Light-Meson Spectroscopy – From COMPASS to AMBER

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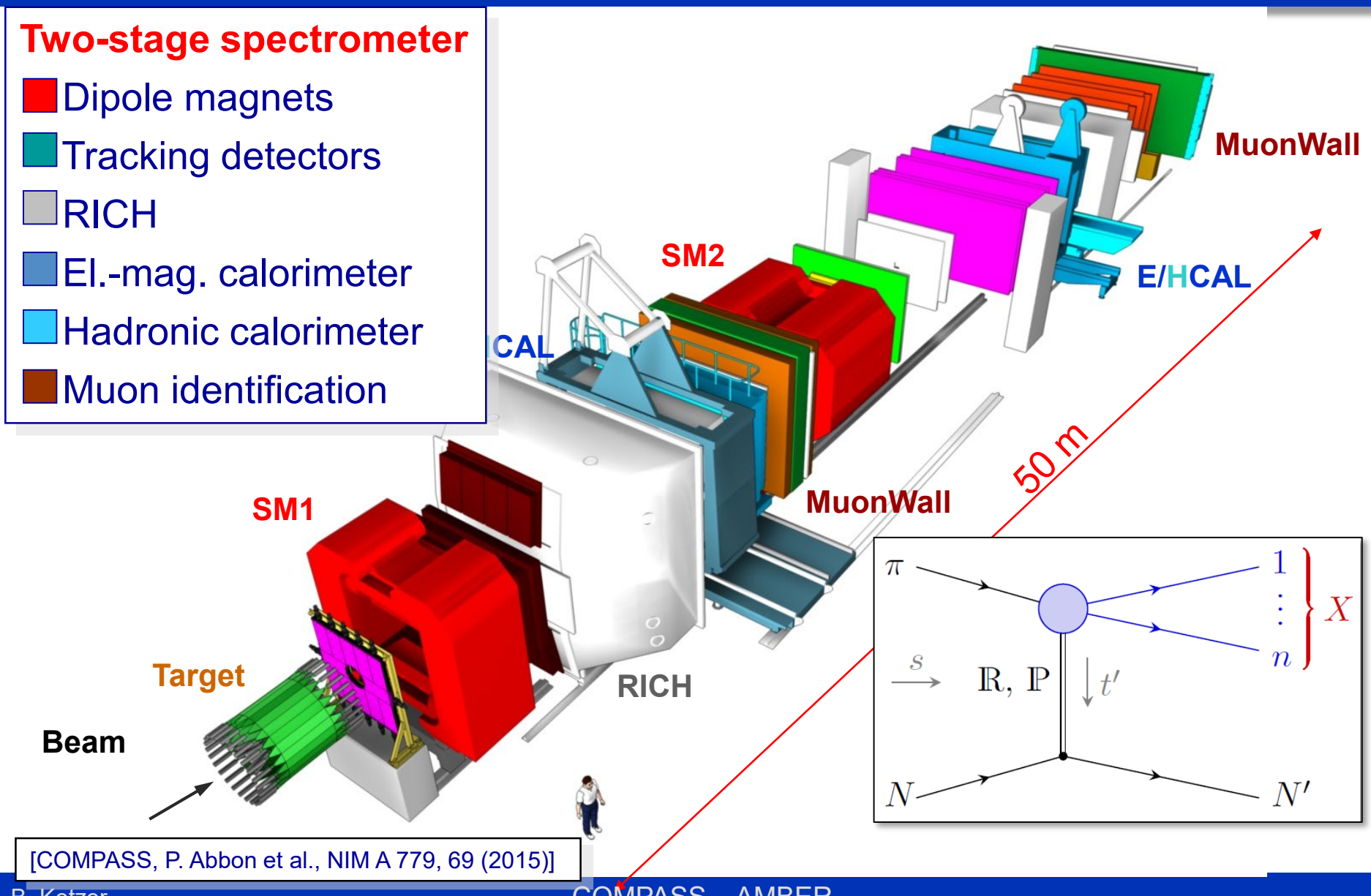
MITP Workshop on Hadron Spectroscopy: The Next Big Steps

22 March 2022

The COMPASS Experiment

Two-stage spectrometer

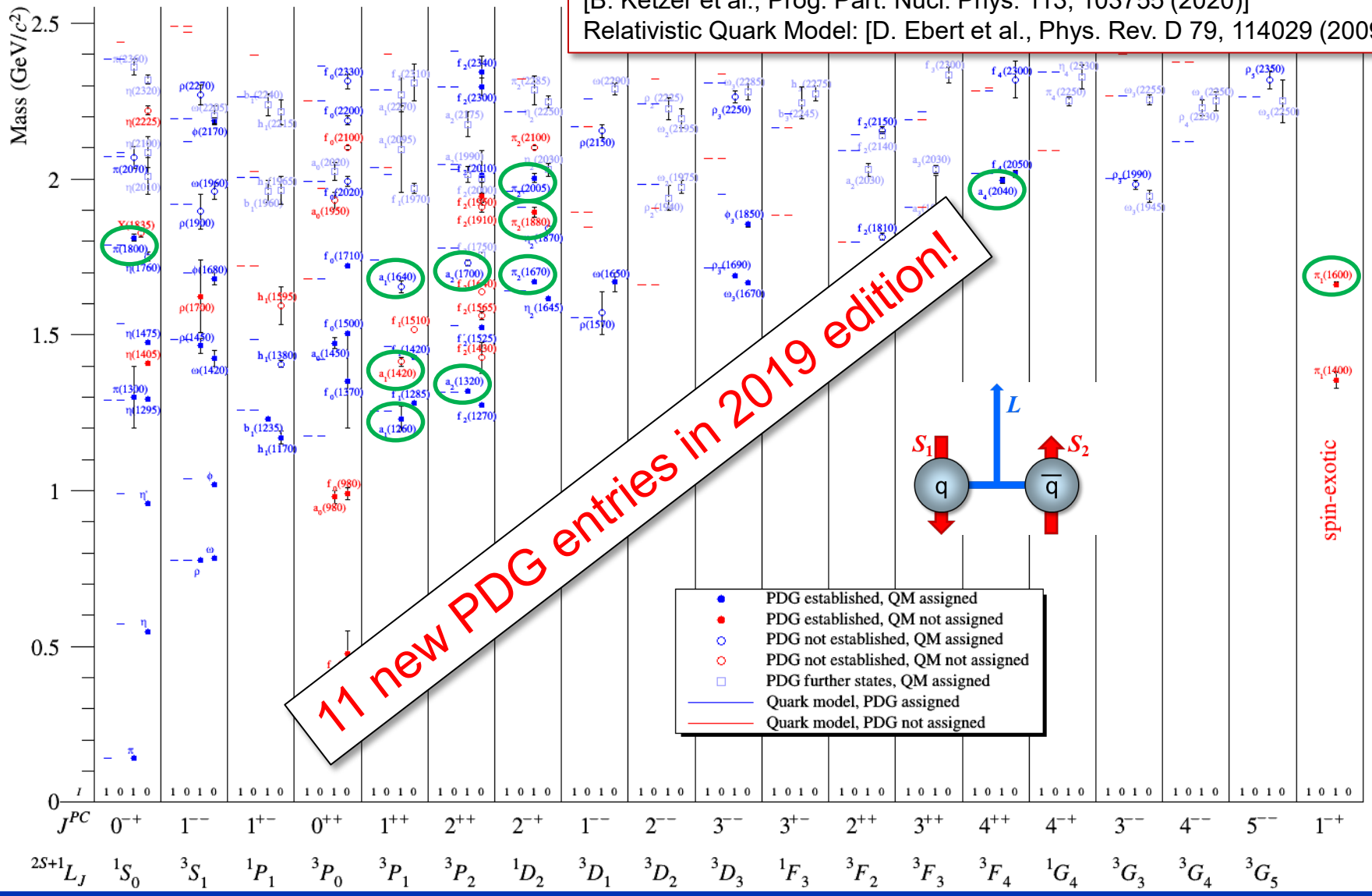
- Dipole magnets
- Tracking detectors
- RICH
- El.-mag. calorimeter
- Hadronic calorimeter
- Muon identification



