Recent Spectroscopy Highlights from COMPASS

HQL2023 TIFR, Mumbai

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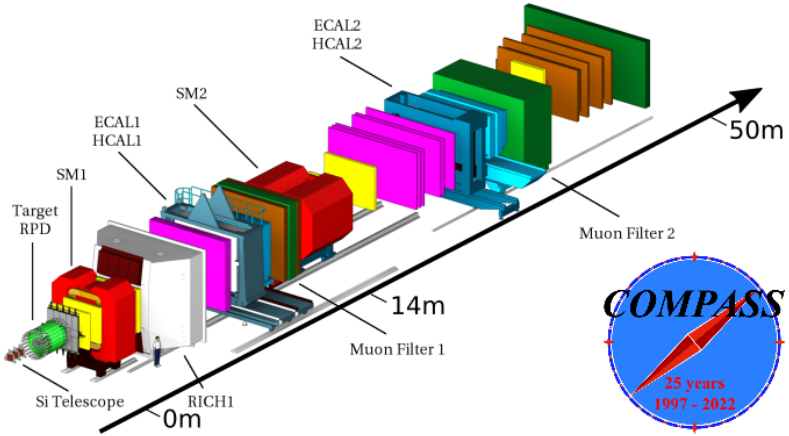
30th November 2023

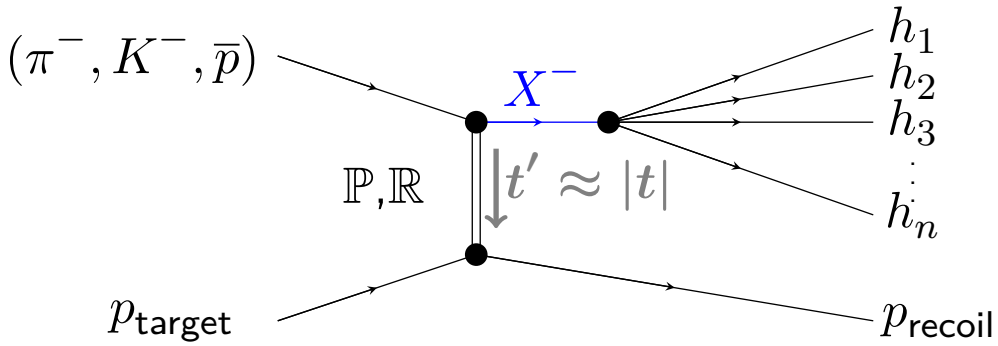
Location of the COMPASS experiment at CERN

[Aerial view of CERN, Credit: Maximilien Brice (CERN), modified]

- **CO**mmon **M**uon **P**roton **A**pparatus for **S**tructure and **S**pectroscopy
- Many different physics programs from 2002-2022



- Resonance search with diffractive production in two years of dedicated data taking
- World largest data set for diffractive $\pi^- p$ and $K^- p$ scattering
- Beam conditions: 190 GeV hadron beam; π^- (96.8%), K^- (2.4%) and $\bar{p}$ (0.8%)



Constituent quark model (CQM)

- $|q, \bar{q}\rangle$ meson with $q = u,\ d,\ s$ and quantum numbers $J^{P(C)}$
  C is only a good quantum number for unflavoured states
- Forbidden J^{PC} in CQM: $J^{PC} = 0^{--}, (odd)^{-+}, (even)^{+-}$
  $\rightarrow$ spin-exotic in unflavoured sector

