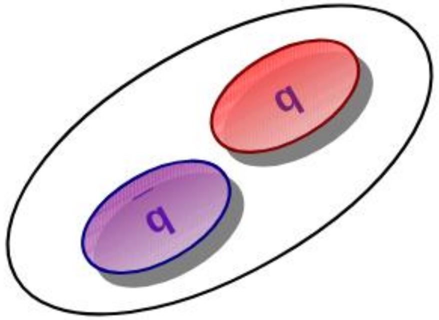
Non-Strange Light-Meson Spectroscopy at COMPASS

Philipp Haas for the COMPASS Collaboration

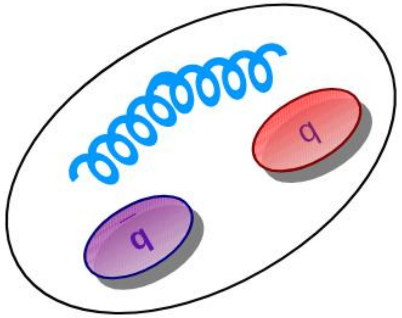
06.06.2023 – HADRON 2023

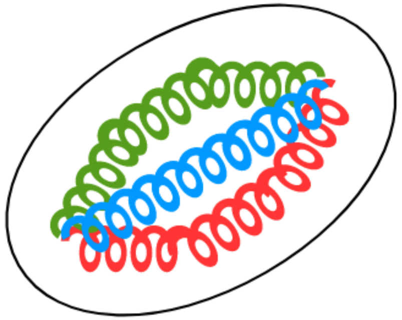
Motivation

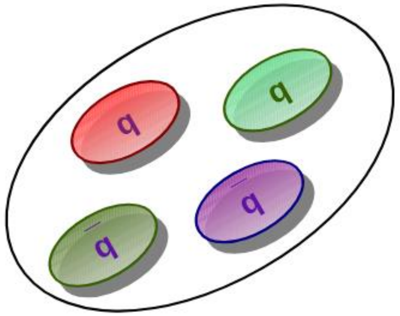


- The Constituent Quark Model predicts mesons as $|q\bar{q}\rangle$ states
- QCD allows meson configurations beyond $|q\bar{q}\rangle$ - so-called exotics:
  - Hybrids $|q\bar{q}\mathrm{g}\rangle$, Glueballs $|\mathrm{gg}\rangle$, Multiquarks $|qq\overline{qq}\rangle$

Exotic mesons at COMPASS
(talk by B. Ketzer, Tue. 15:00)







https://arxiv.org/pdf/1405.4195.pdf

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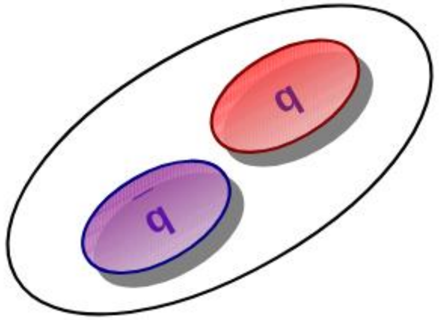

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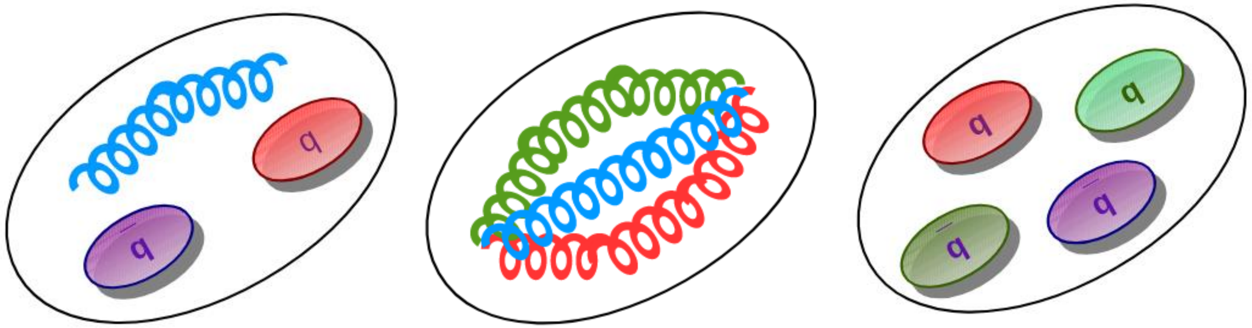

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- Light non-strange $|q\bar{q}\rangle$ states cannot make up states with spin quantum numbers $J^{PC} = 0^{--}, \mathrm{even}^{+-}, \mathrm{odd}^{-+}$
  - "Spin-exotic" mesons
  - Direct access to find states beyond $|q\bar{q}\rangle$ states

Spin-Exotic Light Mesons

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  - Single pole around $1.6\ \mathrm{GeV}/c^2$
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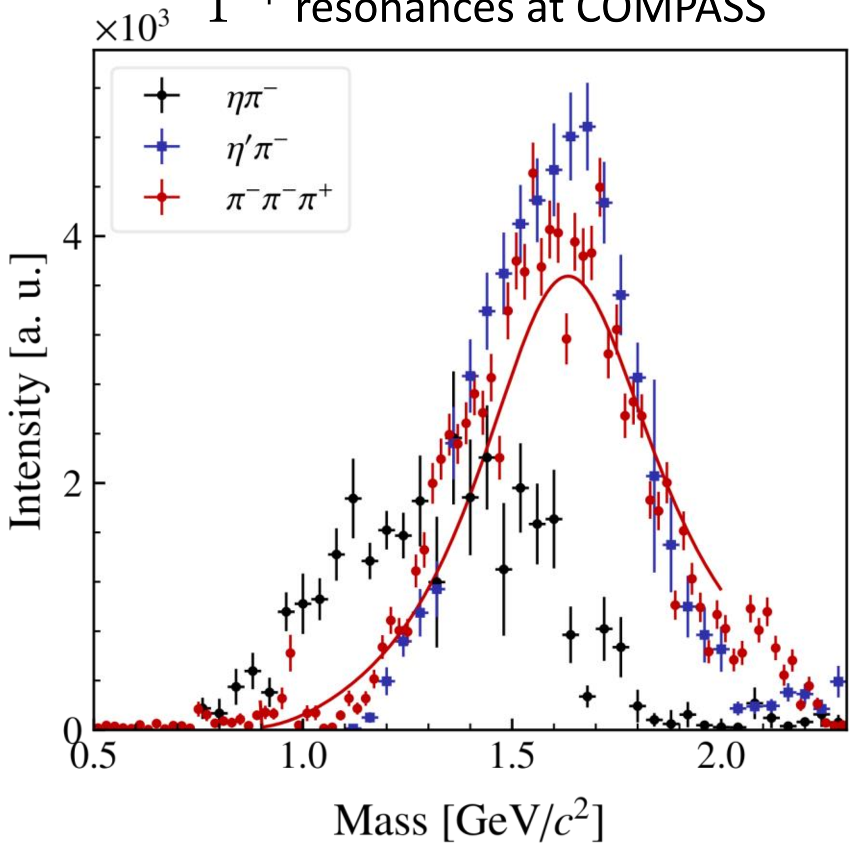
1^{-+} resonances at COMPASS



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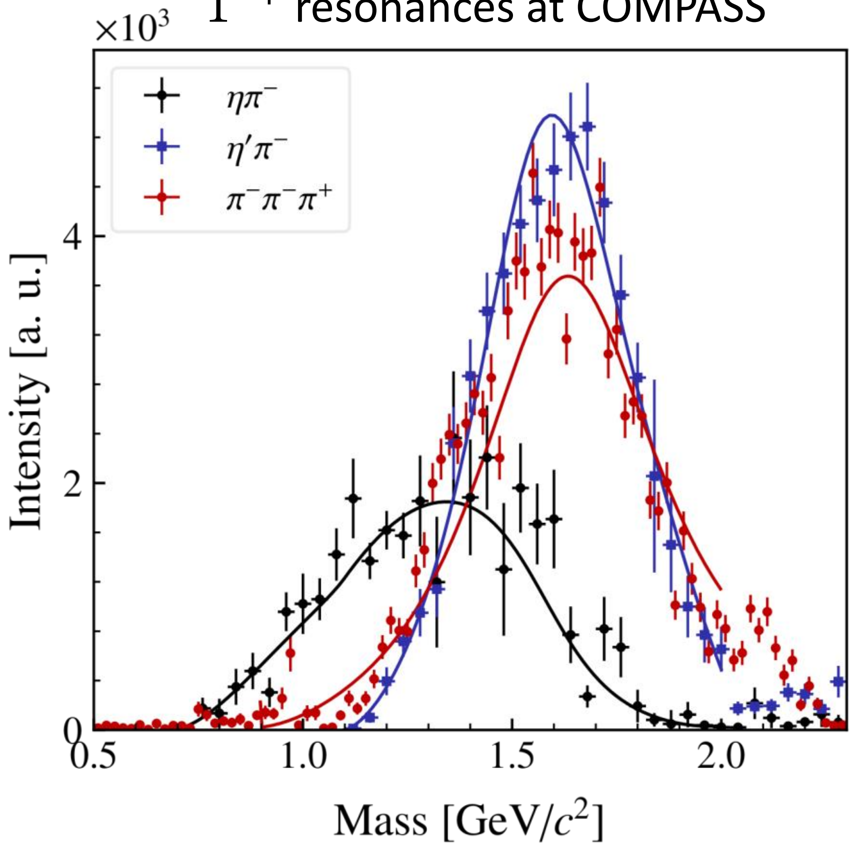

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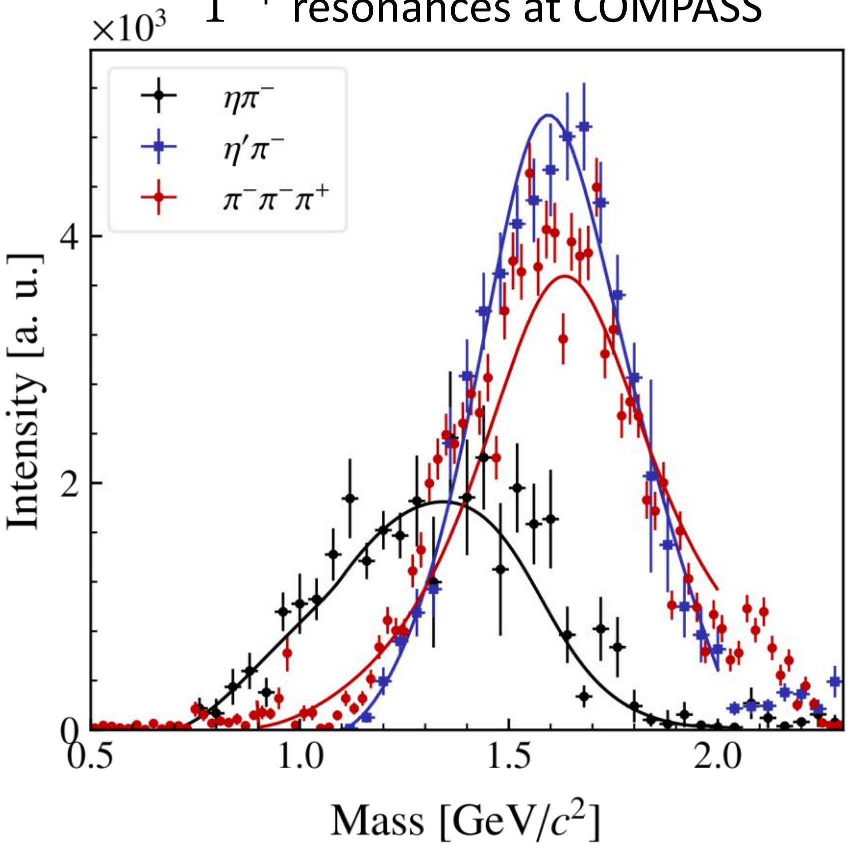
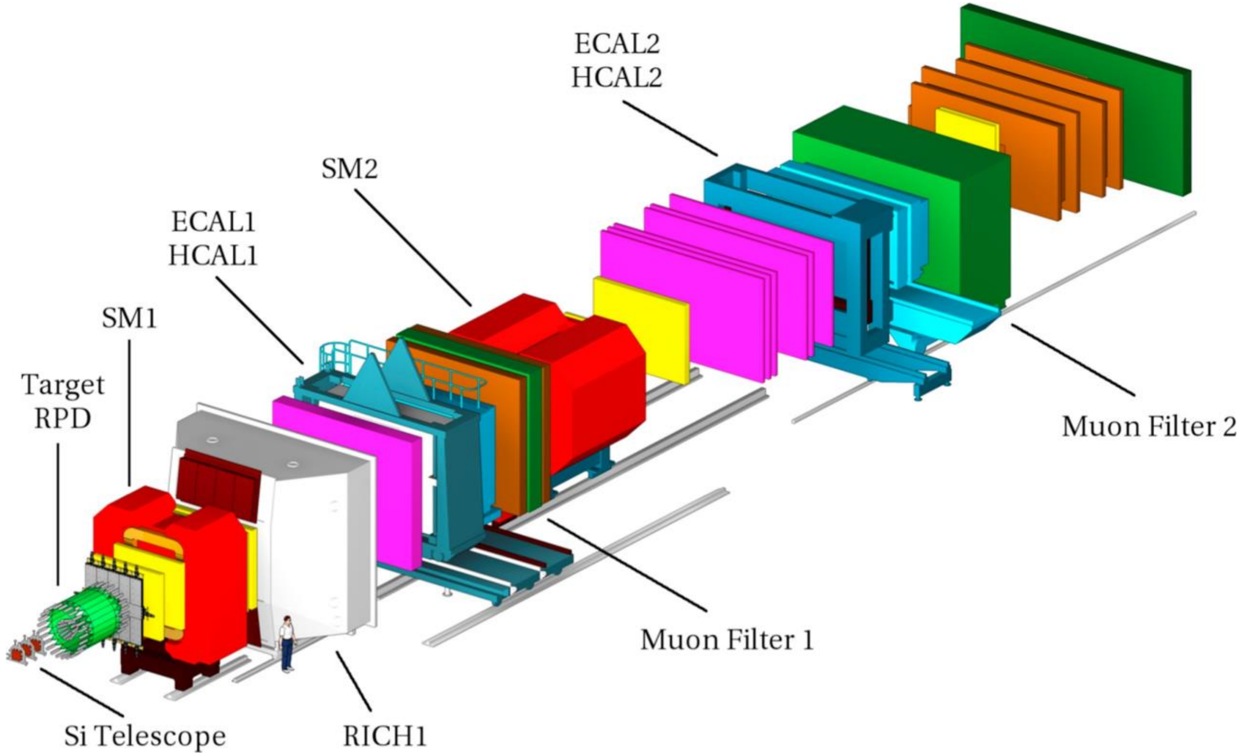
- JPAC found single pole - $\pi_1(1600)$ - sufficient for $\eta^{(\prime)}\pi$ COMPASS data
- BNL claimed $\pi_1(2015)$ in $\omega\pi^-\pi^0$ and $f_1\pi$

1^{-+} resonances at COMPASS



Experimental Setup

- Located at CERN SPS
- 190 GeV/c negative hadron beam
- Various targets:
  - Liquid-hydrogen
  - Heavy solid-state targets
    - Pb, Ni ⟶ Primakoff reactions (talk by D. Ecker, Thu. 17:20)
- Inelastic high-energy $\pi^- p$ scattering
  - Isovector light mesons X^- (a_J and π_J)



Beam:
$97\%\ \pi^-$
$2\%\ K^-$
$1\%\ \bar{p}$

Light-Meson Spectroscopy at COMPASS

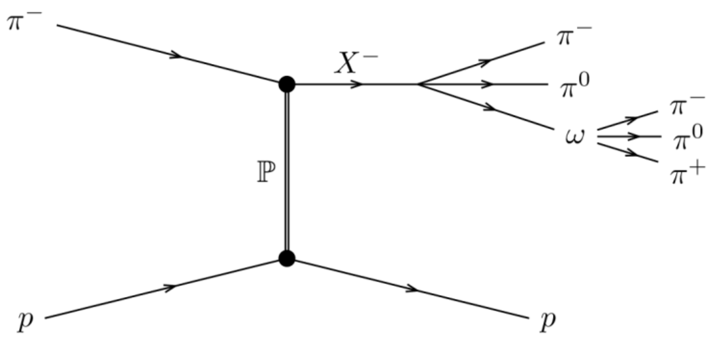
Analyzed channels:

- $\pi^-\pi^-\pi^+ / \pi^-\pi^0\pi^0$
- $\eta\pi^- / \eta'\pi^-$
- $K^-\pi^-\pi^+$ ⟶ Strange-meson spectroscopy (talk by S. Wallner, Thu. 14:00)
- $\omega\pi^-\pi^0$

Upcoming channels under study:

$K_s K^-$	Search for $a_6(2450)$
$K_s K_s \pi$	Investigate nature of $a_1(1420)$
$f_1\pi^-$	Search for π_1 states
$K_s\pi^-$	Strange mesons spectroscopy
$\Lambda\bar{p}$	

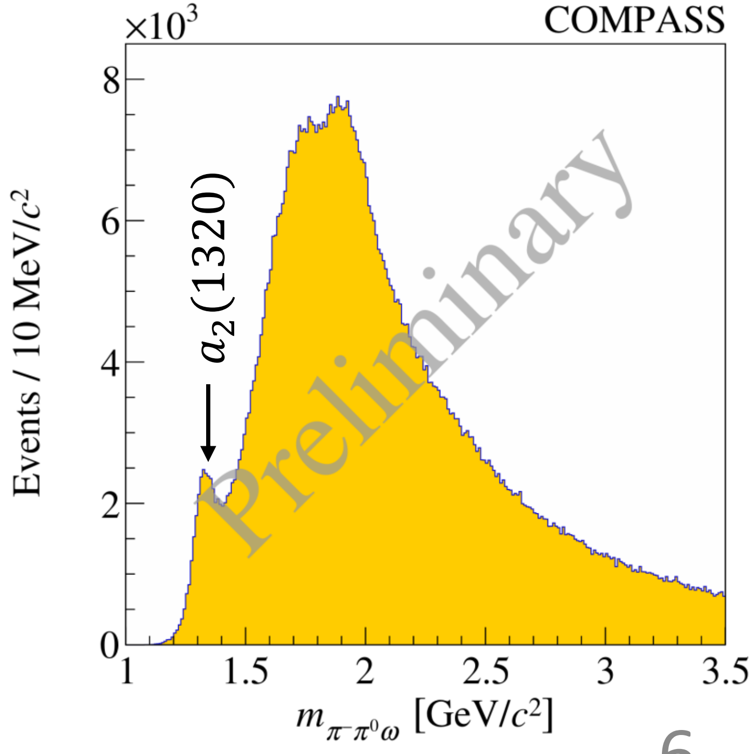
Analysis of $\omega(782)\pi^-\pi^0$



- Overlapping and interfering X^- states
  - m_X spectrum shows no clear peaks above $1.5\ \mathrm{GeV}/c^2$
- Disentangling the different contributions requires partial-wave analysis

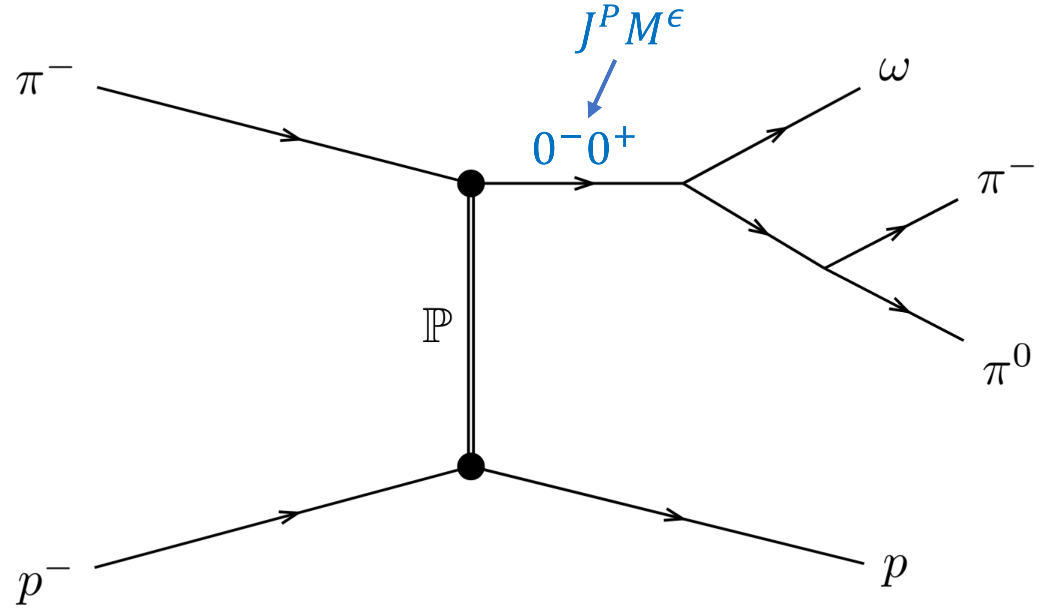
  Talk by J. Beckers on Thu. 14:00: Progress in the Partial-Wave Analysis Methods at COMPASS

- Partial-wave decomposition splits the total amplitude in the different contributions



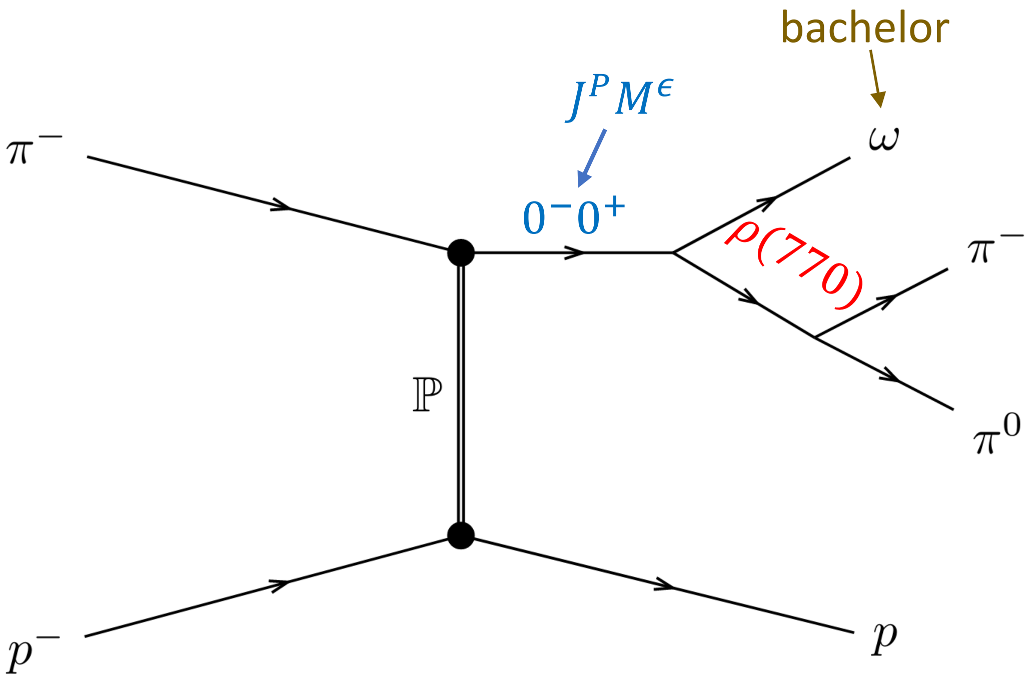
Partial-Wave Decomposition

- Exited meson X^- with quantum numbers 0^-0^+ is produced



Partial-Wave Decomposition

- Exited meson X^- with quantum numbers 0^-0^+ is produced
- Isobar model: X^- decays to $\omega\rho(770)$, where $\rho(770)$ an unstable intermediate state – the isobar