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

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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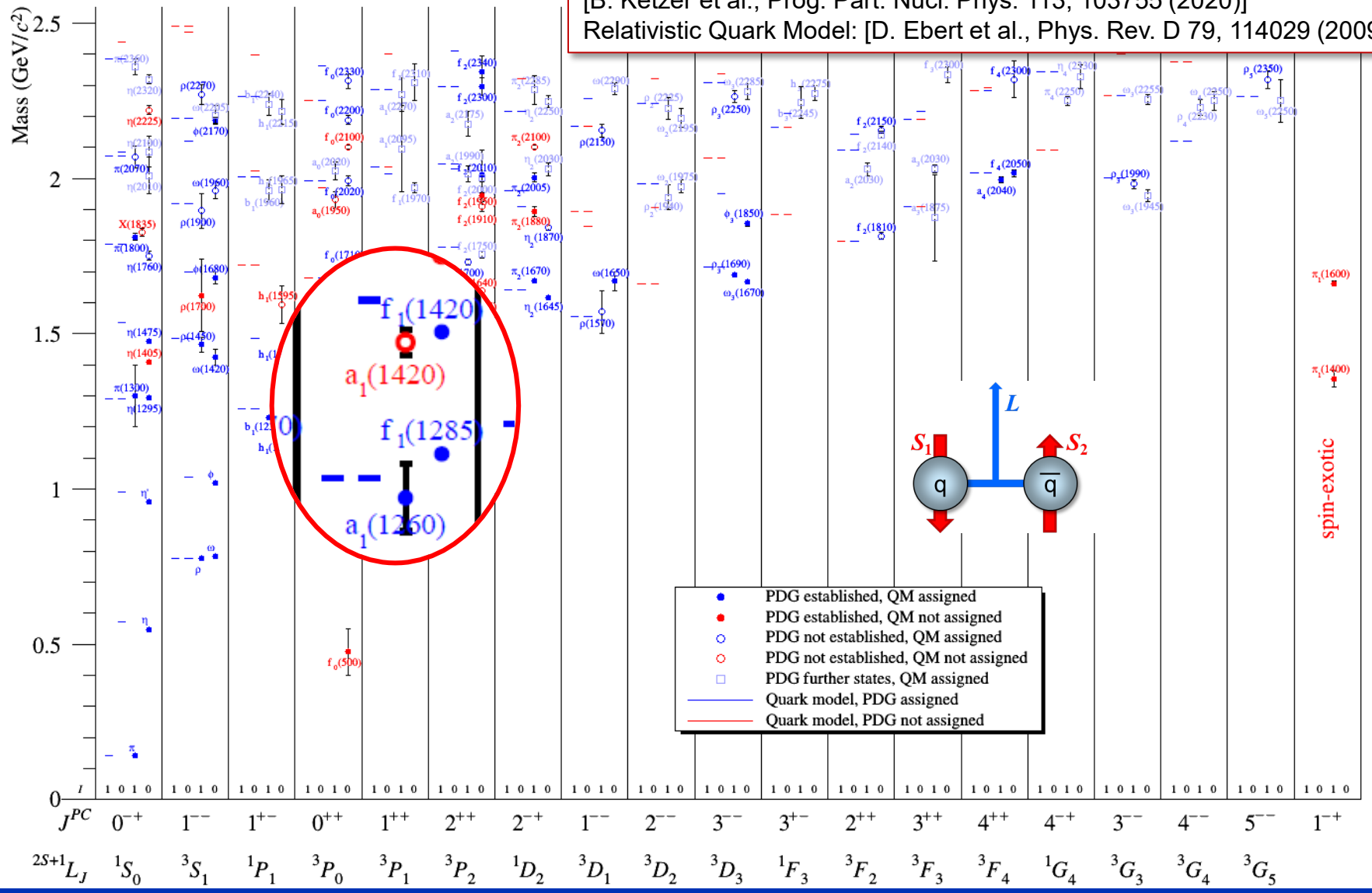
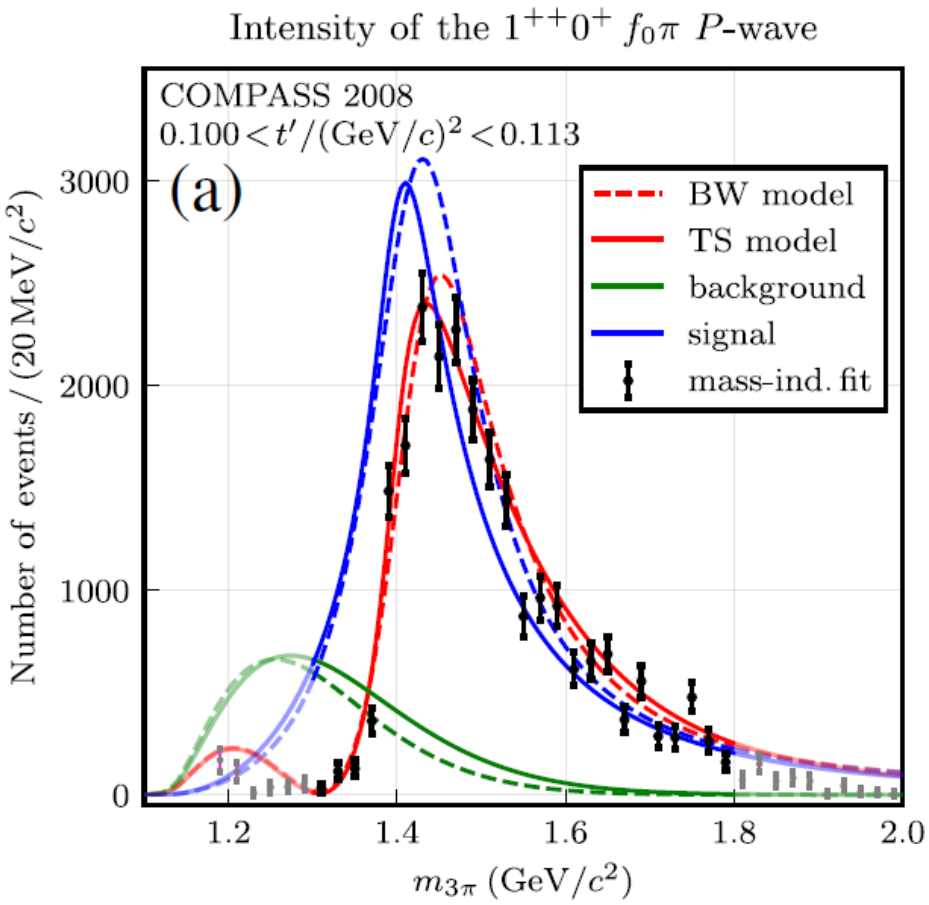
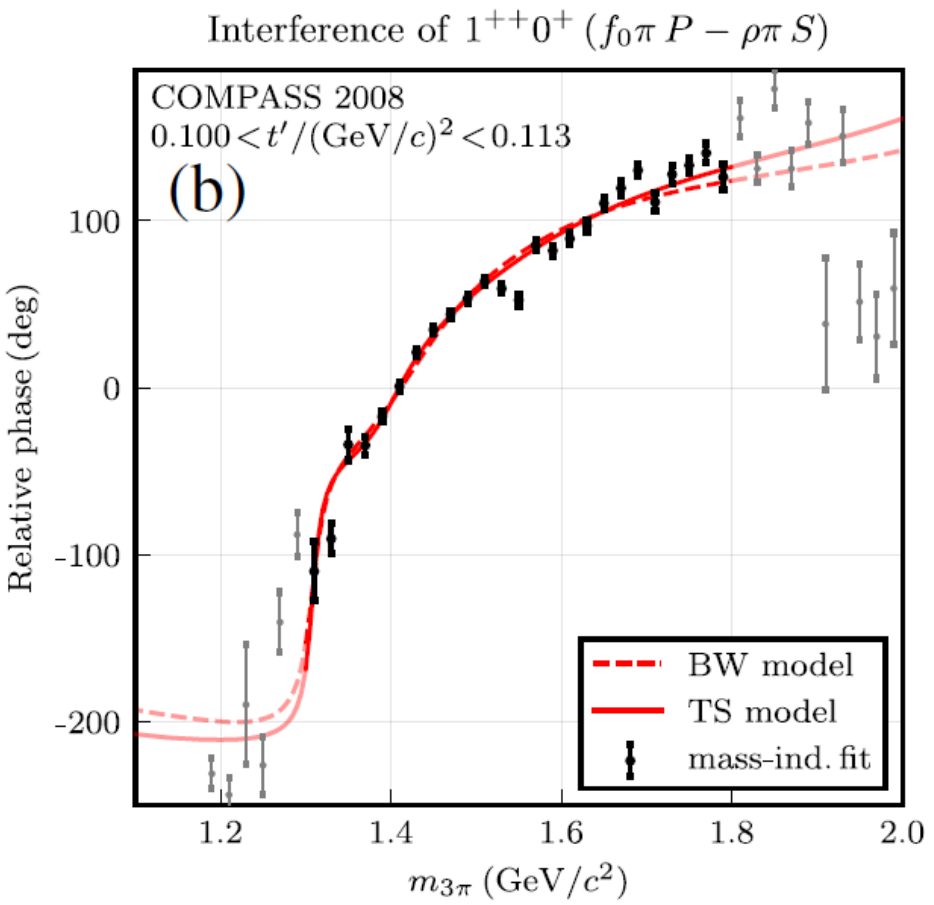


Comparison TS - BW

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





- Similar χ^2_{red} for both fits (slightly better for triangle)
- No new free parameters for $a_1(1420)$ signal by triangle mechanism

Light-Meson Spectrum

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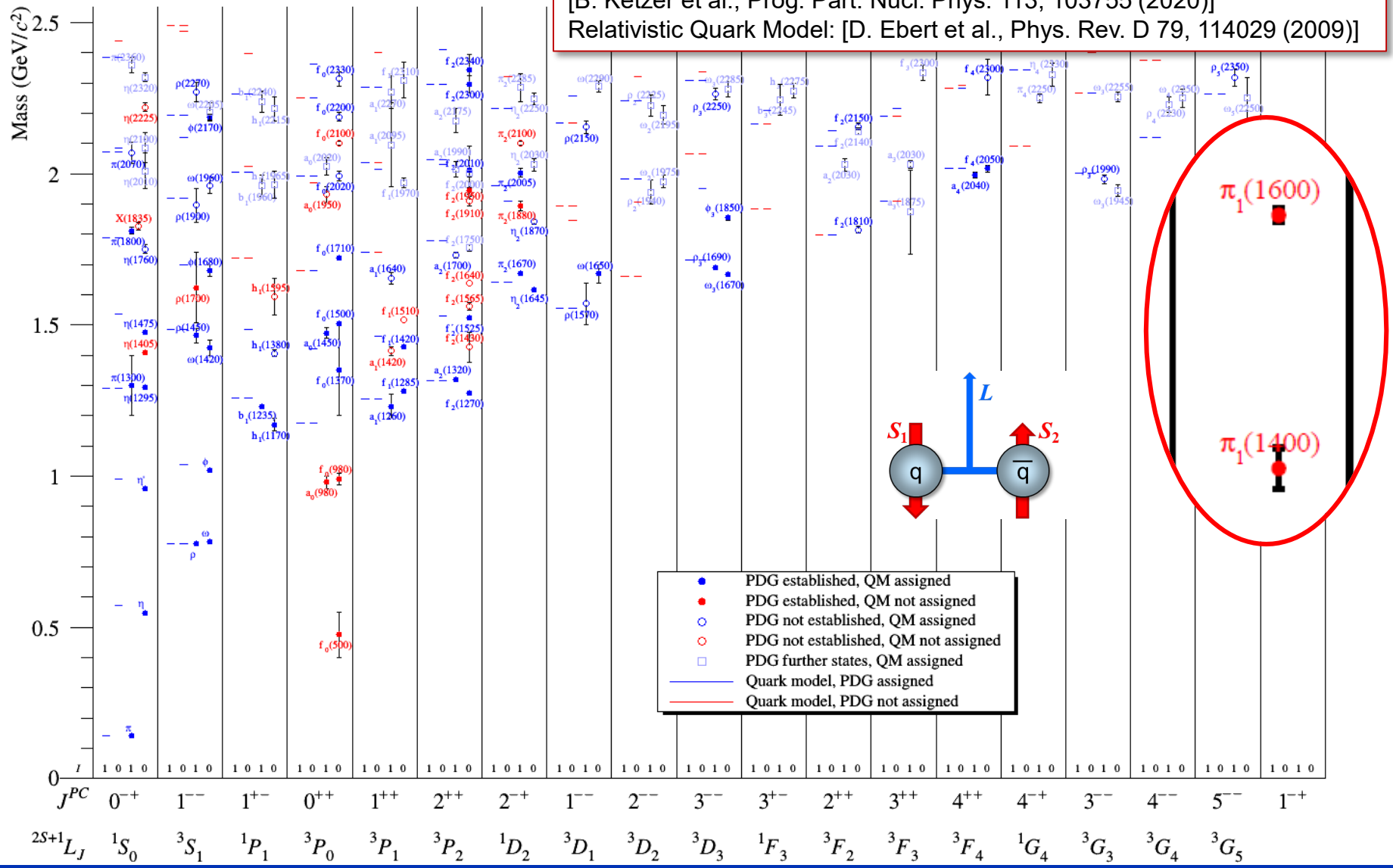
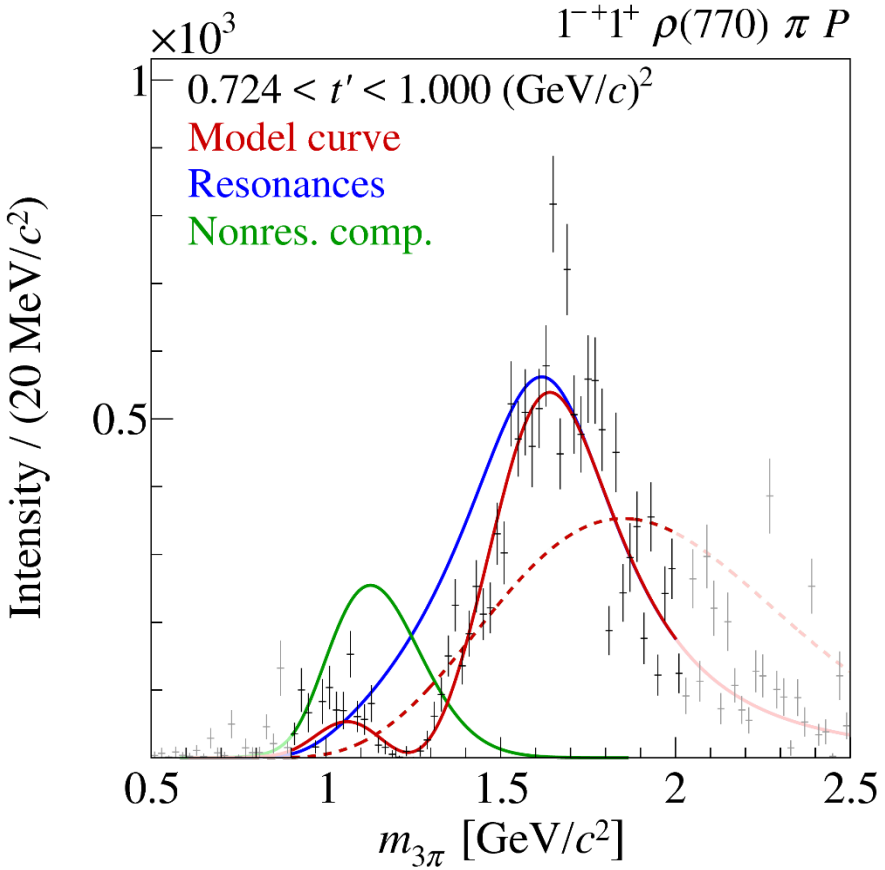
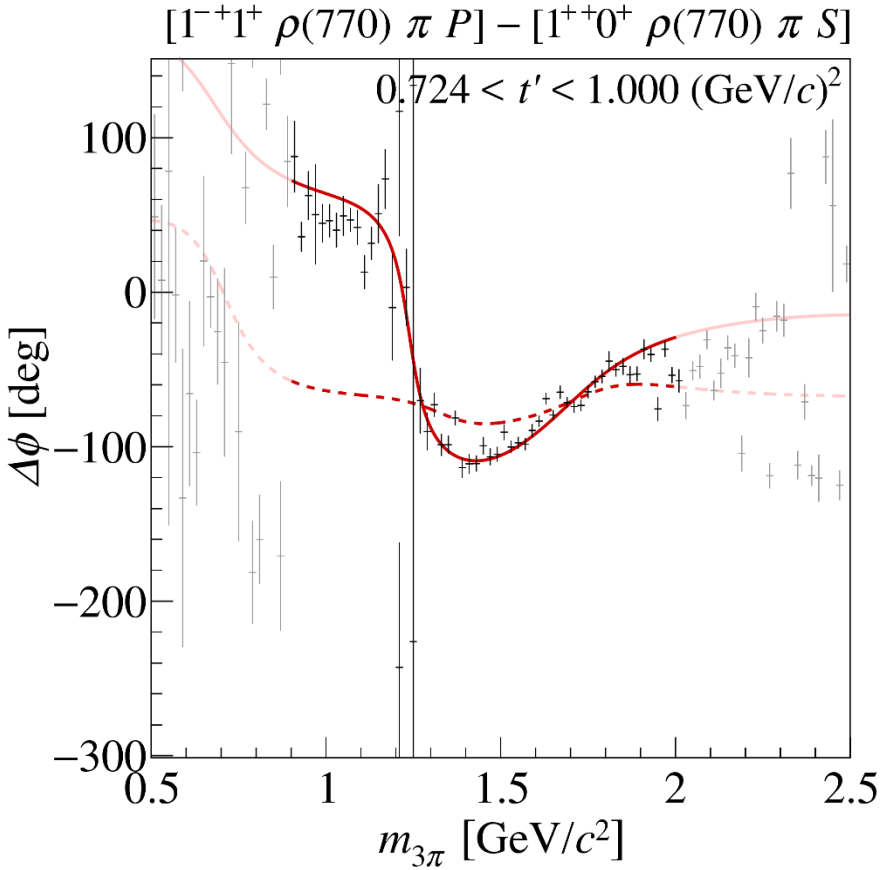


