Meson Spectroscopy at COMPASS

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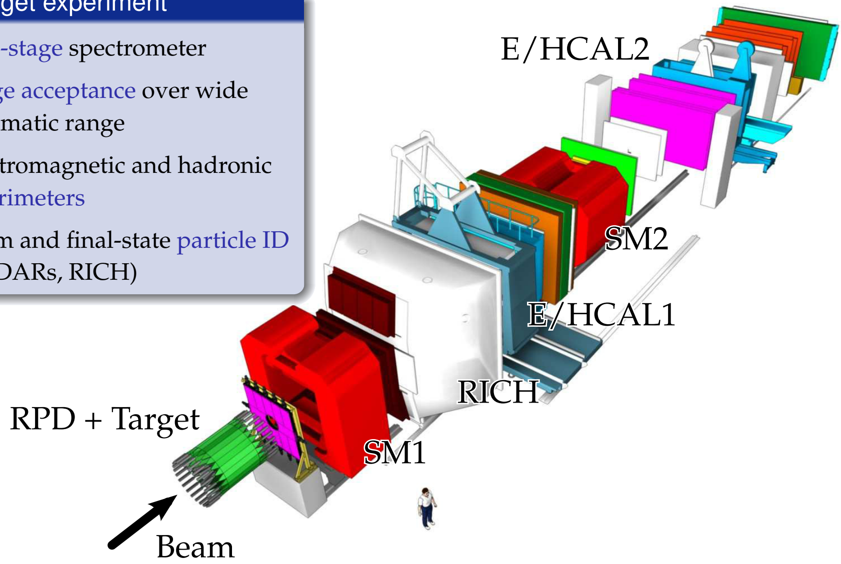
[NIMA **779** (2015) 69]

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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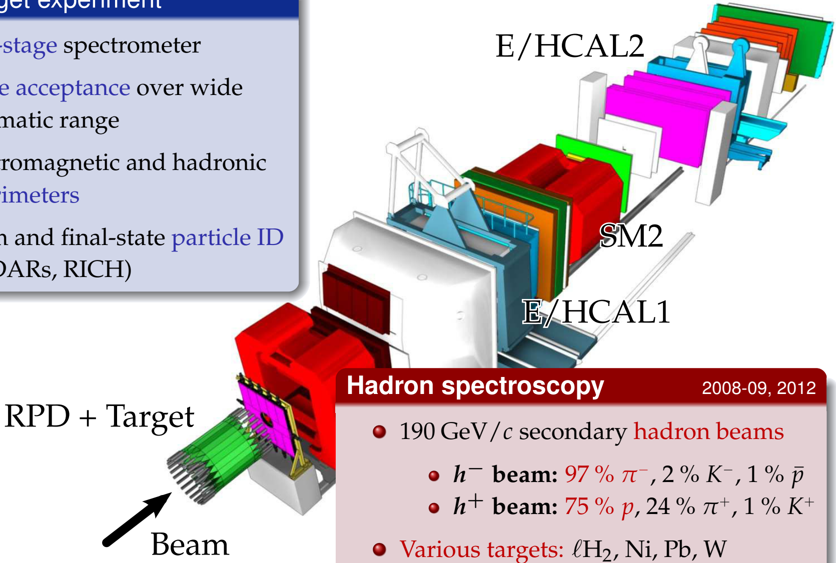

Hadron spectroscopy 2008-09, 2012

- 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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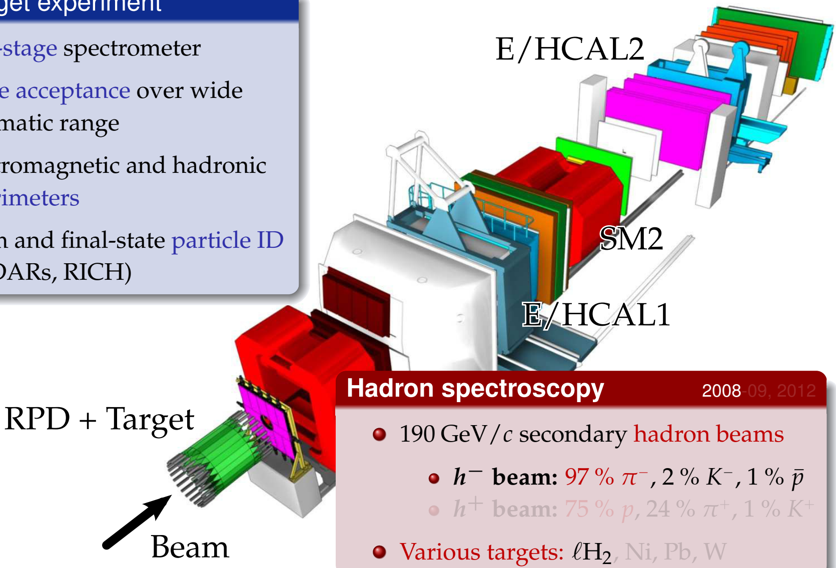

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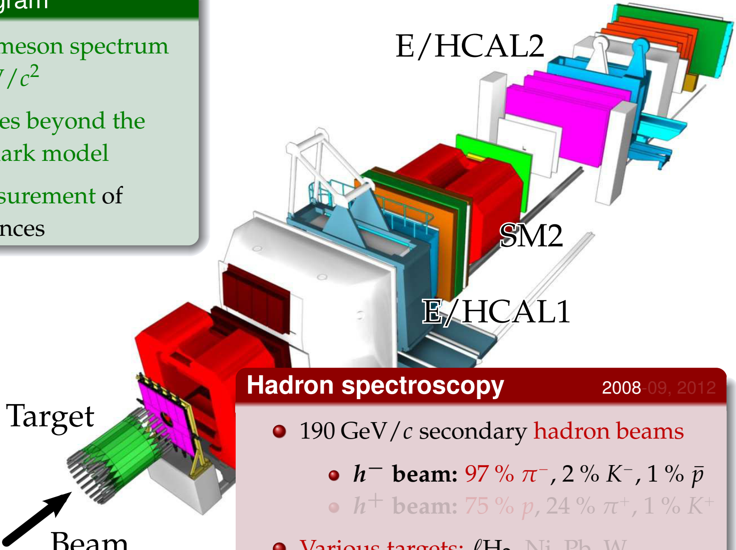
Spectroscopy program

- 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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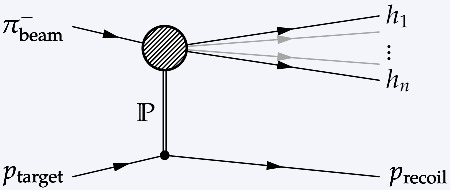
Outline

1. Introduction
   - Meson production in diffractive dissociation
   - Partial-wave analysis method
2. PWA of diffractively produced 3π final states
   - Observation of a new narrow axial-vector meson $a_1(1420)$
   - $J^{PC} = 1^{-+}$ spin-exotic partial wave
3. Conclusions and outlook

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

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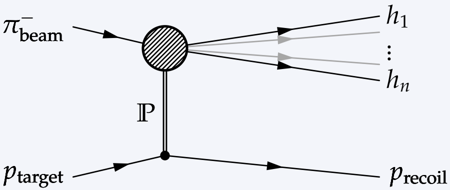
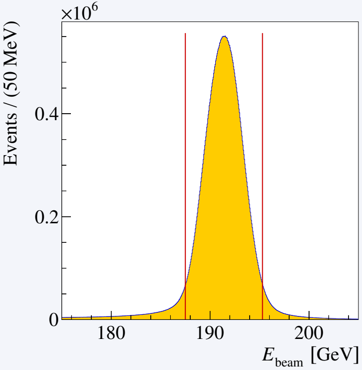


- Exclusive measurement
  - Clean data samples
- Reduced four-momentum transfer squared $t' \equiv |t| - |t|_{\text{min}}$
  - Analyzed range: $0.1 < t' < 1.0\,(\text{GeV}/c)^2$

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



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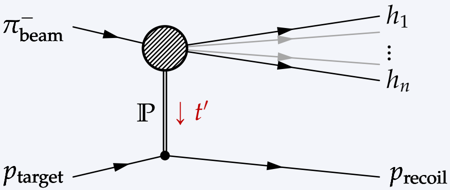

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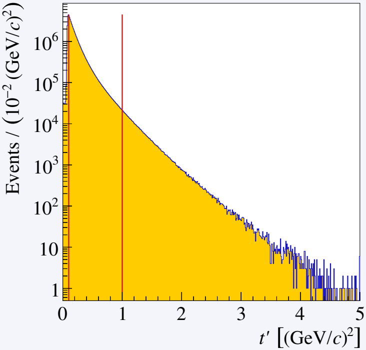

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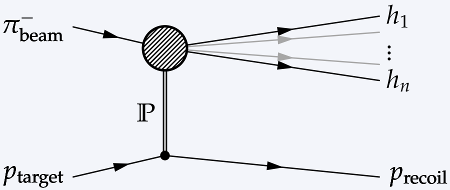

