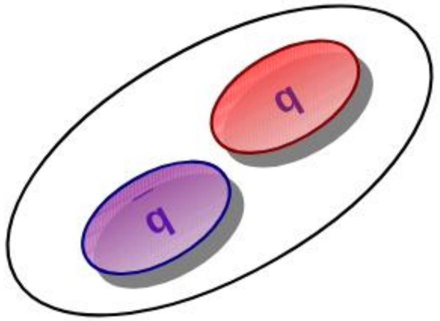
Overview on Hadron Spectroscopy at COMPASS

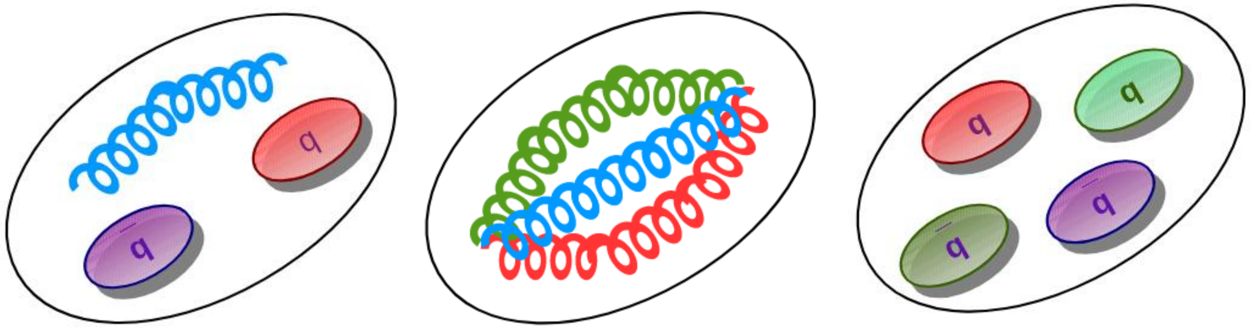
Philipp Haas for the COMPASS Collaboration

12.09.2023 – CHEP 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 $|qq\overline{qq}\rangle$



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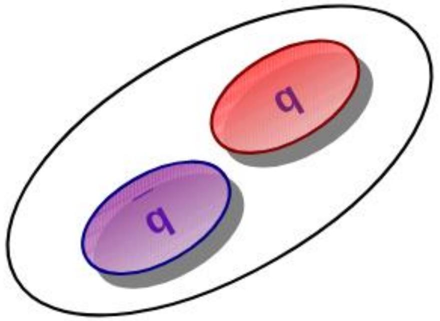

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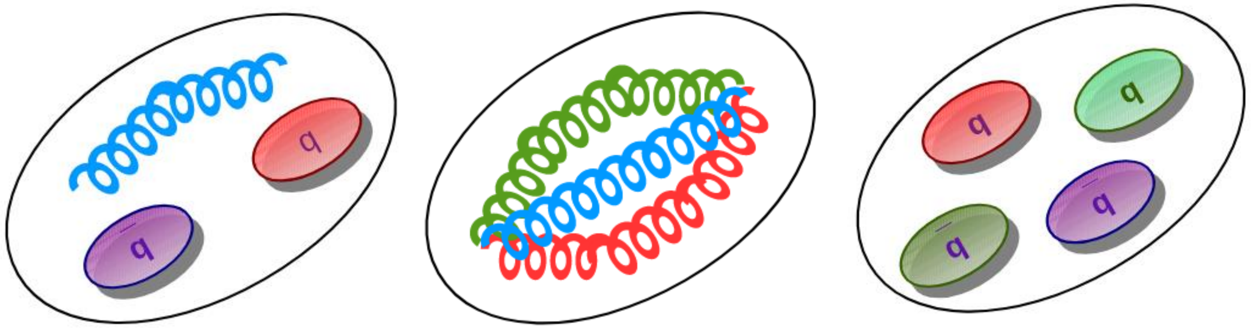

- Types of exotic mesons:
    - Spin-exotic states – J^{PC} not possible for $|q\bar{q}\rangle$: $J^{PC} = 0^{--}, \mathrm{even}^{+-}, \mathrm{odd}^{-+}$
    - Supernumerary states
    - Flavor-exotic states: $|\mathrm{Q}|, |I_3|, |S|, |C|, |B| > 1$

Spin-Exotic Light Mesons

- Lattice QCD predicts the lightest exotic in 1^{-+}
  - Single pole around $1.6\ \mathrm{GeV}/c^2$
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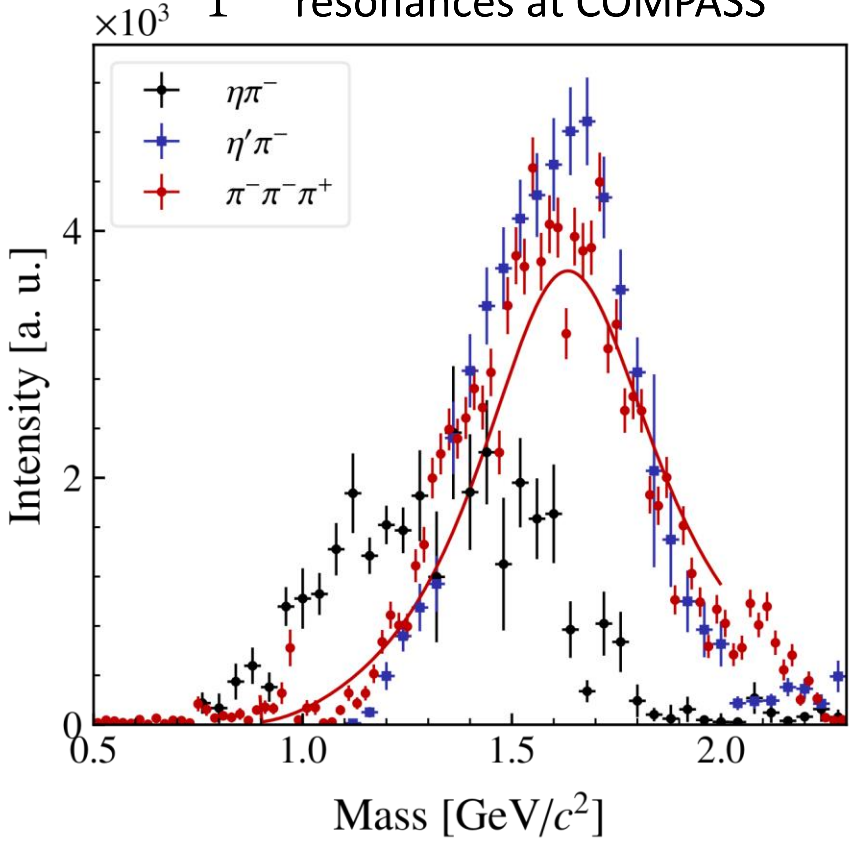
  - Seen at COMPASS and other experiments

1^{-+} resonances at COMPASS



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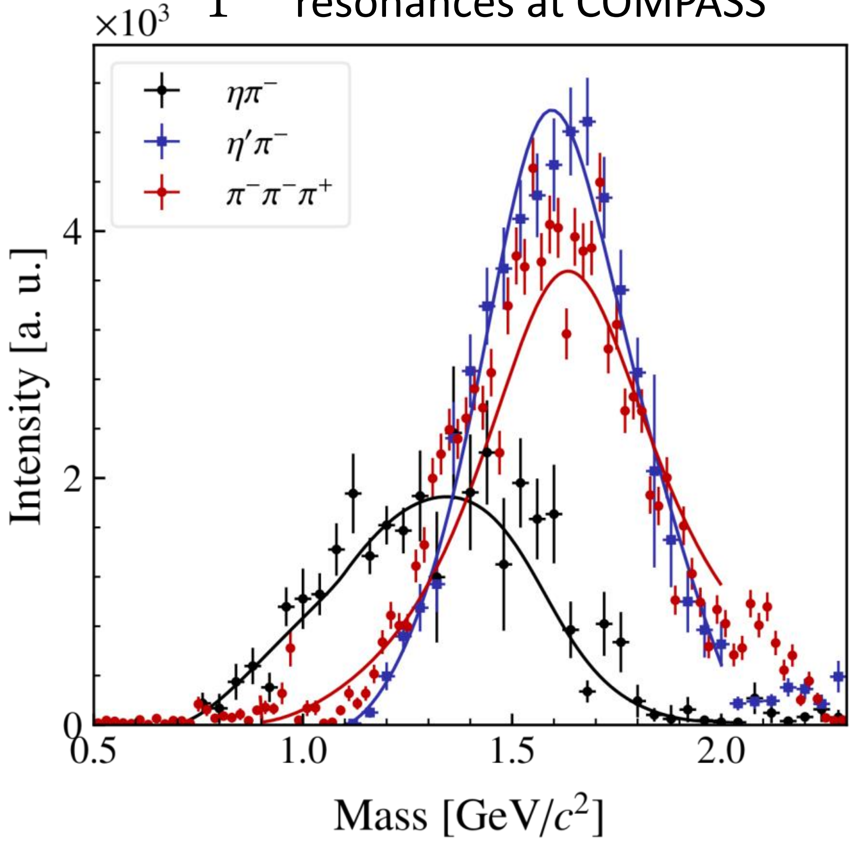

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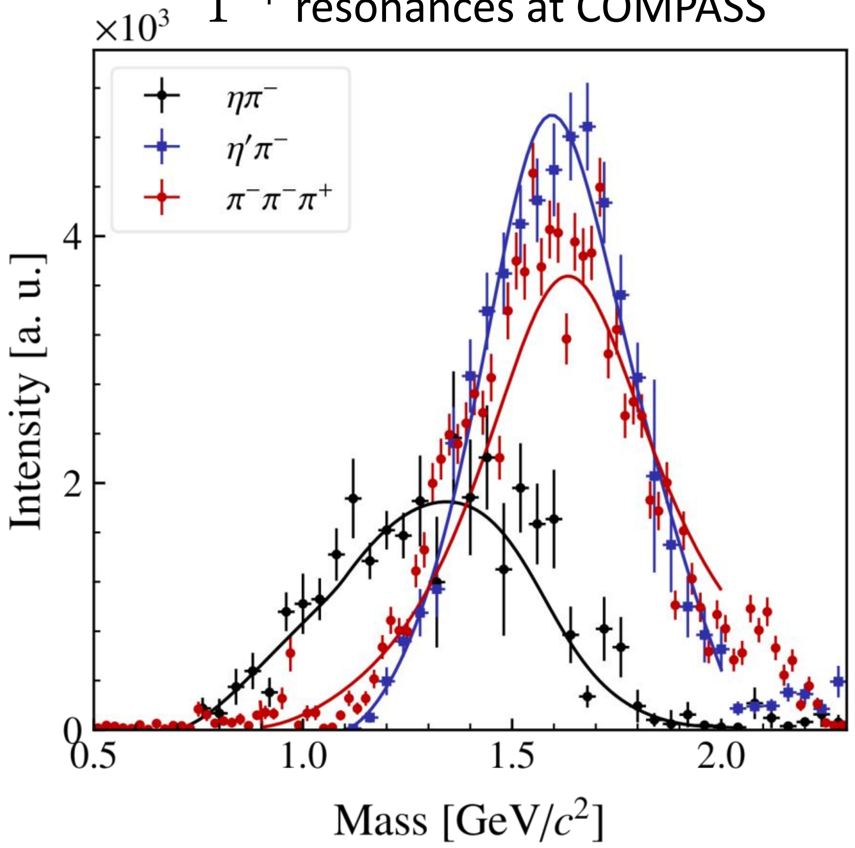
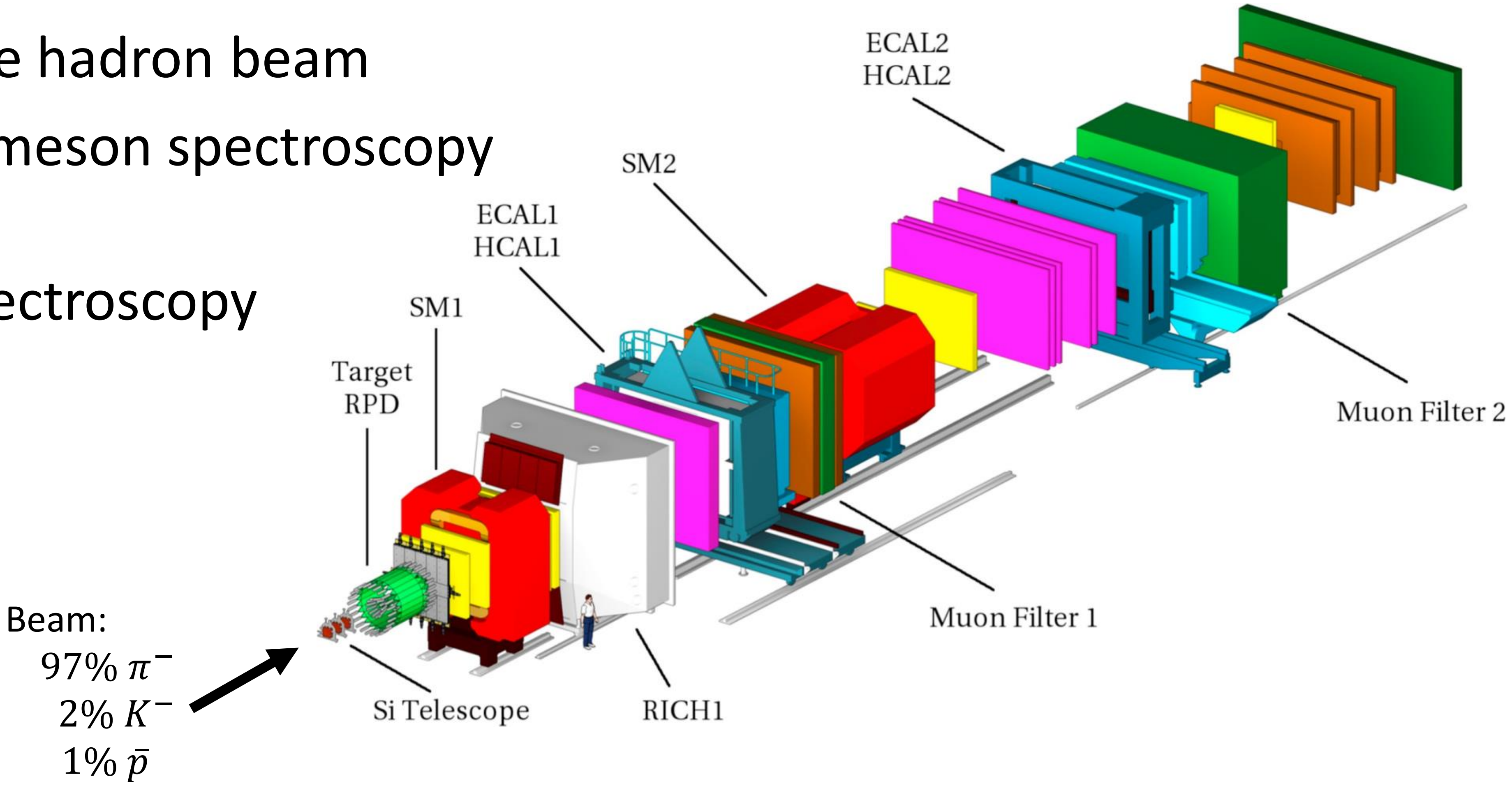
- BNL claimed $\pi_1(2015)$ in $\omega\pi^-\pi^0$ and $f_1\pi$

1^{-+} resonances at COMPASS



Experimental Setup

- Located at CERN SPS
- 190 GeV/c negative hadron beam
- Non-strange light meson spectroscopy
  $\pi^- p$ scattering
- Strange-meson spectroscopy
  $K^- p$ scattering



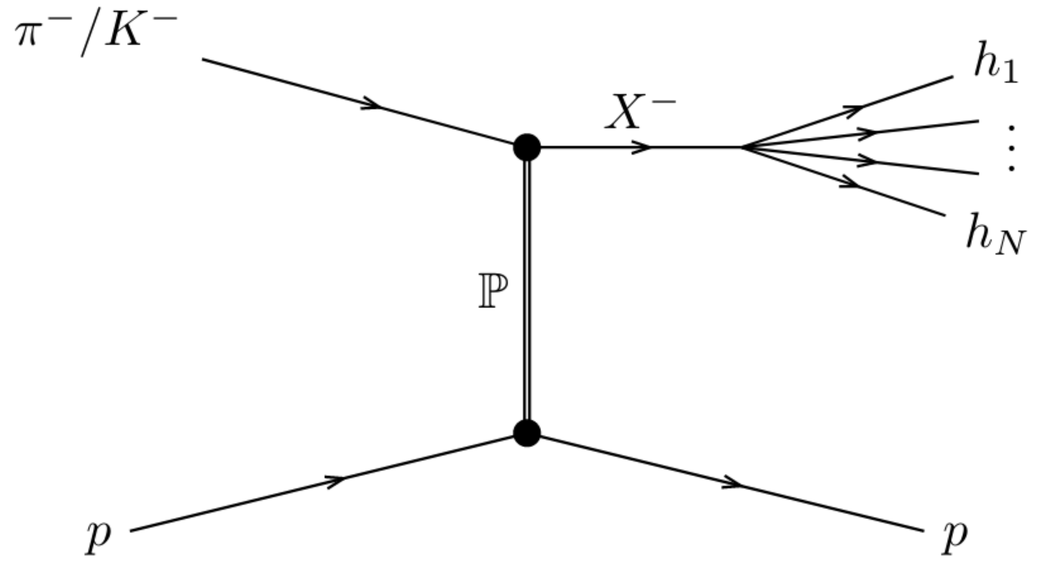
Light-Meson Spectroscopy at COMPASS

Analyzed channels:

- $\pi^-\pi^-\pi^+/\,\pi^-\pi^0\pi^0$
- $\eta\pi^-/\eta'\pi^-$
- $K^-\pi^-\pi^+$
- $\omega\pi^-\pi^0$

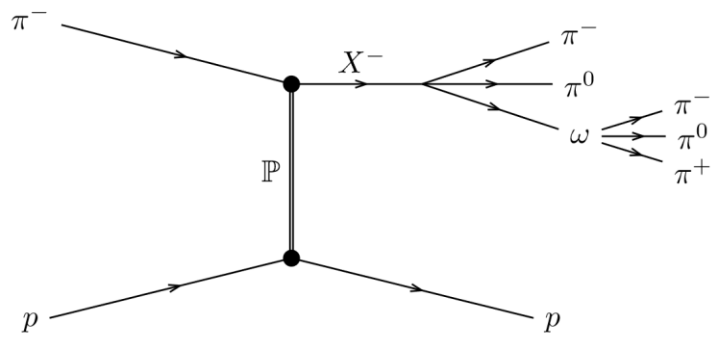
Additional channels under study:

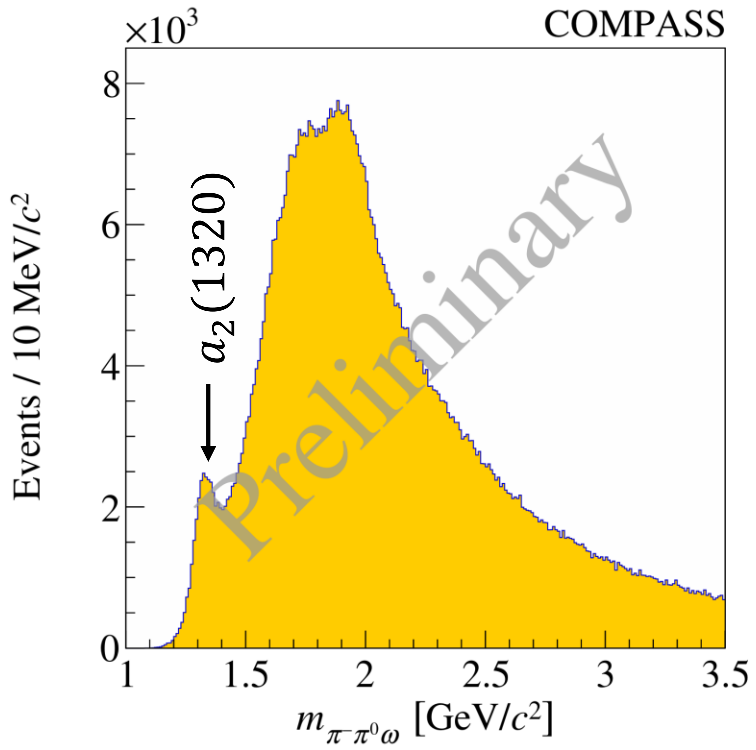
K_sK^-	Search for $a_6(2450)$
$K_sK_s\pi^-$	Investigate nature of $a_1(1420)$
$f_1\pi^-$	Search for π_1 states
$K_s\pi^-$	Strange-meson spectroscopy
$\Lambda\bar{p}$	



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

- Overlapping and interfering X^- states
  - No characteristic peaks in spectrum above 1.5 GeV/c^2
- Disentangling the different contributions with partial-wave analysis
- Partial-wave decomposition:
  Split total intensity into different contributions



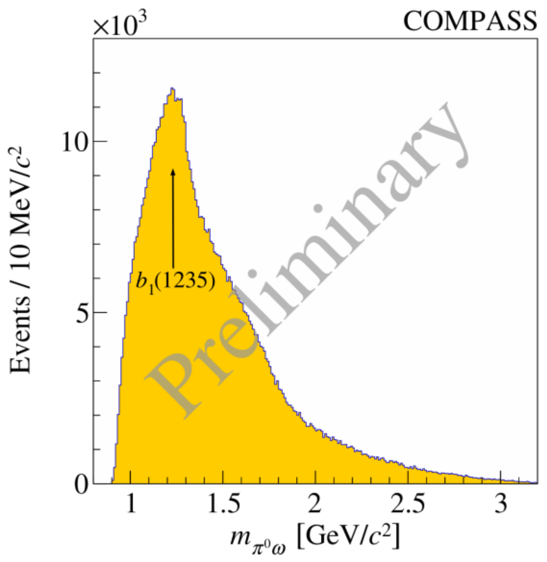


Phase-Space Variables

- Total of 8 phase-space variables
  - Denoted as set of variables τ

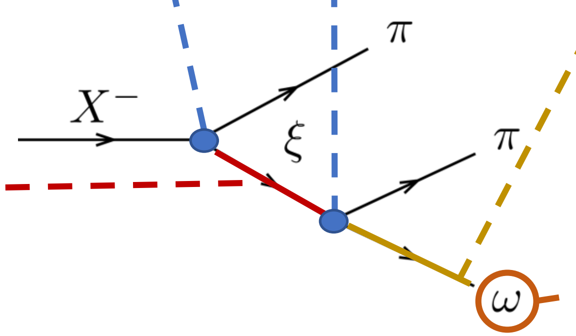
Intermediate mass

m_ξ

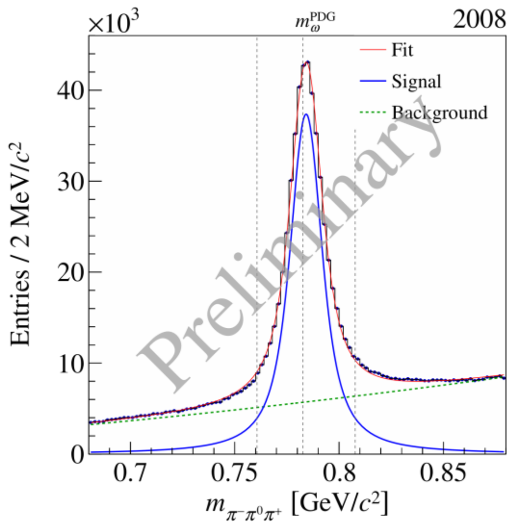


2x two-body decay: (ϕ, θ)

