Resonances of the Systems $\pi^- \eta$ and $\pi^- \eta'$ in the Reaction $\pi^- p \to \pi^- \eta^{(\prime)} p_{\text{slow}}$ at COMPASS

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MLL

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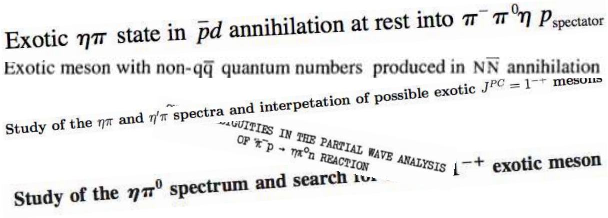
COMPASS
Großgeräte der physikalischen Grundlagenforschung

COMPASS

Why study the $\eta\pi$ and $\eta'\pi$ Final States

Exotic Waves! Exotic Resonances?

- quantum numbers of a P-wave in the $\eta\pi^0$-system are $J^{PC} = 1^{-+}$
- a quark-antiquark system cannot have these ("exotic") quantum numbers
- therefore a P-wave resonance in $\eta\pi$ (or $\eta'\pi$) cannot be attributed to a quark-model state $u\bar{u}$, $d\bar{d}$



Exotic $\eta\pi$ state in $\bar{p}d$ annihilation at rest into $\pi^-\pi^0\eta\ p_{\text{spectator}}$

Exotic meson with non-$q\bar{q}$ quantum numbers produced in $N\bar{N}$ annihilation

Study of the $\eta\pi$ and $\eta'\pi$ spectra and interpetation of possible exotic $J^{PC} = 1^{-+}$ mesons

AMBIGUITIES IN THE PARTIAL WAVE ANALYSIS OF $\pi^- p \to \eta\pi^0 n$ REACTION

Study of the $\eta\pi^0$ spectrum and search for a $J^{PC} = 1^{-+}$ exotic meson

- several experiments observed P-wave state that were interpreted as resonances ($\eta\pi$: $\pi_1(1400)$, $\eta'\pi$: $\pi_1(1600)$)
- yet, this interpretation is not firmly established

KEK's role in this Search

After GAMS claimed an exotic resonance in the $\eta\pi^0$ channel, KEK ran an experiment in order to search for this state in the charged mode $\eta\pi^-$.

Physics Letters B 314 (1993) 246–254

Study of the $\eta\pi^-$ system in the $\pi^- p$ reaction at 6.3 GeV/c

H. Aoyagi [a], S. Fukui [b], T. Hasegawa [c], N. Hayashi [a], N. Horikawa [a], J. Iizuka [a], S. Inaba [d], S. Ishimoto [d], Y. Ishizaki [e], T. Iwata [a], E. Kanatani [c,1], H. Kawai [f], T. Kinashi [a], A. Kishi [a], K. Kobayashi [i,2], Y. Kobayashi [i,3], K. Matsuda [g], T. Matsuda [a], K. Mori [h], T. Nakagawa [i], S. Nakamura [a], T. Nakamura [c], T. Nakanishi [a], A. Narita [i], K. Ohmi [d], C. Ohmori [e], T. Samoto [a,4], H. Shimizu [j], Y. Tajima [k], K. Takamatsu [d], M. Takasaki [d], T. Tsubaki [ℓ,5], K. Tsuchiya [a,3], T. Tsuru [d], I. Yamauchi [m], Y. Yasu [d], H.Y. Yoshida [k,6] and A. Wakai [a]

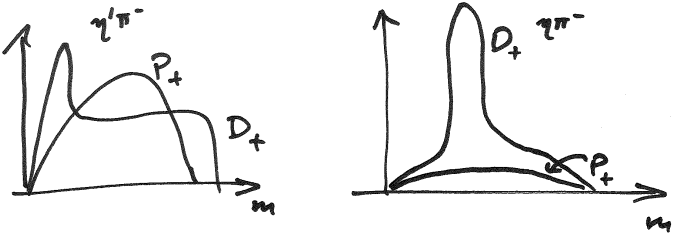
If the enhancement of the P_+ wave obtained in the present experiment can be a resonant state, it may correspond to the $J^{PC} = 1^{-+}$ object which has been observed in the GAMS experiment [2], though the mass value is lower and the width is slightly narrower than those reported by the GAMS experiment.

- results non-conclusive
- since then the situation has only improved slightly

Why is the interpretation difficult?