Partial-Wave Decomposition

- Exited meson X^{-} with quantum numbers $0^{-}0^{+}$ is produced
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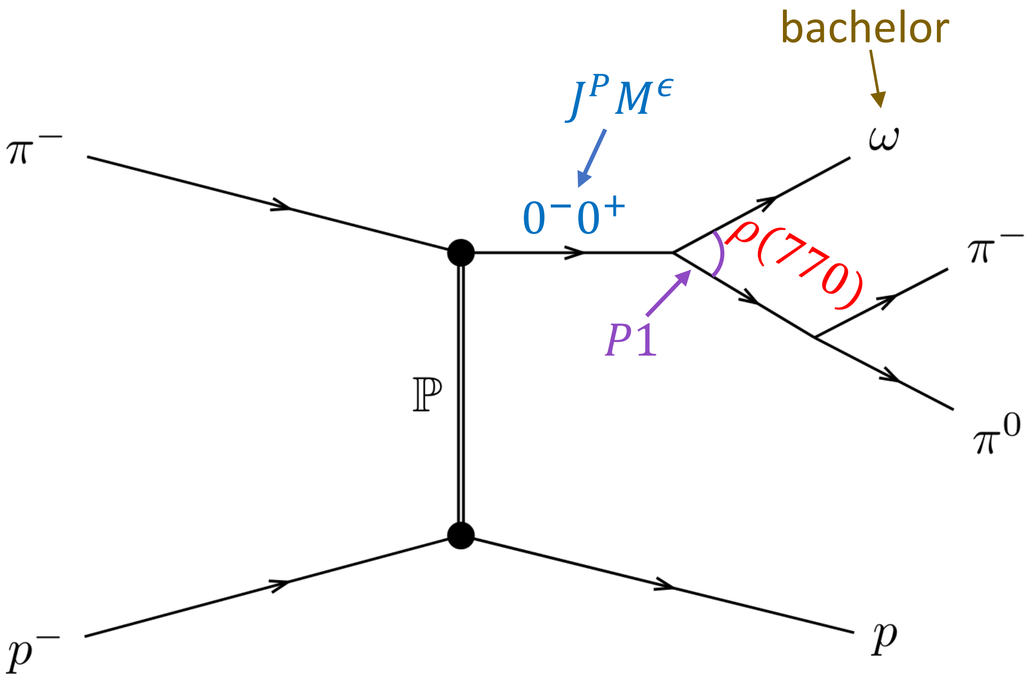
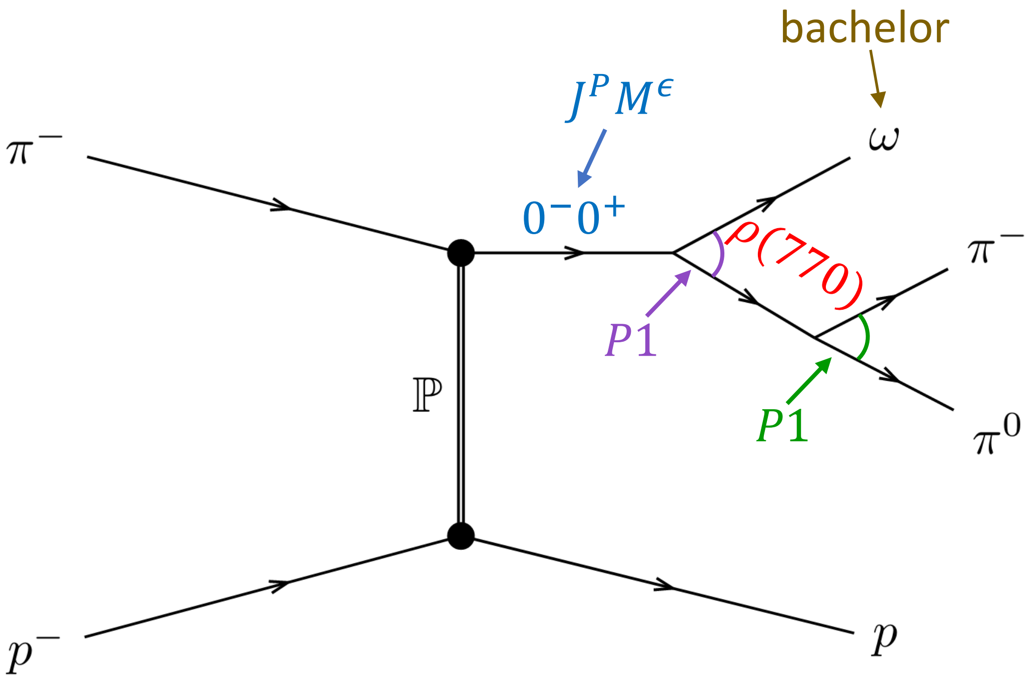
  - $P1$ coupling between ω and $\rho(770)$



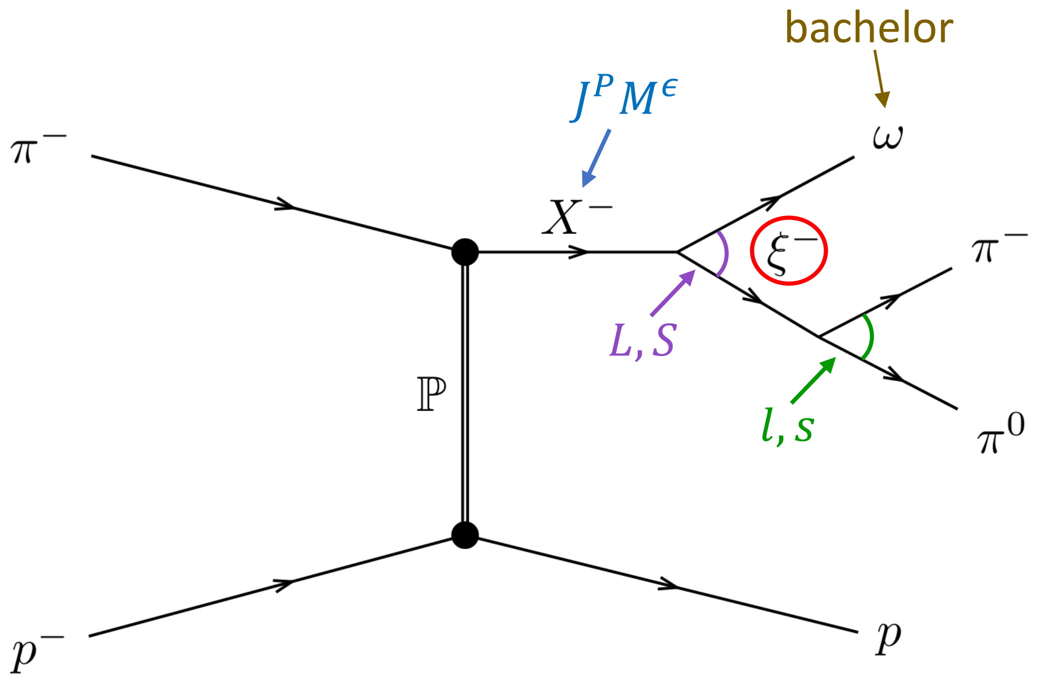
Partial-Wave Decomposition

- Exited meson X^- with quantum numbers $0^- 0^+$ is produced
- Isobar model: X^- decays to $\omega\rho(770)$, where $\rho(770)$ an unstable intermediate state – the isobar
  - $P1$ coupling between ω and $\rho(770)$
- $\rho(770)$ decays to $\pi^-\pi^0$
  - second $P1$ coupling
- $i = 0^- 0^+ [\rho(770) P]\ \omega\ P1$



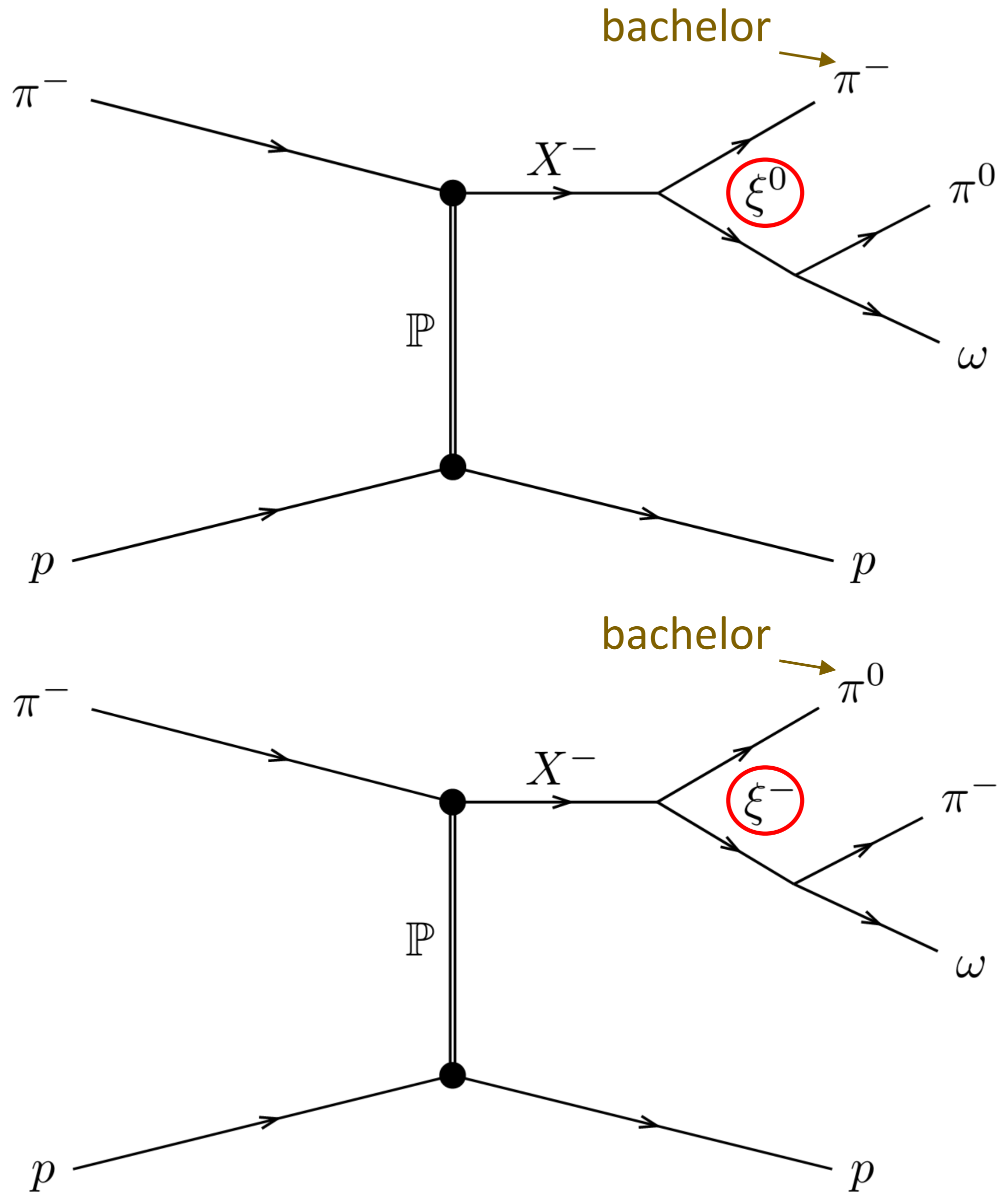
Partial-Wave Decomposition

- Exited meson X^- with quantum numbers $J^P M^\epsilon$ is produced
- Isobar model: X^- decays to $\omega\xi^-$, where ξ^- is an unstable intermediate state – the isobar
  - L, S coupling between ω and ξ^-
- ξ^- decays to $\pi^-\pi^0$
  - second l, s coupling
- $i = J^P M^\epsilon\ [\xi l]\omega LS$



Partial-Wave Decomposition

- Further decay channels of X^-:
  - $\pi^0\xi^-, \pi^-\xi^0$
- Both decays have the same amplitude
  $\Rightarrow$ Coherently sum over both isospin configurations $\pi^0\xi^-, \pi^-\xi^0$
- $i = J^P M^\epsilon\ [\xi l]$ bachelor LS
  - ξ either decays to $\omega\pi$ or $\pi\pi$



Partial-Wave Decomposition

- Coherent superposition of partial-waves:
  - $i = J^P M^\epsilon\ [\xi l]$ bachelor LS

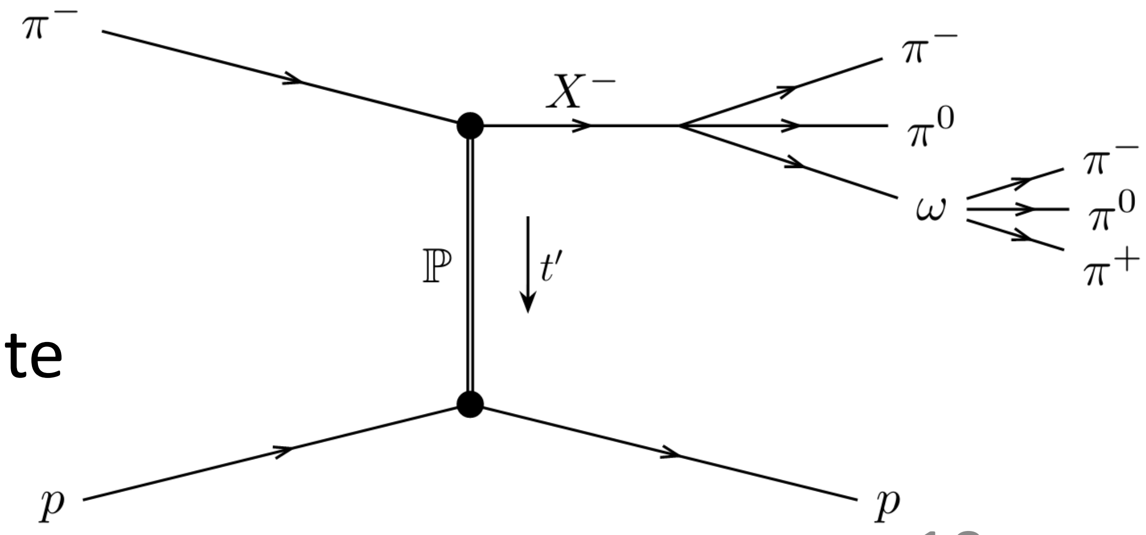
$$I(m_X, t', \tau) = \left| \sum_i \mathcal{T}_i(m_X, t') \psi_i(m_X, \tau) \right|^2$$

with:

m_X: mass of the $\omega(782)\pi^-\pi^0$ system

t': squared four-momentum transfer

τ: phase-space variables of the final state



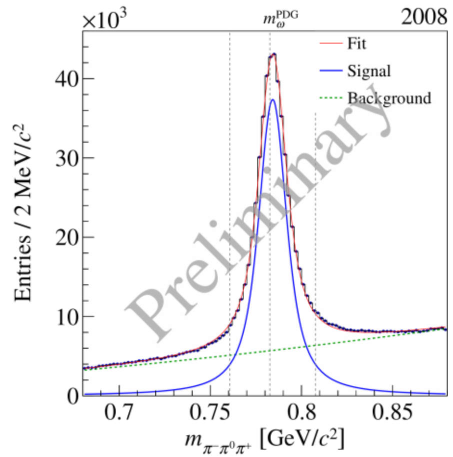
Phase-Space Variables

- τ: Total of 8 phase-space variables

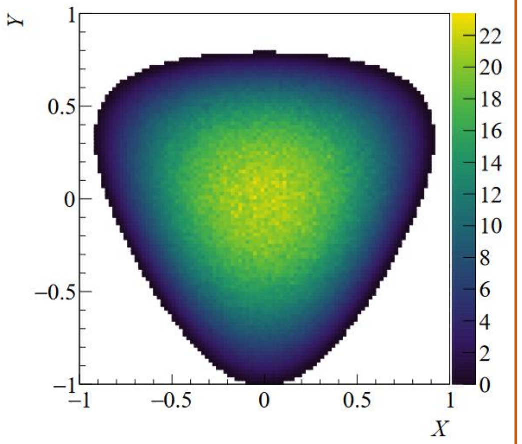
2x two-body decay: (ϕ, θ)

$(\phi_{\text{GJ}}, \theta_{\text{GJ}}), (\phi_{\text{HF}}, \theta_{HF})$

m_ω

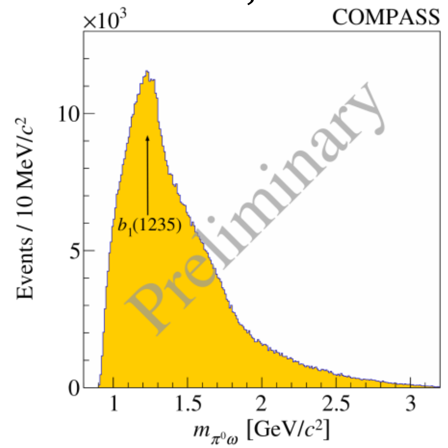


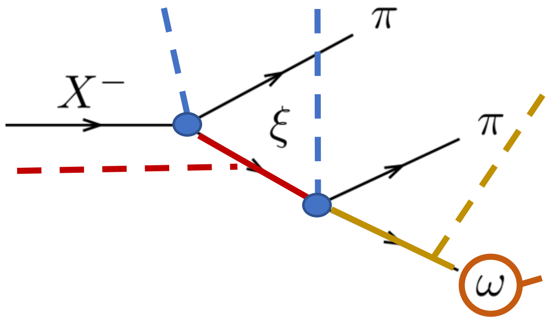
2 $\omega(782)$ Dalitz-Plot variables



Intermediate mass

m_ξ





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- Decay amplitude $\psi_i(m_X, \tau)$: calculated using the isobar model

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- Decay amplitude $\psi_i(m_X, \tau)$: calculated using the isobar model
- Transition amplitude $\mathcal{T}_i(m_X, t')$:

  $\Rightarrow \mathcal{T}_i(m_X, t')$ contains production, propagation, and coupling of i
  - No assumptions about the resonant content of X^-

  $\Rightarrow$ Extract $\mathcal{T}_i(m_X, t')$ by independent maximum-likelihood fits of $I(\tau)$ in bins of (m_X, t')

Partial-Wave Decomposition – Wave Set

- In principle: Infinite number of partial-waves i

$$I(m_X, t', \tau) = \left| \sum_i \mathcal{T}_i(m_X, t') \psi_i(m_X, \tau) \right|^2$$

Partial-Wave Decomposition – Wave Set

- In principle: Infinite number of partial-waves i
- Construct a wave pool of 893 allowed waves by systematic constraints
  - $\xi \to \pi\pi$: $\rho(770)$, $\rho(1450)$, $\rho_3(1690)$
  - $\xi \to \omega\pi$: $b_1(1235)$, $\rho(1450)$, $\rho_3(1690)$
  - $J \leq 8$, $M \leq 2$, $L \leq 8$

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  - $J \leq 8$, $M \leq 2$, $L \leq 8$
- Wave set selected using regularization-based model-selection
  - Unique wave set for each (m_X, t') cell

