Exotic meson candidates in COMPASS

MESON 2023 in Kraków, Poland

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23rd June 2023

Light Mesons: $m < 3\,\mathrm{GeV}/c^2$

Constituent-Quark Model

- $|q\bar{q}'\rangle$ system with $q = u, d, s$
- Quantum numbers $J^{P(C)}$

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Constituent-Quark Model

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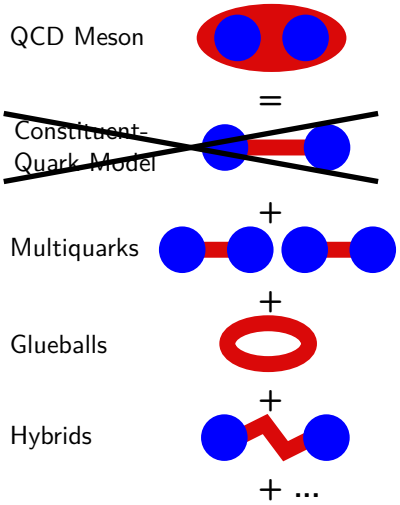
- Quantum numbers $J^{P(C)}$

In unflavoured sector: Spin-exotics

- Not possible in Constituent-Quark Model: $J^{PC} = 0^{--}, (odd)^{-+}, (even)^{+-}$
- Access to exotic states that do not overlap with ordinary mesons

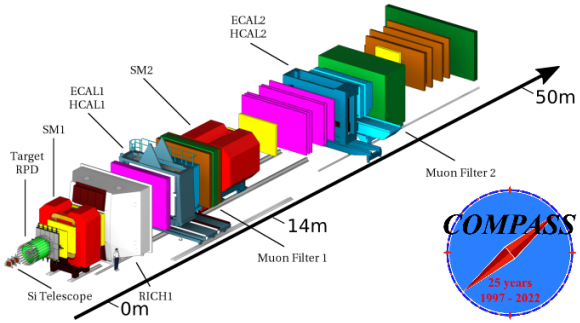
Hybrids

- Excited gluonic flied contributes to J^{PC}
- Predictions from theory: lightest hybrids have $J^{PC} = (0, \mathbf{1}, 2)^{-(+)}, 1^{-(-)}$

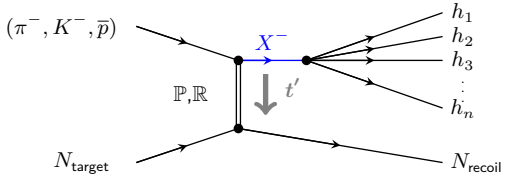


- **CO**mmon **M**uon **P**roton **A**pparatus for **S**tructure and **S**pectroscopy
- Data taken for two decades 2002-2022
- Located at the M2 beam line in the north area of CERN
- Part of the Hadron program: Light-Meson Spectroscopy

Setup for Hadron beams



Diffractive Resonance Production



- Beam hadrons at $190\,\text{GeV}/c$
  $\rightarrow$ mainly Pomeron exchange

Partial-Wave Analysis

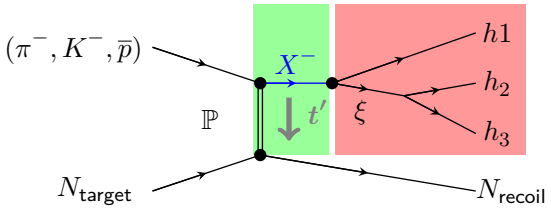
- Analysis in two steps:
  1. Partial-Wave Decomposition: Amplitudes of contributing waves are determined
  2. Resonance-Model Fit: Extraction of resonance parameters (m_0, Γ_0) and couplings

Partial-Wave Decomposition

- Data arranged into bins of (m_X, t')

$$\mathcal{I}(\tau_i) = \left| \sum_a^{N_{\text{waves}}} \mathcal{T}_a \, \Psi_a(\tau_i) \right|^2$$

- Decay Amplitudes Ψ_i are calculated from data using isobar model
- Production amplitudes $\mathcal{T}_i$ are determined in extended Likelihood fit



