Light-Meson Spectroscopy at COMPASS

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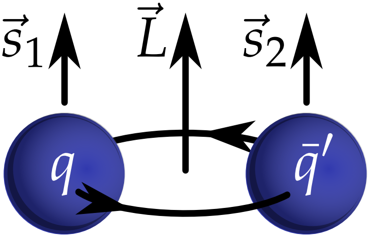
for the COMPASS Collaboration

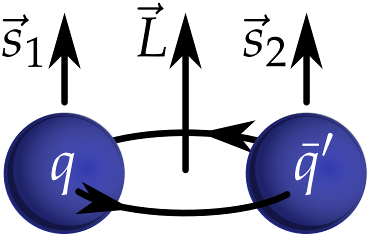
Institute for Hadronic Structure and Fundamental Symmetries - Technical University of Munich

March 3, 2020
Arbeitsgruppentreffen Schleching



Constituent quark model

- States of u, d, and s (anti)quarks
- Total spin $\vec{J} = \vec{S} + \vec{L}$
- Parity $P = (-1)^{L+1}$
- Charge conjugation $C = (-1)^{L+S}$
- Certain J^{PC} combinations not possible
  - $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$



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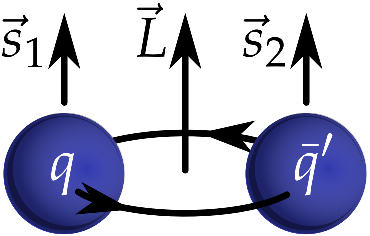

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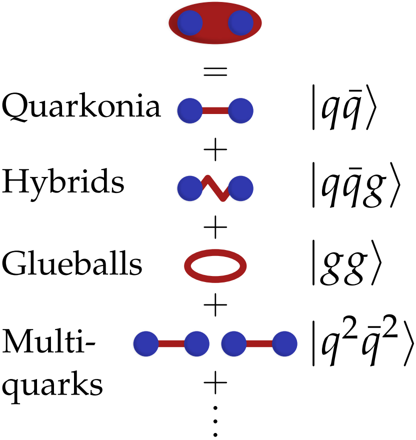
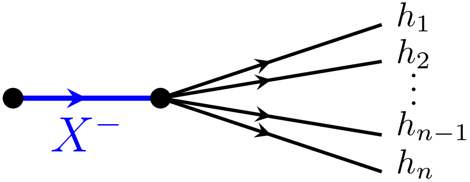
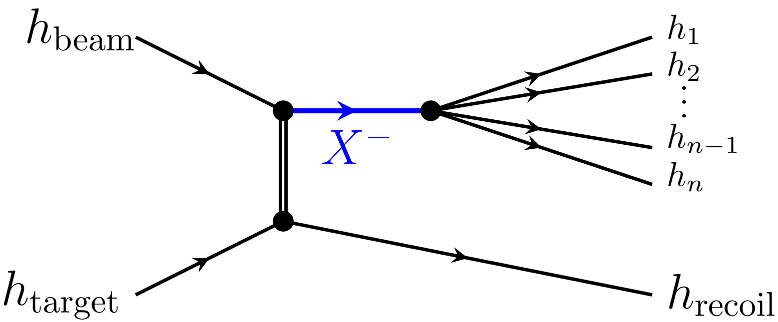


QCD permits additional color-neutral configurations

- Physical mesons: linear superpositions of all allowed basis states with same J^{PC}
- Spin-exotic mesons: No pure $q\bar{q}$



- Excited mesons appear as intermediate states
- Various final states:
  - $\pi^-\pi^-\pi^+$
  - $\eta\pi$, $\eta'\pi$
  - ...
- Diffractive production in high-energy scattering



