-exotic quantum numbers
  - Disputed $J^{PC} = 1^{-+}$ resonance signals
    - $\pi_1(1400)$ in $\pi\eta$ and $\pi_1(1600)$ in $\pi\eta'$
- Comparison of $\pi\eta$ and $\pi\eta'$: information about flavor structure

Reconstruction from exclusive $\pi^-\pi^+\pi^-\gamma\gamma$ final state

- $\eta \to \pi^+\pi^-\pi^0$ with $\pi^0 \to \gamma\gamma$
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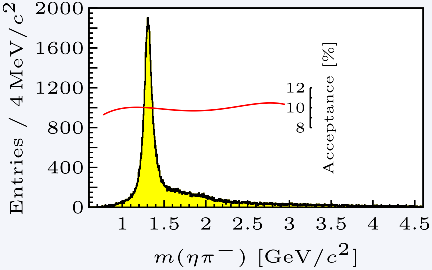
$\pi^-\eta$ invariant mass



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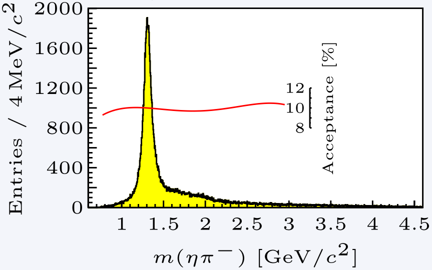
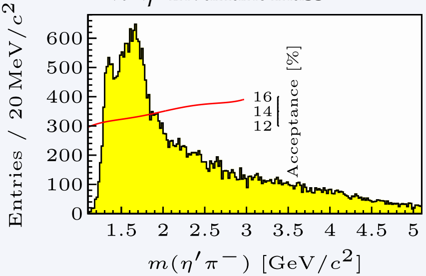


$\pi^-\eta'$ invariant mass



Comparison of $J^{PC} = 2^{++}$ Partial Waves

Quark-line picture for $n = (u, d)$ and pointlike resonances

- $\pi^- \eta$ and $\pi^- \eta'$ partial-wave intensities for spin J related by
  - Different phase space and barrier factors
  - Branching fraction ratio b of η and η' into $\pi^- \pi^+ \gamma\gamma$

$$N_J^{\pi\eta'}(m) \propto b \left[\frac{q^{\pi\eta'}(m)}{q^{\pi\eta}(m)} \right]^{2J+1} N_J^{\pi\eta}(m)$$

- $q =$ breakup momentum

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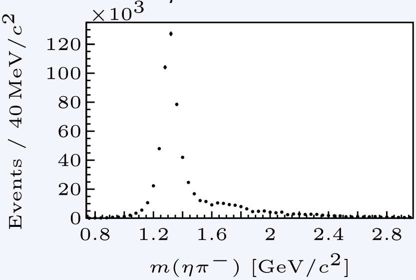

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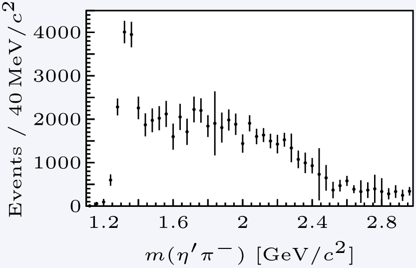

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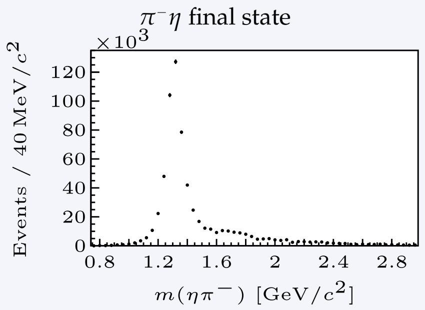
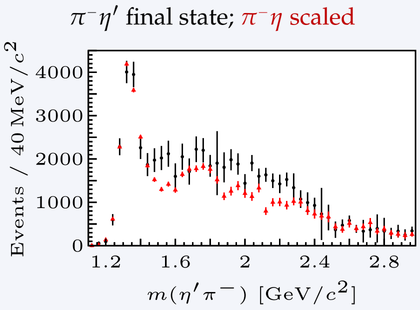
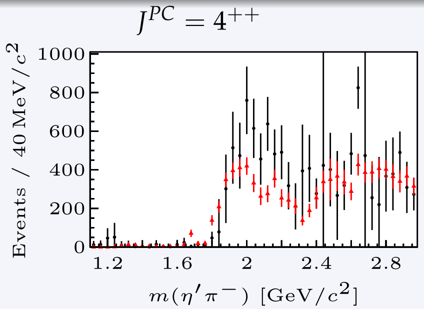
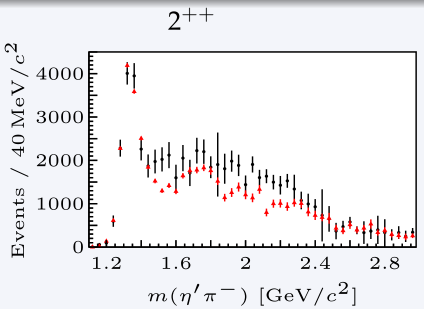
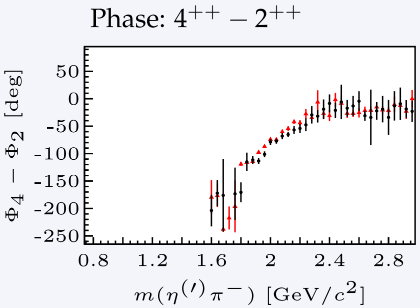




Even-Spin Waves







- Similar even-spin waves
- Intermediate states couple to same final-state flavour content
- Similar physical content also in nonresonant high-mass region

$\pi^-\eta'$ final state; $\pi^-\eta$ scaled

Even-Spin Waves

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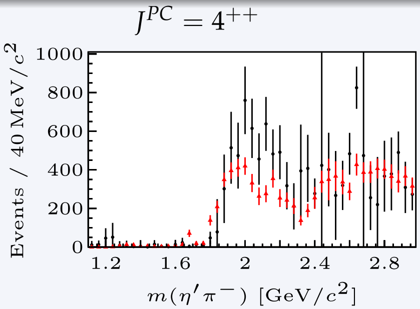

