Light-meson Spectroscopy in Multi-Body Final States

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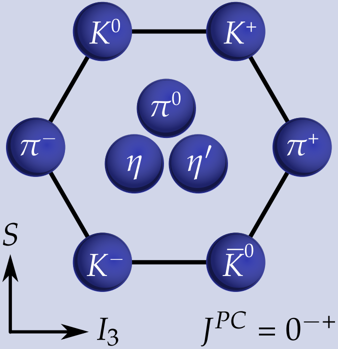
Outline

Quark-Model Meson Nonets

Light-quark mesons

- u, d, and s quarks $\Longrightarrow$ $\mathrm{SU}(3)_{\mathrm{flavor}}$ nonets

Ground-state nonets



- Many more nonets for orbital and radial excitations

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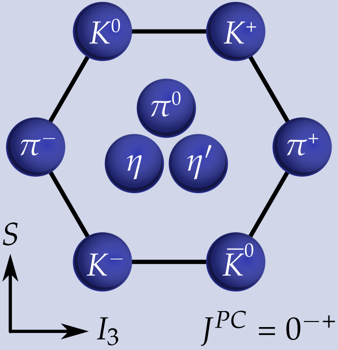

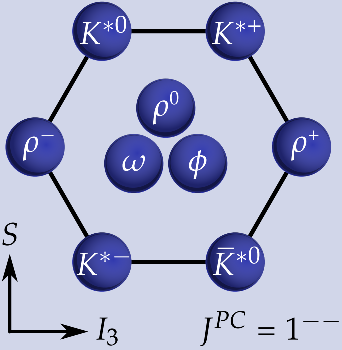

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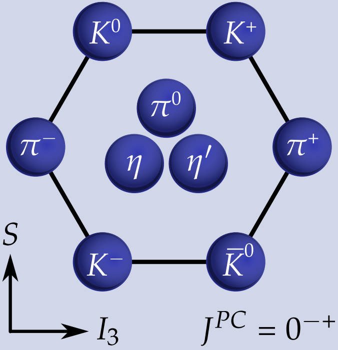

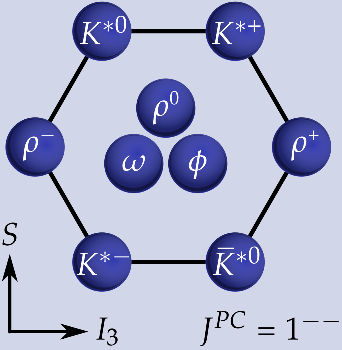

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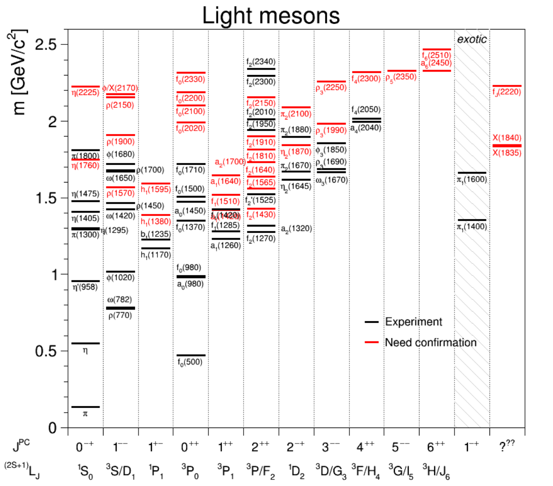
Light-Quark Meson Spectrum



[Courtesy K. Götzen, GSI]

"Light-meson frontier"

- Many states need confirmation in mass region $m \gtrsim 2\ \mathrm{GeV}/c^2$
- Many wide states $\Longrightarrow$ overlap and mixing
- Identification of higher excitations becomes exceedingly difficult

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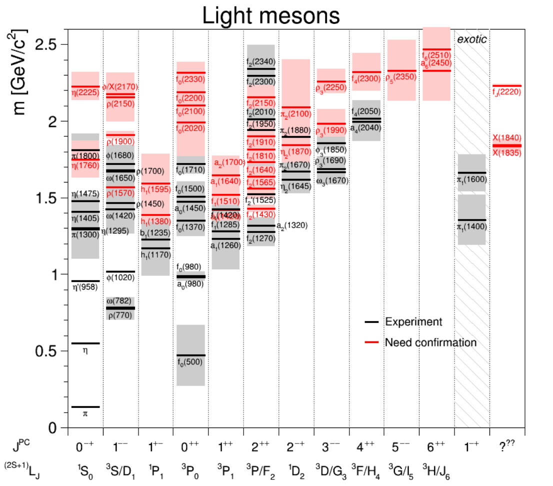

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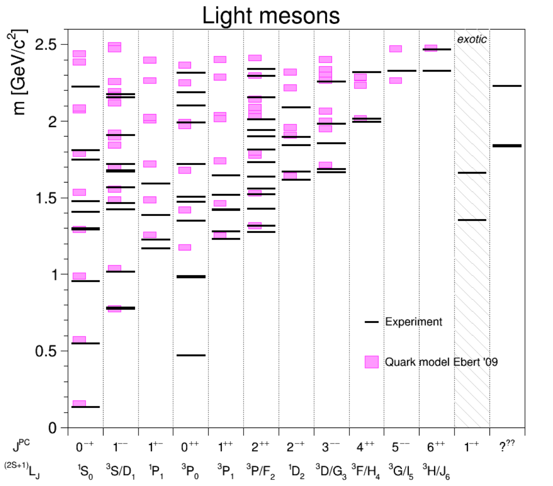

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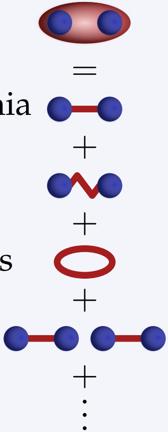


Quarkonia $|q\bar{q}\rangle$

Hybrids $|q\bar{q}g\rangle$

Glueballs $|gg\rangle$

Multi-quarks $|q^2\bar{q}^2\rangle$

QCD permits additional color-neutral configurations

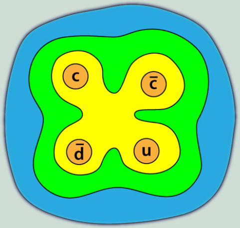
- *Physical mesons:* linear superpositions of *all* allowed basis states
- "Configuration mixing"
- Amplitudes determined by QCD interactions
- Disentanglement of contributions difficult

Beyond the Constituent Quark Model

Best experimental evidence so far from heavy-quark sector

Tetraquark candidates $Z_{c,b}$

- Charged $|c\bar{c}\rangle$- and $|b\bar{b}\rangle$-like states
- E.g. $Z_c^{\pm}(3900) \to J/\psi + \pi^{\pm}$



Pentaquark candidates P_c^+

- Heavy baryon
- Decay mode $P_c^+ \to p + J/\psi$

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- Model calculations suggest some states to be tetraquarks or hybrids
- No definite experimental evidence

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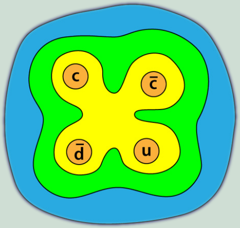

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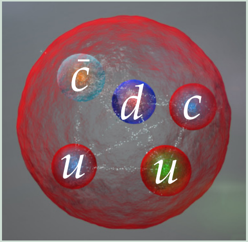

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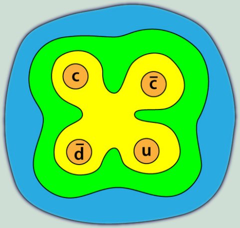

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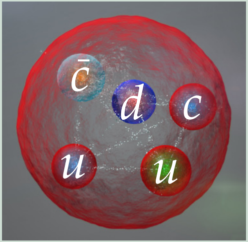

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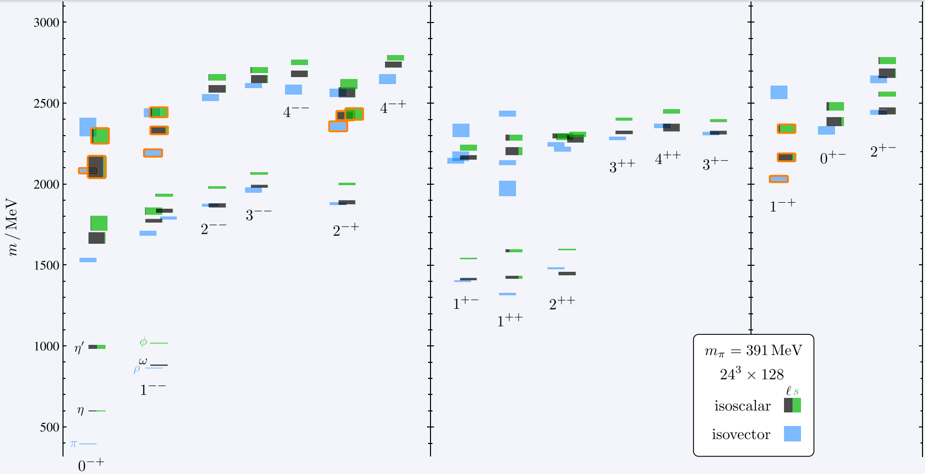
Light-Quark Meson Spectrum from Lattice QCD

State-of-the-art calculation with $m_\pi = 391\ \text{MeV}/c^2$ [Dudek *et al.*, PRD **88** (2013) 094505]

