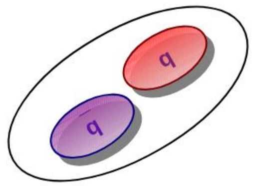
Meson Spectroscopy at COMPASS

Philipp Haas for the COMPASS Collaboration

19.03.2024 – PAW'24

Motivation

- Mesons in the Constituent Quark Model: $|q\bar{q}\rangle$ states



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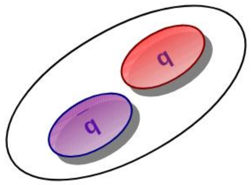

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- Many predicted $|q\bar{q}\rangle$ states unobserved/need confirmation

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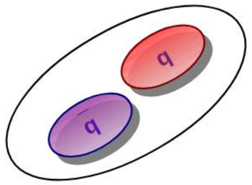
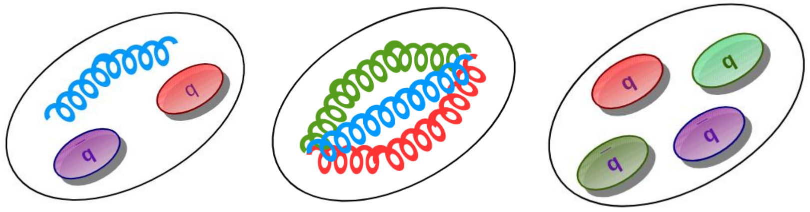


- Many predicted $|q\bar{q}\rangle$ states unobserved/need confirmation

- QCD allows meson configurations beyond $|q\bar{q}\rangle$ - so-called exotics



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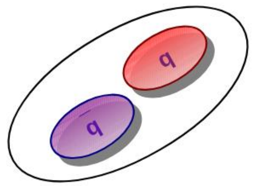

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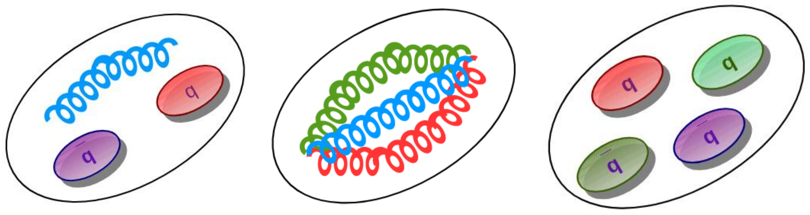


- Meson spectroscopy:

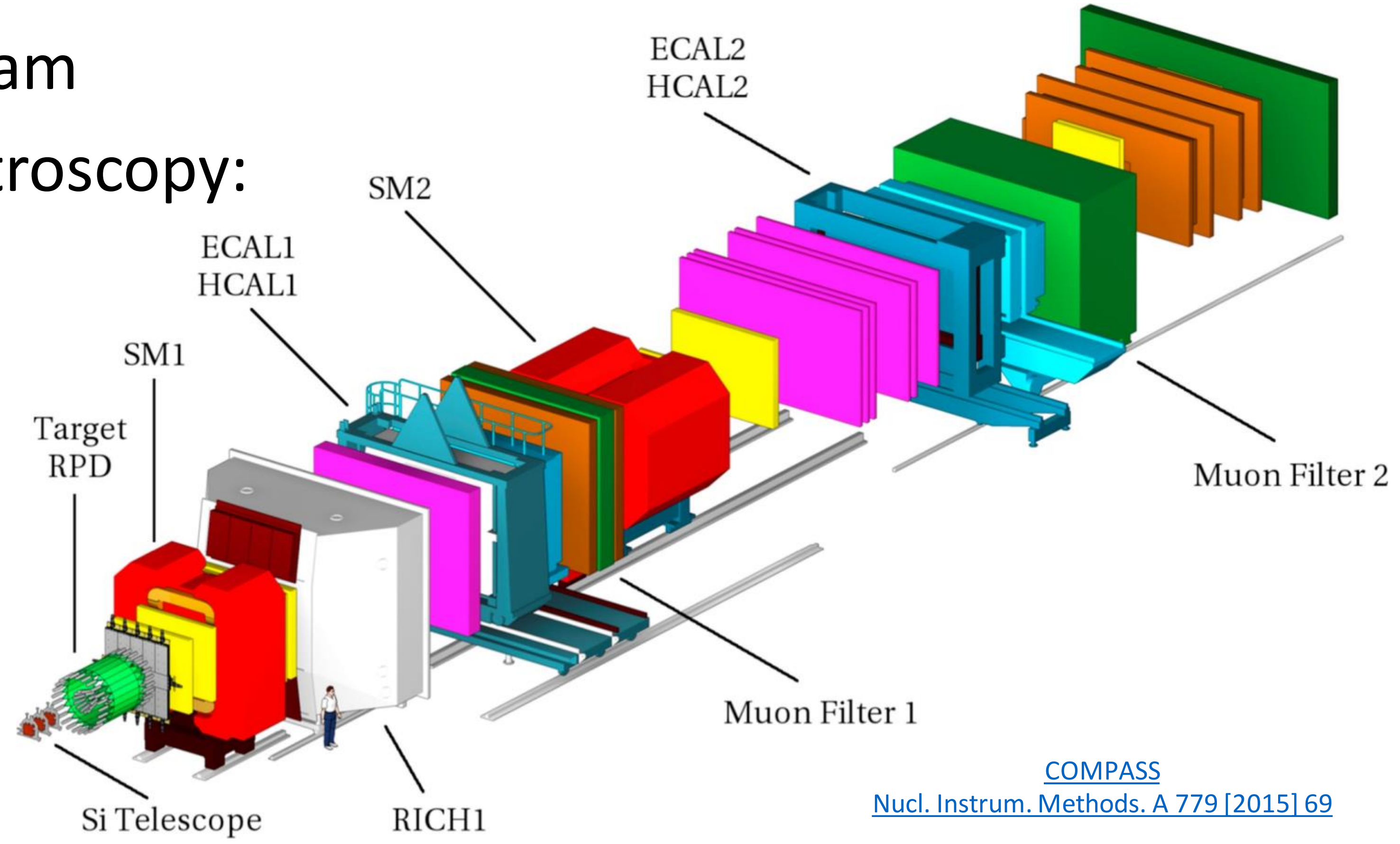
$\Rightarrow$Understand non-perturbative QCD

$\Rightarrow$Input to test SM predictions with experimental data

Experimental Setup

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

Beam:
$97\% \ \pi^-$
$2\% \ K^-$
$1\% \ \bar{p}$



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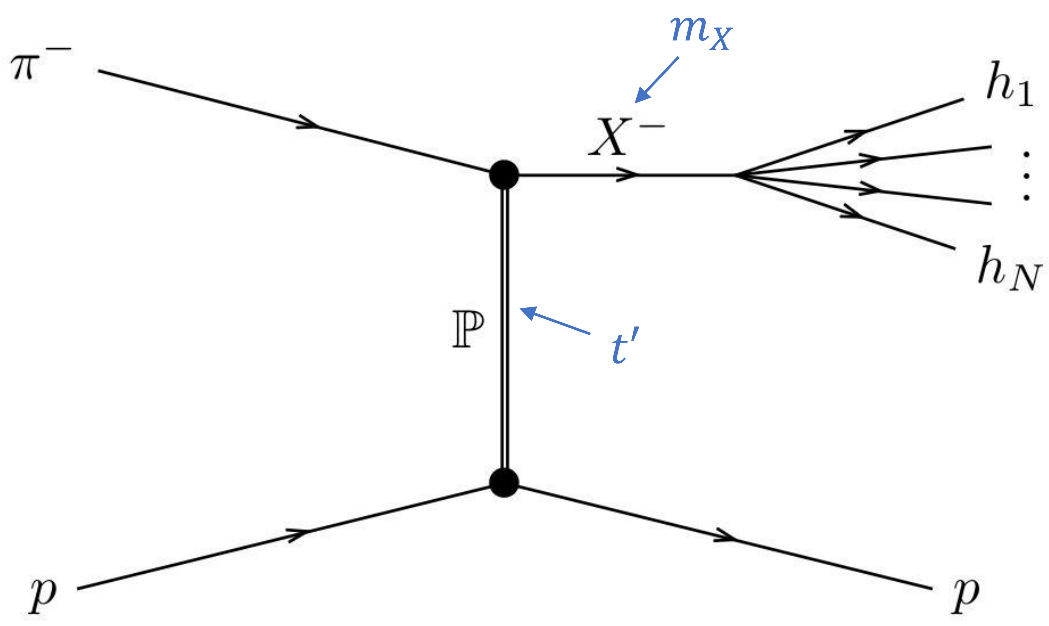
Non-Strange Light-Meson Spectroscopy at COMPASS

- Diffractive scattering of high-energy pion beam
- Excited non-strange meson resonance X^-
- Decay to N hadron final state



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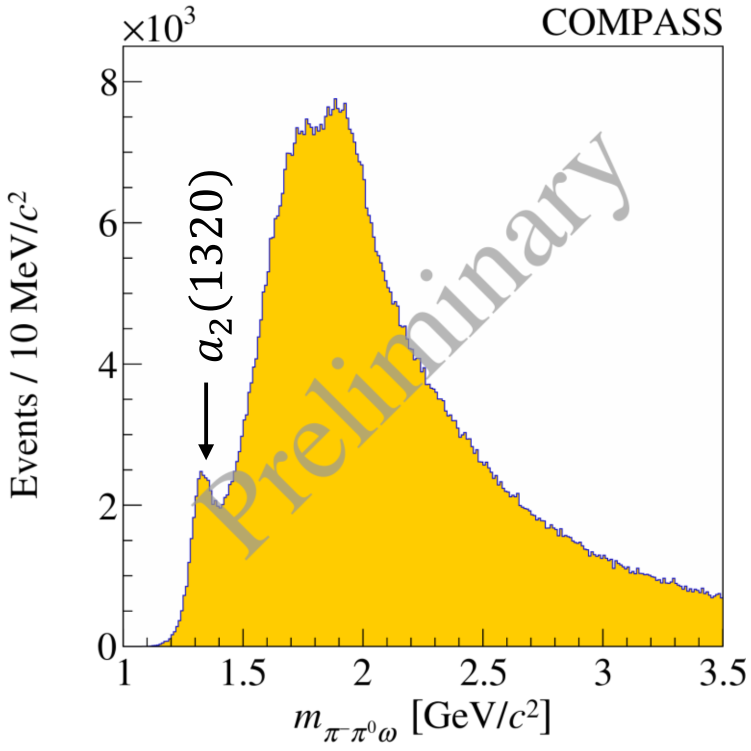
Analyzed channels:

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

Partial-Wave Analysis – Method

Data
Diffractively produced events



Partial-Wave Analysis – Method

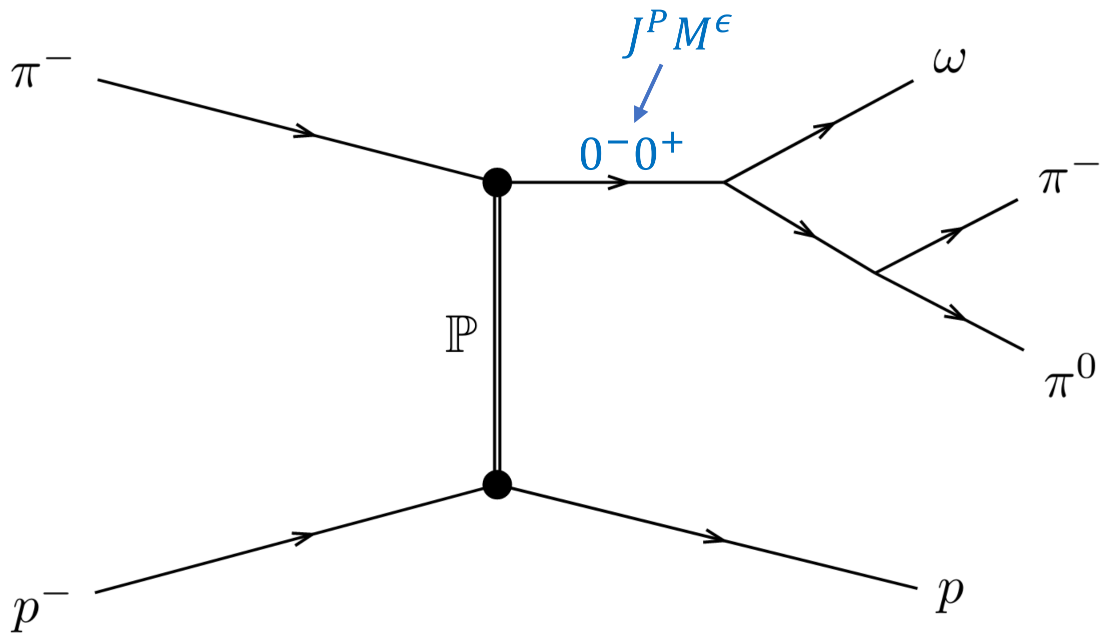
Data
Diffractively produced events

↓ Partial-wave decomposition

Partial waves
Intensities and phases as functions of (m_X, t')