Non CQM states

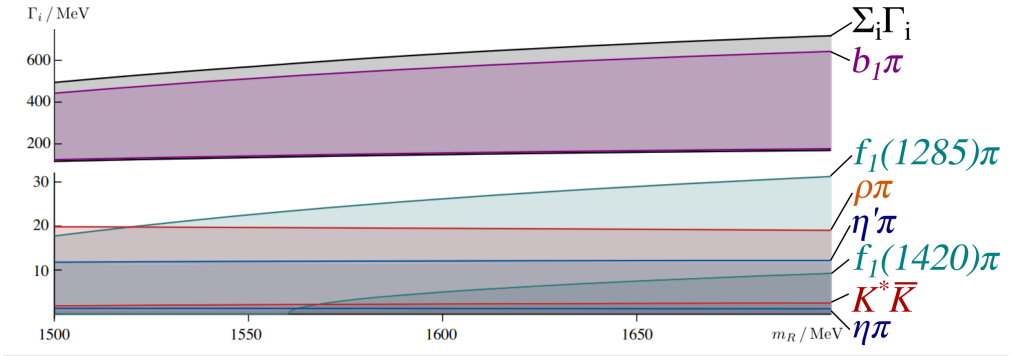
- Multi-quark states
- Glueballs
- Hybrids

In general hard to distinguish from CQM states

Exotics discussed during this talk

- Signals in spin-exotic J^{PC} sector, e.g. 1^{-+}
  $\rightarrow$ must be an exotic meson
- Evidence for more signals in certain J^{PC} than predicted by the CQM
  $\rightarrow$ supernumerous state to the CQM

Theory predictions for the 1^{-+} sector



[PRD 103, (2021) 054502]

- Lattice and several effective models expect the lightest hybrid meson to have quantum numbers 1^{-+}
- Lattice calculation predicts large contribution of $b_1\pi$ final state
  $\rightarrow$ smaller contribution for $f_1(1285)\pi$, $\eta^{(\prime)}\pi$ and $\rho\pi$ final states
- All final states can be investigated with the COMPASS dataset

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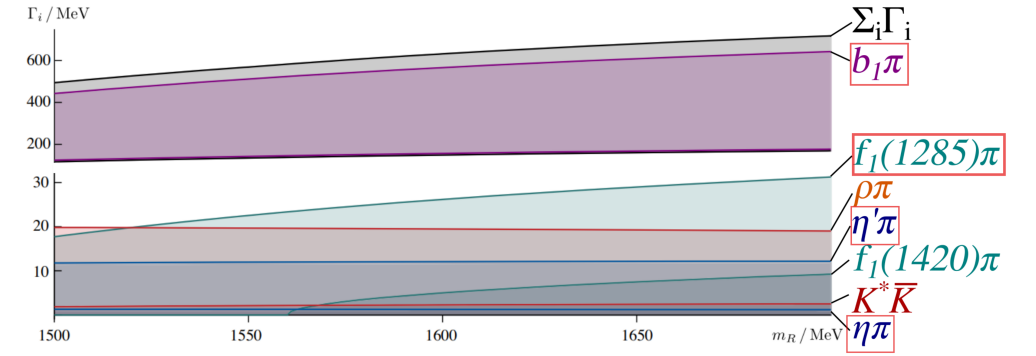

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- Lattice and several effective models expect the lightest hybrid meson to have quantum numbers 1^{-+}
- Lattice calculation predicts large contribution of $b_1\pi$ final state
  $\rightarrow$ smaller contribution for $f_1(1285)\pi$, $\eta^{(\prime)}\pi$ and $\rho\pi$ final states
- This talk focuses on the marked final states

Analysis procedure

- For this talk we focus on the following final states:
  - $\eta^{(\prime)}\pi^-$, $\pi^-\pi^+\pi^-\eta$, $\pi^-\pi^0\omega$, $K^-\pi^-\pi^+$
- Select exclusive events in these final states $\rightarrow$ two stage analysis

1) Partial-wave decomposition separately in each final state
   - Mass independent fit to extract resonance content

Partial-wave decomposition

- Extended likelihood fit per (m_{X^-}, t')-bin with Intensity

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

- Decay amplitudes Ψ_a described in the isobar model $\rightarrow$ chain of two-body decays
- Output: production amplitudes $\mathcal{T}_a$ per partial-wave and (m_{X^-}, t')-bin

