Model dependence of the $\pi_1(1600) \to \rho(770)\,\pi$ signal

Fabian Krinner for the COMPASS collaboration

Max Planck Institut für Physik

in memoriam Simon Eidelman

- Mesons as $q\bar{q}$-states
- Quark spins couple to $S = 0, 1$

$$\vec{S} = \vec{s}_1 + \vec{s}_2$$

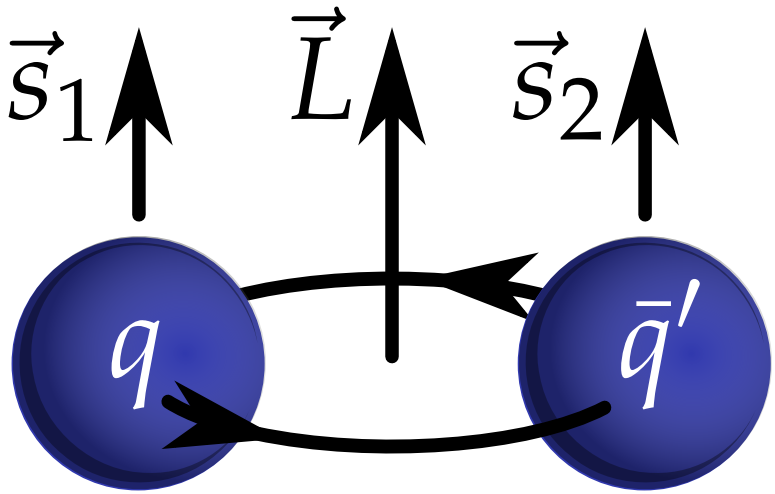
- S and orbital angular momentum $\vec{L}$ couple to total spin

$$\vec{J} = \vec{L} + \vec{S}$$

- Quantum numbers J^{PC}:

$$P = (-1)^{L+1}$$

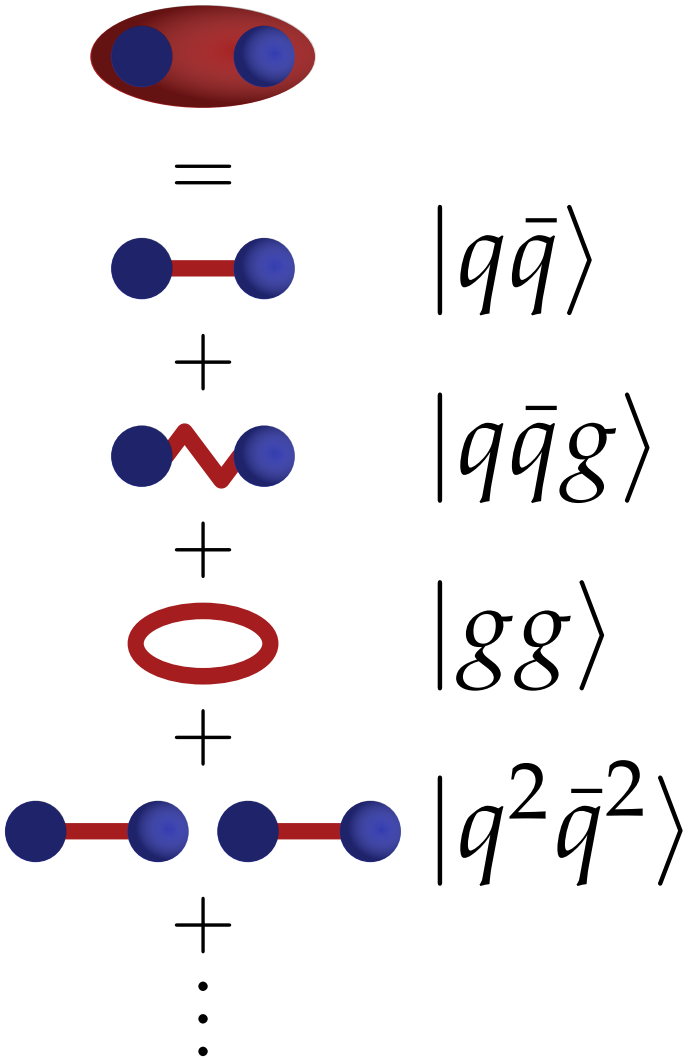
$$C = (-1)^{L+S}$$



- Impossible combinations: $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots$
  - Spin-exotic quantum numbers
  - Beyond constituent quark model

Spin-exotic states
Beyond $q\bar{q}$

- Spin exotic J^{PC}: not $|q\bar{q}\rangle$
- Alternatives:
  - Hybrids: $|q\bar{q}g\rangle$
  - Glueballs: $|gg\rangle$
  - Multi-quark states:
    - ⋆ Tetra-, Hexaquarks: $|q_i\bar{q}_j\rangle$
    - ⋆ Molecules: $|(q\bar{q})(q\bar{q})\rangle$
  - $+$ superpositions
- here: $J^{PC} = 1^{-+}$



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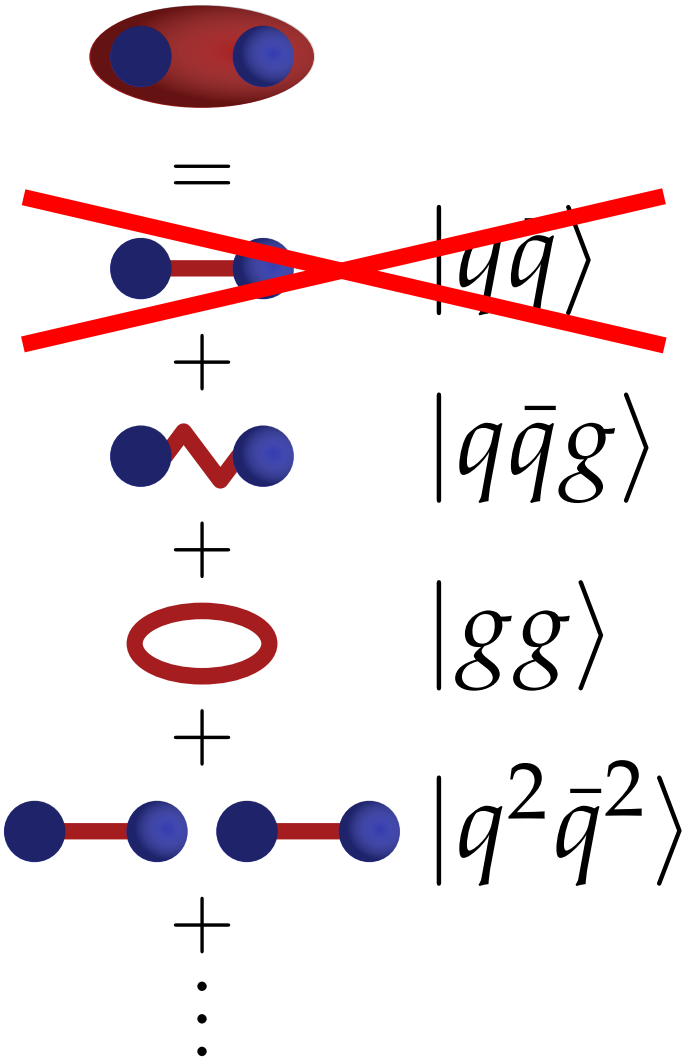