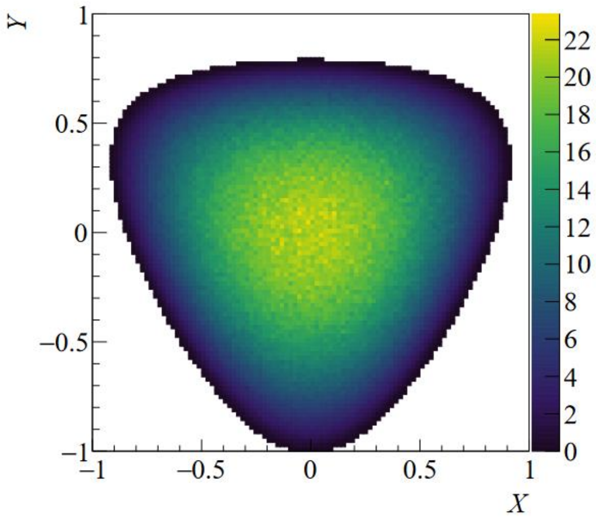
$(\phi_{\mathrm{GJ}}, \theta_{\mathrm{GJ}}), (\phi_{\mathrm{HF}}, \theta_{HF})$



m_ω

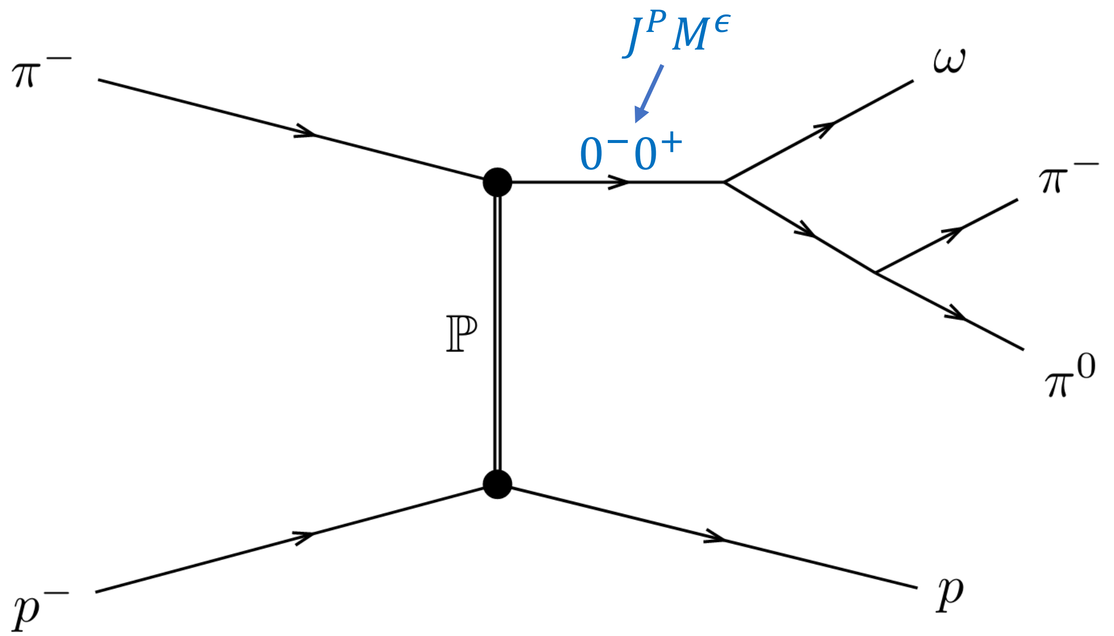


2 $\omega(782)$ Dalitz-Plot variables



Partial-Wave Decomposition

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



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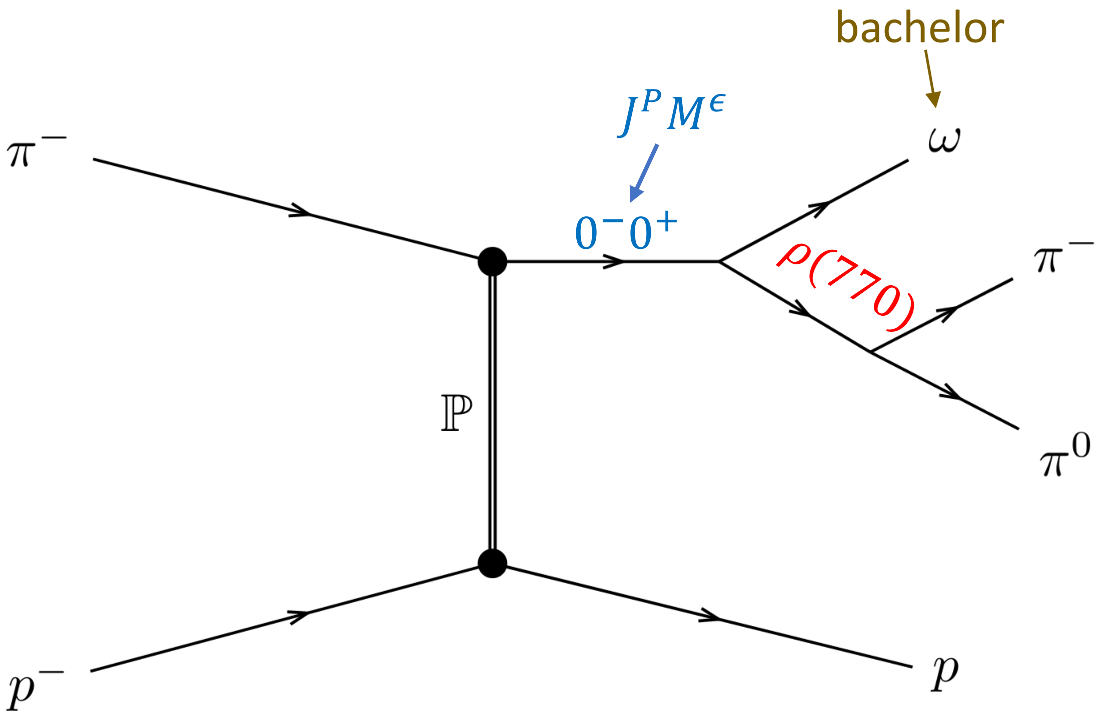
- Exited meson X^- with quantum numbers 0^-0^+
- Isobar model: $X^- \to \omega\rho(770)$
  - Unstable intermediate state/isobar $\rho(770)$



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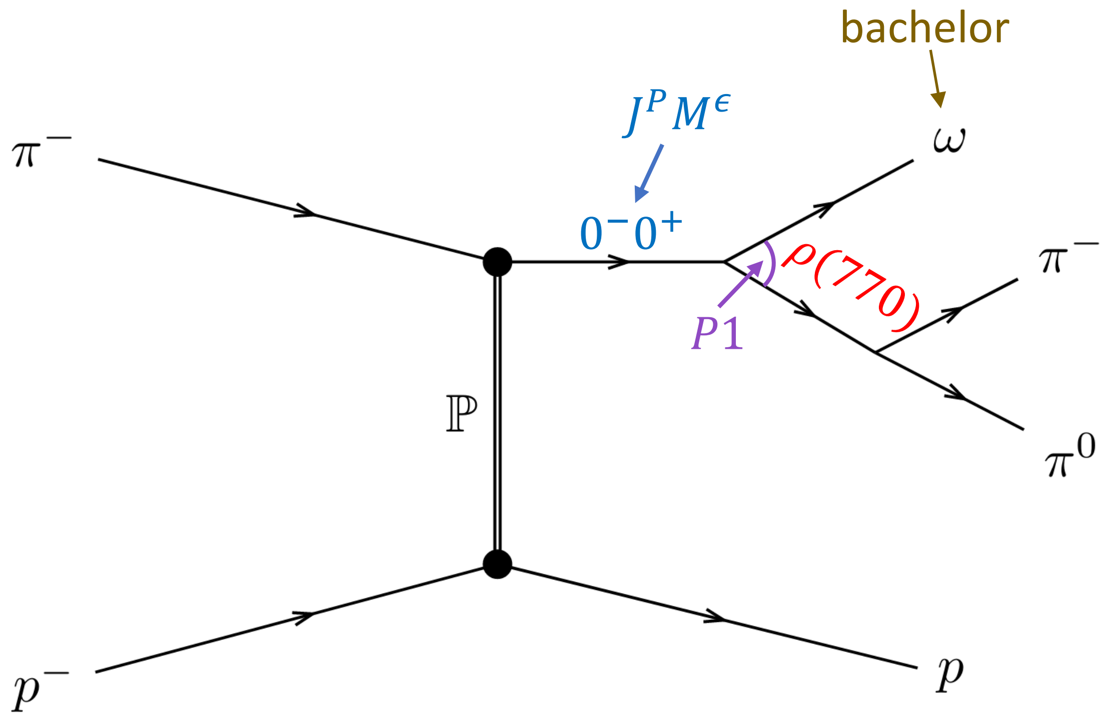

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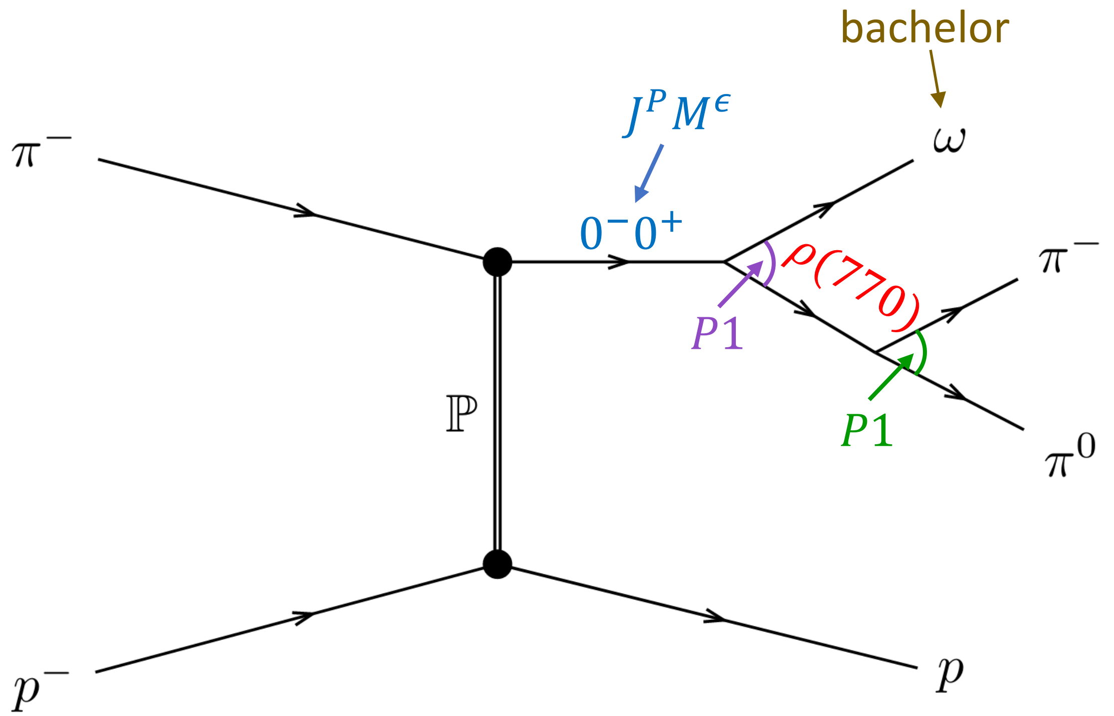
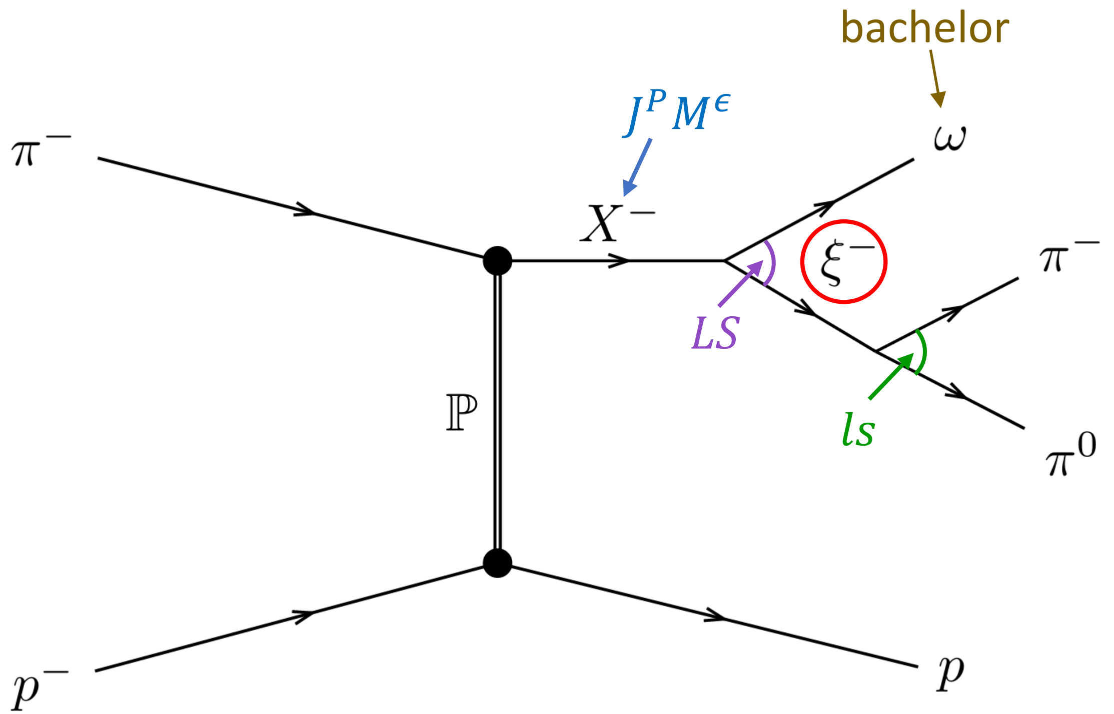
- $\rho(770) \to \pi^-\pi^0$
  - Second $LS = P1$ coupling
- $i = 0^-0^+[\rho(770)P]\ \omega\ P1$



Partial-Wave Decomposition

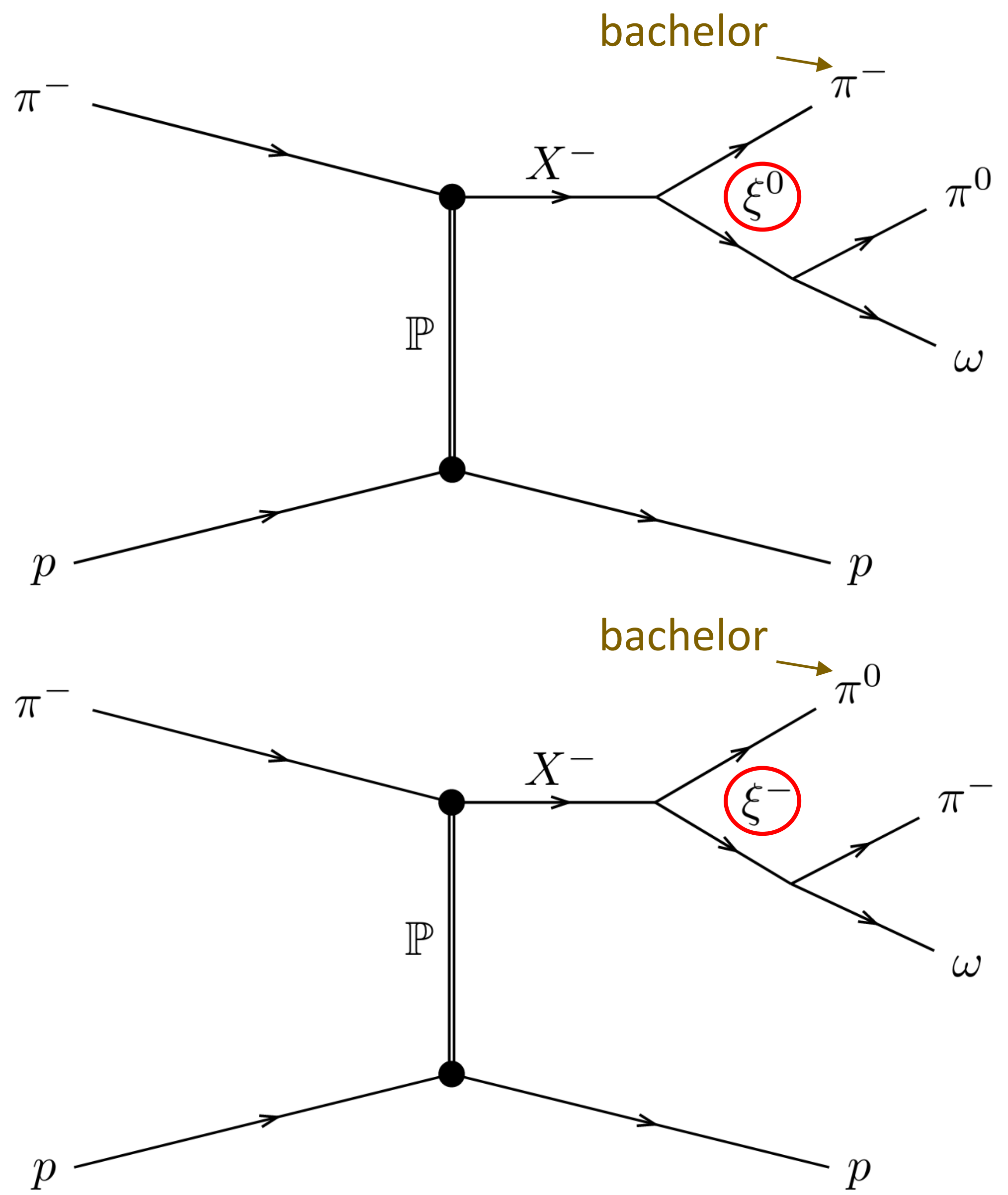
- Exited meson X^- with quantum numbers $J^P M^\epsilon$
- Isobar model: $X^- \to \omega\xi^-$
  - Unstable intermediate state/isobar ξ^-
  - LS coupling between ω and ξ^-
- $\xi^- \to \pi^-\pi^0$
  - Second LS coupling
- $i = J^P M^\epsilon\ [\xi l]\omega LS$



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

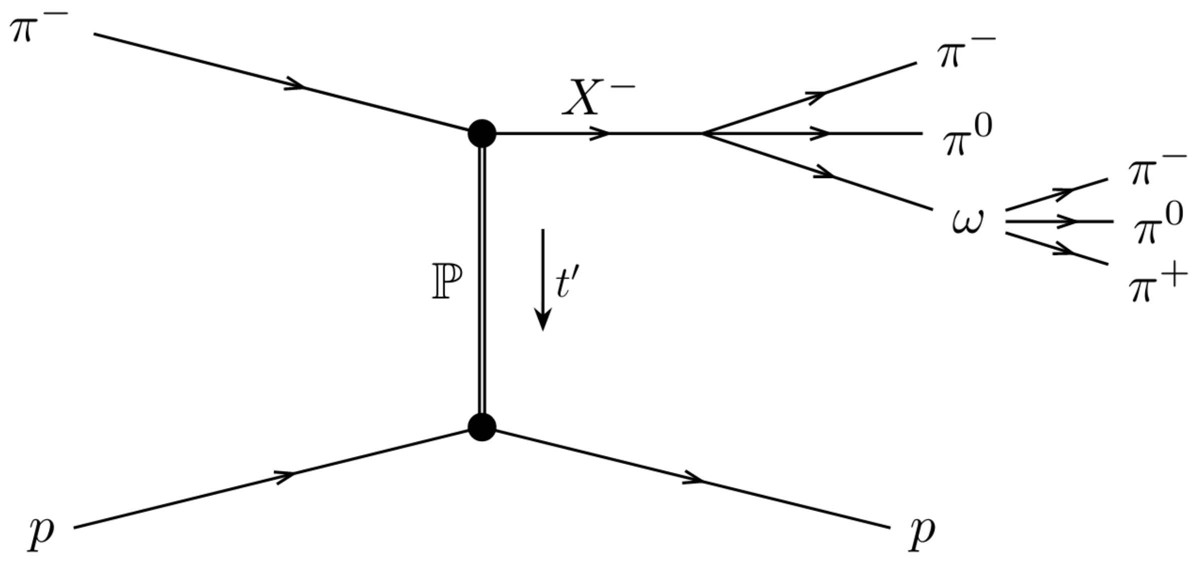
$$I(m_X, t', \tau) = \left| \sum_i \mathcal{T}_i(m_X, t') \psi_i(m_X, \tau) \right|^2$$

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



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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

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

- Pool of 893 waves based on systematic constraints
  - $\xi \rightarrow \pi\pi$: $\rho(770)$, $\rho(1450)$, $\rho_3(1690)$
  - $\xi \rightarrow \omega\pi$: $b_1(1235)$, $\rho(1450)$, $\rho_3(1690)$
  - $J \leq 8$, $M \leq 2$, $L \leq 8$

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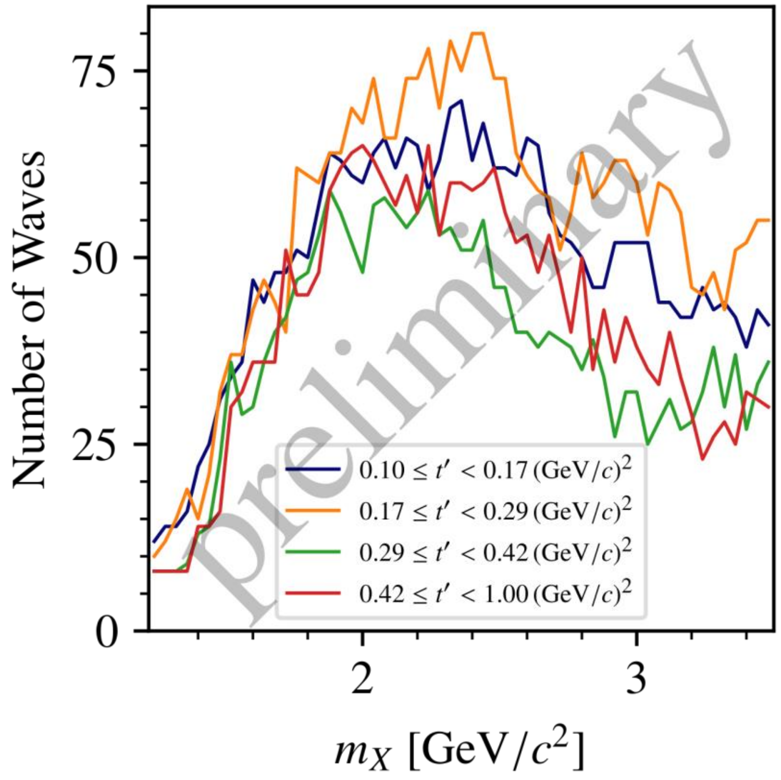
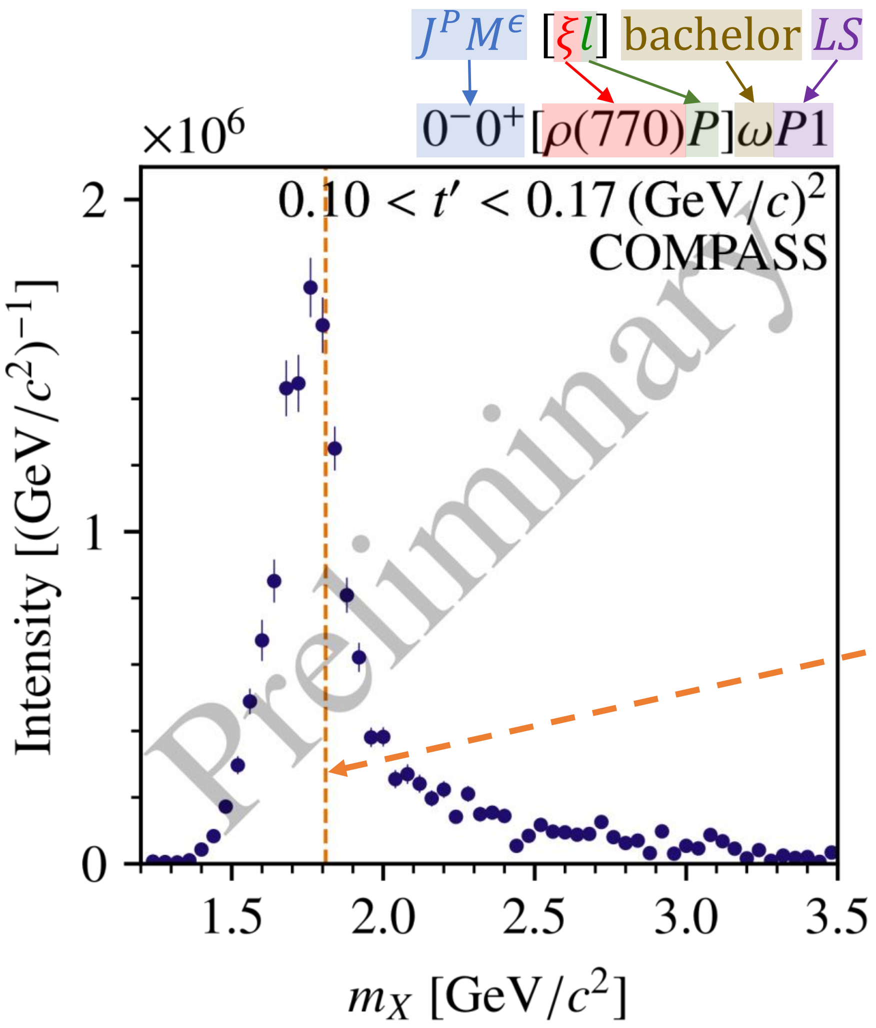
  - $J \leq 8$, $M \leq 2$, $L \leq 8$
- Regularization-based model-selection
  - Unique wave set for each (m_X, t') cell
  - Cauchy regularization:

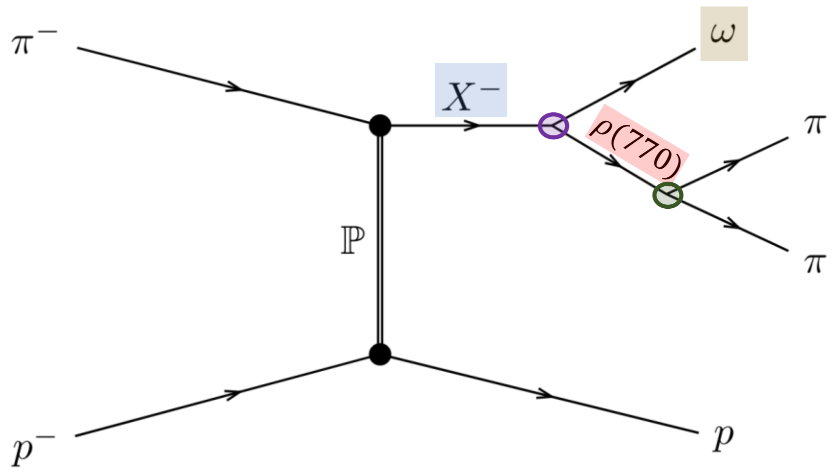
$$\ln \mathcal{L}_{\text{reg}} = -\ln\left[1 + \frac{\mathcal{T}_i^2}{\Gamma^2}\right]$$



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

Radial excitations of the well-known π

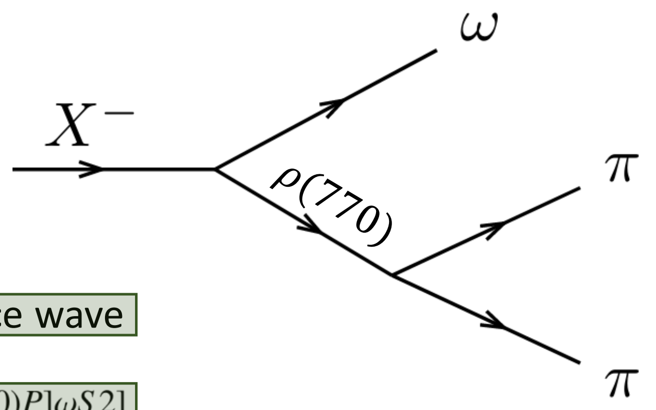


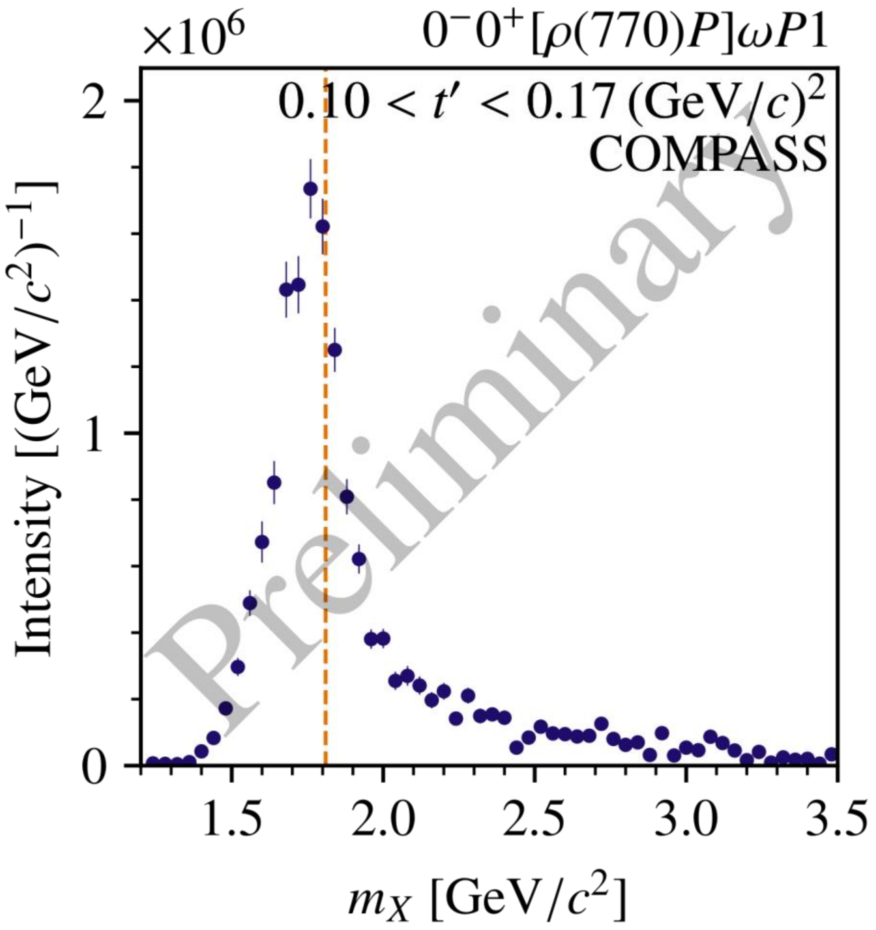


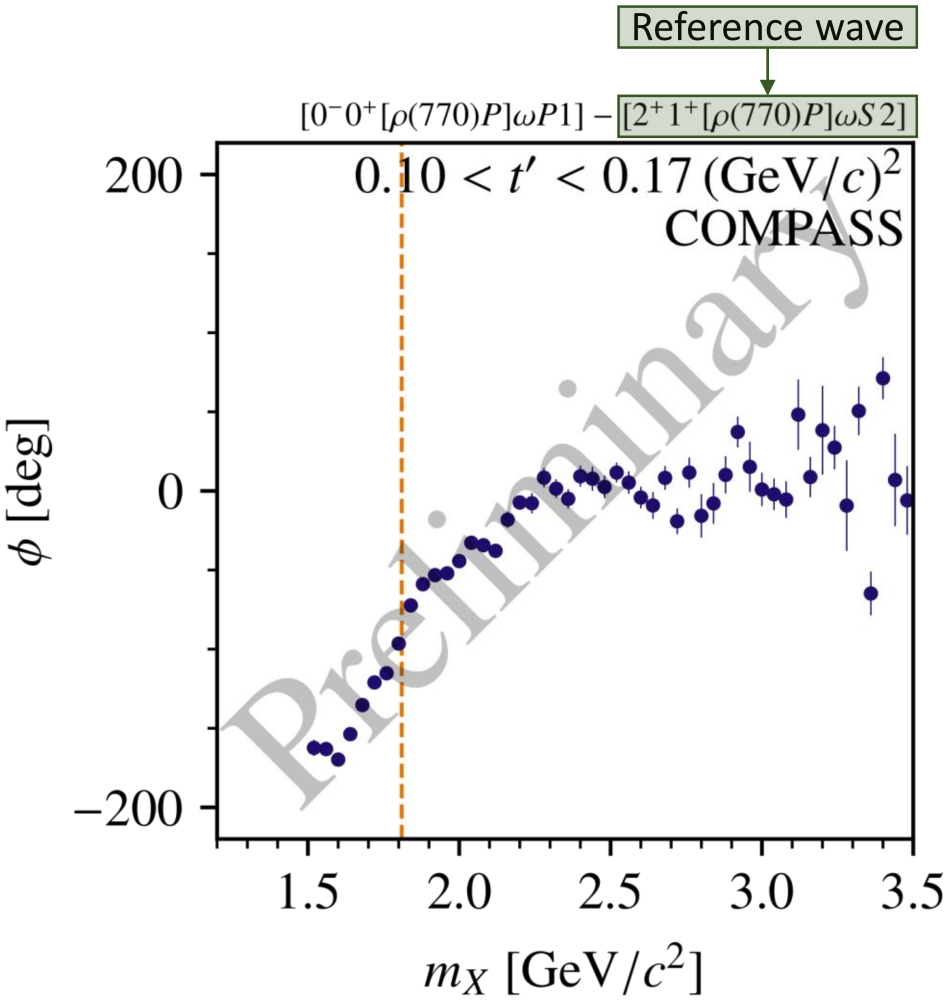
Listed in PDG

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

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







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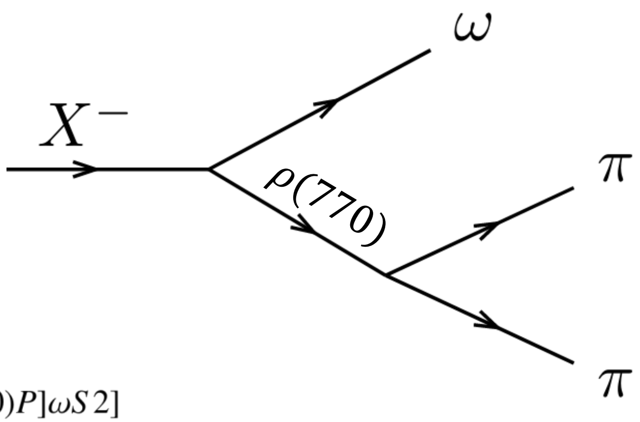

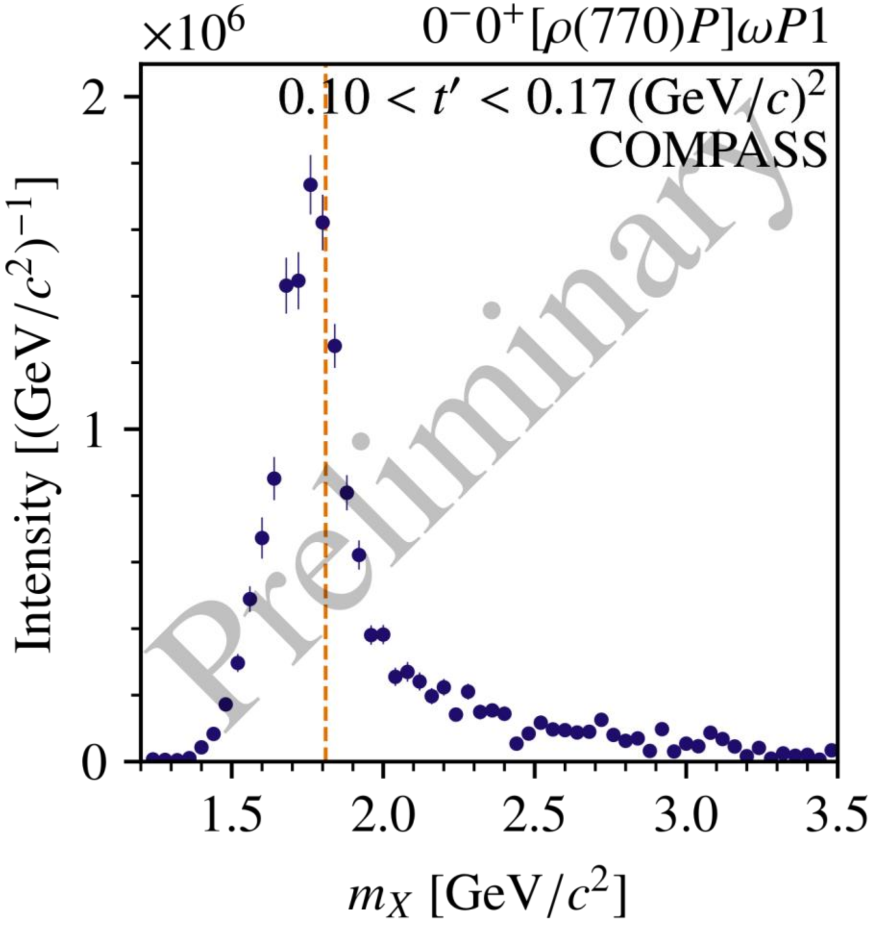

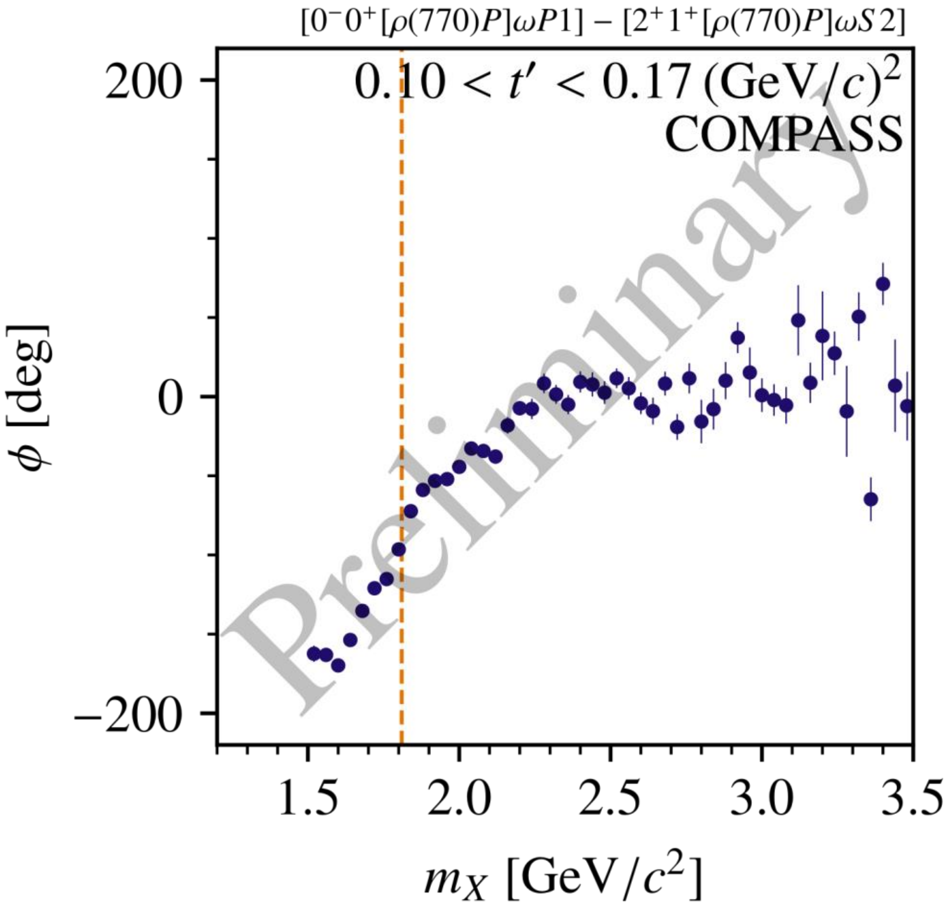

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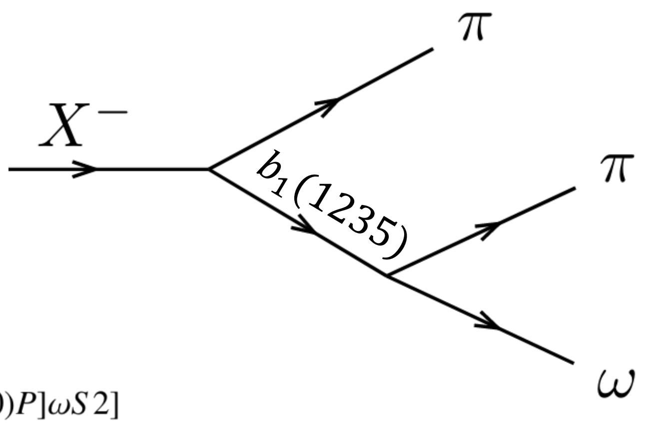
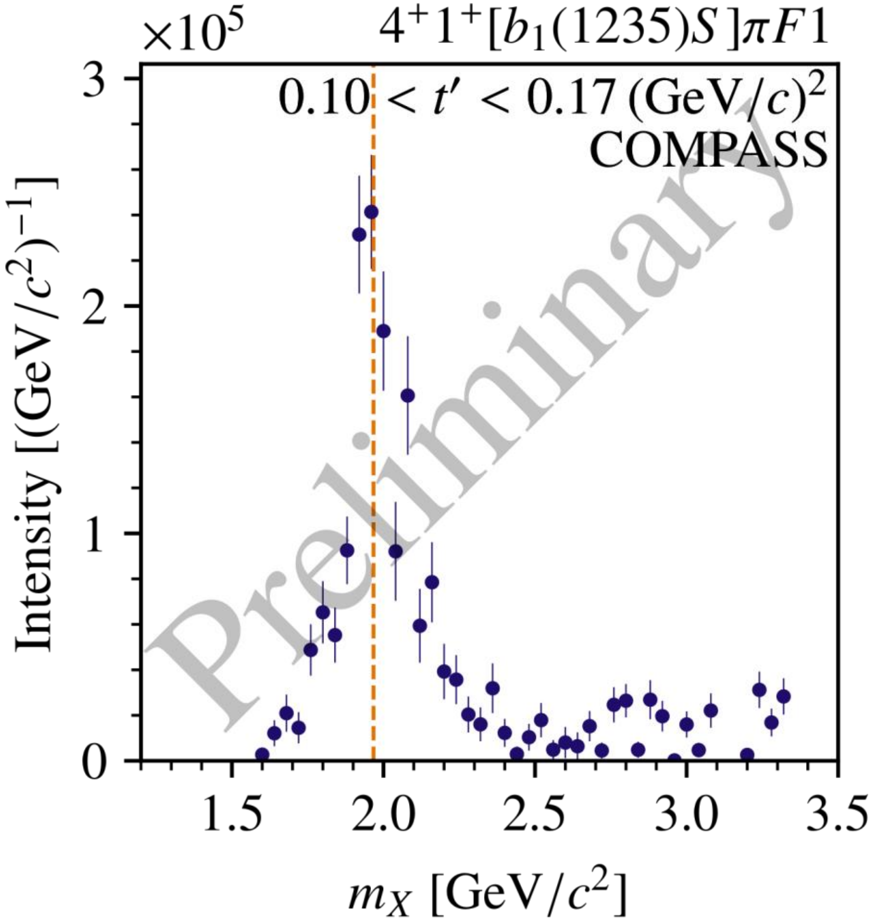
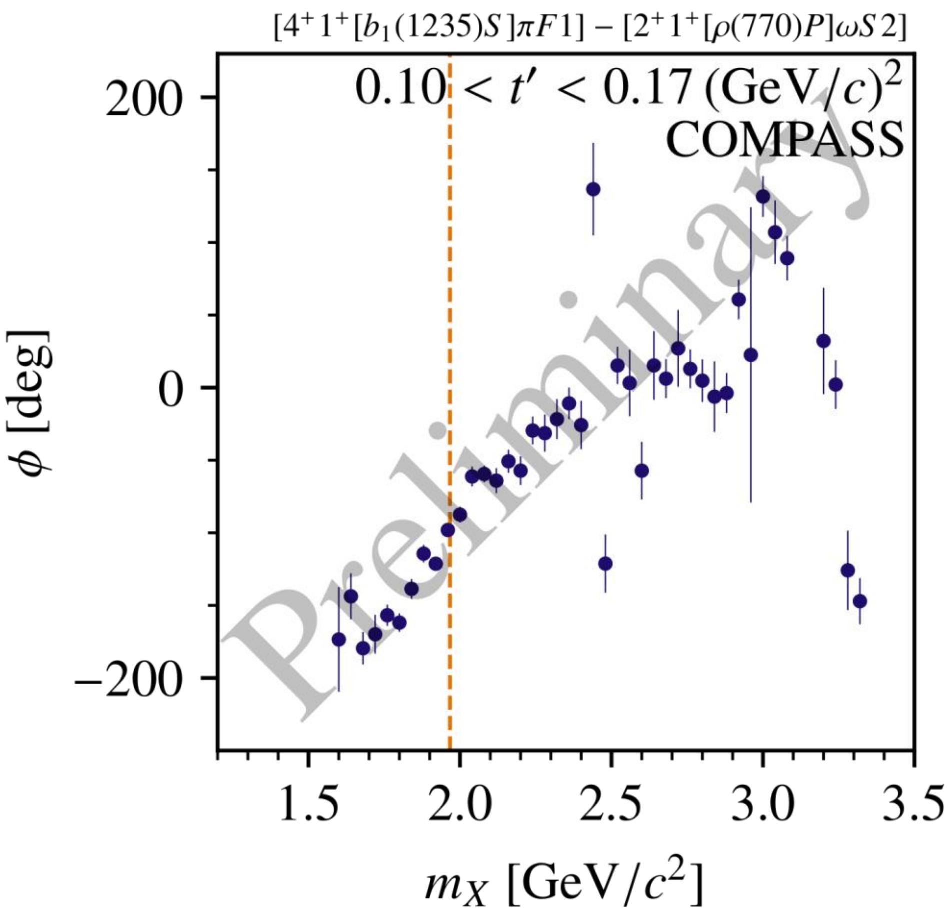