(Diffractive Resonance Production and subsequent two-body decays)

Partial-Wave Analysis

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Partial-Wave Decomposition

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Resonance-Model Fit

- Measured amplitudes are modeled by sum of resonant and non-resonant components ($\mathbb{S}$)

$$\hat{\mathcal{T}}_a(m_X, t') \propto \mathcal{P}_{\mathbb{P}} \sum_{j \in \mathbb{S}_a} \mathcal{C}_a^j(t') \mathcal{D}_j(m_X, t')$$

- Dynamics of resonant components: $\mathcal{D}_{\text{res.}}(m_X)$
- Dynamics of non-resonant component: $\mathcal{D}_{\text{n-res.}}(m_X, t')$

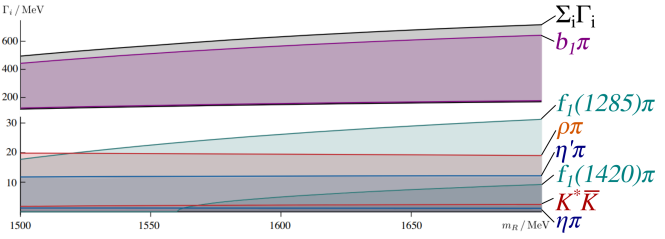
Exotic meson candidate in unflavoured sector

Theory predictions

- Several effective models (e.g. flux-tube, bag model, constituent gluon) expect the lightest hybrid meson to have spin-exotic QN: $\boldsymbol{J^{PC} = 1^{-+}}$

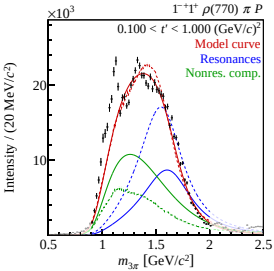
First result from lQCD simulation

- Decay of hybrid meson with $J^{PC} = 1^{-+}$ via several channels
- At $\mathcal{SU}(3)$ symmetry point:
  - $\rightarrow$ $m_{u,d,s} = m_s^{exp.}$
  - $\rightarrow$ $m_\pi \approx 700\,\mathrm{MeV/c^2}$
  - $\rightarrow$ $3m_\pi$ pushed to high energy
- Result: $b_1\pi$ most dominant



[PRD 103, (2021) 054502]

COMPASS



[COMPASS, PRD 98, 2018]

- $46.0\,\mathrm{M}$ events
- $\pi + p \to 3\pi + p$ at $190\,\mathrm{GeV/c}$
- 11 bins
  $0.1 < t' < 1.0\,(\mathrm{GeV/c})^2$
- Result:
  t'-dependence of background
  $m_{\pi_1} = 1600^{+110}_{-60}\,\mathrm{MeV/c^2}$
  $\Gamma_{\pi_1} = 590^{+100}_{-230}\,\mathrm{MeV/c^2}$

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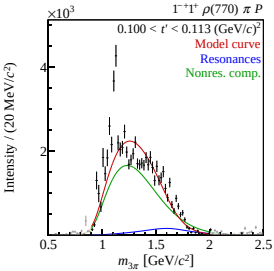

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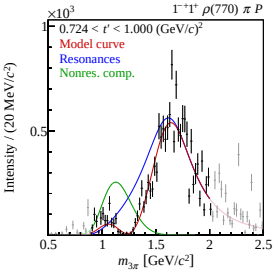

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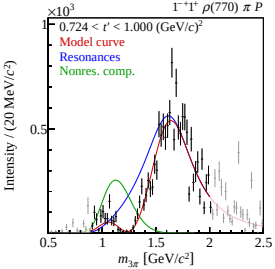

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Freed Isobar Analysis

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- Free the dynamics of the isobar and fit it with data

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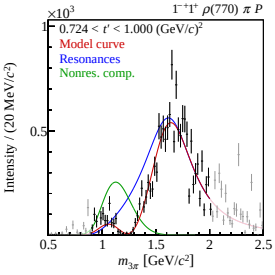

