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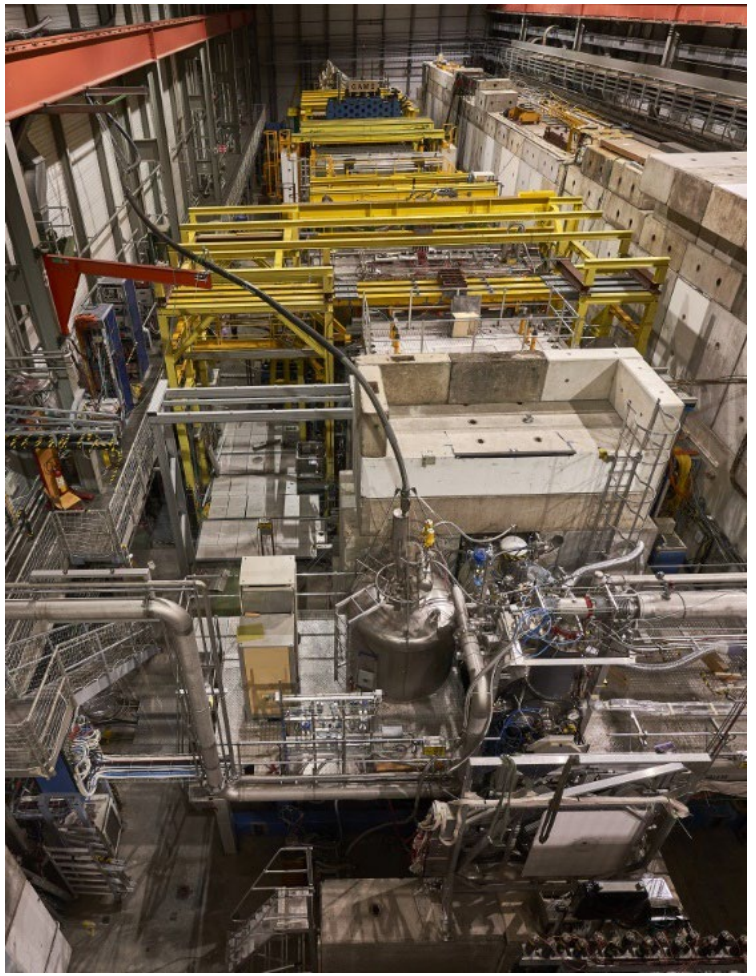
EXOTIC MESONS FROM COMPASS TO AMBER

Apparatus for Meson and Baryon Experimental Research

Bernhard Ketzer
University of Bonn

20th International Conference on Hadron Spectroscopy and Structure (HADRON 2023)
06 June 2023



EXOTIC STATES

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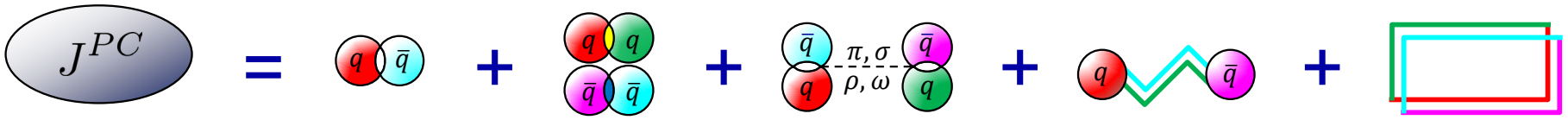
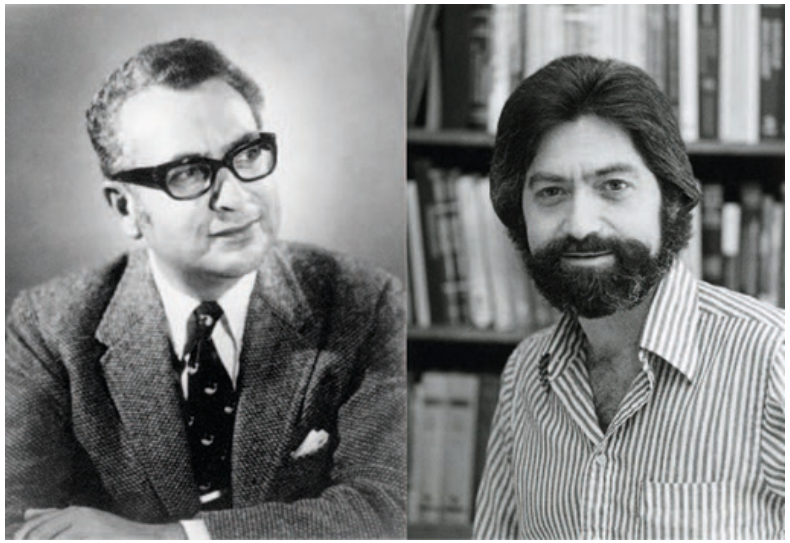


$(q\bar{q})_0$ $(qq)_8(\bar{q}\bar{q})_8$ $(q\bar{q})_0(q\bar{q})_0$ $(q\bar{q})_8 g$ $(gg)_0$

Tetraquark Molecule Hybrid Glueball

+ …



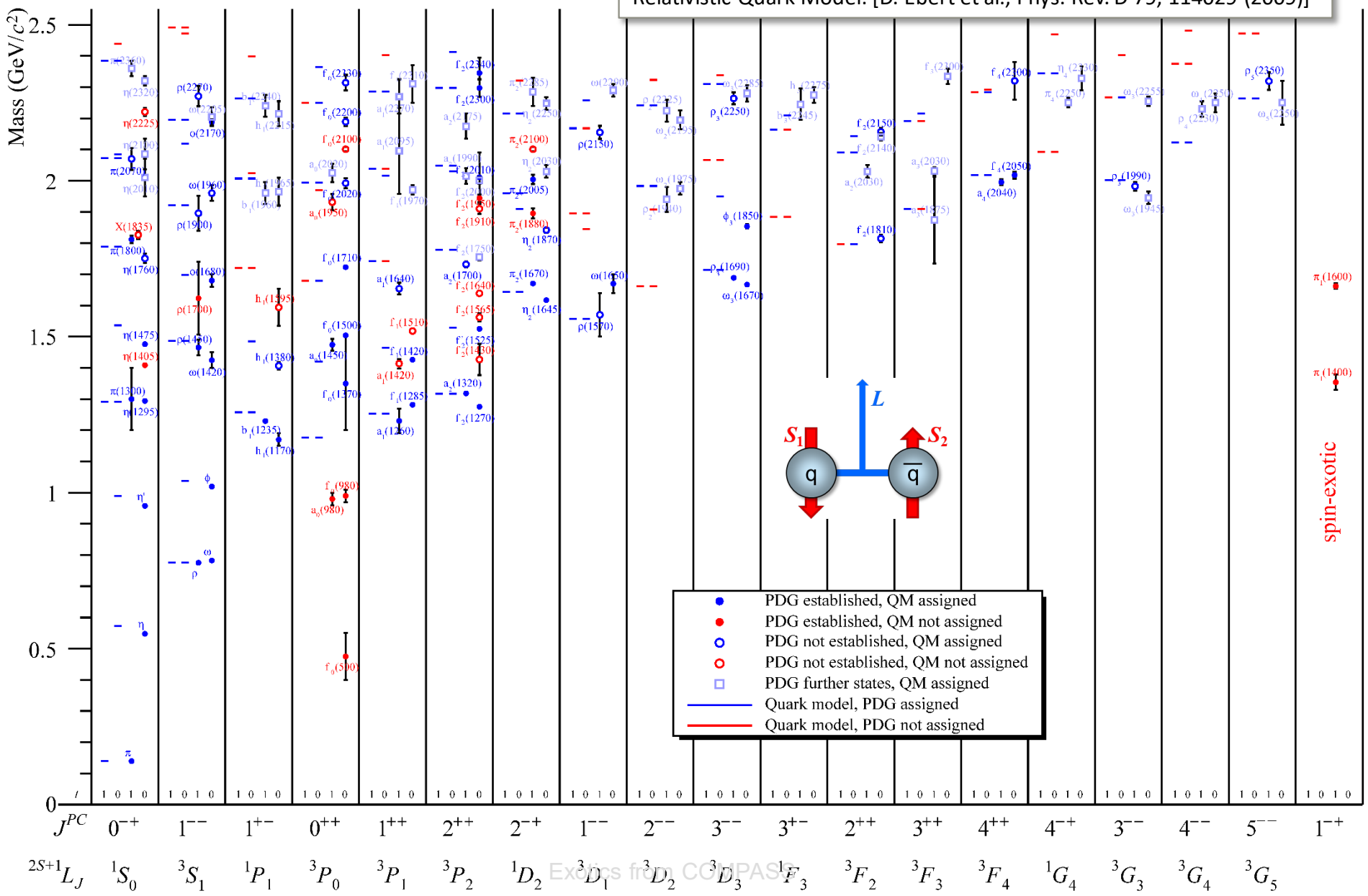
Where are they?

How to identify them?

- Spin-exotic: $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, \ldots$
- Supernumerary states
- Flavor-exotic: $|Q|, |I_3|, |S|, |C| \geq 2$
- Comparison with theory: models, lattice

LIGHT-MESON SPECTRUM

[B. Ketzer et al., Prog. Part. Nucl. Phys. 113, 103755 (2020)]
Relativistic Quark Model: [D. Ebert et al., Phys. Rev. D 79, 114029 (2009)]



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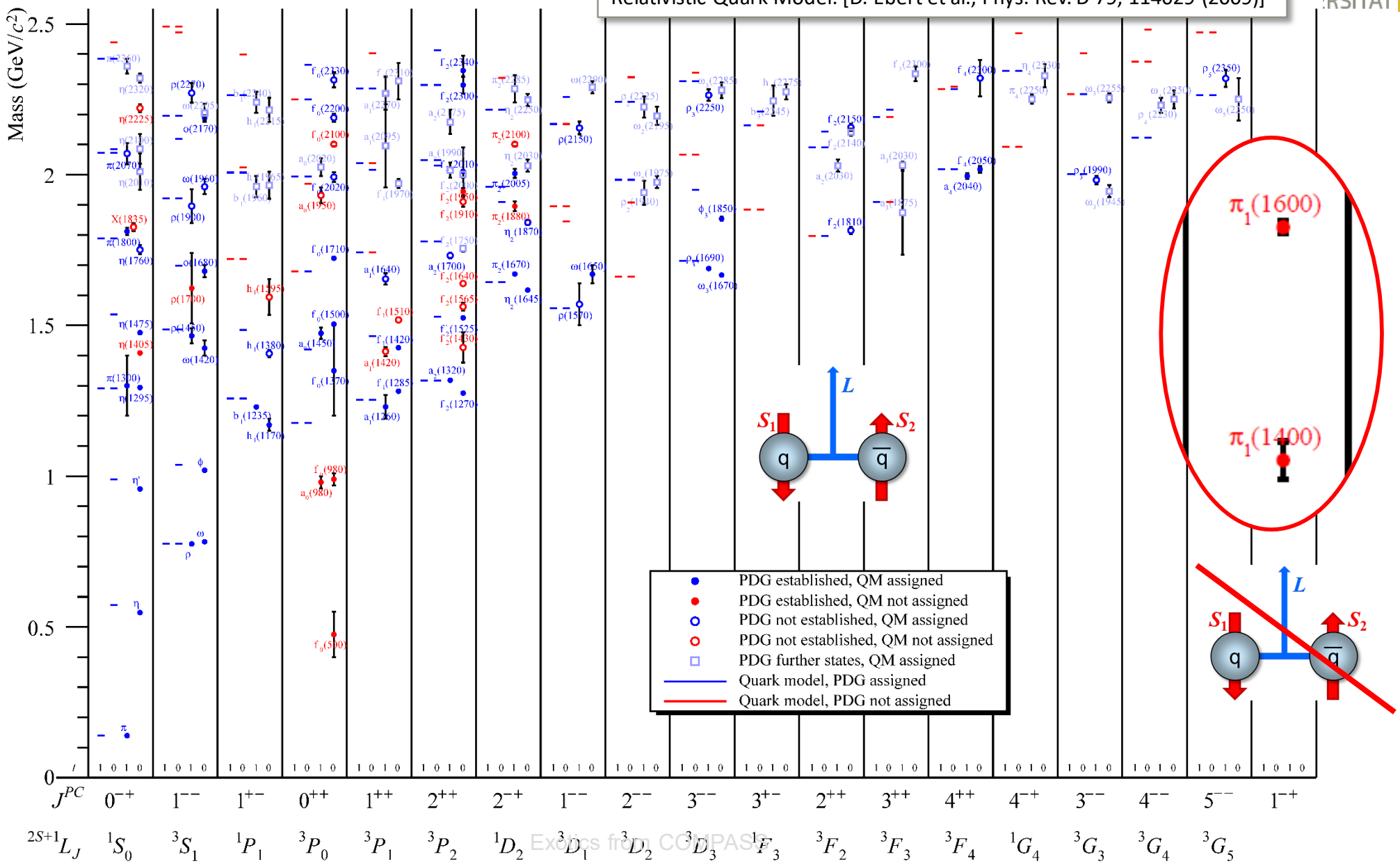