The COMPASS experiment

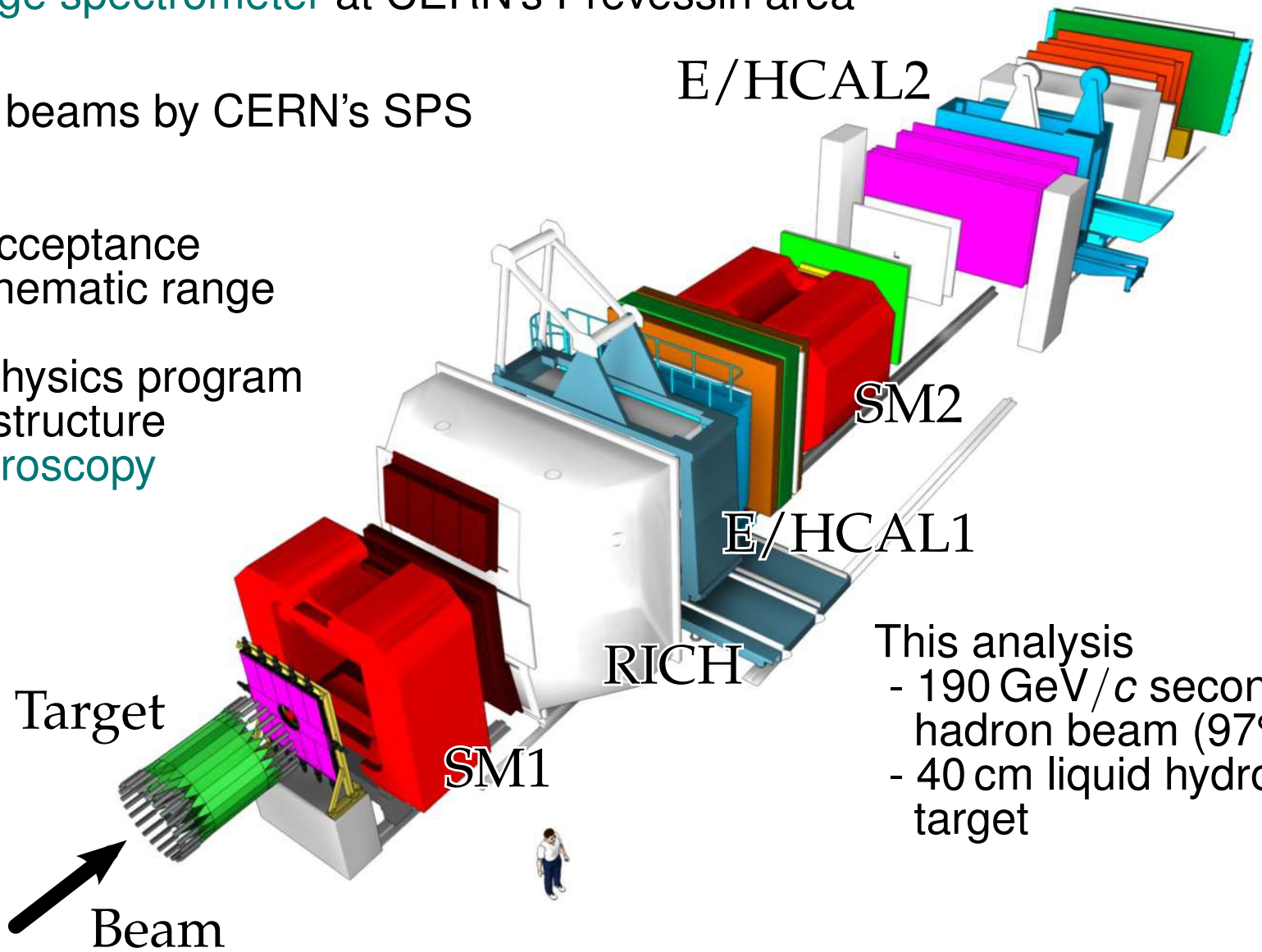
Common **M**uon **P**roton **A**pparatus for **S**tructure and **S**pectroscopy

Two-stage spectrometer at CERN's Prévessin area

Various beams by CERN's SPS

Large acceptance
Wide kinematic range

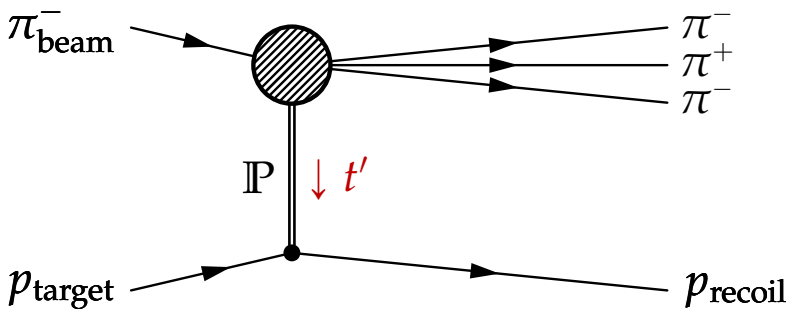
Broad physics program
- Spin-structure
- Spectroscopy

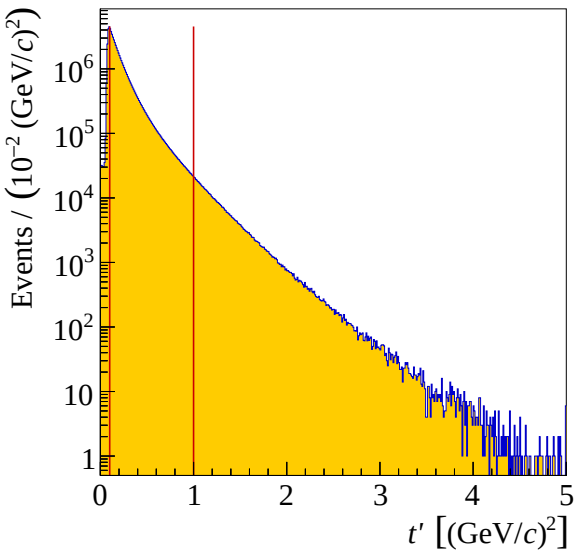


This analysis
- 190 GeV/c secondary hadron beam (97% π^-)
- 40 cm liquid hydrogen target

Diffractive 3π production

- COMPASS: Large data set for the diffractive process
  $\pi^-_{\text{beam}} + \text{p} \to \pi^-\pi^+\pi^- + \text{p}$
- Squared four-momentum transfer t' by Pomeron $\mathbb{P}$
- 46×10^6 exclusive events





COMPASS collaboration, PR **D95** (2017) 032004

Diffractive 3π production

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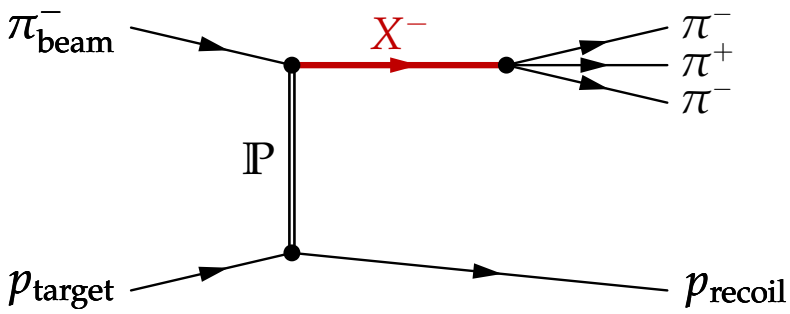
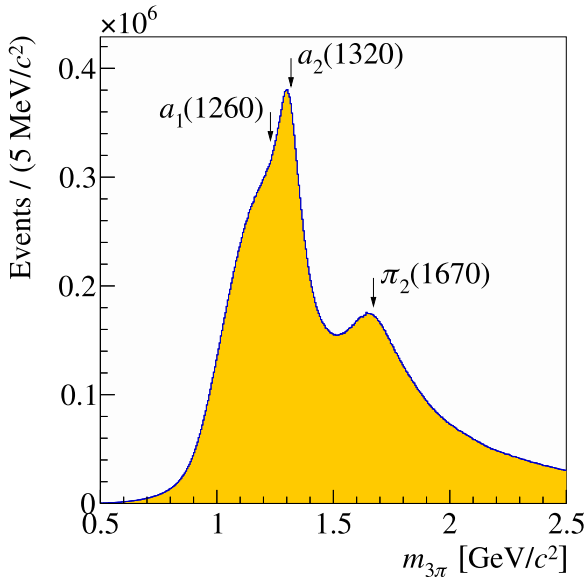
- Rich structure in $\pi^-\pi^+\pi^-$ mass spectrum: Intermediate states X^-

