Light-Meson Spectroscopy at COMPASS

Boris Grube
for the COMPASS Collaboration

Institute for Hadronic Structure and Fundamental Symmetries
Technische Universität München
Garching, Germany

STRONG-2020 Workshop
University of York, 16. September 2021

Constituent Quark Model

Light mesons

- $|q\bar{q}\rangle$ quantum states, with $q = u, d,$ or s
- Organized in $\mathrm{SU}(3)_{\mathrm{flavor}}$ nonets

Quantum numbers

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

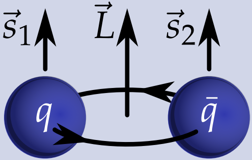
Constituent Quark Model

Light mesons

- $|q\bar{q}\rangle$ quantum states, with $q = u, d,$ or s
- Organized in $\mathrm{SU(3)_{flavor}}$ nonets

Quantum numbers

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



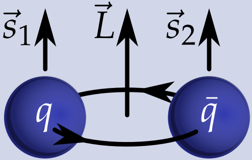
Constituent Quark Model

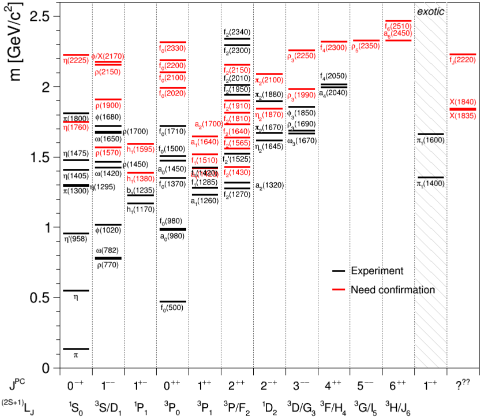
Light mesons

- $|q\bar{q}\rangle$ quantum states, with $q = u, d,$ or s
- Organized in $\mathrm{SU}(3)_{\mathrm{flavor}}$ nonets

Quantum numbers

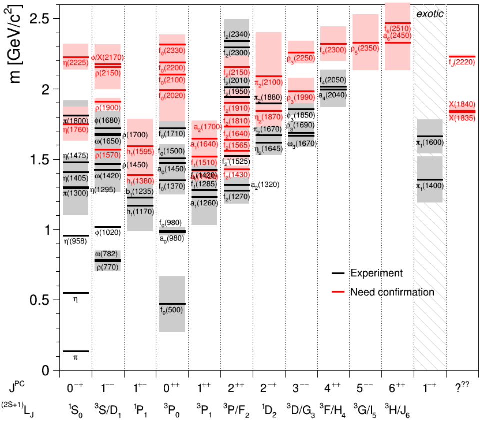
- Quark spins couple to total intrinsic spin $S = 0$ or 1
- Relative orbital angular Momentum $\vec{L}$ and $\vec{S}$ couple to meson spin $\vec{J} = \vec{L} + \vec{S}$
- Parity: $P = (-1)^{L+1}$
- Charge conjugation: $C = (-1)^{L+S}$
- **Forbidden J^{PC} combinations: 0^{--}, even^{+-}, odd^{-+}**





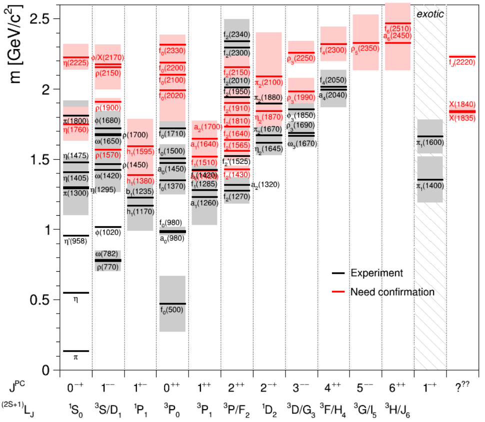
[Courtesy K. Götzen, GSI]

- Rich spectrum
- Many states in mass region $\gtrsim 2\,\mathrm{GeV}/c^2$ need confirmation
- Many wide states
  - Identification requires partial-wave analysis (PWA)
  - Overlap and mixing of states with same J^{PC}



[Courtesy K. Götzen, GSI]

- Rich spectrum
- Many states in mass region $\gtrsim 2\,\mathrm{GeV}/c^2$ need confirmation
- Many wide states
  - Identification requires partial-wave analysis (PWA)
  - Overlap and mixing of states with same J^{PC}

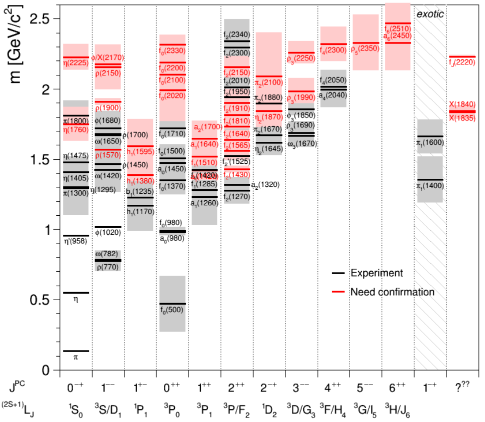


[Courtesy K. Götzen, GSI]

- Rich spectrum
- Many states in mass region $\gtrsim 2\,\mathrm{GeV}/c^2$ need confirmation
- Many wide states
  - Identification requires partial-wave analysis (PWA)
  - Overlap and mixing of states with same J^{PC}

***Goal:* precision measurement**

- Confirm higher excitations
- Complete $SU(3)_{\mathrm{flavor}}$ nonets
- Search for exotic non-$q\bar{q}$ states



[Courtesy K. Götzen, GSI]

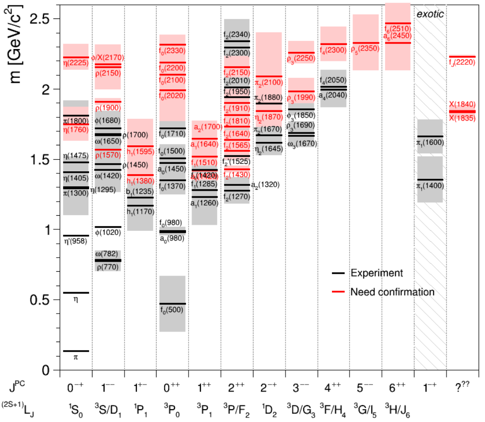
- Rich spectrum
- Many states in mass region $\gtrsim 2\,\text{GeV}/c^2$ need confirmation
- Many wide states
  - Identification requires partial-wave analysis (PWA)
  - Overlap and mixing of states with same J^{PC}

Goal: precision measurement

- Important input for theory and phenomenology
- Understand QCD at low energies, i.e. nature of confinement

Spectrum of Light Non-Strange Mesons

Light-Meson Frontier



[Courtesy K. Götzen, GSI]

- Rich spectrum
- Many states in mass region $\gtrsim 2\,\mathrm{GeV}/c^2$ need confirmation
- Many wide states
  - Identification requires partial-wave analysis (PWA)
  - Overlap and mixing of states with same J^{PC}

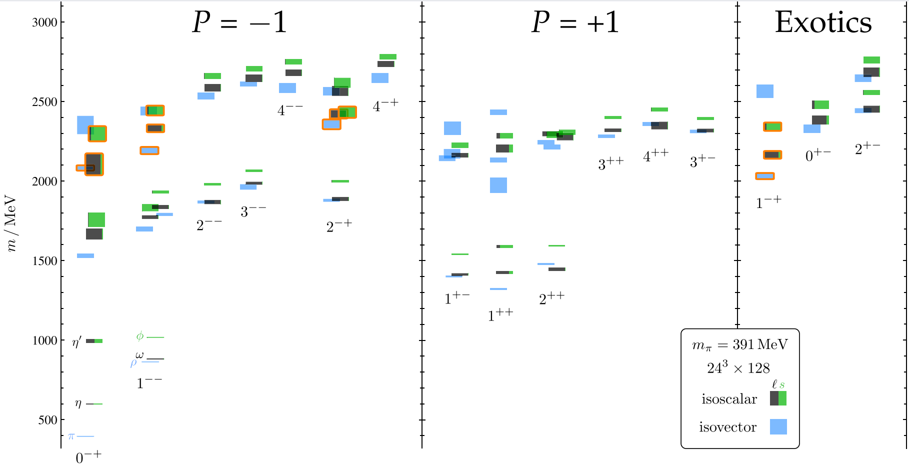
Analyses driven by

- High-quality data
- Advancements in analysis techniques
- More rigorous theoretical PWA models

Light-Meson Spectrum from Lattice QCD

State-of-the-Art Calculation with $m_\pi = 391\ \mathrm{MeV}/c^2$

HadSpec, PRD **88** (2013) 094505



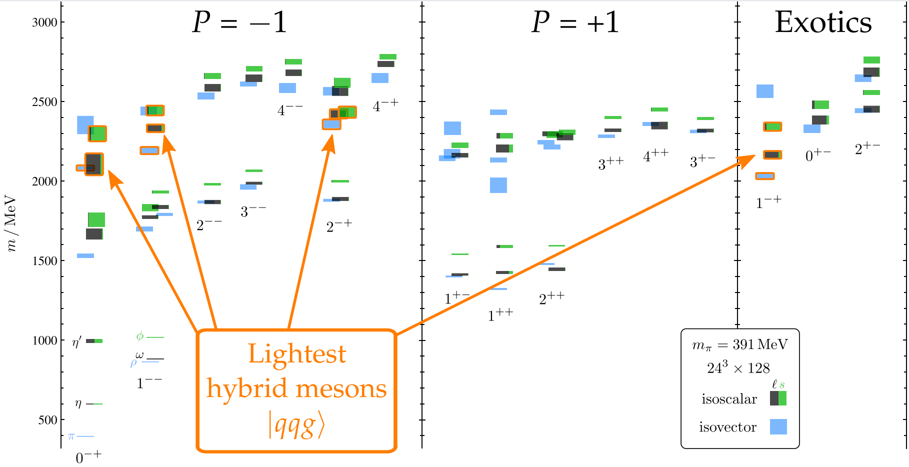
- High towers of excited states
- Hybrid-meson super-multiplet; lightest state with exotic $J^{PC} = 1^{-+}$
- First prediction for partial widths of 1^{-+} state