THE COMPASS EXPERIMENT

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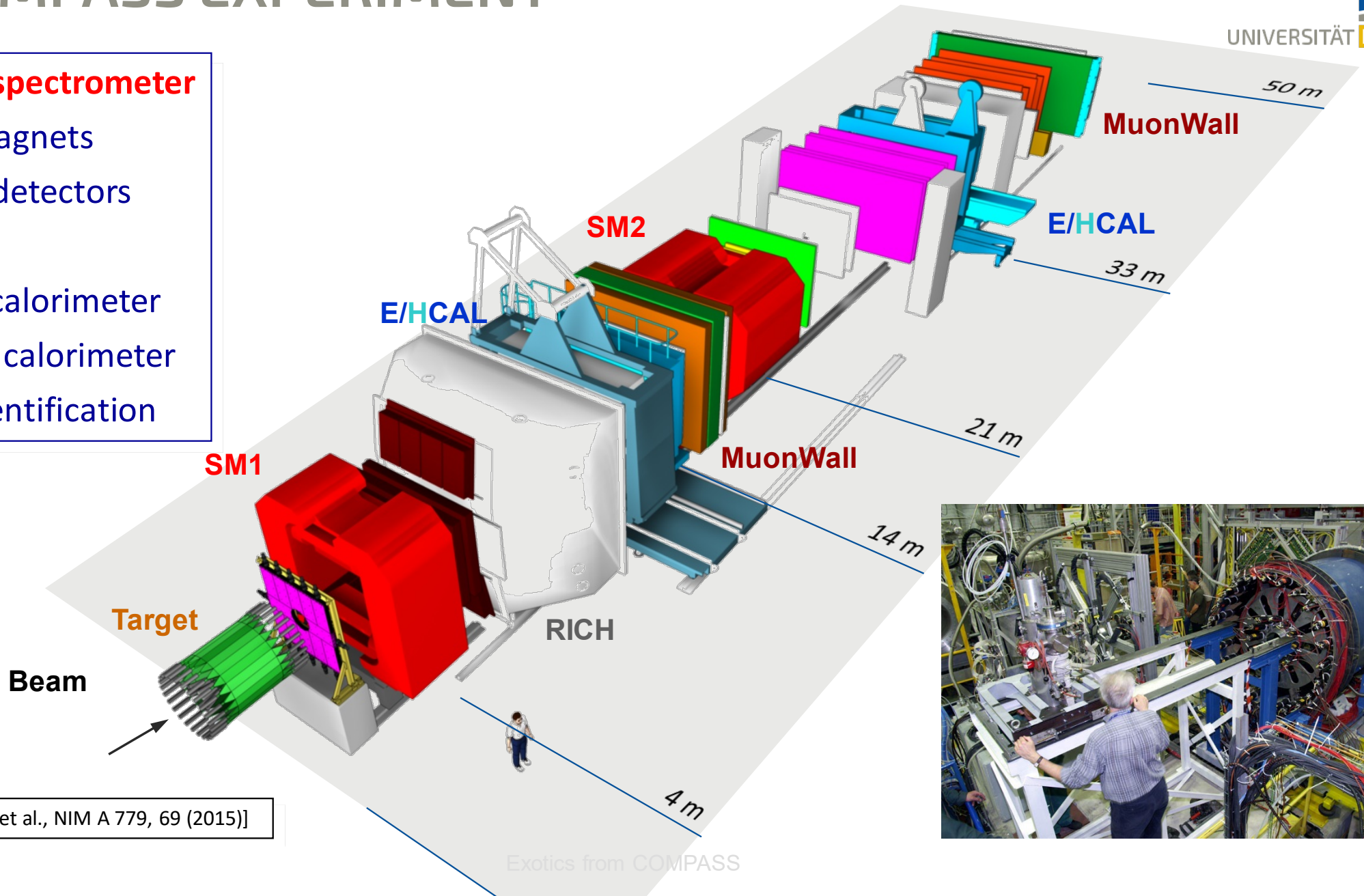
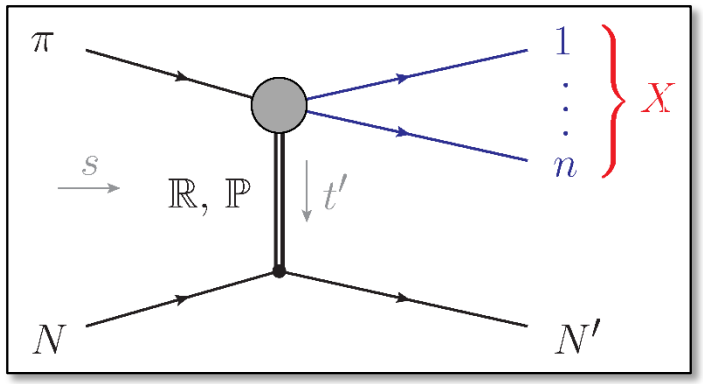
Two-stage spectrometer

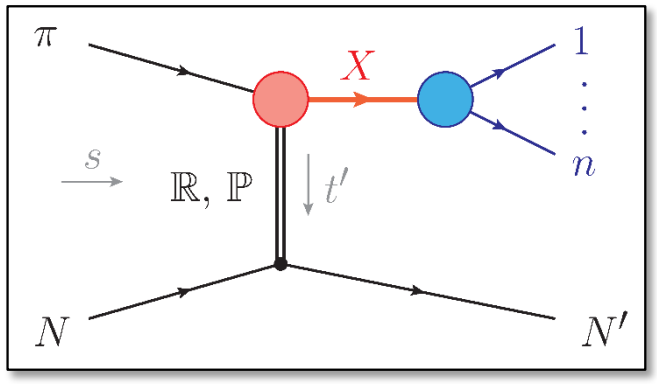
- Dipole magnets
- Tracking detectors
- RICH
- El.-mag. calorimeter
- Hadronic calorimeter
- Muon identification

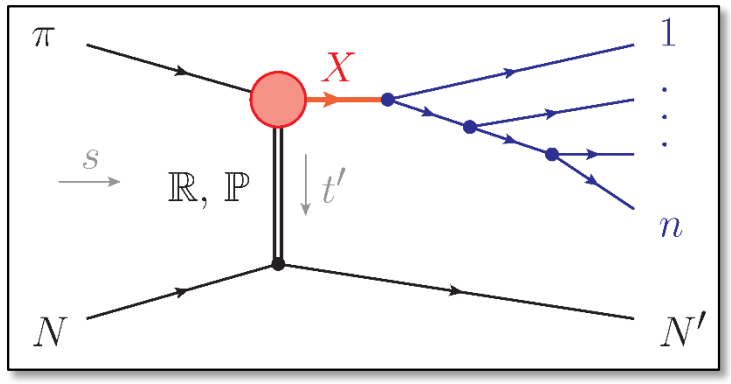


[COMPASS, P. Abbon et al., NIM A 779, 69 (2015)]

PARTIAL-WAVE ANALYSIS







PWA performed in two steps:

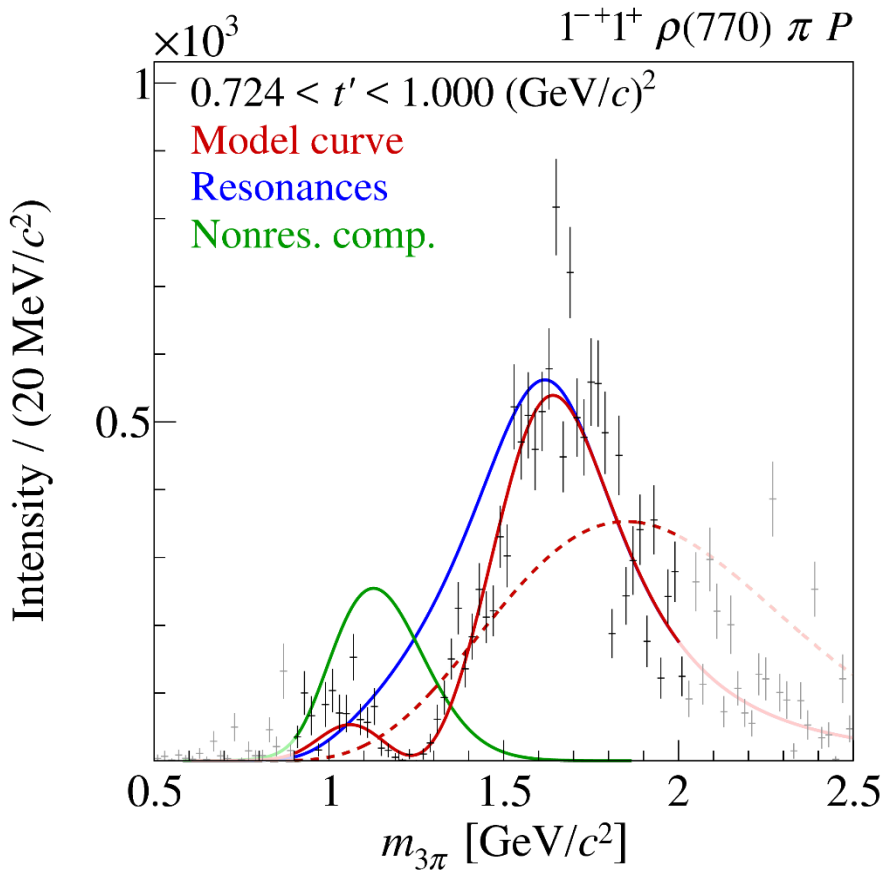
1. Partial-wave decomposition in small bins of m_X and t'

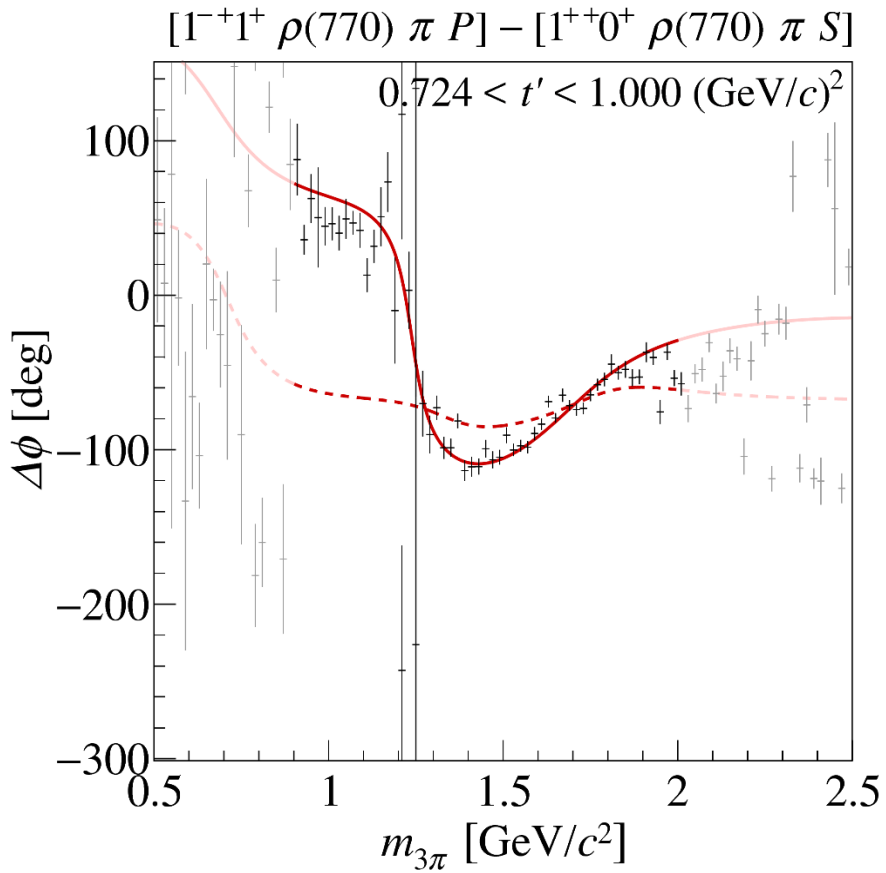
$$\mathcal{I}(\tau_n; m_X, t') = \left| \sum_i^{N_{\text{waves}}} \mathcal{T}_i(m_X, t')\, \Psi_i(\tau_n; m_X) \right|^2$$

   - makes no assumptions on resonance content of partial wave
   - assumes that production and decay of X factorize
   - decay into multi-body final state is described by sequence of 2-body decays (isobars)
   - extended max. likelihood fit, takes into account acceptance of the apparatus

2. Resonance-model fit of spin-density matrix elements $\rho_{ij}(m_X, t') := \mathcal{T}_i(m_X, t')\mathcal{T}_j^*(m_X, t')$
   - determine resonance parameters
   - use only subset of SDM

3π FINAL STATE – 1^{-+} PARTIAL WAVE





Bad description of data without 1^{-+} resonance

⇨ $\pi_1(1600)$ needed to describe data

$M_0 = 1600^{+110}_{-60}\ \mathrm{MeV}/c^2$

$\Gamma_0 = 580^{+100}_{-230}\ \mathrm{MeV}/c^2$

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

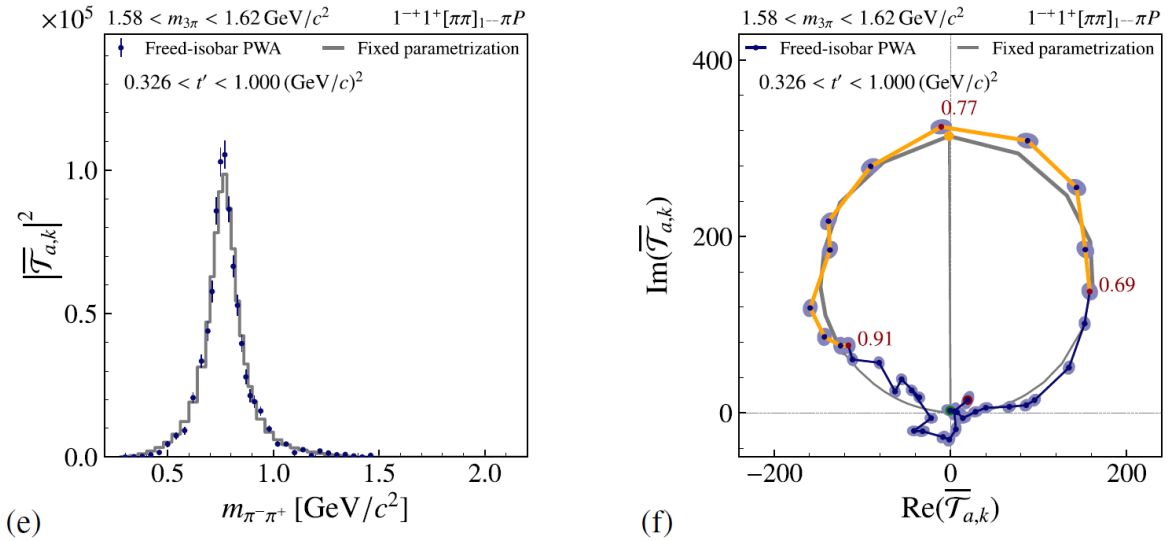
3π FINAL STATE – 1^{-+} PARTIAL WAVE

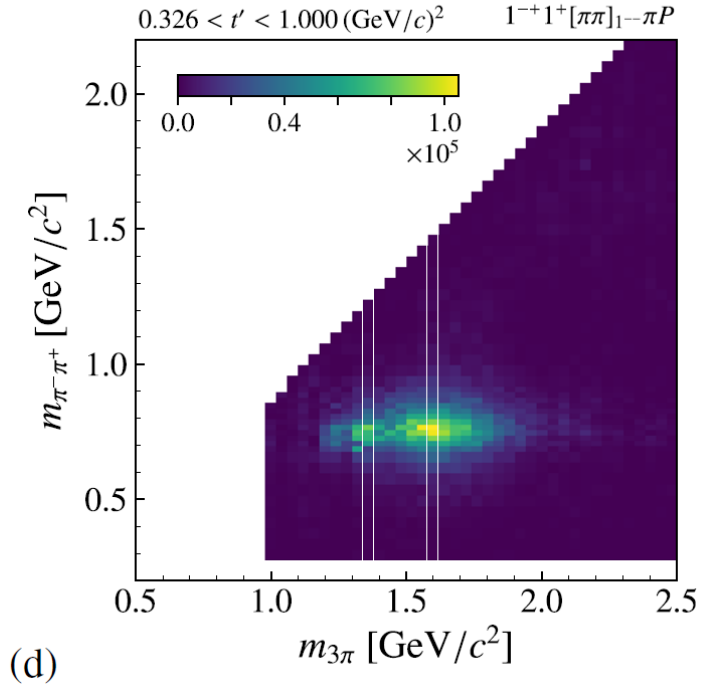
Model bias due to fixed isobar parameterization?