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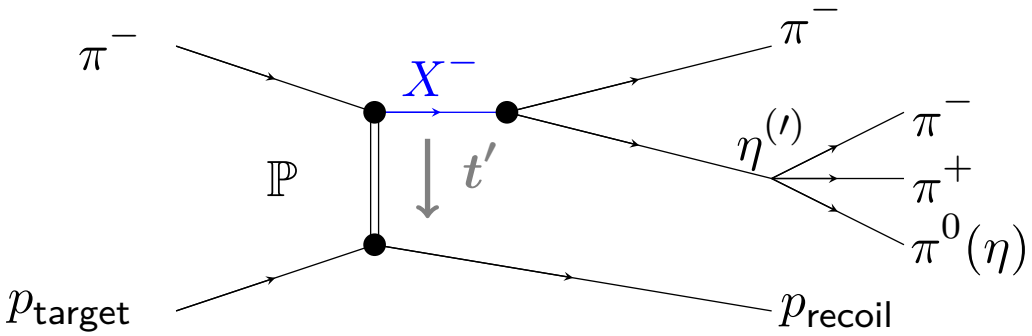
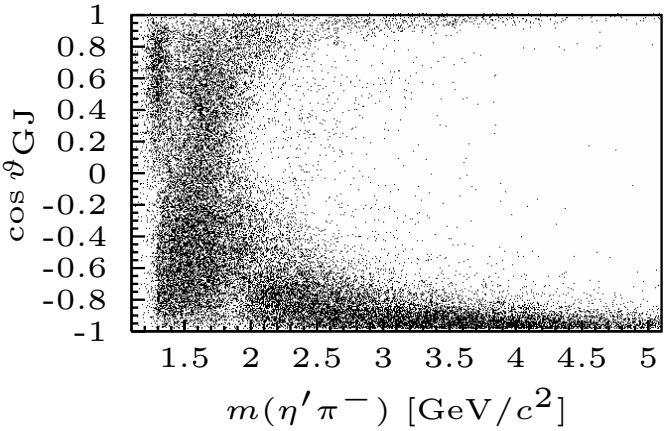
2) Resonance-model fit
   - Mass dependent fit to extract resonance parameters

Resonance-model fit

- Production amplitudes $\mathcal{T}_a$ are modeled as a sum of resonant (only depends on m_X) and non-resonant (depends on m_X and t') components
- In order to separate resonances and background accurately, a binning in t' is needed
- Output: extraction of resonance parameters (m_0, Γ_0) and couplings

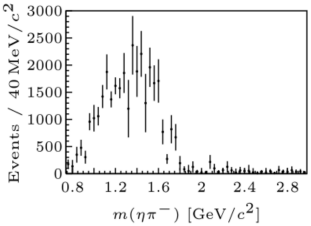

π^-
X^-
π^-
$\eta^{(\prime)}$
π^-
π^+
$\pi^0(\eta)$
$\mathbb{P}$
t'
p_{target}
p_{recoil}

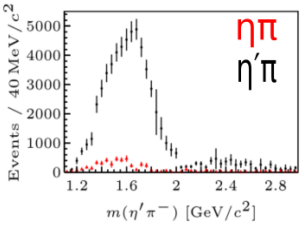
- Angular distribution of $\eta'\pi$ has clear asymmetric structures
- These structures are only possible with interference of odd and even waves
- Clear evidence for spin-exotic

