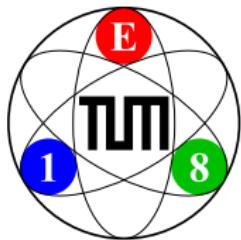


Light-Meson Spectroscopy at COMPASS

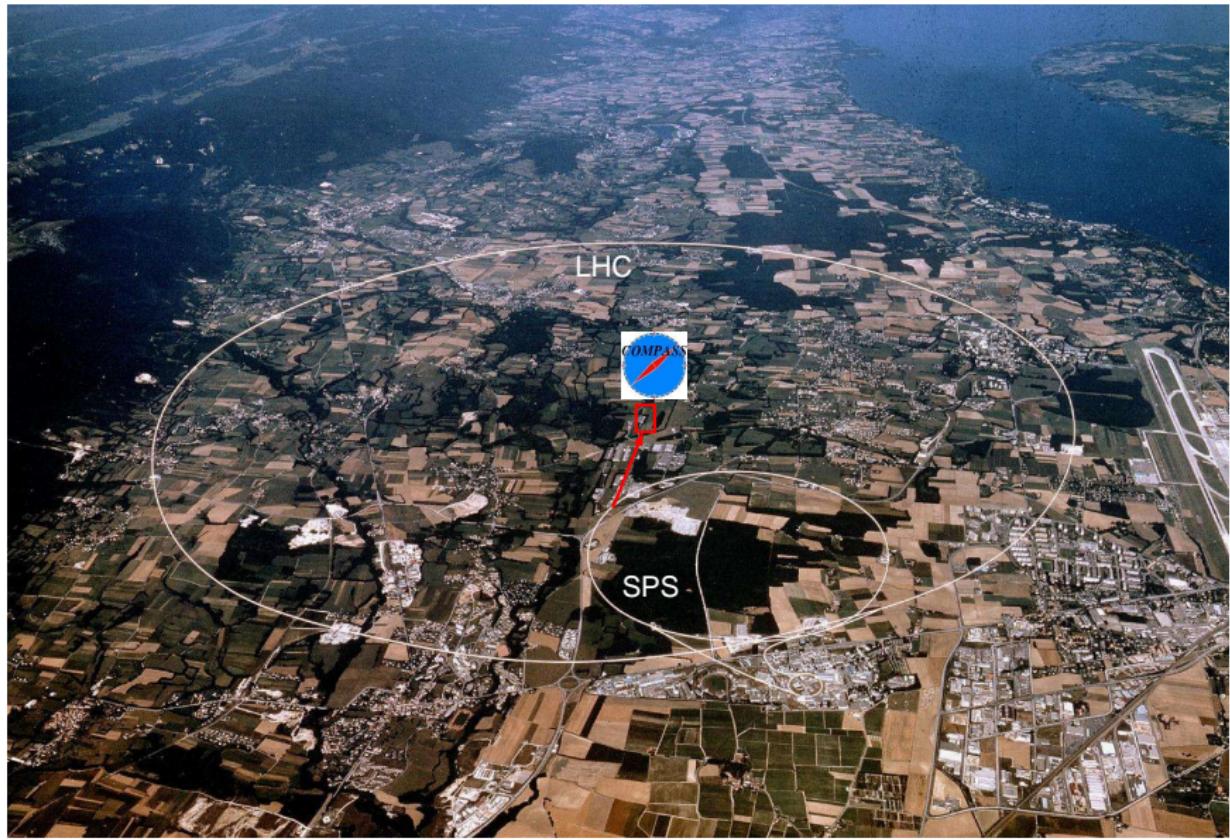
Fabian Krinner
for the COMPASS collaboration

Physik-Department E18
Technische Universität München



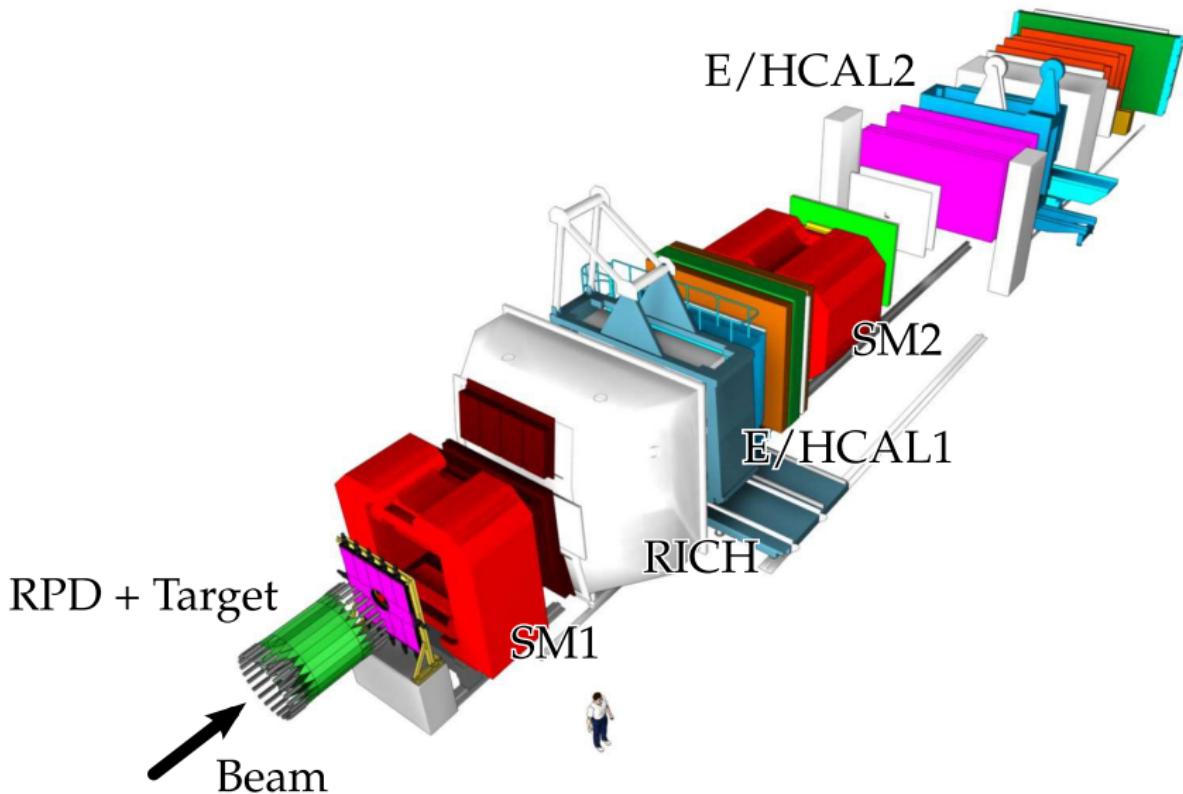
The COMPASS experiment

Located at CERN



The COMPASS experiment

Common Muon Proton Apparatus for Structure and Spectroscopy

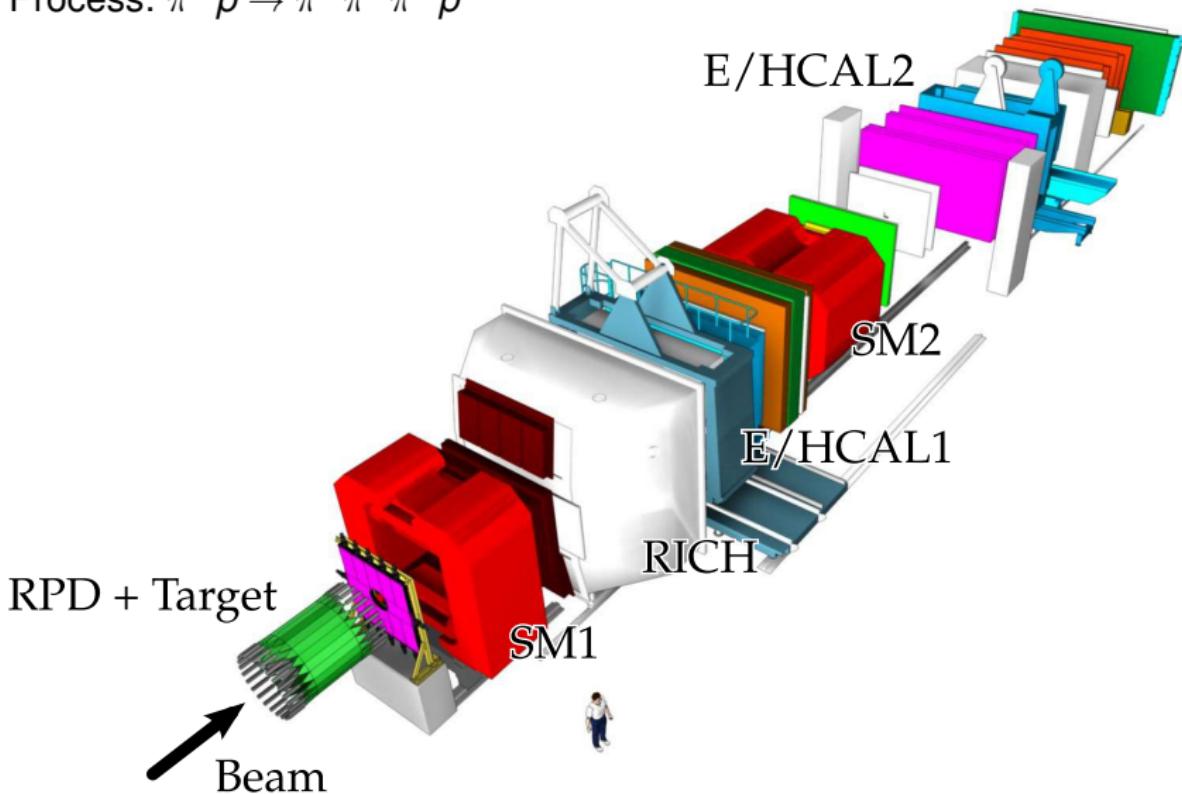


The COMPASS experiment

Common Muon Proton Apparatus for Structure and Spectroscopy



Process: $\pi^- p \rightarrow \pi^-\pi^+\pi^-p$



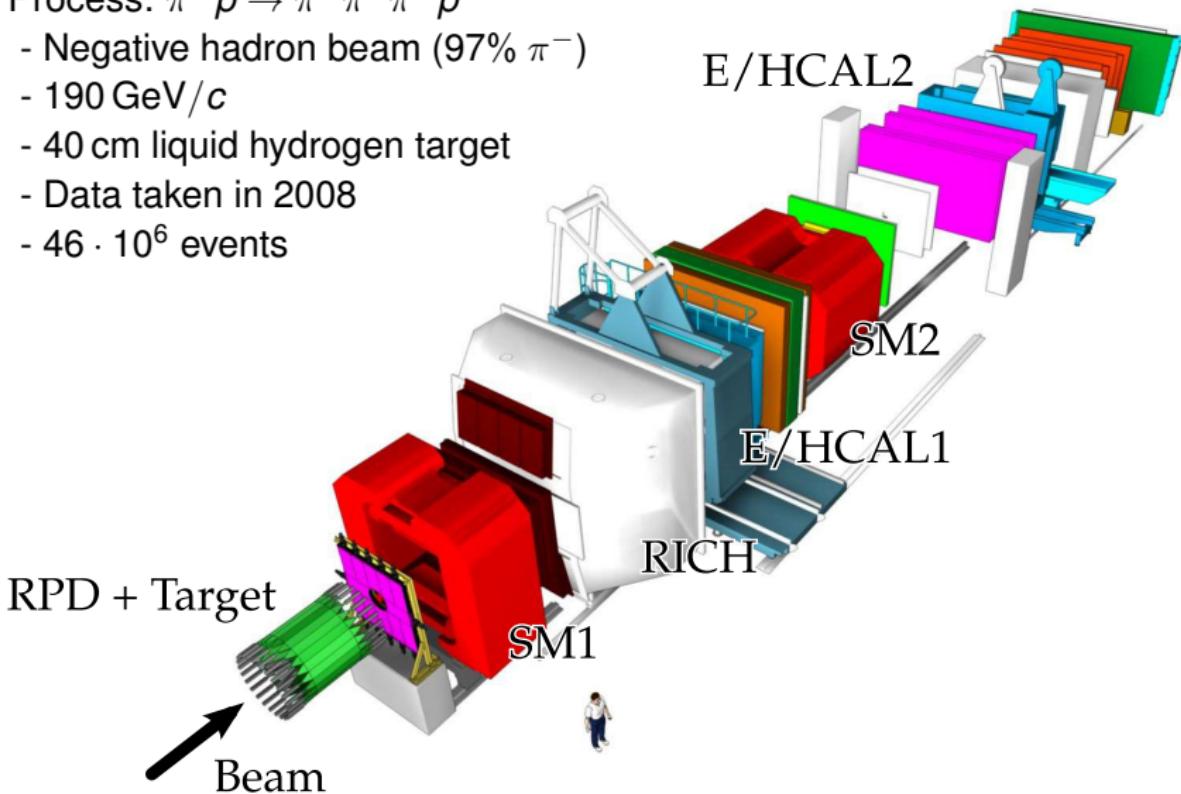
The COMPASS experiment

Common Muon Proton Apparatus for Structure and Spectroscopy

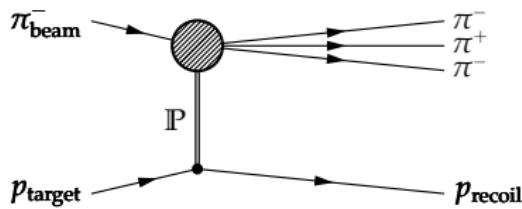


Process: $\pi^- p \rightarrow \pi^-\pi^+\pi^- p$

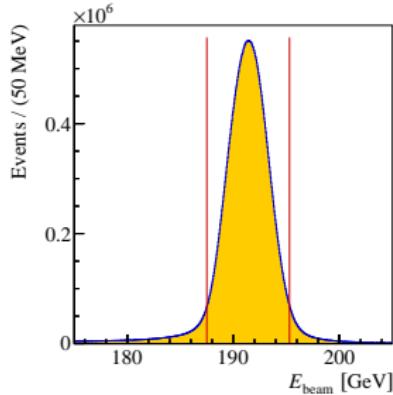
- Negative hadron beam (97% π^-)
- 190 GeV/c
- 40 cm liquid hydrogen target
- Data taken in 2008
- $46 \cdot 10^6$ events



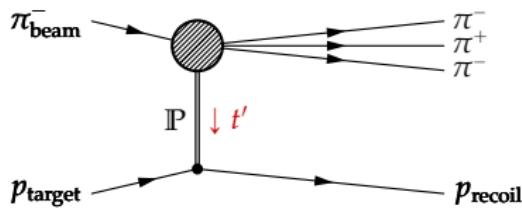
Diffractive 3π production



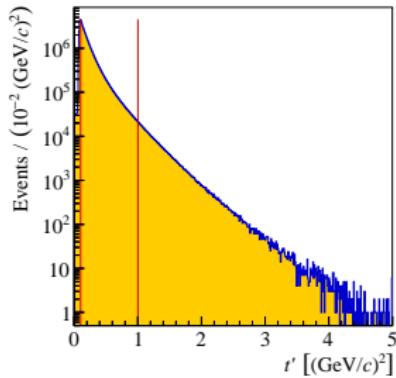
- Exclusive measurement



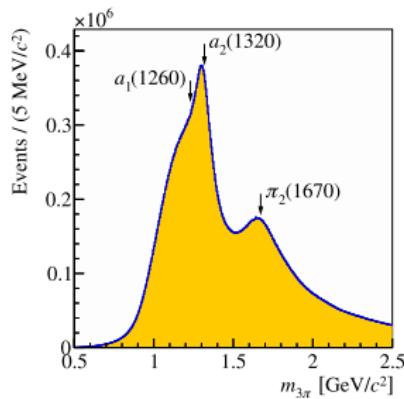
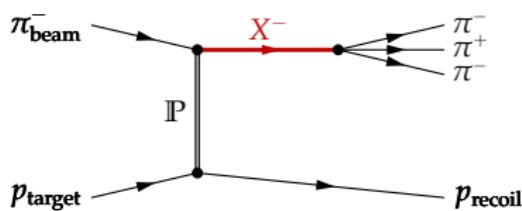
Diffractive 3π production



