Overview of Light-Hadron Spectroscopy and Exotics

Stefan Wallner

Institute for Hadronic Structure and Fundamental Symmetries - Technical University of Munich

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HIEPA 2018

PDG meson listings [PDG 2017]

- 80 light non-strange mesons (47 in summary table)
- $>$ 100 possible further states
- 28 strange mesons (15 in summary table)

Important quantum numbers

$$J^{PC}$$

- J: Spin
- P: Eigenvalue under space inversion
- C: Eigenvalue under charge conjugation

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Light-quark mesons

- $|q\bar{q}\rangle$ states of u, d, and s (anti)quarks $\Rightarrow$ $SU(3)_{flavor}$ nonets

Ground-state nonets

- Many more nonets for orbital and radial excitations

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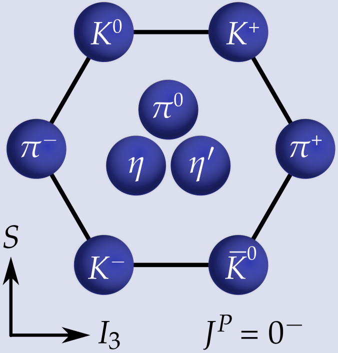
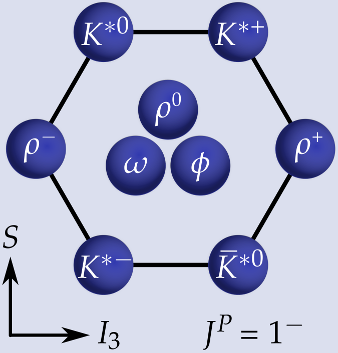
Ground-state nonets





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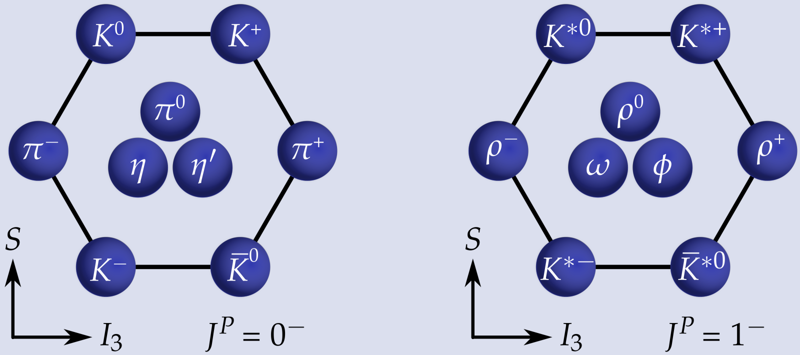

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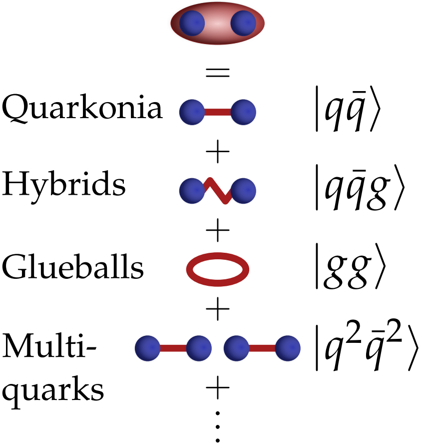
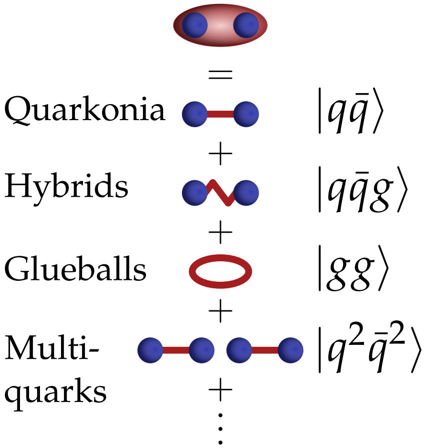
Introduction
Beyond the Constituent Quark Model



QCD permits additional color-neutral configurations

- Physical mesons: linear superpositions of all allowed basis states with same J^{PC}
- Amplitudes in principle determined by QCD interactions
- Disentanglement of contributions difficult
- Light mesons: no definitive experimental evidence yet



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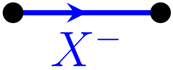
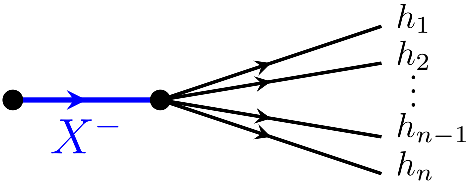
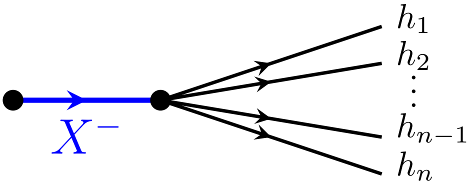


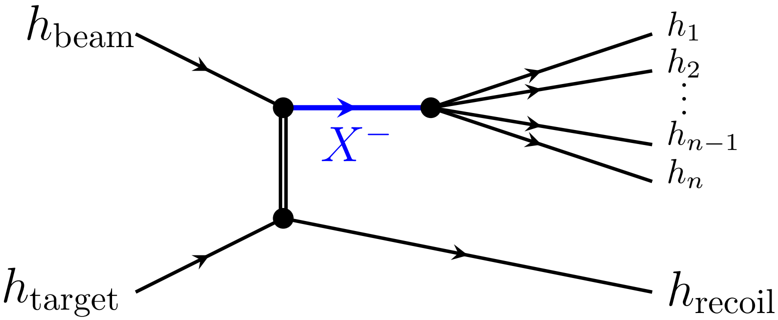
- Excited mesons appear as intermediate states



- Various final states:
  - $\pi^-\pi^-\pi^+$
  - $\eta\pi$
  - ...



- Various reactions to produce them:
  - Heavy-meson decays
  - τ decays
  - t-channel production in high-energy scattering
  - ...



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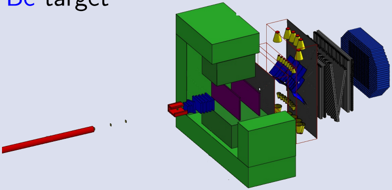
Introduction

Production Experiments

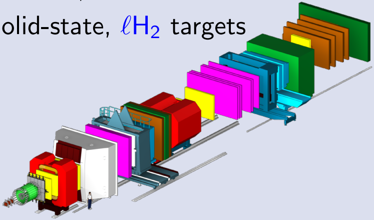
VES

- $29\,\mathrm{GeV}/c$ π^- beam
- Be target



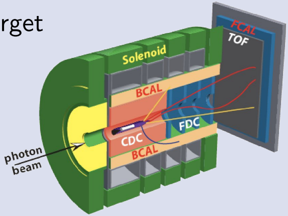
COMPASS

- $190\,\mathrm{GeV}/c$ π^- beam
- Solid-state, ℓH_2 targets



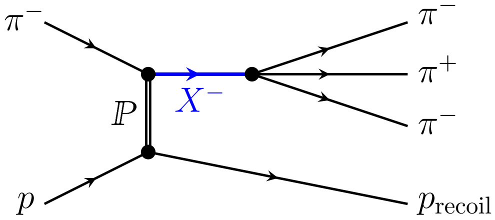
JLab: GlueX

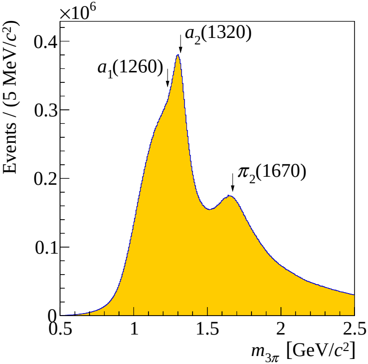
- $12\,\mathrm{GeV}$ linearly polarized γ-beam
- ℓH_2 target



https://halldweb.jlab.org/wiki/index.php/GlueX_Project_Overviews

[Adolph et al., PRD 95, 032004 (2017)]





