Meson spectroscopy at VES and COMPASS

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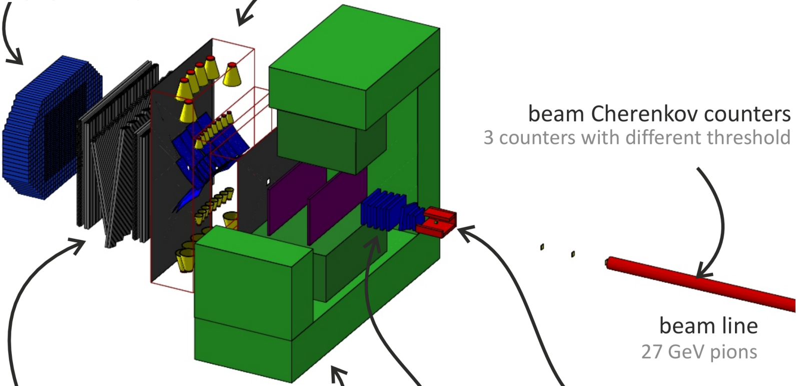
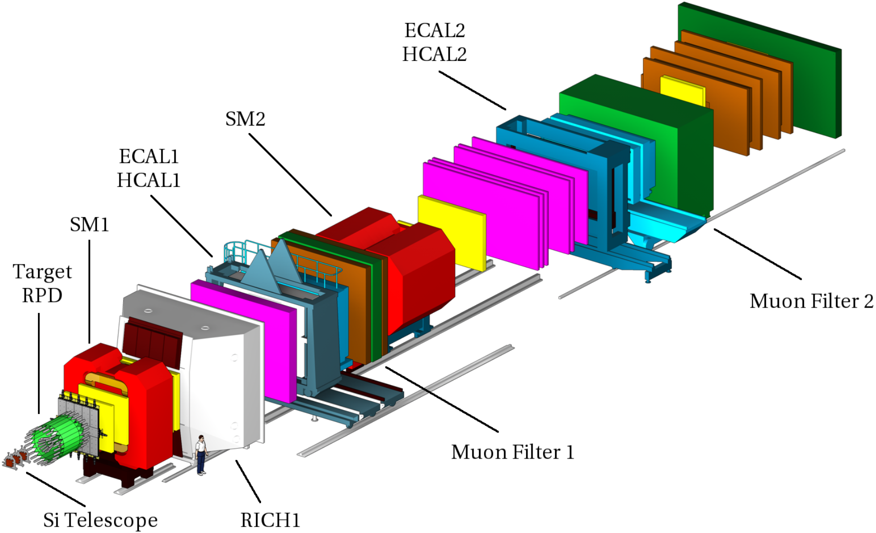
OUTLINE

- Two flagship reactions for VES and COMPASS experiments:
  $\pi^- N \to \pi^-\pi^-\pi^+ N$ and $\pi^- N \to \pi^-\pi^0\pi^0 N$
- Methods of the analysis:
  - The mass-independent PWA with established isobars
  - Isospin relations between $\pi^-\pi^-\pi^+$ and $\pi^-\pi^0\pi^0$ amplitudes
  - Two parametrizations of PWA density matrix: rank=1 and unlimited rank with extracting the Largest-Eigenvalue-Eigenvector (LEV)
  - Resonance-model fits
  - Analysis with free parametrization of $\pi\pi$-isobars
- Results of the analysis:
  - Mass-independent PWA for VES with established shapes of $\pi\pi$-isobars, comparison of isospin relations between $\pi^-\pi^-\pi^+$ and $\pi^-\pi^0\pi^0$ (VES and COMPASS)
  - Selected results for resonance model fits (COMPASS)
  - Comparison of PWA with rank=1 and unlimited rank with extracting the Largest-Eigenvalue-Eigenvector (VES)
  - Selected results for analysis with free parametrization of $\pi\pi$-isobars (COMPASS)