$\Rightarrow$ Freed-isobar technique [F. Krinner et al., PRD 97 (2018) 114008]

- replace fixed $\pi^-\pi^+$ amplitudes for $L = 0,1,2$ by step-like functions in small bins of $m_{\pi\pi}$

  $\Rightarrow$ model-independent isobar amplitudes





[COMPASS, G.D. Alexeev et al., Phys. Rev. D 105, 012005 (2022)]

$\Rightarrow$ confirms decay of $\pi_1(1600)$ to $\rho\pi$

$\Rightarrow$ results consistent with those using fixed isobar parameterizations

$\Rightarrow$ reconciles apparent contradictions of previous analyses as analysis artefacts

HYBRIDS: LATTICE QCD

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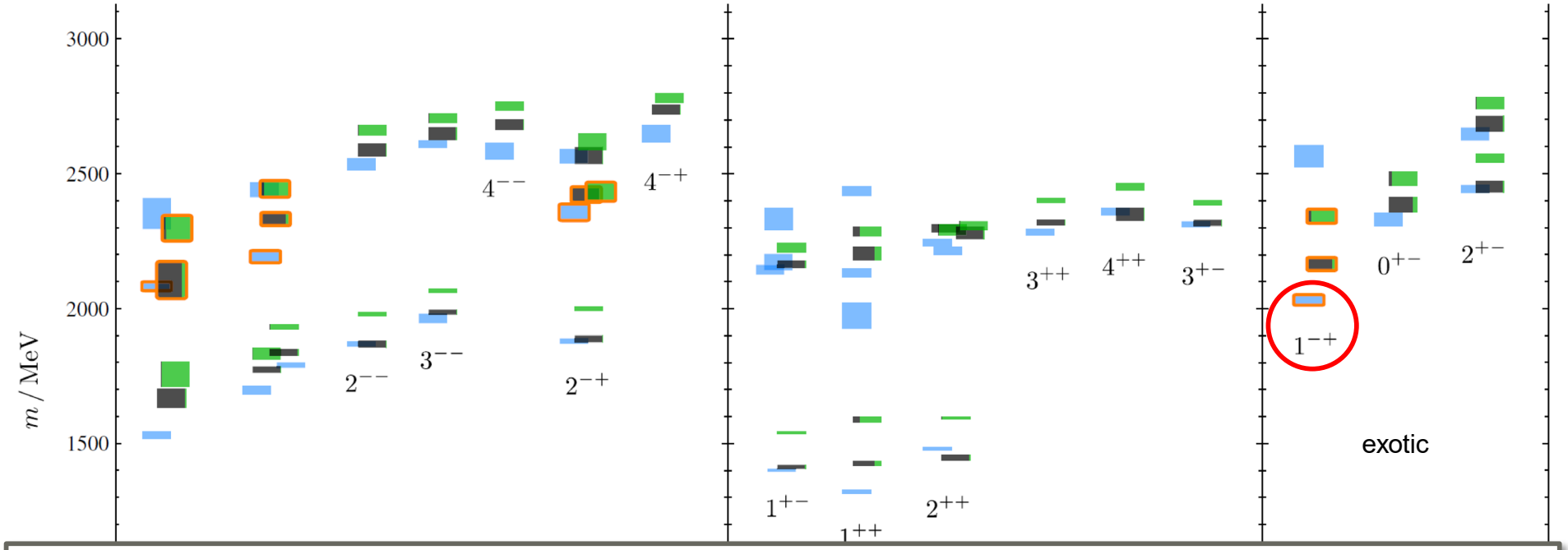
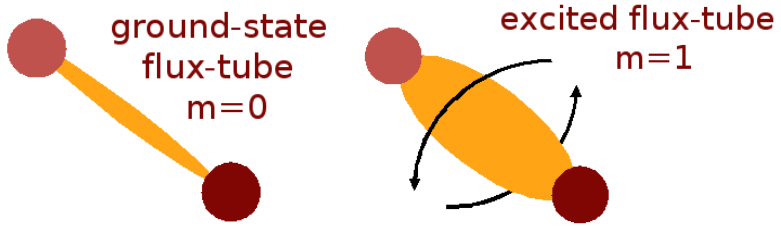


Hybrids:

- excitation of gluonic degrees of freedom
- angular momentum in flux tube
- hybrids also predicted by models



[J. Dudek et al., Hadron Spectrum Collaboration, Phys. Rev. D 88, 094505 (2013)]

HYBRID π_1 DECAYS

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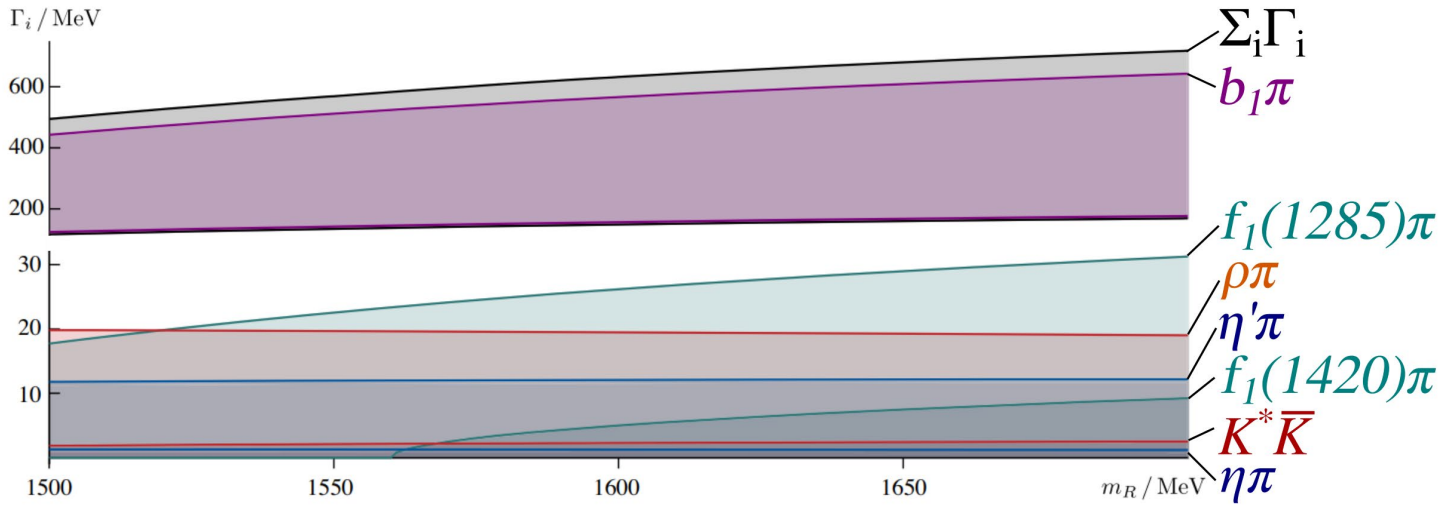
Lattice-QCD:

- hadronic decays of lightest exotic resonance
- SU(3) flavor symmetry
- $m_\pi \sim 700$ MeV
- scattering amplitudes for 8 coupled channels
- analytical continuation to complex plane
- crude extrapolation to physical point

[A.J. Woss, et al., PRD 103 (2021) 054502]



Models:

- Partial widths in MeV

Model	$b_1\pi$	$f_1\pi$	$\rho\pi$	$\eta\pi$	$\eta'\pi$	$\eta(1295)\pi$	Reference
Flux Tube, $^3P_0$	170	60	5 - 20	0 - 10	0 – 10		[Isgur (1985), Close (1995)]
Flux Tube, IKP m=1.6 GeV/c^2	24	5	9			2	[Isgur (1985)]
Flux Tube, PSS m=1.6 GeV/c^2	59	14	8			1	[Page (1999)]
L-QCD m=2.0 GeV/c^2	66	15					[McNeil, Michael (2006)]

FINAL STATES STUDIED AT COMPASS

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- $\pi^- p \to \pi^-\pi^-\pi^+ + p$ ✓
- $\pi^- p \to \pi^-\pi^0\pi^0 + p$ ✓

P. Haas, Tue 14:25

- $\pi^- p \to \omega\pi^-\pi^0 + p$ ✓
- $\pi^- p \to \pi^-\pi^-\pi^+\eta + p$ ✓
- $\pi^- p \to \pi^-\eta + p$ ✓

J. Beckers, Thu 14:00

- $\pi^- p \to \pi^-\eta' + p$ ✓
- $\pi^- p \to \pi^- f_1(1285) + p$ ✓
- $\pi^- p \to \pi^- K_s^0 K_s^0 \pi^- + p$ ✓
- $\pi^- p \to K^- K_s^0 + p$ ✓

S. Wallner, Thu 14:00

- $K^- p \to K^-\pi^-\pi^+ + p$ ✓
- $K^- p \to K_s^0\pi^- + p$ ✓
- $K^- p \to \Lambda\bar{p} + p$ ✓

- $\pi^-\gamma^* \to \pi^-\pi^-\pi^+$ ✓
- $\pi^-\gamma^* \to \pi^-\pi^0\pi^0$ ✓
- $\pi^-\gamma^* \to \pi^-\pi^0$ ✓
- $K^-\gamma^* \to K^-\pi^0$ ✓

D. Ecker, Thu 17:20

$b_1\pi$

$f_1(1285)\pi$

$\rho\pi$

$\eta'\pi$

$f_1(1420)\pi$

$K^*\bar{K}$

$\eta\pi$

$\pi^-\pi^+\pi^-\gamma\gamma$ FINAL STATE

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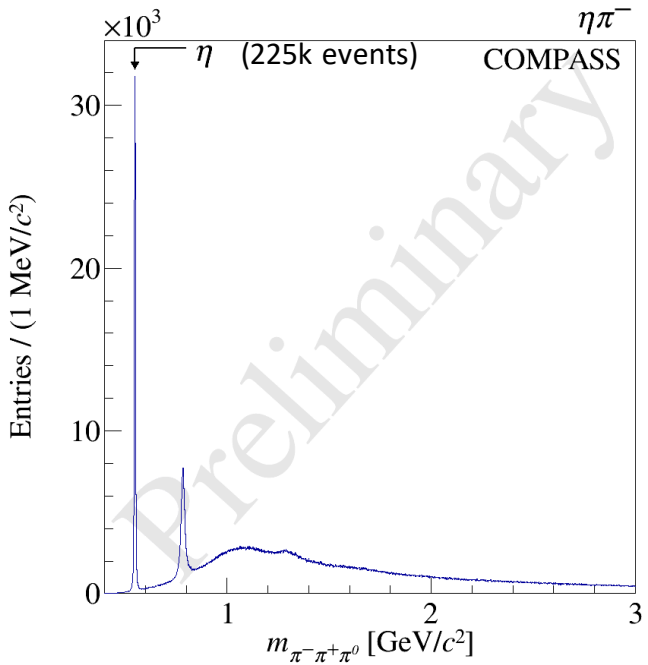
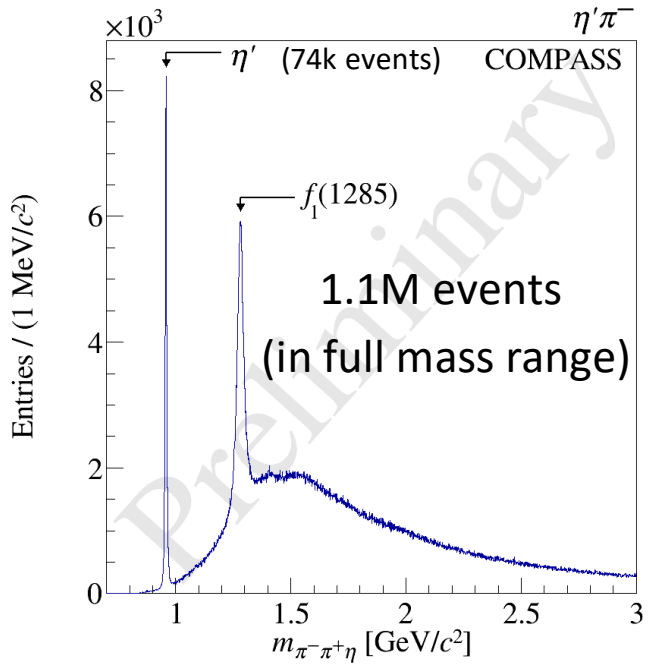
$\Rightarrow$ access to $\eta\pi, \eta'\pi, f_1(1285)\pi$, depending on $\gamma\gamma$ invariant mass