At a production experiment such as COMPASS (GAMS, KEK, VES, BNL E852)

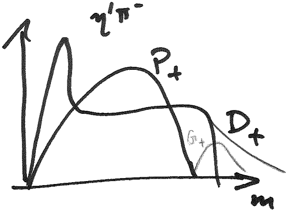
- the only significant wave overlapping the exotic P wave is the D wave ($J^{PC} = 2^{++}$, contains the well-known $a_2(1320)$)
- the structure of the D wave is not understood
- but the interpretation of the P wave requires understanding the D wave, because we only measure relative phases between waves

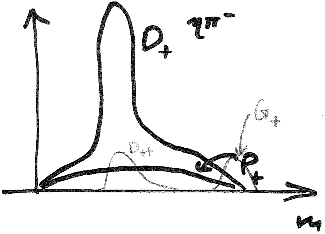


Input from COMPASS

How does COMPASS enhance the picture?

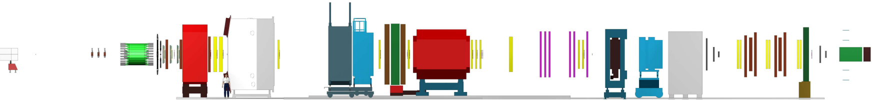
- higher invariant masses
- higher statistics
- additional waves: D_{++} (spin 2, $M = 2$), G_{+} (spin 4, $M = 1$), F_{+} (spin 3, but not yet ready for public consumption)
- knowledge transfer $\eta\pi \leftrightarrow \eta'\pi$





The COMPASS Experiment

Fixed Target Experiment at CERN



The COMPASS experiment at CERN

- high-resolution, two-stage magnetic spectrometer
- particle ID with RICH detector, calorimeters, also μ id
- different beams (muon, hadron, $+$, $-$)
- various targets (polarized, unpolarized)

Covers a wide range of physics

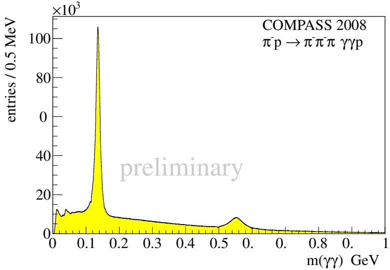
- Muon beam programme: GPDs, transversity, DVCS, ...
- Hadron beam programme: Primakoff effect, light hadron spectroscopy, polarized Drell-Yann, ...

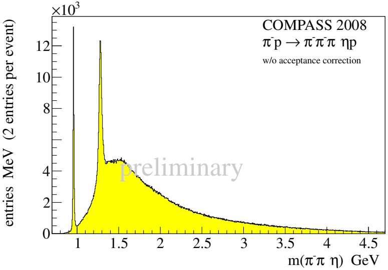
This talk: π^- (190 GeV) beam, proton target, hadron spectroscopy

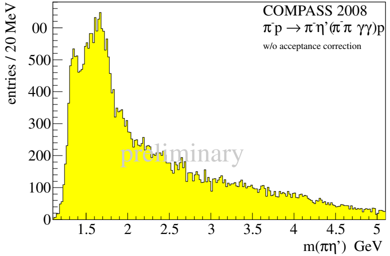
Data Selection for $\pi^- p \to \eta^{(\prime)} \pi^- p$

Selected exclusive final state: slow recoil proton, three tracks $(- - +)$, two photons.

Step-by-step for the $\eta' \pi^-$ final state:





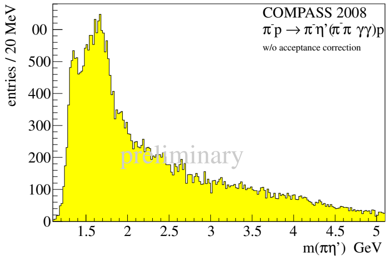


We obtain:

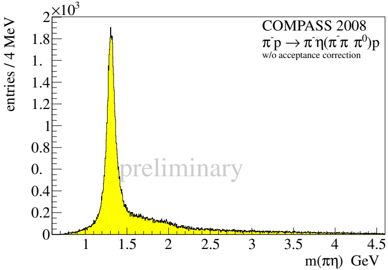
- 18 000 events with $m(\eta'\pi) < 2\,\text{GeV}$, 35 000 total
- inv. masses well above 2 GeV

The Data

Invariant mass of $\pi^-\eta'$



Invariant mass of $\pi^-\eta$

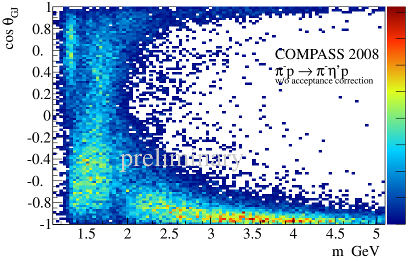


- $\pi^-\eta$ spectrum dominated by $a_2(1320)$
- in $\pi^-\eta'$, the a_2 appears as bump close to threshold
- a broad structure around $1700\,$MeV dominates the $\pi^-\eta'$ spectrum (P wave)

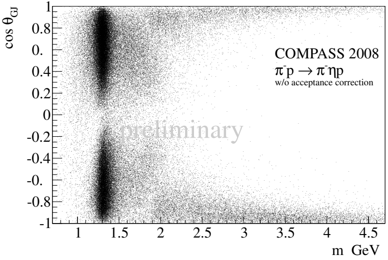
The Data

Now in Several Dimensions!