- Rich spectrum of overlapping and interfering X^-
  - Dominant states
  - “Hidden” states with lower intensity
- Also structure in $\pi\pi$ subsystem
  - ➡ Successive 2-body decay via $\pi\pi$ resonance called isobar
- Also structure in angular distributions

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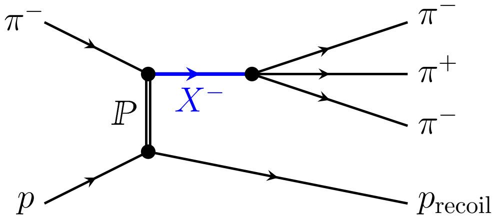

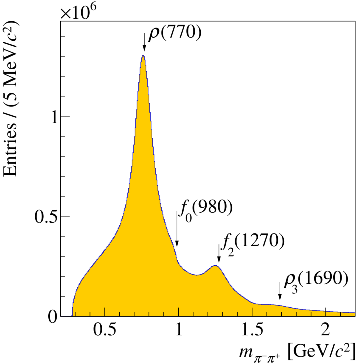

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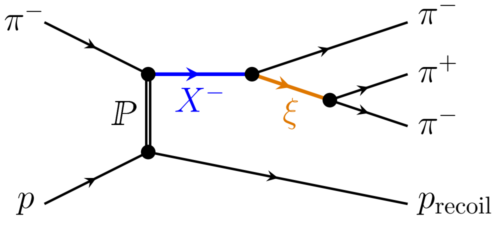

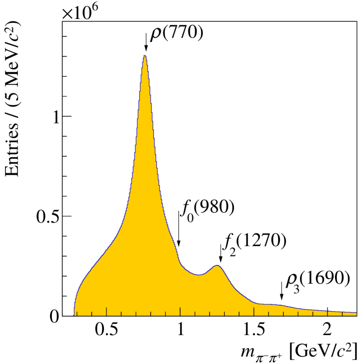

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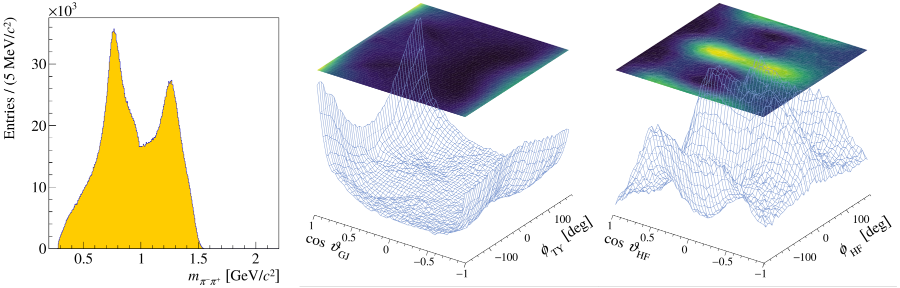
$$1640 < m_{3\pi} < 1680\,\mathrm{MeV}/c^2$$



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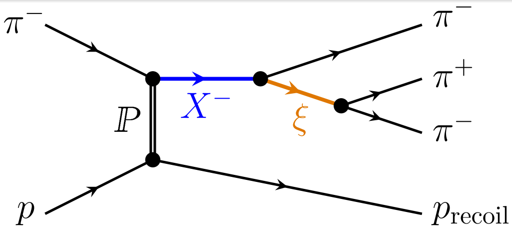
Partial-Wave Analysis

Isobar Model

[Adolph et al., PRD 95, 032004 (2017)]



- For given partial wave $J^{PC}\, M^{\varepsilon}\, \xi\, \pi\, L$ at a fixed mass $m_{3\pi}$
  - ➥ Calculate 5D decay phase-space distribution of final-state particles
- Measured phase-space distribution
  - ➥ contains coherent contributions of various partial waves

$$\mathcal{I}(\tau) = \left|\sum_i^{\text{waves}} \mathcal{T}_i \psi_i(\tau)\right|^2$$

  - ➥ Perform maximum-likelihood fit in bins of $m_{3\pi}$ (mass-independent fit)
    - ➥ Decompose data into partial waves
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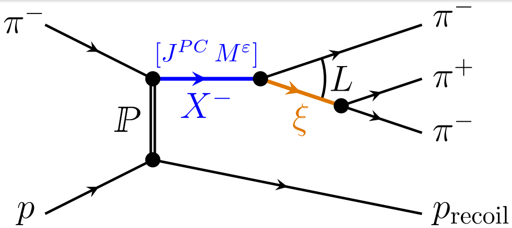

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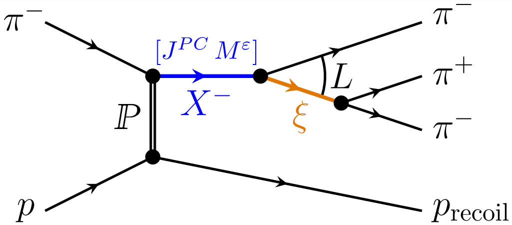

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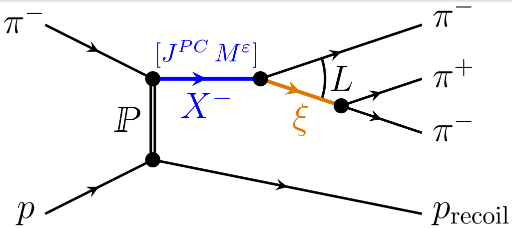

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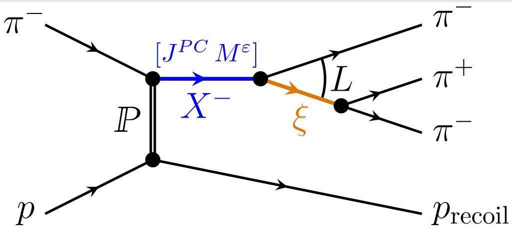

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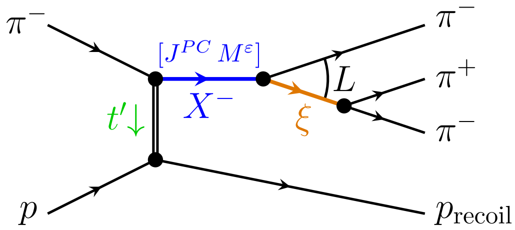


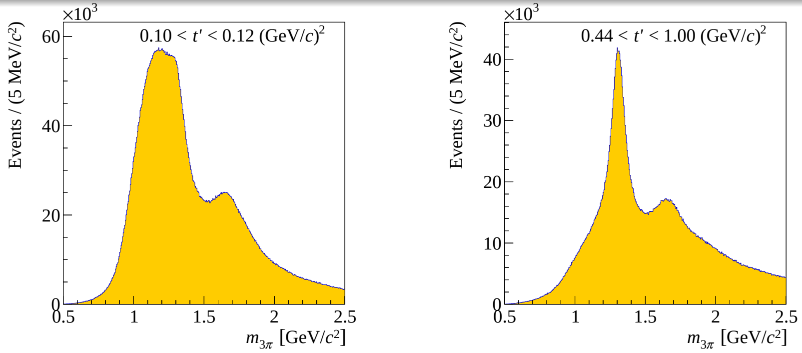
Challenge

- Production also depends on t'

