3 TWENTY-FIVE YEARS OF PHYSICS AT OMEGA

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3.1 Introduction

The OMEGA story is one of success — twenty-five years of success.

The initial concept was for an ‘electronic bubble chamber’ — a large magnetic volume filled with spark chambers, and with the capability of taking a variety of triggers.

OMEGA remained in this form for some seven years, after which it was upgraded to OMEGA´, equipped with multi-wire proportional chambers. It has proved to be a facility of remarkable versatility. It has accommodated pion, kaon, proton, antiproton, photon, hyperon and heavy-ion beams. It has been equipped at different times with three Cherenkovs and three large photon detectors, and has utilized an incredible range of triggers. The energy range covered has gone from 6 GeV at the PS to the highest SPS energy possible: 450 GeV.

The first five years of OMEGA were at the PS, the next twenty at the SPS. The scientific programme divides rather neatly into three parts: the first five years at the PS and then two periods of about ten years each at the SPS.

For the first five years at the PS, i.e. up to 1976, the physics was that of hadronic interactions, with the emphasis on small cross-section processes of topical interest, to study hadron spectroscopy (primarily meson spectroscopy) and production processes (primarily Regge exchange, both meson and baryon). After the move of OMEGA to the SPS, the next ten years (1976–86) saw interest move away from the study of standard hadronic interactions towards photoproduction, charm production, and more generally QCD-motivated studies, although meson spectroscopy remained an important feature. OMEGA was converted to OMEGA´ in 1979. In the last ten years of OMEGA at the SPS (1986–96), the study of beauty production took over from that of charm. Meson spectroscopy was concentrated on glueball searches in central production (double pomeron exchange). A strong heavy-ion programme developed, focusing on strangeness and baryon–antibaryon production. Altogether forty-nine proposals were approved for OMEGA: they are listed in Section 2. This number makes it quite impossible for me to do justice to them all, so I have had to be very selective with those I mention specifically. I hope that my choice of experiments gives some indication of the range and variety of the OMEGA programme, and of its rôle in advancing our understanding of particle physics.

3.2 OMEGA at the PS: the first five years (1971–76)

Twelve experiments were approved for OMEGA during this period, which (with two exceptions: **S133** $\pi\pi$ scattering length, and **S146** charm search) were concerned with light-quark meson spectroscopy or Regge exchange or both. I have selected two of these for specific mention which are very typical of the Regge-exchange and meson-spectroscopy experiments of the time. **S112** was the first experiment approved and **S139** is a good example of an experiment making full use of OMEGA and its multiparticle capability.

S112

J.D. Dowell et al., Nucl. Phys. B108 (1976) 30

ω production in $\pi^- \, p \rightarrow \pi^+\pi^-\pi^0 n$ at 8 and 12 GeV/*c*

The neutron was used as the trigger and the π^0 determined by missing mass. The prime interest was Regge exchange and the experiment covered the momentum-transfer range $0.02 < -t < 0.8$ GeV^2. The intercept and slope of both the natural parity exchange (ρ trajectory) and unnatural parity exchange (*b* trajectory) were obtained using the ω density matrix elements as the analyser. The results

$$\alpha_N(t) = (0.33 \pm 0.09) + (0.99 \pm 0.26)t$$

$$\alpha_U(t) = (-0.06 \pm 0.13) + (0.91 \pm 0.39)t$$

contributed to the conclusion of exchange-degeneracy in the meson sector.

M.J. Corden et al., Nucl. Phys. B137 (1978) 221, Nucl. Phys. B157 (1979) 250

Amplitude analysis of $\pi\pi$ scattering from $\pi^-p \rightarrow (\pi^+\pi^-)n$

The analysis was based on the technique of extrapolating to the pion pole to give the cross-section for $\pi^+\pi^- \rightarrow \pi^+\pi^-$. The $\pi\pi$ mass ranges covered were 0.8 to 2.2 GeV in the first paper and 1.0 to 2.0 GeV in the second. The latter analysis improved on previous solutions, e.g. by not violating unitarity and by being compatible with data in other channels. Among the states they found are those we now know as $f_2(1270)$, $\rho(1450)$, $f_2'(1525)$ and $\rho_3(1690)$, plus one which is not readily identifiable in the Particle Data Tables, with mass 1.935 ± 0.013 GeV and $J^P = 4^+$.