- Exclusive measurement
- Squared Four-momentum transfer
 $t' = t_{\min} - t$ by Pomeron \mathbb{P}

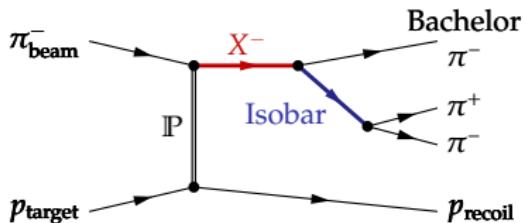


Diffractive 3π production

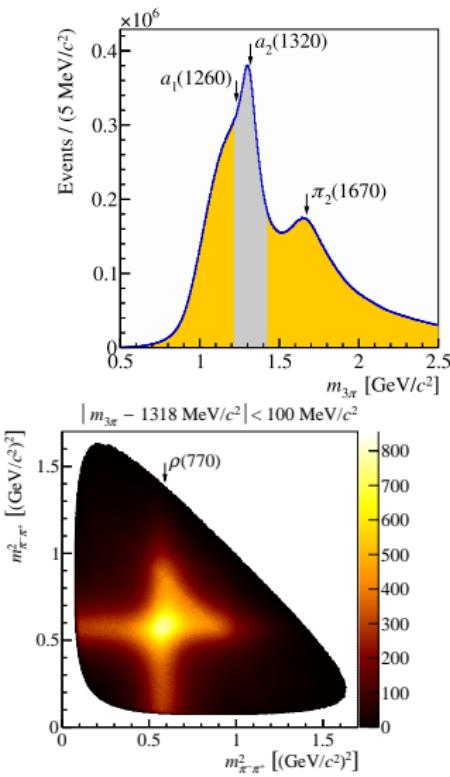


- Exclusive measurement
- Squared Four-momentum transfer $t' = t_{\min} - t$ by Pomeron \mathbb{P}
- Rich structure in $\pi^-\pi^+\pi^-$ mass spectrum

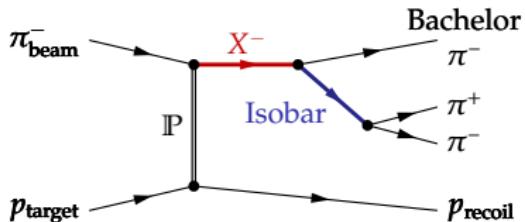
Diffractive 3π production



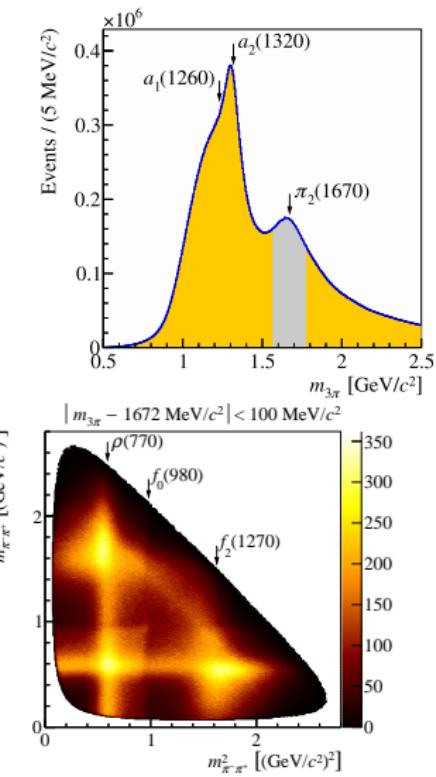
- Exclusive measurement
- Squared Four-momentum transfer $t' = t_{min} - t$ by Pomeron \mathbb{P}
- Rich structure in $\pi^-\pi^+\pi^-$ mass spectrum
- ... and in the $\pi^+\pi^-$ subsystem



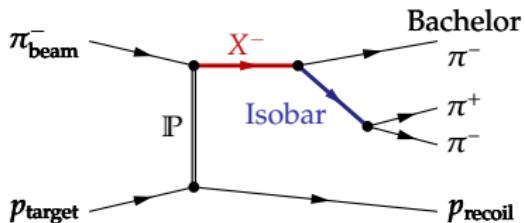
Diffractive 3π production



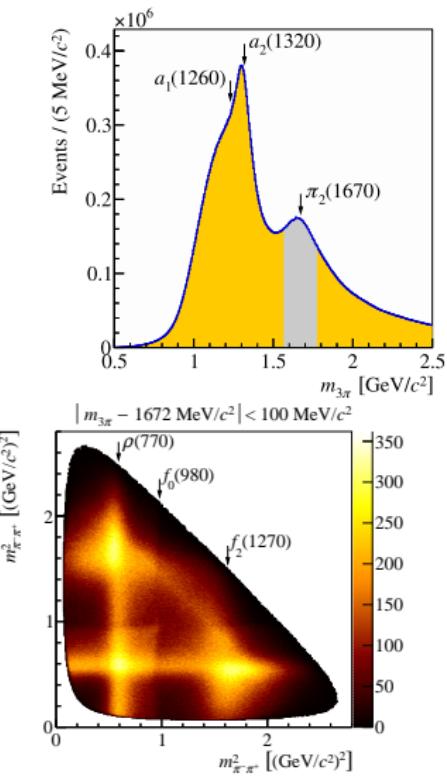
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- Rich structure in $\pi^-\pi^+\pi^-$ mass spectrum
- ... and in the $\pi^+\pi^-$ subsystem
- Correlated with $m_{3\pi}$



Diffractive 3π production



- Exclusive measurement
- Squared Four-momentum transfer $t' = t_{min} - t$ by Pomeron \mathbb{P}
- Rich structure in $\pi^-\pi^+\pi^-$ mass spectrum
- ... and in the $\pi^+\pi^-$ subsystem
- Correlated with $m_{3\pi}$
→ Structures to be analysed in the isobar (resonance) model



Data

Resonance Parameters

Masses and widths of the meson resonances

Data

(I) Partial-Wave
Decomposition

Partial Waves

Intensities and relative phases of the partial waves

Resonance Parameters

Masses and widths of the meson resonances

Analysis procedure

Data

(I) Partial-Wave
Decomposition

Partial Waves

Intensities and relative phases of the partial waves

(II) Resonance-Model Fit

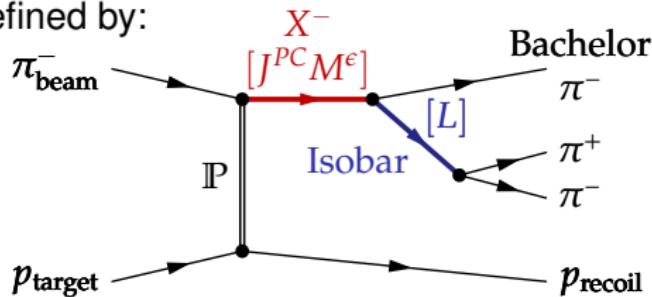
Resonance Parameters

Masses and widths of the meson resonances

$$\text{Intensity } \mathcal{I} = \left| \sum_{\text{waves}} T^{\text{wave}} \mathcal{A}^{\text{wave}} \right|^2$$

Waves defined by:

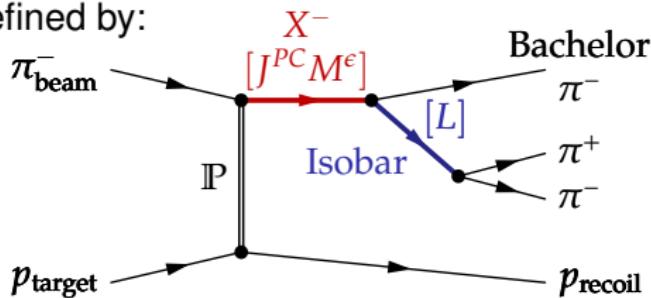
$$J^{PC} M^\varepsilon \xi \pi L$$



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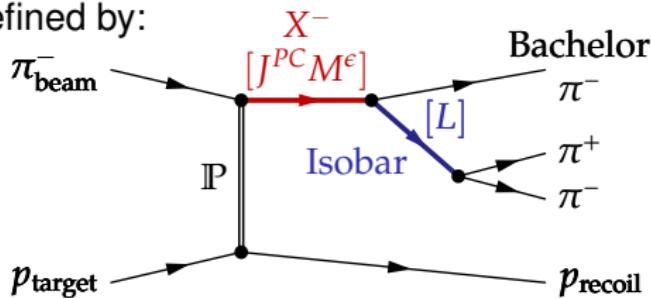


- J^{PC} : Spin and eigenvalues under parity and charge conjugation of X^-

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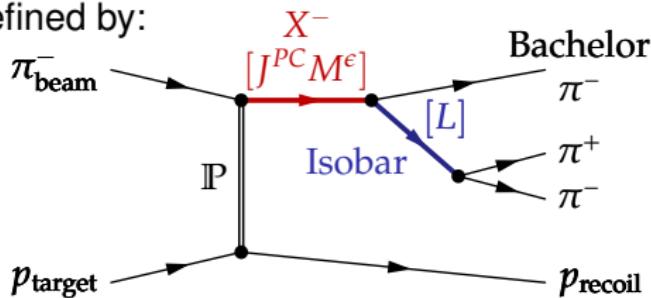


- J^{PC} : Spin and eigenvalues under parity and charge conjugation of X^-
- M^ε : Spin projection and naturality of the exchange particle

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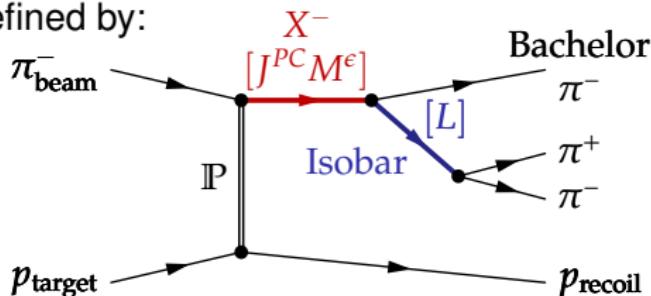


- J^{PC} : Spin and eigenvalues under parity and charge conjugation of X^-
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- ξ : Appearing isobar, e.g. $\rho(770)$

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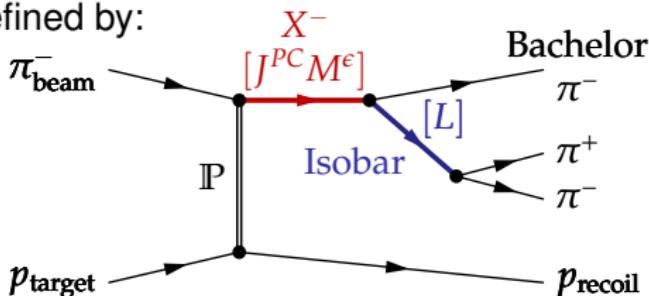


- J^{PC} : Spin and eigenvalues under parity and charge conjugation of X^-
- M^ε : Spin projection and naturality of the exchange particle
- ξ : Appearing isobar, e.g. $\rho(770)$
- π : Indicating the bachelor π^- . The same in all waves

$$\text{Intensity } \mathcal{I} = \left| \sum_{\text{waves}} T^{\text{wave}} \mathcal{A}^{\text{wave}} \right|^2$$

Waves defined by:

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



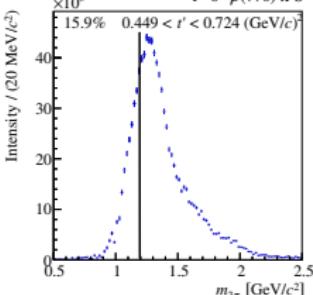
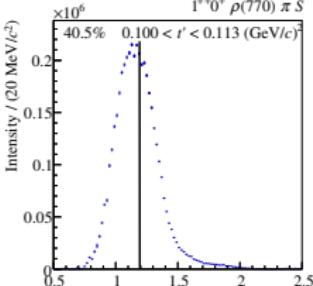
- J^{PC} : Spin and eigenvalues under parity and charge conjugation of Ξ^-
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- ξ : Appearing isobar, e.g. $\rho(770)$
- π : Indicating the bachelor π^- . The same in all waves
- L : Orbital angular momentum between isobar and bachelor pion

Step 1: Partial-Wave Analysis

Selected Waves (1 out of total 88) in one of 11 independent bins in t'

Low t'

$1^{++} 0^+ \rho(770) \pi S$



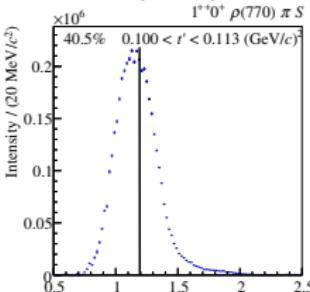
High t'

Step 1: Partial-Wave Analysis

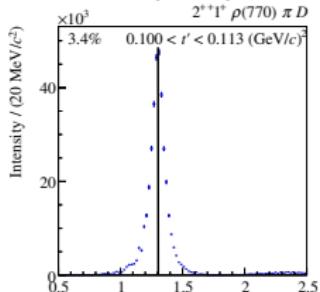
Selected Waves (2 out of total 88) in one of 11 independent bins in t'

Low t'

$$1^{++} 0^+ \rho(770) \pi S$$

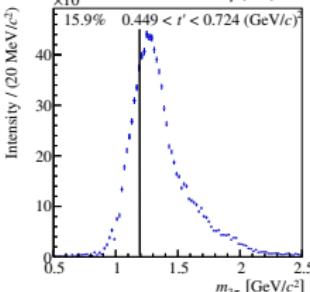


$$2^{++} 1^+ \rho(770) \pi D$$

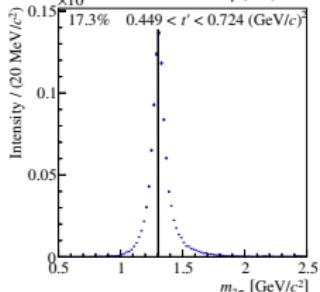


High t'

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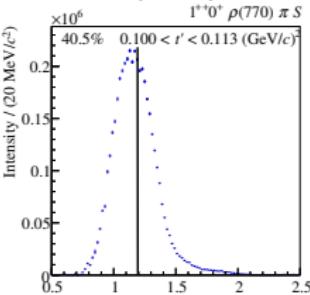


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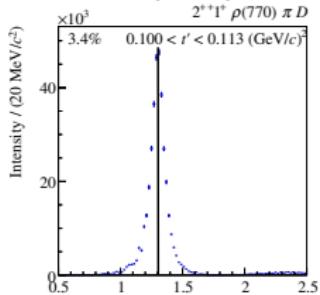
Selected Waves (3 out of total 88) in one of 11 independent bins in t'

Low t'

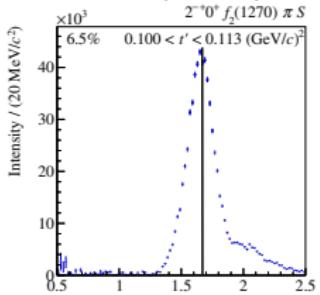
$$1^{++} 0^+ \rho(770) \pi S$$



$$2^{++} 1^+ \rho(770) \pi D$$

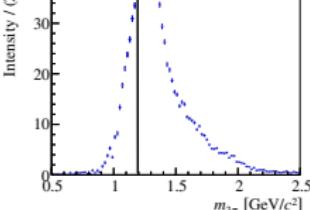


$$2^{-+} 0^+ f_2(1270) \pi S$$

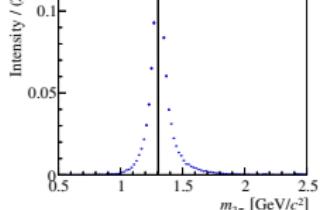


High t'