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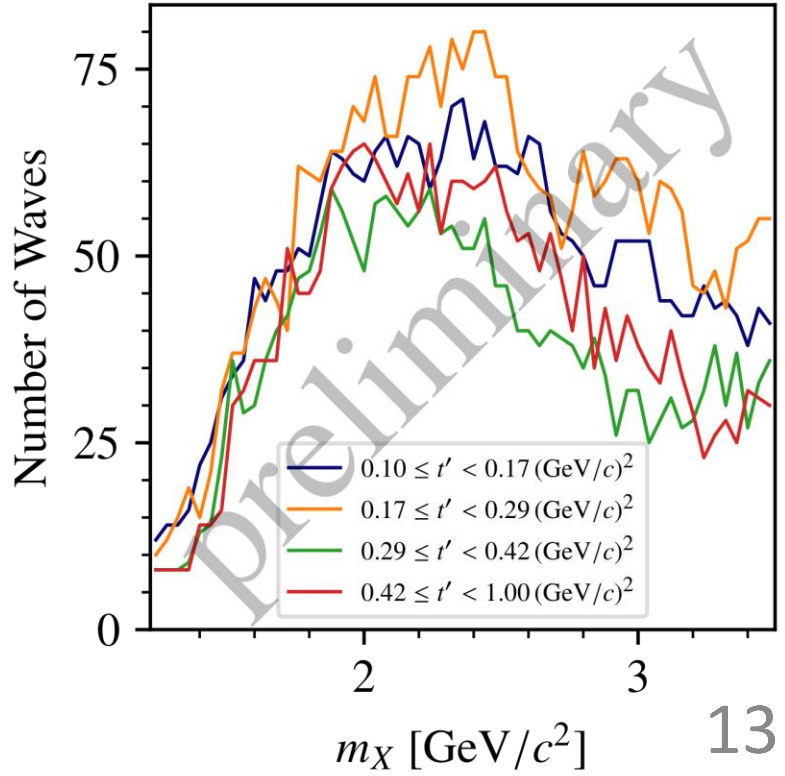
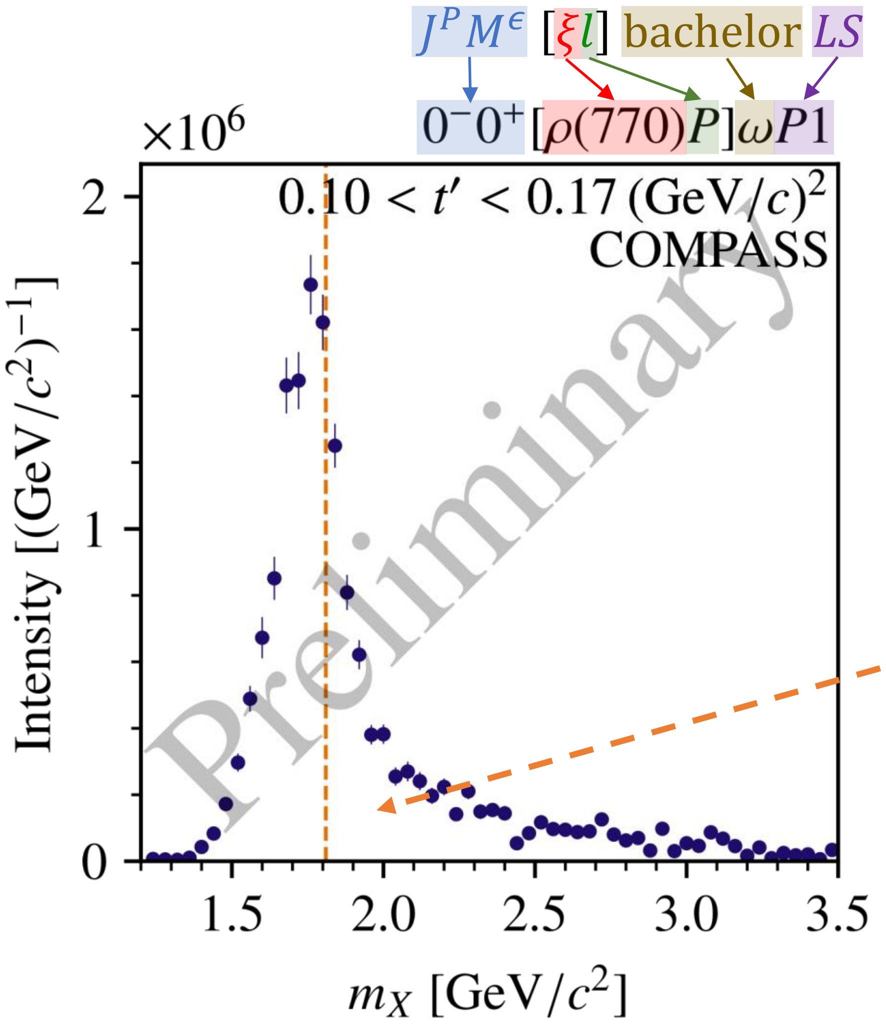
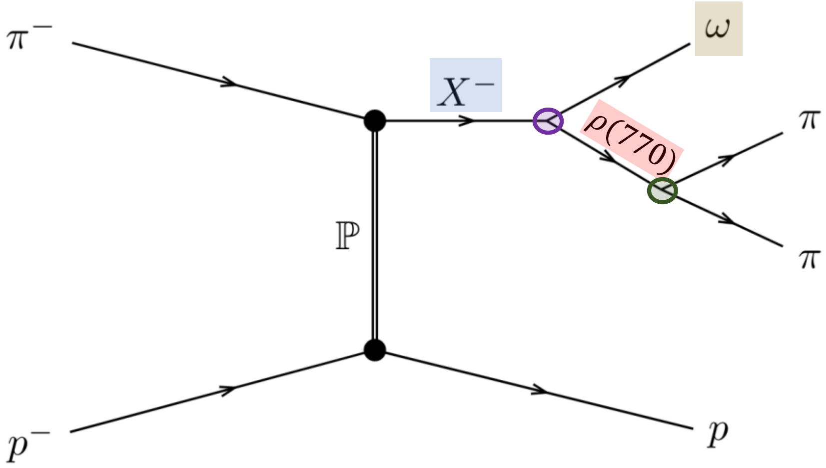


Results $J^{PC} = 0^{-+}$





States listed in PDG

$\pi(1800)$
$m = 1810\,^{+9}_{-11}$ MeV
$\Gamma = 215^{+7}_{-8}$ MeV

- Dashed lines to indicate nominal PDG masses of resonances

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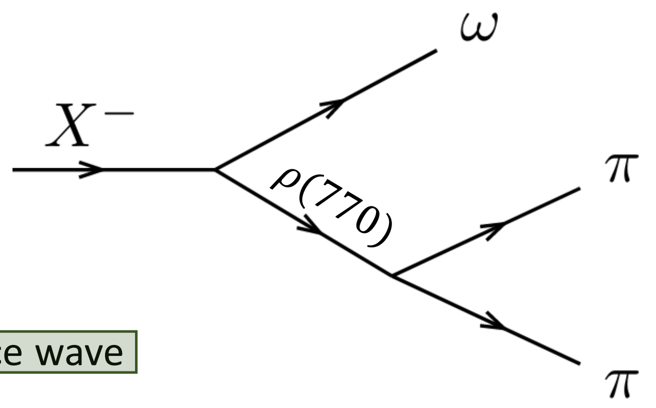

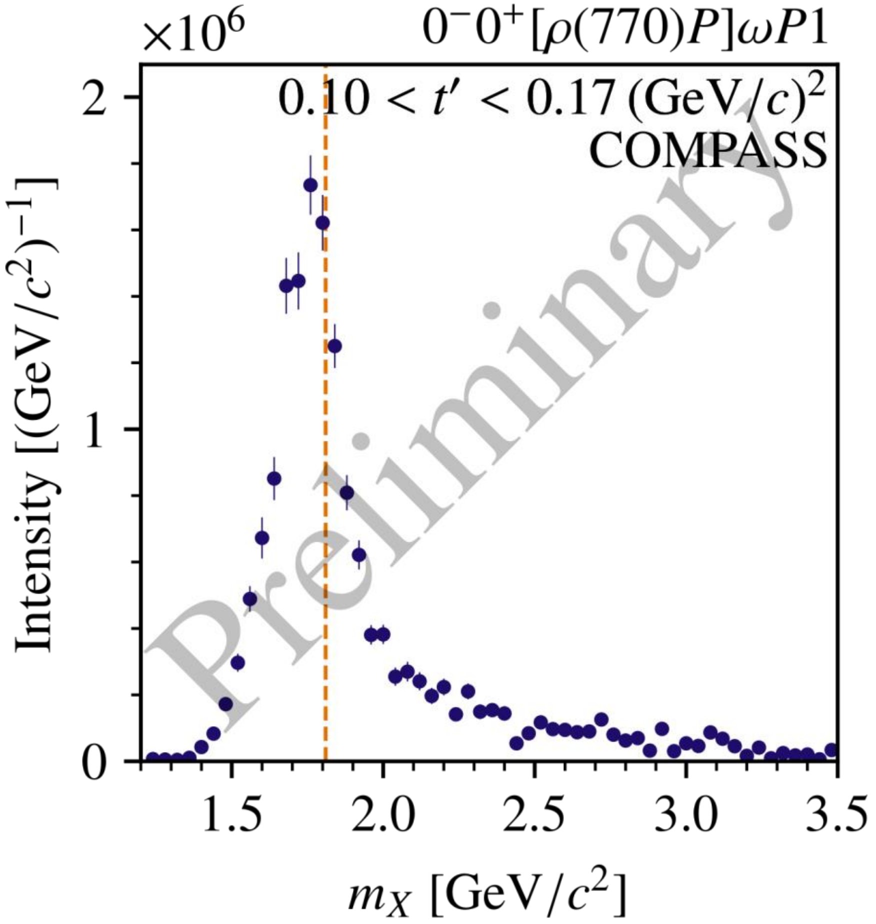

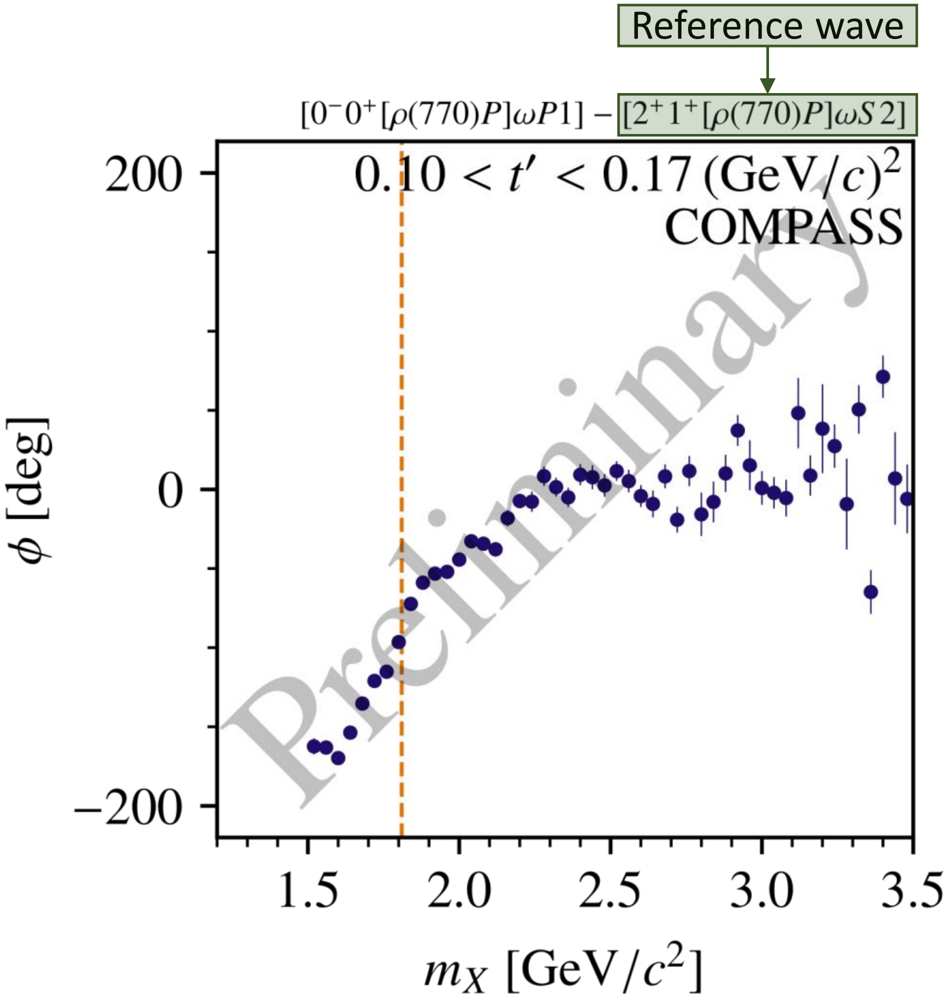

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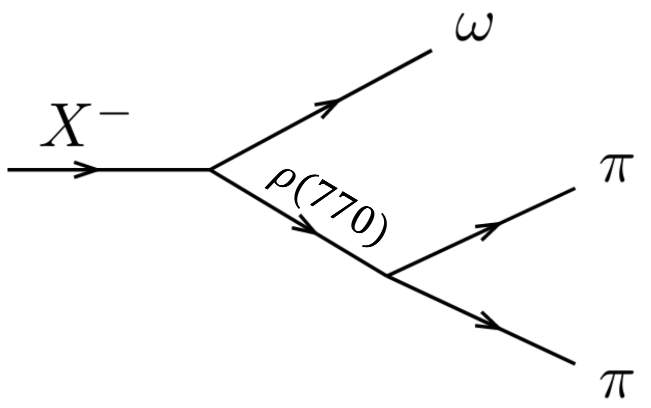

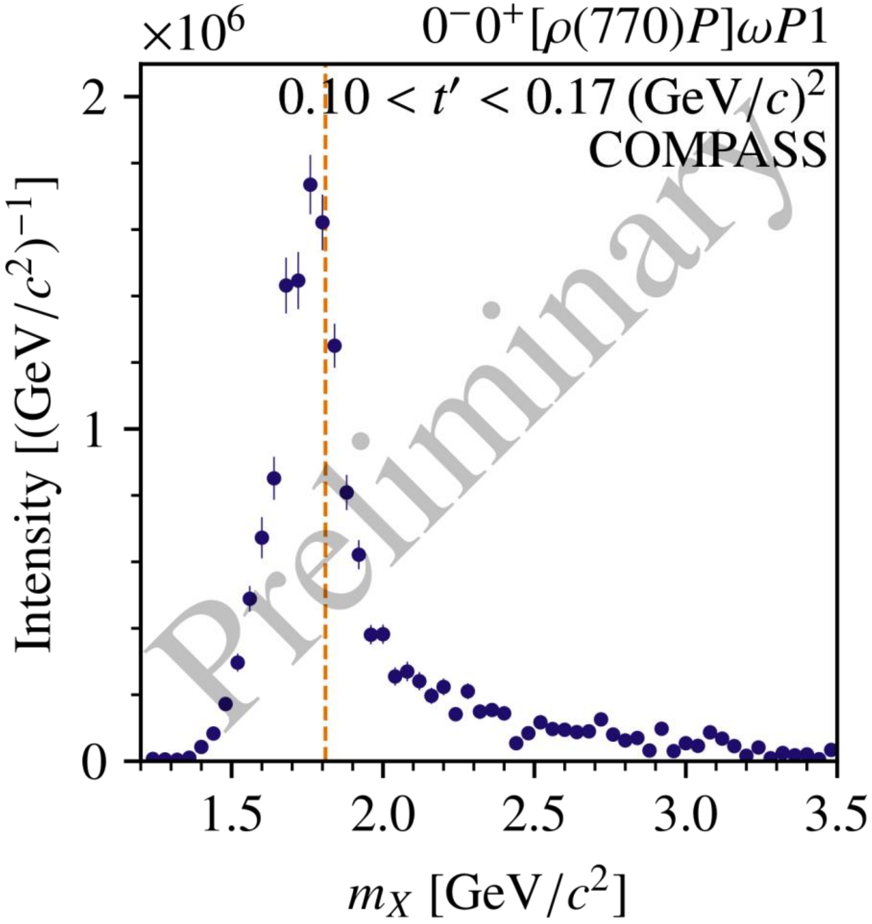

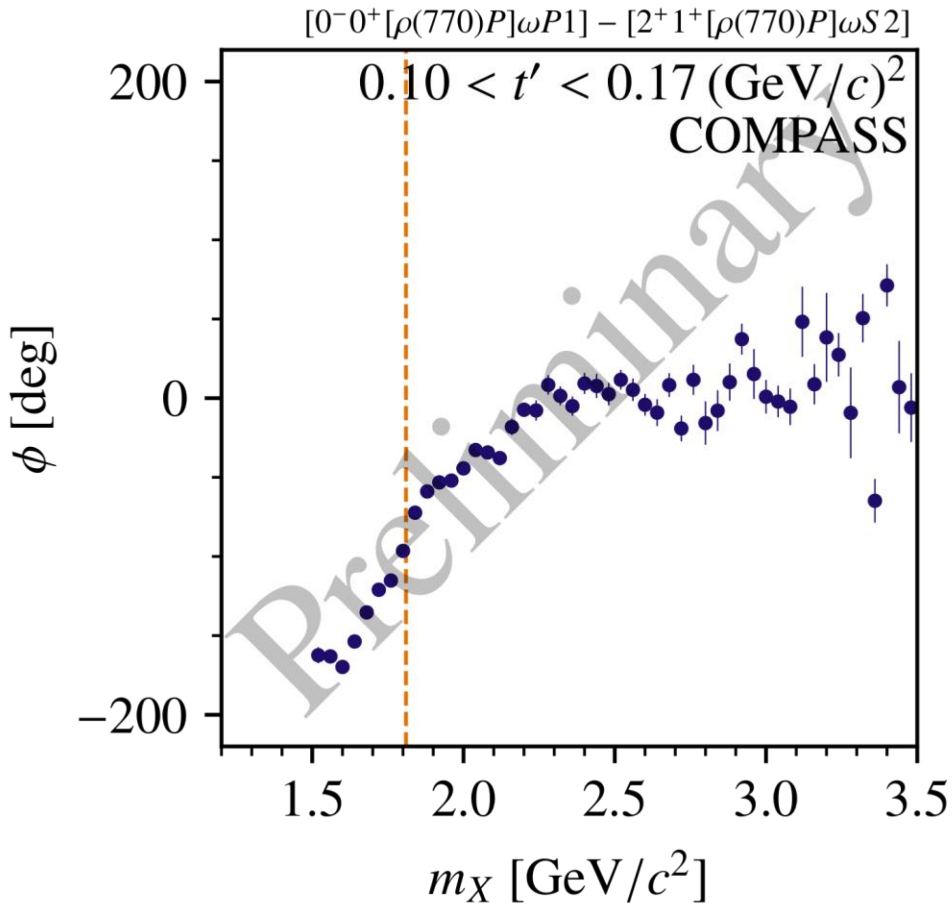

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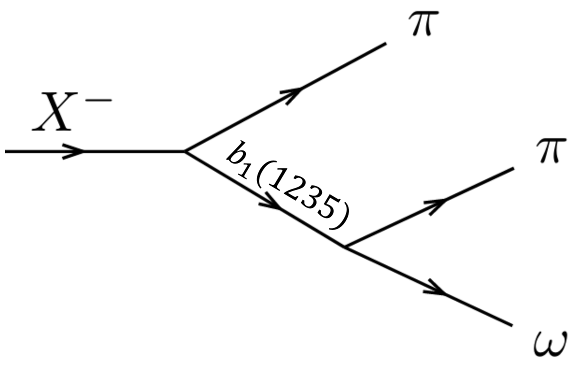
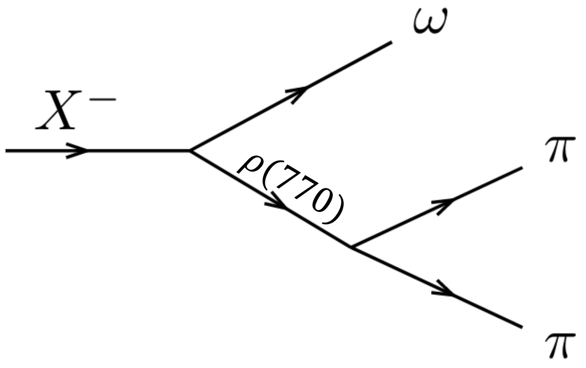
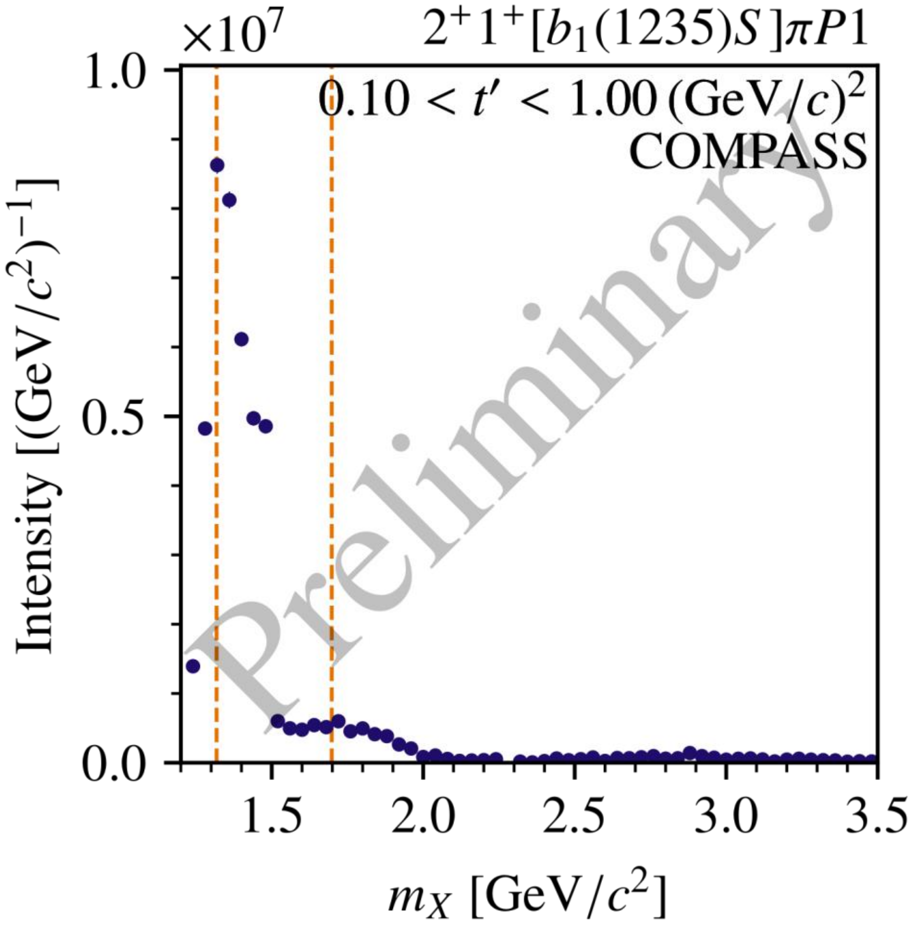
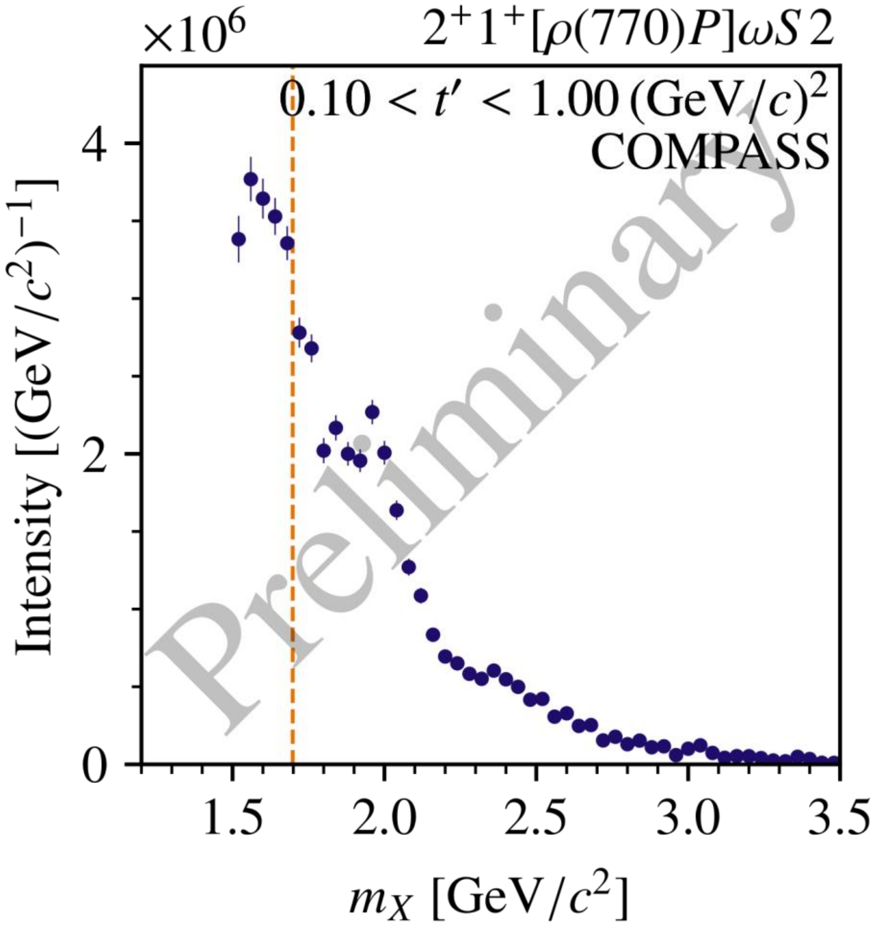
Results $J^{PC} = 2^{++}$