HadSpec, PRD **103** (2021) 054502

Light-Meson Spectrum from Lattice QCD

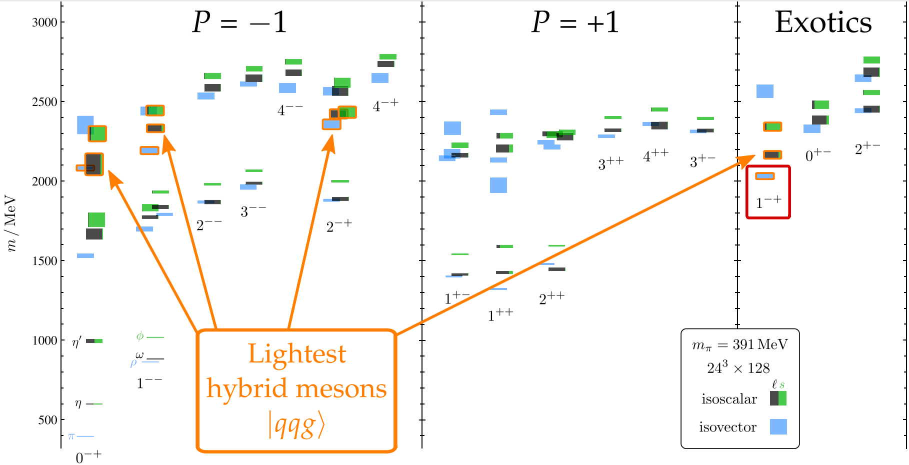
State-of-the-Art Calculation with $m_\pi = 391\ \mathrm{MeV}/c^2$

HadSpec, PRD **88** (2013) 094505



- High towers of excited states
- Hybrid-meson super-multiplet; lightest state with exotic $J^{PC} = 1^{-+}$
- First prediction for partial widths of 1^{-+} state

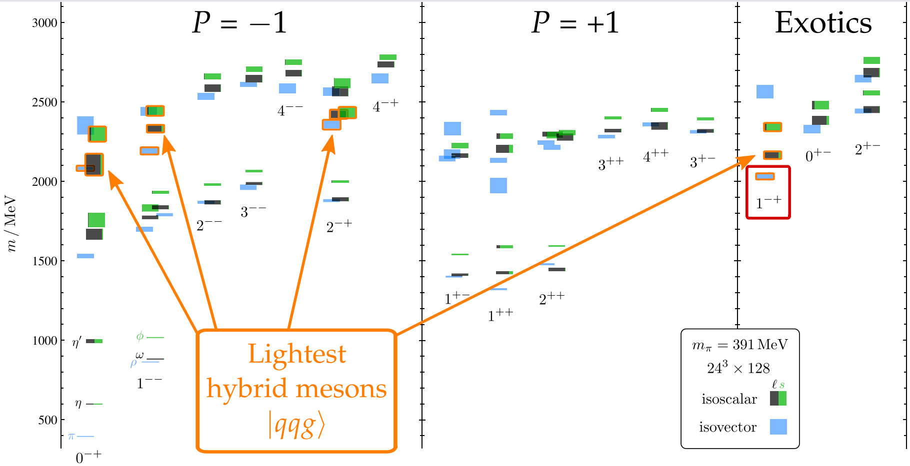
HadSpec, PRD **103** (2021) 054502



- High towers of excited states
- Hybrid-meson super-multiplet; lightest state with exotic $J^{PC} = 1^{-+}$
- First prediction for partial widths of 1^{-+} state HadSpec, PRD **103** (2021) 054502

Light-Meson Spectrum from Lattice QCD

State-of-the-Art Calculation with $m_\pi = 391\ \mathrm{MeV}/c^2$ HadSpec, PRD **88** (2013) 094505

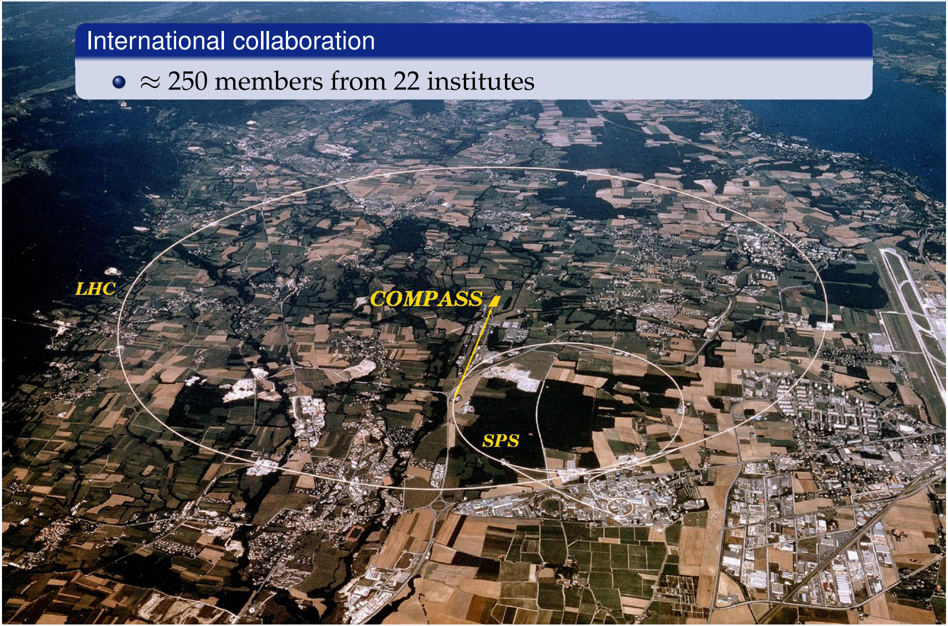


- High towers of excited states
- Hybrid-meson super-multiplet; lightest state with exotic $J^{PC} = 1^{-+}$
- First prediction for partial widths of 1^{-+} state HadSpec, PRD **103** (2021) 054502

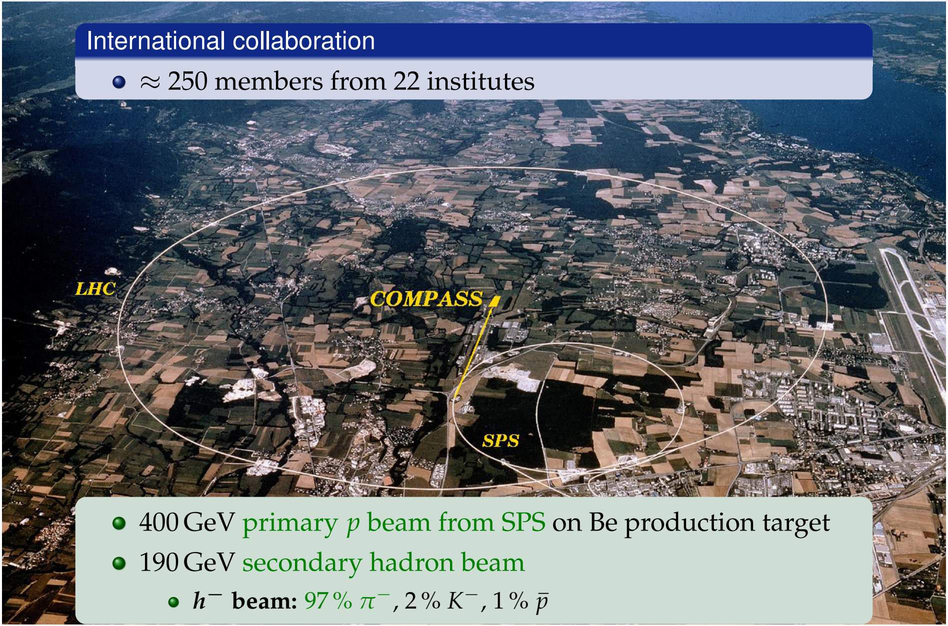
The COMPASS Experiment at the CERN SPS

International collaboration

- $\approx$ 250 members from 22 institutes



The COMPASS Experiment at the CERN SPS



International collaboration

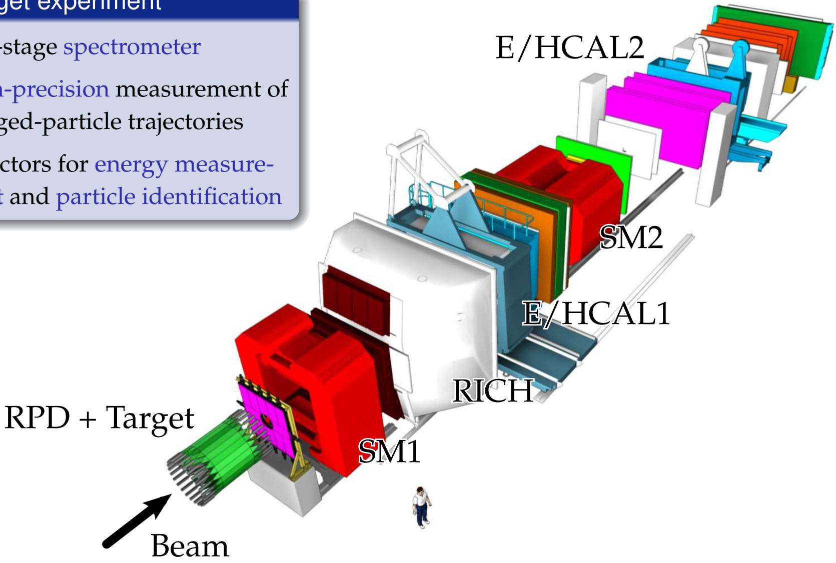
- $\approx$ 250 members from 22 institutes