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- X dissociate into n-body final state
- Rich spectrum of intermediate states X

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

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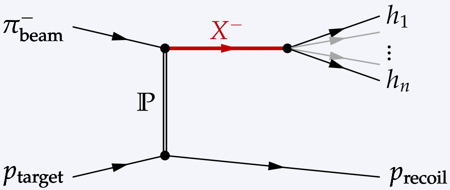

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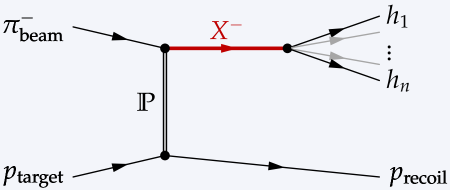

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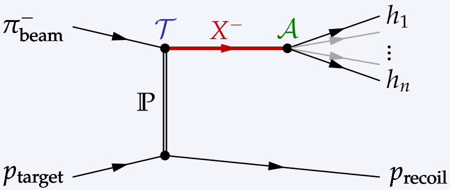

Ansatz: Factorization of production and decay

$$\mathcal{I}(\tau; m_X) = \sum_{\epsilon=\pm1} \left| \sum_i^{\text{waves}} \mathcal{T}_i^\epsilon(m_X)\, \mathcal{A}_i^\epsilon(\tau; m_X) \right|^2$$

- Transition amplitudes $\mathcal{T}_i^\epsilon(m_X)$ $\Longrightarrow$ interesting physics
- Decay amplitudes $\mathcal{A}_i^\epsilon(\tau; m_X)$
  - Describe kinematic distribution of partial waves
  - Calculated using isobar model (for $n > 2$) and helicity formalism (Wigner D-functions)
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  - 190 GeV/c beam momentum $\Longrightarrow$ pomeron ($\epsilon = +1$) dominates

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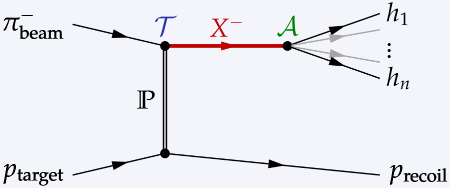

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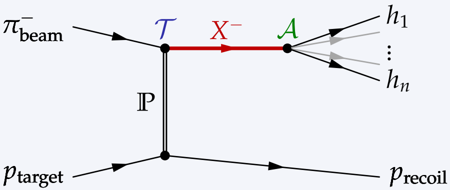

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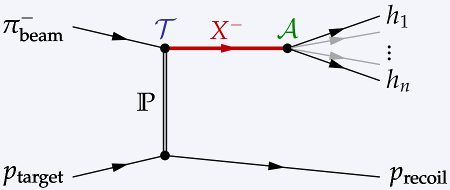

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$$\varrho_{ij}^\epsilon(m_X) = \mathcal{T}_i^\epsilon(m_X)\, \mathcal{T}_j^{\epsilon *}(m_X)$$

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- χ^2 fit of resonance model to spin-density (sub)matrix

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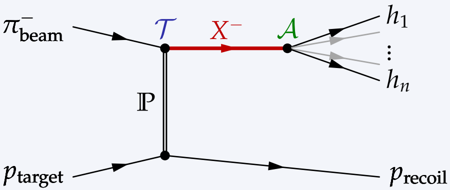

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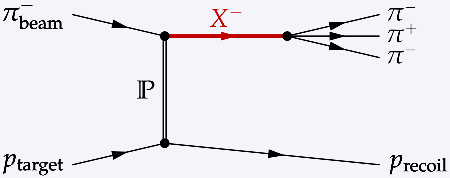
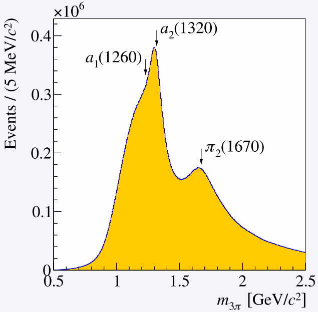
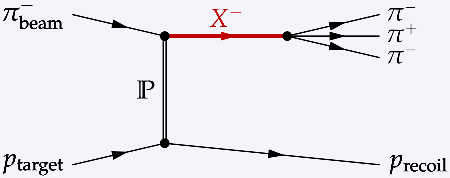
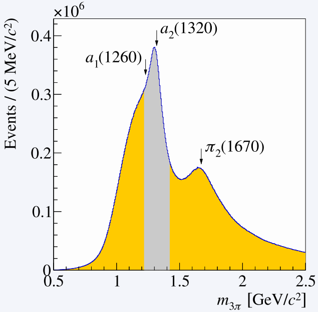


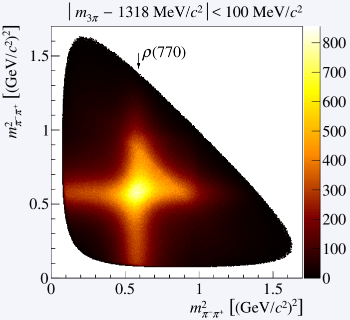


X^- decay via $\pi^+\pi^-$ resonances = *"isobars"*

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







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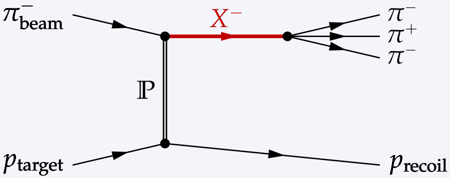

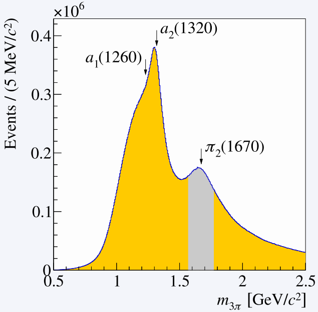

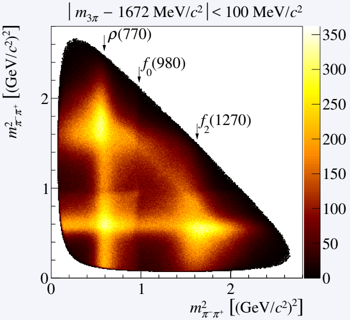

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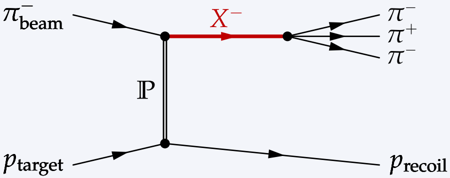

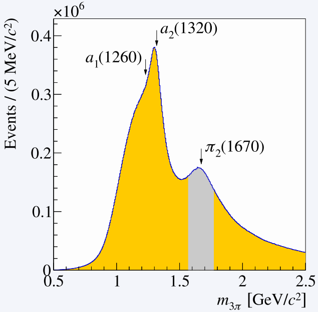

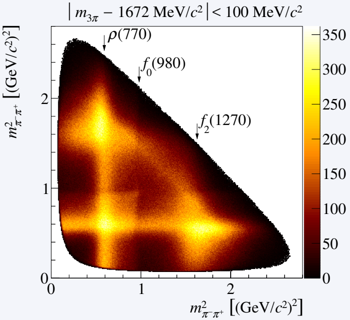

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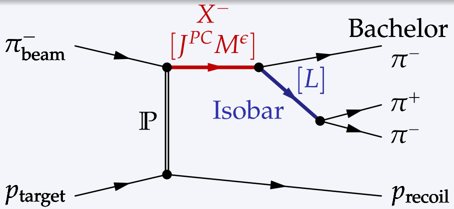

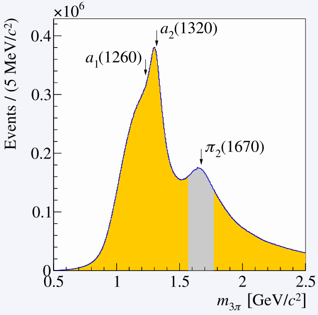

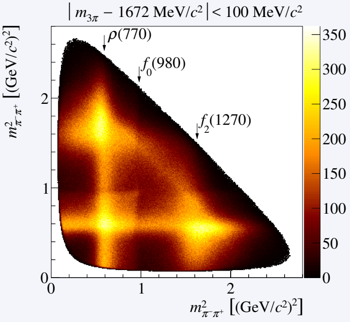

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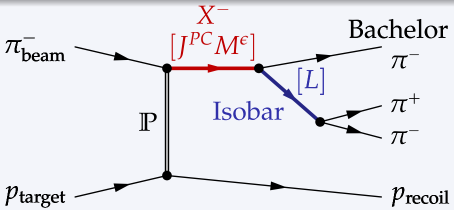
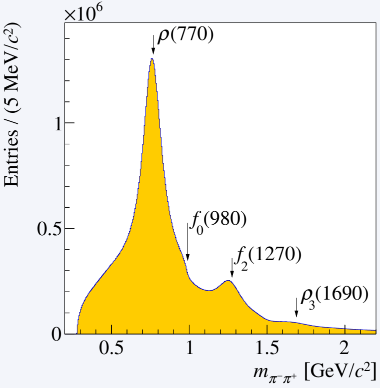
Partial-Wave Analysis: $\pi^-\pi^+\pi^-$ Final State

