

Light-Quark Resonances at COMPASS

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for the COMPASS Collaboration

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

August 3, 2018
XIIIth Quark Confinement and the Hadron Spectrum

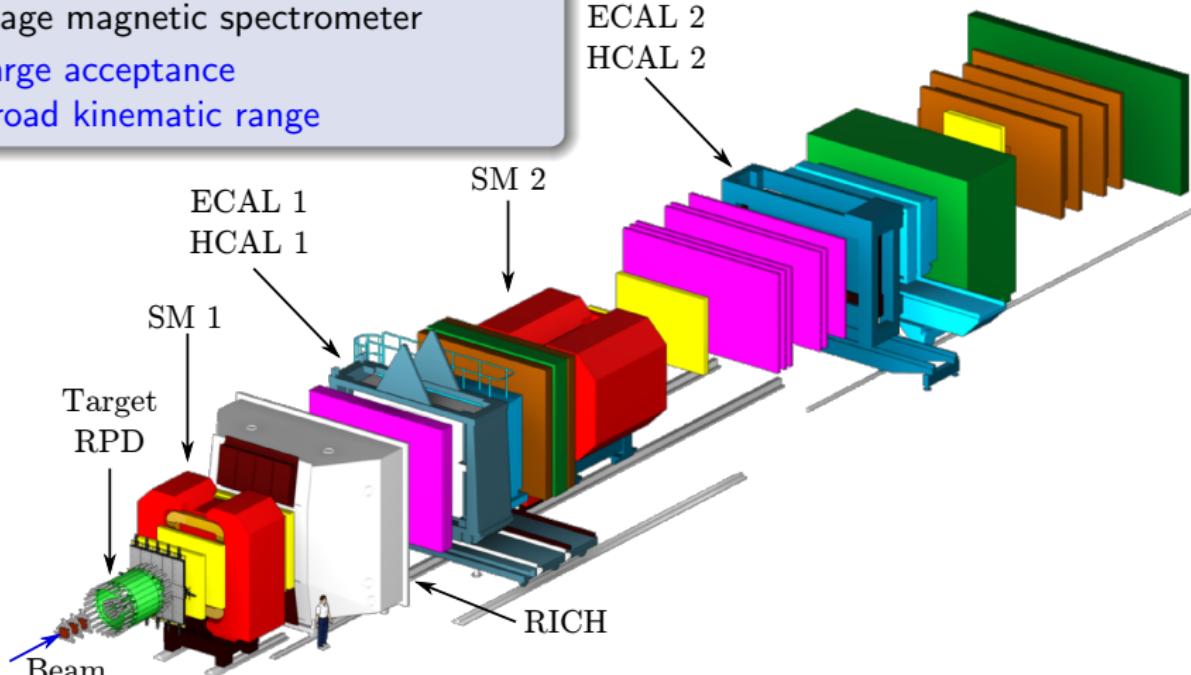


Introduction

COMPASS Setup for Hadron beams

[NIMA 779 (2015) 69]

- ▶ Located at CERN (SPS)
- ▶ $190 \text{ GeV}/c$ secondary π^- beam
- ▶ Various targets: ℓH_2 , Ni, Pb, W
- ▶ Two-stage magnetic spectrometer
 - ▶ Large acceptance
 - ▶ Broad kinematic range

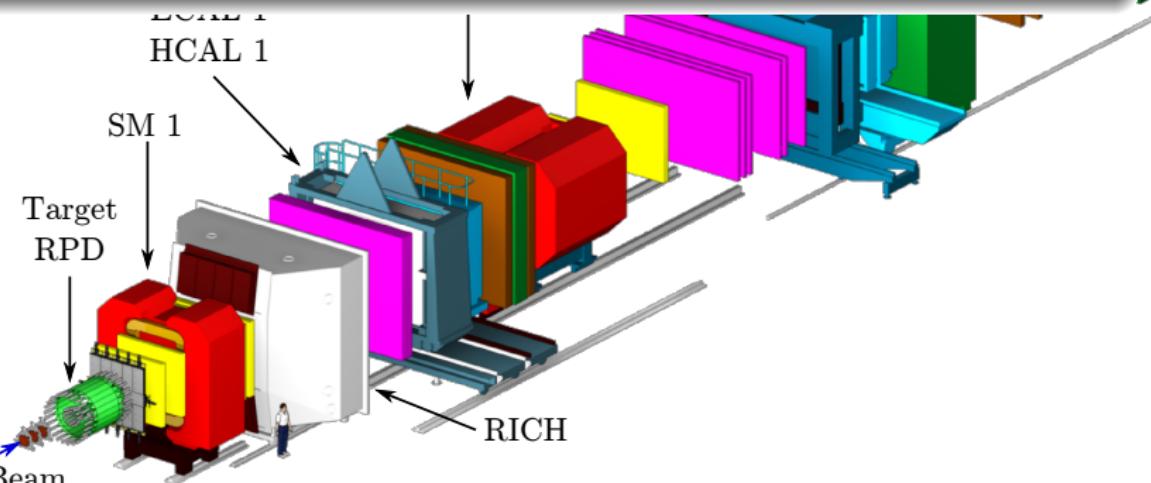


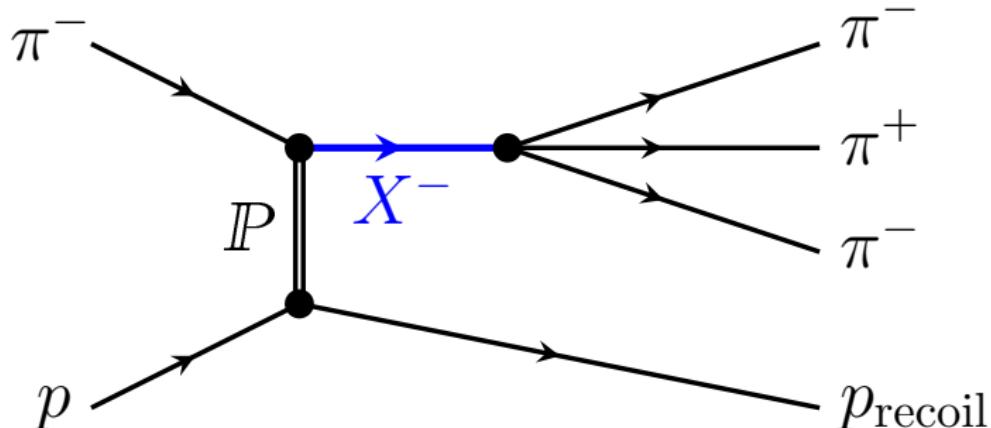
Introduction

COMPASS Setup for Hadron beams

[NIMA 779 (2015) 69]

- ▶ Explore light-meson spectrum for $m \lesssim 2 \text{ GeV}/c^2$
- ▶ High-precision measurement of known states
- ▶ Search for new forms of matter:
 - ▶ Multi-quark states
 - ▶ Hybrids
 - ▶ Glueballs
 - ▶ ...



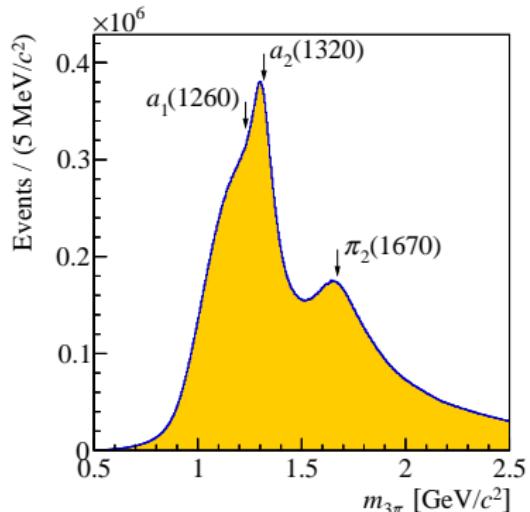
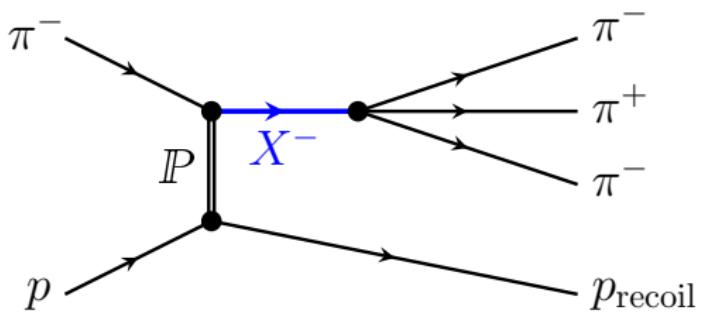


- ▶ Various production processes: **diffractive production** in πp scattering
- ▶ Light mesons appear as intermediate states
- ▶ Observed in decays into quasi-stable particles: $\pi^-\pi^-\pi^+$ final state

Partial-Wave Decomposition

Motivation

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

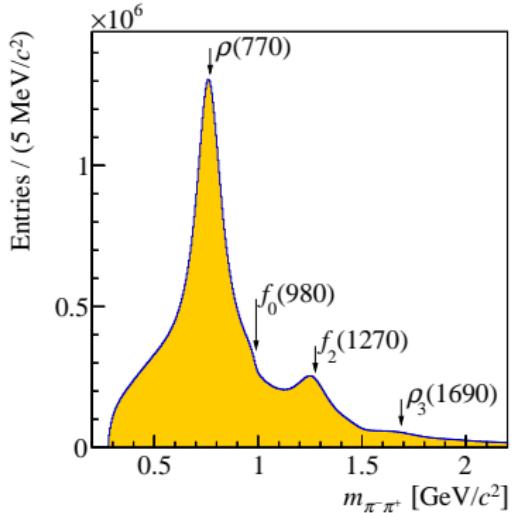
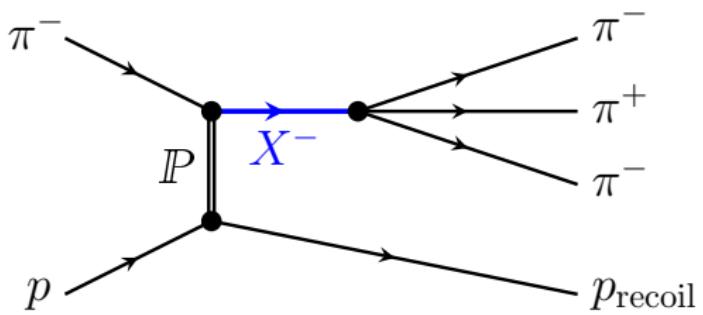


- ▶ Rich spectrum of overlapping and interfering X^-
 - ▶ Dominant well known states
 - ▶ States with lower intensity are “hidden”
- ▶ Also structure in $\pi^-\pi^+$ subsystem
 - ▶ Successive 2-body decay via $\pi^-\pi^+$ resonance called

Partial-Wave Decomposition

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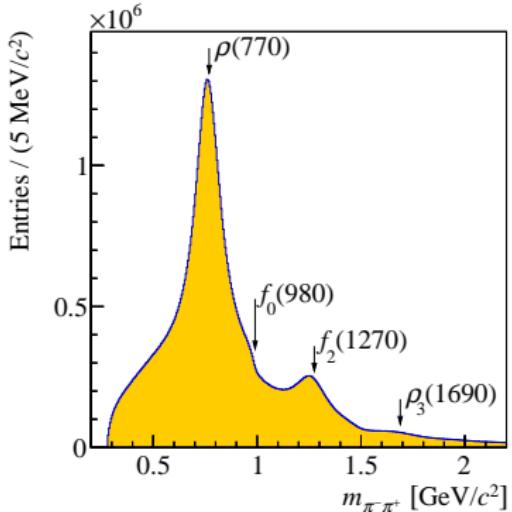
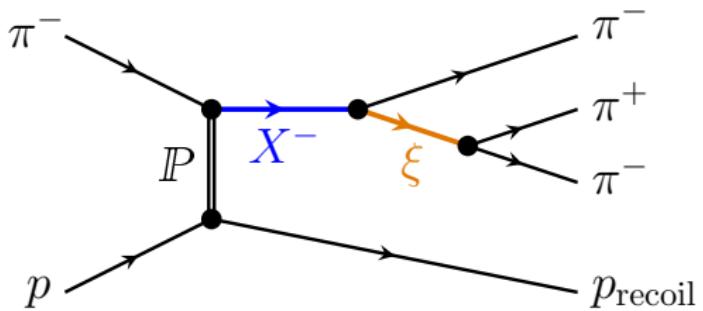


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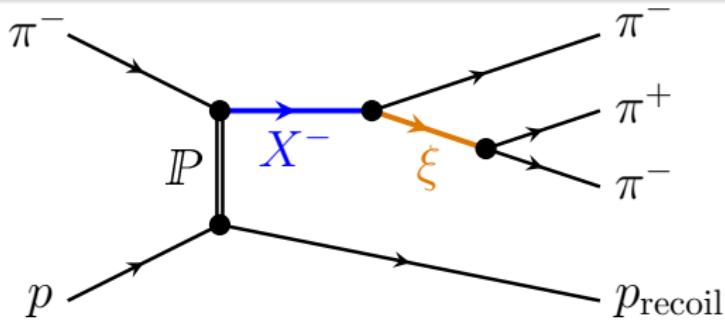
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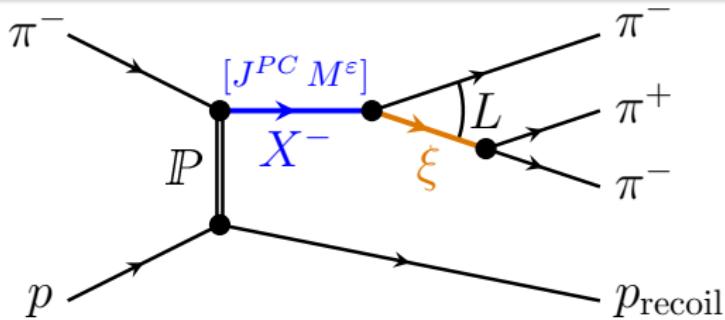
Isobar Model



- Given partial wave $i = J^P C M^P \xi \pi L$ at a fixed invariant mass of 3π system ($m_{3\pi}$)
 - Calculate 5D decay phase-space distribution of final state
- $\psi(\tau)$ describes distribution of wave i in decay phase-space variables τ

Partial-Wave Decomposition

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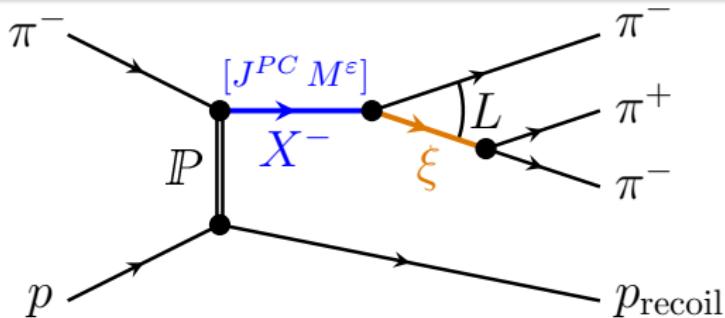


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 - ↳ Total intensity distribution contains contribution of various partial waves
 - ↳ Perform maximum-likelihood fit in bins of $m_{3\pi}$
 - ↳ Decompose data into partial waves
 - ↳ Extract $m_{3\pi}$ dependence of partial-wave amplitudes

$$\mathcal{I}(\tau) = \left| \sum_i T_i \psi_i(\tau) \right|^2$$

Partial-Wave Decomposition

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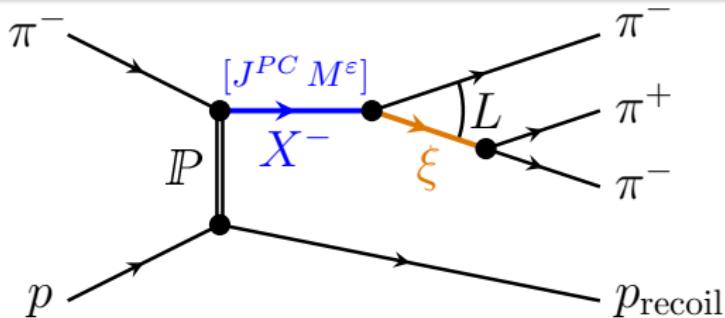
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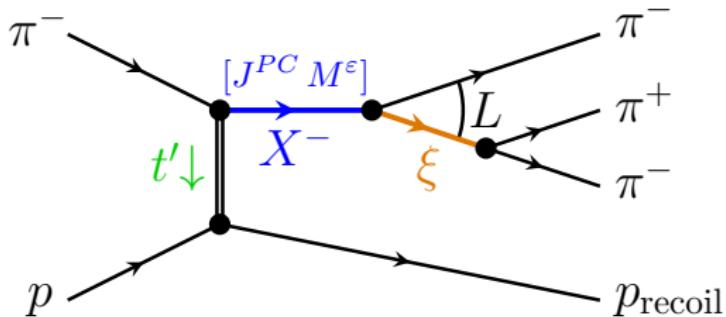


