Using $\bar{p}p$ to study s-channel resonances

The need for polarisation data

$$\bar{p}p \rightarrow R^* \rightarrow A + B \quad \text{(many final states)}$$

Message: There is the prospect of getting complete information on the non-strange meson spectrum up to ~2400 MeV.

A polarisation measurement is needed urgently.

It is a fairly simple, straightforward experiment.

Based on Crystal Barrel data from LEAR

$\bar{p}p \rightarrow$ neutrals. $(\pi^0, \eta, \eta', \omega \rightarrow \pi^0\gamma)$

Collaborators on in-flight analysis:

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+ theoretical help from V.V. Anisovich.

Channels Studied (9 momenta 600 – 1940 MeV/c)

$\bar{p}p \to \pi^0\pi^0$ $\to \eta\eta_1$ $\to \eta\eta'$ $\to \eta\pi^0\pi^0$ – 70K events/momentum $\to \eta\eta\eta$ $\to \pi^+\pi^-$ from PS172		I=0 C=+1 Combined fit complete
$\to \eta\pi^0$ $\to \eta'\pi^0$ $\to 3\pi^0$ $\to \eta\eta\pi^0$		I=1 C=+1 Combined fit in progress
$\to \omega\pi^0$ $\to \omega\eta\pi^0$	$\omega \to \pi^0\gamma$	I=1 C=−1 Almost finished
$\to \omega\pi^0\pi^0$ $\to \omega\eta$	$\omega \to \pi^0\gamma$	I=0 C=−1 Combined fit complete

Will do (a) $\omega \to \pi^+\pi^-\pi^0$, last 4 channels

(b) $\bar{p}p \to K_L^0 K_L^0 \pi^0$? (if backgrounds tolerable)

Study of $\left.\begin{array}{l}\pi^0\pi^0\\ \eta\eta\\ \eta\eta'\end{array}\right\}$ tests SU(3). We are seeing $|n\bar{n}\rangle$ states with one notable exception, $f_0(2100)$

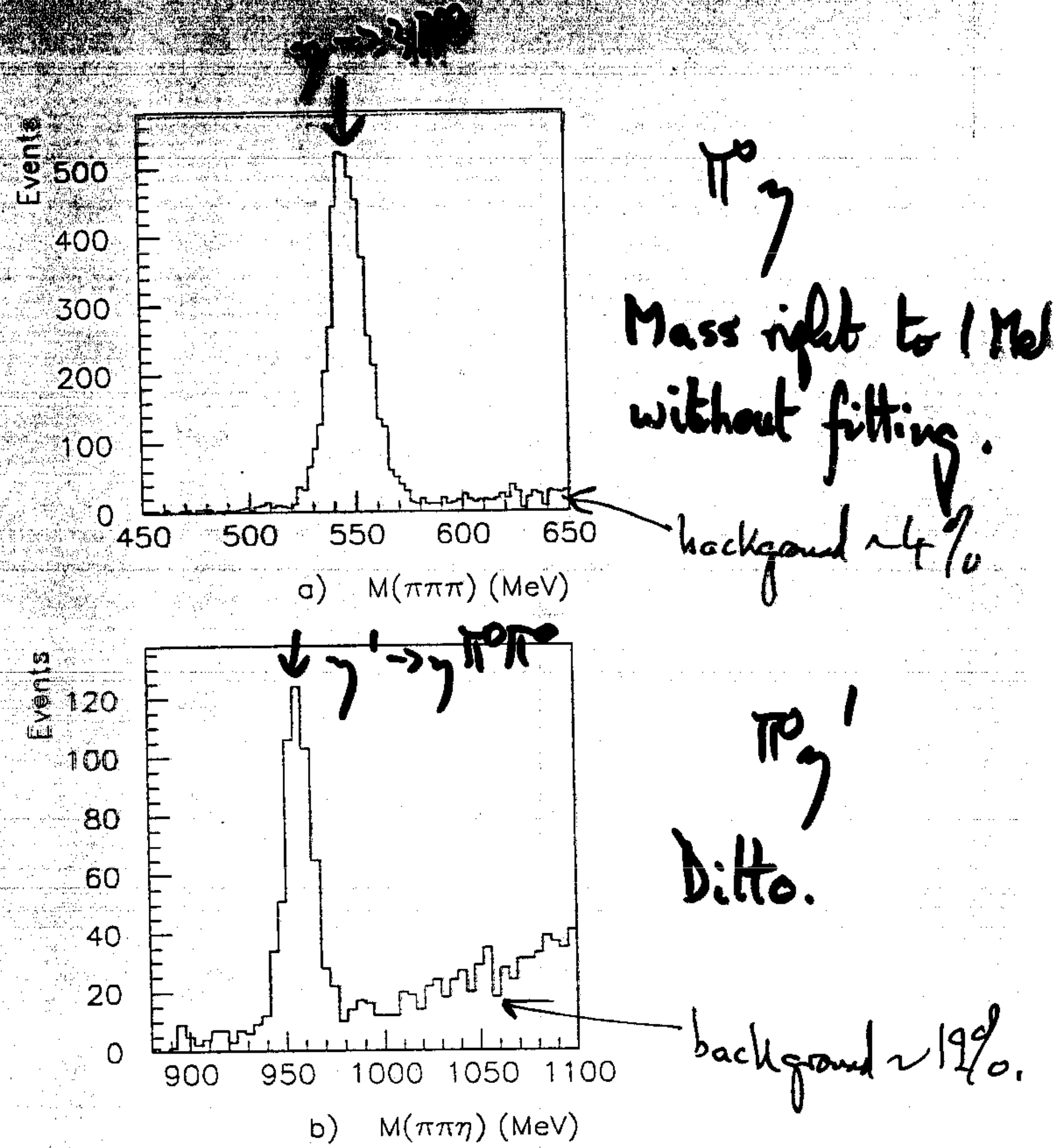


Fig. 1 Distributions of (a) $M(\pi^0\pi^0\pi^0)$ near the η from events fitting $4\pi^0$, after cuts independent of the η, (b) $M(\eta\pi^0\pi^0)$ near the η' from events fitting $\eta 3\pi^0$, after cuts independent of η'. Data are at 1800 MeV/c.

Thumb-nail sketch of Analysis

i) $f_4(2050)$, $a_4(2040)$ } prominent; also $\rho_3(1985)$ for $C=-1$.

These act as interferometers.

2) Peaks are observed in other partial waves.

Phases vary little with respect to interferometers.

$\therefore$ Resonances definitely required in most/all partial waves

3) Parametrise each partial wave as a sum of resonances + background:

$$f = \sum_i \frac{G_i \, B_{\bar{p}p} \, B_{meson}}{M_i^2 - s_i - i M_i \Gamma_i} + \text{Constant}$$

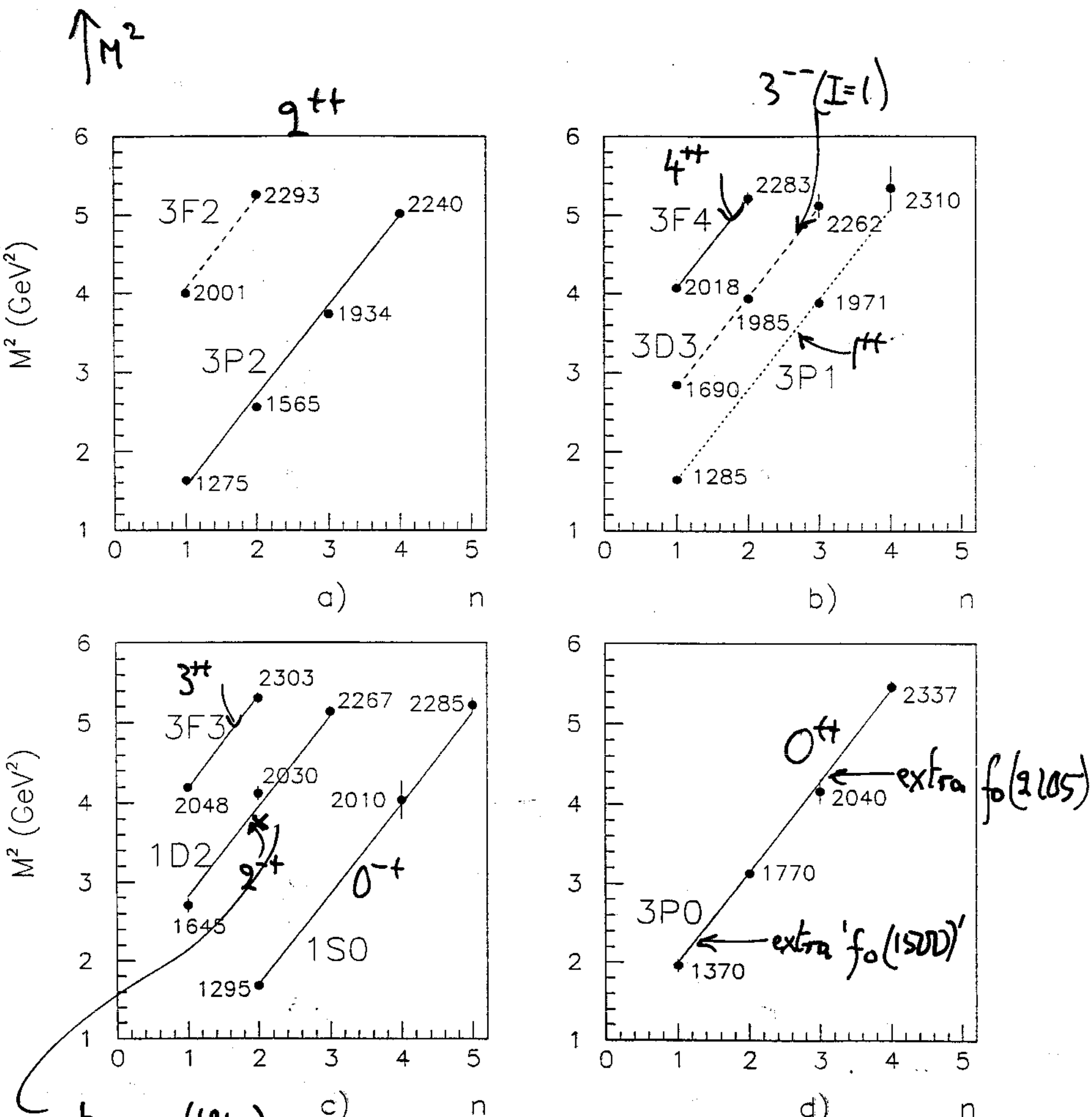
or very broad resonance

Parametrisation satisfies ANALYTICITY.