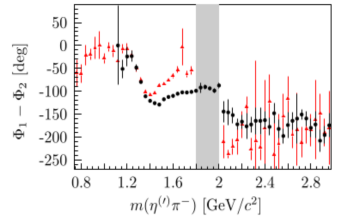


Results in the $\eta^{(\prime)}\pi$ final state

P-Wave ($J^{PC} = 1^{-+}$) $\rightarrow$ spin-exotic candidate







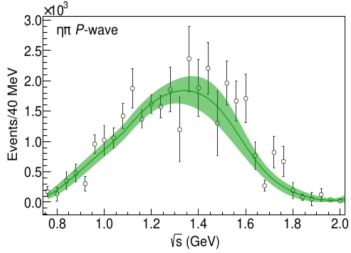
$\eta\pi$ spectrum scaled according to phase space [COMPASS PLB 740, (2015)]

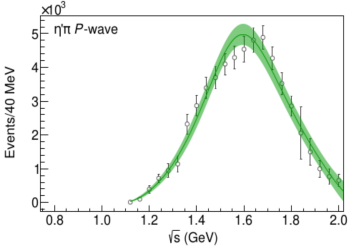
Phases (of P- vs. D-wave) ill-defined for $\eta\pi$ in the grey region

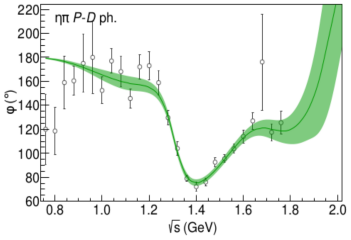
- Two peaks observed
  - $\eta\pi$: peak around 1.4 GeV
  - $\eta'\pi$: peak arount 1.6 GeV
  - Consistent with previous results from BNL, VES and Crystal Barrel
  - BUT, together with JPAC, it was shown, that both signals come from the same pole $\rightarrow$ one resonance $\pi_1(1600)$

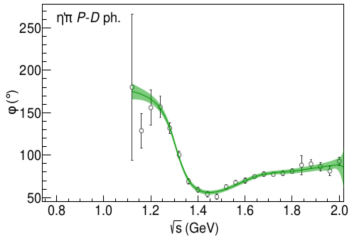
- Resonance-model fit using K-matrix formalism
- Single pole hypothesis is preferred to describe $\eta\pi$ and $\eta'\pi$ data
- Results confirmed by Kopf et al. in coupled channel fit using $\bar{p}p, \pi^- p$ and $\pi\pi$ data

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



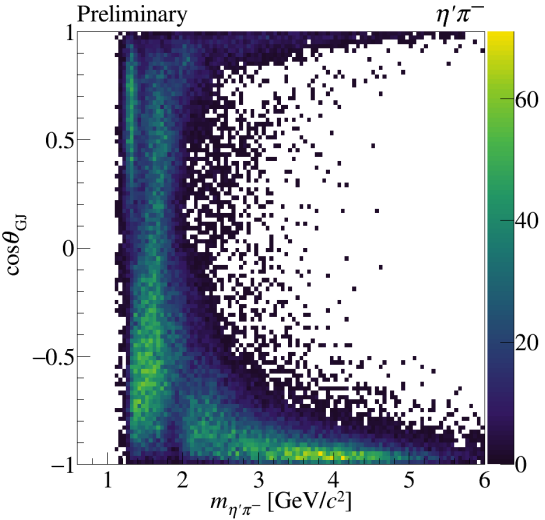






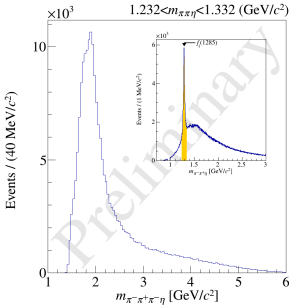
[PRL, 122, 042002 (2019)]

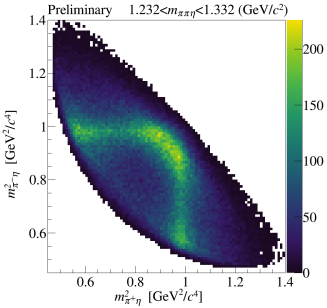
- Results from two years of data taking
- We improved on the calorimeter reconstruction and Monte-Carlo description
- Allows us to separate resonances from background for the first time (t' binning)
- Event selecion is done, partial-wave decomposition in progress
- Double-regge fits for high masses ($m_X \gtrsim 2.4$ GeV/c^2) in collaboration with JPAC