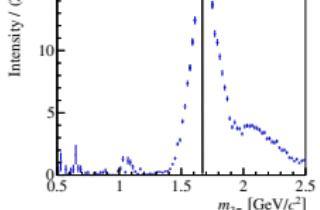
$$1^{++} 0^+ \rho(770) \pi S$$



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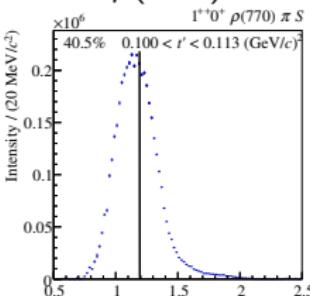


Step 1: Partial-Wave Analysis

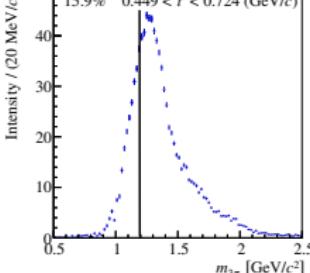
Selected Waves (4 out of total 88) in one of 11 independent bins in t'

Low t'

$1^{++}0^+\rho(770)\pi S$

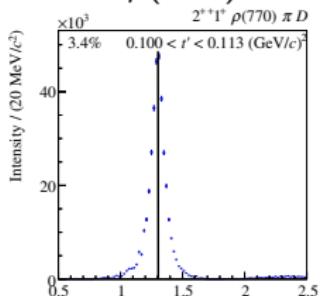


$1^{++}0^+\rho(770)\pi S$

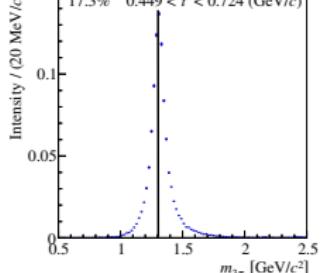


High t'

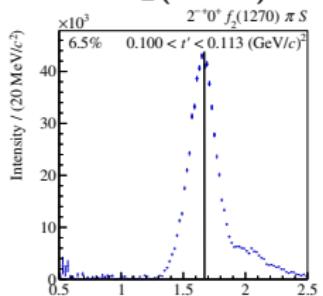
$2^{++}1^+\rho(770)\pi D$



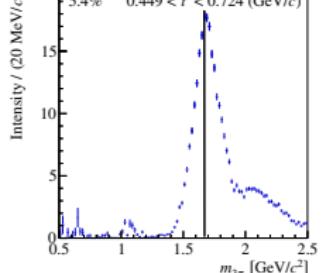
$2^{++}1^+\rho(770)\pi D$



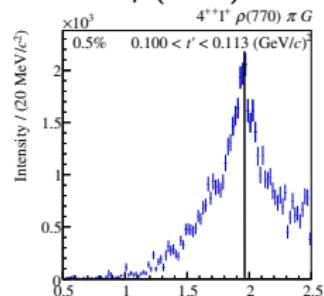
$2^{-+}0^+f_2(1270)\pi S$



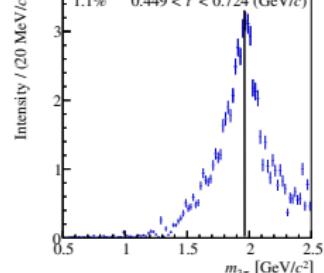
$2^{-+}0^+f_2(1270)\pi S$



$4^{++}1^+\rho(770)\pi G$



$4^{++}1^+\rho(770)\pi G$



Step 2: Resonance-Model Fit

Spin-Density Matrix:

- Diagonal elements: Intensities: $\text{SDM}_{ii} = |T_i|^2$
- Off-diagonal elements: Phases: $\text{SDM}_{ij} = -\text{SDM}_{ji} = \arg(T_i T_j^*)$

Step 2: Resonance-Model Fit

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Resonance model for spin-density matrix

- 14×14 submatrix of 88×88 SDM from partial-wave decomposition

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- 76505 data points

Step 2: Resonance-Model Fit

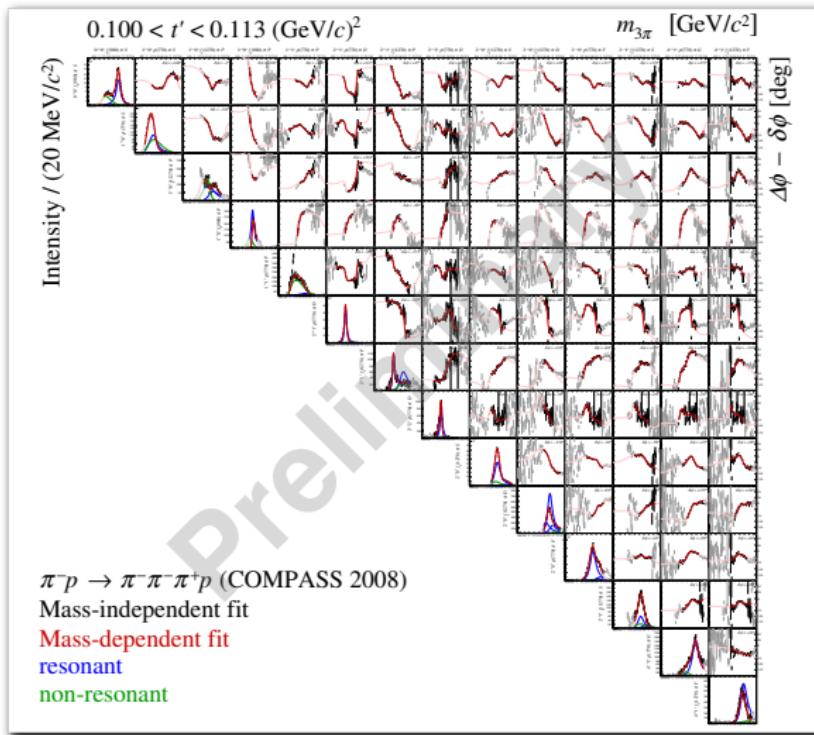
Spin-Density Matrix:

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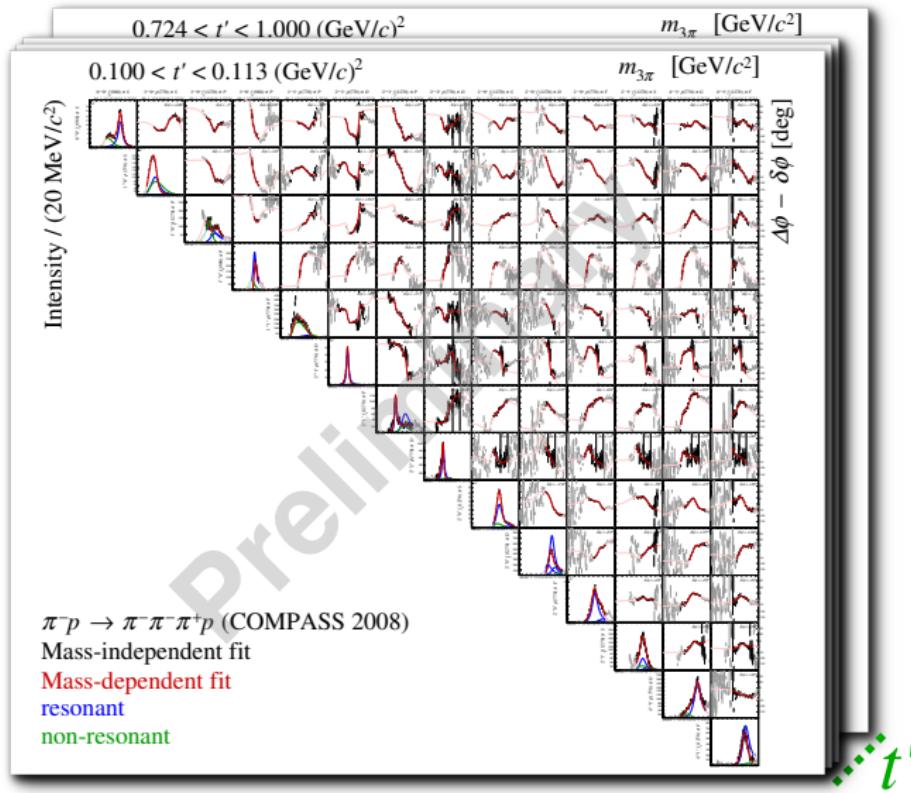
Resonance model for spin-density matrix

- 14×14 submatrix of 88×88 SDM from partial-wave decomposition
- Model resonances with Breit-Wigner amplitudes
- Each wave: One non-resonant background term
 - ▶ Phenomenological parametrization
 - ▶ Partial-Wave projections of the Deck-effect
- All 11 t' bins are fitted simultaneously; resonance parameters are the same in all t' bins
- 76505 data points
- 722 free parameters
 - ▶ Only 51 shape parameters
 - ▶ Rest: Couplings (Complex prefactors of model terms)

Resonance-Model Fit

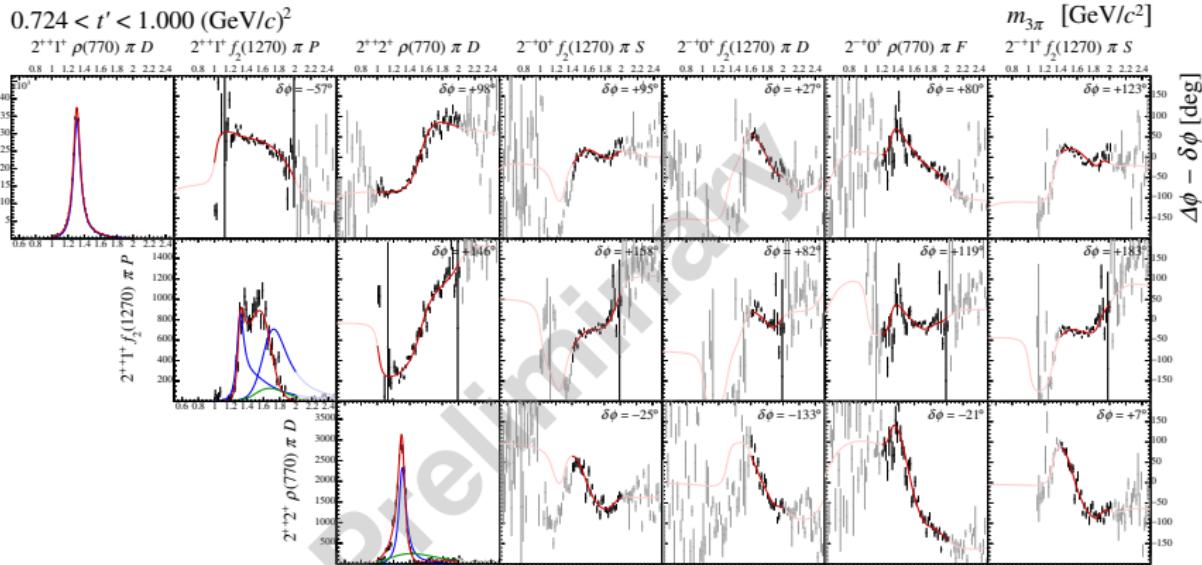


Resonance-Model Fit



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

Intensity / (20 MeV/c²)

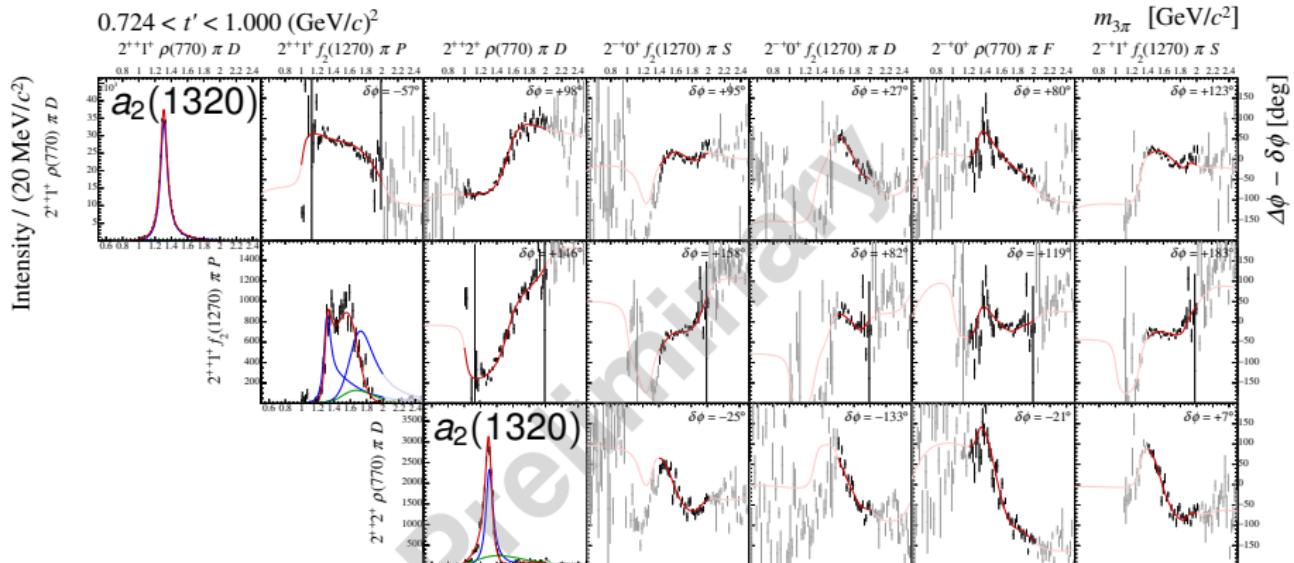
 $2^{++1^+} \rho(770) \pi D$

 $\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$ (COMPASS 2008)

Mass-independent fit

Mass-dependent fit

resonant

non-resonant

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

 $\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$ (COMPASS 2008)