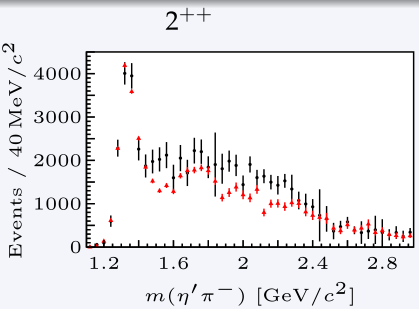

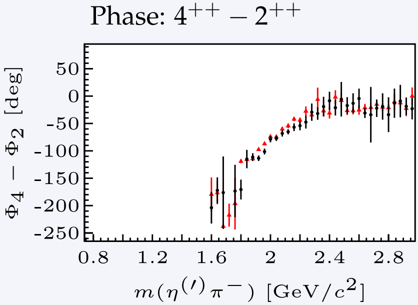

- Resonance-model fit (Breit-Wigner)
- $\dfrac{N(a_2 \to \pi\eta')}{N(a_2 \to \pi\eta)} = (5 \pm 2)\,\%$
- First-time measurement of $\dfrac{N(a_4 \to \pi\eta')}{N(a_4 \to \pi\eta)} = (23 \pm 7)\,\%$

$\pi^-\eta'$ final state; $\pi^-\eta$ scaled

$J^{PC} = 1^{-+}$ Spin-Exotic Wave

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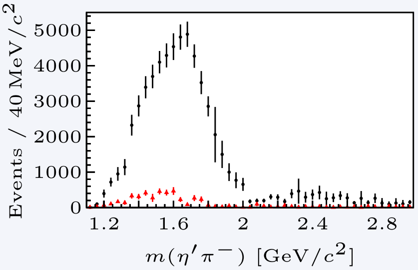
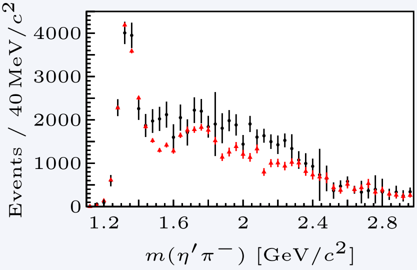
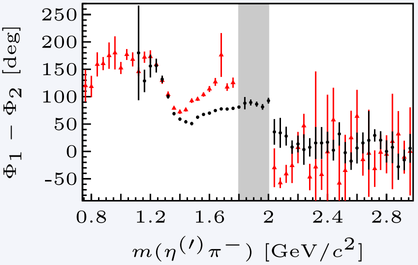
Spin-exotic $J^{PC} = 1^{-+}$



2^{++}



Phase: $1^{-+} - 2^{++}$



- 1^{-+} intensities very different
- Suppression in $\pi\eta$ channel predicted for intermediate $|q\bar{q}g\rangle$ state
- Different phase motion in $1.6\,\mathrm{GeV}/c^2$ region

$\pi^-\eta'$ final state; $\pi^-\eta$ scaled

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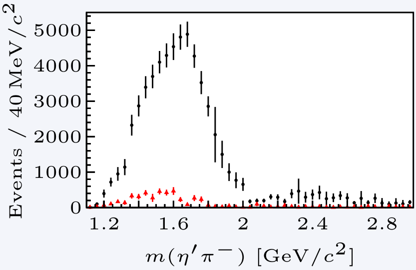
Spin-exotic $J^{PC} = 1^{-+}$



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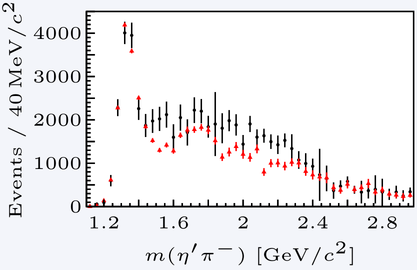

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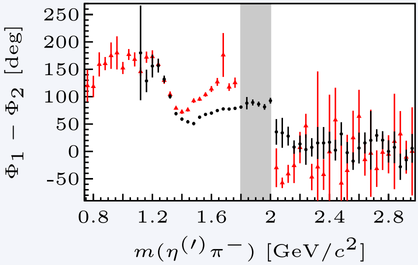
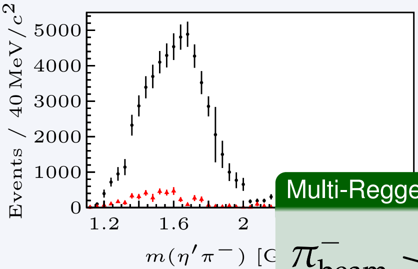


- 1^{-+} resonance interpretation requires better understanding of
  - 2^{++} wave
  - Nonresonant contributions

$\pi^-\eta'$ final state; $\pi^-\eta$ scaled

$J^{PC} = 1^{-+}$ Spin-Exotic Wave

Spin-exotic $J^{PC} = 1^{-+}$



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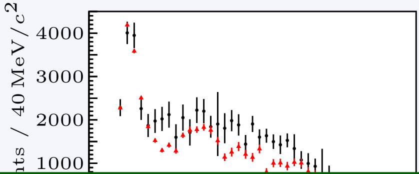

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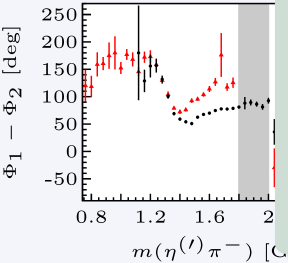
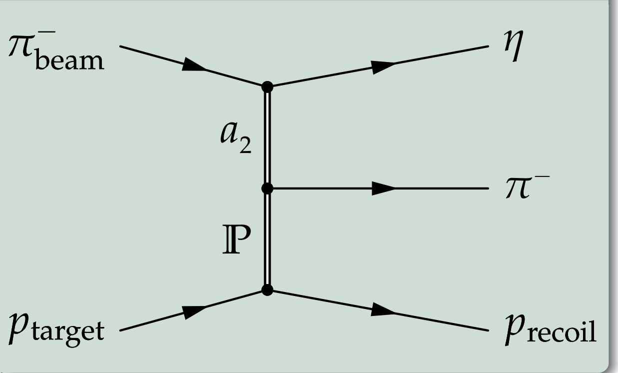


Multi-Regge exchange, e.g.