[arXiv:1509.00992]



Isobar model

- Isobars included into PWA model
  - $[\pi\pi]_S$ — $J^{PC} = 0^{++}$
  - $\rho(770)$ — 1^{--}
  - $f_0(980)$ — 0^{++}
  - $f_2(1270)$ — 2^{++}
  - $f_0(1500)$ — 0^{++}
  - $\rho_3(1690)$ — 3^{--}
- PWA requires precise knowledge of isobar $\rightarrow \pi^+\pi^-$ amplitude



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 in $\pi^-\pi^0$
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Complicated correlation of $m_{3\pi}$ and t'

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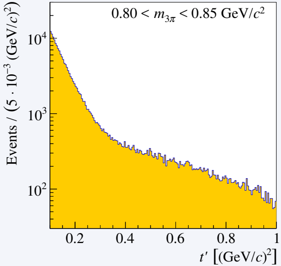
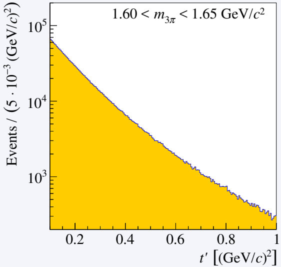
$800 < m_{3\pi} < 850\ \text{MeV}/c^2$



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



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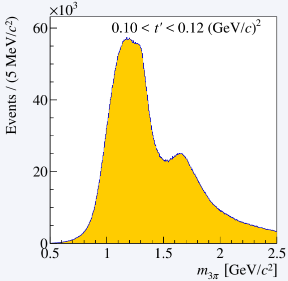
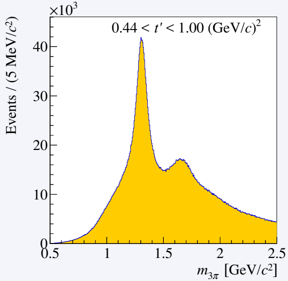
$0.10 < t' < 0.12\ (\text{GeV}/c)^2$



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



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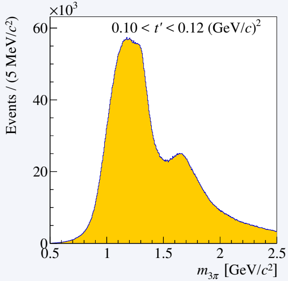

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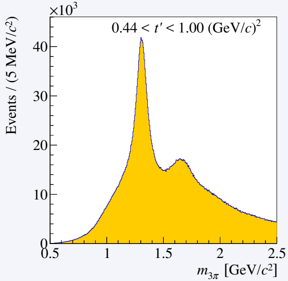
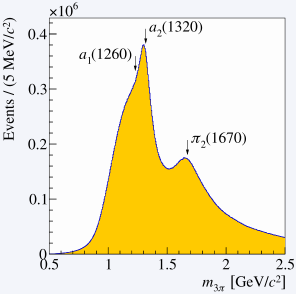


- $\pi^-\pi^+\pi^-$ invariant mass spectrum
- $1^{++}\,0^+\,\rho(770)\pi\,S$
- $2^{++}\,1^+\,\rho(770)\pi\,D$
- $2^{-+}\,0^+\,f_2(1270)\pi\,S$



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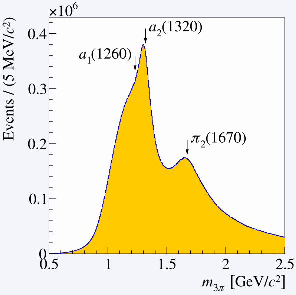

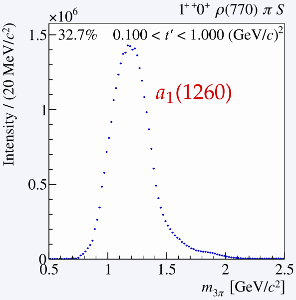

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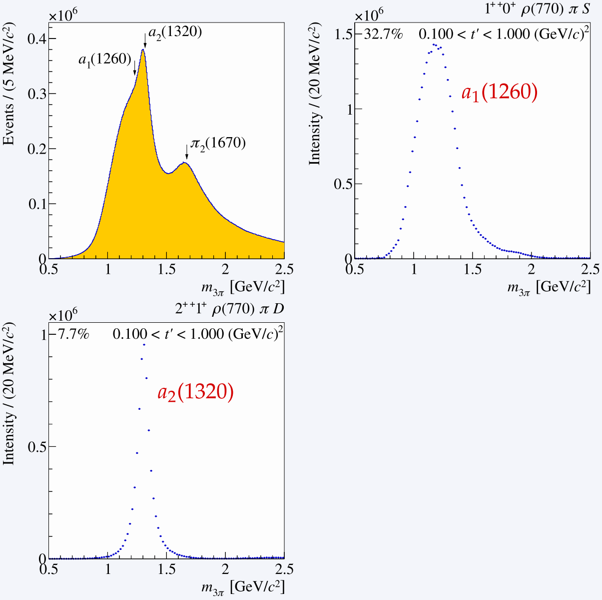

PWA of $\pi^- p \to \pi^-\pi^+\pi^- p_{\text{recoil}}$: Major Waves

[arXiv:1509.00992]

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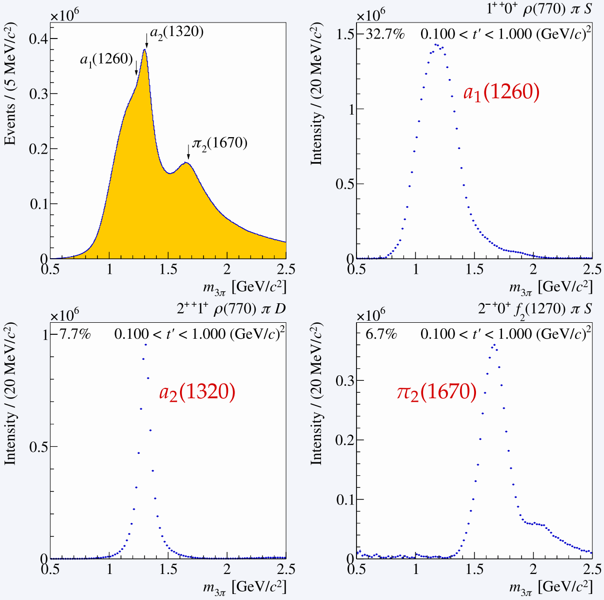

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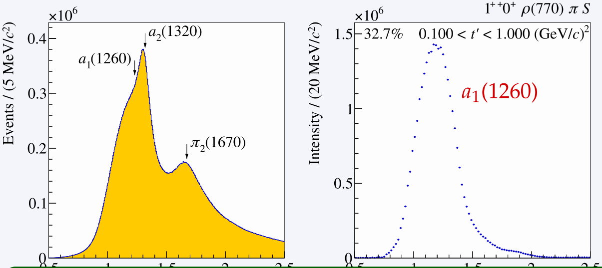
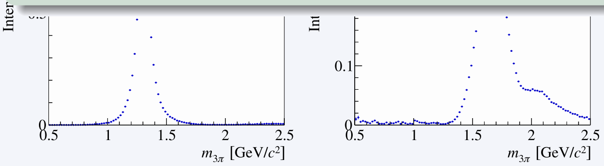


In total **88 partial waves**

- 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]

- $2^{++}\,2^+\,\rho(770)\,\pi\,D$
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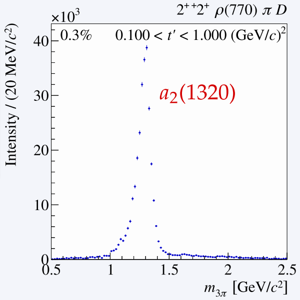

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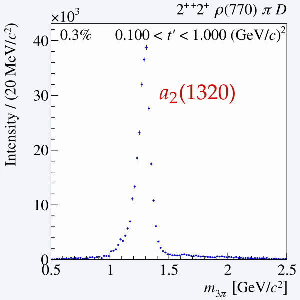

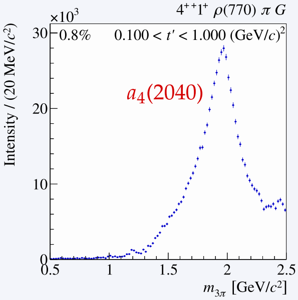

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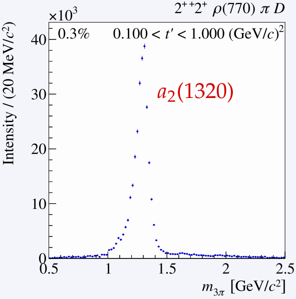