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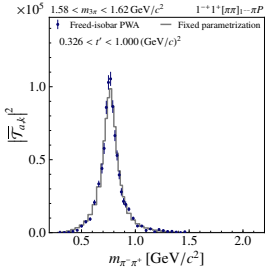
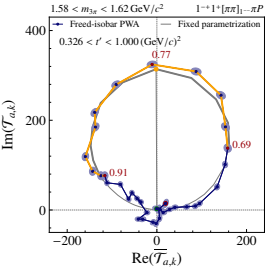
→ Spin-exotic wave shows clear $\rho(770)$ signature

→ Supports assumptions of isobar model





[COMPASS, PRD 105, 2022]

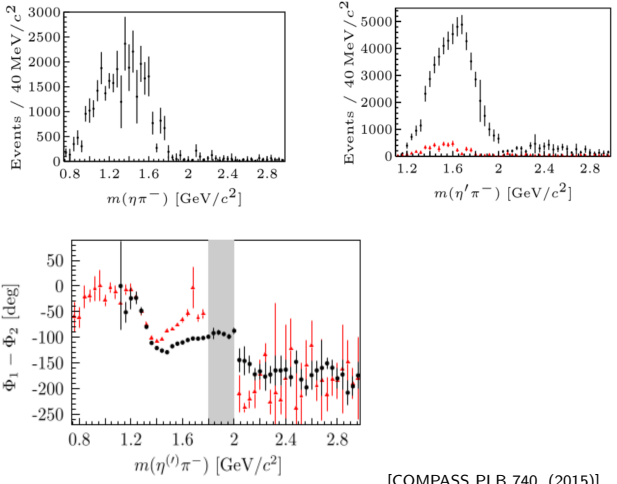
Final state

- $\pi^-\eta^{(\prime)}(\to \pi^+\pi^-\pi^0/\eta(\to \gamma\gamma))$
- No modelation t'
- Precise shower description in ECALs needed

Results from other Experiments

- BNL, VES and Crystal Barrel observed two states:
  - at $1.4\,\mathrm{GeV/c^2}$ in $\eta\pi$
  - at $1.6\,\mathrm{GeV/c^2}$ in $\eta'\pi$

COMPASS data - $1^{-+}\eta^{(\prime)}\pi P$



[COMPASS PLB 740, (2015)]

(Gray region: ill defined phases in $\eta\pi$ data)

Final state

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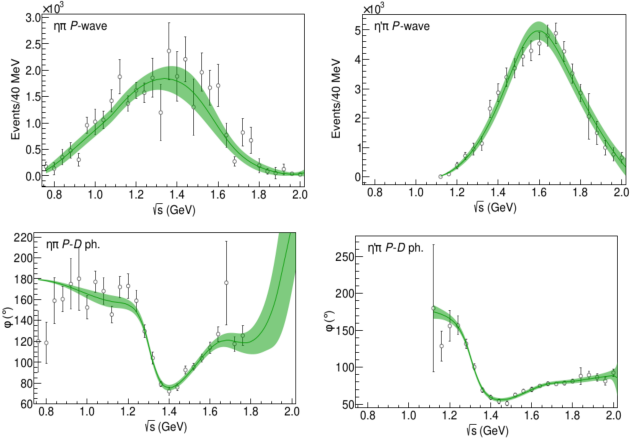
Coupled-channel fit by JPAC

- Performed resonance model fit using K-matrix formalism
- Conclusion: one pole is sufficient to describe both!
  $\to\ m = (1564 \pm 24 \pm 86)\ \text{MeV/c}^2$
  $\to\ \Gamma = (492 \pm 54 \pm 102)\ \text{MeV/c}^2$

COMPASS data with JPAC fit - $1^{-+}\eta^{(\prime)}\pi P$



[PRL, 122, 042002 (2019)]