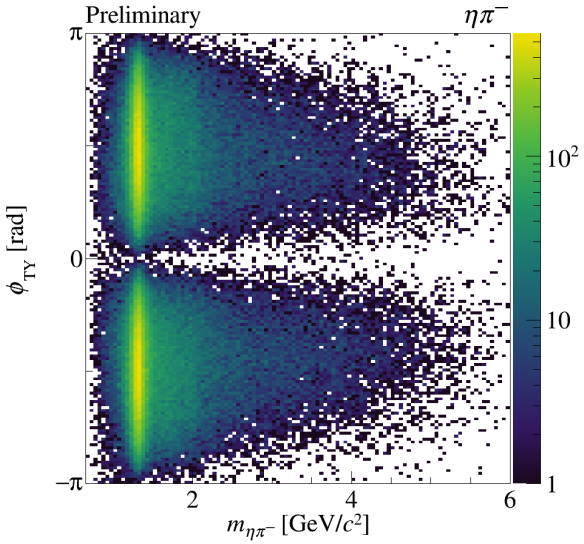


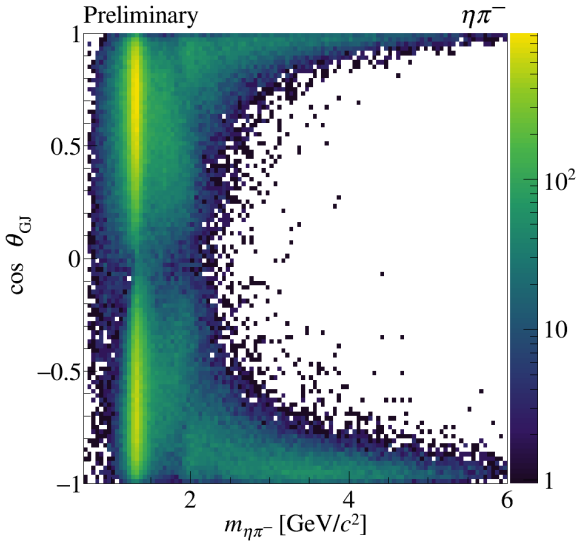
- new data production: improved shower reconstruction from calorimeter
- include full data set for the first time
- about 2× more data than previously published for $\eta\pi, \eta'\pi$
- perform PWA in bins of t' and m_X

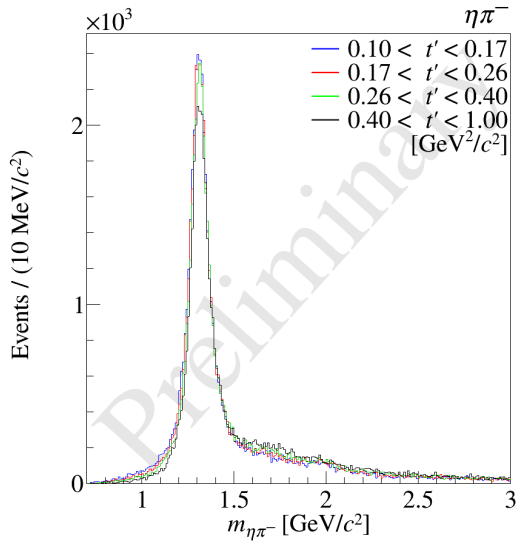
$b_1\pi$

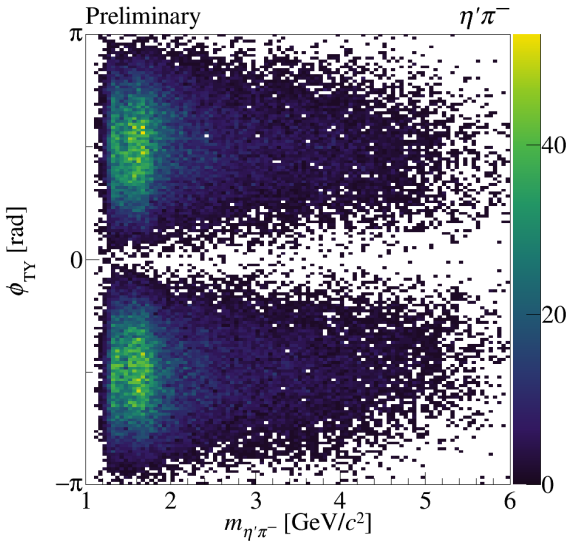
$f_1(1285)\pi$
$\rho\pi$
$\eta'\pi$
$f_1(1420)\pi$
$K^*\overline{K}$
$\eta\pi$

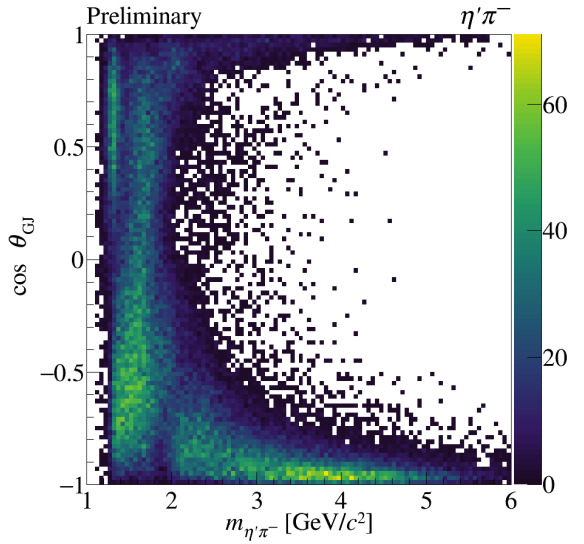
$\eta\pi, \eta'\pi$ FINAL STATES

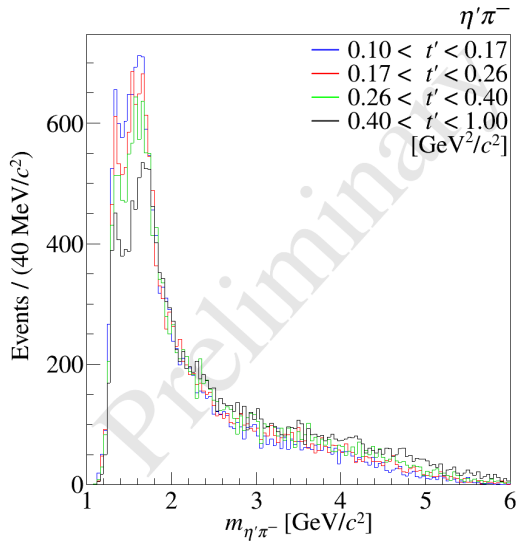








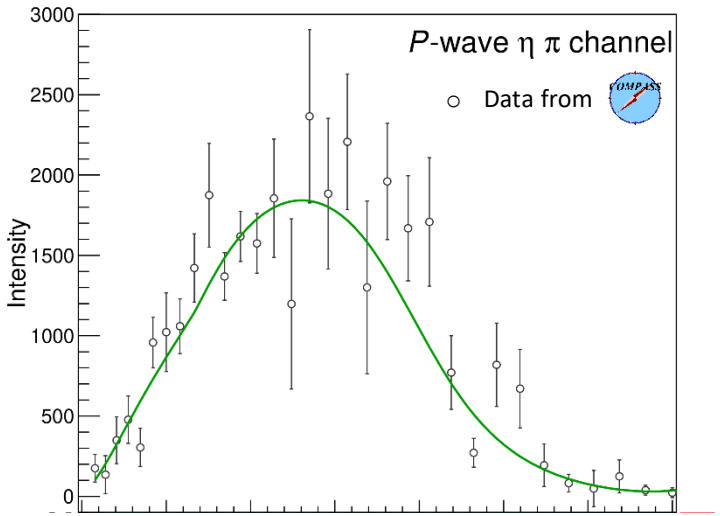


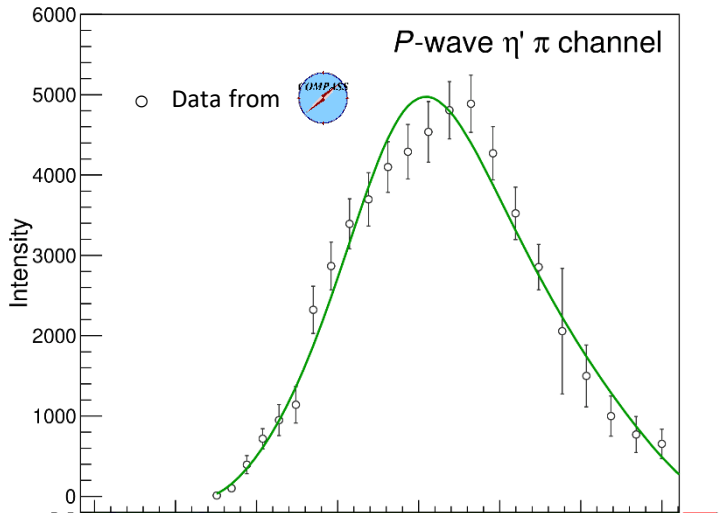


- $b_1\pi$
- $f_1(1285)\pi$
- $\rho\pi$
- $\eta'\pi$
- $f_1(1420)\pi$
- $K^*\bar{K}$
- $\eta\pi$

TWO EXOTIC π_1 MESONS?

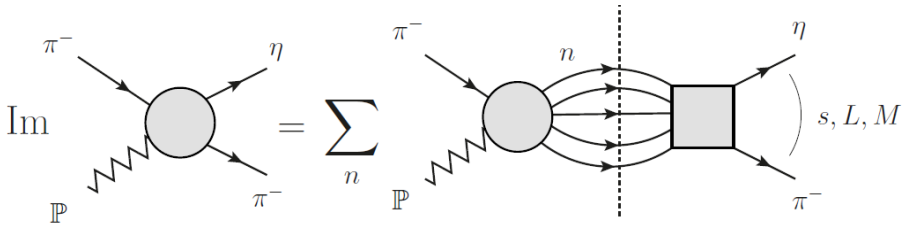
$$\pi^- + p \rightarrow \eta^{(\prime)} + \pi + p$$





Model based on S-matrix theory

- Analyticity
- Unitarity



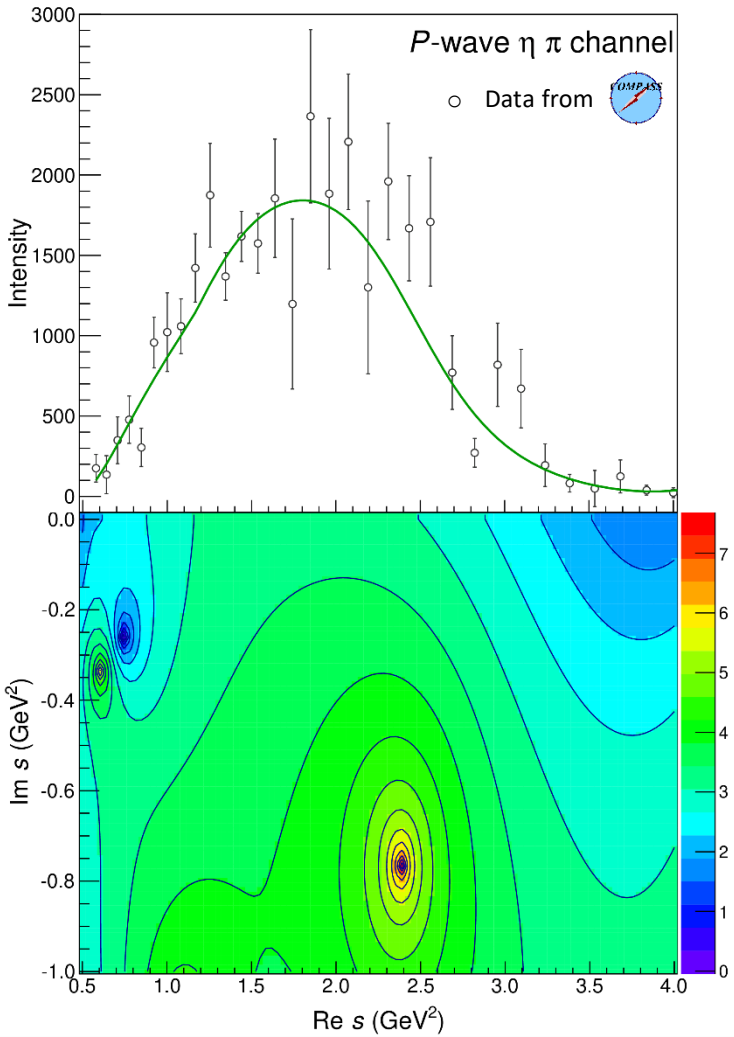
$b_1\pi$

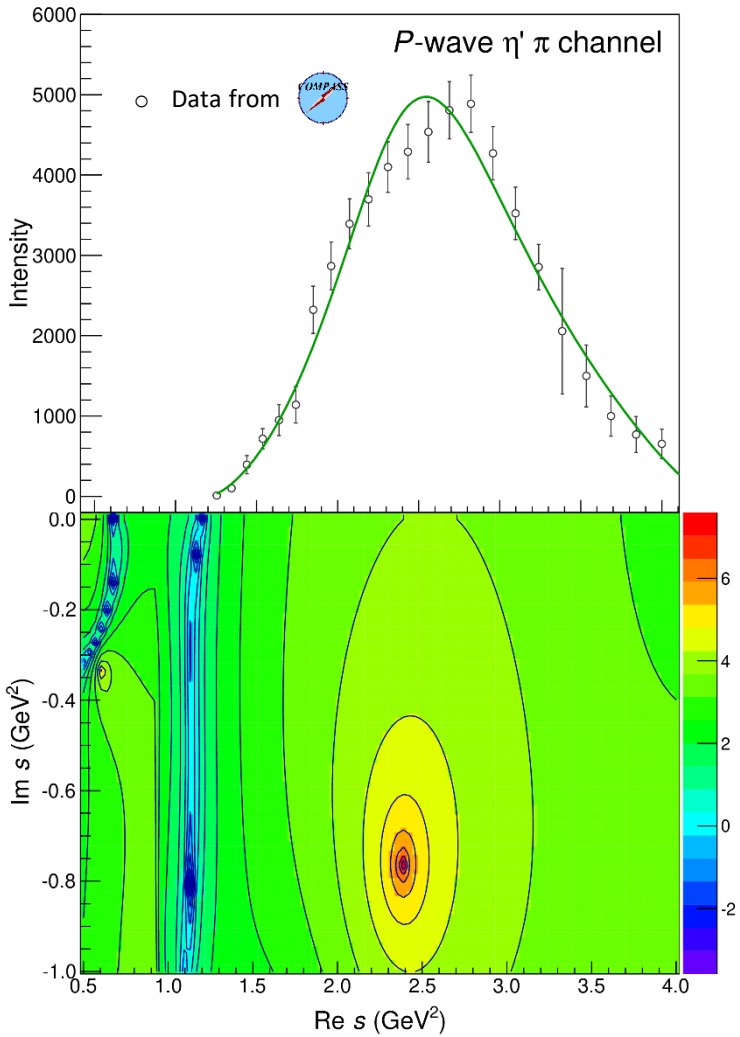
$f_1(1285)\pi$
$\rho\pi$
$\eta'\pi$
$f_1(1420)\pi$
$K^*\bar{K}$
$\eta\pi$