The constant or slowly varying backgrounds may be due to (i) t-channel exchanges, (ii) resonances below threshold.

I=0 C=+1 mesons

A complete spectrum



extra $\eta_2(1860)$

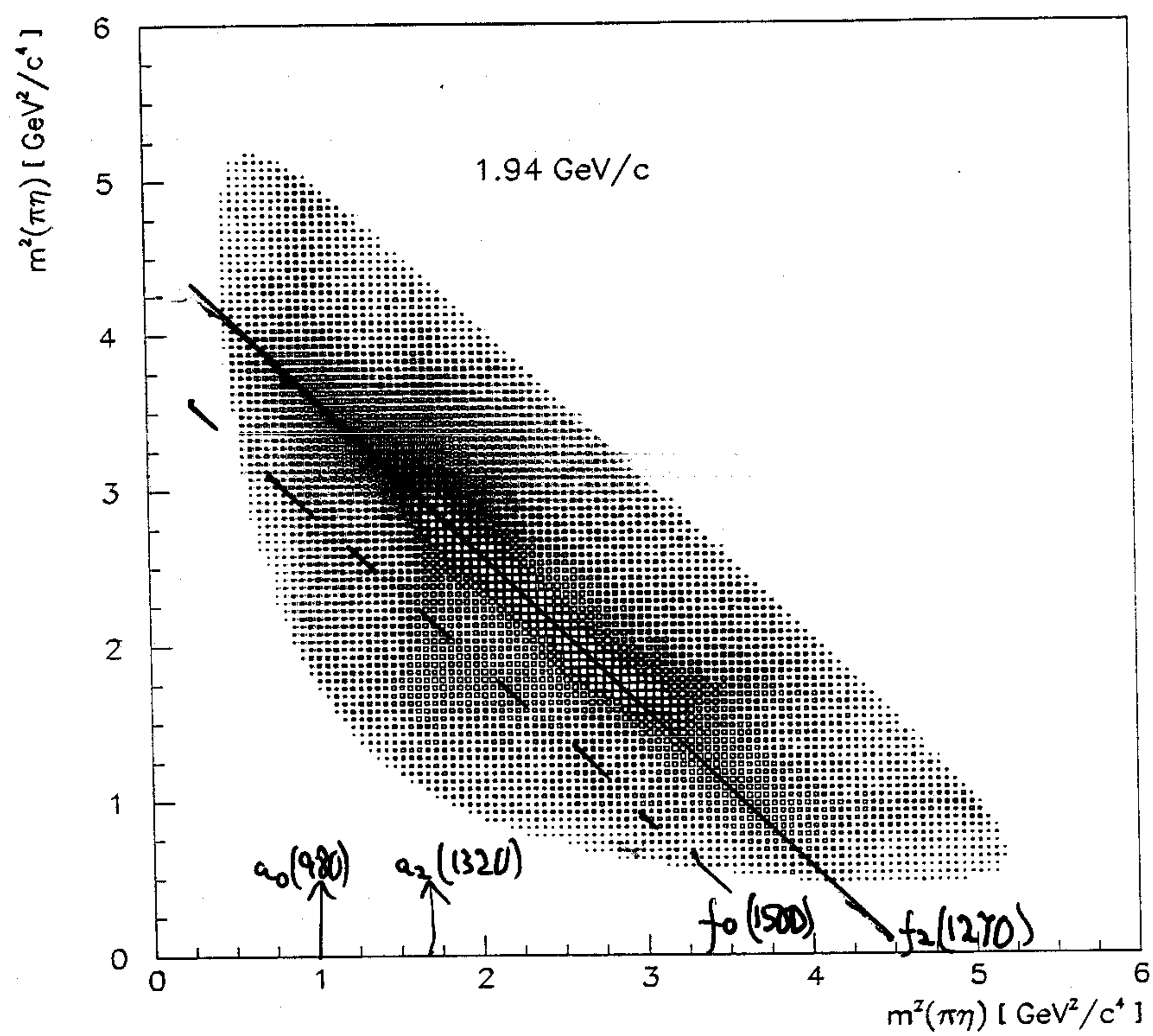
Hybrid?

⟶ radial excitation number

Mean Slope = $1{\cdot}143 \pm 0{\cdot}013$ GeV^2

Every resonance $\geq 2.5\sigma$

Dalitz Plot for $\eta\pi^0\pi^0$



$\eta \pi^0 \pi^0$ results

(a) magnitudes

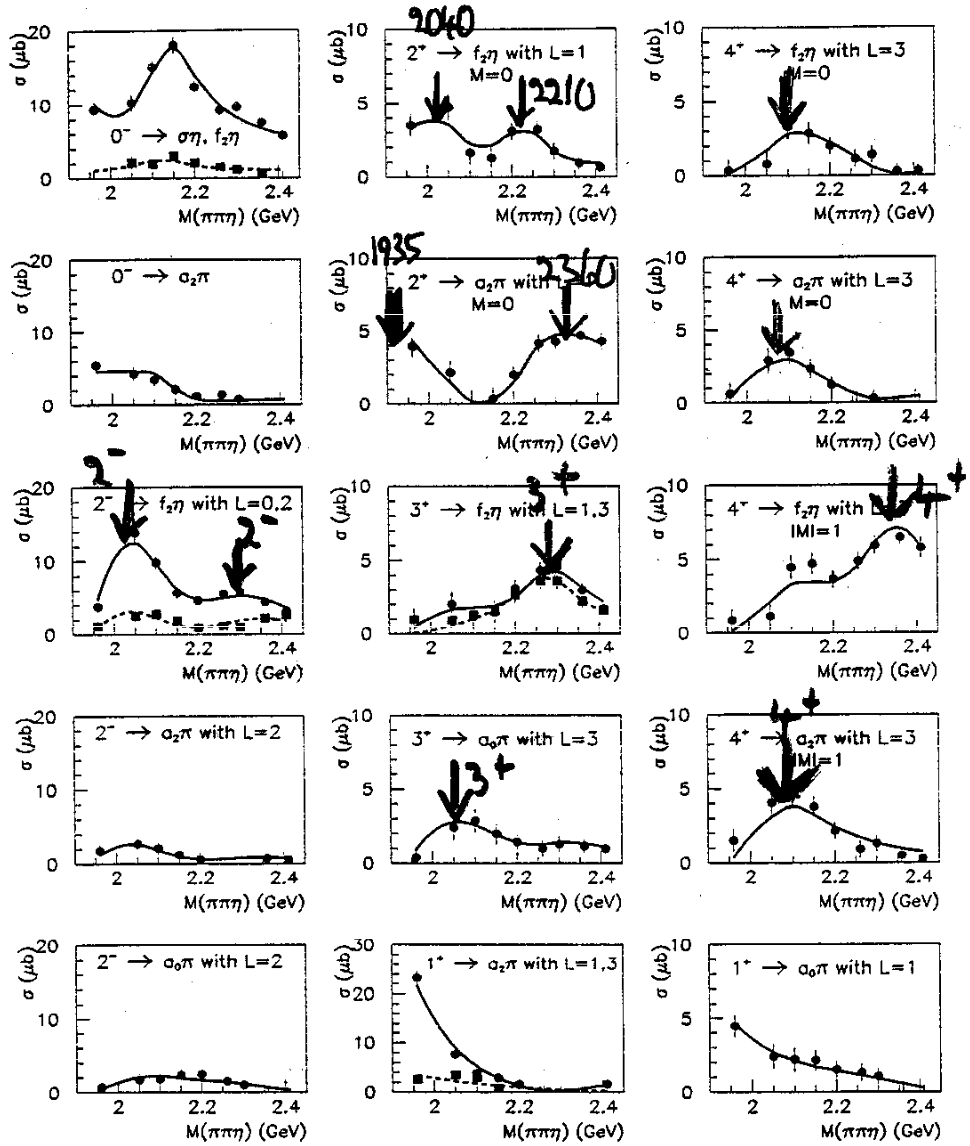


Fig. 11. Cross sections for partial waves making the largest contributions to $\bar{p}p \to \pi^0\pi^0\eta$ with $\eta \to \gamma\gamma$. For diagrams with two components, the first label corresponds to the bigger component. The curves are the fit to the data points in the figure and the relative phases between components.