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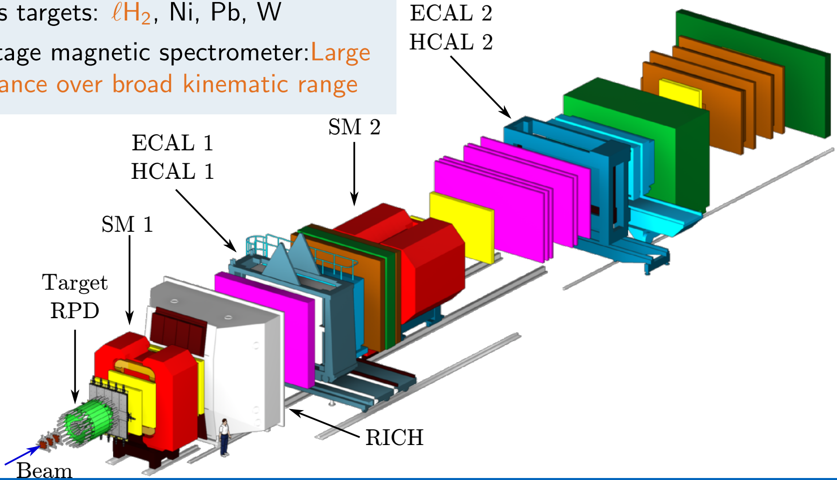
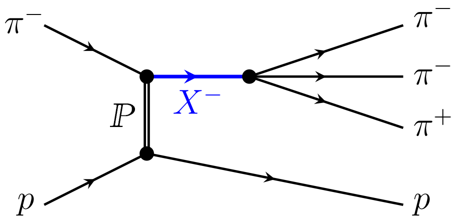
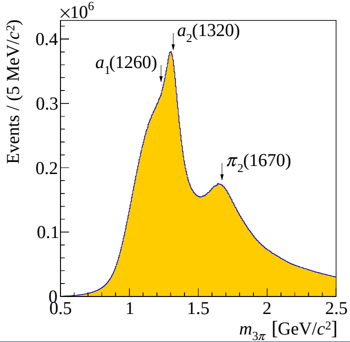
- Located at CERN (SPS)
- 190 GeV/c secondary h^- beams:
  - 97 % π^-, 2 % K^-, 1 % $\bar{p}$
- Various targets: ℓH_2, Ni, Pb, W
- Two-stage magnetic spectrometer:Large acceptance over broad kinematic range



[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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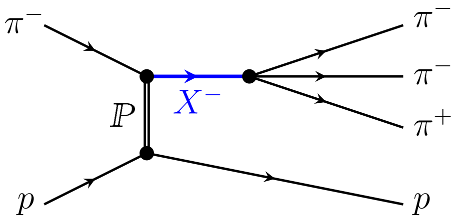

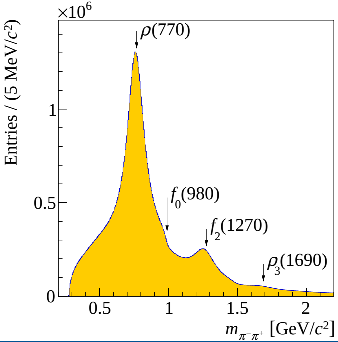

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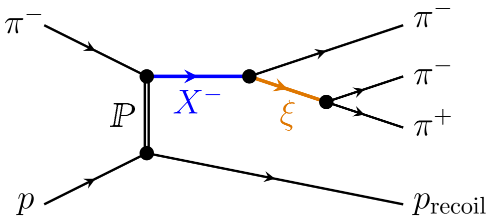

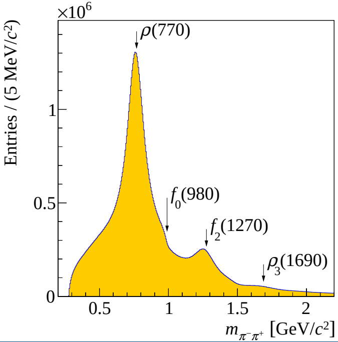

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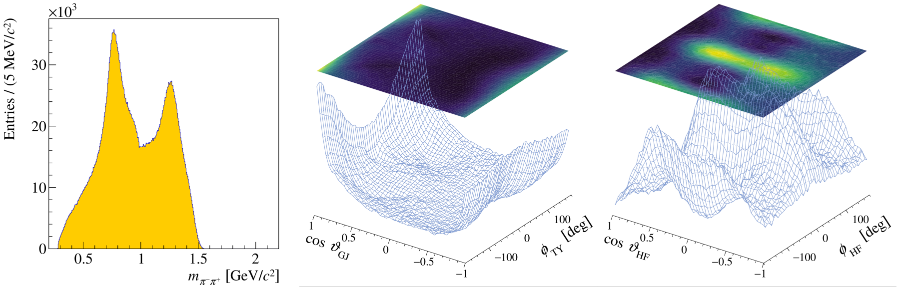
$$1640 < m_{3\pi} < 1680\,\text{MeV}/c^2$$