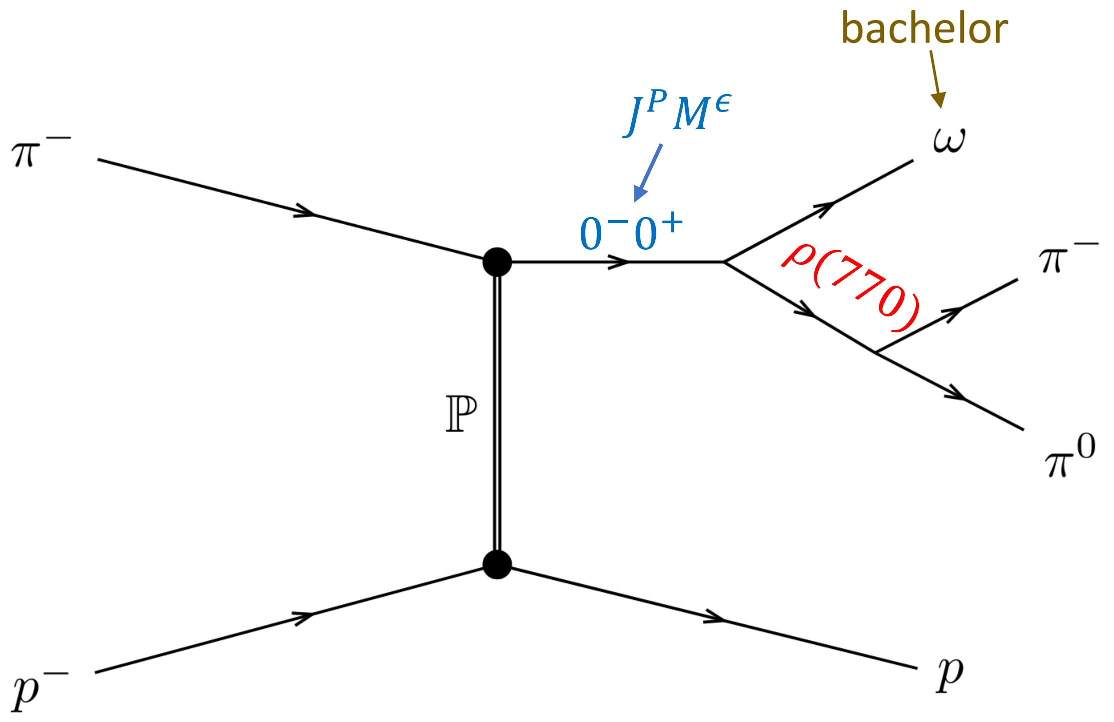
Partial Waves

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



Partial Waves

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



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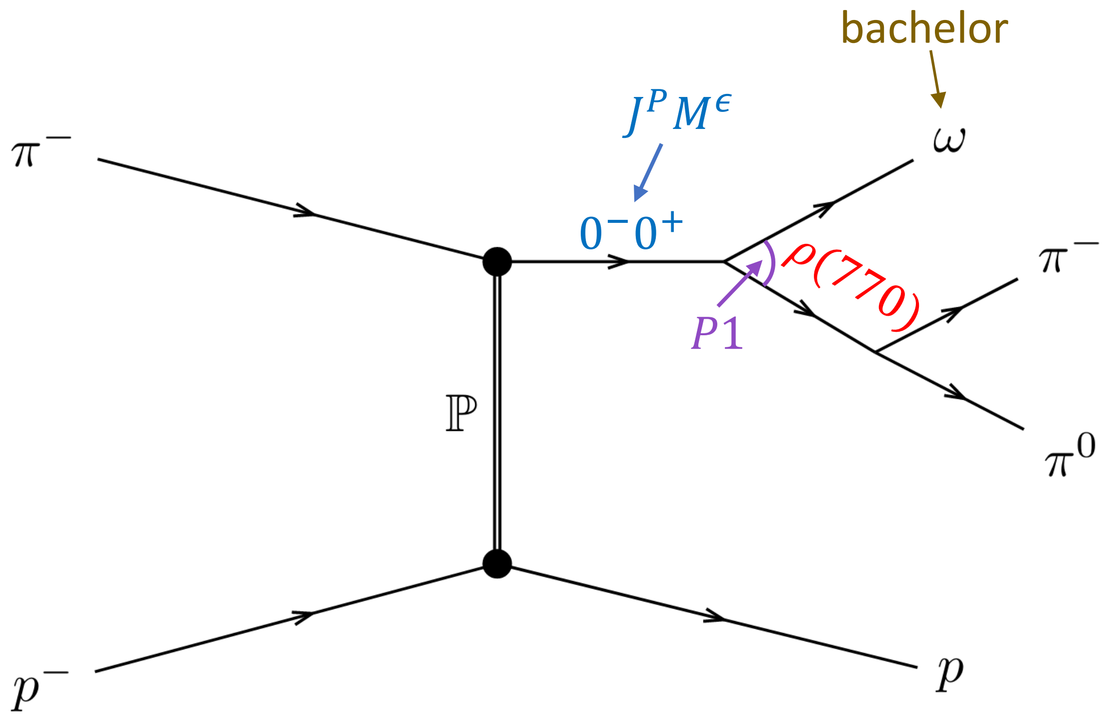

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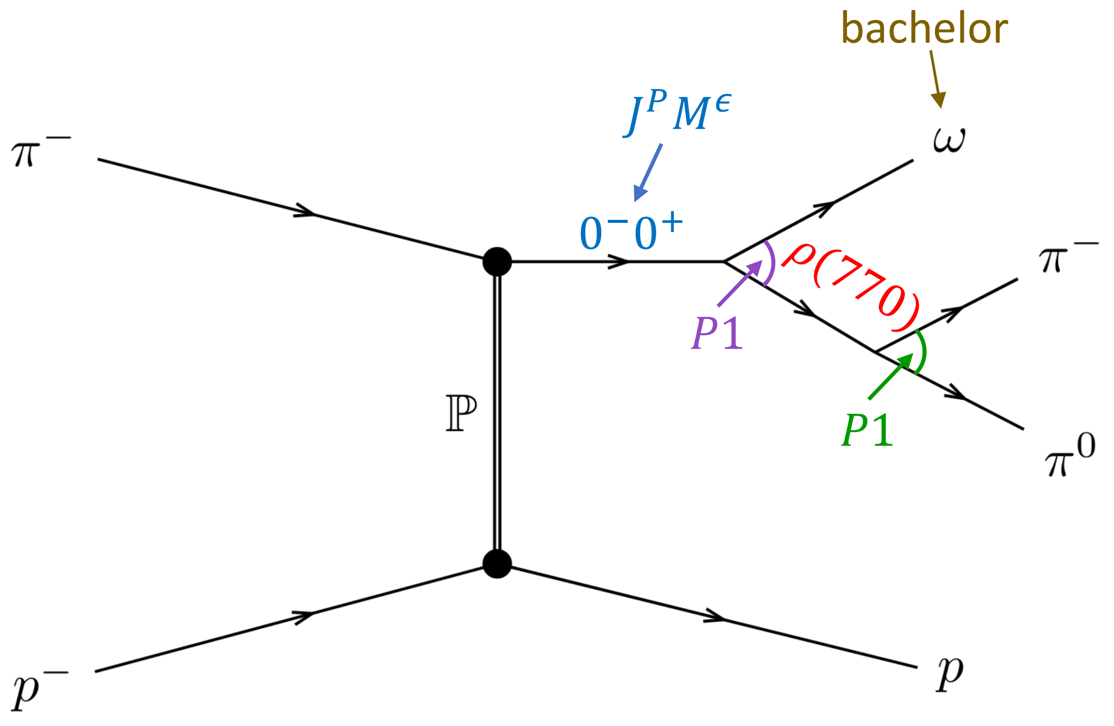
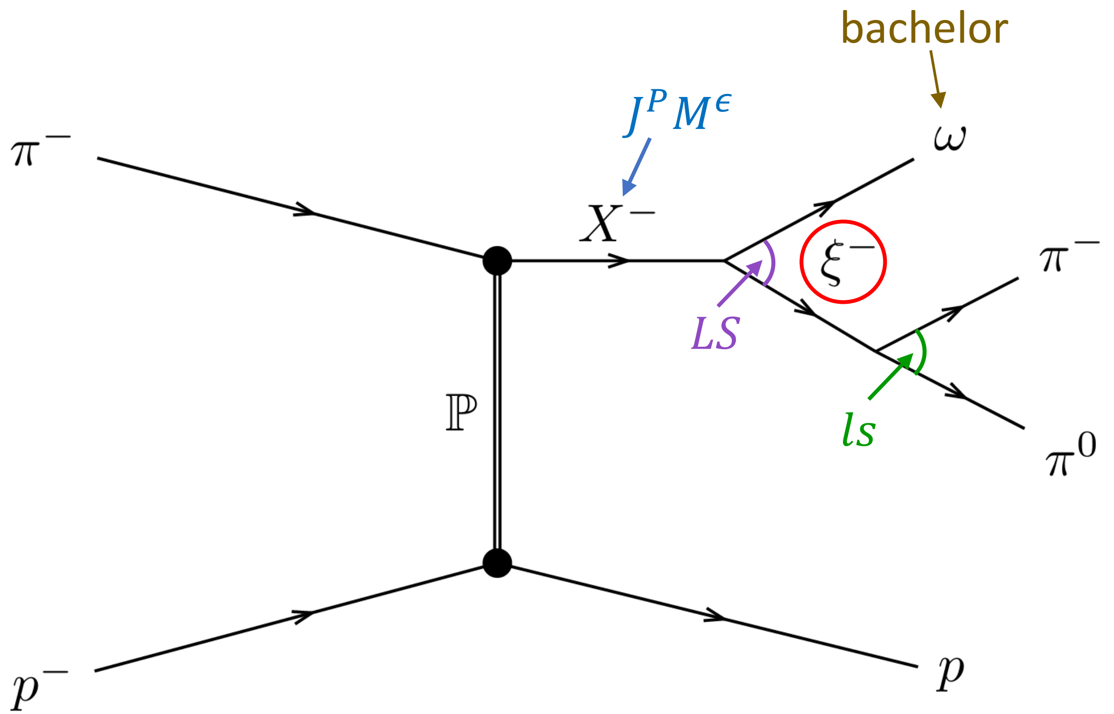
  - $LS = P1$ coupling between ω and $\rho(770)$
- $\rho(770) \to \pi^-\pi^0$
  - Second $ls = P1$ coupling
- $i = 0^-0^+[\rho(770)P]\ \omega\ P1$



Partial Waves

- Excited 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
- $i = J^P M^\epsilon \, [\xi l] \omega LS$



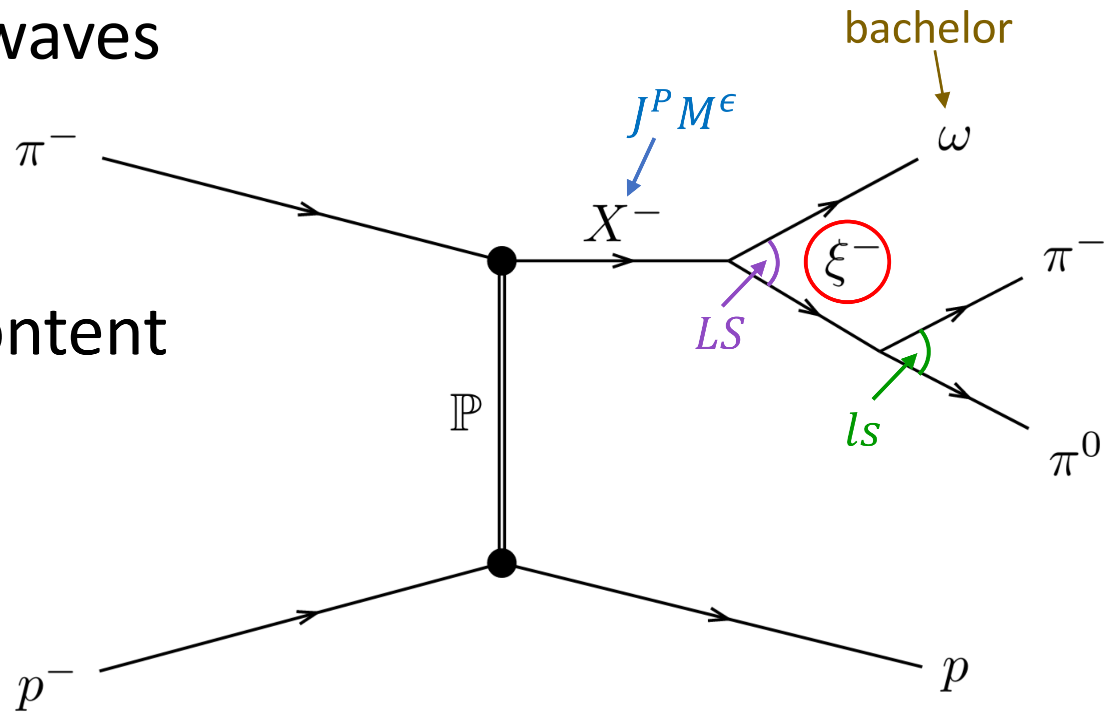
Partial-Wave Decomposition

Model measured intensity and angular distributions

- by a coherent sum over different partial waves

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

- in narrow (m_X, t') cells
- without assumptions about resonance content of X^- in partial waves