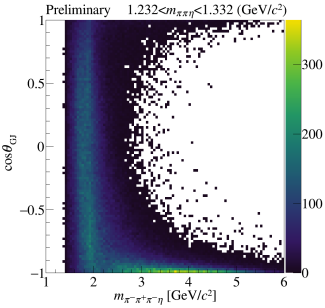


$\pi^- p \to \pi^-\pi^-\pi^+\eta p,\ \eta \to \gamma\gamma$

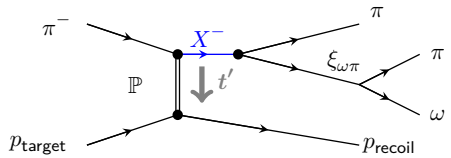
Same state as improved $\eta^{(\prime)}\pi$ analysis. Selected 625k events $\to$ analysis in t' possible







Decay with $\omega\pi$ isobars



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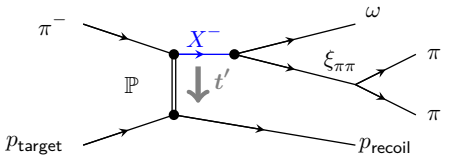
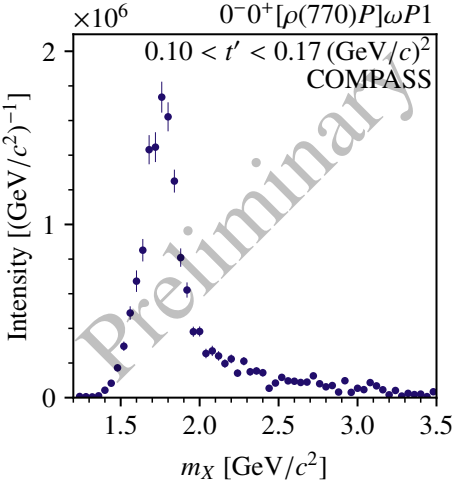
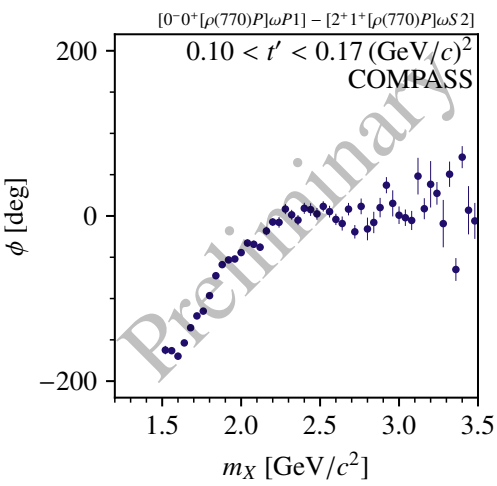


Analysis of the $\omega\pi\pi$ final state

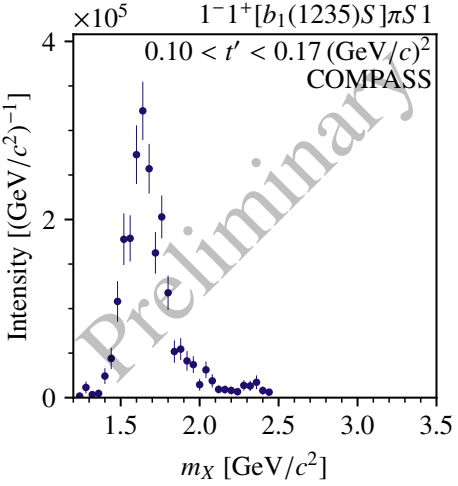
- Selected final state: $\pi^-\pi^0\pi^-\pi^+\pi^0 p \rightarrow$ we require exactly one $\pi^-\pi^+\pi^0$ to be close to the ω mass and discard events with more than one combination
- We assume isospin symmetry and combine $\xi_{\omega\pi^-}$ and $\xi_{\omega\pi^0}$ to $\xi_{\omega\pi}$
  - Exemplary Isobars: $b_1(1235) \rightarrow \omega\pi$ and $\rho(770) \rightarrow \pi\pi$
- Analysis in 4 t' bins and mass bins of 40 MeV