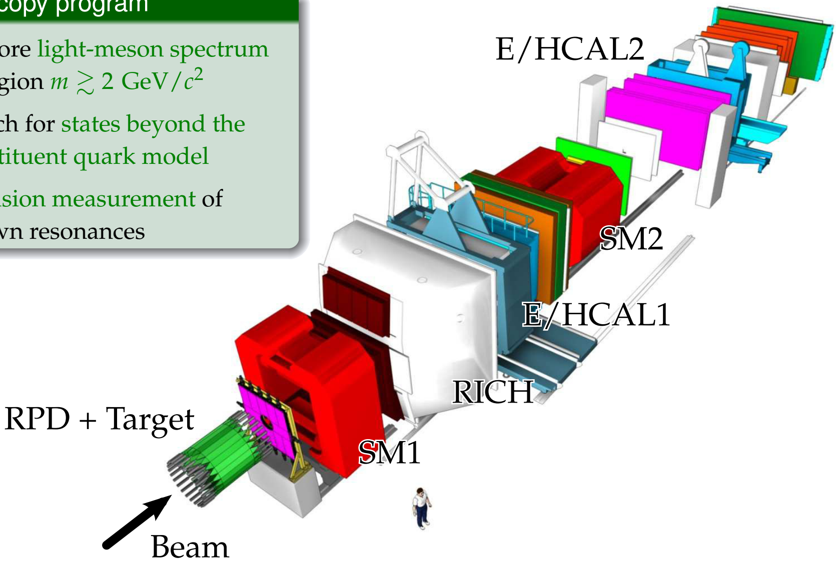


- Essentially recovers quark-model pattern
- High towers of excited states
- Additional hybrid-meson super-multiplet

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

Spectroscopy program

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



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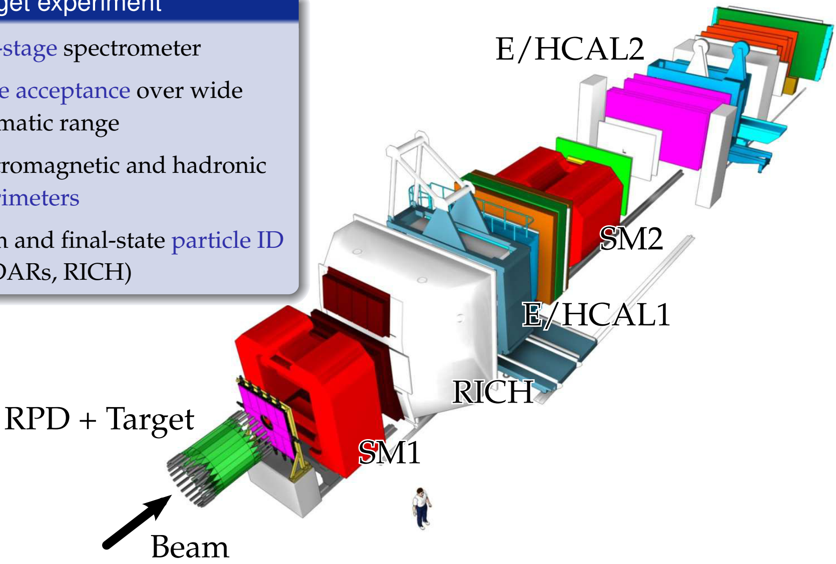
Fixed-target experiment

- 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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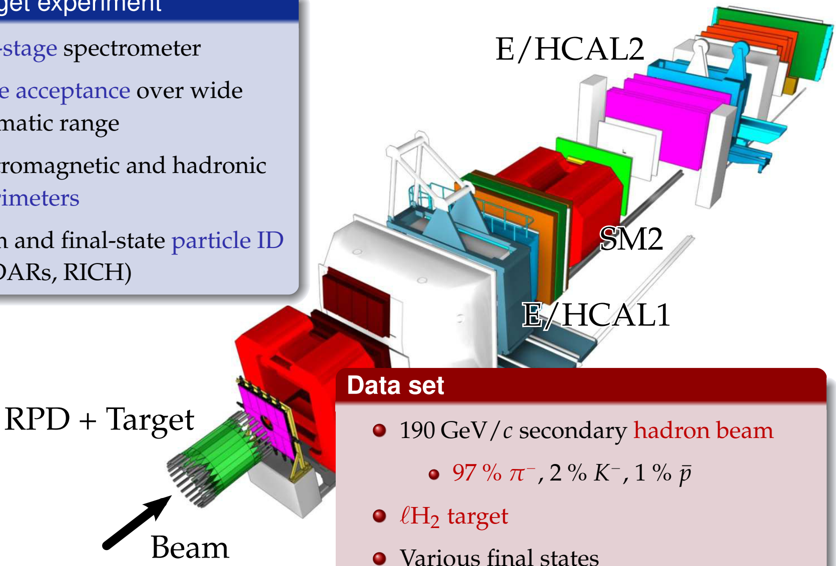
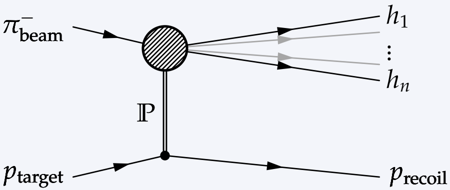


Data set

- 190 GeV/c secondary hadron beam
  - $97\,\%\ \pi^-$, $2\,\%\ K^-$, $1\,\%\ \bar{p}$
- ℓH_2 target
- Various final states

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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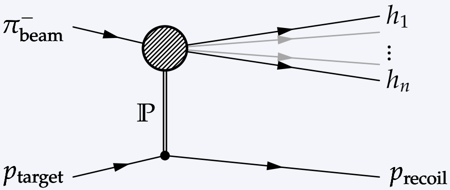

- Beam particle gets excited into intermediate resonances X
- X dissociate into n-body hadronic final state
- Rich spectrum of interfering intermediate states X

Goal: disentangle all contributing resonances X

- Determine their mass, width, and quantum numbers

Method: **partial-wave analysis** (PWA)

- Uses full kinematic information of events
- *Amplitude analysis:* exploits interference of intermediate states
  - Additional phase information $\Longrightarrow$ increased sensitivity

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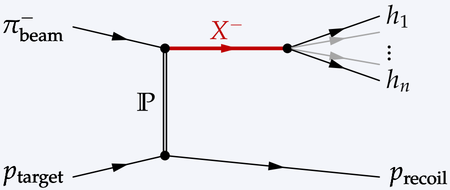

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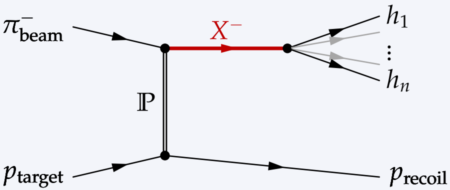

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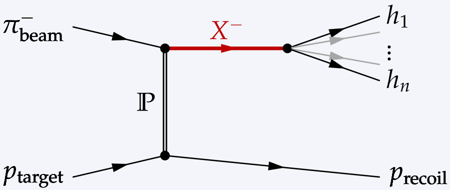

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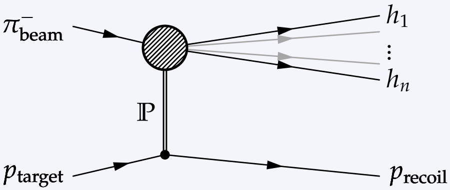
Meson Production in Diffractive Dissociation

Example: $\pi^-\pi^+\pi^-$ final state [arXiv:1509.00992]



- Exclusive measurement
  - Clean data sample
- Squared four-momentum transfer $0.1 < t' < 1.0\,(\text{GeV}/c)^2$
- 50 M $\pi^-\pi^+\pi^-$ events
- Well-known 3π resonances appear in $m_{3\pi}$ spectrum
- *Crosscheck:* 3.5 M $\pi^-\pi^0\pi^0$ events
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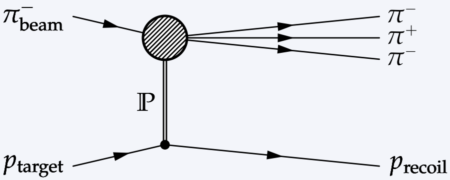

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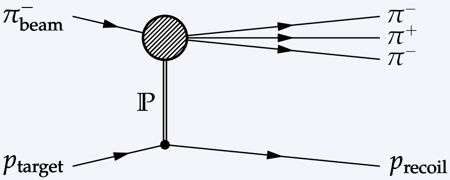

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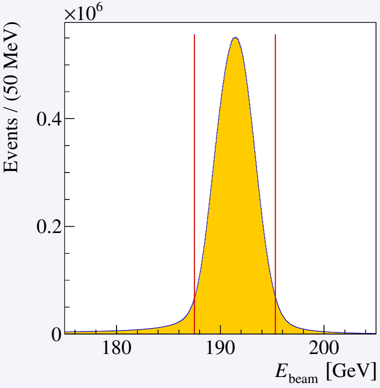

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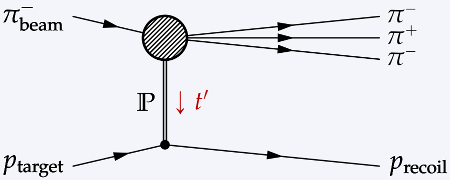

