Partial-Wave Analysis of the $\omega\pi\pi$ Final State at COMPASS

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for the COMPASS collaboration

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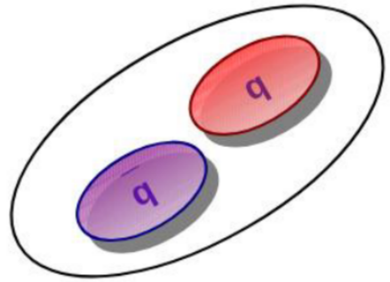
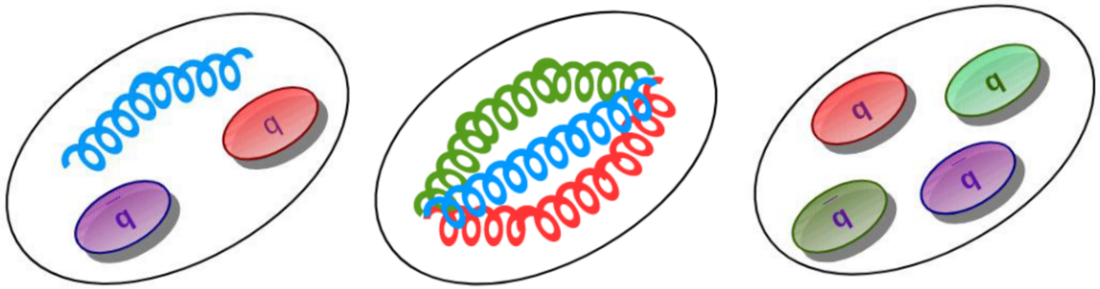
Motivation



- The Constituent Quark Model predicts mesons as $|q\bar{q}\rangle$ states
- QCD allows for more further meson configurations besides $|q\bar{q}\rangle$:
  - Hybrids $|q\bar{q}\mathrm{g}\rangle$, Glueballs $|\mathrm{gg}\rangle$, Multiquarks $|qq\overline{qq}\rangle$

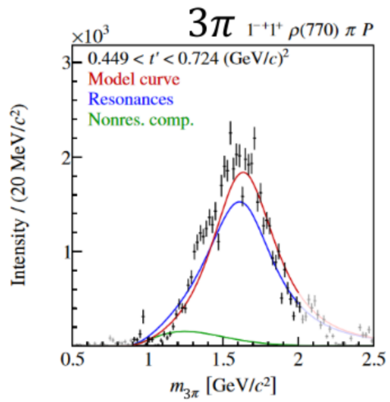


https://arxiv.org/pdf/1405.4195.pdf

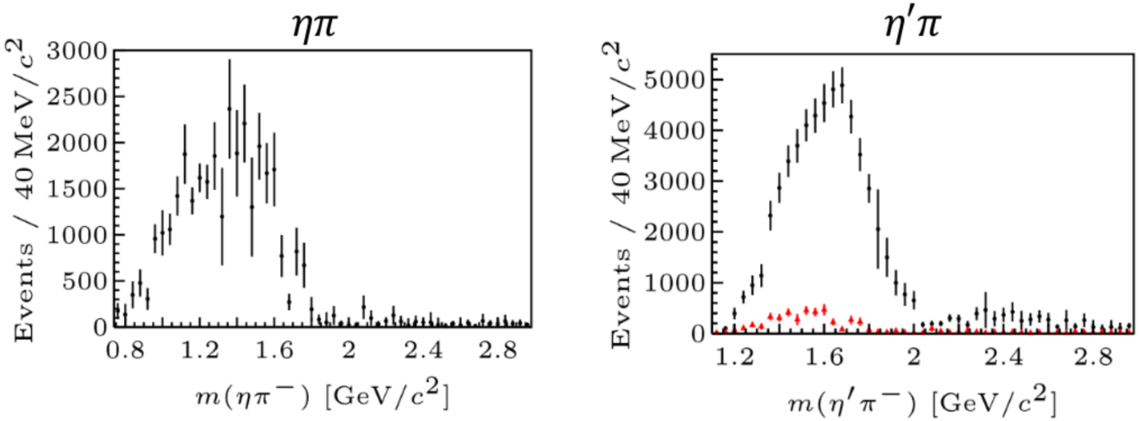
- Light unflavored $|q\bar{q}\rangle$ states cannot make up state with spin-quantum numbers $J^{PC} = 0^{--}, \mathrm{even}^{+-}, \mathrm{odd}^{-+}$
  - Direct access to find states beyond the Quark Model

Motivation

- $\pi_1(1600)$ was found in 3π, $\eta\pi$, and $\eta'\pi$ in COMPASS data



Phys. Rev. D 98 092003



Phys. Lett. B 740 (2015) 303–311

- Lattice QCD predicts
  - Lightest hybrid meson has $J^{PC} = 1^{-+}$ (π_1 state)
  - Dominant decay to $b_1(1235)\pi \rightarrow \omega\pi\pi$
- BNL E852 claimed two π_1 states in $\omega\pi^-\pi^0$: $\pi_1(1600)$ & $\pi_1(2015)$

Motivation

- $\pi_1(1600)$ was found in 3π, $\eta\pi$, and $\eta'\pi$ in COMPASS data

COMPASS has ~5x larger $\omega\pi^-\pi^0$ data set
$\Rightarrow$ Verify claims by BNL E852
$\Rightarrow$ Look for exited mesons not yet seen in $\omega\pi^-\pi^0$

$m_{3\pi}$ [GeV/c^2] $m(\eta\pi^-)$ [GeV/c^2] $m(\eta'\pi^-)$ [GeV/c^2]

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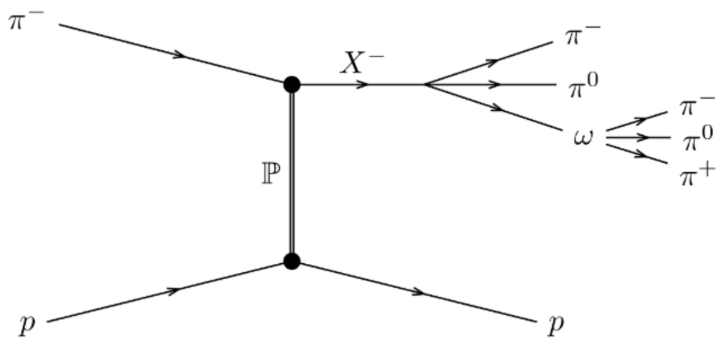
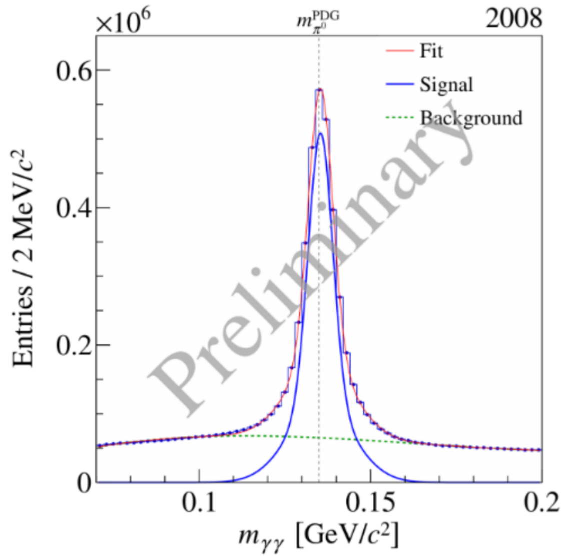
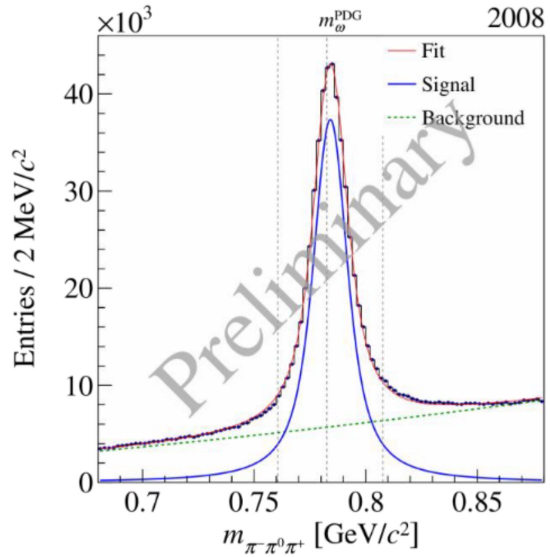
Diffractive Production of $\omega\pi^-\pi^0$ at COMPASS

