Odd and Even Partial Waves of $\eta\pi^-$ and $\eta'\pi^-$ in 191 GeV/c $\pi^- p$

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on behalf of the COMPASS collaboration
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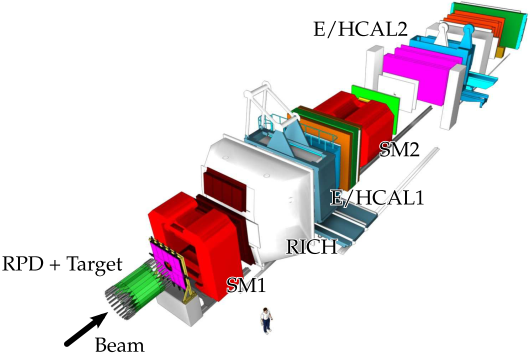
bmb+f - Förderschwerpunkt
COMPASS
Großgeräte der physikalischen Grundlagenforschung

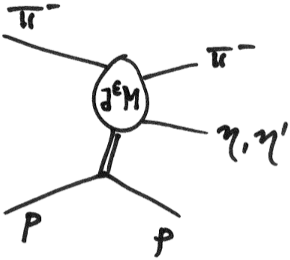
The COMPASS Spectrometer at CERN

COMPASS is a versatile experiment

- variety of beams: muons, hadrons, positive, negative
- variety of targets: polarized, unpolarized, various materials
- variety of physics programs: nucleon spin, hadron spectroscopy, Drell-Yan, Generalized Parton Distributions
- this talk: 191 GeV π^- beam, LH_2 target



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

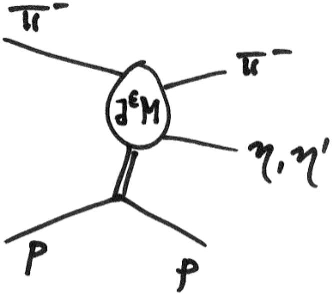


Cut-based selection:

- reaction signature:
  $\pi^-(191\,\mathrm{GeV})p \to \pi^-\pi^-\pi^+\gamma\gamma p_{\mathrm{slow}}$
- non-zero momentum transfer $|t| > 0.1\,\mathrm{GeV}^2$ ensured by trigger on recoiling proton
- reconstruction yields: recoil proton, three tracks emerging from target, two photons in calorimeters
- total momentum conserved
- either $m(\gamma\gamma) = m(\pi^0)$ and subsequently $m(\pi^-\pi^+\pi^0) = m(\eta)$
- or $m(\gamma\gamma) = m(\eta)$ and subsequently $m(\pi^-\pi^+\eta) = m(\eta')$

Yields roughly 35 000 $\pi\eta'$ events and roughly 110 000 $\pi\eta$ events.

Partial-wave Analysis in Mass Bins



Procedure:

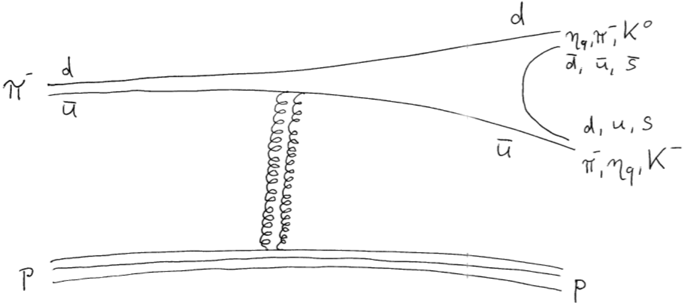
- divide data into mass bins (40 MeV)
- extended log-likelihood fit of each bin to an acceptance-corrected partial-wave model
- quantum numbers defined in the reflectivity basis: spin J, exchange naturality ϵ, spin projection M
- decay to pseudoscalars described in Gottfried-Jackson frame by $Y_M^{\epsilon L}(\theta, \phi) \propto Y_M^L(\theta, \phi) - \epsilon(-)^M Y_{-M}^L(\theta, \phi)$
- in particular, natural exchange implies $Y_M^{+L} \propto \sin M\phi$

Reaction $\pi^- p \to \pi^- \eta^{(\prime)} p$

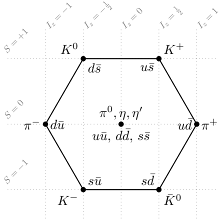
Typical simple reaction.