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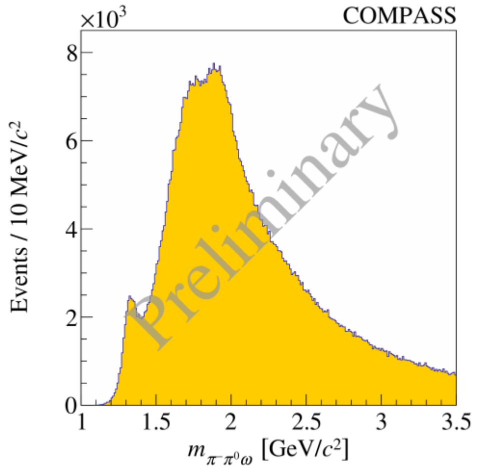

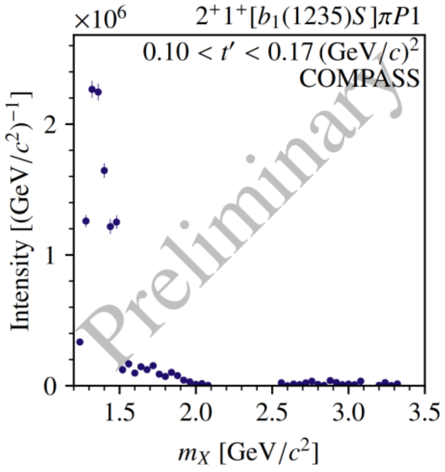

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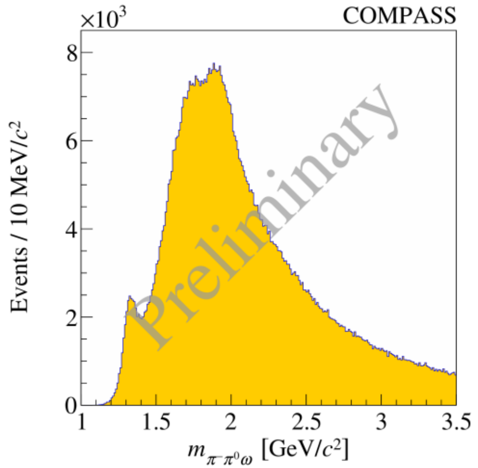

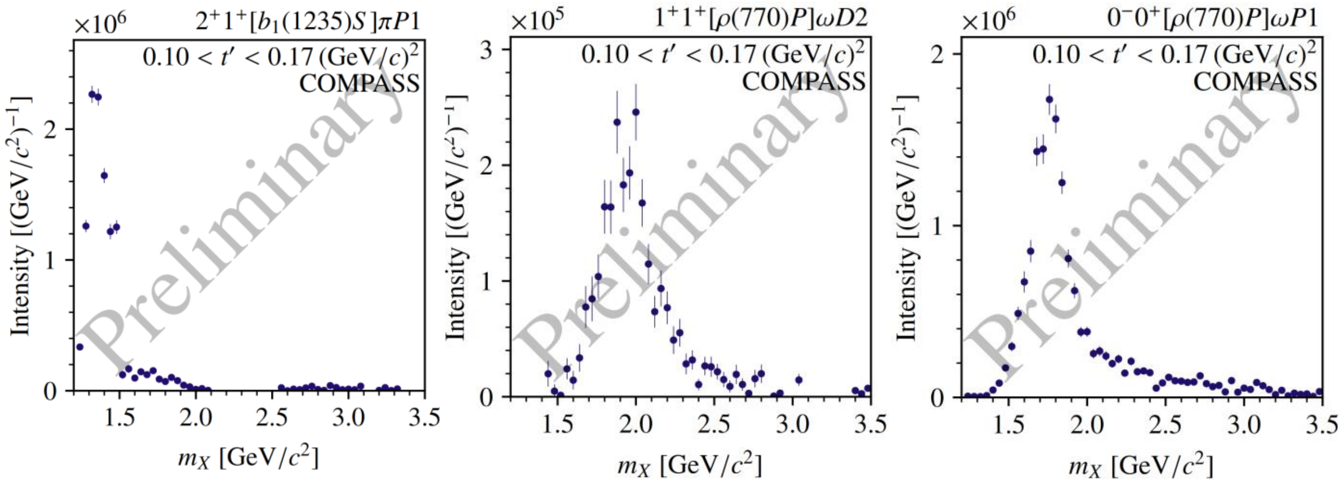

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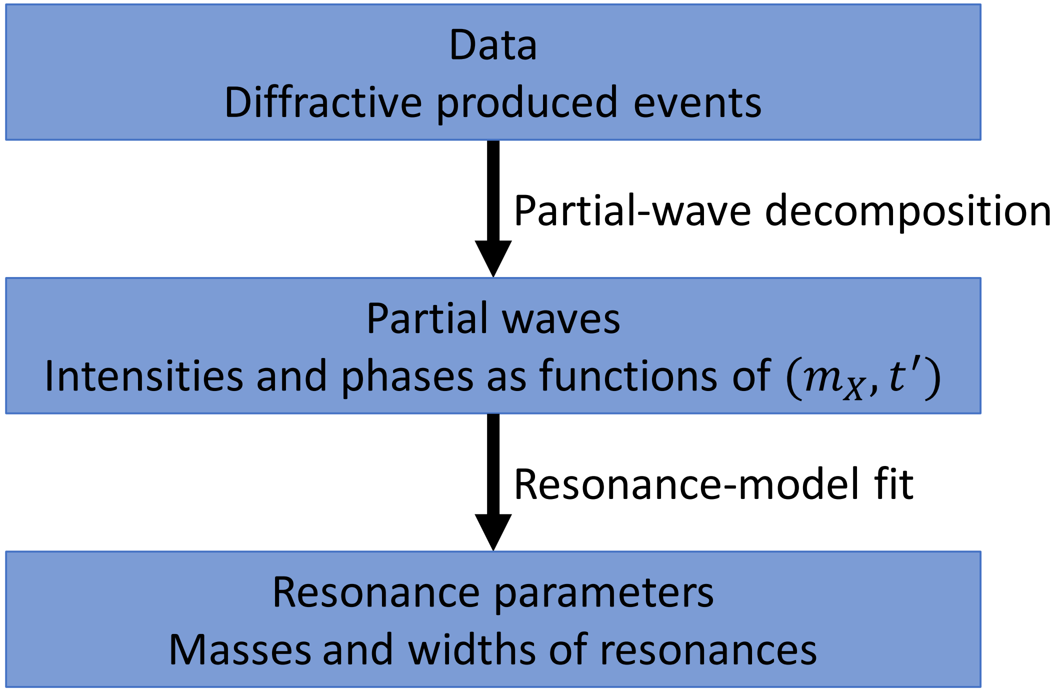
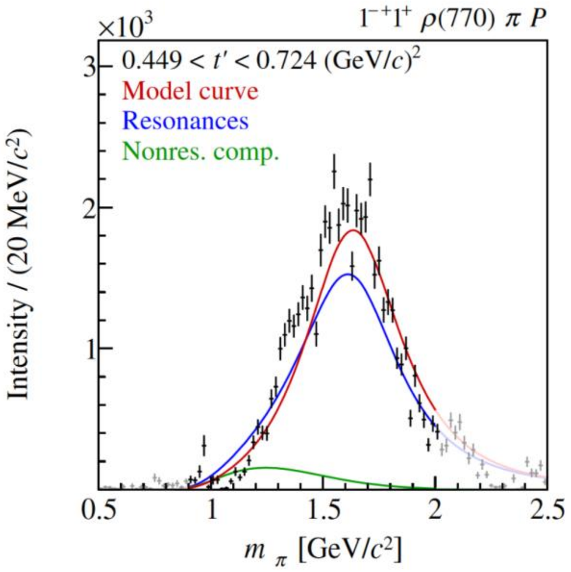


Spin-exotic 1^{-+} at COMPASS

- Non-Strange light mesons: certain J^{PC} not possible for $|q\bar{q}\rangle$ - spin-exotic
- Lattice QCD and models: lightest hybrid meson is spin-exotic 1^{-+}state

Spin-exotic 1^{-+} at COMPASS

$\pi^-\pi^-\pi^+$



Resonance parameters:

m_0 (MeV/c^2)	Γ (MeV/c^2)
1600^{+110}_{-60}	580^{+100}_{-230}

M. Aghasyan et al. (COMPASS)
Phys. Rev. D 98, 092003 [2018]

Spin-exotic 1^{-+} at COMPASS

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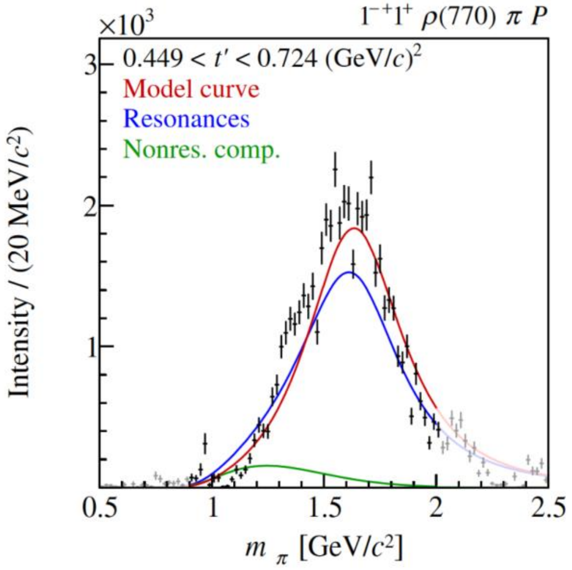

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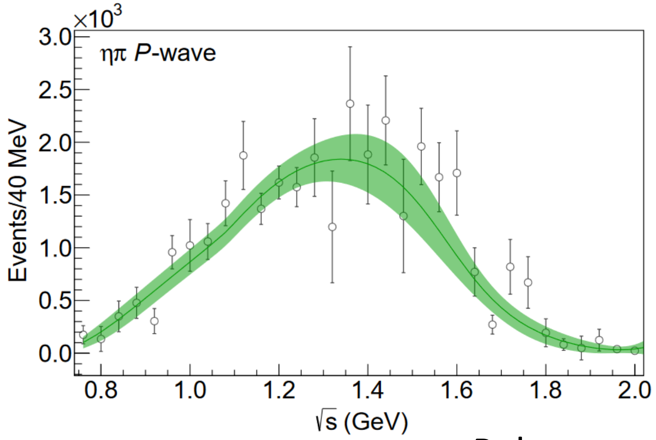
$\eta\pi^-$

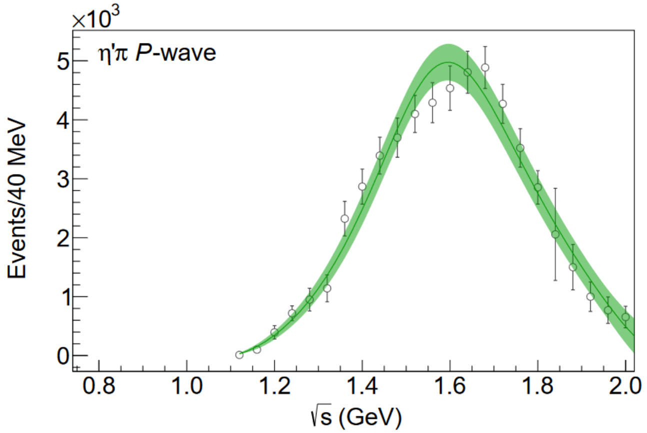
$\pi_1(1400)$?

$\eta'\pi^-$

$\pi_1(1600)$?