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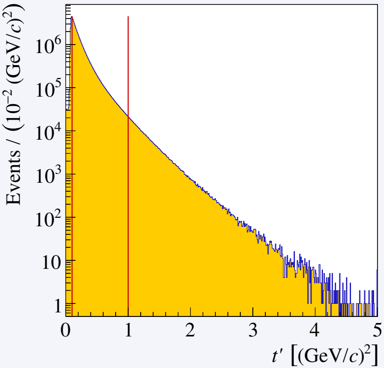

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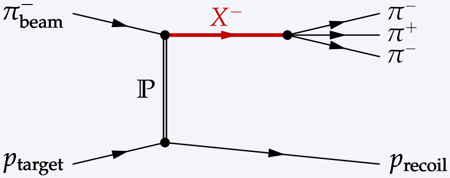

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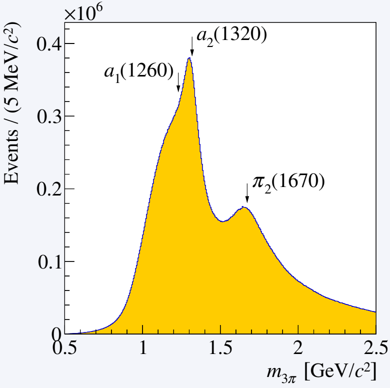

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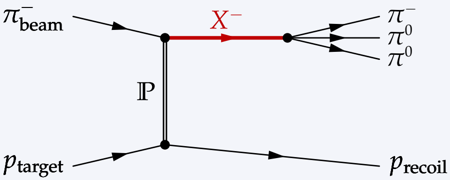

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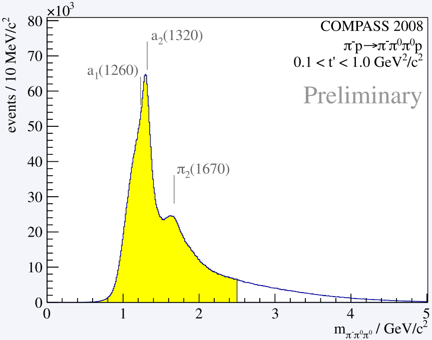
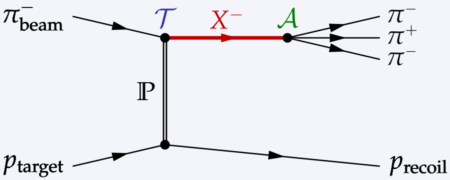




Factorization ansatz

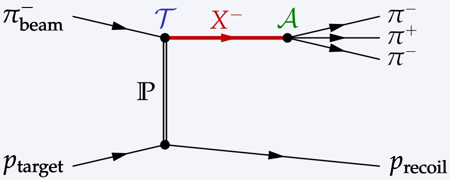
- Production of resonance X is independent of its decay
  - Production described by amplitudes $\mathcal{T}_{\text{wave}}(m_X)$
    - Strengths and relative phases of various $X \implies$ interesting physics
  - Decay of X described by $\mathcal{A}_{\text{wave}}(\tau; m_X)$
    - τ: set of 5 kinematic variables that define 3π final state
    - $\mathcal{A}_{\text{wave}}(\tau; m_X)$ calculable with additional model assumptions
- Model for measured intensity distribution

$$\mathcal{I}(\tau; m_X) = \left| \sum_{\text{waves}} \mathcal{T}_{\text{wave}}(m_X)\, \mathcal{A}_{\text{wave}}(\tau; m_X) \right|^2$$

  - Coherent sum of partial-wave amplitudes

Partial-Wave Decomposition

Example: $\pi^-\pi^+\pi^-$ final state [arXiv:1509.00992]



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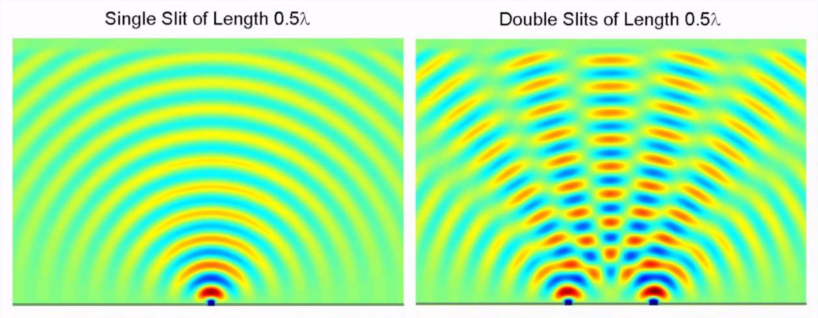
Partial-Wave Analysis: $\pi^-\pi^+\pi^-$ Final State

Loose Analogy: Interference of Light Waves



Diffraction on mask with variable number of slits

- Interference pattern on screen depends on number, position, and width of slits
    - Each slit represents a resonance
    - Width of slit = strength of resonance X
    - Relative position of slits = relative phase difference between X
    - 1D intensity distribution = 5D kinematic distribution of 3π

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

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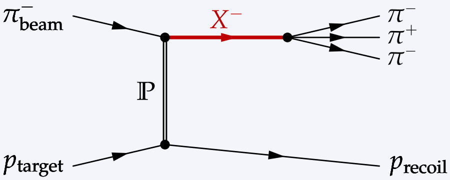

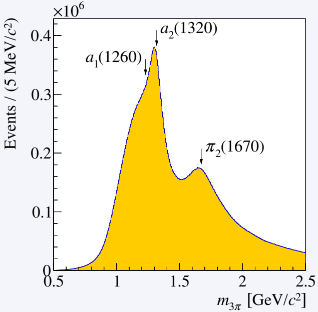

X^- decay via $\pi^+\pi^-$ resonances = "isobars"

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

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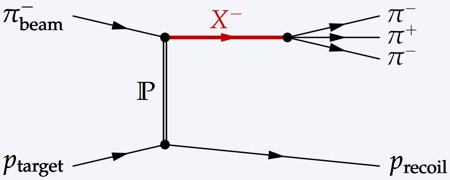

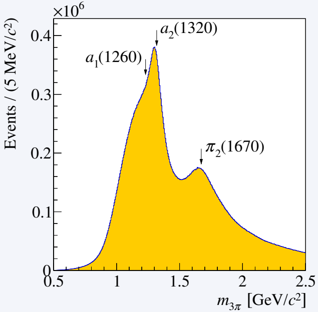

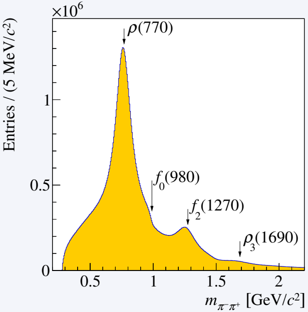

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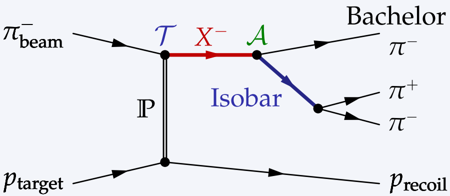

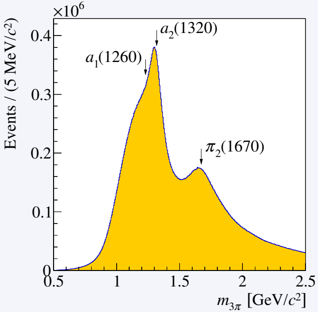

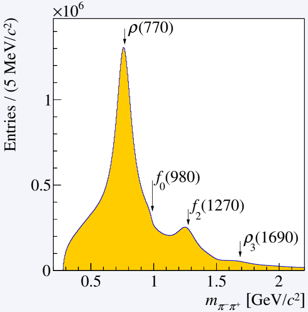

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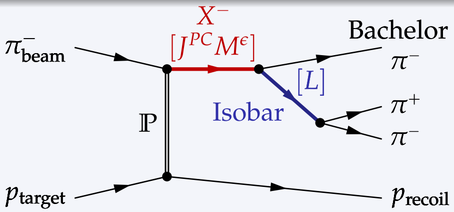

- **"Wave"** = unique combination of X and isobar quantum numbers
- *Notation:* $J^{PC}\,M^{\epsilon}$ isobar $\pi\,L$
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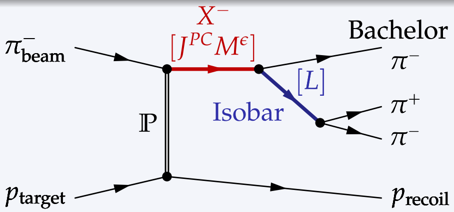