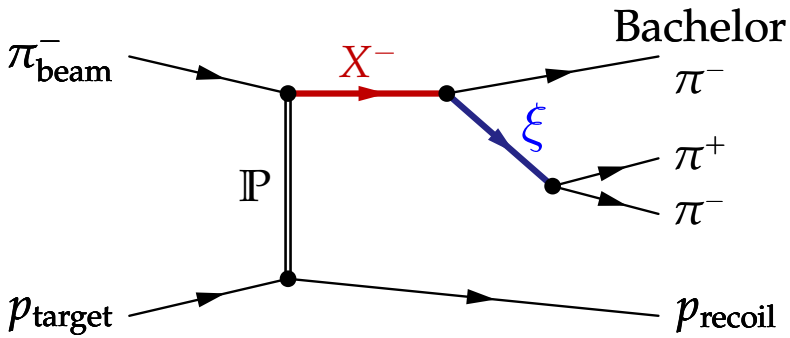


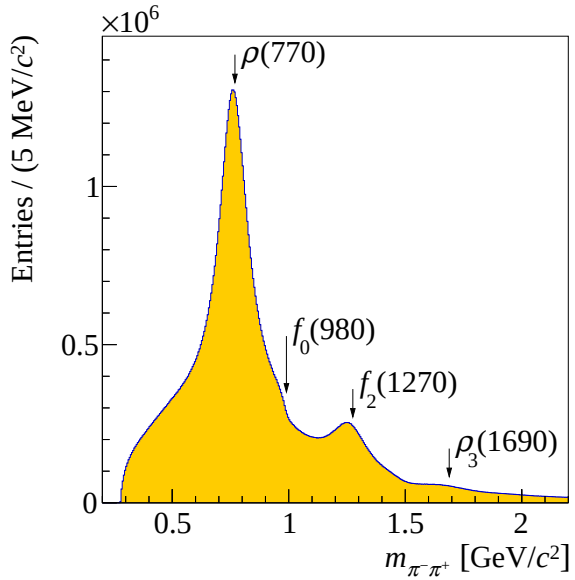


COMPASS collaboration, PR **D95** (2017) 032004

Diffractive 3π production

- COMPASS: Large data set for the diffractive process
  $\pi^-_{\text{beam}} + \text{p} \to \pi^-\pi^+\pi^-_{\text{bachelor}} + \text{p}$
- Squared four-momentum transfer t' by Pomeron $\mathbb{P}$
- 46×10^6 exclusive events
- Rich structure in $\pi^-\pi^+\pi^-$ mass spectrum: Intermediate states X^-
- Also structure in $\pi^+\pi^-$ subsystem: Intermediate states ξ (isobar)





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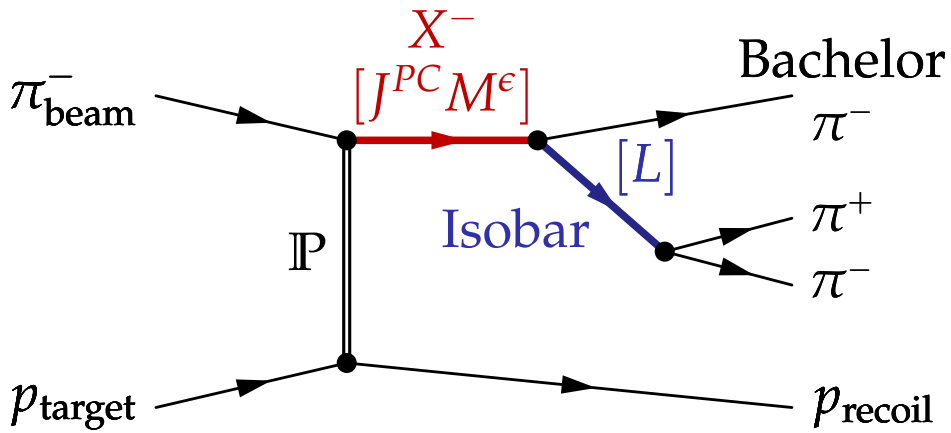
Partial-wave analysis

$$\mathcal{I}\left(\vec{\theta}\right) = \left| \sum_{i}^{\text{wave set}} \mathcal{T}_i \mathcal{A}_i\left(\vec{\theta}\right) \right|^2$$

Waves defined by:

$$i = J^{PC}_{X^-} M^{\varepsilon} \xi \pi L$$



- $J^{PC}_{X^-}$: Spin and eigenvalues under parity and charge conjugation of X^-
- M^{ε}: Spin projection on the beam and naturality of the exchange particle
- ξ: Appearing isobar, e.g. f_0, $\rho(770)$, $f_2(1270)$ with J^{PC}_{ξ}
- π: Indicating the bachelor π^-. Always the same
- L: Orbital angular momentum between isobar and bachelor pion

Sum over waves of a given wave set

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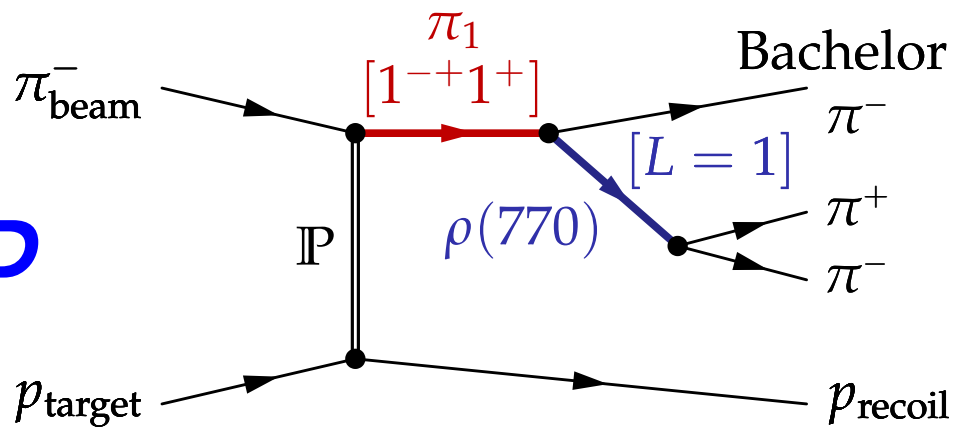

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Sum over waves of a given wave set