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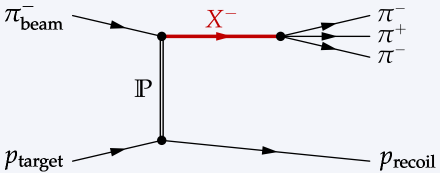
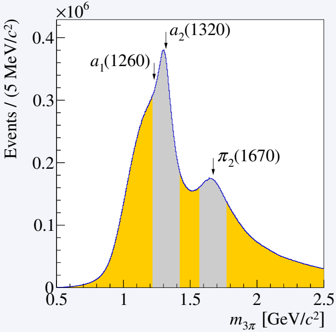
Partial-Wave Analysis: $\pi^-\pi^+\pi^-$ Final State

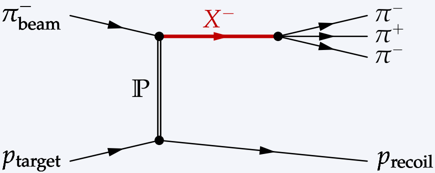


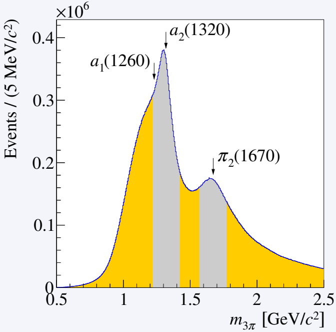


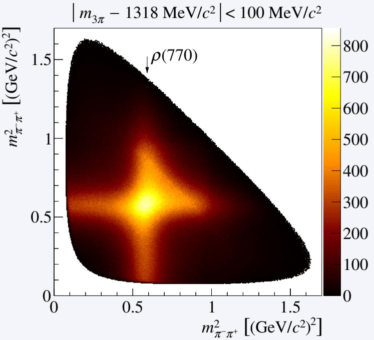
Strong $\pi^+\pi^-$ correlations in $X^- \to \pi^-\pi^+\pi^-$ decay

Partial-Wave Analysis: $\pi^-\pi^+\pi^-$ Final State

[arXiv:1509.00992]







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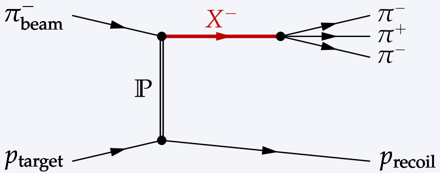

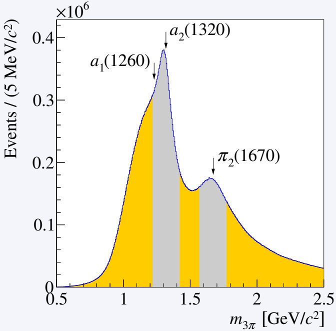

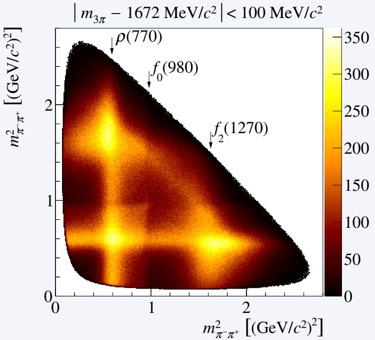

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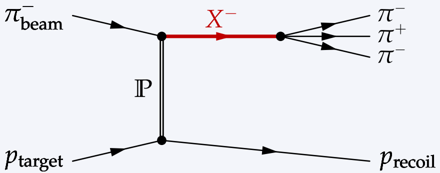

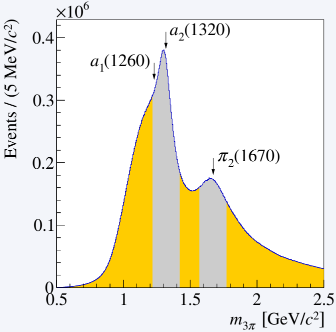

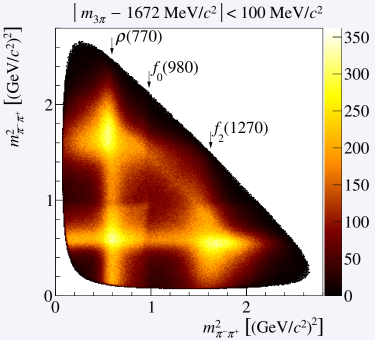

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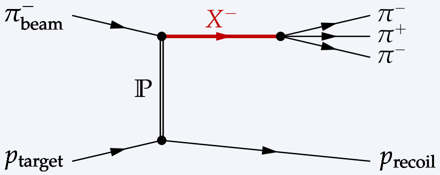

Isobar model

- X^- decays via intermediate $\pi^+\pi^-$ resonance = *"isobar"*
  - $[\pi\pi]_S$ — $J^{PC} = 0^{++}$
  - $\rho(770)$ — 1^{--}
  - $f_0(980)$ — 0^{++}
  - $f_2(1270)$ — 2^{++}
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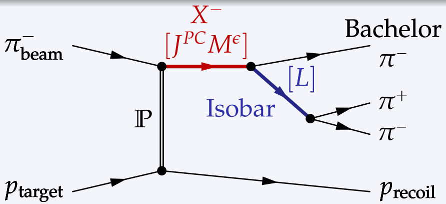
  - $\rho_3(1690)$ — 3^{--}
- PWA requires precise knowledge of isobar $\to \pi^+\pi^-$ amplitude



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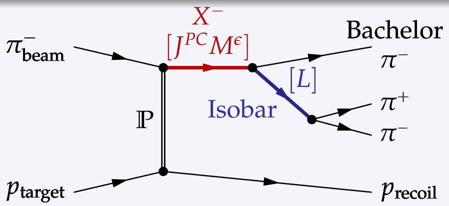

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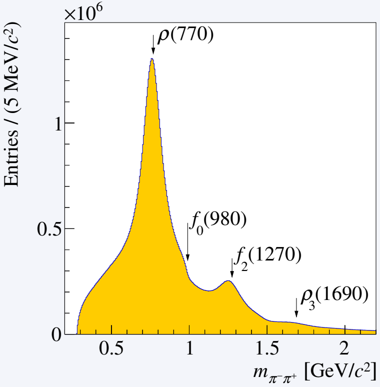

PWA of $\pi^- p \to (3\pi)^- p_{\text{recoil}}$

Two Data Sets

1. $\pi^-\pi^+\pi^-$ (50 M events)
2. Crosscheck with $\pi^-\pi^0\pi^0$ (3.5 M events)
   - Very different acceptance
   - Isobars separated by isospin
     - $I = 1$ isobars: $\pi^-\pi^0$
     - $I = 0$ isobars: $\pi^0\pi^0$

Complex correlation of $m_{3\pi}$ and t'

- Two-dimensional PWA in bins of t' **and** $m_{3\pi}$
  - $\pi^-\pi^+\pi^-$: 11 t' bins
  - $\pi^-\pi^0\pi^0$: 8 t' bins
- Better disentanglement of resonant and nonresonant contributions

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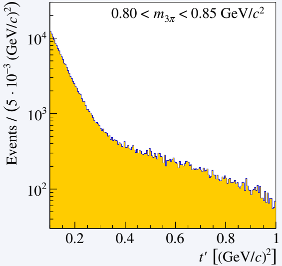
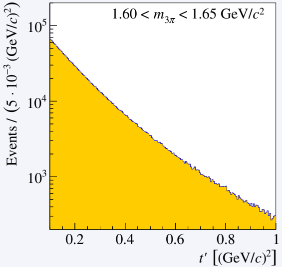
$800 < m_{3\pi} < 850\ \text{MeV}/c^2$