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

TWO EXOTIC π_1 MESONS?

$$\pi^- + p \rightarrow \eta^{(\prime)} + \pi + p$$





- $b_1\pi$
- $f_1(1285)\pi$
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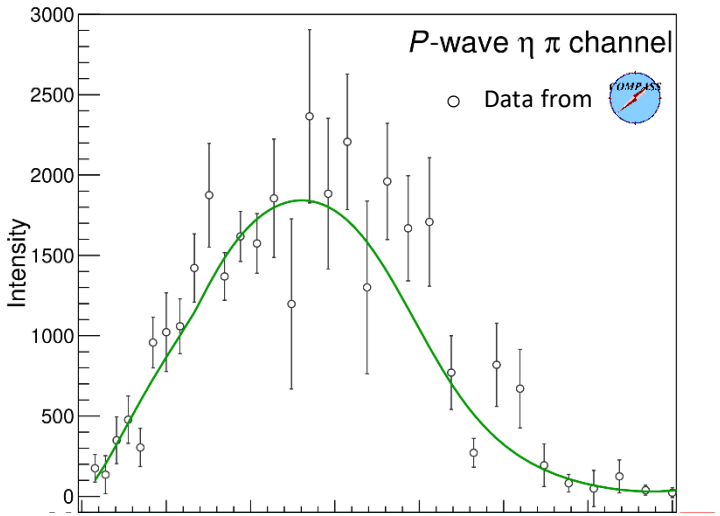
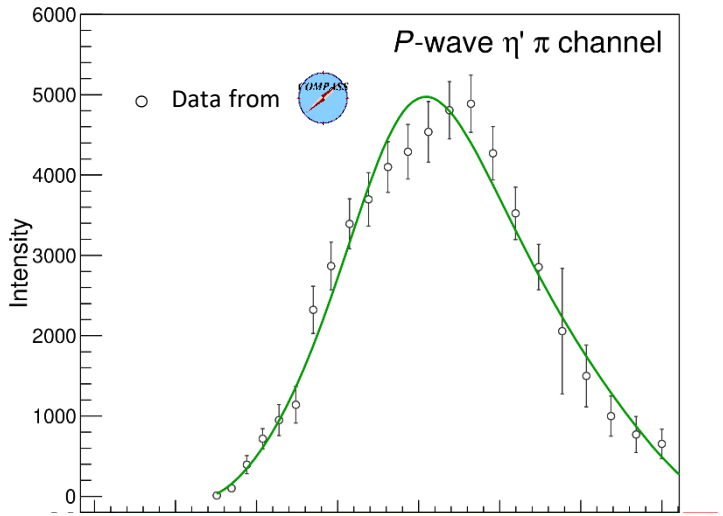
TWO EXOTIC π_1 MESONS?

$$\pi^- + p \rightarrow \eta^{(\prime)} + \pi + p$$





- only a single pole needed to describe both peaks
- consistent with $\pi_1(1600)$

Poles	Mass (MeV)	Width (MeV)
$a_2(1320)$	$1306.0 \pm 0.8 \pm 1.3$	$114.4 \pm 1.6 \pm 0.0$
$a_2'(1700)$	$1722 \pm 15 \pm 67$	$247 \pm 17 \pm 63$
π_1	$1564 \pm 24 \pm 86$	$492 \pm 54 \pm 102$

first coupled-channel extraction of resonance pole of a hybrid candidate

Also compatible with $\bar{p}p$ and $\pi\pi$ scattering data [B. Kopf et al., Eur. Phys. J. C 12, 1056 (2021)]

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

$b_1\pi$

$f_1(1285)\pi$
$\rho\pi$
$\eta'\pi$
$f_1(1420)\pi$
$K^*\bar{K}$
$\eta\pi$

$f_1\pi$ FINAL STATE

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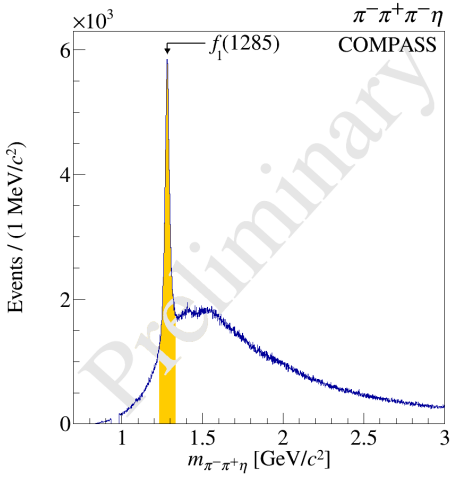
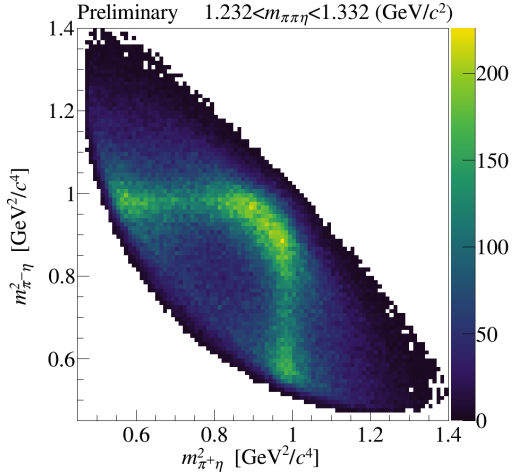
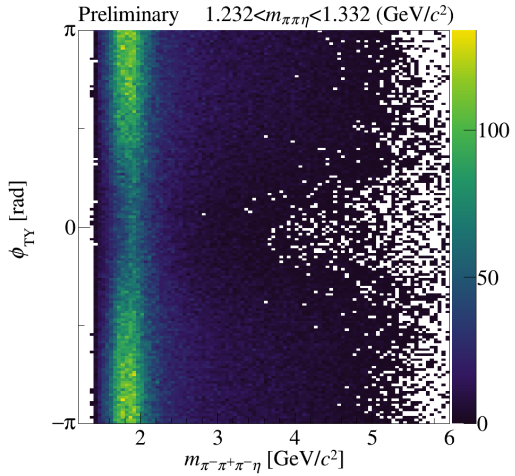
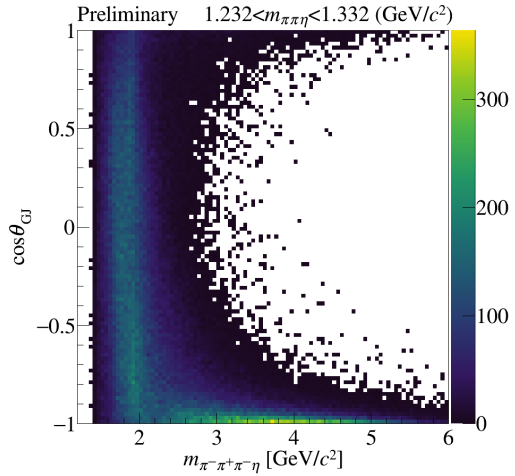
Dominant decay: $f_1 \to a_0(980)\pi$

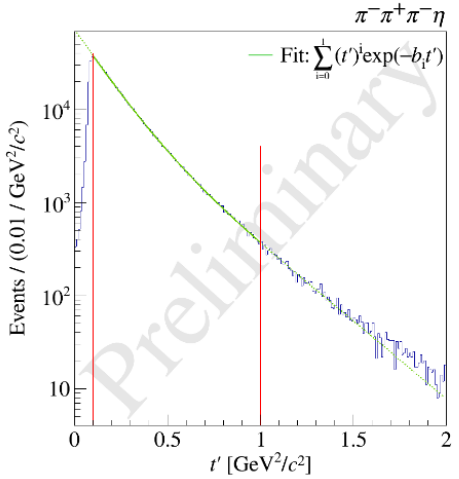


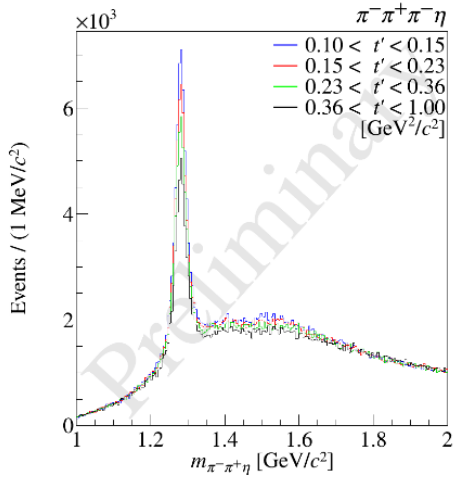






t' dependence





- $b_1\pi$
- $f_1(1285)\pi$
- $\rho\pi$
- $\eta'\pi$
- $f_1(1420)\pi$
- $K^*\bar{K}$
- $\eta\pi$

$b_1\pi$ FINAL STATE

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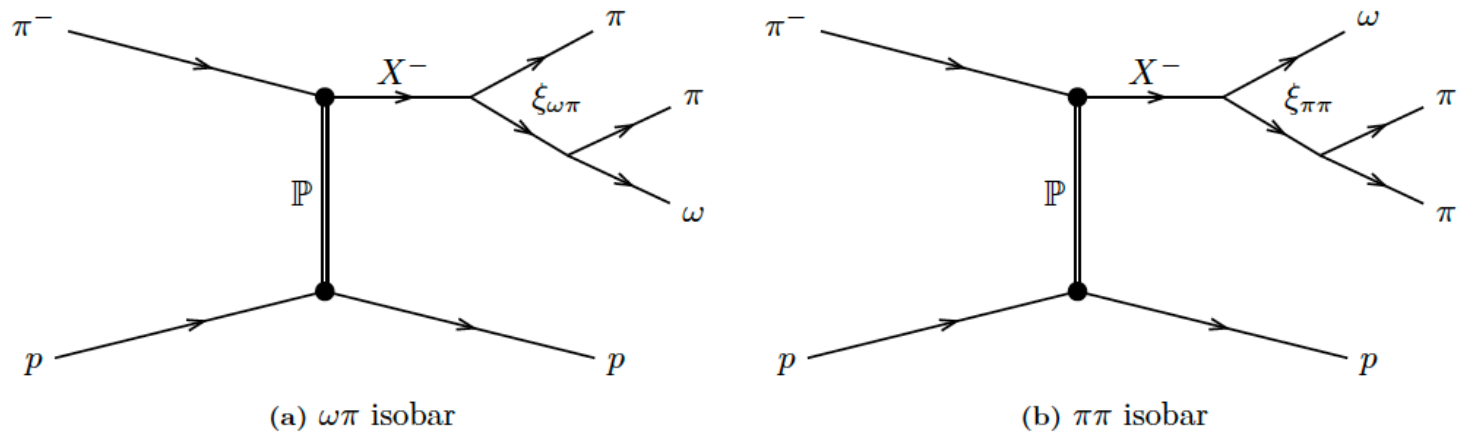
$\pi^-\pi^+\pi^-$ 4γ final states $\Rightarrow$ access to $b_1\pi \to \omega\pi\pi$



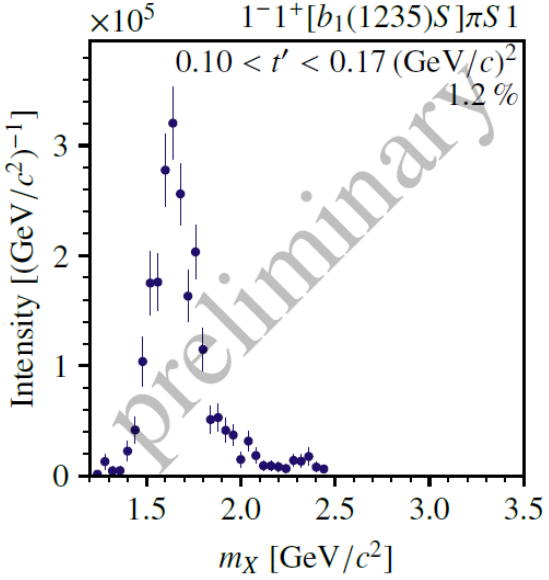
(a) $\omega\pi$ isobar (b) $\pi\pi$ isobar

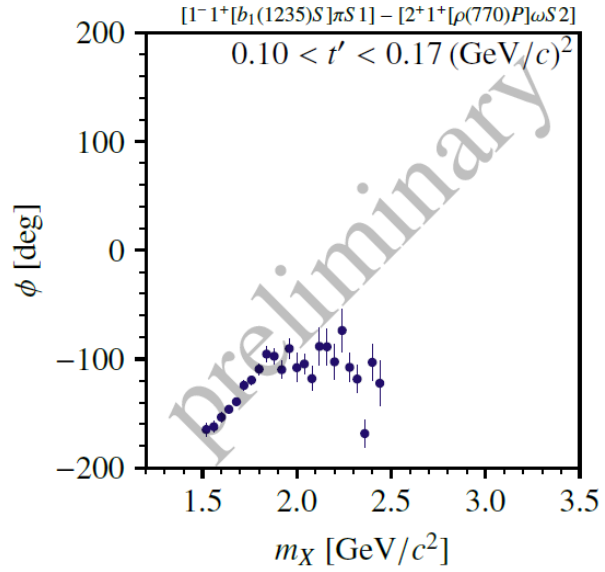
- new data production: improved shower reconstruction from calorimeter
- full COMPASS data set
- 720 k exclusive events of $\pi^-\pi^0\omega(782)$
  - $\Rightarrow$ largest data sample world-wide: 5 × more data than BNL E852
  - $\Rightarrow$ perform fit in 4 bins in t' × 57 bins in m_X