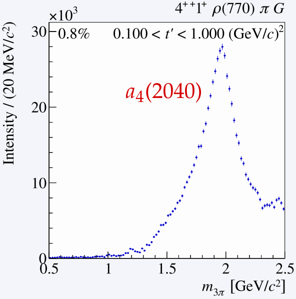

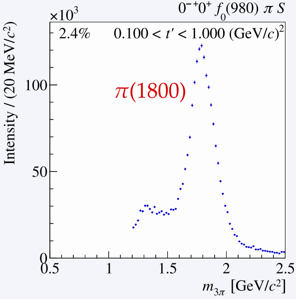

PWA of $\pi^- p \to \pi^-\pi^+\pi^- p_{\text{recoil}}$: Selected Small Waves

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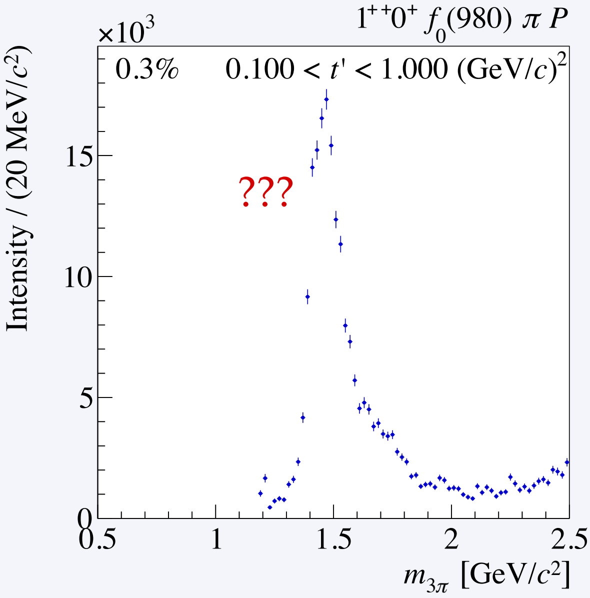
  - **Unexpected peak around 1.4 GeV/c^2**
  - Small intensity: $\approx 0.3\%$



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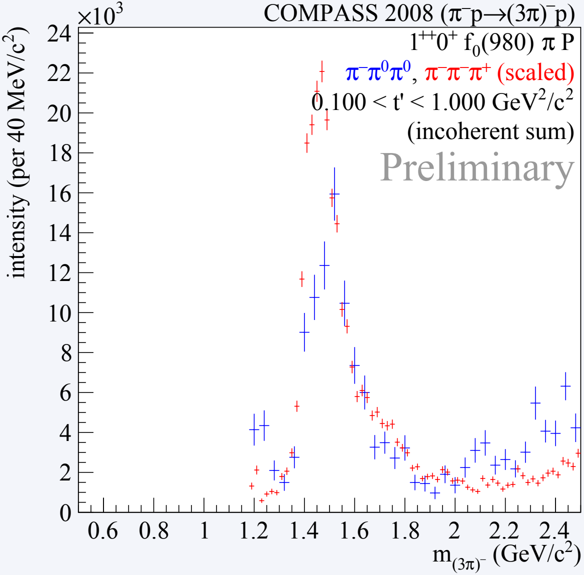
$\pi^- \pi^0 \pi^0$ final state

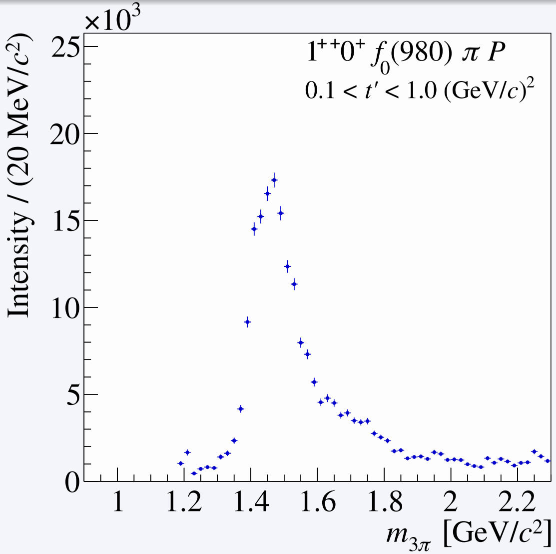
- Very different detector acceptance
- **Similar signal**



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

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

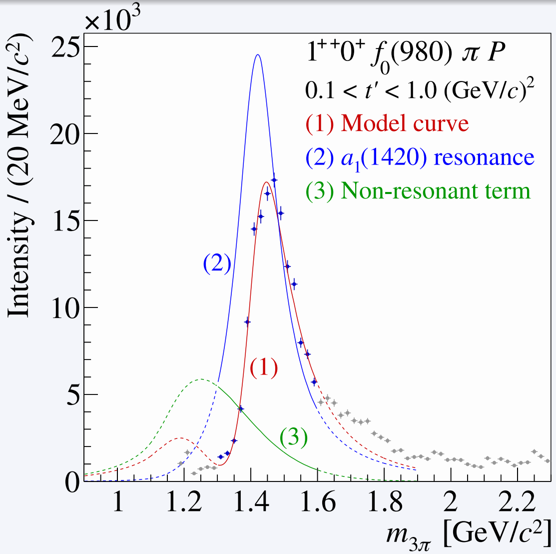
Resonance-Model Fit



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

Resonance-Model Fit

[PRL **115** (2015) 082001]



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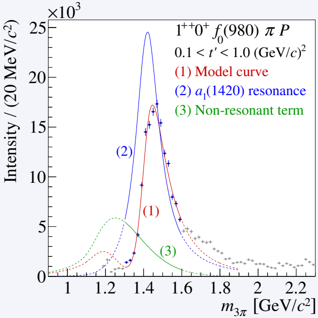

- 1^{++} peak consistent with Breit-Wigner resonance
- $a_1(1420)$:
  $M_0 = 1414^{+15}_{-13}\ \mathrm{MeV}/c^2$
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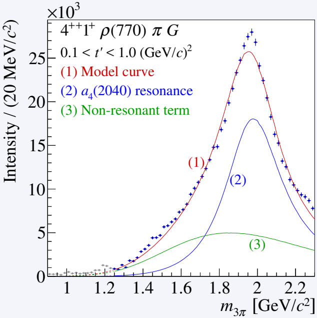

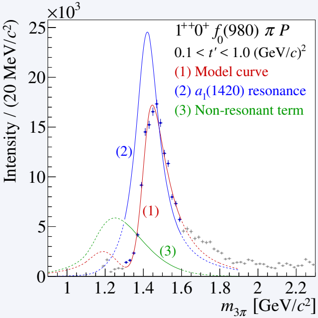

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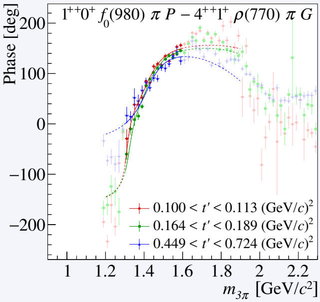

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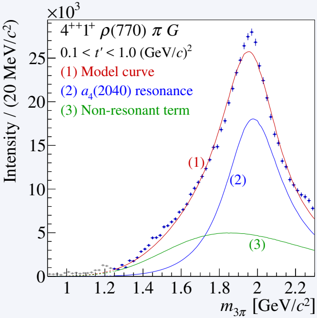

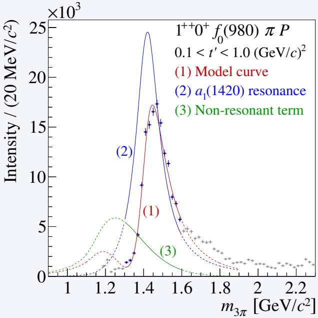

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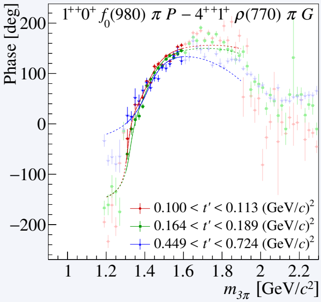

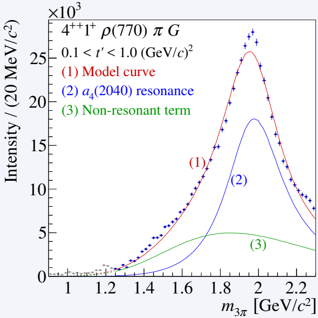

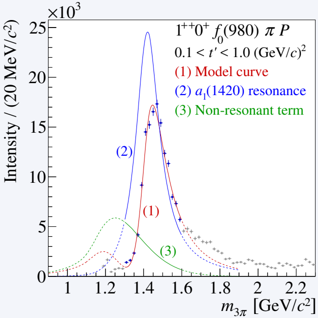

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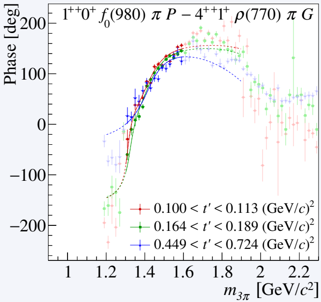
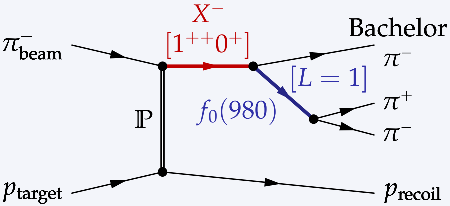


Is the $a_1(1420)$ a Model Artifact?