The VES detector



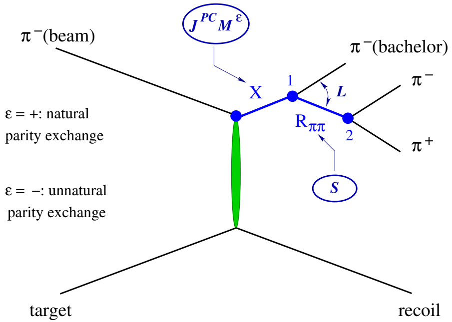
The COMPASS detector



The measurement conditions, the statistics of 3π states

- VES
  - $p_{beam} = 29$ GeV$/c$
  - Nucleus Be target, no detection of the recoil particle
  - Momentum transferred squared $0 < t' < 1$ GeV$^2/c^2$
  - $\pi^- Be \to \pi^-\pi^-\pi^+ Be$ $87x10^6$ events
  - $\pi^- Be \to \pi^-\pi^0\pi^0 Be$ $32x10^6$ events
- COMPASS
  - $p_{beam} = 190$ GeV$/c$
  - LiH target, Recoil Proton Detector
  - Momentum transferred squared $0.1 < t' < 1$ GeV$^2/c^2$
  - $\pi^- p \to \pi^-\pi^-\pi^+ p$ $46x10^6$ events
  - $\pi^- p \to \pi^-\pi^0\pi^0 p$ $3.5x10^6$ events

π^--beam dissociation on nucleon or nucleus target



- Reggeon exchange, naturality $\eta = P_R(-1)^{J}{}_R$
- Gottfried-Jackson frame: SCM of X: $Z_{GJ} \| \vec{p}^{\,*}_{beam}$, $Y_{GJ} = [\vec{p}^{\,*}_{recoil} \times \vec{p}^{\,*}_{beam}]$
- Reflectivity basis for system of mesons:
  $|JM^{\varepsilon}> = |JM> - \varepsilon P(-1)^{J-M}|J-M>$
- At high beam energies: reflectivity ε equal to naturality η
- unpolarised target: $\varepsilon = \pm 1$ states do not interfere

Mass-independent PWA events density:

$$\mathcal{I}(m,t',\tau) = \sum_{\varepsilon=\pm 1} \sum_{r=1}^{N_r} \left| \sum_i T^{\varepsilon}_{i,r}(m,t') \psi^{\varepsilon}_i(m,\tau) \right|^2 + FLAT$$

The decay amplitudes $\psi^{\varepsilon}_i(\tau)$ are enumerated by their quantum numbers $i, \varepsilon = J^{PC} M^{\varepsilon}\ [isobar]\ \pi\ L$ and have no free parameters
Transition amplitudes $T^{\varepsilon}_{ir}(m,t')$ fitted independently in each $(m,\ t')$ - bin
Events density expressed through spin-density matrix:

$$\mathcal{I}(m,t',\tau) = \sum_{\varepsilon=\pm 1} \sum_{i,j} \rho^{\varepsilon}_{i,j}(m,t') \psi^{\varepsilon}_i(m,\tau) \psi^{\varepsilon *}_j(m,\tau), \quad \rho^{\varepsilon}_{i,j} = \sum_{r=1}^{N_r} T^{\varepsilon}_{i,r} {T^{\varepsilon}_{j,r}}^*$$

For COMPASS data $N_r = 1$ is chosen, for VES - two models are tried: $N_r = 1$ and unlimited rank and extracting Eigenvector with Largest Eigenvalue

Isospin relations between $\pi^-\pi^-\pi^+$ and $\pi^-\pi^0\pi^0$

Decay amplitudes for I=1 of 2π isobar (i.e. $\rho\pi$) in case of $I(3\pi)=1$ are connected:

$$\sqrt{\tfrac{1}{2}}\left(\tfrac{1}{\sqrt{2}}[(\pi^-_{(1)}\pi^+)\pi^-_{(2)} + (\pi^-_{(2)}\pi^+)\pi^-_{(1)}]\right) \leftrightarrow -\sqrt{\tfrac{1}{2}}\left(\tfrac{1}{\sqrt{2}}[(\pi^-\pi^0_{(1)})\pi^0_{(2)} + (\pi^-\pi^0_{(2)})\pi^0_{(1)}]\right)$$