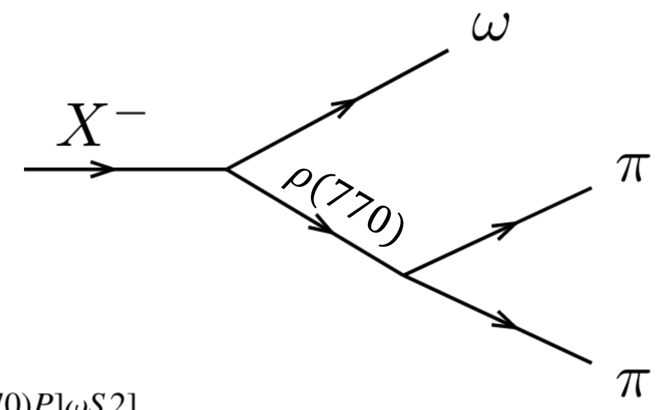


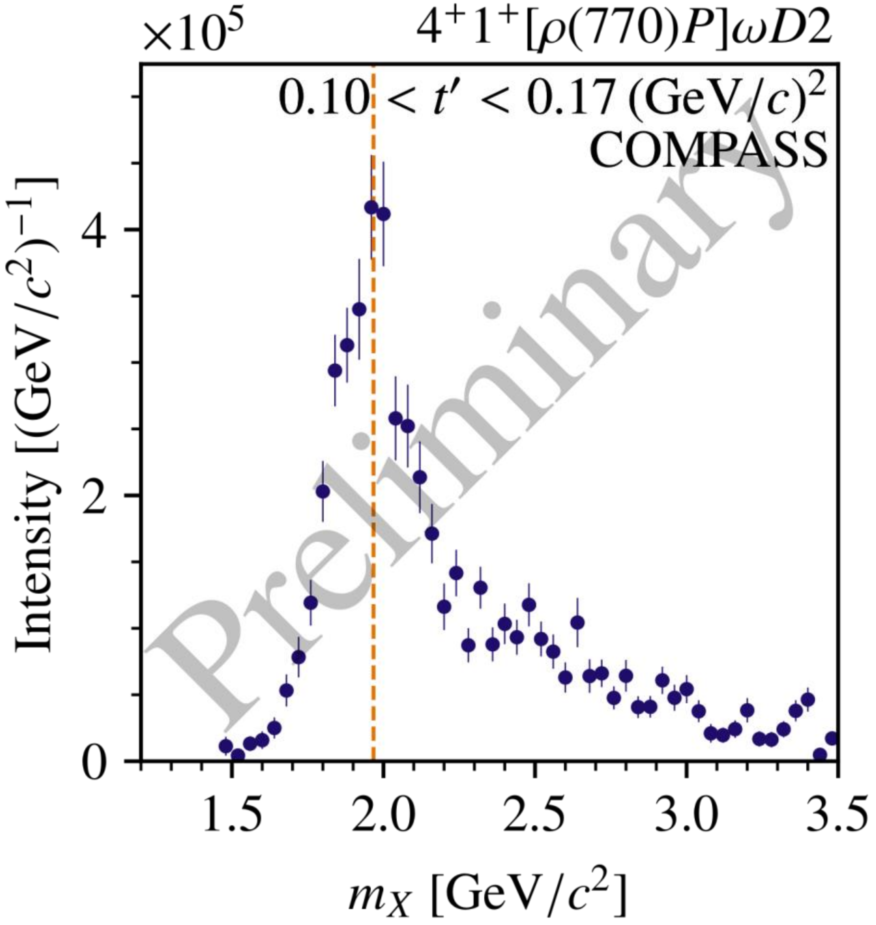


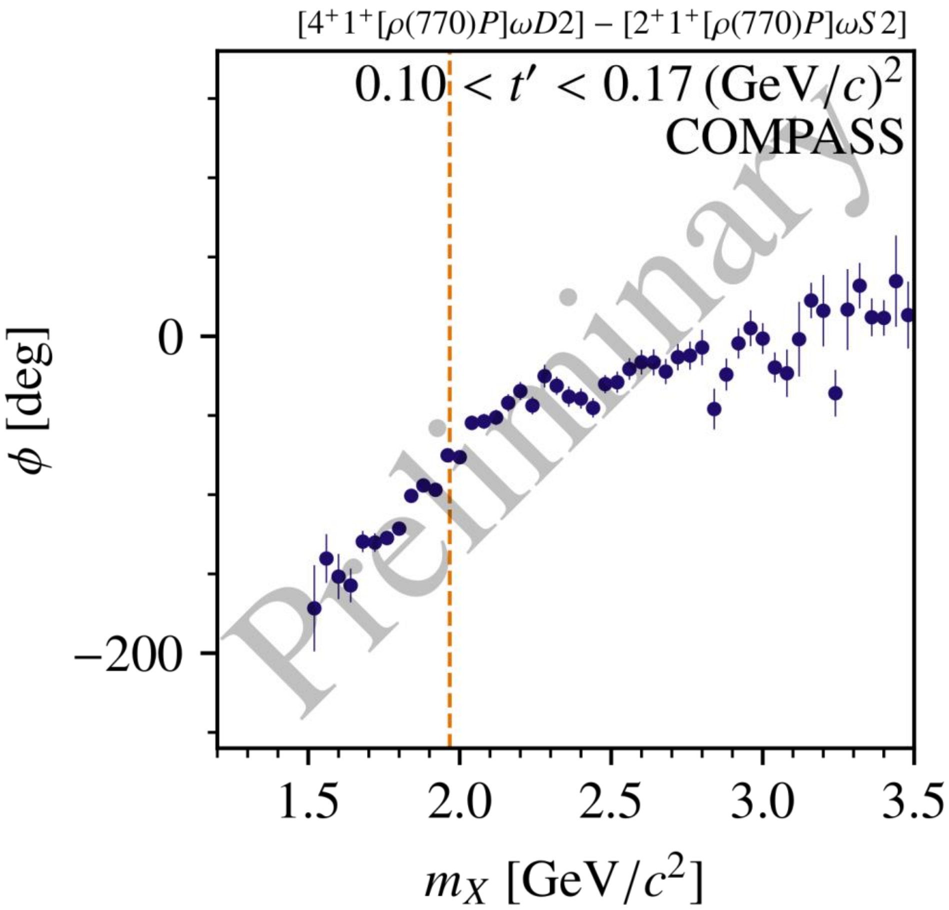
Listed in PDG

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

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







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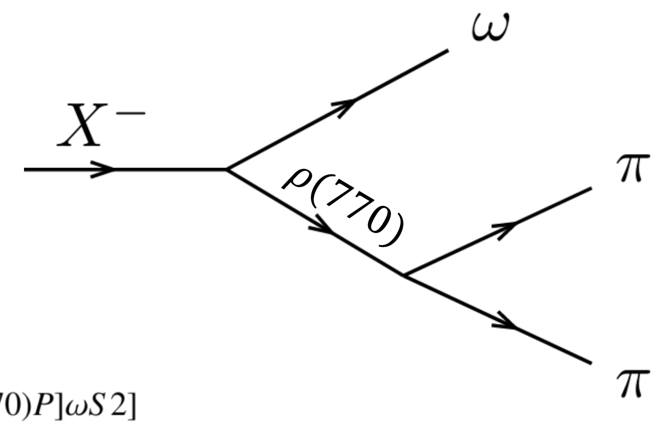
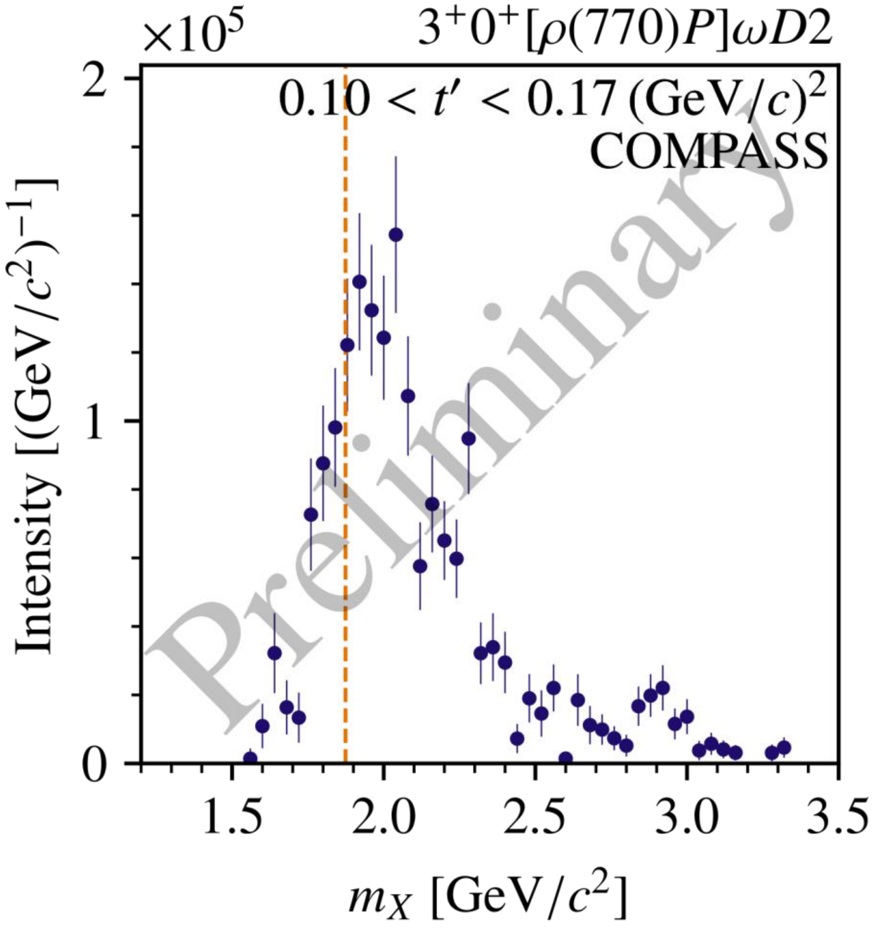
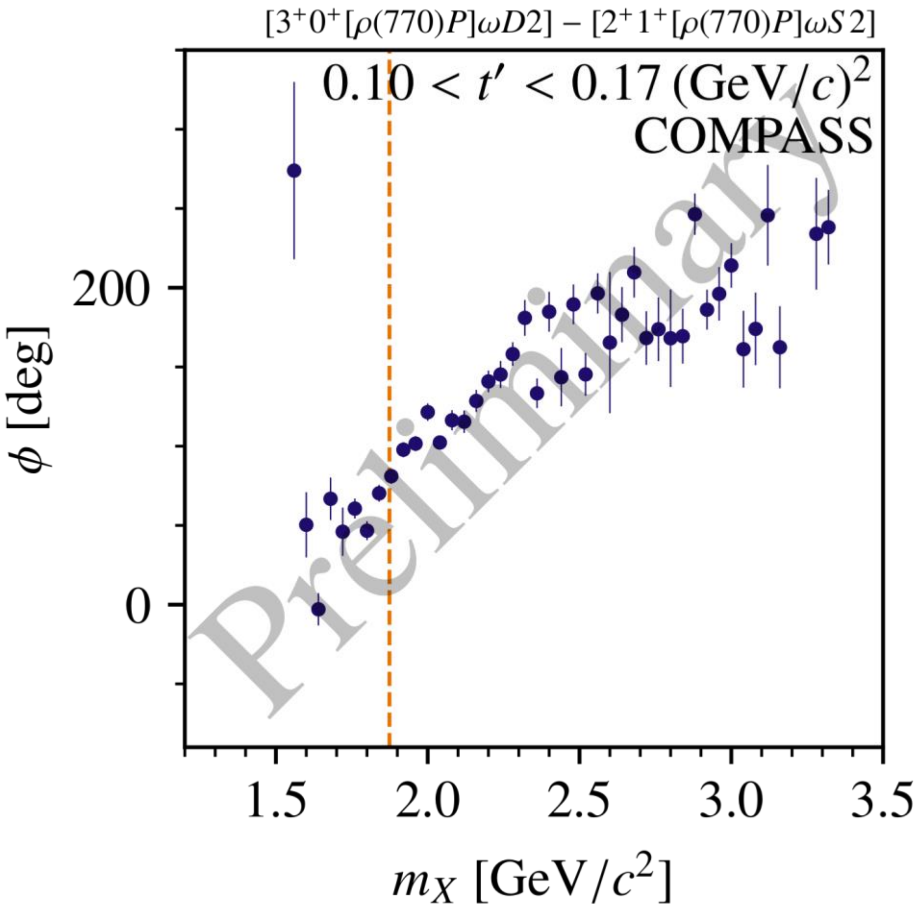






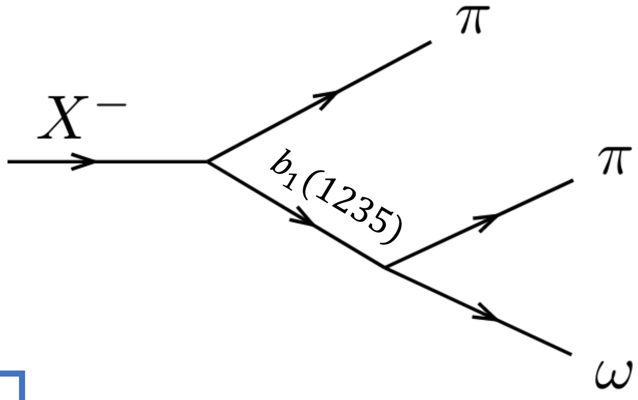
Listed in PDG

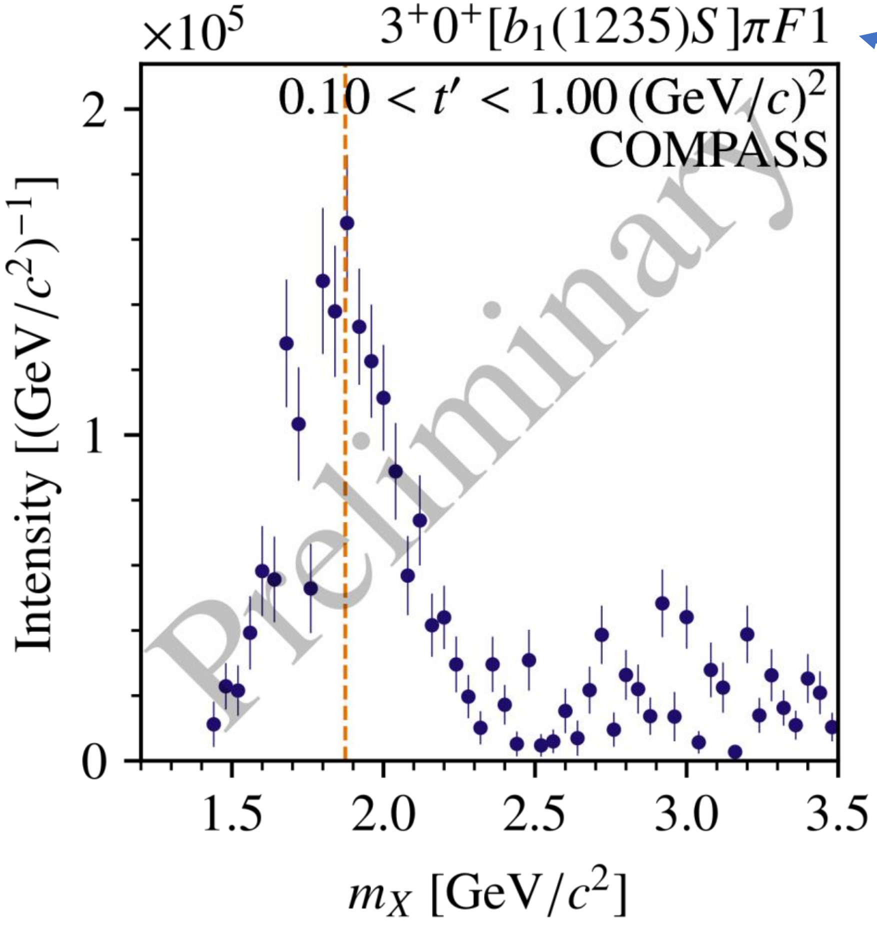
$a_3(1875)$
$m = 1874 \pm 105$ MeV
$\Gamma = 385 \pm 166$ MeV

Seen only in $\pi^-\pi^-\pi^+$ at BNL E852

Further state in PDG: $a_3(2030)$

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





Consistent 3^{++} signal visible in both $\rho(770)\omega$ and $b_1(1235)\pi$

Listed in PDG

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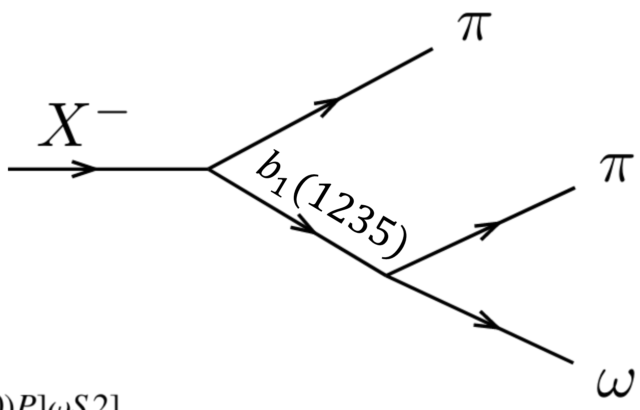
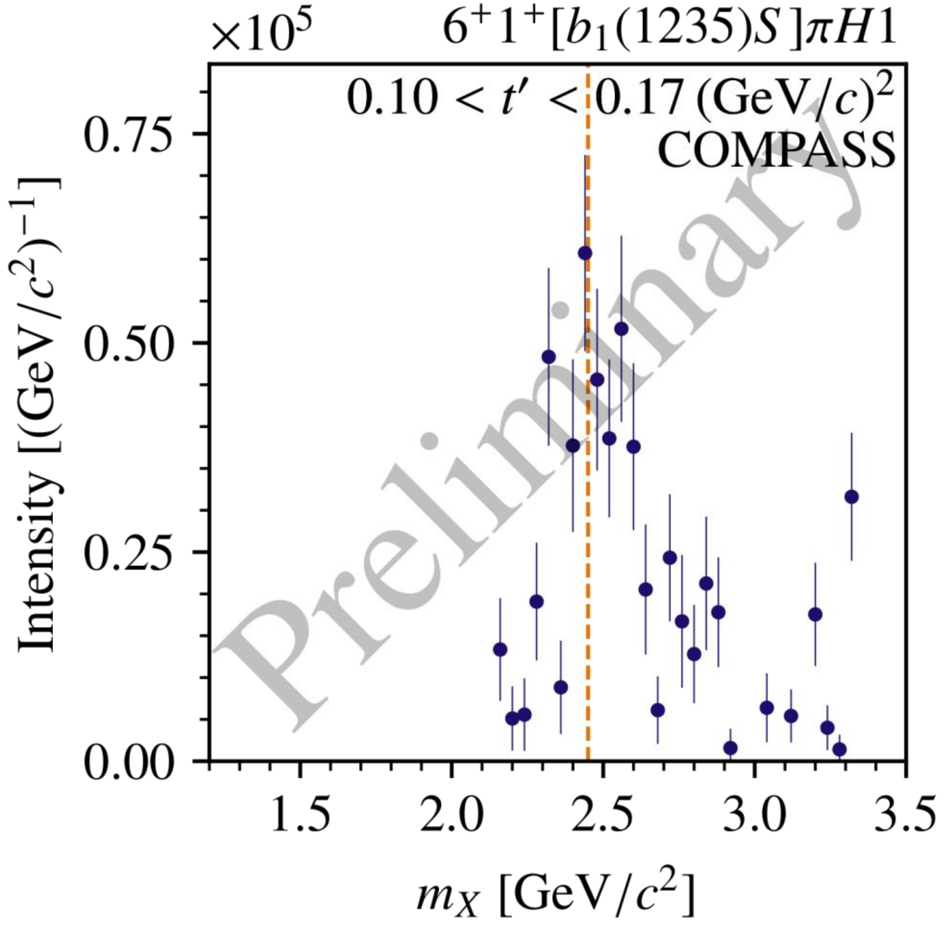
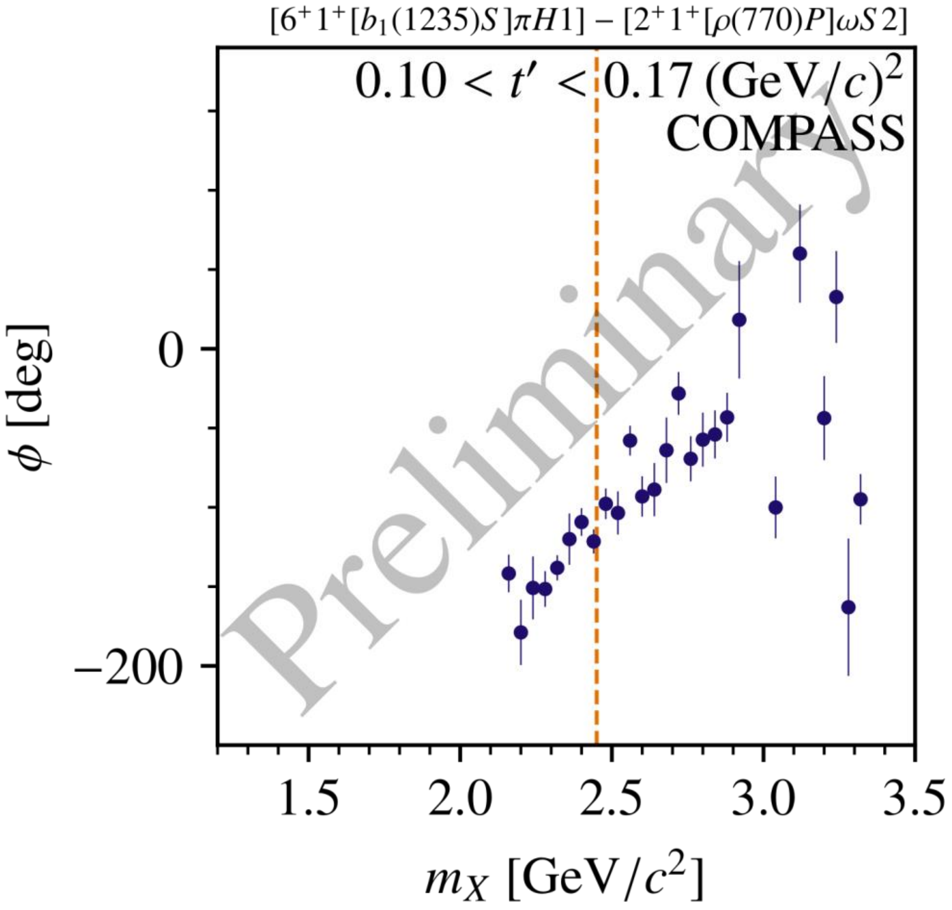
Further state in PDG: $a_3(2030)$

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







Listed in PDG

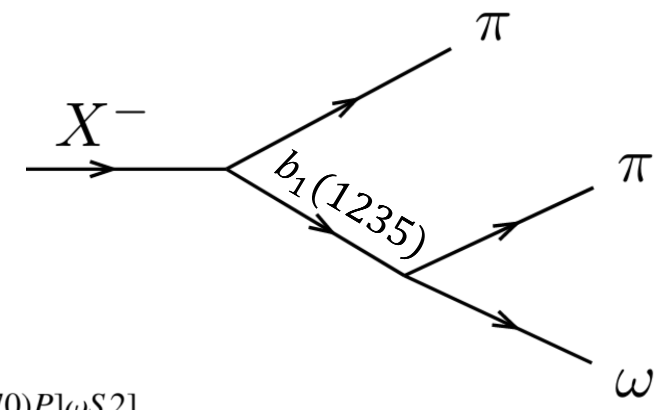
$a_6(2450)$
$m = 2450 \pm 130$ MeV
$\Gamma = 400 \pm 250$ MeV

Seen only in $K_S K$

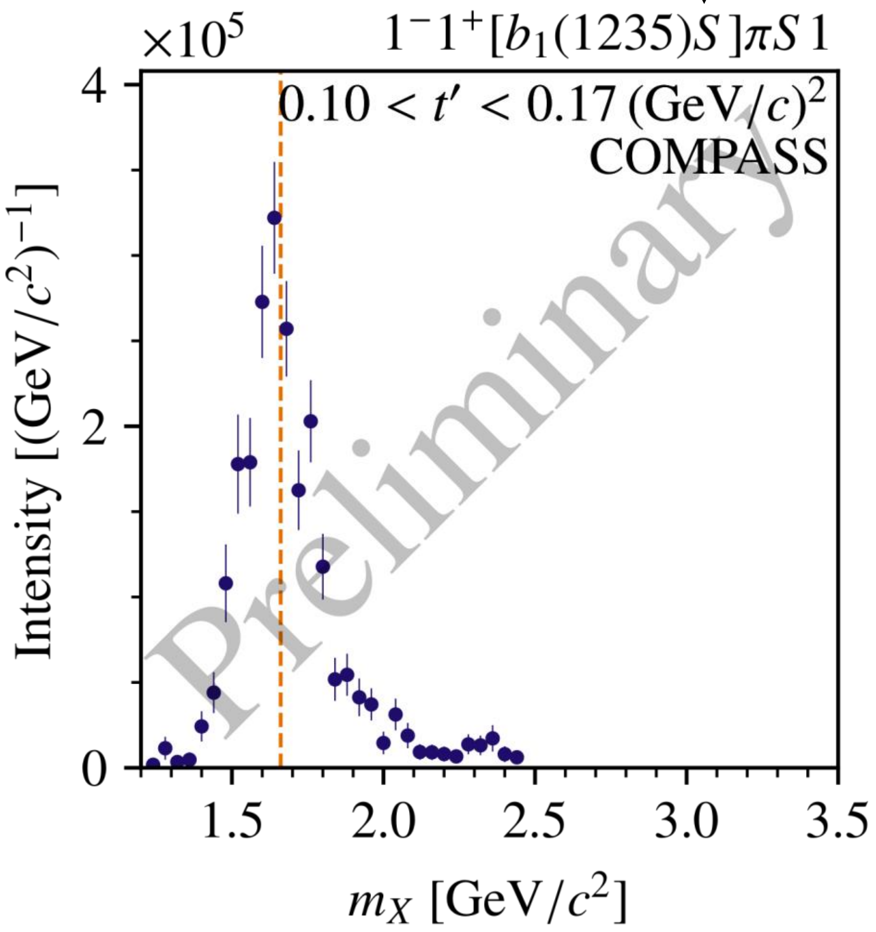
Recap $J^{PC} = 1^{-+}$

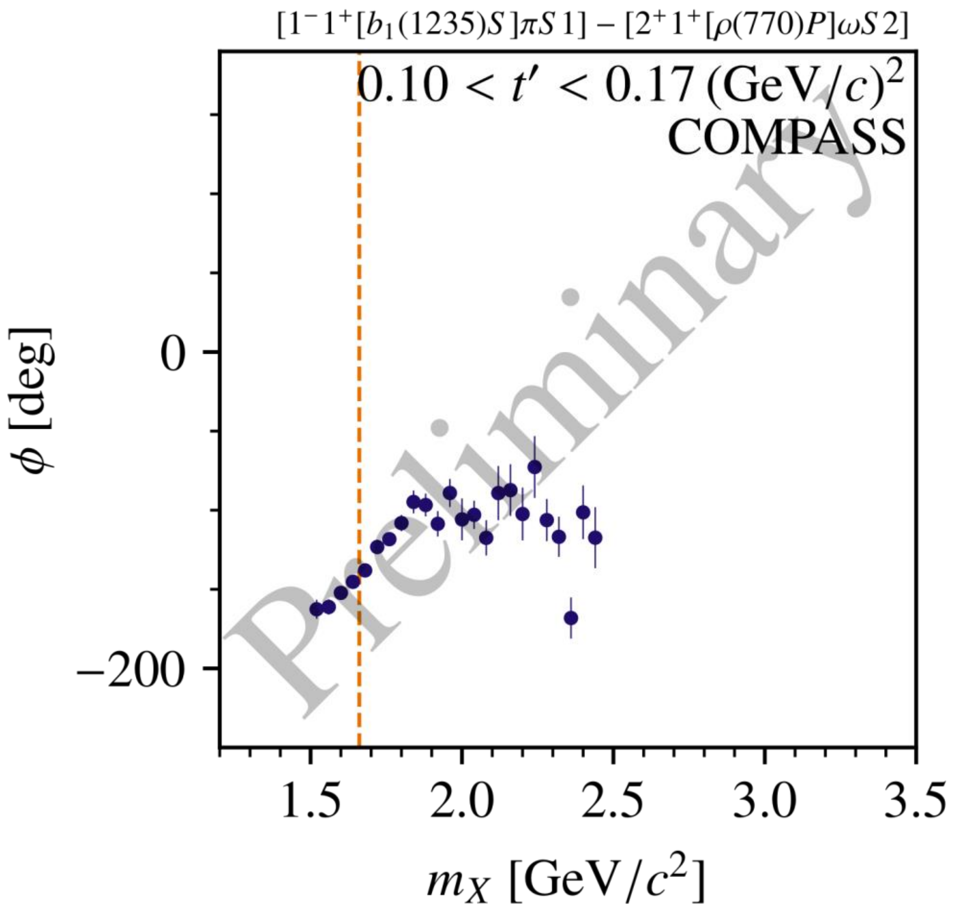
- Spin-exotic quantum numbers
- Lattice-QCD predictions:
  - Lightest hybrid meson at around $1.6\ \mathrm{GeV}/c^2$
  - Dominant decay to $b_1(1235)\pi$
- COMPASS has found $\pi_1(1600)$ in $3\pi, \eta\pi, \eta'\pi$