b) phases

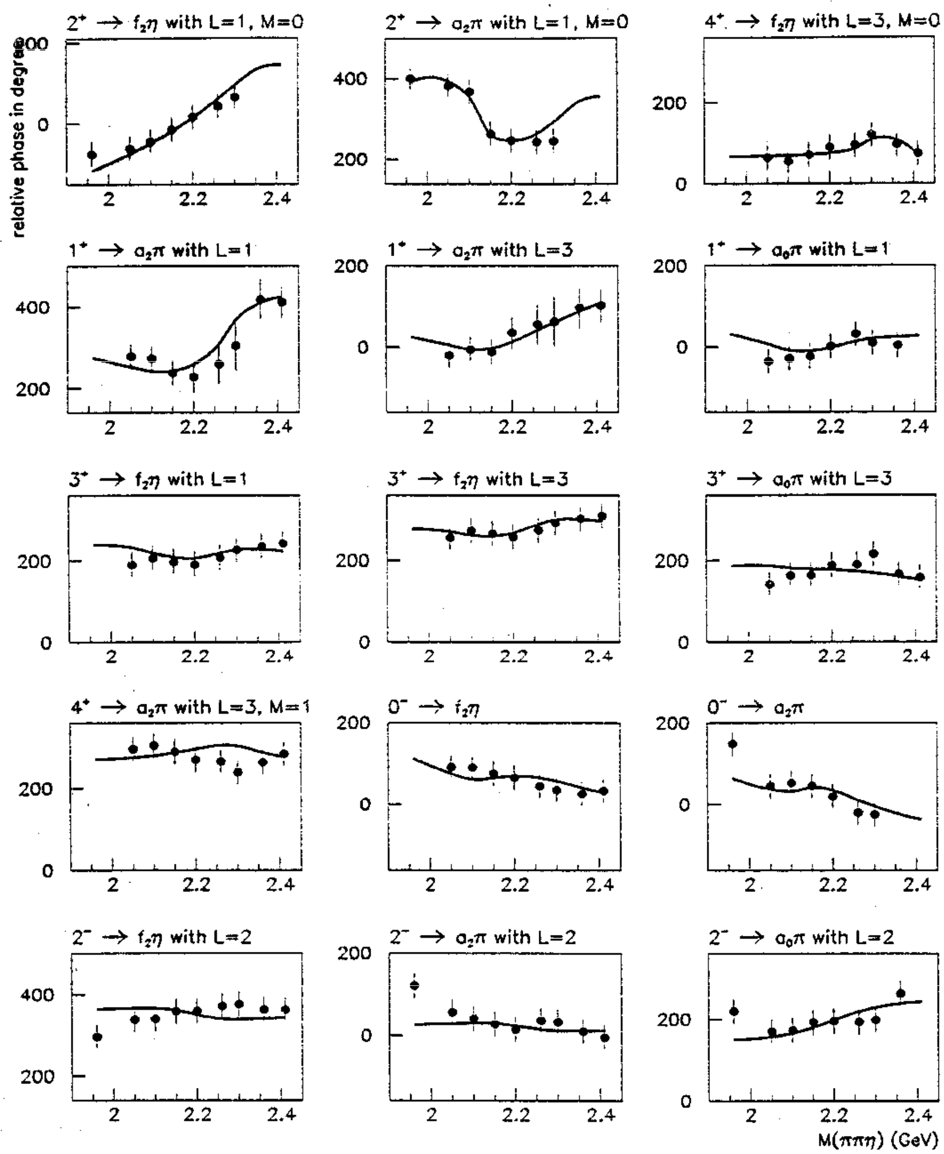


Fig. 13. Relative phases (data points with error bars) obtained from the partial wave analysis and used for the fit (curves) to get Argand plots together with masses and widths of the resonances. The phases for 2^+ and 4^+ with M=0 are relative to $4^+ \to a_2\pi$ with L=3 and M=0; the phases for 1^+, 3^+ and 4^+ with M=1 are relative to $4^+ \to f_2\eta$ with L=3 and M=1; the phases for 0^- and 2^- are relative to $2^- \to f_2\eta$ with L=0.

(c) Argand diagrams

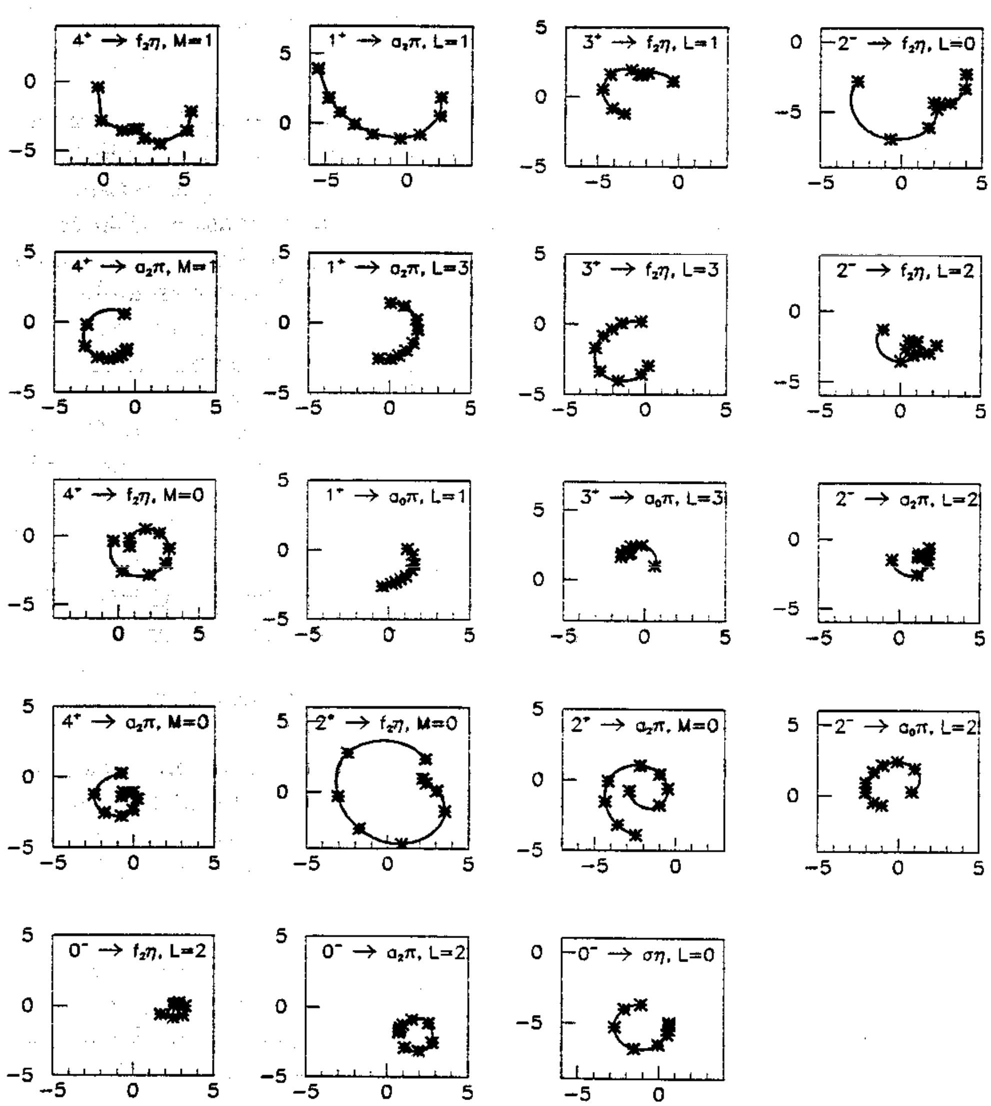


Fig. 15. Argand plots corresponding to curves in Figs.11 and 13.