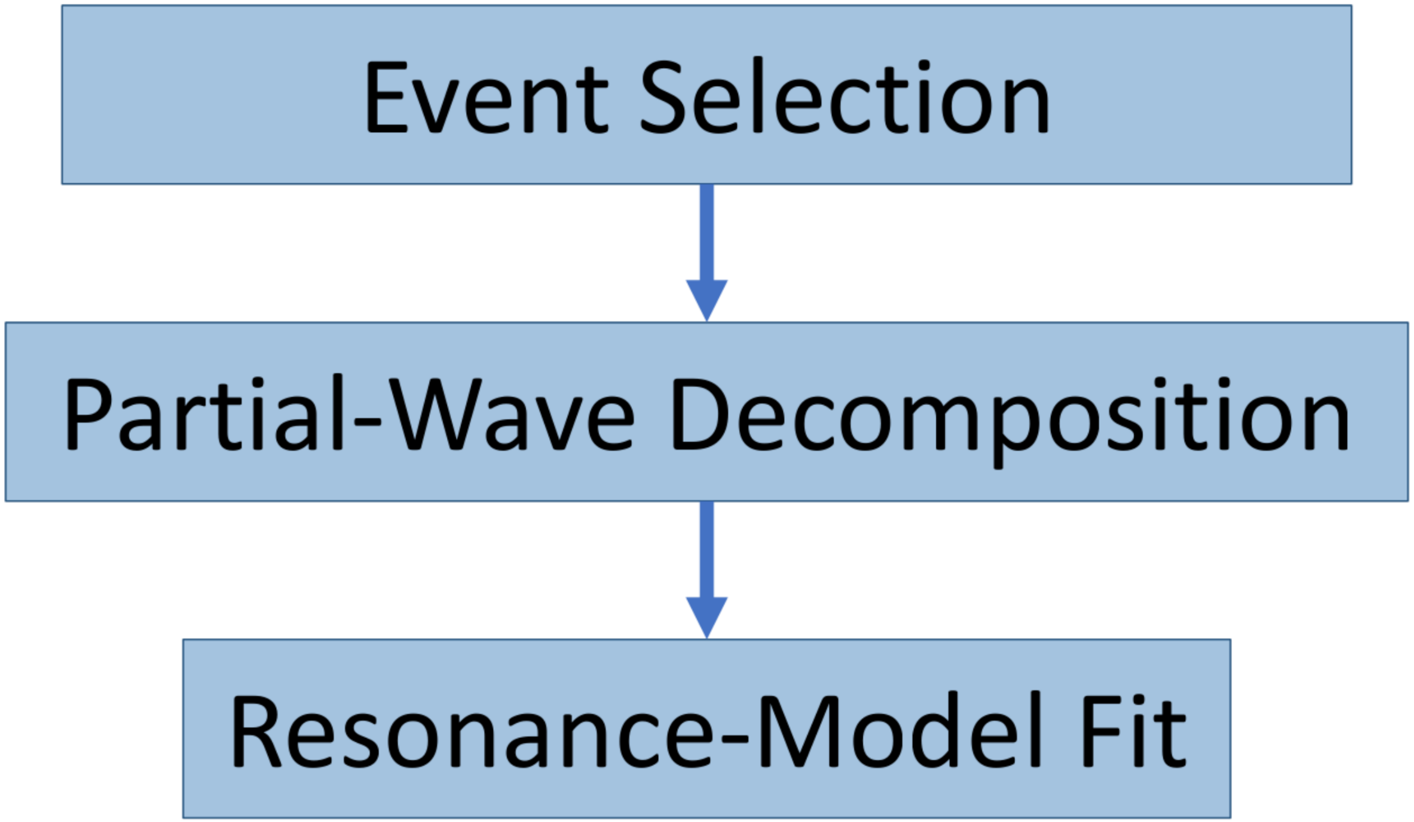






- Measured final state: $\pi^-\pi^-\pi^+4\gamma + p$
- 720,000 selected events

Partial-Wave Analysis: 2-Step Approach



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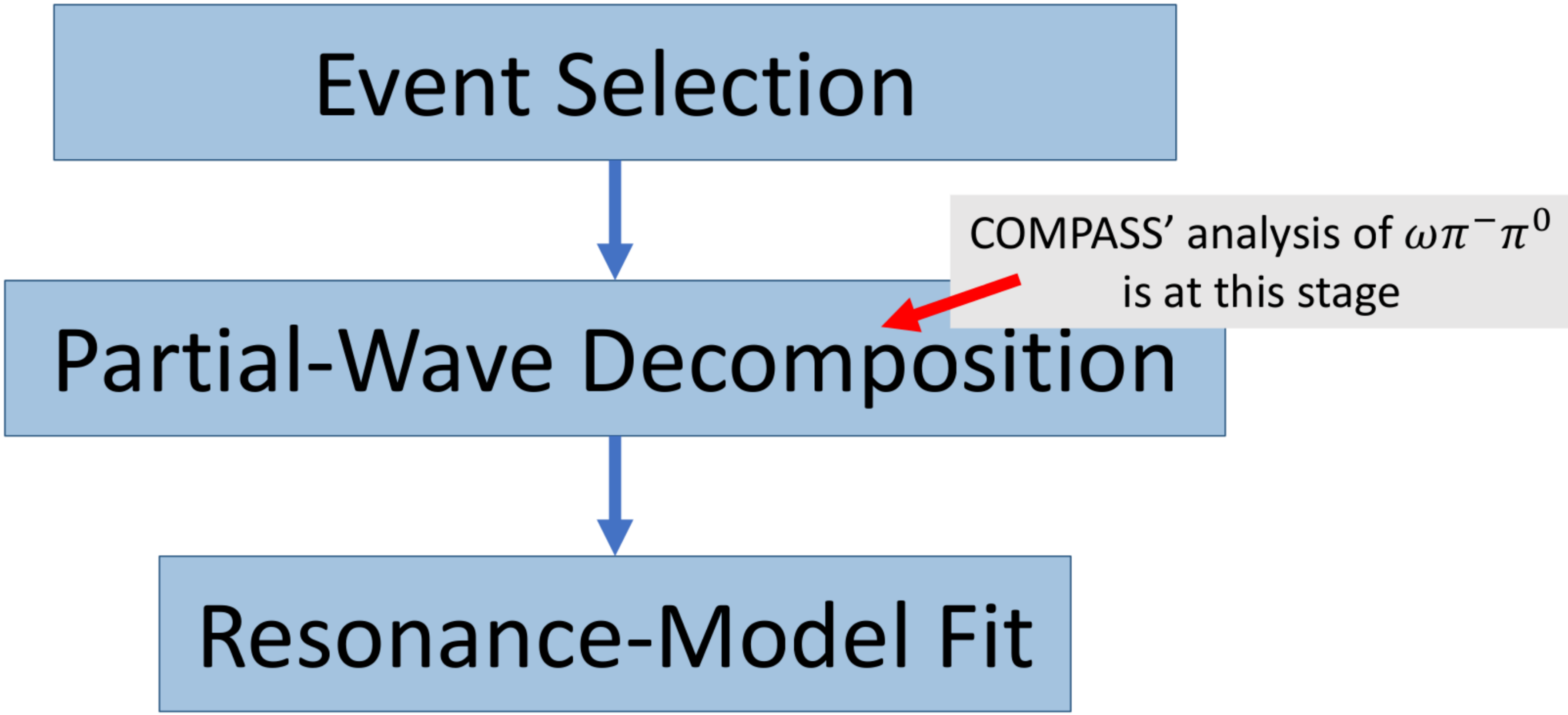
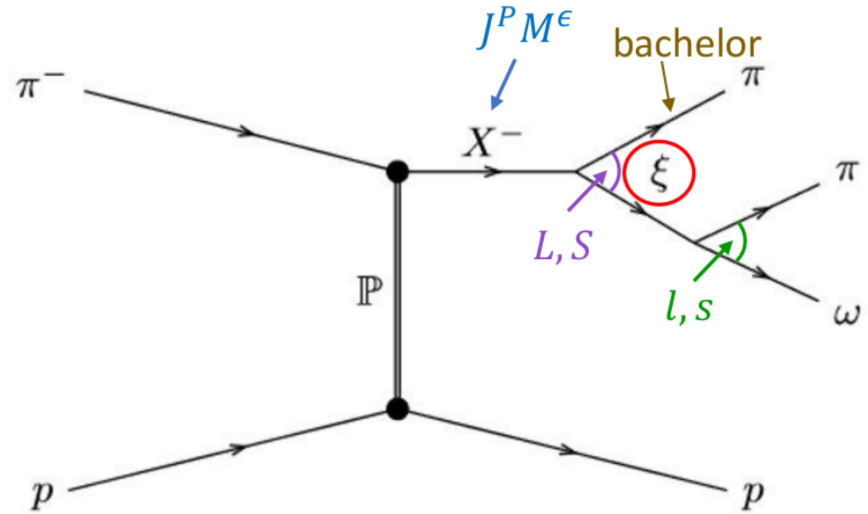