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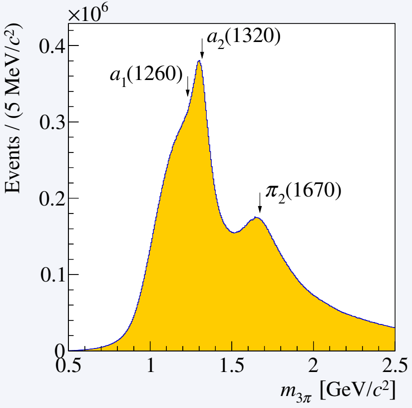
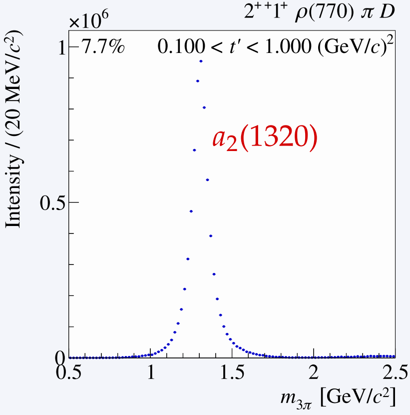
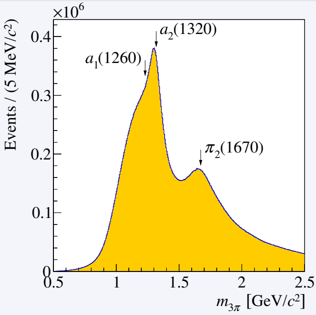
- Partial-wave decomposition performed independently in narrow $m_{3\pi}$ bins
  - In each bin: fit of 5-dimensional intensity distribution
  - *Result:* production amplitudes $\mathcal{T}_{\text{wave}}(m_{3\pi})$
- PWA makes no assumptions about 3π resonances

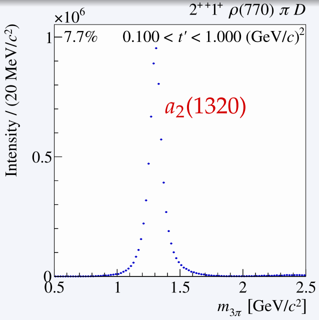




PWA $\pi^-\pi^+\pi^-$ Final State: Major Waves

[arXiv:1509.00992]





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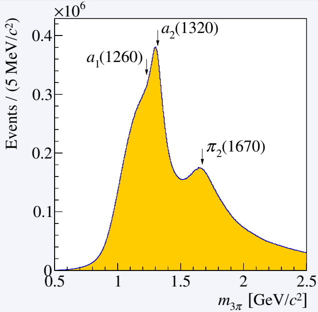

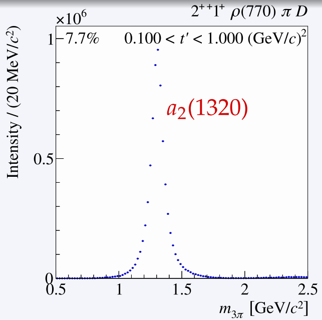

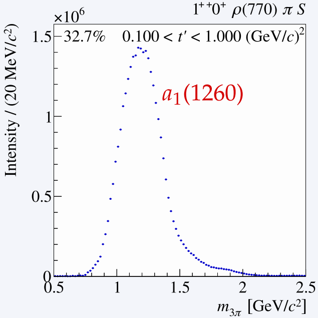

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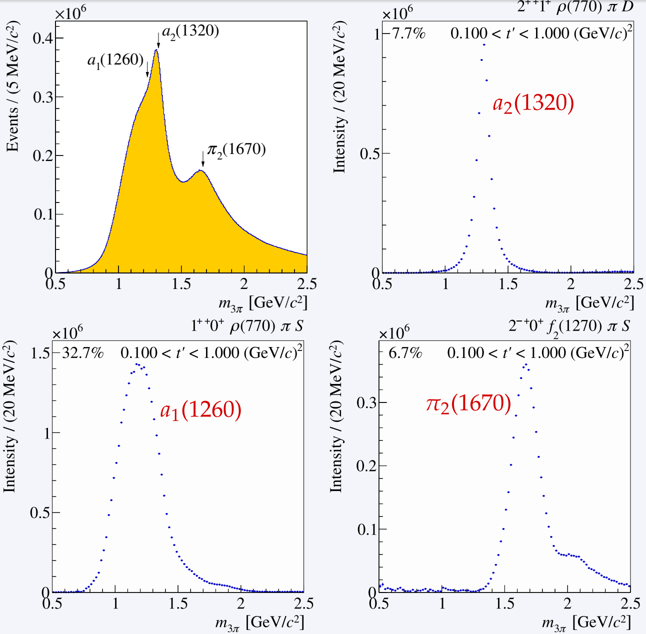

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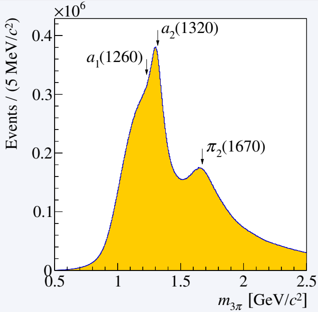

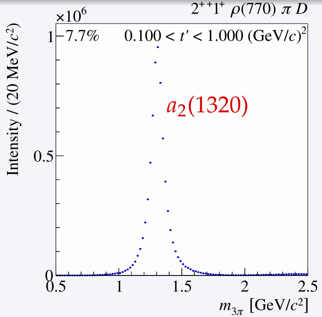

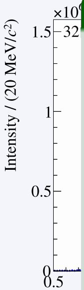

PWA model

- In total 88 partial waves
  - Spin J up to 6
  - Orbital angular momentum L up to 6
- Largest wave set ever used for 3π analysis
- *Challenge:* model selection
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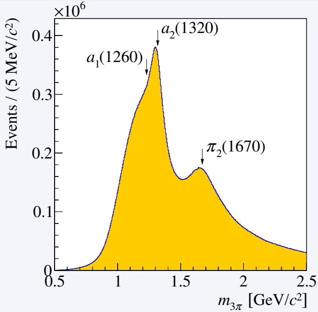

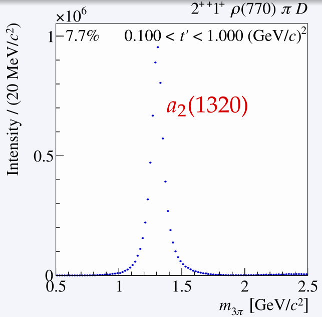

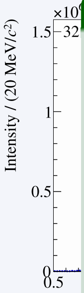

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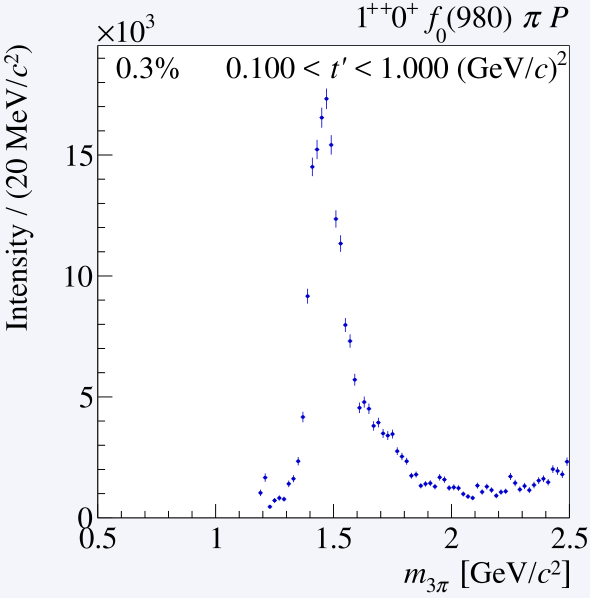
PWA $\pi^-\pi^+\pi^-$ Final State: A New $a_1(1420)$ Meson?

[arXiv:1509.00992]

- **Unexpected peak around 1.4 GeV/c^2**
- Small intensity: only 0.3% relative contribution

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

- Very different acceptance
- **Similar signal**



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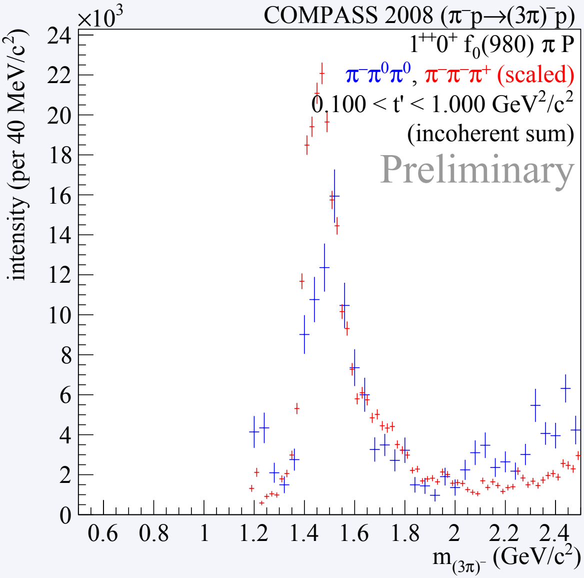
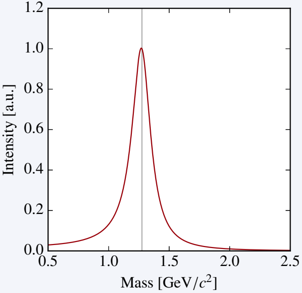


$\pi^-\pi^0\pi^0$

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

Experimental Signatures of a Resonance

Example: Single Narrow Relativistic Breit-Wigner Resonance



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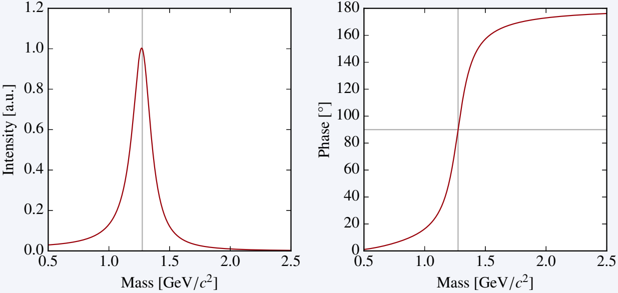