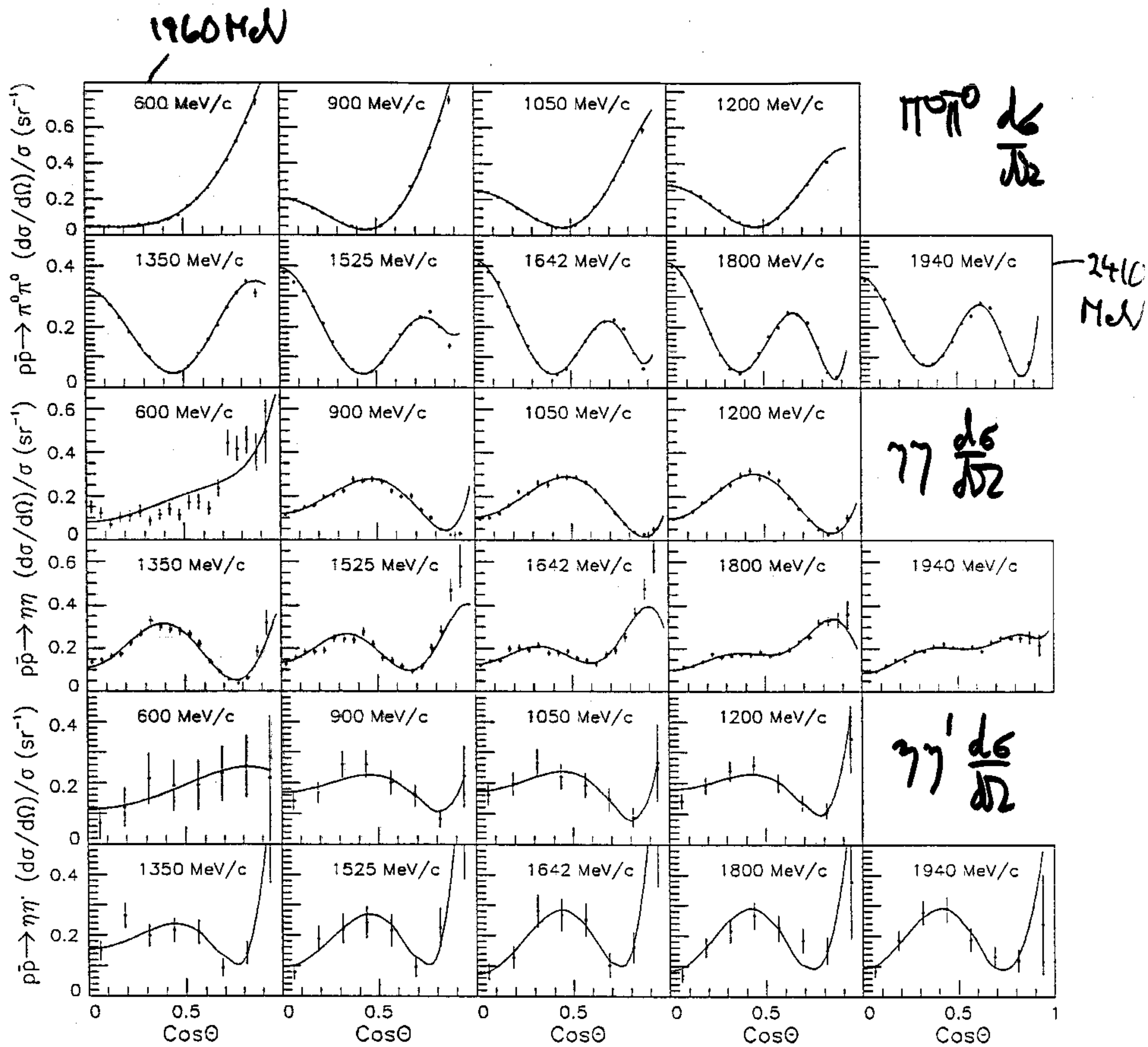


Fig. 4. Differential cross sections for $\pi^0\pi^0$, $\eta\eta$ and $\eta\eta'$ compared with the fit (full curves).

$\frac{d\sigma}{d\Omega}$ ($\pi^+\pi^-$) compared to fit: H = Hasan et al
(PS172) E = Eisenhandler et al

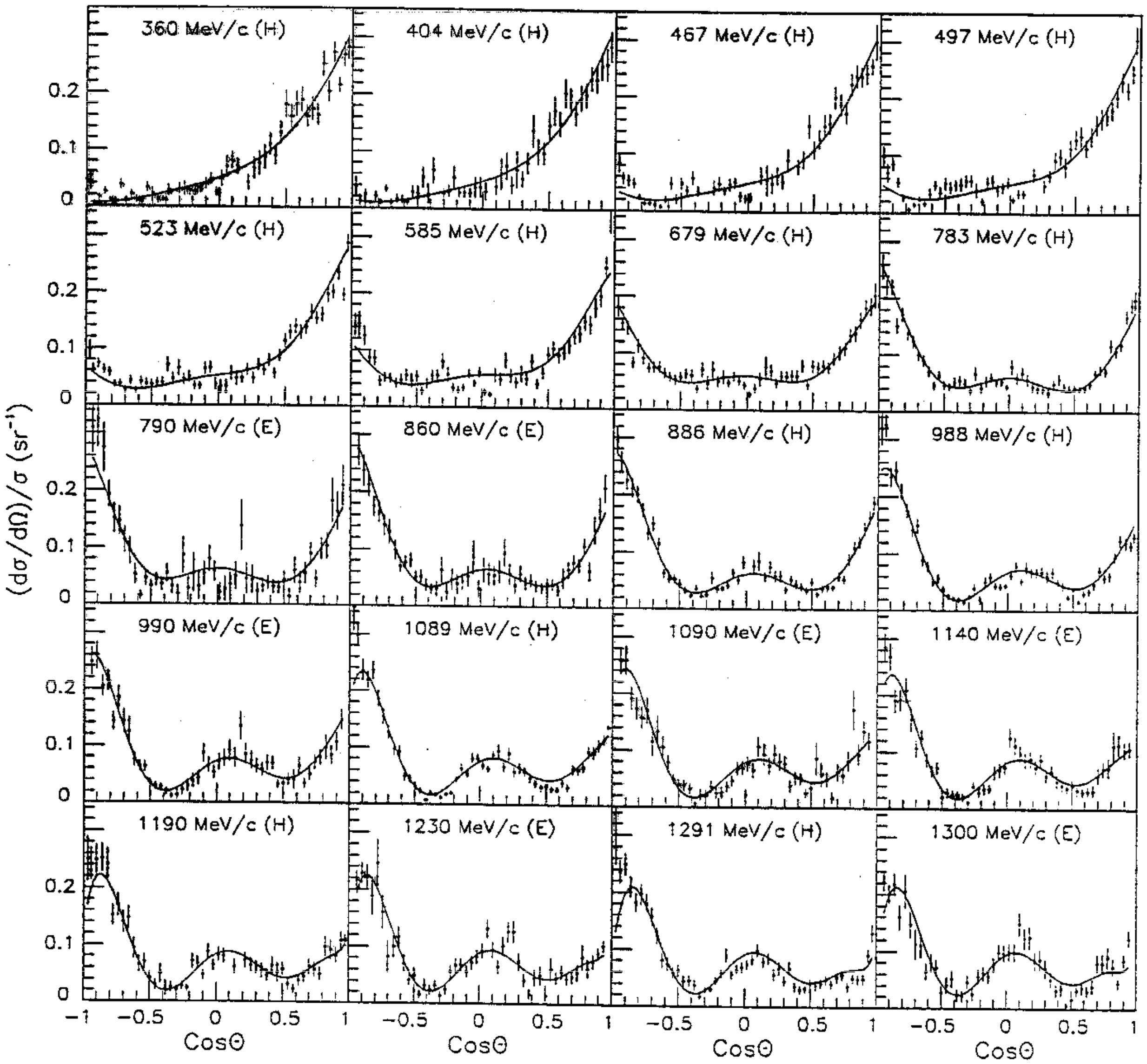


Fig. 1. Differential cross sections from 360 to 1300 MeV/c, compared with the fit (full curves); panels labelled H are data of Hasan et al. and those labelled E are from Eisenhandler et al. Each distribution is normalised so as to integrate to 2π.

$\frac{d\sigma}{d\Omega}$ ($\pi^+\pi^-$) continued.