Partial-Wave Decomposition

- Exited meson X^- with quantum numbers $J^P M^\epsilon$ is produced
- Isobar model: X^- decays to $\pi\xi$/ $\omega\xi$, where ξ is an instable intermediate state
  - L, S coupling between bachelor and ξ
- ξ decays to $\omega\pi/\pi\pi$
  - second l, s coupling



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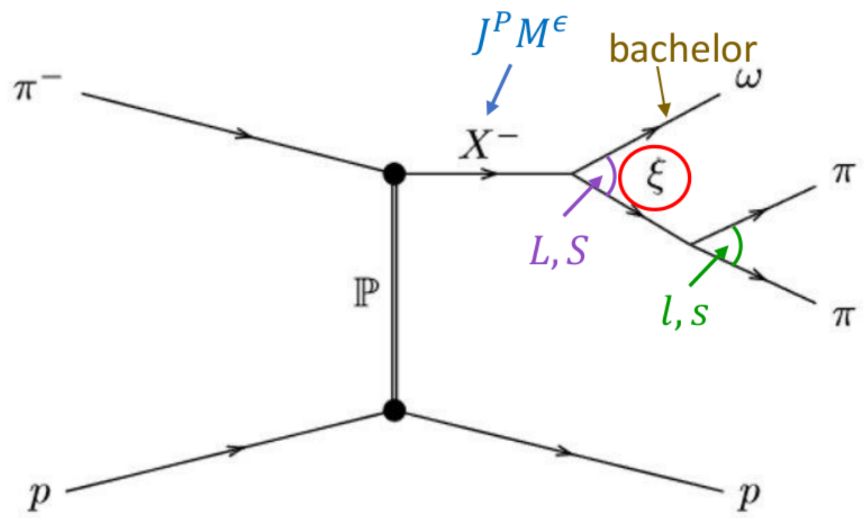


Partial-Wave Decomposition

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

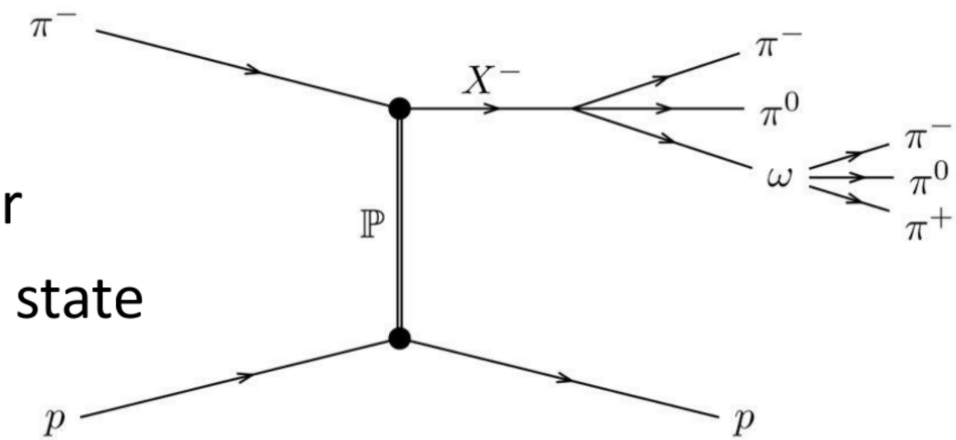
$$I(m_X, t', \tau) = \left| \sum_i \mathcal{T}_i(m_X, t')\psi_i(m_X, \tau) \right|^2$$

with:

m_X: total mass

t': squared four-momentum transfer

τ: phase-space variables of the final state



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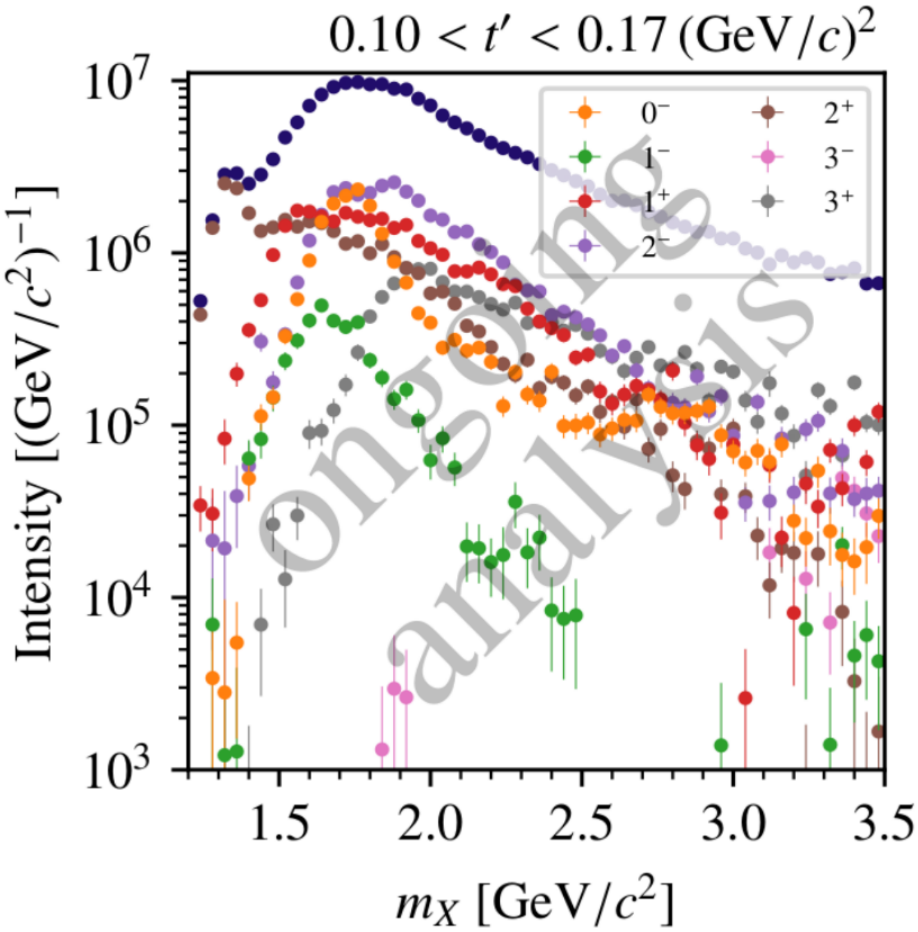
- Decay amplitude $\psi_i(m_X, \tau)$: calculated using the isobar model
- Transition amplitude $\mathcal{T}_i(m_X, t')$: coupling strength of wave i

  $\Rightarrow \mathcal{T}_i(m_X, t')$ describes all resonances in i

  $\Rightarrow$ Fitted in bins of (m_X, t')

Wave-Set

- In principle: Infinite number of partial-waves i
- Wave-set selected with model selection techniques
- Considered waves for this analysis:
  - $J \leq 7, M \leq 2, \epsilon = +$
  - $\xi \to \pi\pi$: $\rho(770)$, $\rho_3(1690)$
  - $\xi \to \omega\pi$: $b_1(1235)$, $\rho(1450)$, $\rho_3(1690)$