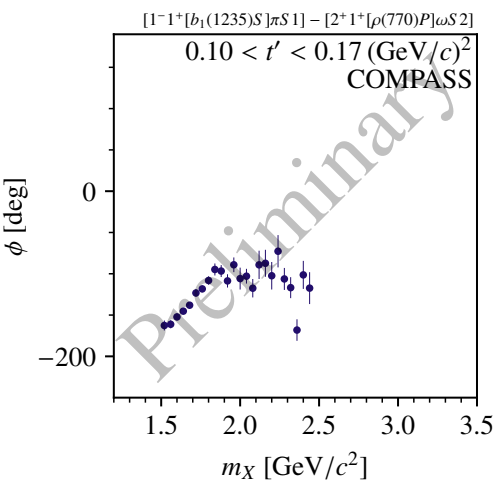
Clean signal for a $\pi(1800)$



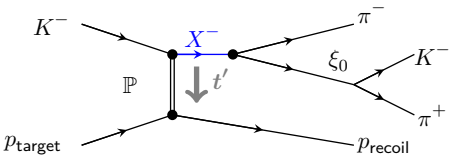


Clean signal for a spin-exotic $\pi_1(1600)$

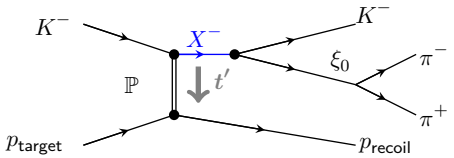




Decay with $K^-\pi^+$ isobars

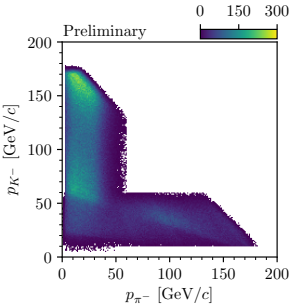


Decay with $\pi^-\pi^+$ isobars



Analysis of the $K^-\pi^+\pi^-$ final state

- Now we investigate K^-p scattering $\rightarrow$ allows us to investigate strange resonances
- Due to RICH acceptance, we are limited to a certain kinematic range
- Analysis in 4 t' bins and mass bins of 20 MeV for $m_{K\pi\pi} < 2$ GeV and 40 MeV above

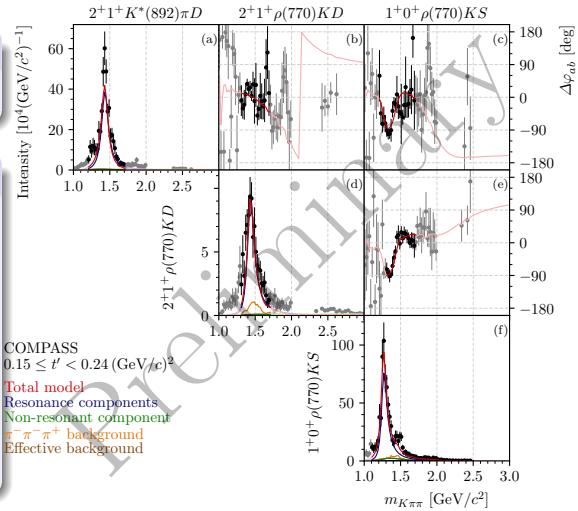


PDG

Established resonances: $K_2^*(1430)$

Our analysis

- $m_0 = (1430.9 \pm 1.4^{+3.1}_{-1.5})$ MeV/c^2
- $\Gamma_0 = (111 \pm 3^{+4}_{-16})$ MeV/c^2
- We see it in different decays
- In agreement with previous measurements
- Cleaner signal then previous measurements