Coupled-channel analysis of COMPASS data by JPAC:
One pole is sufficient to describe both partial waves





Pole parameters:

m_0 (MeV/c^2)	Γ (MeV/c^2)
$1564 \pm 24 \pm 86$	$492 \pm 54 \pm 102$

A. Rodas et al. (JPAC), Phys. Rev. Lett. 122, 042002 [2019]

Extended Analysis incl. Crystal Barrel:
B. Kopf et al., Eur. Phys. J.C 81, 1056 [2021]

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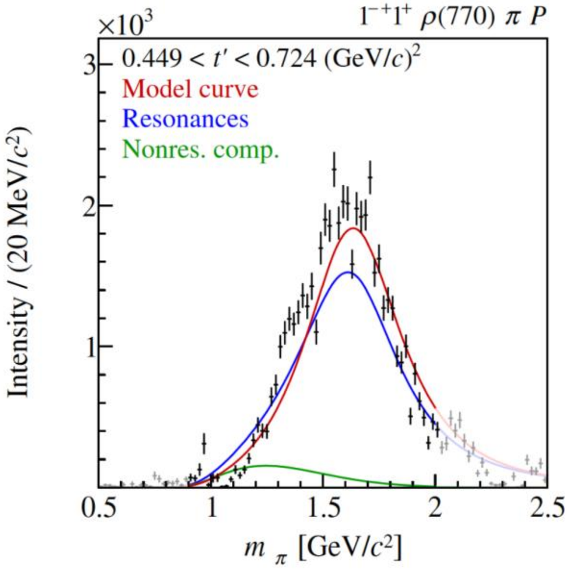

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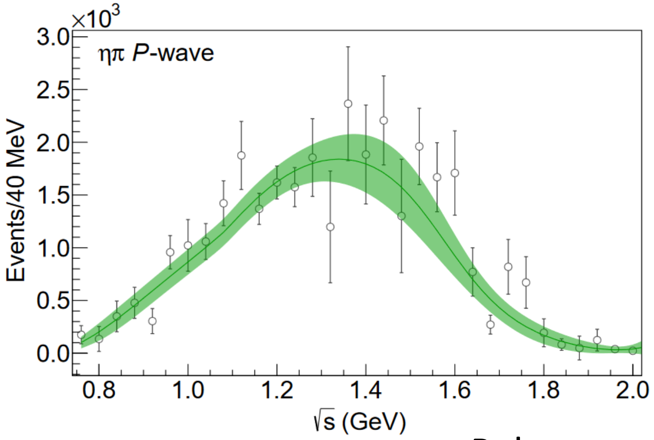

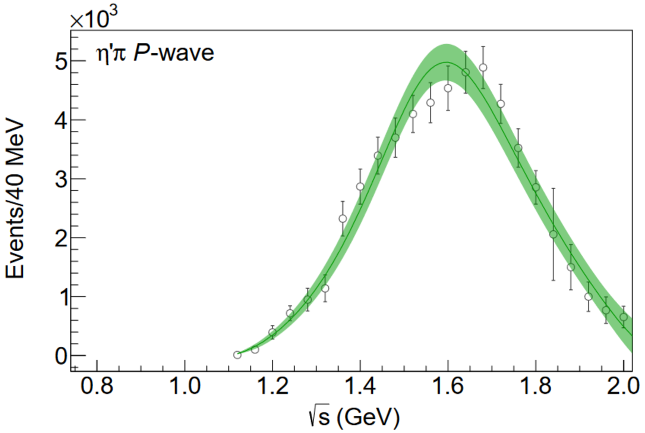

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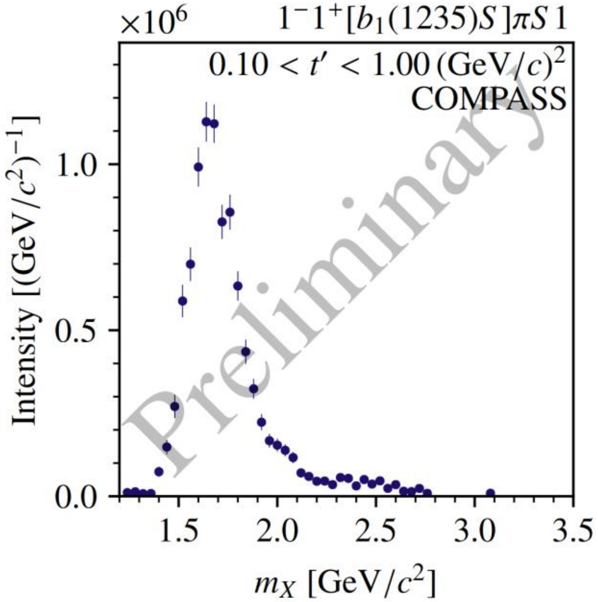
$\omega(782)\pi^-\pi^+$

- Resonance-like signal in 1^{-+}
- Resonance-model fit in progress



Non-Strange Light-Meson Spectroscopy at COMPASS

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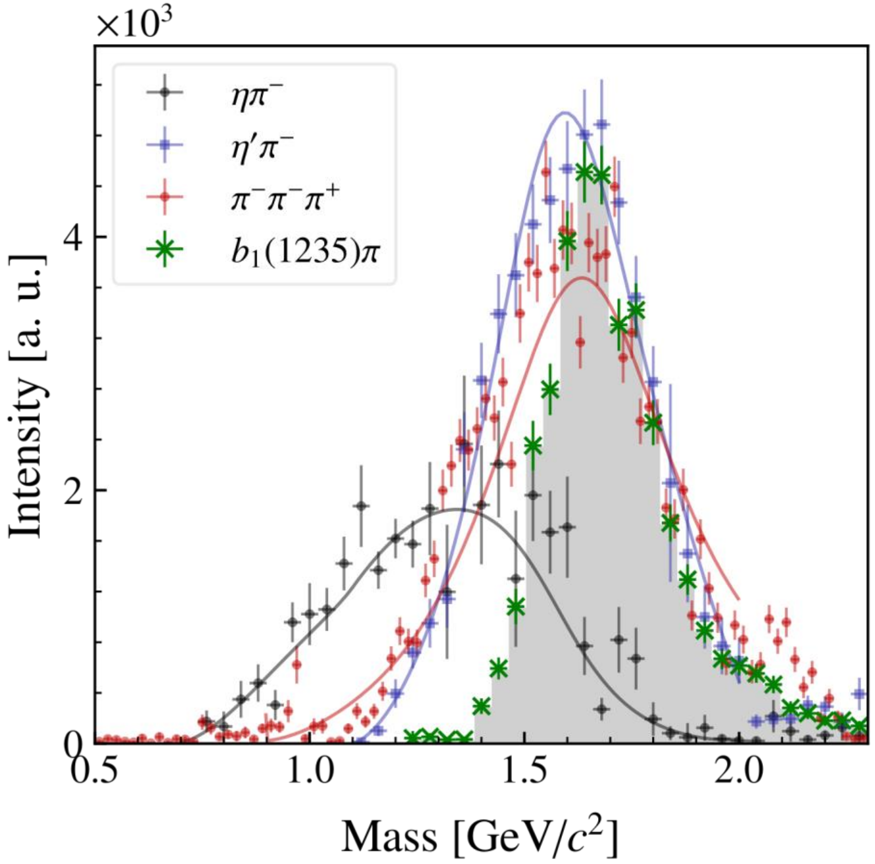
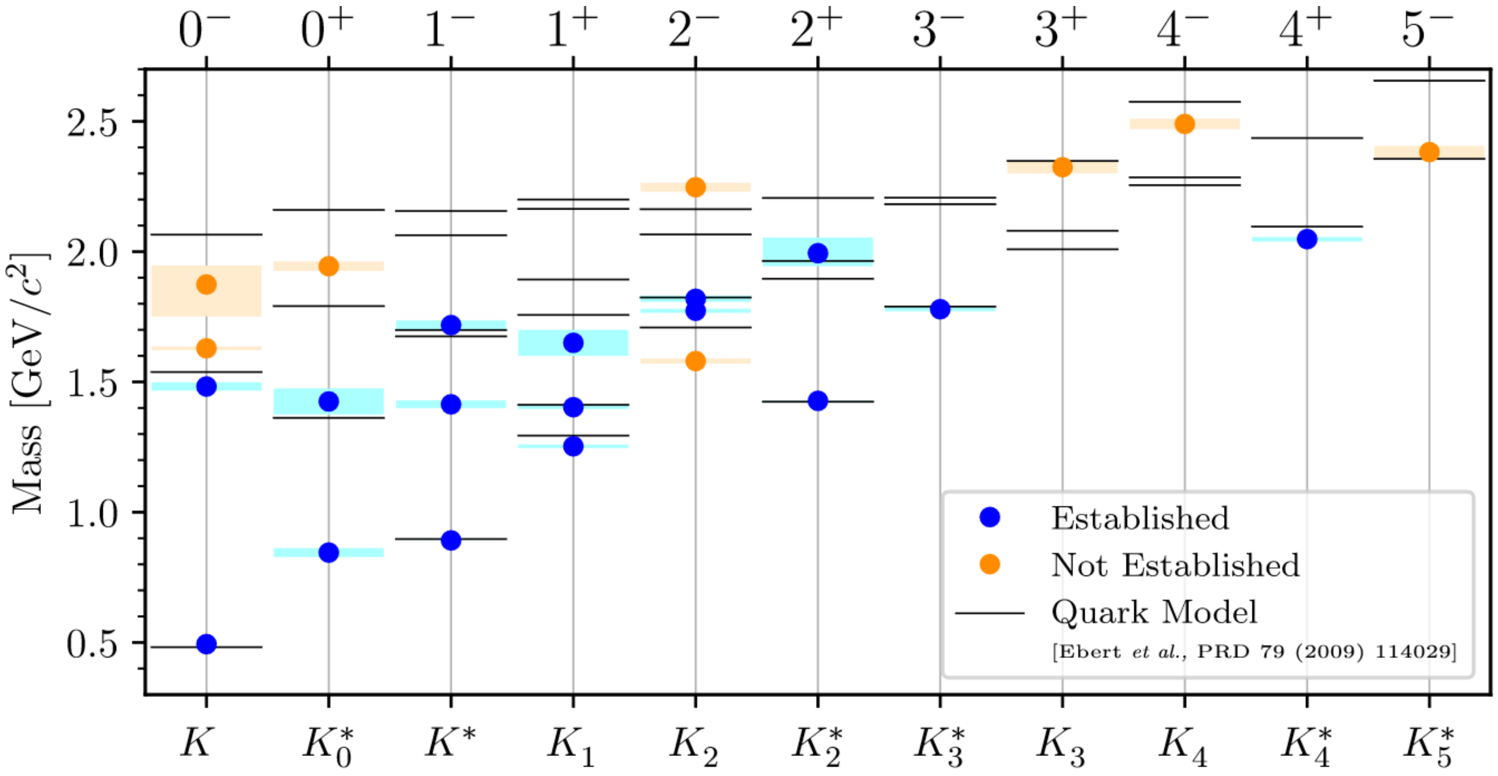
Spin-exotic 1^{-+} signals at COMPASS



⇒Non-strange light-meson spectrum well studied by COMPASS

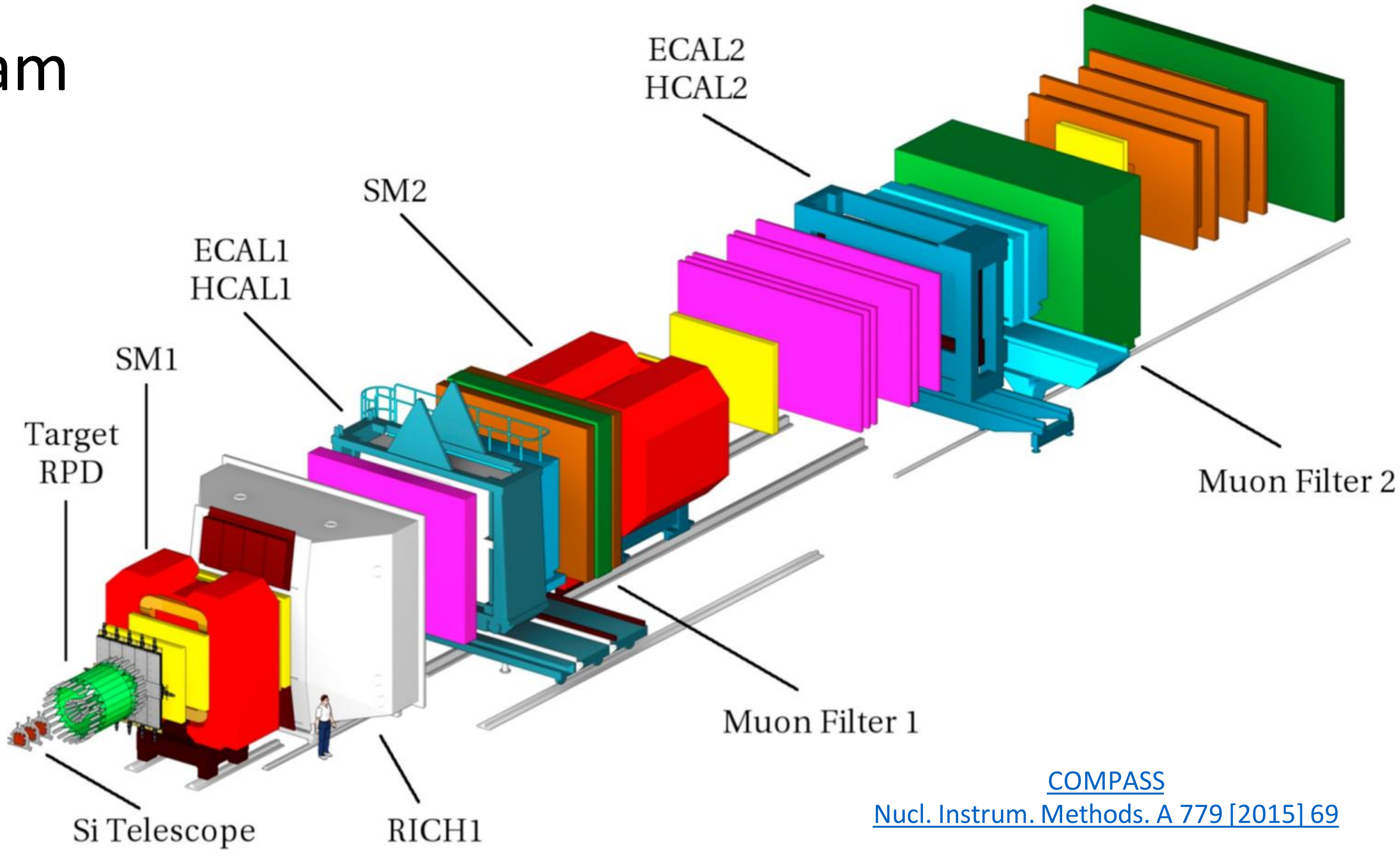
Strange-Meson Spectrum

- Many states predicted by the Constituent Quark Model not observed
- Most experimental results published 30+ years ago
- No established exotic strange meson (except $K_0^*(700)/\kappa$)