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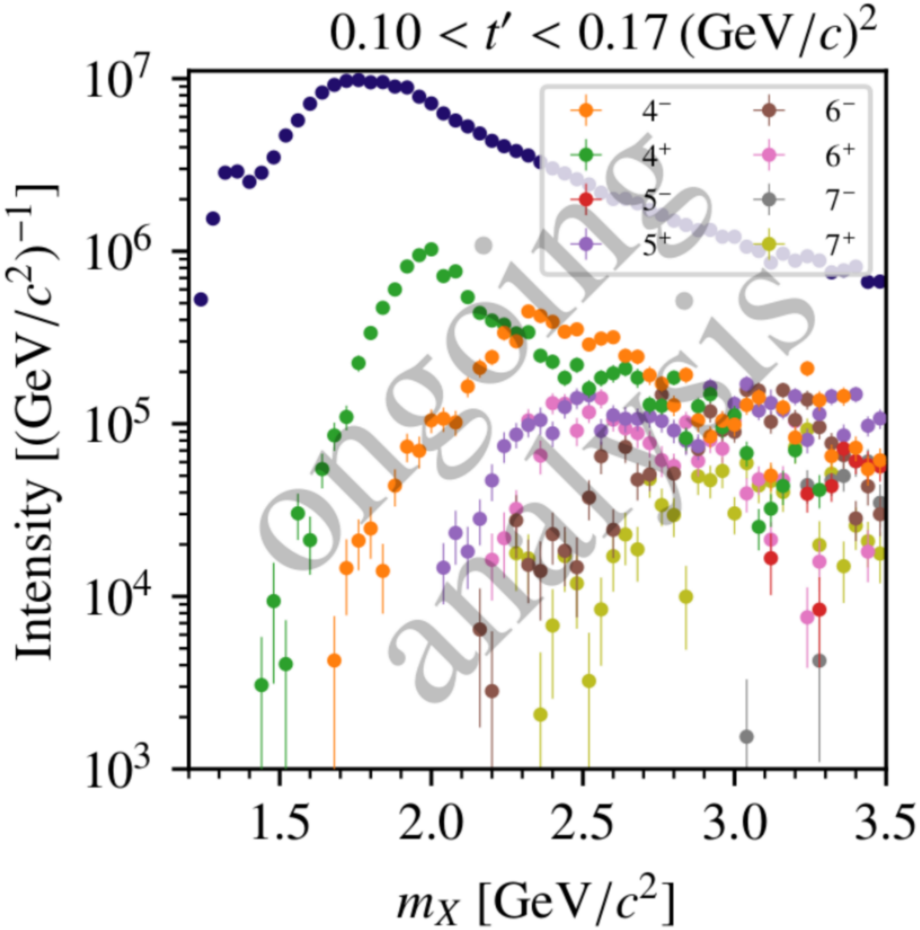
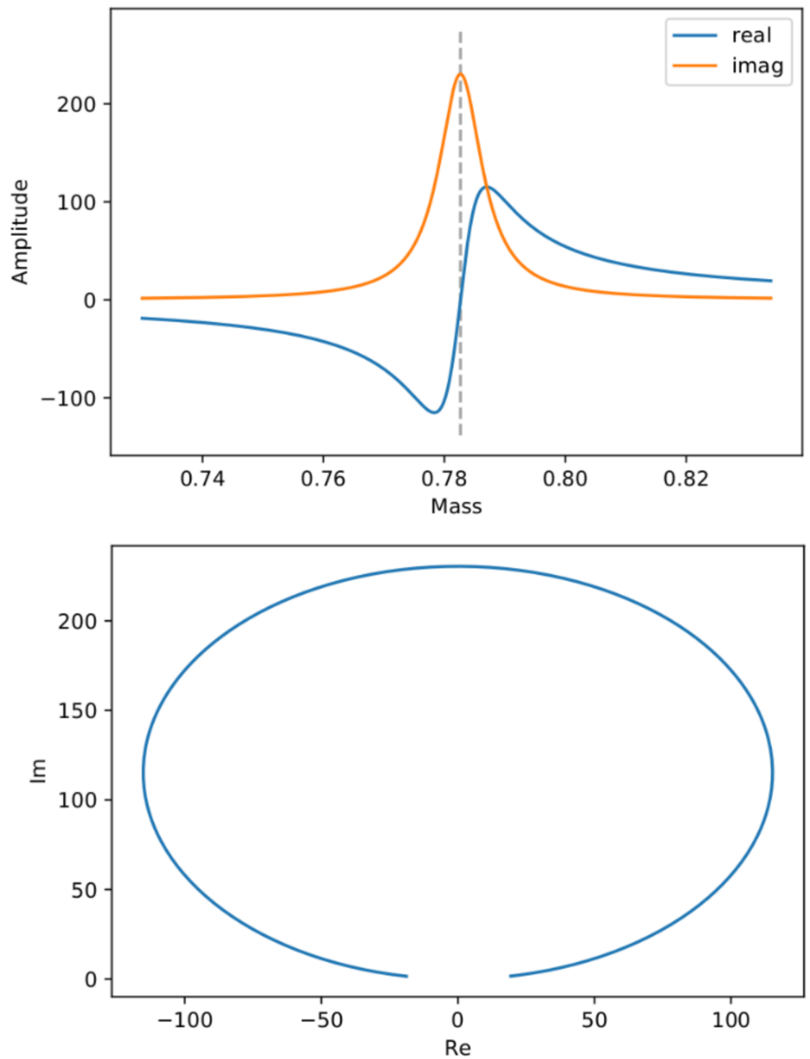
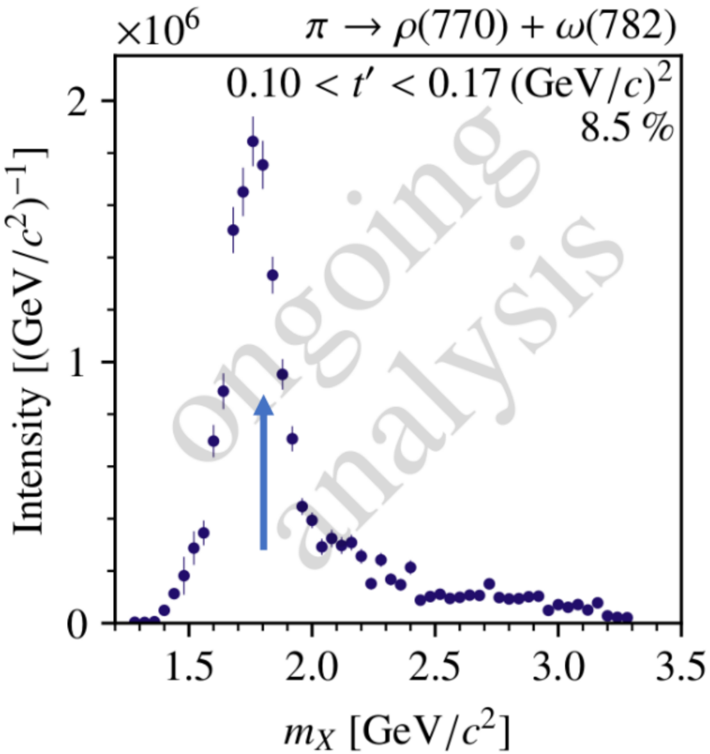


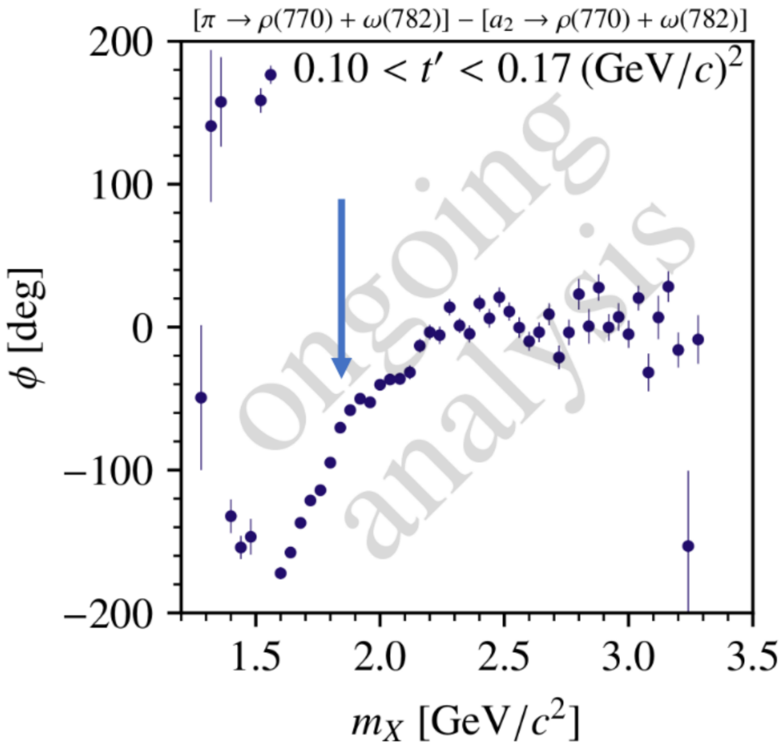
Results

- A state is a mass resonance in the partial-wave
- Easiest description: Breit-Wigner resonance
  - Peak in intensity
  - Phase motion of 180°
    - Only difference in phase $\Delta\phi$ between two waves is measurable