- 400 GeV primary p beam from SPS on Be production target
- 190 GeV secondary hadron beam
  - **h^- beam:** 97 % π^-, 2 % K^-, 1 % $\bar{p}$

C. Adolph, NIMA **779** (2015) 69

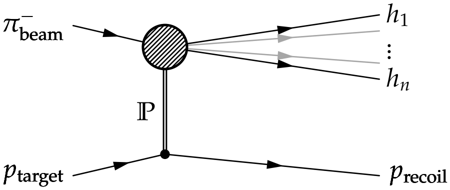
Fixed-target experiment

- Two-stage spectrometer
- High-precision measurement of charged-particle trajectories
- Detectors for energy measurement and particle identification

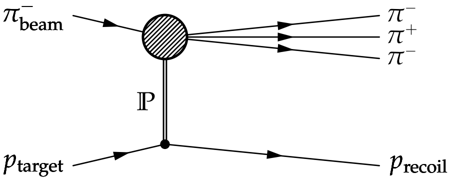


Production of excited light Mesons at COMPASS

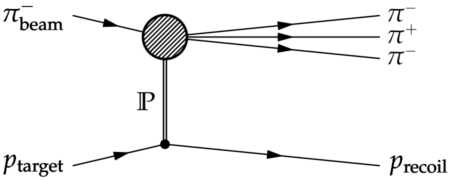
Example: $\pi^-\pi^-\pi^+$ Final State — COMPASS, PRD **95** (2017) 032004



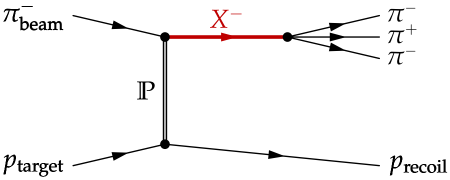
- "Golden" channel
- 46×10^6 $\pi^-\pi^-\pi^+$ events
  - Ca. $10\times$ more data than previous experiments
- Well-known 3π mesons appear in $m_{3\pi}$ spectrum
- Squared four-momentum transfer $0.1 < t' < 1.0\,(\text{GeV}/c)^2$
- Resonances in $\pi^-\pi^+$ subsystem



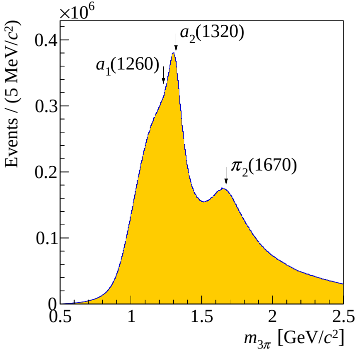
- "Golden" channel
- 46×10^6 $\pi^-\pi^-\pi^+$ events
  - Ca. $10\times$ more data than previous experiments
- Well-known 3π mesons appear in $m_{3\pi}$ spectrum
- Squared four-momentum transfer $0.1 < t' < 1.0\,(\text{GeV}/c)^2$
- Resonances in $\pi^-\pi^+$ subsystem



- "Golden" channel
- 46×10^6 $\pi^-\pi^-\pi^+$ events
  - Ca. $10\times$ more data than previous experiments
- Well-known 3π mesons appear in $m_{3\pi}$ spectrum
- Squared four-momentum transfer $0.1 < t' < 1.0\ (\text{GeV}/c)^2$
- Resonances in $\pi^-\pi^+$ subsystem



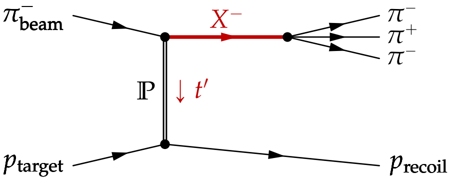
- "Golden" channel
- 46×10^6 $\pi^-\pi^-\pi^+$ events
  - Ca. $10\times$ more data than previous experiments
- Well-known 3π mesons appear in $m_{3\pi}$ spectrum
- Squared four-momentum transfer $0.1 < t' < 1.0\,(\text{GeV}/c)^2$
- Resonances in $\pi^-\pi^+$ subsystem



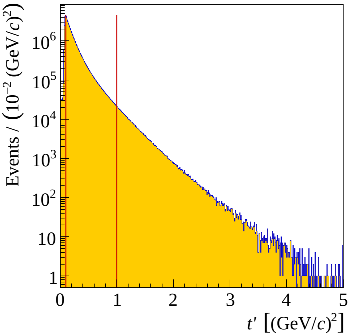
Production of excited light Mesons at COMPASS

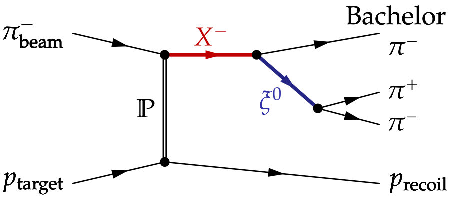
Example: $\pi^-\pi^-\pi^+$ Final State

COMPASS, PRD **95** (2017) 032004

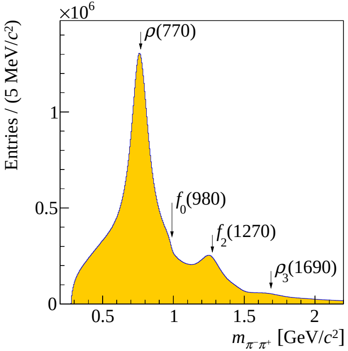


- "Golden" channel
- 46×10^6 $\pi^-\pi^-\pi^+$ events
  - Ca. $10\times$ more data than previous experiments
- Well-known 3π mesons appear in $m_{3\pi}$ spectrum
- Squared four-momentum transfer $0.1 < t' < 1.0\,(\text{GeV}/c)^2$
- Resonances in $\pi^-\pi^+$ subsystem





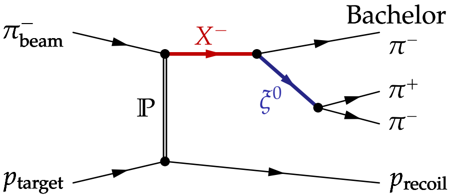
- "Golden" channel
- 46×10^6 $\pi^-\pi^-\pi^+$ events
  - Ca. 10× more data than previous experiments
- Well-known 3π mesons appear in $m_{3\pi}$ spectrum
- Squared four-momentum transfer $0.1 < t' < 1.0\,(\text{GeV}/c)^2$
- Resonances in $\pi^-\pi^+$ subsystem



Production of excited light Mesons at COMPASS

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

COMPASS, PRD **95** (2017) 032004

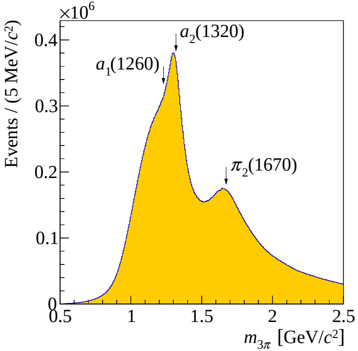


Goal: disentangle all contributing resonances X

- Determine their mass, width, and quantum numbers

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

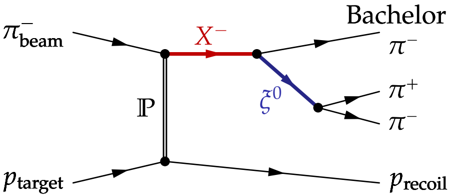
- Exploits full kinematic information of measured final-state particles
- *Amplitude analysis:* takes into account interference of intermediate states and extracts phases



Production of excited light Mesons at COMPASS

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

COMPASS, PRD **95** (2017) 032004

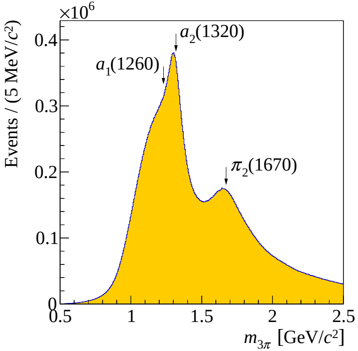


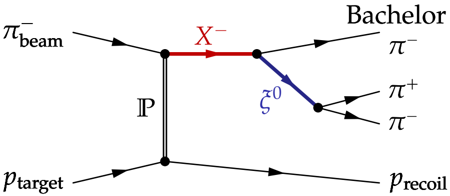
Goal: disentangle all contributing resonances X

- Determine their mass, width, and quantum numbers

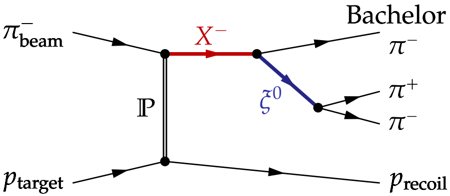
Method: partial-wave analysis (PWA)

- Exploits full kinematic information of measured final-state particles
- *Amplitude analysis:* takes into account interference of intermediate states and extracts phases



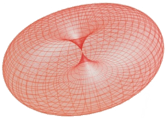


- Spin-parity quantum numbers of a resonance determine angular distribution of daughter particles
- *Analogy:* multipole radiation in classical electrodynamics
- Determine spin-parity quantum numbers of X and ξ from measured angular distributions of final-state particles