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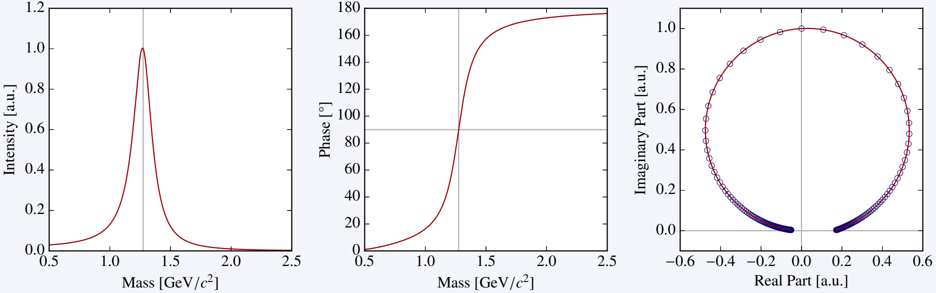

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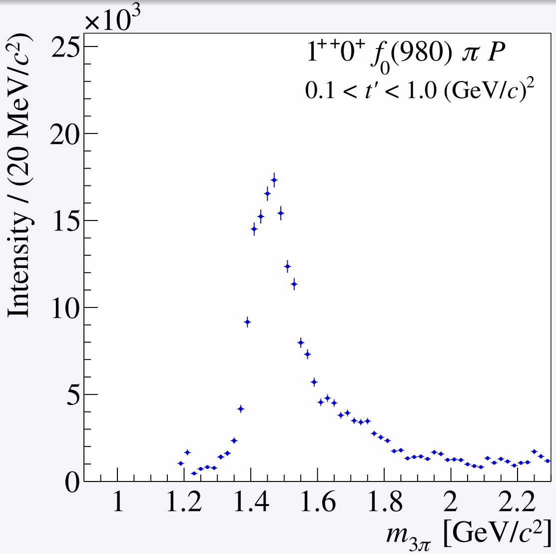
Resonance-Model Fit

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



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

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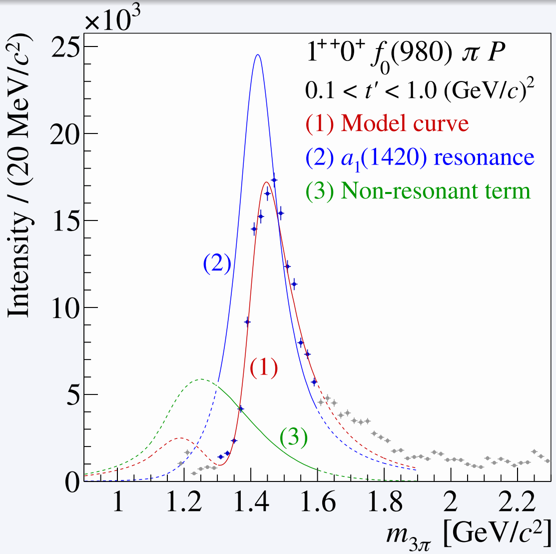

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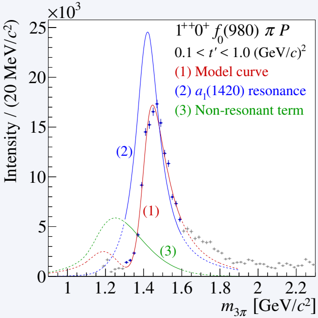

- 1^{++} peak consistent with Breit-Wigner resonance
- $a_1(1420)$ parameters
  Mass: 1414^{+15}_{-13} MeV$/c^2$
  Width: 153^{+8}_{-23} MeV$/c^2$
- *Work in progress:* extension to 14 partial waves

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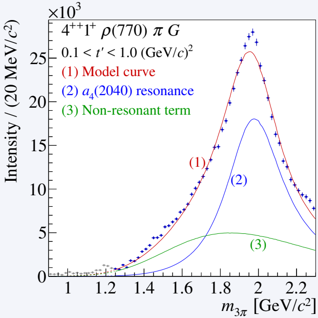

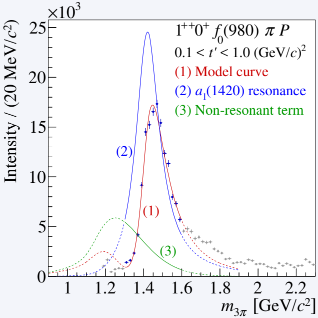

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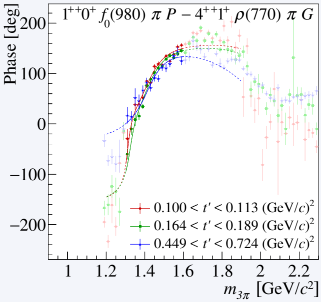

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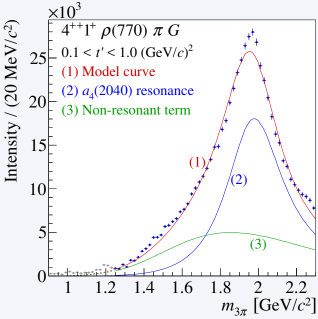

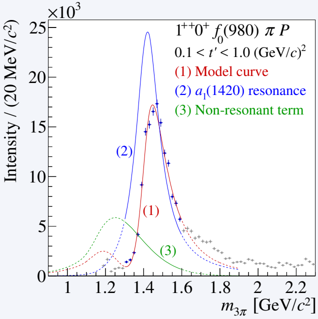

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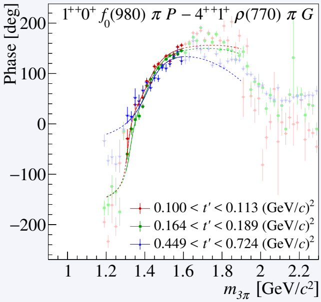

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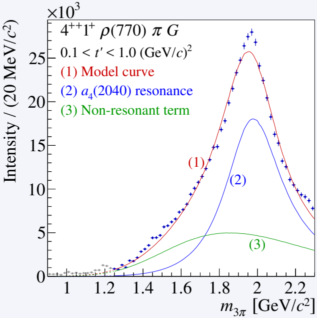

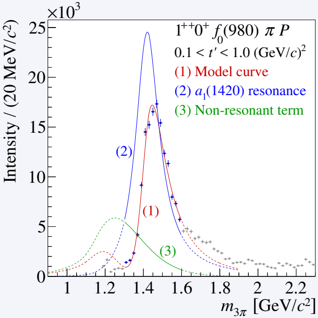

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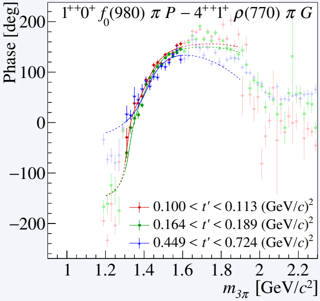
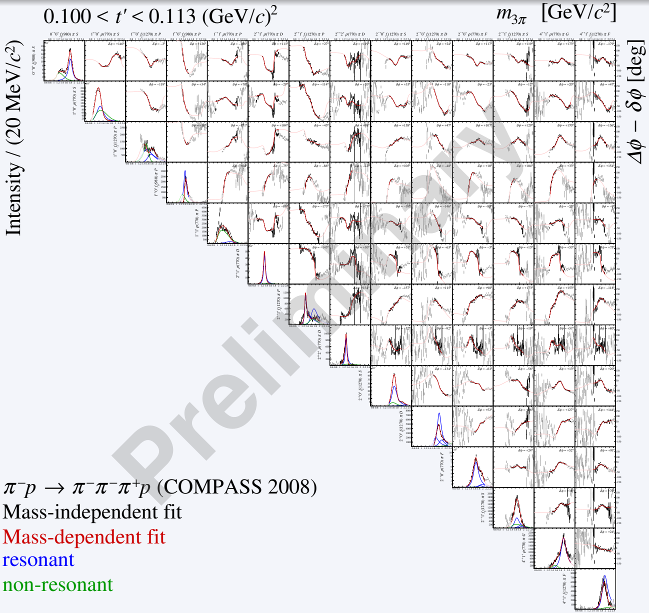


Resonance-Model Fit

14 Waves described by 11 Resonances



$\times$ 11 t' bins

$\pi^- p \to \pi^-\pi^-\pi^+ p$ (COMPASS 2008)

Mass-independent fit

Mass-dependent fit

resonant

non-resonant

Resonance-Model Fit

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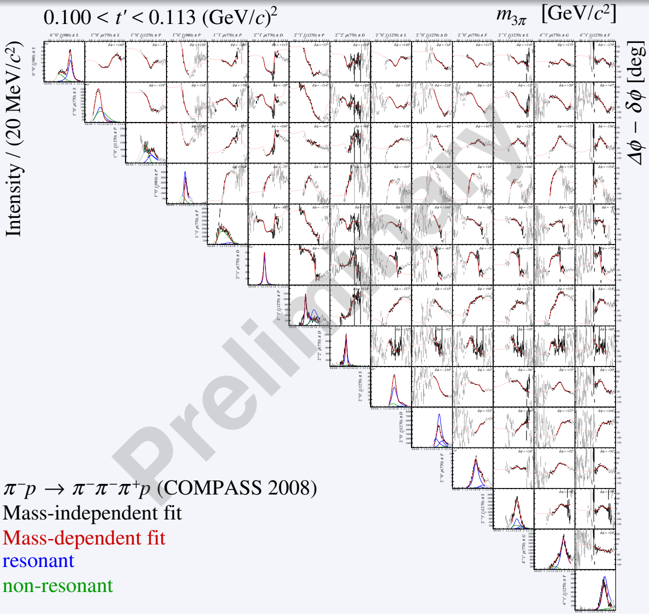