Results - π



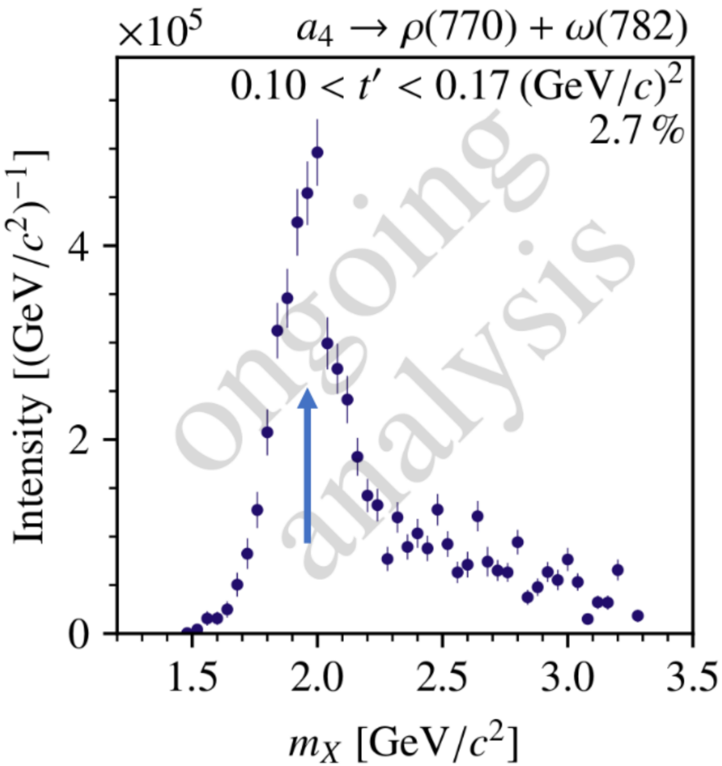


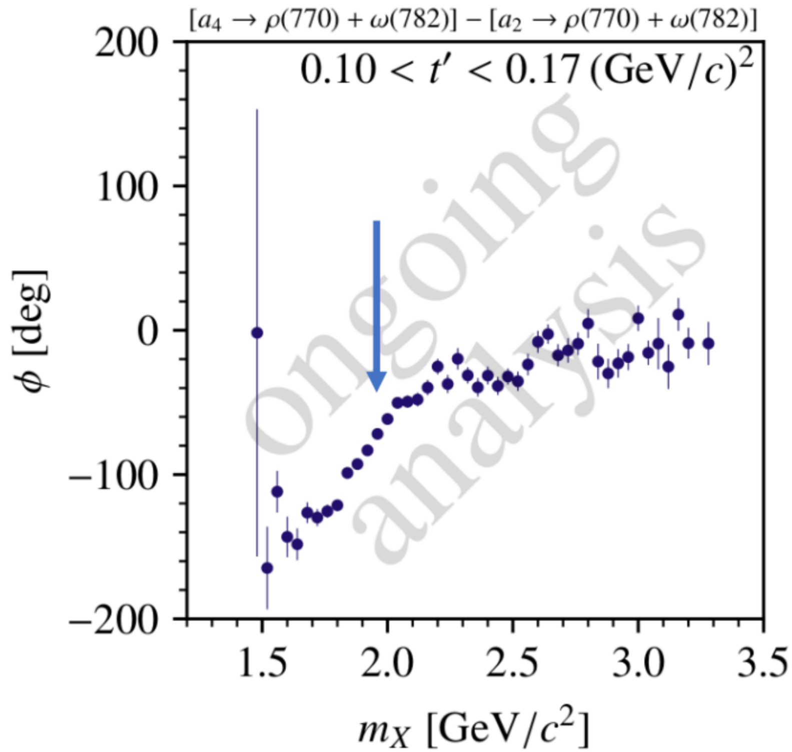
$\pi(1800)$

$m = 1810\,^{+9}_{-11}$ MeV

$\Gamma = 215^{+7}_{-8}$ MeV

Results - a_4





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

Conclusion

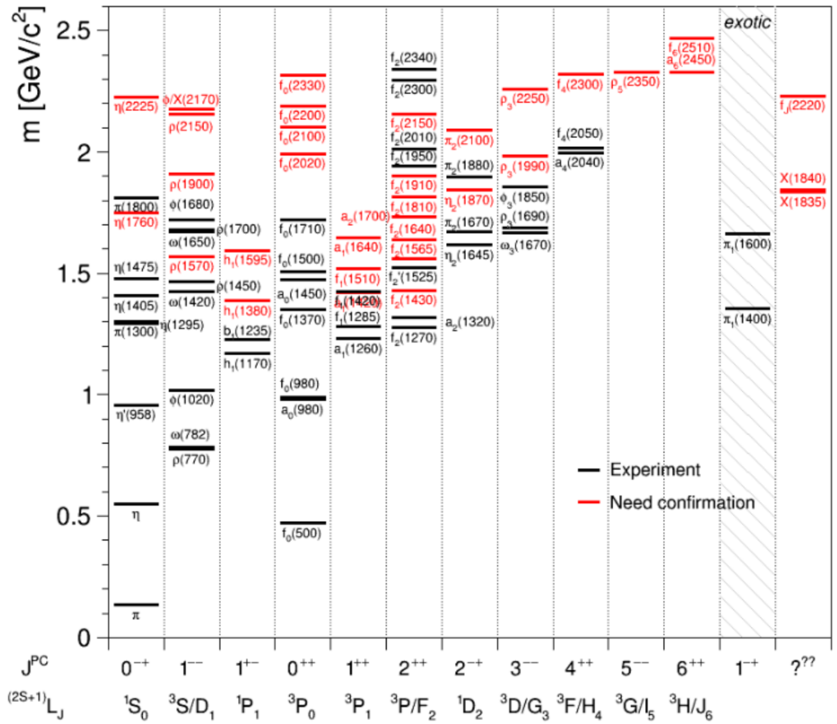
- Signal for known resonances visible
  - $\Rightarrow$ Partial-wave decomposition gives reasonable results for $\omega\pi^-\pi^0$

Outlook

- Further improvements of the partial-wave decomposition:
  - Extend the wave-set and improve selection
- Resonance-model fit is the next big step
  - Verification of BNL E852's claims of two π_1 states in $b_1(1235)\pi$
  - Search for mesons not yet seen in $\omega\pi^-\pi^0$
  - Extraction of resonance parameters