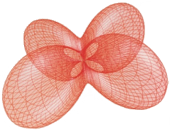


- Spin-parity quantum numbers of a resonance determine angular distribution of daughter particles
- *Analogy:* multipole radiation in classical electrodynamics
- Determine spin-parity quantum numbers of X and ξ from measured angular distributions of final-state particles

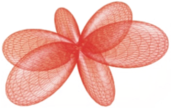
Dipole
($J = 1$)



Quadrupole
($J = 2$)

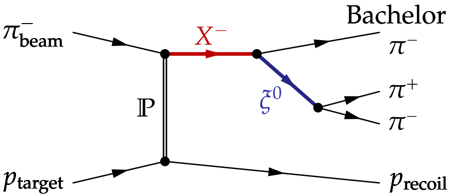


Octupole
($J = 3$)



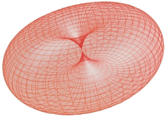
Partial-Wave Analysis using the Isobar Model

Example: $\pi^-\pi^-\pi^+$ Final State — COMPASS, PRD **95** (2017) 032004

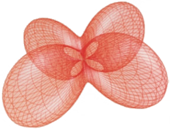


- Spin-parity quantum numbers of a resonance determine angular distribution of daughter particles
- *Analogy:* multipole radiation in classical electrodynamics
- Determine spin-parity quantum numbers of X and ξ from measured angular distributions of final-state particles

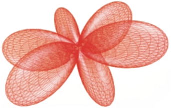
Dipole ($J = 1$)

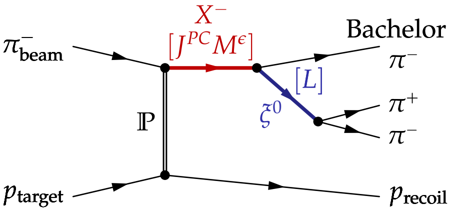


Quadrupole ($J = 2$)



Octupole ($J = 3$)





For $m_{3\pi}$ = const, 3π kinematic distribution is completely defined by

- Quantum numbers of X
- Orbital angular momentum L between ξ and bachelor π
- Isobar resonance $\xi \Longrightarrow$ model for $m_{\pi^-\pi^+}$ dependence of amplitude; e.g. Breit-Wigner amplitude for $\rho(770) \to \pi^-\pi^+$

***Partial wave:* short-hand notation**

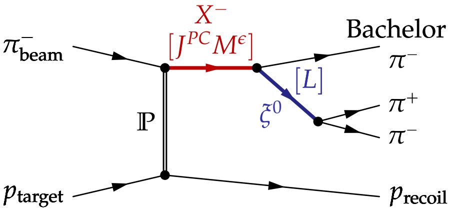
$$J^{PC}\, M^\varepsilon\, \xi\, \pi\, L$$

- Represents specific 5-dimensional kinematic distribution

Partial-Wave Analysis: Isobar Model

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

COMPASS, PRD **95** (2017) 032004



For $m_{3\pi} =$ const, 3π kinematic distribution is completely defined by

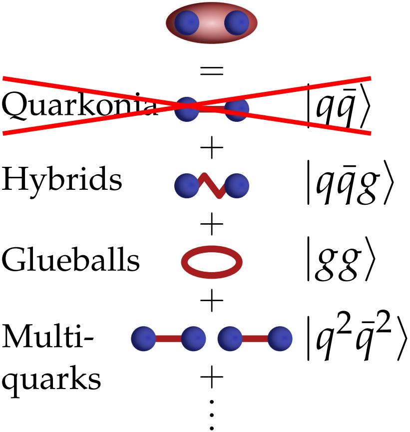
- Quantum numbers of X
- Orbital angular momentum L between ξ and bachelor π
- Isobar resonance $\xi \implies$ model for $m_{\pi^-\pi^+}$ dependence of amplitude; e.g. Breit-Wigner amplitude for $\rho(770) \to \pi^-\pi^+$

Partial wave: short-hand notation

$$J^{PC}\, M^\varepsilon\, \xi\, \pi\, L$$

- Represents specific 5-dimensional kinematic distribution

Spin-Exotic Mesons

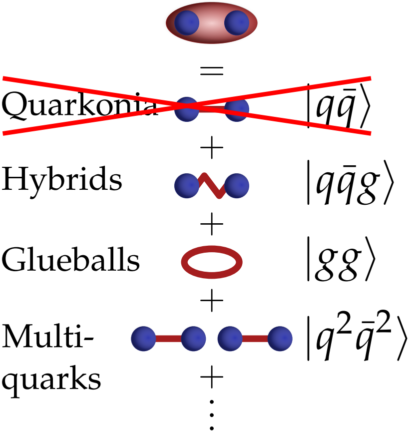


- States with $J^{PC} = 0^{--}$, even^{+-}, or odd^{-+} forbidden for $|q\bar{q}\rangle$
- Finding them would be unambiguous proof for configurations beyond $|q\bar{q}\rangle$

3 candidates in light-meson sector

1. $\pi_1(1400)$: seen in $\eta\pi$
2. $\pi_1(1600)$: seen in $\rho(770)\pi$, $\eta'\pi$, $b_1(1235)\pi$, and $f_1(1285)\pi$
3. $\pi_1(2015)$ (needs confirmation): seen in $b_1(1235)\pi$, and $f_1(1285)\pi$

- All have $J^{PC} = 1^{-+}$
- Some claims are controversial



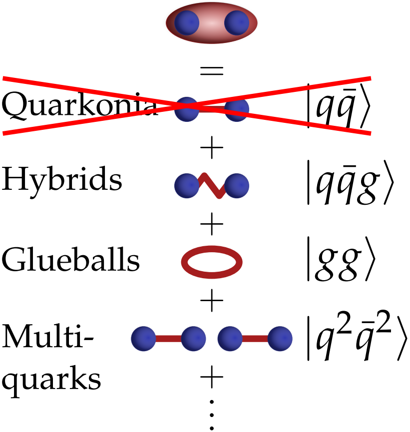
- States with $J^{PC} = 0^{--}$, even^{+-}, or odd^{-+} forbidden for $|q\bar{q}\rangle$
- Finding them would be unambiguous proof for configurations beyond $|q\bar{q}\rangle$

3 candidates in light-meson sector

1. $\pi_1(1400)$: seen in $\eta\pi$
2. $\pi_1(1600)$: seen in $\rho(770)\pi$, $\eta'\pi$, $b_1(1235)\pi$, and $f_1(1285)\pi$
3. $\pi_1(2015)$ (needs confirmation): seen in $b_1(1235)\pi$, and $f_1(1285)\pi$

- All have $J^{PC} = 1^{-+}$
- Some claims are controversial

Spin-Exotic Mesons



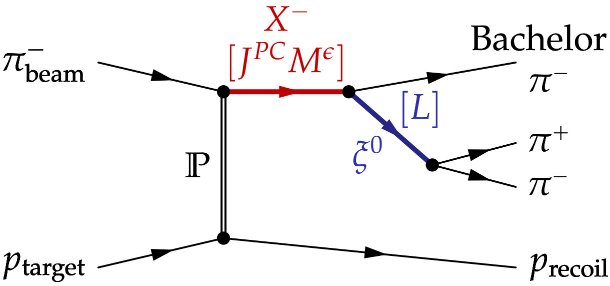
- States with $J^{PC} = 0^{--}$, even^{+-}, or odd^{-+} forbidden for $|q\bar{q}\rangle$
- Finding them would be unambiguous proof for configurations beyond $|q\bar{q}\rangle$

3 candidates in light-meson sector

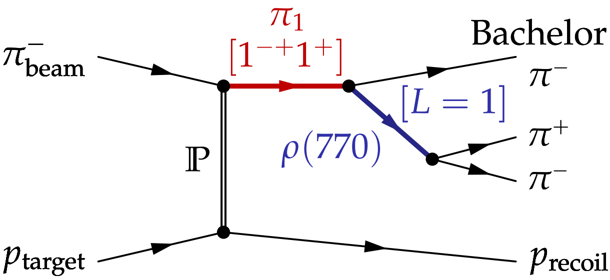
1. $\pi_1(1400)$: seen in $\eta\pi$
2. $\pi_1(1600)$: seen in $\rho(770)\pi$, $\eta'\pi$, $b_1(1235)\pi$, and $f_1(1285)\pi$
3. $\pi_1(2015)$ (needs confirmation): seen in $b_1(1235)\pi$, and $f_1(1285)\pi$

- All have $J^{PC} = 1^{-+}$
- Some claims are controversial

Model for Partial-Wave Decomposition



- Wave set with 88 waves
  - Spin J up to 6
  - Orbital angular momentum L up to 6
  - 6 isobar resonances: $[\pi\pi]_S$, $\rho(770)$, $f_0(980)$, $f_2(1270)$, $f_0(1500)$, and $\rho_3(1690)$
- Includes spin-exotic $1^{-+} \to \rho(770)\pi$ P wave



- Wave set with 88 waves
  - Spin J up to 6
  - Orbital angular momentum L up to 6
  - 6 isobar resonances: $[\pi\pi]_S$, $\rho(770)$, $f_0(980)$, $f_2(1270)$, $f_0(1500)$, and $\rho_3(1690)$
- Includes spin-exotic $1^{-+} \to \rho(770)\pi$ P wave

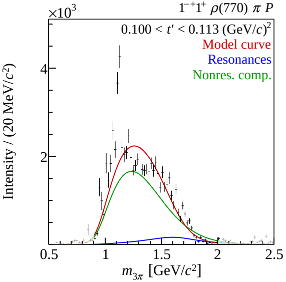
Spin-exotic $1^{-+} \to \rho(770)\pi\, P$ Wave

- Shape of intensity distribution changes dramatically with t'
- Low t': mostly non-resonant
- High t': mostly $\pi_1(1600)$