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Partial-Wave Decomposition

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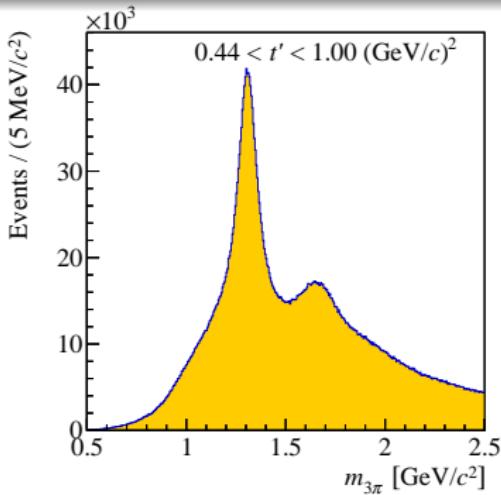
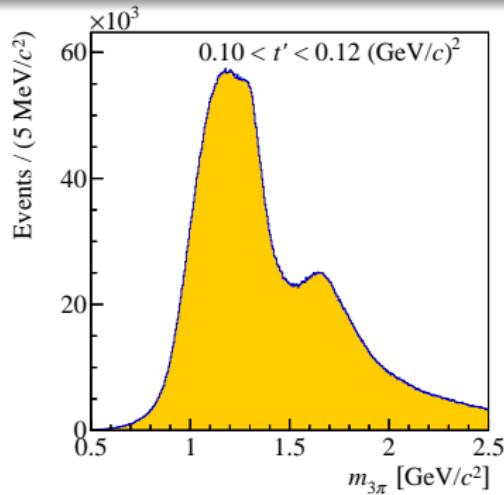
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- ▶ Production also depends on t'
- ▶ Large data set ($\approx 50 \text{ M}$ exclusive events)
 - ▶ Perform PWA also in narrow bins of t' (t' -resolved analysis)
 - ▶ Extract m_{X^-} And t' dependence of partial-wave amplitudes

Partial-Wave Decomposition

Isobar Model

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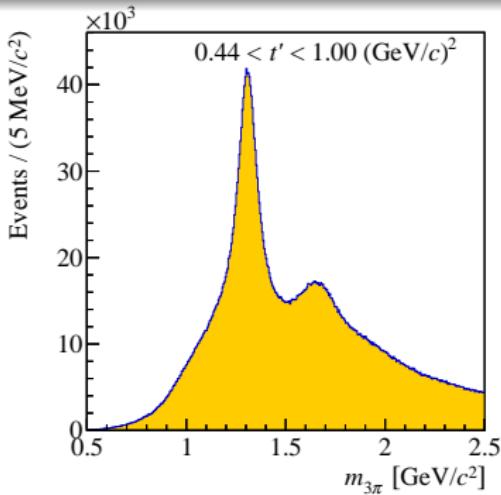
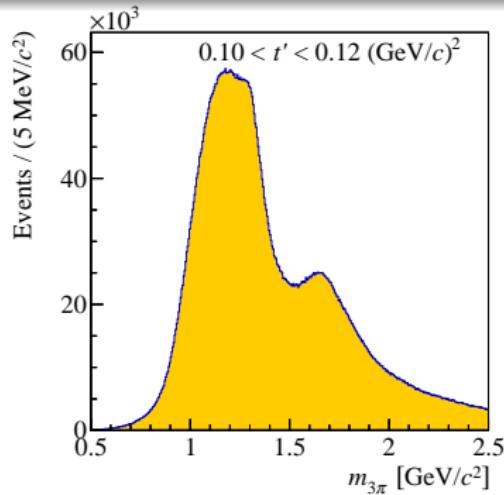
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Partial-Wave Decomposition

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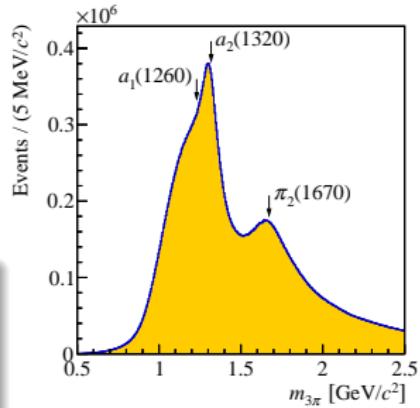
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Partial-Wave Decomposition

Results

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



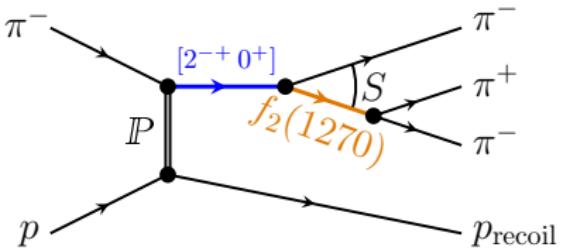
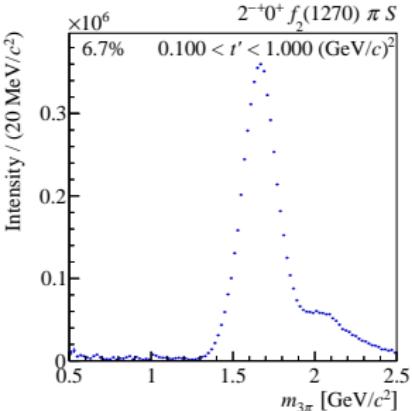
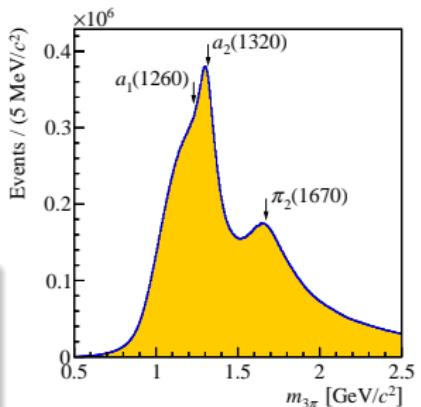
- Decompose into 88 partial waves
- $2^{-+} 0^+ f_2(1270) \pi S$
 - π_2
- In 11 bins in t'
- $4^{++} 1^+ \rho(770) \pi G$
 - $a_4(2040)$

Partial-Wave Decomposition

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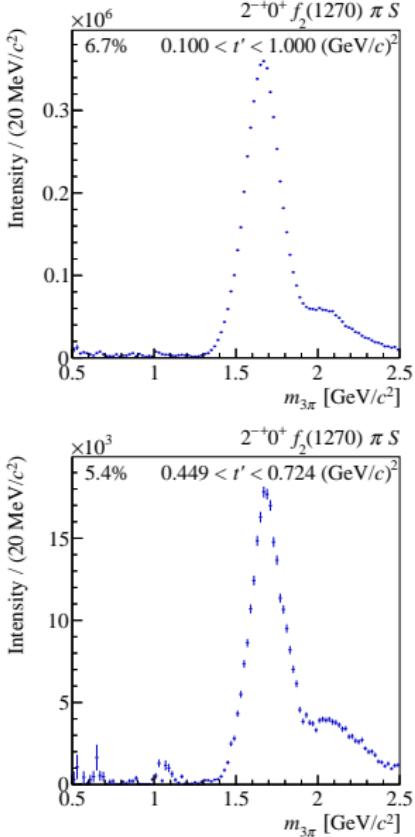
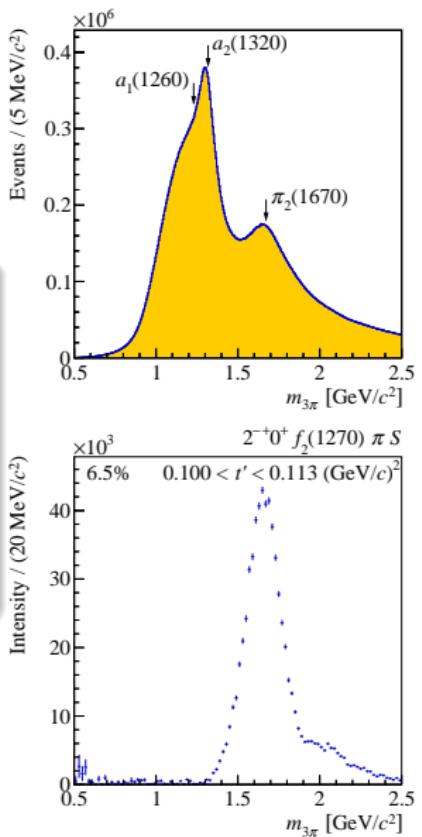


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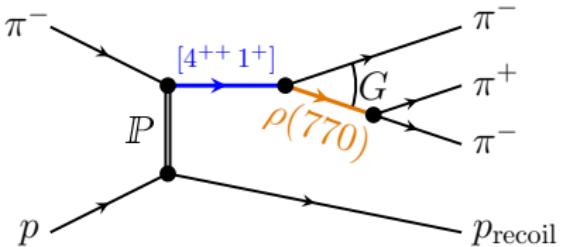
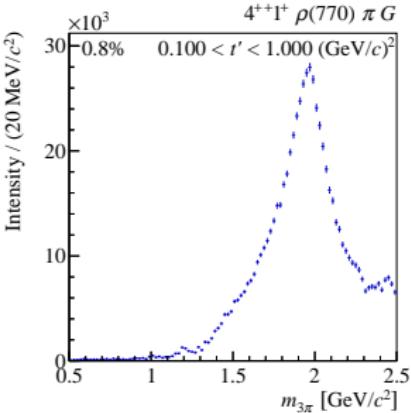
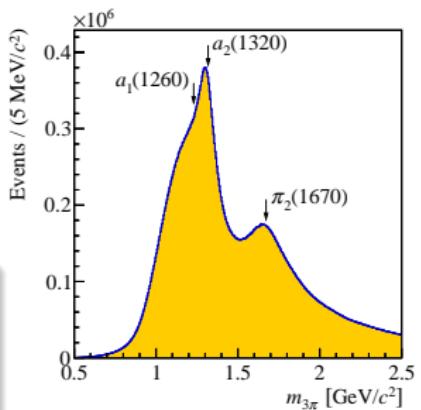


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Resonance-Model Fit

Method

Data

Resonance Parameters

Masses and widths of the meson resonances

Resonance-Model Fit

Method

Data

(I) Partial-Wave
Decomposition

Partial Waves

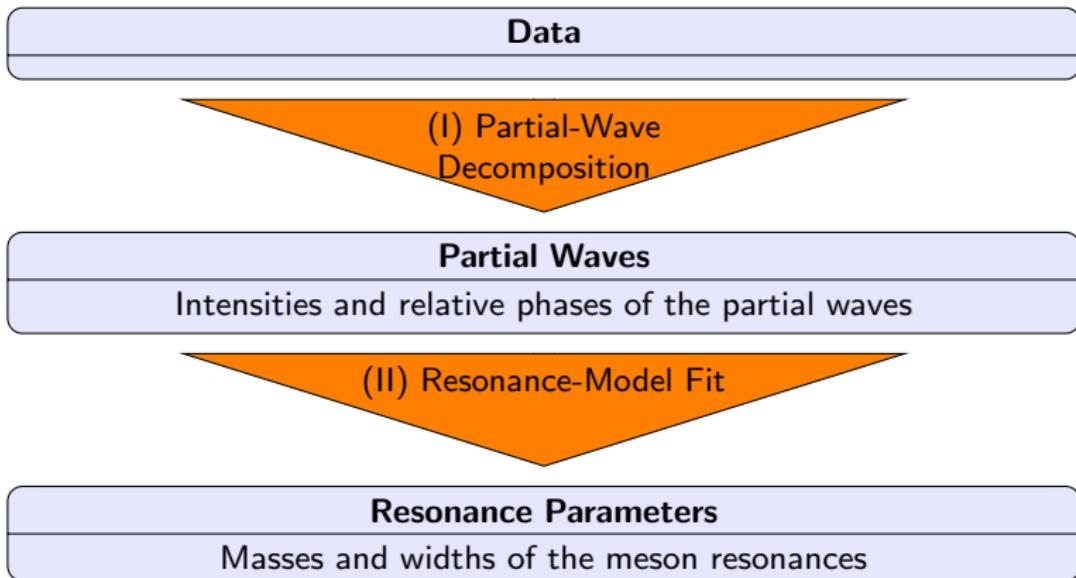
Intensities and relative phases of the partial waves

Resonance Parameters

Masses and widths of the meson resonances

Resonance-Model Fit

Method



Resonance-Model Fit

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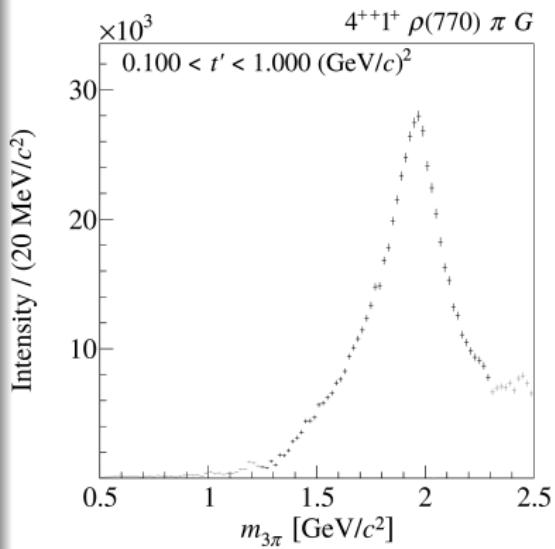
[arXiv:1802.05913]

Modeling $m_{3\pi}$ dependence

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

$$\mathcal{T}_a(m_{3\pi}, t') = \sum_{j \in \mathbb{S}_a} \mathcal{C}_a^j(t') \cdot \mathcal{D}_j(m_{3\pi}, t'; \zeta_j)$$