Backup Slides

Mesons in QCD

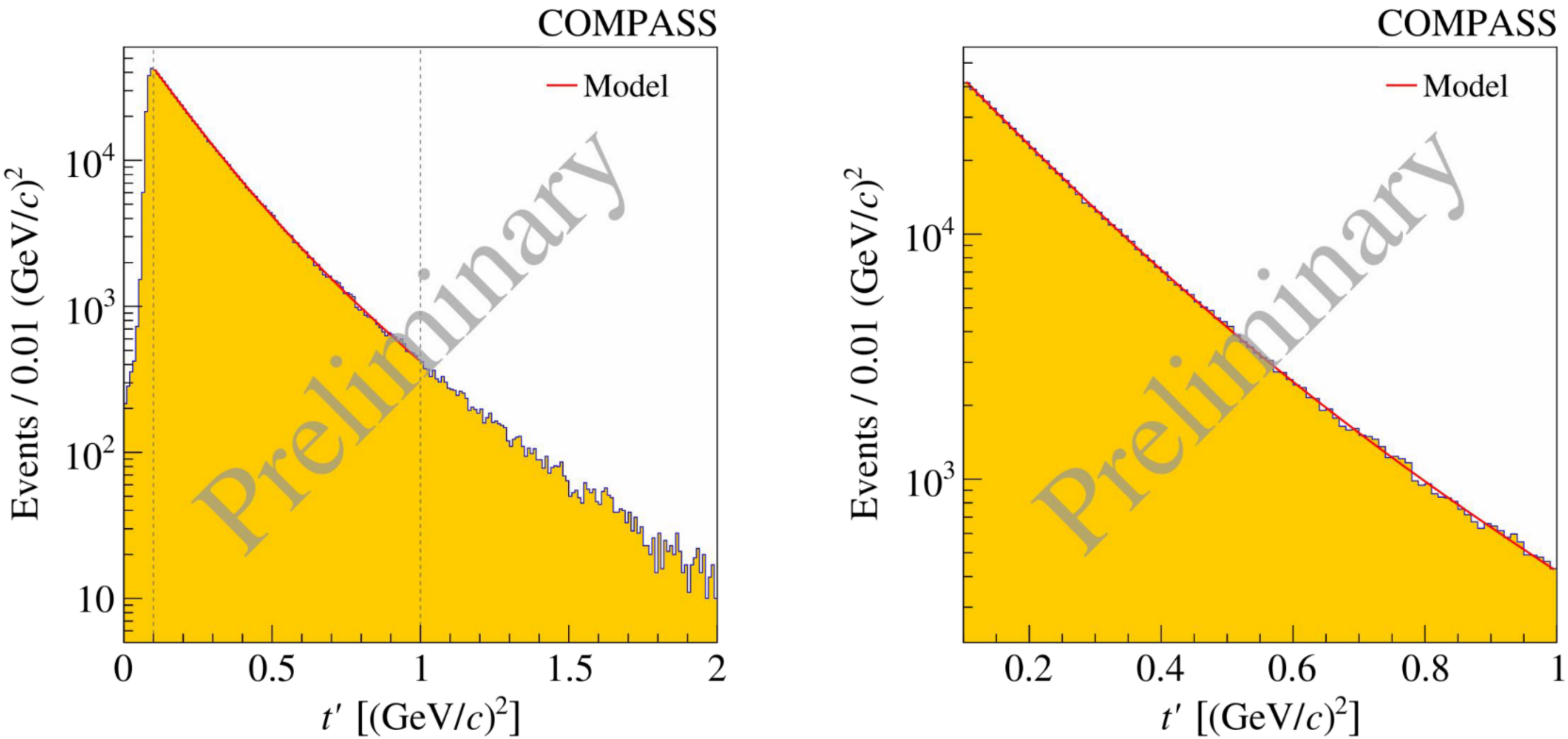


- Many short-lived, exited states with similar masses

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

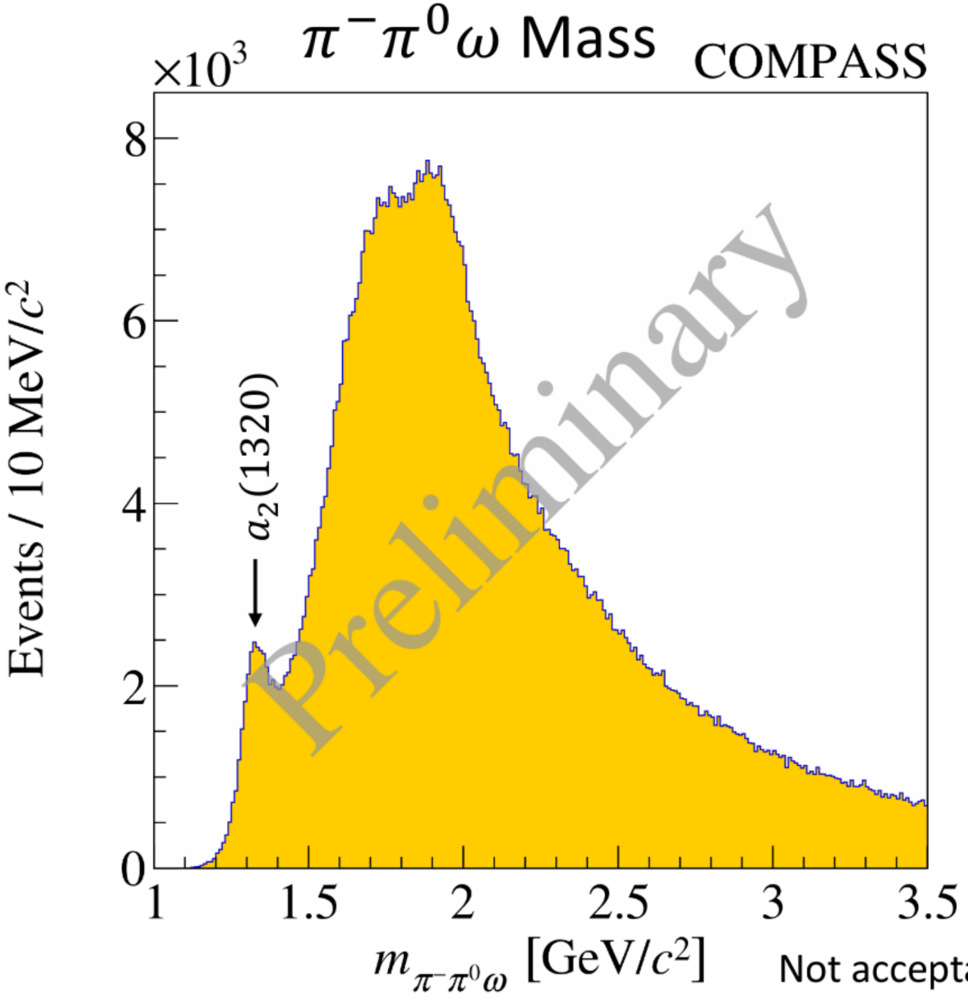
$\Rightarrow$PWA necessary to determine contributions of certain X