Final state

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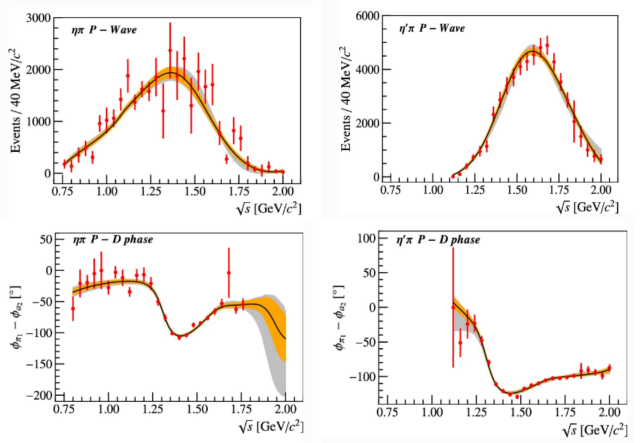
Confirmed by Kopf et al. in c.c. fit using $\bar{p}p$, $\pi^- p$ and $\pi\pi$ data

COMPASS data with fit from Kopf et al.



[Kopf et al., EPJ C 81, 1056, (2021)]

Final state

- PWA: $\omega\pi^-\pi^0$
- Final state: of $\pi^-\pi^+\pi^-\pi^0(\gamma\gamma)\pi^0(\gamma\gamma)$

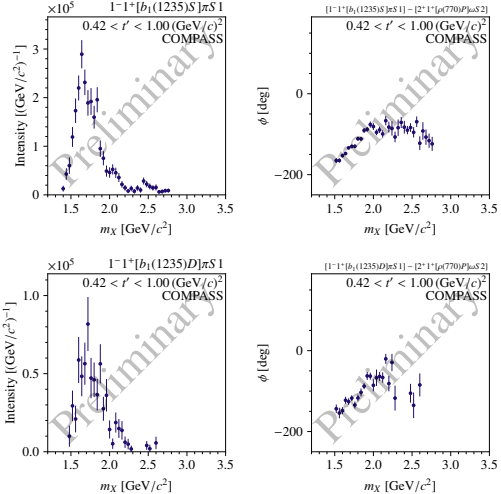
COMPASS data

- Selected 720k $\omega\pi^-\pi^0$ events
  $\to$ Analysis in t' possible
- New results from Partial-Wave decomposition
- Clear signal and phase motion in expected region

Results from other Experiments

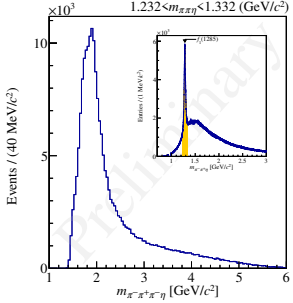
- BNL and VES observed spin-exotic 1^{-+} state at $\sim 1.6\,\mathrm{GeV/c^2}$
- BNL observed a second state

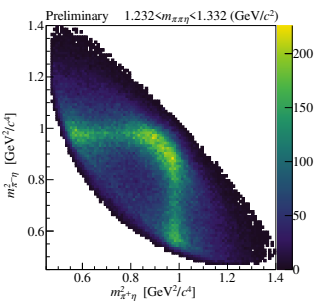
COMPASS data vs. BNL data



$f_1(1285)\pi^-$ at COMPASS

- Final state $\pi^-\pi^+\pi^-\eta(\gamma\gamma)$
- Selected 625k $\pi^-\pi^+\pi^-\eta$ events
  $\to$ Analysis in t' possible
- Next Step: PWA



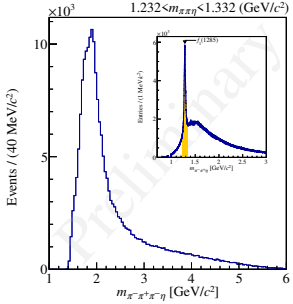


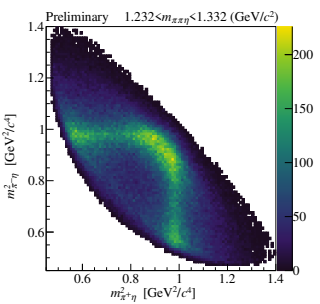
$f_1(1285)\pi^-$ at COMPASS

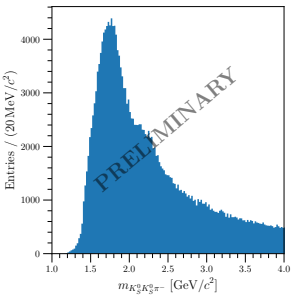
- Final state $\pi^-\pi^+\pi^-\eta(\gamma\gamma)$
- Selected 625k $\pi^-\pi^+\pi^-\eta$ events
  $\to$ Analysis in t' possible
- Next Step: PWA