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Partial-Wave Analysis

Motivation

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Partial-Wave Analysis

Isobar Model

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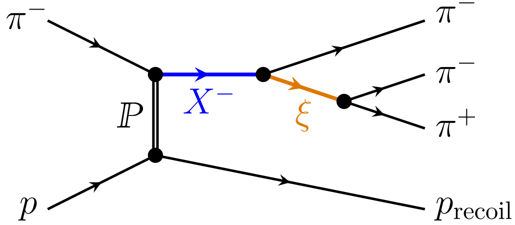

- Partial wave $a = J^{PC} M^{\varepsilon} \xi \pi L$ at fixed mass $m_{3\pi}$
  - ➥ Calculate 5D decay phase-space distribution of final-state particles
- $\psi_a(\tau)$ describes distribution of wave a in decay phase-space variables τ
- Total intensity distribution: Coherent sum of partial-wave amplitudes

$$\mathcal{I}(\tau) = \left| \sum_{a}^{\text{waves}} \mathcal{T}_a \, \psi_a(\tau) \right|^2$$

- Perform maximum-likelihood fit in cells of $m_{3\pi}$ and t'
  - ➥ Decompose data into partial waves
  - ➥ Extract $m_{3\pi}$ and t' dependence of partial-wave amplitudes

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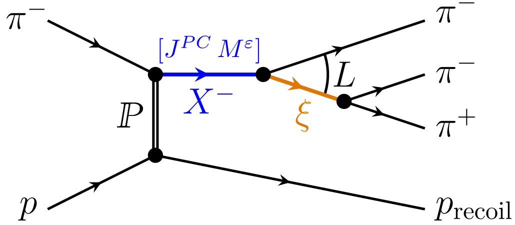

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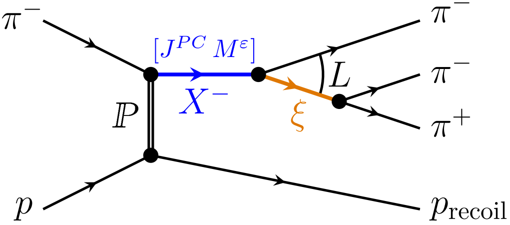

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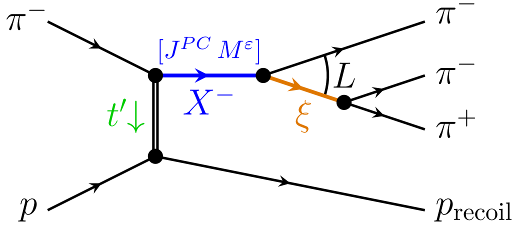

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Data

(I) Partial-Wave Decomposition

Partial Waves

Intensities and relative phases of the partial waves

Resonance Parameters

Masses and widths of the meson resonances

Data

(I) Partial-Wave Decomposition

Partial Waves

Intensities and relative phases of the partial waves

(II) Resonance-Model Fit

Resonance Parameters

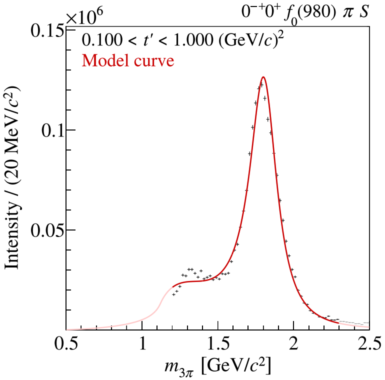
Masses and widths of the meson resonances

Modeling $m_{3\pi}$ dependence

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

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

- Resonances: Breit-Wigner amplitude
- Non-resonant terms: Phenomenological parameterization