S139

C. Evangelista et al., Nucl. Phys. B178 (1981) 197

A study of the reaction $\pi^-p \rightarrow X^-p$

Here $X^- \equiv \pi^-\pi^0$, $\pi^+\pi^-\pi^-$, $\pi^+\pi^-\pi^-\pi^0$, $\pi^+\pi^+\pi^-\pi^-\pi^-$, $\pi^+\pi^+\pi^-\pi^-\pi^-\pi^0$. The π^0 was obtained by missing mass. This experiment is an excellent early example of the multiparticle capability of OMEGA. Both Regge-exchange and meson spectroscopy were studied. Results included the following.

$\pi^-\pi^0$: production of ρ^- dominated by natural parity exchange (the ω trajectory), and confirmation that $J^P = 3^-$ for the $\rho_3(1690)$.

$\pi^+\pi^-\pi^-$: the $a_2(1320)$ (in the $\rho\pi$ mode) and the $\pi^2(1670)$ (in the $f^0\pi^-$ mode) were observed and their production found to be dominated by natural parity exchange. The lower mass region was dominated by $\rho\pi$ in 1^+S0^+, which was probably the $a_1(1260)$, but suppressed by the trigger.

$\pi^-\pi^-\pi^0$: the $b_1(1235)$ (in the $\omega\pi$ mode) and the $\rho_3(1690)$ (in the $\omega\pi$, $\rho^-\rho^0$, $a^0{}_2\pi^-$ and $a^-{}_2\pi^0$ modes) were both observed.

X^0: the $\eta'(958)$ and the $\eta(1295)$ were both observed in the $\eta\pi^+\pi^-$ mode.

3.3 OMEGA at the SPS: the next ten years (1976–86)

Twenty-six experiments were approved for OMEGA during this period, many of which were still concerned with spectroscopic studies. However, there was a distinct move to the study of charm production and perturbative QCD. From these I have selected nine, which form four distinct groups.

- J/ψ production: **WA12** and **WA39**.
- Charm photoproduction: **WA34**, **WA45** and **WA58**.
- Photoproduction: **WA4**, **WA57** and **WA69**.
- Prompt photons: **WA70**.

This period also saw the first experiment on central meson production, **WA76**, which became an important feature of meson-spectroscopy studies on OMEGA.

WA12, WA39

M.J. Corden et al., Phys. Lett. 68B (1977) 96

Experimental comparison of J/ψ production by $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$ beams at 39.5 GeV/c.

WA12 was a beam-dump experiment, WA39 used a hydrogen target. Conventional wisdom is that J/ψ production is by gluon–gluon fusion, either to a χ_c state which decays radiatively to J/ψ or more directly to J/ψ+gluon. The interest in this experiment, quite apart from being one of the earliest J/ψ experiments at CERN, was that the p-data showed quite conclusively that there is an important OZI-violating component. The ratio $\sigma(p)/\sigma(p) = 0.15 \pm 0.08$ requires that in production the J/ψ couples to the valence quarks of the nucleon. It is necessary to go to a kinematical region where the gluon density is large compared to the quark density before gluon fusion becomes the dominant mechanism. In the WA12 experiment, the peak cross-section was centred around $x_F = 0.36$, i.e. close to the maximum of the valence-quark structure function of the proton.

WA34, WA45, WA58

M.I. Adamovich et al., Phys. Lett. 89B (1980) 427

Observation of a charmed neutral meson produced in a high energy photon interaction

M.I. Adamovich et al., Phys. Lett. 99B (1981) 271

Observation of pairs of charmed particles produced by high-energy photons centreline in nuclear emulsions

M.I. Adamovich et al., Phys. Lett. 140B (1984) 119

Charged charmed-particle lifetime

The technique used was one which had been pioneered in neutrino beams, namely to observe the charmed particle decay in an emulsion by using external measurement of the decay products to track back close to the decay point. In the case of the photon beam, OMEGA provided the means to measure the external tracks. Experiment WA34 observed the production and decay of a bar D^0, which was the first observation and complete measurement *in a photon beam*. WA45 found six events showing pairs of charmed particles, one of which was associated Λ^+_c D^0 production. Finally, WA58 found fourteen events with two charm particles, at least one of which was charged, and three events with a single charged charm particle. This was sufficient to give measurements of $\tau_{D\pm}$ and $\tau_{\Lambda+c}$. Micrographs of the decays are depicted in Fig. 3.1.