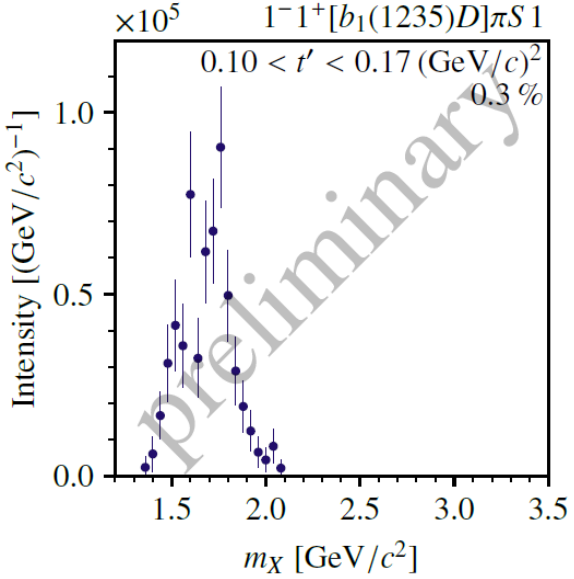
$b_1\pi$

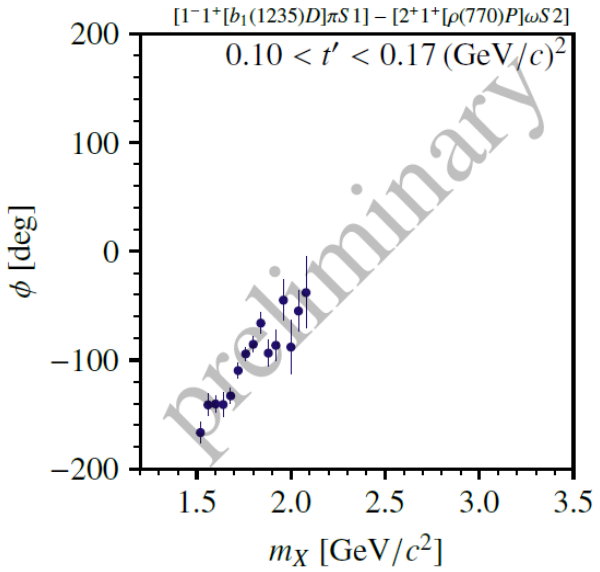
$f_1(1285)\pi$
$\rho\pi$
$\eta'\pi$
$f_1(1420)\pi$
$K^*\overline{K}$
$\eta\pi$

$b_1\pi$ FINAL STATE

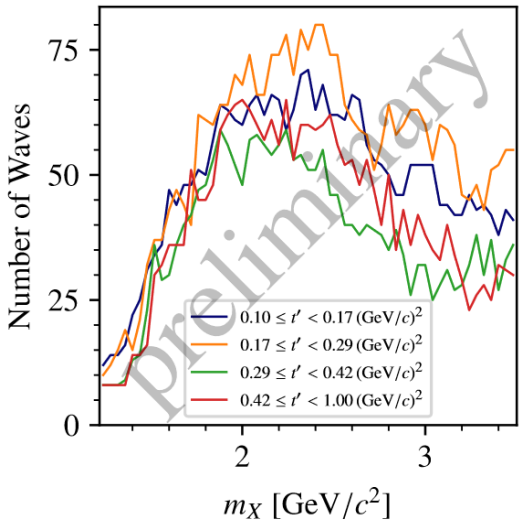






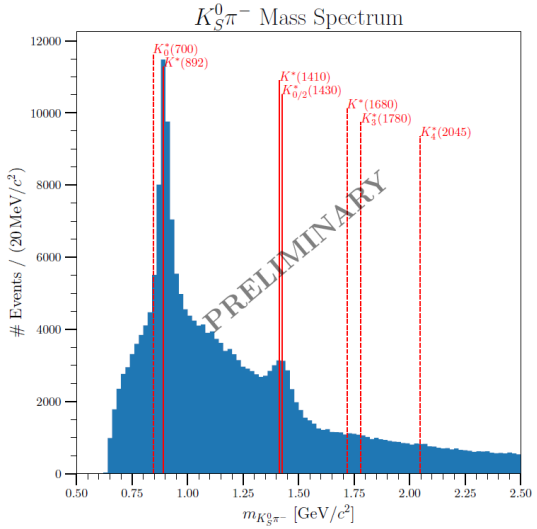


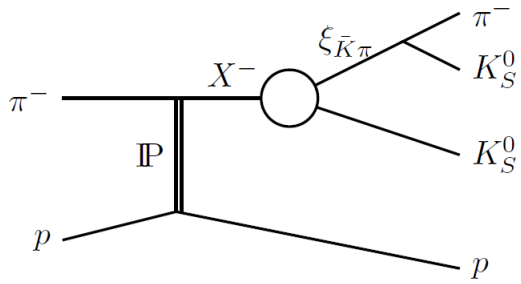
- PWA: select about 70 waves from a pool of 893 waves (+ flat), depending on t' and m_X
- Clear signal in spin-exotic 1^{-+} $b_1\pi$ S and D-waves at 1.6 GeV/c^2
- BNL E852: second state $\pi_1(2015)$

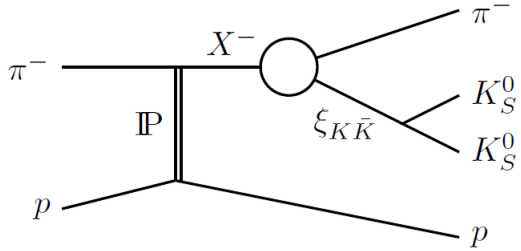


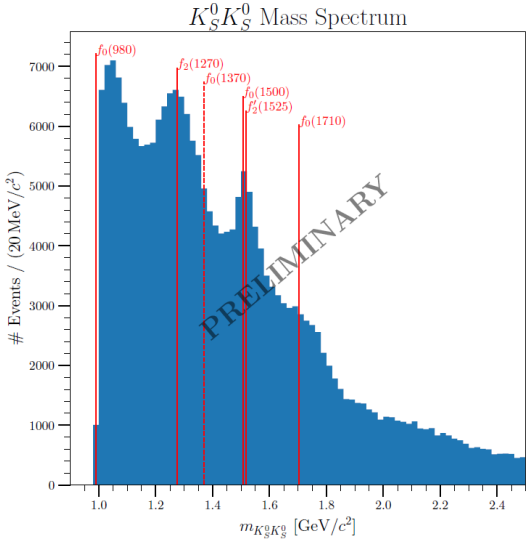
$b_1\pi$
$f_1(1285)\pi$
$\rho\pi$
$\eta'\pi$
$f_1(1420)\pi$
$K^*\bar{K}$
$\eta\pi$

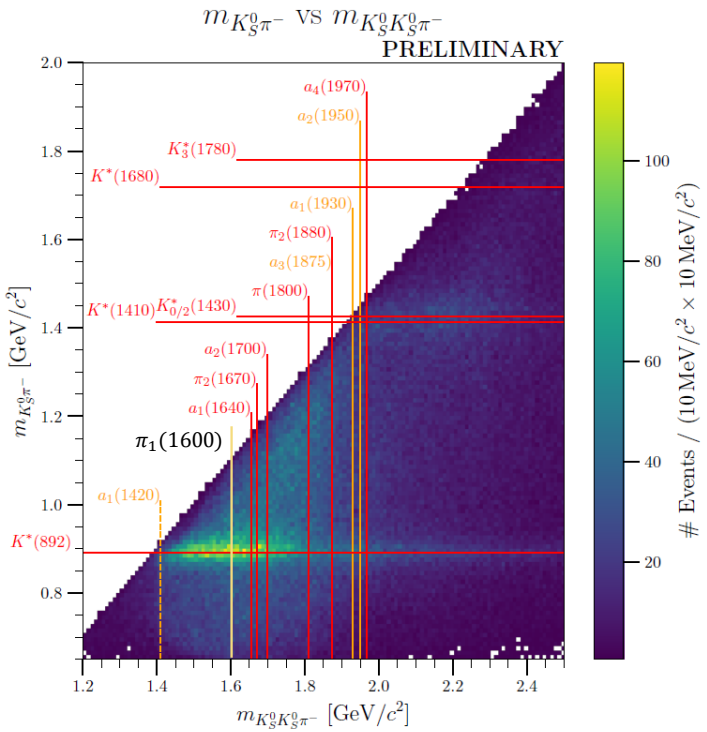
$K_S^0 K_S^0 \pi$ FINAL STATE











- COMPASS full data set: 244k events
- All a_J, π_J states accessible
- Spin-exotic $\pi_1(1600)$ expected to decay to $K^*\bar{K}$
- Search for $a_1(1420)$
- K_S^0 identified by secondary vertex: $K_S^0 \to \pi^+\pi^-$
- Identification of X $\to K^+K^-\pi$ limited at low masses due to RICH constraints

$b_1\pi$

$f_1(1285)\pi$
$\rho\pi$
$\eta'\pi$
$f_1(1420)\pi$
$K^*\bar{K}$
$\eta\pi$

HYBRID π_1 MULTIPLET

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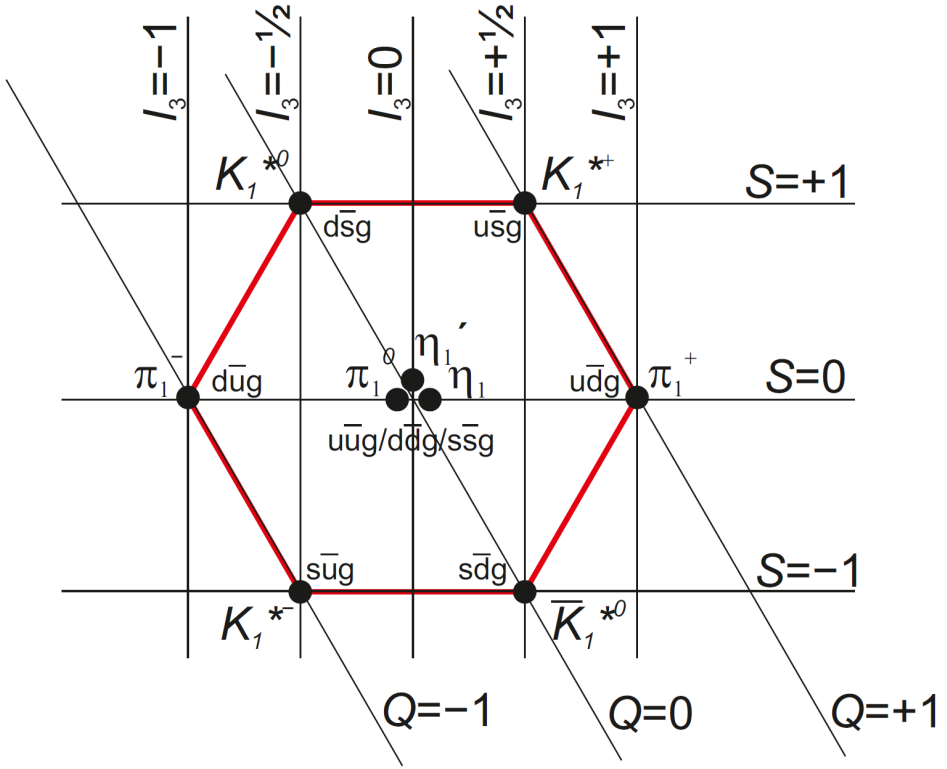
So far:

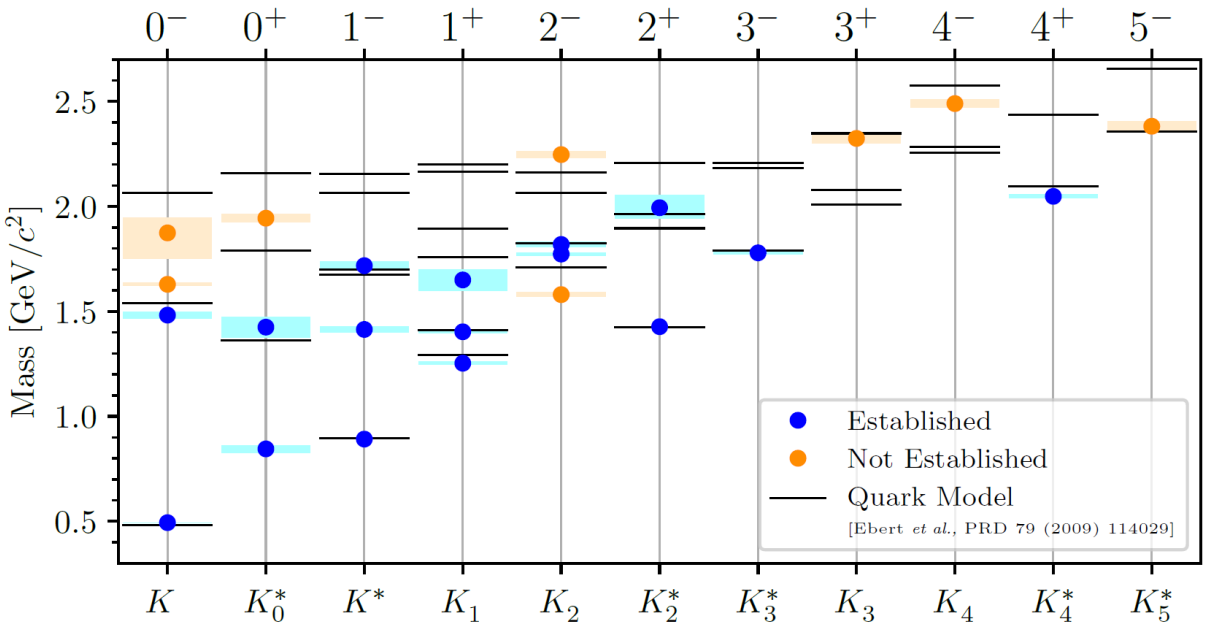
- resonant nature of only one member of the 1^{-+} multiplet confirmed
- branching fractions to dominant decay channels will be extracted