Same dalitz-plot structure $\rightarrow$ N($\pi^-\pi^0\pi^0$):N($\pi^-\pi^-\pi^+$)=1:1

Decay amplitudes for I=0 of 2π isobar (i.e. $f_0\pi$ or $f_2\pi$) channels are always connected :

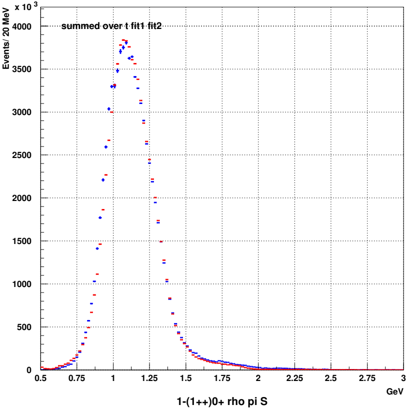
$$\sqrt{\tfrac{2}{3}}\left(\tfrac{1}{\sqrt{2}}[(\pi^-_{(1)}\pi^+)\pi^-_{(2)} + (\pi^-_{(2)}\pi^+)\pi^-_{(1)}]\right) \leftrightarrow -\sqrt{\tfrac{1}{3}}\left((\pi^0_{(1)}\pi^0_{(2)})\pi^-\right)$$

Different Dalitz-plot structure.
Narrow isobar and $m(3\pi) >> m_{isob} + m_\pi$ $\rightarrow$ N($\pi^-\pi^0\pi^0$):N($\pi^-\pi^-\pi^+$)=0.5:1
Case of broad, overlapping isobars for $\pi^-\pi^-\pi^+$ - ratio can be siginficantly larger or smaller than 0.5

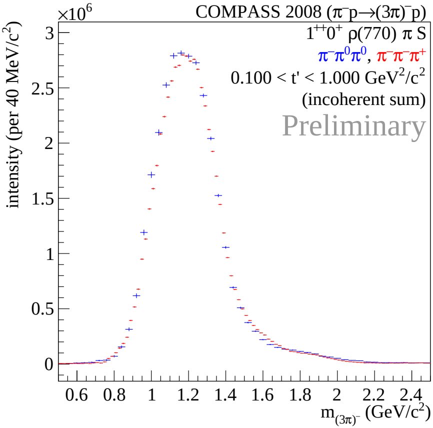
All corresponding relative phases in $\pi^-\pi^0\pi^0$ and $\pi^-\pi^-\pi^+$ are equal - in case of appropriate choosing of directions of "spin analyzers" - π^-- direction in 2π center-of-mass for both systems