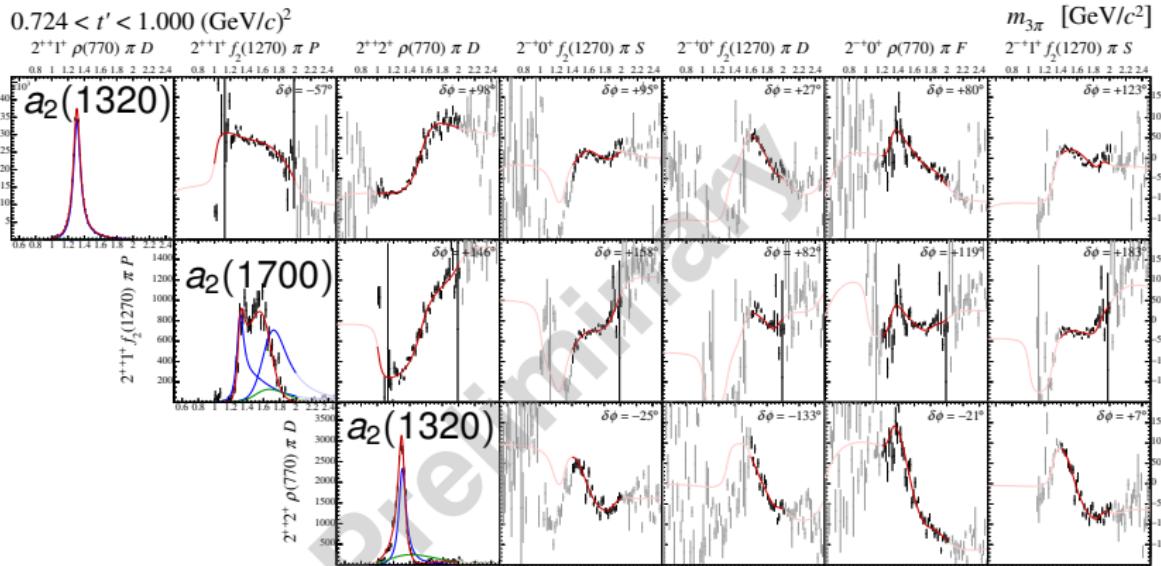
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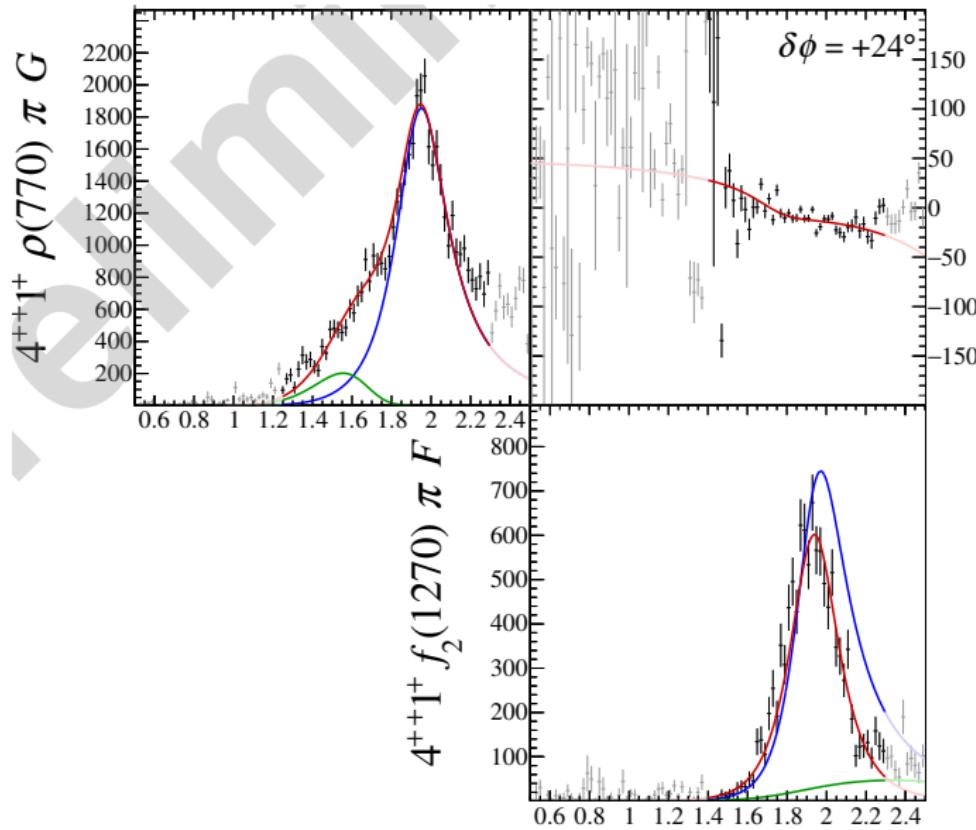
Mass-independent fit

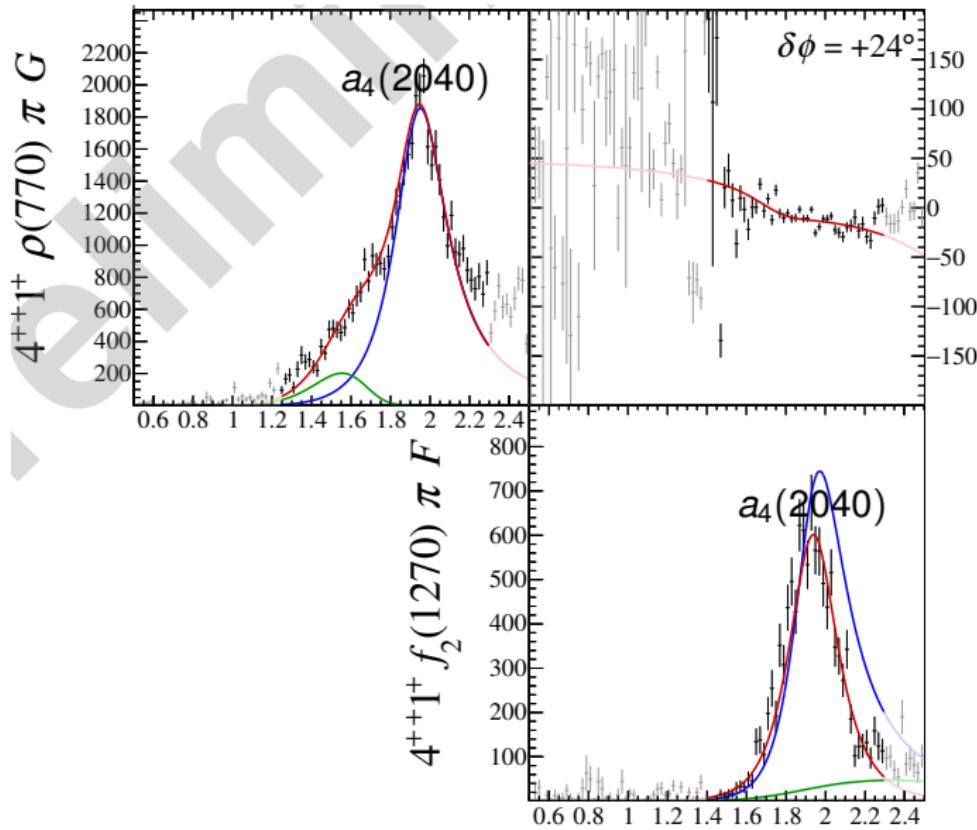
Mass-dependent fit

resonant

non-resonant

$J^{PC} = 4^{++}$ sector

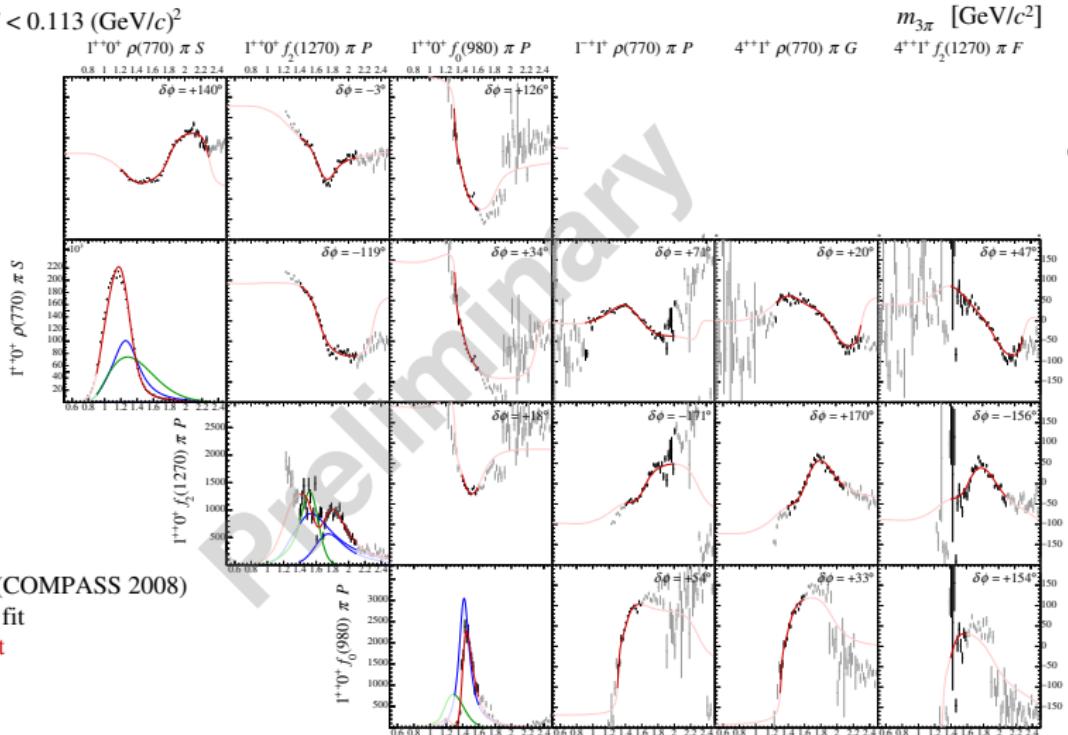




$J^{PC} = 1^{++}$ sector

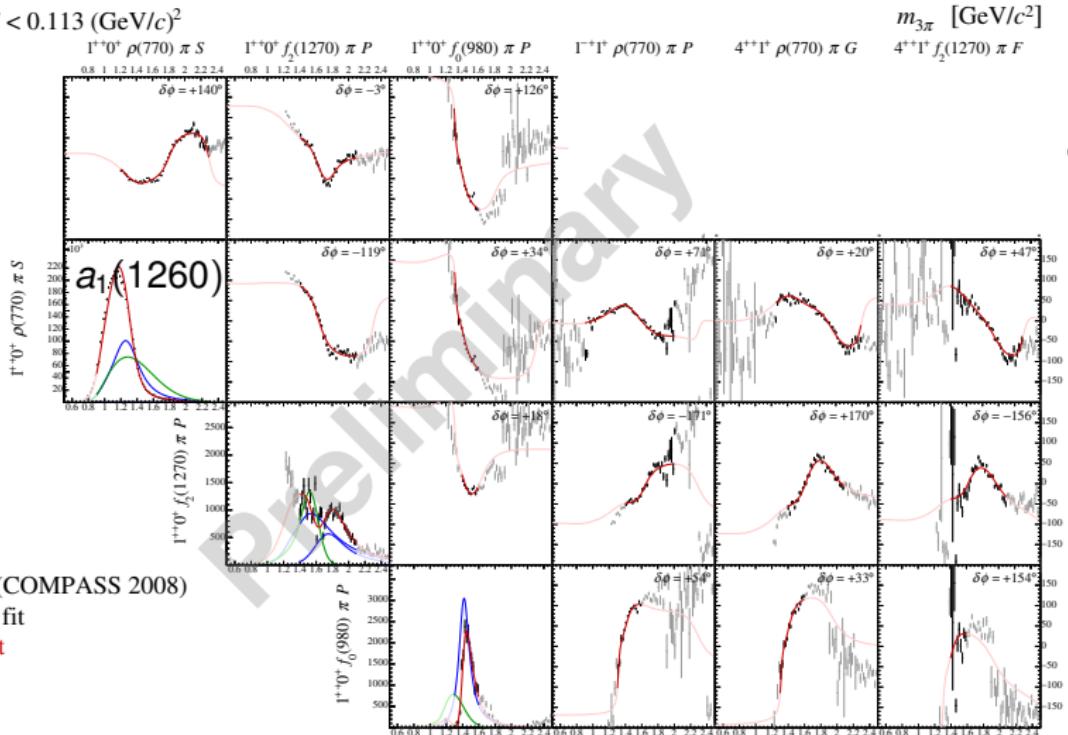
Intensity / (20 MeV/c²)

$0.100 < t' < 0.113$ (GeV/c)²



Intensity / (20 MeV/c²)

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$\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$ (COMPASS 2008)

Mass-independent fit

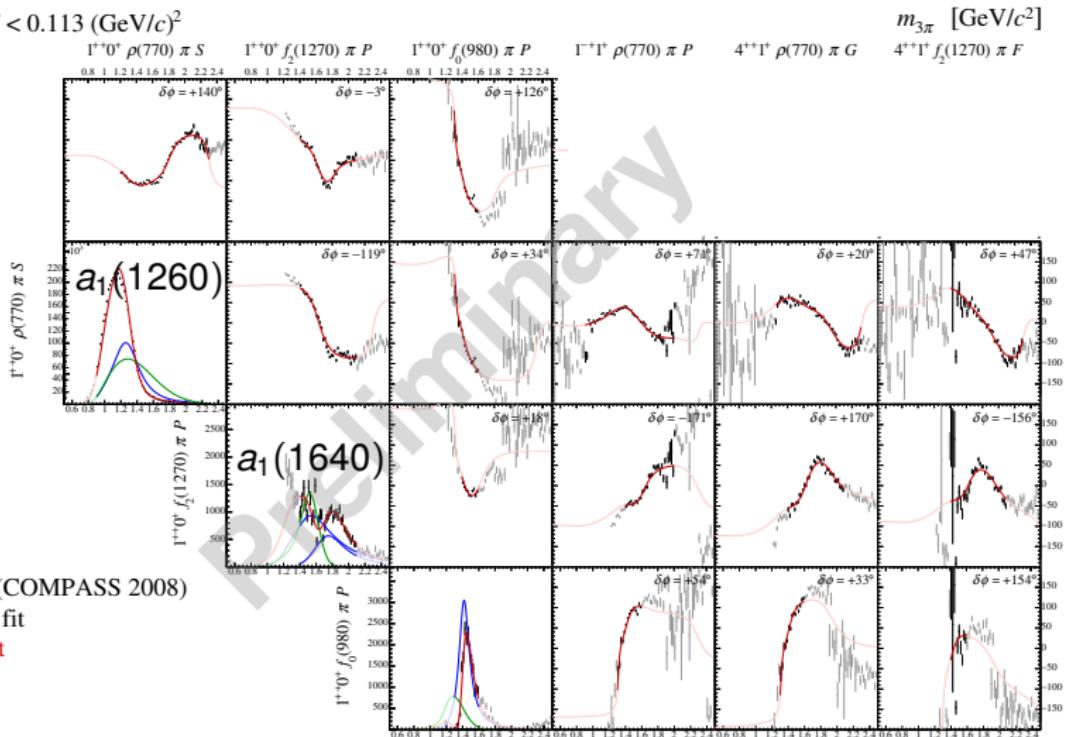
Mass-dependent fit

resonant

non-resonant

$0.100 < t' < 0.113 \text{ (GeV}/c^2)$

Intensity / $(20 \text{ MeV}/c^2)$



$\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$ (COMPASS 2008)

Mass-independent fit

Mass-dependent fit

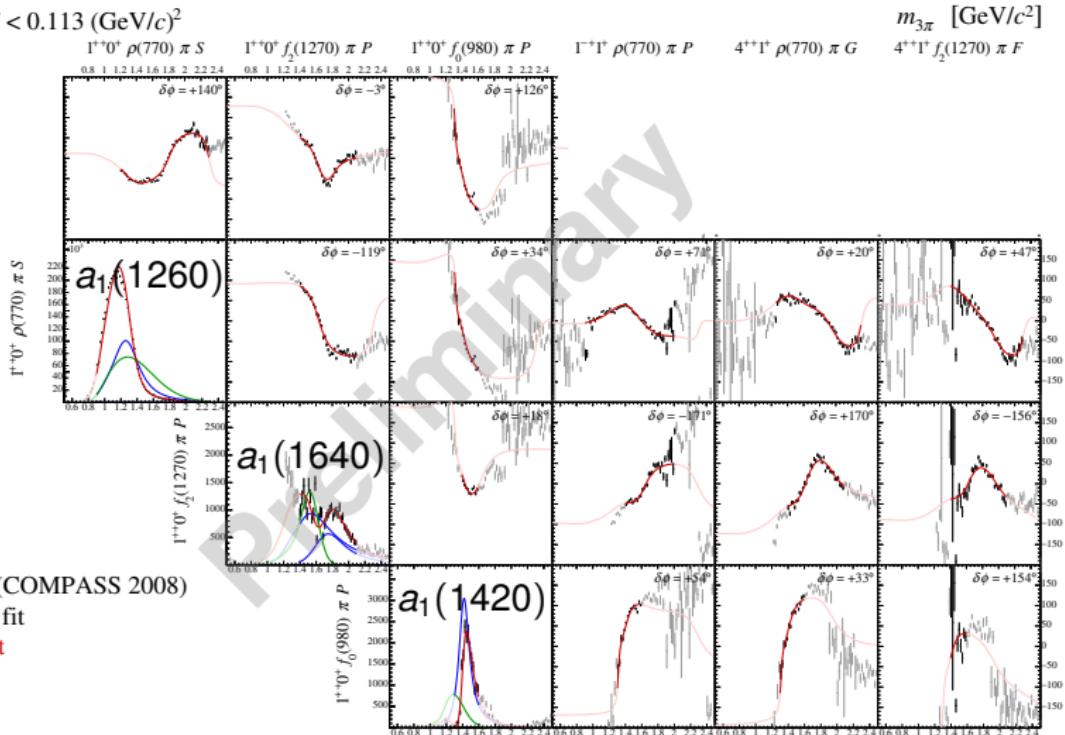
resonant

non-resonant

Intensity / (20 MeV/c²)