Spin-exotic wave
Previous results

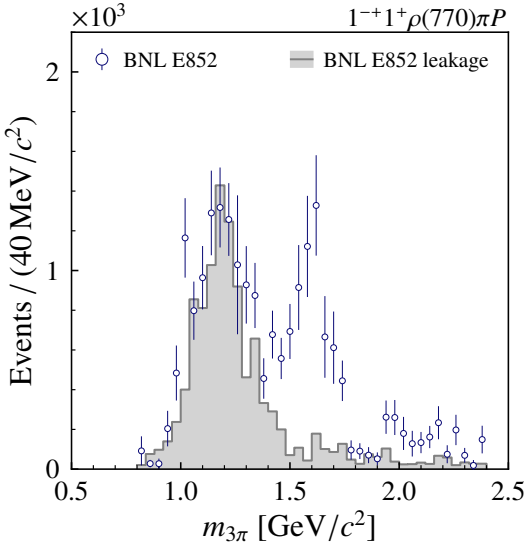


Fig 18(b) of *Phys. Rev. D* **65** (2002) 072001

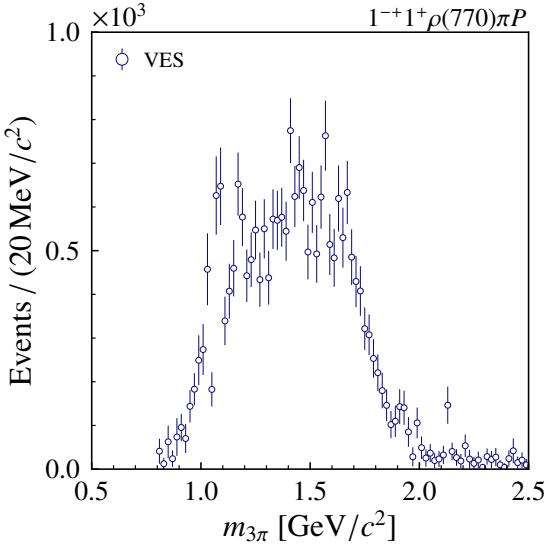
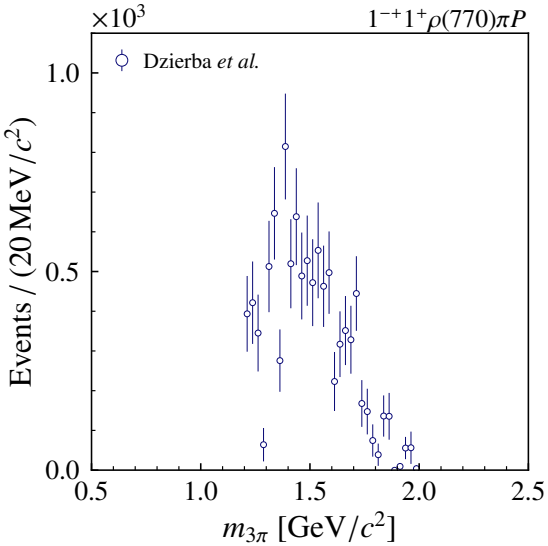


Fig. 4(a) in *Nucl. Phys.* **A675** (2000) 155-160



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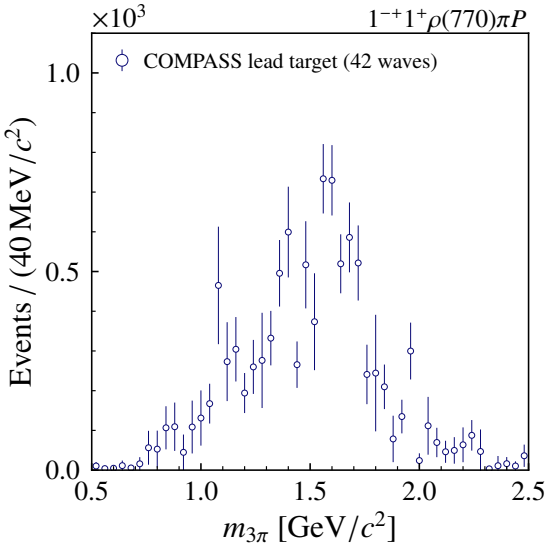
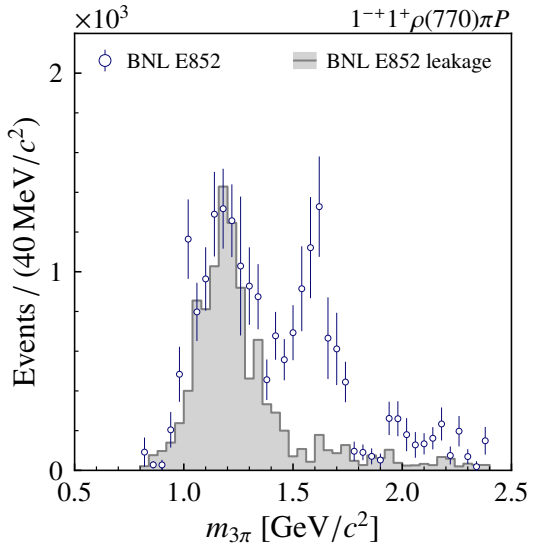


Fig. 2(d) in *Phys. Rev. Lett.* **104** (2010) 241803

Spin-exotic wave
BNL E852

- 1st analysis
  - 21 partial waves
  - t' dependence modeled
  - Peak at low masses: leakage
  - Narrow peak at 1.6 GeV/c^2: π_1 (1600)
- 2nd analysis
  - 36 partial waves
  - $t' \leq 0.53(\,\mathrm{GeV}/c)^2$, binned
  - "π_1 (1600)-peak" artifact from missing 2^{-+} waves
  - π_1 (1600) non-existent



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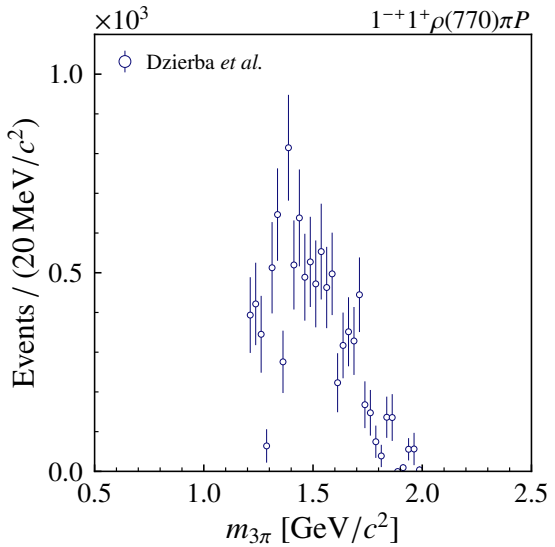

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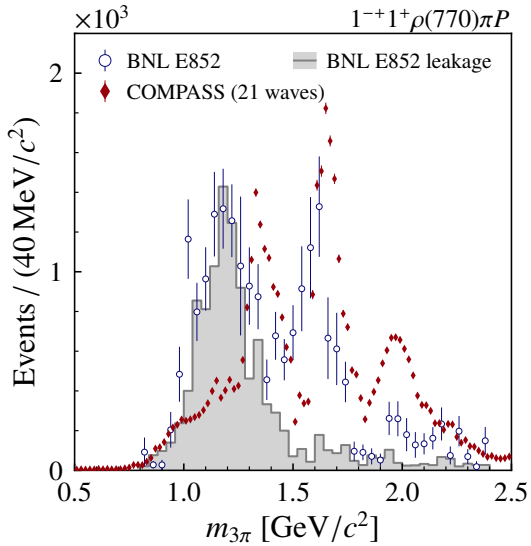
- Reproduced with COMPASS 2008

To be published



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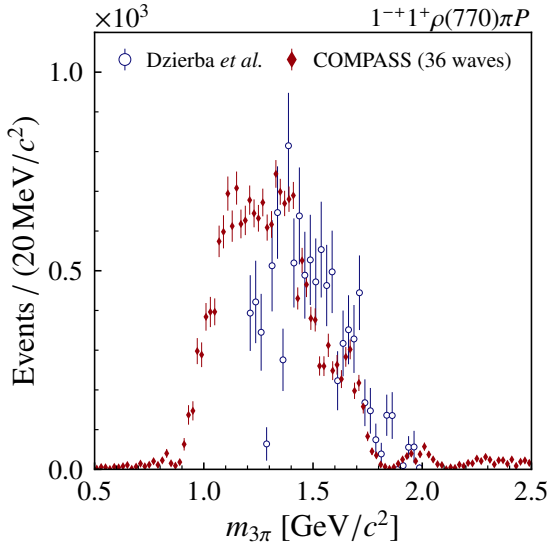