Experimental Setup

- Located at CERN SPS
- 190 GeV/c negative hadron beam
- Strange-meson spectroscopy
  $K^{-}p$ scattering



Beam:
$97\%\ \pi^{-}$
$2\%\ K^{-}$
$1\%\ \bar{p}$

[COMPASS](#)
[Nucl. Instrum. Methods. A 779 [2015] 69](#)

Experimental Setup – Particle ID

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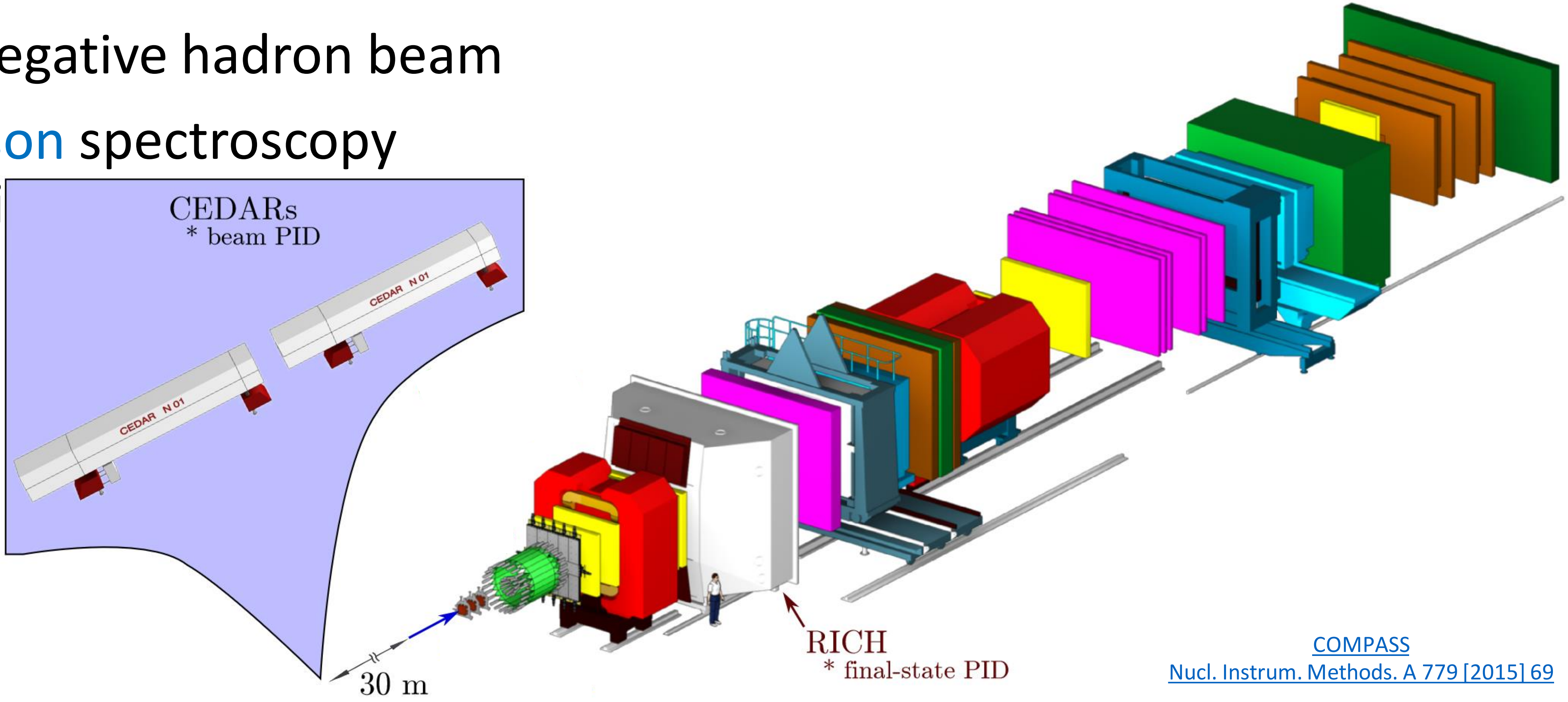

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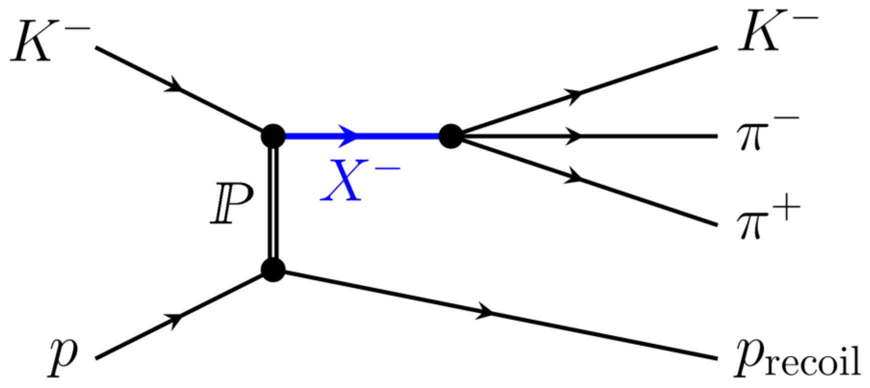
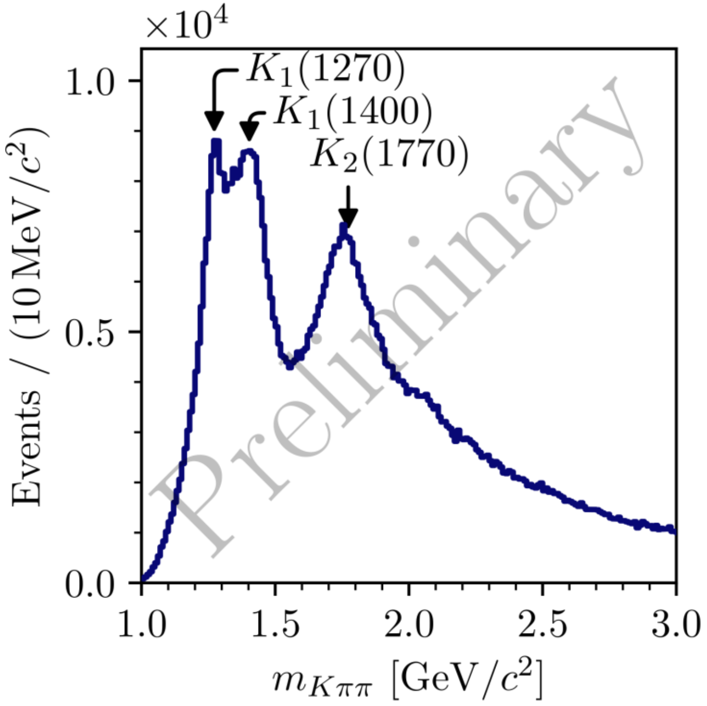
Strange-Meson Spectroscopy in $K^-\pi^-\pi^+$

- World's largest $K^-\pi^-\pi^+$ data set
  - 720k diffractive events
- Well-known states are dominant
  - $\Rightarrow$ Less well-known states not visible in $m_{K\pi\pi}$ spectrum
  - $\Rightarrow$ Partial-wave analysis reveals rich spectrum



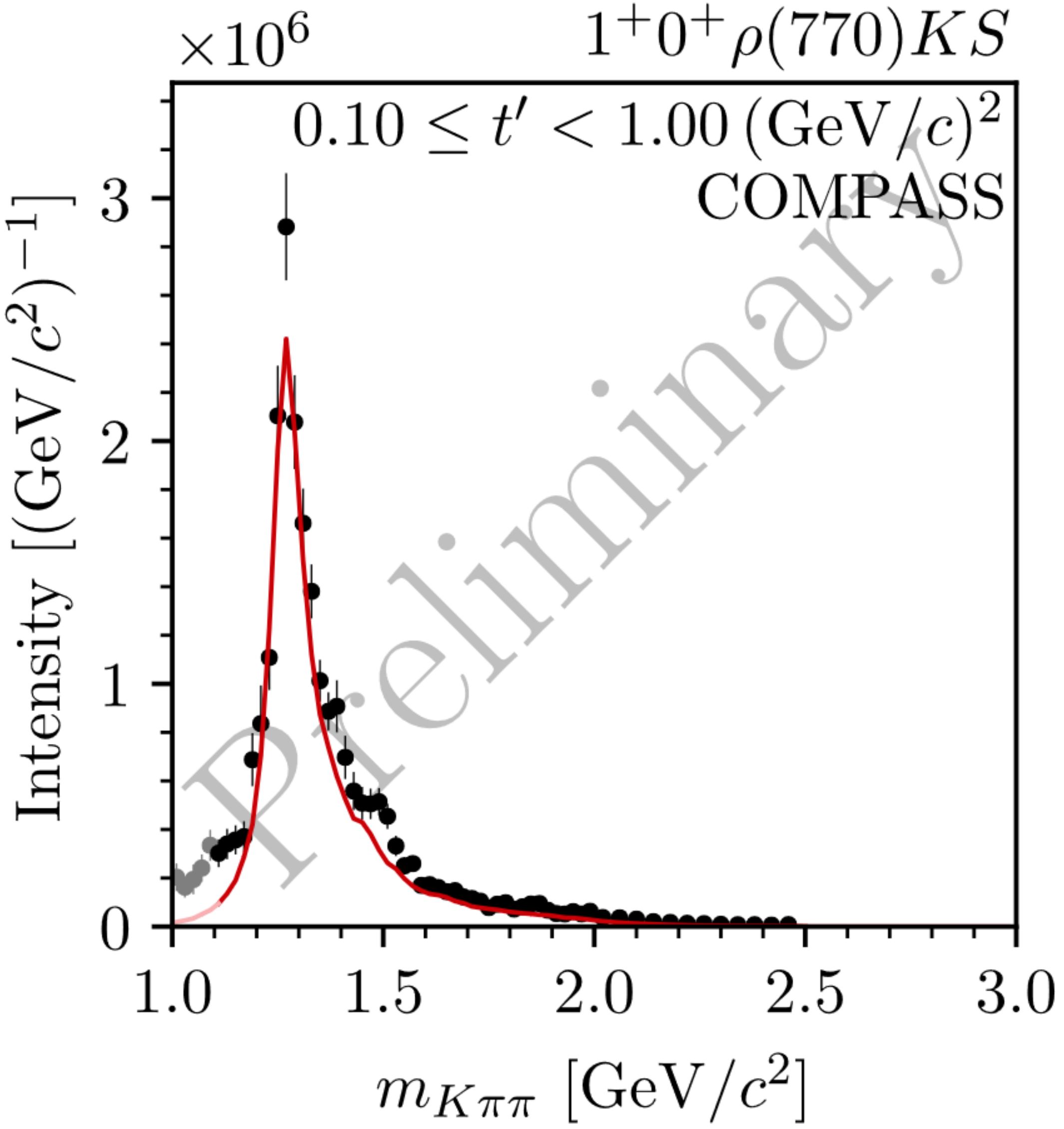


Limited final state PID of $K^-\pi^-\pi^+$

- Significant backgrounds from $\pi^-\pi^-\pi^+$, $K^-K^-K^+$,…
  ⇒Partial-wave model includes background contributions
- Final state PID only works for $p \lesssim 50\ \mathrm{GeV}/c$
  ⇒Artifacts in certain partial waves for $m_{K\pi\pi} \lesssim 1.5\ \mathrm{GeV}/c^2$

Resonance-Model Fit of $K^-\pi^-\pi^+$

- Model m_X dependence of partial waves as sum of contributions:



Resonance-Model Fit of $K^-\pi^-\pi^+$

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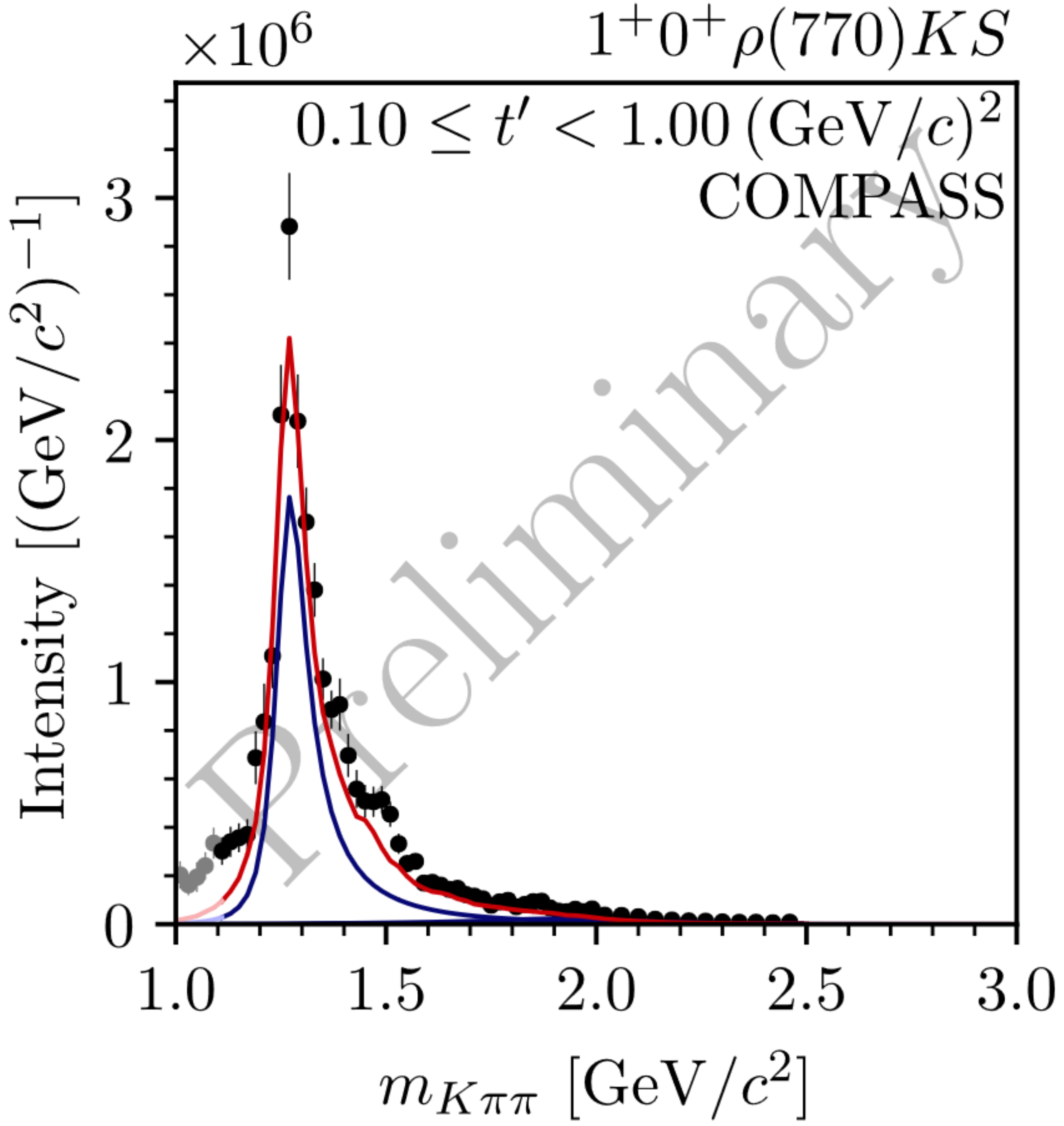
  - Breit-Wigner amplitudes of $K\pi\pi$ resonances



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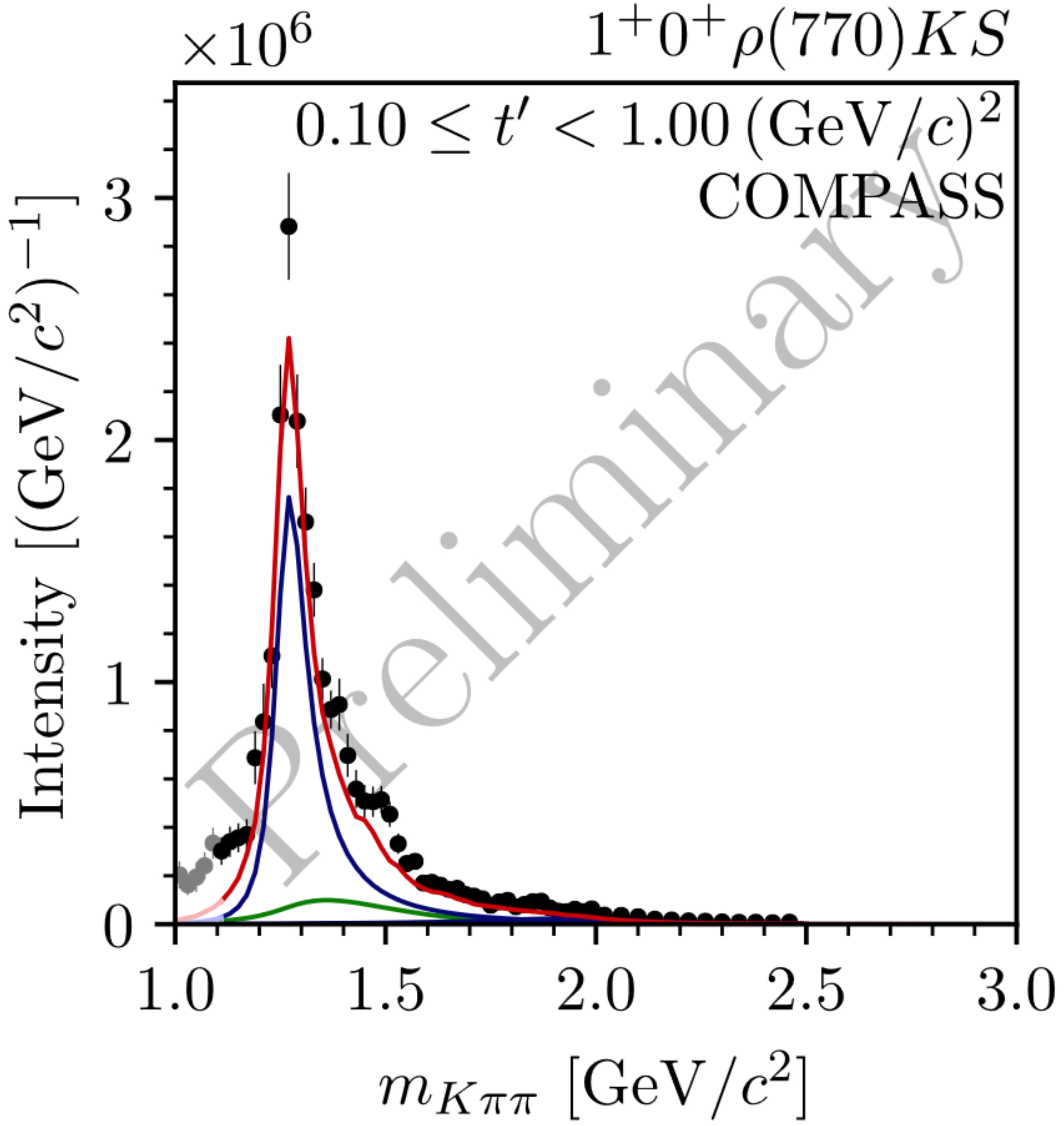

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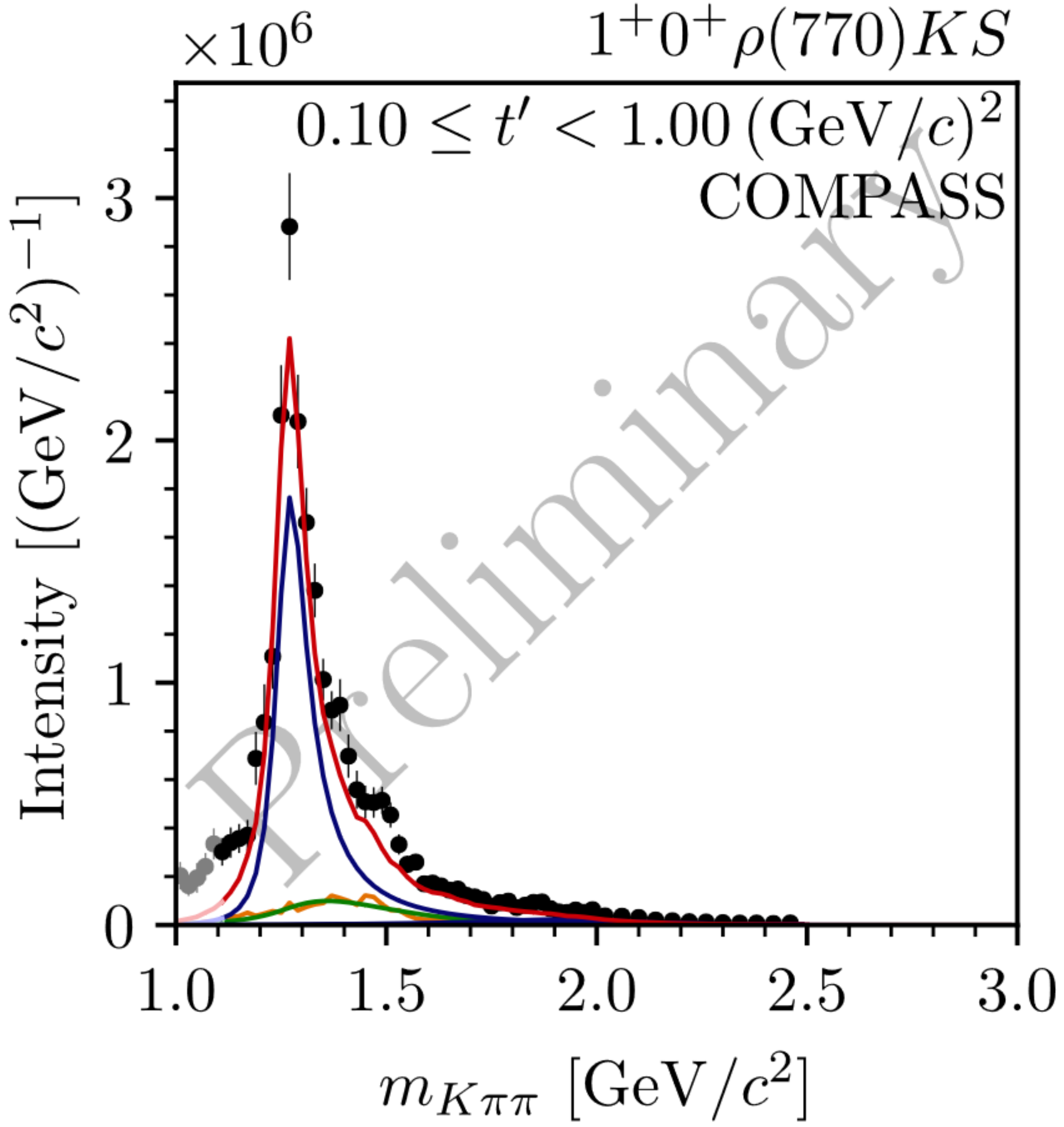
  - Incoherent $\pi^-\pi^-\pi^+$ background modeled by COMPASS $\pi^-\pi^-\pi^+$ analysis