1^{-+} Partial Wave





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

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

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

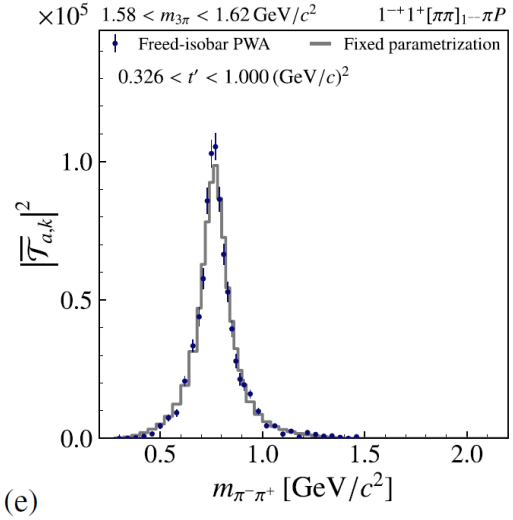
$$\Gamma_0 = 580^{+100}_{-230}\ \mathrm{MeV}/c^2$$

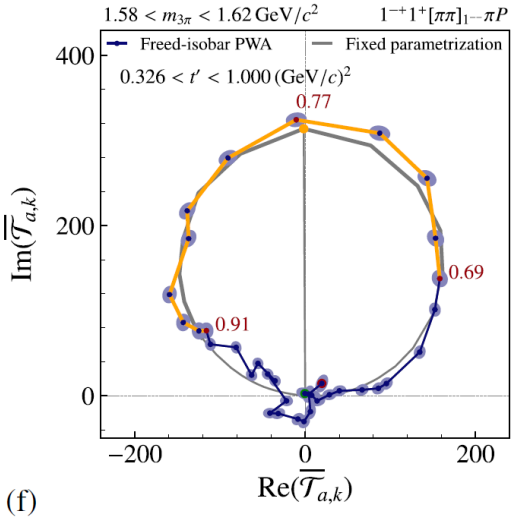
[M. Aghasyan et al. (COMPASS), Phys. Rev. D 98, 092003 (2018)]

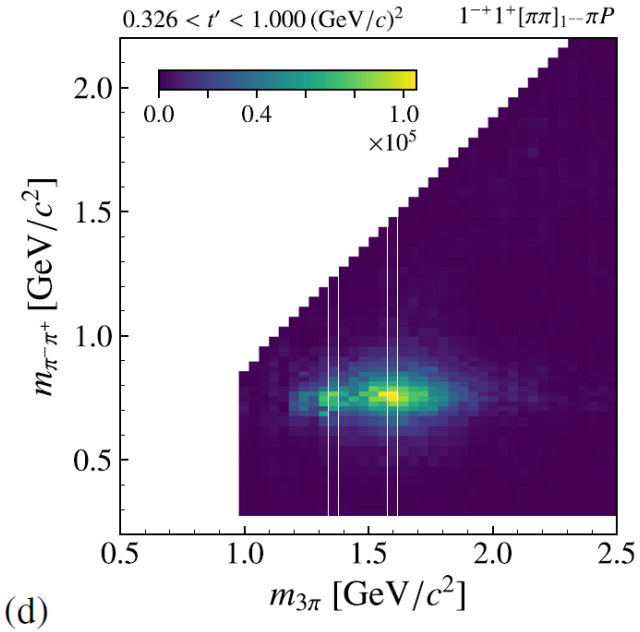
1^{-+} Partial Wave

Freed-isobar analysis

- replace fixed $\pi^-\pi^+$ amplitudes by model-independent waves ($L = 0,1,2$)
- correct for ambiguities (zero modes)







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

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

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

Hybrid π_1 Decays

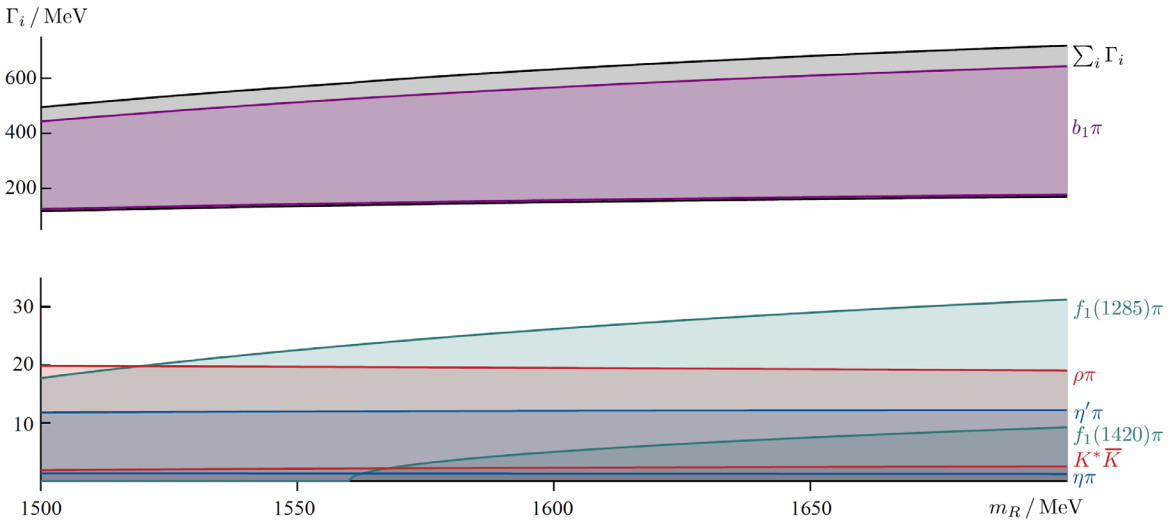
Model	$b_1\pi$	$f_1\pi$	$\rho\pi$	$\eta\pi$	$\eta'\pi$	$\eta(1295)\pi$	Reference
Flux Tube, $^3P_0$	170	60	5 - 20	0 - 10	0 – 10		[Isgur (1985), Close (1995)]
Flux Tube, IKP m=1.6 GeV/c^2	24	5	9			2	[Isgur (1985)]
Flux Tube, PSS m=1.6 GeV/c^2	59	14	8			1	[Page (1999)]
L-QCD m=2.0 GeV/c^2	66	15					[McNeil,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

Partial widths in MeV

Recent L-QCD results:

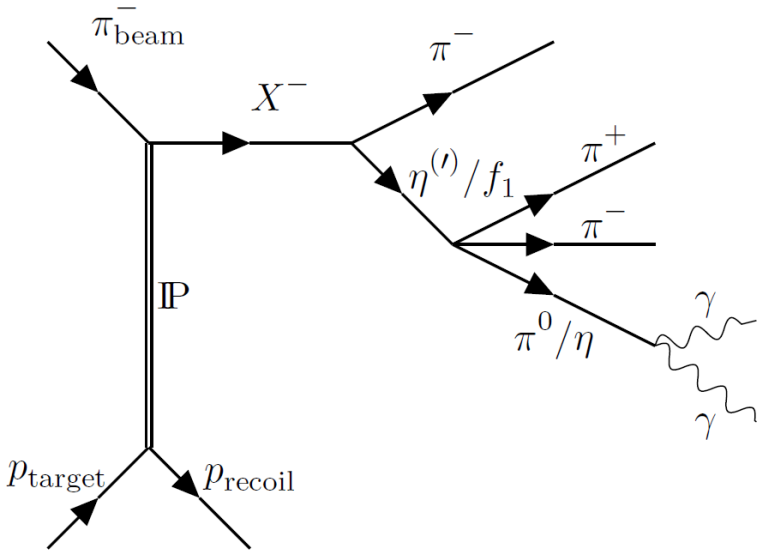
- hadronic decays of lightest exotic resonance
- SU(3) flavor symmetry
- $m_\pi \sim 700$ MeV
- scattering amplitudes for 8 coupled channels
- analytical continuation to complex plane

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



Hybrid Decay Modes in COMPASS

$\pi^-\pi^+\pi^-\gamma\gamma$ final states $\Rightarrow$ access to $\eta\pi, \eta'\pi, f_1\pi$



$\eta \xrightarrow{22.9\,\%} \pi^+\pi^-\pi^0$ with $\pi^0 \xrightarrow{98.8\,\%} \gamma\gamma$

$\eta' \xrightarrow{42.9\,\%} \pi^+\pi^-\eta$ with $\eta \xrightarrow{39.4\,\%} \gamma\gamma$

$f_1 \xrightarrow{35\,\%} \pi^+\pi^-\eta$ with $\eta \xrightarrow{39.4\,\%} \gamma\gamma$

- new data production: improved shower reconstruction from calorimeter
- include full data set for the first time
- about 2× more data than previously published for $\eta\pi, \eta'\pi$