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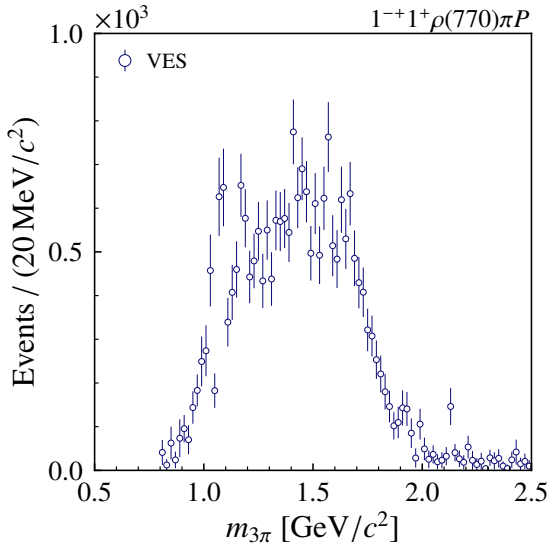
Spin-exotic wave
VES & COMPASS

- VES (beryllium target)
  - 44 partial waves
  - $0.03 < t' < 1.0 (\mathrm{GeV}/c)^2$
  - t' modeled
  - π_1 (1600) inconclusive
- COMPASS 2004 (lead target)
  - 42 partial waves
  - $0.1 < t' < 1.0 (\mathrm{GeV}/c)^2$
  - t' modeled
  - π_1 (1600) present



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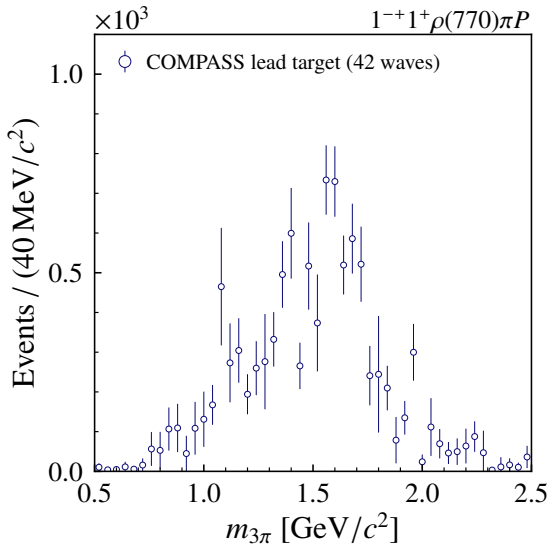

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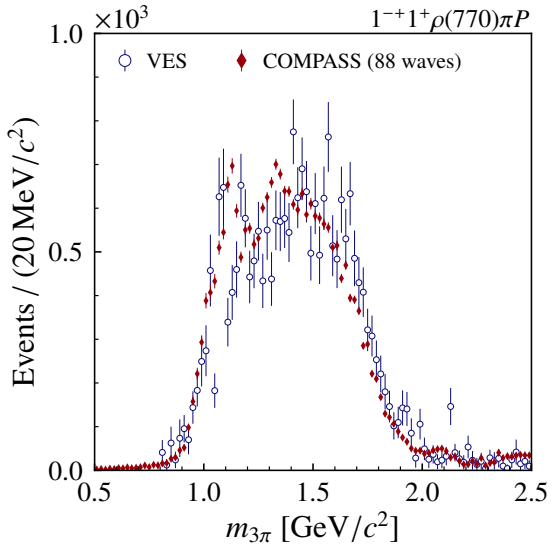
- COMPASS 2004 (lead target)
  - 42 partial waves
  - $0.1 < t' < 1.0 (\mathrm{GeV}/c)^2$
  - t' modeled
  - π_1 (1600) present
- Comparison with COMPASS 2008;
  - VES: similar to COMPASS 2008 t' summed
  - COMPASS 2004: similar to high t'



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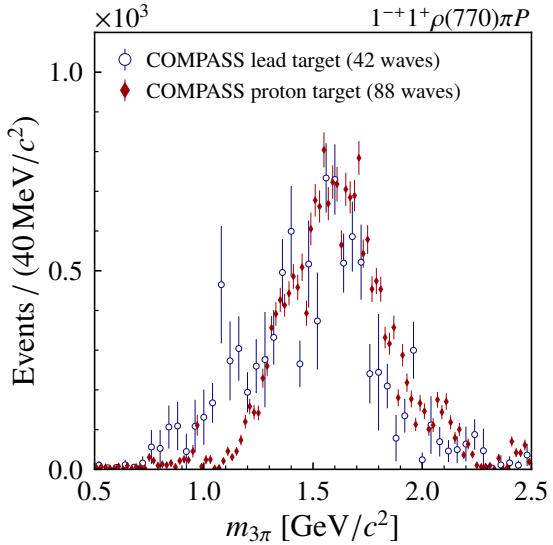

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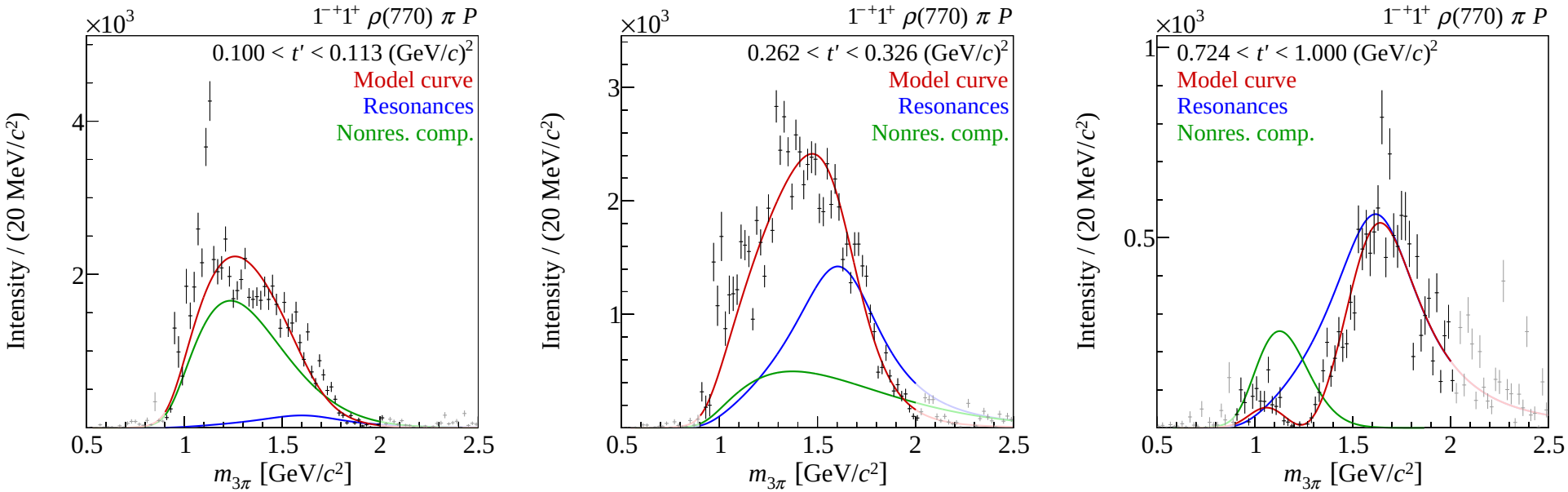
Spin-exotic wave
COMPASS analysis model

- Variation of spin-exotic signal due to:
  - Missing partial waves (e.g. $J^{PC} = 2^{-+}$)
  - Non-resonant contributions at low t'
- COMPASS 2008 data set: 46×10^6 exclusive event
  - Tackle these two effects
- Big PWA wave-set
  - 88 wave model
- t' dependence
  - 11 t' bins



COMPASS *Phys. Rev. D* **98** (2018) 9, 092003

- Resonance model fit to 14 partial waves simultaneously
- Extensive systematic studies

$$m_{\pi_1(1600)} = 1600^{+110}_{-60}(\text{sys.})\,\text{MeV}/c^2; \quad \Gamma_{\pi_1(1600)} = 580^{+100}_{-230}(\text{sys.})\,\text{MeV}/c^2$$

Spin-exotic wave
Origin of discrepancies

BNL E852 1st

- Narrow signal
- Small wave-set
- Missing $J^{PC}_{X^-} = 2^{-+}$ waves
- Leakage from π_2

