Spectroscopy of Strange Mesons and First Observation of a Strange Crypto-Exotic State with $J^P = 0^-$ with COMPASS

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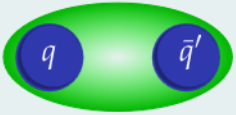
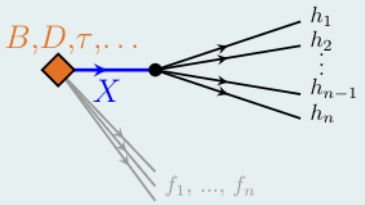
CERN EP Seminar
May 20, 2025

Light-Meson Spectroscopy

Understanding the meson spectrum



Input to other fields of physics



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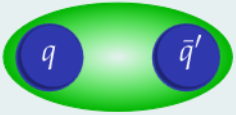
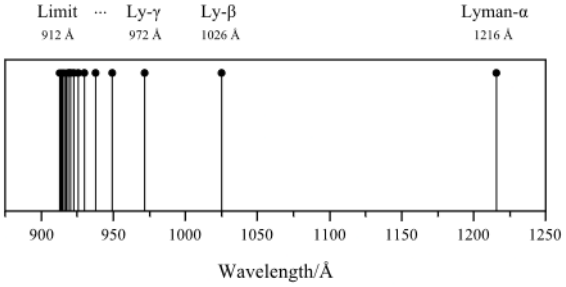
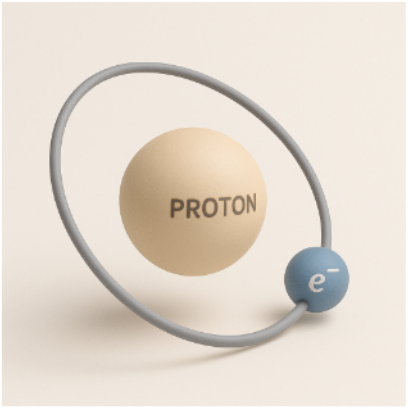


Input to other fields of physics

- Study excitation spectrum of electromagnetically bound system (hydrogen atom)
  - ➥ Improve our understanding of QED
- High-precision spectroscopy measurement of fine and hyperfine structure





[DJIndica], [Adriferr]

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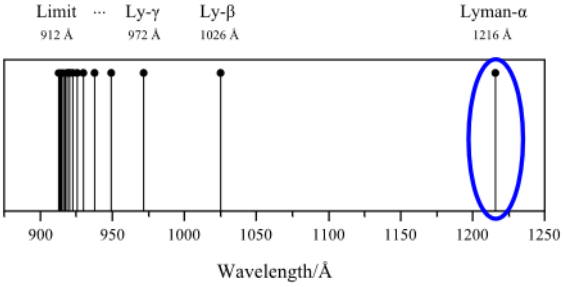

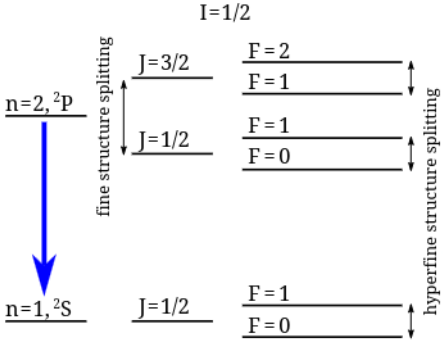

[DJIndica], [Adriferr]

- Study systems bound by strong interaction
  - ➥ Improve our understanding of QCD at low energies
- Simplest system: quark-antiquark state
  - Total spin: J
  - Parity: $P = (-1)^{L+1}$
  - Charge-conjugation: $C = (-1)^{L+S}$
  - Isospin: I
  - Mass and width
  - Light mesons: $q = u, d, s$
    - Strange-mesons: One s quark
    - Strange mesons are not C-parity Eigenstates
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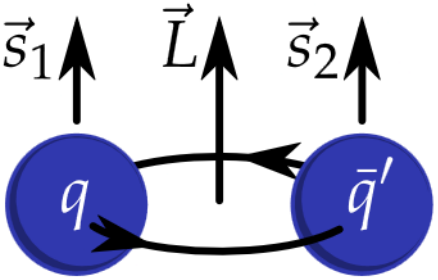

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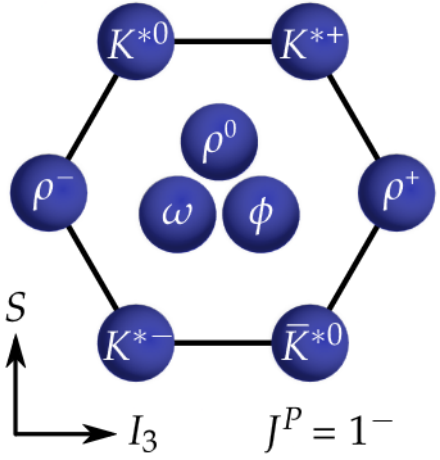
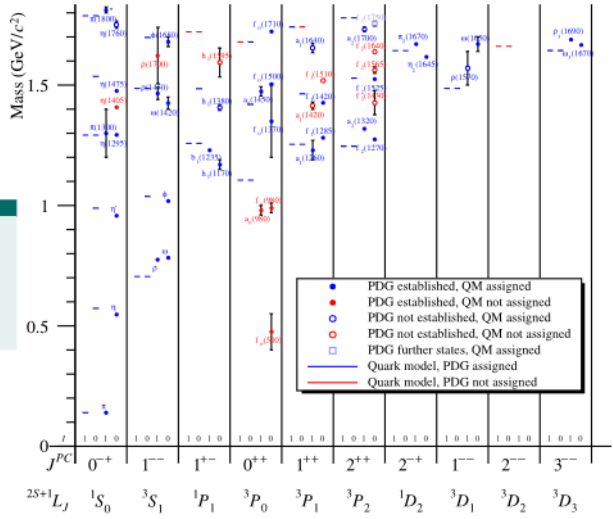
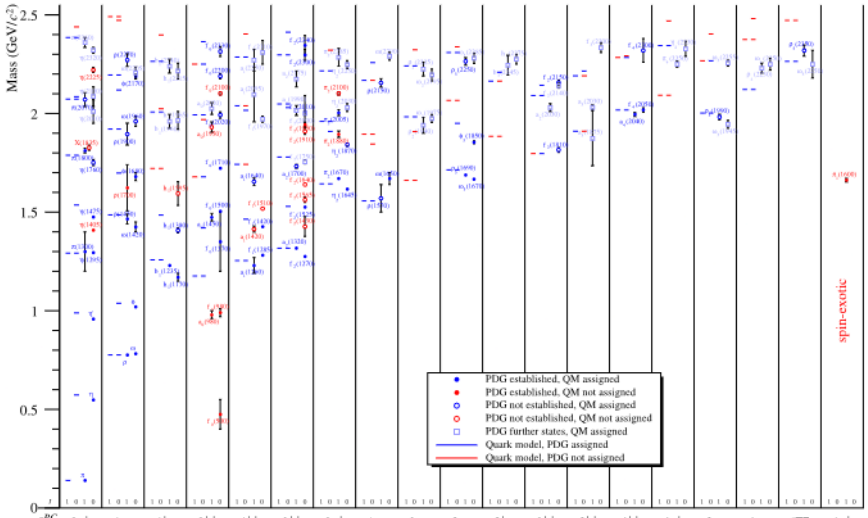


- Quark-model predicts pattern of excited mesons
- Tower of radial excitation for each J^{PC}
- Non-strange light-meson spectrum well explored




Mass (GeV/c²)
2.5
2
1.5
1
0.5
0
spin-exotic
PDG established, QM assigned
PDG established, QM not assigned
PDG not established, QM assigned
PDG not established, QM not assigned
PDG further states, QM assigned
Quark model, PDG assigned
Quark model, PDG not assigned
J^{PC}
0^{-+} 1^{--} 1^{+-} 0^{++} 1^{++} 2^{++} 2^{-+} 1^{--} 2^{--} 3^{--} 3^{+-} 2^{++} 3^{++} 4^{++} 4^{-+} 3^{--} 4^{--} 5^{--} 1^{-+}
$^{2S+1}L_J$
$^1S_0$ $^3S_1$ $^1P_1$ $^3P_0$ $^3P_1$ $^3P_2$ $^1D_2$ $^3D_1$ $^3D_2$ $^3D_3$ $^1F_3$ $^3F_2$ $^3F_3$ $^3F_4$ $^1G_4$ $^3G_3$ $^3G_4$ $^3G_5$

- QCD permits more configurations
  - Gluonic excitations, multi-quark states, ...
  - Exotic mesons
  - Real meson can be superposition
- Some J^{PC} combinations not possible for $q\bar{q}'$
  - Spin-exotic quantum numbers
  - Unambiguously identify states beyond $q\bar{q}'$
  - $\pi_1(1600)$ with $J^{PC} = 1^{-+}$ studied by COMPASS
  - Predicted by Lattice QCD calculations

Quarkonia  $|q\bar{q}\rangle$

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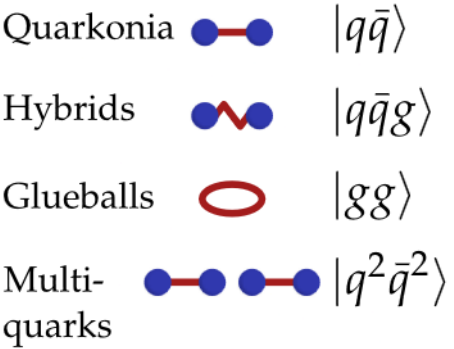

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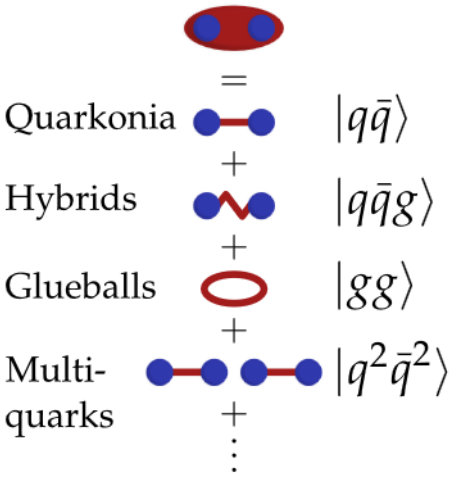

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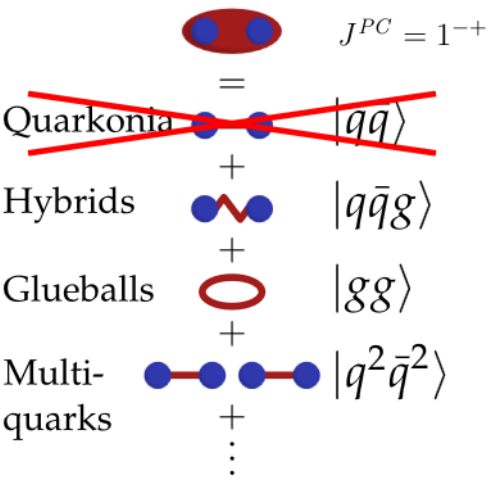