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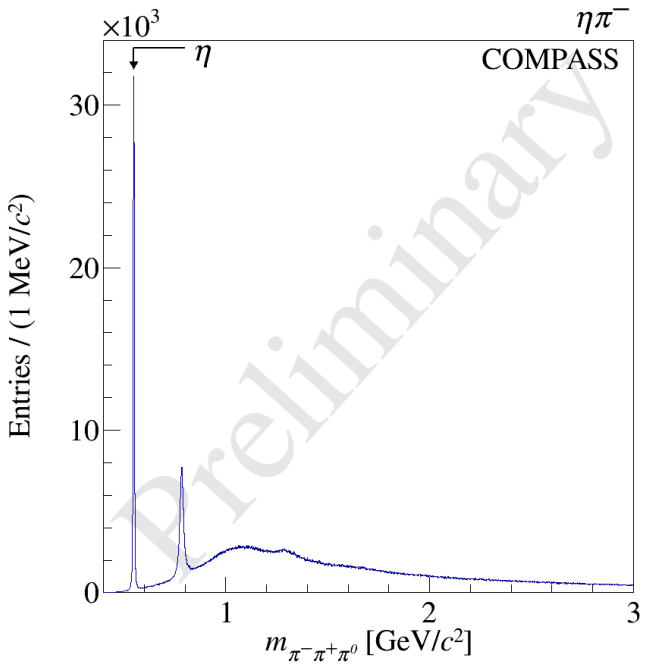

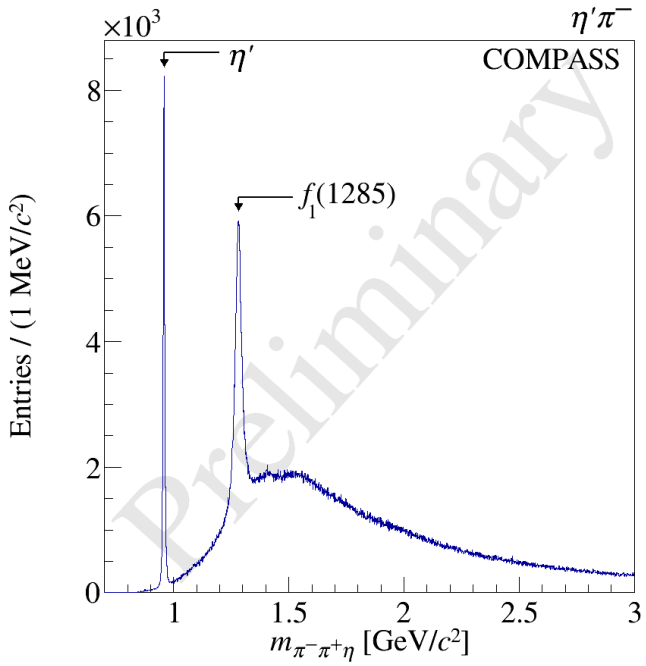

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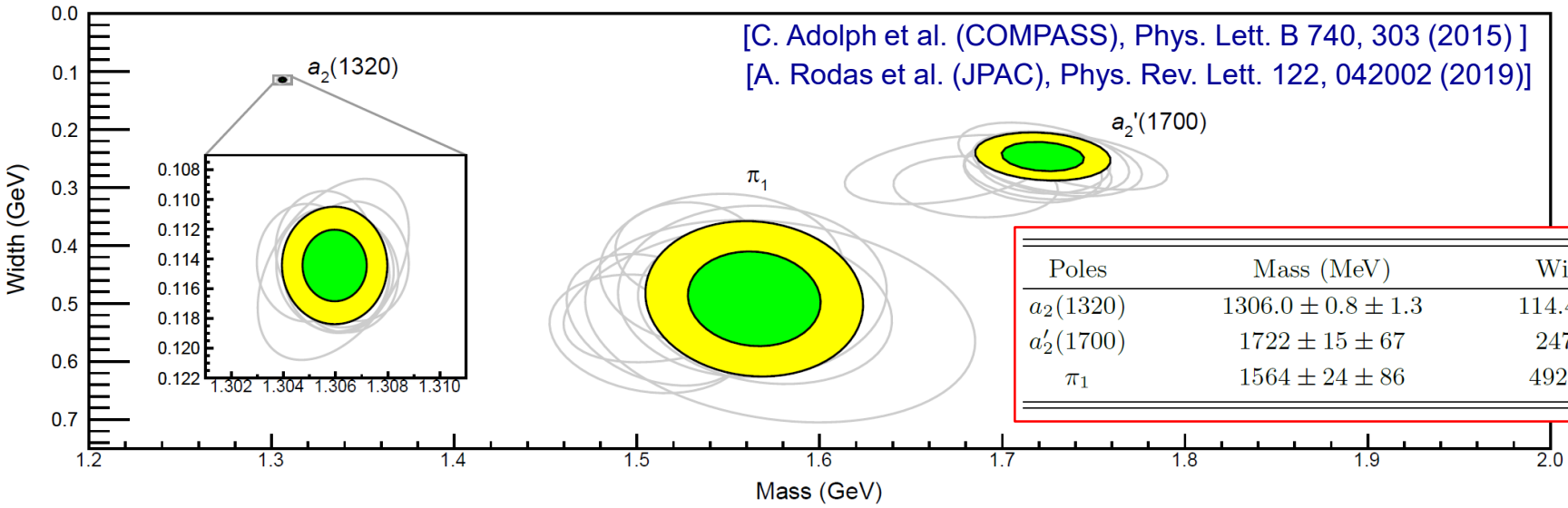

Poles	Mass (MeV)	Width (MeV)
$a_2(1320)$	$1306.0 \pm 0.8 \pm 1.3$	$114.4 \pm 1.6 \pm 0.0$
$a_2'(1700)$	$1722 \pm 15 \pm 67$	$247 \pm 17 \pm 63$
π_1	$1564 \pm 24 \pm 86$	$492 \pm 54 \pm 102$

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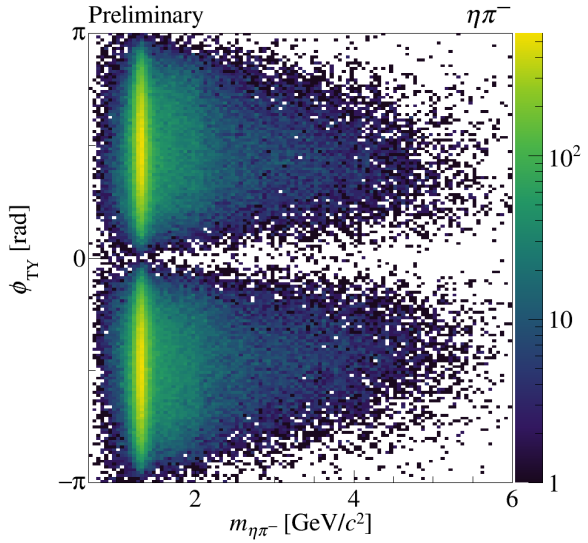
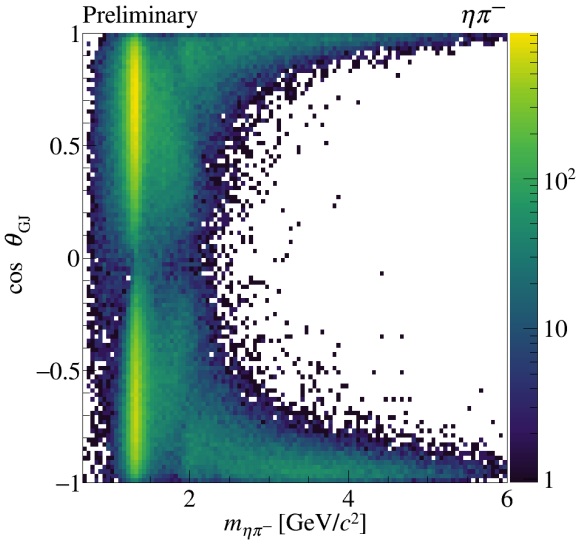
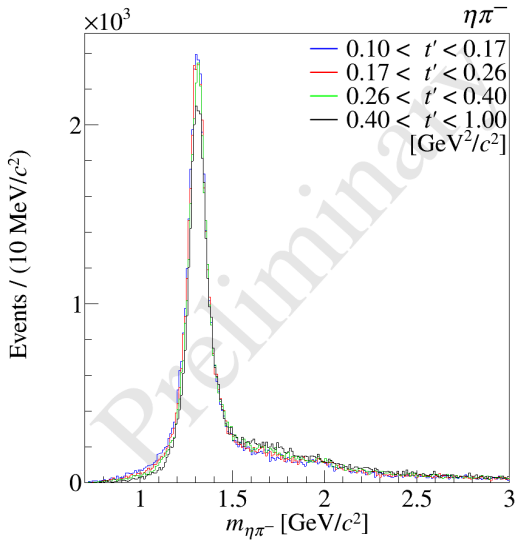
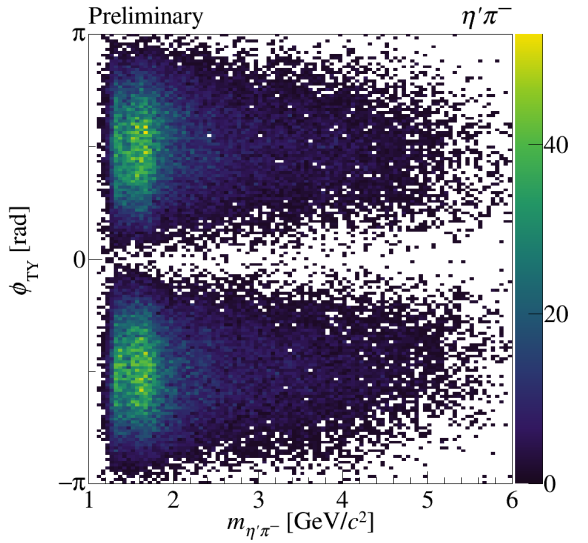
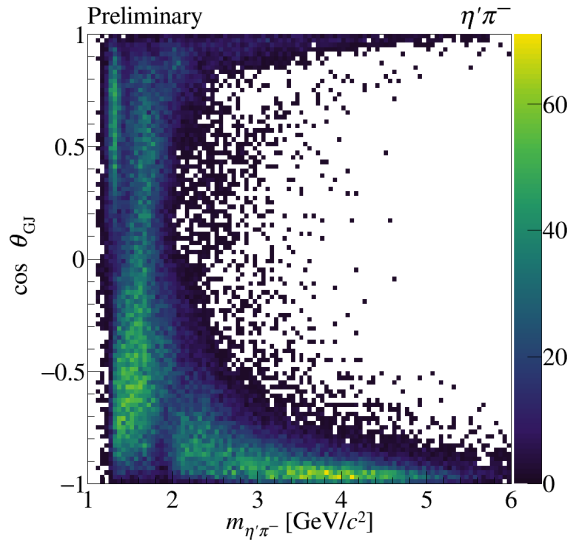
$\eta\pi^-$ / $\eta'\pi^-$ Final States