BNL E852 2nd

- Broad structure
- $t' \leq 0.53(\,\mathrm{GeV}/c)^2$
- $\pi_1\,(1600)$ obscured by non-resonant

VES

- Broad structure
- No t' binning
- $\pi_1\,(1600)$ obscured by non-resonant

COMPASS 2004

- $\pi_1\,(1600)$ visible
- whole t' range
- Lead target: $M = 1$ enhanced?
- Non-resonant contributions suppressed

BNL E852 1st

- Narrow signal
- Small wave-set
- Missing $J^{PC}_{X^-} = 1^{-+}$ wave
- Leakage from π_2

BNL E852 2nd

- Broad structure
- $t' < 0.53(\,\mathrm{GeV}/c)^2$
- π_1 (1600) obscured by non-resonant

RESOLVED

VES

- Broad structure
- No t' binning
- π_1 (1600) obscured by non-resonant

COMPASS 2004

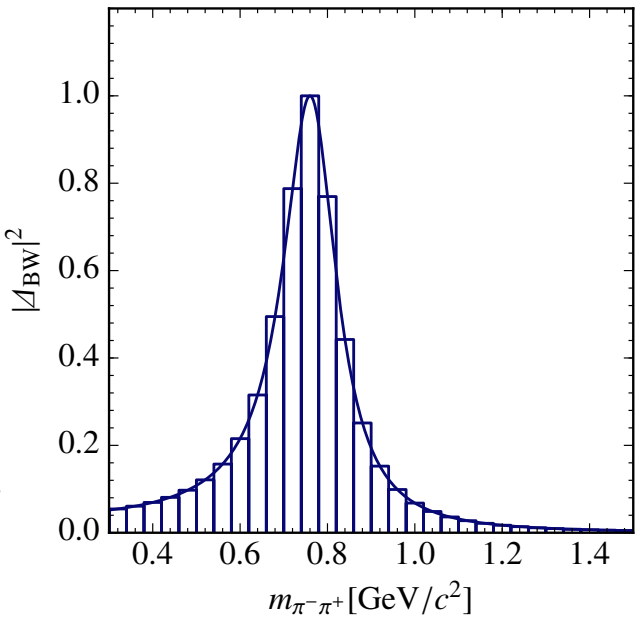
- π_1 (1600) visible
- whole t' range
- Lead target: $M = 1$ enhanced?
- Non-resonant contributions suppressed

Spin-exotic wave
Remaining model dependence?

- COMPASS model: largest remaining model dependence:
  - Fixed parameterization of isobars
- However: $1^{-+}1^{+}\rho(770)\,\pi P$ still modeled
  - Fixed shape of $\rho(770)$ as model assumption
  - Breit-Wigner amplitude, no free parameters
- Use freed-isobar approach
  - Replace fixed shape by step-like functions

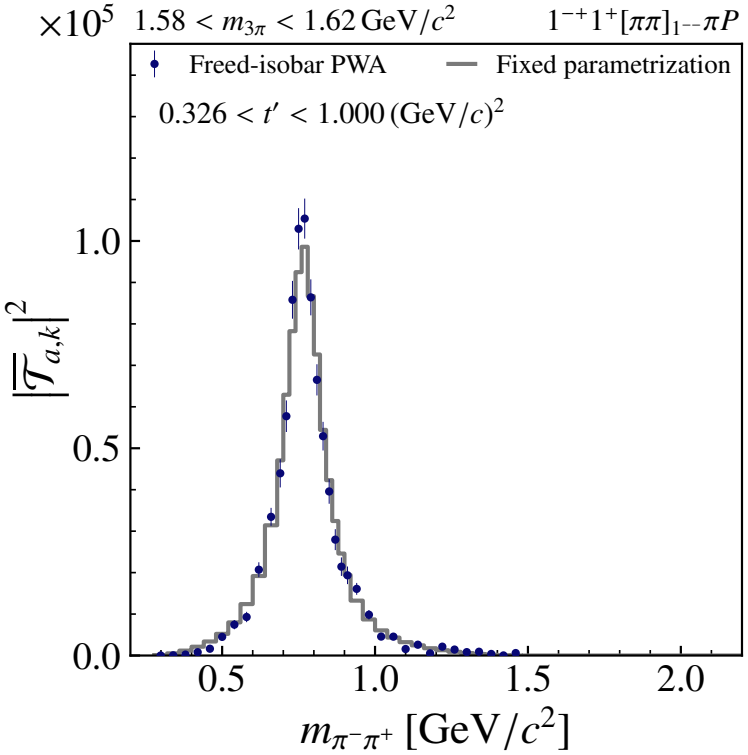
$$\Delta_i^{\text{bin}}(m_{\pi^-\pi^+}) = \begin{cases} 1, & \text{if } m_{\pi^-\pi^+} \text{ in the bin.} \\ 0, & \text{otherwise.} \end{cases}$$

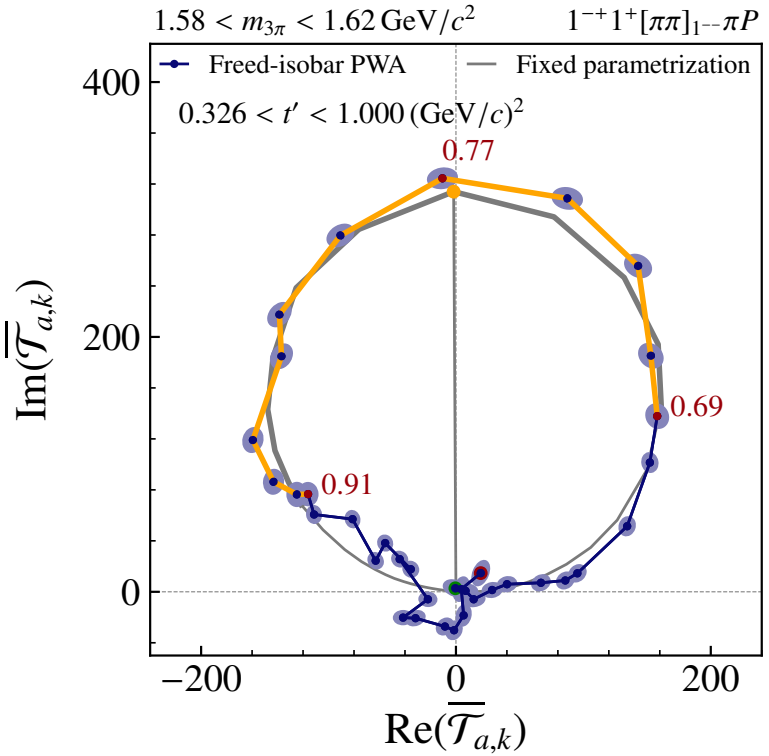
  - Cover kinematically allowed range
  - Every step: individual partial wave
  - Extract $\rho(770)$ shape from the data