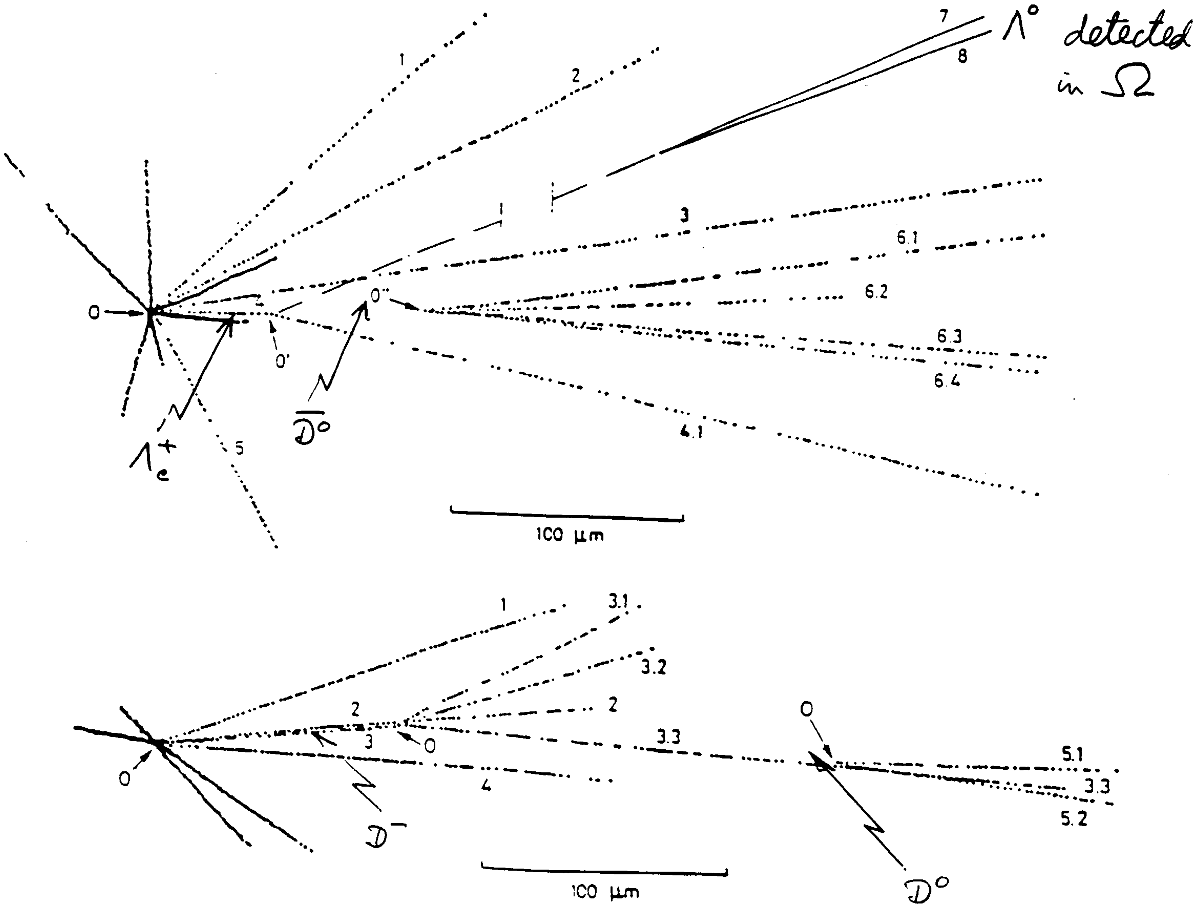

Fig. 3.1: Micrographs of (a) Λ^+_c $\overline{D}^0$ photoproduction and (b) D^- D^0 photoproduction in emulsion from **WA45**.

WA4, WA57, WA69

R.J. Apsimon et al., Z. Phys. C43 (1989) 63

Inclusive photoproduction of single charged particles at high p_T

R.J. Apsimon et al., Z. Phys. C46 (1990) 35

Study of the point-like interaction of the photon using energy flows centreline in photo- and hadro-production