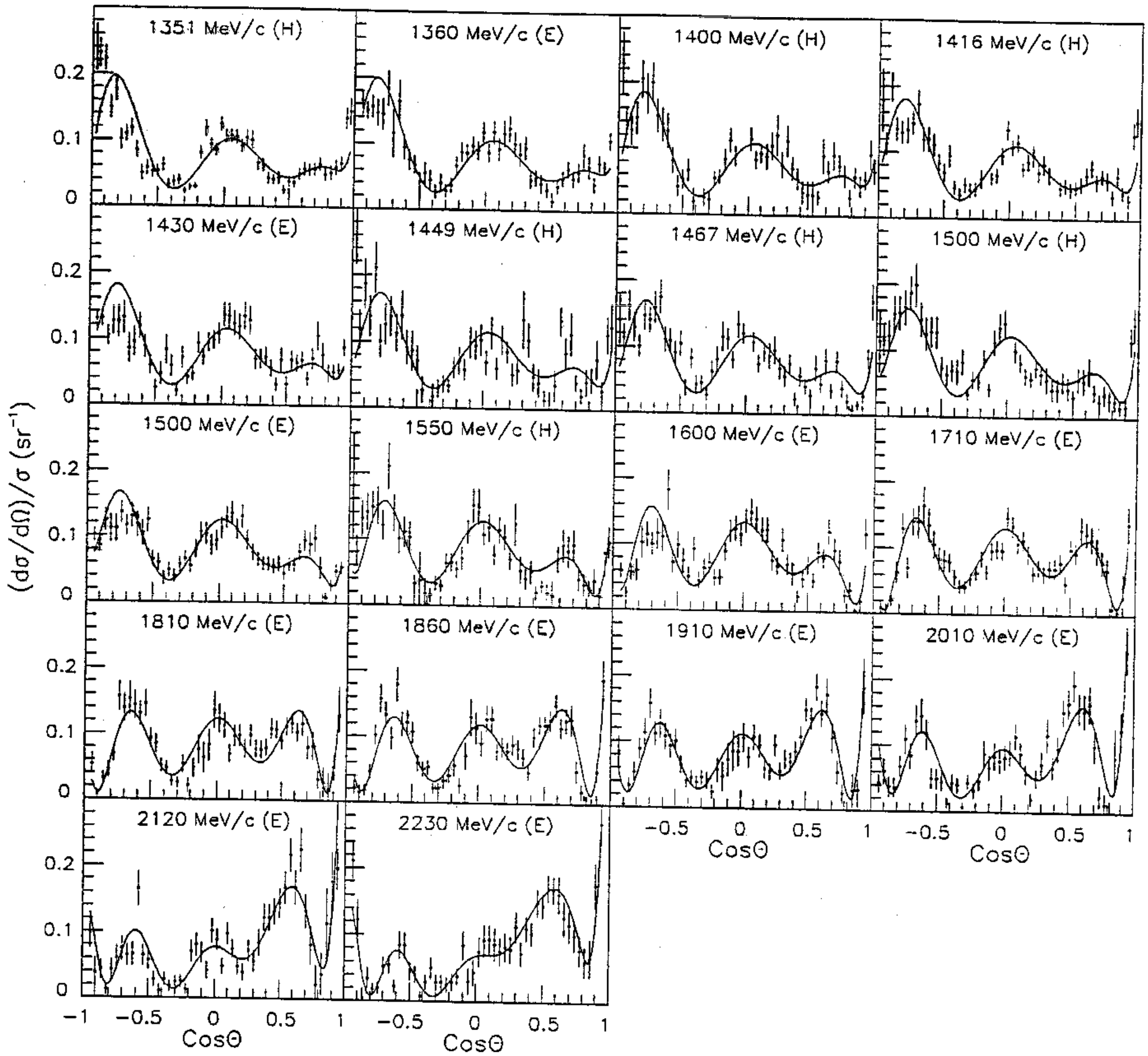
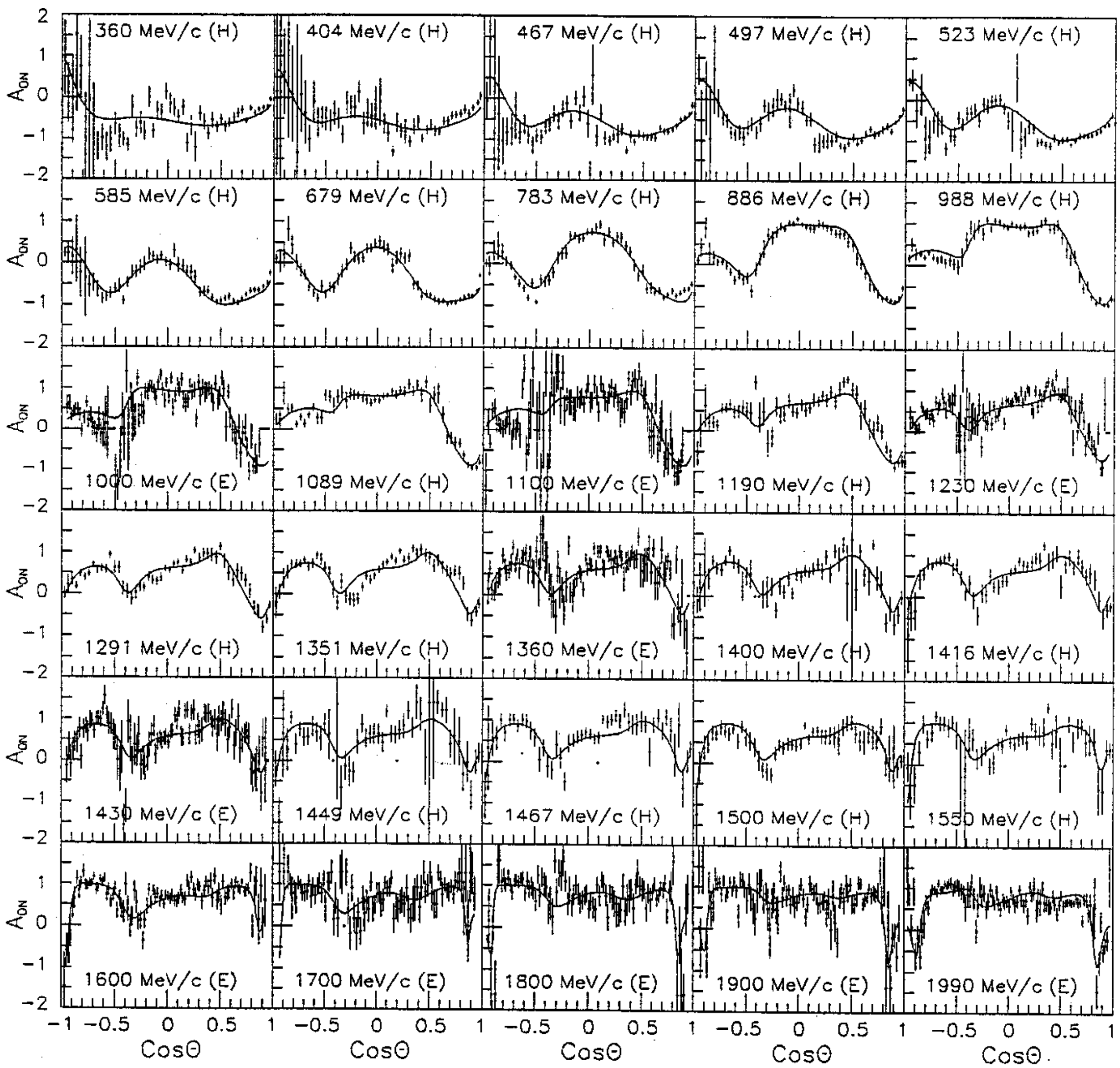


Fig. 2. As Fig. 1, 1351 to 2230 MeV/c.

very valuable for separating $^3P_2$ from $^3F_2$, etc.