$J^{PC}M^{\varepsilon} = 1^{++}0^{+}\rho(770)\pi S$-intensity

VES

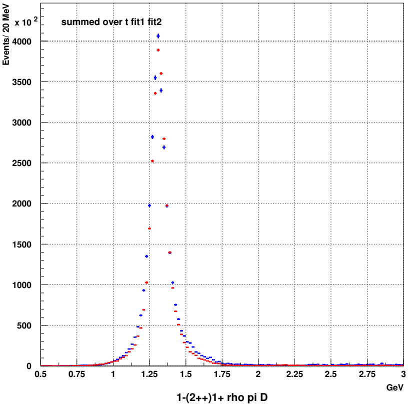


COMPASS

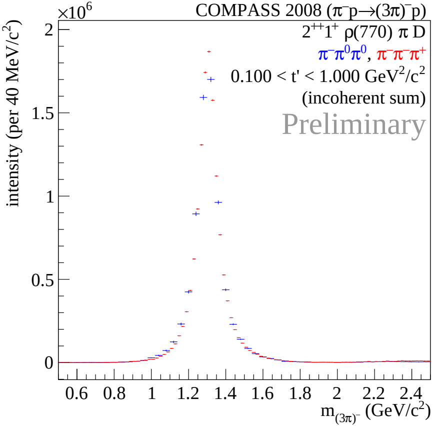


$J^{PC}M^{\varepsilon} = 2^{++}1^{+}\rho(770)\pi D$-intensity

VES

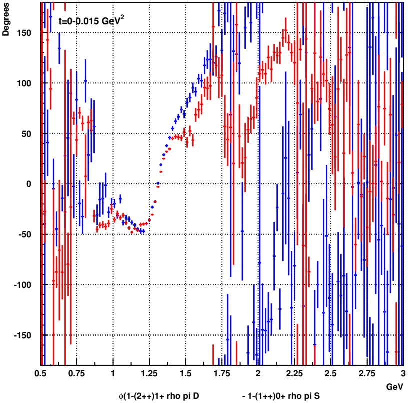


COMPASS

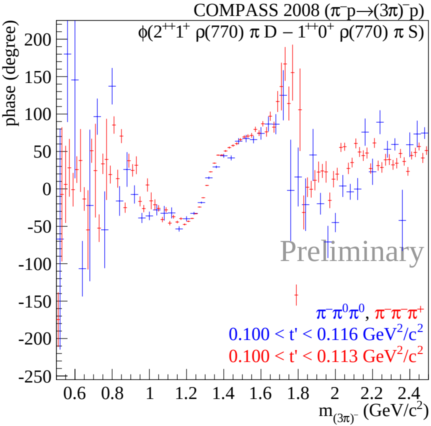


$J^{PC}M^{\varepsilon} = 2^{++}1^{+}\rho(770)\pi D$-phase relative to $1^{++}0^{+}\rho\pi S$

VES



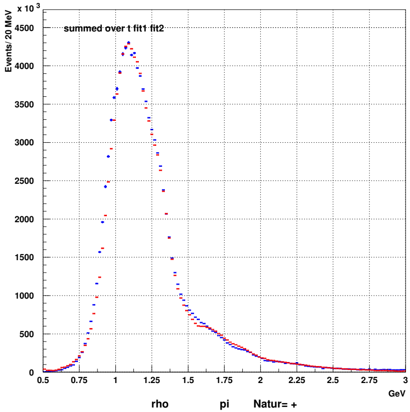
COMPASS



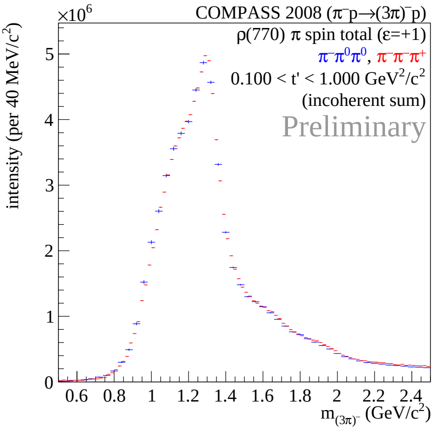
The relative phases between waves containing 3π-resonances do not depend on beam energy and t'

The total intensity of $\rho(770)\pi$ with $\varepsilon = +1$

VES



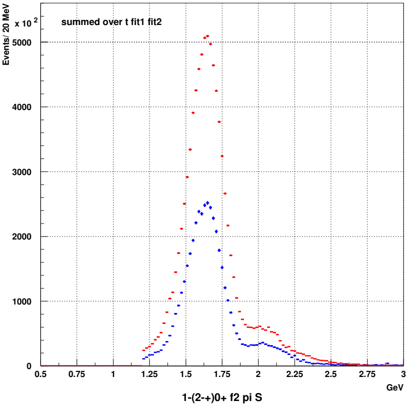
COMPASS



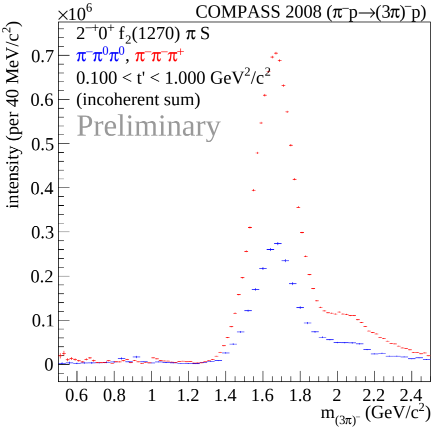
The $\varepsilon = +1$ dominates over $\varepsilon = -1$ (latest also do not show isospin relations)