R.J. Apsimon et al., Z. Phys. C50 (1991) 179

Separation of minimum and higher twist in photoproduction of high-p_T mesons

These three photoproduction experiments produced a multiplicity of papers. **WA4** concentrated on charm production and light-quark vector-meson physics. **WA57** was aimed primarily at vector-meson spectroscopy. **WA69** studied high-p_T processes in photon and hadron interactions, and by comparing these was able to extract the point-like interaction of the real photon and confront predictions of perturbative QCD. Vector-meson dominance implies that the photon is hadron-like, and this can be simulated by the appropriate combination of pion and kaon data. However, it has in addition a point-like interaction and because of this photons should have a harder p_T single-particle distribution than pions or kaons, and a double-peaked energy flow in the forward direction. (At sufficiently high energy, e.g. at HERA, this resolves into two jets.) The hadron-like component of the photon dominates at low p_T, and for $p_T \leq 1$ GeV the ratio of photon data to pion/kaon data is flat over a wide range of x_F. This allows a ‘vector dominance factor’ to be determined and a precise comparison of the meson and photon data to be made. Figure 3.2 shows the p_T distributions, the ratio of photon to meson renormalized data, and the difference between the renormalized data and second-order QCD. Figure 3.3 shows the energy flow distributions for the photon-induced and renormalized hadron-induced events, and the subtracted energy-flow data compared to QCD Monte Carlo predictions. **WA69** had the distinction of being the first experiment to make significant use of a Ring Image Cherenkov.

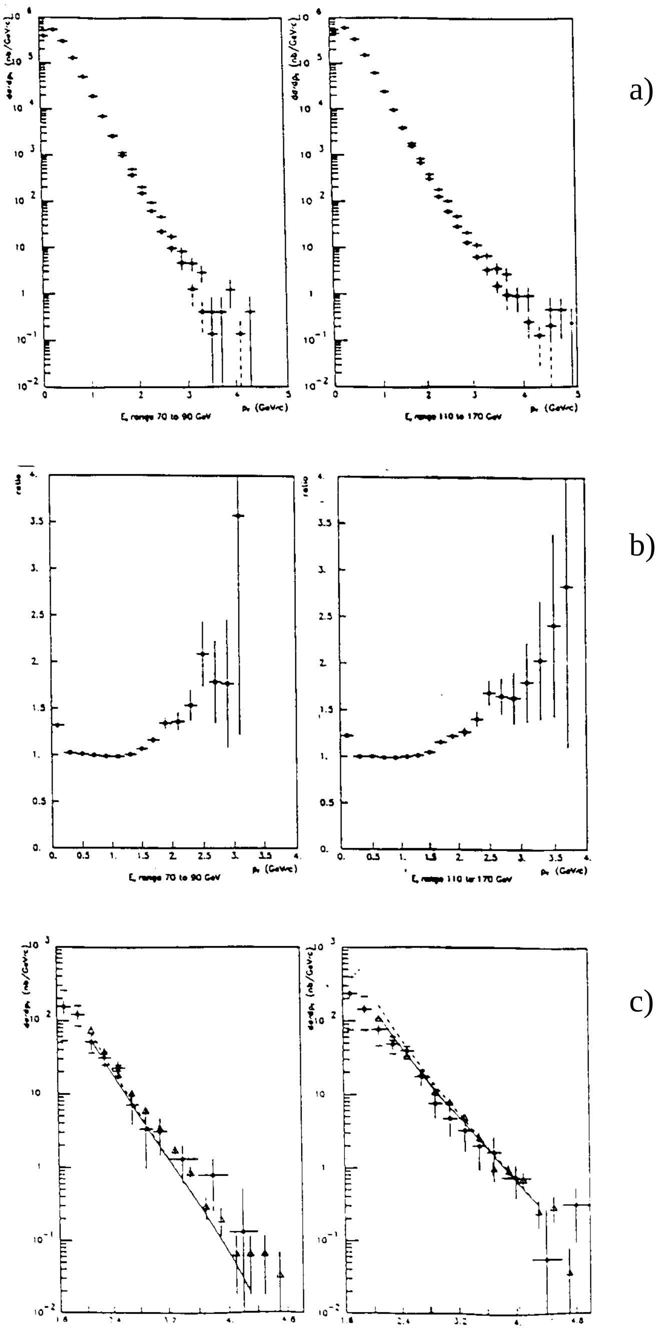

Fig. 3.2: a) Single particle inclusive cross-sections from **WA69** as a function of p_T integrated over x_F from 0.0 to 1.0. The full circles correspond to photon-beam data and the open circles to the scaled meson-beam data. b) The ratio of the cross-sections for the photon data to the scaled hadron data as a function of p_T integrated over x_F from 0.0 to 0.7. c) The subtracted p_T distributions integrated over x_F from 0.0 to 0.7, for p_T = 1.6 GeV. The superimposed curves are the result of second order QCD calculations and the triangular points indicate a QCD Monte Carlo prediction (LUCIFER).