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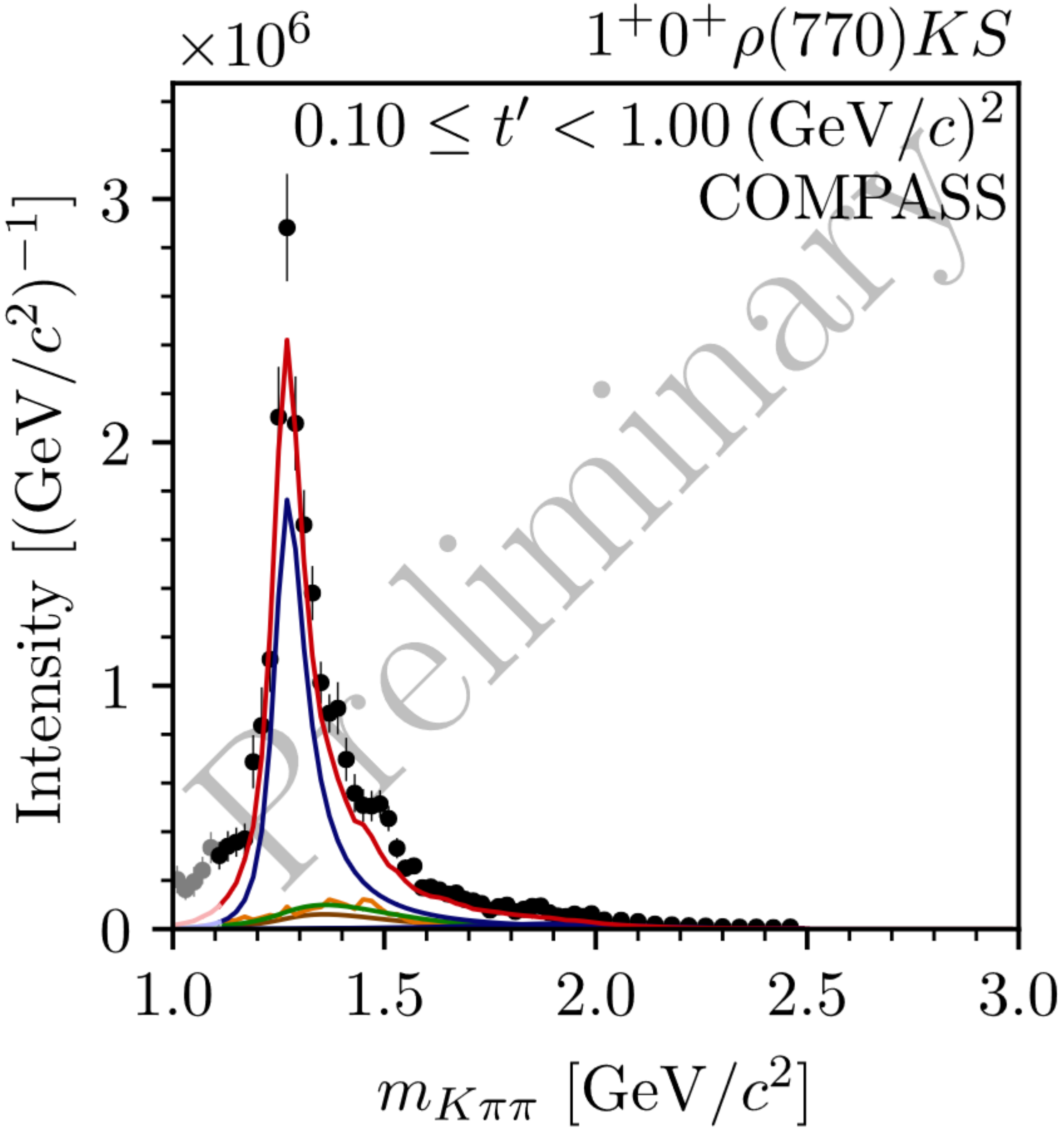
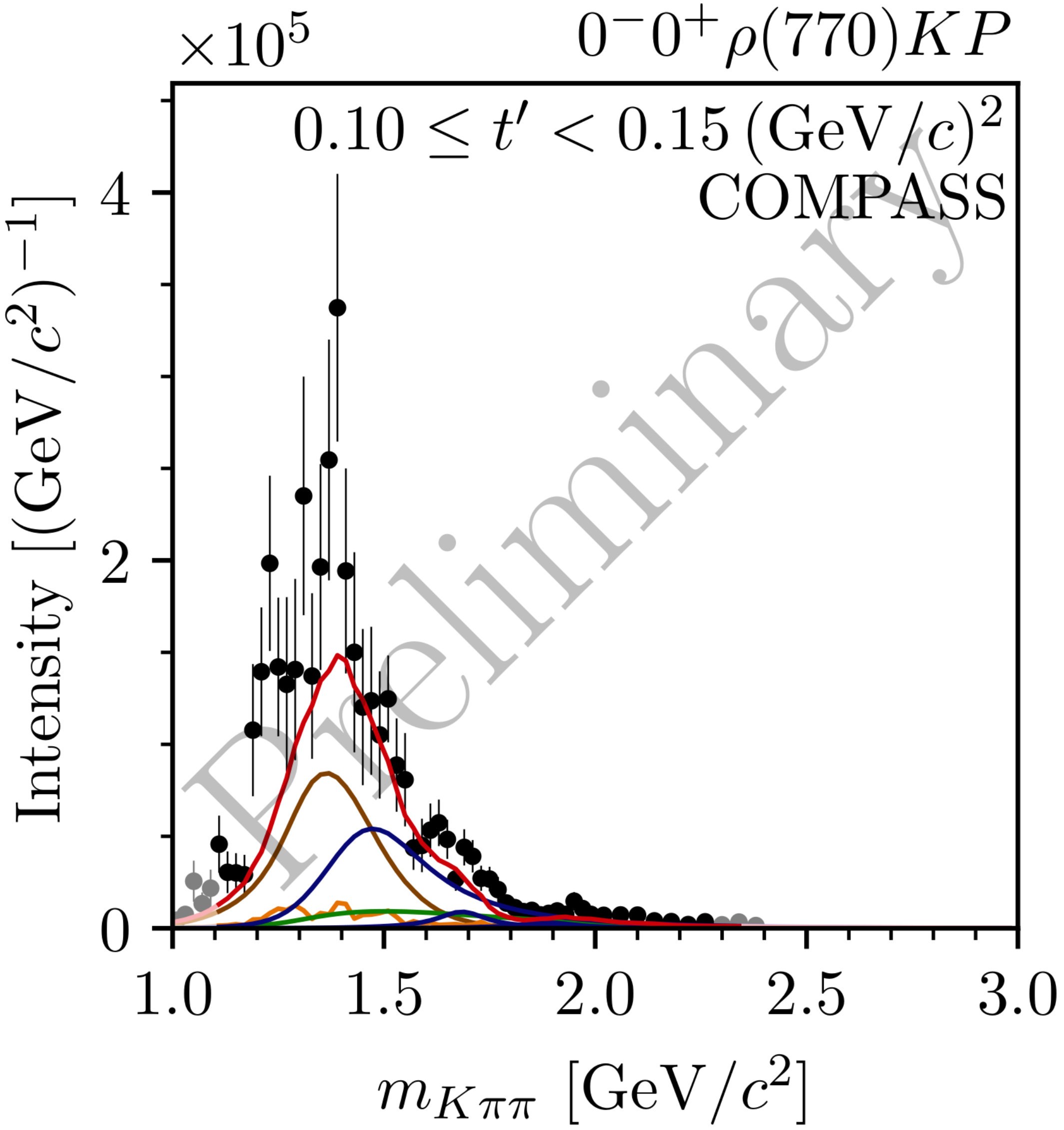
  - Incoherent effective background for other background processes



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

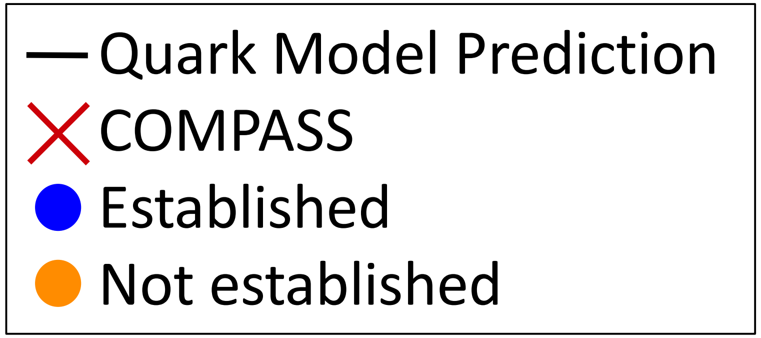
- $K(1460)$ peak at about 1.4 GeV/c^2
  - Established state
  - Increased background below 1.5 GeV/c^2

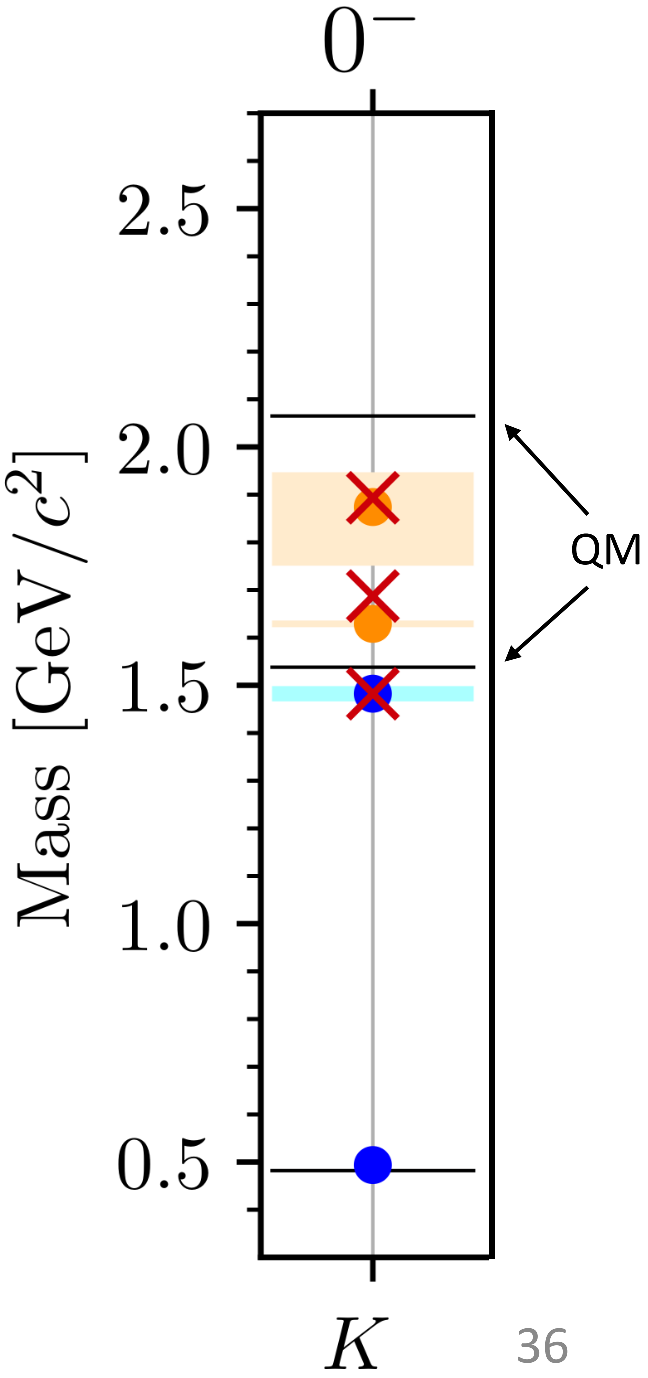
  $\Rightarrow$ Fixed Breit-Wigner resonance
- $K(1630)$ peak at about 1.7 GeV/c^2
  - 8.3σ statistical significance
- $K(1830)$ peak at about 2.0 GeV/c^2
  - 5.4σ statistical significance