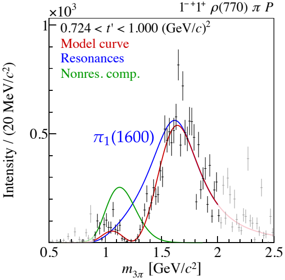
Resonance parameters

- $\pi_1(1600)$
  $m_0 = (1600\,^{+110}_{-60})\ \text{MeV}/c^2$
  $\Gamma_0 = (580\,^{+100}_{-230})\ \text{MeV}/c^2$
- Large systematic uncertainties

Lowest t' bin



Highest t' bin

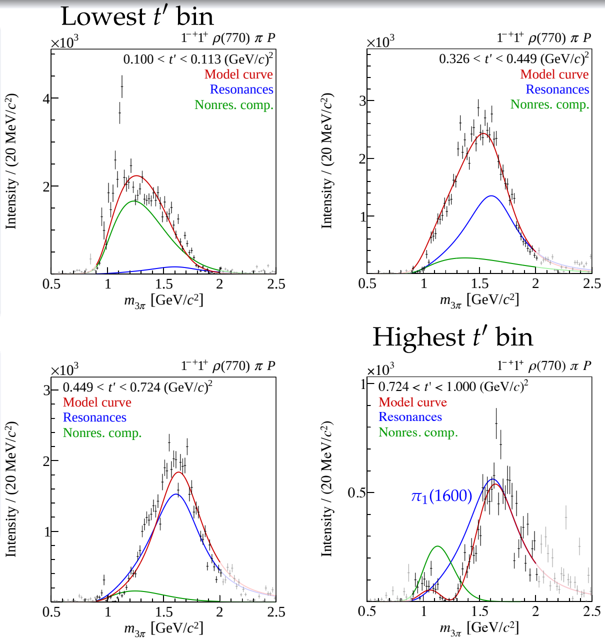


Spin-exotic $1^{-+} \to \rho(770)\pi\, P$ Wave

- Shape of intensity distribution changes dramatically with t'
- Low t': mostly non-resonant
- High t': mostly $\pi_1(1600)$

Resonance parameters

- $\pi_1(1600)$
  $m_0 = (1600\,^{+110}_{-60})\ \mathrm{MeV}/c^2$
  $\Gamma_0 = (580\,^{+100}_{-230})\ \mathrm{MeV}/c^2$
- Large systematic uncertainties



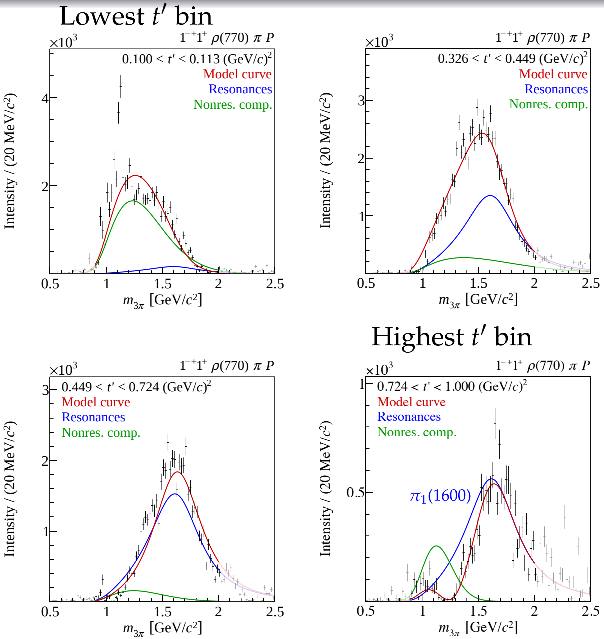
Spin-exotic $1^{-+} \to \rho(770)\pi\ P$ Wave

COMPASS, PRD **98** (2018) 092003

- Shape of intensity distribution changes dramatically with t'
- Low t': mostly non-resonant
- High t': mostly $\pi_1(1600)$

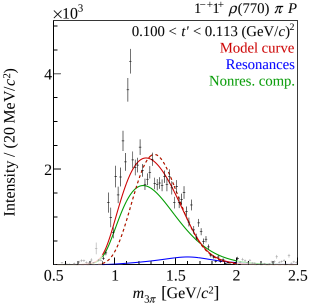
Resonance parameters

- $\pi_1(1600)$
  $m_0 = (1600\,^{+110}_{-60})\ \mathrm{MeV}/c^2$
  $\Gamma_0 = (580\,^{+100}_{-230})\ \mathrm{MeV}/c^2$
- Large systematic uncertainties



Spin-exotic $1^{-+} \to \rho(770)\pi\, P$ Wave

Lowest t' bin



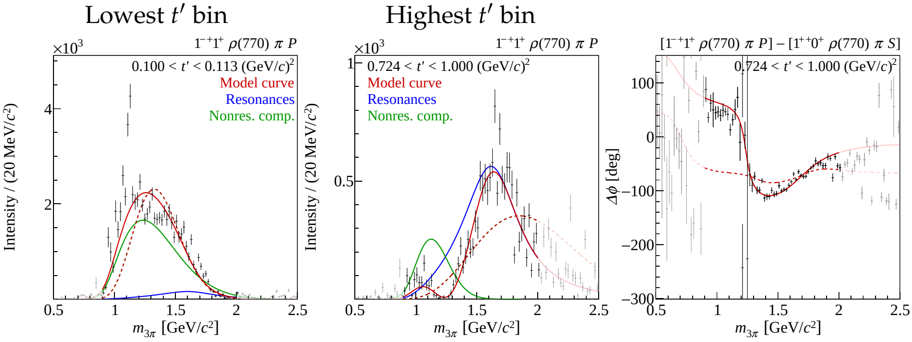
- Data at high t' cannot be described without $\pi_1(1600)$ component (dashed curves)

t'-resolved analysis

- $\pi_1(1600)$ masked by non-resonant component for $t' \lesssim 0.5\,(\text{GeV}/c)^2$
- Solves long-standing puzzle of seemingly contradictory BNL E852 results

Spin-exotic $1^{-+} \to \rho(770)\pi\ P$ Wave

COMPASS, PRD **98** (2018) 092003



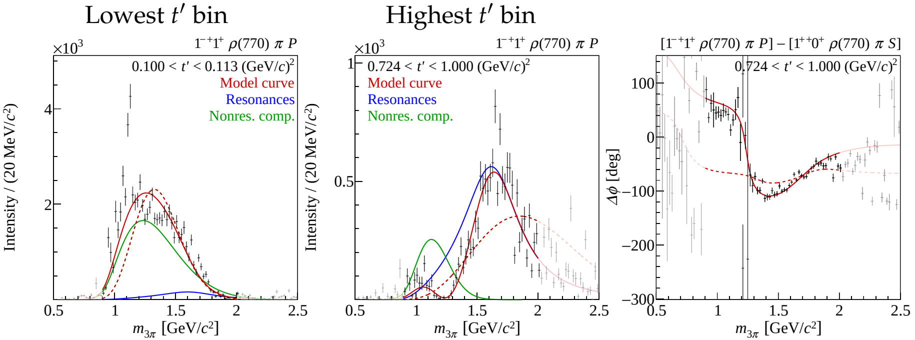
- Data at high t' cannot be described without $\pi_1(1600)$ component (dashed curves)

t'-resolved analysis

- $\pi_1(1600)$ masked by non-resonant component for $t' \lesssim 0.5\ (\mathrm{GeV}/c)^2$
- Solves long-standing puzzle of seemingly contradictory BNL E852 results

Spin-exotic $1^{-+} \to \rho(770)\pi\, P$ Wave

COMPASS, PRD **98** (2018) 092003



- Data at high t' cannot be described without $\pi_1(1600)$ component (dashed curves)

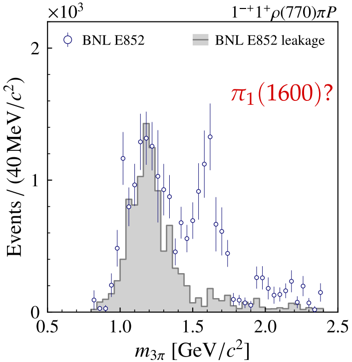
t'-resolved analysis

- $\pi_1(1600)$ masked by non-resonant component for $t' \lesssim 0.5\ (\mathrm{GeV}/c)^2$
- Solves long-standing puzzle of seemingly contradictory BNL E852 results

BNL E852 Results on $\pi_1(1600) \to \rho(770)\pi$ explained

18.3 GeV$/c$ π^- beam on p target

E852, PRL **81** (1998) 5760



E852, PRD **73** (2006) 072001

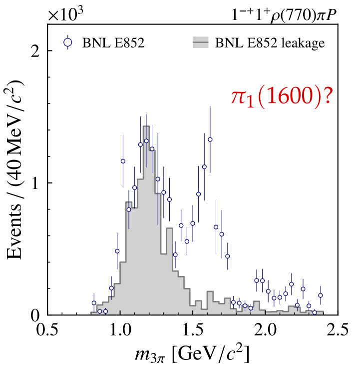
- 2.5×10^5 events
- $0.05 < t' < 1.0\,(\mathrm{GeV}/c)^2$
- PWA: 21 waves

- COMPASS data reproduce previous findings [arXiv:2108.01744]