- ▶ Dynamic amplitudes $\mathcal{D}_j(m_{3\pi}, t'; \zeta_j)$
 - ▶ For resonances: Breit-Wigner amplitude
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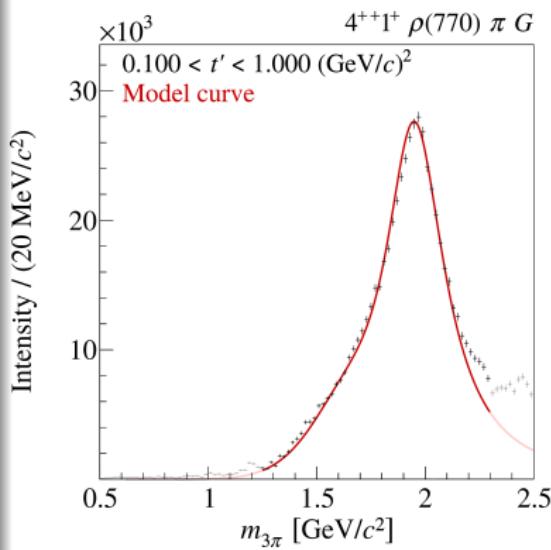
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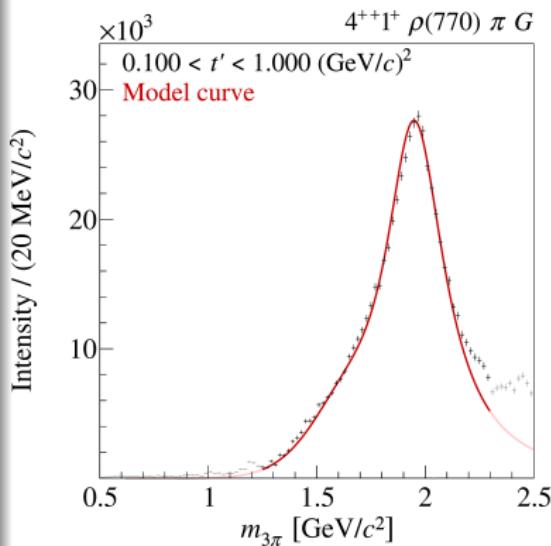
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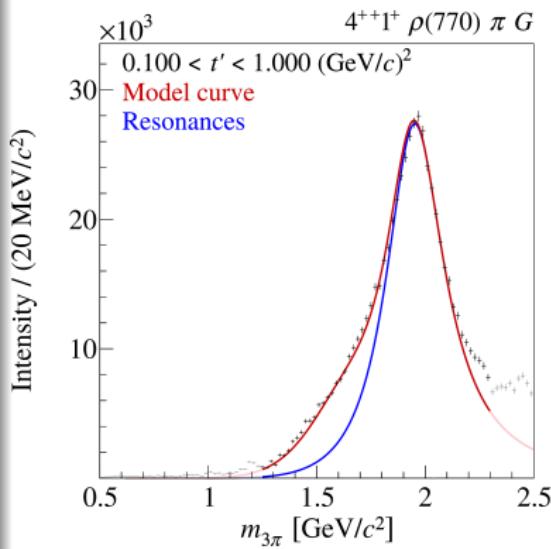
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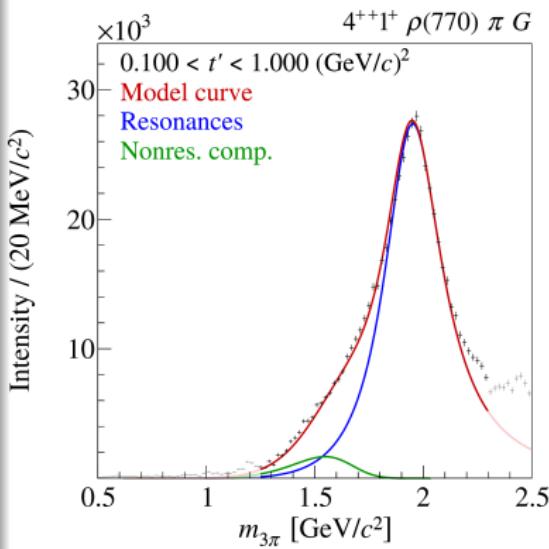
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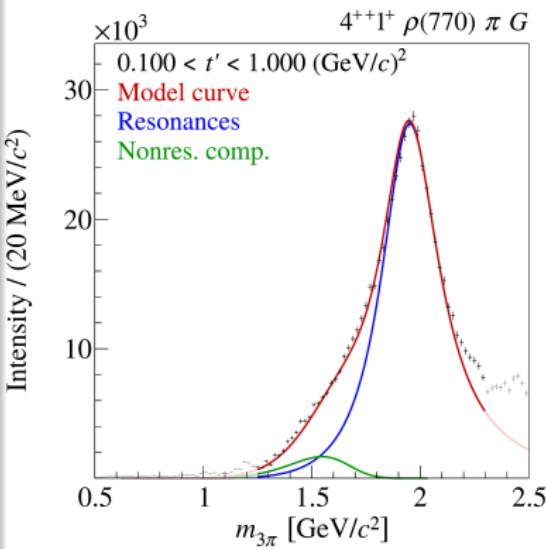
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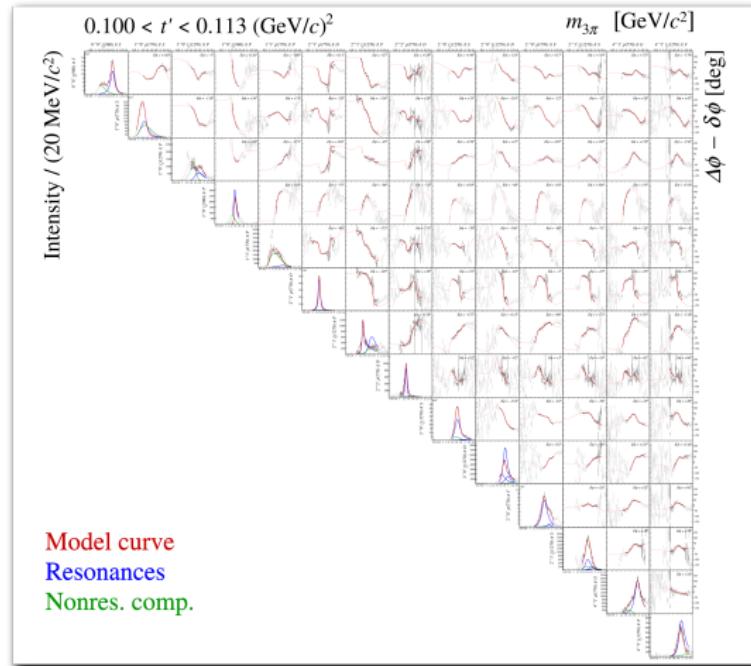
The fit

- ▶ Describe large fraction of data consistently
 - ▶ Simultaneously fit 14 waves ($\approx 60\%$ of total intensity)
 - ▶ Including 11 resonance components ($a_1, a_2, a_4, \pi, \pi_1, \pi_2$)
- ▶ Extract t' dependence of model components
- ▶ Computationally very expensive
 - ▶ 14×14 spin-density matrix $\times 11$ t' bins
 - ▶ 76505 data points
 - ▶ 722 real fit parameters (51 shape parameters)
- ▶ Many systematic effects may influence the fit result
 - ▶ Parameterization of resonances and non-resonant terms
 - ▶ Selected subset of waves
 - ▶ ...
- ▶ We performed extensive systematic studies

Resonance-Model Fit

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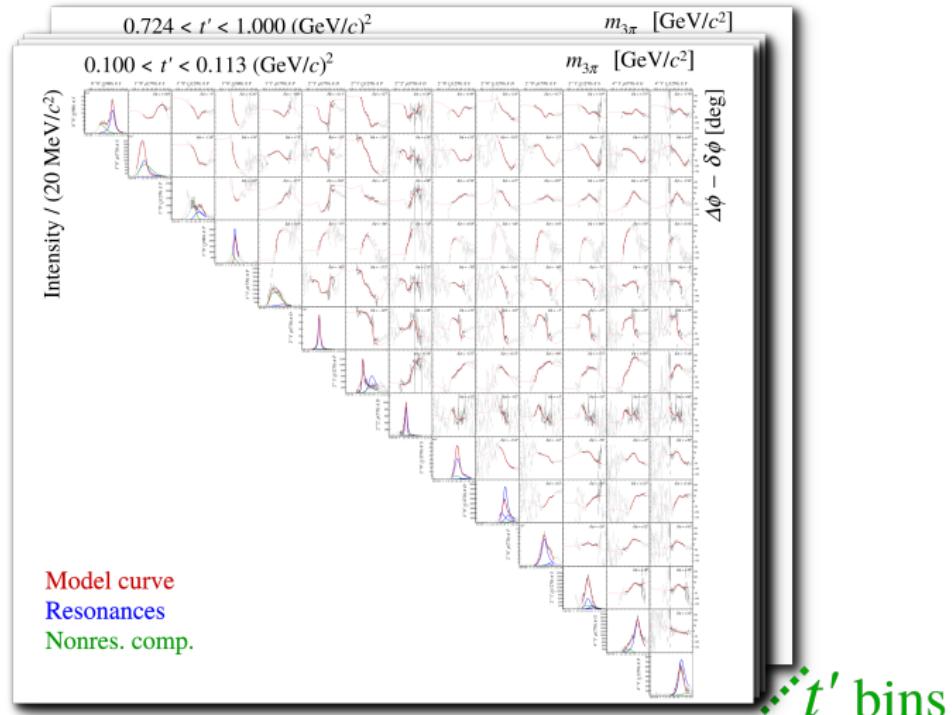
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Resonance-Model Fit

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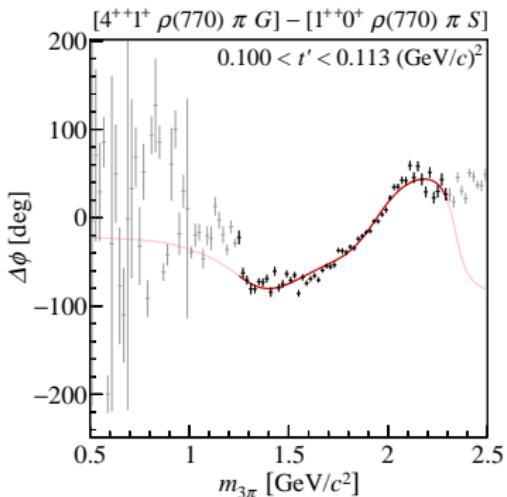
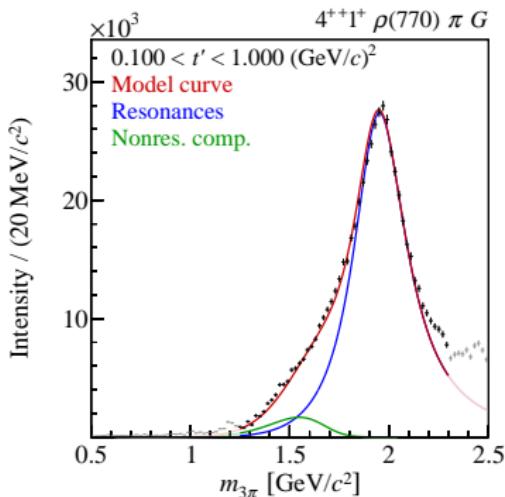
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4^{++} Waves

[arXiv:1802.05913]

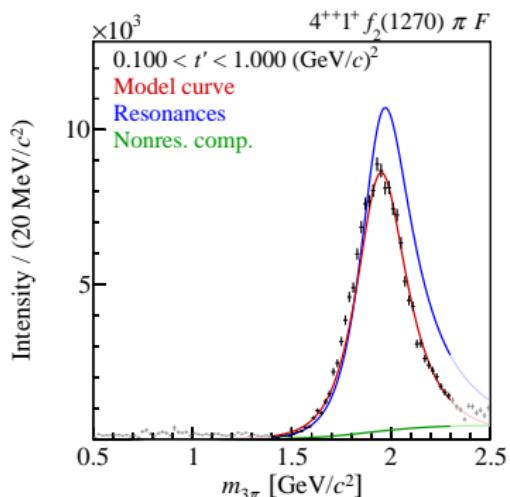
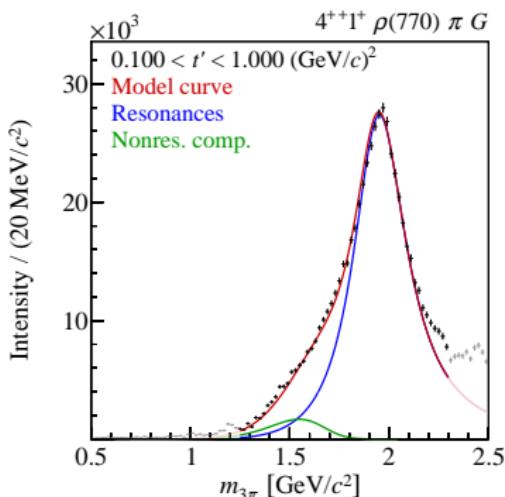


$$J^{PC} = 4^{++}: a_4(2040): m_0 = 1935^{+11}_{-13} \text{ MeV}/c^2, \Gamma_0 = 333^{+16}_{-21} \text{ MeV}/c^2$$

- ▶ Good description of $a_4(2040)$ peak and phase motion
 - ▶ $a_4(2040)$ parameters insensitive with respect to variations of the fit model
 - ▶ Most accurate and precise measurement so far
- ▶ $a_4(2040)$ signal also appearing in $f_2(1270)\pi F$ decay
 - ▶ Branching-fraction ratio: $\frac{\text{BF}[a_4(2040) \rightarrow \rho(770)\pi]}{\text{BF}[a_4(2040) \rightarrow f_2(1270)\pi]} = 2.9^{+0.6}_{-0.4}$

4^{++} Waves

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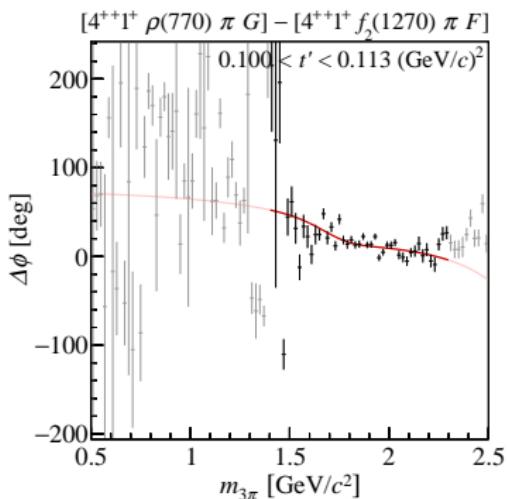
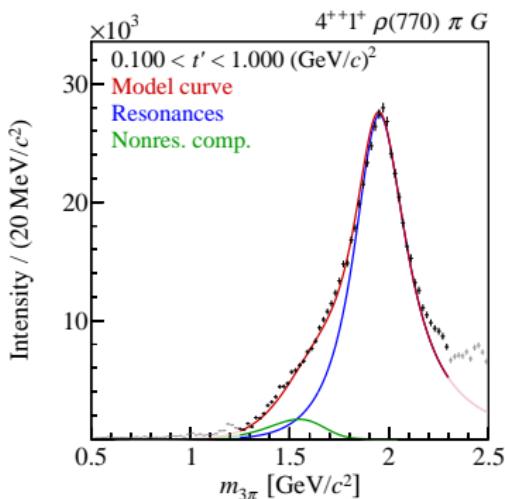


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 - ▶ $a_4(2040)$ parameters insensitive with respect to variations of the fit model
 - ▶ Most accurate and precise measurement so far
- ▶ $a_4(2040)$ signal also appearing in $f_2(1270) \pi F$ decay
 - ▶ Branching-fraction ratio: $\frac{\text{BF}[a_4(2040) \rightarrow \rho(770)\pi]}{\text{BF}[a_4(2040) \rightarrow f_2(1270)\pi]} = 2.9^{+0.6}_{-0.4}$

4^{++} Waves

[arXiv:1802.05913]



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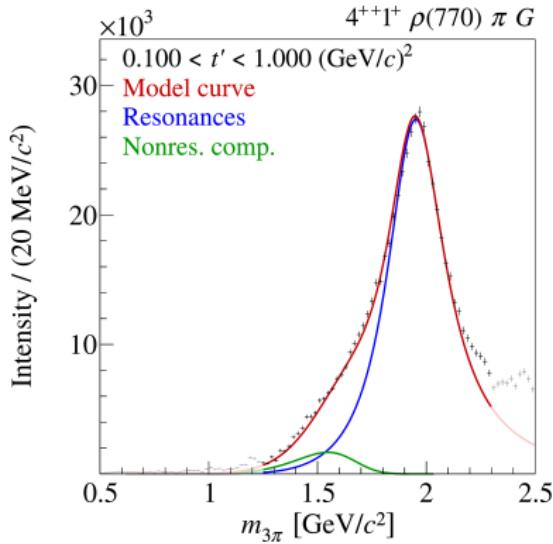
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Extraction of t' spectra

- ▶ Integrate the intensity
 - ▶ over $m_{3\pi}$
 - ▶ for each component individually
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- ▶ Fit the t' spectra with exponential model

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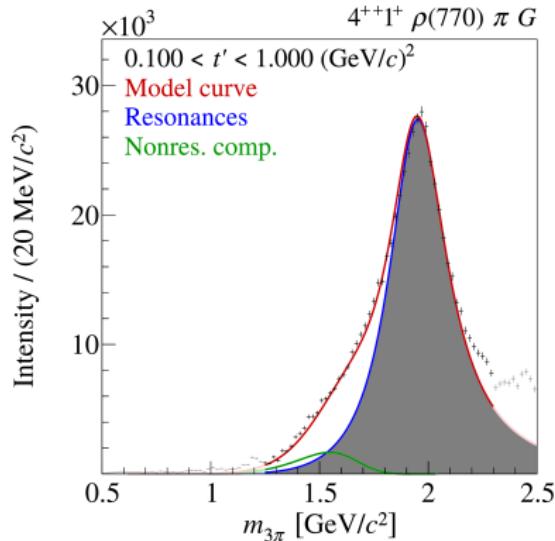