$K^*\overline{K}$ at COMPASS

- Final state $\pi^- K^0_S(\pi^+\pi^-) K^0_S(\pi^+\pi^-)$
- Selected 240k $\pi^- K^0_S K^0_S$ events
  $\to$ Analysis in t' possible
- Next Step: PWA



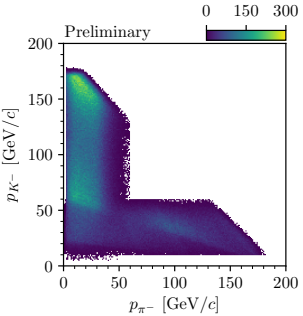




Exotic meson candidate in strange sector

COMPASS: Data

- $K^- + p \to K^-\pi^+\pi^- p$ at $190\,\mathrm{GeV/c}$
- $720\,\mathrm{k}$ events
- Four t'-bins in range $0.1 < t' < 1.0\,(\mathrm{GeV/c})^2$
- Limited by PID in spectrometer

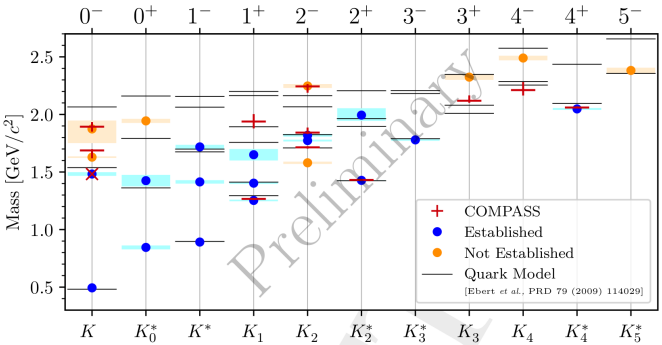


COMPASS: Resonance-Model Fit

- Agreement with at least five established states
- Agreement with at least three not established states

PDG: Light Strange Sector

- 25 states listed, nine need further confirmation



Light Strange-Mesons: $m < 3\,\mathrm{GeV/c^2}$

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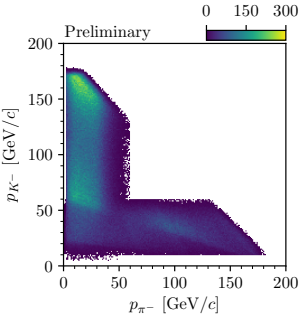
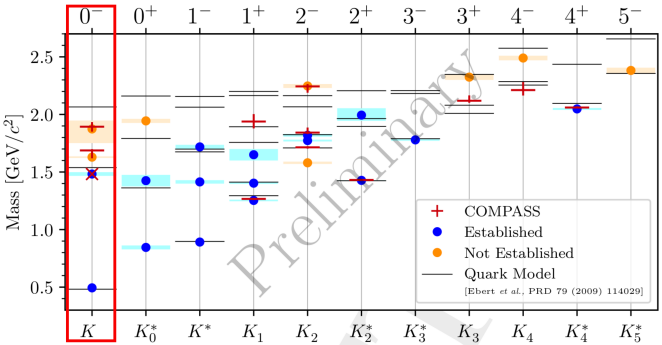


Exotic state in 0^- sector?