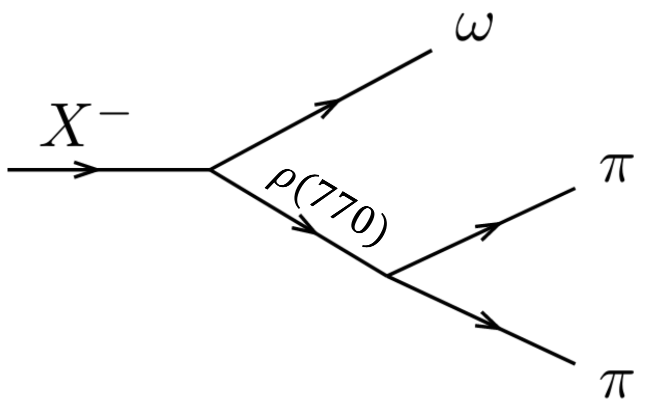


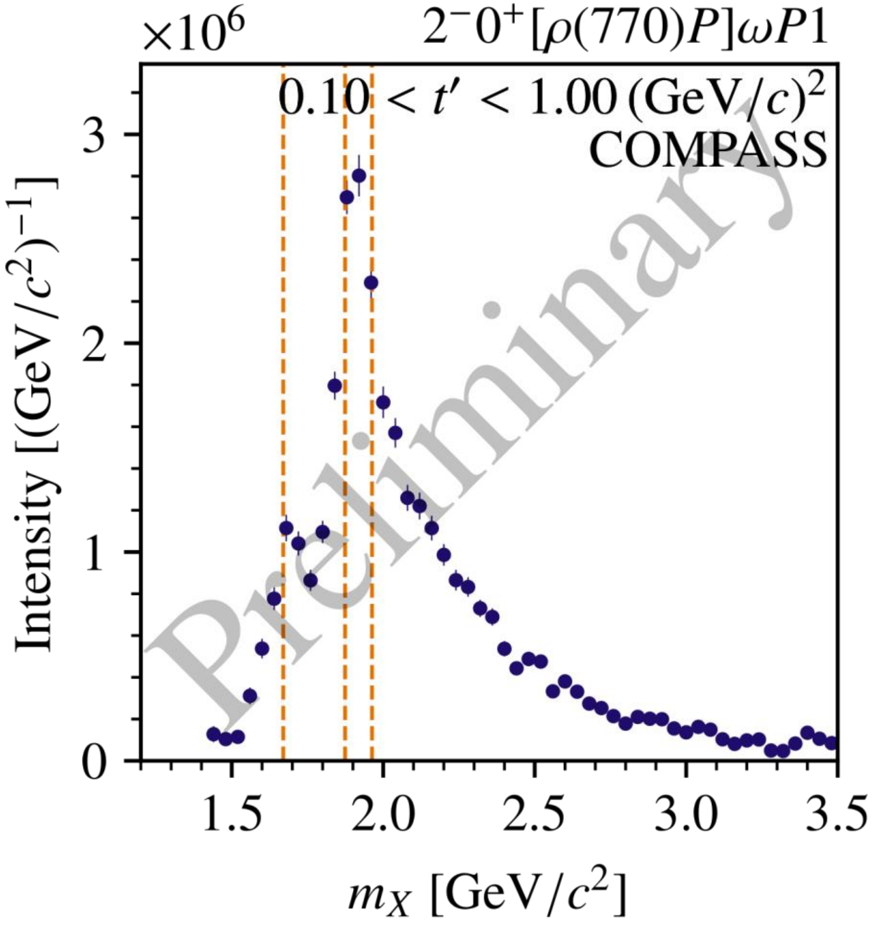
States listed in PDG

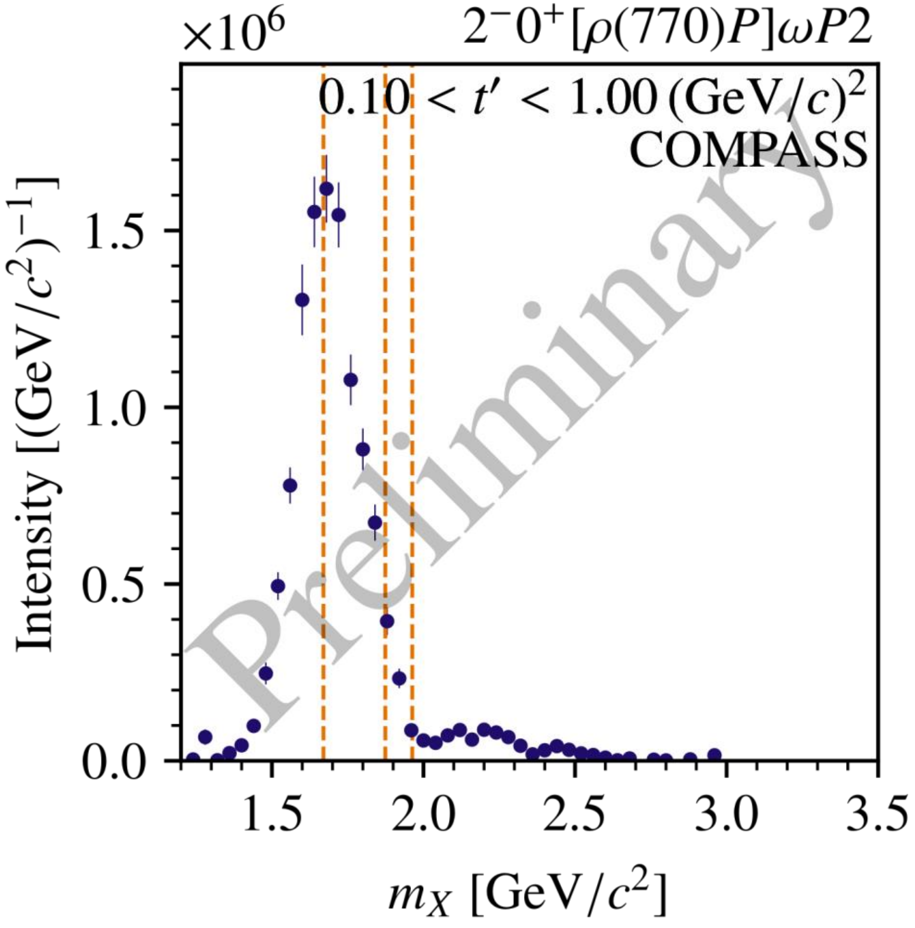
$a_2(1320)$
$m = 1318.2 \pm 0.6$ MeV
$\Gamma = 105^{+1.7}_{-1.9}$ MeV

$a_2(1700)$
$m = 1698 \pm 40$ MeV
$\Gamma = 265 \pm 60$ MeV

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







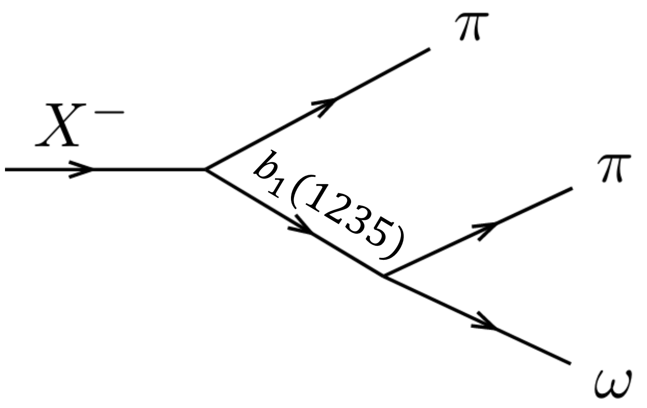
States listed in PDG

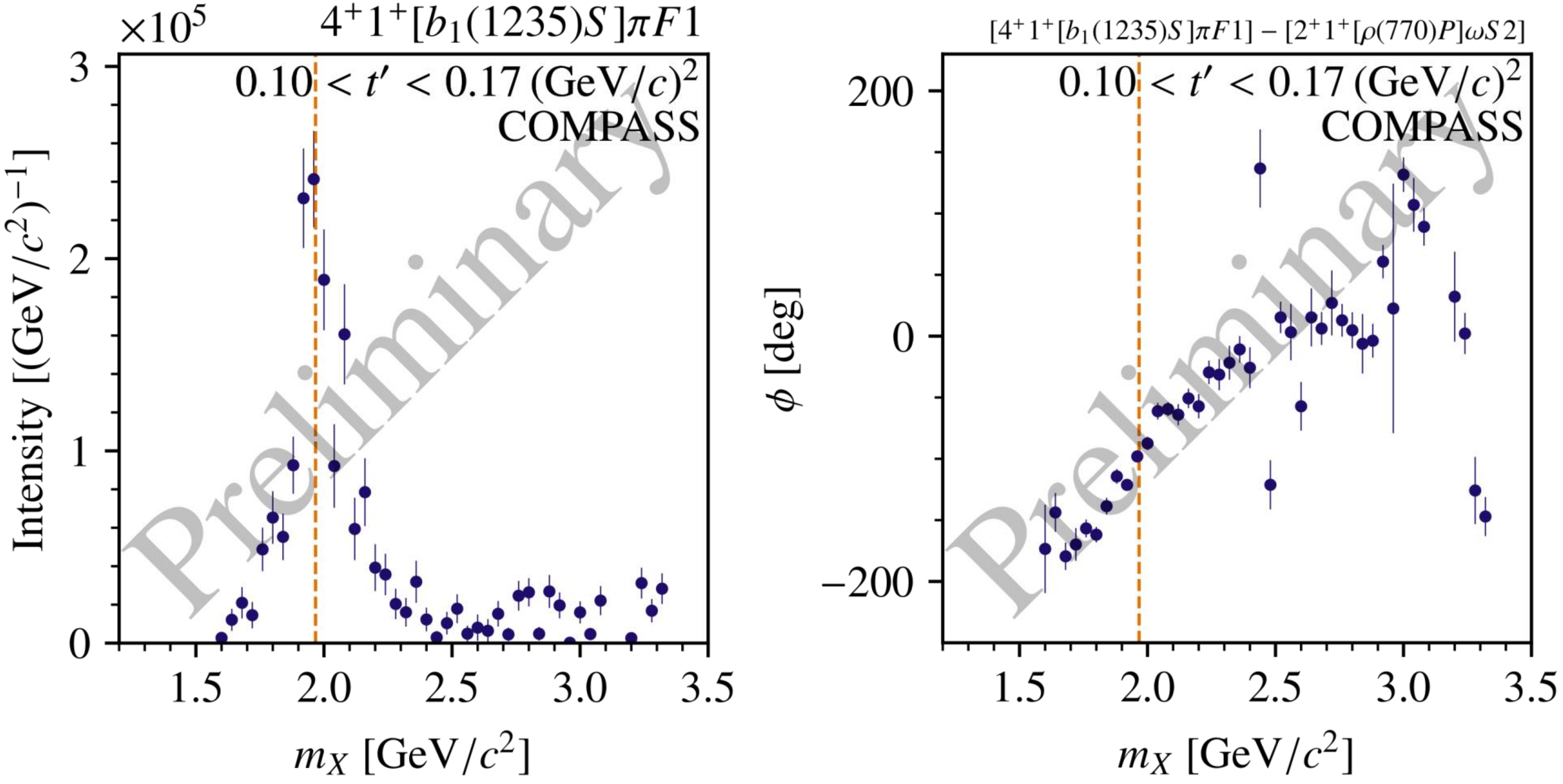
$\pi_2(1670)$
$m = 1670^{+2.9}_{-1.2}$ MeV
$\Gamma = 258^{+8}_{-9}$ MeV