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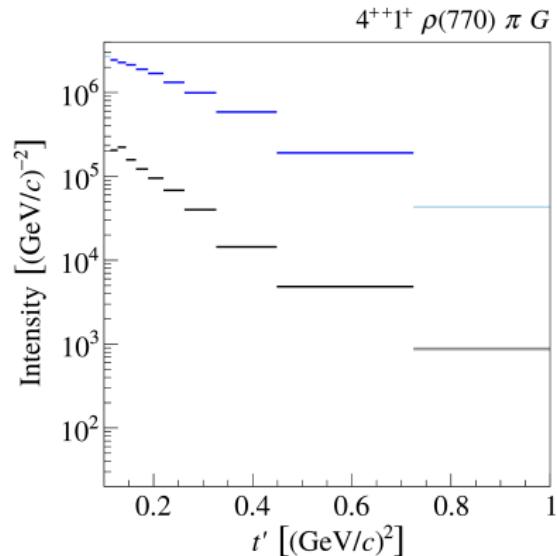


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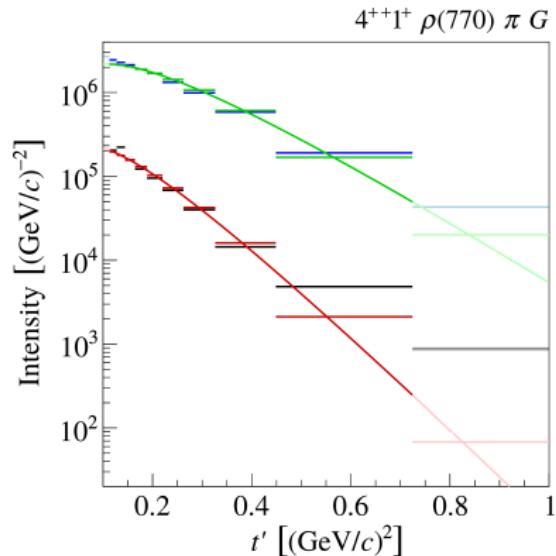


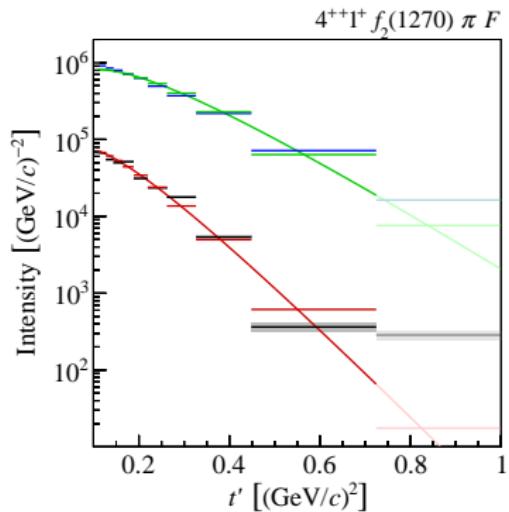
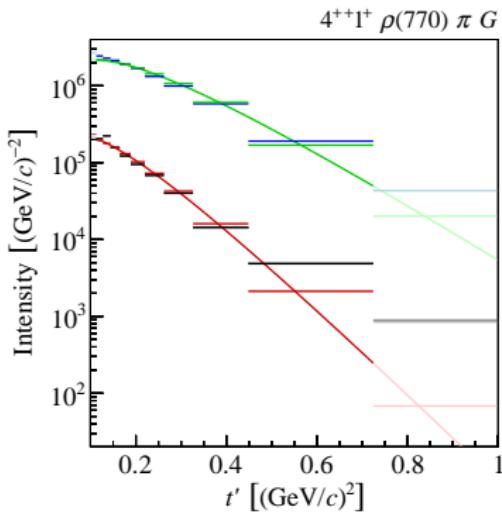
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$J^{PC} = 4^{++}: a_4(2040)$

- ▶ Slope parameter $b_{a_4(2040)} = 9.2^{+0.8}_{-0.5} (\text{GeV}/c)^{-2}$
 - ▶ The same in both decay modes by model constrains
- ▶ Model underestimates data at high t'
- ▶ Non-resonant contributions show **steeper falling t' spectrum**
 - ▶ $b_{\rho(770)}^{\text{Non.-Res.}} = 14 \pm 4 (\text{GeV}/c)^{-2}$, $b_{f_2(1270)}^{\text{Non.-Res.}} = 14.5^{+1.8}_{-3.7} (\text{GeV}/c)^{-2}$

Model constraints on t' dependence

$$\mathcal{C}_{f_2(1270)}^{a_4(2040)}(t') = f_2(1270) \mathcal{B}_{\rho(770)}^{a_4(2040)} \cdot \mathcal{C}_{\rho(770)}^{a_4(2040)}(t')$$

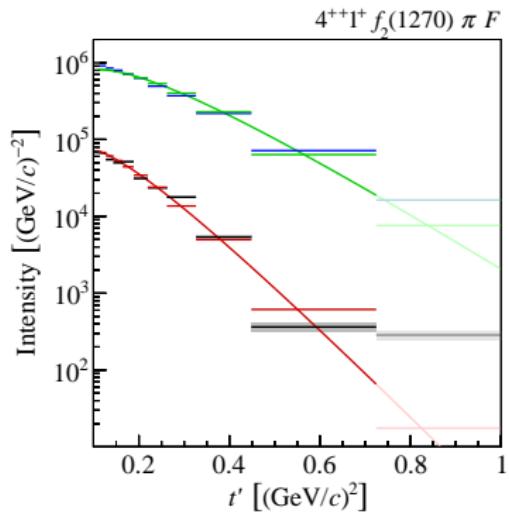
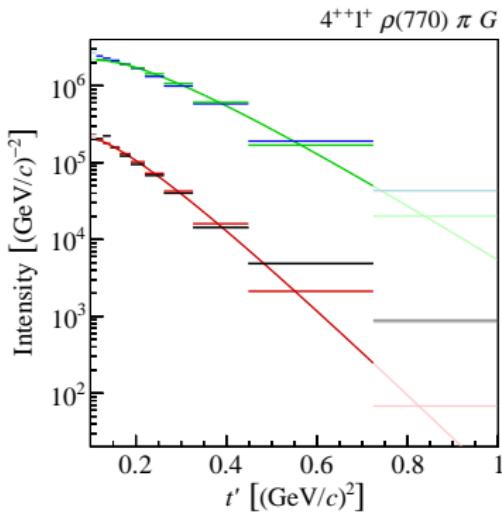
- ▶ Only production process should depend on t'
 - Same state in different decay modes should have the same t' dependence
- ▶ Complex-valued branching amplitude \mathcal{B} represents relative strength and phase
- ▶ Test of this assumption in a systematic study

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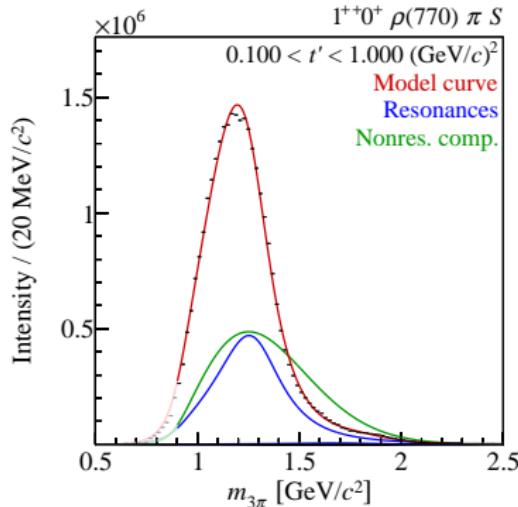
4^{++} Waves t' Spectra

[arXiv:1802.05913]



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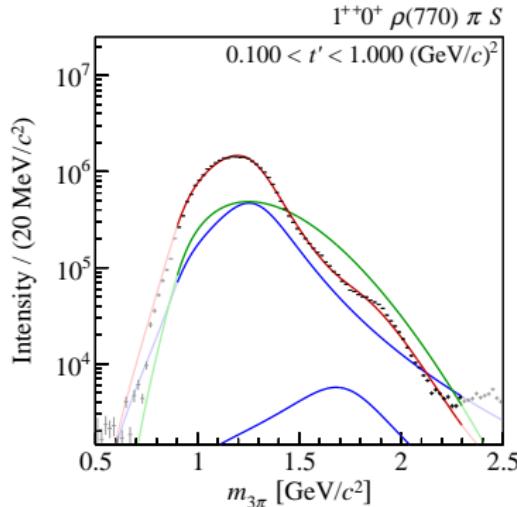


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 - ▶ Model cannot well describe the details of the intensity spectrum
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1^{++} Waves

[arXiv:1802.05913]

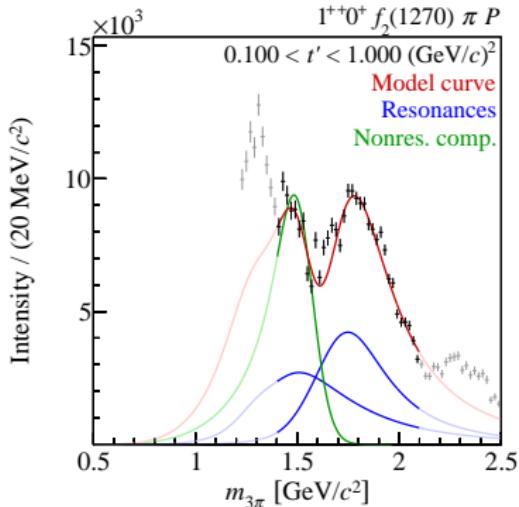
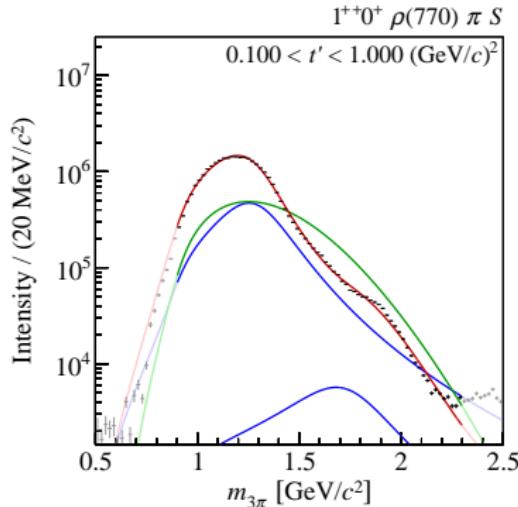


$J^{PC} = 1^{++}: a_1(1260), a_1(1640)$

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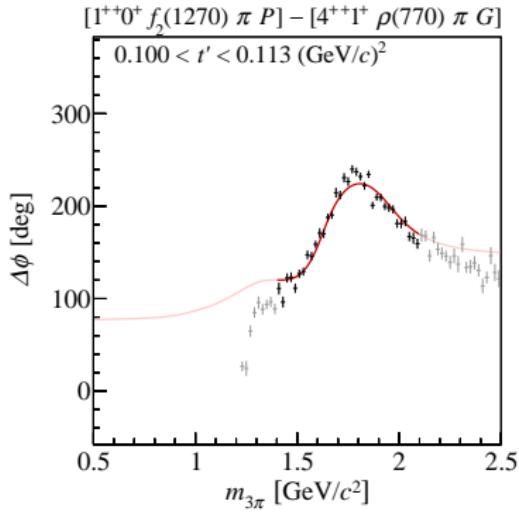
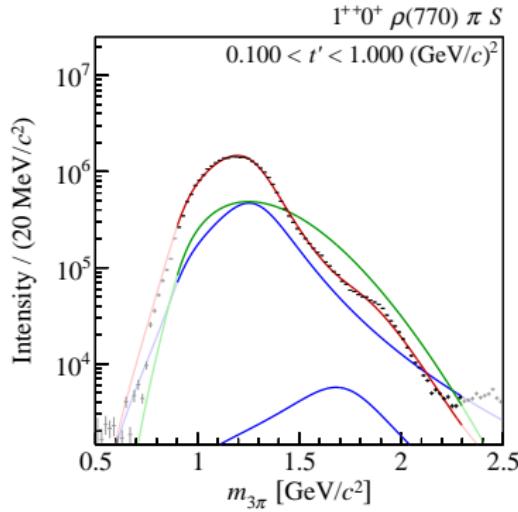


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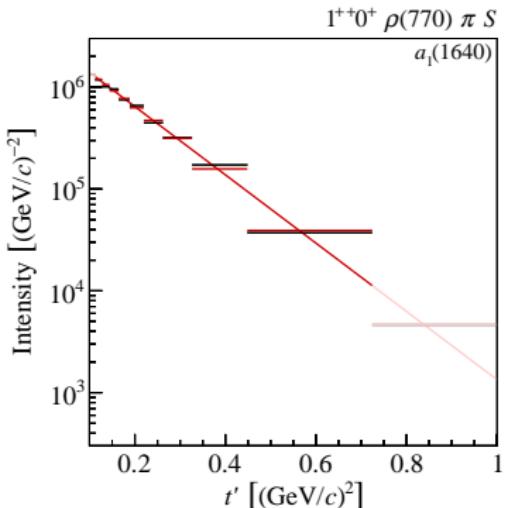
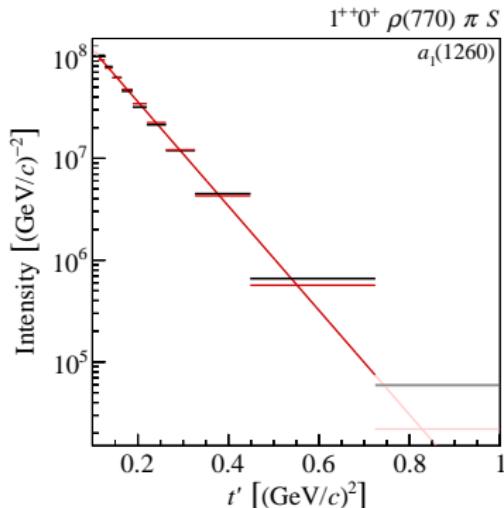
1^{++} Waves

[arXiv:1802.05913]



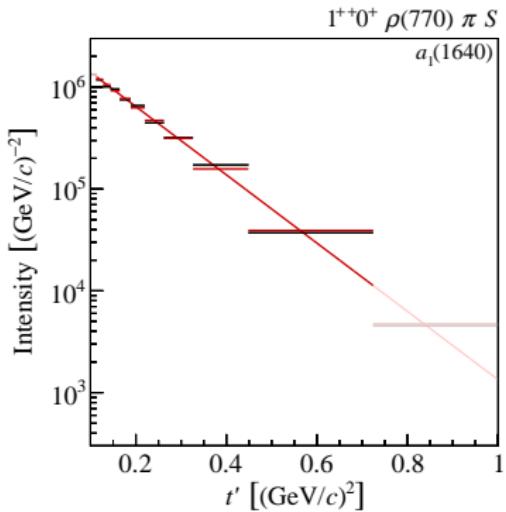
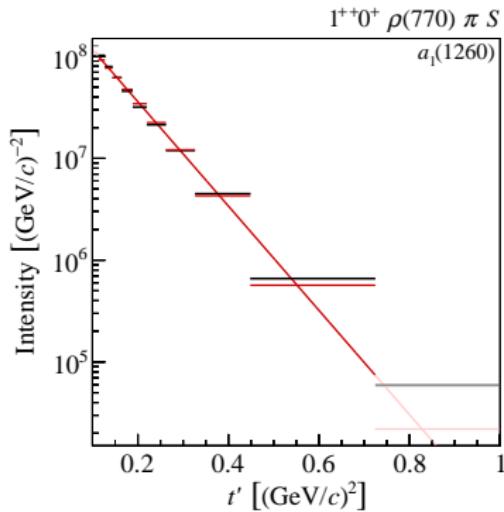
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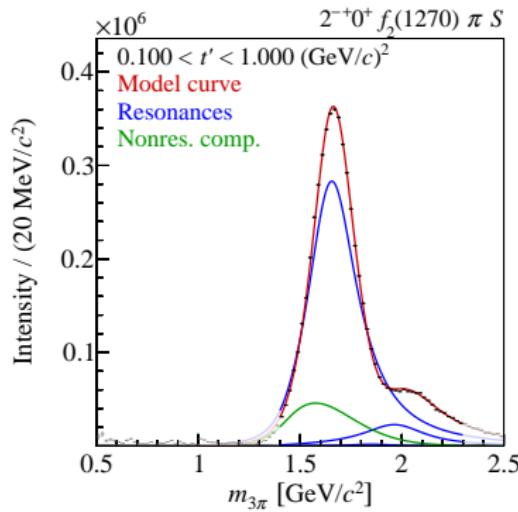
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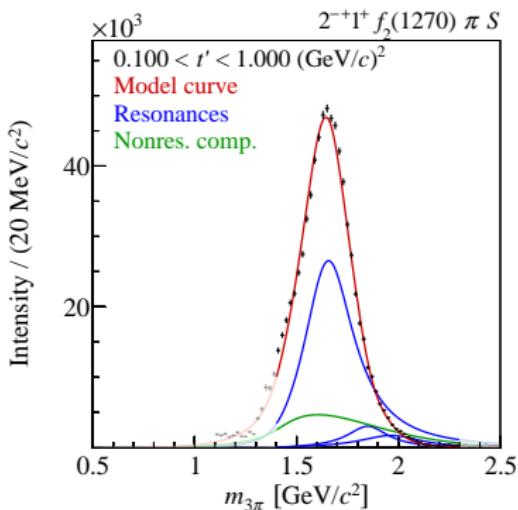
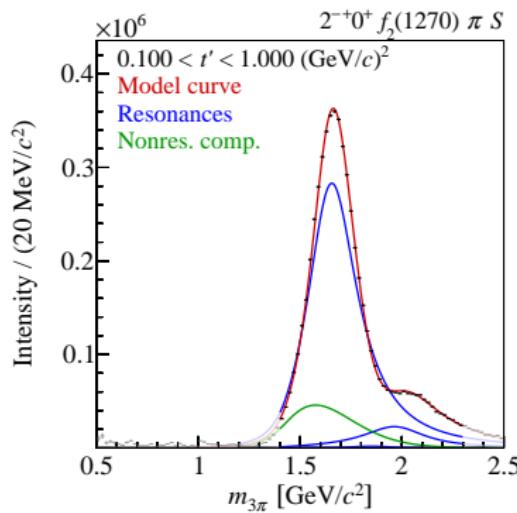