Need to:

- observe other members
- including ones with strangeness
- BES III https://arxiv.org/abs/2202.00621
- AMBER https://arxiv.org/abs/2202.00623

STRANGE MESONS

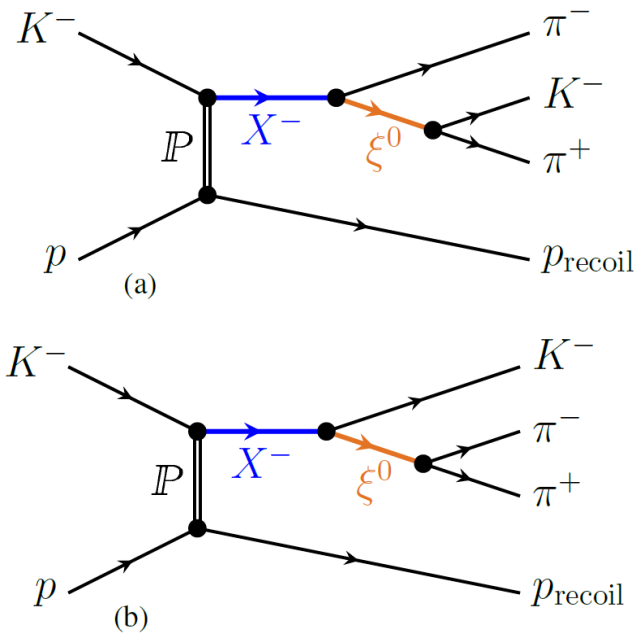


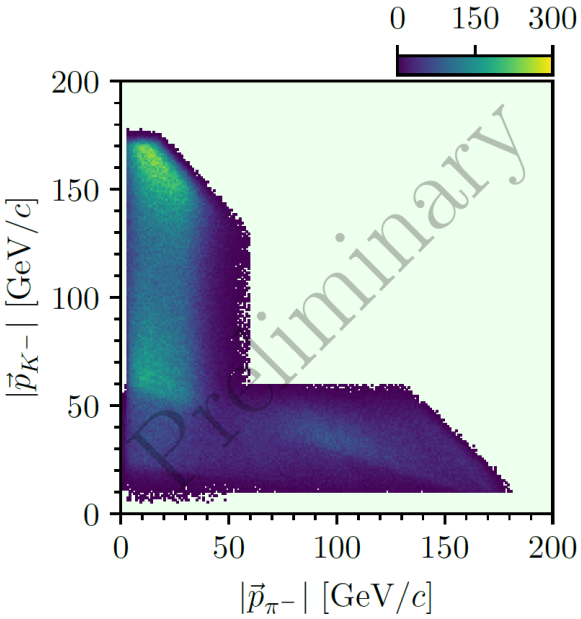
- 25 kaon states listed by PDG ($M < 3.1$ GeV), 9 of those need confirmation
- many predicted quark-model states still missing
- most measurements performed more than 30 years ago

COMPASS:

- h^- beam has ~2.4% admixture of K^-
- tagged by CEDAR detectors
- final state $K^-\pi^-\pi^+$: 720 k events

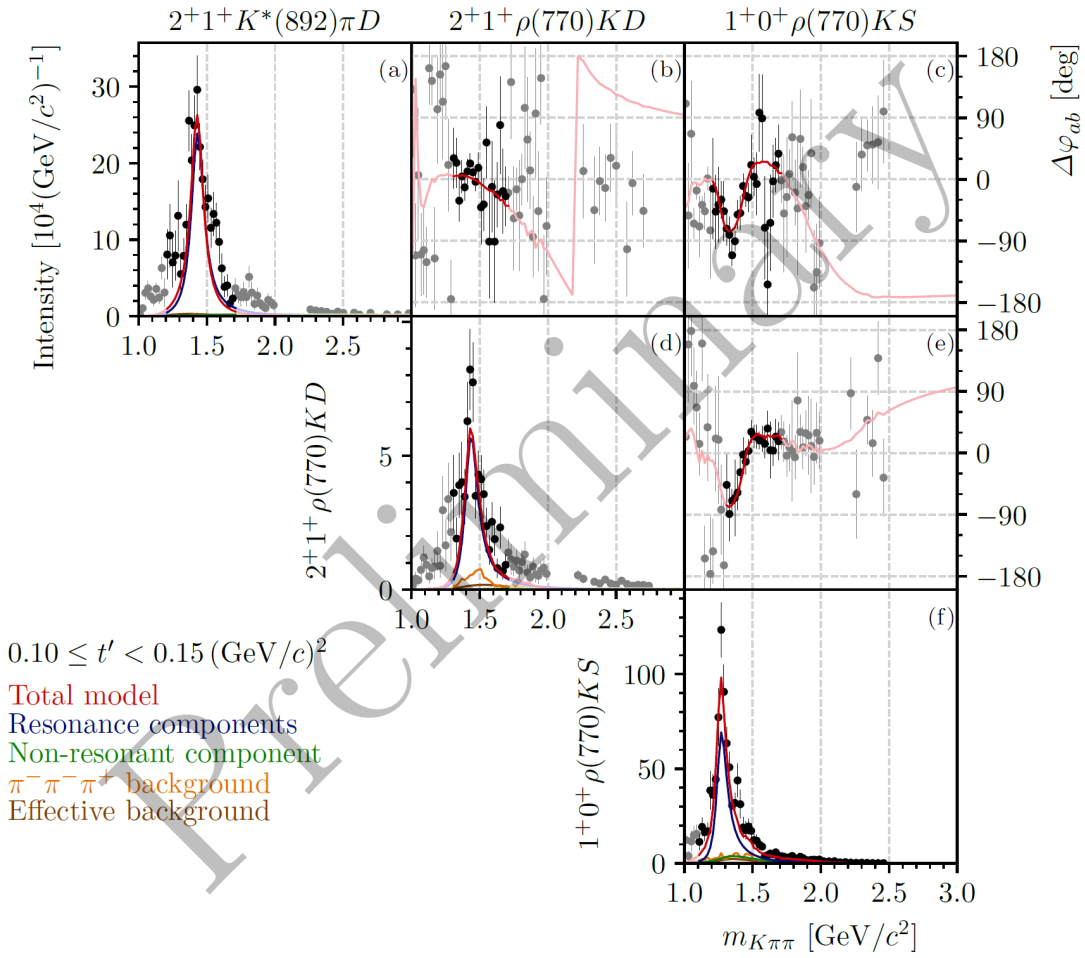
  ⇒ access to all kaon states: K_J, K_J^*
- limited by PID in RICH





STRANGE MESONS

- $J^P = 2^+$: clear $K_2^*(1430)$ signal in $K^*(892)\pi$ and ρK D-waves



STRANGE MESONS

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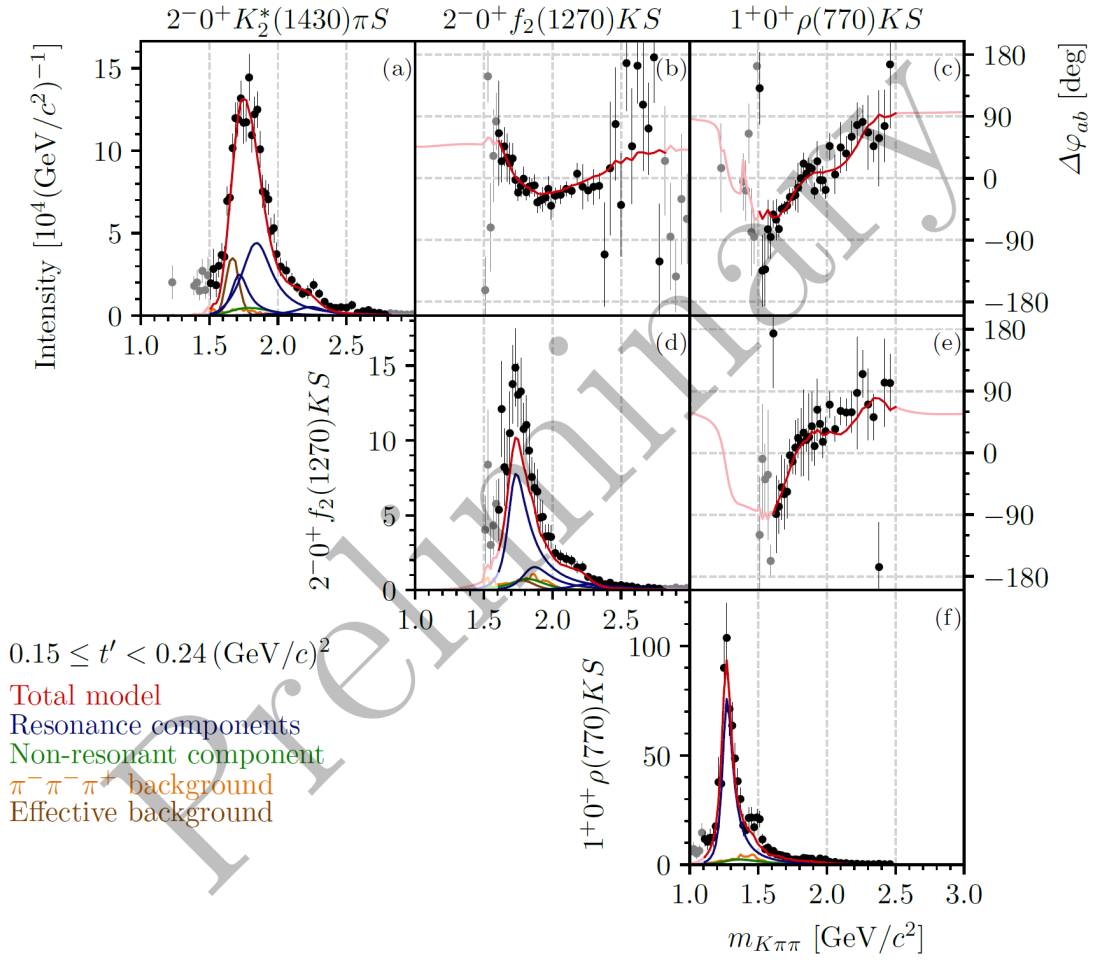
- $J^P = 2^+$: clear $K_2^*(1430)$ signal in $K^*(892)\pi$ and ρK D-waves
- $J^P = 2^-$: complicated t'-dependence of intensities
  - $K_2(1820)$ dominant in $K_2^*(1430)\pi$ S-wave
  - $K_2(1770)$ dominant in $f_2 K$ S-wave
  - $K_2(2250)$ visible in both waves