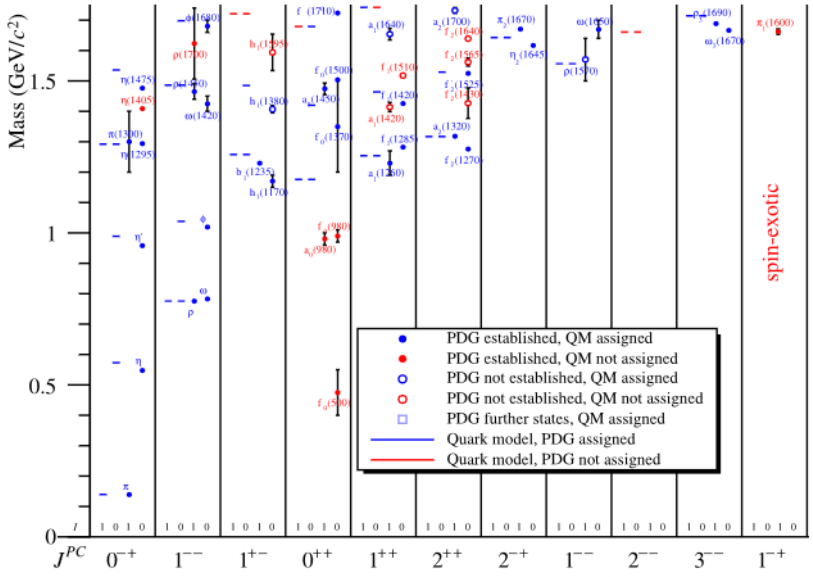
Mass (GeV/c^2)
0
0.5
1
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J^{PC}
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1^{+-}
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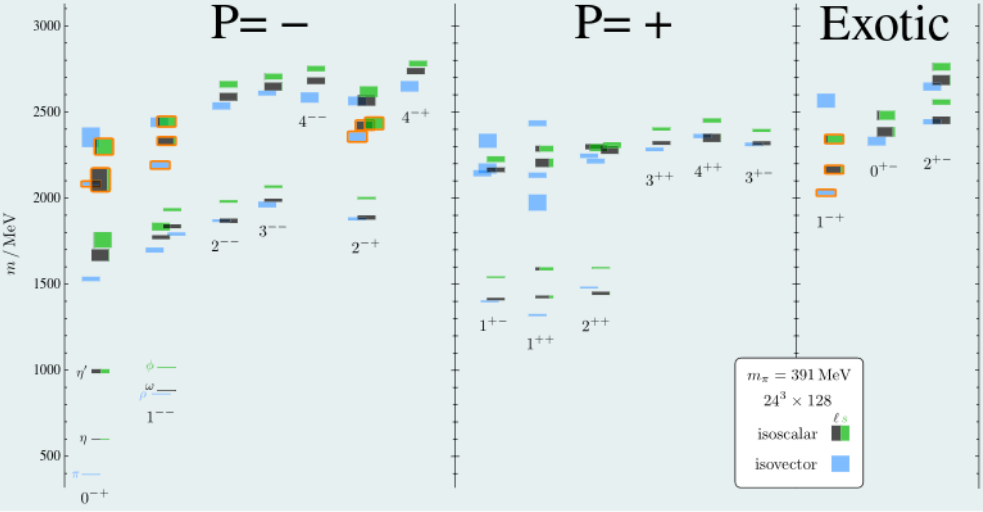
[PRD 88 (2013) 094505]

Lattice QCD prediction of non-strange light-meson spectrum



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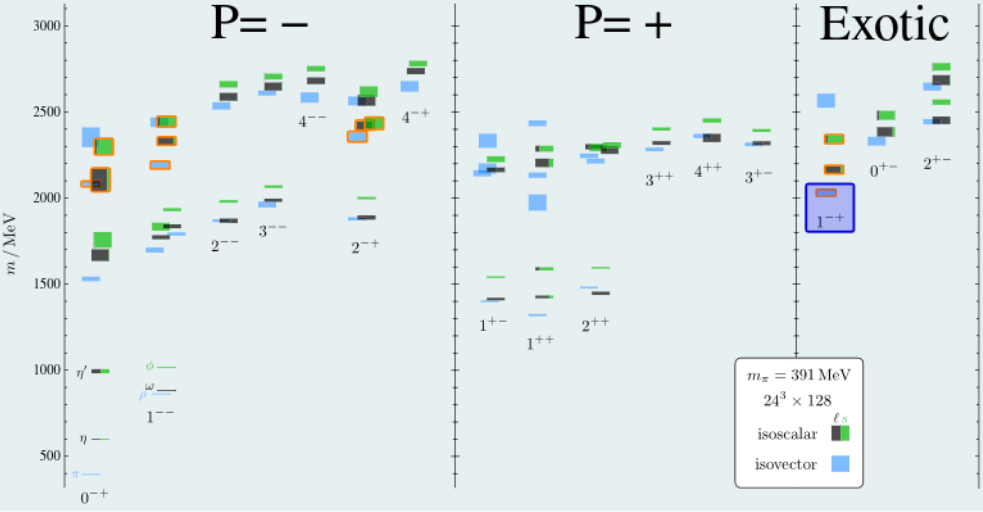

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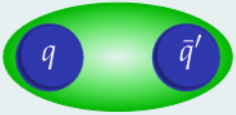
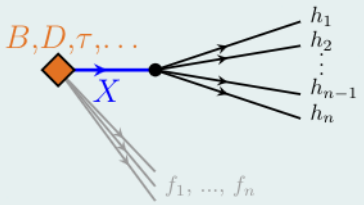
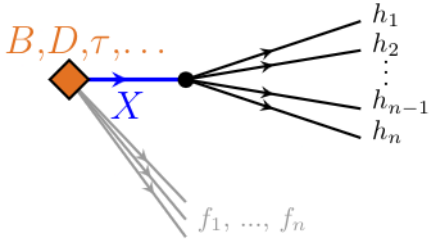


Input to other fields of physics



Light-Meson Spectroscopy

- Light mesons appear as resonances in multi-body hadronic decays of heavy mesons or τ leptons
- Studied in searches for
  - CP violation
  - physics beyond the Standard Model
- Often rare decays
  - Small data samples
  - Large backgrounds
- Precise knowledge of the light-meson spectrum needed as input for decay models



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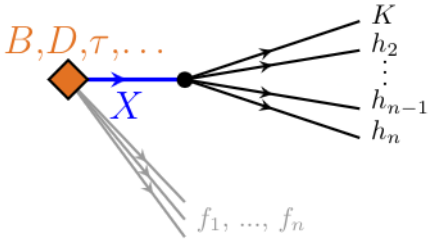
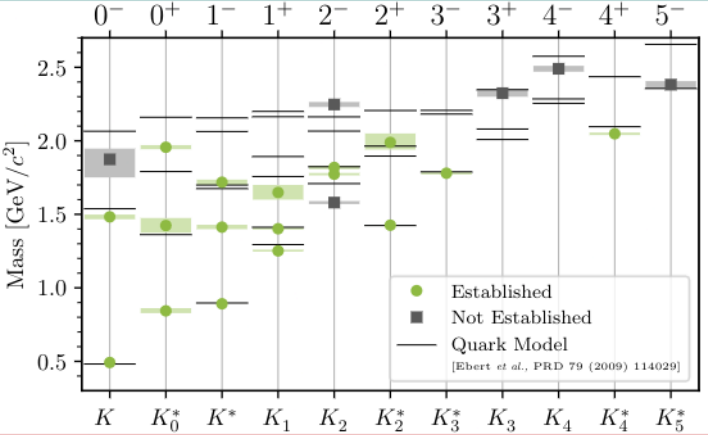


The Strange-Meson Spectrum

[PDG 2024]

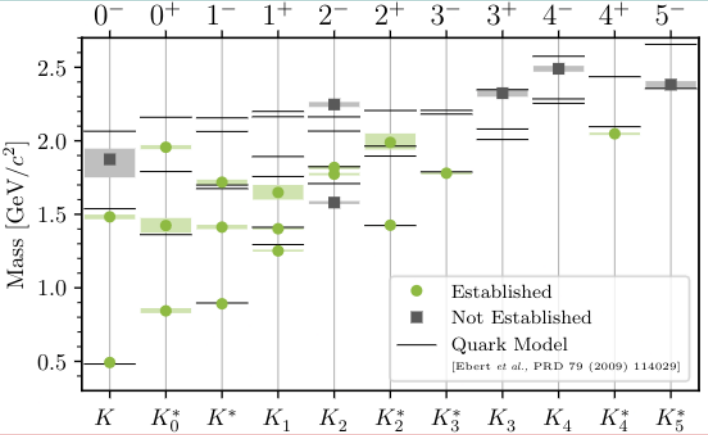


Box heights indicate mass uncertainties

- PDG lists 17 established states, 8 need further confirmation
- Dense spectrum of expected quark-model states
- Many predicted states have not yet been observed

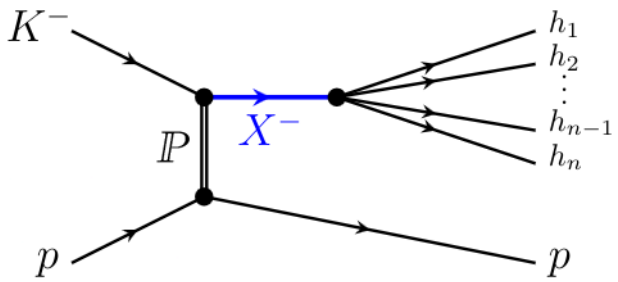
The Strange-Meson Spectrum

[PDG 2024]

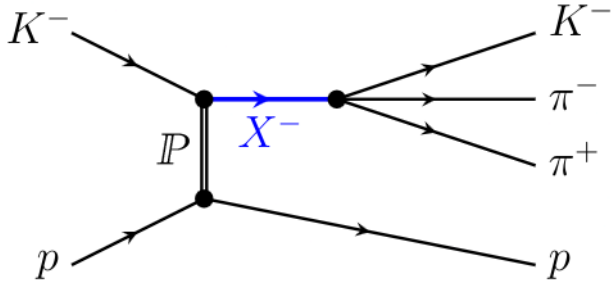


Box heights indicate mass uncertainties

- No exotic quantum numbers for strange mesons
  - ➥ Appear only as supernumerary states, so-called crypto-exotic states
- No clear candidates for crypto-exotic strange mesons except for $K_0^*(700)/\kappa$



- Diffractive scattering of high-energy kaon beam
- Beam kaon excited to intermediate strange-meson resonances X^-
- Decay to multi-body hadronic final states
- $K^-\pi^-\pi^+$ final state allows us to study
  - in principle all strange mesons
  - a wide mass range
  - different decay modes