BNL E852 Results on $\pi_1(1600) \to \rho(770)\pi$ explained

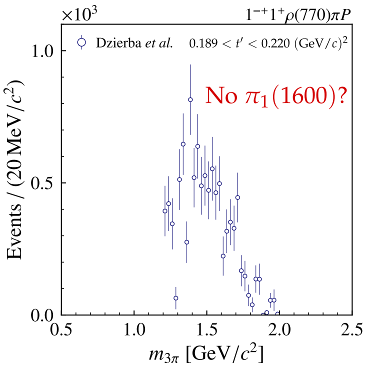
18.3 GeV / c π^- beam on p target

E852, PRL **81** (1998) 5760



- 2.5×10^5 events
- $0.05 < t' < 1.0\ (\text{GeV}/c)^2$
- PWA: 21 waves

E852, PRD **73** (2006) 072001



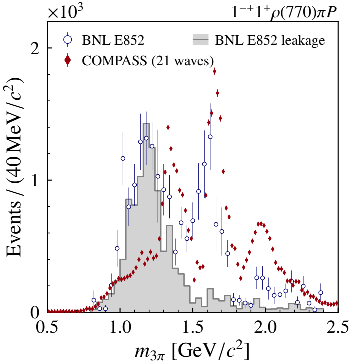
- 2.6×10^6 events
- $0.08 < t' < 0.53\ (\text{GeV}/c)^2$
- PWA: 36 waves

- COMPASS data reproduce previous findings [arXiv:2108.01744]

BNL E852 Results on $\pi_1(1600) \to \rho(770)\pi$ explained

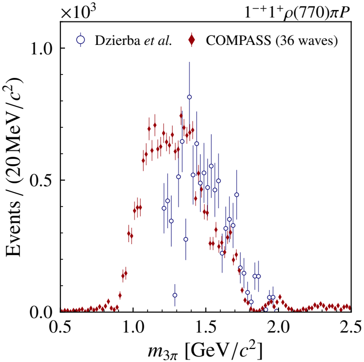
18.3 GeV$/c$ π^- beam on p target

E852, PRL **81** (1998) 5760



- 2.5×10^5 events
- $0.05 < t' < 1.0$ (GeV$/c$)^2
- PWA: 21 waves

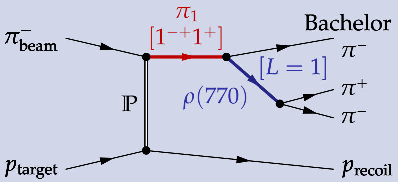
E852, PRD **73** (2006) 072001



- 2.6×10^6 events
- $0.08 < t' < 0.53$ (GeV$/c$)^2
- PWA: 36 waves

- COMPASS data reproduce previous findings *[arXiv:2108.01744]*

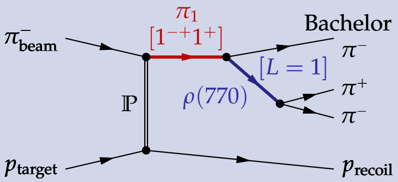
Model Dependence of the $\pi_1(1600)$ Signal? *[arXiv:2108.01744]*

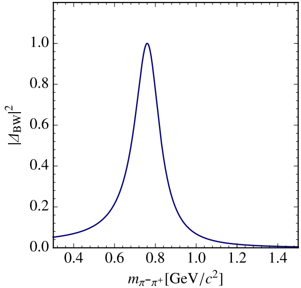


- Conventional PWA requires complete knowledge of $\xi^0 \to \pi^-\pi^+$ amplitude
    - Employed parametrization for amplitudes of $\rho(770)$ isobar might deviate from data
- *Novel technique:* **"freed-isobar" PWA**

  Krinner *et al.*, PRD **97** (2018) 114008
    - Replace fixed isobar parametrizations by step-like functions
    - Extract isobar amplitude from data
    - Reduced model dependence

Model Dependence of the $\pi_1(1600)$ Signal? *[arXiv:2108.01744]*

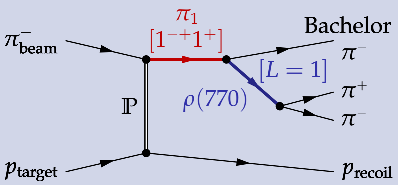




- Conventional PWA requires complete knowledge of $\xi^0 \to \pi^-\pi^+$ amplitude
  - Employed parametrization for amplitudes of $\rho(770)$ isobar might deviate from data
- *Novel technique:* **"freed-isobar" PWA**

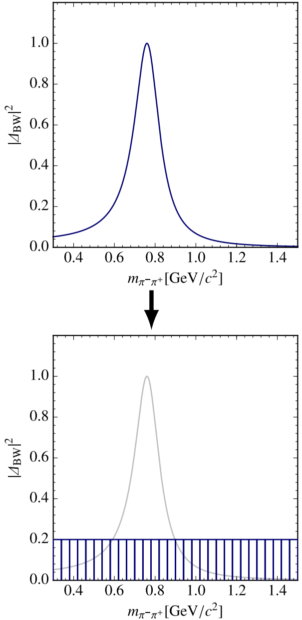
  Krinner *et al.*, PRD **97** (2018) 114008
  - Replace fixed isobar parametrizations by step-like functions
  - Extract isobar amplitude from data
  - Reduced model dependence

Model Dependence of the $\pi_1(1600)$ Signal?



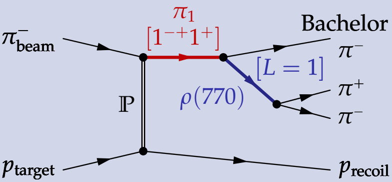
- Conventional PWA requires complete knowledge of $\xi^0 \to \pi^-\pi^+$ amplitude
  - Employed parametrization for amplitudes of $\rho(770)$ isobar might deviate from data
- *Novel technique:* **"freed-isobar" PWA**

  Krinner *et al.*, PRD **97** (2018) 114008
  - Replace fixed isobar parametrizations by step-like functions
  - Extract isobar amplitude from data
  - Reduced model dependence



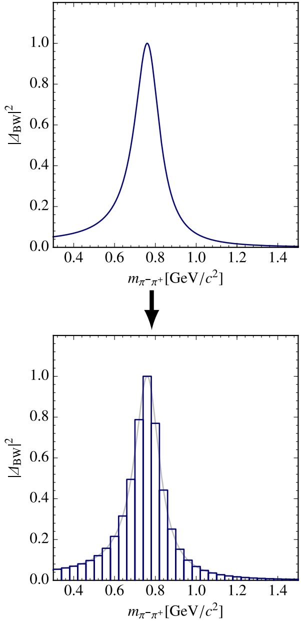
Model Dependence of the $\pi_1(1600)$ Signal?

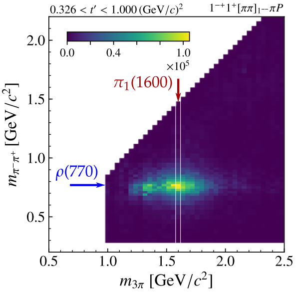
[arXiv:2108.01744]



- Conventional PWA requires complete knowledge of $\xi^0 \to \pi^-\pi^+$ amplitude
  - Employed parametrization for amplitudes of $\rho(770)$ isobar might deviate from data
- *Novel technique:* **"freed-isobar" PWA**

  Krinner *et al.*, PRD **97** (2018) 114008
  - Replace fixed isobar parametrizations by step-like functions
  - Extract isobar amplitude from data
  - Reduced model dependence





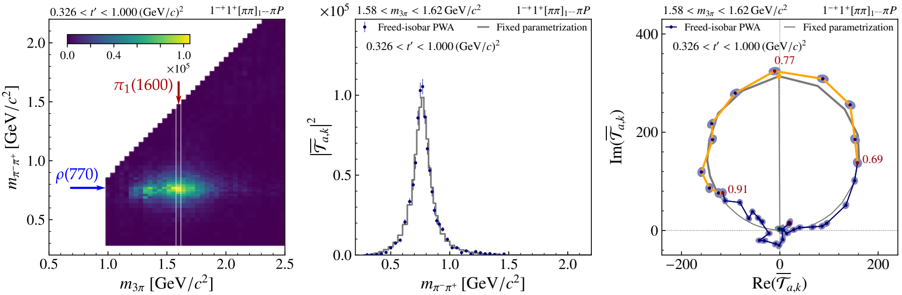
- Intensity peak at $m_{3\pi} \approx 1.6\,\text{GeV}/c^2$ and $m_{\pi^-\pi^+} \approx 0.8\,\text{GeV}/c^2$
- Clear $\rho(770)$ signal: peak in intensity + circular structure in Argand diagram

- $\rho(770)$ parametrization used in conventional PWA agrees fairly well with measured amplitude of $\pi^-\pi^+$ subsystem

$\pi^-\pi^+$ Amplitude in $1^{-+} \to [\pi\pi]_{1^{--}} + \pi^-$

$0.326 < t' < 1.000\,(\mathrm{GeV}/c)^2$

[arXiv:2108.01744]

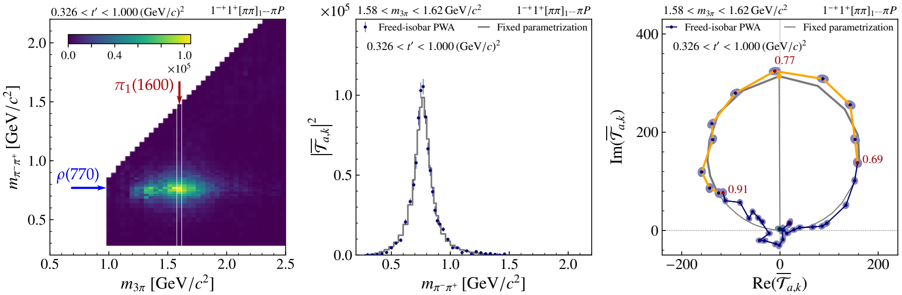


- Intensity peak at $m_{3\pi} \approx 1.6\,\mathrm{GeV}/c^2$ and $m_{\pi^-\pi^+} \approx 0.8\,\mathrm{GeV}/c^2$
- Clear $\rho(770)$ signal: peak in intensity + circular structure in Argand diagram