- Calculation of decay amplitudes $\mathcal{A}_{\text{wave}}(\tau)$ needs precise knowledge of isobar $\to \pi^+\pi^-$ amplitude
- At least 3 isobars with $J^{PC} = 0^{++}$
  - $[\pi\pi]_{S\text{-wave}}$
  - $f_0(980)$
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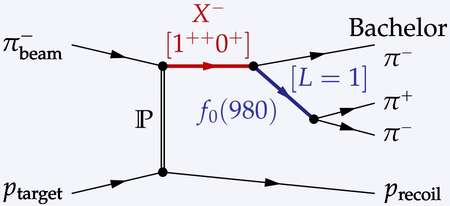

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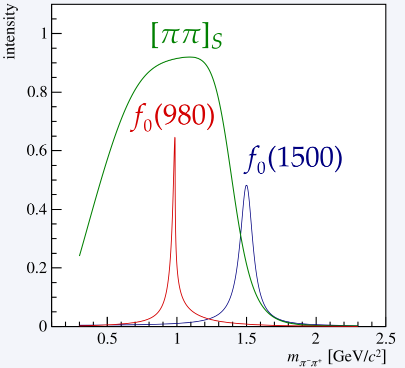

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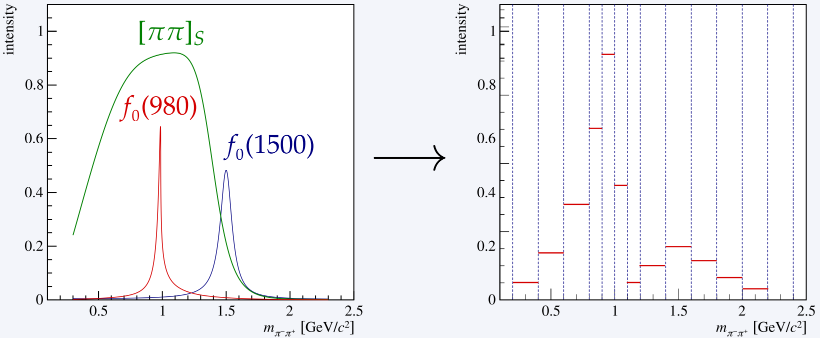
Novel analysis method

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
  - *Advantage:* drastic reduction of model bias
  - *Caveat:* significant increase in number of fit parameters



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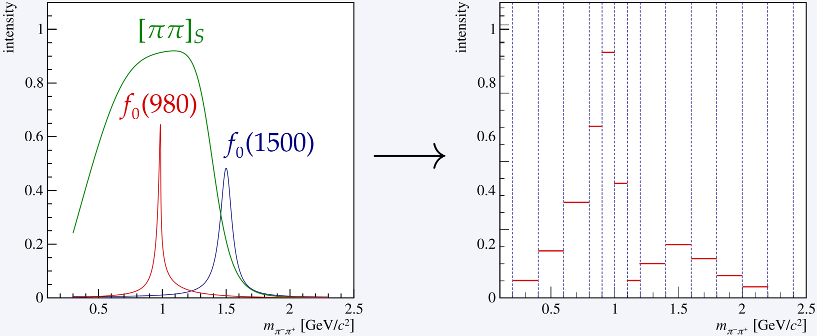
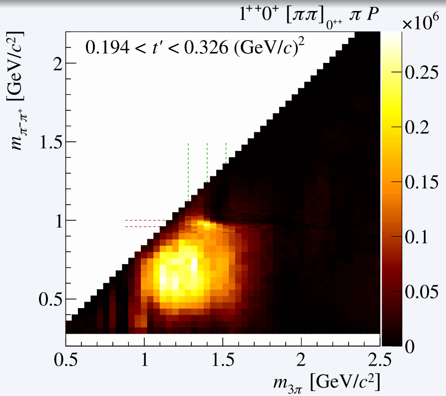


$\pi\pi$ S-Wave Amplitude in $J^{PC} = 1^{++}$ 3π Wave [arXiv:1509.00992]



- Correlation of 3π intensity around $1.4\,\text{GeV}/c^2$ with $f_0(980)$
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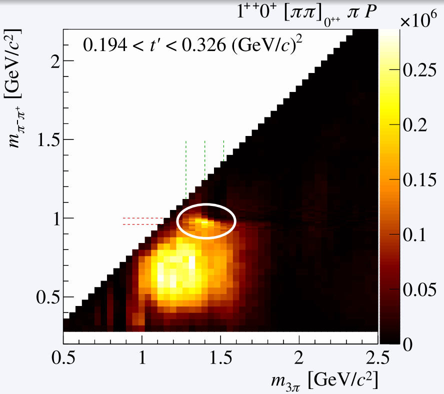

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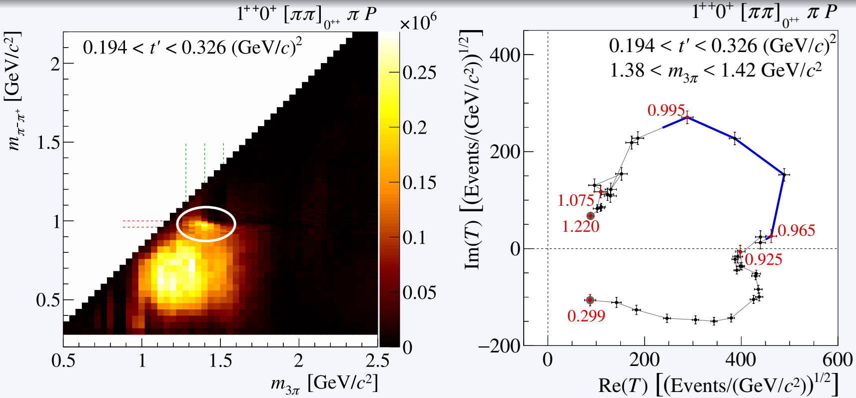

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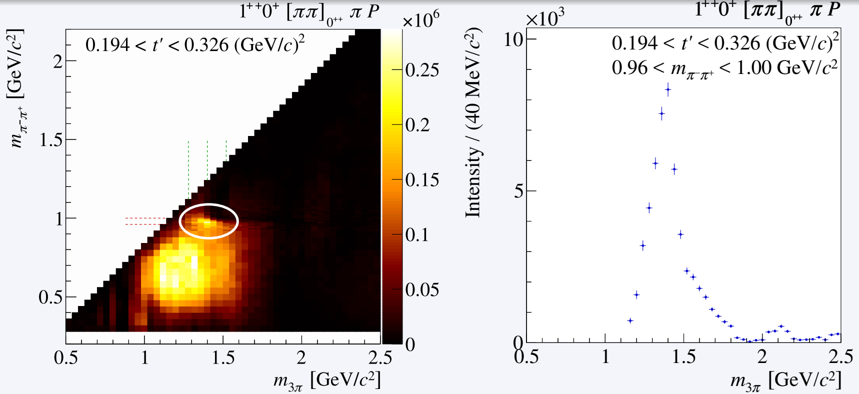

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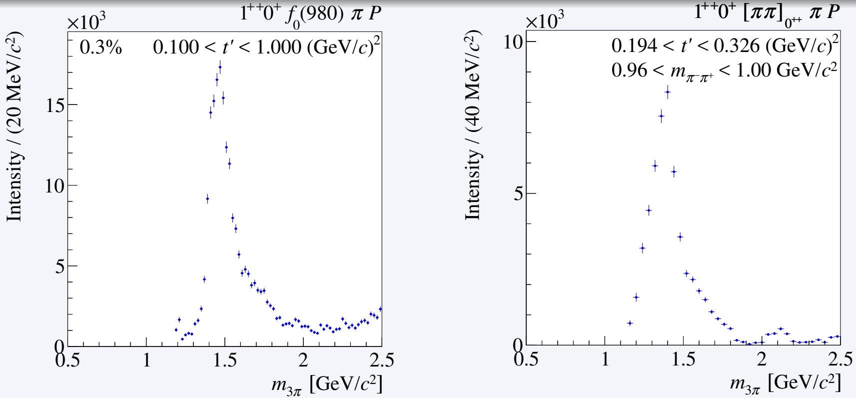

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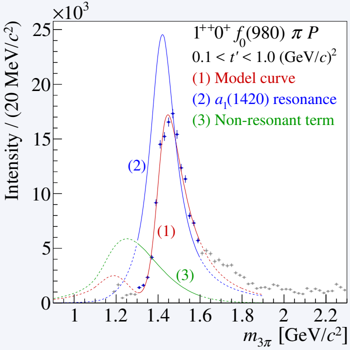
What is the Nature of the $a_1(1420)$? [PRL **115** (2015) 082001]