Freed-isobar approach

Results

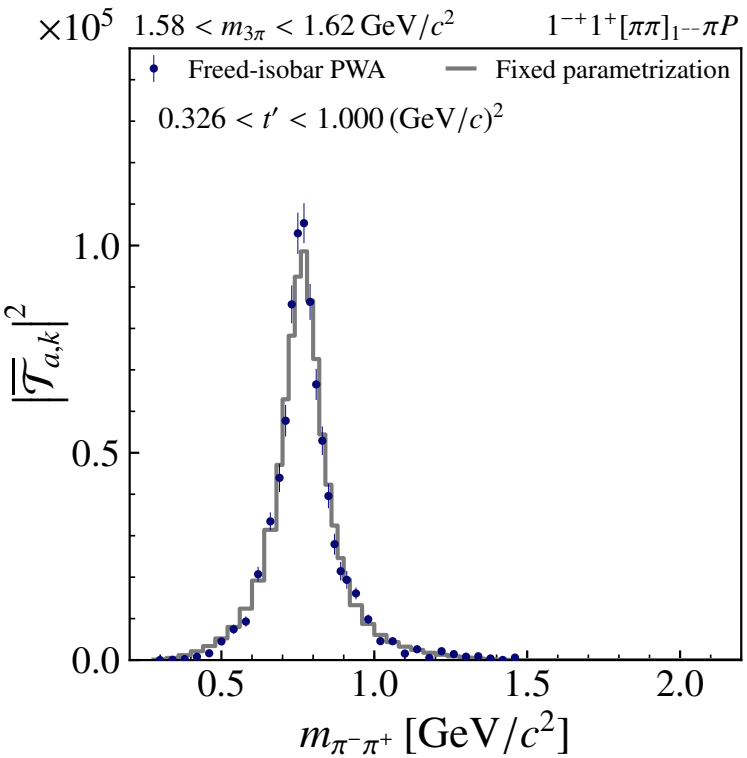


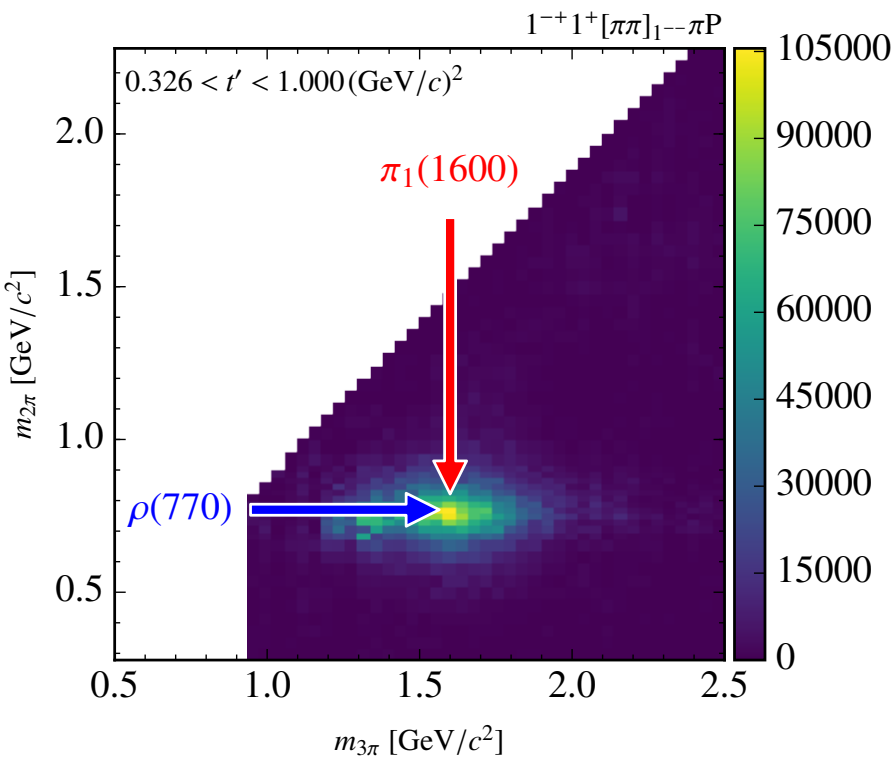


On top of the π_1 (1600) resonance

Freed-isobar approach

Results

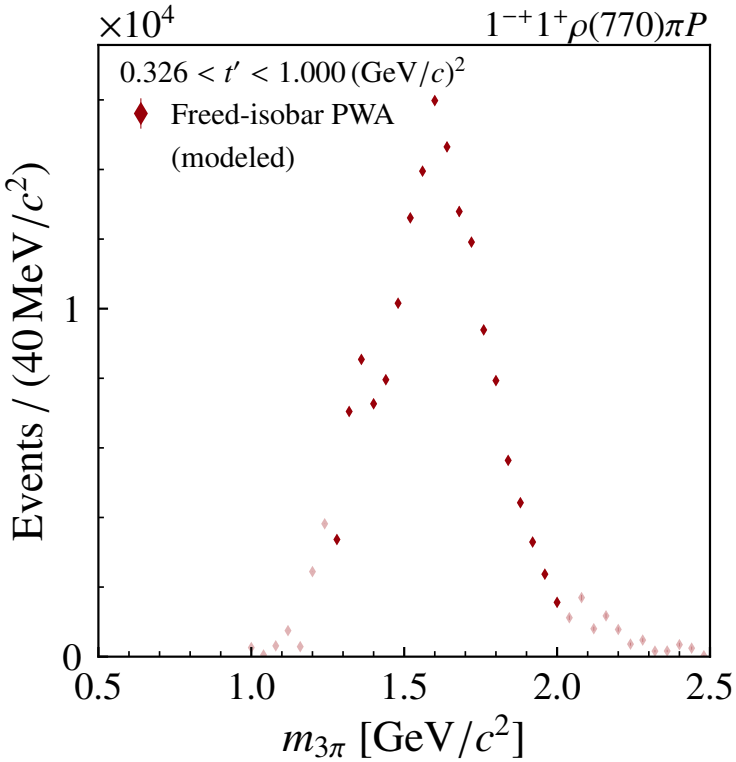




Clear $\pi_1(1600) \to \rho(770)\,\pi$ without assumptions on resonance content

Freed-isobar approach

Resonance model fit



Freed-isobar approach

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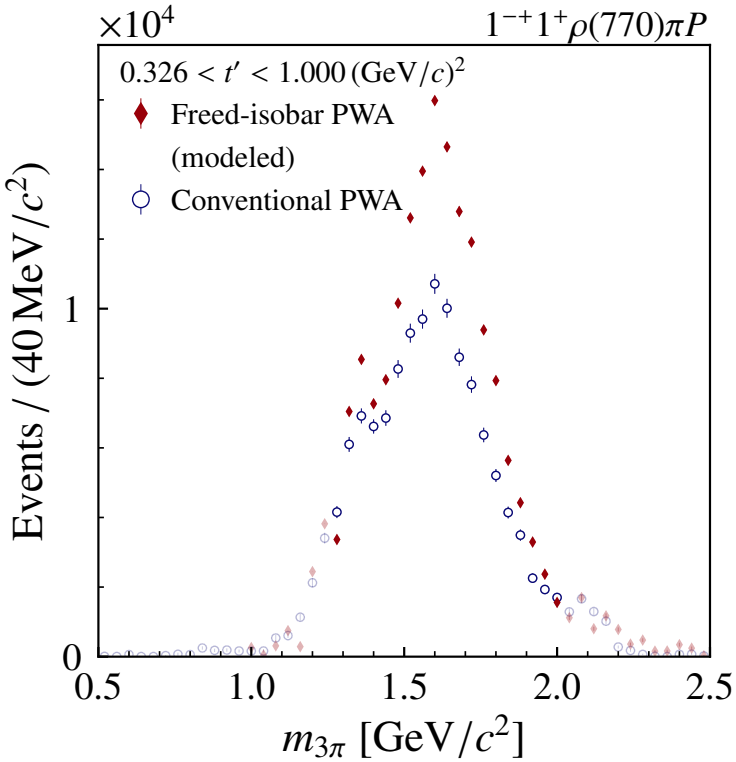