$\pi_2(1880)$
$m = 1874^{+26}_{-5}$ MeV
$\Gamma = 237^{+33}_{-30}$ MeV

$\pi_2(2005)$
$m = 1963^{+17}_{-27}$ MeV
$\Gamma = 370^{+16}_{-90}$ MeV

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

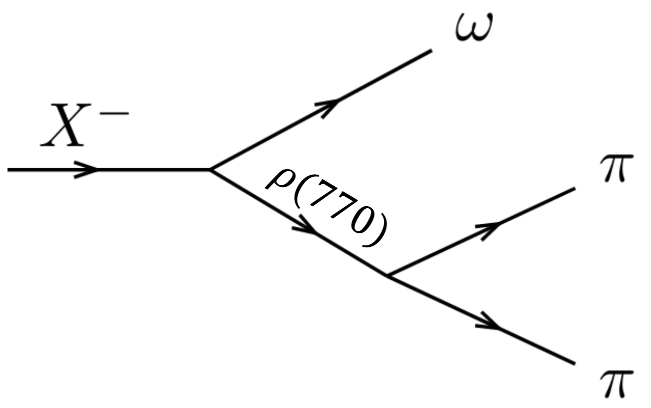


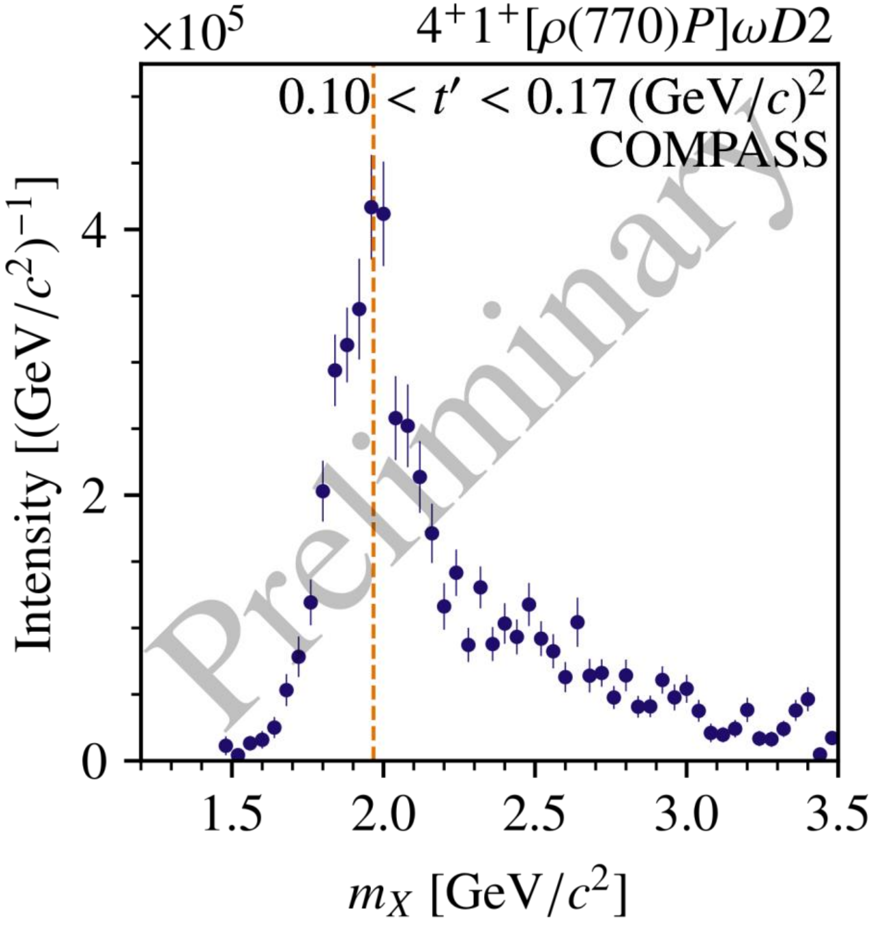


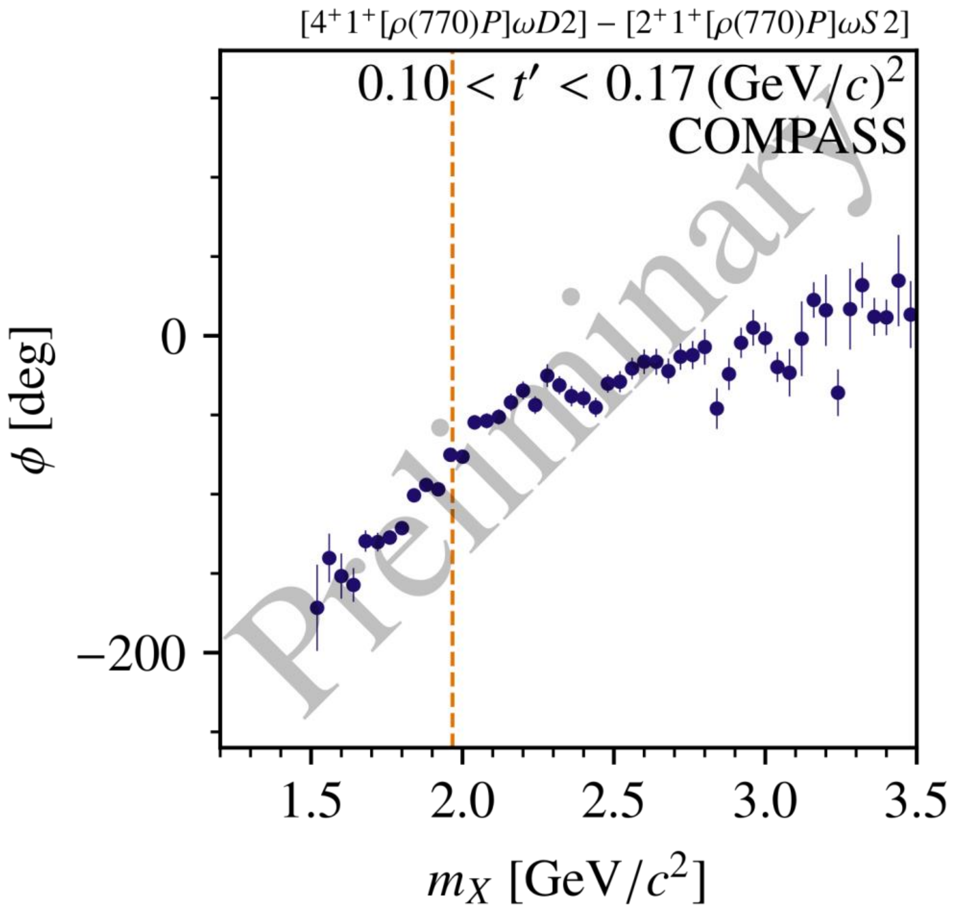
States listed in PDG

$a_4(1970)$
$m = 1967 \pm 16$ MeV
$\Gamma = 324^{+15}_{-18}$ MeV

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



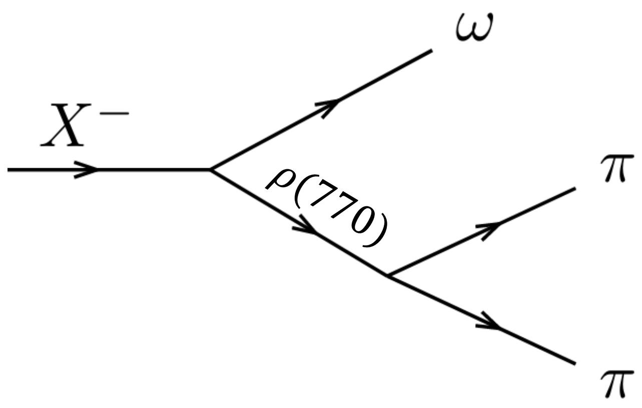


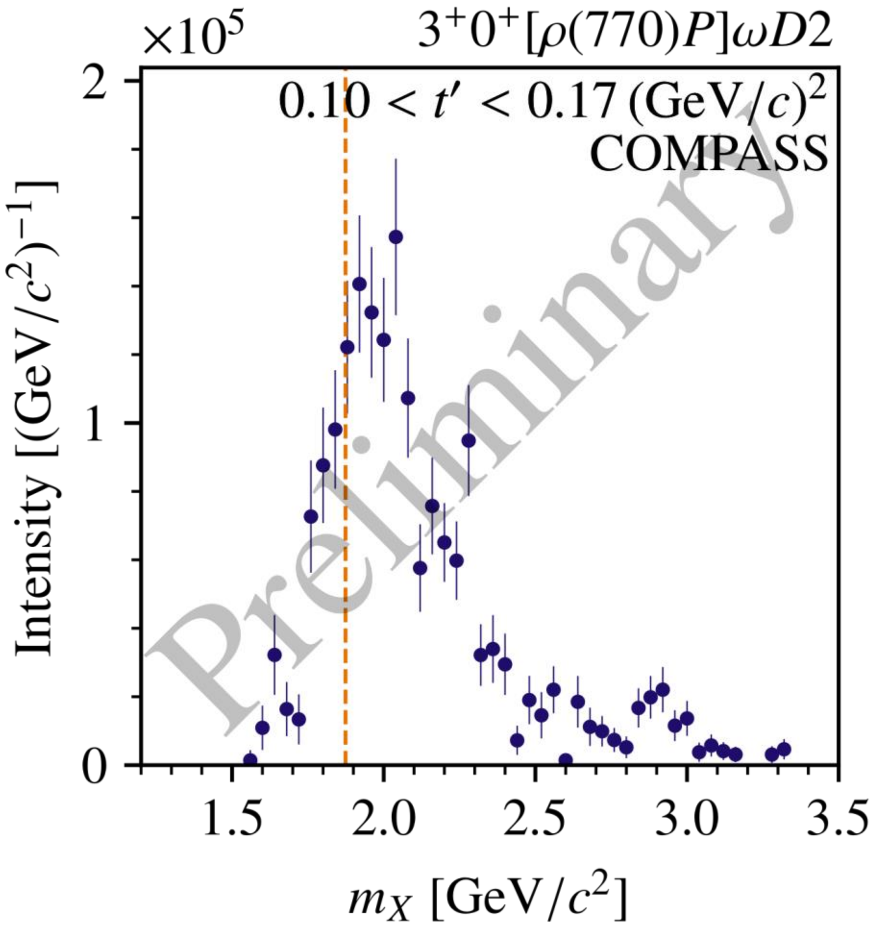


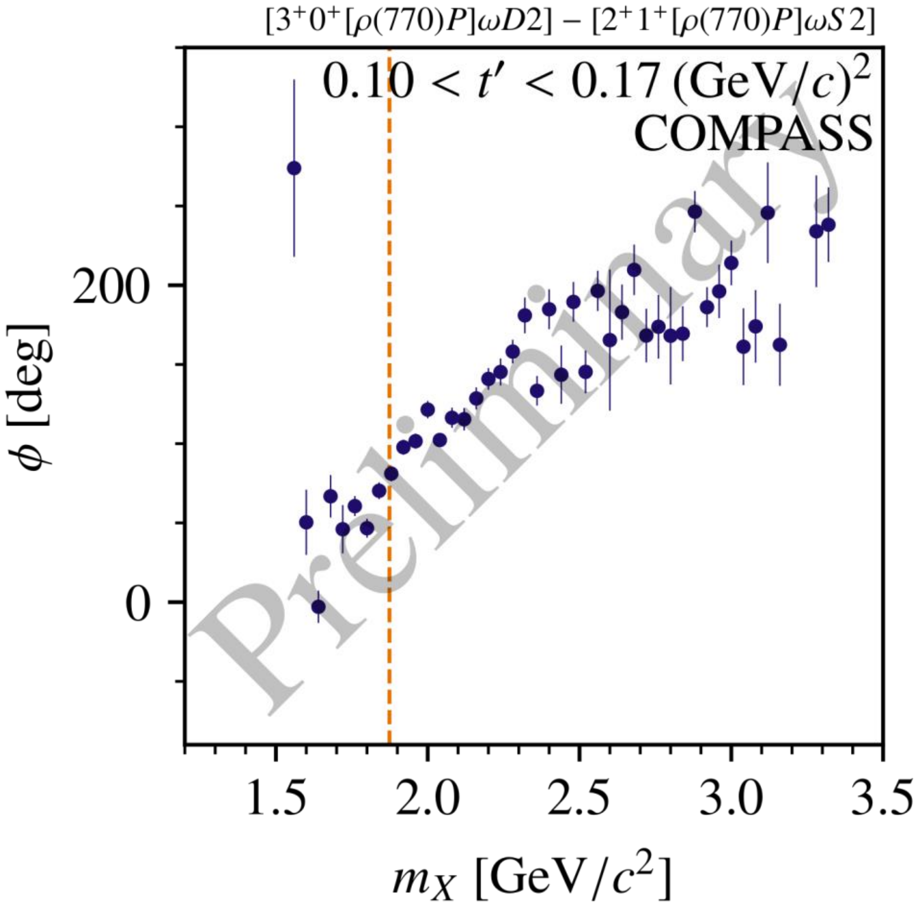
States listed in PDG

$a_4(1970)$
$m = 1967 \pm 16$ MeV
$\Gamma = 324^{+15}_{-18}$ MeV

Results $J^{PC} = 3^{++}$







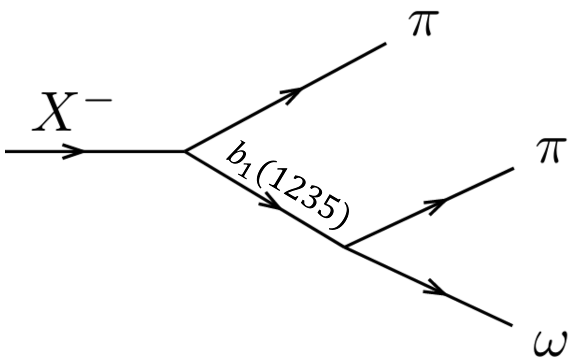
States listed in PDG

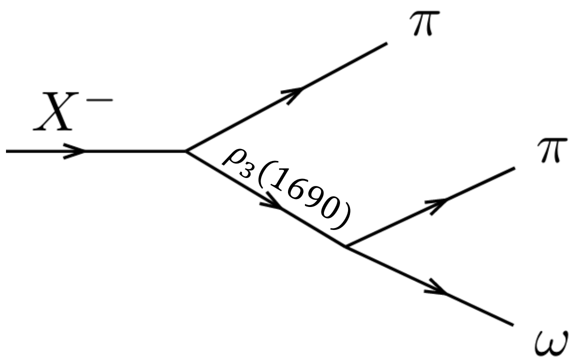
$a_3(1875)$
$m = 1874 \pm 105$ MeV
$\Gamma = 385 \pm 166$ MeV

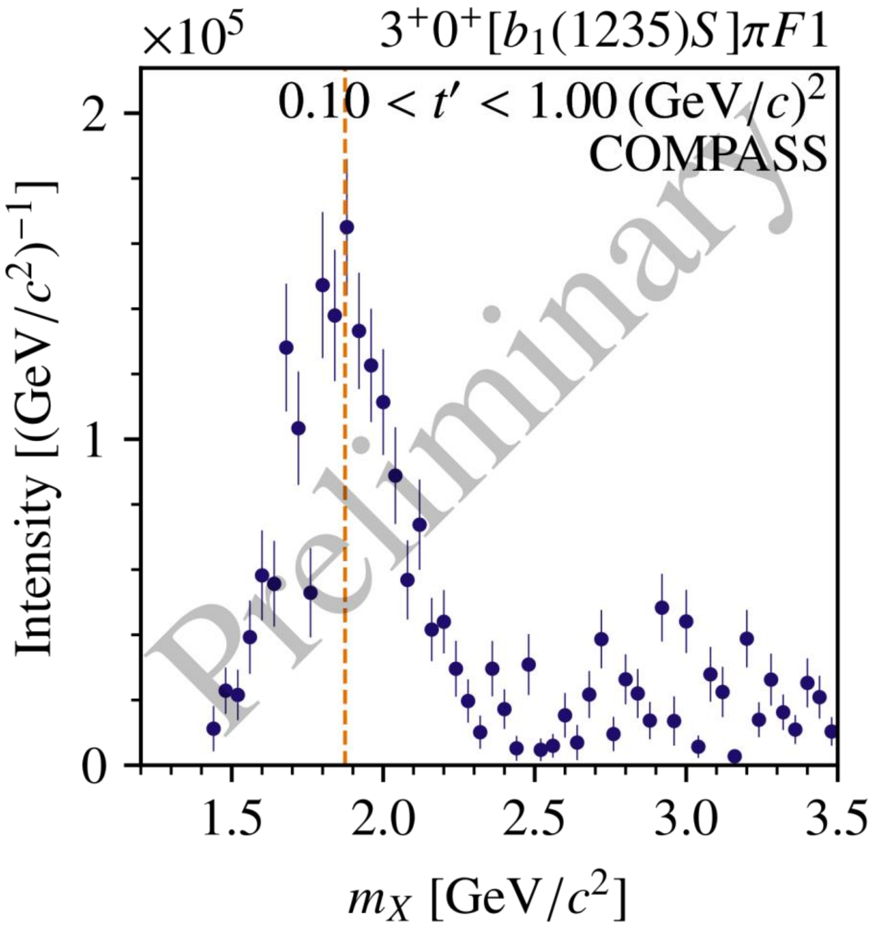
This only has been seen in $\pi^-\pi^-\pi^+$ at BNL E852

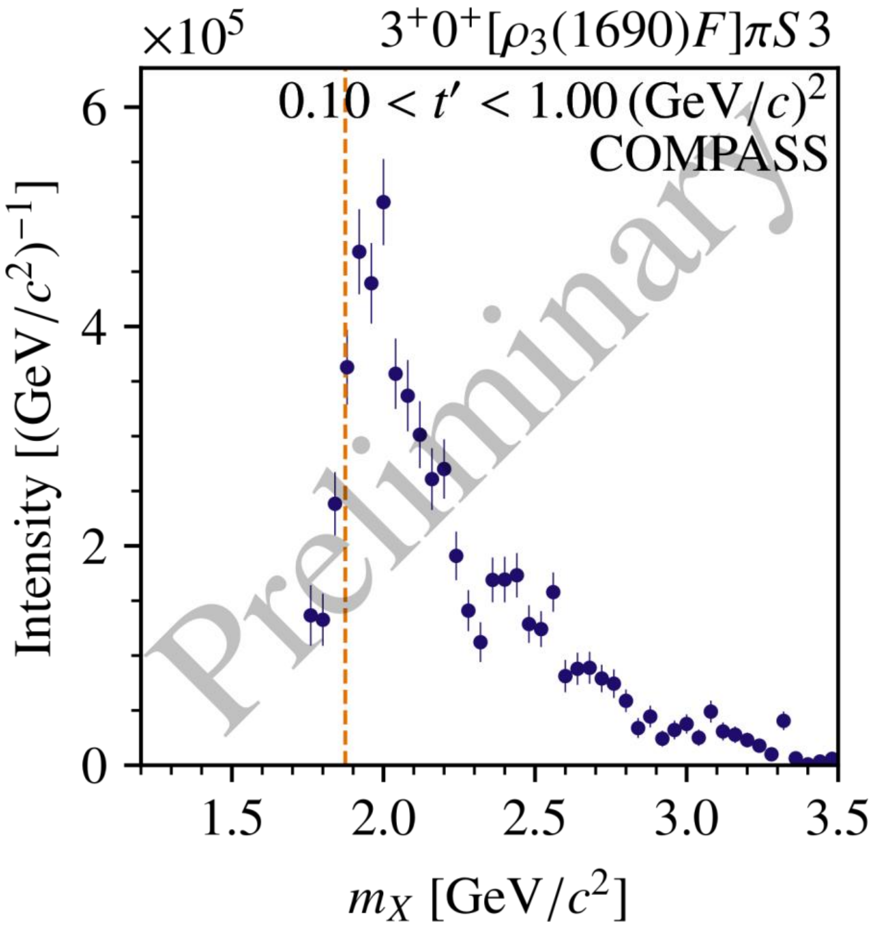
The PDG further lists a $a_3(2030)$

Results $J^{PC} = 3^{++}$









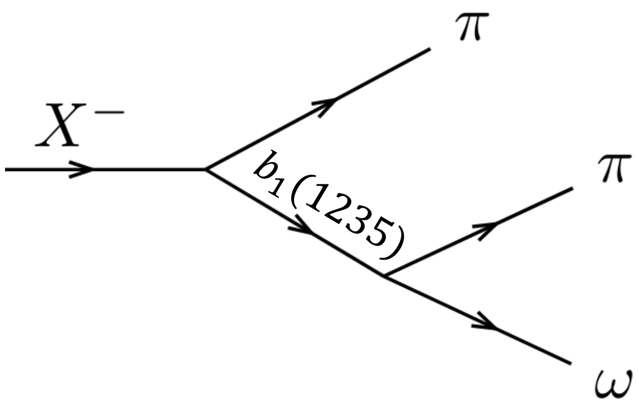
States listed in PDG

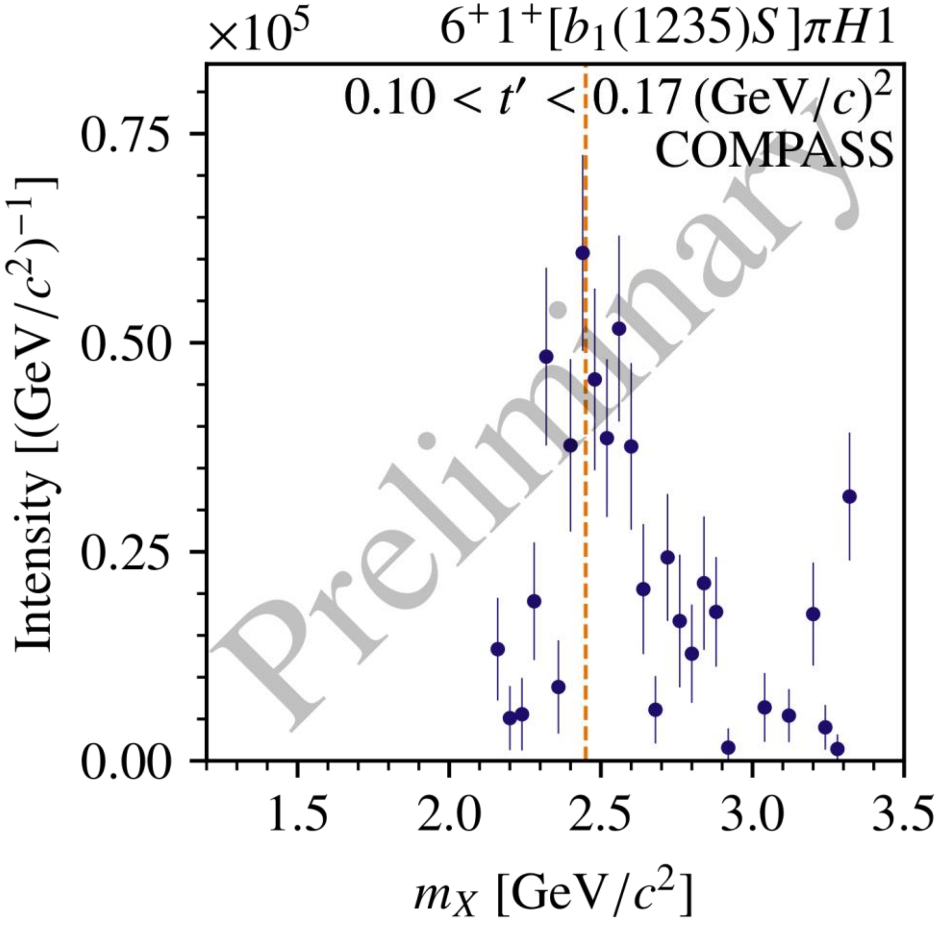
$a_3(1875)$
$m = 1874 \pm 105$ MeV
$\Gamma = 385 \pm 166$ MeV

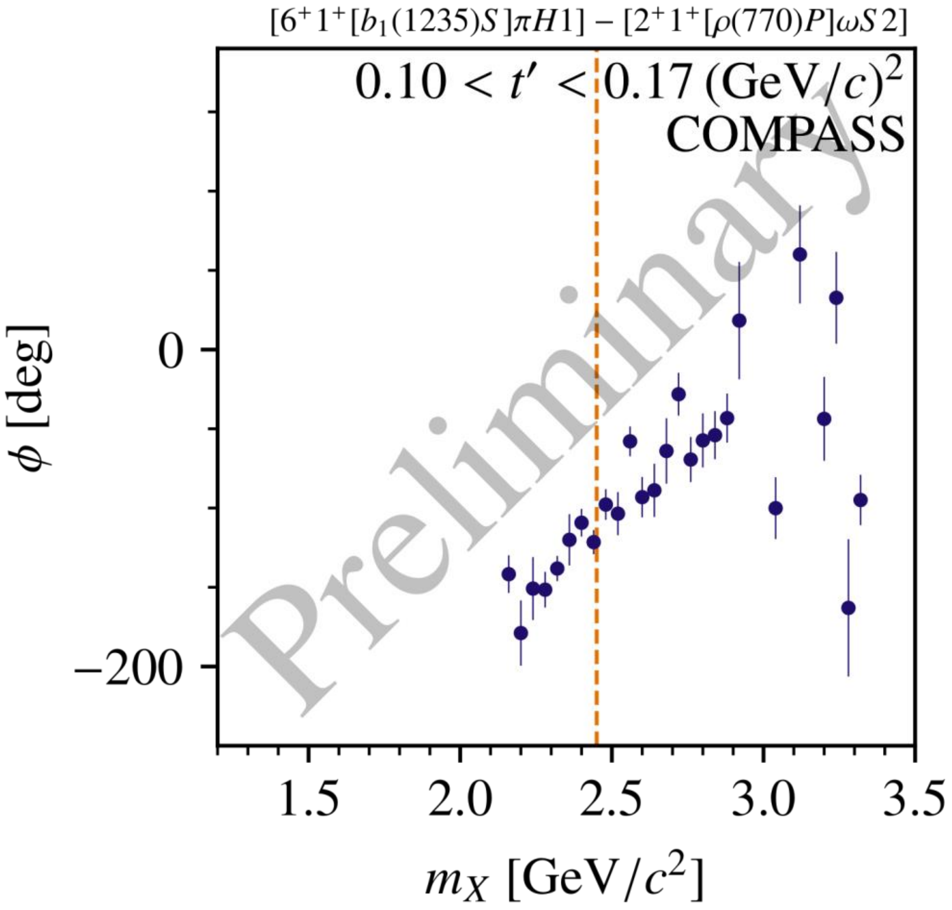
This only has been seen once in $\pi^-\pi^-\pi^+$

The PDG also lists a $a_3(2030)$

Results $J^{PC} = 6^{++}$





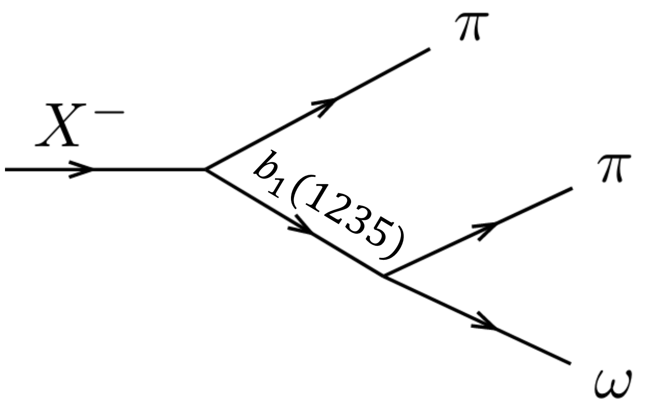


States listed in PDG

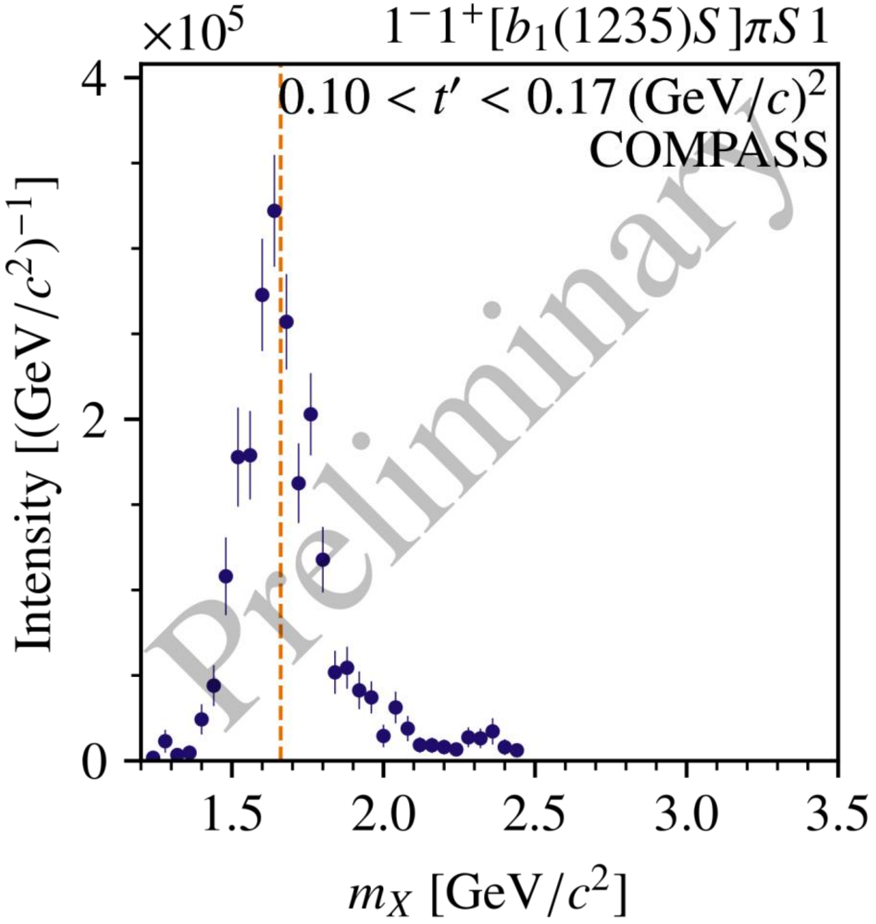
$a_6(2450)$
$m = 2450 \pm 130$ MeV
$\Gamma = 400 \pm 250$ MeV