$\sigma^{-} \eta^+ f_0(980) \pi S$

$0.100 < t' < 0.113$ (GeV/c)²



$\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$ (COMPASS 2008)

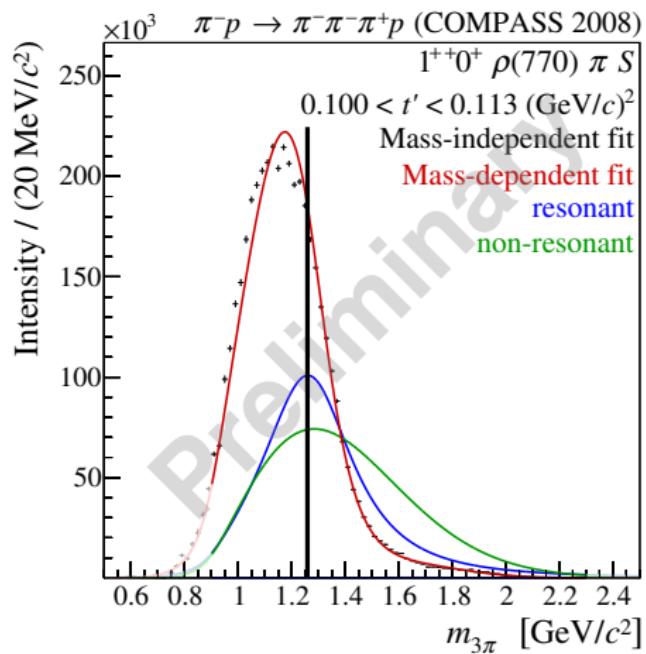
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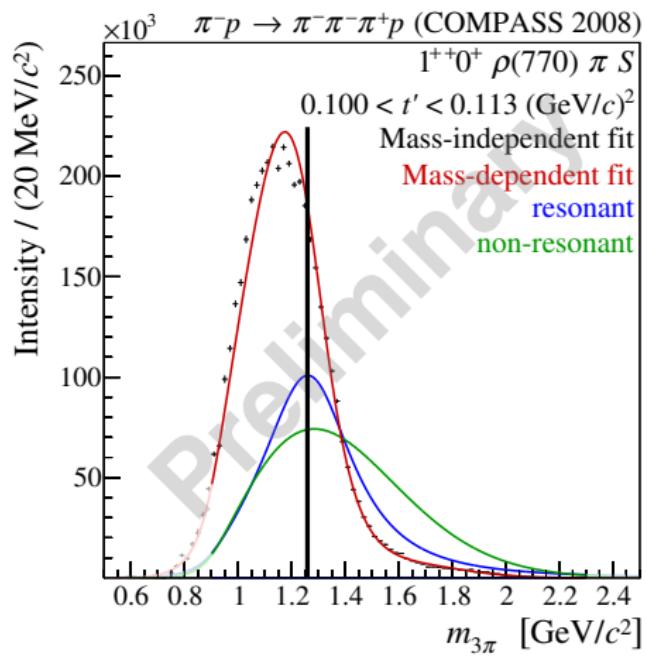
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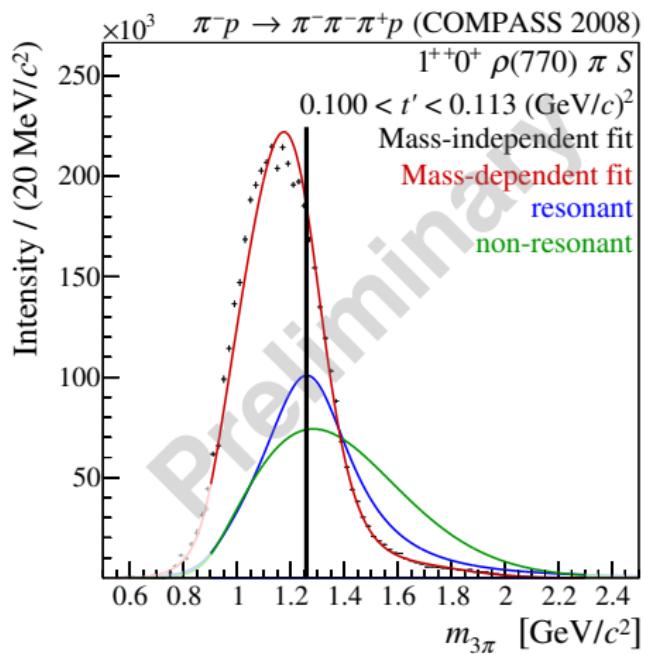
- Resonance parameters do not depend on production mechanism



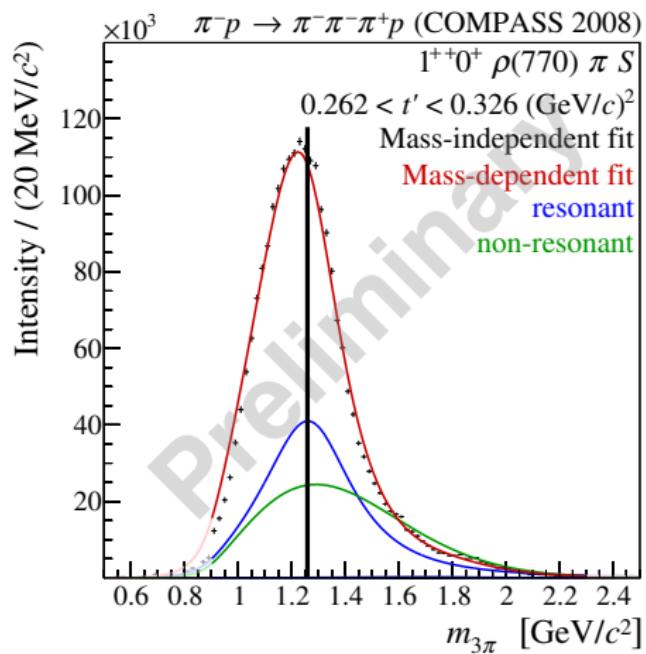
- Resonance parameters do not depend on production mechanism
- Couplings and non-resonant parts may vary with t'



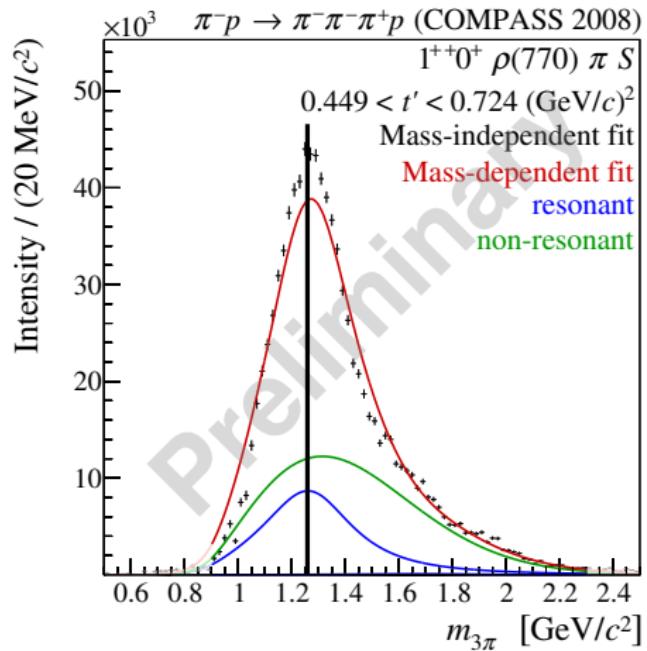
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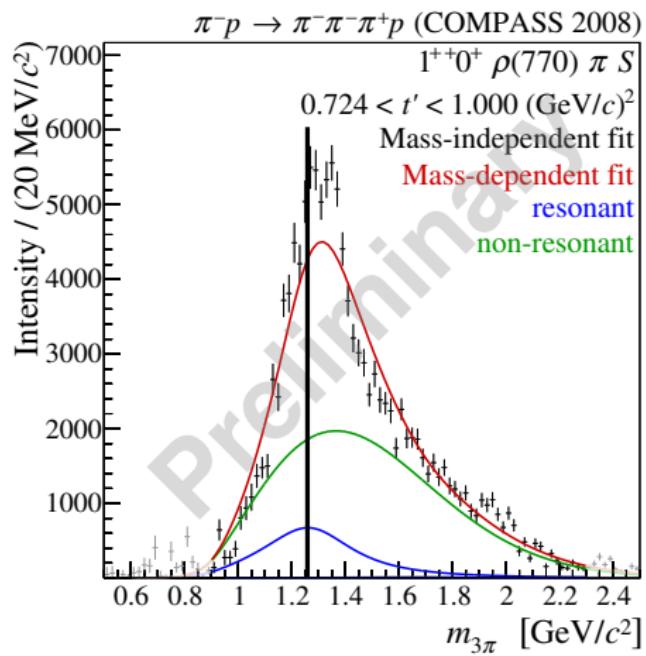
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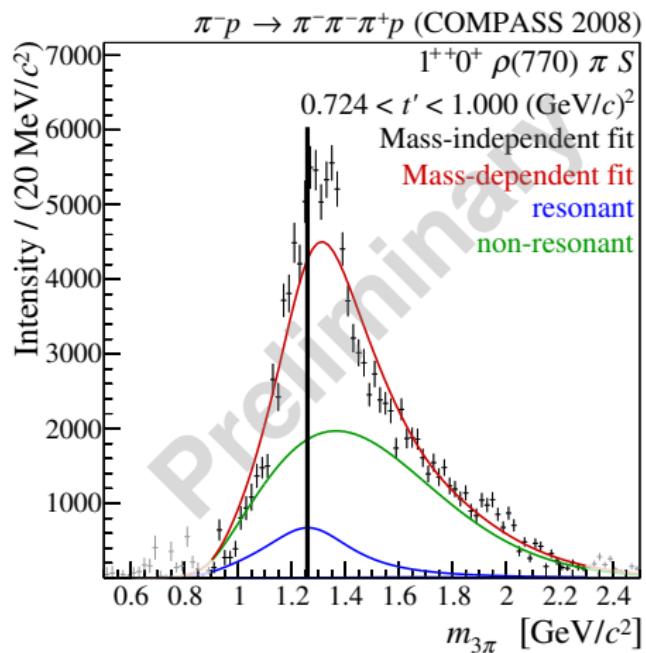


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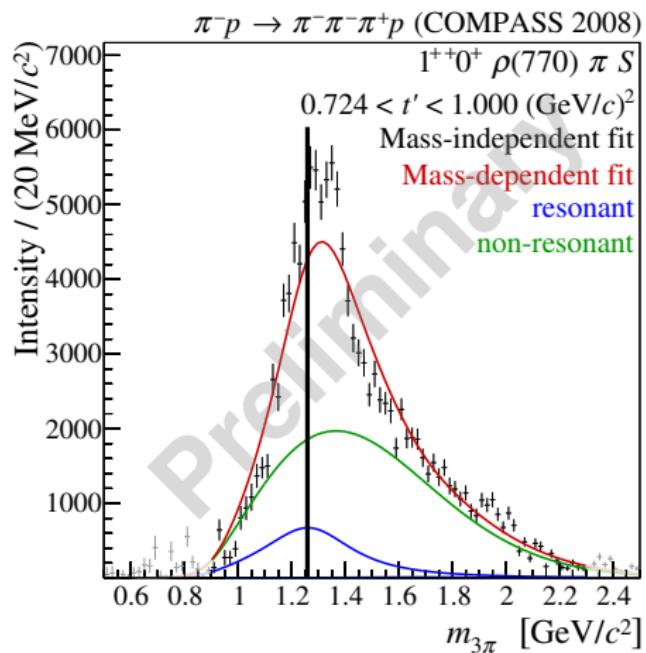


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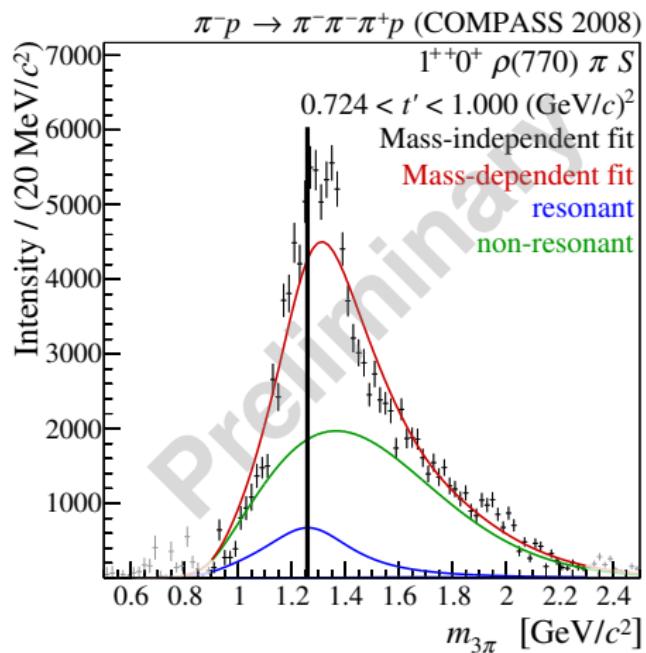
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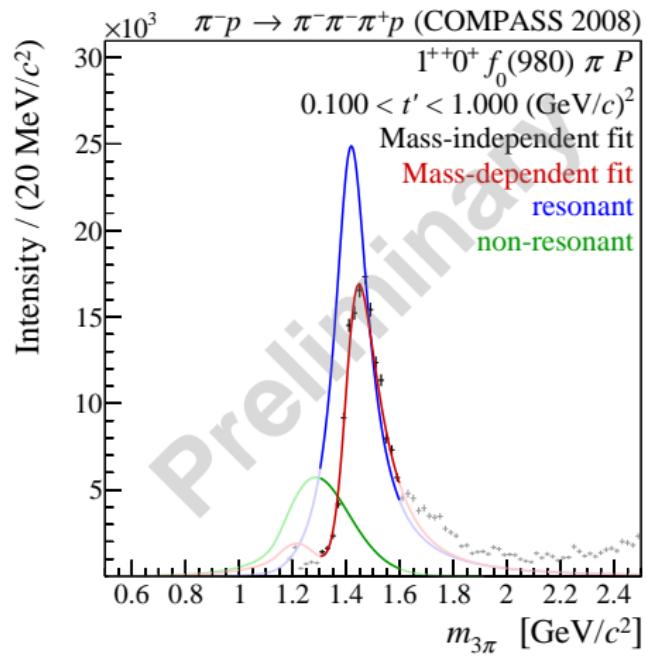
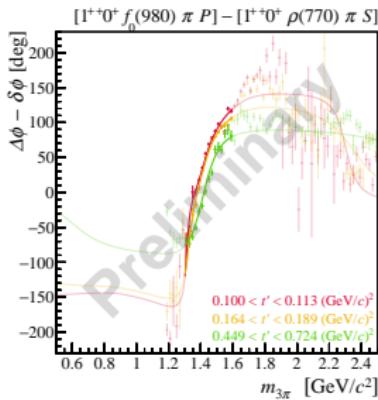