Freed-isobar approach

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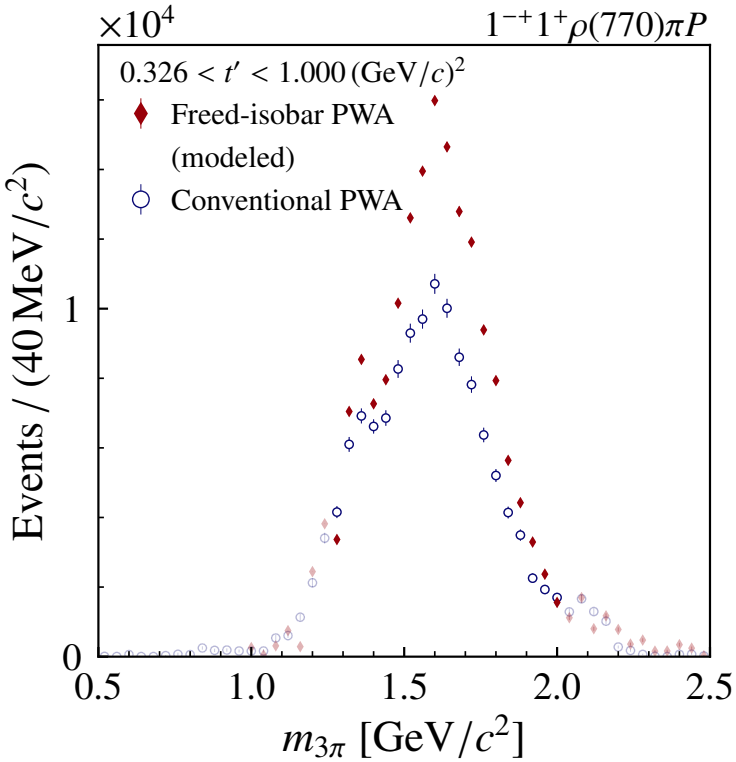

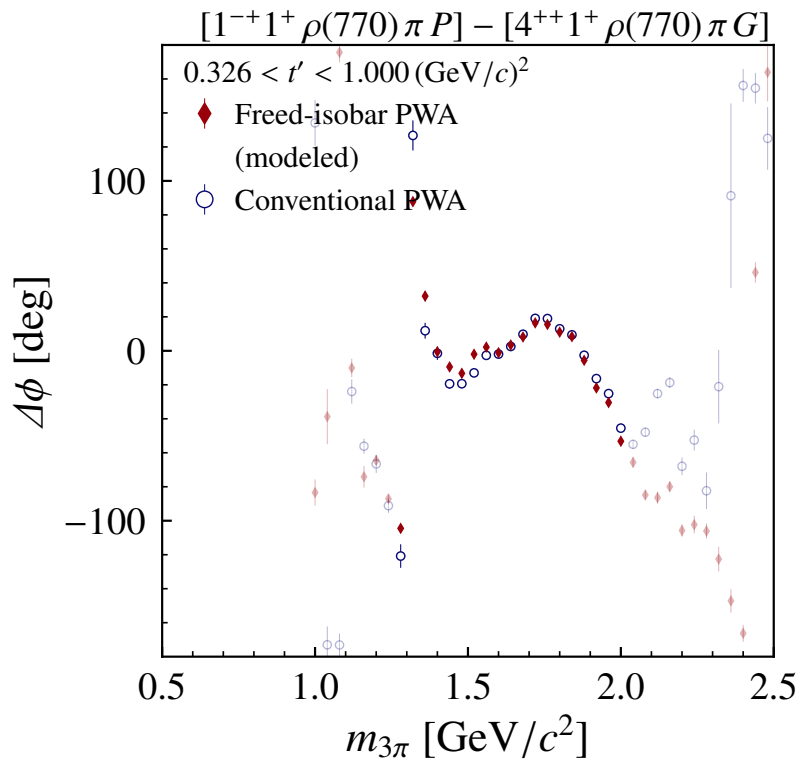

Freed-isobar approach

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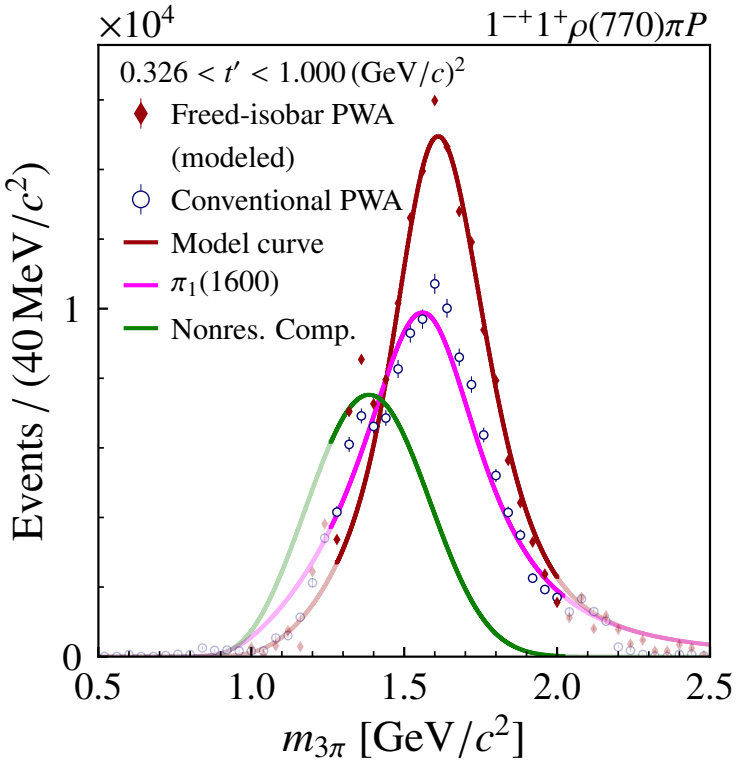

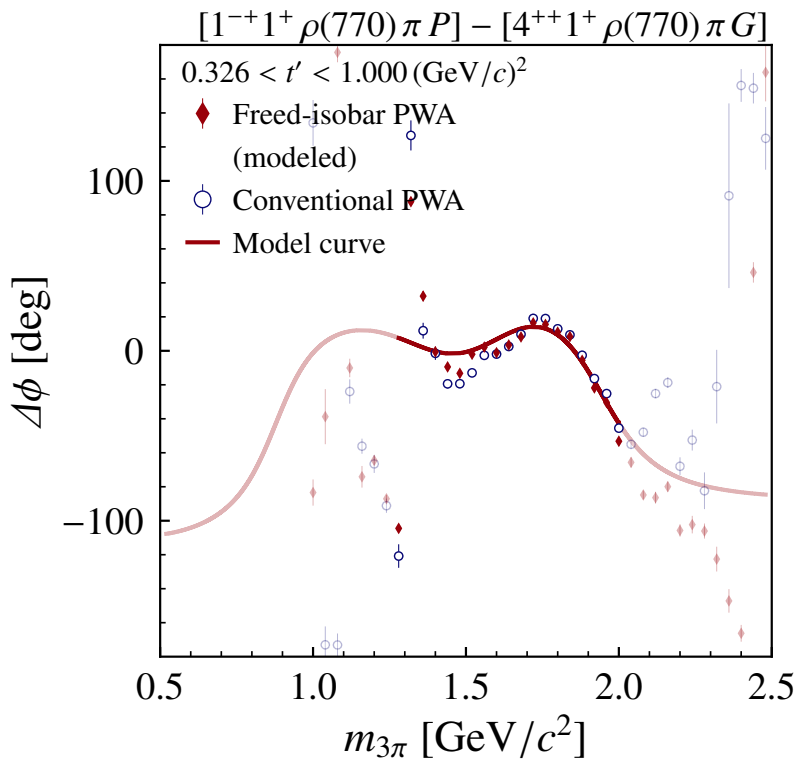

Summary & conclusions

π_1 (1600)

- Spin-exotic quantum numbers
- Not a $q\bar{q}$-state

$1^{-+}1^{+}\rho(770)\,\pi P$ wave

- Various, seemingly contradicting results
- Large model dependence:
  - Partial-wave set
  - Treatment of t' dependence
- Resolved using COMPASS 2008 data

COMPASS

- Freed-isobar approach:
  - Isobar model valid
- π_1 (1600) not an artifact
- Convincing evidence for π_1 (1600) $\rightarrow \rho(770) + \pi$

Outlook

- Further π_1 (1600) decay channels

$$\eta^{(\prime)}\pi; \quad b_1\pi; \quad f_1\pi$$