- Large data set ($\approx$ 50 M exclusive events)
  - ➥ Perform PWA also in narrow bins of t' (t'-resolved analysis)
  - ➥ Extract $m_{3\pi}$ AND t' dependence of partial-wave amplitudes

Partial-Wave Analysis
t' Binning

[Adolph et al., PRD 95, 032004 (2017)]



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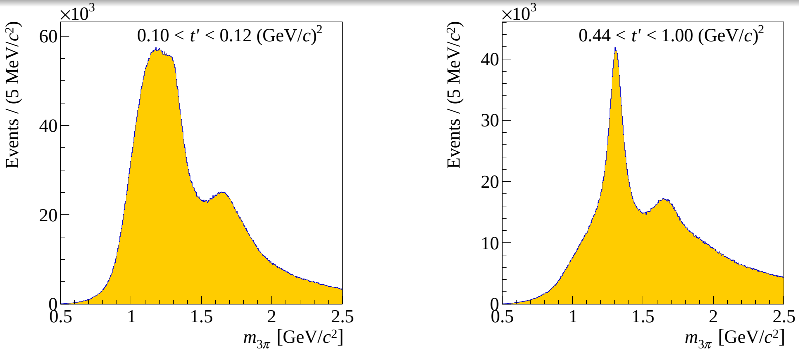

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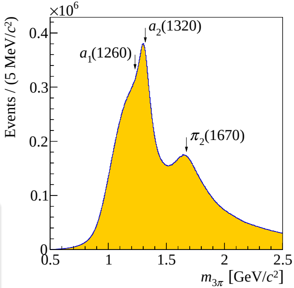

- $1^{++}\,0^{+}\,\rho(770)\,\pi\,S$
  - $a_1(1260)$
- $2^{++}\,1^{+}\,\rho(770)\,\pi\,D$
  - $a_2(1320)$
- $2^{-+}\,0^{+}\,f_2(1270)\,\pi\,S$
  - $\pi_2(1670)$

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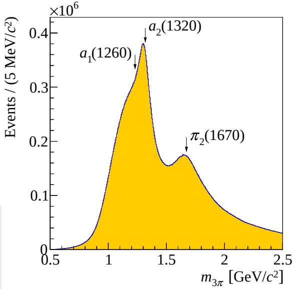

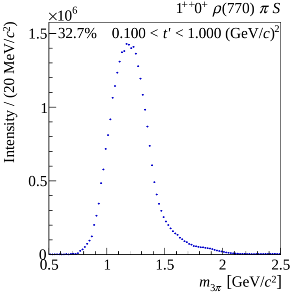

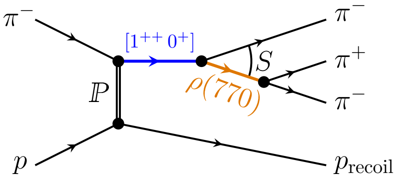

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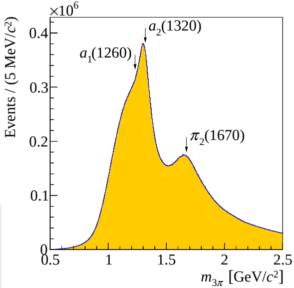

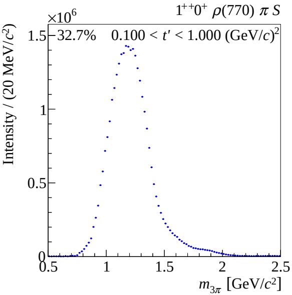

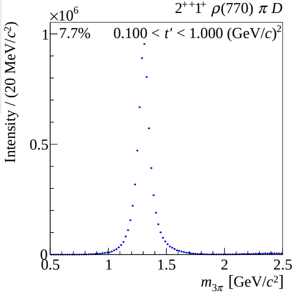

Partial-Wave Analysis

Results

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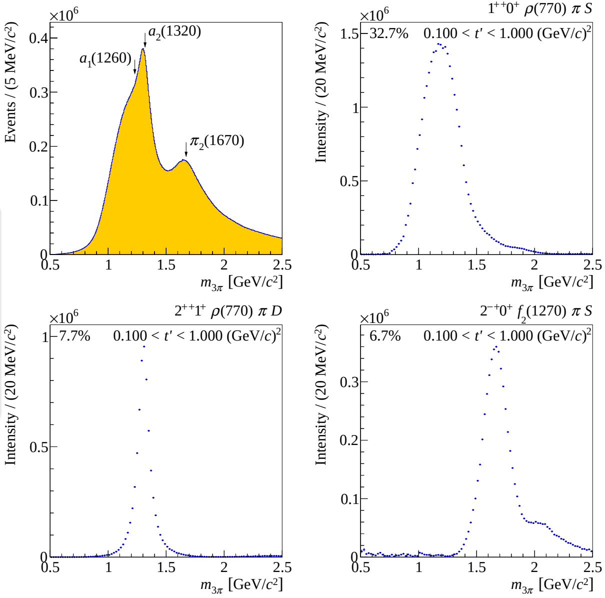

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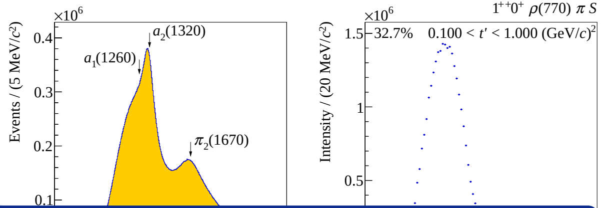
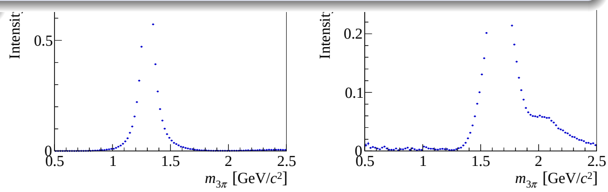


Wave set for $\pi^- + p \to \pi^-\pi^-\pi^+ + p_{\text{recoil}}$

- 88 partial waves
  - Most comprehensive analysis so far in PWA of 3π final state
  - Spin J up to 6
  - Angular momentum L up to 6
  - 6 different $\pi^-\pi^+$ isobars



Data

Resonance Parameters

Masses and widths of the meson resonances

Resonance-Model Fit
Method

Data

(I) Partial-Wave Decomposition

Partial Waves

Intensities and relative phases of the partial waves

Resonance Parameters

Masses and widths of the meson resonances

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(I) Partial-Wave Decomposition

Partial Waves

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(II) Resonance-Model Fit

Resonance Parameters

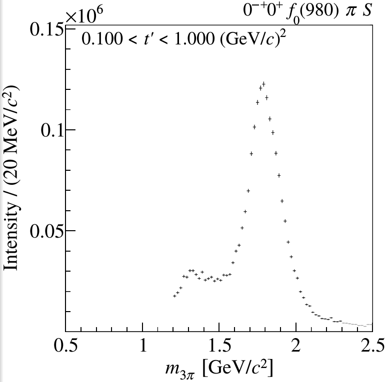
Masses and widths of the meson resonances

Modeling $m_{3\pi}$ dependence

- Parameterize $m_{3\pi}$ dependence of partial-wave amplitudes (intensity & phase)

$$\mathcal{T}_\alpha(m_{3\pi}, t') = \sum_{k \in \text{Comp}_\alpha} \mathcal{C}_\alpha^k(t') \cdot \mathcal{D}^k(m_{3\pi}, t'; \zeta_k)$$