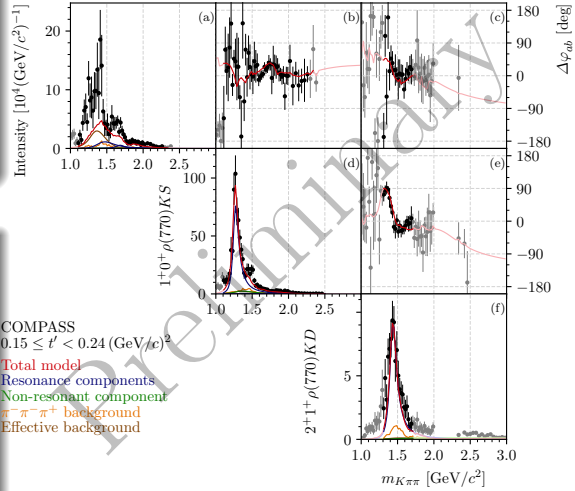


PDG and quark model

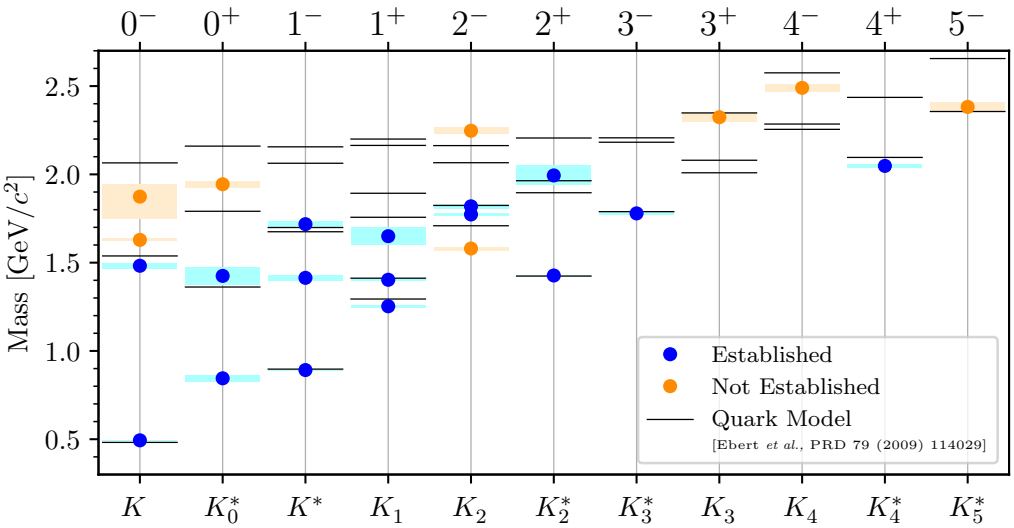
- Quark model: two excited states
- Established resonances: $K(1460)$
- Need further confirmation: $K(1630)$ and $K(1830)$

Our analysis

- 1.4 GeV/c^2 peak $\rightarrow$ $K(1460)$ (effected by known artifacts)
- 1.7 GeV/c^2 peak $\rightarrow$ $K(1630)$ 8.3σ statistical significance
- Weak 2 GeV/c^2 signal$\rightarrow$ $K(1830)$ 5.4σ statistical significance