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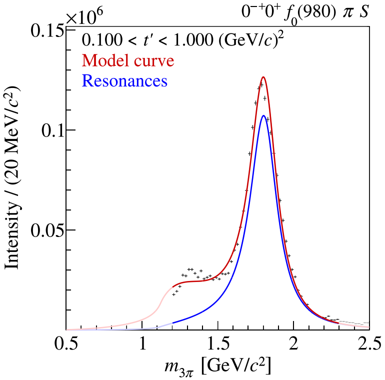

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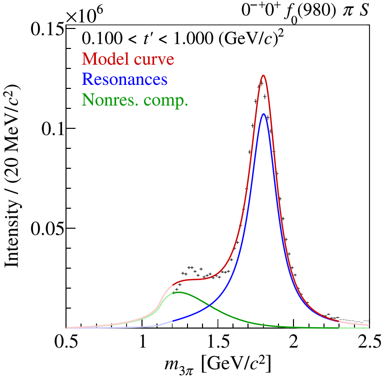
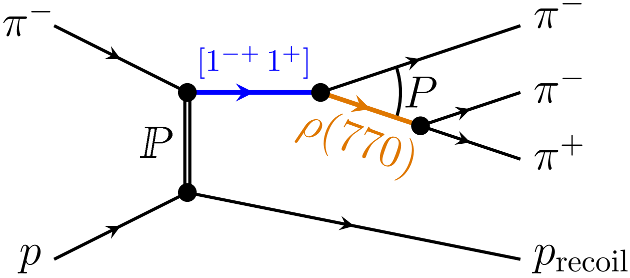
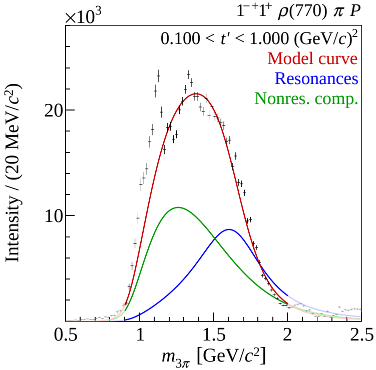


$J^{PC} = 1^{-+}$ State

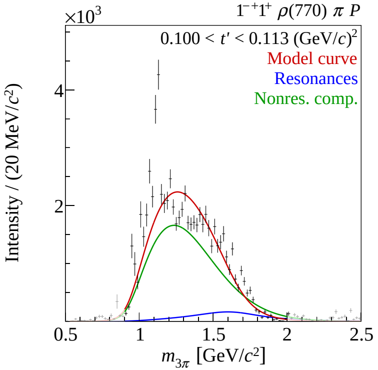


- 1^{-+}: spin-exotic π_1-like quantum numbers
  - Forbidden quantum numbers for $q\bar{q}$ system (non-rel.)
  - Lattice-QCD: lightest hybrid predicted with 1^{-+} quantum numbers



$\pi_1(1600)$

- Large non-resonant contribution in spin-exotic 1^{-+} wave, but ...
- Strong modulation with t' is exploited in t'-resolved analysis
- No description of data at high t' without Breit-Wigner component



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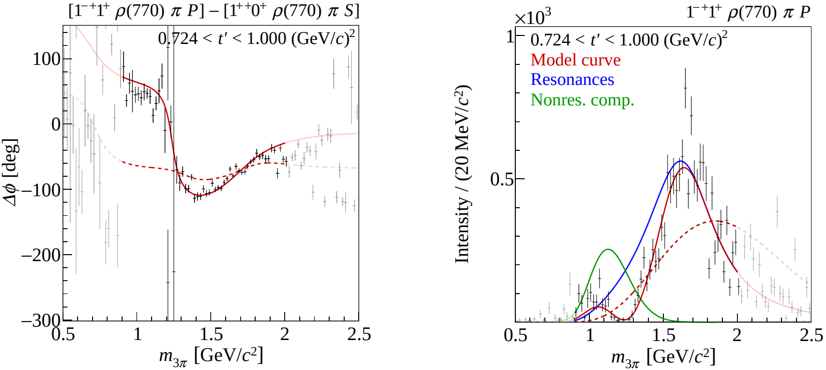
Resonance-Model Fit

[Aghasyan *et al.* PRD 98 (2018) 092003]