- Dynamic functions $\mathcal{D}^k(m_{3\pi}, t'; \zeta_k)$
  - For resonances: Breit-Wigner amplitude
  - For non-resonant term: Phenomenological parameterization
- "Coupling amplitudes" $\mathcal{C}_\alpha^k(t')$
  - Determine strength and phase of components
  - Independent coupling amplitude for each t' bin



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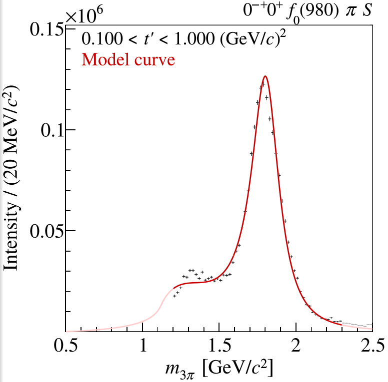

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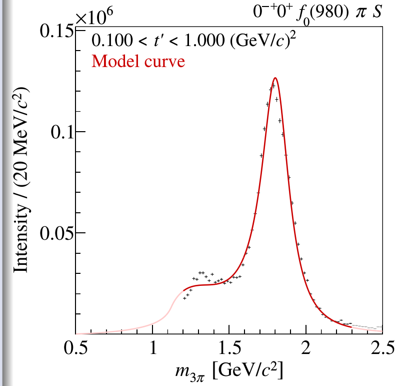

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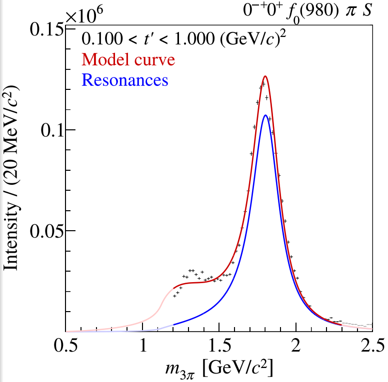

Modeling $m_{3\pi}$ dependence

- Parameterize $m_{3\pi}$ dependence of partial-wave amplitudes (intensity & phase)

$$\mathcal{T}_\alpha(m_{3\pi}, t') = \sum_{k \in \text{Comp}_\alpha} \mathcal{C}_\alpha^k(t') \cdot \mathcal{D}^k(m_{3\pi}, t'; \zeta_k)$$

- Dynamic functions $\mathcal{D}^k(m_{3\pi}, t'; \zeta_k)$
  - For resonances: Breit-Wigner amplitude
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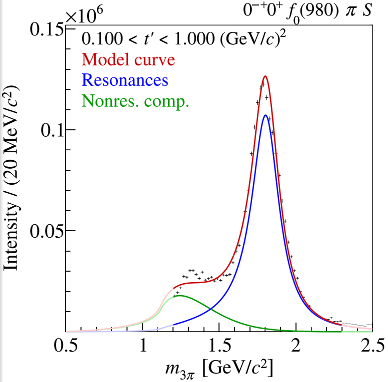

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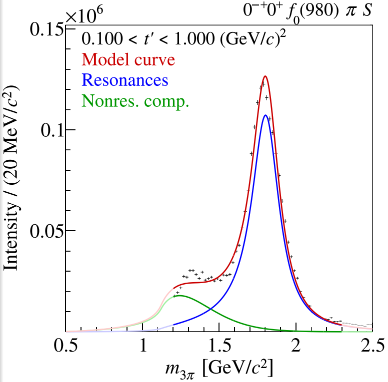
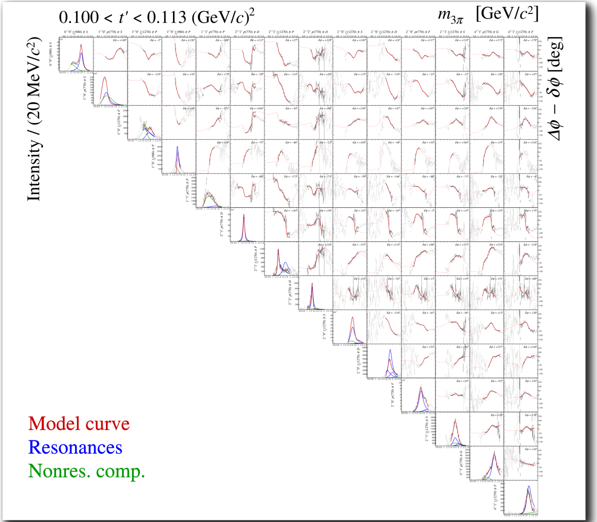


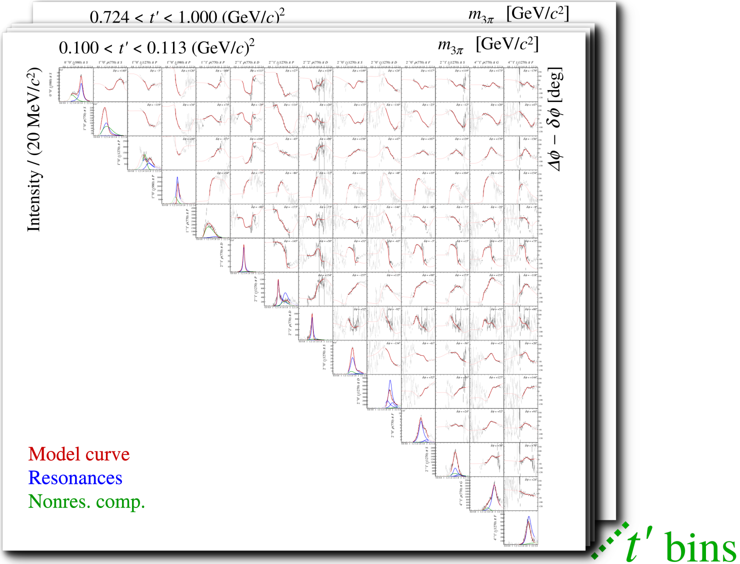
The fit

- Describes large fraction of data consistently
  - Simultaneous fit of 14 waves ($\approx 60\,\%$)
  - Described by 11 resonances: a_1, a_2, a_4, π, π_1, π_2
- Extract t' dependence of model components



0.100 < t' < 0.113 (GeV/c)²
m₃π [GeV/c²]
Intensity / (20 MeV/c²)
Δφ − δφ [deg]
Model curve
Resonances
Nonres. comp.

[arXiv:1802.05913]



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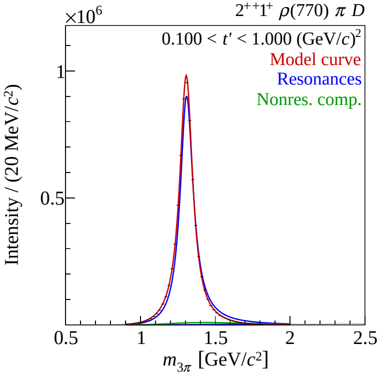


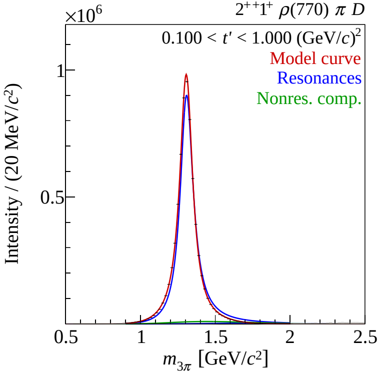
$a_2(1320)$

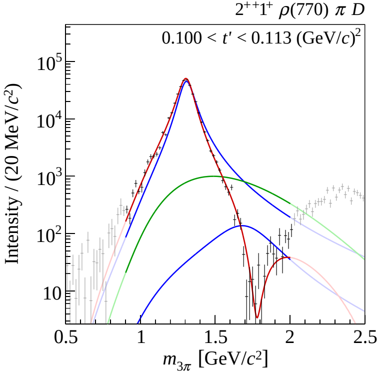
- Good description of clear peak
  - Very stable with respect to variations of the fit model
- Potential $a_2(1700)$ appearing
  - Strongest evidence in $f_2(1270)\ \pi\ P$ decay