The $K^-\pi^+\pi^-$ final state



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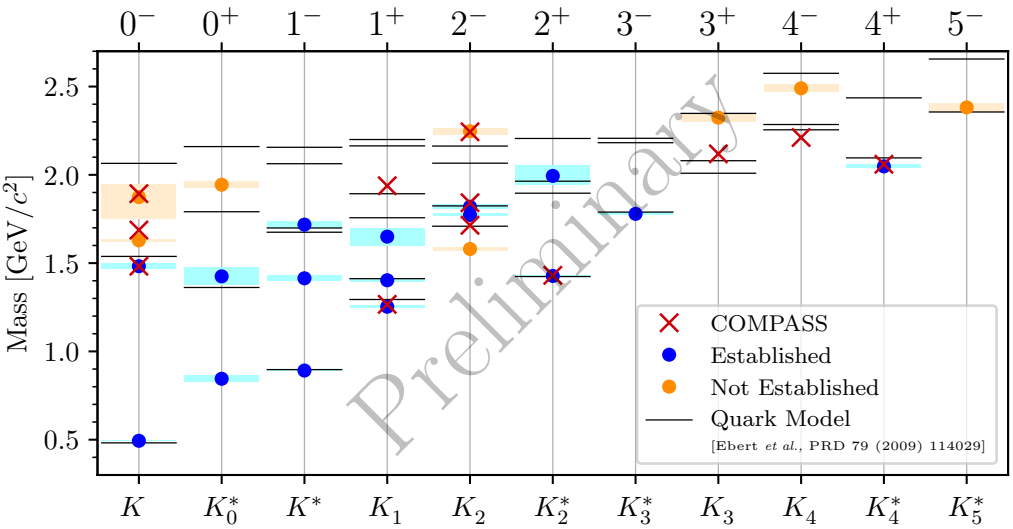


Summary

- COMPASS has a very rich spectroscopy program for the light quark sector
- We found evidence for the spin-exotic $\pi_1(1600)$ in $\eta^{(\prime)}\pi, 3\pi$ (not shown in this talk) and $\omega\pi\pi$
- Complete partial-wave analysis for the $K^-\pi^+\pi^-$ final state
  - Evidence for an exotic state in the 0^- sector

Outlook

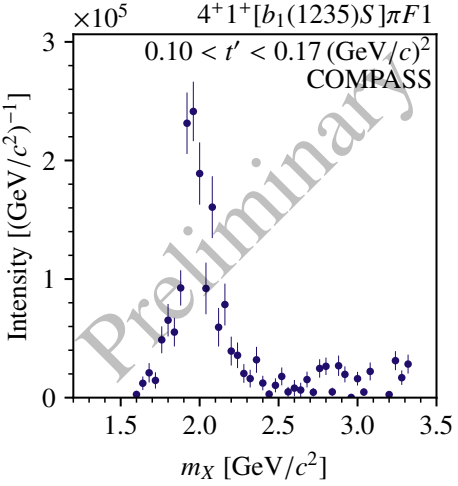
- Resonance-model fit for $\omega\pi\pi$
- Partial-wave analysis for improved $\eta^{(\prime)}\pi$ data set and the full $3\pi\eta$ final state

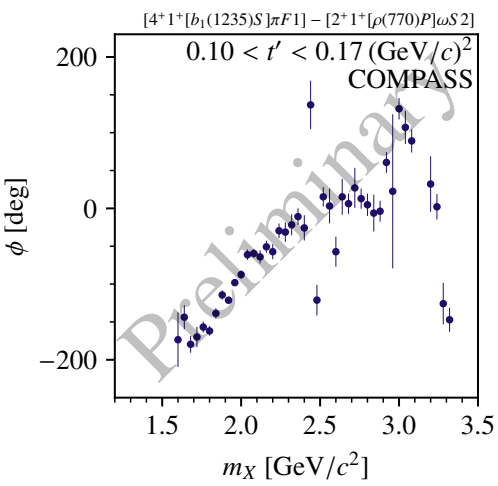
AMBER
Apparatus for Meson and Baryon Experimental Research

Successor for COMPASS with a dedicated spectroscopy program with Kaon beam

Backup

Clean signal for a $a_4(1975)$





Clean signal for a spin-exotic $\pi_1(1600)$