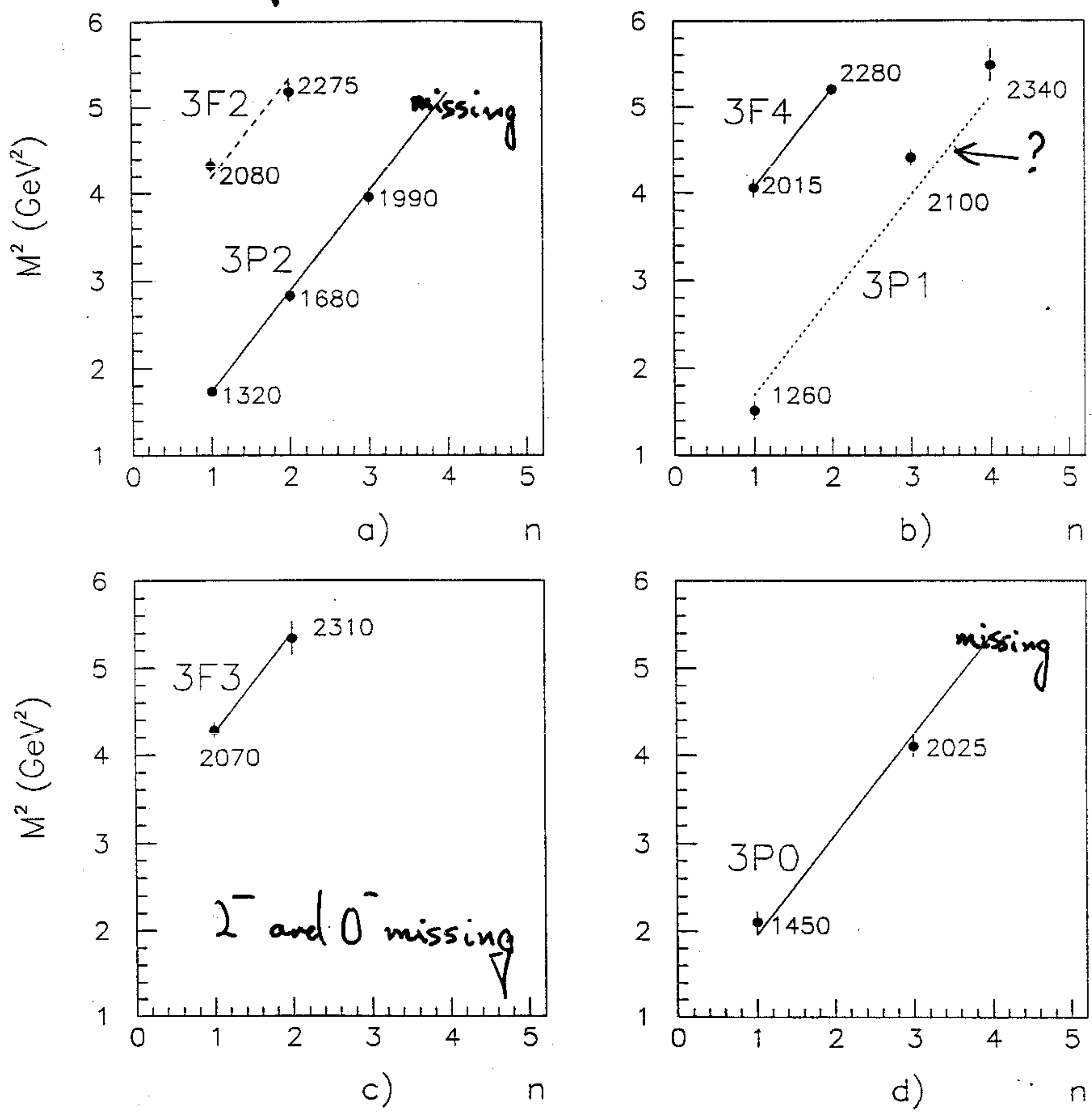
$P(\bar{p}p \to \pi^+\pi^-)$

PS172

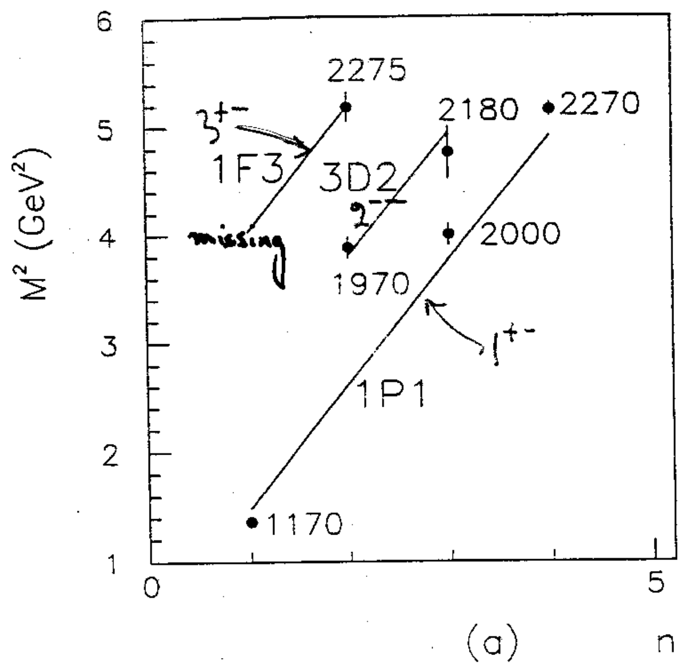


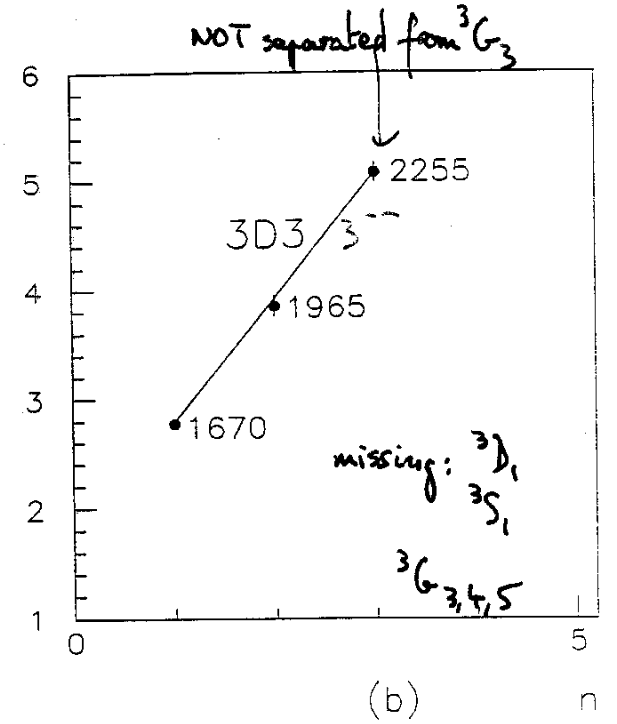
I = 1 C = +1 — { $3\pi^0$, $\eta\pi^0$

Less complete, less accurate

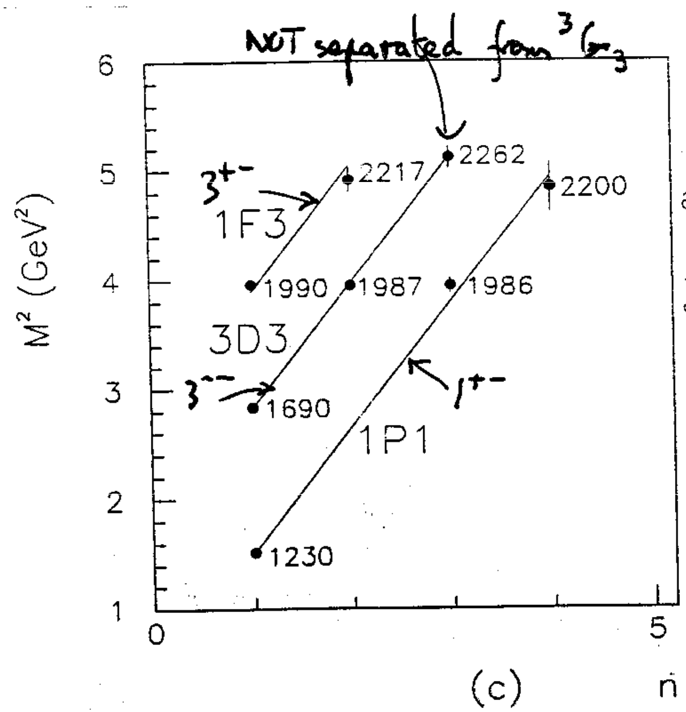


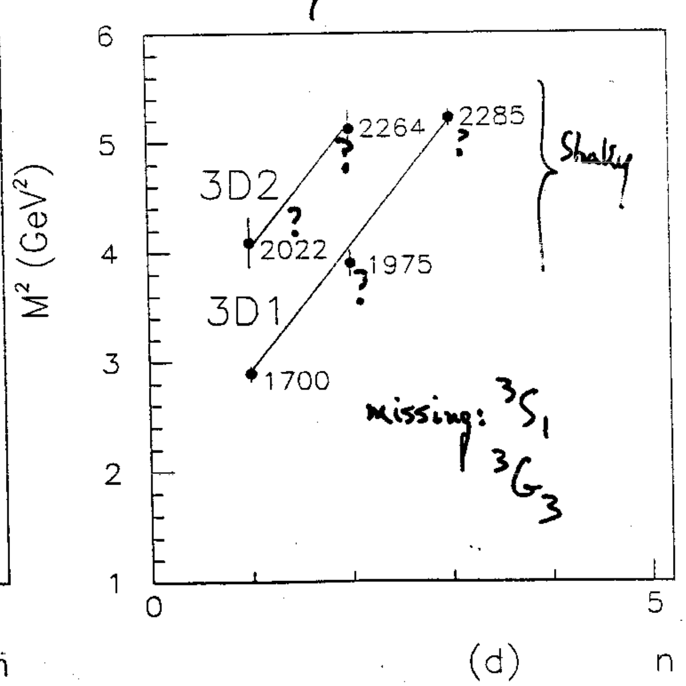
C=−1 I=0 Many missing states





C=−1 I=1 preliminary.
Masses may move





This programme needs completing.

We ARE seeing exotics with $I=0$, $C=+1$.
It is VITAL to complete the $I=1$ $C=+1$ spectrum for comparison.

What is needed?

a) Charged data

b) $KK\pi$ final state

$\boxed{\text{c) POLARISATION data}}$

particularly $\left.\begin{array}{l} 3\pi^0 \\ \pi^0\eta \end{array}\right\}$

Other channels also useful, eg $\eta\pi^0\pi^0$, $\omega\pi^0$, $\omega\eta$, $\omega\pi^0\pi^0$.

$\frac{d\sigma}{d\Omega}$ measures $|f_i|^2 + 2\mathrm{Re}(f_i f_j)^*$

$P\frac{d\sigma}{d\Omega}$ measures $\mathrm{Im}(f_i f_j^*)$, hence fixing PHASES

It also separates helicity amplitudes f_{++} and f_{+-}, hence $L = J \pm 1$

eg $^3P_2$ and $^3F_2$
$^3S_1$ and $^3D_1$
$^3D_3$ and $^3G_3$
$^3D_2$ and $^3G_4$.

$$\frac{d\sigma}{d\Omega} = |F_{++}|^2 + |F_{+-}|^2$$

$$F_{++} = \frac{1}{4} \sum_J (2J+1) f_{++}^J P_J(\cos\theta)$$

$$F_{+-} = \frac{1}{4} \sum_J \frac{2J+1}{\sqrt{J(J+1)}} f_{+-}^J P_J^1(\cos\theta)$$

$$\left.\begin{aligned} f_{++} &= \sqrt{\frac{J}{2J+1}}\, T_{J-1,J} - \sqrt{\frac{J+1}{2J+1}}\, T_{J+1,J} \\ f_{+-} &= \sqrt{\frac{J+1}{2J+1}}\, T_{J-1,J} + \sqrt{\frac{J}{2J+1}}\, T_{J+1,J} \end{aligned}\right\} \text{$L = J \pm 1$ contribute with different coefficients}$$

$$A_{ON} \frac{d\sigma}{d\Omega} = Tr\left(F^{+} \sigma_y F\right) = 2\, \mathrm{Im}\left(F_{++}^* F_{+-}\right).$$

Phase Sensitive

Sensitive to $J \pm 1$.

<u>NB:</u> A_{OS} and A_{OL} non-zero for inelastic processes
Also spin transfers to final state. } MANY new observables

A_{OS} comes 'free' from events in the plane of the polarisation.

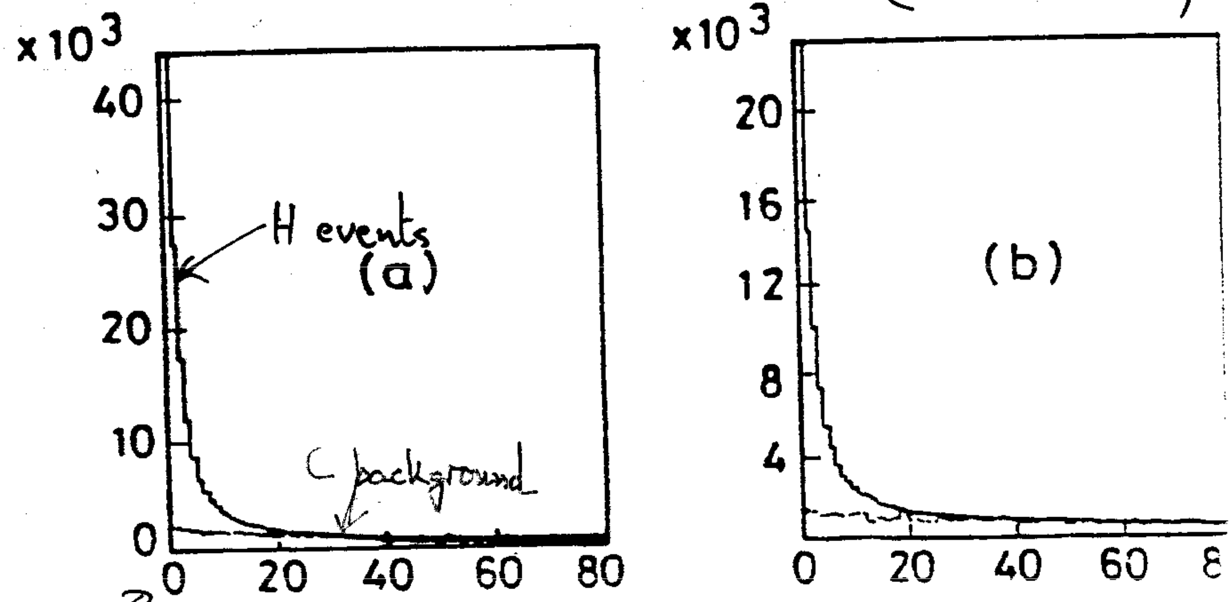
The experiment

Need dilution fridge for ~4π access
+ detector with ~4π acceptance
+ good γ detection.

eg Crystal Barrel or Crystal Ball or SND (Novosibirsk)

Separation of H events

Fermi momentum in C = 200 MeV/c (120 MeV/c in p_x, p_y, p_z).
Need to measure transverse momenta ±10 MeV (≡ ±20 mrad)



Actual data from $pp \to pn\pi^+$ (LAMPF), PRC40(1989)2203.