- $\rho(770)$ parametrization used in conventional PWA agrees fairly well with measured amplitude of $\pi^-\pi^+$ subsystem

$\pi^-\pi^+$ Amplitude in $1^{-+} \to [\pi\pi]_{1^{--}} + \pi^-$

$0.326 < t' < 1.000\,(\mathrm{GeV}/c)^2$ *[arXiv:2108.01744]*

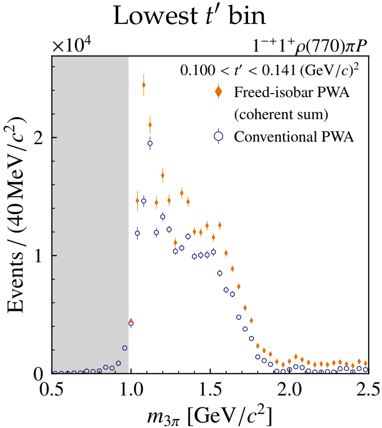


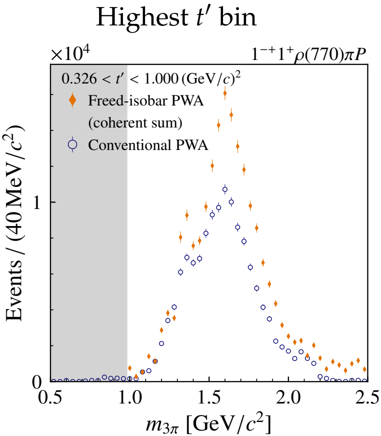
- Intensity peak at $m_{3\pi} \approx 1.6\,\mathrm{GeV}/c^2$ and $m_{\pi^-\pi^+} \approx 0.8\,\mathrm{GeV}/c^2$
- Clear $\rho(770)$ signal: peak in intensity + circular structure in Argand diagram

- $\rho(770)$ parametrization used in conventional PWA agrees fairly well with measured amplitude of $\pi^-\pi^+$ subsystem

Comparison with Conventional PWA

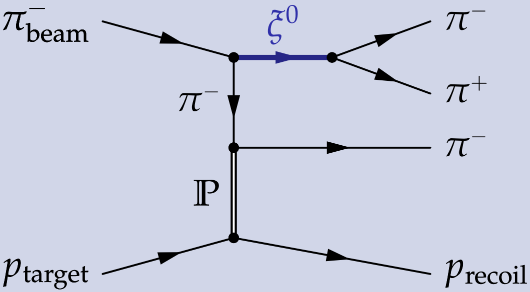
Coherent Sum over full $m_{\pi^- \pi^+}$ Range





- Freed-isobar PWA confirms existence of $\pi_1(1600) \to \rho(770)\pi$

Dominant non-resonant amplitude: Deck effect



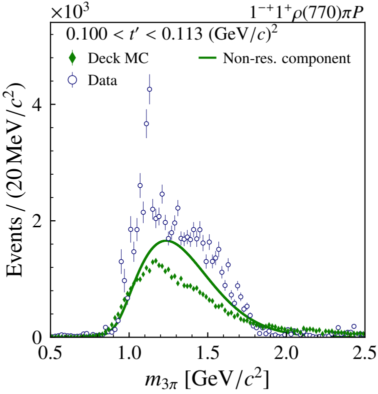
- MC pseudodata generated according to simple model for Deck amplitude — based on ACCMOR, NPB **182** (1981) 269
  - Upper vertex: amplitude from $\pi\pi$ scattering up to F-wave — Hyams *et al.*, NPB **64** (1973) 134
- Partial-wave decomposition using same 88-wave set as for real data

Spin-exotic $1^{-+} \to \rho(770)\pi\, P$ Wave

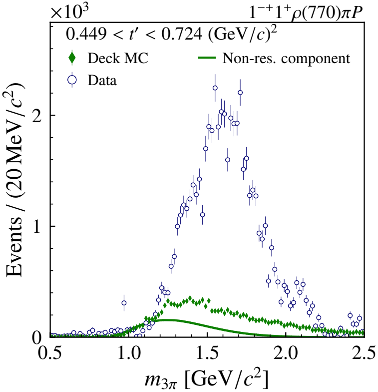
Model for the Non-Resonant Component

[arXiv:2108.01744]

Low t'



High t'



- Deck intensity normalized to intensity of non-resonant component in resonance-model fit for $t' \lesssim 0.5\,(\mathrm{GeV}/c)^2$
  - Similar shape of mass spectra for $t' \lesssim 0.5\,(\mathrm{GeV}/c)^2$
  - Different shape at high t'

COMPASS has acquired high-precision data sets on pion diffraction

- Performed most detailed and comprehensive PWA of $\pi^-\pi^-\pi^+$ and $\eta^{(\prime)}\pi$ so far
- Studied 11 resonances of a_J and π_J families $\Longrightarrow$ PDG 2019
- Confirmation of disputed $\pi_1(1600) \to \rho(770)\pi$

Ongoing search for exotic mesons

- Analyze additional final states, e.g.
  - $\pi^-\pi^0\omega(782)$
  - $\pi^-\pi^-\pi^+\eta$
  - $\pi^-\pi^\mp \overset{(-)}{K}{}^0_S K^\pm$
  - …
- Tight collaboration with theorists to improve analysis model

Detailed study of kaon spectrum

- Diffraction of K^- beam on p target into $K^0_S\pi^-$, $K^-\pi^-\pi^+$, …

COMPASS has acquired high-precision data sets on pion diffraction

- Performed most detailed and comprehensive PWA of $\pi^-\pi^-\pi^+$ and $\eta^{(\prime)}\pi$ so far
- Studied 11 resonances of a_J and π_J families $\Longrightarrow$ PDG 2019
- Confirmation of disputed $\pi_1(1600) \to \rho(770)\pi$

Ongoing search for exotic mesons

- Analyze additional final states, e.g.
  - $\pi^-\pi^0\omega(782)$
  - $\pi^-\pi^-\pi^+\eta$
  - $\pi^-\pi^\mp \overset{(-)}{K}{}^0_S K^\pm$
  - …
- Tight collaboration with theorists to improve analysis model

Detailed study of kaon spectrum

- Diffraction of K^- beam on p target into $K^0_S\pi^-$, $K^-\pi^-\pi^+$, …

COMPASS has acquired high-precision data sets on pion diffraction

- Performed most detailed and comprehensive PWA of $\pi^-\pi^-\pi^+$ and $\eta^{(\prime)}\pi$ so far
- Studied 11 resonances of a_J and π_J families $\Longrightarrow$ PDG 2019
- Confirmation of disputed $\pi_1(1600) \to \rho(770)\pi$

Ongoing search for exotic mesons

- Analyze additional final states, e.g.
  - $\pi^-\pi^0\omega(782)$
  - $\pi^-\pi^-\pi^+\eta$
  - $\pi^-\pi^\mp \overset{(-)}{K}{}^0_S K^\pm$
  - …
- Tight collaboration with theorists to improve analysis model

Detailed study of kaon spectrum

- Diffraction of K^- beam on p target into $K^0_S\pi^-$, $K^-\pi^-\pi^+$, …

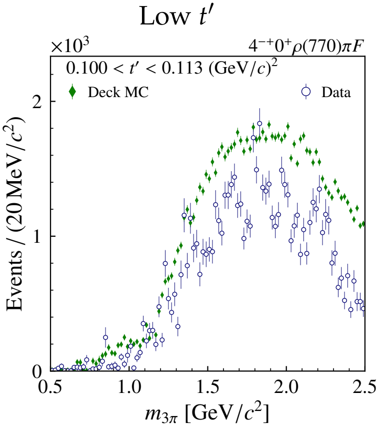
Backup Slides

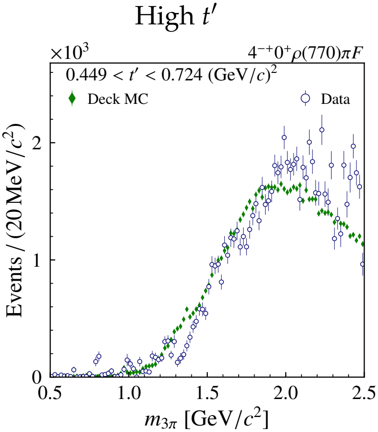
6 Deck model in high-spin waves

7 $\pi_1(1600)$ in $\eta\pi$ and $\eta'\pi$

Model for the Non-Resonant Component

High-Spin Waves





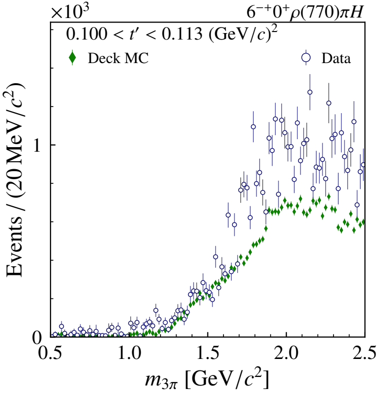
- Deck intensity normalized to intensity of non-resonant component in resonance-model fit for $t' \lesssim 0.5\ (\text{GeV}/c)^2$
  - Similar shape of mass spectra for full t' range

Model for the Non-Resonant Component

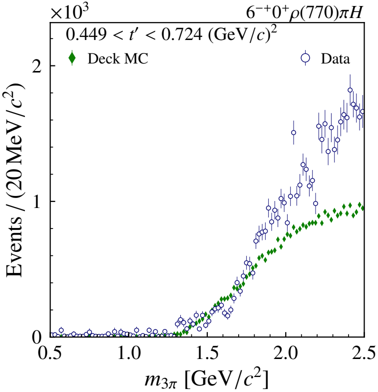
High-Spin Waves

[arXiv:2108.01744]