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



b_1 S-wave decay

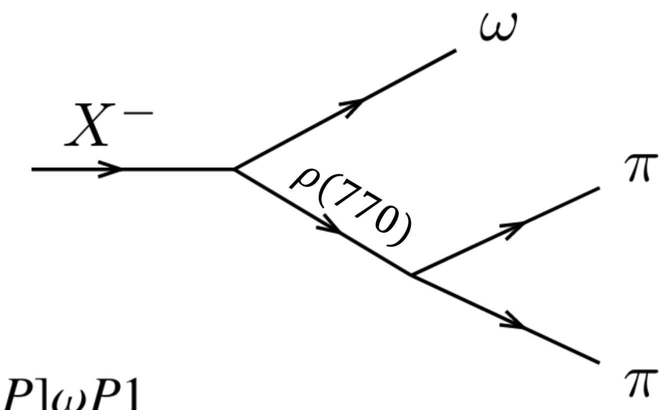


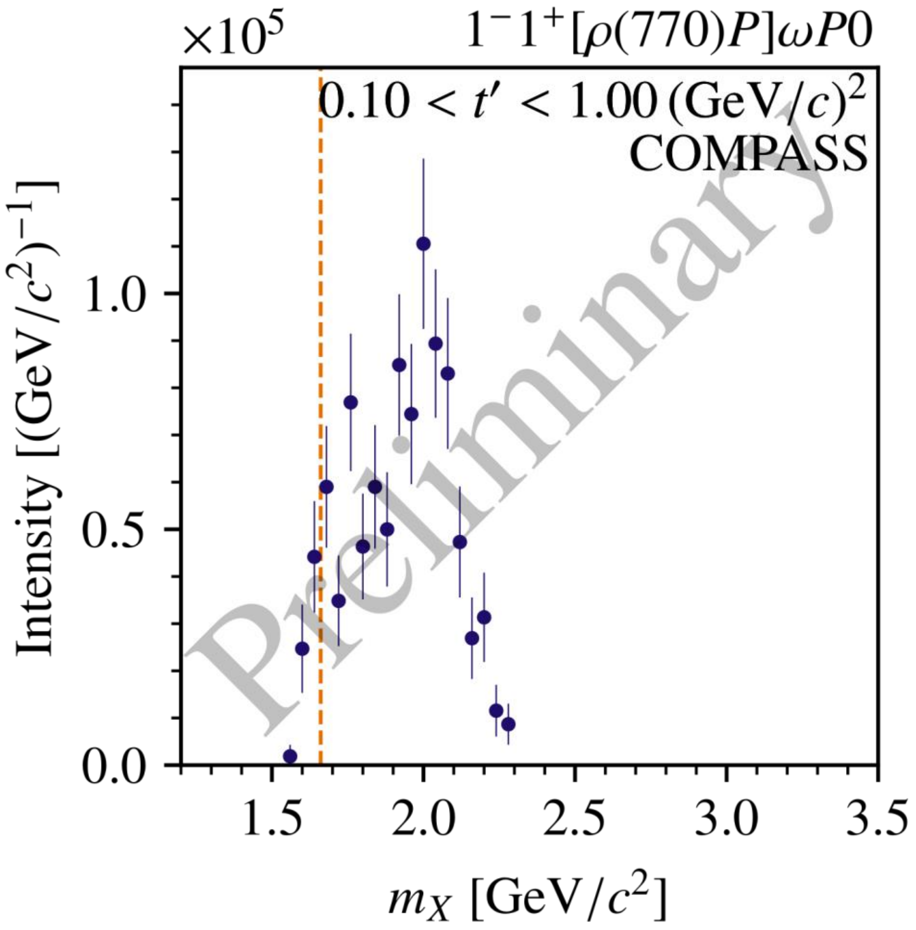


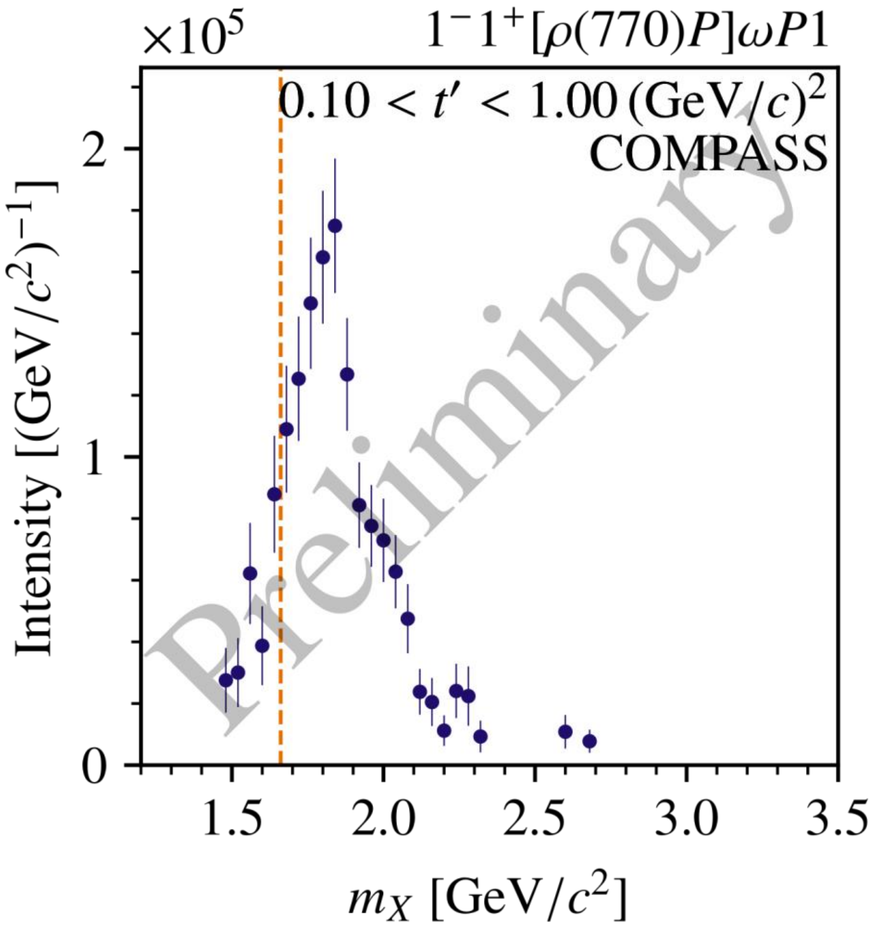
Listed in PDG

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

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





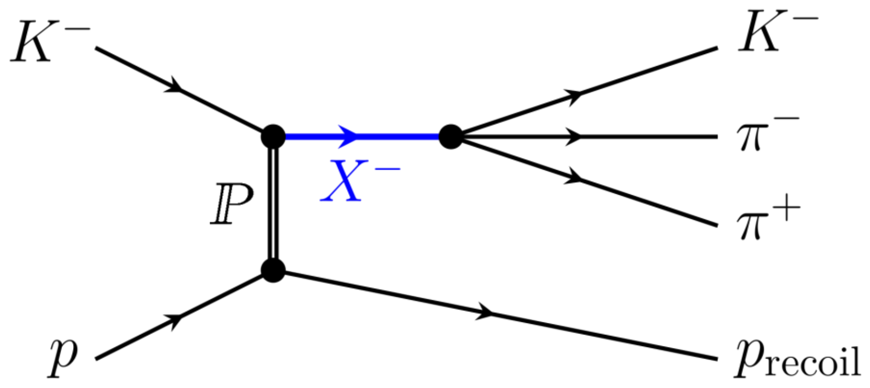


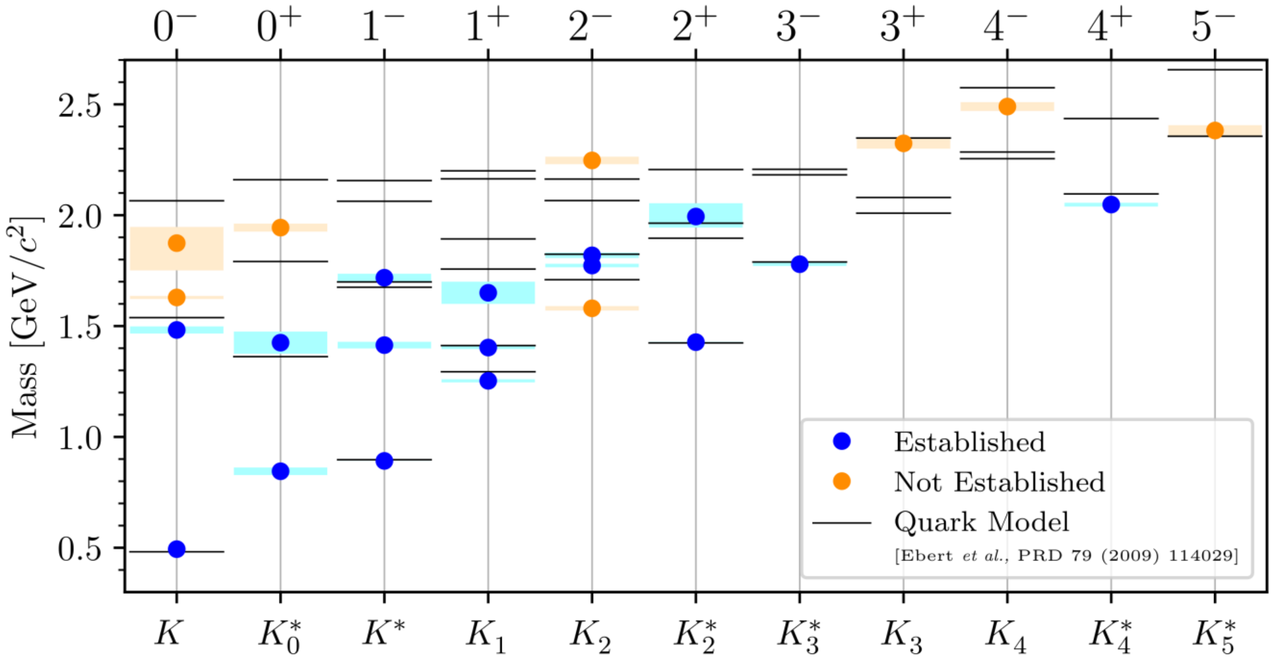
Listed in PDG

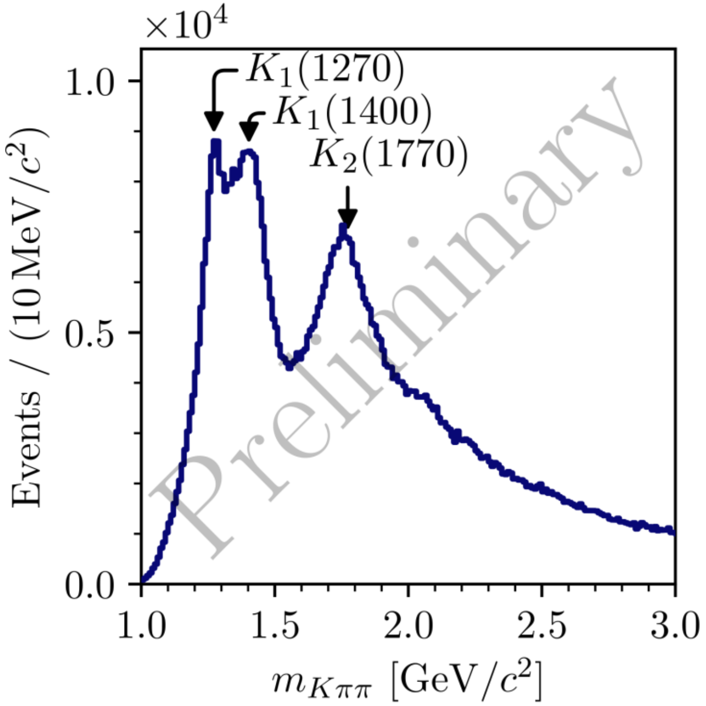
$\pi_1(1600)$
$m = 1661^{+15}_{-11}$ MeV
$\Gamma = 240 \pm 50$ MeV

Strange-Meson Spectroscopy in $K^-\pi^-\pi^+$

- 720k diffractive $K^-\pi^-\pi^+$ events
- 16 established states, 9 need further confirmation
- Missing states from quark-model prediction
- Many measurements performed 30+ years ago



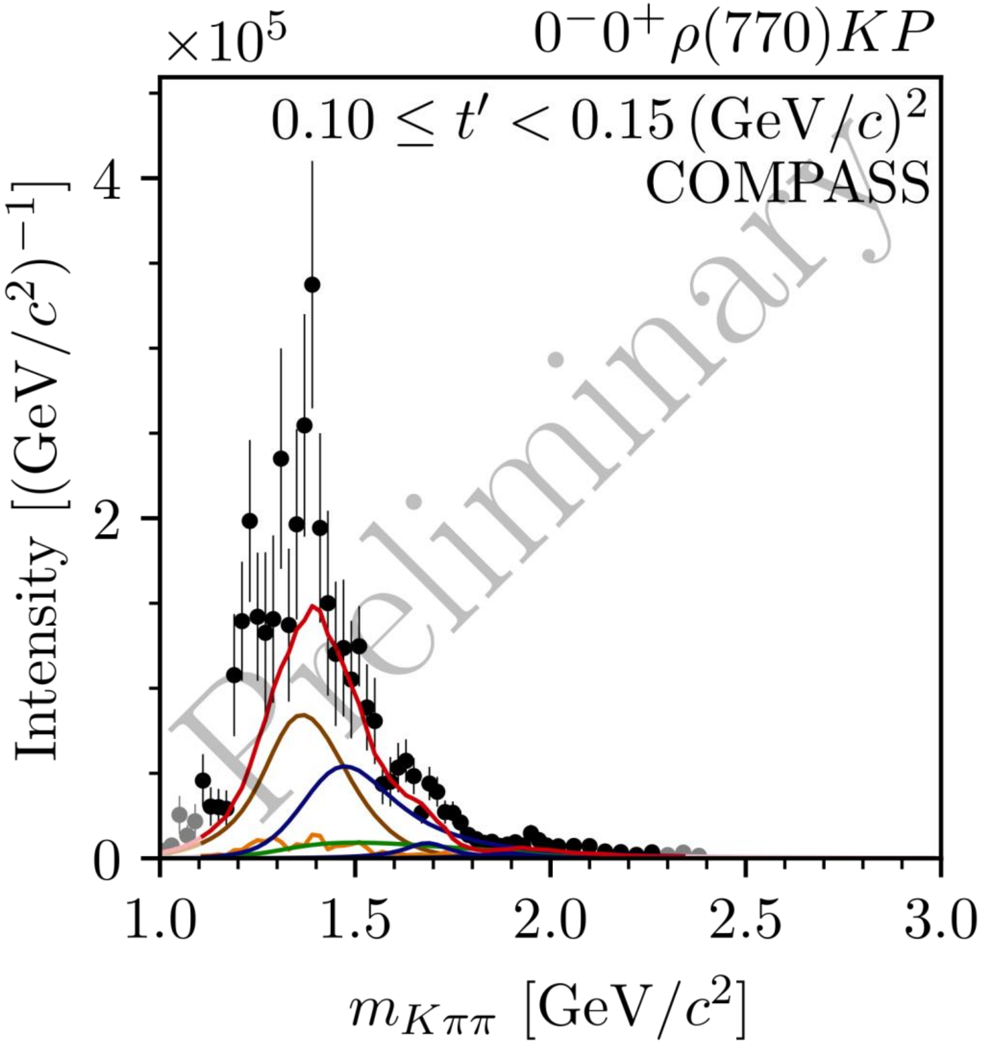




Strange Mesons with $J^P = 0^-$

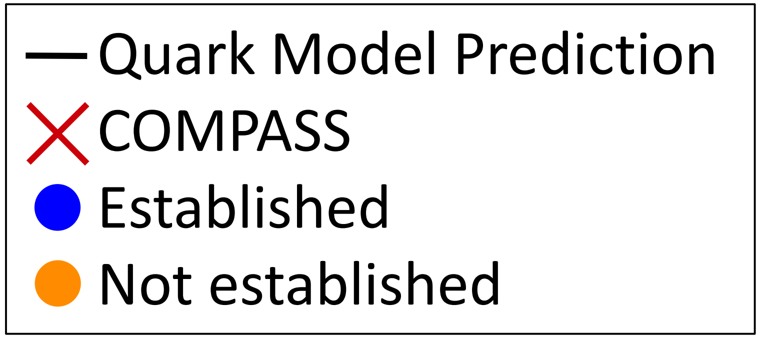
- $K(1460)$ peak at about $1.4\ \mathrm{GeV}/c^2$
  - Leakage effects in the final-state PID below $1.5\ \mathrm{GeV}/c^2$

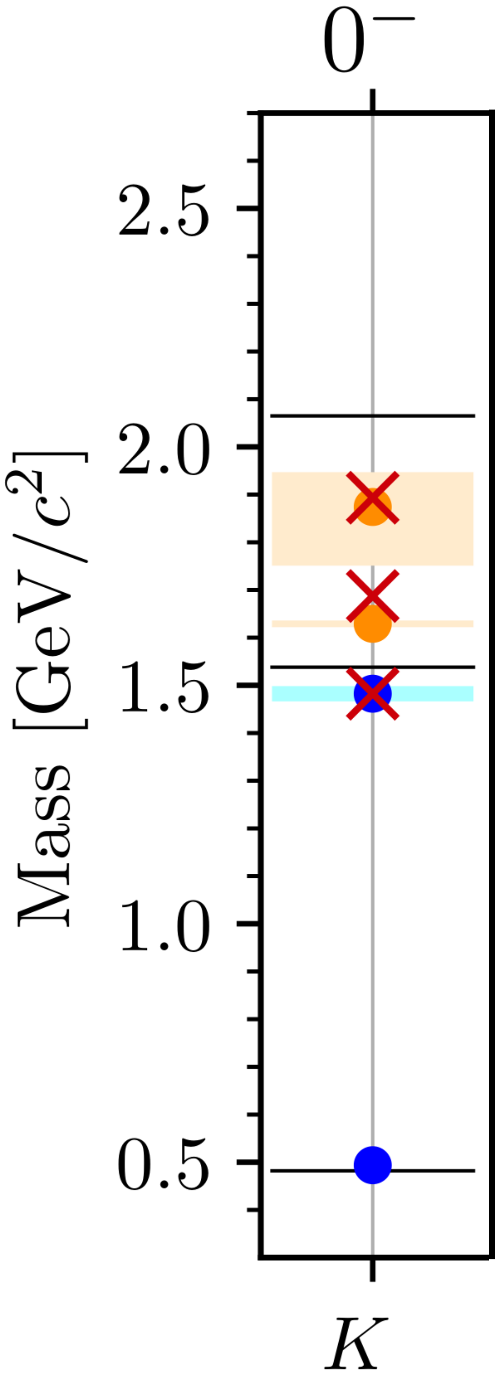
  $\Rightarrow$ fixed Breit-Wigner resonance
- $K(1630)$ peak at about $1.7\ \mathrm{GeV}/c^2$
  - 8.3σ statistical significance
- $K(1830)$ peak at about $2.0\ \mathrm{GeV}/c^2$
  - 5.4σ statistical significance



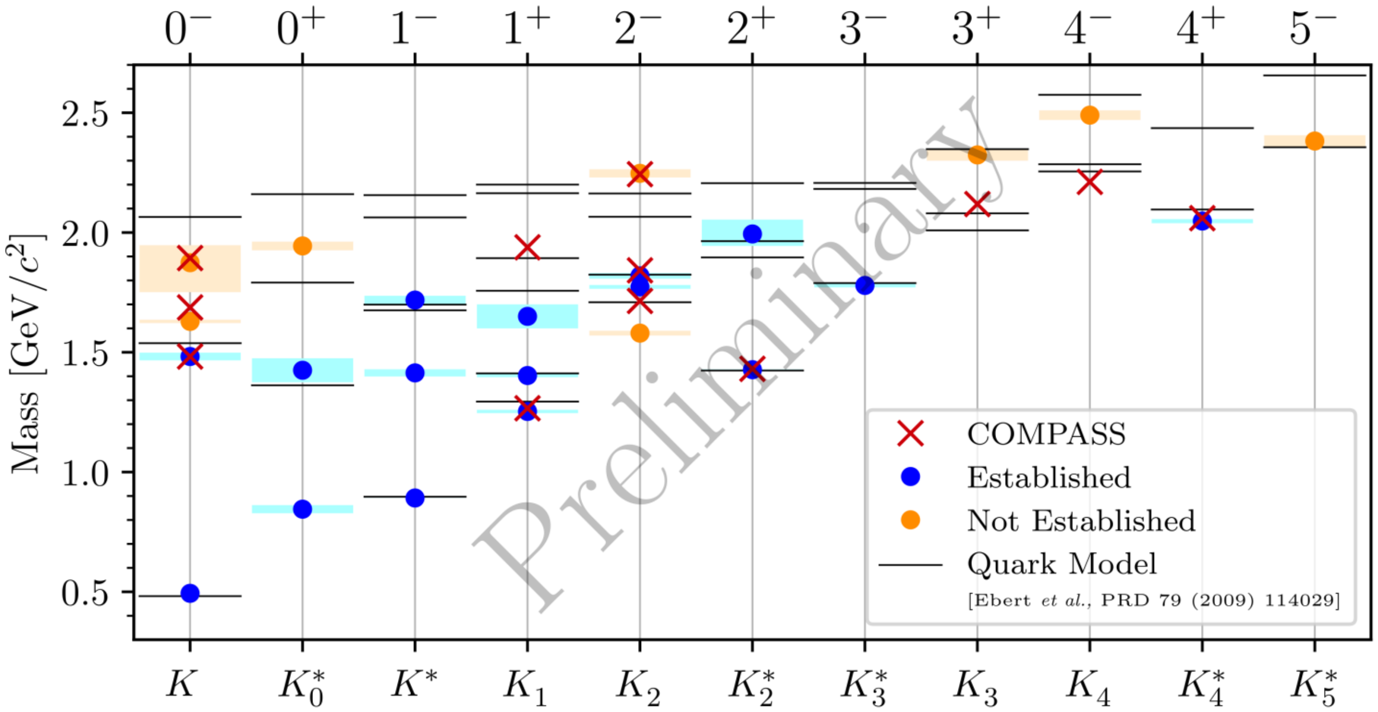
Strange Mesons with $J^P = 0^-$

- Quark model predicts 2 exited 0^- states
- Indications for 3 states in one analysis
  - $\Rightarrow$ Supernumerary state $K(1630)$
  - $\Rightarrow$ Possible candidate for exotic strange meson; other explanations possible





Strange Mesons



- Most comprehensive analysis of $K^-\pi^-\pi^+$
  - 11 states extracted from COMPASS data

Conclusion

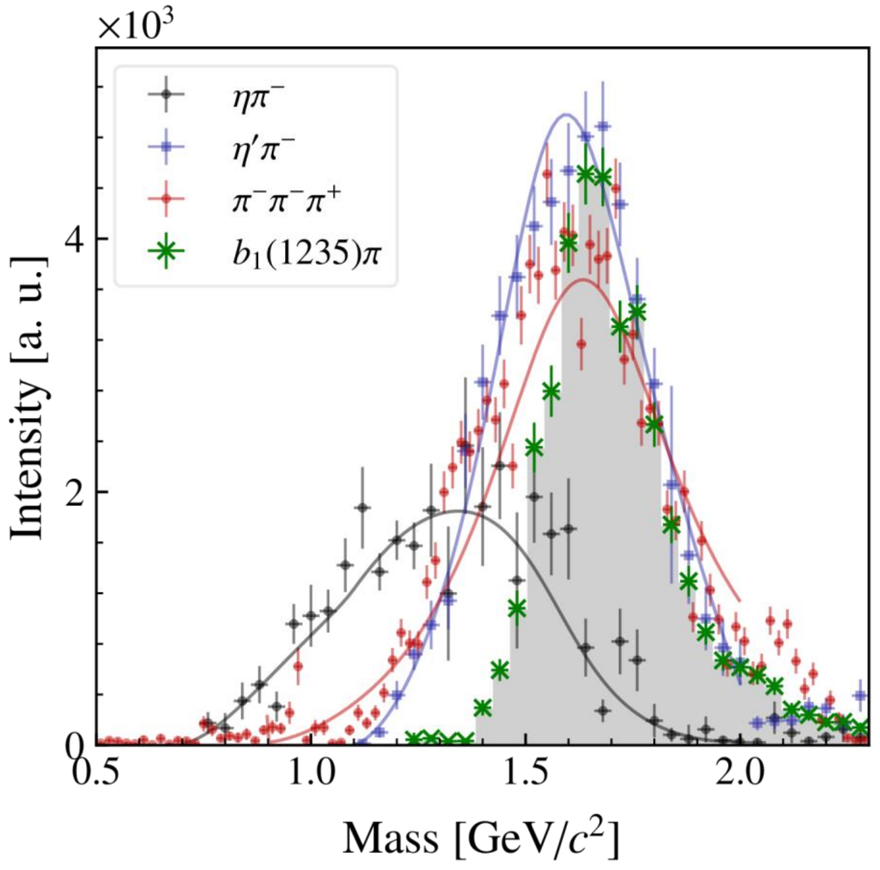
$\omega\pi^-\pi^0$:

- Resonance-like signals for many well-established states visible
  - Clear peak for $\pi_1(1600) \to b_1(1235)\pi$
- Possible signals for further states
  - $a_3(1975), a_6(2450), \pi_1 \to \rho(770)\omega$

$K^-\pi^-\pi^+$:

- Most comprehensive analysis of this final state
- Possible exotic strange-meson: Supernumerary state in $J^P = 0^-$

1^{-+} signal in different COMPASS final states



Outlook

COMPASS:

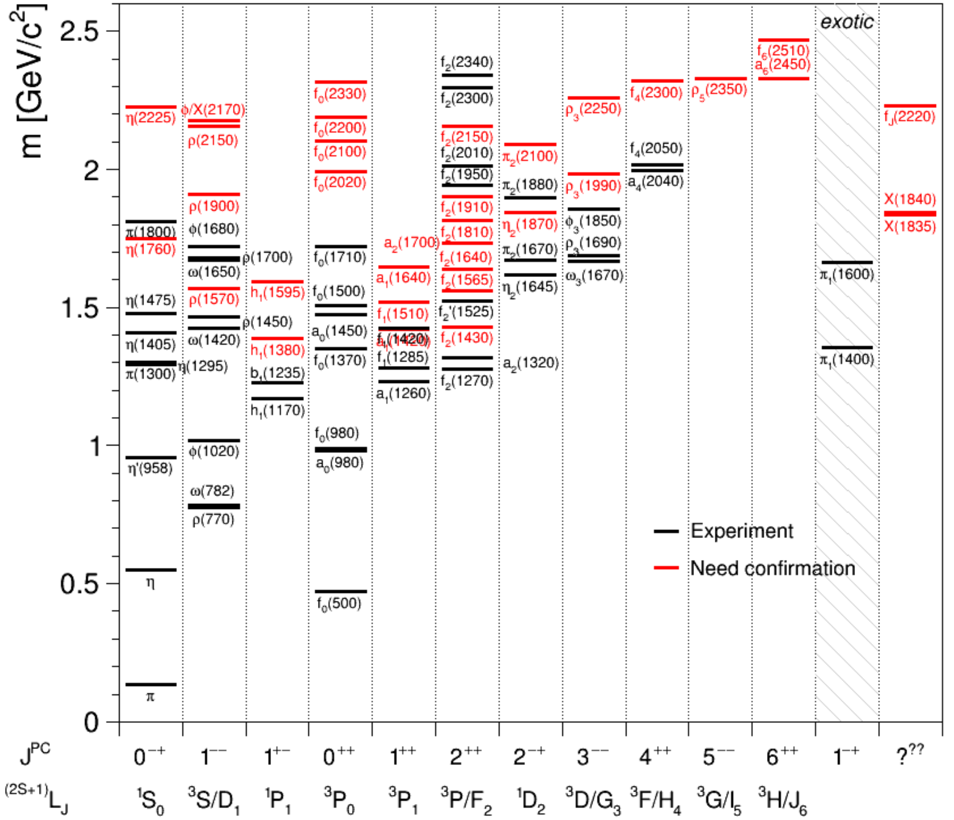
- Resonance-model fit of $\omega\pi^-\pi^0$ to extract resonance parameters
  - First studies yield promising results
- Upcoming analyses of many final states:
  - $f_1\pi^-$, $K_S K^-$, $K_S K_S \pi^-$, $K_S \pi^-$, $\Lambda\bar{p}$

AMBER:

- Proposal for high-precision strange-meson spectroscopy
  - $10-20 \times 10^6$ $K^-\pi^-\pi^+$ events with a high-intensity beam
  - Additional PID for extended momentum coverage

Backup

Mesons in QCD



- Many short-lived, exited states with similar masses

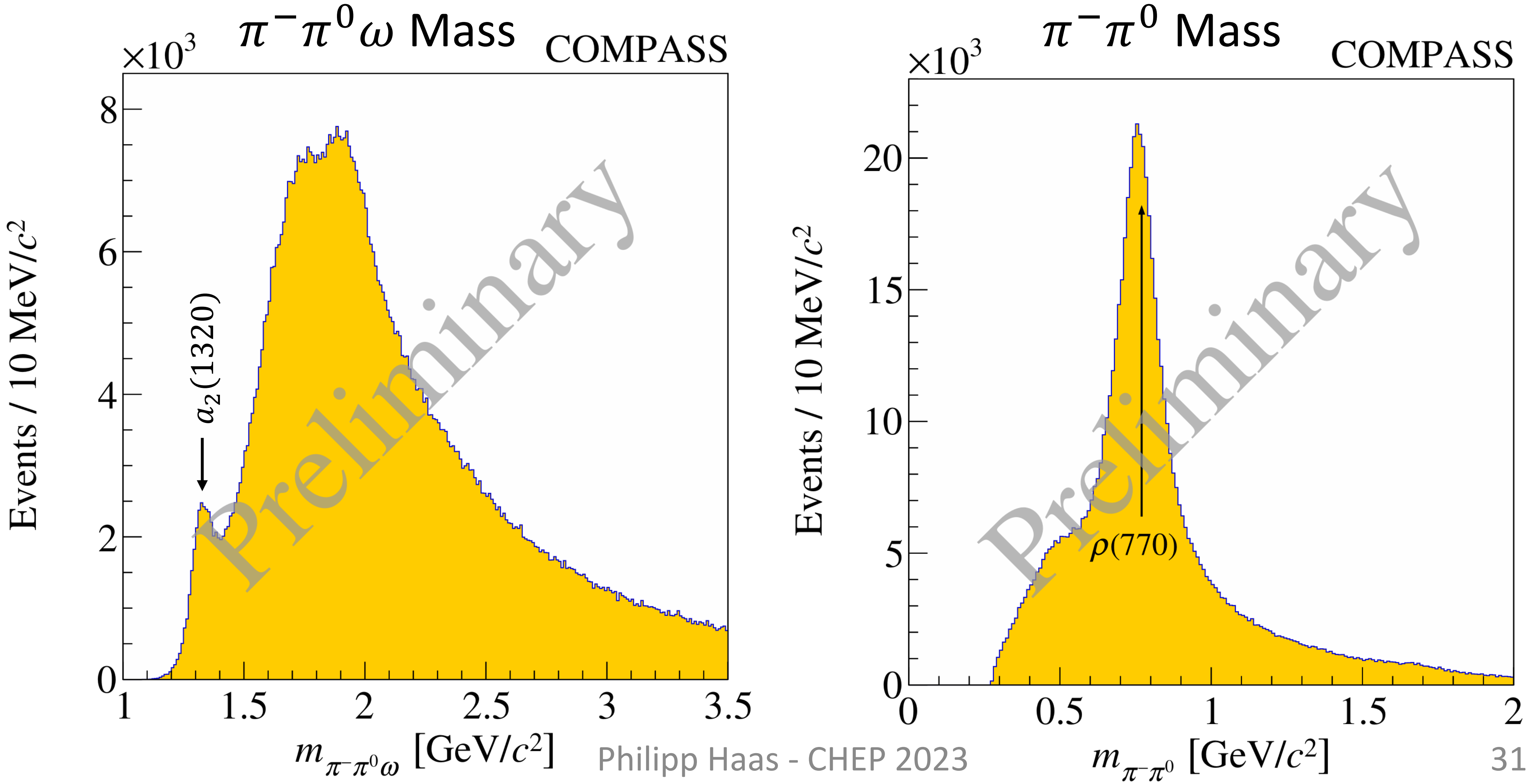
⇒ All possible intermediate states X for one final-state configuration interfere

⇒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 - $\omega(782)\pi^-\pi^0$

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

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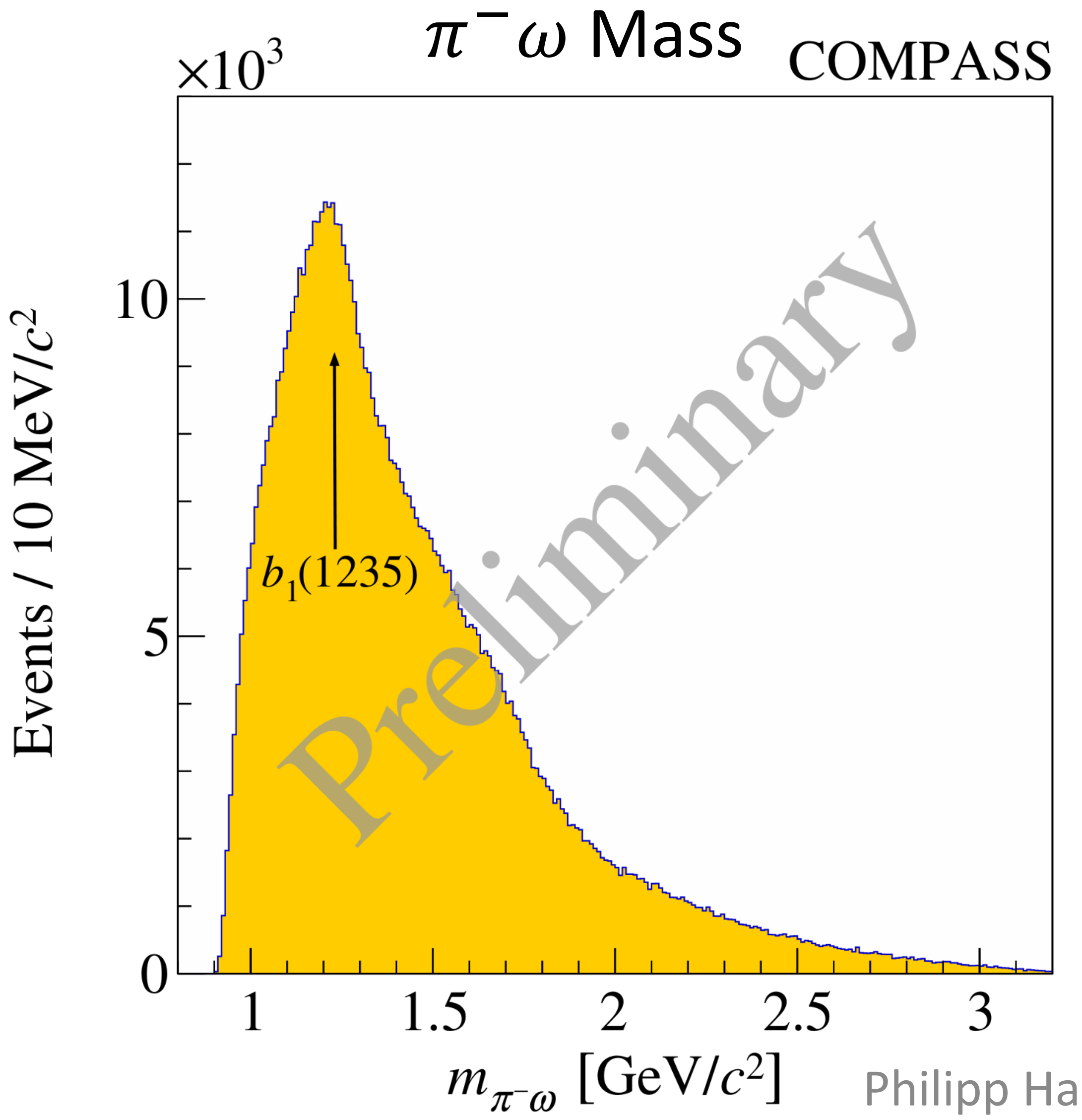
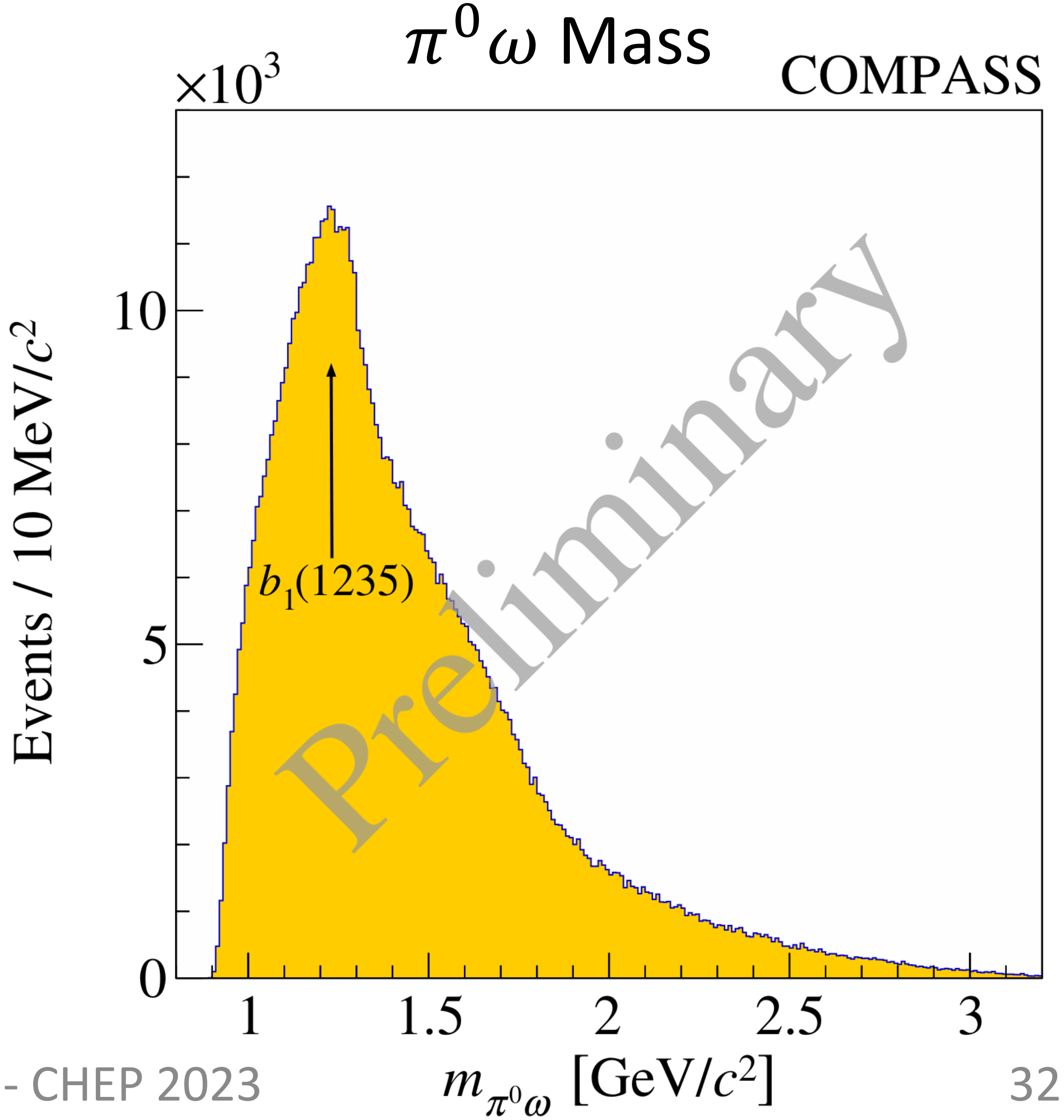
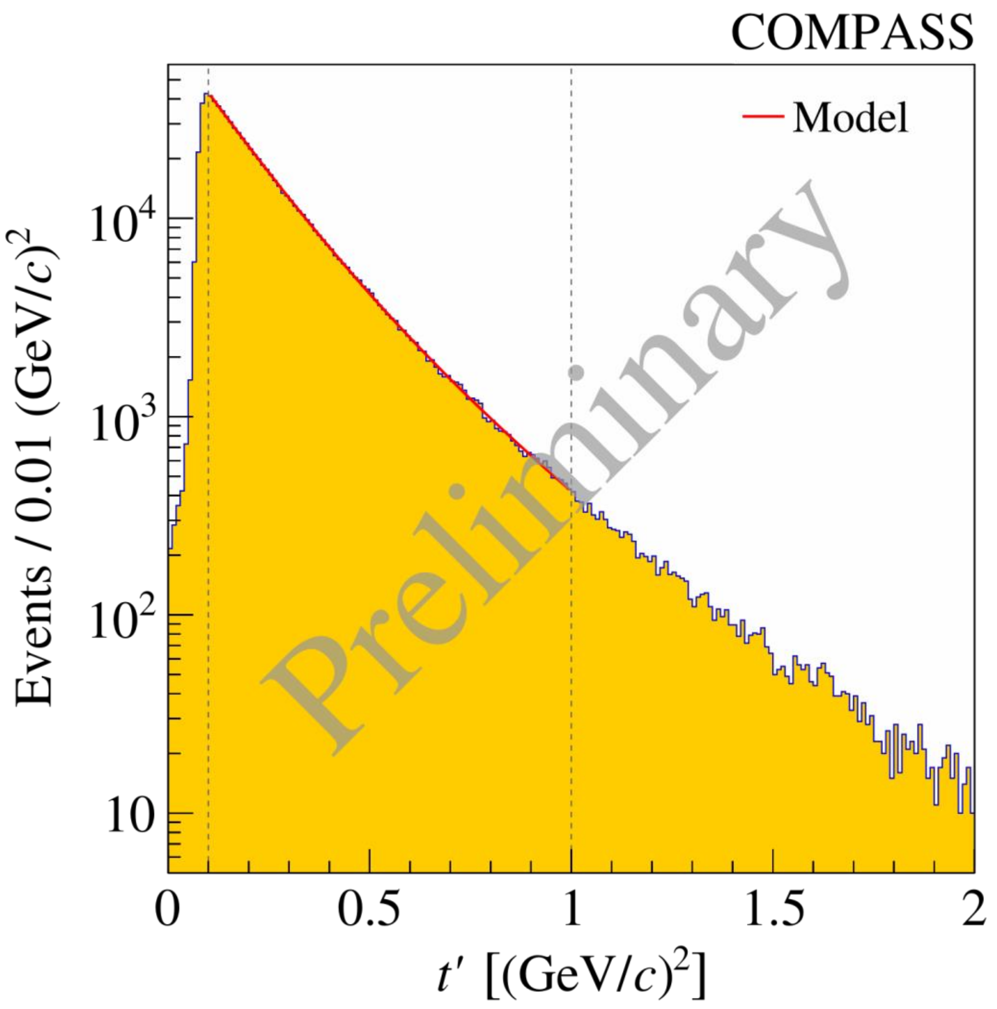
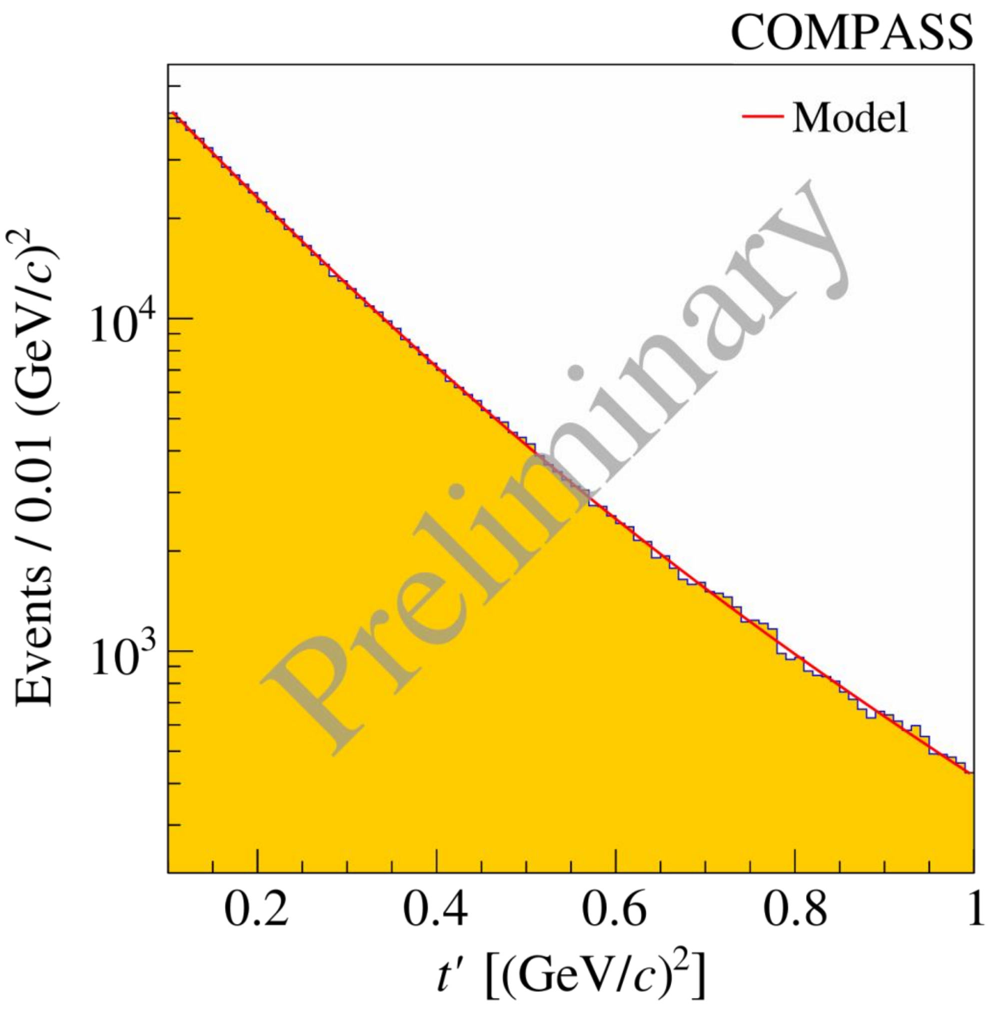