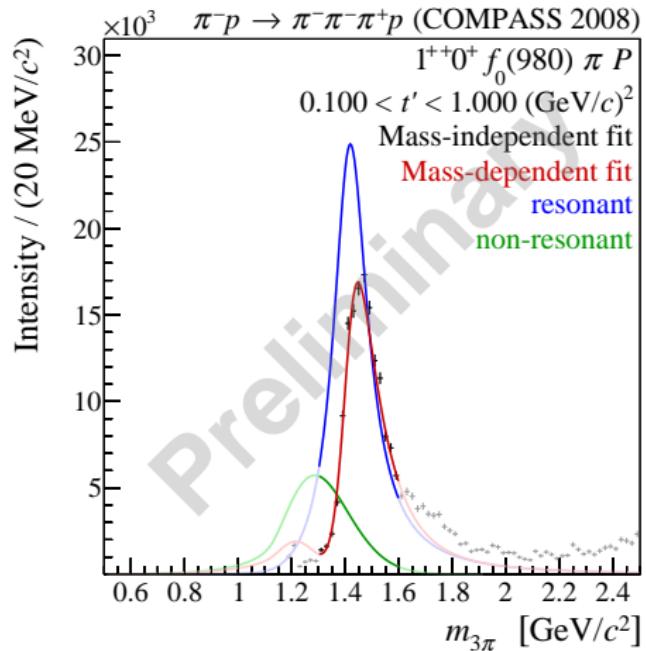
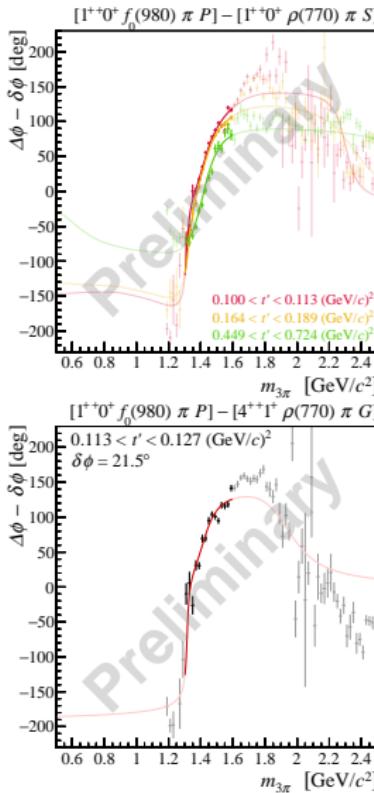
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- Weak signal for excited $a_1(1640)$; only visible in log-scale



$a_1(1420)$

A new signal: (Phys. Rev. Lett. 115, 082001 (2015))

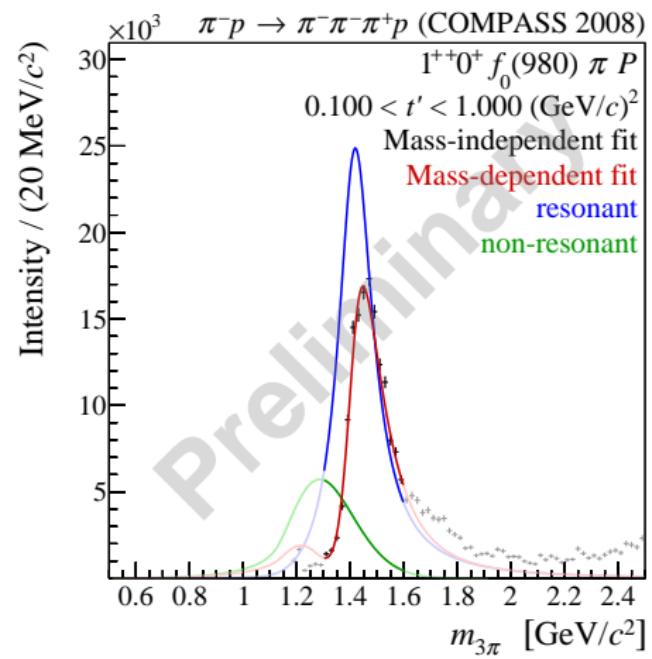




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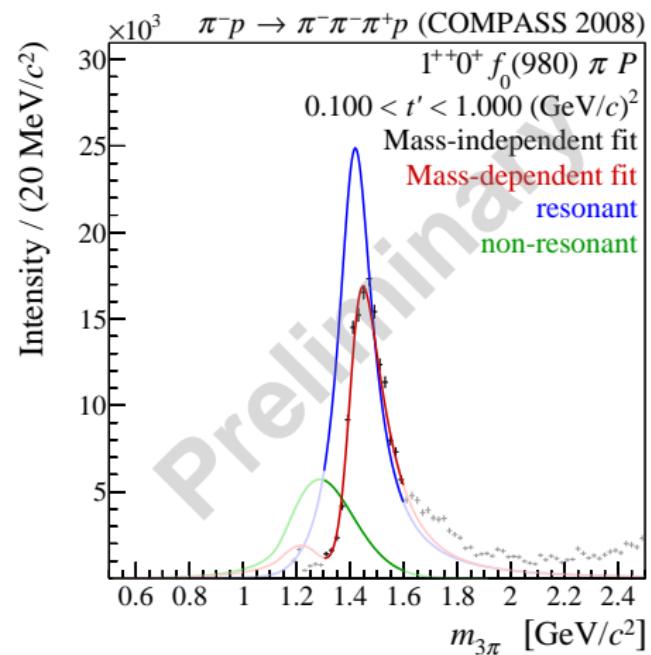
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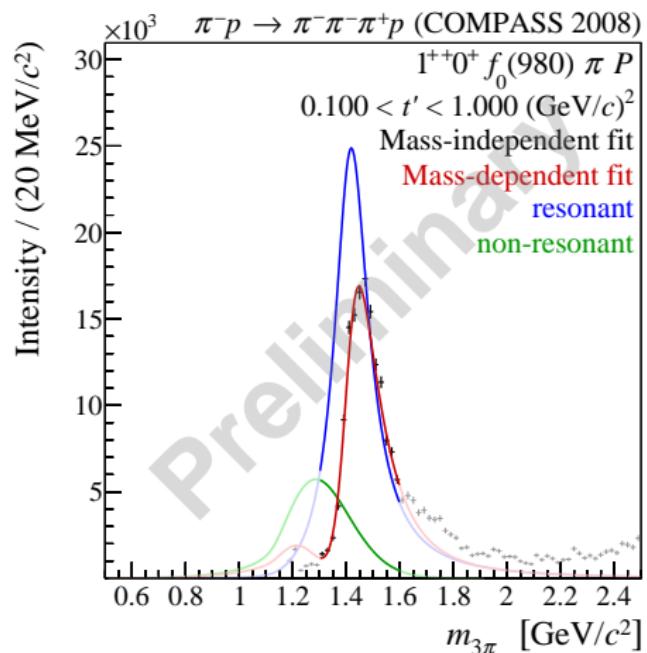
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M. Mikhasenko, B. Ketzer, A. Sarantsev: Phys. Rev. D 91, 094015 (2015)
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- Mass:
 $m_{a_1(1420)} = 1411.8^{+1.0}_{-4.4} \text{ MeV}/c^2$
Width:
 $\Gamma_{a_1(1420)} = 158^{+8}_{-8} \text{ MeV}/c^2$



Summary of the $a_J(\dots)$

$J^{PC} = 2^{++}$ sector:

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(Nearly no non-resonant contribution)
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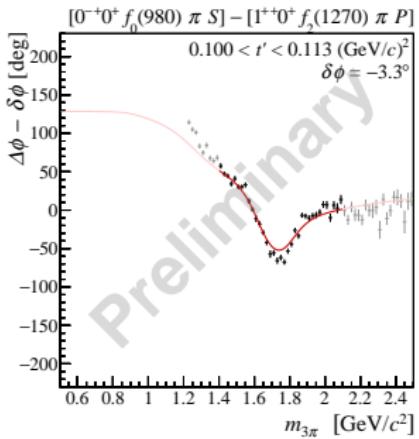
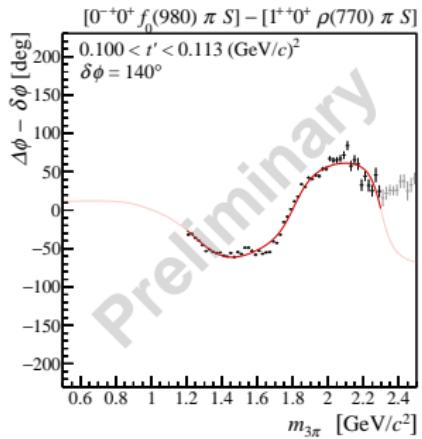
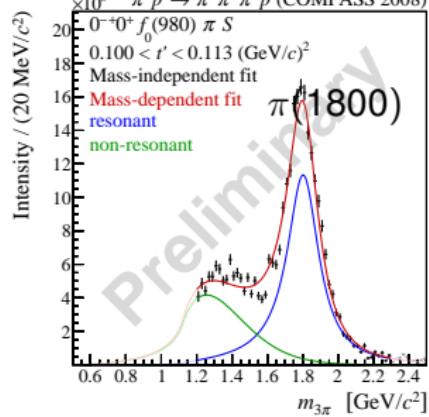
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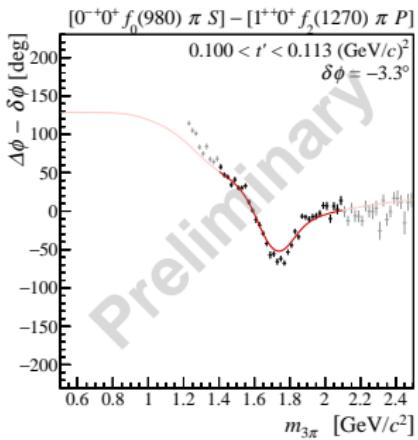
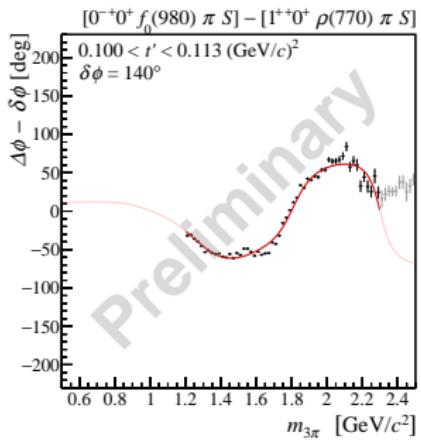
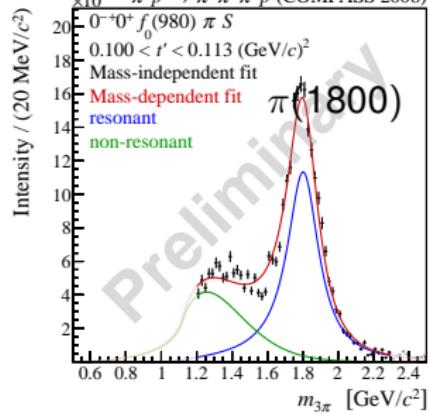
- $a_1(1260)$ and $a_1(1640)$ resonances in the main 1^{++} waves
- Distinguish from non-resonant part due to t' dependence
- New $a_1(1420)$ signal found in the $1^{++}0^+ f_0(980)\pi$ P wave

$$0^{-+} 0^+ f_0(980) \pi S$$

The $0^{-+}0^+ f_0(980)\pi S$ wave

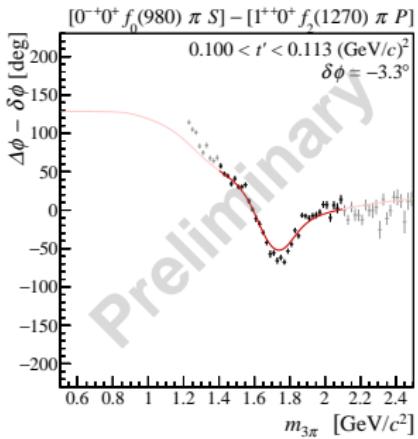
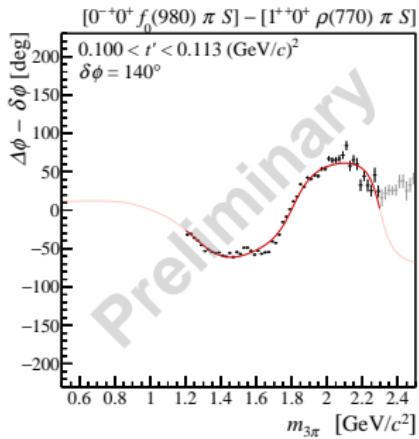
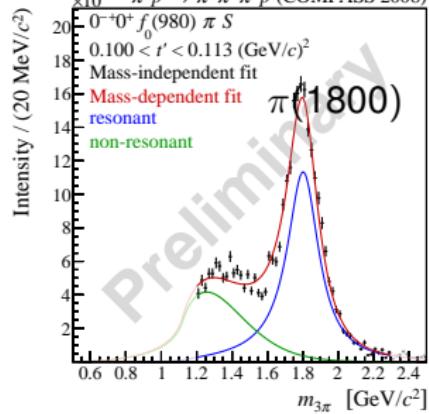


The $0^{-+}0^+ f_0(980)\pi S$ wave



$$m_{\pi(1800)} = 1802.6^{+8}_{-3.5} \text{ MeV}/c^2 ; \Gamma_{\pi(1800)} = 218^{+11}_{-6} \text{ MeV}/c^2$$

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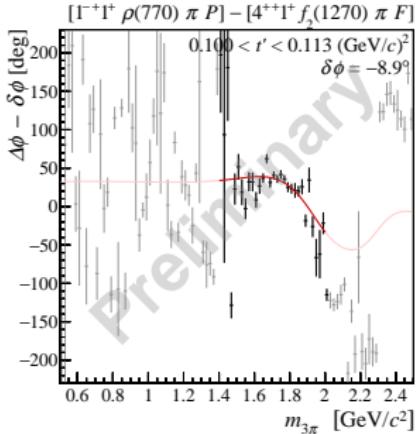
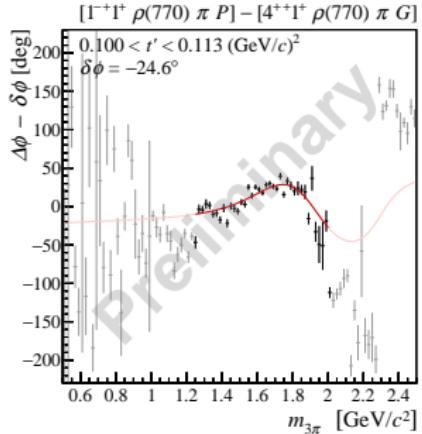
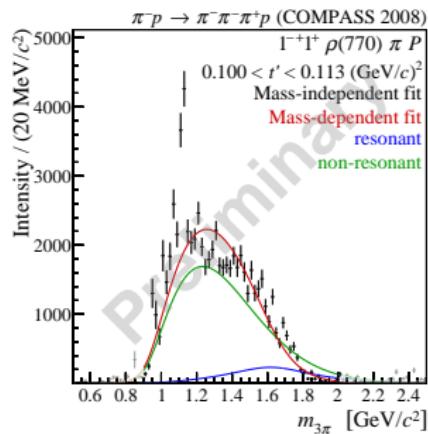


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$$m_{\pi(1800)}^{\text{PDG}} = 1812 \pm 12 \text{ MeV}/c^2 ; \Gamma_{\pi(1800)}^{\text{PDG}} = 208 \pm 12 \text{ MeV}/c^2$$