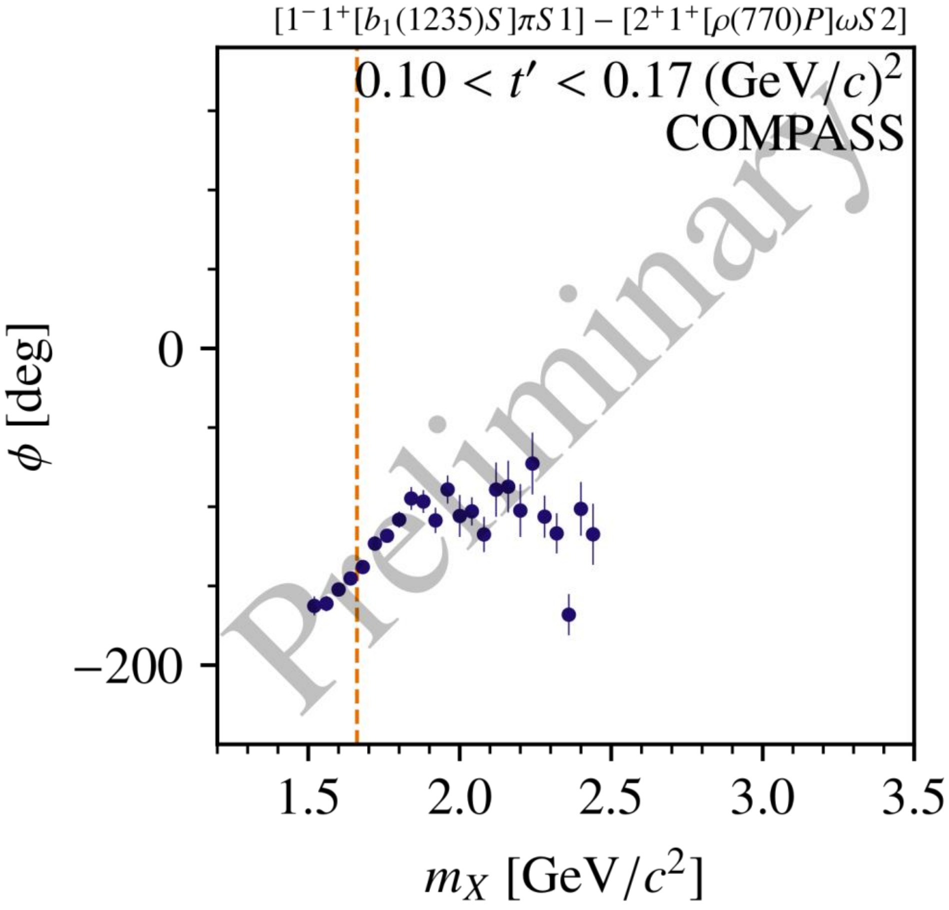
This only has been seen once in $K_S K$

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



b_1 S-wave decay

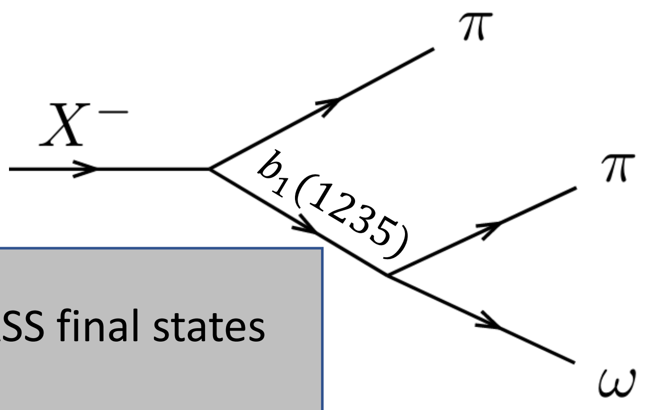




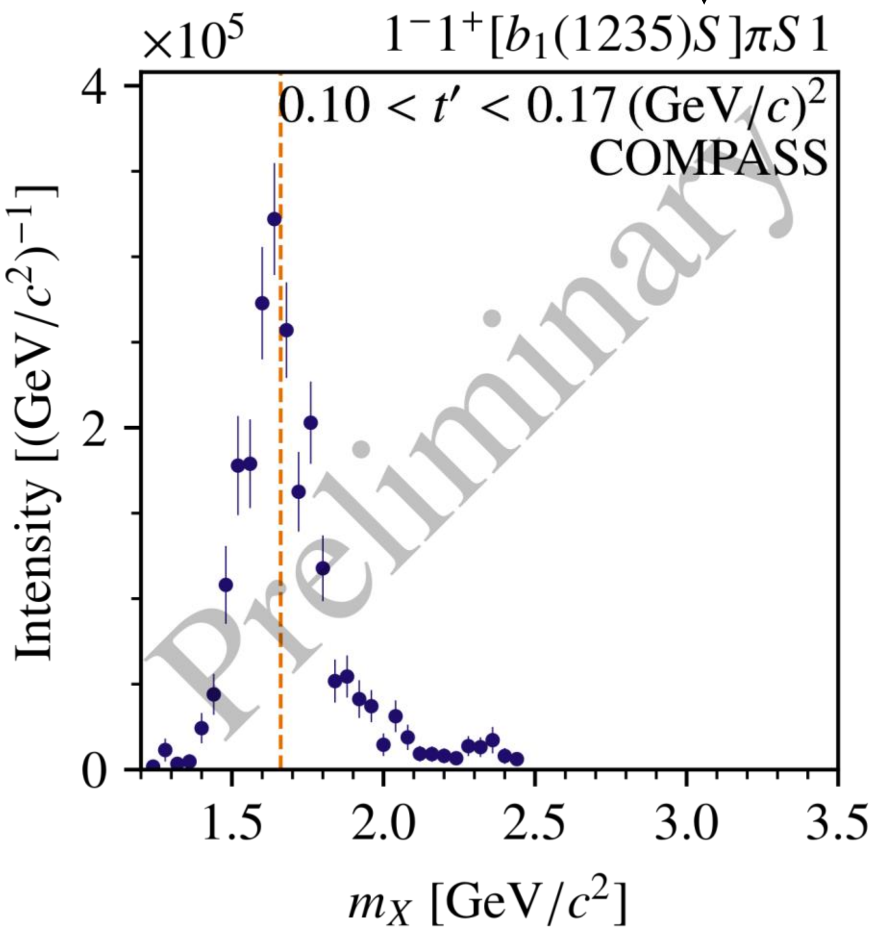
States listed in PDG

$\pi_1(1600)$
$m = 1661^{+15}_{-11}$ MeV
$\Gamma = 240 \pm 50$ MeV

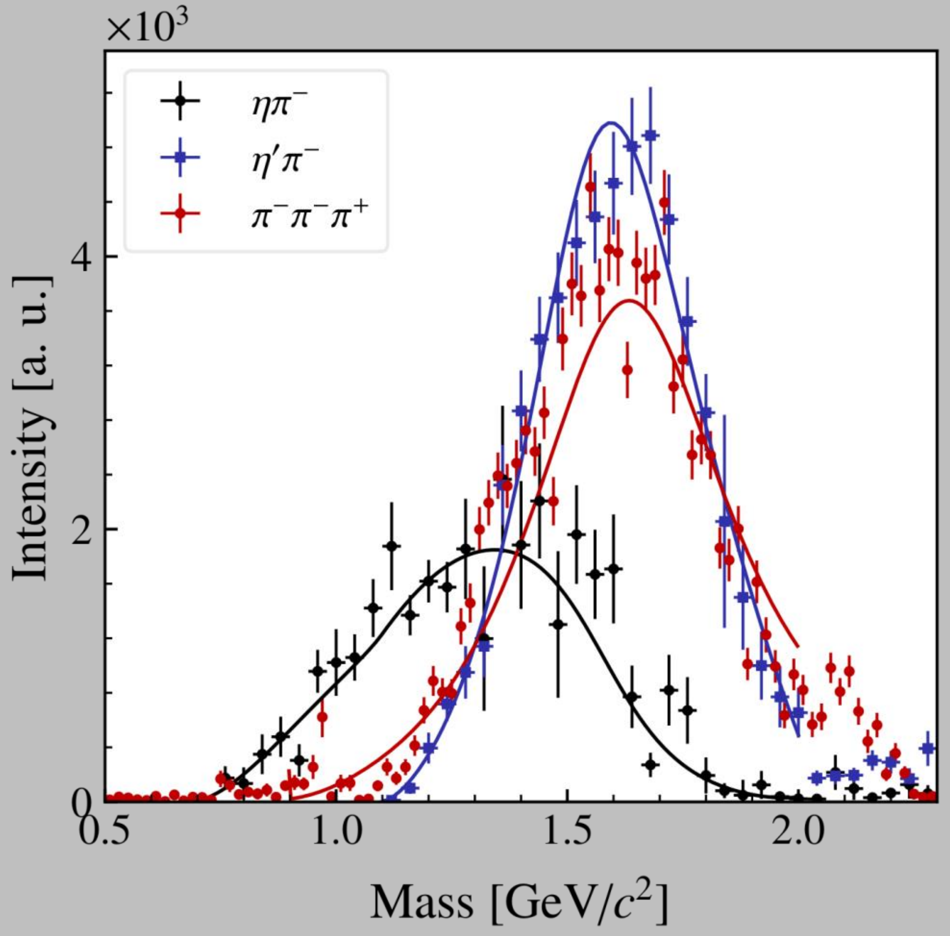
Results $J^{PC} = 1^{-+}$



b_1 S-wave decay



Comparison to 1^{-+} in other COMPASS final states



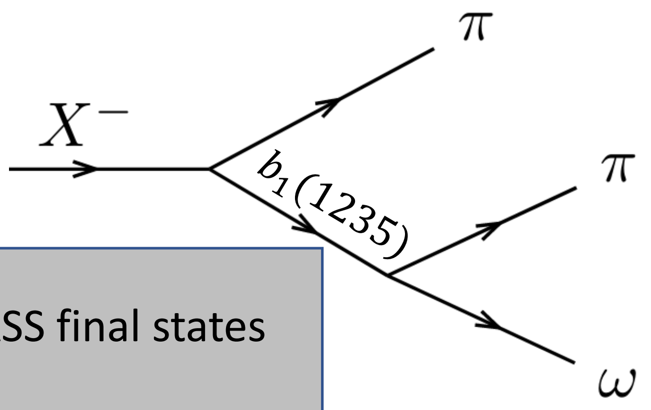
...tes listed in PDG

$\pi_1(1600)$

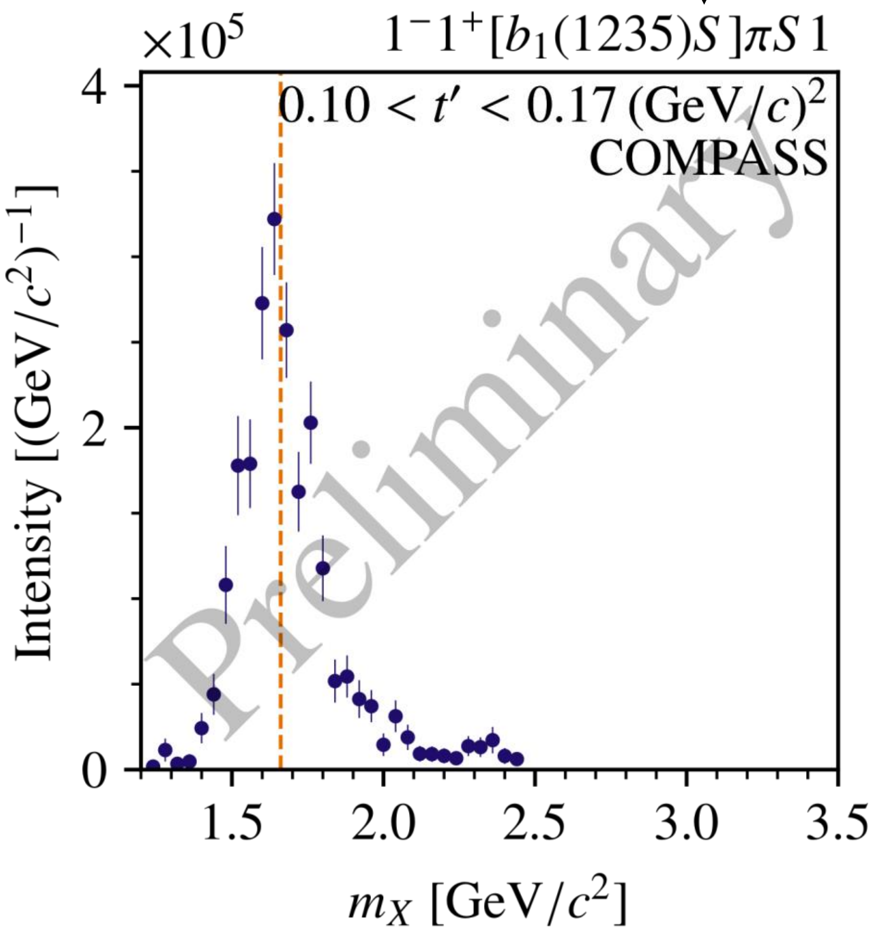
... $= 1661^{+15}_{-11}$ MeV

... $= 240 \pm 50$ MeV

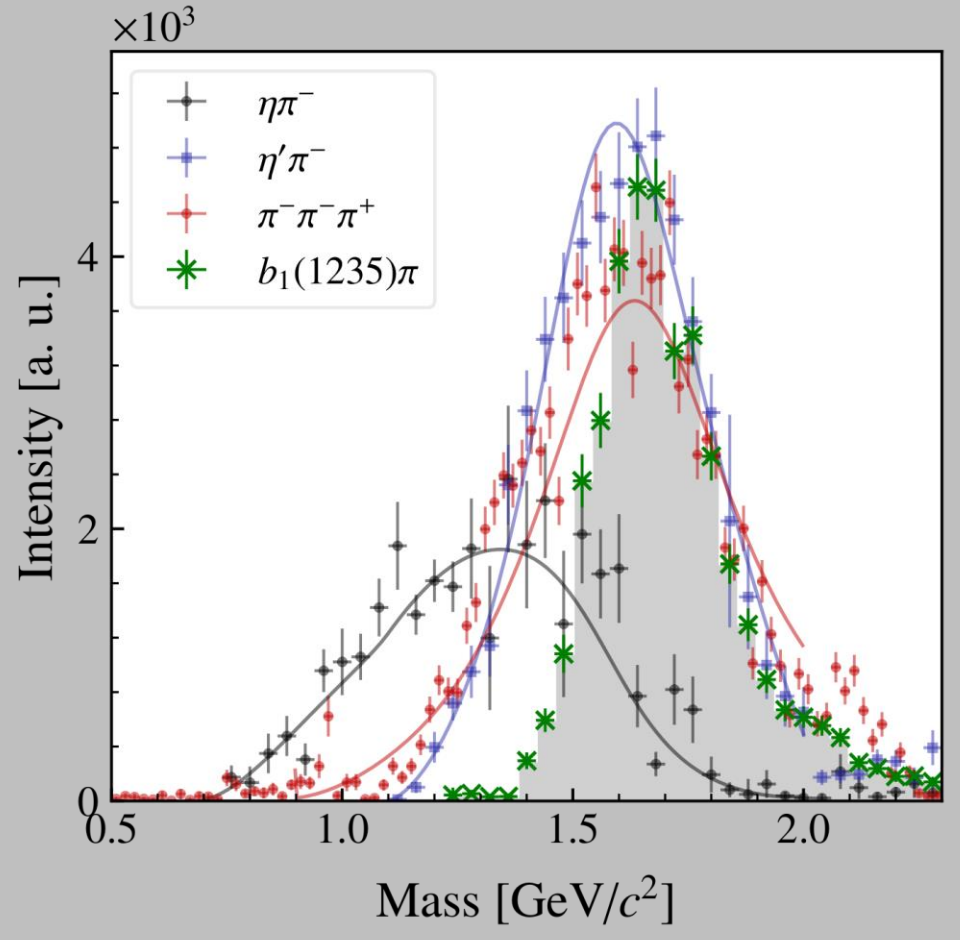
Results $J^{PC} = 1^{-+}$



b_1 S-wave decay



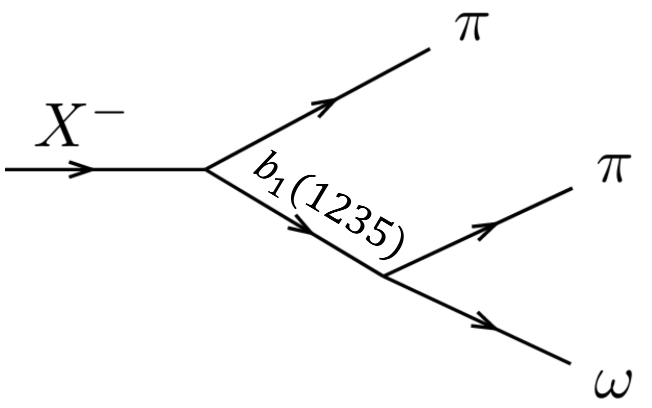
Comparison to 1^{-+} in other COMPASS final states



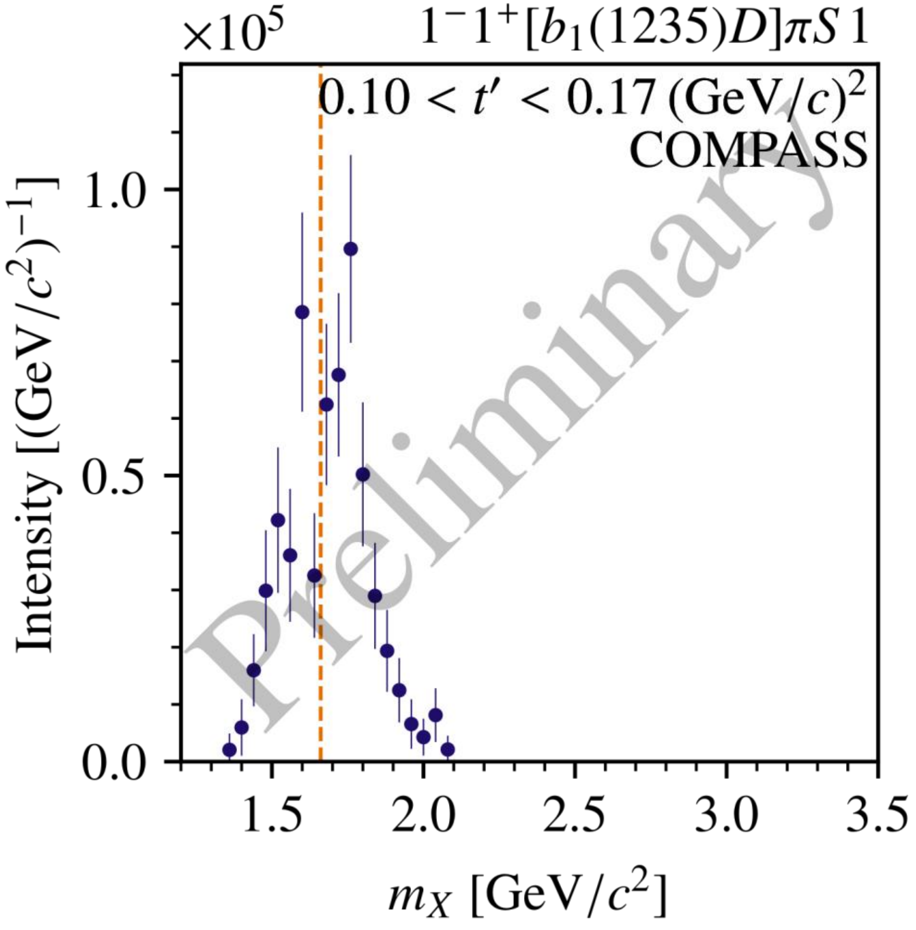
ates listed in PDG

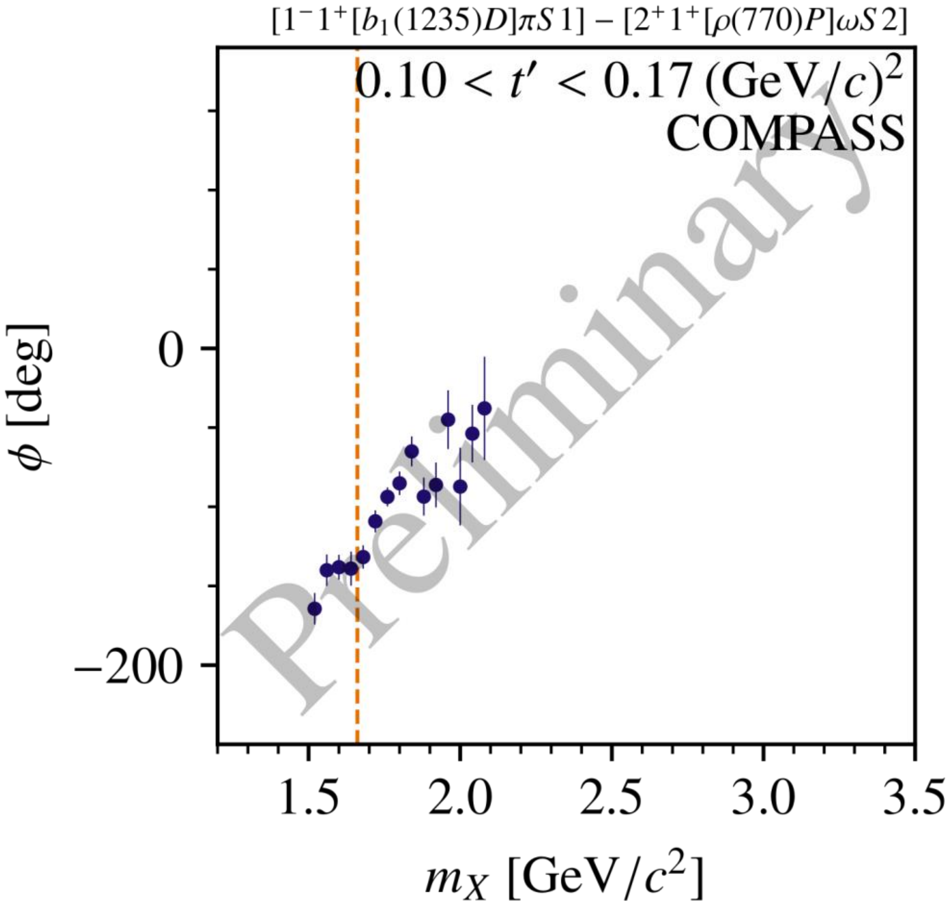
$\pi_1(1600)$
$= 1661^{+15}_{-11}$ MeV
$= 240 \pm 50$ MeV

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



b_1 D-wave decay





States listed in PDG

$\pi_1(1600)$
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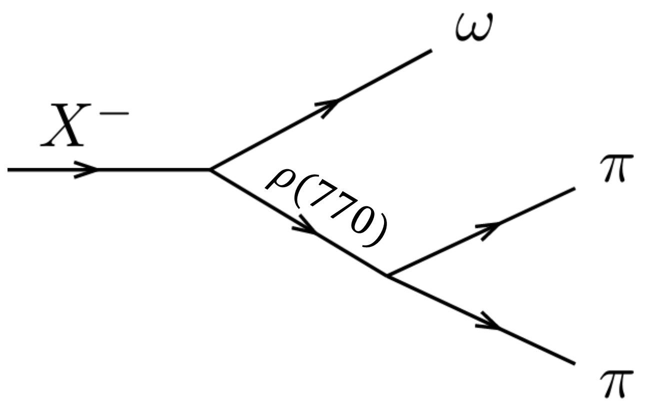
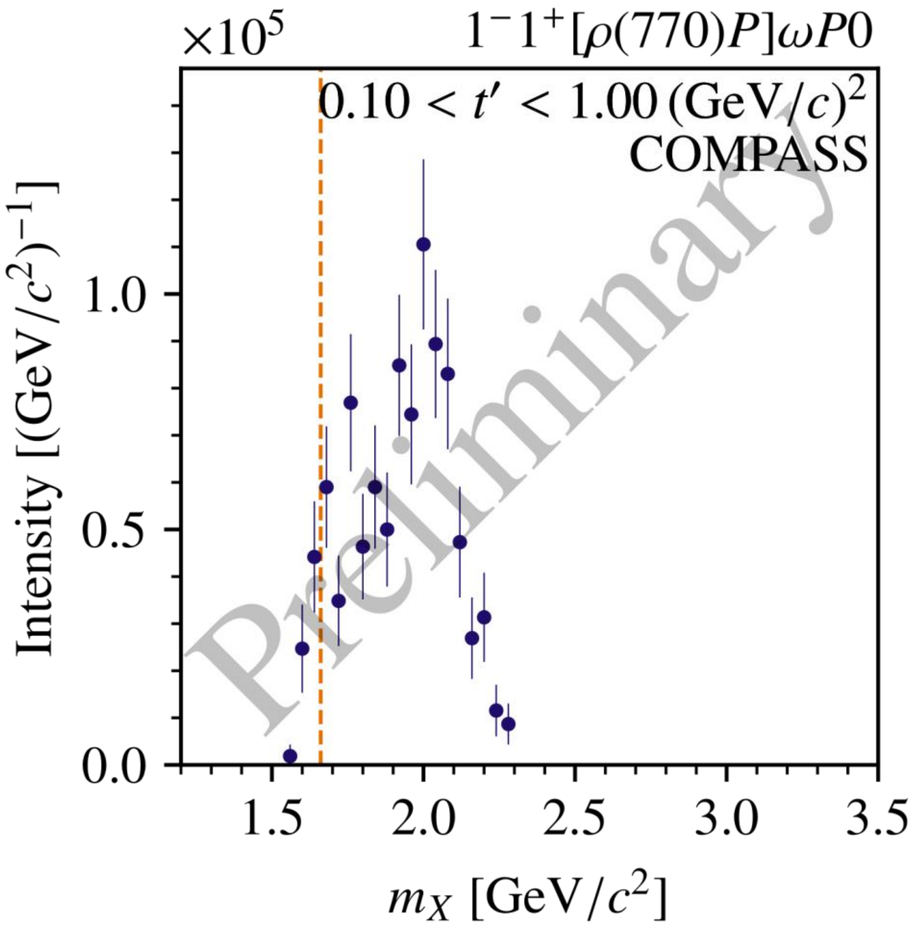
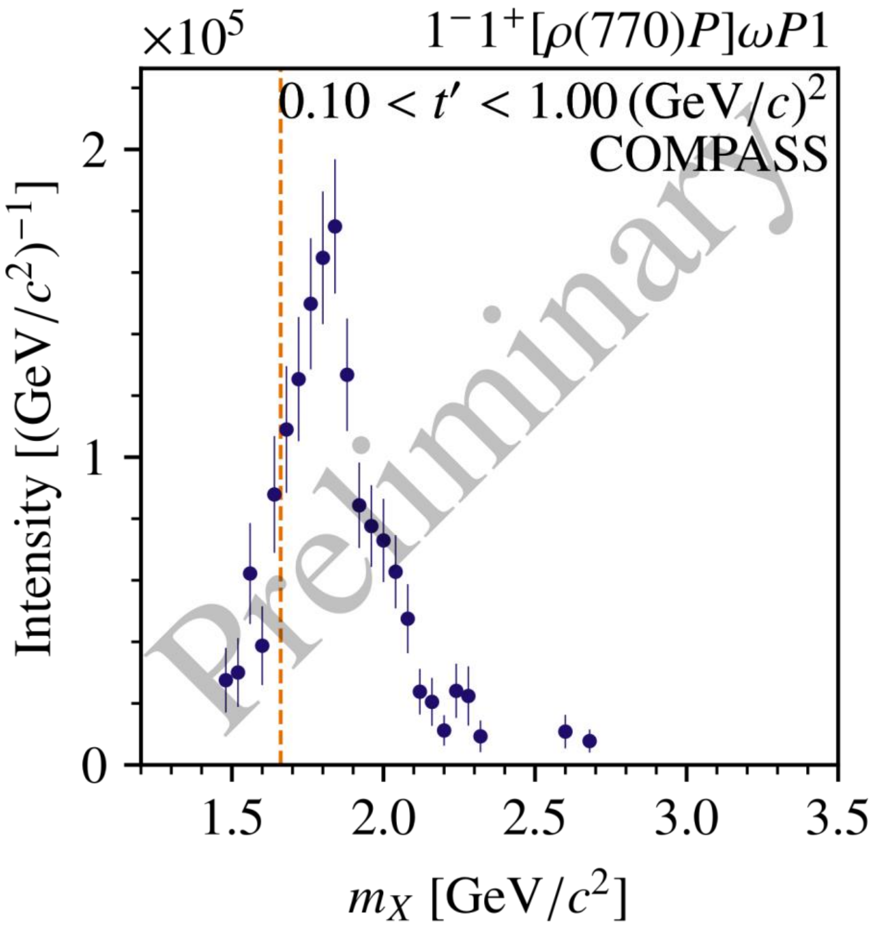
Results $J^{PC} = 1^{-+}$