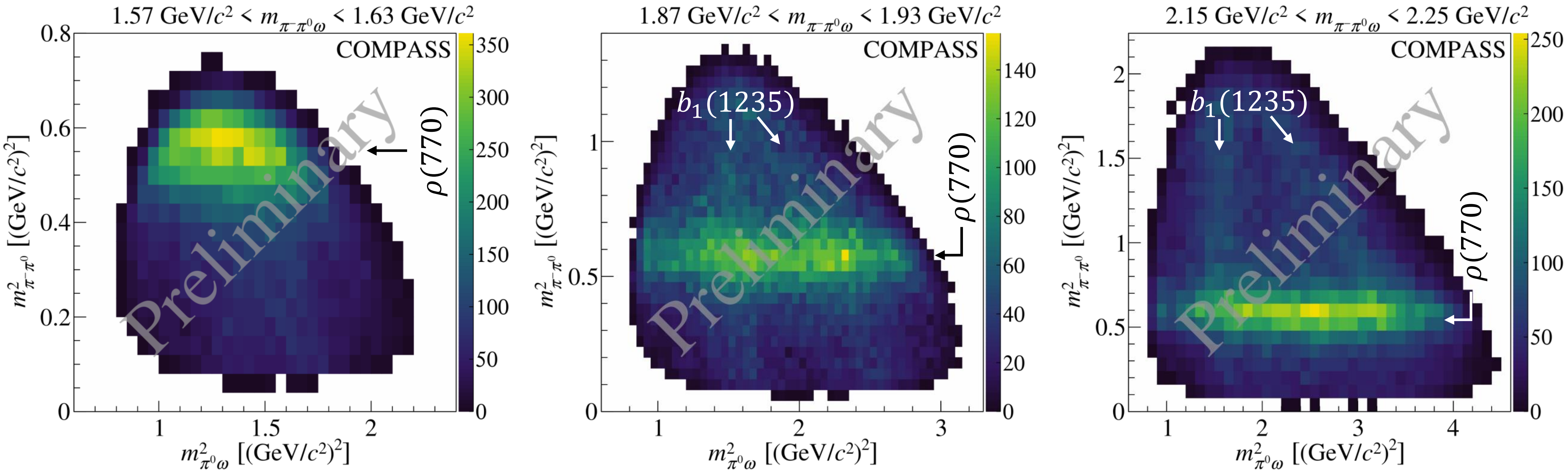


t' Distribution - $\omega(782)\pi^-\pi^0$



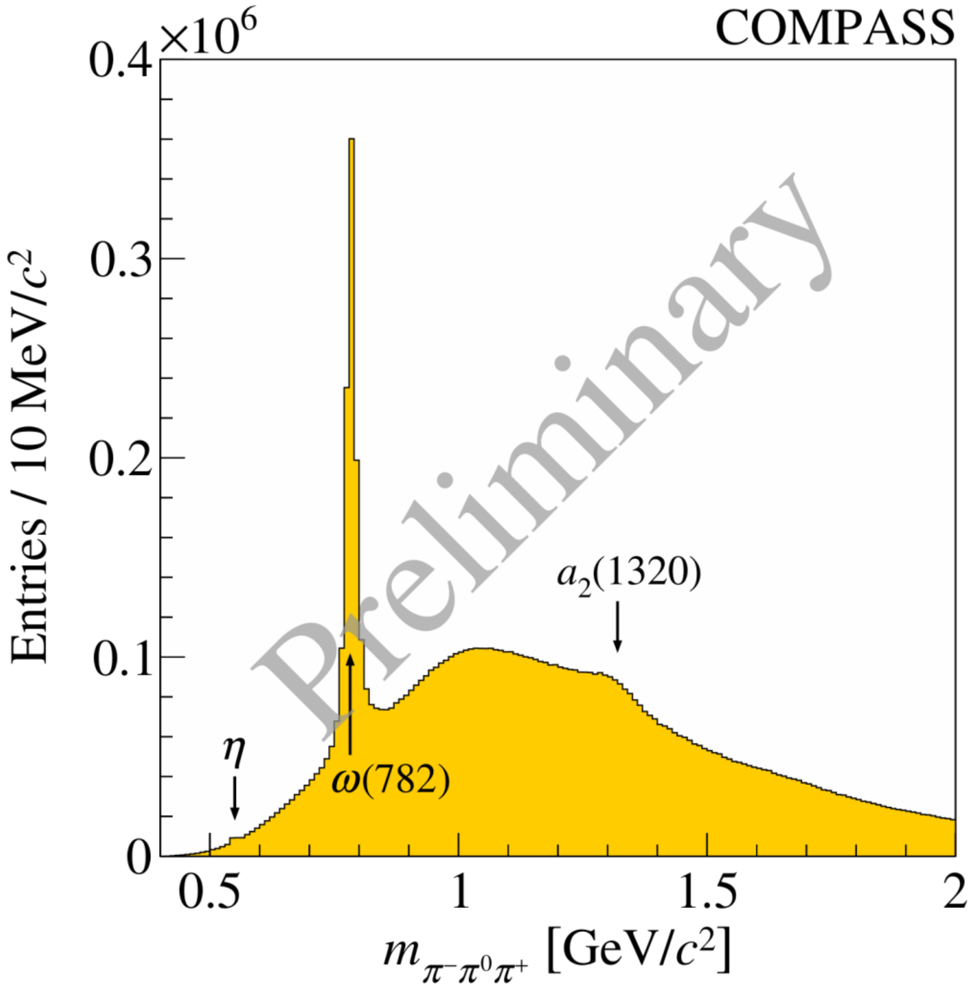


Dalitz Plots - $\omega(782)\pi^-\pi^0$



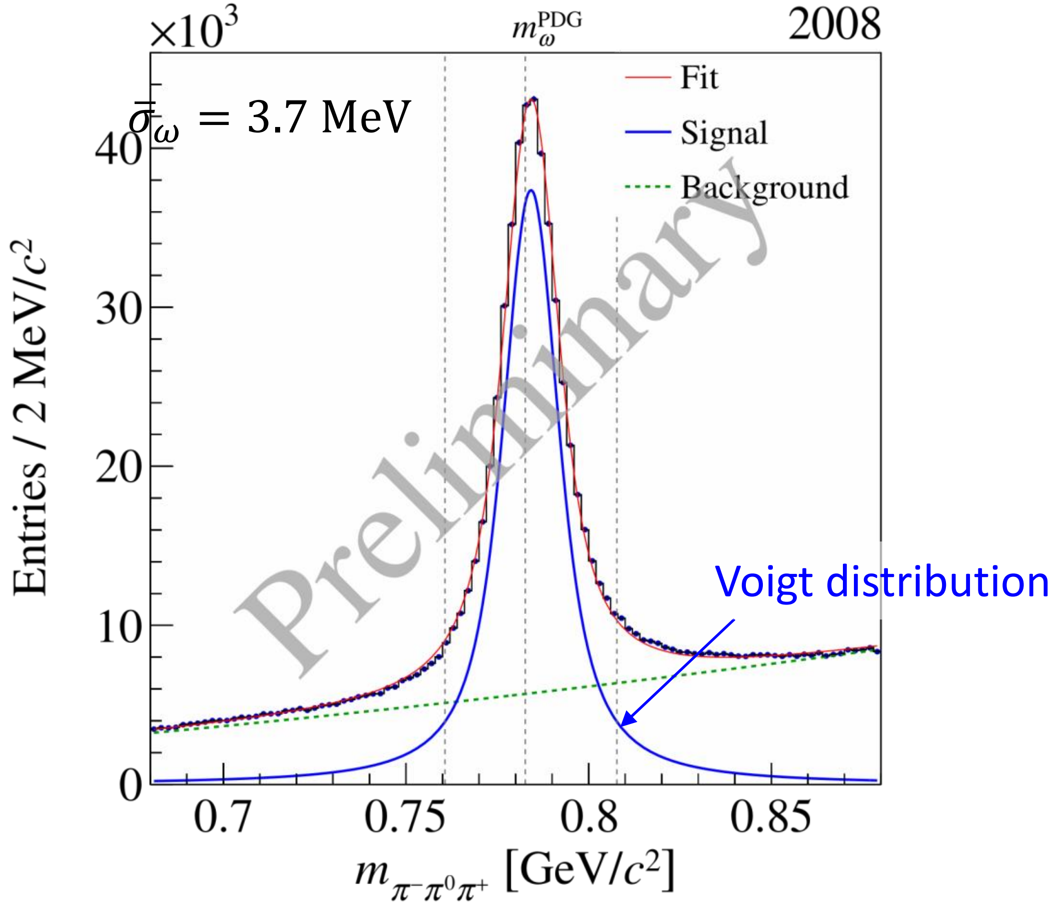
$\omega(782)$ Selection - $\omega(782)\pi^-\pi^0$

- 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

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

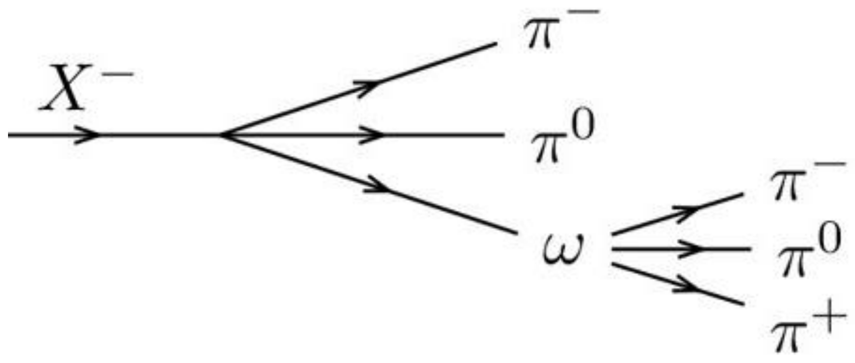
- Decay amplitude $\psi_i(m_X, \tau)$: calculated using the isobar model
- $\mathcal{T}_i(m_X, t')$ contains production, propagation, and coupling of
    - No assumptions about the resonant content of X^-
- Extract $\mathcal{T}_i(m_X, t')$ by independent maximum-likelihood fits of $I(\tau)$ in bins of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

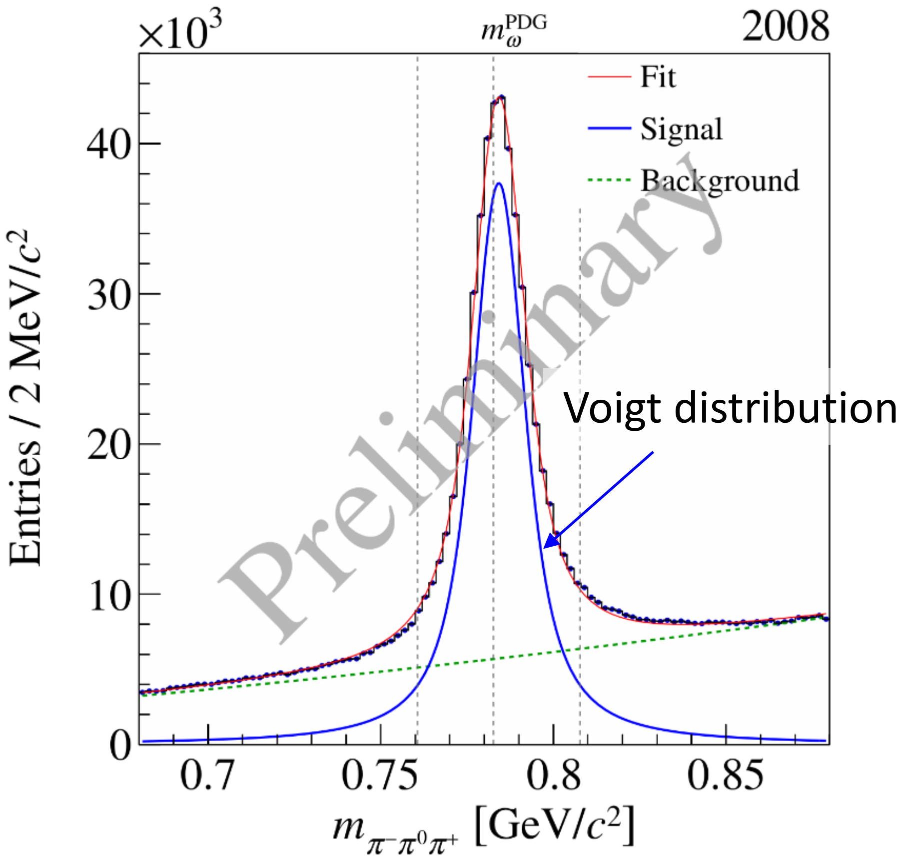
$$\psi_i = \Sigma_{\lambda_\omega} \psi_{i,X\to\omega\pi\pi}^{\lambda_\omega} \psi_{\omega\to3\pi}^{\lambda_\omega}$$

- $\psi_{i,X\to\omega\pi\pi}^{\lambda_\omega}$ calculated with isobar model
- $\psi_{\omega\to3\pi}^{\lambda_\omega} = \mathcal{D}(m_\omega) D_0^{\lambda_\omega} |p^+ \times p^-|$
  - $\mathcal{D}(m_\omega)$ 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

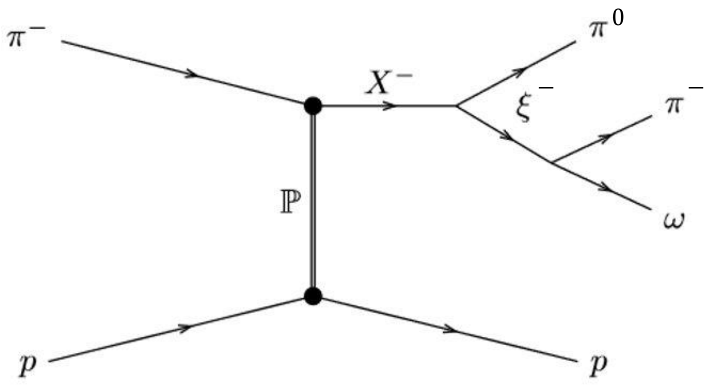
- Problem: m_ω is only measured with limited resolution
  - $\Rightarrow$ Intensity level: Convolution of BW with resolution function => m_ω follows Voigt distribution
  - $\Rightarrow$ Convolution of the full intensity is not feasible
- Solution: Neglect self-interference of ω as only one $\pi^-\pi^0\pi^+$ 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

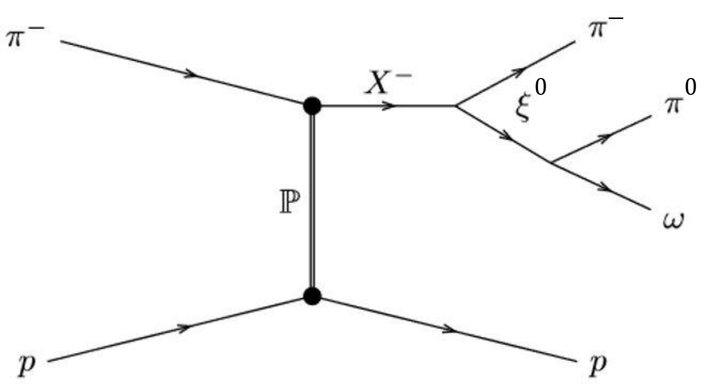


Isospin Symmetrization

- $X^- \rightarrow \xi^-\pi^0$ 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

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



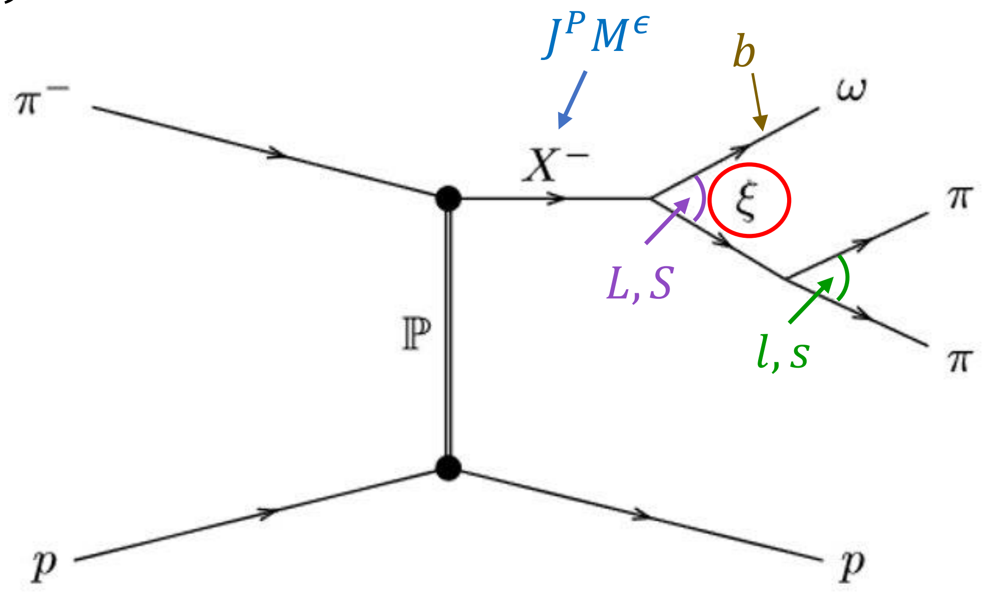


Wave Selection

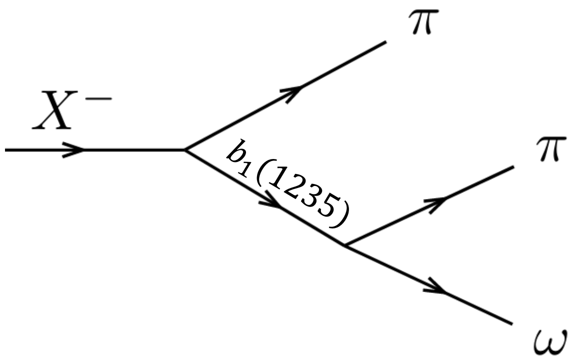
- Method used for 3π, 5π and $K\pi\pi$
- Modified log-likelihood with penalties:
  - Cauchy regularization to suppress small waves
  - Connected bins over m_X to smoothen $\mathcal{T}_i(m_X)$
- Wave pool:
  - $J \leq 8, M \leq 2, \epsilon = +$
  - $\xi \to \pi\pi$: $\rho(770), \rho(1450), \rho_3(1690)$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

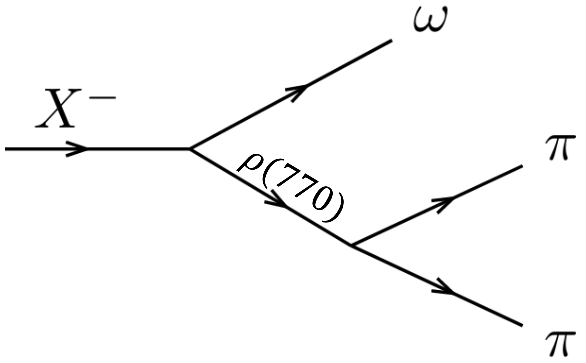
Notation:

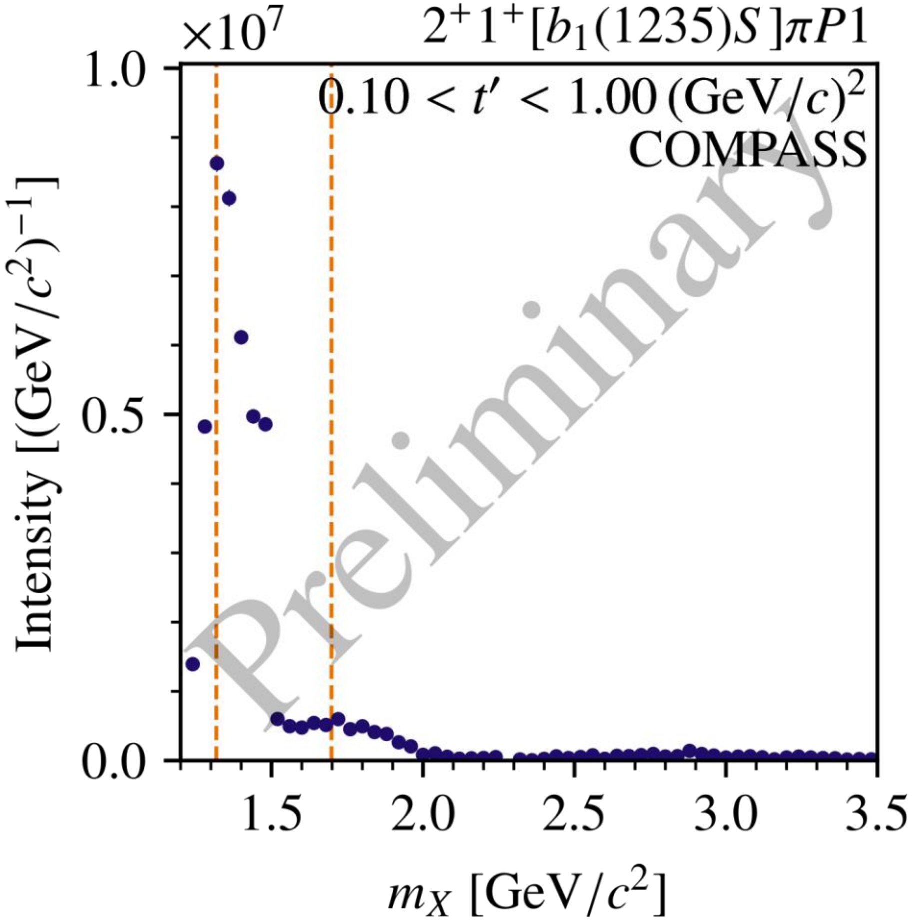
$i = J^P M^\epsilon \, [\xi l] \, b \, LS$

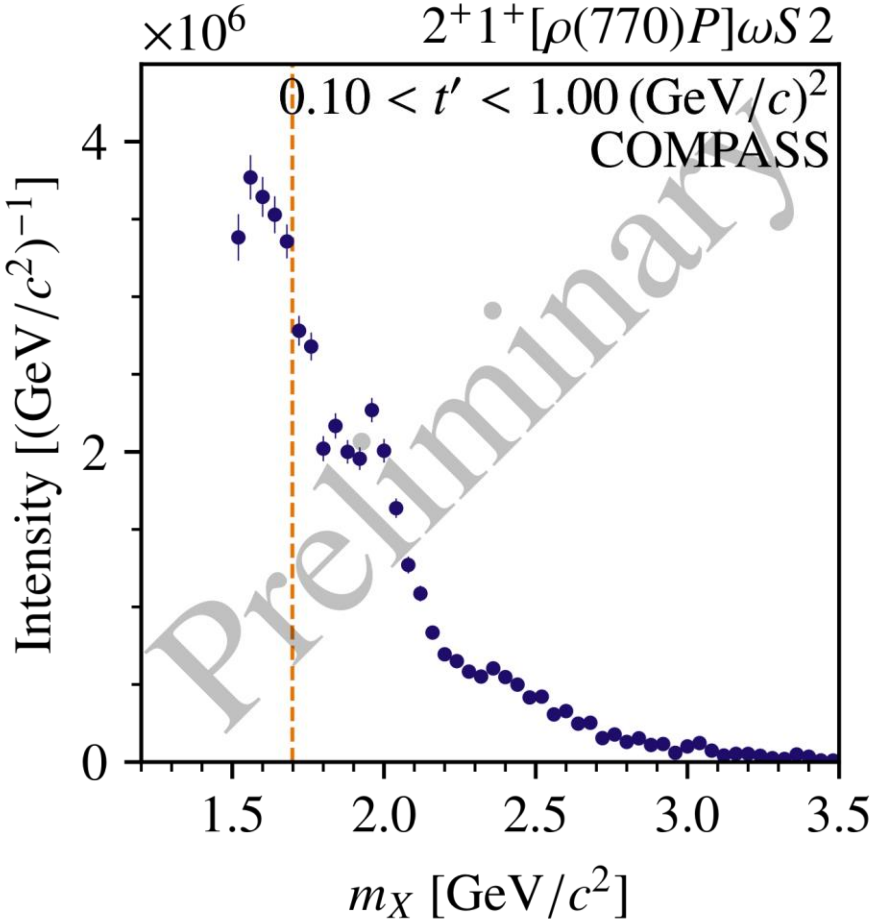


Results $J^{PC} = 2^{++}$







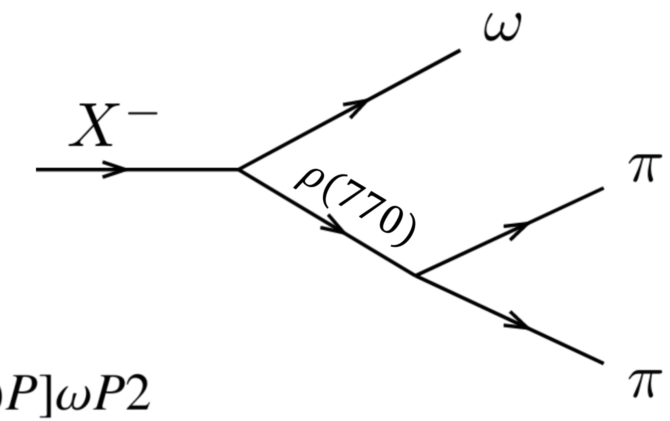


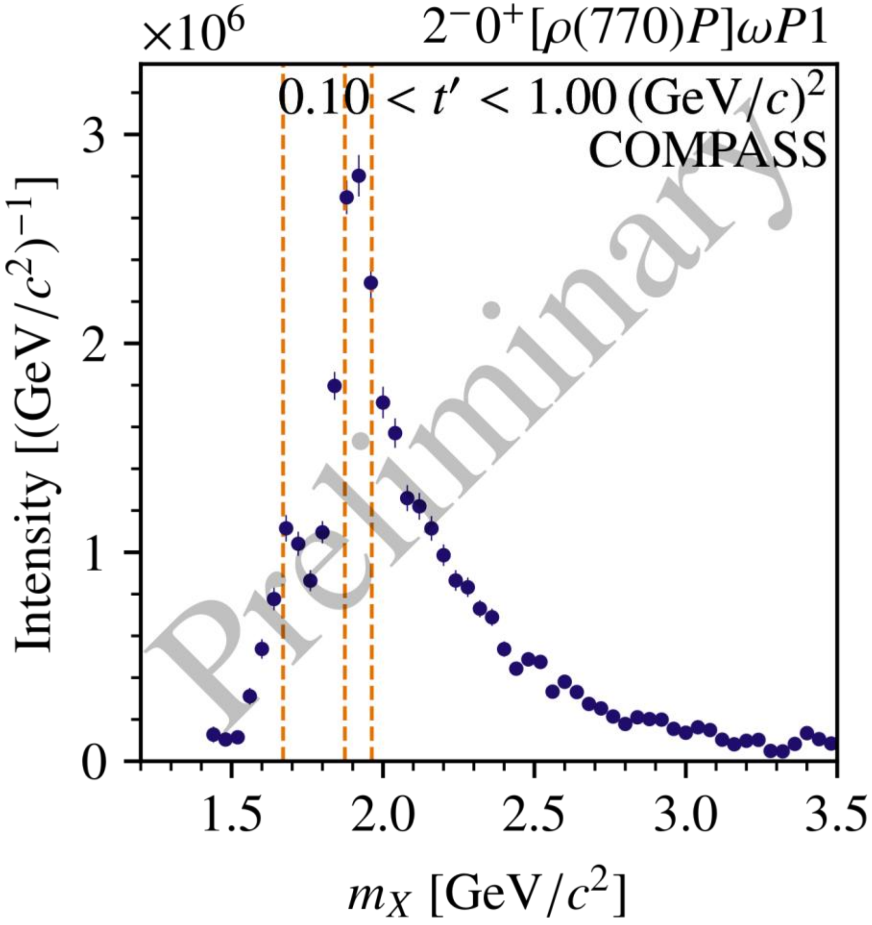
Listed in PDG

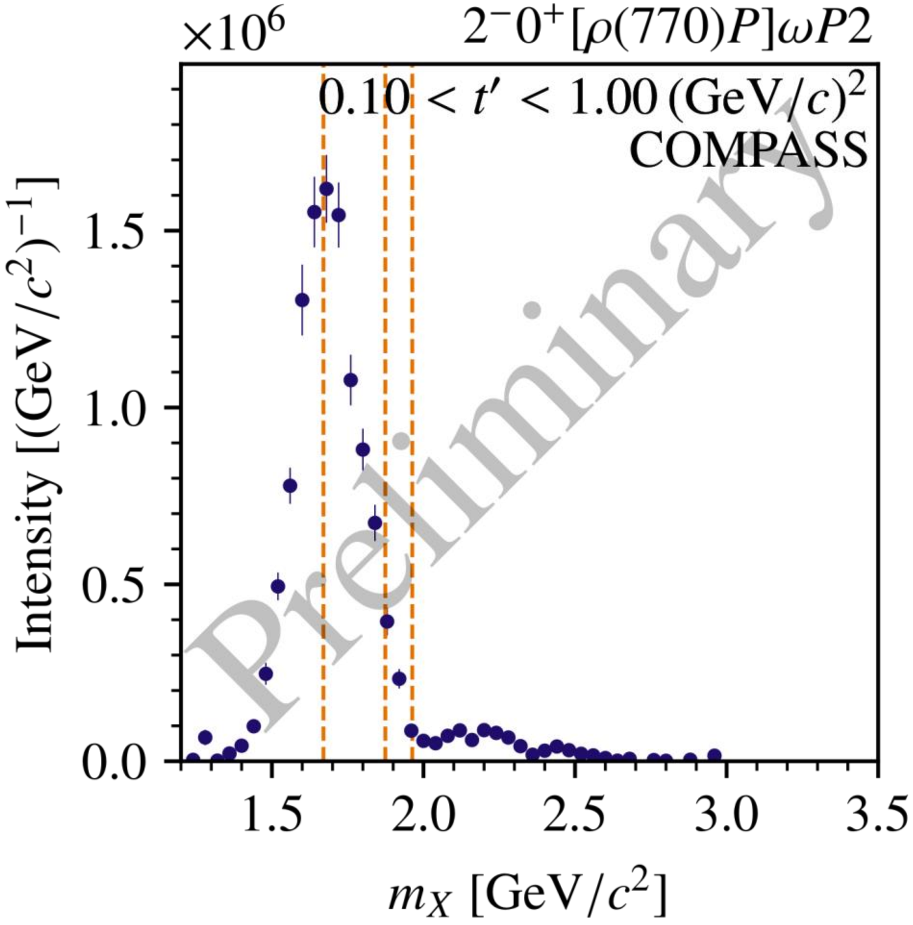
$a_2(1320)$
$m = 1318.2 \pm 0.6$ MeV
$\Gamma = 105^{+1.7}_{-1.9}$ MeV