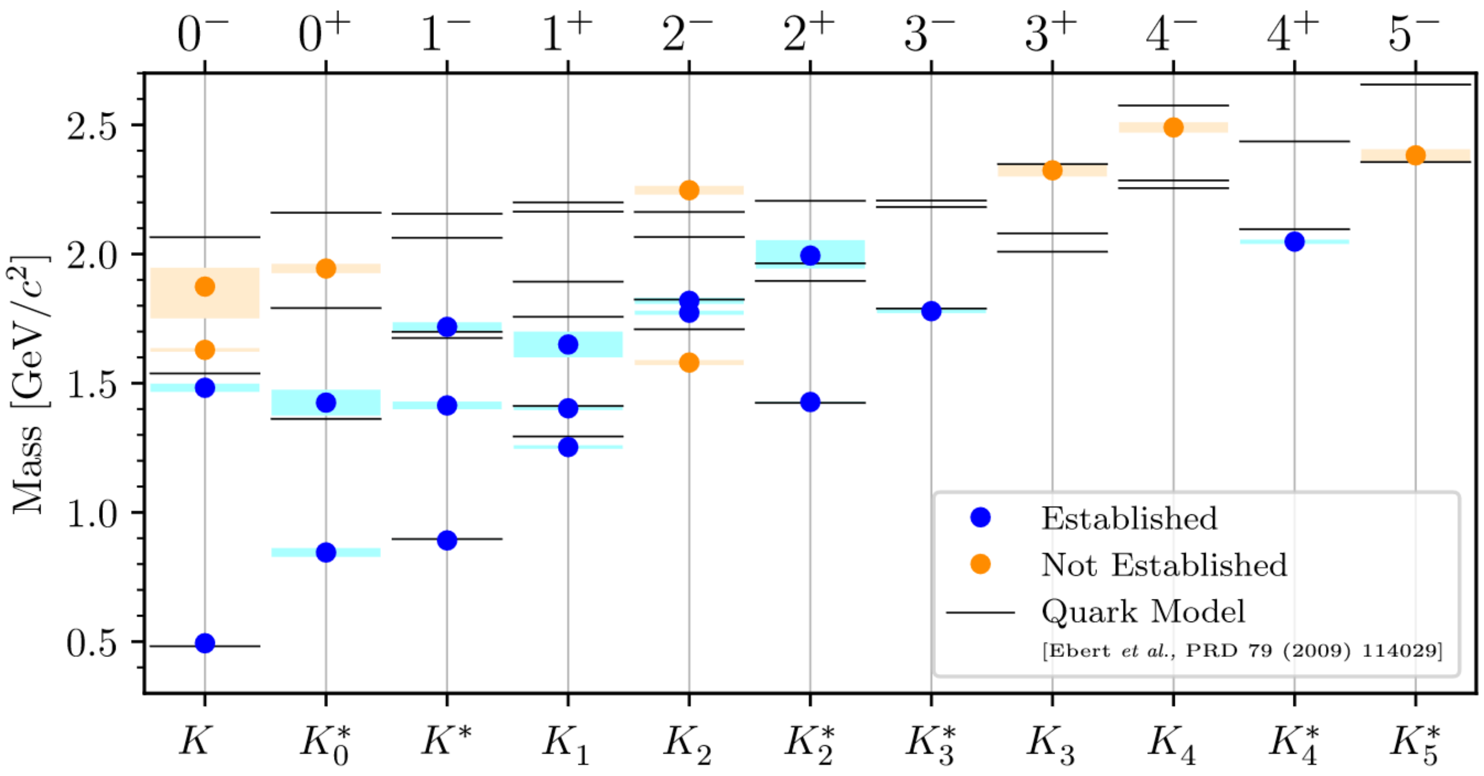
Strange Mesons with $J^P = 0^-$

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





Strange Mesons



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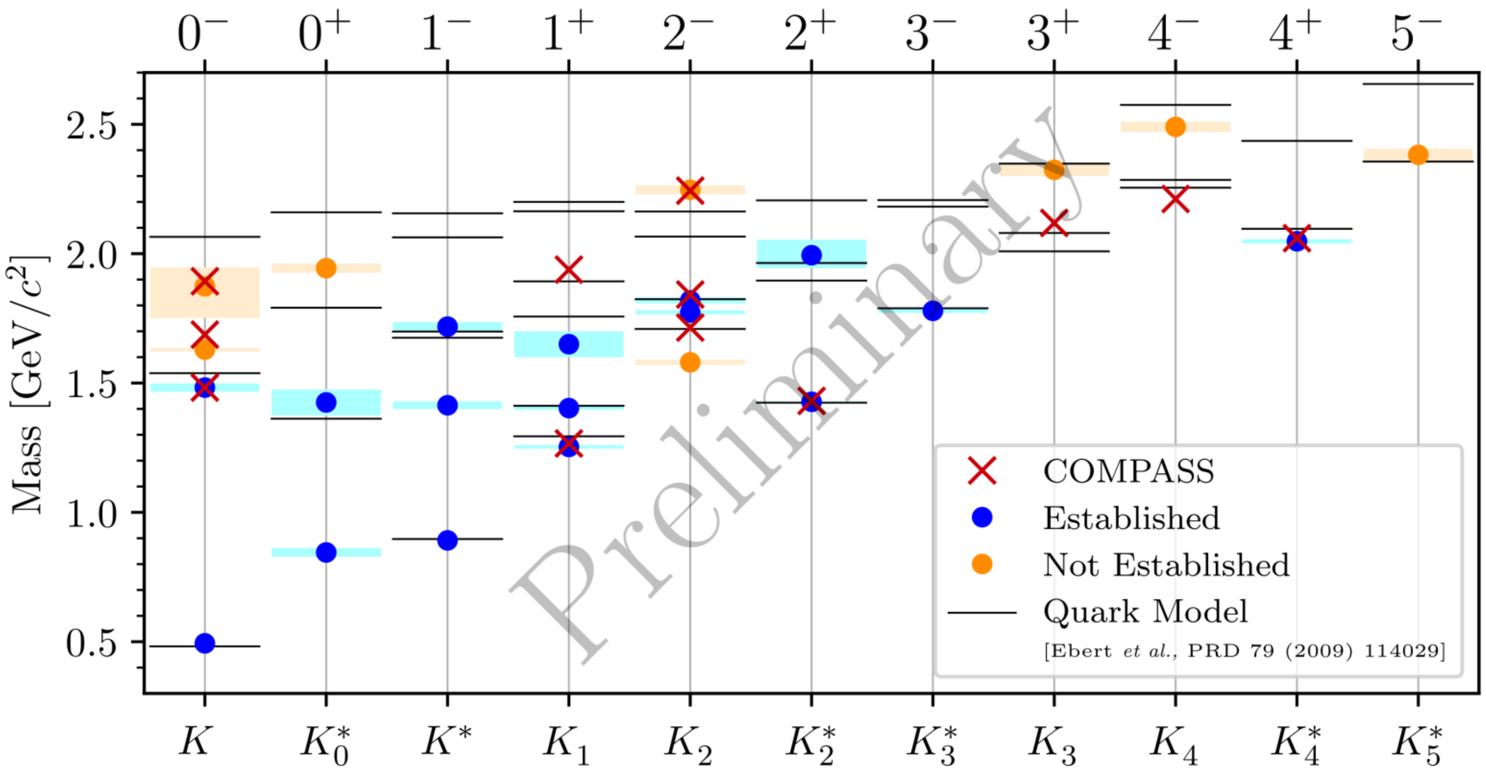
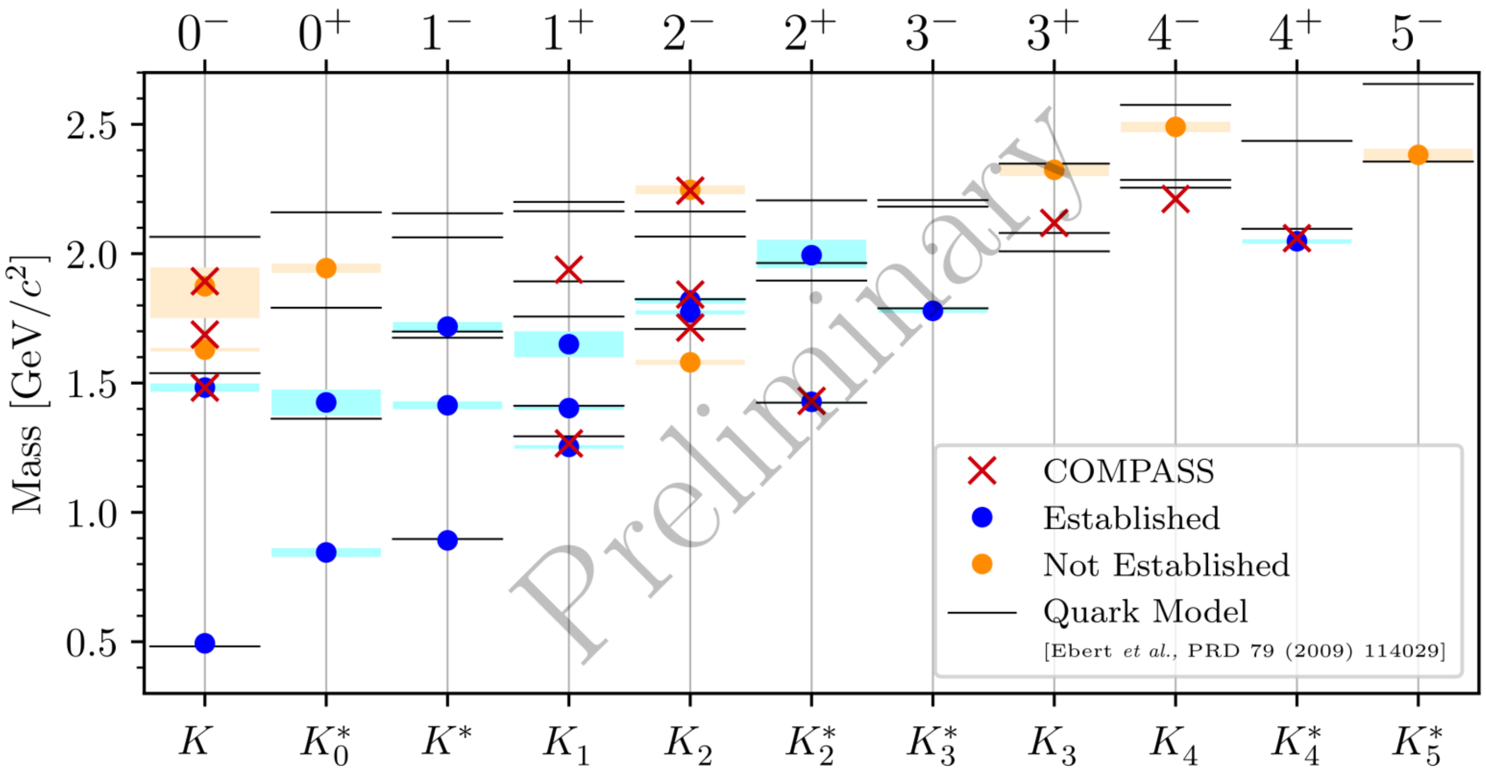


- Most comprehensive analysis of $K^-\pi^-\pi^+$
  - 11 states extracted from COMPASS data

Strange Mesons



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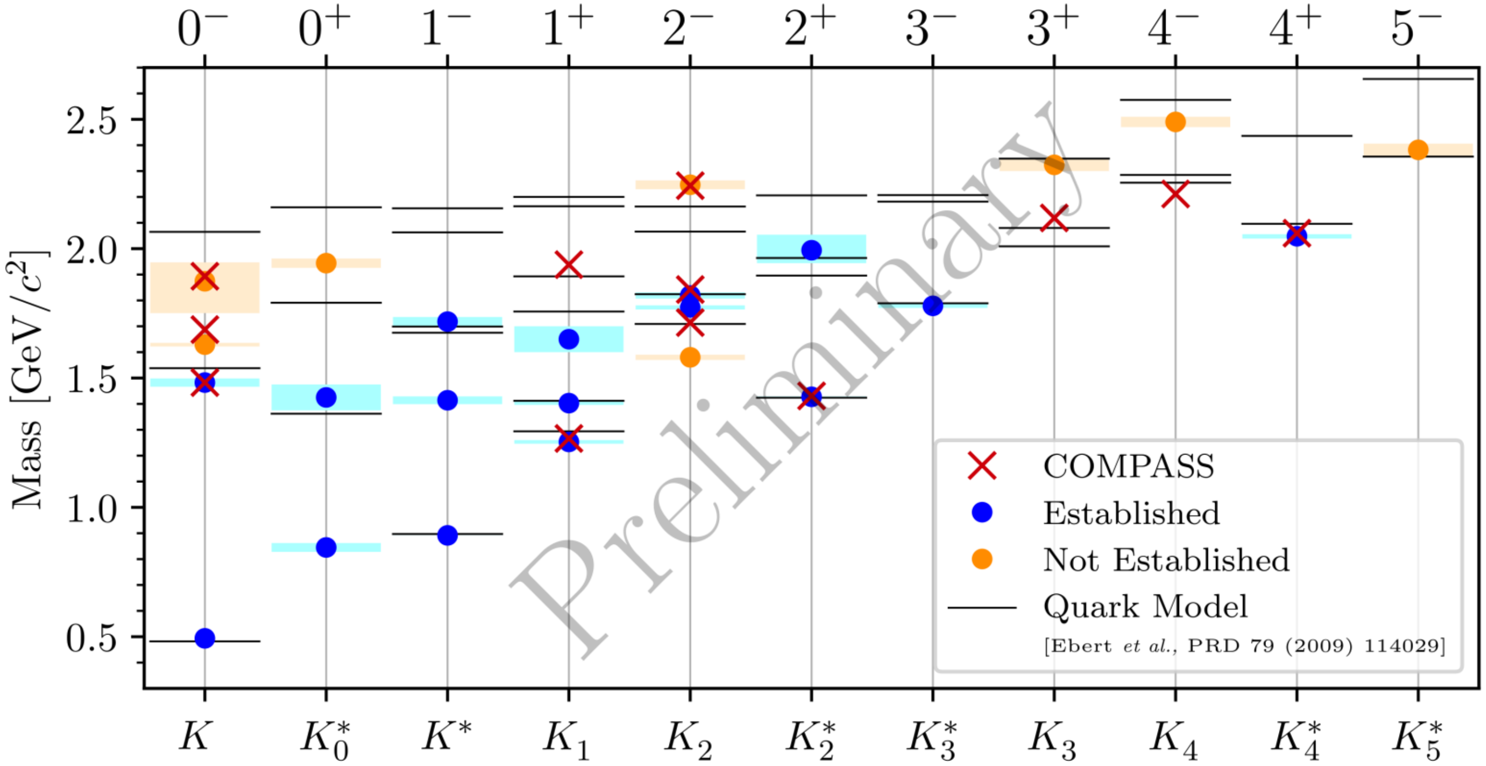
⇒Strange light-meson spectrum is studied by COMPASS

Strange Mesons



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

⇒Strange light-meson spectrum is studied by COMPASS
But limited due to final state PID

Conclusion & Outlook

- COMPASS contributes to the knowledge of the light meson spectrum by studying many different final states in great detail
  - Exotic $\pi_1(1600)$ observed in multiple final states
- Most comprehensive analysis of the $K^-\pi^-\pi^+$ final state
  - Measured resonance parameters of 11 states
  - Exotic strange-meson candidate: Supernumerary state in $J^P = 0^-$
- Active analysis of other final states: $f_1\pi^-$, $K_S K^-$, $K_S K_S \pi^-$, $K_S\pi^-$, $\Lambda\bar{p}$

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  - Measured resonance parameters of 11 states
  - Exotic strange-meson candidate: Supernumerary state in $J^P = 0^-$
- Active analysis of other final states: $f_1\pi^-$, $K_S K^-$, $K_S K_S \pi^-$, $K_S\pi^-$, $\Lambda\bar{p}$
- AMBER phase-II: Strange-meson spectroscopy

  $\Rightarrow$Promising experiment to probe strange-meson spectrum with even higher precision

  B. Seitz: Status of the AMBER Phase-2 Proposal Preparation (Tue, 14:30)

Backup

Limited final state PID of $K^-\pi^-\pi^+$

- Significant backgrounds from $\pi^-\pi^-\pi^+, K^-K^-K^+,\ldots$
  - $\Rightarrow$Partial-wave model includes background contributions
- Limited acceptance
  - $\Rightarrow$Artifacts in certain partial waves for $m_{K\pi\pi} \lesssim 1.5$ GeV