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2^{-+} Waves

[arXiv:1802.05913]

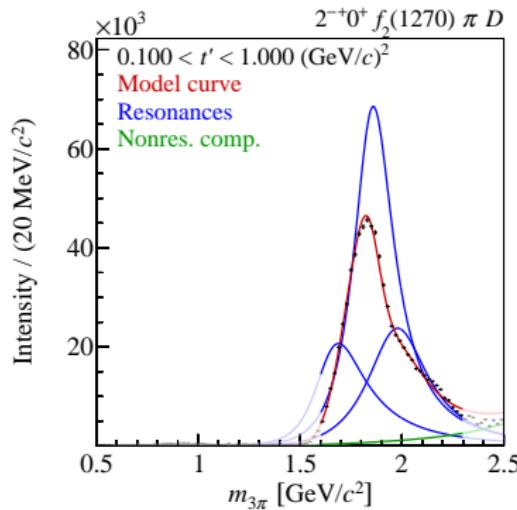


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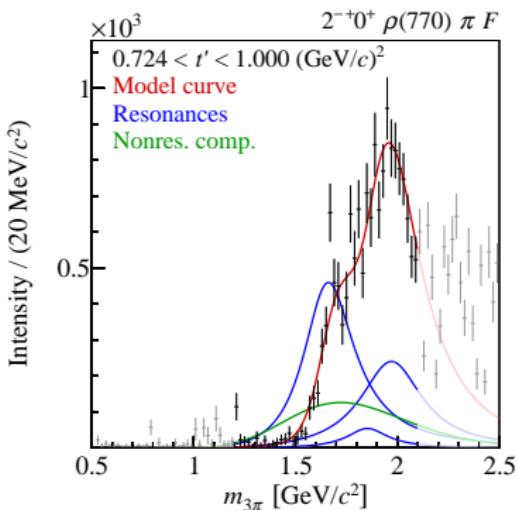
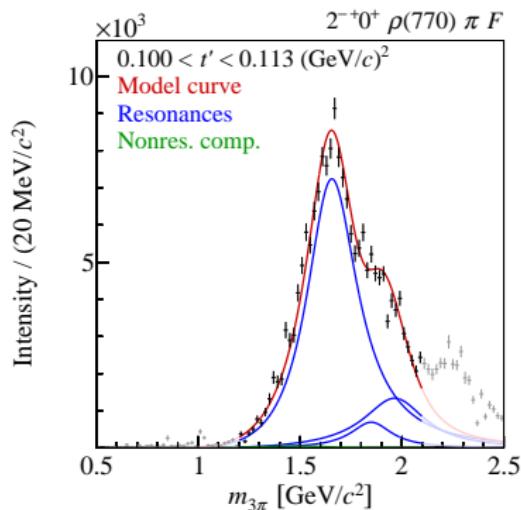


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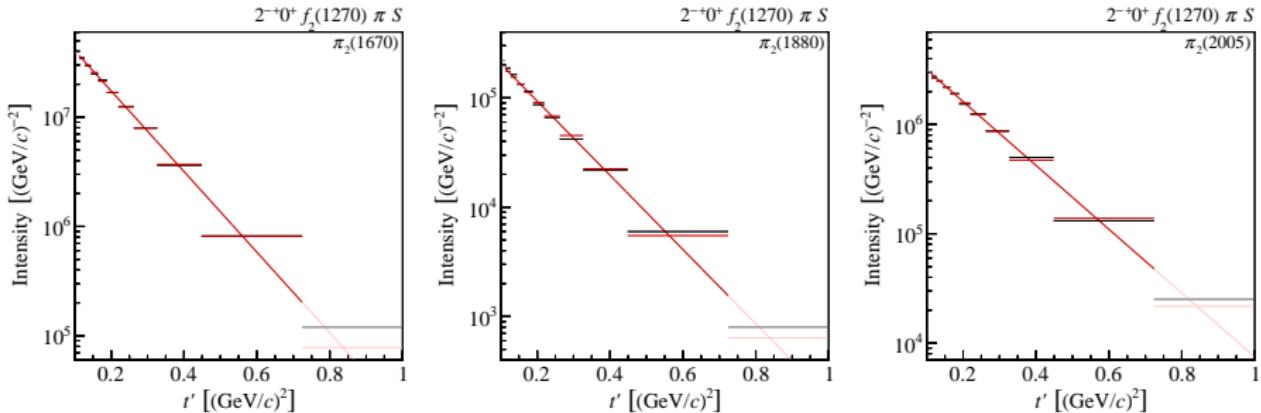


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2^{-+} Waves t' Spectra

[arXiv:1802.05913]

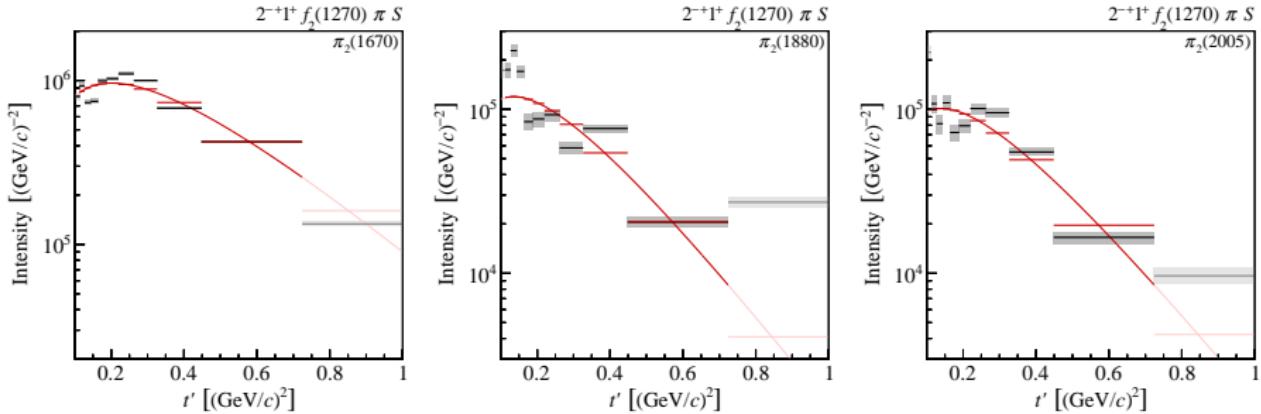


2^{-+} waves with $M = 0$

- ▶ t' spectra in good agreement with exponential model
- ▶ Slope parameter decreases with increasing resonance mass
 - ▶ $b^{\pi_2(1670)} = 8.5^{+0.9}_{-0.5} (\text{GeV}/c)^{-2}$, $b^{\pi_2(1880)} = 7.8^{+0.5}_{-0.9} (\text{GeV}/c)^{-2}$,
 - ▶ $b^{\pi_2(2005)} = 6.7^{+0.4}_{-1.3} (\text{GeV}/c)^{-2}$
 - ▶ Helps to better separate the resonances

2^{-+} Waves t' Spectra

[arXiv:1802.05913]



2^{-+} waves with $M = 1$

- ▶ Small wave \Rightarrow Components extracted less reliably
- ▶ Slope parameters of $\pi_2(1880)$ and $\pi_2(2005)$ compatible with $M = 0$ waves
- ▶ Slope parameter of $\pi_2(1670)$ of $5.0 (\text{GeV}/c)^{-2}$ significantly smaller

t' Dependence of Relative Phases of Coupling Amplitudes

[arXiv:1802.05913]

$$\mathcal{T}_a(m_{3\pi}, t') = \sum_{j \in \mathbb{S}_a} \mathcal{C}_a^j(t') \cdot \mathcal{D}_j(m_{3\pi}, t'; \zeta_j)$$

Relative phase of coupling amplitudes of component j in wave a
w.r.t. component k in wave b

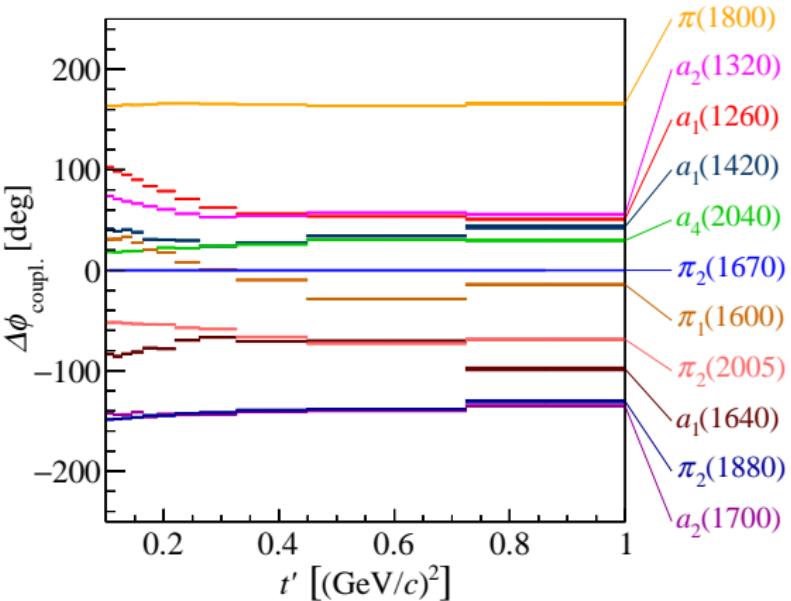
$$\Delta\phi_{\text{coupl.}}^{j,a;k,b}(t') = \arg \left[\mathcal{C}_a^j(t') \cdot \mathcal{C}_b^k{}^*(t') \right]$$

t' Dependence of Relative Phases of Coupling Amplitudes

Overview over Resonances

[arXiv:1802.05913]

- ▶ Relative to $\pi_2(1670)$
- ▶ For $t' \gtrsim 0.3 \text{ (GeV}/c)^2$ phases level off
- ▶ Large relative offset for ground and excited states
 - ▶ Except for $a_1(1420)$
- ▶ Ground states: $\Delta\phi \lesssim \pm 60^\circ$



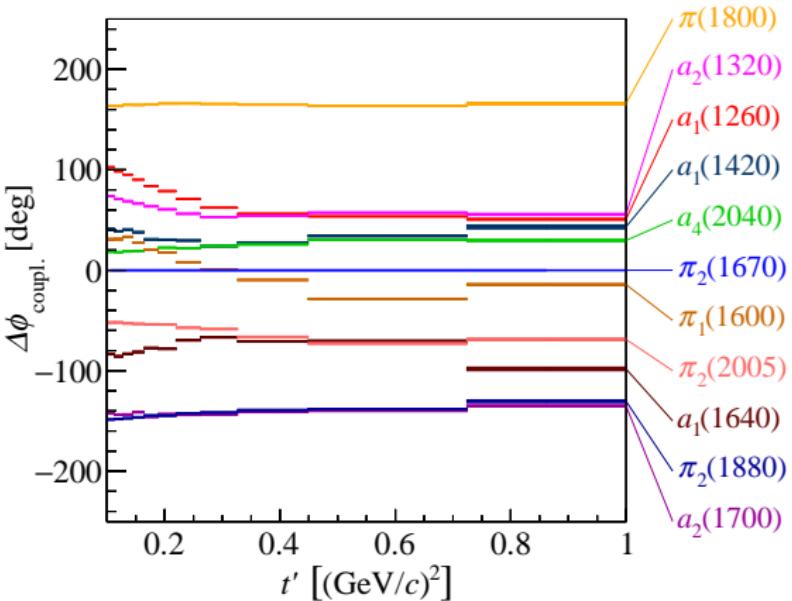
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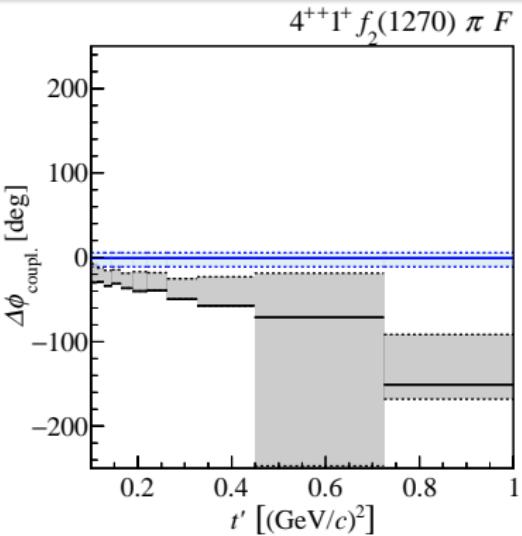
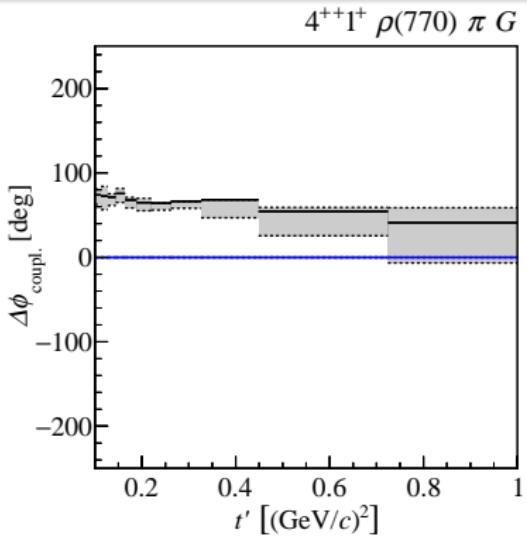


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t' Dependence of Relative Phases of Coupling Amplitudes

4⁺⁺ Waves

[arXiv:1802.05913]