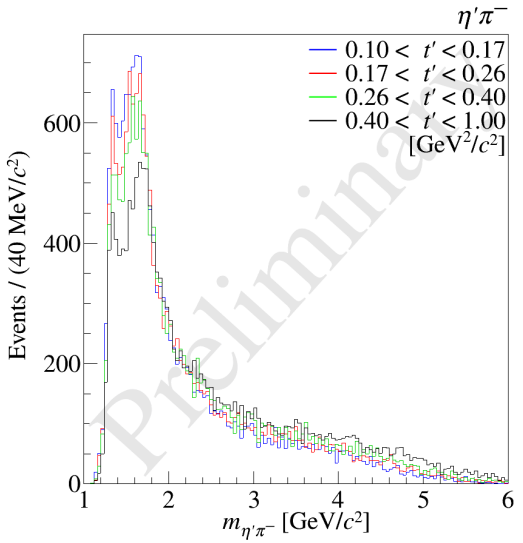






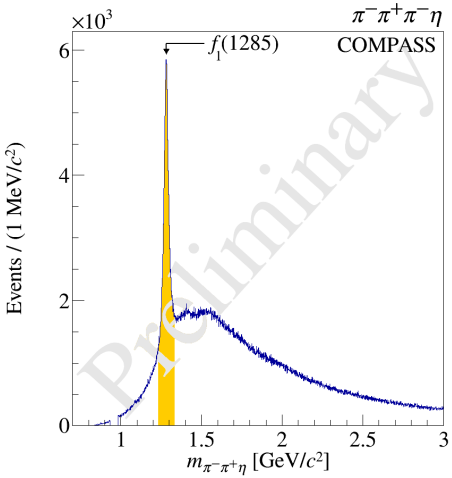


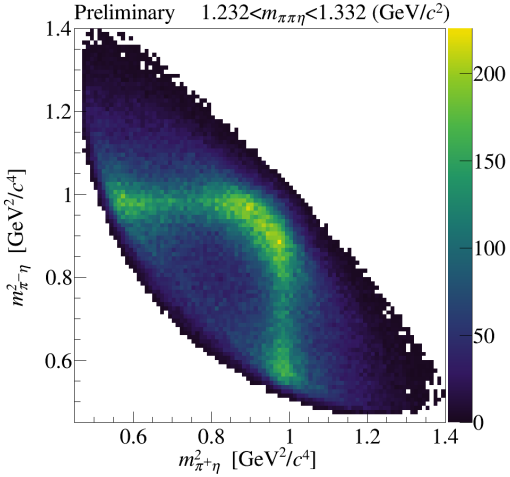




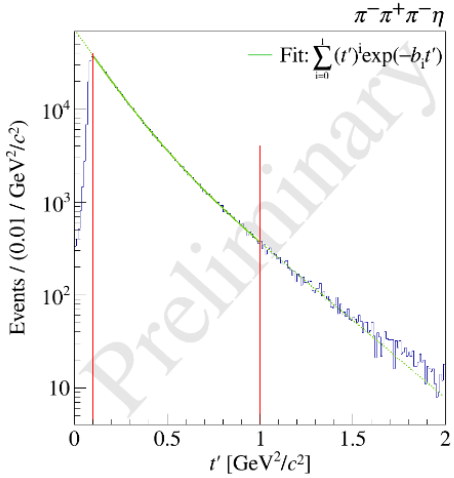
$f_1\pi$ Final State

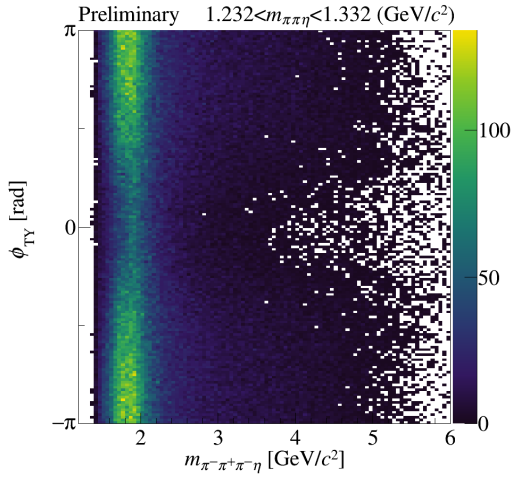
Dominant decay: $f_1 \to a_0(980)\pi$

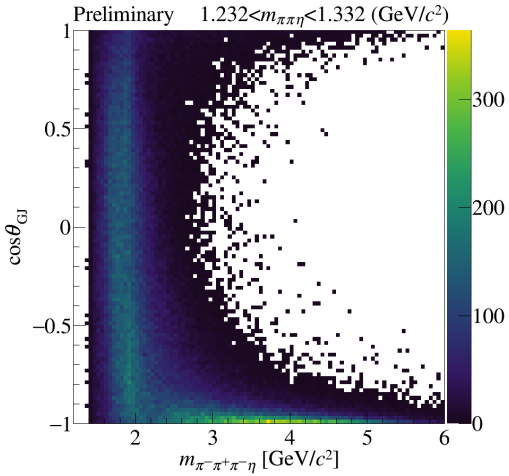


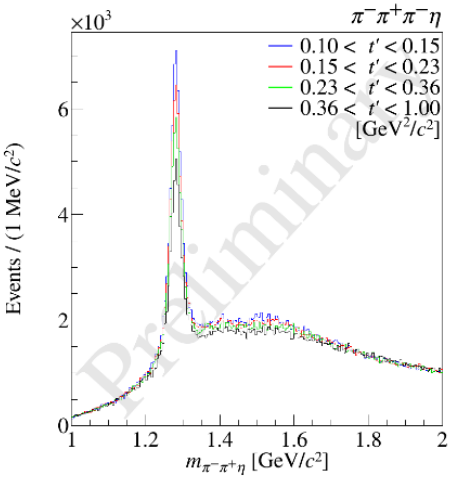


t' dependence



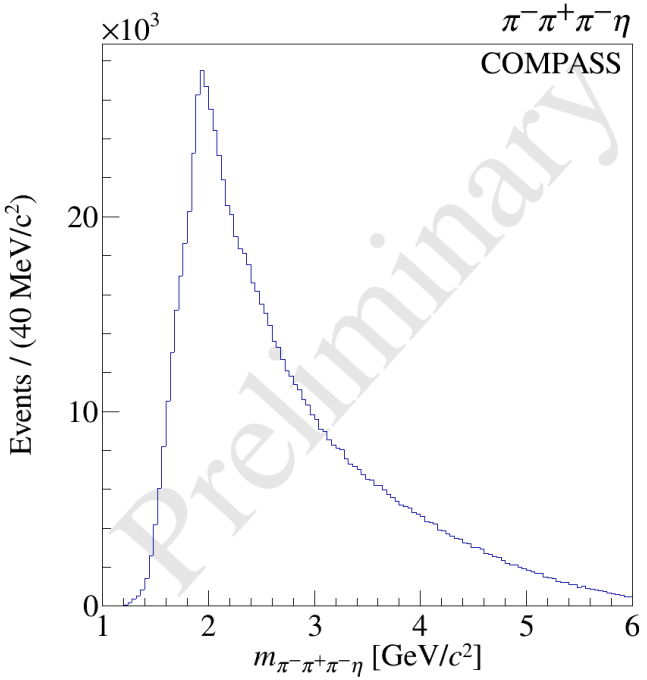


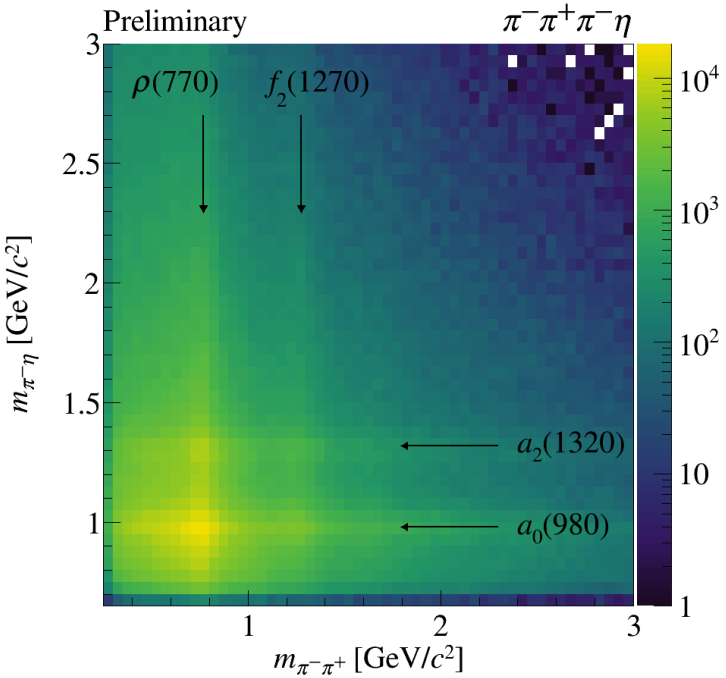




$\pi^-\pi^+\pi^-\eta$ Final State

- PWA to be performed in full mass range
- $\eta'\pi$ excluded
- in addition: $\pi^+\pi^-$ and $\eta\pi$ isobars



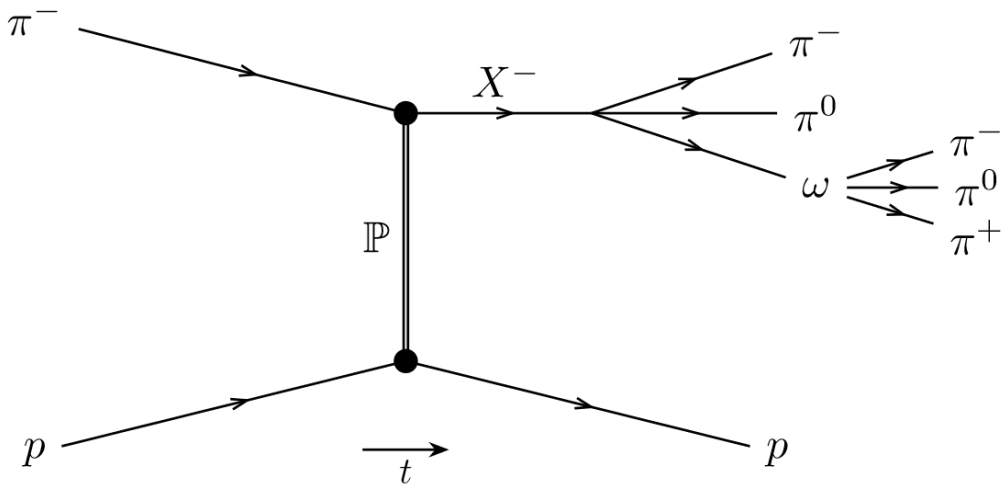


Dominant decays:

- $X^- \to f_1(1285) + \pi^-$
- $X^- \to a_2(1320) + \eta$
- $X^- \to a_0(980) + \rho$
- $X^- \to a_0(980) + f_2(1270)$
- $X^- \to a_2(1320) + \rho$

$b_1\pi$ Final State

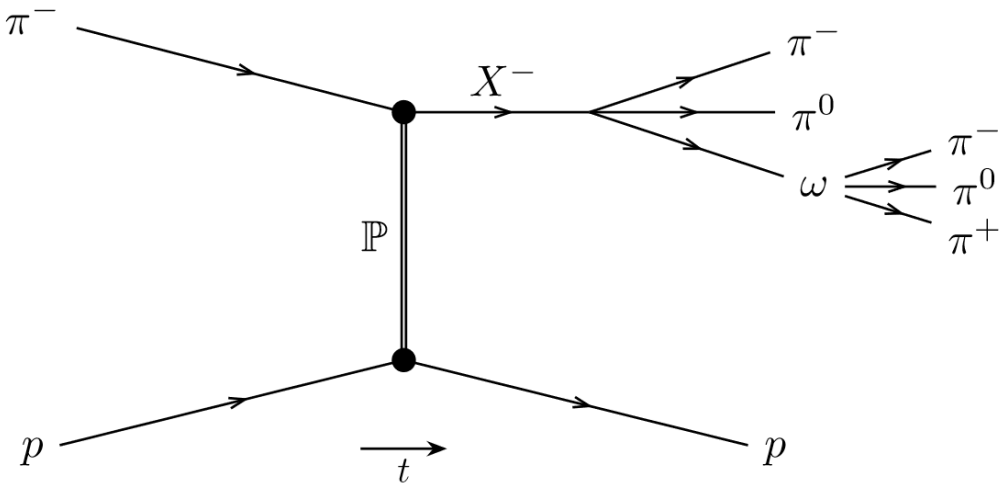
$\pi^-\pi^+\pi^-$ 4γ final states $\Rightarrow$ access to $b_1\pi \to \omega\pi\pi$