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

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







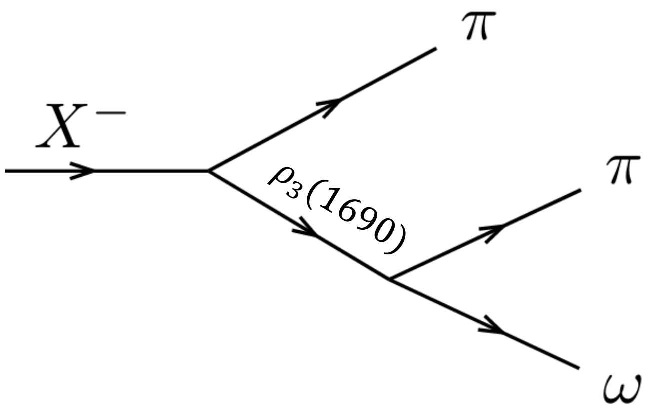
Listed in PDG

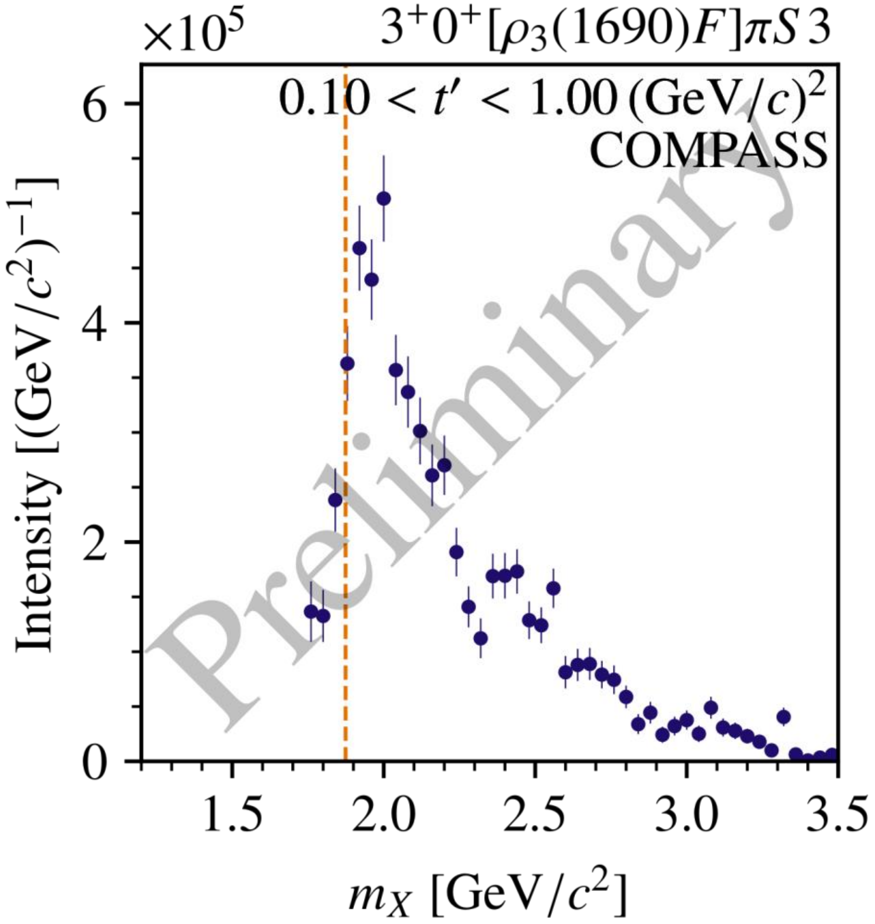
$\pi_2(1670)$
$m = 1670^{+2.9}_{-1.2}$ MeV
$\Gamma = 258^{+8}_{-9}$ MeV

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

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

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





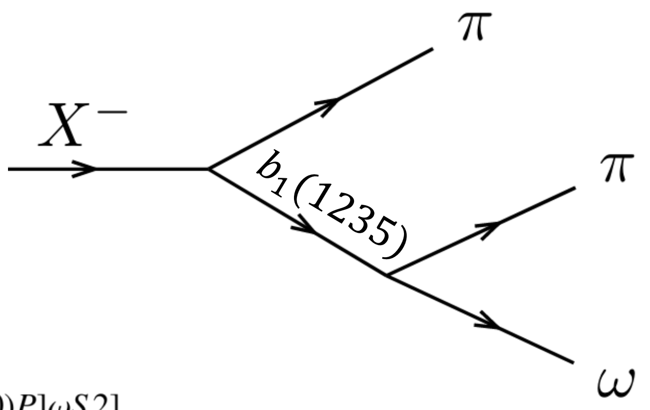
Listed in PDG

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

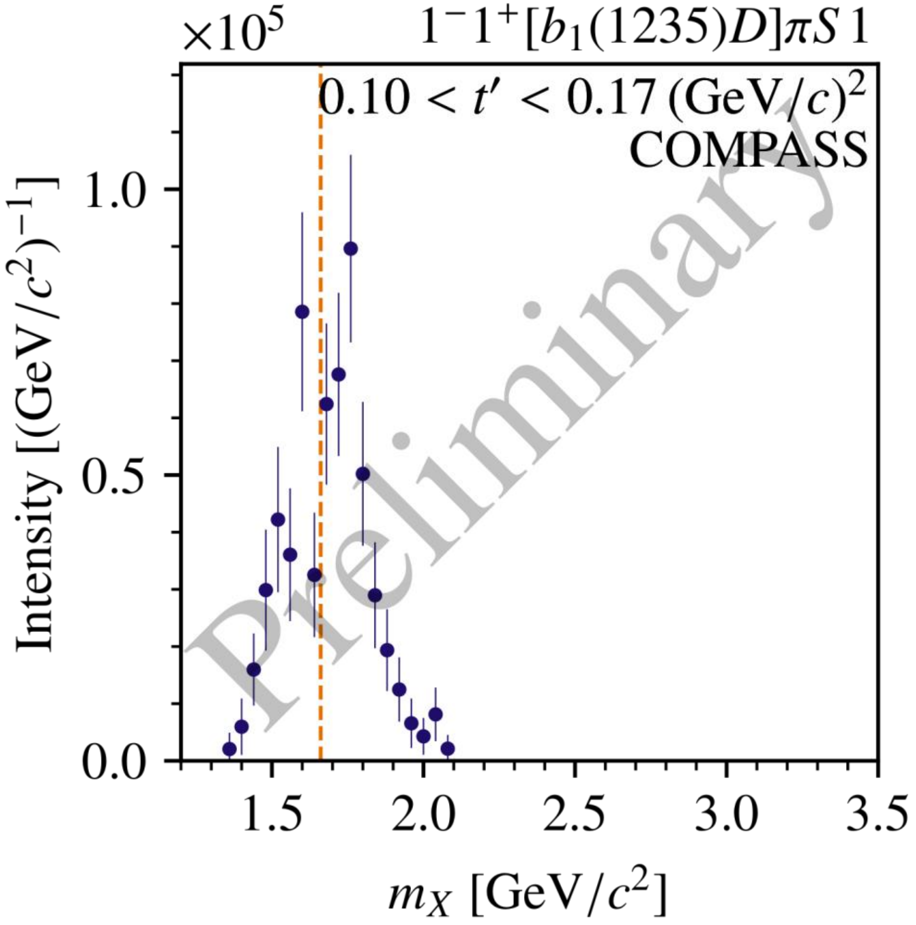
Seen only in $\pi^-\pi^-\pi^+$ at BNL E852

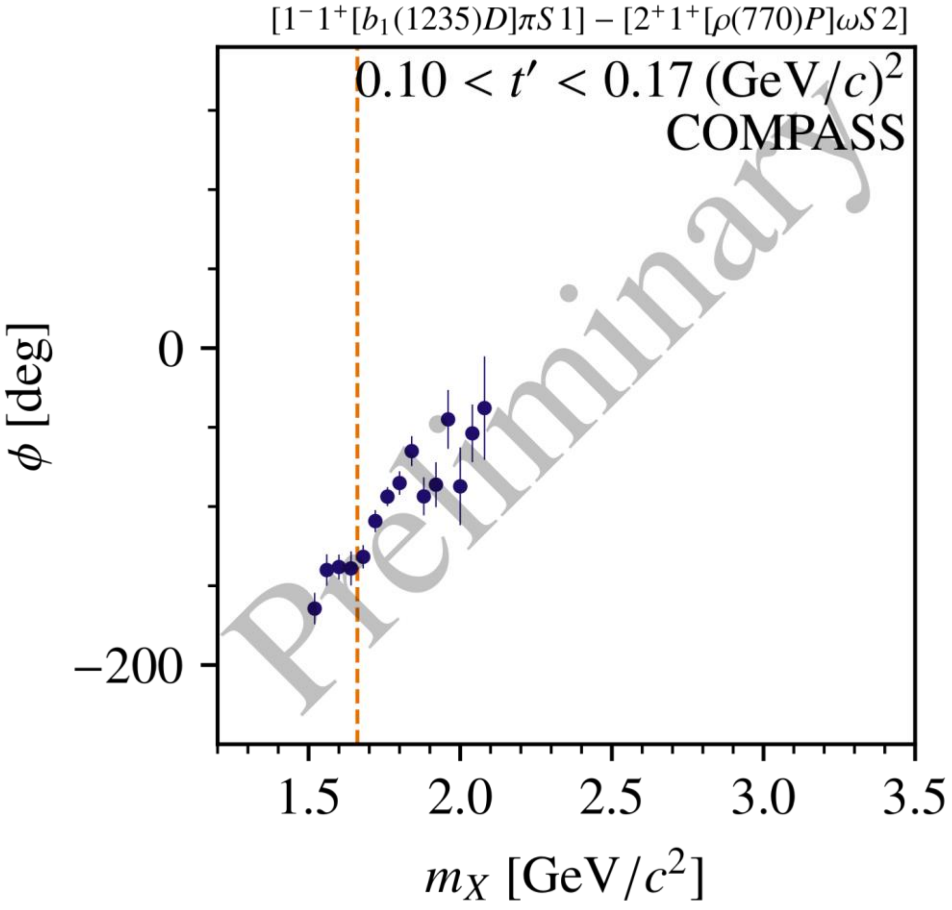
Further state in PDG: $a_3(2030)$

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



b_1 D-wave decay

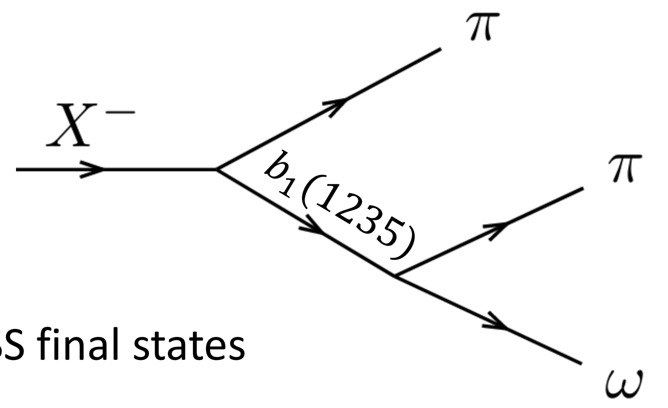




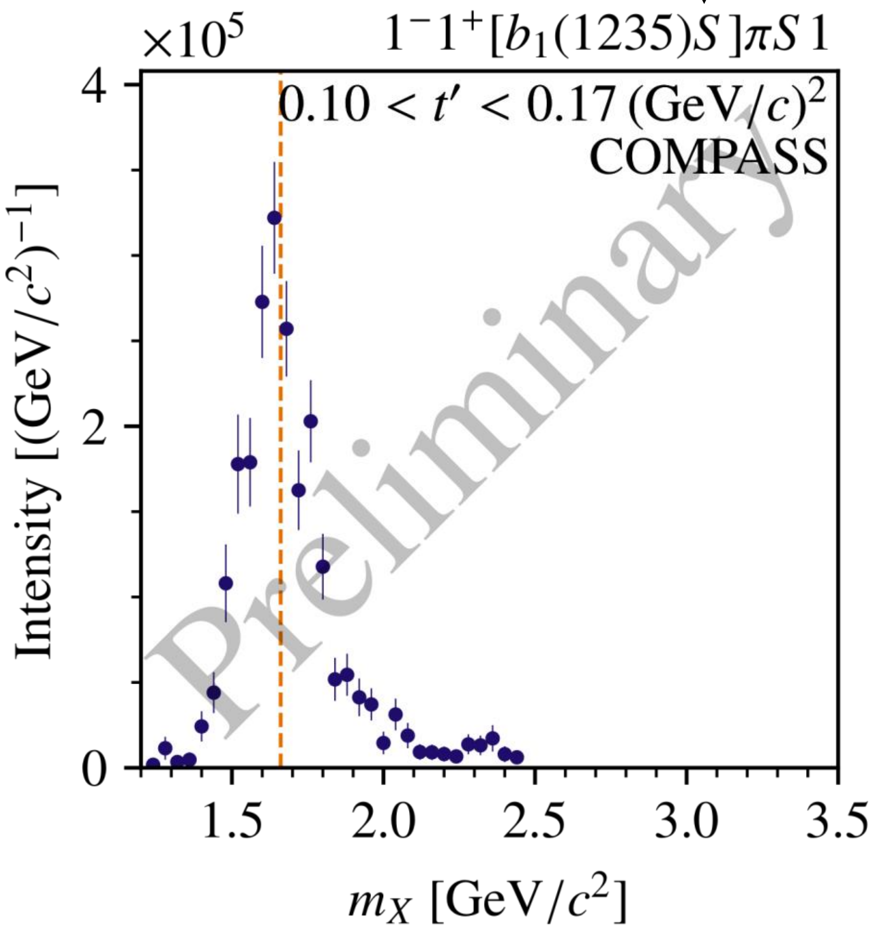
Listed in PDG

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

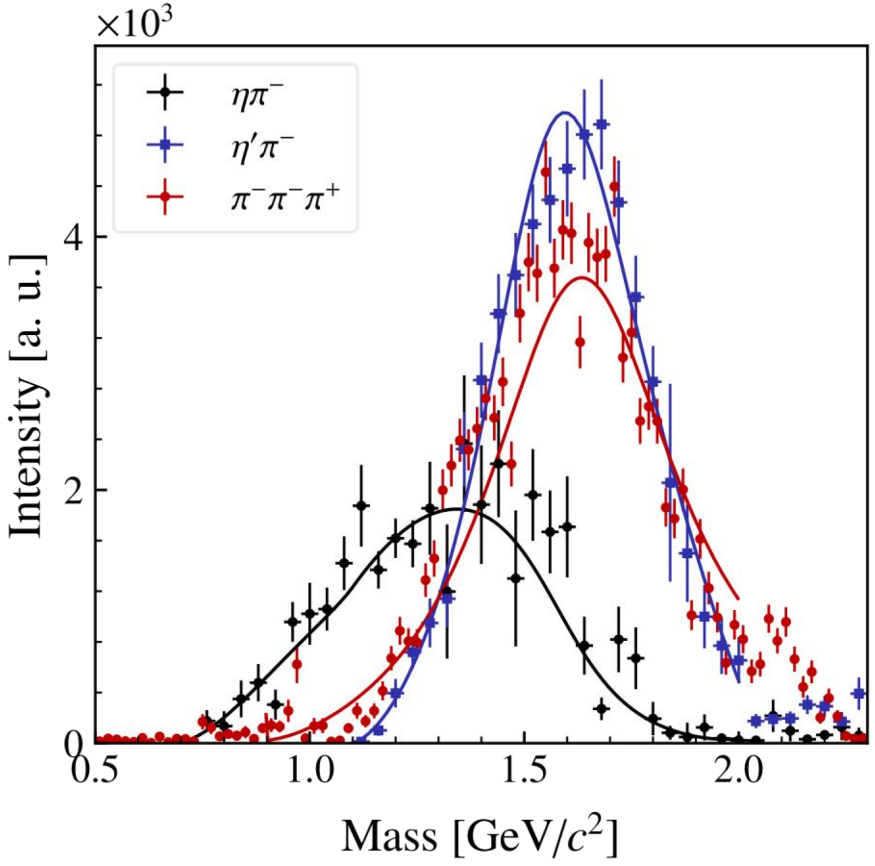
Results $J^{PC} = 1^{-+}$



b_1 S-wave decay



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



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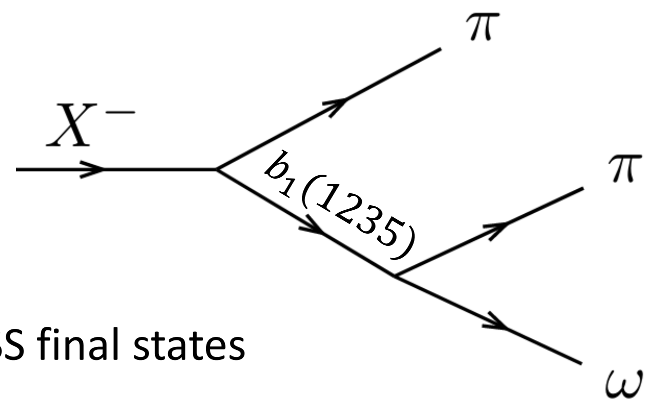
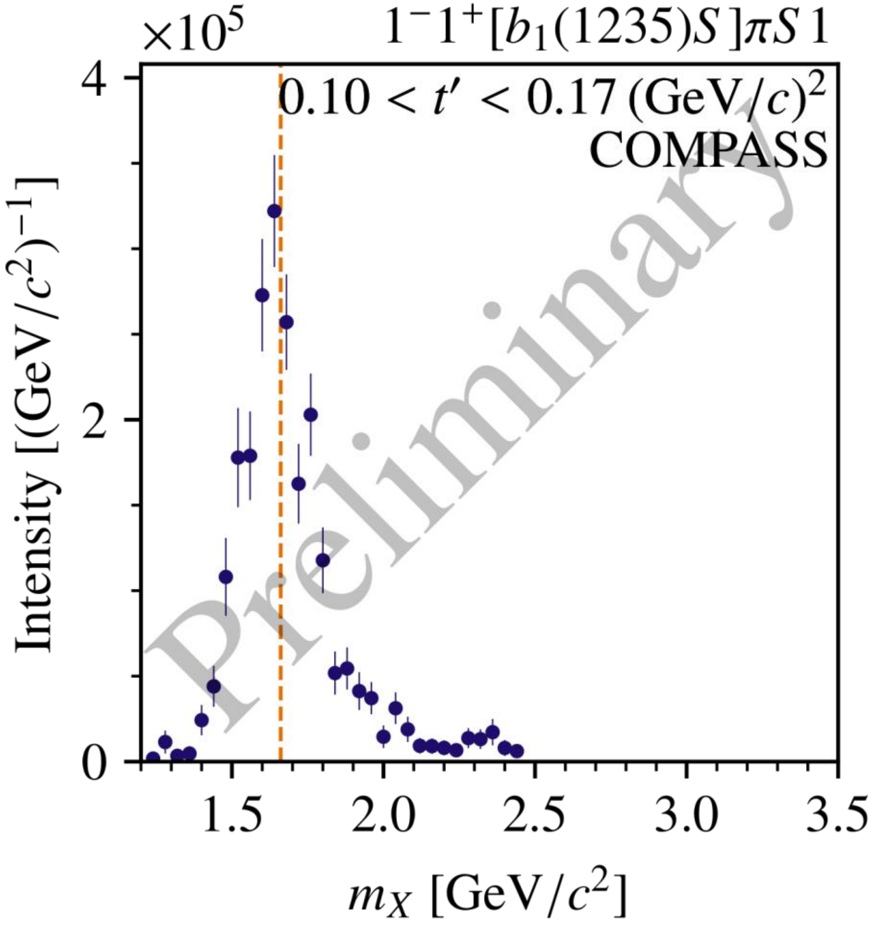
$m = 1661^{+15}_{-11}$ MeV
$\Gamma = 240 \pm 50$ MeV

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



b_1 S-wave decay



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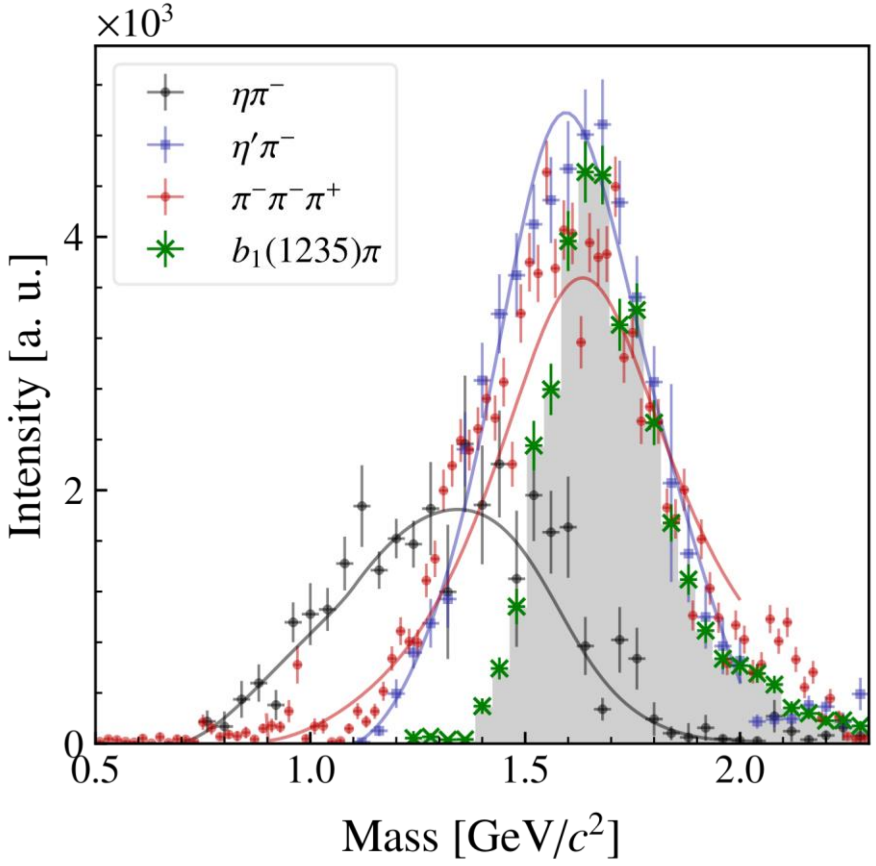

Listed in PDG

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

Flat Wave

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