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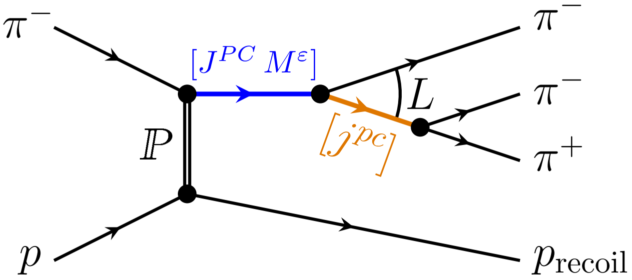
Freed-Isobar Analysis



- 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

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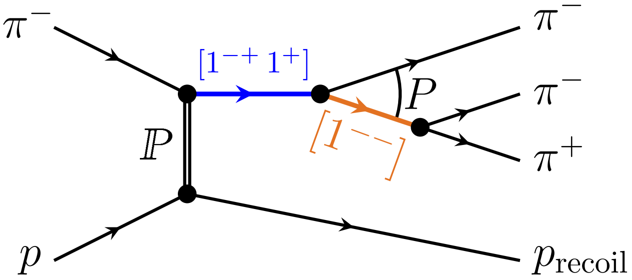

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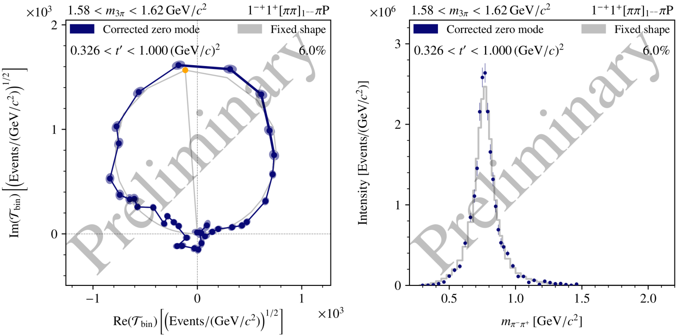
$1580 < m_{3\pi} < 1620\,\text{MeV}$



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

Freed-Isobar Analysis

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

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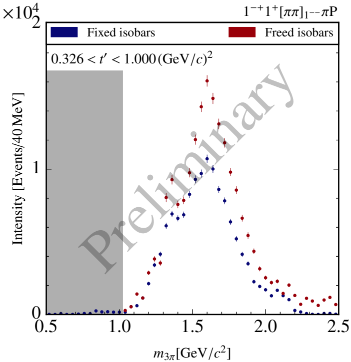

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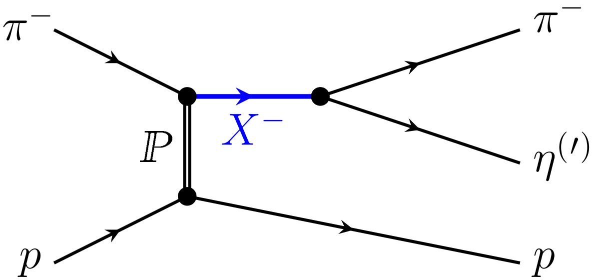
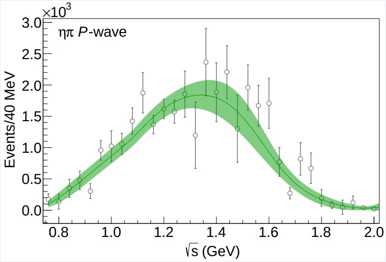
JPAC Coupled-Channel Analysis of $\eta\,\pi$ and $\eta'\pi$



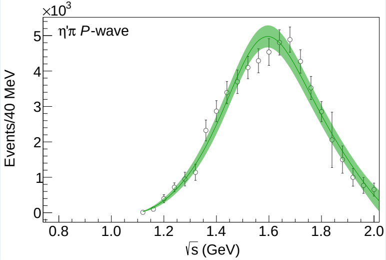
- Golden channels for spin-exotic states
- Partial-wave amplitudes from COMPASS [PLB 740 (2015) 303]
- Analytic and unitary coupled-channel model based on S-matrix principles
  - Resonances are poles in the amplitude

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

$\eta\pi$



$\eta'\pi$



- Data requires single pole in amplitude of 1^{-+} waves
- Consistent with Breit-Wigner mass and width from $\pi^-\pi^-\pi^+$