States listed in PDG

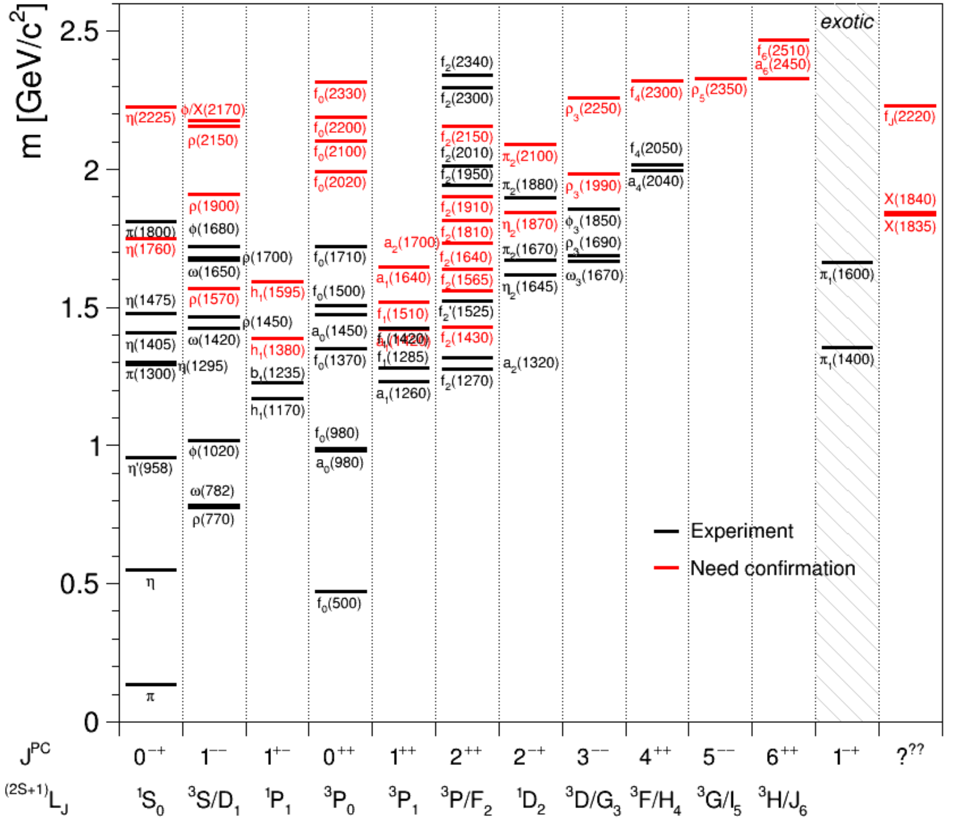
$\pi_1(1600)$
$m = 1661^{+15}_{-11}$ MeV
$\Gamma = 240 \pm 50$ MeV

Conclusion and Outlook

- Resonance-like signals for many well-established states visible
  - Clear peak for $\pi_1(1600) \rightarrow b_1(1235)\pi$
- Possible signals for further states: $a_3(1975)$, $a_6(2450)$, $\pi_1 \rightarrow \rho(770)\omega$
- Next step: Resonance-model fit to extract resonance parameters
  - First studies yield promising results

Backup

Mesons in QCD



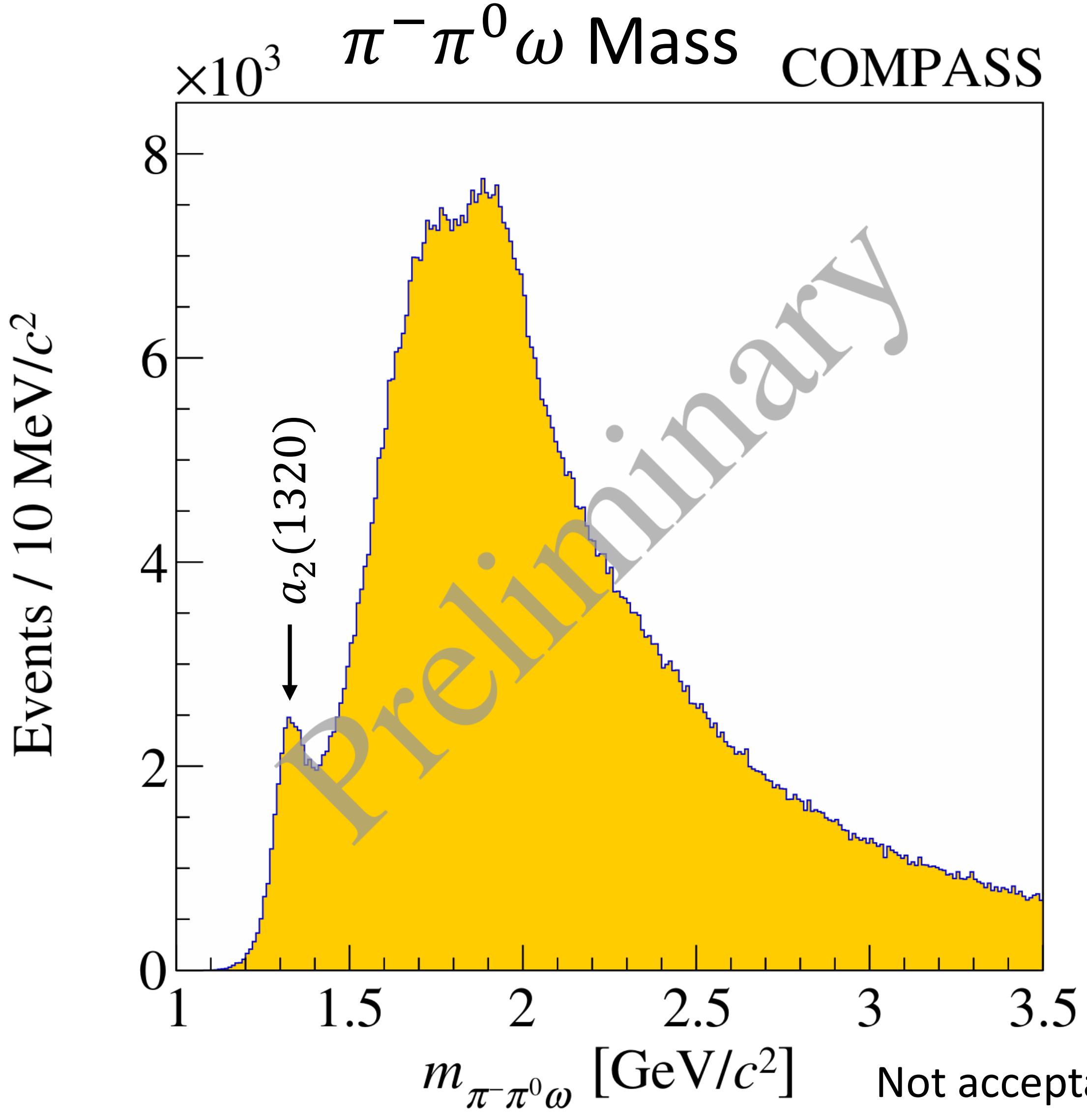
- Many short-lived, exited states with similar masses

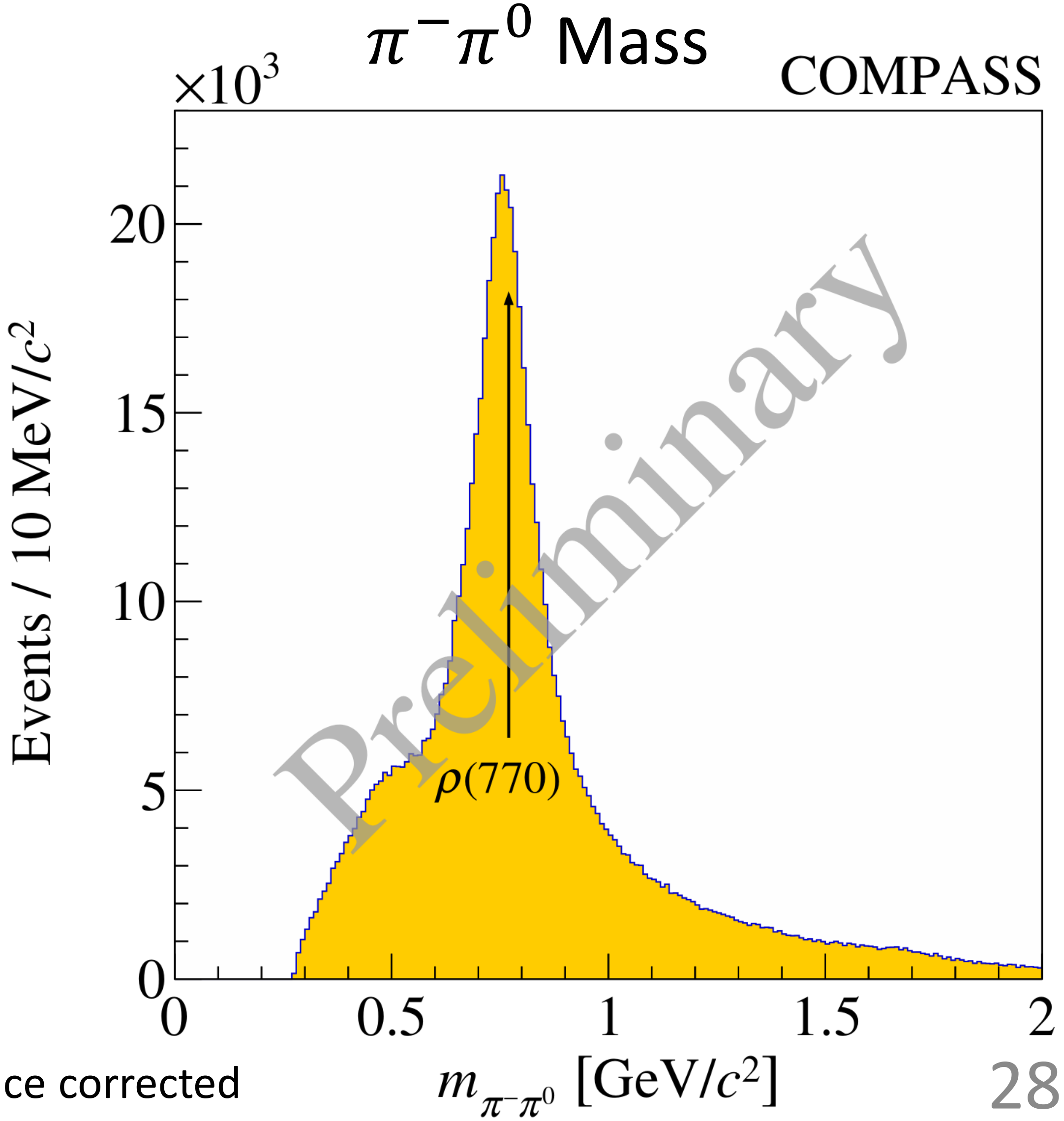
$\Rightarrow$ All possible intermediate states X for one final-state configuration interfere

$\Rightarrow$PWA necessary to determine contributions of certain X

Kinematic Distributions - $\omega(782)\pi^-\pi^0$

- Total of 720,000 selected $\pi^-\pi^0\omega(782)$ events





Not acceptance corrected

Kinematic Distributions - $\omega(782)\pi^-\pi^0$

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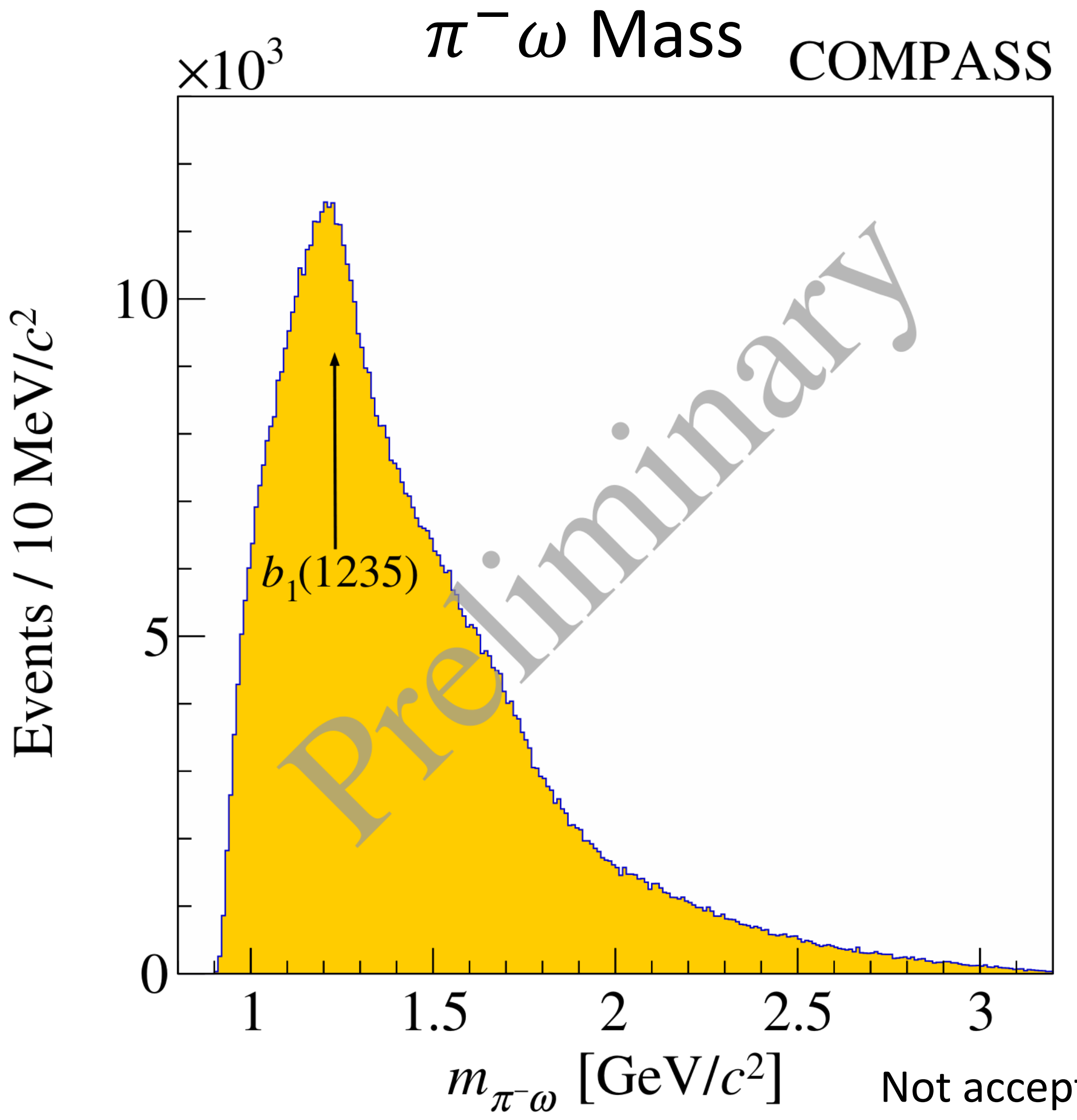
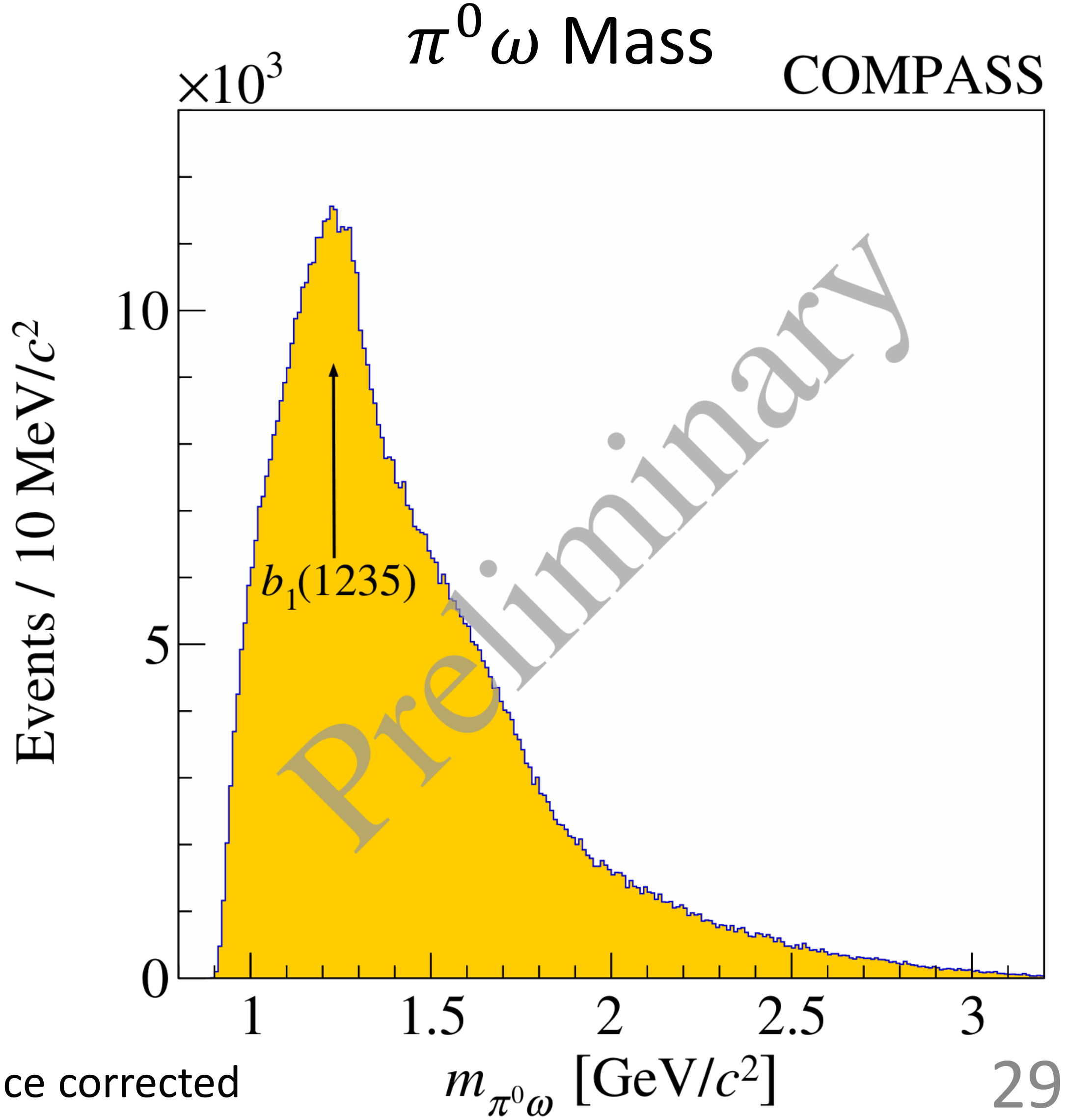
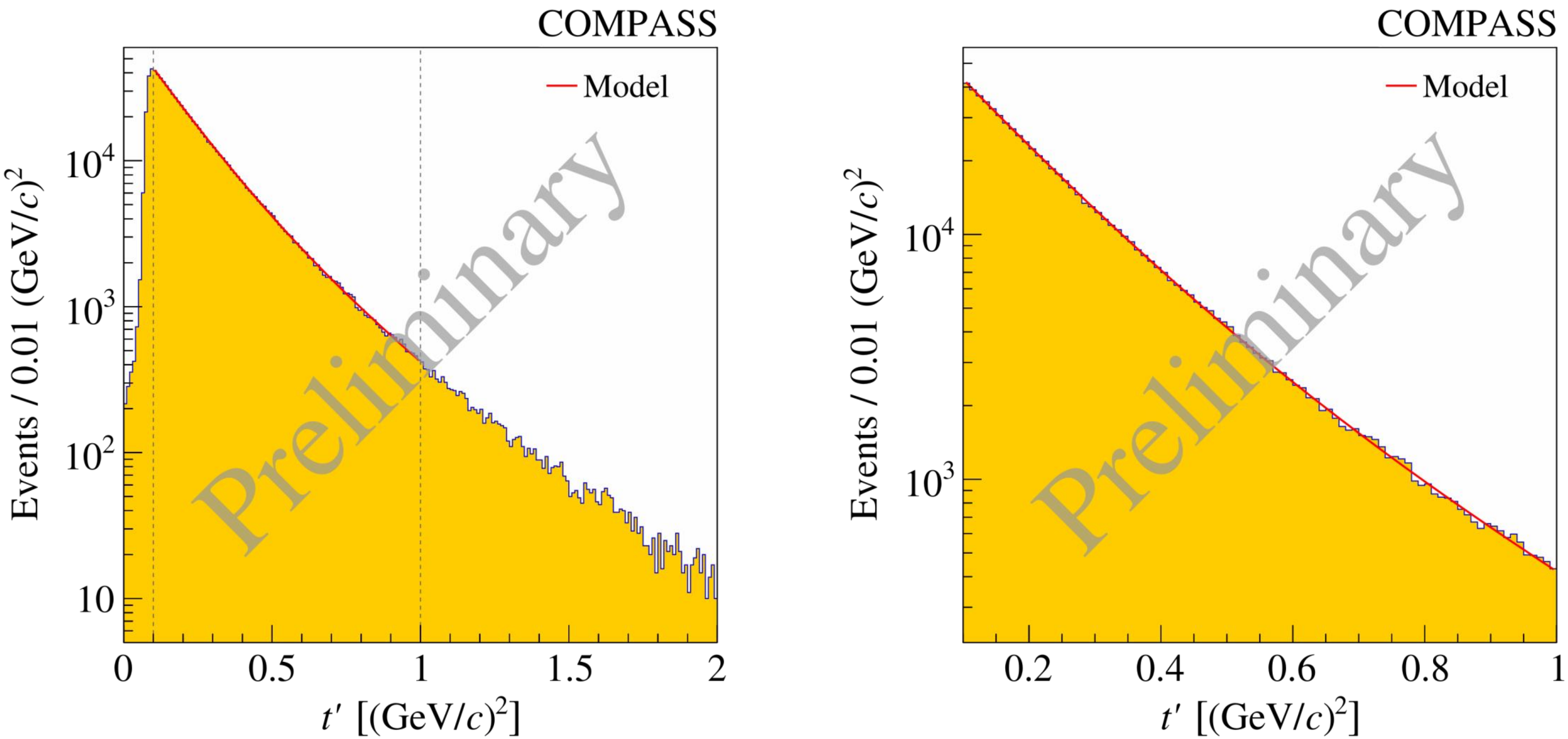