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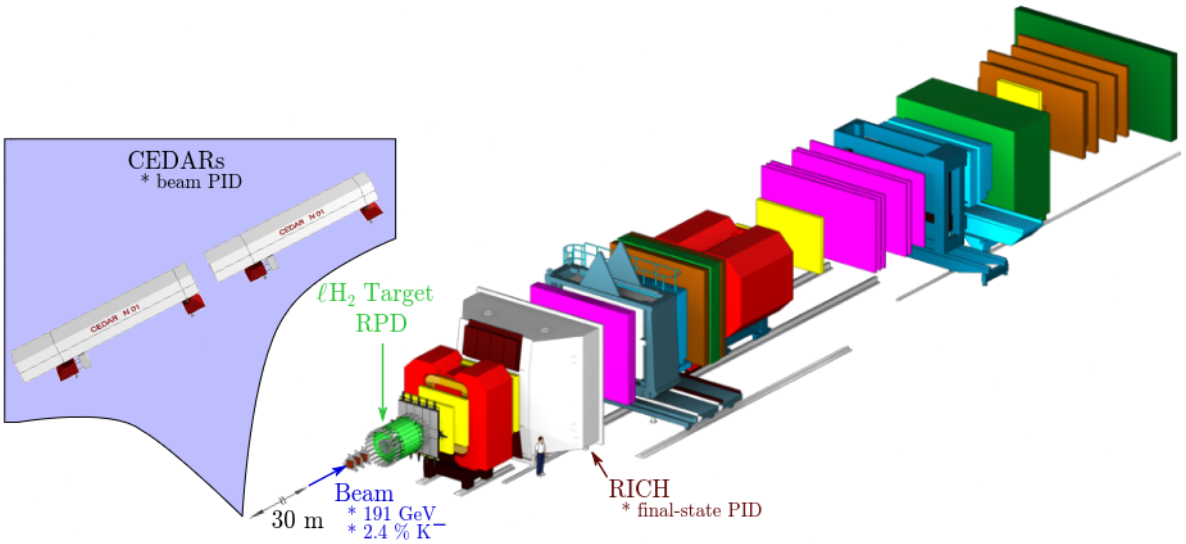
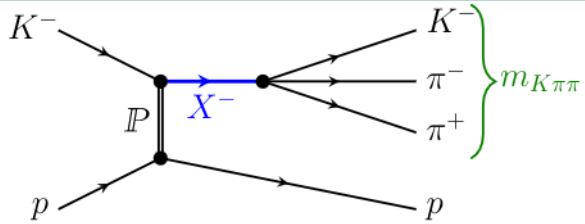
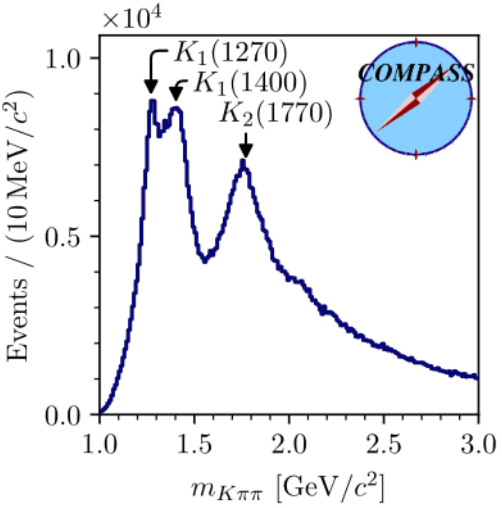
- Fixed-target experiment at M2 beam line in CERN North Area

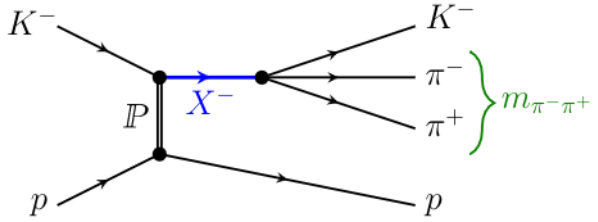
[COMPASS, Nucl. Instrum. Methods **779** (2015) 69]



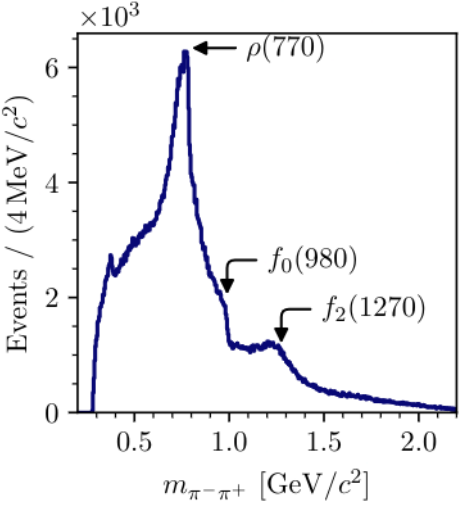


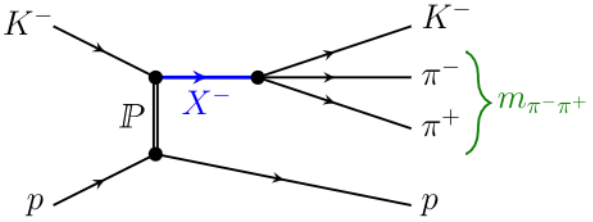
- World's largest data set of about 720 k events
  - About $3.5\times$ larger then ACCMOR data (1981)
- Rich spectrum of overlapping and interfering X^-
  - Dominant well-known states
  - States with lower intensity are "hidden"





- Rich structures in 5D phase-space distribution of $K^-\pi^-\pi^+$ final state
  - $\pi^-\pi^+$ and $K^-\pi^+$ subsystems dominated by known two-body resonances
  - Complex angular distributions
- Characteristic for the quantum numbers and decay paths of X^- resonances





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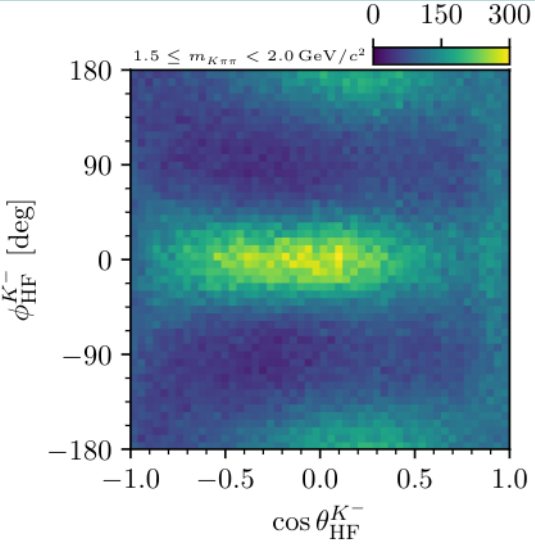
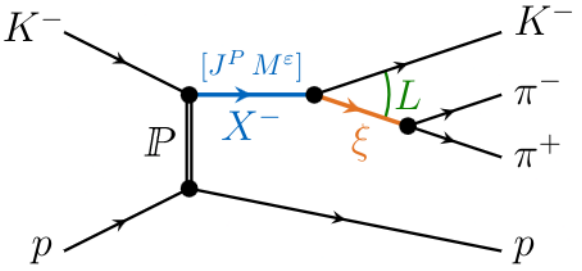


Partial wave: $J^P\, M^\varepsilon\, \xi\, b^-\, L$

- J^P spin and parity
- M^ε spin projection
- ξ two-body resonance
- b^- spectator particle
- L orbital angular momentum



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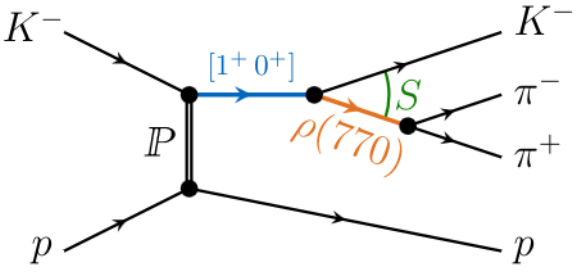

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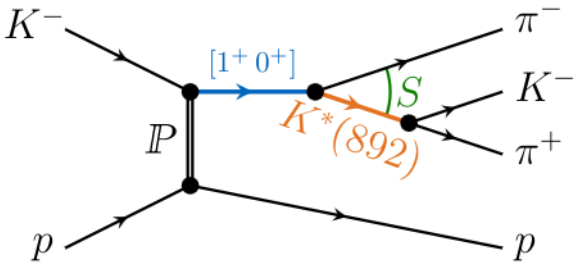

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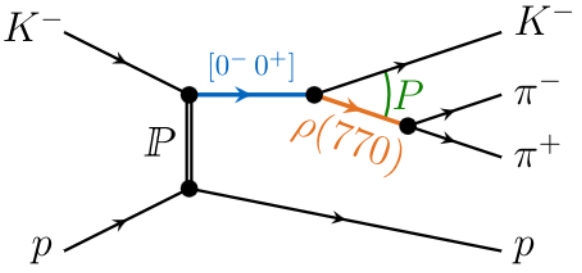
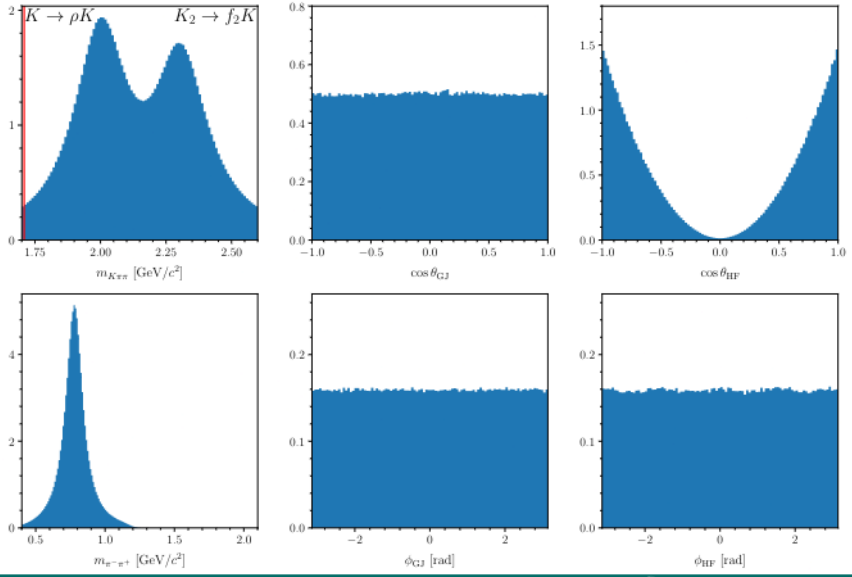
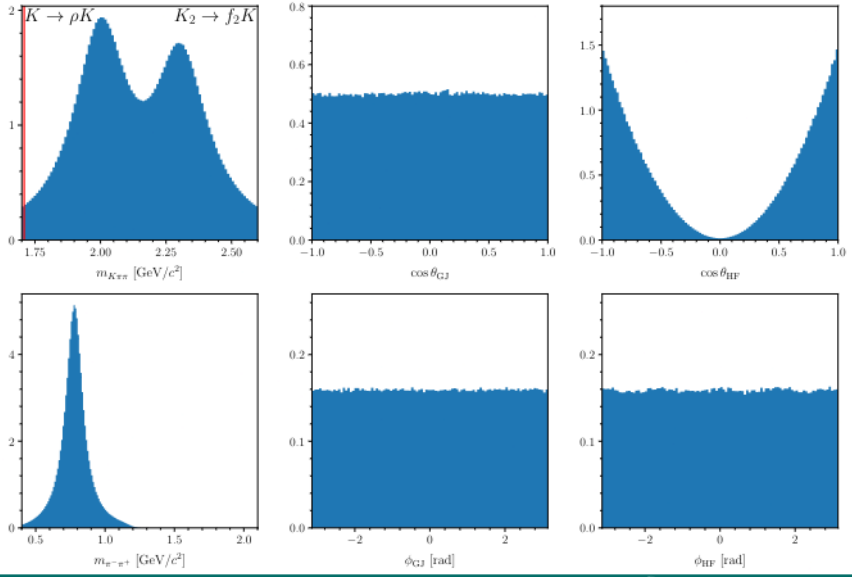



$K \to \rho K$
$K_2 \to f_2 K$
$m_{K\pi\pi}$ [GeV/c^2]
$\cos\theta_{GJ}$
$\cos\theta_{HF}$
$m_{\pi^-\pi^+}$ [GeV/c^2]
ϕ_{GJ} [rad]
ϕ_{HF} [rad]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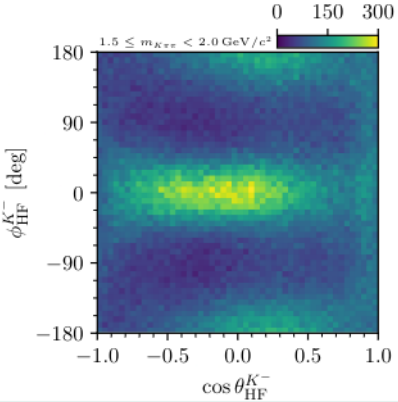
ϕ_{GJ} [rad]
ϕ_{HF} [rad]