$m(\pi^-\eta')$ vs. $\cos\theta_{\mathrm{GJ}}(\eta')$

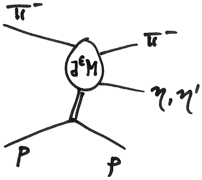


$m(\pi^-\eta)$ vs. $\cos\theta_{\mathrm{GJ}}(\eta)$



- horizontal: inv. mass (as before), vertical: $\cos\theta_{\eta^{(\prime)}}$ in Gottfried-Jackson frame (that is: $\eta\pi$ rest frame, angles are such that $\cos\theta = 1$ means "η along beam")
- $a_2(1320)$ clearly visible, hints of $a_4(2040)$
- P-waves visible (asymetry!)
- for high masses the data are concentrated on the edges

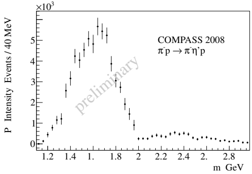
Partial-wave Analysis in Mass Bins

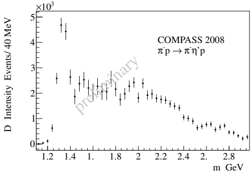


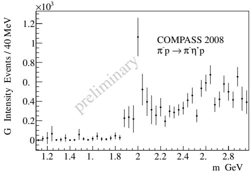
Procedure:

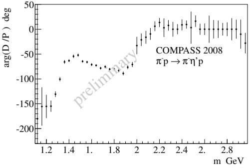
- divide data into mass bins (40 MeV)
- fit of each bin to an acceptance-corrected partial-wave model defined in the reflectivity basis

Results for $\pi^- \eta'$:

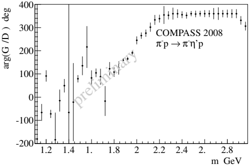








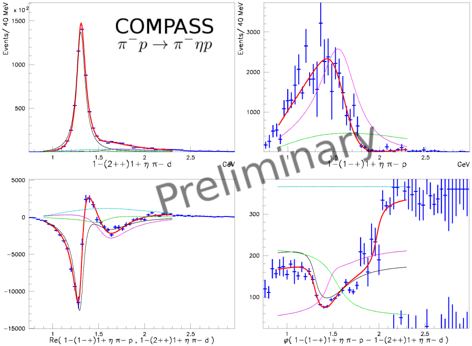
First row:
Intensity of P_+, D_+, G_+
Second row:
Relative phases of
$D_+ - P_+$, $G_+ - D_+$



Modelling Physics

“Mass-dependent PWA” of $\pi^-\eta$

Fit of a model to the data, e.g. $\pi^-\eta$



Colors: binned fit, model fit, others: components

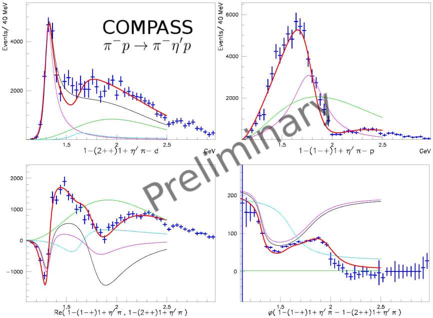
Model:

- depicted: D_+, P_+ waves
- two BWs in D_+ (dynamical BW for $a_2(1320)$)
- one BW in P_+
- coherent exponential BG with phase-space factors in both waves

Modelling Physics

“Mass-dependent PWA” of $\pi^-\eta'$

For comparison D_+, P_+ in $\pi^-\eta'$



Colors: binned fit, model fit, others: components

- D_+ wave: as before, but second BW mass fixed at $m = 1600\,\text{MeV}$
- P_+ wave: one Breit-Wigner, exponetial BG as before
- fits the data but very much non-BW in P_+-wave description

Improvement desirable!