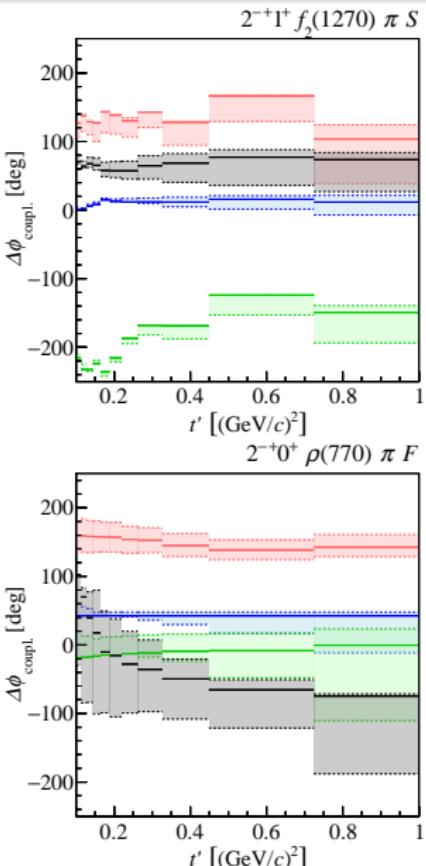
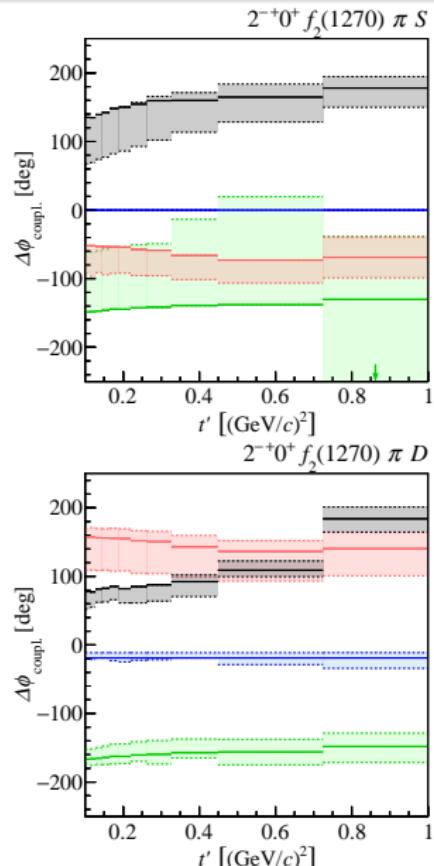


- ▶ $a_4(2040)$ phase variation with t' the same in both decay modes by model constrains
- ▶ Relative phase between $\rho(770)\pi G$ and $f_2(1270)\pi F$ decay close to 0°
 - ▶ With small systematic uncertainties
- ▶ Non-resonant components show slight variation of phase with t' w.r.t. $a_4(2040)$

t' Dependence of Relative Phases of Coupling Amplitudes

2^{-+} Waves

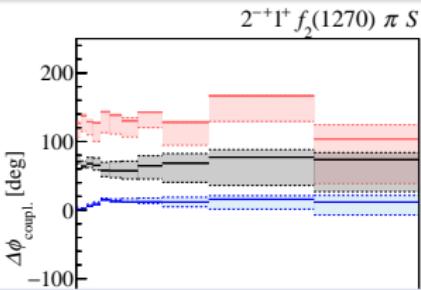
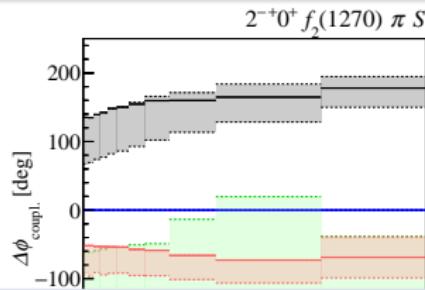
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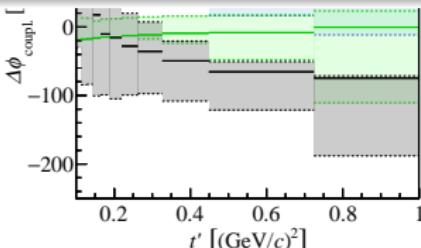
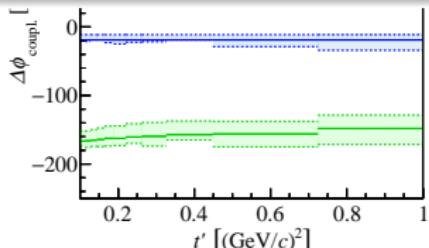
t' Dependence of Relative Phases of Coupling Amplitudes

2^{-+} Waves

[arXiv:1802.05913]



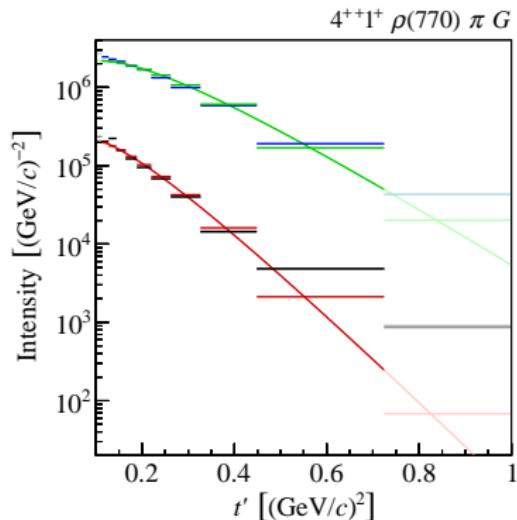
- ▶ $\pi_2(1670)$ shows similar phase in all decay modes except $\rho(770)\pi F$ decay
 - ▶ Similar phase in $M = 0$ and $M = 1$ $f_2(1270)\pi S$ decay
- ▶ $\pi_2(1880)$ shows -180° offset w.r.t. $\pi_2(1670)$ in $f_2(1270)\pi D$ decay
 - ▶ Similar in both $f_2(1270)\pi S$ waves
- ▶ $\pi_2(2005)$ shows 150° offset w.r.t. $\pi_2(1670)$ in $\rho(770)\pi F$ decay
 - ▶ Similar in $f_2(1270)\pi D$ decay and $f_2(1270)\pi S$ decay with $M = 1$



Summary

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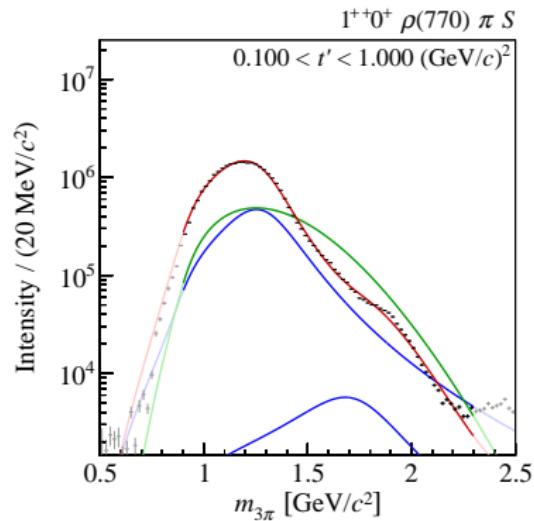
- ▶ Largest resonance-model used so far
 - ▶ Simultaneously fitting 14 partial waves
- ▶ t' -resolved resonance-model fit
 - ▶ Extract t' dependence of resonant and non-resonant components
 - ▶ Typically, non-resonant terms show steeper t' spectrum
- ▶ Measurement of ground and excited states
- ▶ Including four 2^{++} partial waves
 - ▶ Resonance parameters and t' dependence of $\pi_2(1670)$, $\pi_2(1880)$, and $\pi_2(2005)$
- ▶ Measured t' dependence of relative phases
 - ▶ Resonance phases consistent with common production mechanism



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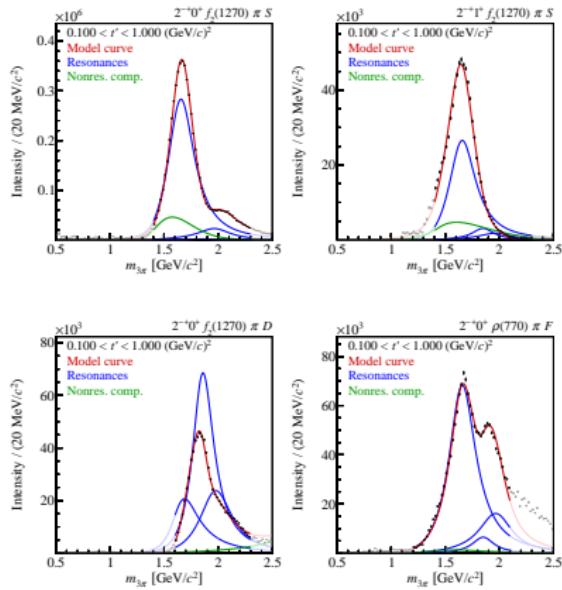
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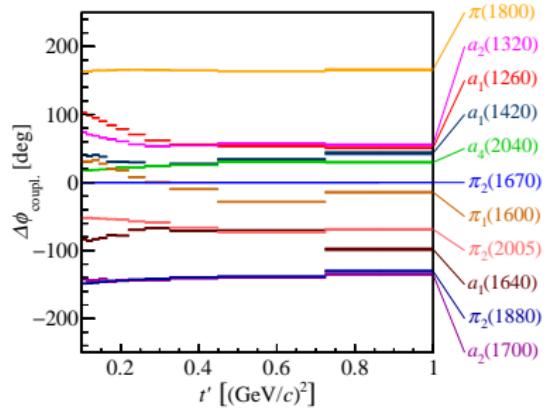
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- ▶ Largest resonance-model used so far
 - ▶ Simultaneously fitting 14 partial waves
- ▶ t' -resolved resonance-model fit
 - ▶ Extract t' dependence of resonant and non-resonant components
 - ▶ Typically, non-resonant terms show steeper t' spectrum
- ▶ Measurement of ground and excited states
- ▶ Including four 2^{-+} partial waves
 - ▶ Resonance parameters and t' dependence of $\pi_2(1670)$, $\pi_2(1880)$, and $\pi_2(2005)$
- ▶ Measured t' dependence of relative phases
 - ▶ Resonance phases consistent with common production mechanism



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Further analysis projects

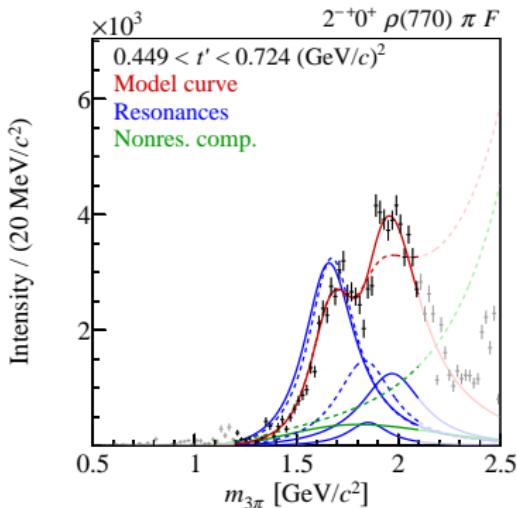
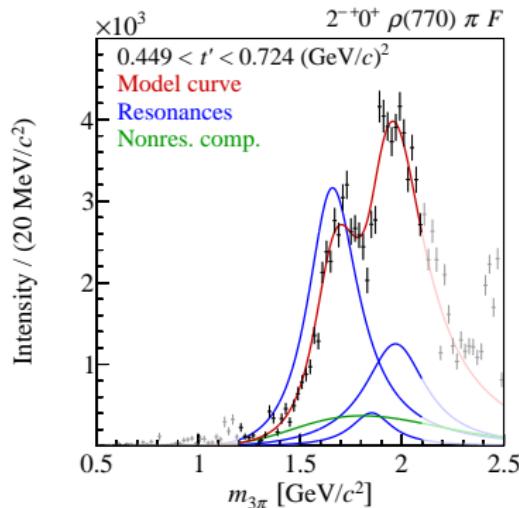
- ▶ Freed-isobar analysis
 - ▶ Study $\pi^-\pi^+$ subsystem
- [Adolph et al., PRD 95, 032004 (2017)]
- ▶ Further final states:
 $\pi^-\pi^0\pi^0$, $\pi^-\omega\pi^0$, ...
- ▶ Strange-meson spectroscopy:
 $K^- + p \rightarrow K^-\pi^-\pi^+ + p_{\text{recoil}}$

Backup

Outline

- 9 Backup
- 10 2^{-+} Waves
- 11 1^{++} Waves
- 12 Freed-Isobar Method
- 13 Crosscheck with $\pi^-\pi^0\pi^0$

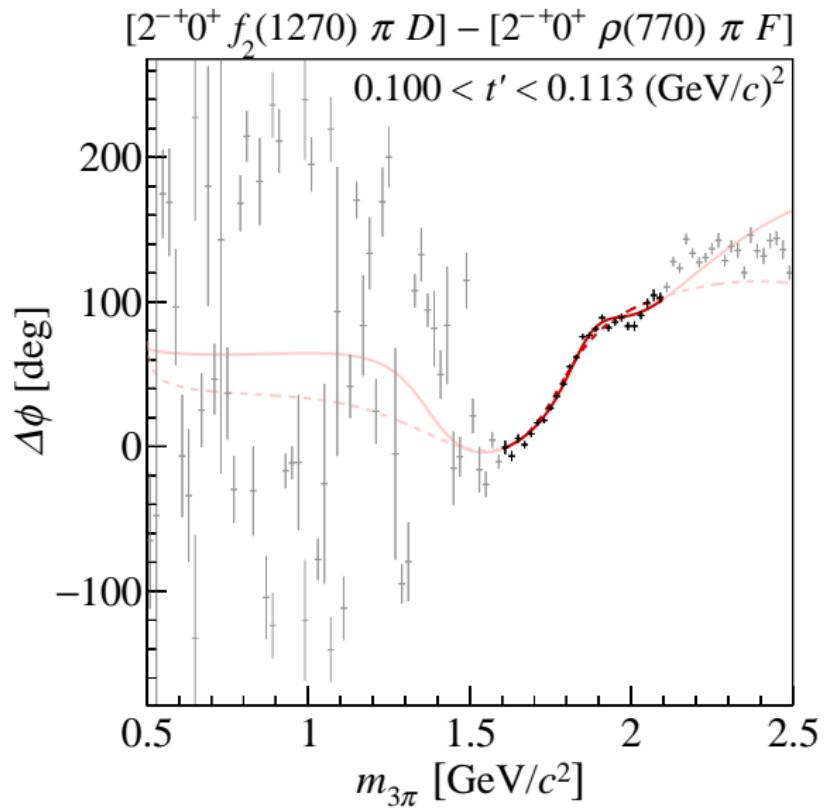
2^{-+} Waves

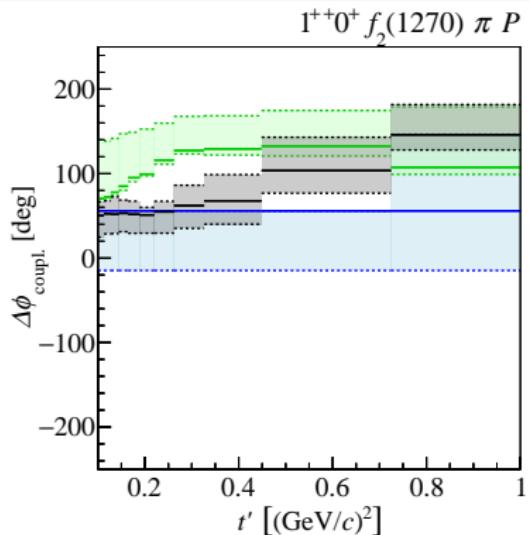
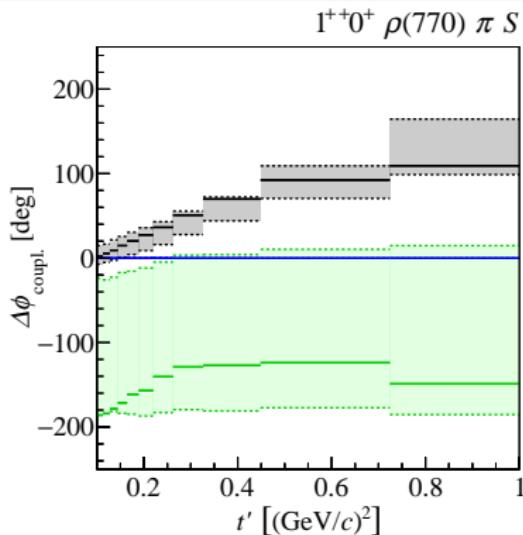