STRANGE MESONS

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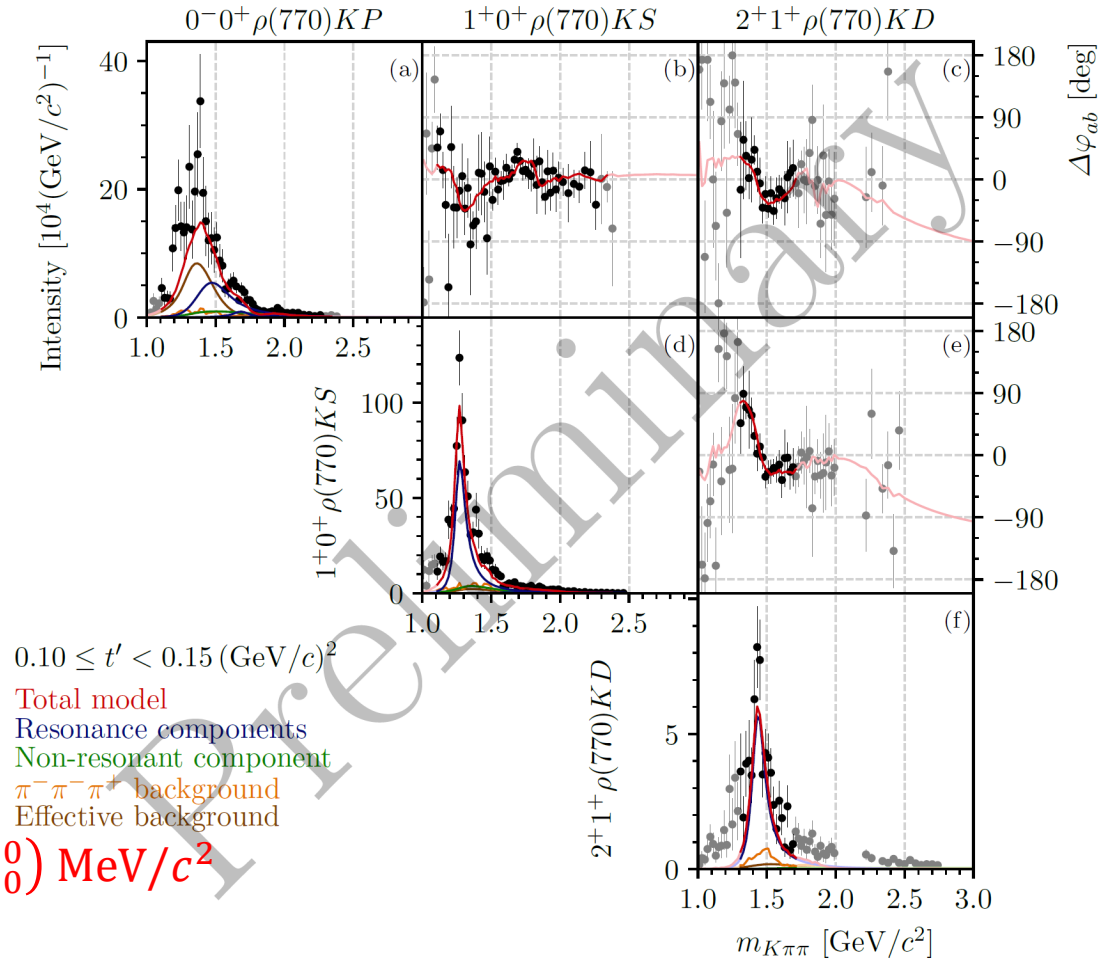
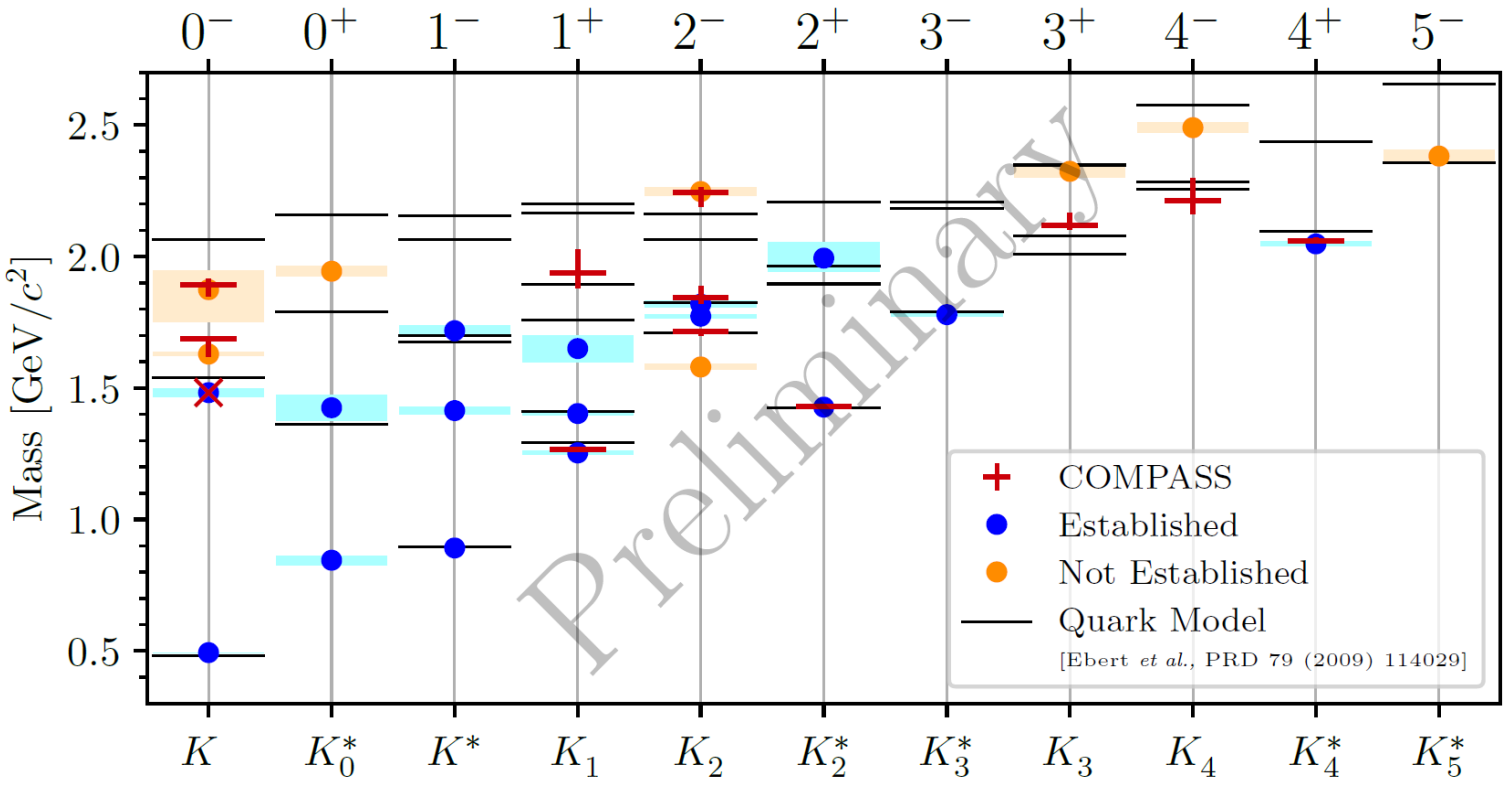
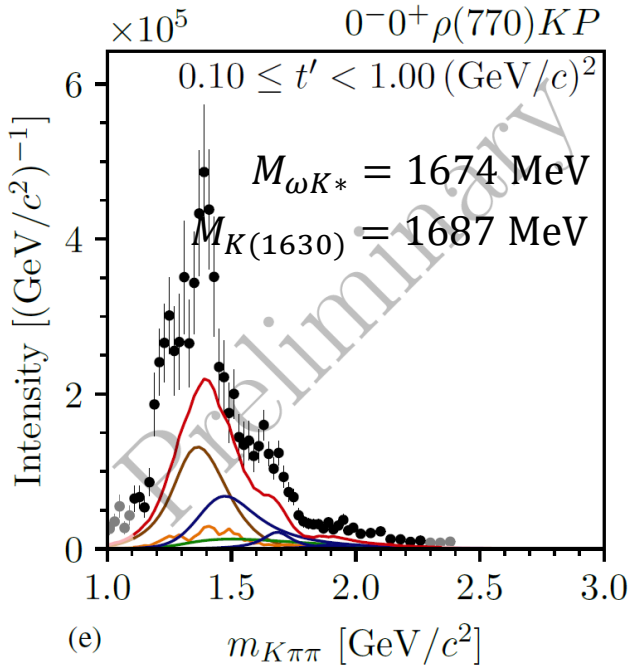
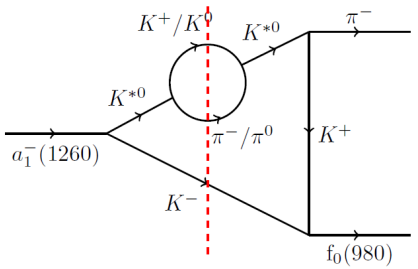
  - $K_2(1770)$ dominant in $f_2 K$ S-wave
  - $K_2(2250)$ visible in both waves
- $J^P = 0^-$:
  - $K(1460)$ signal in ρK P-wave, but affected by leakage
    $\Rightarrow$ fix parameters to PDG
  - stable peak and clear phase motion at 1.7 GeV
    $\Rightarrow K(1630)$ signal, significance 8.3σ
    $\Rightarrow m = \left(1687 \pm 10^{+2}_{-67}\right)\mathrm{MeV}/c^2, \Gamma = \left(140 \pm 20^{+50}_{-50}\right)\mathrm{MeV}/c^2$
  - shoulder at 1.9 GeV, but no clear phase motion
    $\Rightarrow$ evidence for $K(1830)$, phase motion compensated by resonances in reference waves



SUMMARY OF KAON SPECTRUM





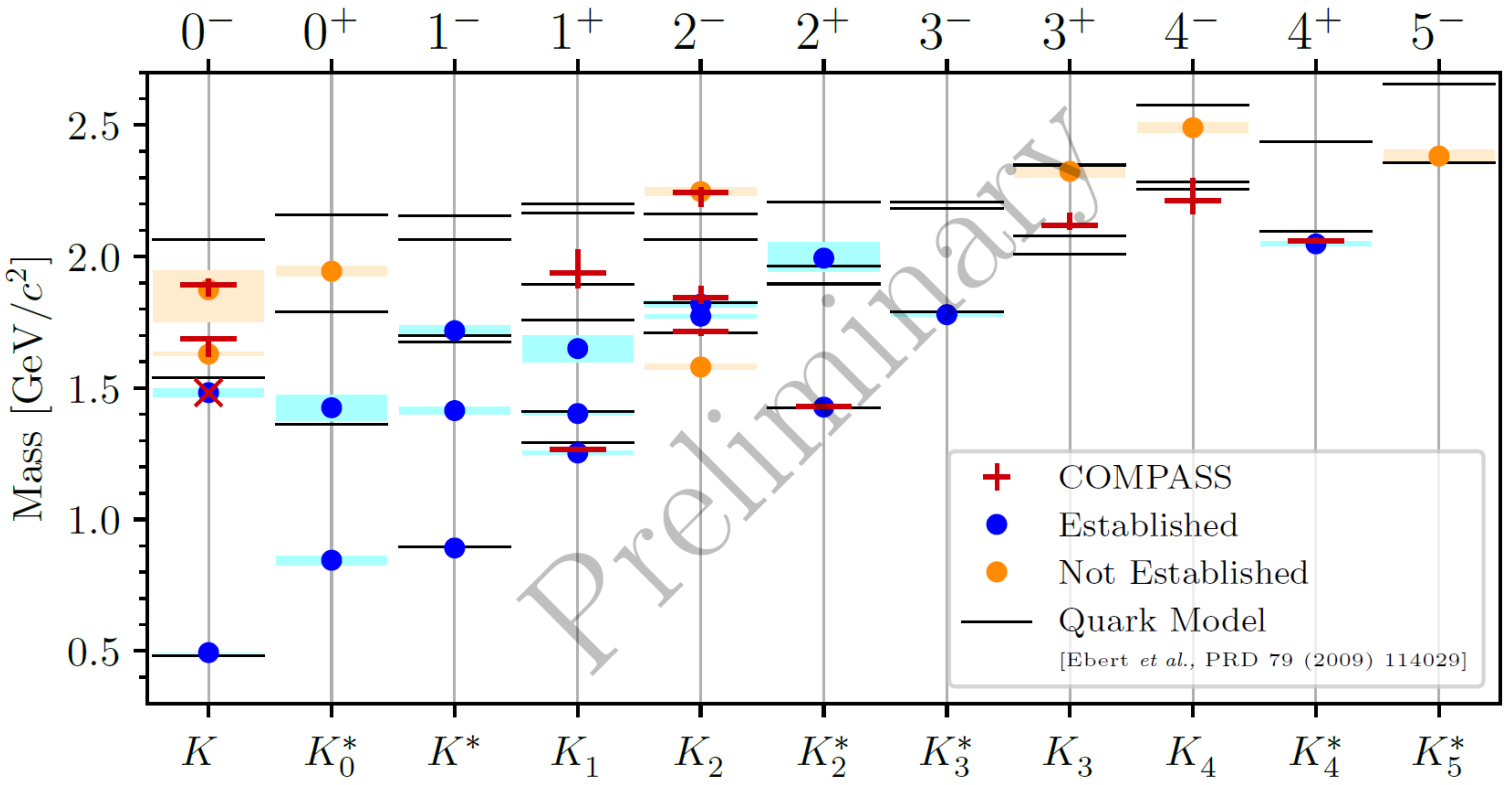


Triangle singularity (?)

- 11 strange mesons found in COMPASS data ⇒ results to be published soon
- evidence for 3 excited K states
- quark model only predicts 2: $K(1460), K(1830)$?
- $K(1630)$ supernumerary ⇒ candidate for exotic strange meson

[COMPASS, M.G. Alexeev et al., PRL 127, 082501 (2021)]

SUMMARY OF KAON SPECTRUM



Requirements:

- High intensity of K in secondary beam

  ⇒ Beam studies ongoing (RF and conventional)

- High-efficiency / high-purity beam particle identification
- Final-state PID at higher momenta (depending on beam momentum)
- Full solid-angle coverage for photons / electrons

Goal for AMBER:

$10 - 20 \times 10^6$ exclusive $K^-\pi^-\pi^+$ events

Talk by O. Denisov: Fri 14:00

⇒ Monte-Carlo simulation campaign ongoing

⇒ Proposal to be submitted to SPSC in 2024

⇒ Additional ideas and collaborators welcome!

CONCLUSIONS AND OUTLOOK

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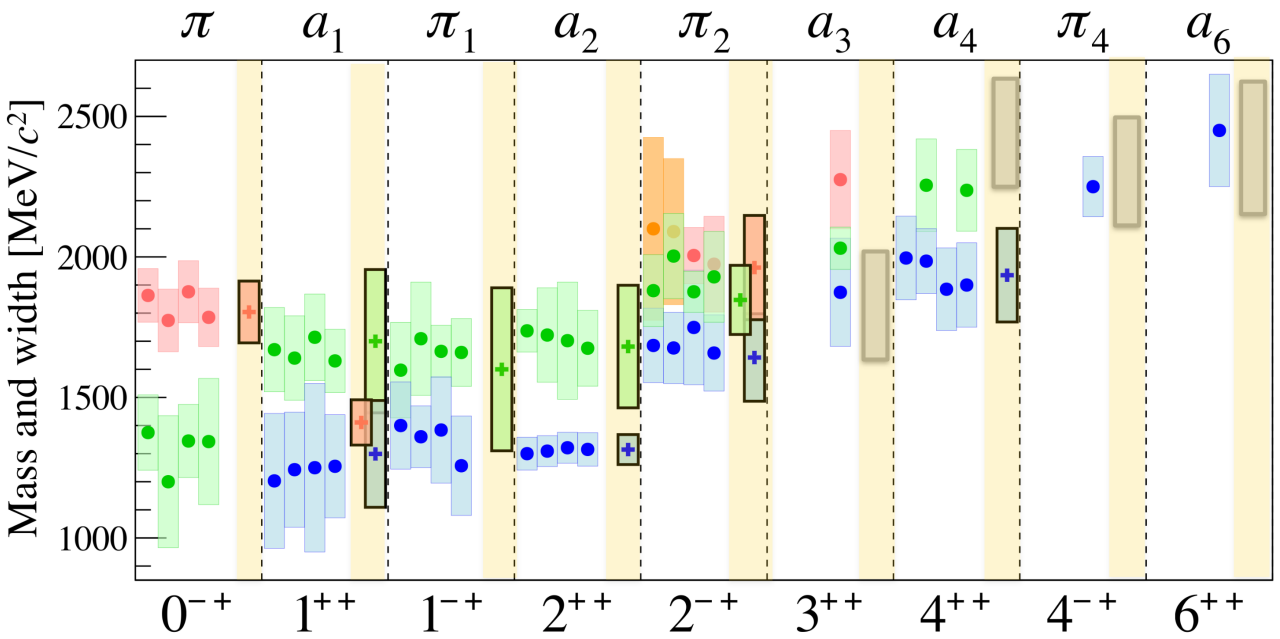
- QCD in the strong coupling regime still far from being understood
- Pattern of exotic hadron states not yet clear
- COMPASS has unique data set on diffractive production of light mesons ⇒ gives access to all π_J, a_J states in wide mass range



- AMBER:
  - Phase I started: PbarX measurement ongoing
  - will perform precision spectroscopy of K_J and K_J^* states in Phase II