$J^{PC} = 2^{++}$ States

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

[arXiv:1802.05913]





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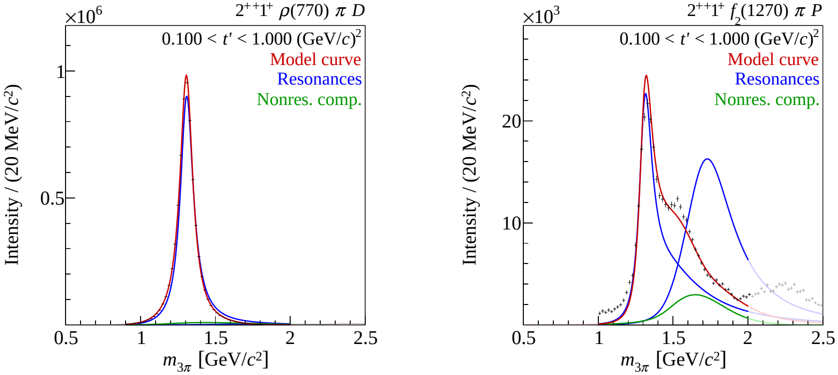

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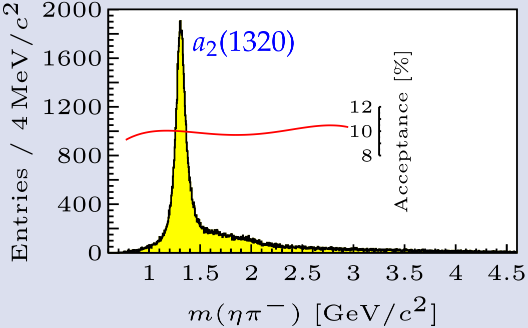
$J^{PC} = 2^{++}$ States

$\eta\pi$ Final State at COMPASS

[Phys.Lett. B740 (2015) 303-311]

$\eta\pi$ invariant mass distribution



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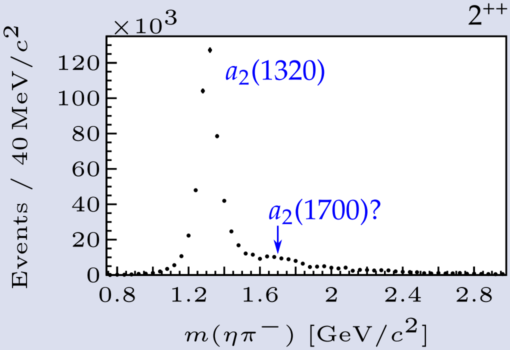
- D-wave contribution dominant
  - Possible $a_2(1700)$ in high-mass shoulder of $a_2(1320)$

D-wave intensity



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[Phys.Lett. B779 (2018) 464-472]

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  - Breit-Wigner models only for narrow isolated resonances
- Improve the employed models $\Rightarrow$ collaboration with JPAC
- Developed analytic model based on relativistic S-matrix principles

$J^{PC} = 2^{++}$ wave in $\eta\pi$

- $a_2(1320)$ pole
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- $a_2(1700)$ pole
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  - Width is 160 MeV$/c^2$ larger in $\pi^-\pi^-\pi^+$ analysis
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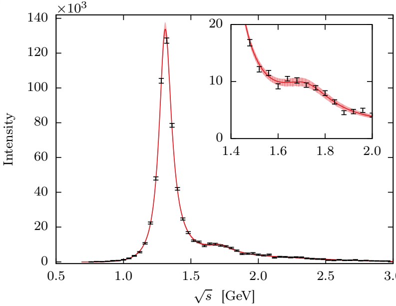
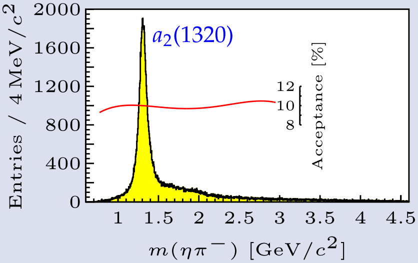


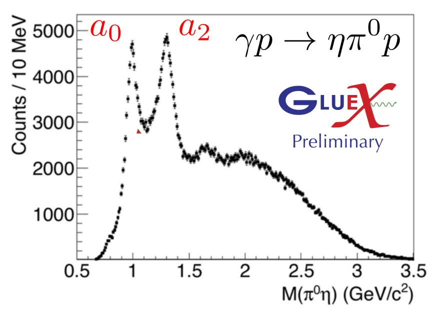
COMPASS

[Phys.Lett. B740 (2015) 303-311]



GlueX

[J. Stevens, $K\pi$-workshop, 2018, JLab]



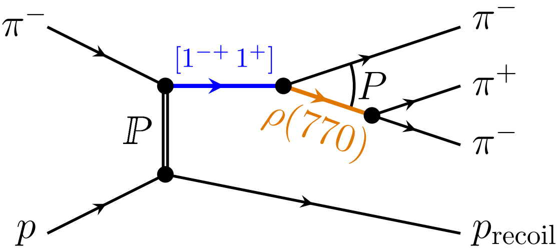
GlueX data on $\eta\pi$ final state

- Similar data-set size as COMPASS
- $2\times$ more data expected in 2018

[J. Stevens, $K\pi$-workshop, 2018, JLab]: https://www.jlab.org/conferences/pki2018/talks/WED/stevens.pdf

$J^{PC} = 1^{-+}$ State

Partial-Wave Decomposition



- 1^{-+}: spin-exotic π_1-like quantum numbers
    - Forbidden quantum numbers for $q\bar{q}$ system (non-rel.)
    - Lattice-QCD: lightest hybrid predicted with 1^{-+} quantum numbers
- Broad intensity distribution
- Strong evolution with t'

$J^{PC} = 1^{-+}$ State

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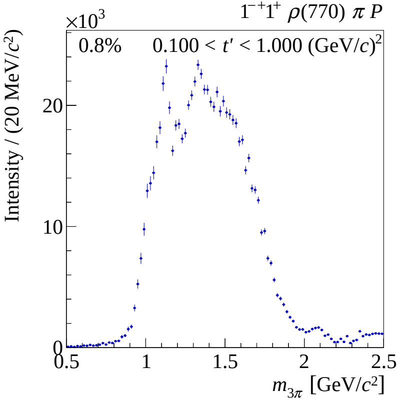

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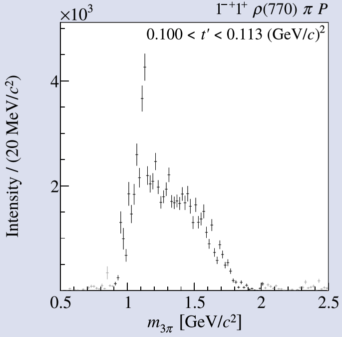
Partial-Wave Decomposition

[Adolph et al., PRD 95, 032004 (2017)]

Low t'