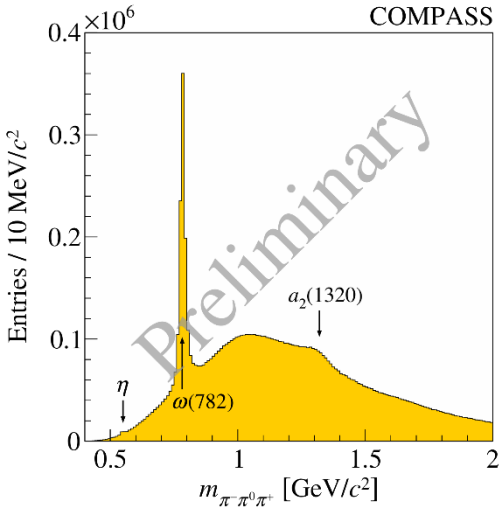


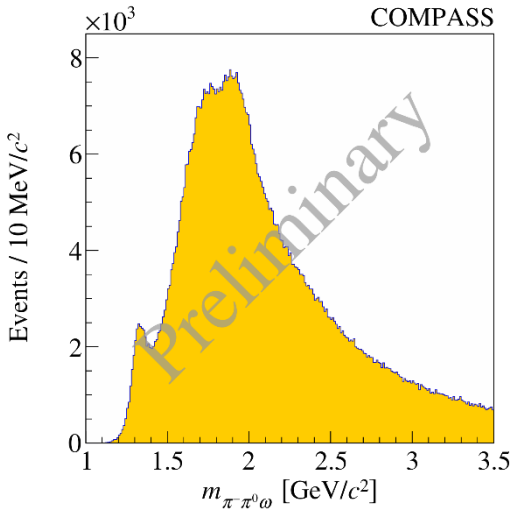
- new data production: improved shower reconstruction from calorimeter
- full COMPASS data set
- 720 k exclusive events of $\pi^-\pi^0\omega(782)$
  $\Rightarrow$ largest data sample world-wide
  $\Rightarrow$ 5 × more data than BNL E852

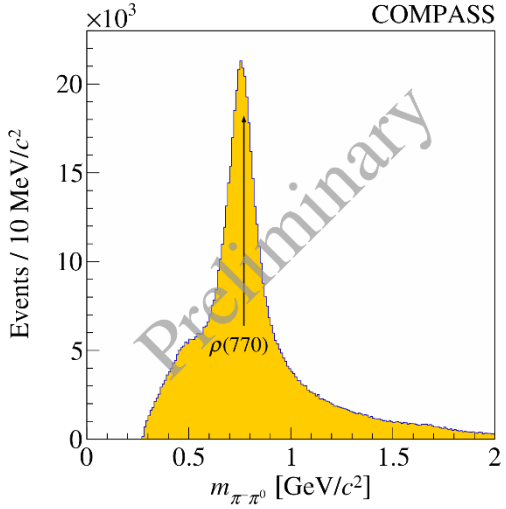
$b_1\pi$ Final State

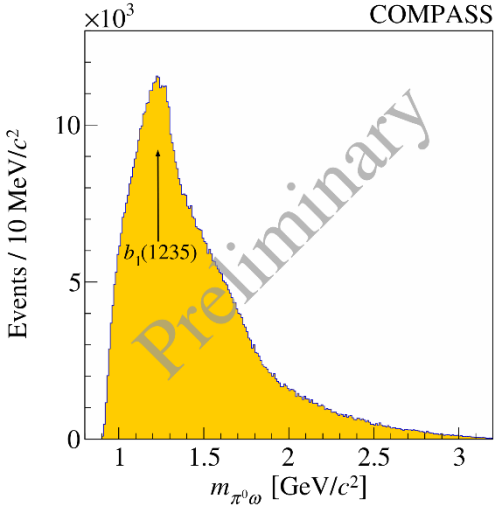
$\pi^-\pi^+\pi^-$ 4γ final states $\Rightarrow$ access to $b_1\pi \to \omega\pi\pi$











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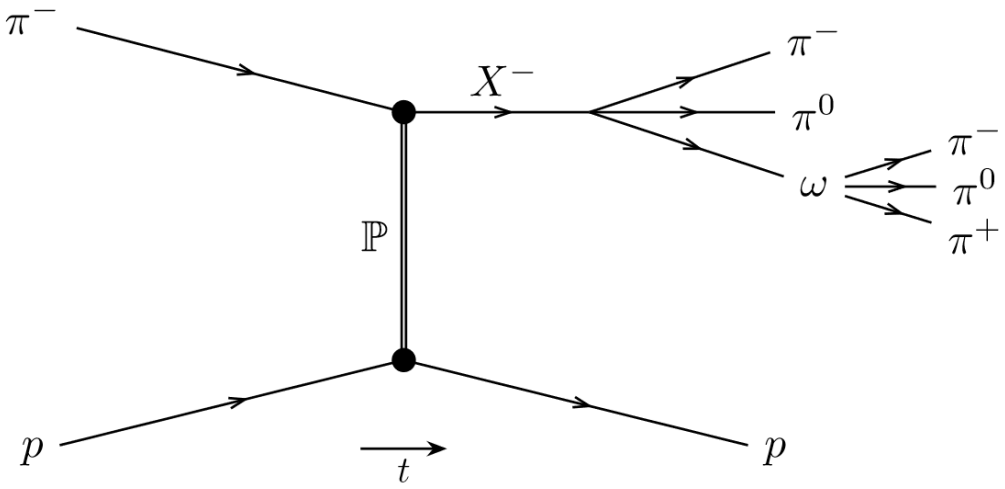
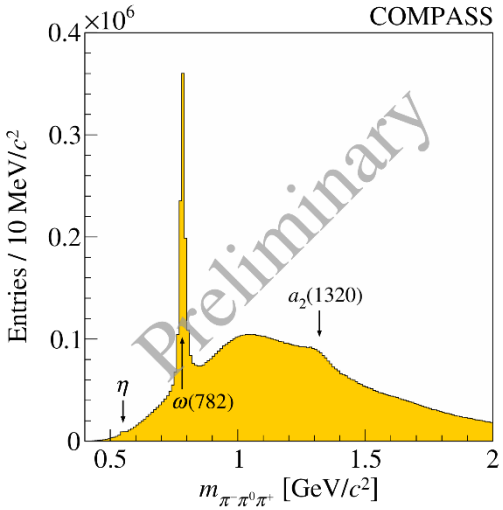
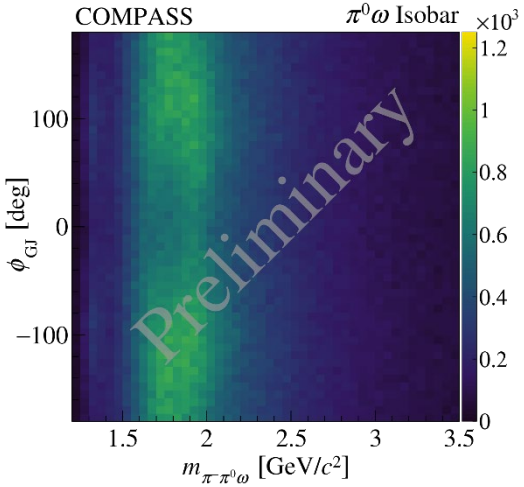
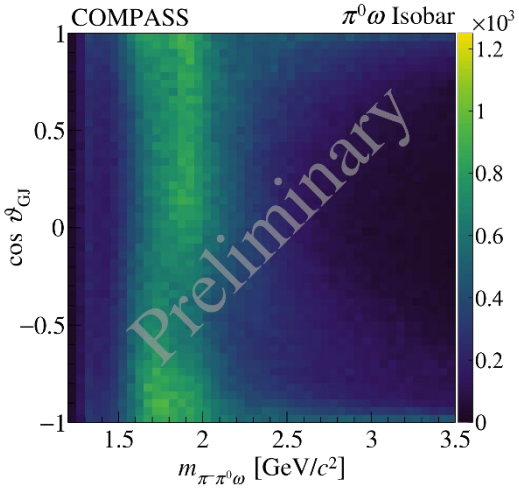
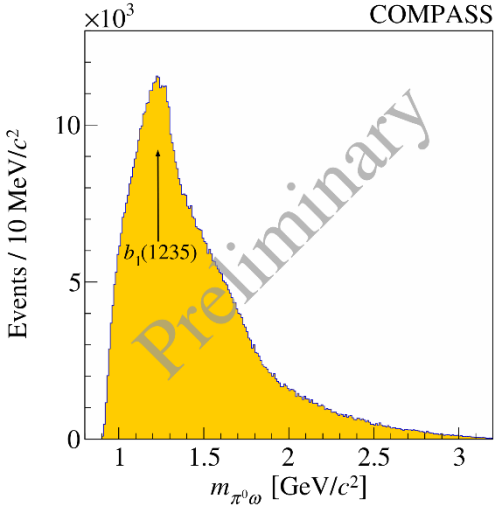










Hybrid Decay Modes in COMPASS

Number of exclusive events in kin. range of experiment

	$\eta\pi$	$\eta'\pi$	$\pi^-\pi^+\pi^-\eta$	$\pi^-\pi^0\omega$
COMPASS	225 k	74 k	1066 k	720 k
BNL E852	47 k	6 k	83 k	145 k

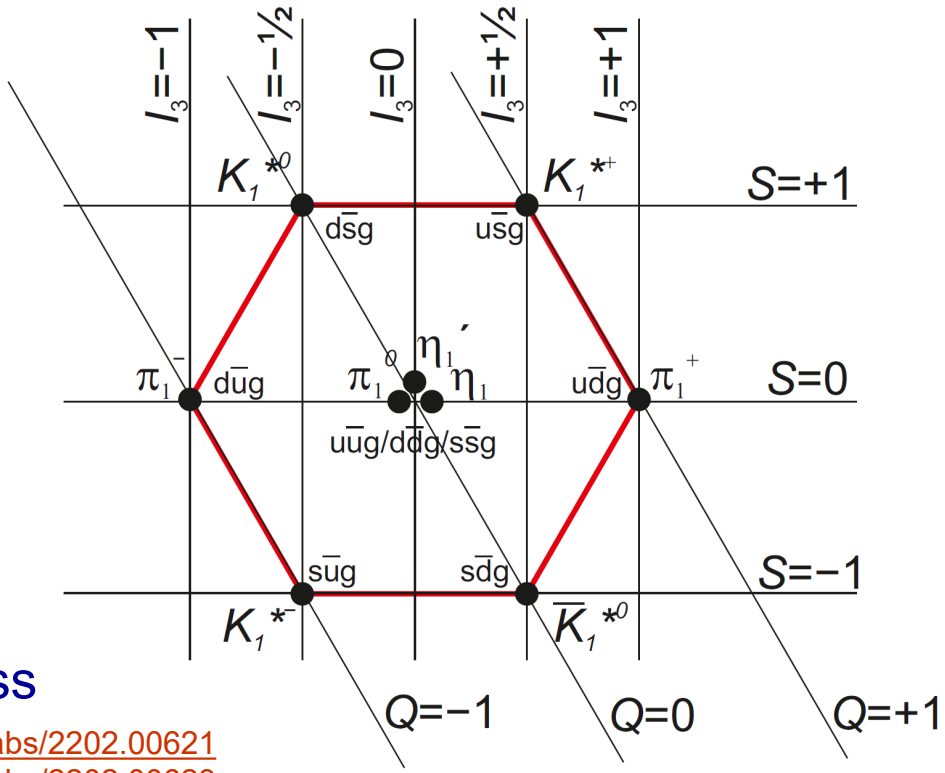
Outlook: PWA

- $\Rightarrow$ perform 2-D PWA in bins of m_X and t'
- $\Rightarrow$ extend mass range up to 3.5 - 4 GeV
- $\Rightarrow$ need to consider resonances in all 2-body systems
- $\Rightarrow$ acceptance correction: need large MC samples (e.g. @Frontera)
- $\Rightarrow$ coupled-channel analysis

Hybrid π_1 Multiplet

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
- AMBER

https://arxiv.org/abs/2202.00621
https://arxiv.org/abs/2202.00623

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN

Letter of Intent (Draft 2.0)