Still unclear

- $J^{PC} = 1^{++}$ ground state is $a_1(1260)$
  - Mass: 1230 ± 40 MeV$/c^2$
  - Width: 250 to 400 MeV$/c^2$
- No quark-model states expected at 1.4 GeV$/c^2$
  - First excited 1^{++} state expected to be heavier and wider
- Isospin partner of narrow $f_1(1420)$?
- $a_1(1420)$ has peculiar decay mode
  - Only seen in $f_0(980)\pi$ decay
  - $f_0(980)$ has large $s\bar{s}$ content
  - Some models explain $f_0(980)$ as tetra-quark state
- $a_1(1420)$ lies suspiciously close to $K\bar{K}^*$ threshold



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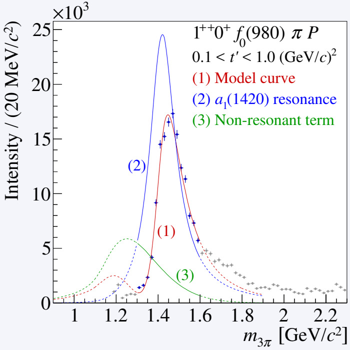

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Several proposed explanations

Genuine resonance

- Two-quark-tetraquark mixed state [Wang, arXiv:1401.1134]
- Tetraquark with mixed flavor symmetry [Chen *et al.*, PRD **91** (2015) 094022]

Effect in $a_1(1260)$ production

- Two-channel unitarized Deck amplitude + direct $a_1(1260)$ production [Basdevant and Berger, PRL **114** (2015) 192001 and arXiv:1501.04643]

Effect in $a_1(1260)$ decay

- Singularity in triangle diagram [Mikhasenko *et al.*, PRD **91** (2015) 094015]
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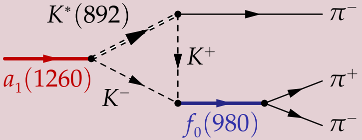
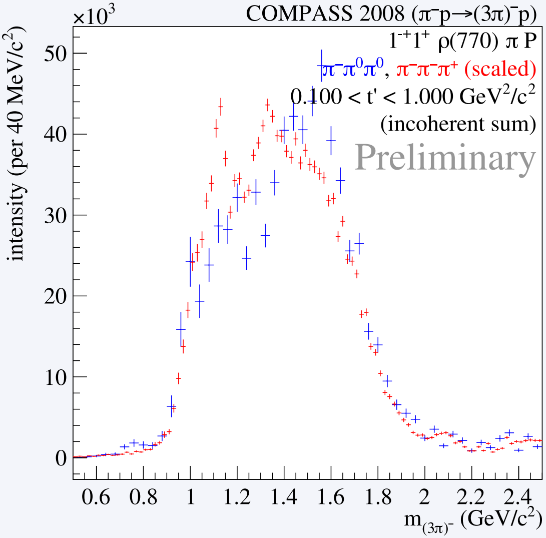


- Similar diagrams proposed to explain some X, Y, Z states and pentaquark candidate P_c in heavy-meson sector

- Broad intensity bump
- Similar in both 3π channels



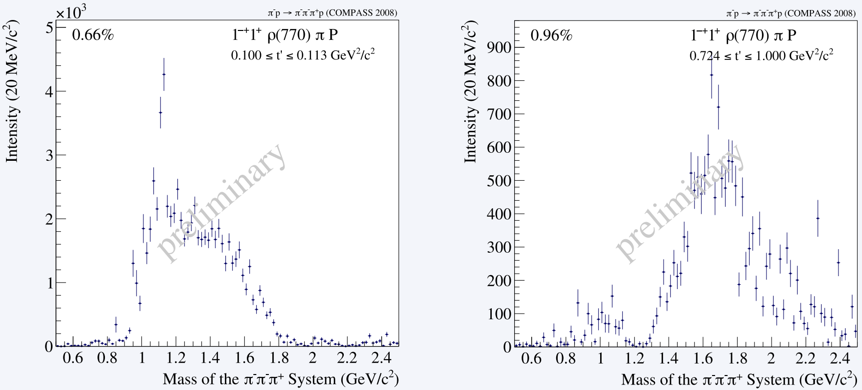
$\pi^-\pi^0\pi^0$

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

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

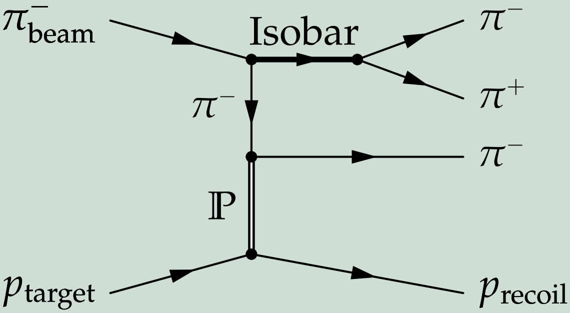
Drastic Change of Mass Spectrum with t'

"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

Deck effect



- MC pseudodata generated according to model of Deck amplitude

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

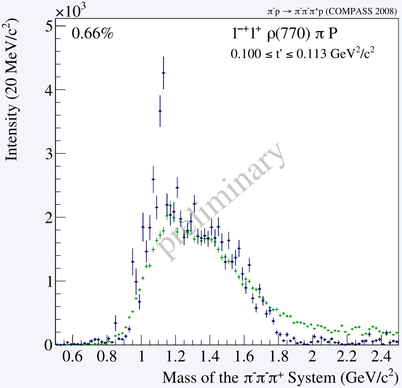
  see D. Ryabchikov's contribution for further details

- Analyzed like real data

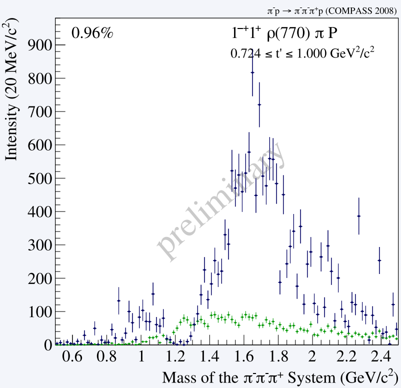
Spin-Exotic $J^{PC} = 1^{-+}$ Signal in $\pi^-\pi^+\pi^-$ PWA

Deck-Model for Nonresonant Component

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



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



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

One Last Thing...

Leptoproduction of $\psi(2S)$ and $X(3872)$ at COMPASS

- Muon beam with 160 to 200 GeV/c on ^{6}LiD and NH_3 targets
- $\psi(2S)$ and $X(3872)$ observed in $J/\psi\pi^+\pi^-$
- Production = "reversal" of $\psi(2S)$ and $X(3872)$ decays
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- Full muon-beam data set (2003 to 2010)
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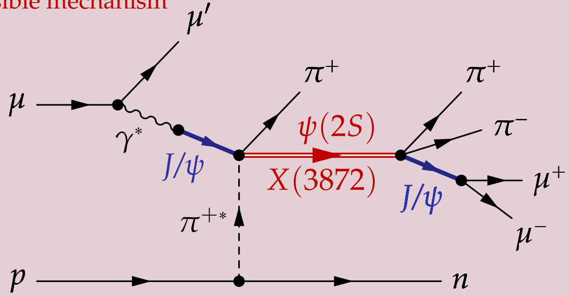

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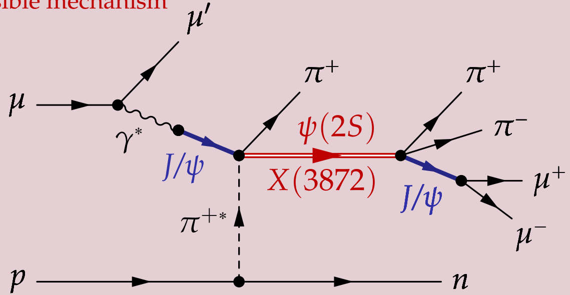

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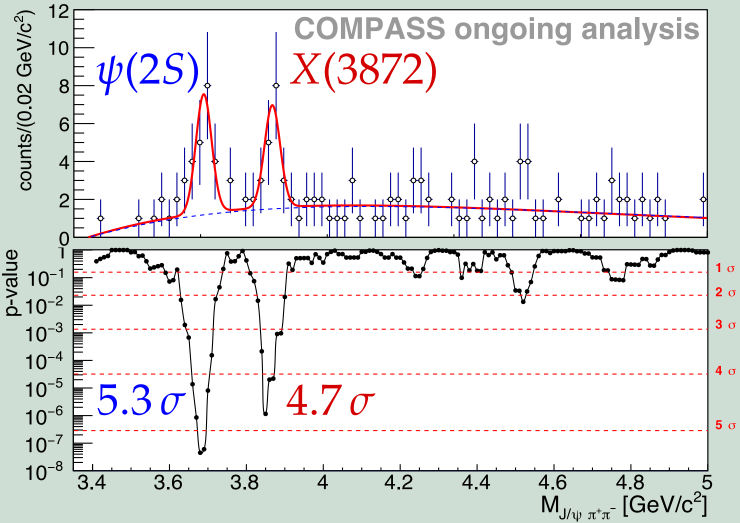
$J/\psi\pi^+\pi^-$ invariant mass spectrum