- Constituent-Quark Model predicts two excited states
- Three exited signals are observed

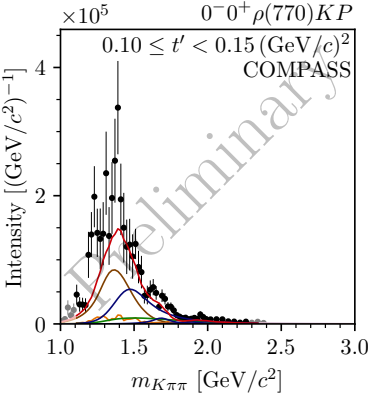
PDG: Light Strange Sector

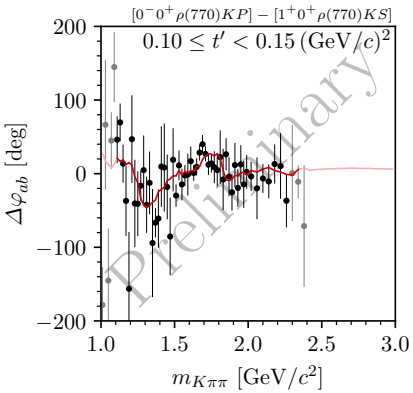
- 25 states listed, nine need further confirmation



Exotic state in 0^- sector?

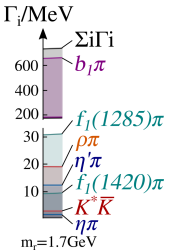
- Only $0^-0^+\rho(770)KP$ wave is reliable
- Three resonances needed:
  1. $K(1460)$ fixed PDG values $m = 1482.4$ MeV/c^2 and $\Gamma = 335.6$ MeV/c^2
  2. $K(1630)$, $m = 1687 \pm 10^{+2}_{-67}$ MeV/c^2 and $\Gamma = 140 \pm 20^{+50}_{-50}$ MeV/c^2 ($\sigma = 8.3$)
  3. $K(1830)$, $m = 1893 \pm 17^{+13}_{-39}$ MeV/c^2 and $\Gamma = 160 \pm 40^{+60}_{-80}$ MeV/c^2





Summary & Outlook

Exotic candidate in unflavoured sector with $J^{PC} = 1^{-+}$ ($\pi_1(1600)$):



Modified: [PRD 103, (2021) 054502]

Channel	Final state	Status	Outlook
$\rho\pi$	$\pi^-\pi^+\pi^-$	-[COMPASS, PRD 98, 2018] -[COMPASS, PRD 105, 2022]	-Increase data set - Use new analysis techniques
$\eta^{(\prime)}\pi$	$\pi^-\pi^+\pi^-\pi^0/\eta$	-[COMPASS PLB 740, (2015)] -[JPAC, PRL 122 (2019)]	- Increase data set - Improve shower reconstruction
$b_1\pi$	$\omega\pi^-\pi^0$	- Partial-Wave Decomposition	- Resonance-Model Fit
$f_1(1285)\pi$	$\pi^-\pi^+\pi^-\eta$	- Event Selection	- PWA
$K^*\overline{K}$	$K_S\overline{K}_S\pi$	- Event Selection	- PWA

Exotic candidate in strange sector:

- Analysis limited by PID
- Clear evidence for three excited states in $J^P = 0^-$ sector
  $\rightarrow$ Exotic candidate $K(1630)$

Outlook:

- $K^- + p \rightarrow K^0_S\pi^- + p$ & $K^- + p \rightarrow \Lambda\overline{p} + p$

AMBER
Apparatus for Meson and Baryon Experimental Research

Back Up

Freed Isobar Analysis

- In conventional analysis dynamical shape of isobars are fixed in decay amplitude
- Free the dynamics of the isobar and fit it with data:

$$\mathcal{I}(\tau_i) = \left| \sum_{a}^{N_{\text{waves}}} \sum_{k}^{N_{m_\xi \text{ bins}}} \mathcal{T}_{a,k} \Psi'_{a,k}(\tau_i) \right|^2$$

with

$$\mathcal{T}_a \to \mathcal{T}_{a,k} = \mathcal{T}_a \mathfrak{T}_{a,k}$$

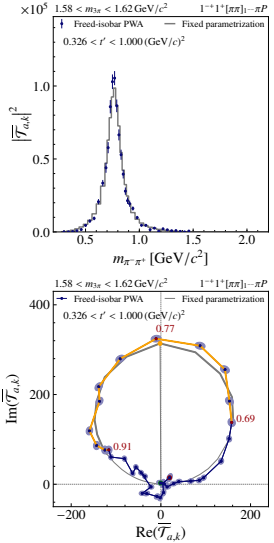
- The set $\mathfrak{T}_{a,k}$ describes the dynamics of the isobar in wave (a)