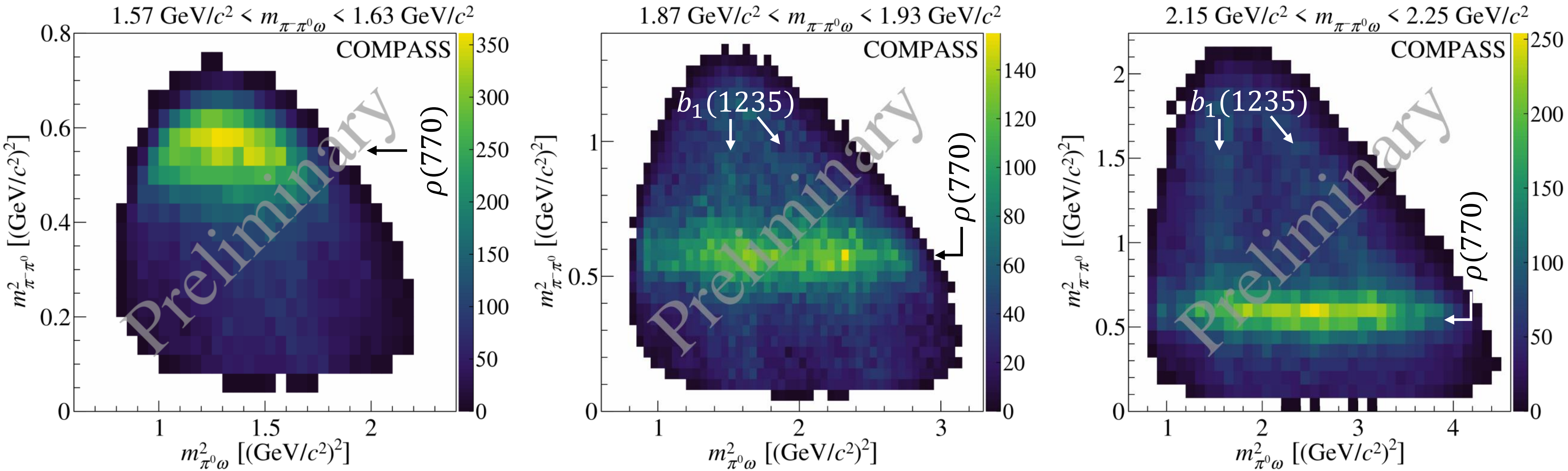


Not acceptance corrected

t′ Distribution - $\omega(782)\pi^-\pi^0$

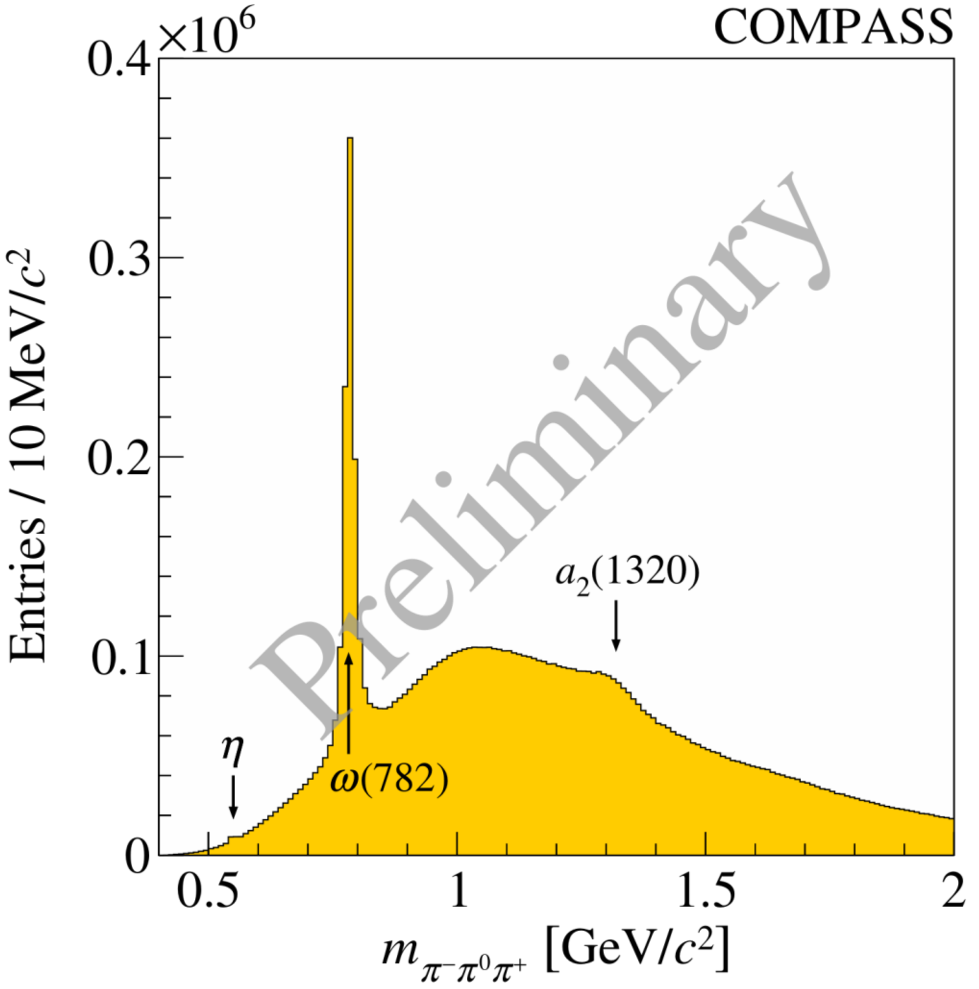


Dalitz Plots - $\omega(782)\pi^-\pi^0$



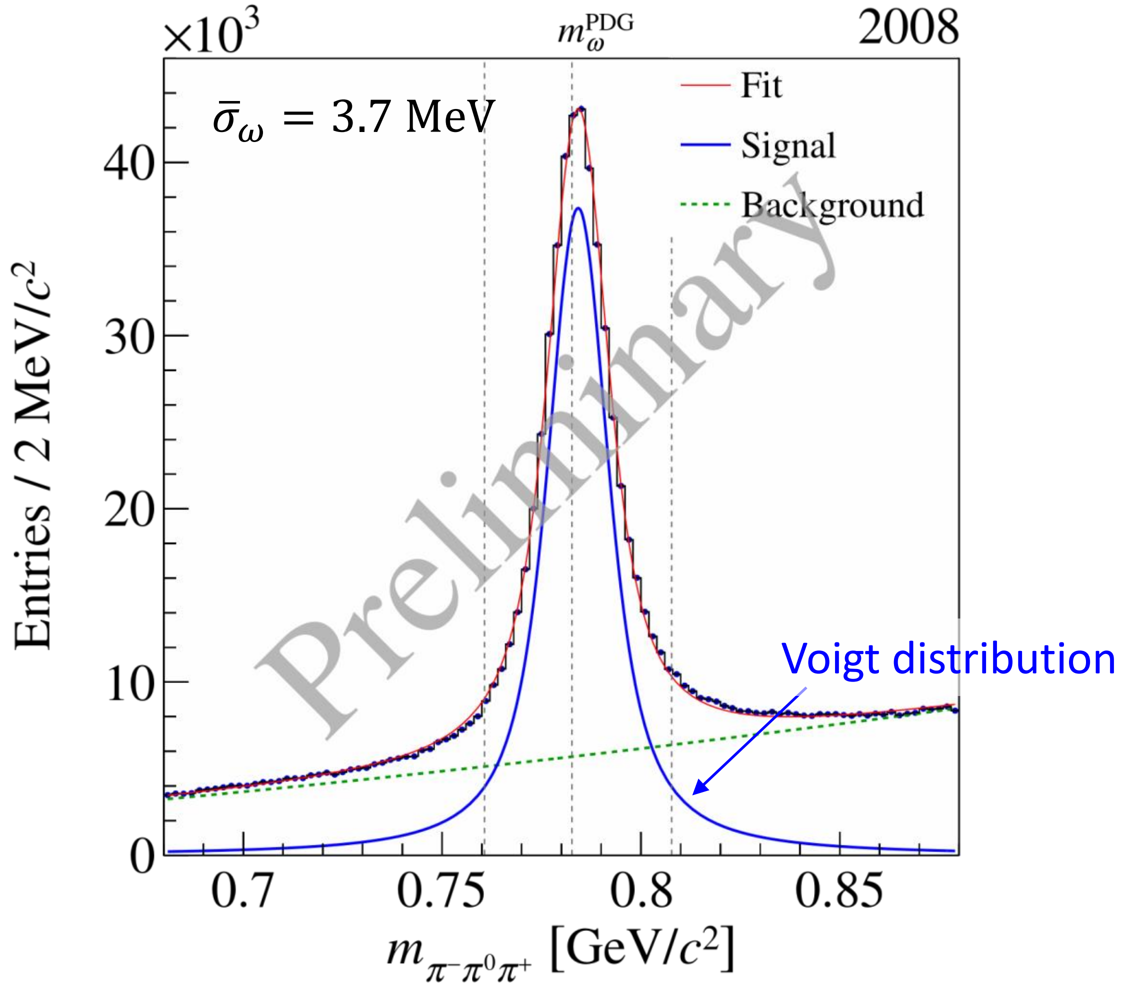
$\omega(782)$ Selection - $\omega(782)\pi^-\pi^0$

- Reconstruction of $\omega(782)$ from $\pi^-\pi^0\pi^+$ decay



$\omega(782)$ Selection - $\omega(782)\pi^-\pi^0$

- Reconstruction of $\omega(782)$ from $\pi^-\pi^0\pi^+$ decay
- Select events with exactly one $\pi^-\pi^0\pi^+$ combination within $\pm\, 3\sigma_\omega$ around the fitted m_ω



Partial-Wave Decomposition

$$I(m_X, t', \tau) = \left|\sum_i \mathcal{T}_i(m_X, t')\psi_i(m_X, \tau)\right|^2$$

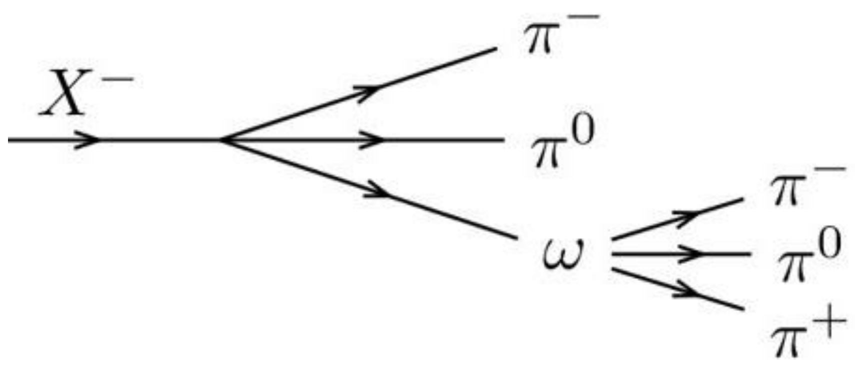
- Decay amplitude $\psi_i(m_X, \tau)$: calculated using the isobar model
- $\mathcal{T}_i(m_X, t')$ contains production, propagation, and coupling of
  - No assumptions about the resonant content of X^-
- Extract $\mathcal{T}_i(m_X, t')$ by independent maximum-likelihood fits of $I(\tau)$ in bins of (m_X, t')
  - Approximate $\mathcal{T}_i$ by fitting step-wise constant functions in bins of (m_X, t')

$\omega(782)$ Decay in PWA Model

- Factorisation of the decay amplitude

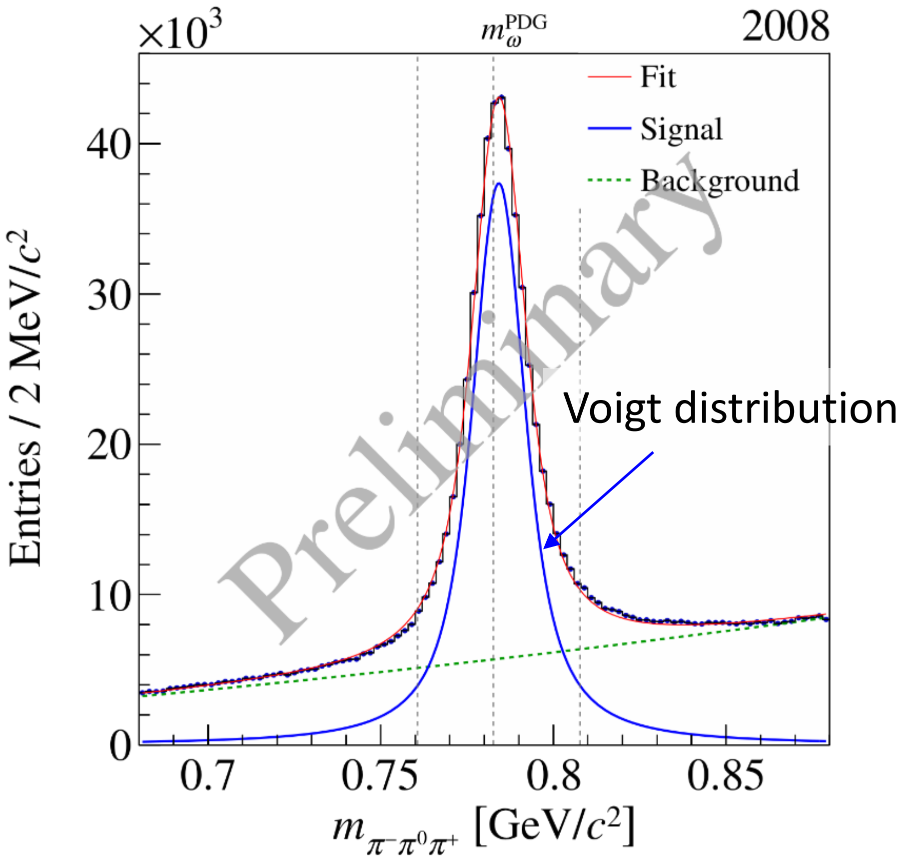
$$\psi_i = \Sigma_{\lambda_\omega} \psi_{i,X\to\omega\pi\pi}^{\lambda_\omega} \psi_{\omega\to 3\pi}^{\lambda_\omega}$$

- $\psi_{i,X\to\omega\pi\pi}^{\lambda_\omega}$ calculated with isobar model
- $\psi_{\omega\to 3\pi}^{\lambda_\omega} = \mathcal{D}(m_\omega) D_0^{\lambda_\omega} |p^+ \times p^-|$
  - $\mathcal{D}(m_\omega)$ is the Breit-Wigner (BW) of ω
  - $D_0^{\lambda_\omega}$ and $|p^+ \times p^-|$ describe the orientation of ω and its P-wave Dalitz plot, respectively
    - Both are independent of m_ω



$\omega(782)$ Decay in PWA Model

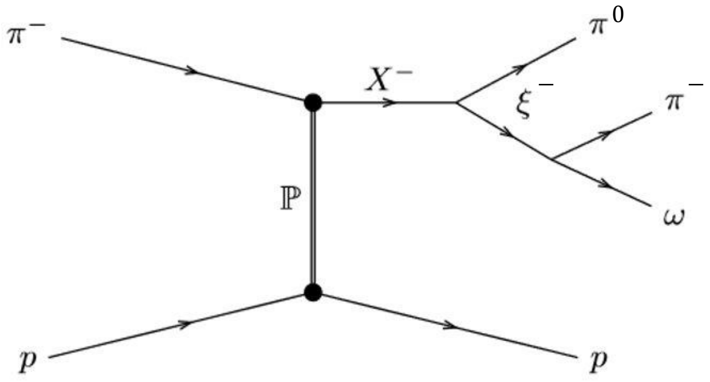
- Problem: m_ω is only measured with limited resolution
  - $\Rightarrow$ Intensity level: Convolution of BW with resolution function => m_ω follows Voigt distribution
  - $\Rightarrow$ Convolution of the full intensity is not feasible
  - Solution: Neglect self-interference of ω as only one $\pi^-\pi^0\pi^+$ combination has a large amplitude
    - $\Rightarrow$ $\mathcal{D}(m_\omega)$ factorises out of the intensity: $I(m_X, t', \tau, m_\omega) = \tilde{I}(m_X, t', \tau)|\mathcal{D}(m_\omega)|^2$
    - $\Rightarrow$ $|\mathcal{D}(m_\omega)|^2$ is modelled as Voigt distribution with parameters from fitted data

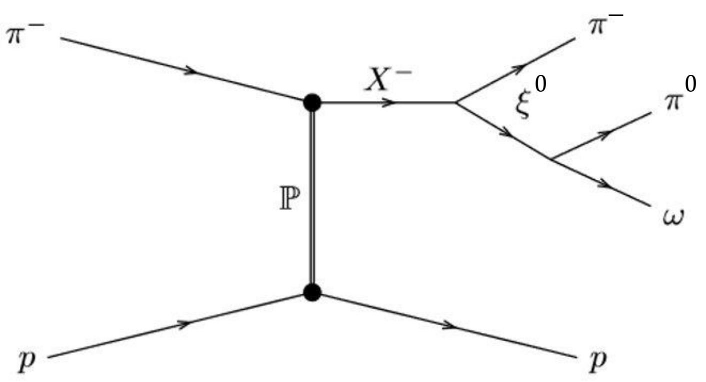


Isospin Symmetrization

- $X^- \rightarrow \xi^- \pi^0$ and $X^- \rightarrow \xi^0 \pi^-$ have the same amplitude (modulo a sign due to isospin Clebsch-Gordons)
  - $\Rightarrow \mathcal{T}_i(m_X, t')$ is the same and we model the total decay amplitude as

$$\psi_i = +\frac{1}{2}\psi_{i,\xi^0\pi^-} - \frac{1}{2}\psi_{i,\xi^-\pi^0}$$



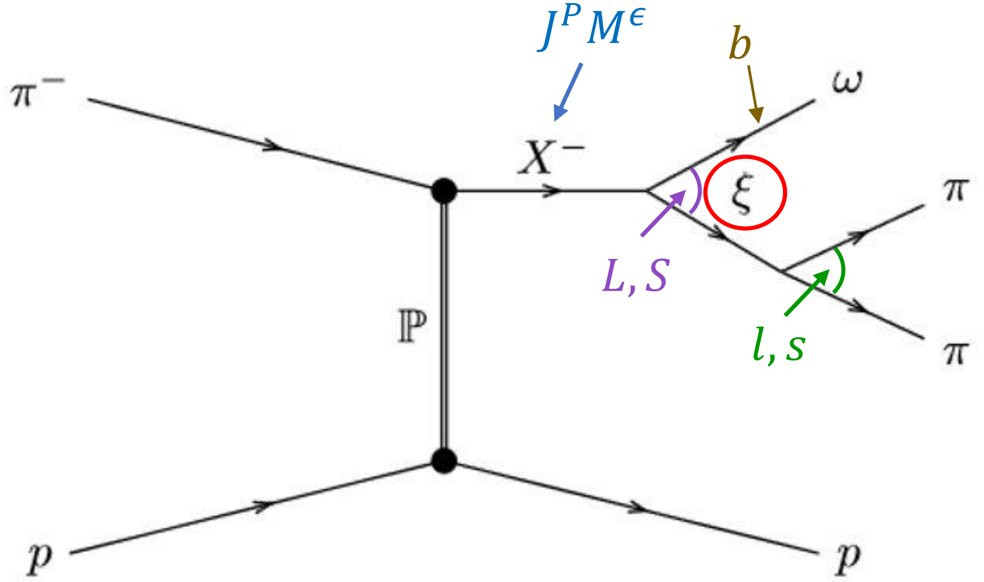


Wave Selection

- Method used for 3π, 5π and $K\pi\pi$
- Modified log-likelihood with penalties:
  - Cauchy regularization to suppress small waves
  - Connected bins over m_X to smoothen $\mathcal{T}_i(m_X)$
- Wave pool:
  - $J \leq 8, M \leq 2, \epsilon = +$
  - $\xi \to \pi\pi$: $\rho(770), \rho(1450), \rho_3(1690)$
  - $\xi \to \omega\pi$: $b_1(1235), \rho(1450), \rho_3(1690)$
  - $L \leq 8$
  - 893 waves + flat wave

Notation:

$i = J^P M^\epsilon\ [\xi l]\ b\ LS$



Flat Wave

- Isotropic in 5-body phase-space
- Used to describe background