$1600 < m_{3\pi} < 1650\ \text{MeV}/c^2$



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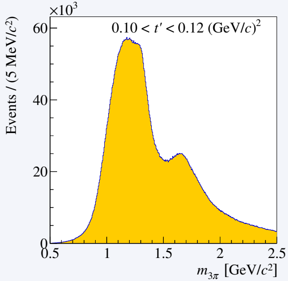
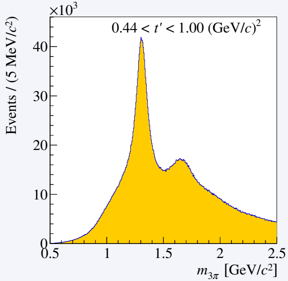
$0.10 < t' < 0.12\,(\text{GeV}/c)^2$



$0.44 < t' < 1.00\,(\text{GeV}/c)^2$



PWA of $\pi^- p \to \pi^-\pi^+\pi^- p_{\text{recoil}}$: Major Waves [arXiv:1509.00992]

- $\pi^-\pi^+\pi^-$ invariant mass spectrum
- $1^{++}0^+ \rho(770)\pi S$: $a_1(1260)$
- $2^{++}1^+ \rho(770)\pi D$: $a_2(1320)$
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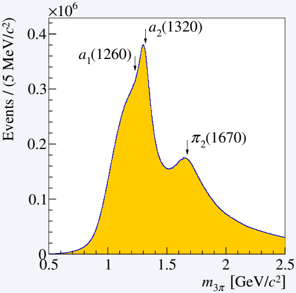

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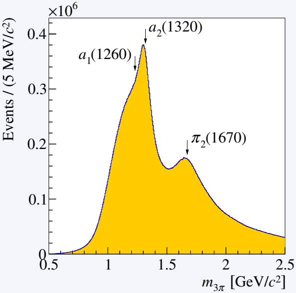

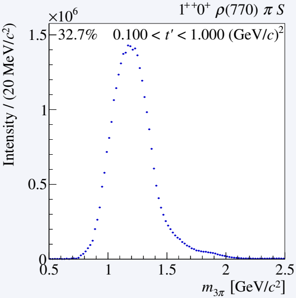

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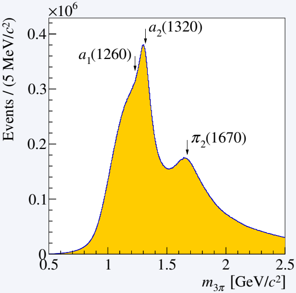

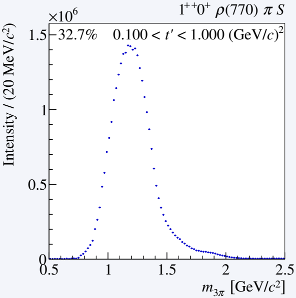

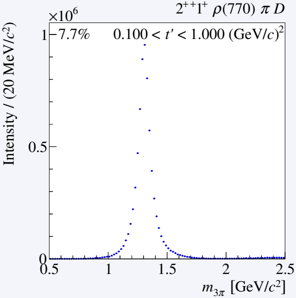

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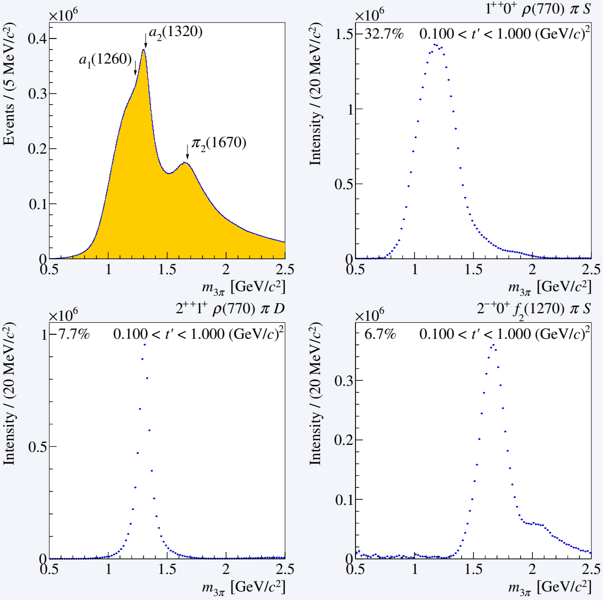

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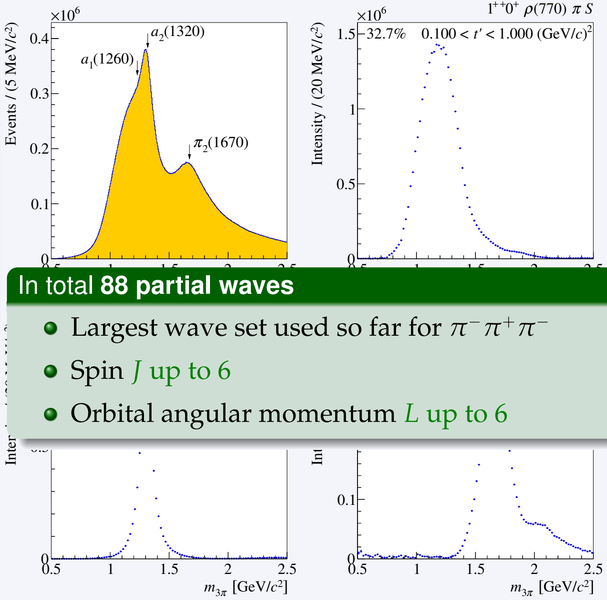


In total **88 partial waves**

- Largest wave set used so far for $\pi^-\pi^+\pi^-$
- Spin J up to 6
- Orbital angular momentum L up to 6

PWA of $\pi^- p \to \pi^-\pi^+\pi^- p_{\text{recoil}}$: Selected Small Waves

[arXiv:1509.00992]

$4^{++}\,1^+\,\rho(770)\pi G$

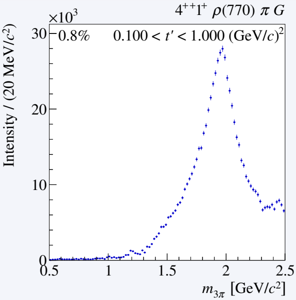
- $a_4(2040)$

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

- $\pi(1800)$

$1^{++}\,0^+\,f_0(980)\pi P$

- **Unexpected peak around 1.4 GeV/c^2**
- Small intensity: $\approx 0.3\%$
- Similar signal in $\pi^-\pi^0\pi^0$