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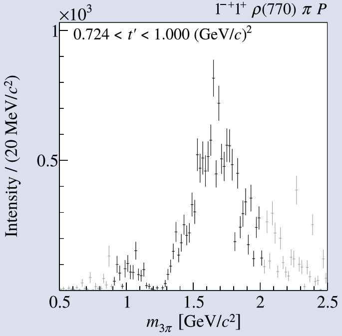

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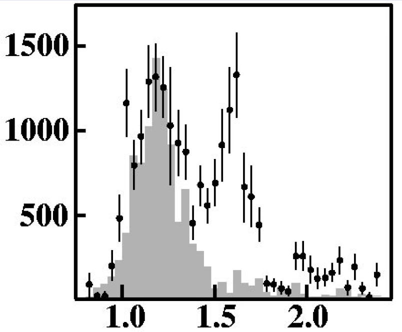
BNL E852 21 waves



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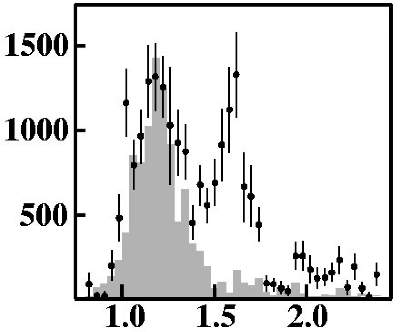
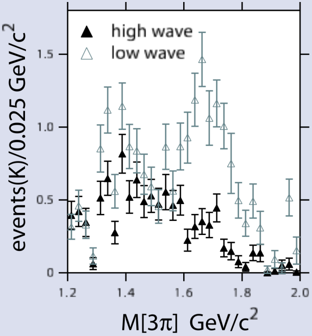


BNL E852 36 (high) vs 21 (low) waves



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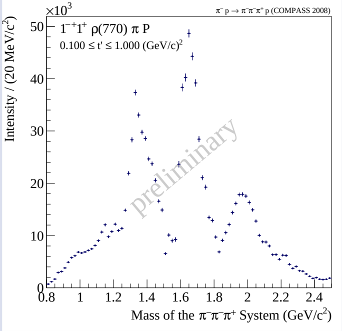
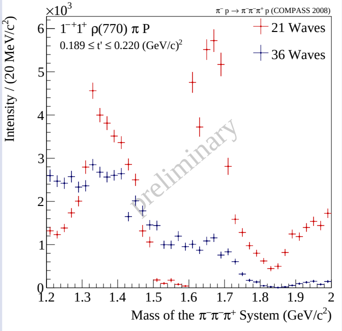
$J^{PC} = 1^{-+}$ State

History

COMPASS 2008 21 waves



COMPASS 2008 36 waves



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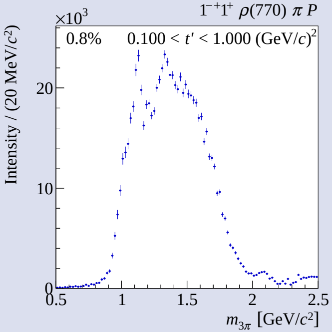
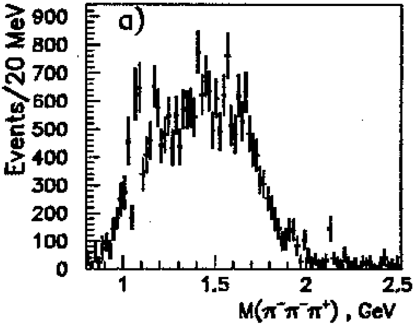


VES



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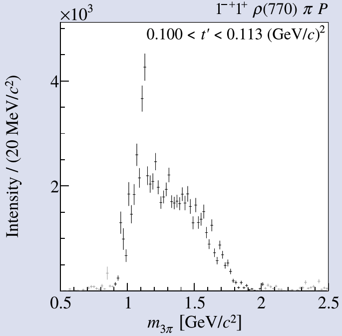
COMPASS 2008 88 waves (low t')



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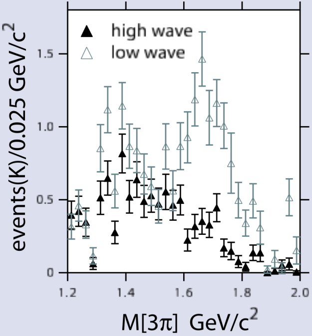

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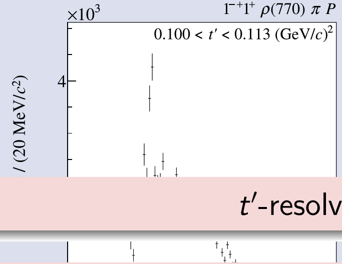

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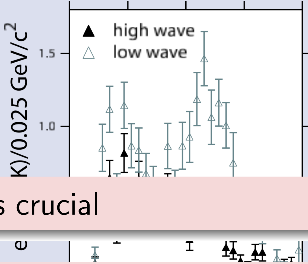

t'-resolved analysis is crucial

Wave set used in PWA model is crucial
$\Rightarrow$ Work in progress: Methods to infer wave-set from data

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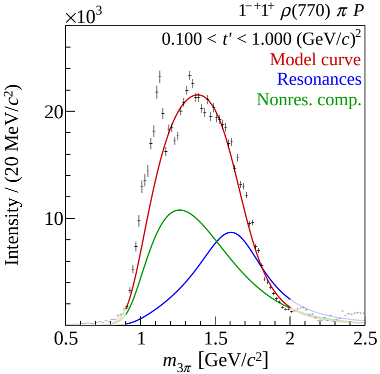

$\pi_1(1600)$, $m_0 = 1600\,^{+100}_{-50}$ MeV$/c^2$, $\Gamma_0 = 610\,^{+70}_{-240}$ MeV$/c^2$

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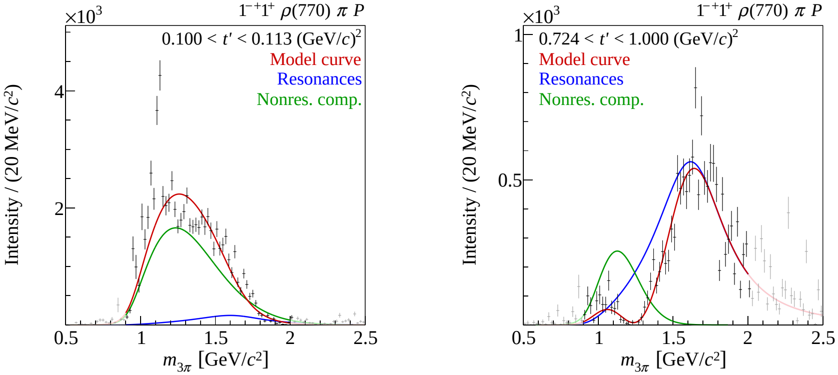
- No description of data at high t' without Breit-Wigner component

$J^{PC} = 1^{-+}$ State

Resonance-Model Fit

[arXiv:1802.05913]



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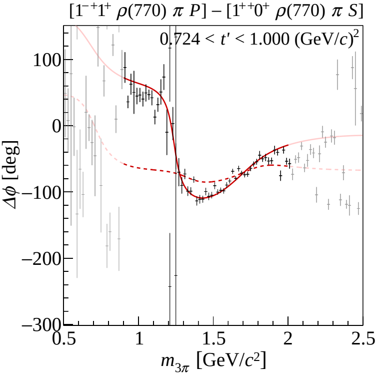