- Model intensity distribution in $K^-\pi^-\pi^+$ phase-space τ
- Various partial waves a contribute to data and interfere
- Factorize transition and decay of X^-
  - Decay amplitude $\psi_a(\tau)$ known
  - Transition amplitude T_a
    - contains information on X^- resonance
    - measured from data using unbinned maximum-likelihood fit to 5D phase-space distribution
- Set of considered waves in $\sum_a$ determined using regularization-based model-selection techniques



$$I(\tau) = |\mathcal{A}|^2$$

- Model intensity distribution in $K^-\pi^-\pi^+$ phase-space τ
- Various partial waves a contribute to data and interfere
- Factorize transition and decay of X^-
  - Decay amplitude $\psi_a(\tau)$ known
  - Transition amplitude $\mathcal{T}_a$
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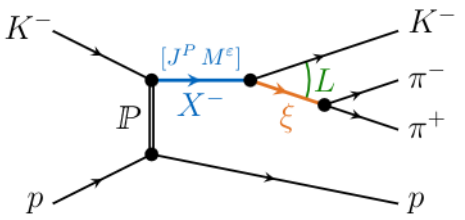

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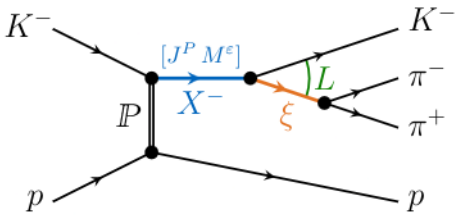

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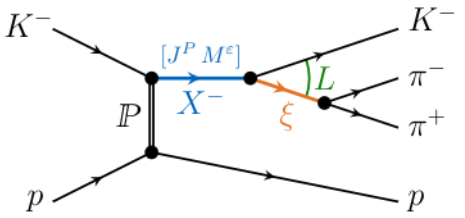

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Data: 720 k diffractively produced $K^-\pi^-\pi^+$ candidates

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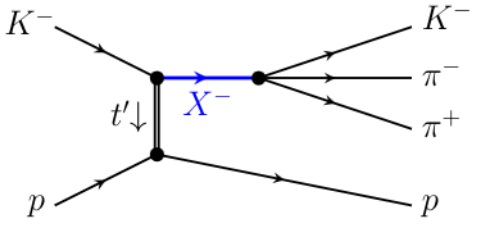
(I) Partial-Wave Decomposition
Performed independently in narrow $(m_{K\pi\pi}, t')$ cells
No assumption about $K\pi\pi$ resonances

Partial waves: Intensities and relative phases as a function of $(m_{K\pi\pi}, t')$



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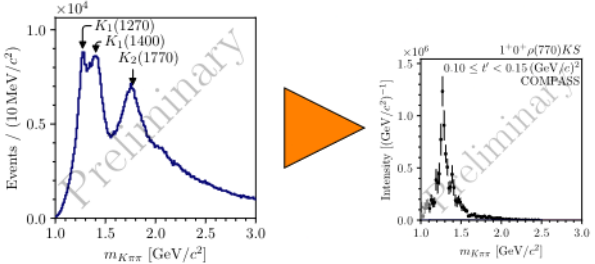

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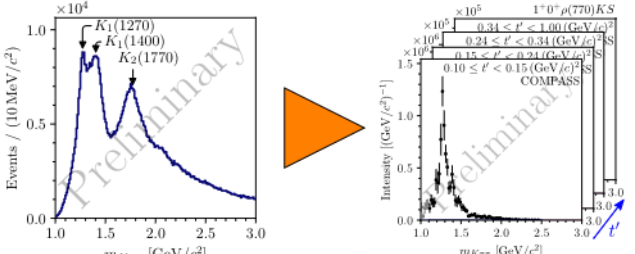

Partial-Wave Analysis of the $K^-\pi^-\pi^+$ Final State

Analysis Scheme

Data: 720 k diffractively produced $K^-\pi^-\pi^+$ candidates

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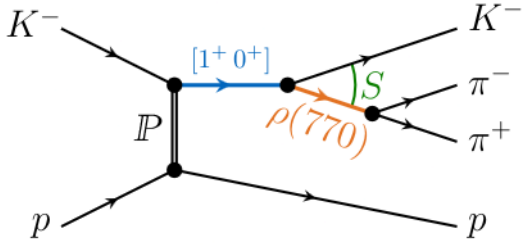
Partial waves: Intensities and relative phases as a function of $(m_{K\pi\pi}, t')$

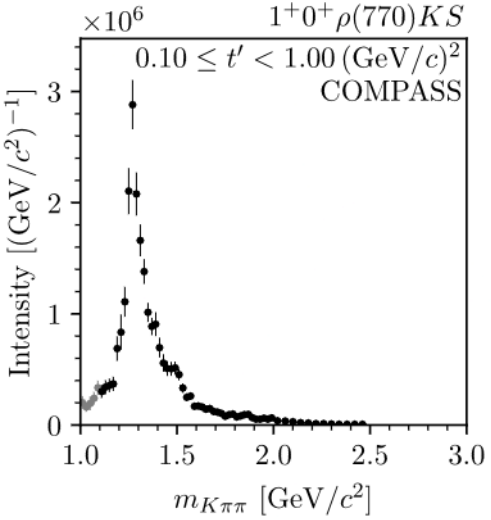
(II) Resonance-Model Fit
Model $m_{K\pi\pi}$ dependence of partial waves
$K\pi\pi$ resonances and background

Resonance parameters: Masses and widths of the strange-meson resonances

Partial-Wave Analysis of the $K^-\pi^-\pi^+$ Final State

Resonance-Model Fit





Partial-Wave Analysis of the $K^-\pi^-\pi^+$ Final State

Resonance-Model Fit

- Partial-wave amplitudes in $(m_{K\pi\pi}, t')$ bins
- Model $m_{K\pi\pi}$ dependence of partial-wave amplitudes
- Breit-Wigner amplitudes for $K^-\pi^-\pi^+$ resonance components
- Coherent non-resonant component accounts for other $K^-\pi^-\pi^+$ production mechanisms
- Developed scheme to handle incoherent backgrounds
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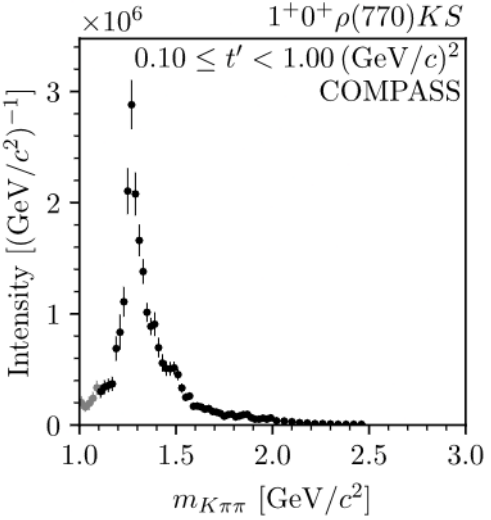

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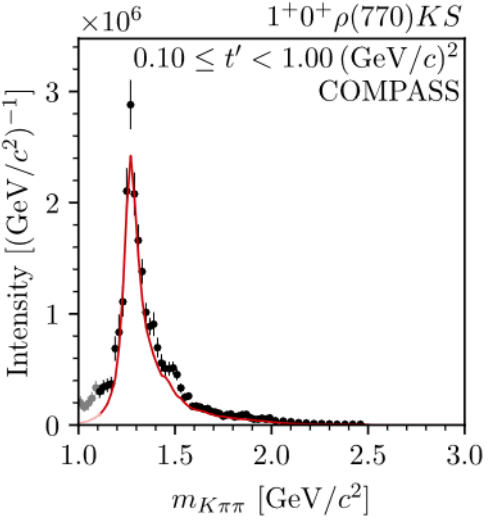

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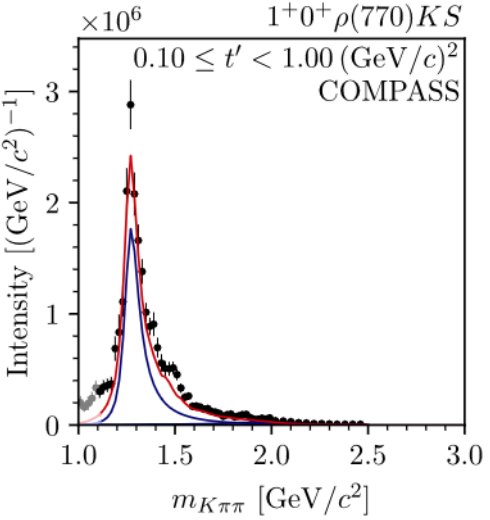

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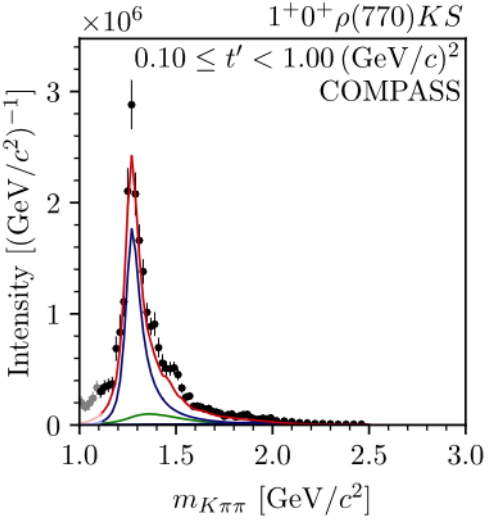

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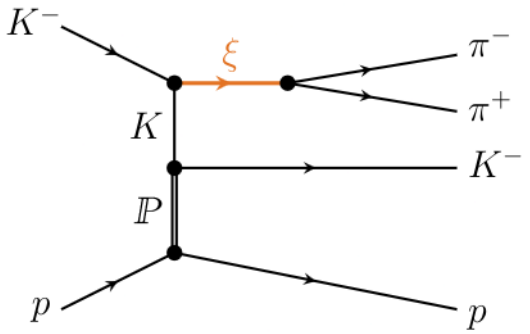

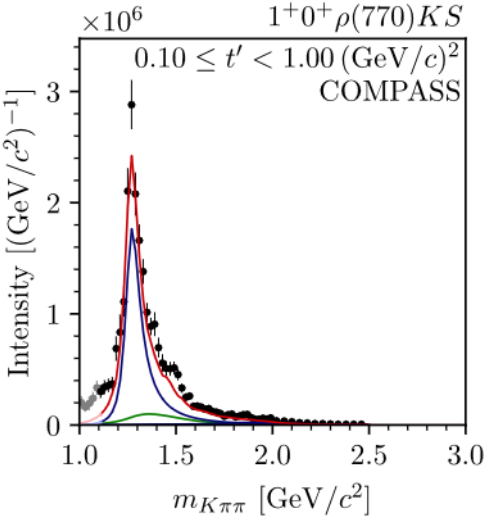

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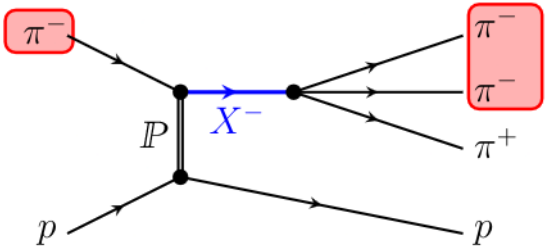