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Virtue of a large Data Set: Analysis in narrow t' Bins

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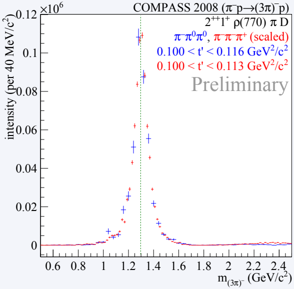

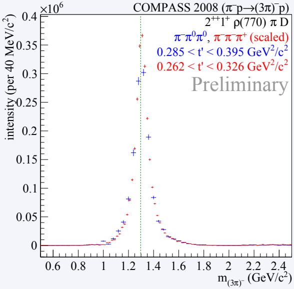

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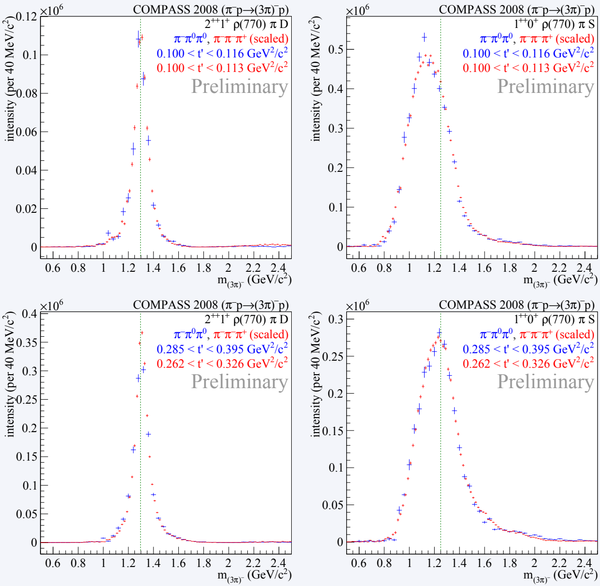

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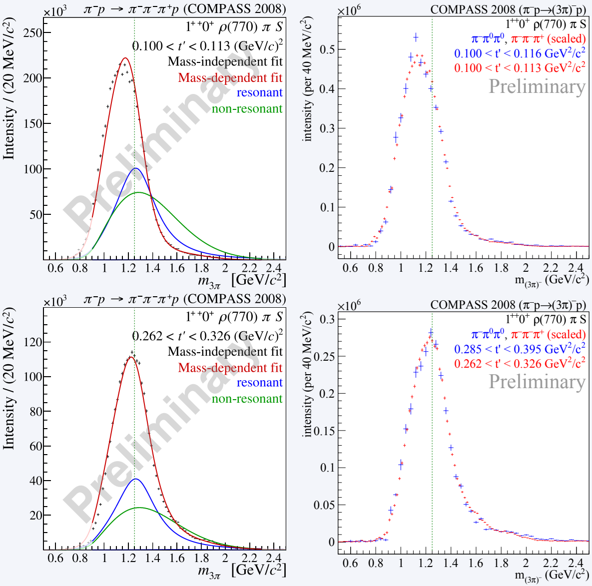
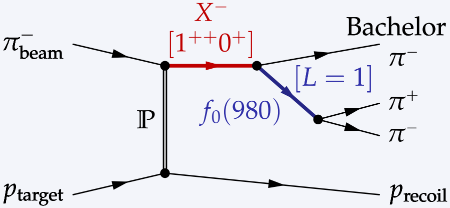


Is the $a_1(1420)$ a Model Artifact?



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- At least 3 isobars with $J^{PC} = 0^{++}$
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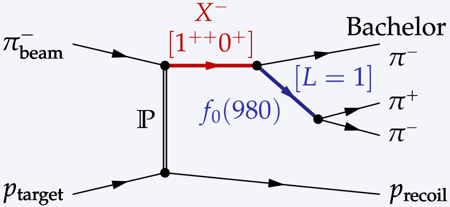

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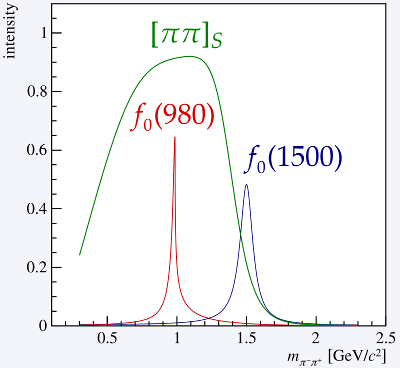

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Novel analysis method

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
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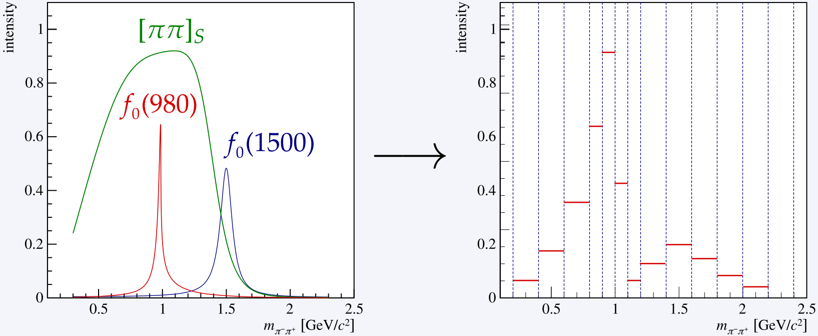

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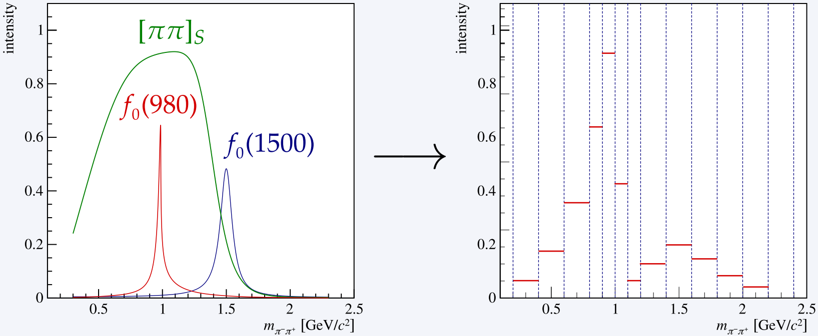
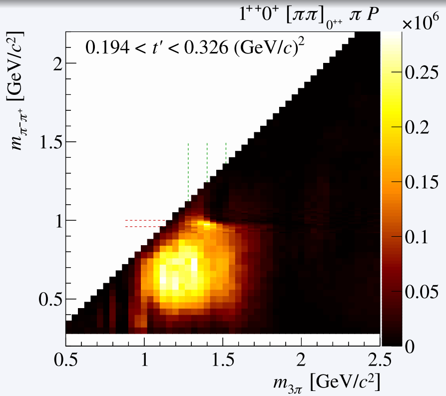


$\pi\pi$ S-Wave Amplitude in $J^{PC} = 1^{++}$ 3π Wave [arXiv:1509.00992]



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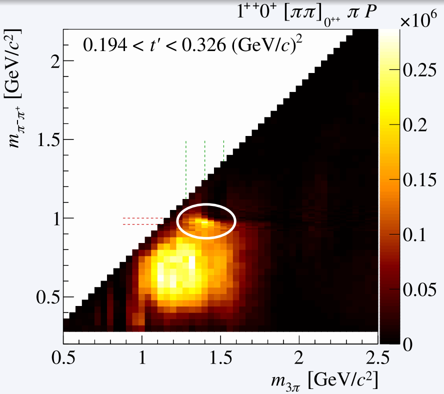

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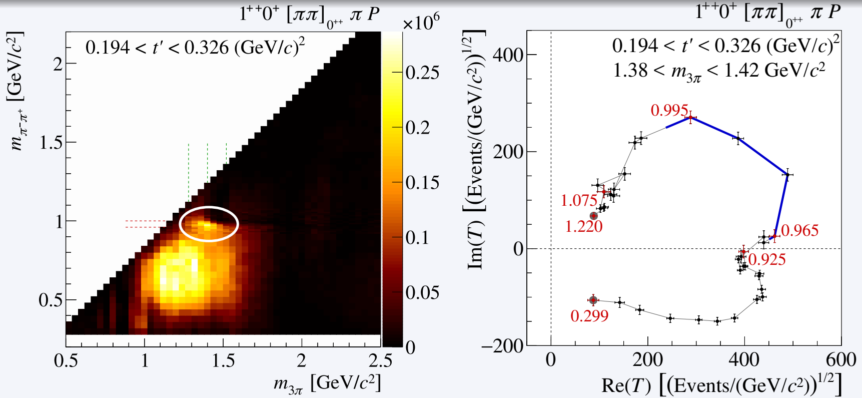