Rates in Crystal Barrel (4.4 cm long target)

~50 events/s with 10^5 $\bar{p}$/s in H. (limited by data acquisition)
C/H ≃ 2.3/1.
Hence ~15 H events/s if same limit on acquisition.
Need 10^7 events / momentum, i.e. a few days.
Beware of pile-up in the detector
Need data 450 (150) 1950 MeV/c : 11 momenta

Exotics

There are certainly 'extra' (non $q\bar{q}$) states with $I=0$, $C=+1$.
Candidates for glueballs/hybrids.

a) $f_0(1370)$ and $f_0(1500)$ are too close both to be $|n\bar{n}\rangle$.

b) $f_0(2105)$ is produced STRONGLY in $\bar{p}p$, but decays

$$\frac{\pi^0\pi^0}{\eta\eta} = 0.71 \pm 0.7, \text{ compared to prediction } \frac{1}{(0.8)^4} = 2.45.$$

If fitted as $\cos\Phi\left(\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}\right) + \sin\Phi|s\bar{s}\rangle$, $\Phi = 58 \pm 5^\circ$.

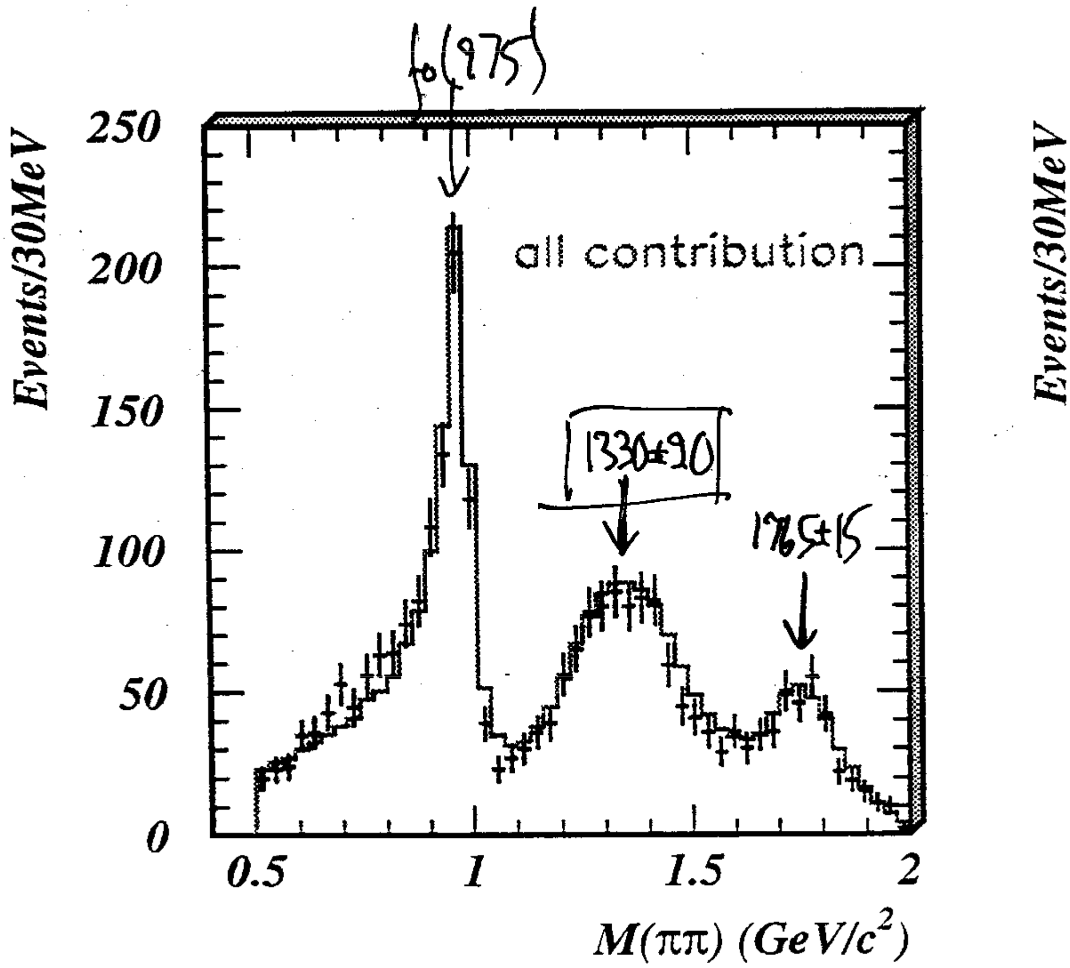
For a glueball, $\Phi = 35.6^\circ$.

c) There is an extra, broad $f_2(1980)$ appearing in $\pi^0\pi^0$, $\eta\eta$ and $\eta\pi^0\pi^0$. In central production, it behaves differently to well known $q\bar{q}$ states.

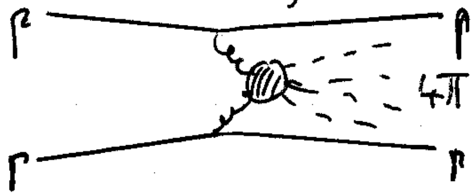
d) There is a broad $\eta(2190)$ in $J/\psi \to \gamma VV$, ← ρ, ω, K^*, ϕ.
flavour-blind within errors ($\pm 30\%$)
Phys. Lett. B 458 (1999) 571.

e) There is an extra 2^{-+} at 1860 MeV, a hybrid candidate.

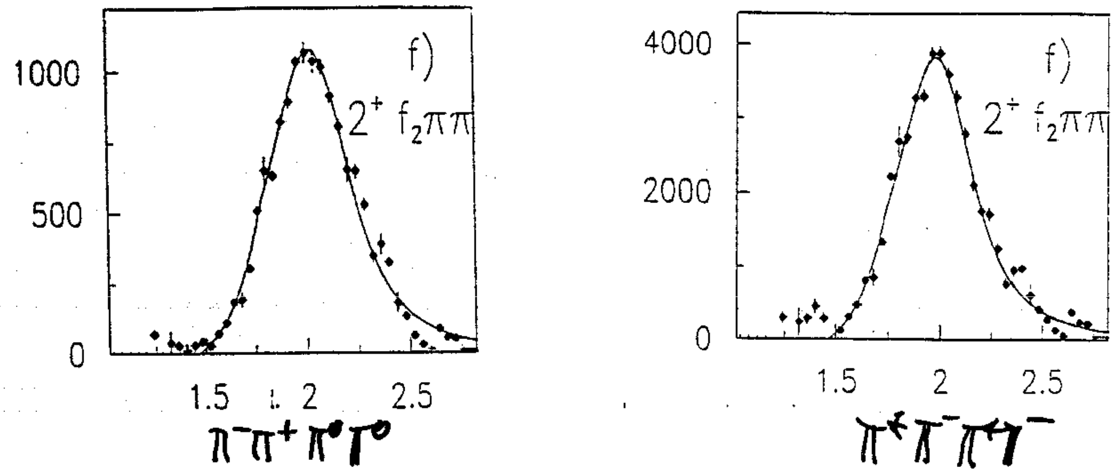
New BES data: $J/\psi \to \phi(\pi^+\pi^-)$



Central Production of 4π (WA102)

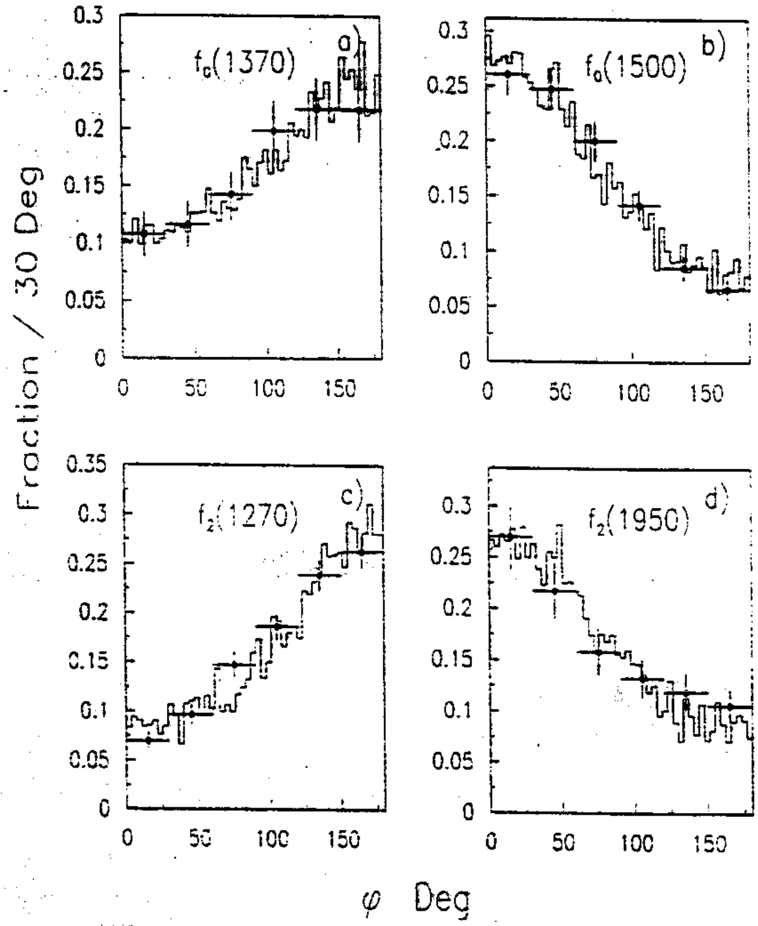


PLB 471 (2000) 440



M = 1990 MeV

$\Gamma \approx 440$ MeV



Close, Kirk & Schuler

PLB 477 (2000) 13

Lattice QCD calculations.