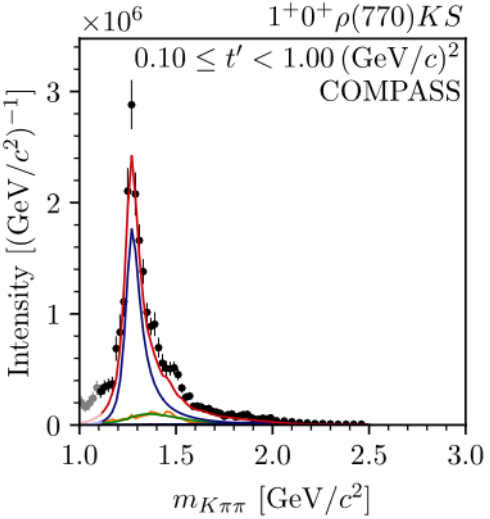

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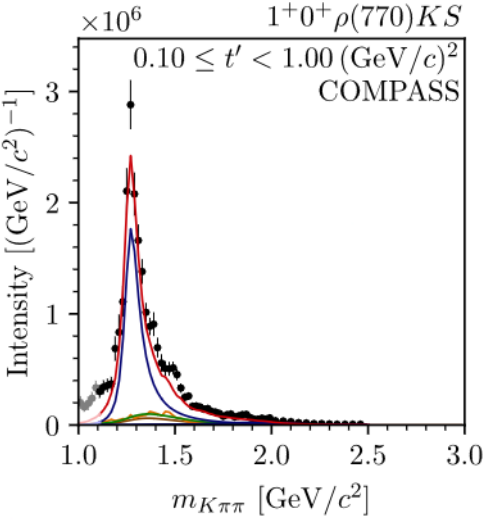

- Simultaneously fit 14 partial waves
- Modeled by 13 strange-meson resonances
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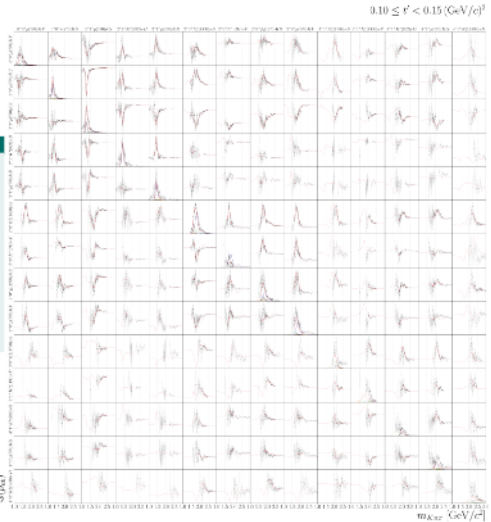

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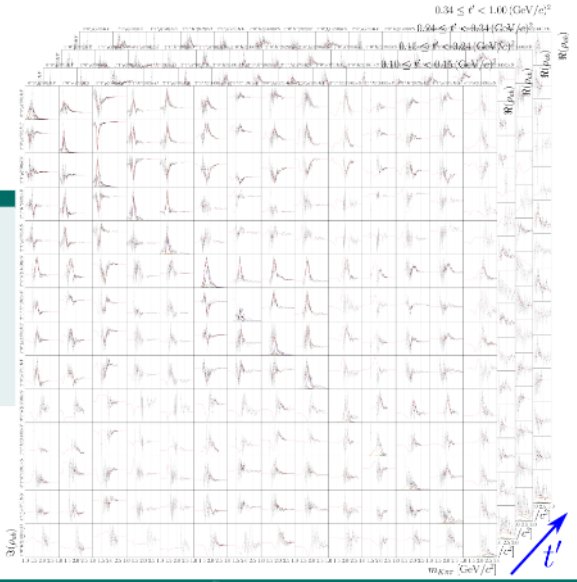
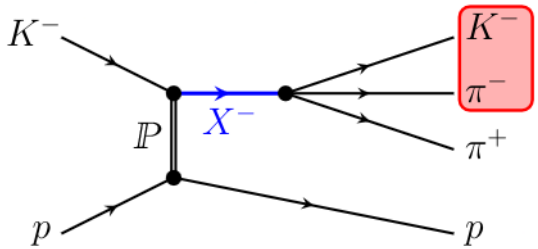


Partial-Wave Analysis of the $K^-\pi^-\pi^+$ Final State

Ambiguous Identification of Final-State Particles

- Analysis requires to identify one of the two negative particles
- Limited acceptance due to limited kinematic range of final-state PID
  - Reduced distinguishability of certain partial waves
  - Analysis artifacts in some waves for $m_{K\pi\pi} \lesssim 1.6\,\mathrm{GeV}/c^2$
- Only a sub-set of partial waves affected
  - Verified in extensive systematic and Monte Carlo input-output studies



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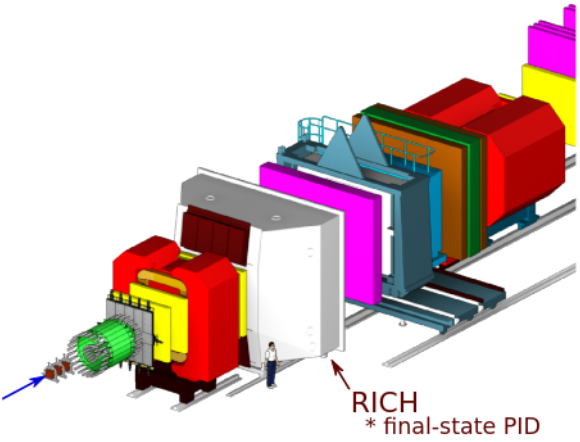

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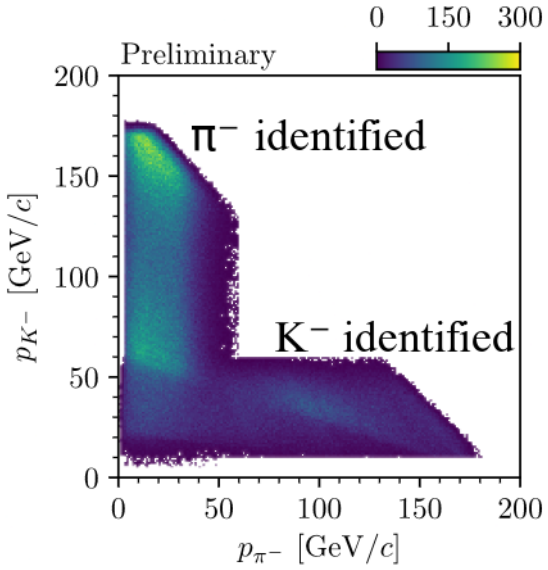

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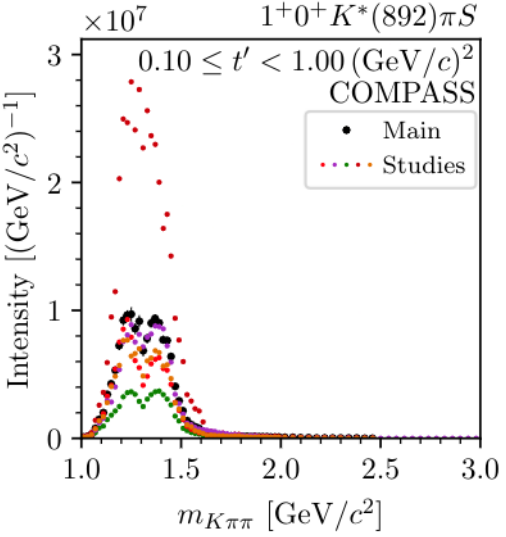

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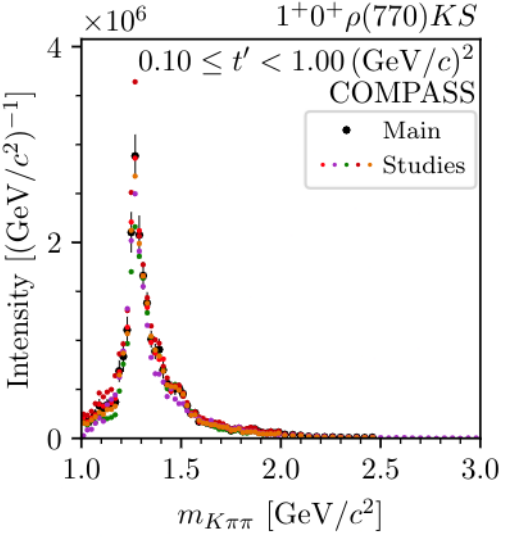

- ✗ K_1 Mesons with $J^P = 1^+$
- ✗ K_4^* Mesons with $J^P = 4^+$
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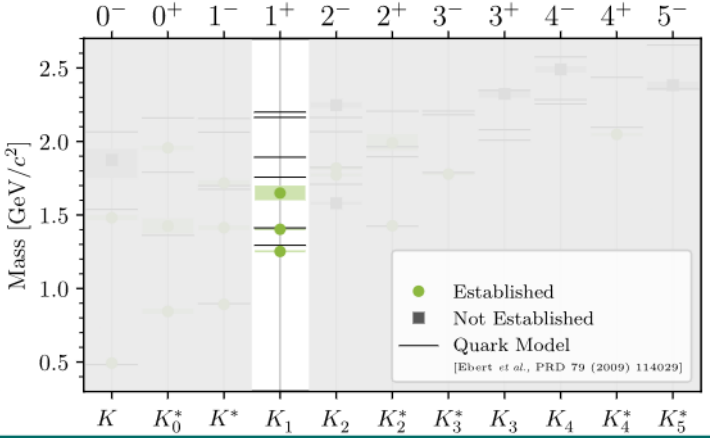
K_1 Mesons

[arXiv:2504.09470]

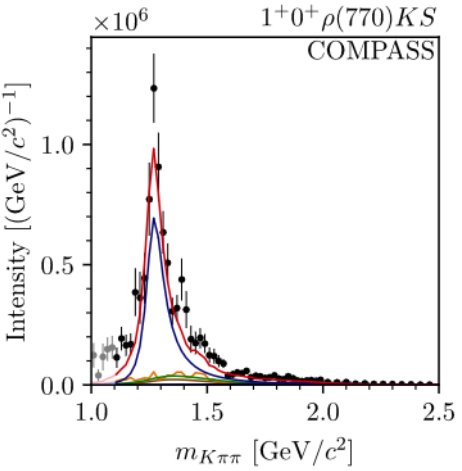


PDG (2022)

- Two near-by states $K_1(1270)$ and $K_1(1400)$
- Excited $K_1(1650)$

[arXiv:2504.09470]

- Study K_1 states in $\rho(770)K$ decay with $M^\varepsilon = 0^+$
- Dominated by $K_1(1270)$
- Indications for excited K_1'
  - in high-mass tail
  - mainly in $M^\varepsilon = 1^+$ wave



total resonance model, resonances, non-resonant, $\pi\pi\pi$ background, effective background

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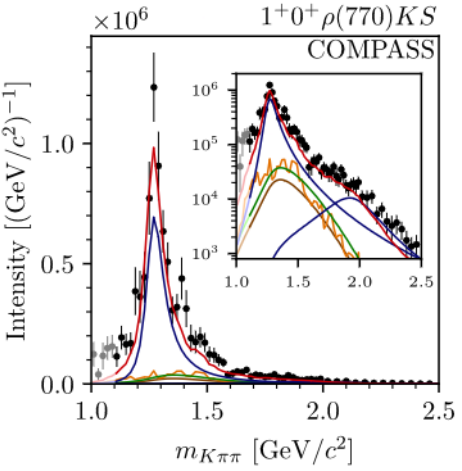