Evidence for $\pi_2(2005)$

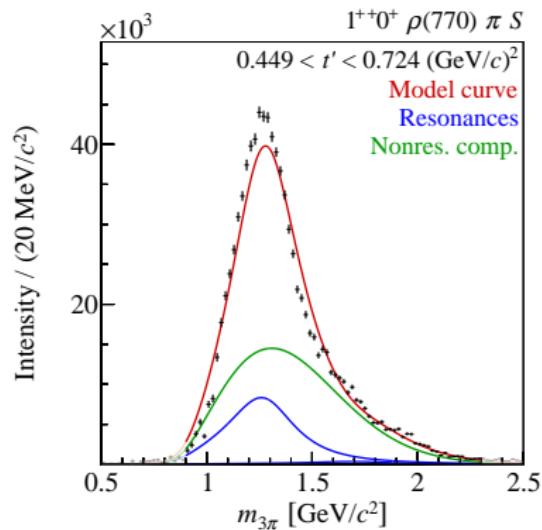
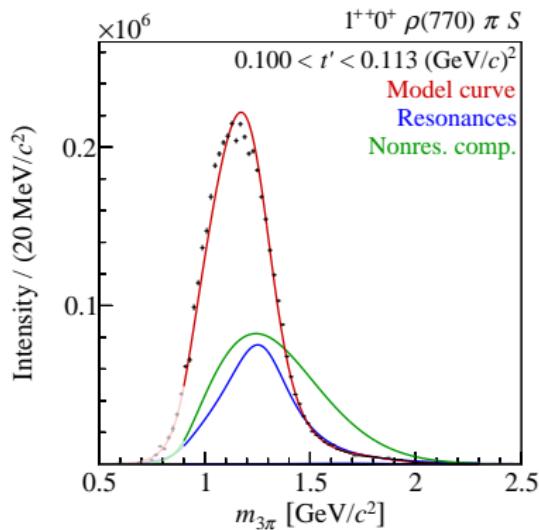
- ▶ Worse description of intensity spectra and phase motions without $\pi_2(2005)$

2^{-+} Waves



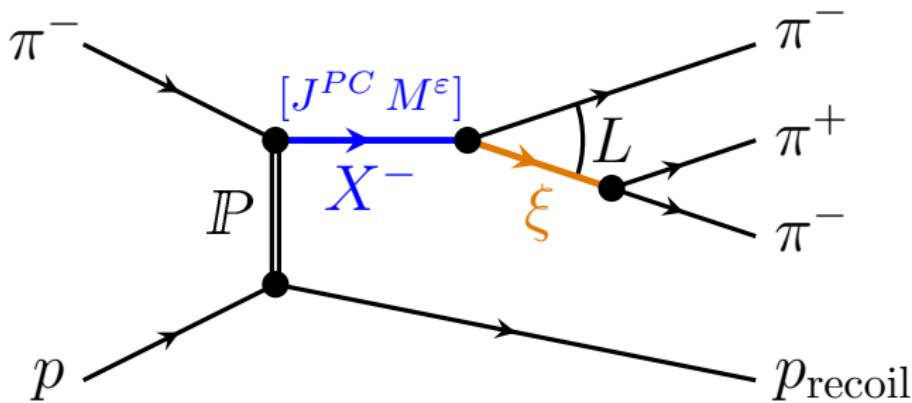


- ▶ Relative phase between $\rho(770) \pi S$ and $f_2(1270) \pi P$ decays about 50°
 - ▶ With large systematic uncertainties
- ▶ Non-resonant components show strong variation of phase with t' w.r.t. $a_1(1260)$
- ▶ $a_1(1640)$ phase offset of about 130° w.r.t. $a_1(1260)$ in $f_2(1270) \pi P$ decay
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Freed-Isobar Method



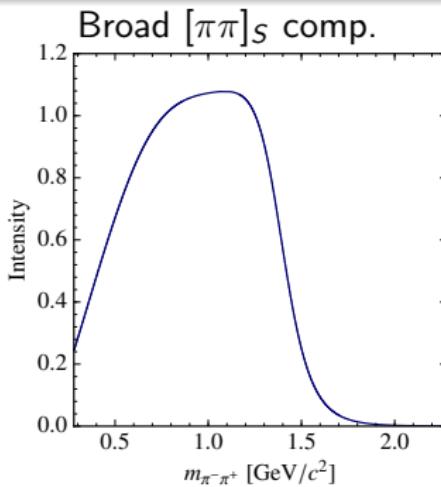
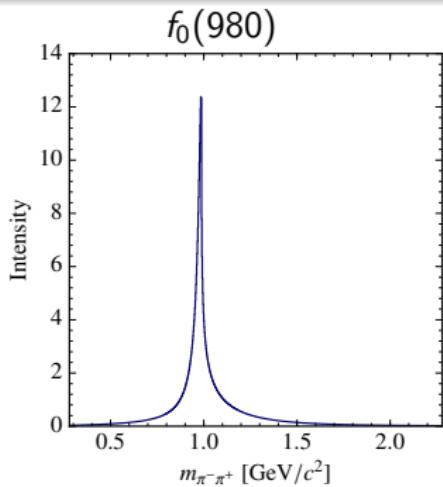
Challenge

Need knowledge of isobar amplitude to calculate decay amplitudes $\psi_i(\tau)$

• How good are the parameterizations?

- Single isobar may not be approximated well by a Breit-Wigner amplitude
- Effects of rescattering may distort the isobar shape

Freed-Isobar Method



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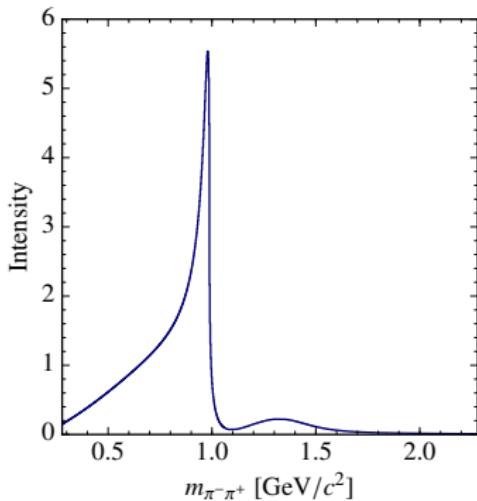
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Freed-Isobar Method

Extract isobar amplitudes from data

- Replace model for isobar amplitude with step-like amplitude
- Extract binned shape from data
- Computationally more expensive
 - Up to 100 additional parameters per wave with freed isobar
- Needs large data sets

Total $[\pi\pi]_S$ isobar amplitude

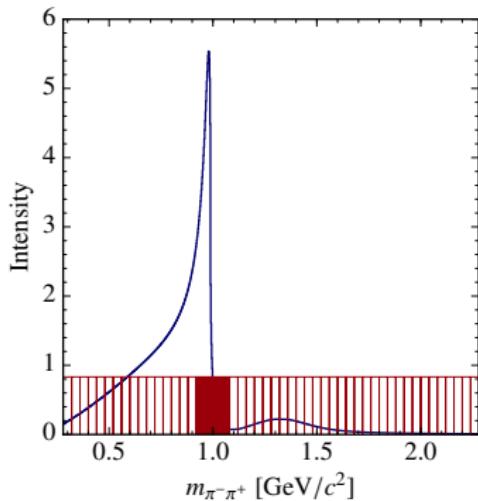


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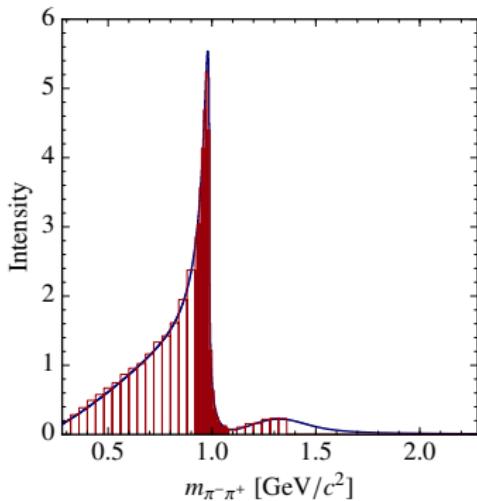


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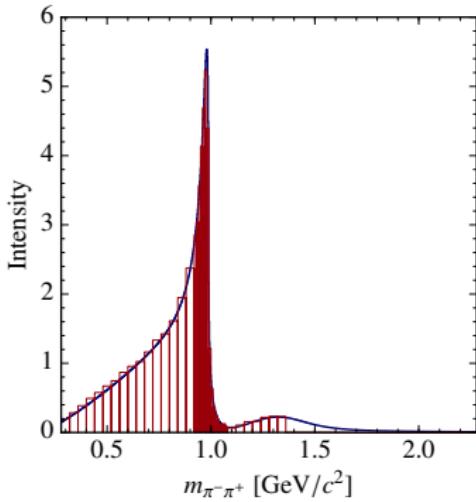


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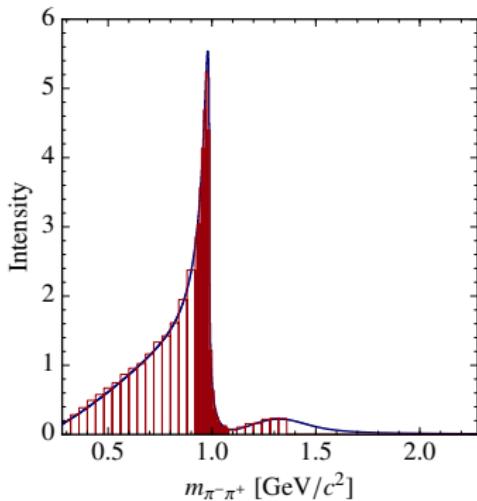


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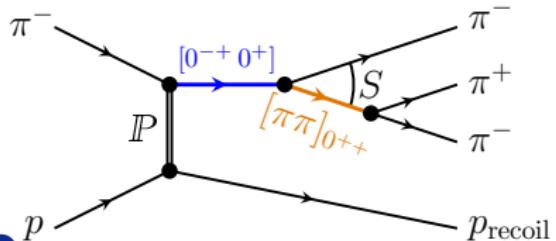
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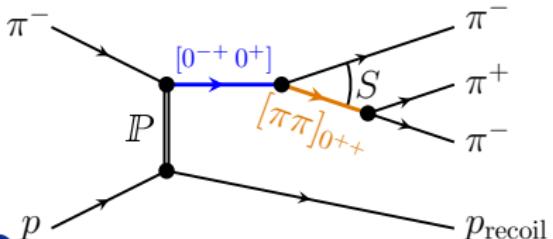
Freed-Isobar Method



Example: $0^{-+} 0^+ [\pi\pi \text{ S-wave}] \pi S$ wave

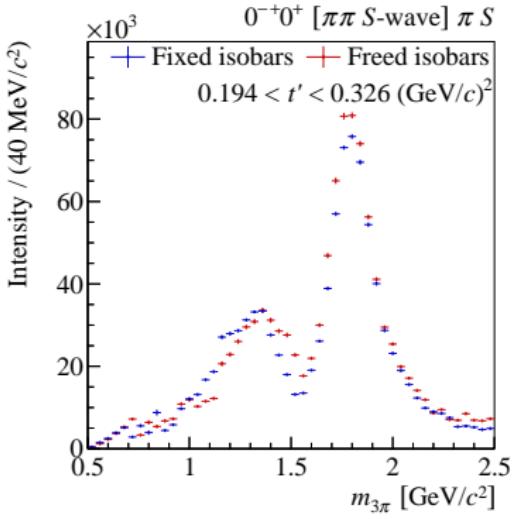
- ▶ Comparison of $0^{-+} 0^+ [\pi\pi \text{ S-wave}] \pi S$ wave intensity between
 - ▶ sum of all conventional isobar waves
 - ▶ freed-isobar method
- ▶ Compatible shapes
- ▶ $\pi(1800)$ peak prominent

Freed-Isobar Method



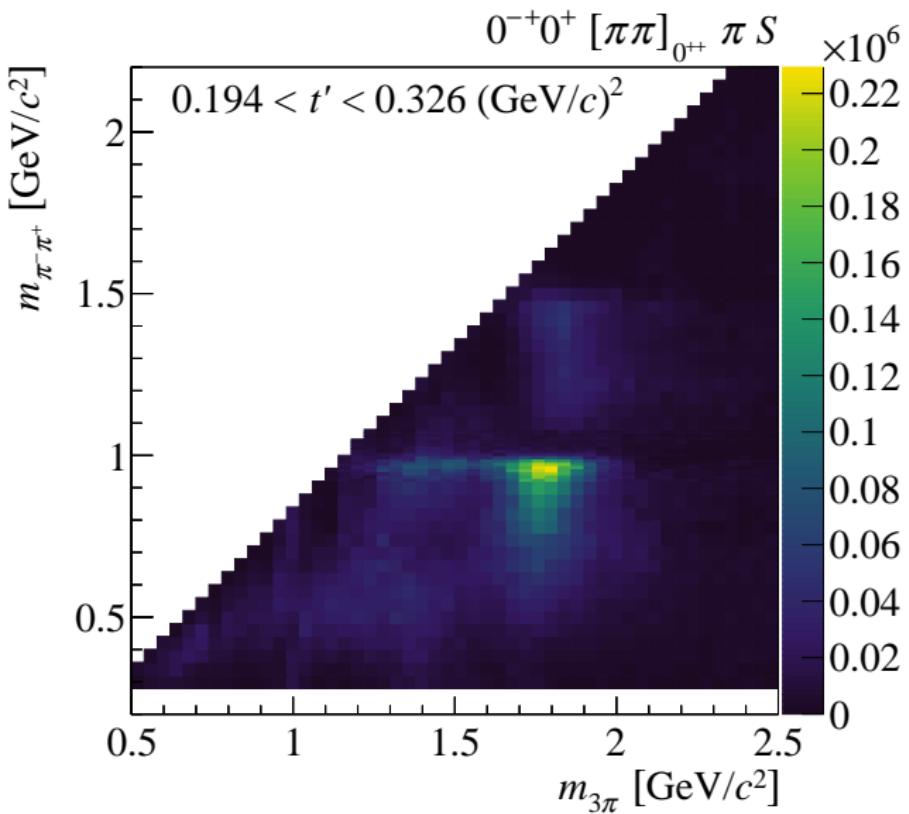
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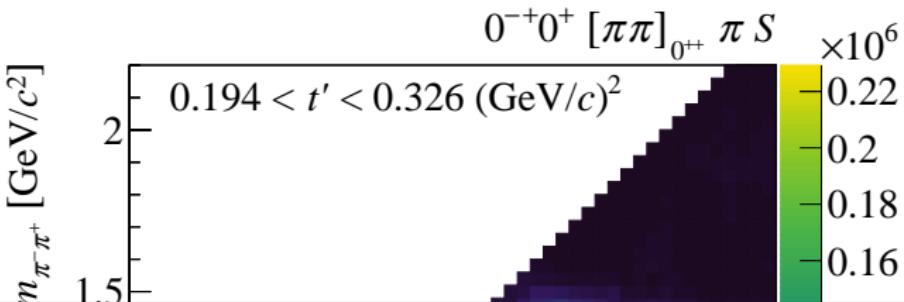
[Adolph et al., PRD 95, 032004 (2017)]



This is not a Dalitz-plot

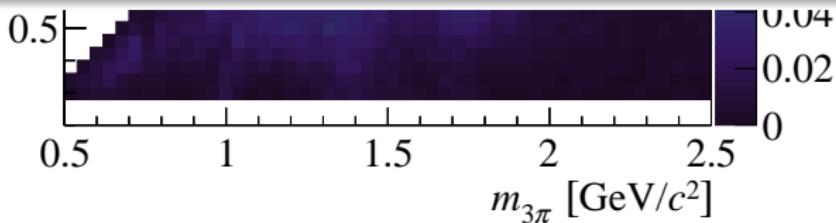
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Investigate the $\pi\pi$ subsystem with $J^{PC} = 0^{-+}$

- ▶ No constraints on $\pi\pi$ resonances
- ▶ Extract $\pi\pi$ amplitude (intensity & phase)
 - ▶ Extract $\pi\pi$ resonances
- ▶ Investigate effects of rescattering