$M_{\psi(2S)} = 3680 \pm 8\ \text{MeV}/c^2$

$M_{X(3872)} = 3860 \pm 8\ \text{MeV}/c^2$

Conclusions

World's largest $\pi^-\pi^+\pi^-$ data set

- PWA reliably extracts even very small signals

Novel analysis techniques

- 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

Unexpected new axial-vector signal $a_1(1420)$

- Independently confirmed in $\pi^-\pi^0\pi^0$
- Nature still unclear; several possible explanations
- **COMPASS data will put models to the test**

Nonresonant contributions play important role

- First studies using Deck models
- Improved models needed $\Longrightarrow$ collaboration with JPAC

see contributions by A. Szczepaniak, A. Jackura, V. Pauk, and V. Mathieu

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Outlook

Other ongoing analyses

- Pion diffraction into $\pi^-\eta^{(\prime)}$, $\pi^-\eta\eta$, $\pi^-\pi^0\omega$, $K\bar{K}\pi$, $K\bar{K}\pi\pi$, …
- Kaon diffraction into $K^-\pi^+\pi^-$
- Central-production reactions
- $\pi\gamma$ scattering using Primakoff reactions on heavy targets
- Leptoproduction of $X(3872)$

Outline

4. Backup slides
   - PWA of diffractively produced 3π final states
   - PWA of diffractively produced $\pi^-\eta$ and $\pi^-\eta'$ final states

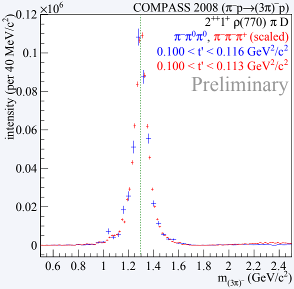
PWA of $\pi^- p \to (3\pi)^- p_{\text{recoil}}$: Low t' vs. High t'

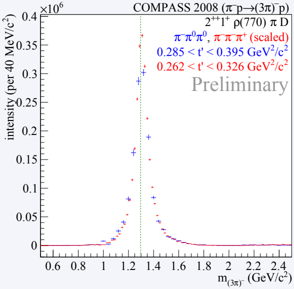
$2^{++} 1^+ \rho\pi D$

- Peak does not change with t'

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

- Peak *moves* with t'
- Strong nonresonant contribution





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

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

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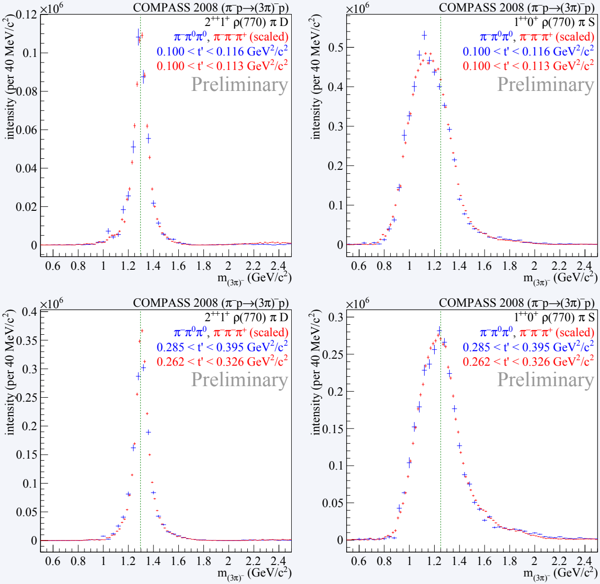

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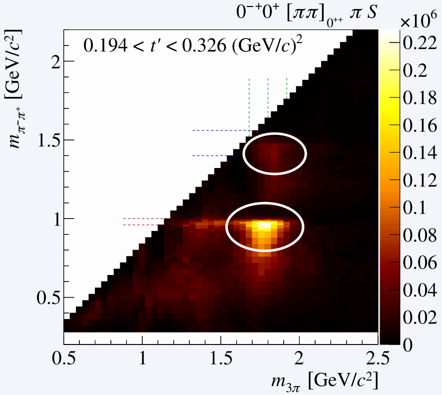
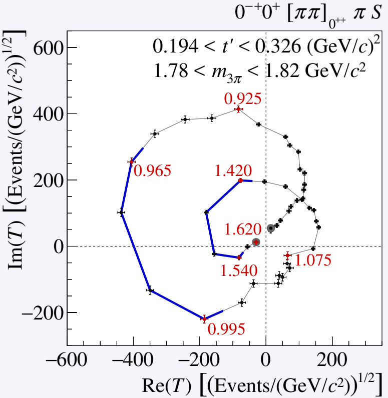
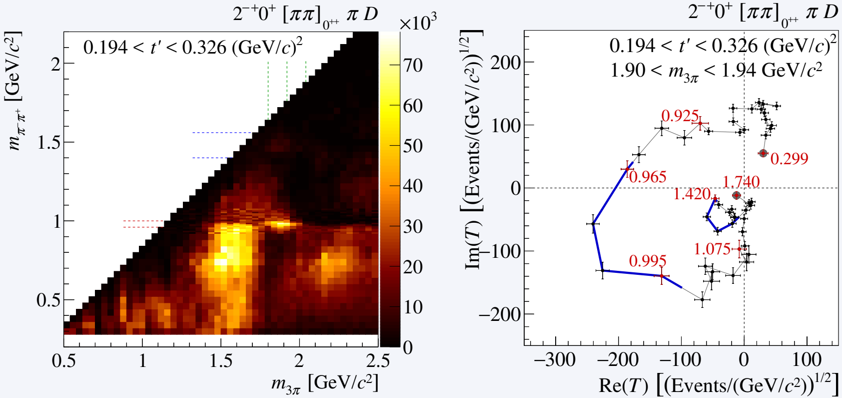




- Coupling of $\pi(1800)$ to $f_0(980)\pi$ and $f_0(1500)\pi$ decay modes

$\pi\pi$ S-Wave Amplitude in $J^{PC} = 2^{-+}$ 3π Wave [arXiv:1509.00992]



- Correlation of intensity around $m_{3\pi} = 1.9$ GeV/c^2 with $f_0(980)$
- $f_0(980)$ semicircle in Argand diagram
- Coupling of $\pi_2(1880)$ to $f_0(980)\pi$ decay mode

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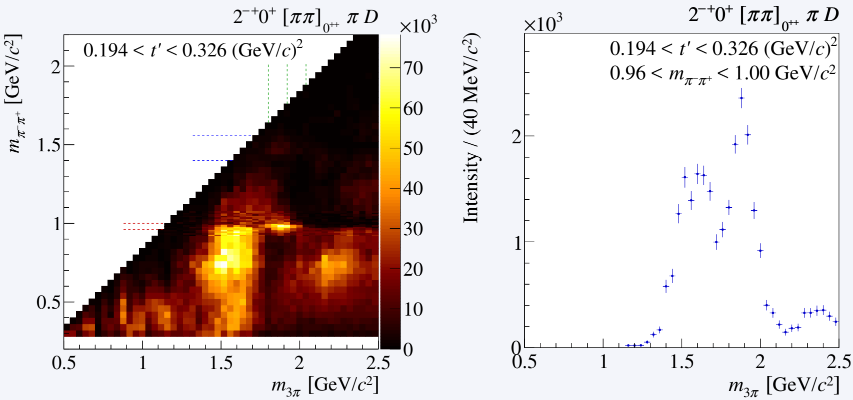

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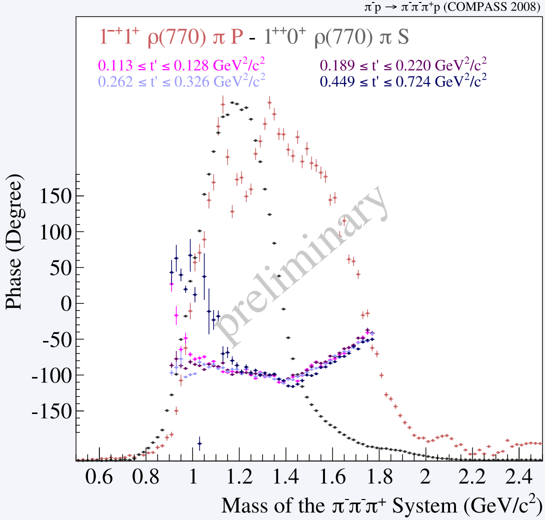
Spin-Exotic $J^{PC} = 1^{-+}$ Signal in $\pi^-\pi^+\pi^-$ PWA

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'

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

[PLB **740** (2015) 303]

- 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 $\pi^0 \to \gamma\gamma$
- $\eta' \to \pi^+\pi^-\eta$ with $\eta \to \gamma\gamma$

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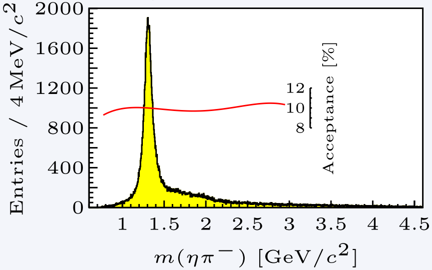
$\pi^-\eta$ invariant mass