Results:

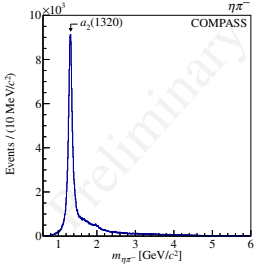
- Same result as conventional fit

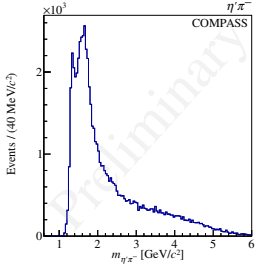
→ Spin-exotic wave shows clear $\rho(770)$ signature

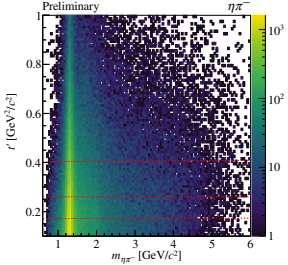
→ Supports assumptions of isobar model

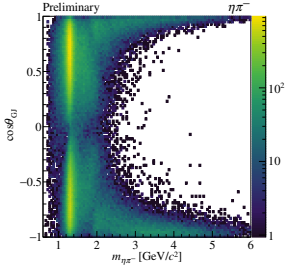


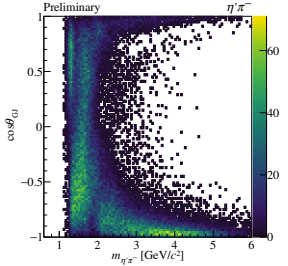
Updated kinematic distributions: $\eta^{(\prime)}\pi^-$

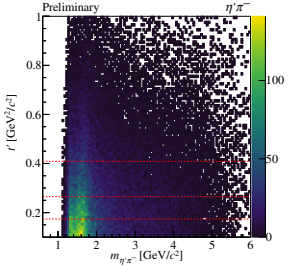












Final state

- PWA: $\omega\pi^-\pi^0$
- Final state: of $\pi^-\pi^+\pi^-\pi^0(\gamma\gamma)\pi^0(\gamma\gamma)$

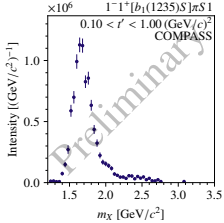
COMPASS data

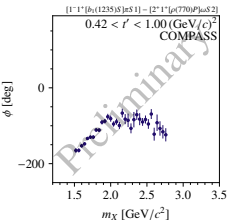
- Selected 720k $\omega\pi^-\pi^0$ events
  $\to$ Analysis in t' possible
- New results from Partial-Wave decomposition
- Clear signal in expected region

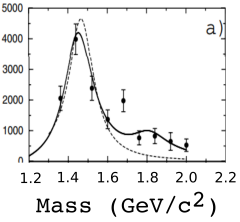
Results from other Experiments

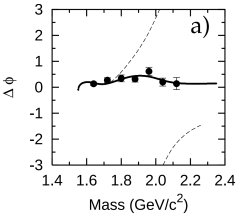
- BNL and VES observed spin-exotic 1^{-+} state at $\sim 1.6\,\mathrm{GeV/c^2}$
- BNL observed a second state