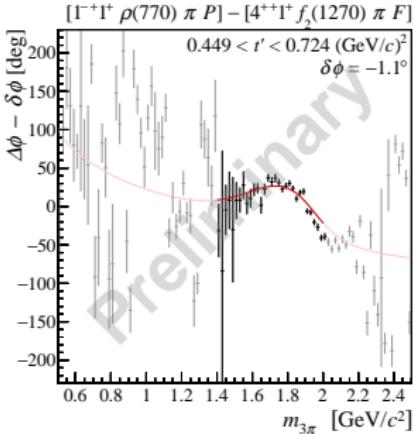
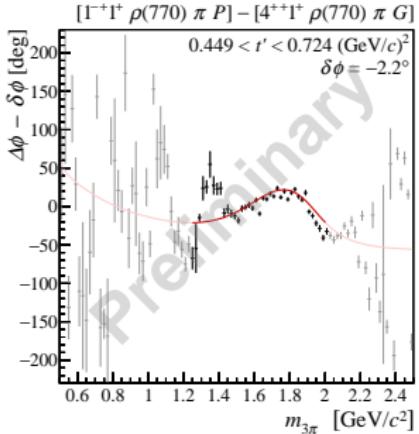
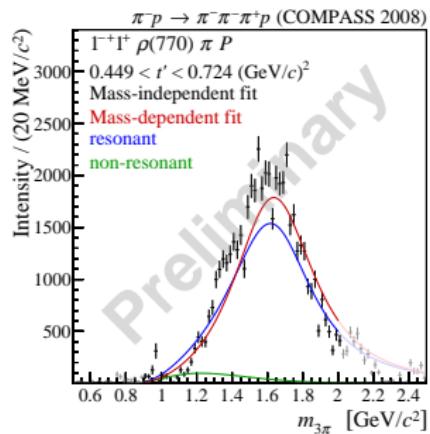
$$1^{-+} 1^+ \rho(770) \pi P$$

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



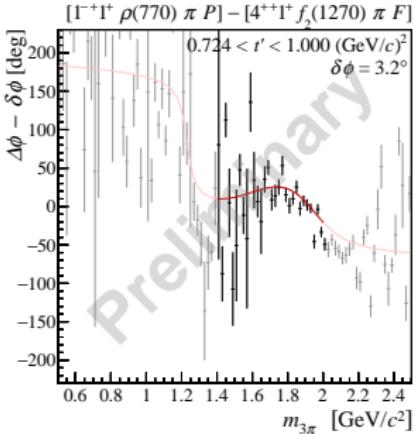
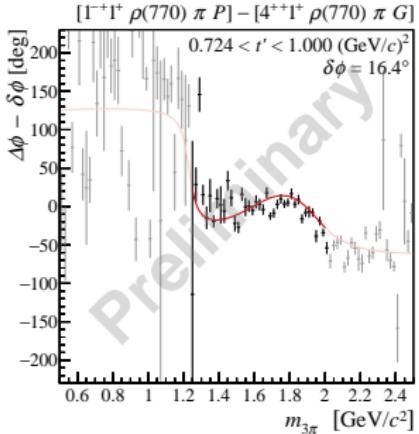
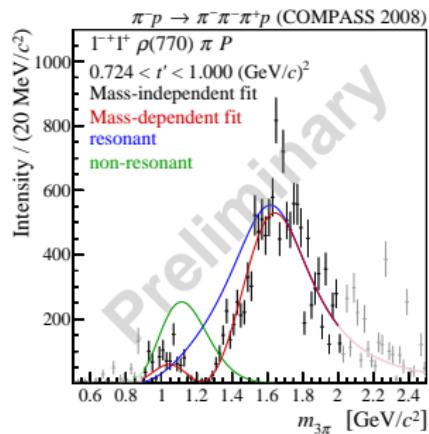
Resonant component very weak at low t'

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



Resonant component more important at higher t'

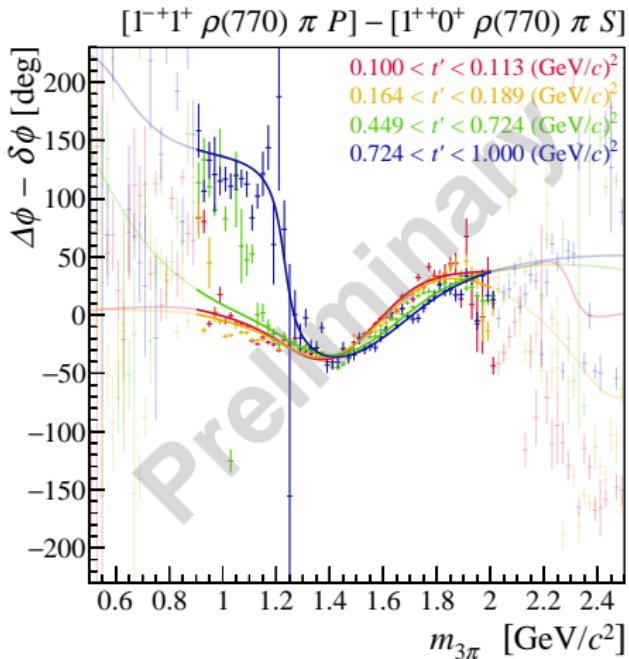
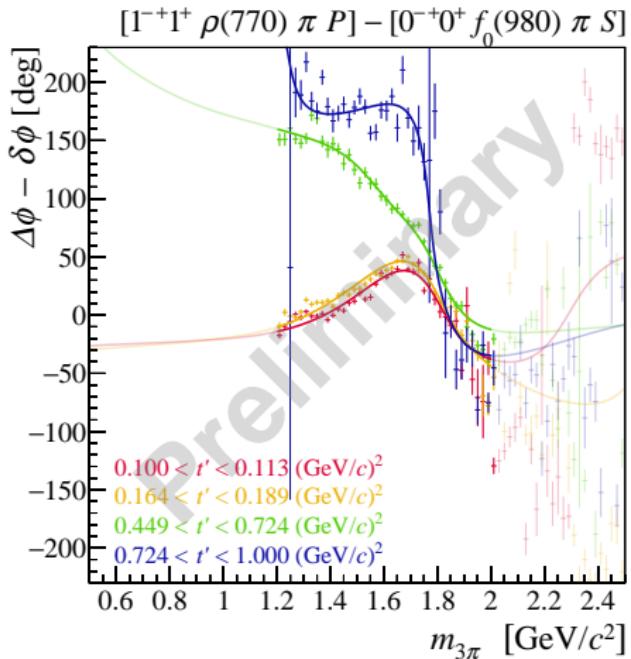
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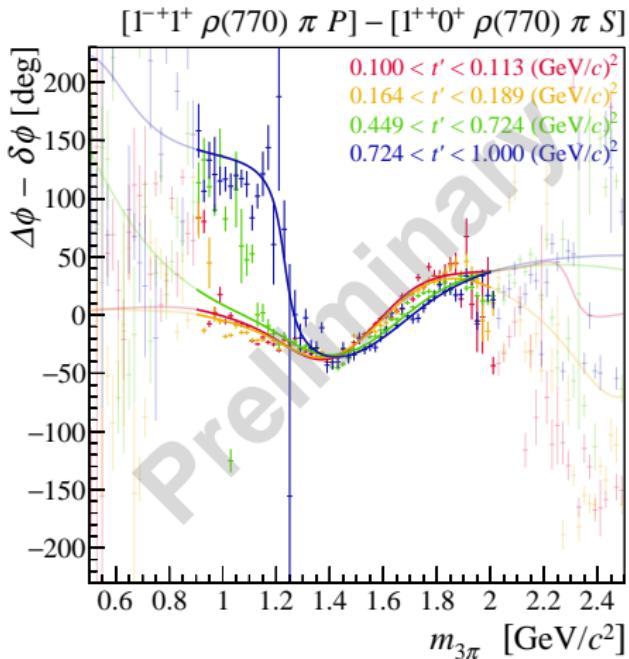
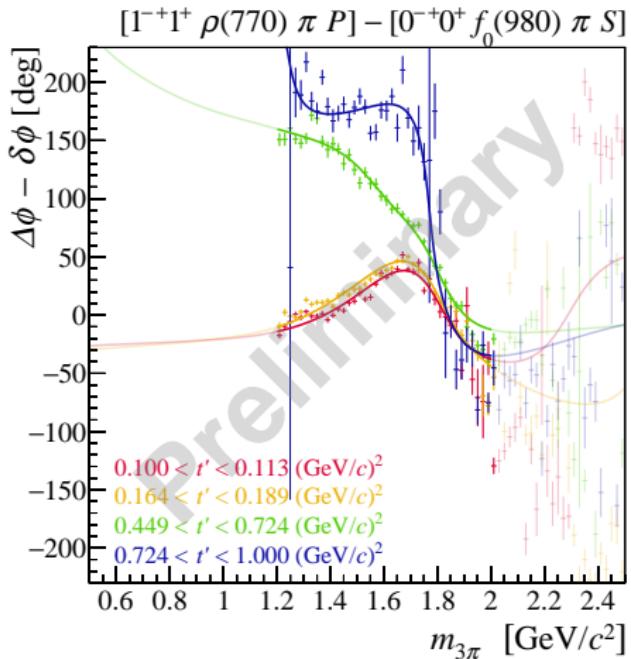
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Phase-motion



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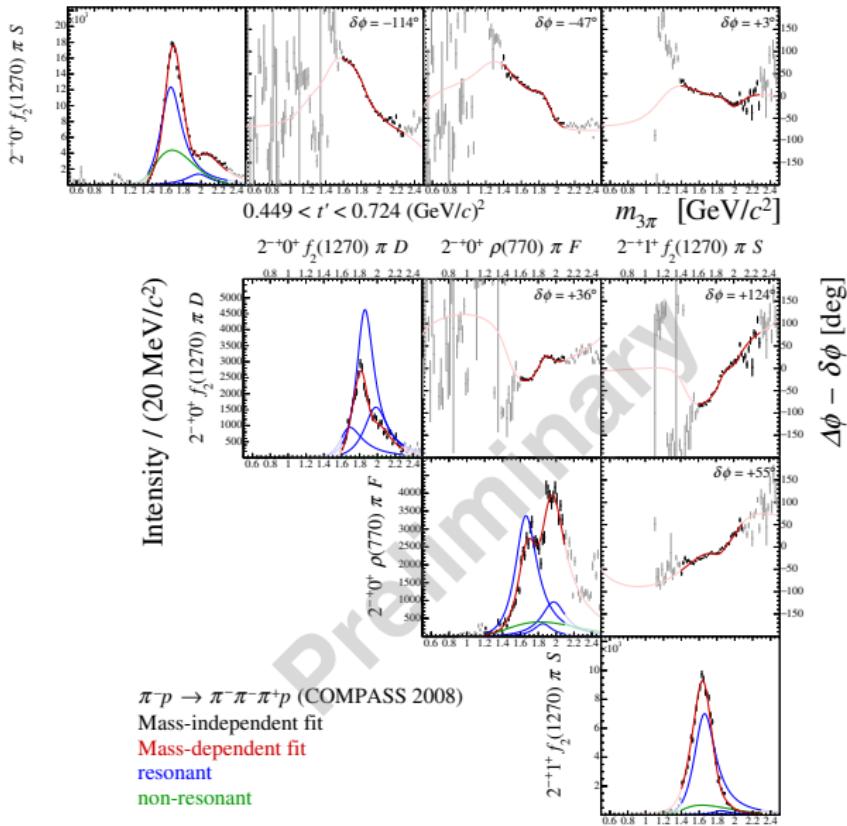
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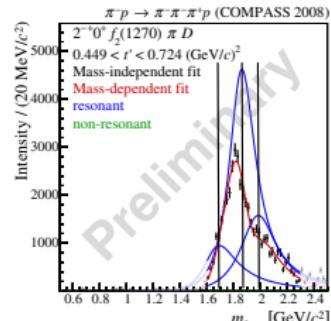
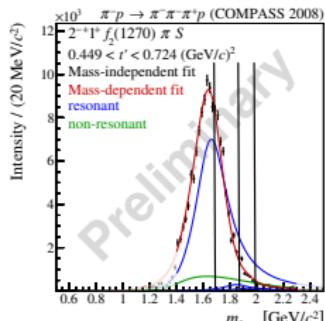
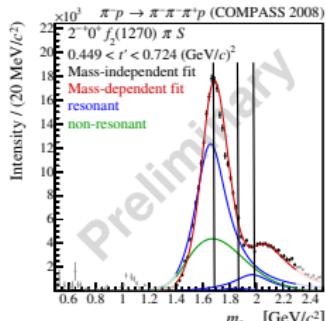
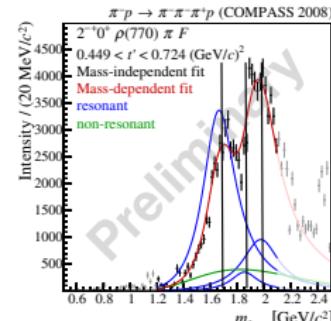
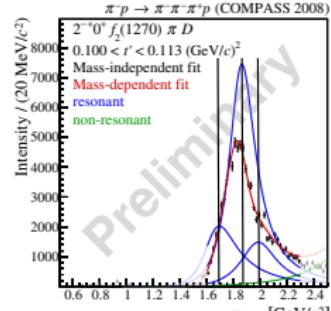
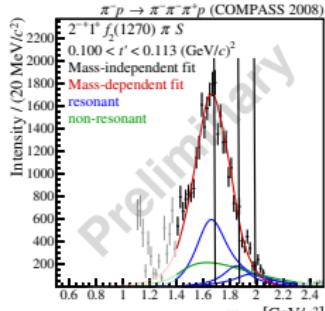
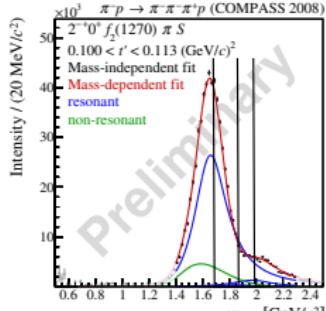
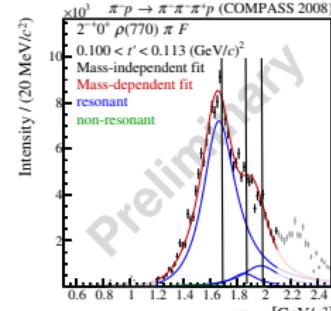


Rather broad $\pi_1(1600)$

$J^{PC} = 2^{-+}$ sector

$J^{PC} = 2^{-+}$ sector



$J^{PC} = 2^{-+}$ sectorThree $\pi_2(\dots)$ resonancesLow t' $2^{-+} 0^+ \rho(770) \pi F$ $2^{-+} 0^+ f_2(1270) \pi S$ $2^{-+} 1^+ f_2(1270) \pi S$ $2^{-+} 0^+ f_2(1270) \pi D$ High t'