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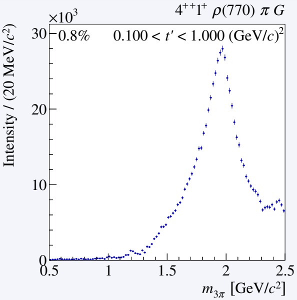

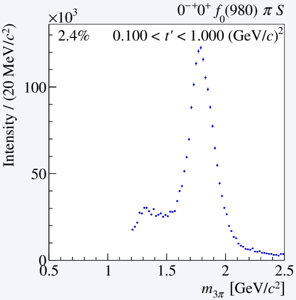

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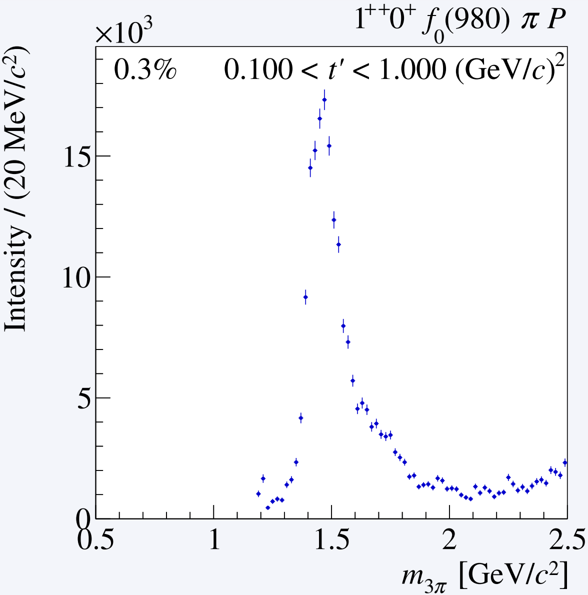

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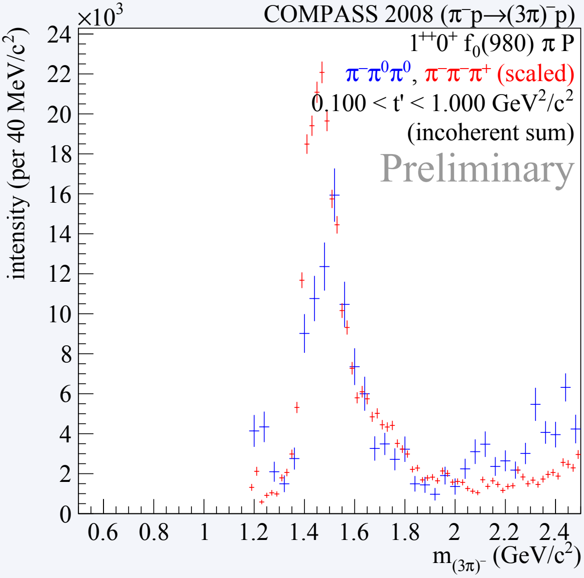


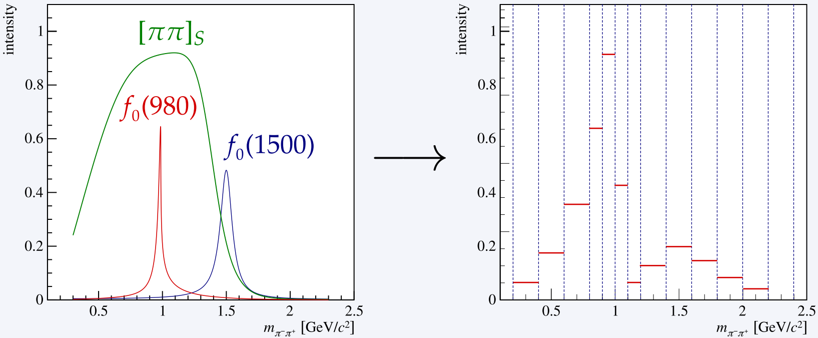
$\pi^-\pi^0\pi^0$

$\pi^-\pi^+\pi^-$ scaled for each plot

Is Peak in $1^{++}0^+ f_0(980)\pi P$ Wave a Model Artifact?

Novel analysis method (inspired by E791 analysis, PRD **73** (2006) 032204)

- Replace $J^{PC} = 0^{++}$ isobar parametrizations by piece-wise constant amplitudes in $m_{\pi^+\pi^-}$ bins
- Extract $m_{3\pi}$ dependence of $J^{PC} = 0^{++}$ isobar amplitude from data
  - Drastic reduction of model bias
  - *Caveat:* significant increase in number of fit parameters



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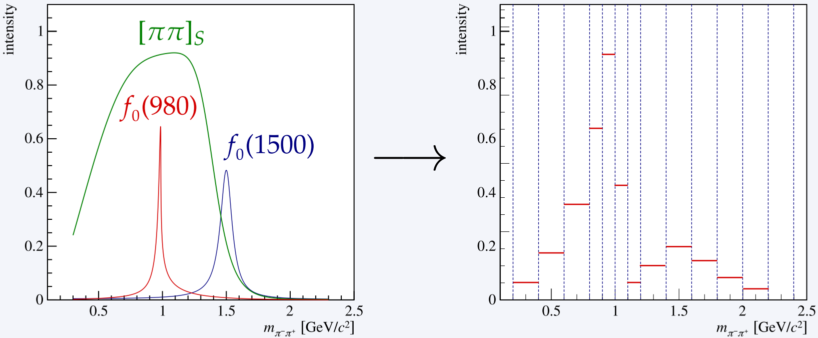
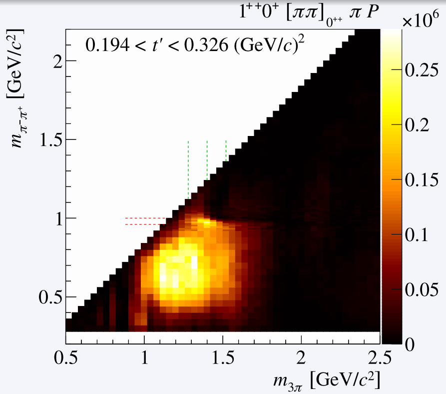


$\pi\pi$ S-Wave Amplitude in $J^{PC} = 1^{++}$ 3π Wave [arXiv:1509.00992]



- Correlation of 3π intensity around $1.4\,\mathrm{GeV}/c^2$ with $f_0(980)$
- $f_0(980)$ semicircle in Argand diagram
- Confirms that $f_0(980)\pi$ signal is *not* an artifact of isobar parametrization