Similarity of $\pi^-\eta$, $\pi^-\eta'$

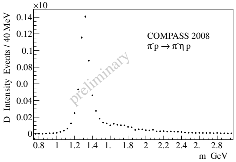
An interesting result is the similarity between the two final states, which can be observed by applying the following recipe:

- multiply the amplitudes obtained in the $\pi^-\eta$ fit results by the following factor (q = mass-dependent breakup momentum):

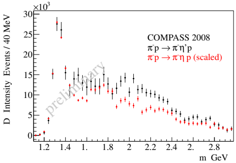
$$\left(\frac{q_{\pi\eta'}}{q_{\pi\eta}}\right)^{J+1/2} \times \text{Amplitude(Spin } J)$$

- overlay the scaled $\pi^-\eta$ data on the $\pi^-\eta'$ data taking into account the branching fracitons of the η', η decays

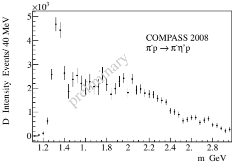
Example with D_+ wave:



D_+ wave in $\pi^-\eta$



Scaled Overlay



D_+ wave in $\pi^-\eta'$

η-η' Mixing

In the quark model, there are two isospin-zero states in the fundamental octet of the light quarks u, d, s:

- the $SU(3)_{\text{flavor}}$ singlet η_1 and the octet η_8
- these mix to form the physical states $\eta(548)$, $\eta'(958)$

Alternatively, but easier to understand, one can introduce the flavor basis,

- $\eta_q = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$ and $\eta_s = s\bar{s}$
- the physical states are then again obtained via mixing:

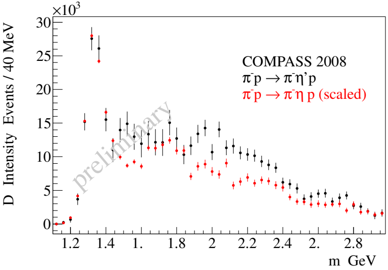
$$\eta = \eta_q \cos\phi - \eta_s \sin\phi$$
$$\eta' = \eta_s \sin\phi + \eta_q \cos\phi$$

- for every reaction that can be drawn in terms of quark lines, the relative η and η' cross-sections should be determined by ϕ: the η' couples preferentially to $s\bar{s}$, the η to $n\bar{n}$.

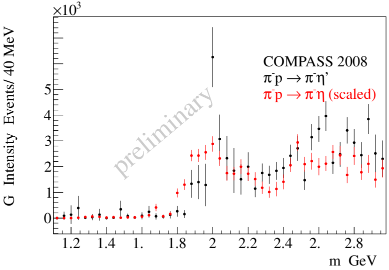
NB: This is just the simples model for η-η' mixing. Glueball, different decay constants, …

Overlay of Even Waves

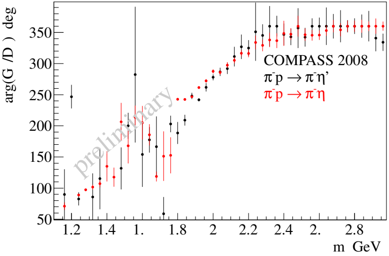
D_+ wave



G_+ wave



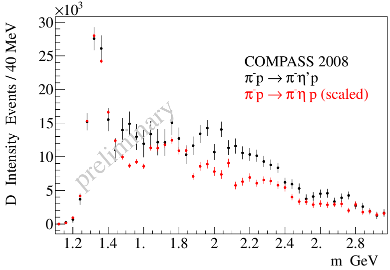
Phase difference $(G_+ - D_+)$



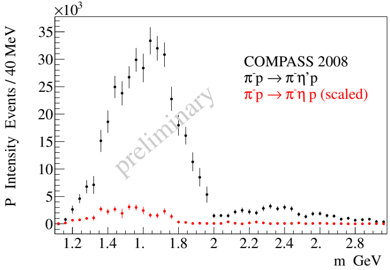
Very similar in $\pi^-\eta$, $\pi^-\eta'$. Reasonable for $n\bar{n}$ resonances (η-η' mixing). But it's unlikely that all of this is resonant. (Absolute scale may have large systematics.)

Overlays of D_+, P_+ Waves

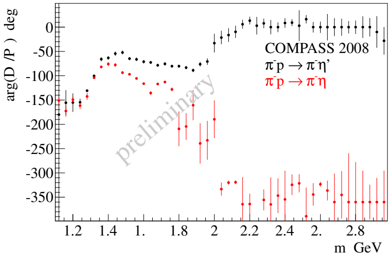
D_+ wave



P_+ wave



Phase diffrence $(D_+ - P_+)$



P_+ wave behaves entirely differently. There are theoretical arguments for a suppression of the P-wave in initial states involving valence glue (hybrid meson?).

Summary

COMPASS has performed partial-wave analyses of the $\pi^- \eta$ and $\pi^- \eta'$ channels

- a resonance-only interpretation appears difficult

Most striking results:

- Similarity between the even partial waves
- Dissimilarity for odd (“exotic”) waves

Publication forthcoming. It also contains

- resonance parameters of known resonances (a_2, a_4)
- measurement of branchign fraction (input for η-η' mixing angle determination)
- the spin-3 wave and its scaling behavior

Thanks!