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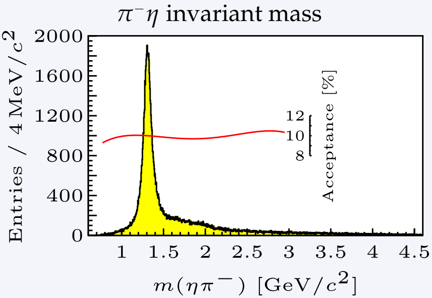

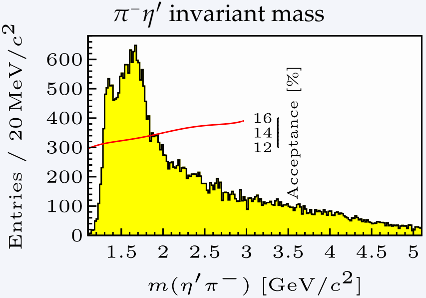

Comparison of $J^{PC} = 2^{++}$ Partial Waves

[PLB **740** (2015) 303]

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

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

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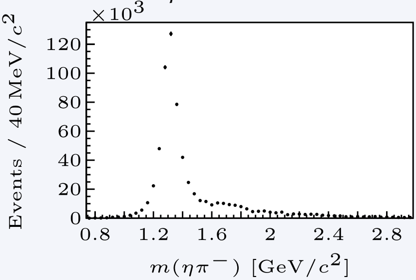
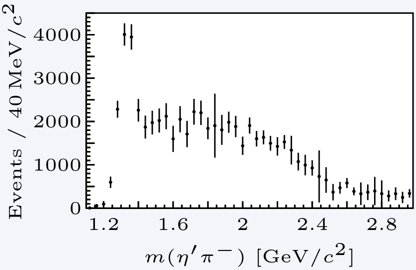


$\pi^-\eta'$ final state



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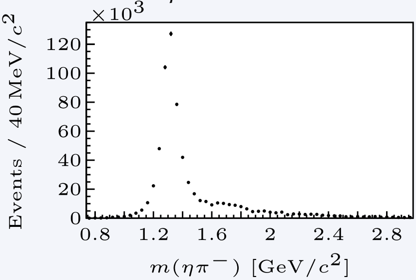
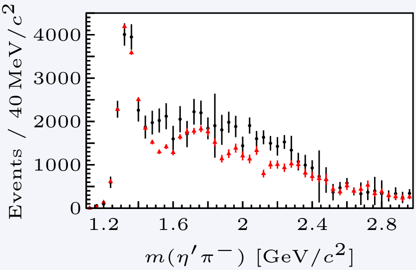
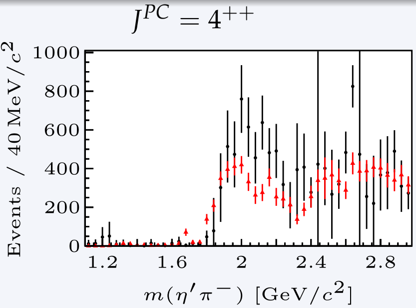


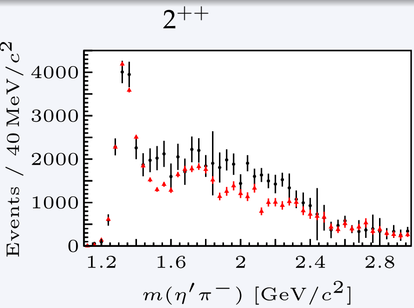
$\pi^-\eta'$ final state; $\pi^-\eta$ scaled

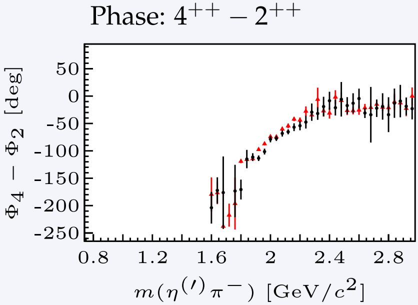


Even-Spin Waves

[PLB **740** (2015) 303]





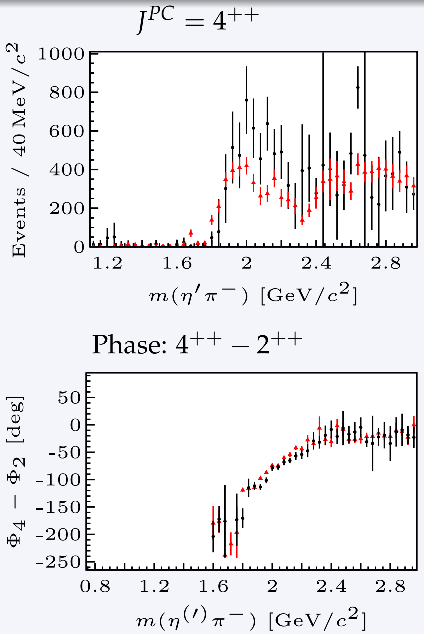


- Similar even-spin waves
- Intermediate states couple to same final-state flavour content
- Similar physical content also in nonresonant high-mass region

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

Even-Spin Waves

[PLB **740** (2015) 303]

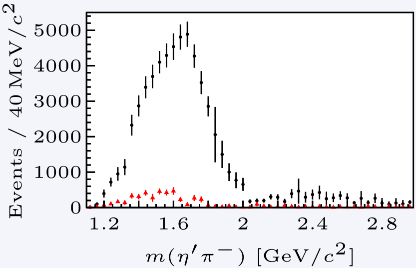


- Resonance-model fit (Breit-Wigner)
- $$\frac{N(a_2 \to \pi\eta')}{N(a_2 \to \pi\eta)} = (5 \pm 2)\,\%$$
- First-time measurement of $$\frac{N(a_4 \to \pi\eta')}{N(a_4 \to \pi\eta)} = (23 \pm 7)\,\%$$

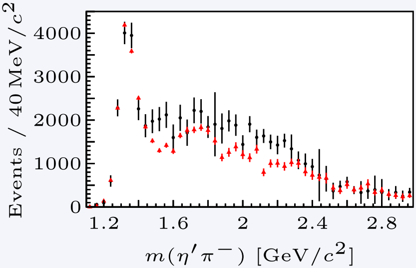
$\pi^-\eta'$ final state; $\pi^-\eta$ scaled

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

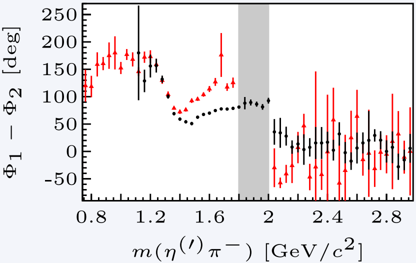
Spin-exotic $J^{PC} = 1^{-+}$



2^{++}



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

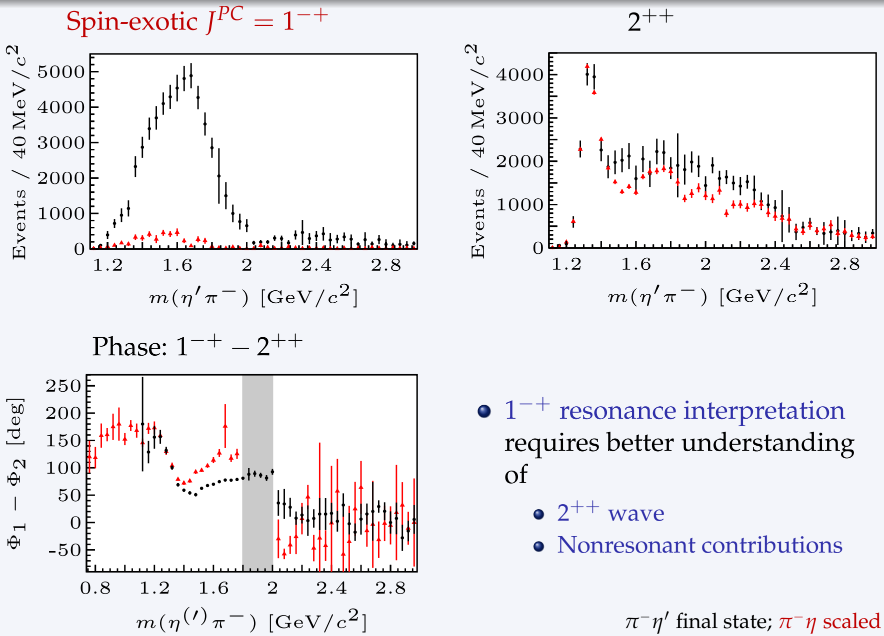


- 1^{-+} intensities very different
- Suppression in $\pi\eta$ channel predicted for intermediate $|q\bar{q}g\rangle$ state
- Different phase motion in $1.6\,\mathrm{GeV}/c^2$ region

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

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

[PLB **740** (2015) 303]



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

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

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

[PLB **740** (2015) 303]