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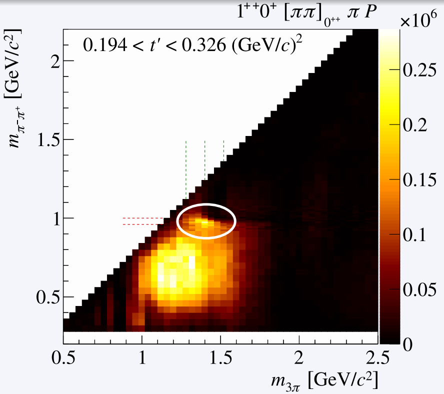

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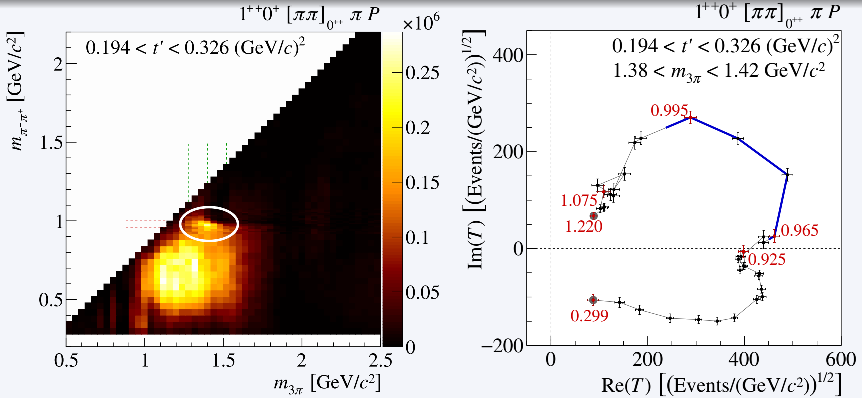

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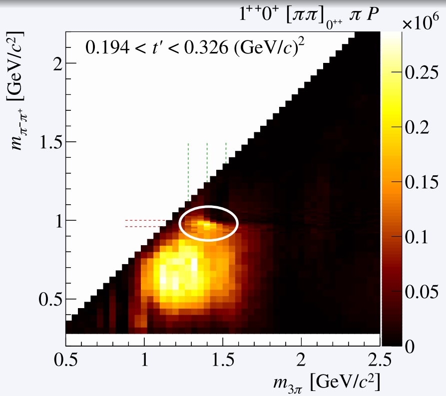

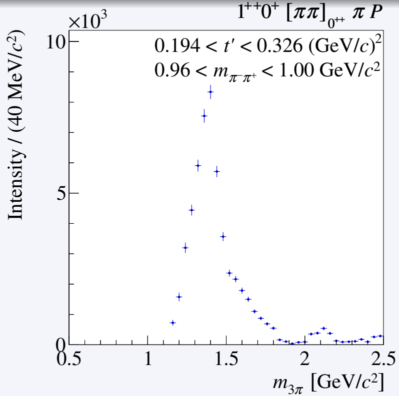

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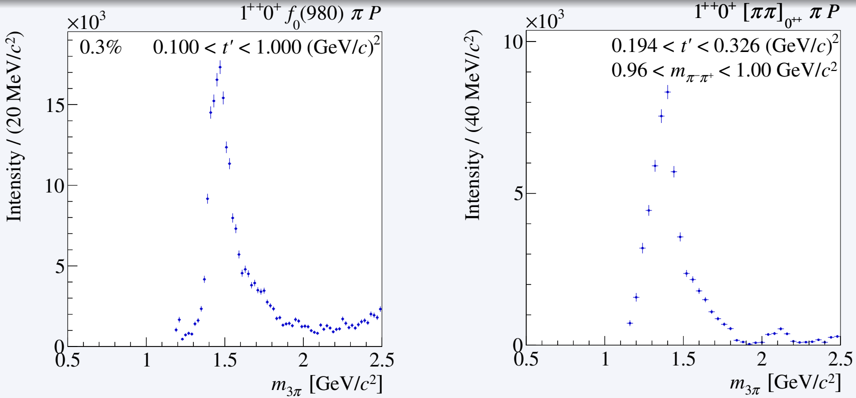

- Correlation of 3π intensity around 1.4 GeV/c^2 with $f_0(980)$
- $f_0(980)$ semicircle in Argand diagram
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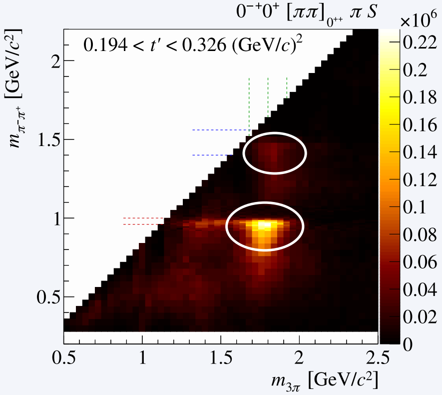
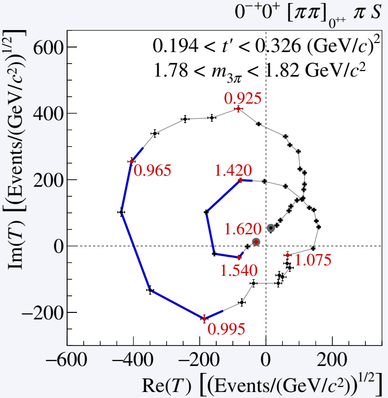
$\pi\pi$ S-Wave Amplitude in $J^{PC} = 0^{-+}$ 3π Wave [arXiv:1509.00992]