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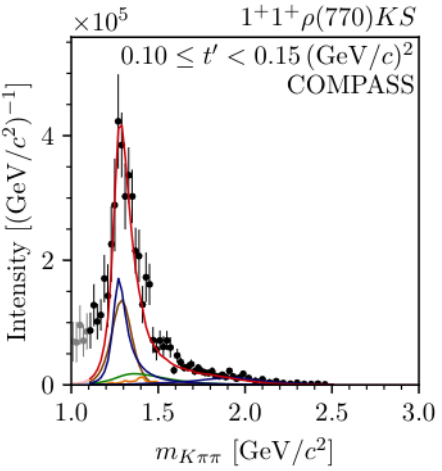

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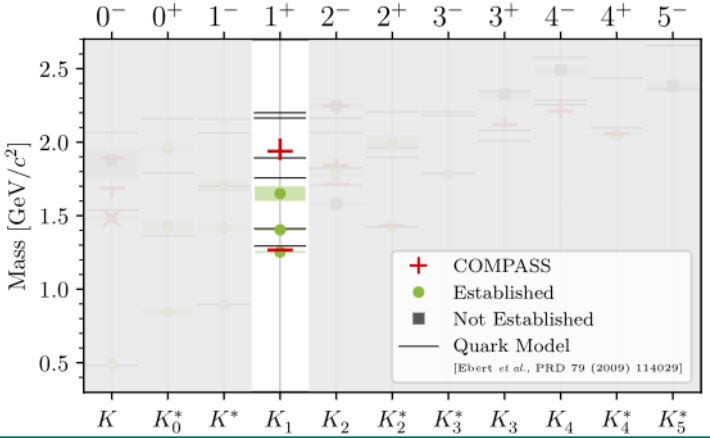
K_1 Mesons

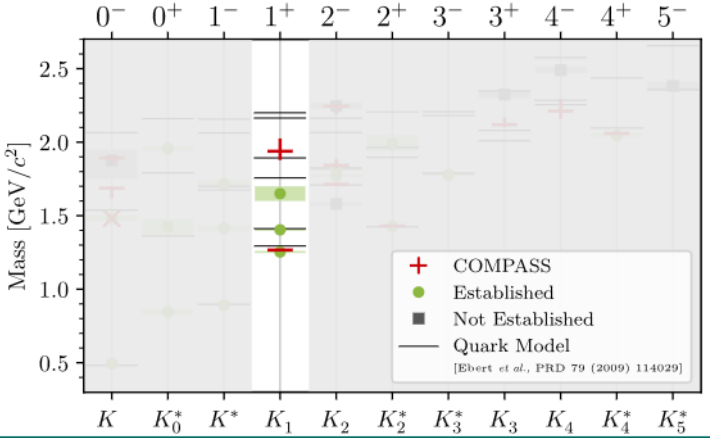


$K_1(1270)$

- Resonance parameters in agreement with previous measurements

K_1 Mesons

[arXiv:2504.09470]



K_1'

- Larger mass and width compared to $K_1(1650)$ from single measurement [NPB 276 (1986) 667]
- Our estimates consistent with recent measurement in $B^+ \to J/\psi\phi K^+$ at LHCb [PRL 127 (2021) 082001]

- ✓ K_1 Mesons with $J^P = 1^+$
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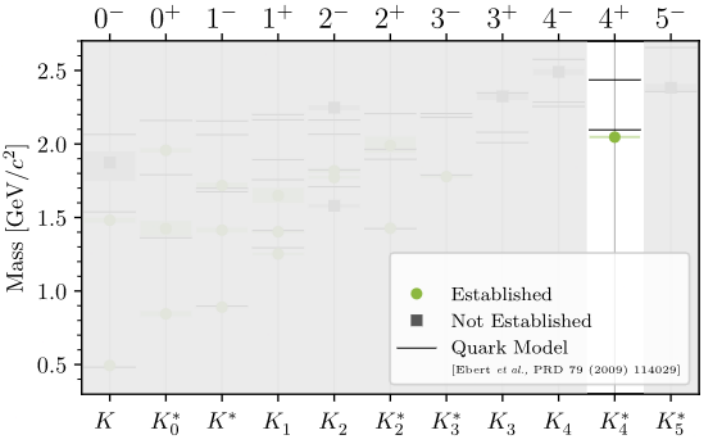
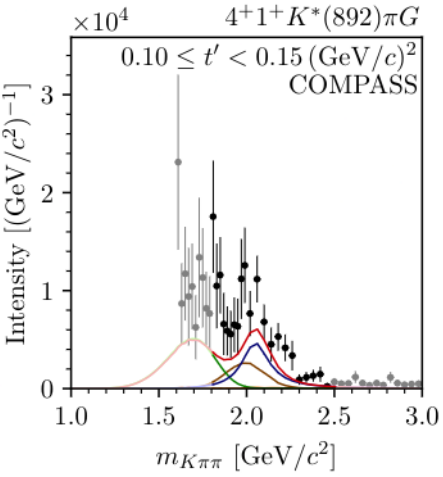


PDG

- $K_4^*(2045)$ established state

[arXiv:2504.09470]

- $K_4^*(2045)$ signal at per-mil level
  - in $K^*(892)\ \pi$ decay
  - in $\rho(770)\ K$ decay
- Interference terms described well
- Accompanied by rising phase



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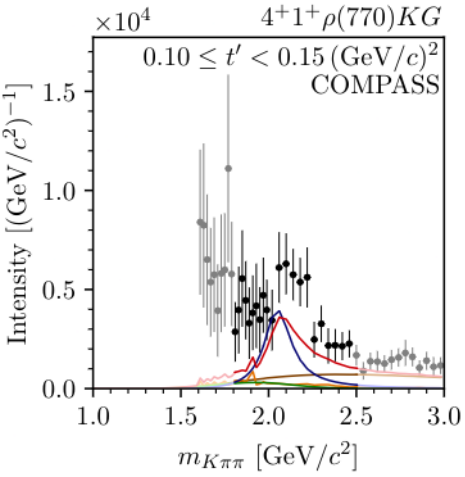
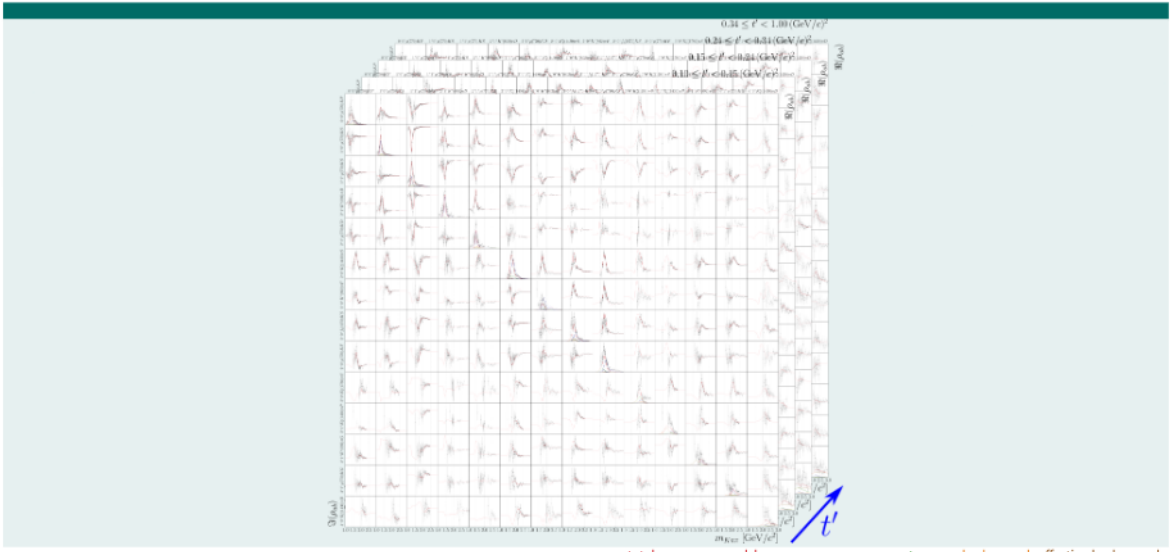


total resonance model, resonances, non-resonant, $\pi\pi\pi$ background, effective background

[arXiv:2504.09470]



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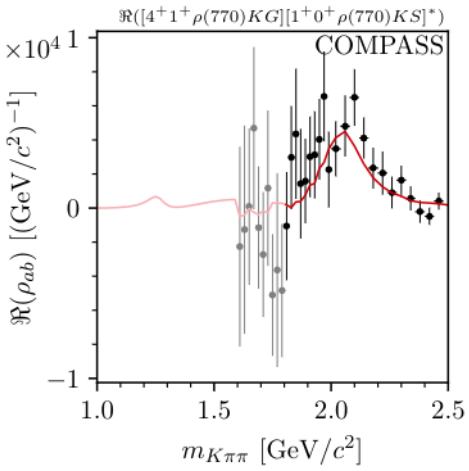
[arXiv:2504.09470]

- $K_4^*(2045)$ signal at per-mil level
  - in $K^*(892)\ \pi$ decay
  - in $\rho(770)\ K$ decay
- Interference terms described well
- Accompanied by rising phase



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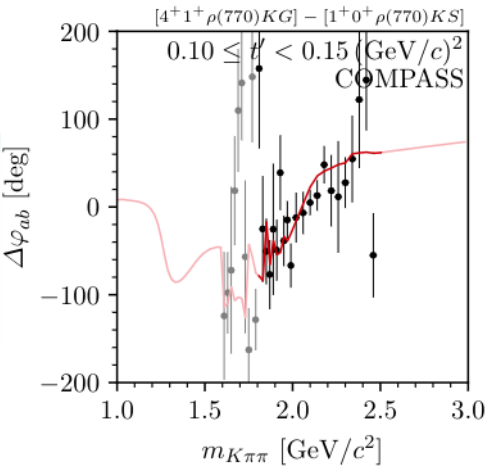

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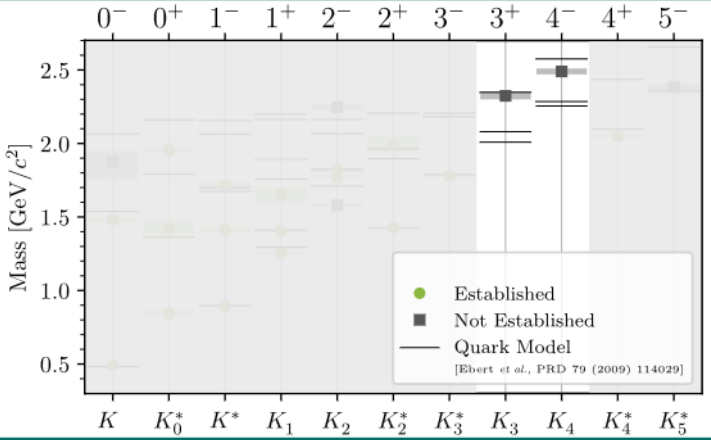
- ✓ K_1 Mesons with $J^P = 1^+$
- ✓ K_4^* Mesons with $J^P = 4^+$
- ✗ K_3 Mesons with $J^P = 3^+$ and K_4 Mesons with $J^P = 4^-$
- ✗ K Mesons with $J^P = 0^-$

K_3 and K_4 Mesons

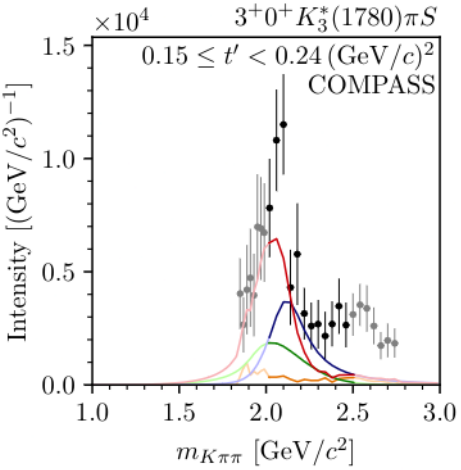
[arXiv:2504.09470]