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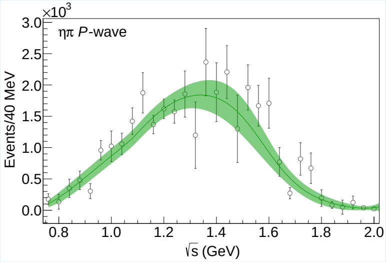

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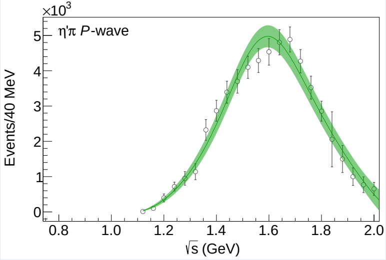

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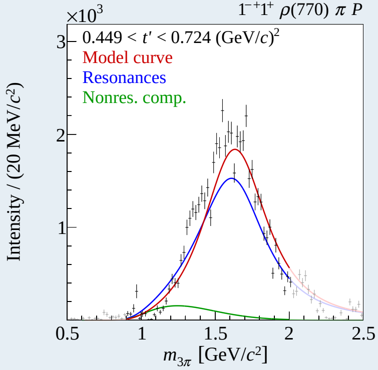
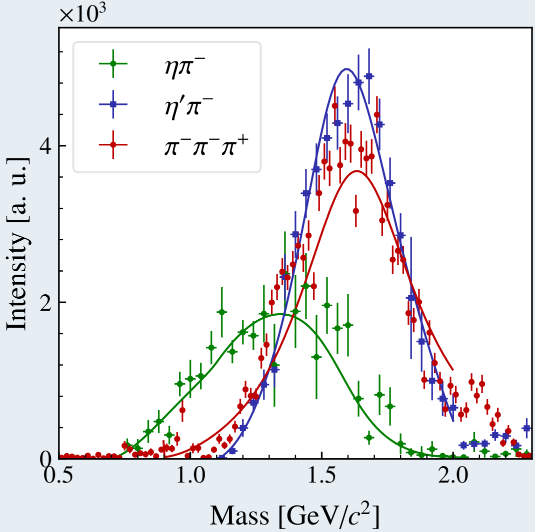


Summary: Studies of Spin-Exotics at COMPASS

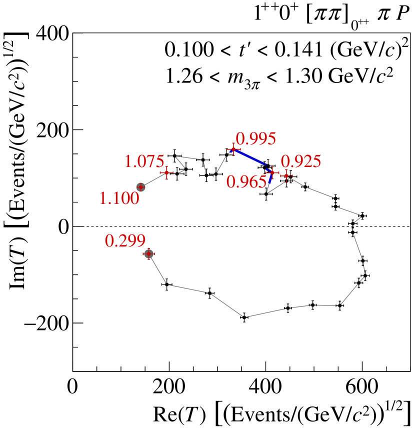
Intensity of $J^{PC} = 1^{-+}$ Wave in $\eta^{(\prime)}\pi$ and $\pi\pi\pi$

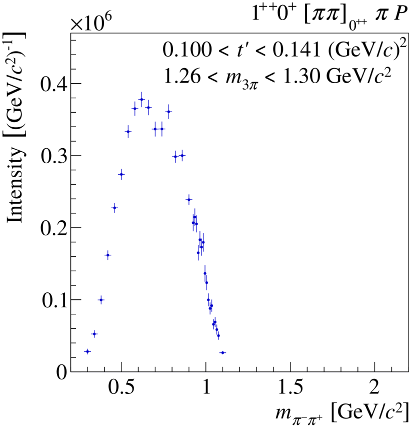


[Courtesy B. Grube]

Freed-Isobar Analysis: Study $\pi\pi$ in 3−Body Environment

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





$[\pi\pi]_S$ Wave from $J^{PC} = 1^{++}$ and $J^{PC} = 0^{-+}$

- Study $\pi^-\pi^+$ system with $j^{pc} = 0^{++}$
  - At different $m_{3\pi}$
  - For different J^{PC} of the $\pi^-\pi^-\pi^+$ system