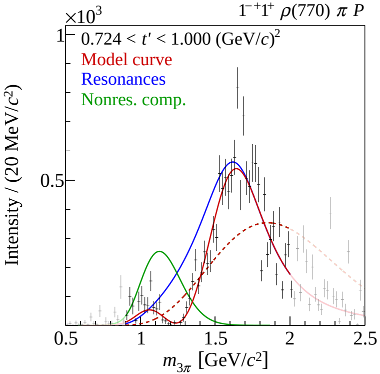

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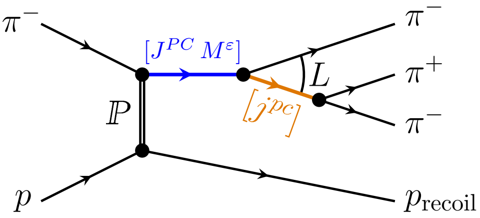
Freed-Isobar Method

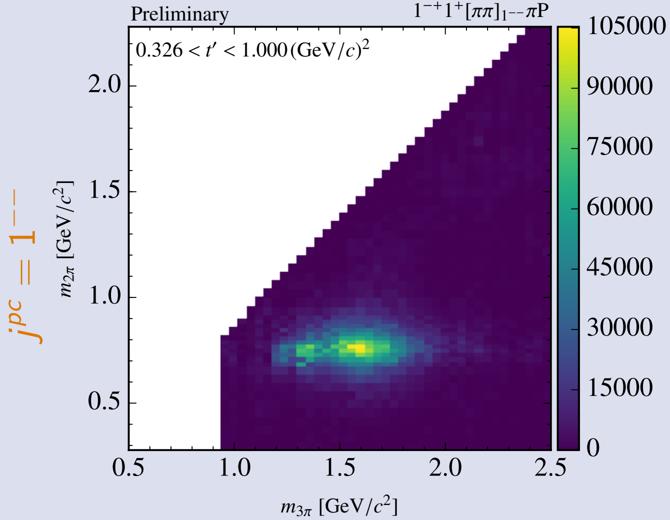
[arXiv:1711.10828]



- Allows to study $\pi^-\pi^+$ isobar amplitude
  - for specific j^{pc} of $\pi^-\pi^+$ isobar system
  - for specific J^{PC} of $\pi^-\pi^-\pi^+$ system
  - as a function of $m_{3\pi}$
- Study many different isobar amplitudes simultaneously

Freed-Isobar Method

$J^{PC} = 1^{-+}$ Wave with freed $j^{pc} = 1^{--}$ Isobar Amplitude



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

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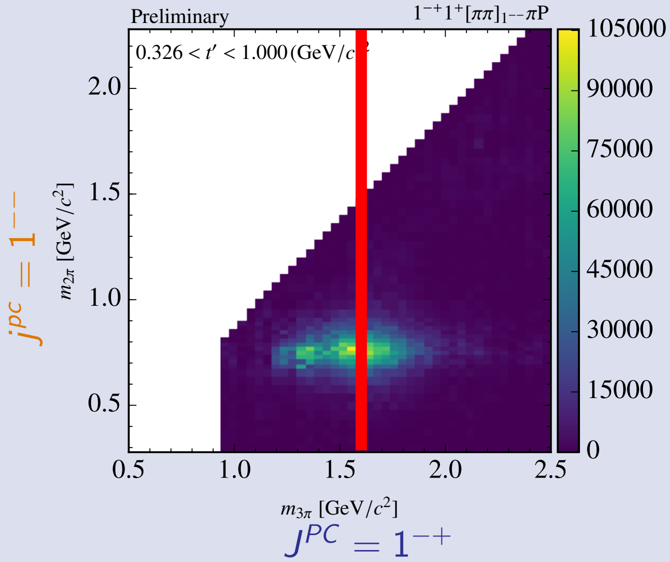

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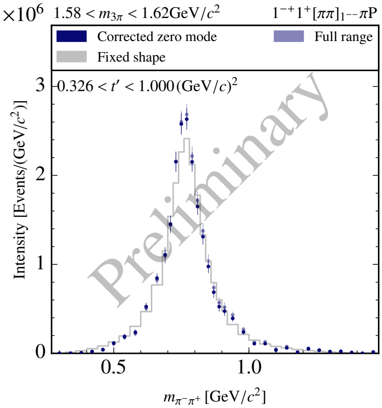

- Study $\pi^-\pi^+$ amplitude as a function of $m_{3\pi}$
- $m_{\pi^-\pi^+}$ spectrum shows good agreement with $\rho(770)$ Breit-Wigner
- Extract $m_{\pi^-\pi^+}$ dependence of complex-valued amplitude
- Shape of $m_{3\pi}$ spectrum is in fair agreement with fixed-isobar analysis
  - ➥ $\pi_1(1600)$ signal at about 1.6 GeV/c^2 robust

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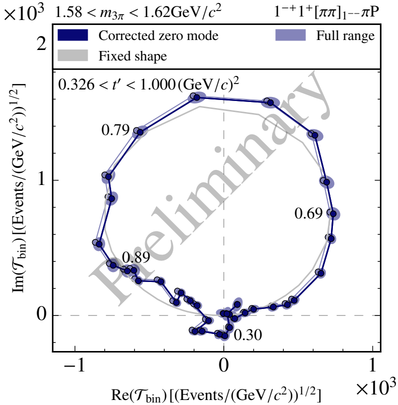

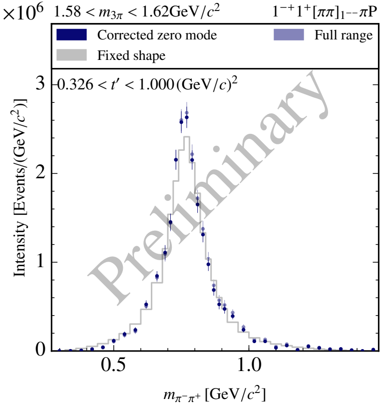

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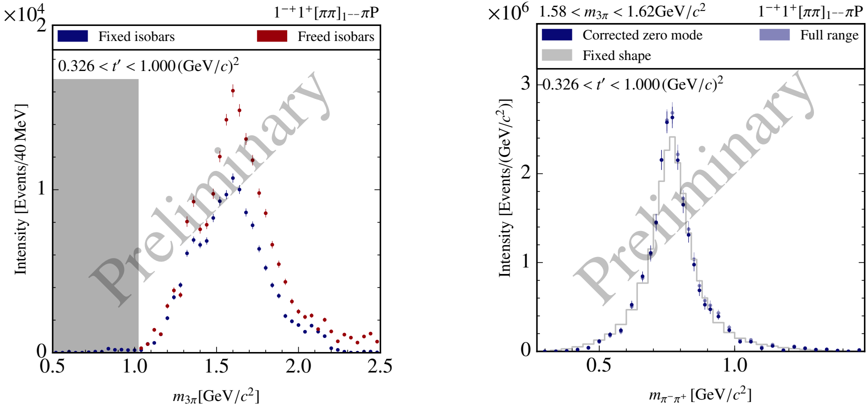

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$a_1(1420)$

$m_0 = 1411\,^{+4}_{-5}\ \mathrm{MeV}/c^2$, $\Gamma_0 = 151\,^{+11}_{-14}\ \mathrm{MeV}/c^2$