- $K_3(2320)$ and $K_4(2500)$ listed by the PDG
- Need further confirmation
- Seen only in $\Lambda\overline{p}$ final state by few experiments

[arXiv:2504.09470]

- Observe K_3 signal at about 2.1 GeV/c^2
  - in $K_3^*(1780)\pi$ and $K_2^*(1430)\pi$ decays
- Evidence for K_4 signal at about 2.2 GeV/c^2
  - in $K_2^*(1430)\pi$ decay



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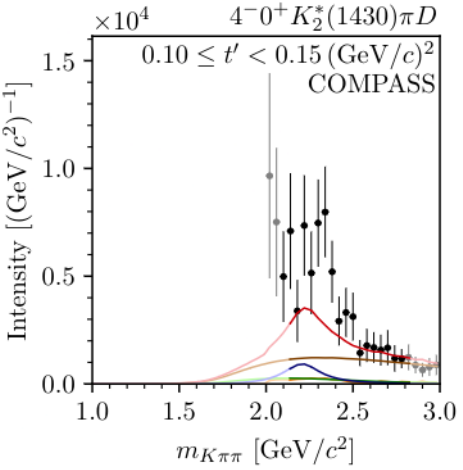

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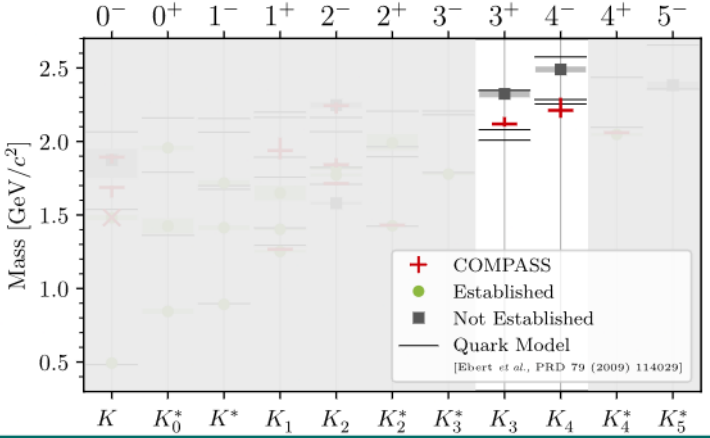
K_3 and K_4 Mesons

[arXiv:2504.09470]



- Widths of both states in agreement with previous observations
- Masses significantly lower, however in good agreement with quark-model predictions for ground states
  - ➥ Potential first observation of K_3 and K_4 ground states, while excited states observed in $\Lambda\overline{p}$ decay

- ✓ K_1 Mesons with $J^P = 1^+$
- ✓ K_4^* Mesons with $J^P = 4^+$
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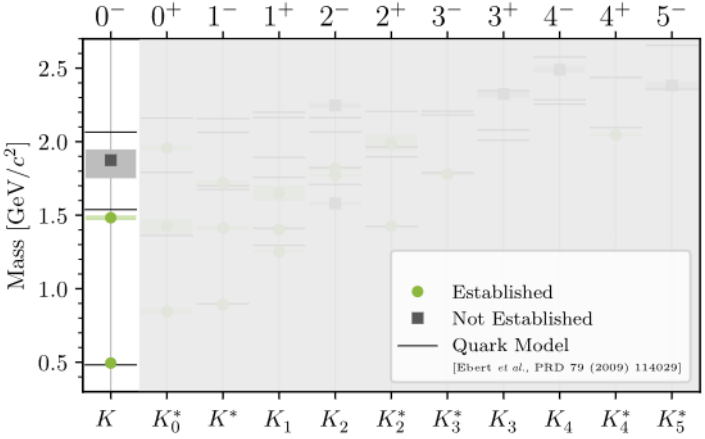

- $K(1460)$ established
- $K(1830)$ needs further confirmation

[arXiv:2504.09470]

COMPASS $K^-\pi^-\pi^+$ data

- Peak at about 1.4 GeV/c^2
  - Established $K(1460)$
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- Second peak at about 1.7 GeV/c^2
  - Excited $K(1690)$ signal
    - About $8\,\sigma$ statistical significance
  - Accompanied by rising phase
  - Measured width inconsistent with "$K(1630)$" in PDG [PTEP 8 (2020) 083C01]
- Third signal at about 2.0 GeV/c^2
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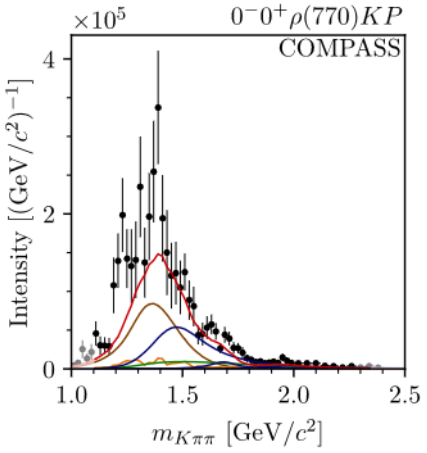

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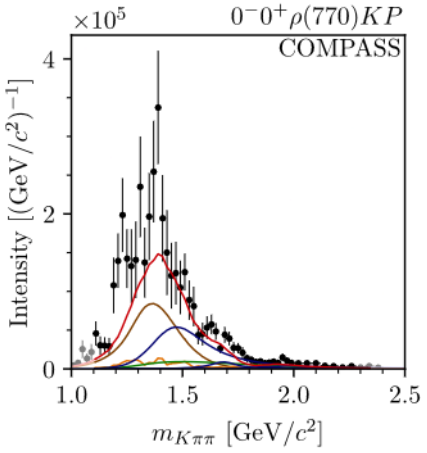

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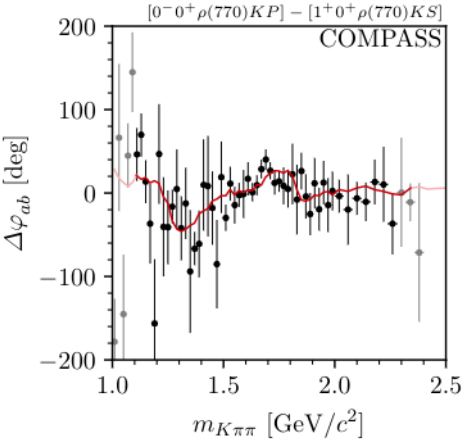

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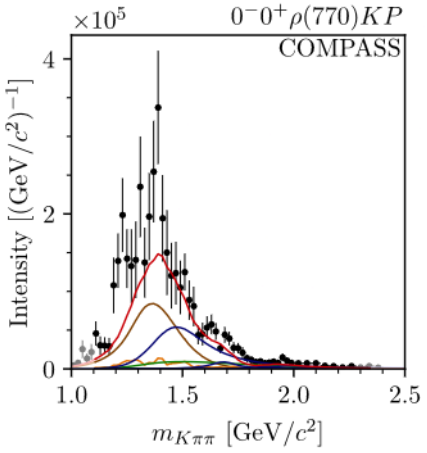

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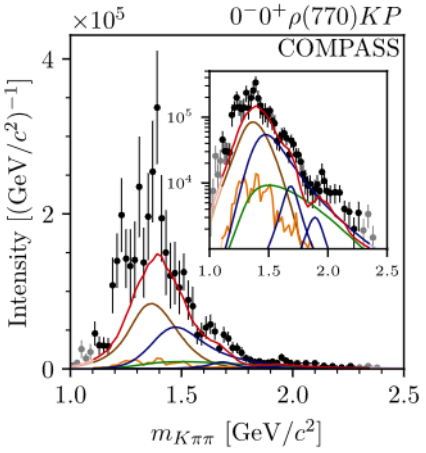

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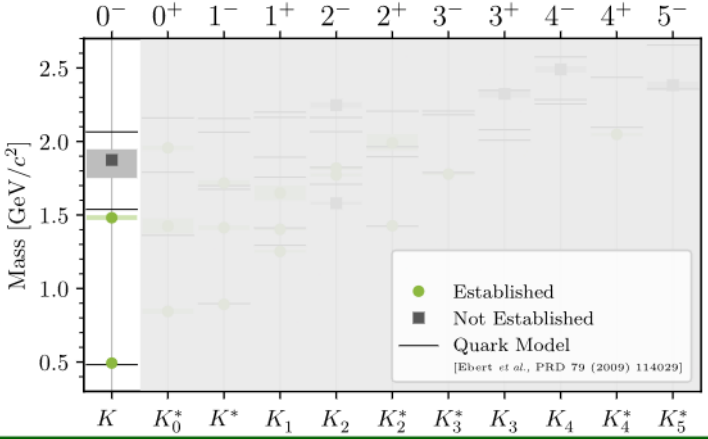

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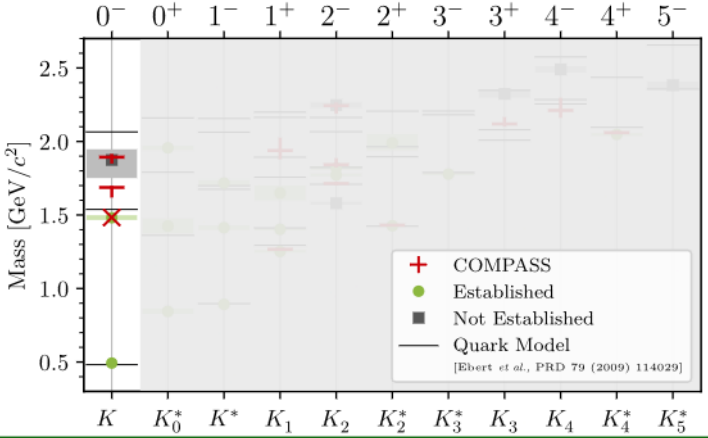

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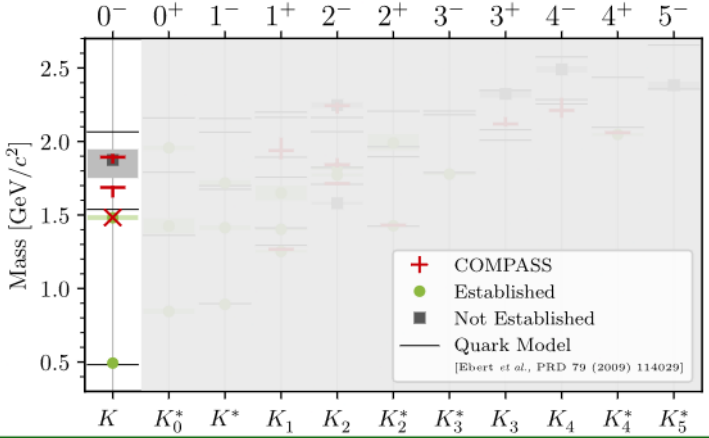

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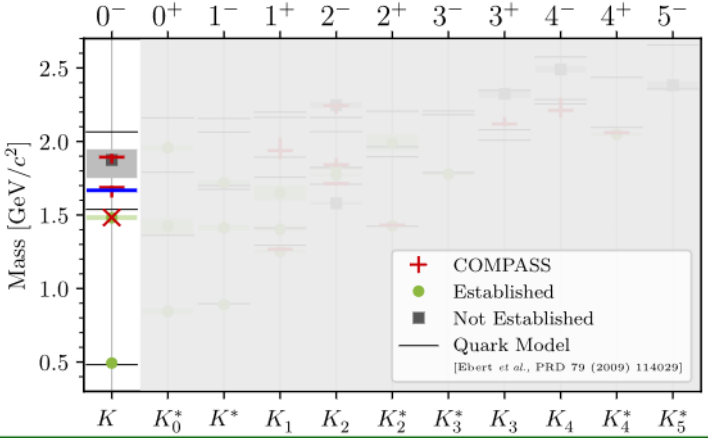