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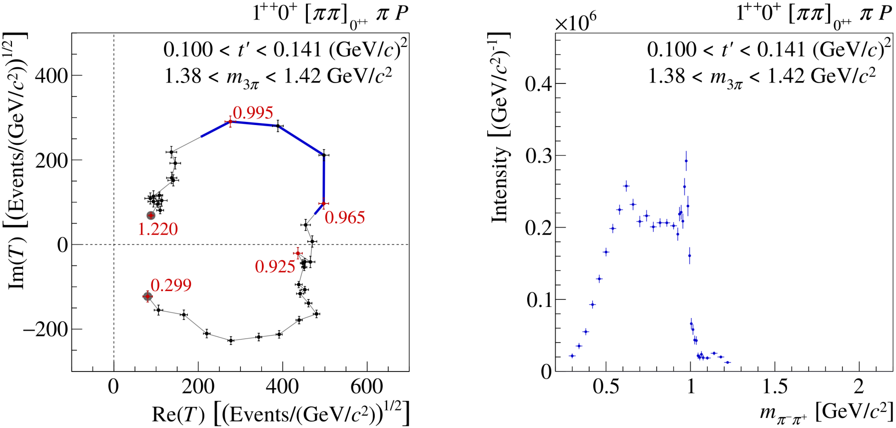

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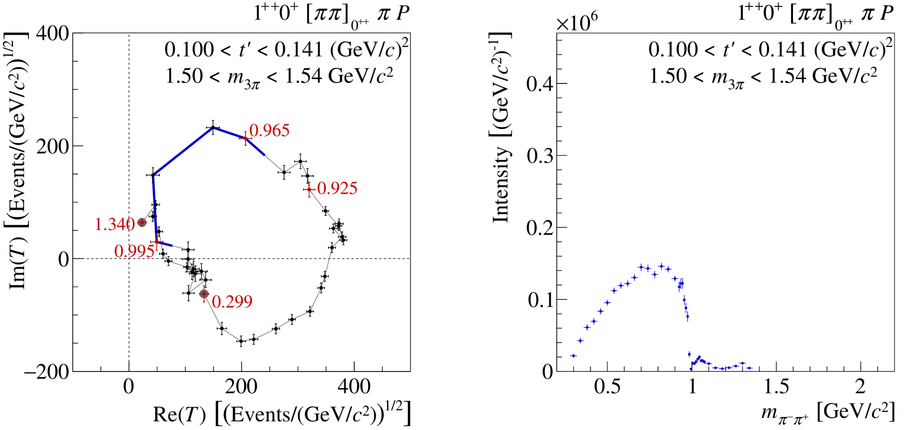

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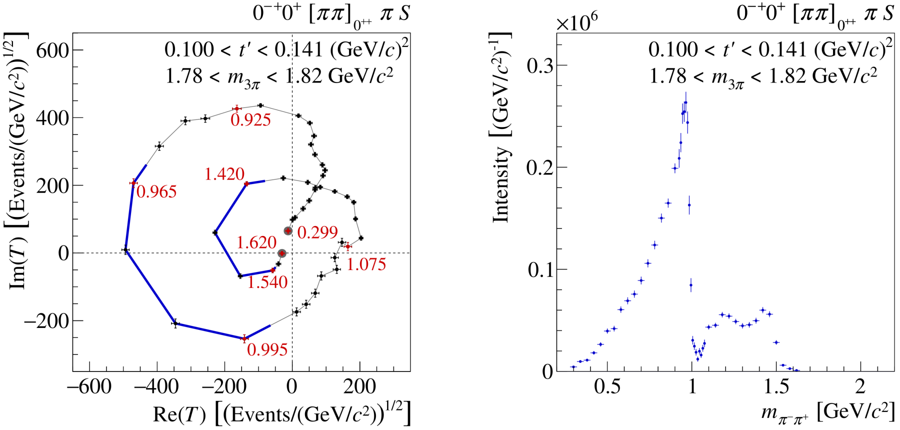
- Study $\pi^-\pi^+$ system with $j^{pc} = 0^{++}$
  - At different $m_{3\pi}$
  - For different J^{PC} of the $\pi^-\pi^-\pi^+$ system

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



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Backup

Outline