Low t'



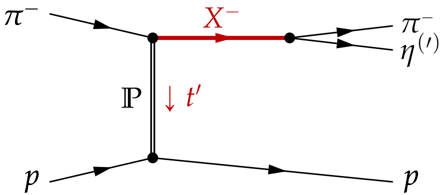
High t'



- Deck intensity normalized to intensity of non-resonant component in resonance-model fit for $t' \lesssim 0.5\,(\text{GeV}/c)^2$
  - Similar shape of mass spectra for full t' range

JPAC Coupled-Channel Analysis of $\eta\pi$ and $\eta'\pi$

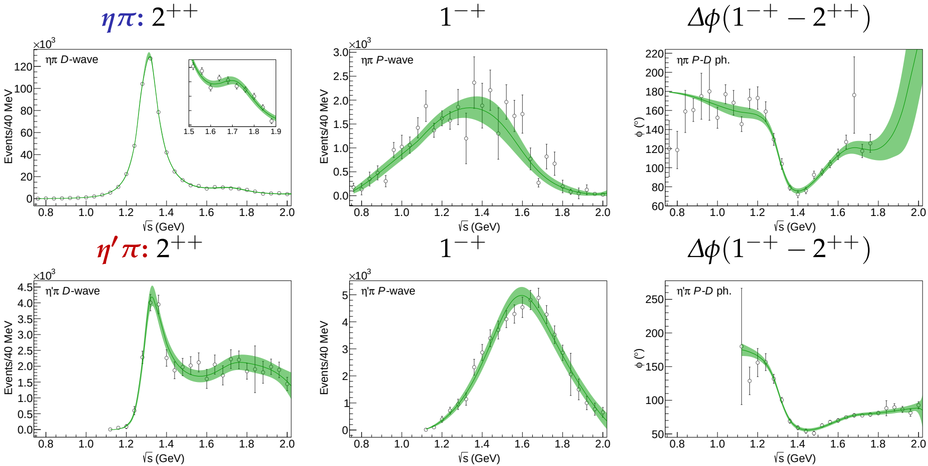
Rodas *et al*. [JPAC], PRL **122** (2019) 042002



- Partial-wave amplitudes from COMPASS PLB **740** (2015) 303
- Analytical and unitary model based on S-matrix principles

JPAC Coupled-Channel Analysis of $\eta\pi$ and $\eta'\pi$

Rodas *et al.* [JPAC], PRL **122** (2019) 042002

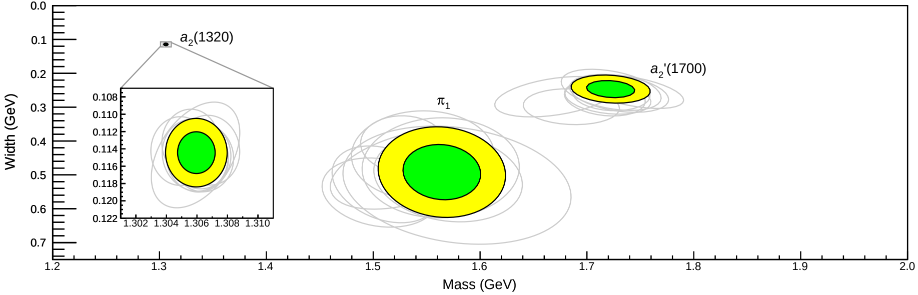


- Partial-wave amplitudes from COMPASS — PLB **740** (2015) 303
- Analytical and unitary model based on *S*-matrix principles

JPAC Coupled-Channel Analysis of $\eta\pi$ and $\eta'\pi$

Resonance Pole Parameters

Rodas *et al.* [JPAC], PRL **122** (2019) 042002

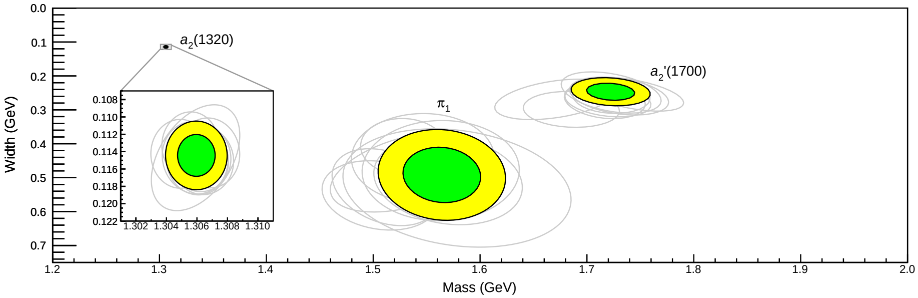


- Only single 1^{-+}-wave pole required to describe peaks at 1.4 and 1.6 GeV/c^2
  - $m_0 = (1564 \pm 24_{\text{stat.}} \pm 86_{\text{sys.}})\ \mathrm{MeV}/c^2$
  - $\Gamma_0 = (492 \pm 54_{\text{stat.}} \pm 102_{\text{sys.}})\ \mathrm{MeV}/c^2$
  - Consistent with $\pi_1(1600)$
  - First measurement of pole parameters of $\pi_1(1600)$
- Raises doubts about existence of $\pi_1(1400)$

JPAC Coupled-Channel Analysis of $\eta\pi$ and $\eta'\pi$

Resonance Pole Parameters

Rodas *et al.* [JPAC], PRL **122** (2019) 042002

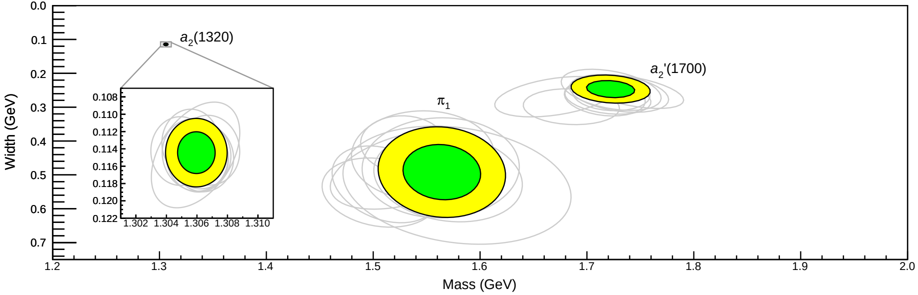


- Only single 1^{-+}-wave pole required to describe peaks at 1.4 and 1.6 GeV/c^2
  - $m_0 = (1564 \pm 24_{\text{stat.}} \pm 86_{\text{sys.}})$ MeV/c^2
  - $\Gamma_0 = (492 \pm 54_{\text{stat.}} \pm 102_{\text{sys.}})$ MeV/c^2
  - Consistent with $\pi_1(1600)$
  - First measurement of pole parameters of $\pi_1(1600)$
- Raises doubts about existence of $\pi_1(1400)$

JPAC Coupled-Channel Analysis of $\eta\pi$ and $\eta'\pi$

Resonance Pole Parameters

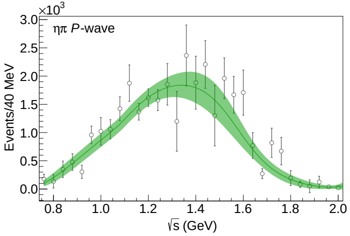
Rodas *et al.* [JPAC], PRL **122** (2019) 042002



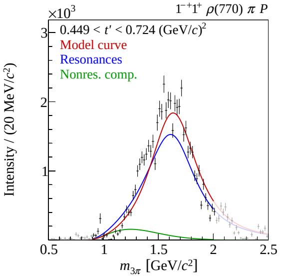
- Only single 1^{-+}-wave pole required to describe peaks at 1.4 and 1.6 GeV/c^2
  - $m_0 = (1564 \pm 24_{\text{stat.}} \pm 86_{\text{sys.}})\,\mathrm{MeV}/c^2$
  - $\Gamma_0 = (492 \pm 54_{\text{stat.}} \pm 102_{\text{sys.}})\,\mathrm{MeV}/c^2$
  - Consistent with $\pi_1(1600)$
  - First measurement of pole parameters of $\pi_1(1600)$
- Raises doubts about existence of $\pi_1(1400)$

The $\pi_1(1600)$: Three Sides of the Same Coin

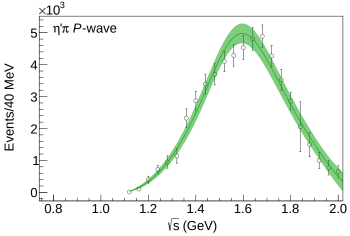
$\eta\pi$: $0.1 < t' < 1.0\,(\mathrm{GeV}/c)^2$



3π: $0.449 < t' < 0.724\,(\mathrm{GeV}/c)^2$

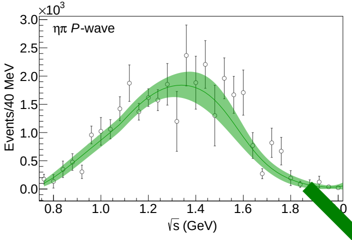


$\eta'\pi$: $0.1 < t' < 1.0\,(\mathrm{GeV}/c)^2$

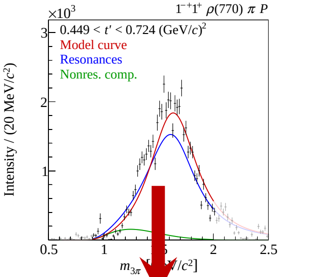


The $\pi_1(1600)$: Three Sides of the Same Coin

$\eta\pi$: $0.1 < t' < 1.0\,(\mathrm{GeV}/c)^2$



3π: $0.449 < t' < 0.724\,(\mathrm{GeV}/c)^2$



$\eta'\pi$: $0.1 < t' < 1.0\,(\mathrm{GeV}/c)^2$