Morningstar & Peardon, Phys. Rev. D60 (1999) 034509.

The absolute mass scale of glueball masses has errors $\simeq \pm 15\%$.

But mass <u>ratios</u> are predicted much more accurately.

Ratios	Prediction	Experiment
$2^{++}/\text{lowest } 0^{++}$	$1.39 \pm .04$	$\frac{f_2(1980)}{f_0(1500)} = 1.32 \pm .03$
$2^{nd}\, 0^{++}/1^{st}\, 0^{++}$	$1.54 \pm .11$	$\frac{f_0(2105)}{f_0(1500)} = 1.40 \pm .02$
$0^{-+}/\text{lowest } 0^{++}$	$1.50 \pm .04$	$\frac{\eta(2190)}{f_0(1500)} = 1.46 \pm .03$
$0^{-+}/2^{++}$	$1.081 \pm .012$	$\frac{\eta(2190)}{f_2(1980)} = 1.043 \pm .036$

Nonetheless, glueballs and $q\bar{q}$ are doubtless mixed.

This mixing is not yet understood/agreed.

Conclusions

1) $\bar{p}p$ is a good place to study s-channel meson resonances

2) The $I=0$, $C=+1$ spectrum appears to be complete, but should be tested with further data.

3) $I=1, C=+1$
$I=1, C=-1$
$I=0, C=-1$
look similar to $I=0, C=+1$.

but errors are larger and many states are missing.

4) A vital element for $I=0$, $C=+1$ came from polarisation data for $\pi\pi$

5) I am confident that polarisation data would complete the spectroscopy up to 2400 MeV.

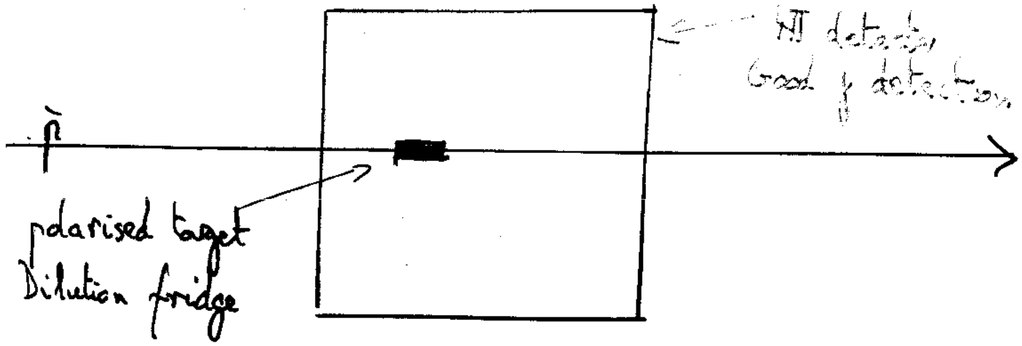
6) It is particularly vital to complete the $I=1$, $C=+1$ spectrum, as a template to help identify exotic states.

Primary Aim: $P\frac{d\sigma}{d\Omega}$ for $\left.\begin{matrix}3\pi^0\\ \pi^0\eta\end{matrix}\right\}$. Also valuable: $\left.\begin{matrix}\eta\pi^0\pi^0\\ \pi^0\pi^0\\ \eta\eta\\ \omega\pi^0;\ \omega\eta\\ \omega\pi^0\pi^0.\end{matrix}\right\}$

7) This would be a fairly straightforward experiment, taking ~3 months of beam at $\sim 10^5\ \bar{p}/s$.

Needs a) dilution fridge, b) Crystal Barrel or Crystal Ball or SND.

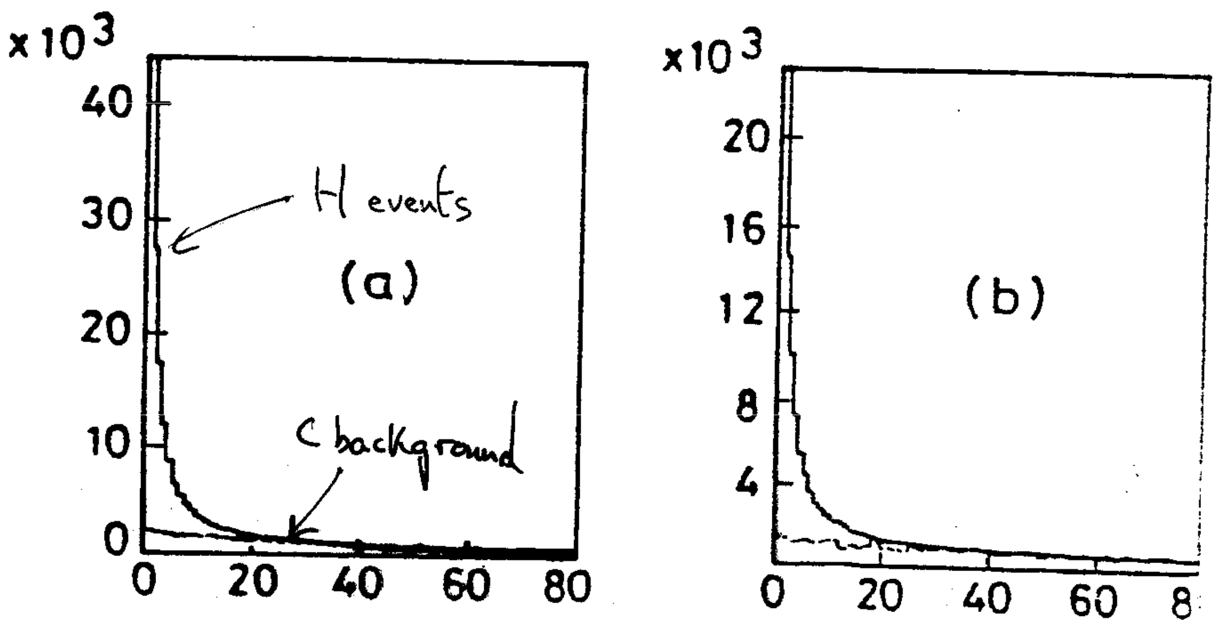
The experiment



Separation of H events

Fermi momentum in C or N = 200 MeV/c (120 MeV/c in p_x, p_y, p_z).
Need to measure transverse momenta ±10 MeV/c.
Mean γ momentum ≃ 400 MeV/c, so this implies ±50 mrad, which should be easy (Crystal Barrel ± 10 mrad)

Illustration from $p\uparrow \to pn\pi^+$ (expt E815 at LAMPF)



$\frac{\text{Background}}{\text{Signal}} \sim 8\%$.

Rates in Crystal Barrel

4.4 cm long LH_2 target

~ 90 events/s with 10^5 $\bar{p}$/s (limited by data acquisition)

If NH_3 used, $\frac{N}{H} = \frac{7^{2/3}}{3} = 1.2$

Hence ~ 22.5 H events/s $\not\equiv$ if data acquisition still a limitation.

Need ~ 10^7 events/momentum, ie 5 days/momentum.

Should double this for calibrations, running ε, etc.

∴ Total running $\simeq$ 110 days for 11 momenta.

Need data at 450 (150) 1950 MeV/c. (11 momenta)

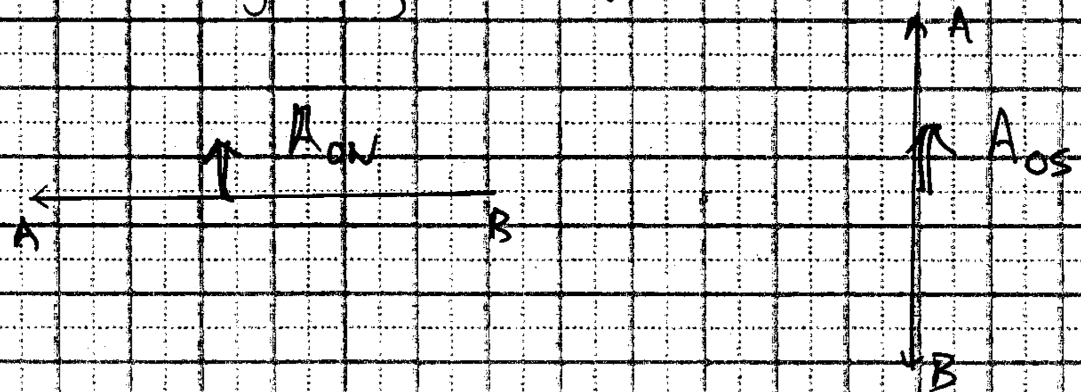
Beware pile-up limitations on beam rate.

Certainly require a good $\bar{p}/\pi^-$ ratio.

A detail

For inelastic channels, A_{OS} and A_{OL} are non-zero.

A_{OS} comes free from asymmetries in the plane of polarisation



One also gets free transfer of polarisation from the initial state to final state particles/resonances with spin eg. ω, $f_2(1270)$, $a_2(1320)$.

(In NN physics, A_{SL} turned out a very valuable measurement)