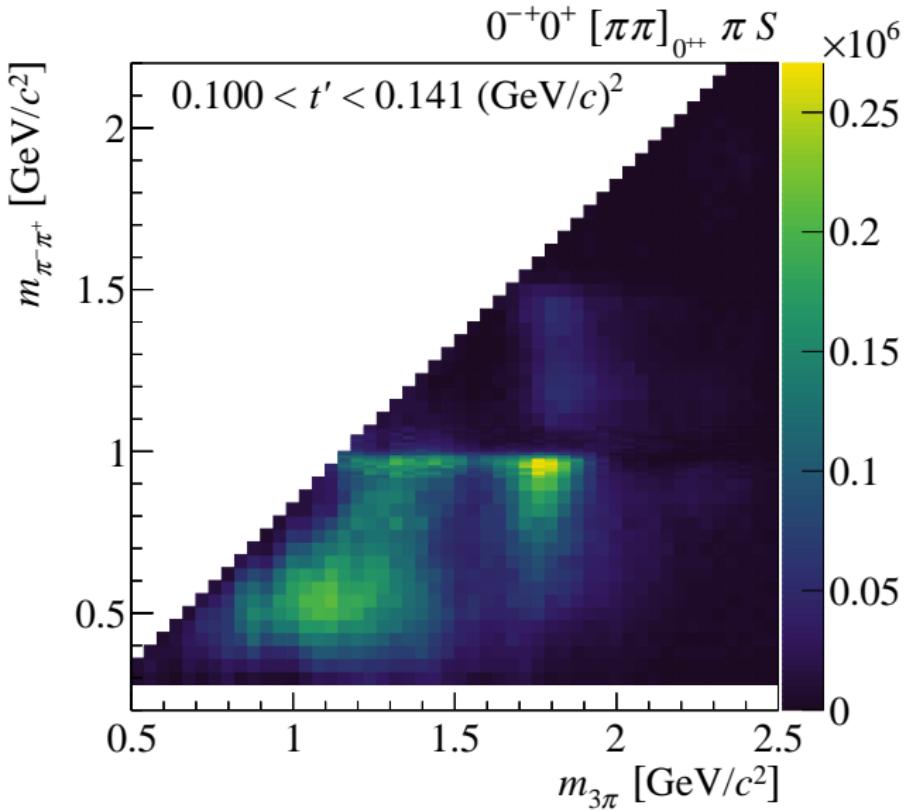


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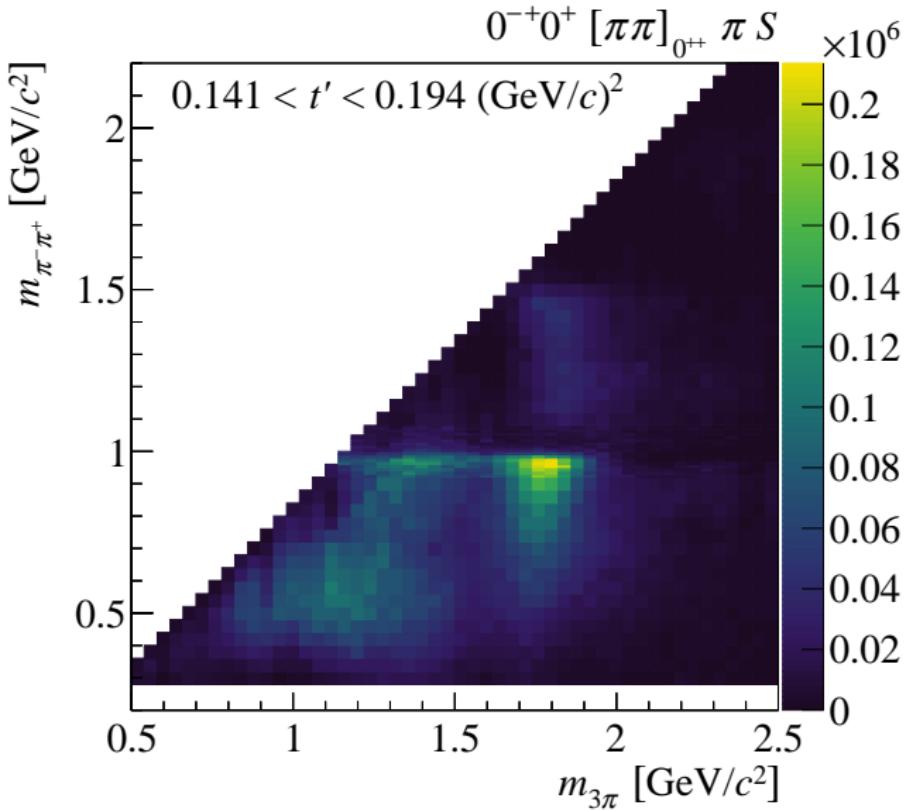


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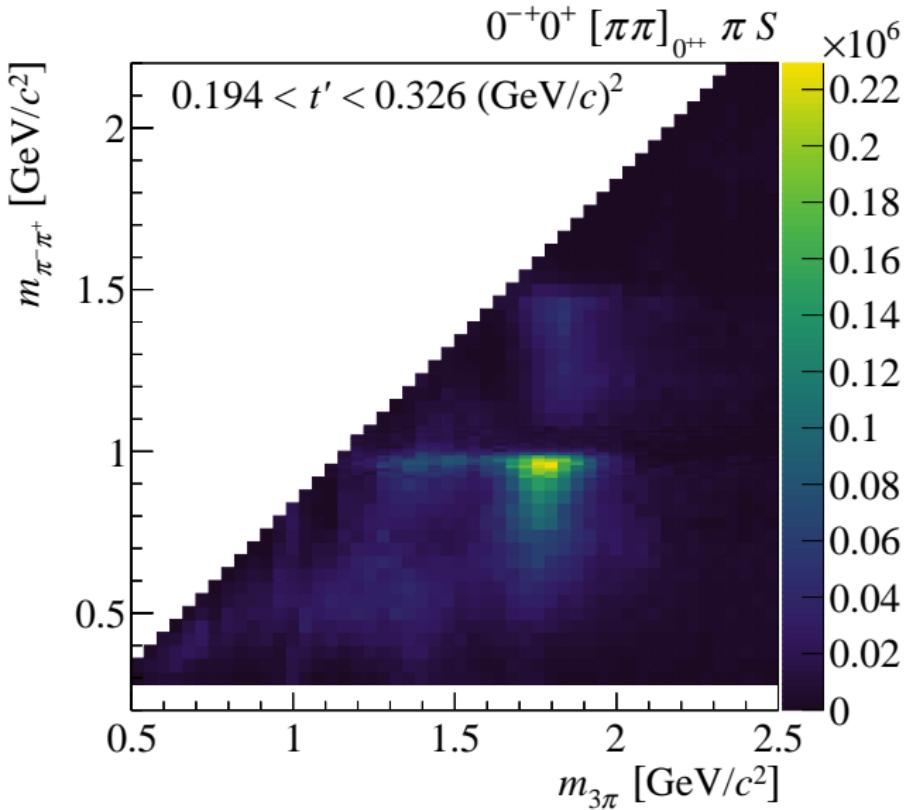


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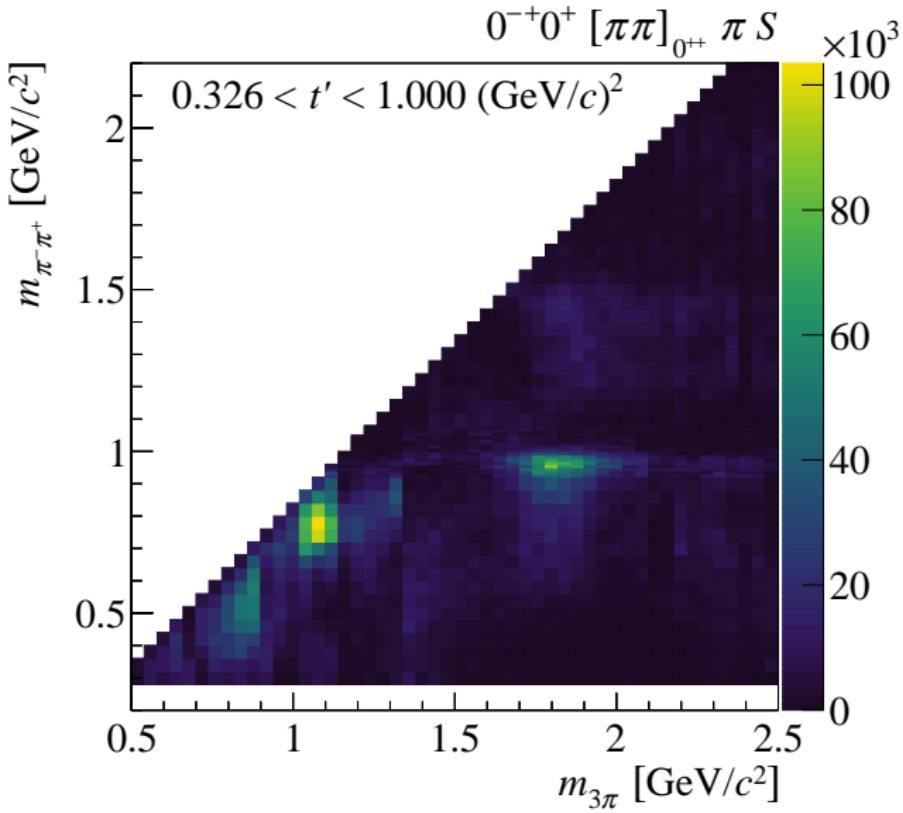


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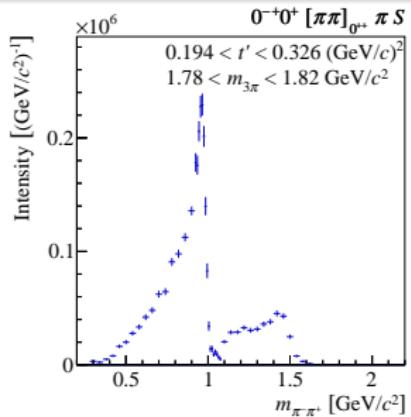


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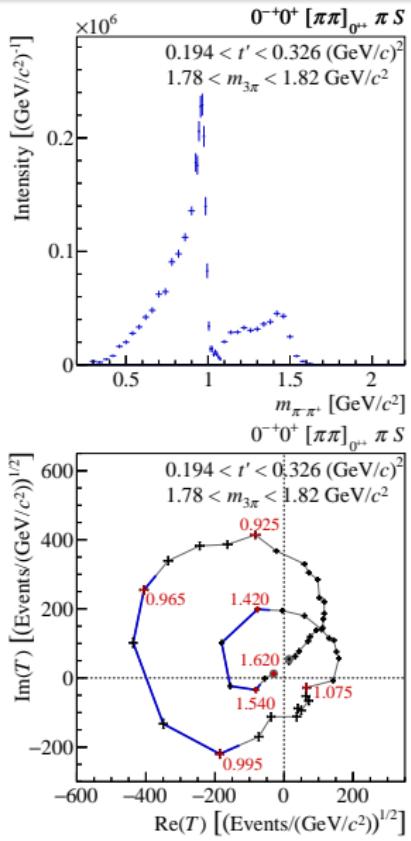
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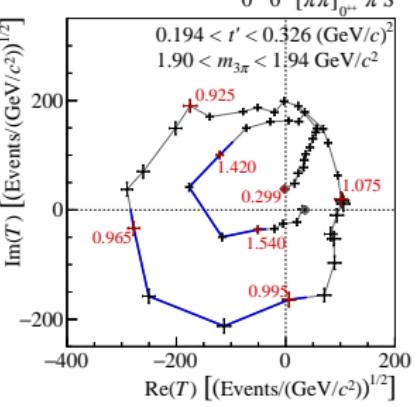
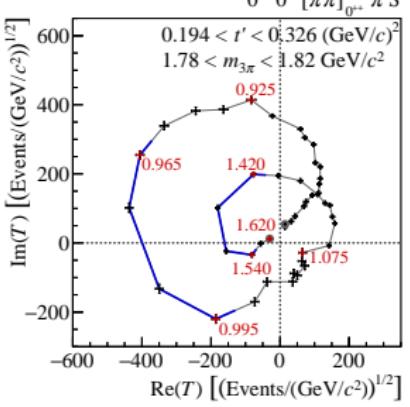
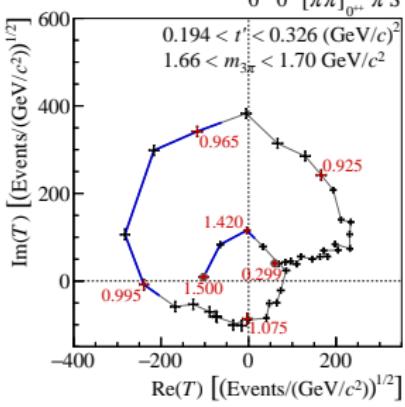
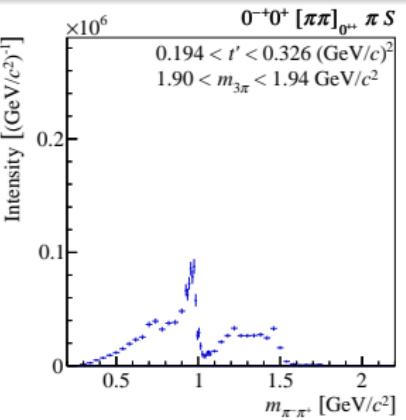
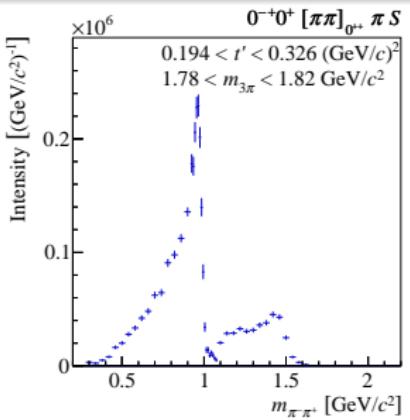
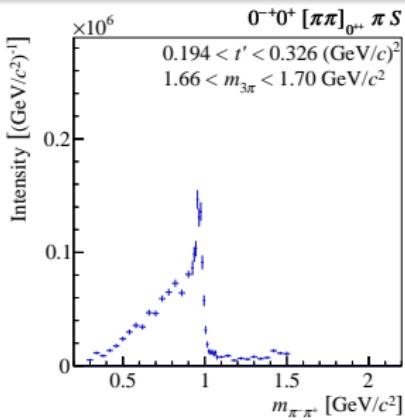
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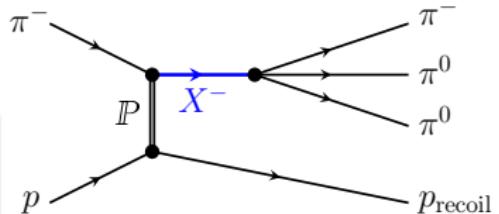
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Crosscheck with $\pi^-\pi^0\pi^0$

Two data sets

- ▶ Large data set of $\pi^-\pi^0\pi^0$ final state (3.5×10^6 events)
- ▶ Access to the same resonances X^-
- ▶ Very different acceptance
- ▶ Neutral and charged isobars
 - ▶ $I = 1$ isobars: $\pi^-\pi^0$
 - ▶ $I = 0$ isobars: $\pi^0\pi^0$



Comparison

- ▶ Similar signals in both data sets
- ▶ Also for weaker signals

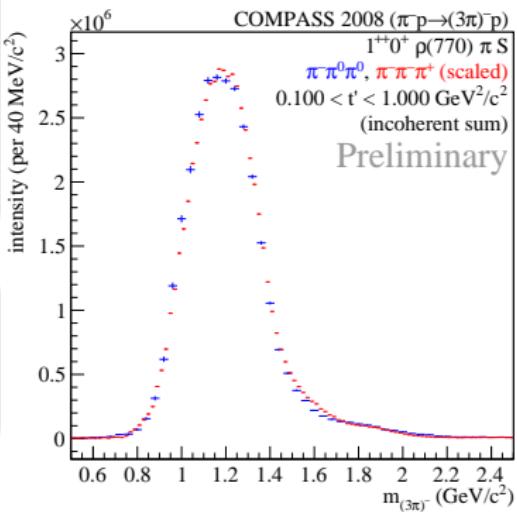
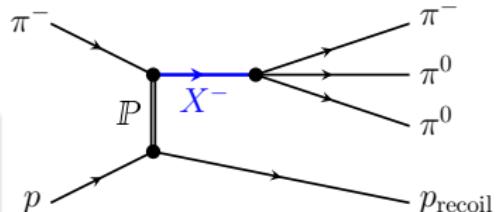
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