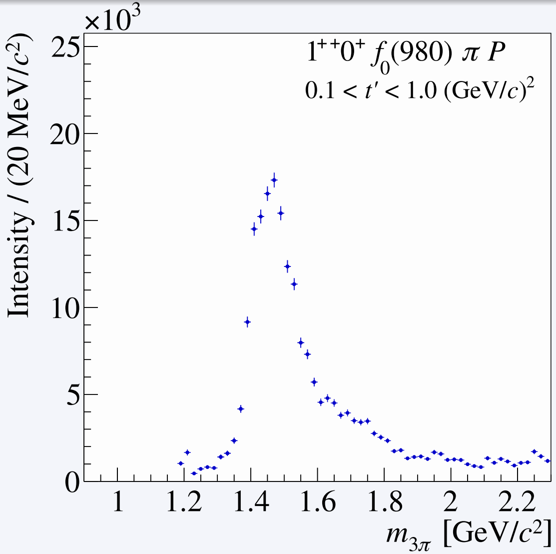




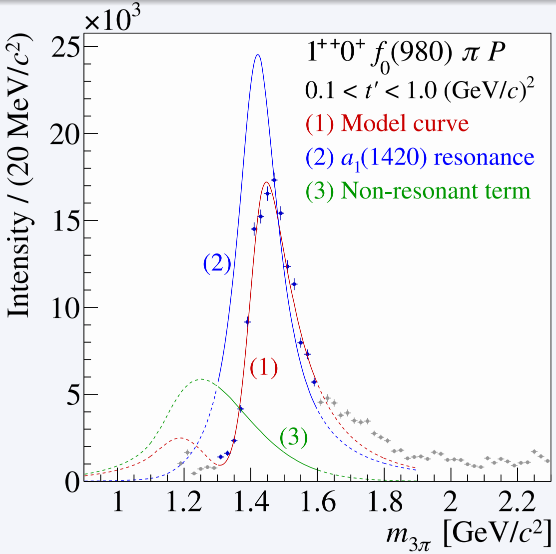
- Coupling of $\pi(1800)$ to $f_0(980)\pi$ and $f_0(1500)\pi$ decay modes

See talk 1E2 by F. Krinner (Thu, 8:55)

Resonance-Model Fit



- Coherent sum of resonant (Breit-Wigner) and nonresonant terms



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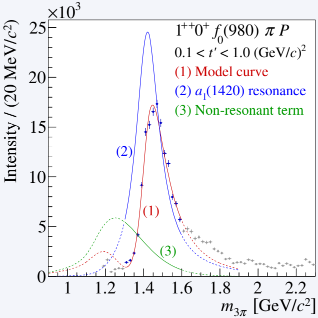
Resonance-Model Fit

PRL **115** (2015) 082001



- 1^{++} peak consistent with Breit-Wigner resonance
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  $M_0 = 1414^{+15}_{-13}$ MeV/c^2
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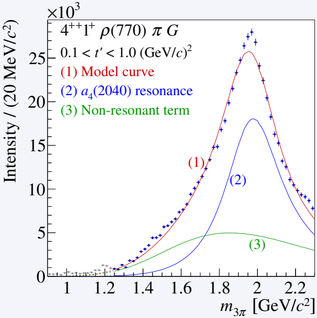

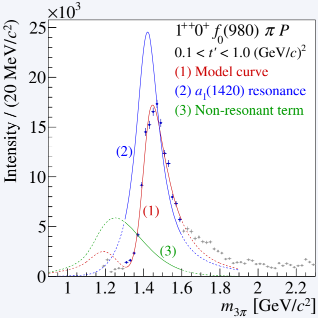

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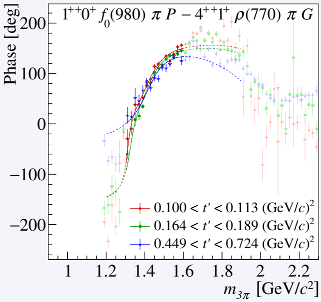

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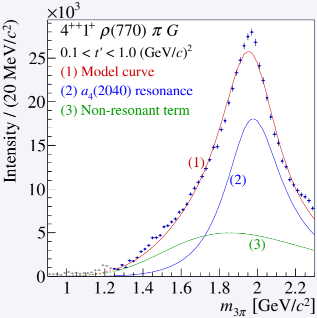

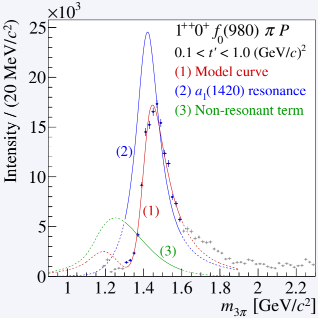

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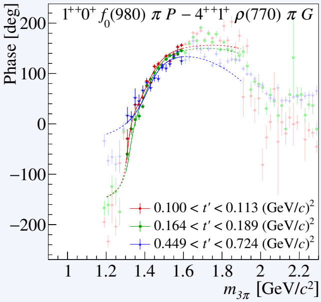

Nature unclear

- No quark-model states expected at $1.4\,\text{GeV}/c^2$
- Ground state $a_1(1260)$ very close and wider
- Seen only in $f_0(980)\pi$ decay mode
- Isospin partner of narrow $f_1(1420)$?
- Suspiciously close to $K\bar{K}^*$ threshold

$a_1(1420)$

Several proposed explanations

- Two-quark-tetraquark mixed state [Wang, arXiv:1401.1134]
- Tetraquark with mixed flavor symmetry

  [Chen *et al.*, PRD **91** (2015) 094022]
- Two-channel unitarized Deck amplitude + direct $a_1(1260)$ production

  [Basdevant and Berger, PRL **114** (2015) 192001 and arXiv:1501.04643]

  See talk 1B4 by E. Berger (Mon, 5:30)
- Singularity (branching point) in triangle diagram

  [Mikhasenko *et al.*, PRD **91** (2015) 094015]

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$a_1(1420)$

PRL **115** (2015) 082001

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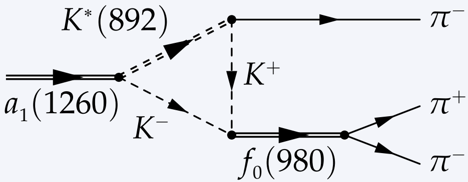
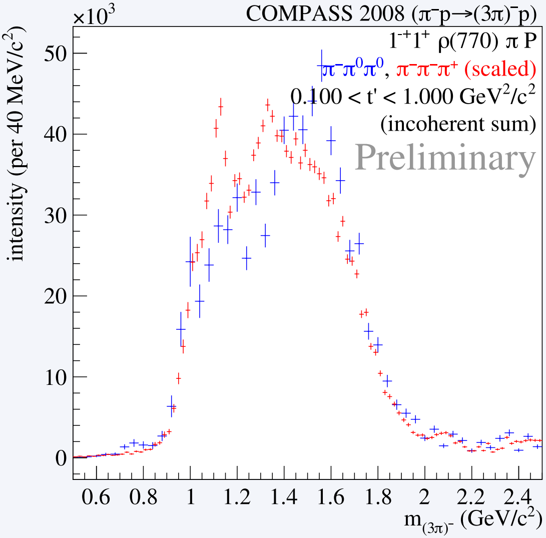