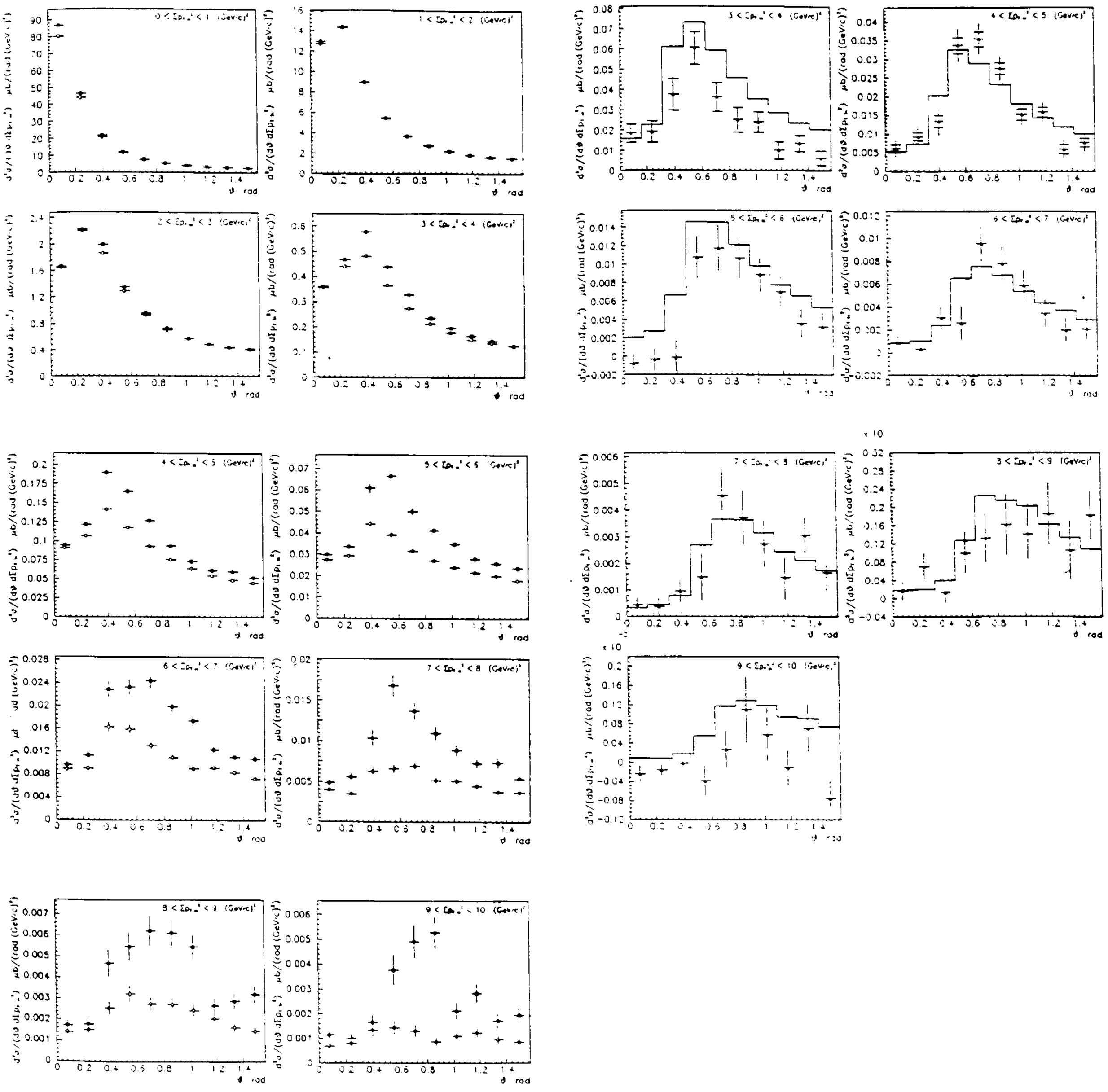

Fig. 3.3: a) The energy flow distributions from **WA69** for photon-beam (black squares) and scaled meson-beam (open circles) data, for increasing values of $\Sigma\ p^2_{\mathrm{Tin}}$. b) Subtracted energy flow data compared with a QCD Monte Carlo prediction (LUCIFER).