COMPASS data vs. BNL data

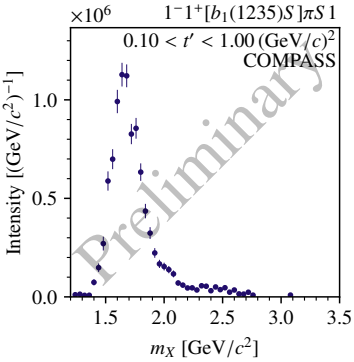


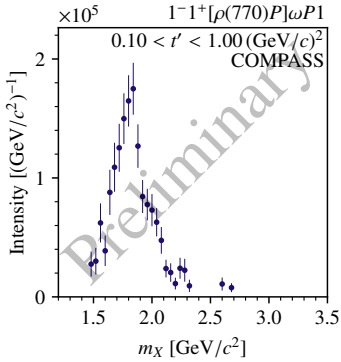


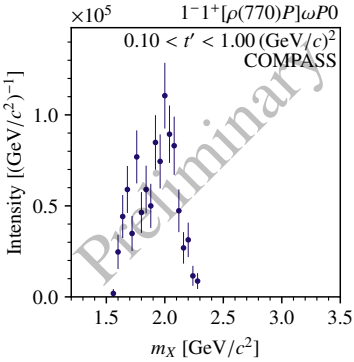




[BNL, PRL 94, 032002, (2005)]

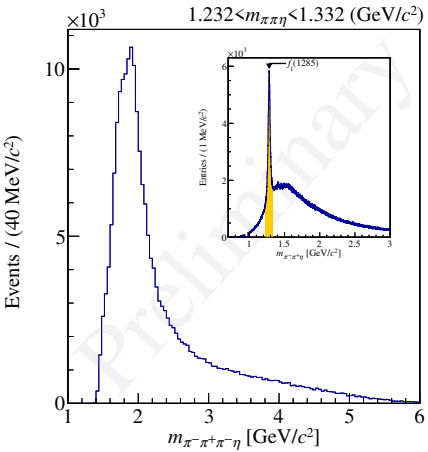


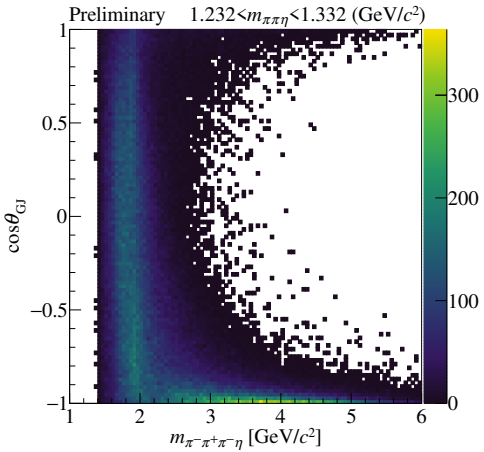




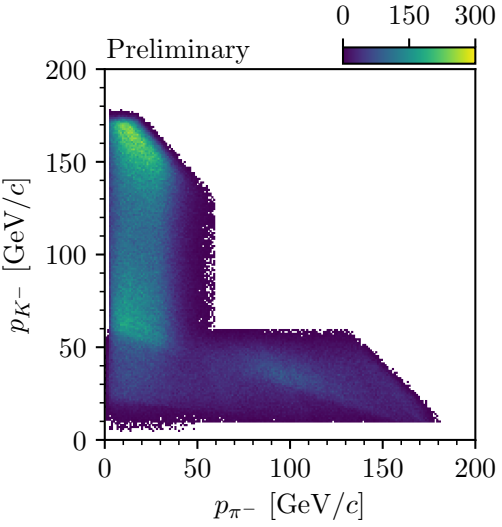
- LQCD: if $\pi_1 \to \rho\omega$ is present, then it is very small

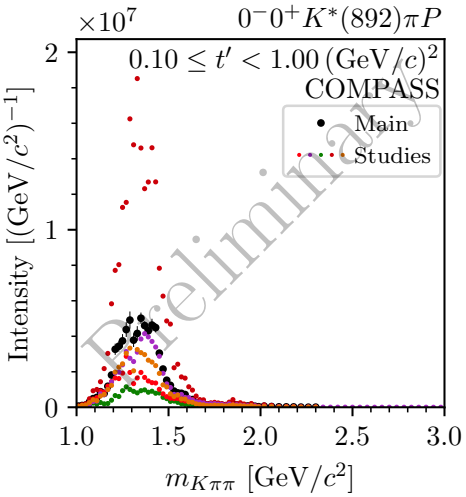
Kinematic distributions: $X \to f_1(1285)\pi^-$





Effekt of limited PID





Kinematic distributions: $K^- + p \to K^0_S \pi^- + p$