A New QCD facility at the M2 beam line of the CERN SPS

October 17, 2018

- Proton radius measurement using muon-proton elastic scattering
- Hard exclusive reactions using a muon beam and a transversely polarised target
- Drell-Yan and charmonium production
- Measurement of antiproton production cross sections for Dark Matter Search
- Spectroscopy with low-energy antiprotons
- Spectroscopy of kaons
- Study of the gluon distribution in the kaon via prompt-photon production
- Low-energy tests of QCD using Primakoff reactions
- Production of vector mesons and excited kaons off nuclei

https://arxiv.org/abs/1808.00848

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COMPASS++ / AMBER

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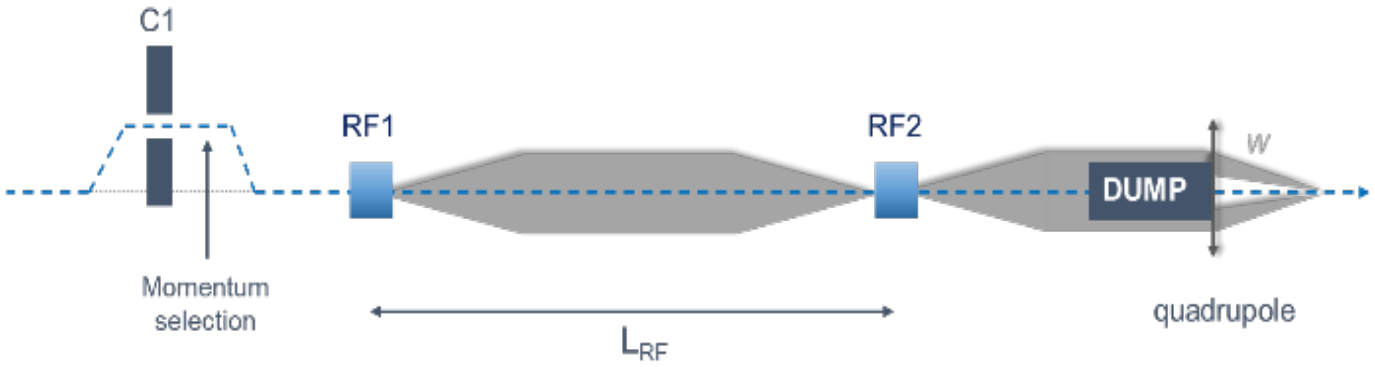
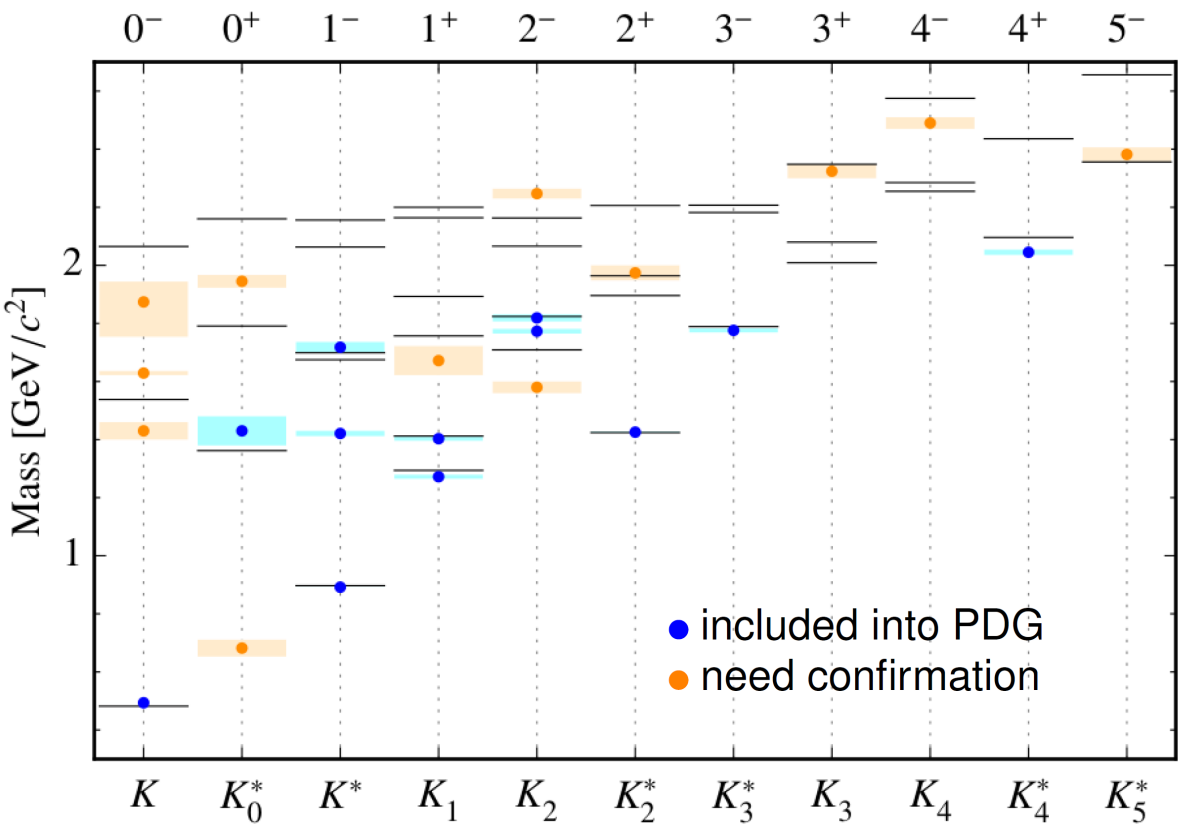
Kaon Beam: RF Separation

Panofsky-Schnell-System with two cavities (CERN 68-29)



- Particle species: same momenta but different velocities, $\Delta p\,/p \sim 1\%$
- Time-dependent transverse kick by RF cavities in dipole mode
- Longitudinal separation of particle species after L_{RF}
- RF1 kick compensated or amplified by RF2, depending on phase difference $\Delta\varphi = 2\pi(L_{RF} f/c)\,(\beta_1^{-1} - \beta_2^{-1})$
- Dump of unwanted species (in center beam dump)
- For large momenta: $\beta_1^{-1} - \beta_2^{-1} \approx (m_1^2 - m_2^2)/2p^2$
- Need high-frequency RF cavities ($f \approx 3.9$ GHz) due to $L_{RF} \approx 830$ m

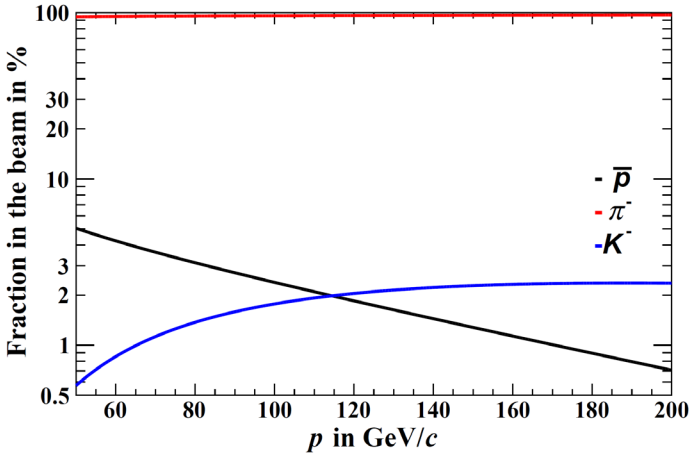
Kaon Excitation Spectrum



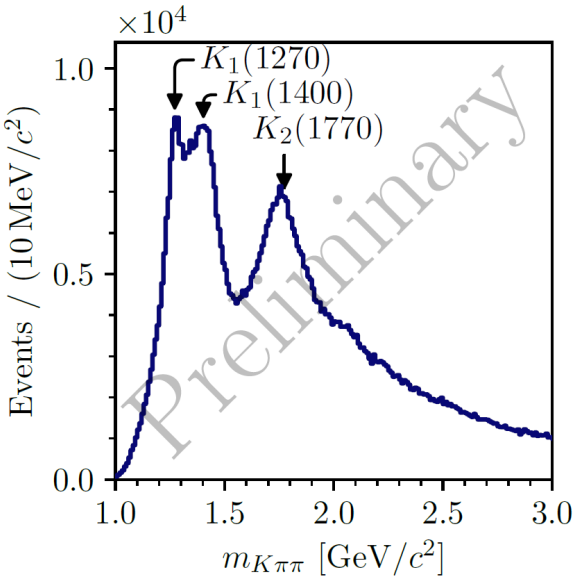
- 25 kaon states listed by PDG ($M < 3.1$ GeV), 13 of those need confirmation
- many predicted quark-model states still missing
- some hints for supernumerary states

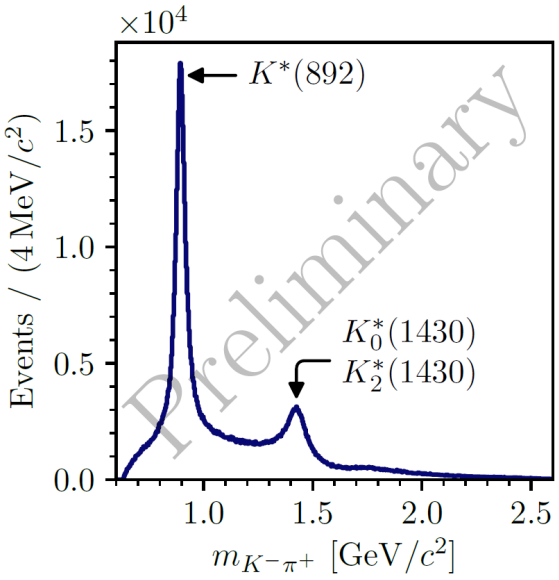
Preparatory Work

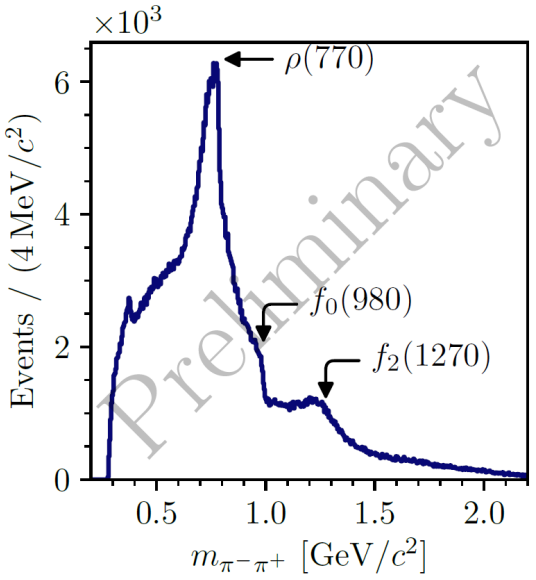
- existing data: h^- beam has ~2.4% admixture of K^-
- tagged by CEDAR detectors
- final states:
  - $K^-\pi^-\pi^+$ (720 k events) ⇒ access to all kaon states: K_J, K_J^*
  - $K_S\pi^-$, $K_S \to \pi^-\pi^+$ (60 k ev.) ⇒ access to K_J^* (natural parity series)
  - $\Lambda\bar{p}$, $\Lambda \to p\pi^-$ (4k ev.) ⇒ access to all kaon states: K_J, K_J^* (higher masses)