- exchanging the roles of the quarks in the beam pion exchanges the final-state mesons, hence ...
- this type of reaction leads to completely forward-backward symmetric production of π and η' (no odd-even interference, in particular)

Additionally, this $\eta^{(\prime)}$ will only contain light quark contributions.



Quark Structure of the Light Isoscalars



The $\eta(548)$ and $\eta'(958)$ mesons are mixtures of the $SU(3)_{\text{flavour}}$ singlet and octet states η_1, η_8. In practice it is more useful to think of them as mixtures in the quark flavour basis $\eta_q \propto u\bar{u} + d\bar{d}$, $\eta_s = s\bar{s}$.

$$\begin{pmatrix} \eta \\ \eta' \end{pmatrix} = \begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} \eta_q \\ \eta_s \end{pmatrix}$$

From this, cross-section ratios can be related to the angle $\phi = 39.3^\circ \pm 1.0^\circ$.

Illustration: What do the Data Look Like: the η peak

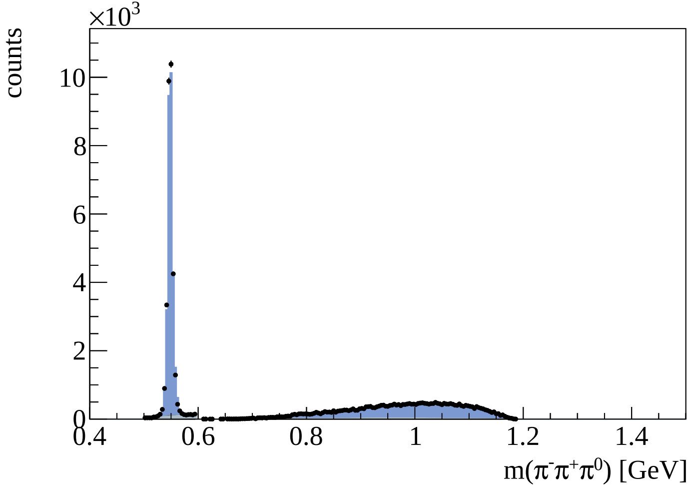
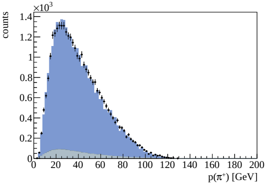
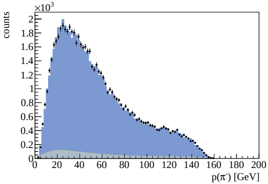


Figure : $m(\pi^-\pi^+\pi^0)$ (two combinations per event). Black dots: data. Light blue: natural-exchange waves. Gray: non-η background. Dark blue: unnatural-exchange waves (negligible). Masses restricted to $m(\pi\eta) \in [m_\pi + m_{\eta'}, m_{a_2}]$.

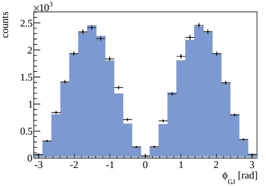
Illustration: What do the Data Look Like II



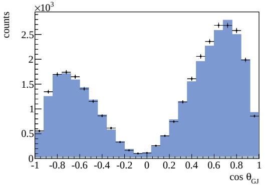
(a) $p(\pi^+)$



(b) $p(\pi^-)$ (2 entries p.ev.)



(c) ϕ_{GJ}; $\sin^2\phi$ implies $M = 1$ dominant

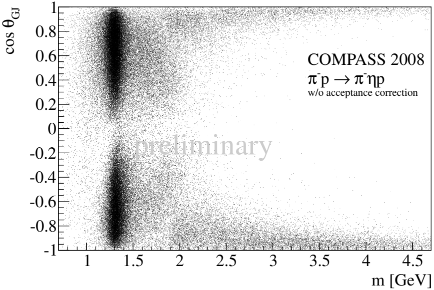


(d) $\cos\theta_{GJ}$

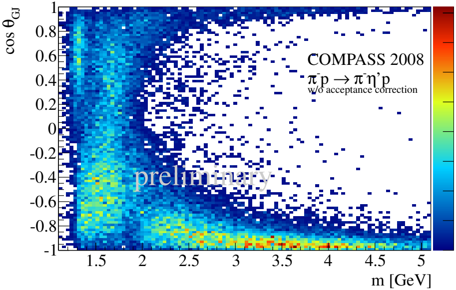
Figure : Black dots: data. Light blue: natural-exchange waves. Gray: non-η background. Dark blue: unnatural-exchange waves (negligible).