$J^{PC} = 2^{-+}$ sector

Three $\pi_2(\dots)$ resonances

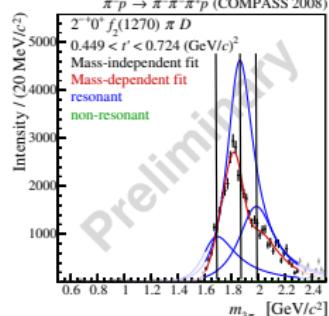
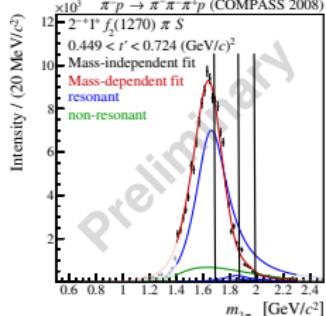
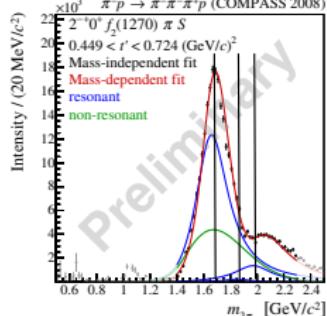
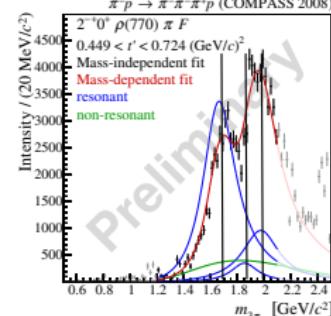
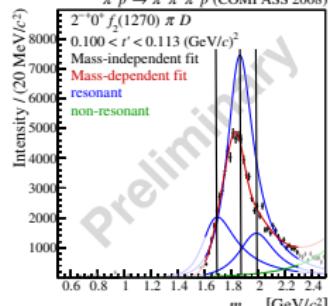
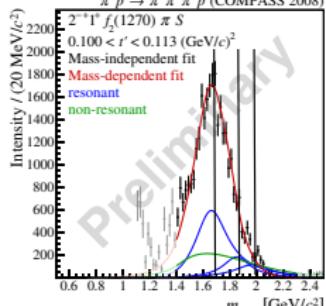
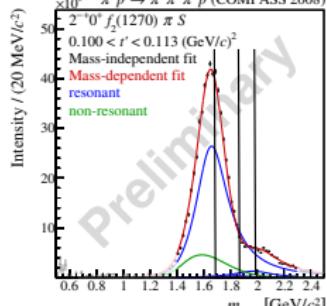
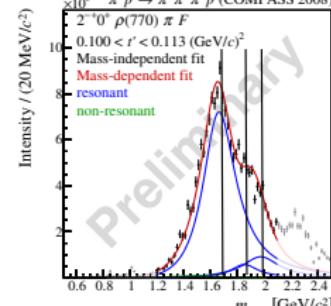
Low t'

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$2^{-+} 0^+ f_2(1270) \pi S$

$2^{-+} 1^+ f_2(1270) \pi S$

$2^{-+} 0^+ f_2(1270) \pi D$



High t'

$\pi_2(1670)$, $\pi_2(1880)$ and $\pi_2(2005)$

Summary of the $\pi_J(\dots)$

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- Three 2^{-+} resonances included
- $\pi_2(1670)$, $\pi_2(1880)$ and $\pi_2(2005)$
 - ▶ $\pi_2(1670)$ dominant in $f_2(1270)\pi S$ -wave decays
 - ▶ $\pi_2(1880)$ dominant in $f_2(1270)\pi D$ -wave decays
 - ▶ $\pi_2(2005)$ only seen once before

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 - ▶ Randomization of start-parameters
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 - ▶ Variation of the fit-model:
 - ★ Resonance content
 - ★ Resonance parametrizations
 - ★ Non-resonant parametrizations

Extensive systematic studies

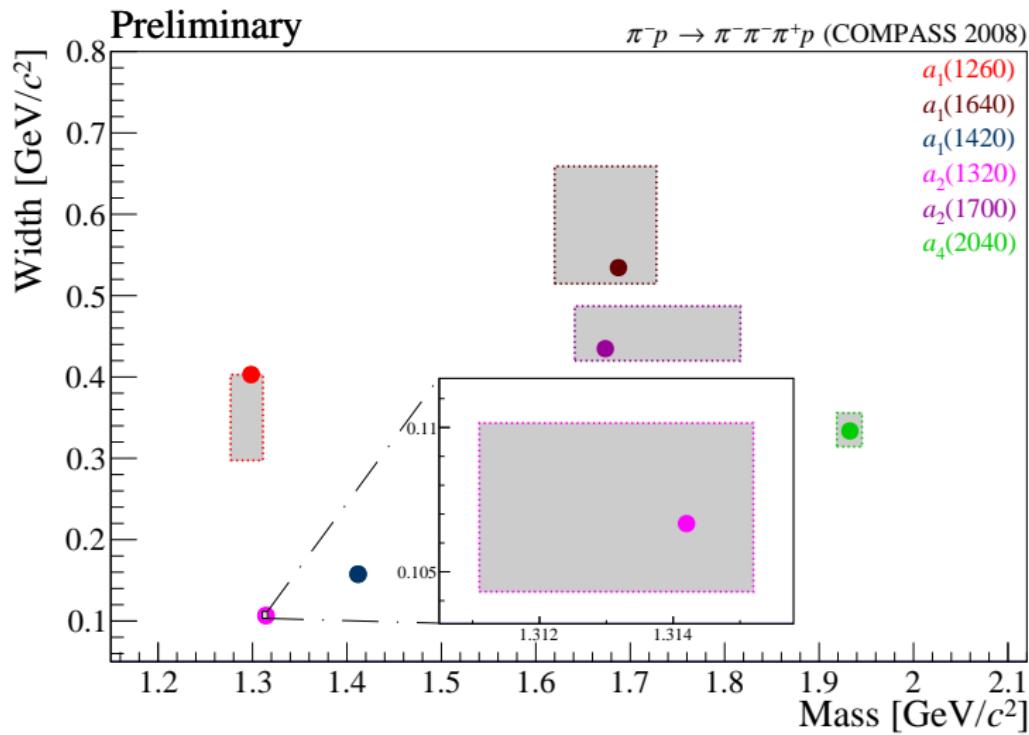
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 - ▶ Release order of fit-parameters
- More than 200 systematic studies performed
- Studies include:
 - ▶ Variation of the set of fitted waves
 - ▶ Variation of the fit-model:
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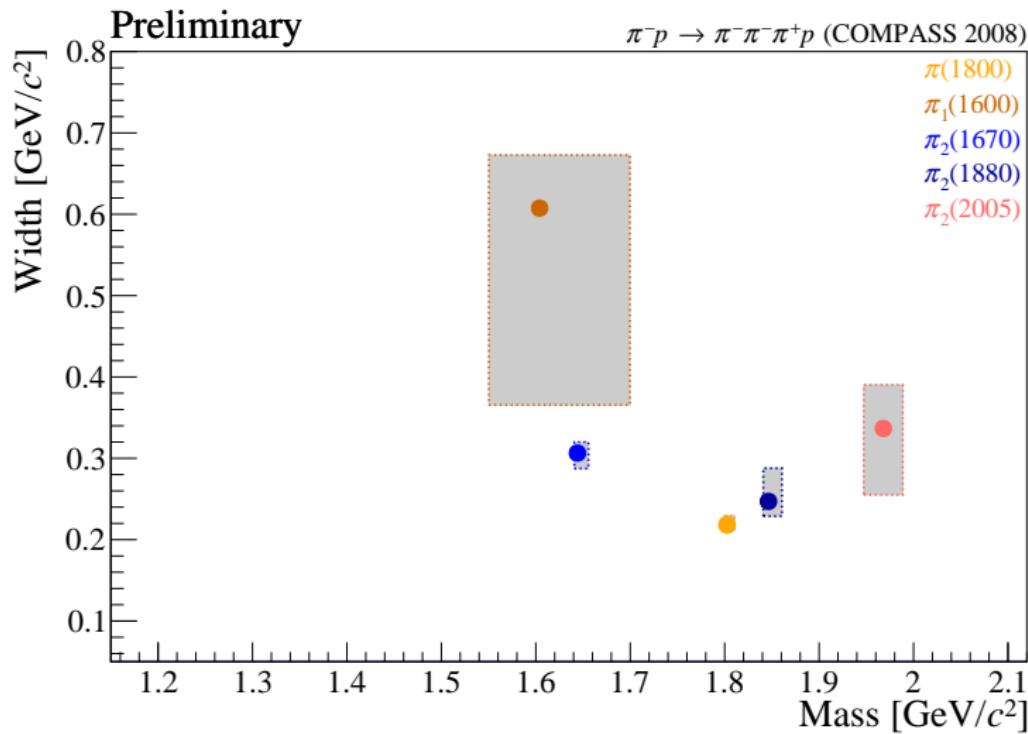
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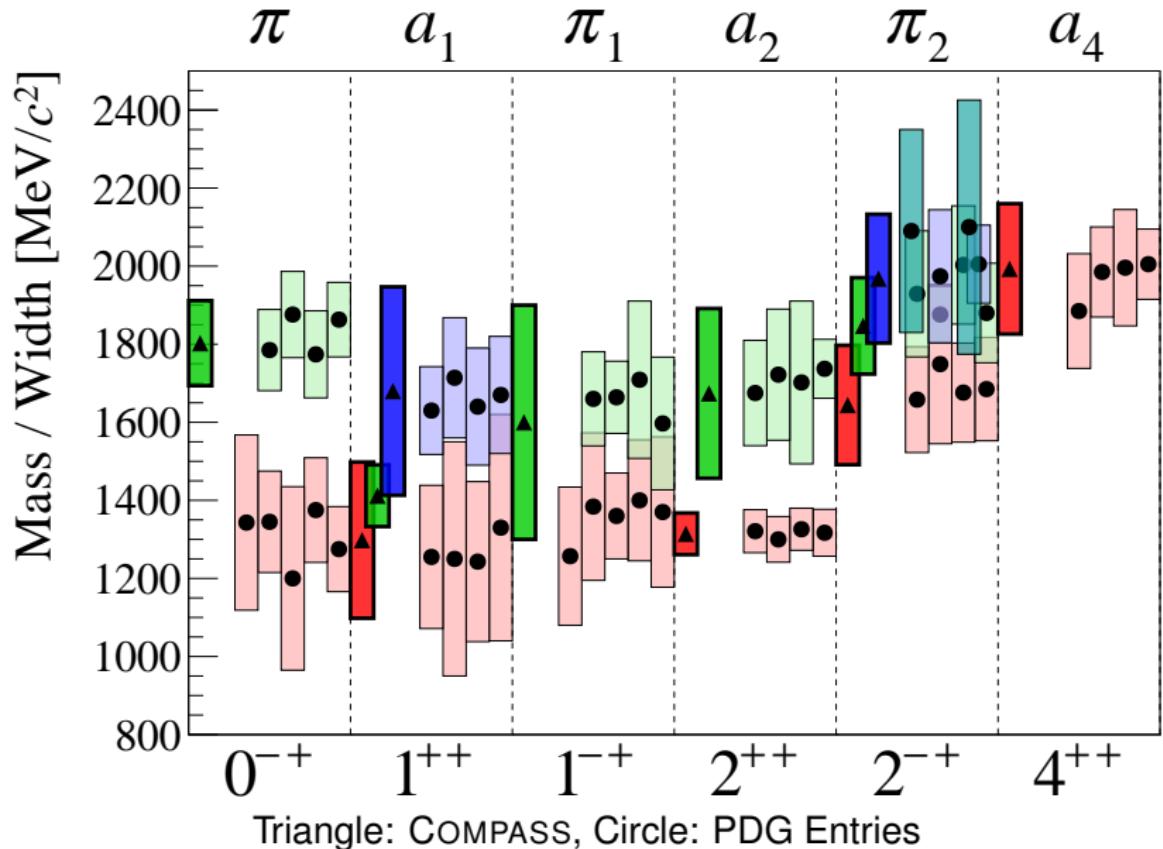
Parameters of $a_J(\dots)$ resonances



Parameters of $\pi_J(\dots)$ resonances

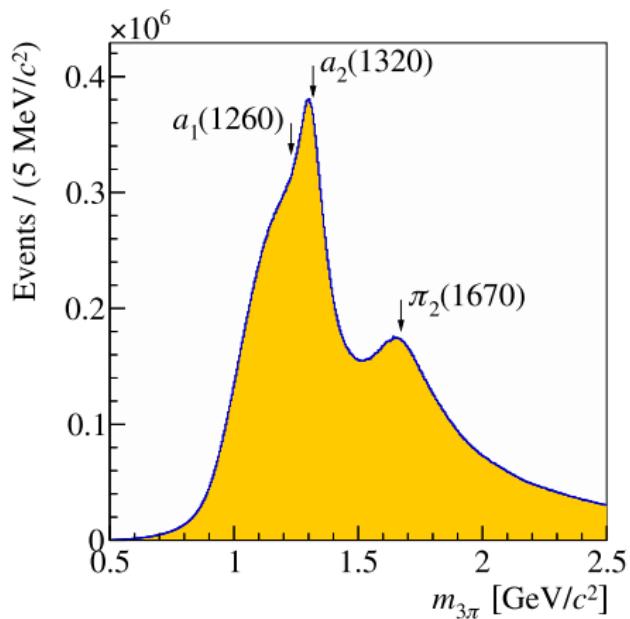


Results



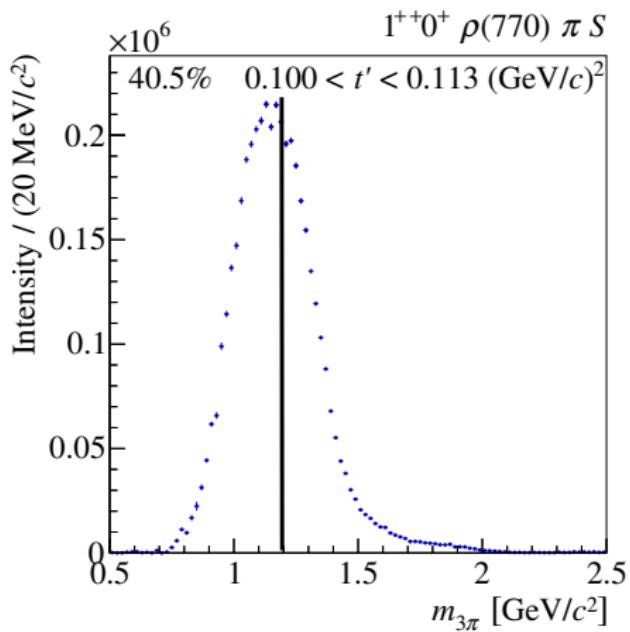
Conclusions

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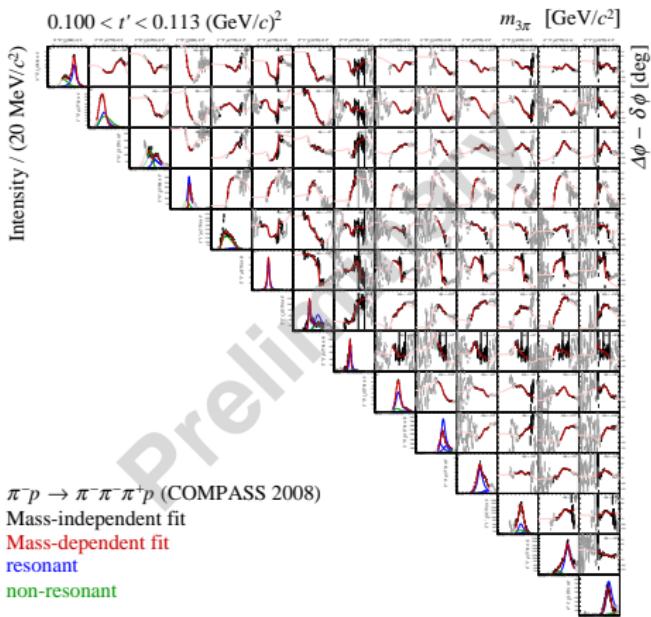
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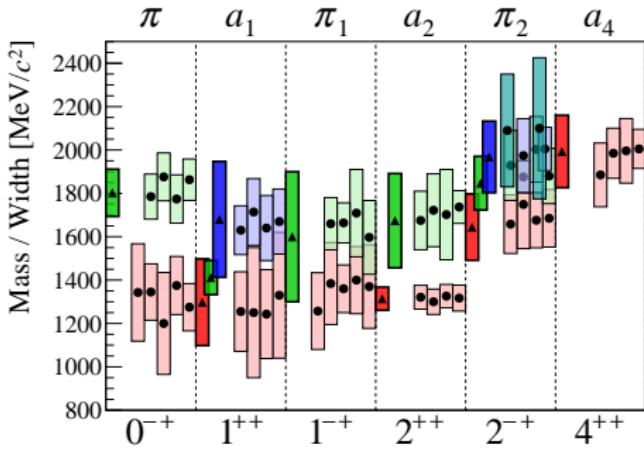
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- Publication in preparation