$K^-\pi^-\pi^+$ Final State





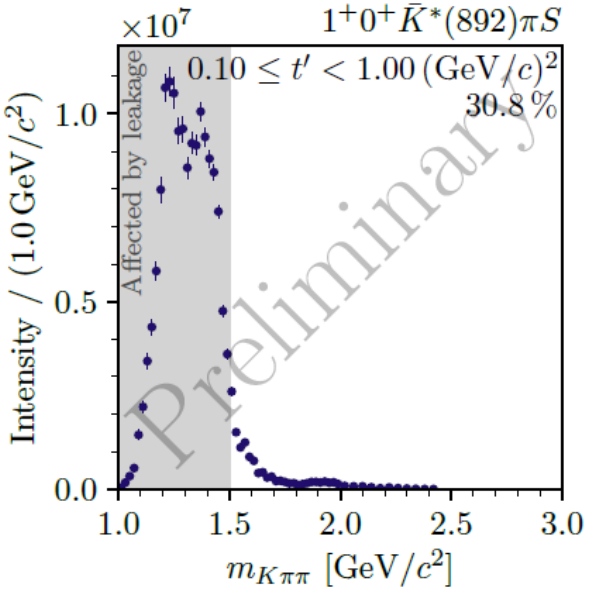


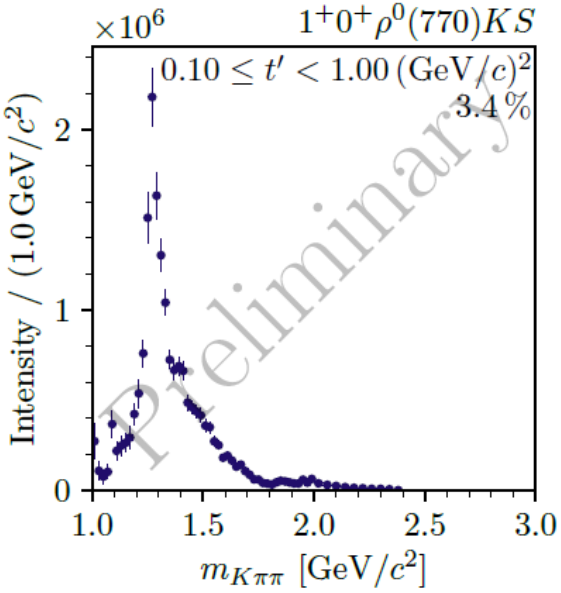
Study reaction $K^- + p \to K^-\pi^-\pi^+ + p$ by tagging beam kaons (2.4%)

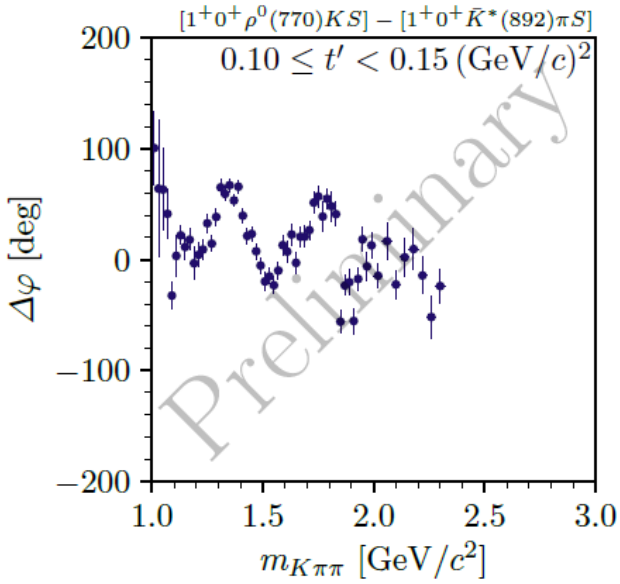
⇒ access to all kaon states: K_J, K_J^*

⇒ world‘s largest data set so far: 720 000 exclusive events

$K^-\pi^-\pi^+$ Final State - PWA

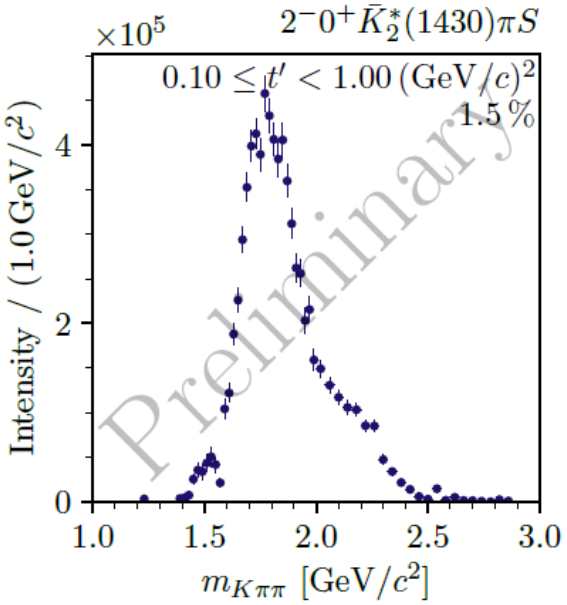


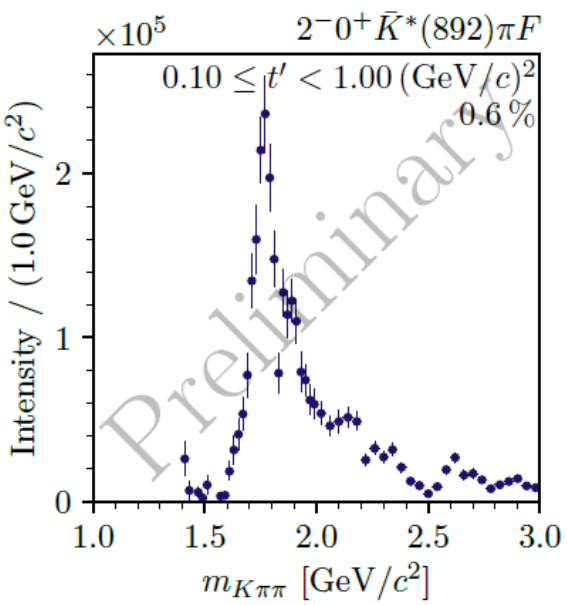


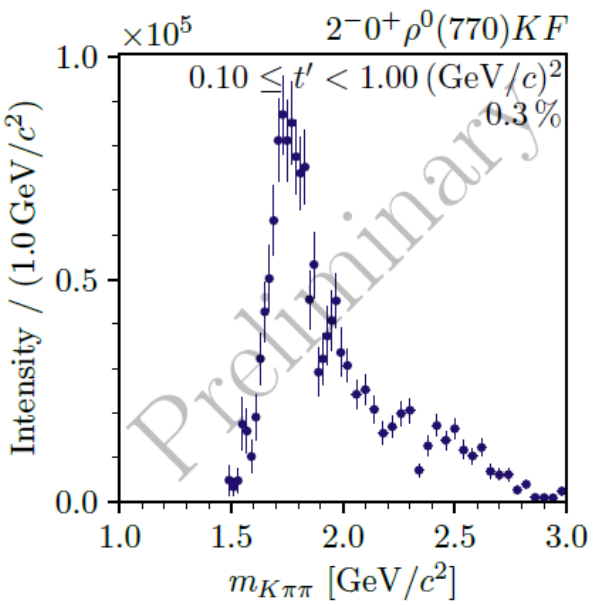


- $1^+0^+\ K^*(892)\pi\ S$ wave most dominant (~ 30% of total intensity)
- $K_1(1270)$ and $K_1(1400)$ visible, but large syst. effects for $m < 1.5$ GeV (due to limited PID)
- $K_1(1270)$ also visible in $1^+0^+\ \rho K\ S$ wave, plus shoulder at ~1.6 GeV ($K_1(1650)?$)

$K^-\pi^-\pi^+$ Final State - PWA



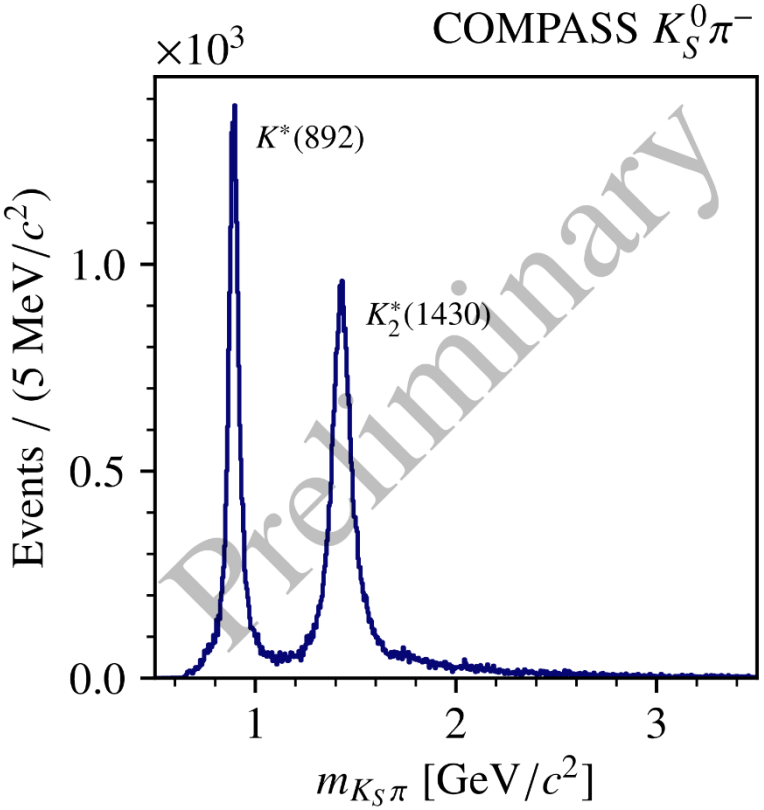


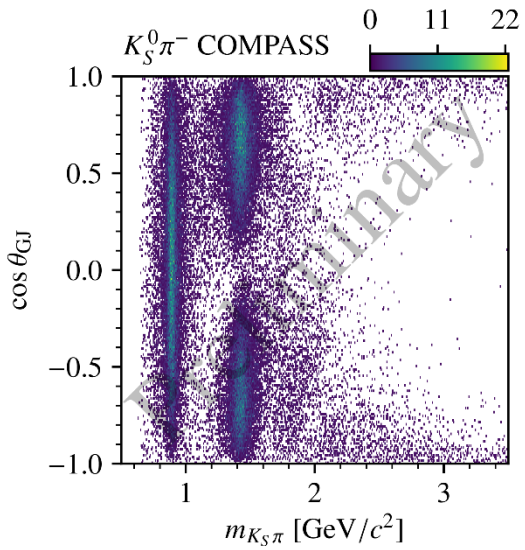


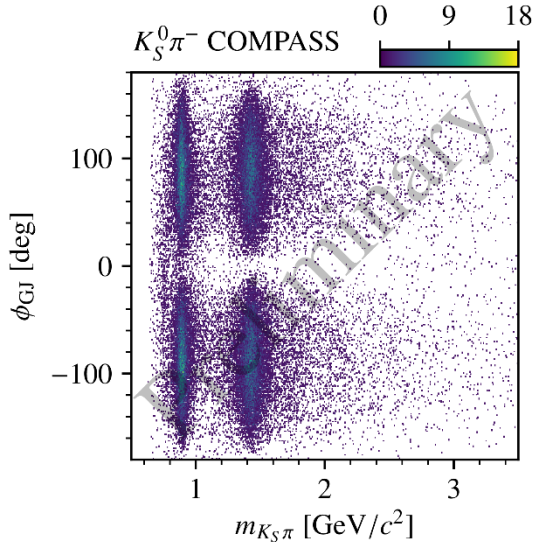
- Broad peak and shoulder in $2^-0^+\ K_2^*(1430)\pi\ S$ wave: $K_2(1770)$, $K_2(1820)$, $K_2(2250)$?
- Various structures in $2^-0^+ K^*(892)\pi\ F$ and $2^-0^+\ \rho K\ F$ waves
- need resonance-model fit to clarify nature of observed signal

Goal for AMBER: collect 20×10^6 exclusive $K^-\pi^-\pi^+$ events in one year

$K^0_S\pi^-$ Final State







Conclusions and Outlook

- QCD in the strong coupling regime still far from being understood
- Identify (exotic) multiplets and measure decay patterns
- Need large data samples for
  - complementary production mechanisms
  - different final states
- Advanced analysis methods
  - simple BW fits may be misleading
  - reaction models satisfying principles of S-matrix theory
- Advances in Lattice QCD (multi-particle scattering states)
- AMBER: will perform precision spectroscopy of K_J and K_J^* states (among other measurements related to hadron structure)