Another view of the data

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



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

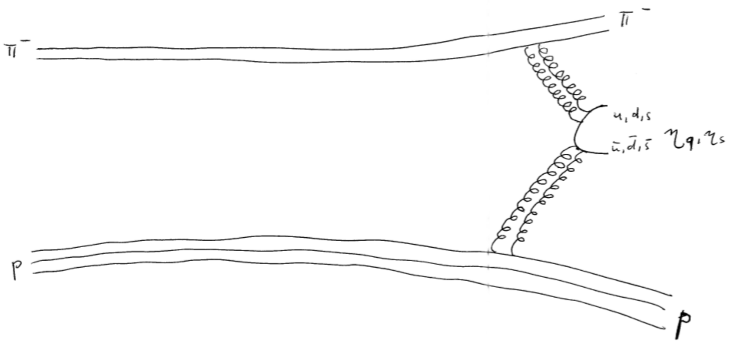


Clearly not symmetric: especially at high masses, ηs and η's prefer to be produced in the backward direction. The production is more complicated.

Production of a Slow $\eta^{(\prime)}$

A possible mechanism is depicted below. Unlike the previous mechanism, an $\eta^{(\prime)}$ produced in this way will contain in equal parts $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$.
The different composition of the η and η' will then lead to

- different degree of asymmetry in $\pi^-\eta$ and $\pi^-\eta'$
- this expresses itself as different relative weight of odd and even partial waves.



Scaling of Intensities, Two Predictions

We are aware of two predictions concerning the relations between partial waves in $\eta\pi$ and $\eta'\pi$:

- Close and Lipkin (1987), Chung et al. (2002) predicted based on flavor symmetry that an initial state containing glue would be suppressed in the spin-one wave of $\pi\eta$ compared to $\pi\eta'$.
  VES verified this, taking this as indication of the hybrid nature of the $P-$wave object. But C&L's argument applies to all odd spins!
- The quark-line picture leads to an OZI-like prediction for resonance decays, according to which (hep-ph/9711229, hep-ph/9802409):

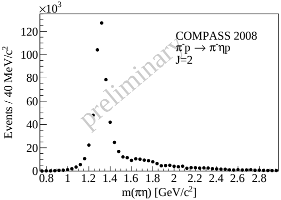
$$\frac{\mathrm{BR}(a_J \to \pi\eta')}{\mathrm{BR}(a_J \to \pi\eta)} = \tan^2\phi \left(\frac{q_{\eta'\pi}(m)}{q_{\eta\pi}(m)}\right)^{2J+1}$$

  ($q_{\eta\pi}(m), q_{\eta'\pi}(m)$ are the breakup momenta at mass m, $J = 2$ or 4). a_2 decays agree with prediction, a_4 not yet measured.

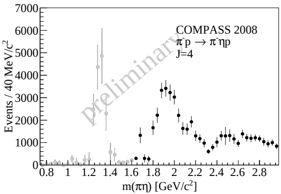
So what we do is this: we take the $\pi^-\eta$ partial-wave results, scale them with the above factor and overlay them on the $\pi^-\eta'$ partial-wave results.

The even waves, spin two and four

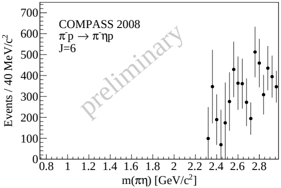
We show briefly the $\eta\pi^-$ fit results



(a) D-wave, $J = 2$



(b) G-wave, $J = 4$

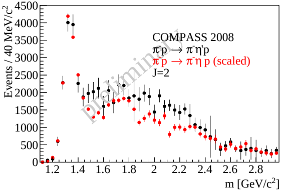


(c) I-wave, $J = 6$

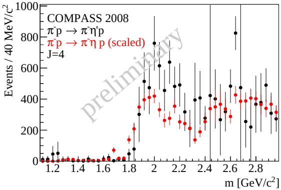
Here we see the known resonances $a_2(1320)$, $a_4(2040)$ (and some leakage from the a_2), and maybe the $a_6(2450)$ (so far only seen in KK).
We know take the data from each bin, multiply it with the phase-space factor from above, correct for the final-state branchings, and overlay this on the $\eta'\pi$ fit results.