Spin-Exotic $J^{PC} = 1^{-+}$ Signal in $(3\pi)^-$ PWA

- Broad intensity bump
- Similar in both channels



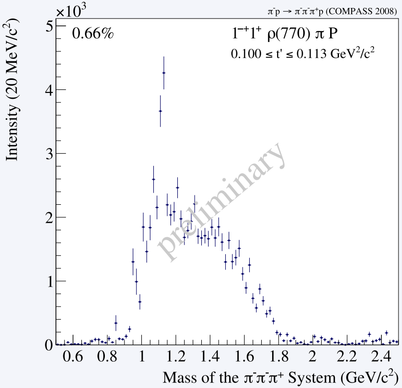
$\pi^-\pi^0\pi^0$

$\pi^-\pi^+\pi^-$ scaled

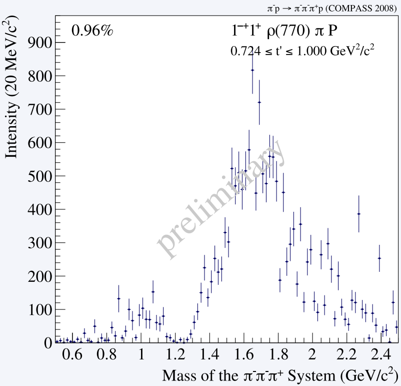
Spin-Exotic $J^{PC} = 1^{-+}$ Signal in $\pi^-\pi^+\pi^-$ PWA

Drastic Change of Mass Spectrum with t'

"Low" $t' \approx 0.1\ (\text{GeV}/c)^2$



"High" $t' \approx 0.8\ (\text{GeV}/c)^2$

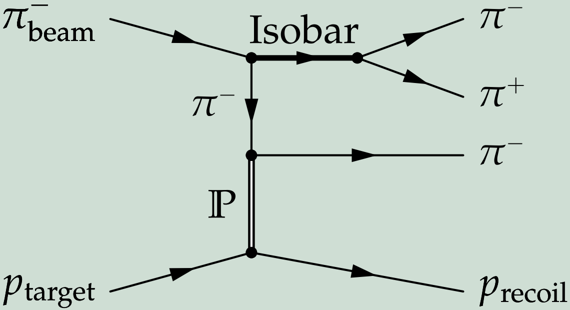


- Dominant nonresonant contribution
  - Needs to be better understood in order to extract resonance content

Spin-Exotic $J^{PC} = 1^{-+}$ Signal in $\pi^-\pi^+\pi^-$ PWA

Model for Nonresonant Component

Deck effect



- MC pseudodata generated according to model of Deck amplitude

  based on ACCMOR, NPB **182** (1981) 269

- Analyzed like real data

Spin-Exotic $J^{PC} = 1^{-+}$ Signal in $\pi^-\pi^+\pi^-$ PWA

Deck-Model for Nonresonant Component

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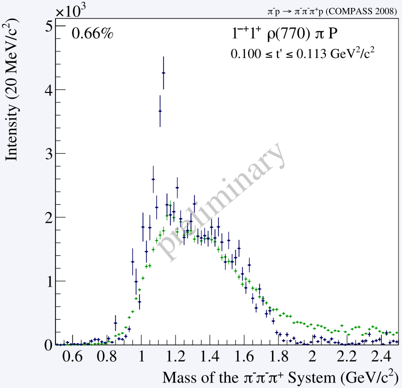

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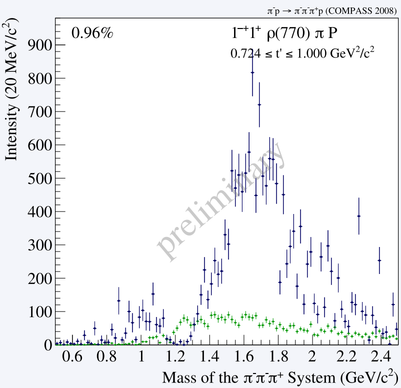
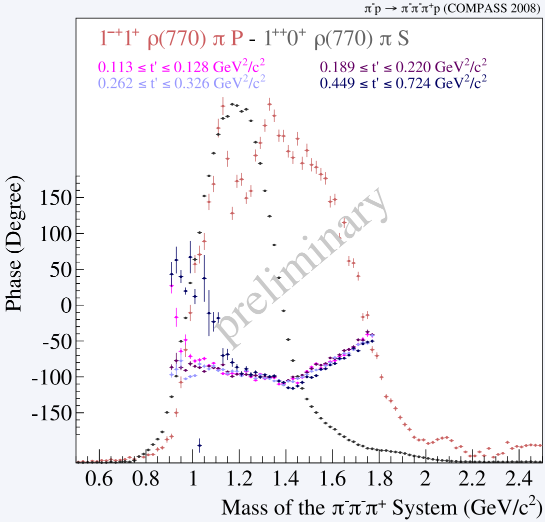


- Deck MC scaled to t'-summed intensity
  - Similar mass spectrum at low t'
  - Different shape at high t'

Spin-Exotic $J^{PC} = 1^{-+}$ Signal in $\pi^-\pi^+\pi^-$ PWA

Relative Phase w.r.t. $1^{++}\,0^+\,\rho(770)\pi S$ Wave



- Slow phase 60° motion in 1.6 GeV/c^2 region independent of t'

Outline

1. Introduction
   - Meson production in diffractive dissociation
   - Partial-wave analysis method

2. PWA of diffractively produced $\pi^-\eta$ and $\pi^-\eta'$ final states

3. PWA of diffractively produced 3π final states
   - Observation of a new narrow axial-vector meson $a_1(1420)$
   - $J^{PC} = 1^{-+}$ spin-exotic partial wave

4. Conclusions and outlook

Conclusions and Outlook

Precise data on pion diffraction

- PWA reliably extracts even very small signals
  - New axial-vector state $a_1(1420)$ in $(3\pi)^-$ final states
- Novel analysis schemes:
  - PWA in bins of t'
    - Better separation of resonant and nonresonant contribution
  - Extraction of $\pi\pi$ S-wave amplitude from $\pi^-\pi^+\pi^-$ system
    - Study dependence on 3π source
    - Study rescattering effects
    - Extension to higher $\pi\pi$ waves

Conclusions and Outlook

Nonresonant contributions play important role

- Limit extraction of resonance parameters
- First studies using Deck models
- Extraction of nonresonant contributions from data
  - Collaboration with JPAC: Veneziano amplitudes + finite-energy sum rules

Other ongoing analyses

- Pion diffraction into $\pi^-\eta\eta$, $\pi^-\pi^0\omega$, $K\bar{K}\pi$, $K\bar{K}\pi\pi$, …
- Kaon diffraction into $K^-\pi^+\pi^-$
- Central-production reactions See talk 1E1 by A. Austregesilo (Thu, 8:30)
- $\pi\gamma$ scattering using Primakoff reactions on heavy targets See talk 6C4 by M. Krämer (Thu, 11:45)

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