$J^{PC}M^{\varepsilon} = 2^{-+}0^{+} f_2(1270)\pi S$-intensity

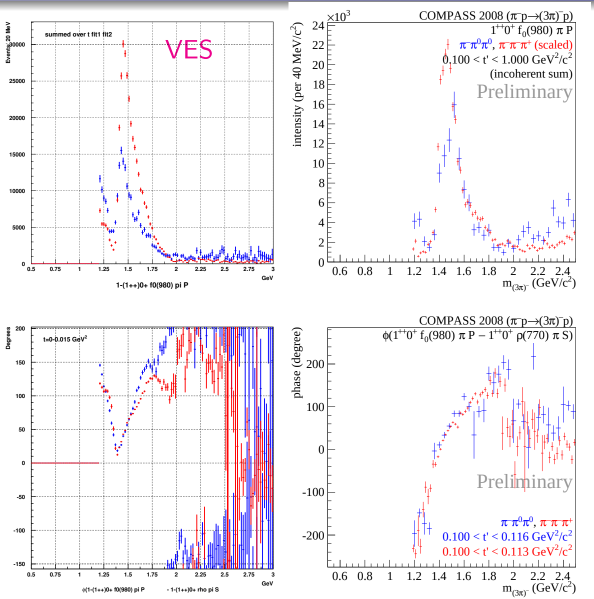
VES



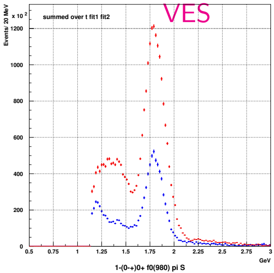
COMPASS

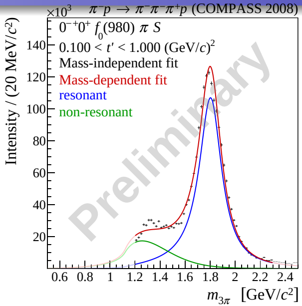


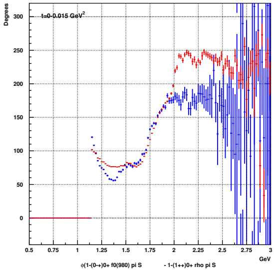
$J^{PC}M^{\varepsilon} = 1^{++}0^{+} f_0(980)\pi P$-intensity, phase

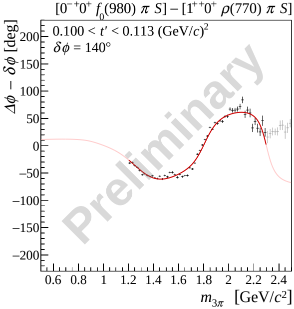


$J^{PC}M^{\varepsilon} = 0^{-+}0^{+} f_0(980)\pi S$-intensity, phase



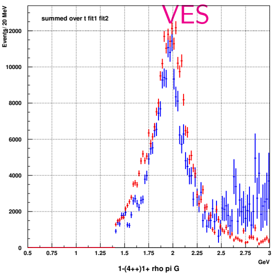


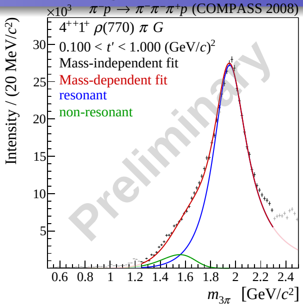


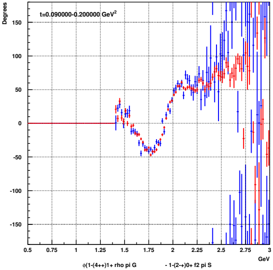


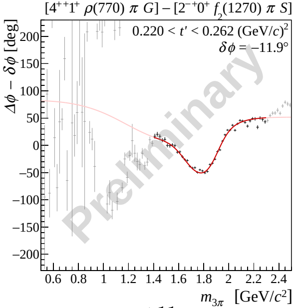
Clear $\pi(1800)$ signal, no $\pi(1300)$-signal