The even waves, spin two and four

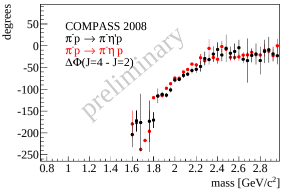
We show the scaled $\eta\pi^-$ in red, the $\eta'\pi^-$ in black.



(d) D-wave, $J = 2$



(e) G-wave, $J = 4$

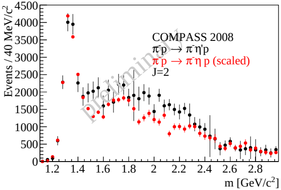


(f) Phase $L = 4 - L = 2$

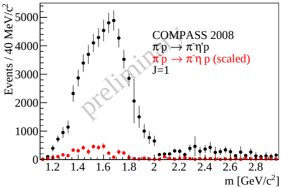
Note how close the $\eta\pi$ points fall on the $\eta'\pi$ points, the agreement in the relative phase (not affected by scaling) is almost perfect.

“The” spin-exotic wave, spin one

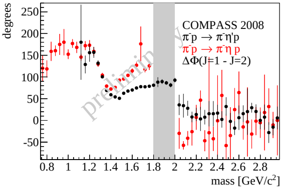
We show the scaled $\eta\pi^-$ in red, the $\eta'\pi^-$ in black.



(g) D-wave, $J = 2$



(h) P-wave, $J = 1$

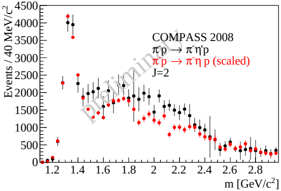


(i) Phase $L = 1 - L = 2$

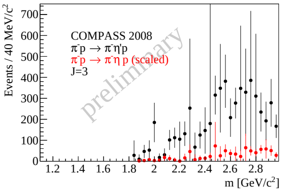
The spin-one wave behaves completely different: strongly suppressed in $\pi\eta$, phases agree up to $a_2(1320)$, then behaves differently. (Points removed due to badly defined phase in low-intensity region.)

Another spin-exotic wave, spin three

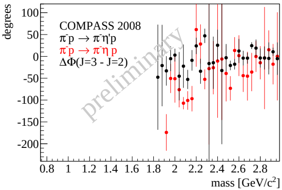
We show the scaled $\eta\pi^-$ in red, the $\eta'\pi^-$ in black.



(j) D-wave, $J = 2$



(k) P-wave, $J = 1$



(l) Phase $L = 1 - L = 2$

The spin-three wave behaves like the spin-one wave: strongly suppressed in $\pi\eta$. Again broad bump in $\pi\eta'$. Not much phase-motion can be made out.

Instead of More Plots

Instead of bombarding you with plots, here are the relative intensities of the various waves. Note the different systematics of odd and even waves.

Table : Relative intensities of the $L = 1 - 6$ and $L = 2$, $M = 2$ partial waves resulting from the PWA fits integrated over the mass range up to $3\,\mathrm{GeV}/c^2$. Experimental acceptance is taken into account. The total $\eta'\pi^-$ to $\eta\pi^-$ intensity ratio in this mass range amounts to 0.19 ± 0.02. The phase-space corrected intensity ratio R_{corr} = ratio of red histogram to black histogram, is given in the third column.