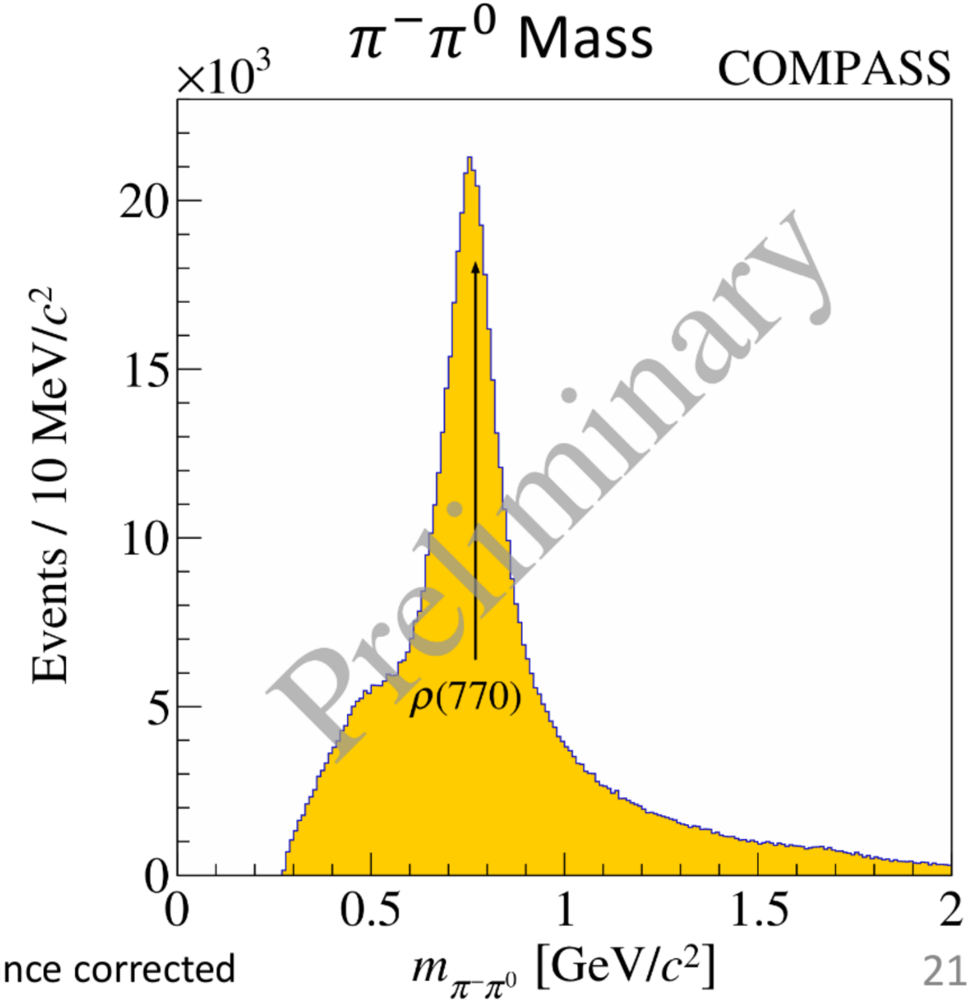
t’ Distribution



3. Kinematic Distributions

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





Not acceptance corrected

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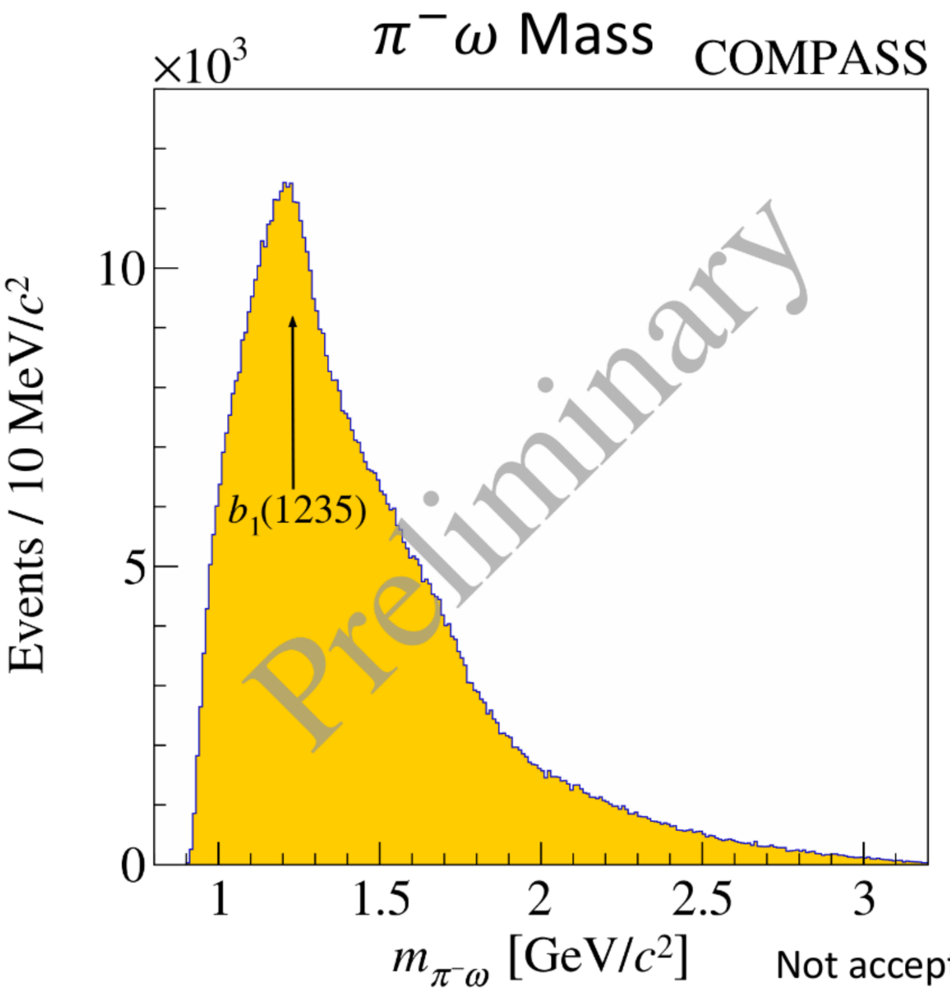

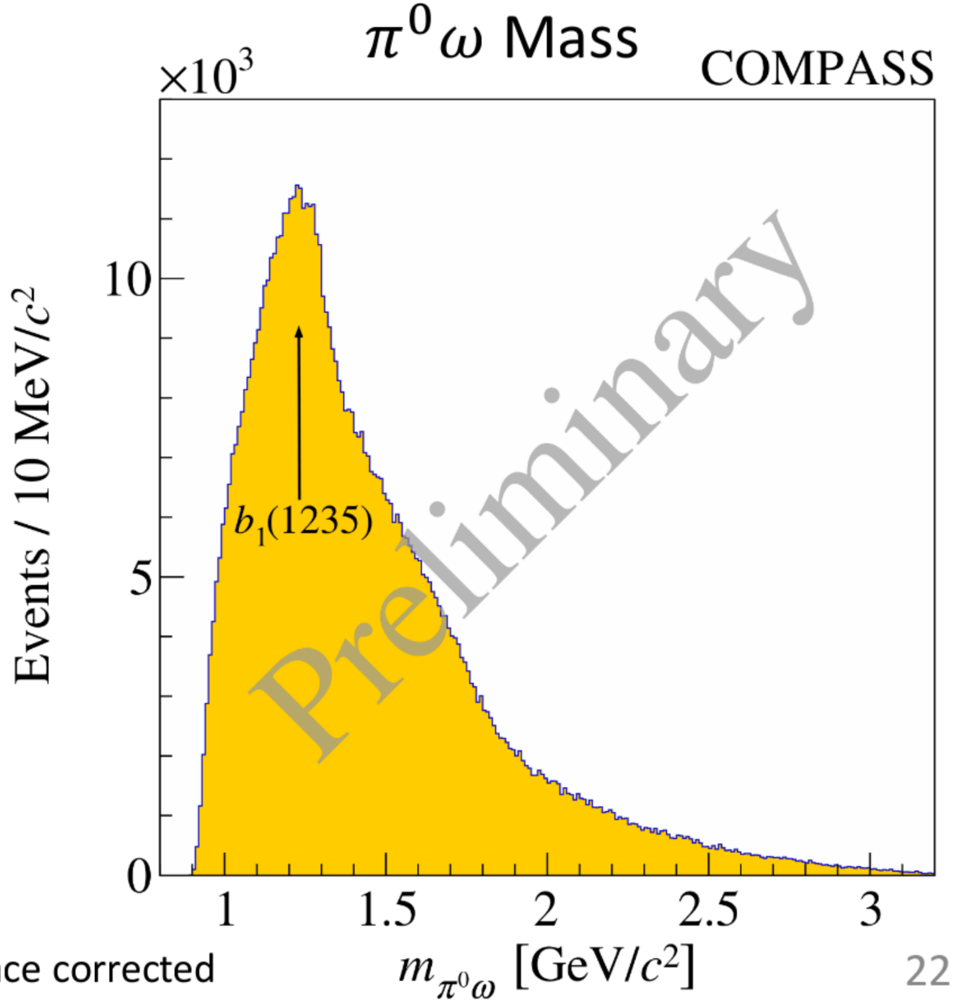

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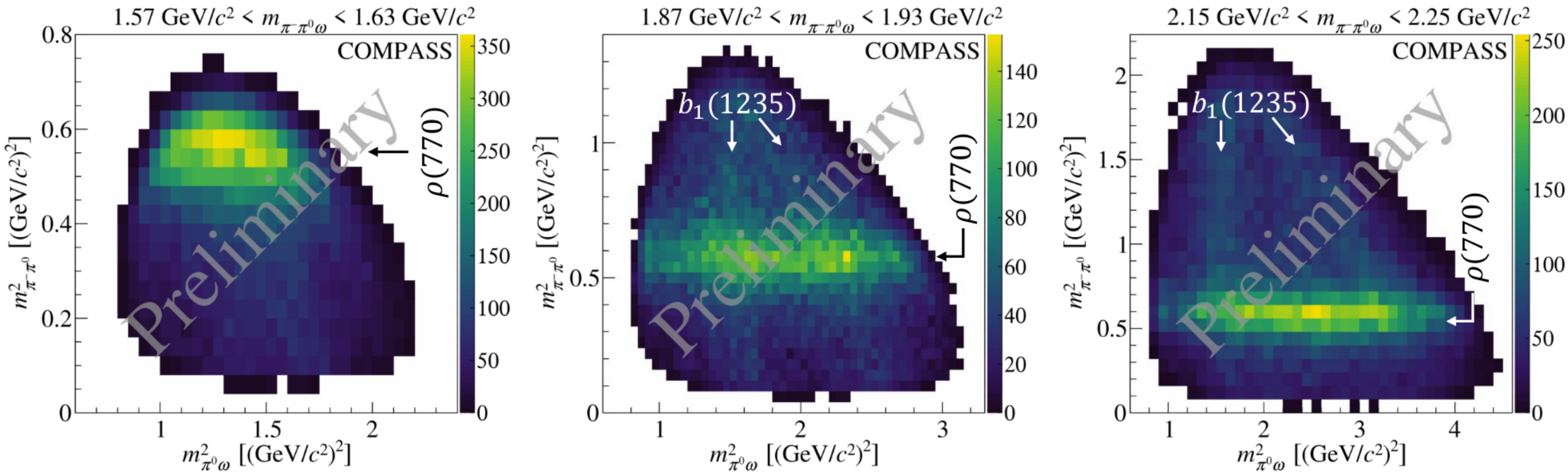
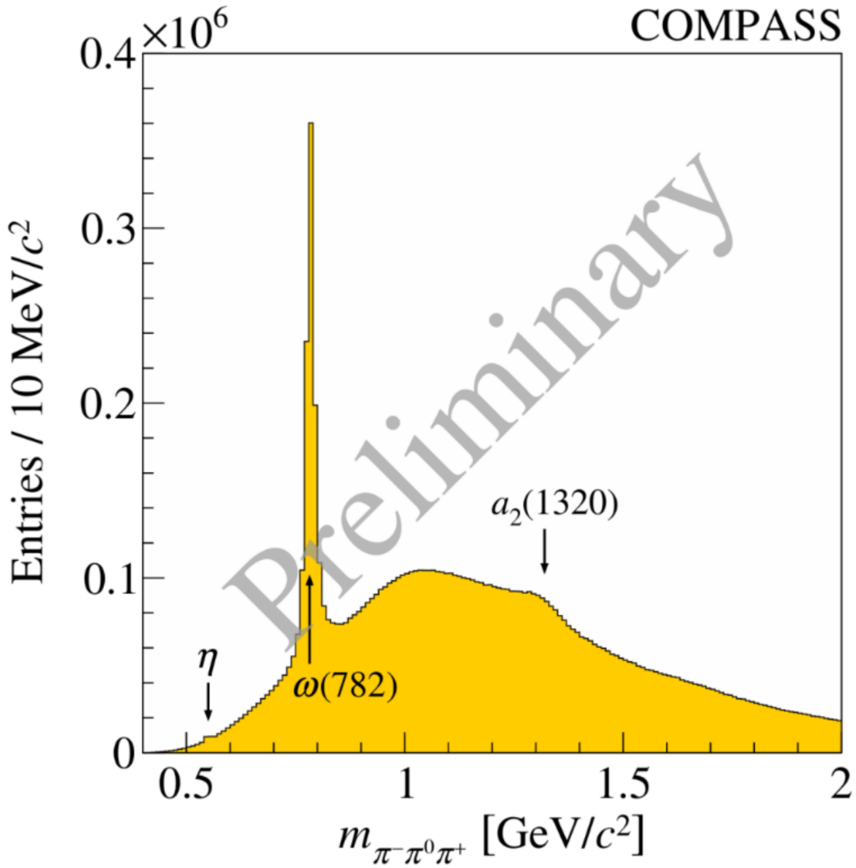
Dalitz Plots