$J^{PC}M^{\varepsilon} = 4^{++}1^{+}\rho(770)\pi G$-intensity, phase









$M = 1980 \pm 10,\ \Gamma = 300 \pm 40$ MeV$/c^2$

$M = 1935^{+11}_{-13},\ \Gamma = 0.333^{+10}_{-21}$ MeV $/c^2$

Unlimited rank density matrix approach

Coherent part of the density matrix R is the largest part of the matrix which has rank 1 and behaves like vector of amplitudes. Let

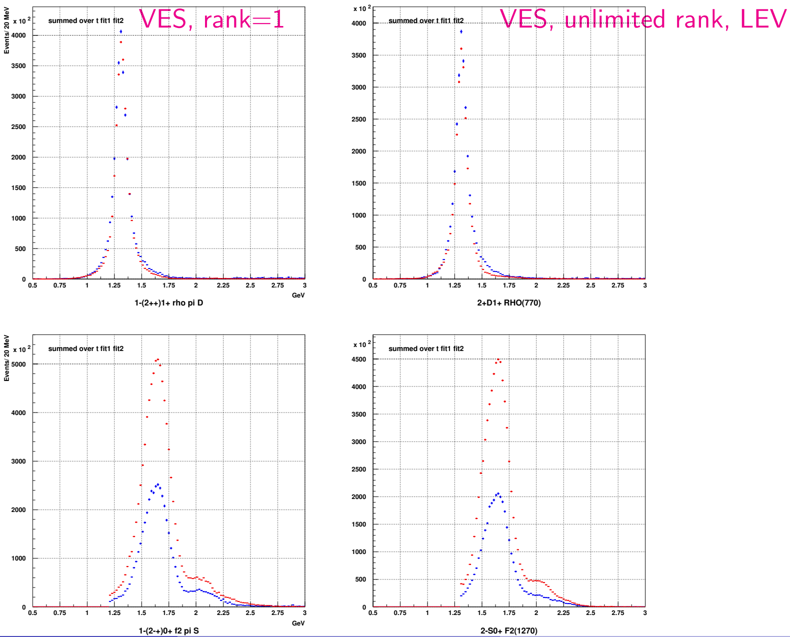
$$R = \sum_{k=1}^{d} e_k * V_k * V_k^+ \quad \text{where} \quad \begin{cases} e_k \text{ is k-}th\text{ eigenvalue} \\ V_k \text{ is k-}th\text{ eigenvector} \end{cases}$$

Let $e_1 \gg e_2 > \ldots > e_d > 0$. Leading term R_L is coherent part of density matrix and R_S is the rest (incoherent part). This decomposition is stable w.r.t. variations of R matrix elements.

$$R = R_L + R_S, \quad R_L = e_1 * V_1 * V_1^+, \quad R_S = \sum_{k=2}^{d} e_k * V_k * V_k^+$$

Experience shows that resonances tend to concentrate in R_L.

VES: rank=1 (left) and unlimited rank, LEV (right)



PWA with fixed shapes of isobars vs. freed isobares

Decay amplitude with established isobars:

The decay amplitude $\psi_i^\varepsilon(\tau)$ contains angular part and $\pi^-\pi^+$ isobar Breit-Wigner function and is bose-symmetrized by swapping $(1) \leftrightarrow (3)$ in $\pi^-_{(1)}\pi^+_{(2)}\pi^-_{(3)}$ system:

$$\psi_i^\varepsilon(\tau) = A_i^\varepsilon(\Omega_{12}, \Omega_1^*) BW_{j(i)}(m_{12}) + A_i^\varepsilon(\Omega_{32}, \Omega_3^*) BW_{j(i)}(m_{32})$$

Decay amplitudes with freed isobars:

The fixed amplitude of $\pi^-\pi^+$ isobar is replaced by sum of step-like functions with complex coefficients: $BW(m)_j \to \sum_\beta \omega_{j,\beta} \Pi_\beta(m)$

In that case $[isobar] \to (\pi\pi)_s$ and wave notation is $J^{PC} M^\varepsilon\ (\pi\pi)_s\ \pi\ L$

The full free-isobarred amplitude for $J^{PC} M^\varepsilon$ sector:

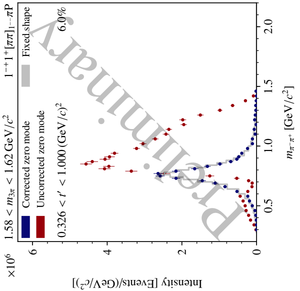
$$F_{J^P M^\varepsilon}(\tau) = \sum_k \sum_\beta \omega_{k,\beta} \left[A^\varepsilon_{J^P M^\varepsilon,k}(\Omega_{12}, \Omega_1^*) \Pi_\beta(m_{12}) + A^\varepsilon_{J^P M^\varepsilon,k}(\Omega_{32}, \Omega_3^*) \Pi_\beta(m_{32}) \right]$$
$$= \sum_k \sum_\beta \omega_{k,\beta} \hat{\Psi}_{J^P M^\varepsilon,k,\beta}(\tau)$$

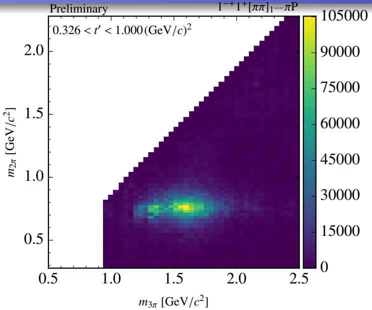
where k sums over different L, s for fixed $J^P M^\varepsilon$

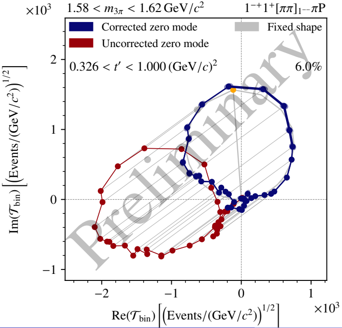
We found linear dependences inside the set of free-isobaric decay amplitudes $\hat{\Psi}_{J^P M^\varepsilon,k,\beta}(\tau)$, called zero modes.

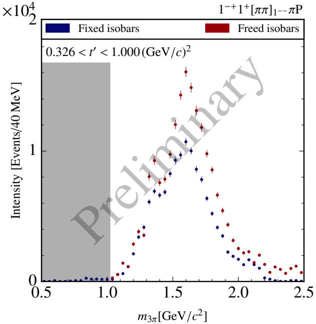
For two amplitudes: $0^{-+}(\pi\pi)_S \pi S$ and $0^{-+}(\pi\pi)_P \pi P$ - one real-valued function of zero mode found. For one amplitude: $1^{-+}(\pi\pi)_P \pi P$ - one zero mode.

$J^{PC} = 1^{-+}(\pi\pi)_P\pi$ - free shape of $\rho(770)$ COMPASS









CONCLUSIONS, OUTLOOK

- Analysis of 3π states in VES and COMPASS shows the dominance of diffractive production mechanism for both beam energies and different t'-ranges:
  - The positive reflectivity dominates for both beam energies
  - The isospin relations between $\pi^-\pi^-\pi^+$ and $\pi^-\pi^0\pi^0$ demonstrate 1:1 and for $f\pi$ have 0.5:1
  - Relative phases match for corresponding pairs of waves in $\pi^-\pi^-\pi^+$ and $\pi^-\pi^0\pi^0$
  - The relative phases between resonant 3π waves do not depend on beam energy and on t'
- VES has compatible statistics of $\pi^-\pi^-\pi^+$ and $\pi^-\pi^0\pi^0$ and enhanced production of $J^{PC}M^{\varepsilon} = 1^{++}0^+$ states:
  - perspective study of $a_1(1420)$-phenomenon in both 3π-final states
  - perspective to perform "free-isobarred" analysis in both 3π-final states
- COMPASS analysis with freed isobars was first time performed for $J^{PC}M^{\varepsilon} = 1^{-+}1^+(\pi\pi)_P\pi\ P$:
  - The continuous ambiguities were resolved by applying Breit-Wigner model for $(\pi\pi)_P$ freed amplitude
  - The obtained $(\pi\pi)_P$ model-independent amplitude is well described by $\rho(770)$ Breit-Wigner