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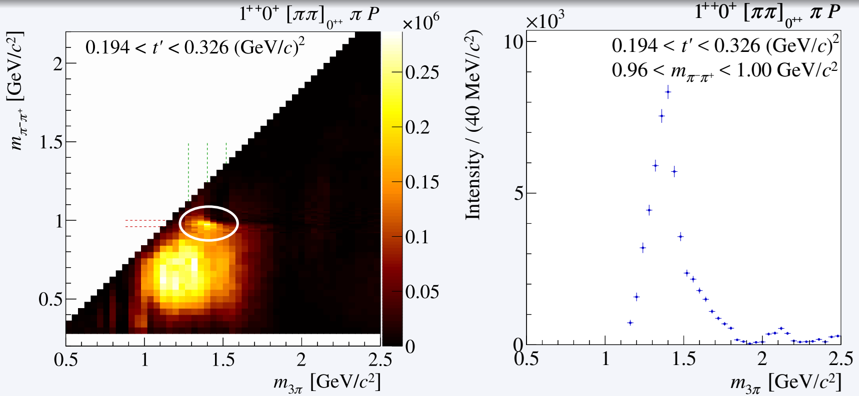

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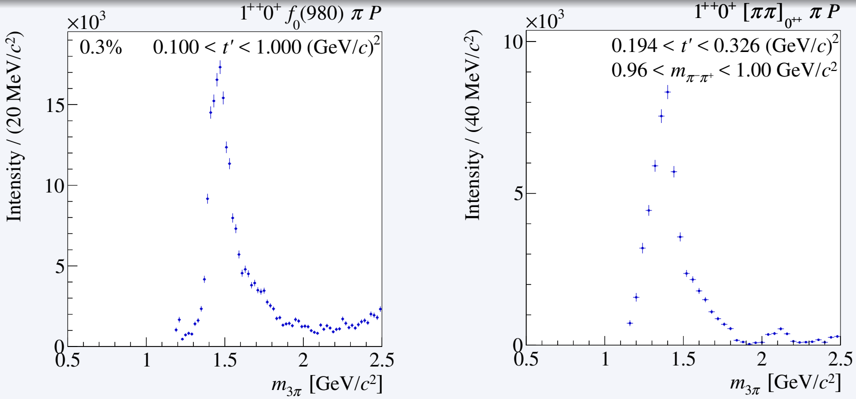

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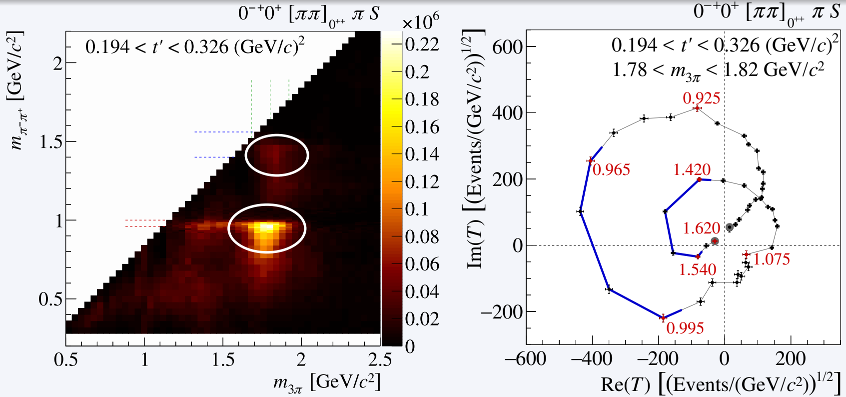
$\pi\pi$ S-Wave Amplitude in $J^{PC} = 0^{-+}$ 3π Wave [arXiv:1509.00992]



- Coupling of $\pi(1800)$ to $f_0(980)\pi$ and $f_0(1500)\pi$ decay modes
- $\pi\pi$ S-wave phase similar to the one extracted from $D_s^+ \to \pi^+\pi^-\pi^+$ (black) BABAR, PRD **79** (2009) 032003
- Input/constraint for CP violation analyses in multi-body heavy-meson decays?

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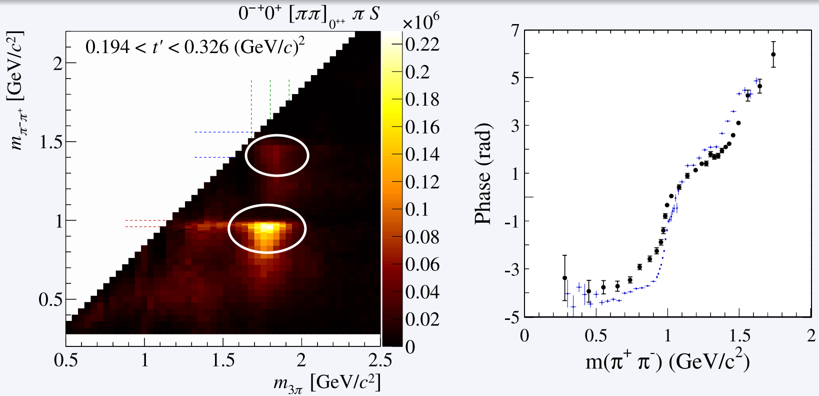

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What is the Nature of the $a_1(1420)$? [PRL **115** (2015) 082001]

Still unclear

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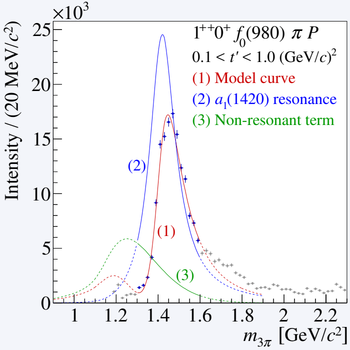
- $a_1(1420)$ lies suspiciously close to $K\bar{K}^*$ threshold



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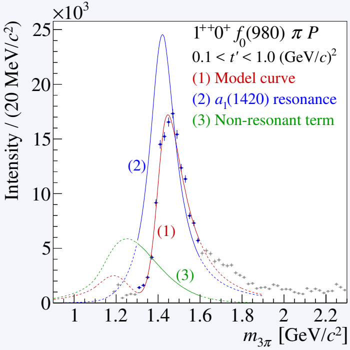

What is the Nature of the $a_1(1420)$?

Several proposed explanations

A 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 production of $a_1(1260)$

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

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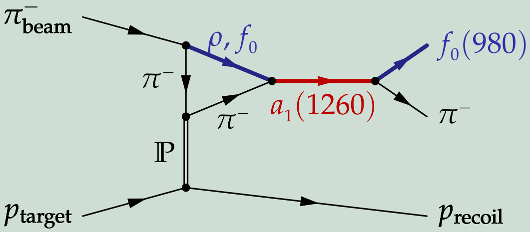

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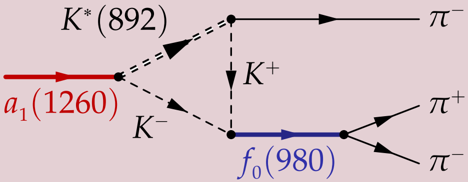
Effect in decay of $a_1(1260)$

- Singularity in triangle diagram [Mikhasenko *et al.*, PRD **91** (2015) 094015] [Aceti *et al.*, arXiv:1606.06893]



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

Conclusions and Outlook

Multi-body final states

- Ideal laboratory to study hadronic resonances and hadron dynamics
- For large data sets, PWA extracts even very small signals reliably
  - E.g. new axial-vector signal $a_1(1420)$

Novel analysis techniques

- *Freed-isobar method:* new insights into dynamics of $\pi\pi$ subsystem in the presence of third π
  - *Work in progress:* extension to $\pi\pi$ subsystems with $J^{PC} = 1^{--}$ and 2^{++}
    - *Challenge:* resolution of mathematical ambiguities caused by Bose symmetrization of final state
- *t'-resolved analysis:* better separation of resonant and nonresonant contributions
- Tight collaboration with theorists to improve analysis model

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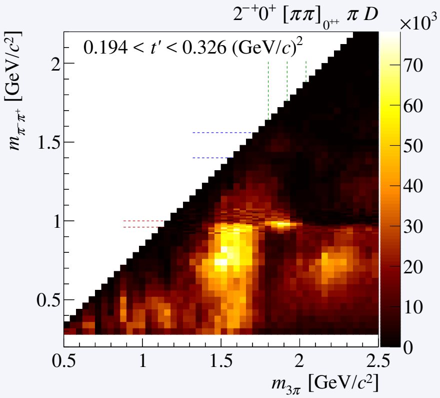
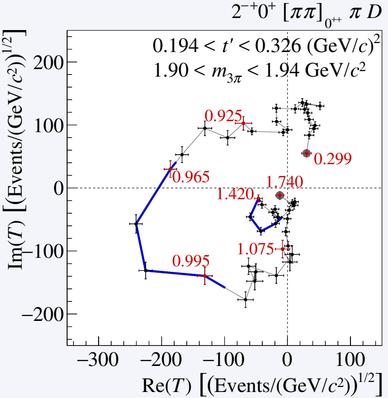
Outline

5. Backup slides
   - $\pi\pi$ S-wave amplitude in $J^{PC} = 2^{-+}$ 3π wave
   - $J^{PC} = 1^{-+}$ spin-exotic partial wave
   - Resonance-model fit