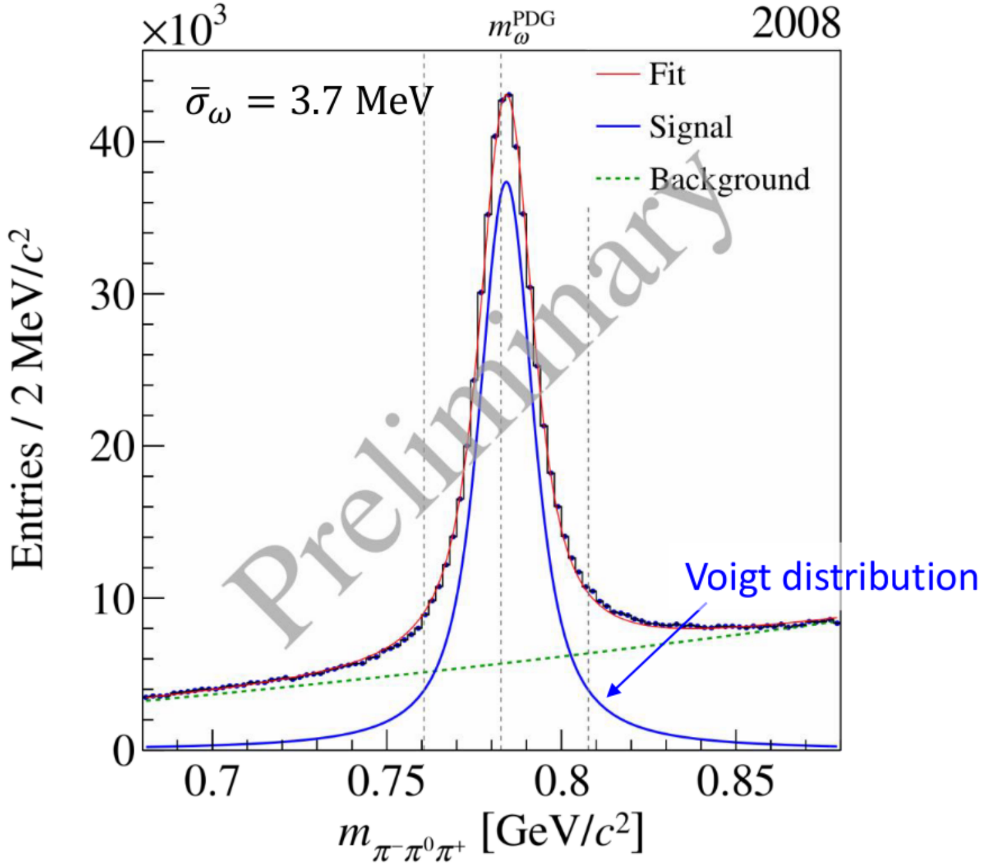
$\omega(782)$ Selection

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



$\omega(782)$ Selection

- 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

$$\mathcal{T}_i(m_X, t')\psi_i(m_X, \tau)$$

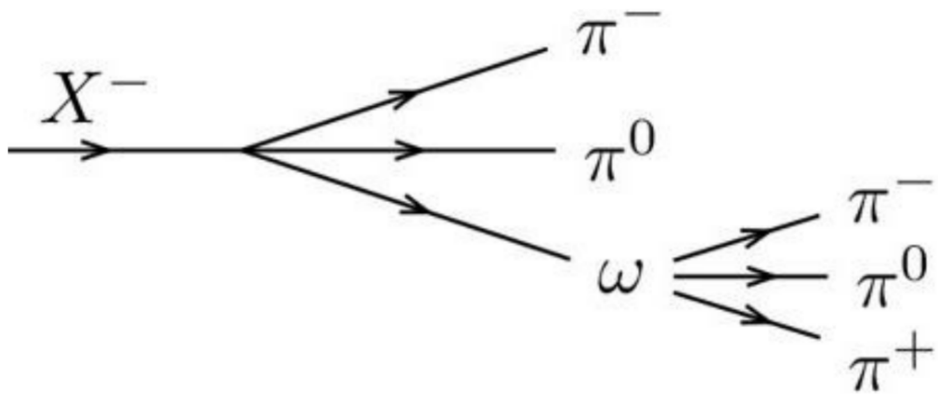
- Decay amplitude $\psi_i(m_X, \tau)$: calculated using the isobar model
- Transition amplitude $\mathcal{T}_i(m_X, t')$: coupling strength of wave i
  - $\Rightarrow \mathcal{T}_i(m_X, t')$ describes all resonances in i
- Fitting $\mathcal{T}_i$ as arbitrary function is not computationally feasible
  - $\Rightarrow$ Approximate $\mathcal{T}_i$ by fitting step-wise constant functions in bins of (m_X, t')
    - 4 bins in t' x 57 bins in m_X = 228 bins
  - $\Rightarrow$ Benefit: independent fit in each bin

Modification of PWD for ω Decay

- Factorisation of the decay amplitude

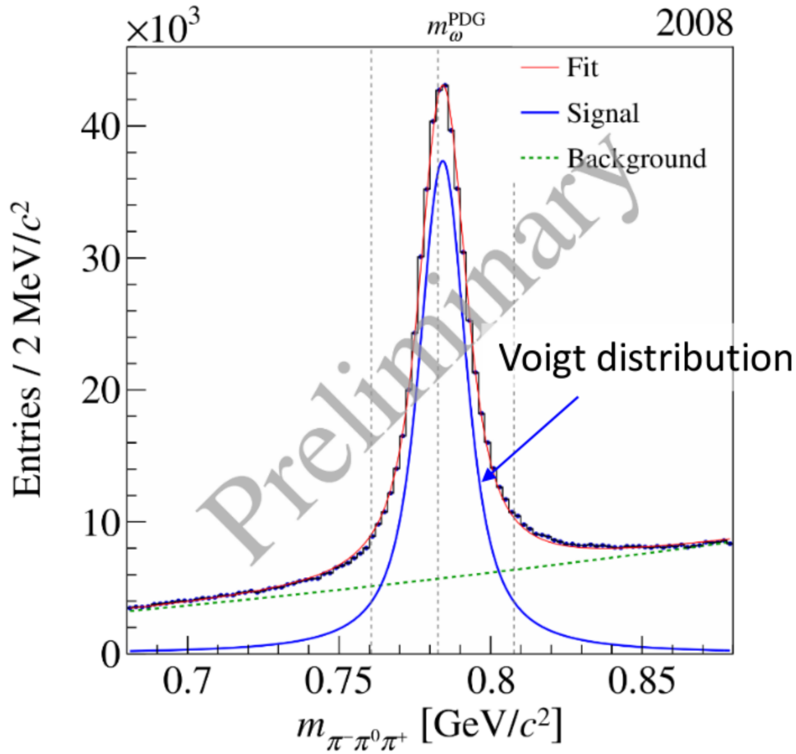
$$\psi_i = \Sigma_{\lambda_\omega} \psi_{i,X\to\omega\pi\pi}^{\lambda_\omega} \psi_{\omega\to 3\pi}^{\lambda_\omega}$$

- $\psi_{i,X\to\omega\pi\pi}^{\lambda_\omega}$ 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



Modification of PWD for ω Decay

- 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



Wave Selection

- Method used for 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:
  - $J \leq 7, M \leq 2, \epsilon = +$
  - $\xi \to \pi\pi$: $\rho(770)$, $\rho_3(1690)$
  - $\xi \to \omega\pi$: $b_1(1235)$, $\rho(1450)$, $\rho_3(1690)$
  - $L \leq 7, S \leq 2$ except for $\rho_3(1690) \to \omega\pi$ $(S = 3)$
  - 434 waves + flat wave

Notation:

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