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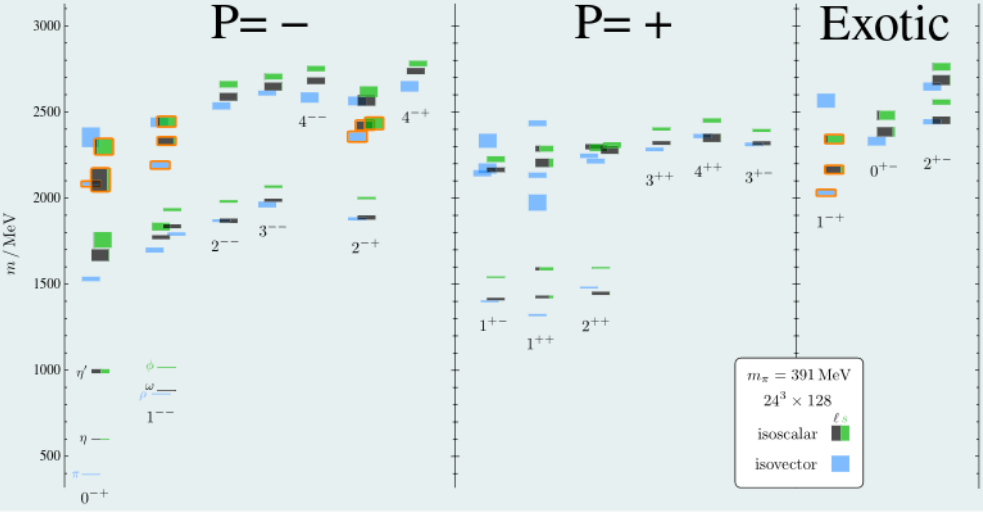
[PRD 88 (2013) 094505]

Lattice QCD prediction of non-strange light-meson spectrum



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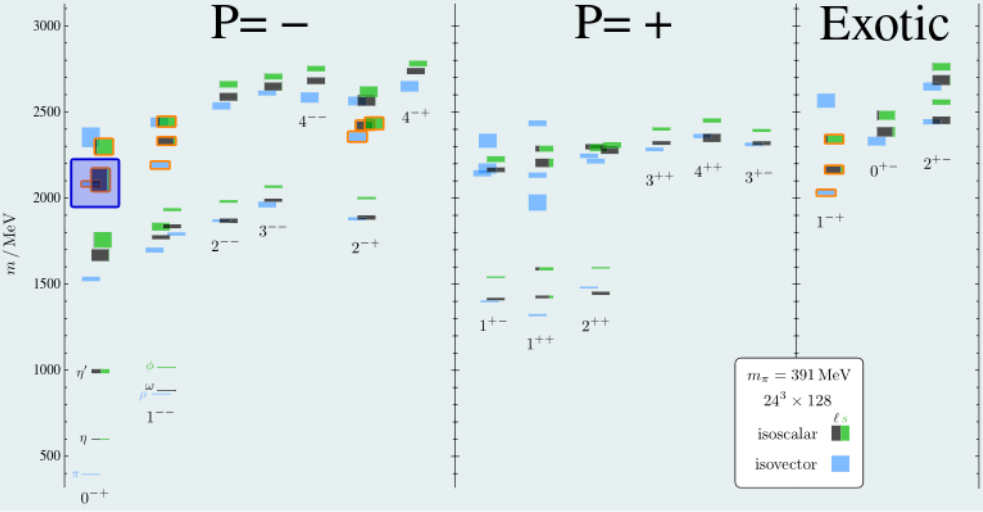

High-Precision Strange-Meson Spectroscopy at AMBER

- AMBER: QCD facility at M2 beam line
  - Approved phase-1 currently ongoing [CERN-SPSC-2019-022]
  - Plans for Phase-2 beyond long shutdown 3 of LHC [arXiv:1808.00848]
    - High-precision strange-meson spectroscopy measurement
- Efficient final-state particle identification
  - Reduce the beam momentum to fit the current momentum range
- High intensity and high energy kaon beam
- Overcome limitations of COMPASS data sample
  - Access to all decay modes in $K^-\pi^-\pi^+$ final state
  - $30\times$ larger sample

AMBER

Apparatus for Meson and Baryon Experimental Research

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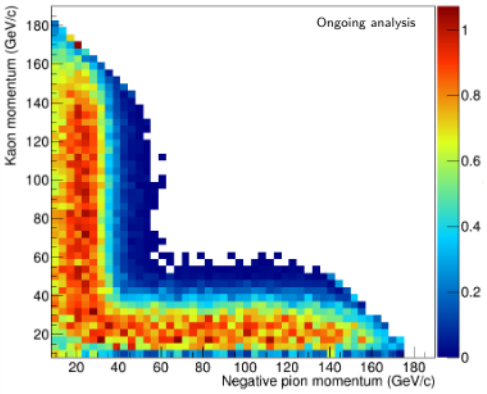
$p_{\text{beam}} = 190\,\text{GeV}/c$



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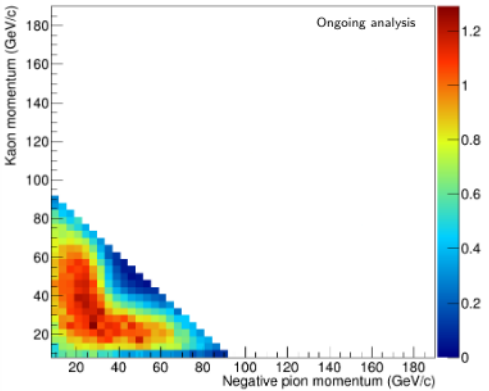

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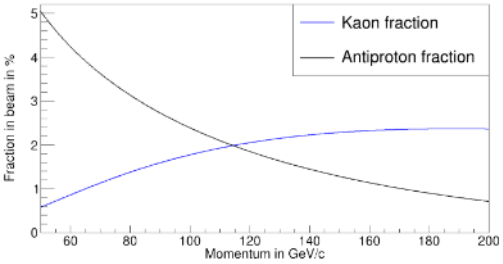
K^- beam



[F. Metzger, Physics Beyond Colliders Meeting]

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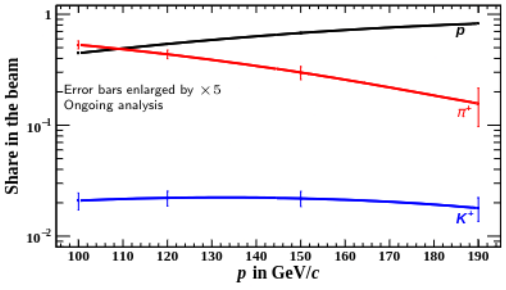

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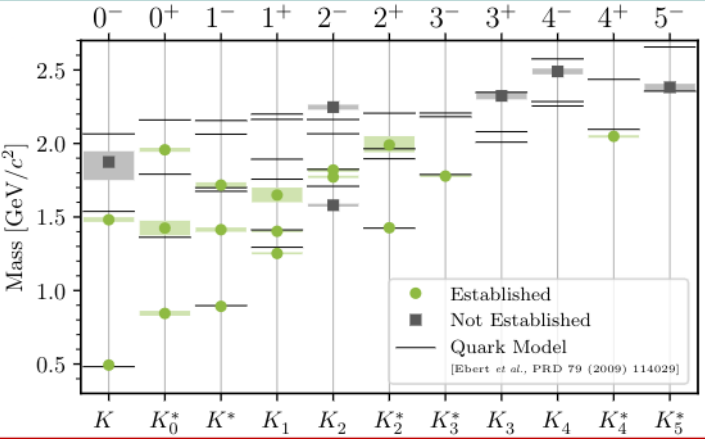
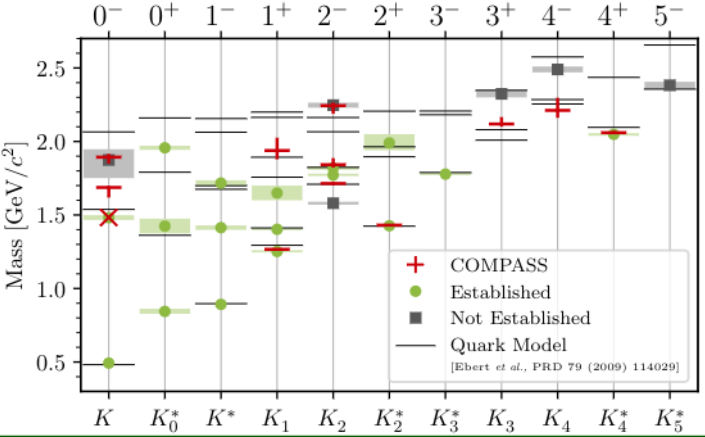
Summary



The Strange-Meson Spectrum

- Many strange mesons require further confirmation
- Search for strange partners of exotic non-strange light mesons

Summary



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- World's largest data sample on $K^-\pi^-\pi^+$ $\Rightarrow$ Most detailed and comprehensive analysis
- First candidate for exotic strange-meson signal with $J^P = 0^-$

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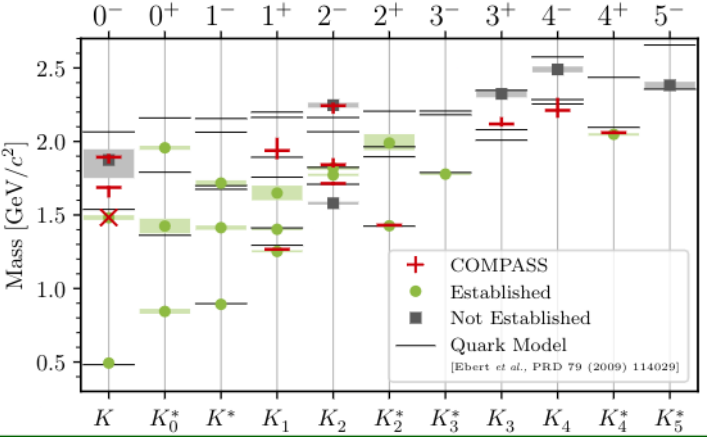

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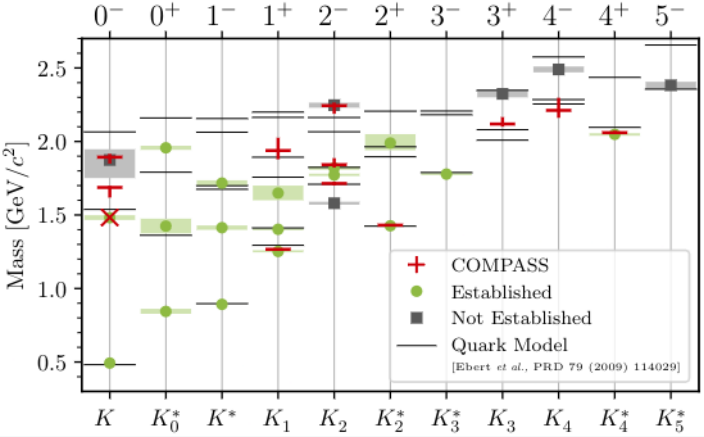

Outlook

- Future measurements using heavy-meson and τ lepton decays at LHCb, Belle II, BES, ...
- AMBER at CERN: Proposal for high-precision strange-meson spectroscopy measurement