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





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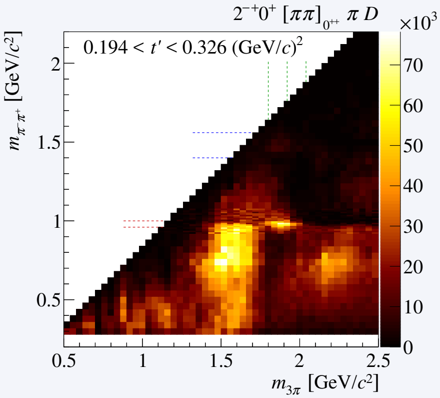

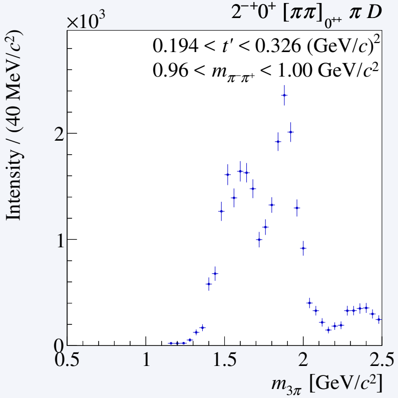

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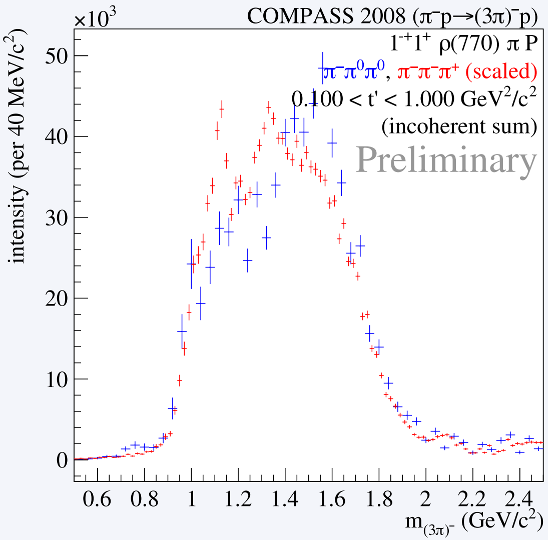
Spin-Exotic $J^{PC} = 1^{-+}$ Signal in $(3\pi)^-$ PWA

- Broad intensity bump
- Similar in both 3π channels

- Similar to $\pi\eta'$ channel

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



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

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

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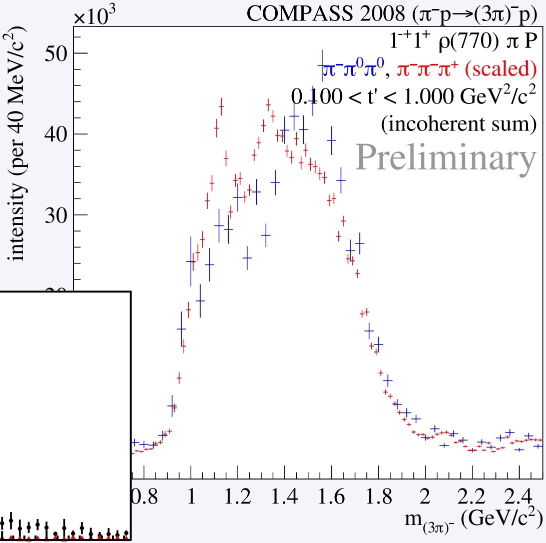
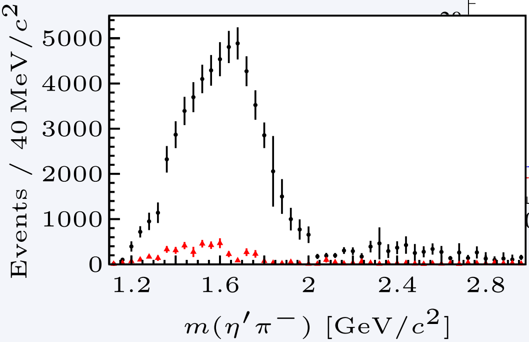
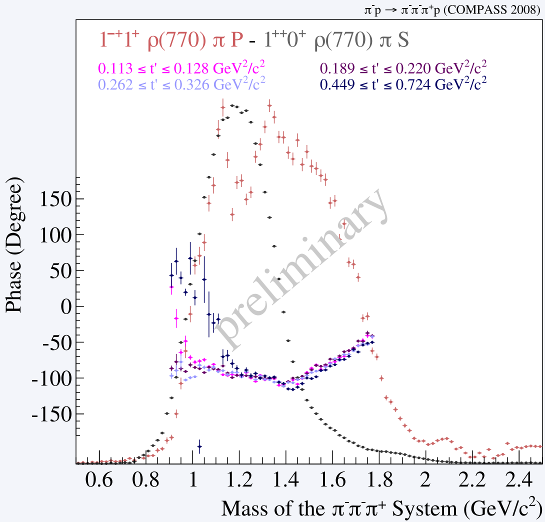




Spin-Exotic $J^{PC} = 1^{-+}$ Signal in $\pi^-\pi^+\pi^-$ PWA

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

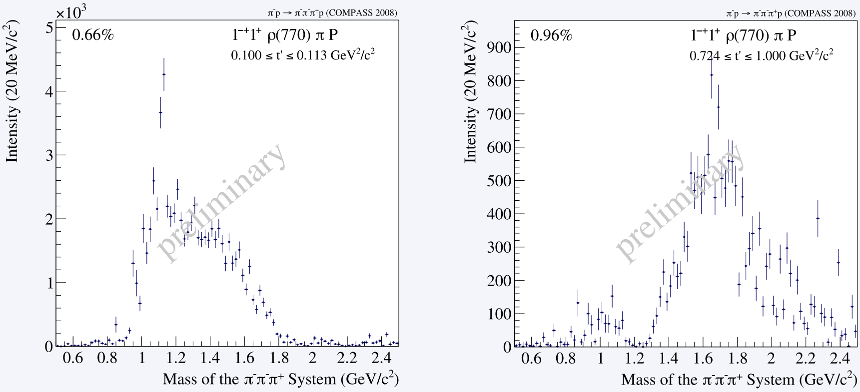


- Slow phase 60° motion in 1.6 GeV/c^2 region independent of t'

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

Drastic Change of Mass Spectrum with t'

"Low" $t' \approx 0.1\ (\mathrm{GeV}/c)^2$ "High" $t' \approx 0.8\ (\mathrm{GeV}/c)^2$

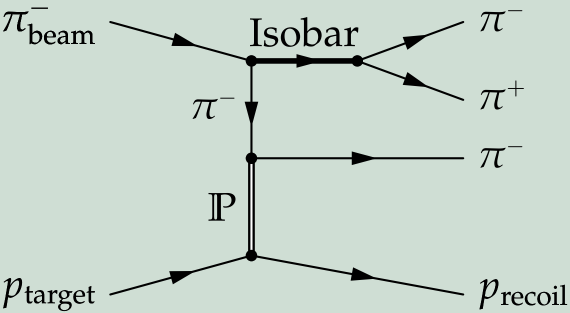


- Dominant nonresonant contribution
  - Needs to be better understood in order to extract resonance content

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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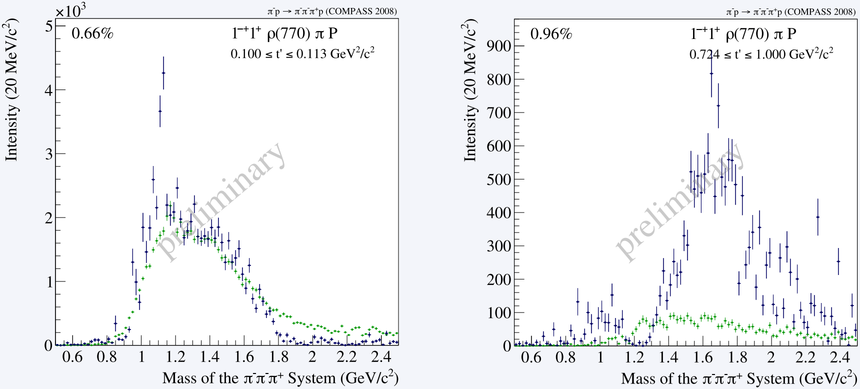
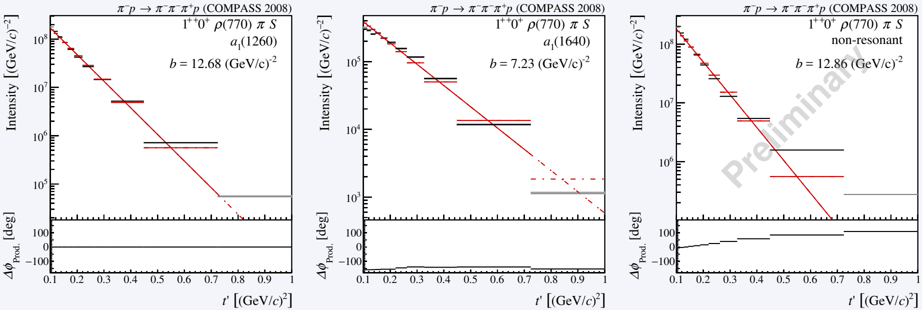


- Deck MC scaled to t'-summed intensity
  - Similar mass spectrum at low t'
  - Different shape at high t'

$\pi^-\pi^+\pi^-$ Resonance-Model Fit

t' Dependence of Model Components

Example: model components in $1^{++}\,0^+\,\rho(770)\,\pi\,S$ wave



Can t' dependences of amplitudes be modelled?