- Narrow peak at about $1.4\ \mathrm{GeV}/c^2$
- Modeled by Breit-Wigner resonance: $a_1(1420)$
- Mass too close to $a_1(1260)$ ground state
  - ➡ $a_1(1420)$ does not fit into $q\bar{q}$ spectrum
- Nature of this signal still unclear?
  - Tetra-quark state
    [Phys. Rev. D 91, 094022 (2015), Phys.Rev. D96 (2017) no.3, 034030]
  - Interference effect between $a_1(1260)$ and Deck-like contributions [Phys.Rev.Lett. 114 (2015)]
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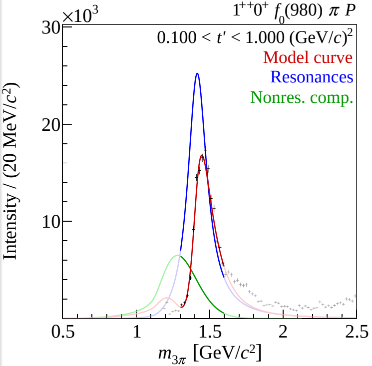

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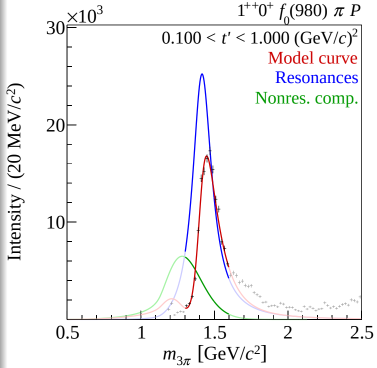
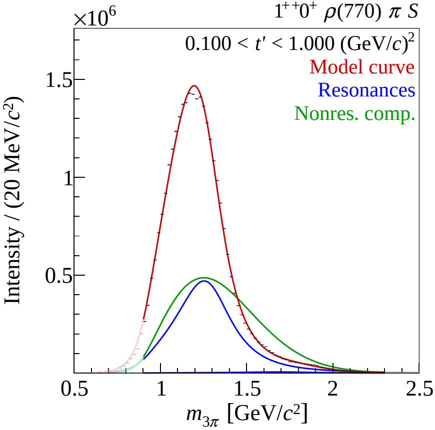


$J^{PC} = 1^{++}$ States

$\rho(770)\ \pi\ S$ Decay

[arXiv:1802.05913]



$a_1(1260)$, $m_0 = 1299^{+12}_{-28}\,\text{MeV}/c^2$, $\Gamma_0 = 380 \pm 80\,\text{MeV}/c^2$

- Broad peak in intensity spectrum
- Large spread in $a_1(1260)$ parameters from previous measurements
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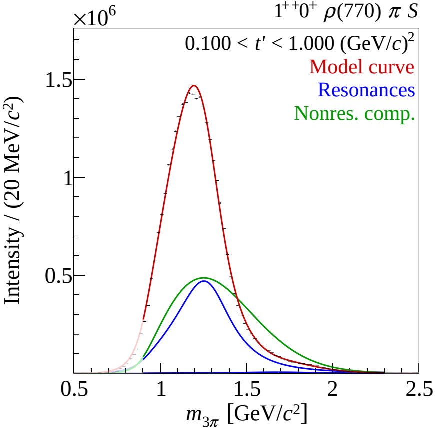

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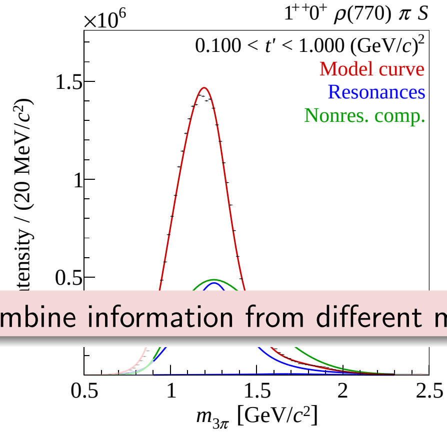

Need to combine information from different measurements

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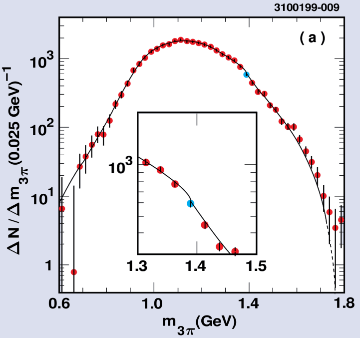
$J^{PC} = 1^{++}$ States

$\pi\pi\pi$ States in τ Decays

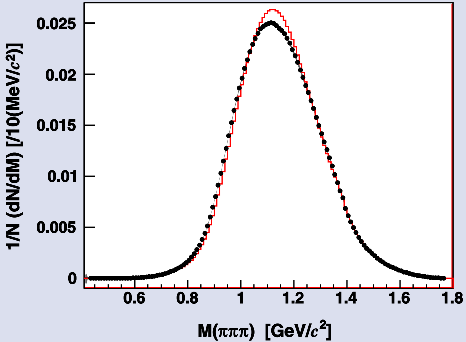
CLEO

[Phys.Rev. D61 (2000) 012002]



BELLE

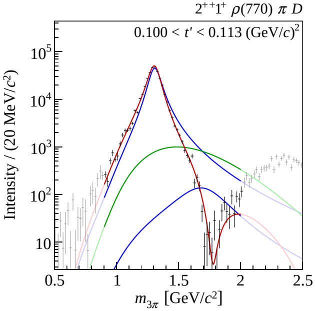
[Phys.Rev. D81 (2010) 113007]



- Observation of $\tau \rightarrow \pi\pi\pi + \nu_\tau$ in $\tau^+\tau^-$ production
- Clean data samples
  - Tagging of τ decay via the second τ
  - No other hadrons involved $\Rightarrow$ No non-resonant contributions
- Clarify nature of $a_1(1260)$, $a_1(1420)$, $a_1(1640)$, ...

Conclusion

- Light-hadron spectroscopy is a active field
  - High-precision measurement of ground and excited states: $a_2(1320)$, $a_2(1700)$, $a_1(1260)$, ...
  - Study of exotic states: $\pi_1(1600)$, $a_1(1420)$, ...
- Many high-precision data upcoming
  - GlueX, Belle II, ...
- Limited by systematic effects $\Rightarrow$ develop advanced methods and models
  - ➥ Tight collaboration with theorists



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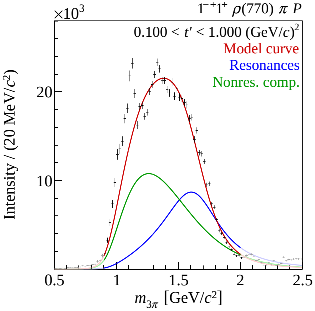

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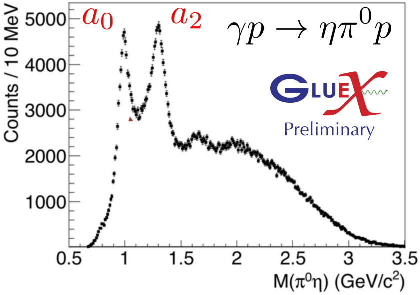

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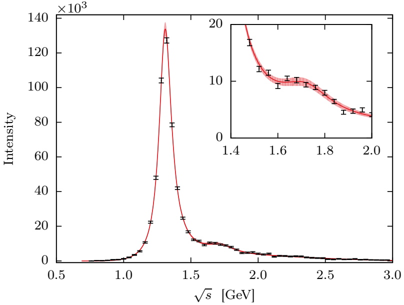

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Future results from COMPASS

- Extended freed-isobar analysis
  - $\pi^-\pi^+$ j^{pc}: 0^{++}, 1^{--}, ..
  - $\pi^-\pi^-\pi^+$ J^{PC}: 0^{-+}, 1^{++}, 1^{-+}, ...
- Spectroscopy of kaons
  - $K^- + p \rightarrow K^-\pi^-\pi^+ + p_{\text{recoil}}$
  - ...
- ...

Backup

Outline