L	$\frac{I_L(\eta\pi^-)}{I_{\mathrm{total}(\eta\pi)}}$ [%]	$\frac{I_L(\eta'\pi^-)}{I_{\mathrm{total}(\eta'\pi)}}$ [%]	R_{corr}
1	4.4	41.7	0.17 ±0.01
2	81.9	42.3	0.94 ±0.02
2, $M = 2$	4.4	1.4	
3	0.3	3.7	0.16 ±0.05
4	6.9	8.4	0.83 ±0.07
5	0.1	0.9	0.15 ±0.12
6	0.7	1.2	0.68 ±0.15

Resonance Parameters

We extract the following parameters for the known resonances:

$$m(a_2) = 1315 \pm 12\,\text{MeV}, \quad \Gamma(a_2) = 119 \pm 14\,\text{MeV}, \tag{1}$$

and

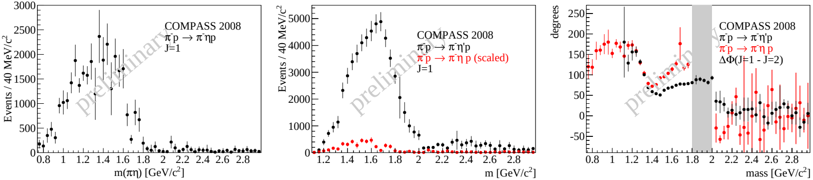
$$m(a_4) = 1900^{+80}_{-20}\,\text{MeV}, \quad \Gamma(a_4) = 300^{+80}_{-100}\,\text{MeV}, \tag{2}$$

(consistent with our 3π analyses)
For their relative branchings we measure:

$$\frac{BR(a_2 \to \eta'\pi)}{BR(a_2 \to \eta\pi)} = (5 \pm 2)\%, \quad B_4 \equiv \frac{BR(a_4 \to \eta'\pi)}{BR(a_4 \to \eta\pi)} = (23 \pm 7)\% \tag{3}$$

These exceed the theory predictions (possible reason: they didn't take resonance-shape effects into account), but we agree with VES's measurement of the a_2 branching

Why no parameters for the exotic spin-one wave



(m) P-wave, $L = 1$, in $\eta\pi^-$ (n) P-wave, $L = 1$, overlaid (o) Phase $L = 1 - L = 2$

Breit-Wigner parameters very model-dependent. Vanishing near 2 GeV and slower phase-motion in $\pi\eta'$ requires strong interference with a background. Different fit models can lead to large variance in fitted resonance parameters. Also, natural question: if these bumps are resonances, why not also in spin 3, spin 5?

Theory input welcome!

Summary

We have analyzed COMPASS 2008 data for the reactions $\pi^- p \to \pi^- \eta p$ and $\pi^- p \to \pi^- \eta' p$.

Main findings:

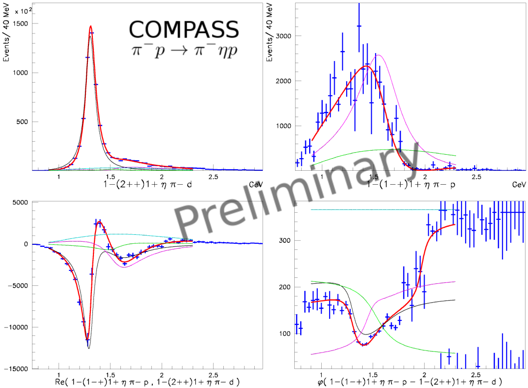
- even partial-waves very similar between the $\pi^- \eta$ and $\pi^- \eta'$ systems after taking phase-space factors into account
- odd partial-waves relatively enhanced in the $\pi^- \eta'$ system

Other results:

- measurement of resonance parameters of a_2, a_4
- measurement of their relative branchings

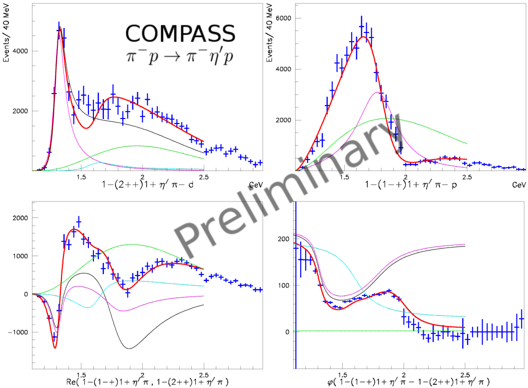
Backup

Mass-dependent Fits



Example mass-dependent fit to $\eta\pi$ data. Note strong interference in spin 1, top right. But there are also other fits (which I cannot show you).

Mass-dependent Fits



Example mass-dependent fit to $\eta'\pi$ data. Again, large interference in spin 1, top right. But again, different fit models vary widely.