WA70

M. Bonesini et al., Z. Phys. C38 (1988) 371

Production of high transverse-momentum photons and neutral pions
in proton–proton interactions at 280 GeV/*c*

M. Bonesini et al., Z. Phys. C37 (1988) 535

High transverse-momentum prompt-photon production by π^- and π^+ on protons at 280 GeV/*c*

E. Bonvin et al., Z. Phys. C41 (1989) 591

Double prompt-photon production at high transverse momentum in π^- on protons at 280 GeV/*c*

These three publications represent the other major part of the OMEGA QCD physics, and are complementary to WA69. In the first publication a quantitative comparison was made of the prompt-γ cross-section in p–p collisions with second-order QCD and gave good agreement within systematic errors for $p_T \geq 4.25$ GeV if a soft gluon structure function was used. At the time of the experiment, little was known about the details of the gluon structure function and this represented a significant clarification. The second paper made the same comparison for incident π^+ and π^- beams, and confirmed the soft nature of the gluon structure function of the proton. The pion structure functions were taken from Drell-Yan (for the quark structure function) and J/ψ production (for the gluon structure function). The comparisons are shown in Figs. 3.4–3.7. The third publication presented clear evidence for double prompt-photon events with a 6-σ signal for $p_T \geq 3.0$ GeV. The cross-section was consistent with second-order QCD. Comparing $\pi^-\ p \rightarrow \gamma\gamma\ X$ with $\pi^-\ p \rightarrow \gamma\ X$ allows a determination of α_S. The value found is in good agreement with the latest PDG values, as is demonstrated in Fig. 3.8. An interesting feature of this experiment was the use of a lead liquid-scintillator electromagnetic detector for the photon detection: another first for OMEGA.

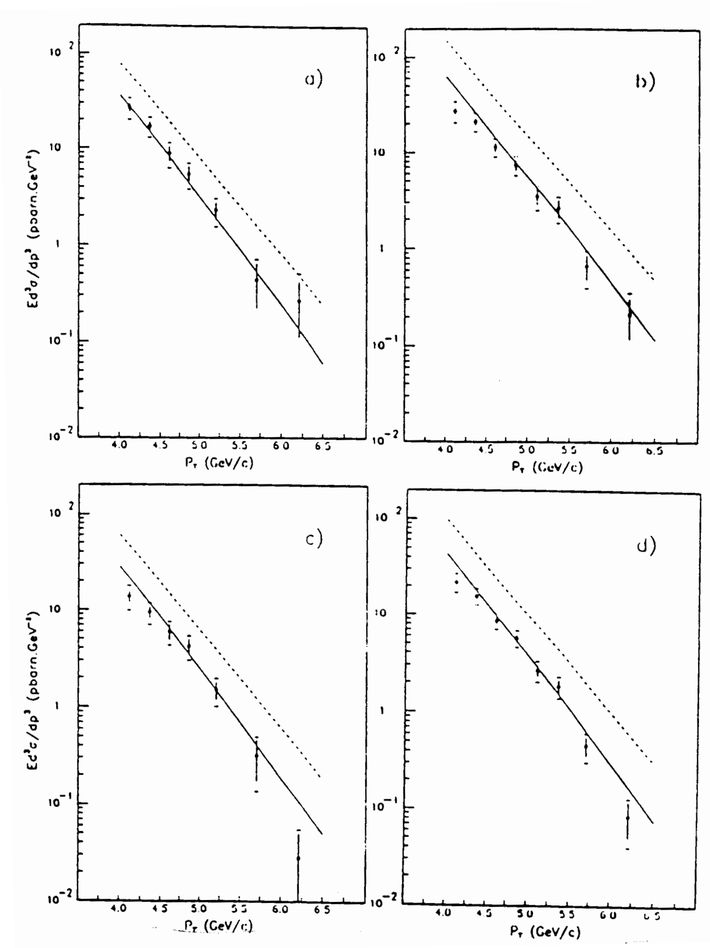

Fig. 3.4: a–d) Invariant cross-sections from **WA70** for pp $\rightarrow \gamma$ X for $-0.35 < x_F < -0.15$, $-0.15 < x_F < 0.15$, $0.15 < x_F < 0.45$ and $-0.35 < x_F < 0.45$ respectively. The curves are the predictions of perturbative QCD for a soft gluon structure function (solid line) and a hard gluon structure function (dashed line).

3.4 OMEGA at the SPS: the last ten years (1986–96)

Ten experiments were approved for OMEGA in this final phase. Two physics programmes are the subject of separate contributions, so I will simply mention them here. The first is a search for glueballs in central meson production: **WA91** and **WA102**. Central production is expected to be gluon rich as at high energy it is dominated by pomeron–pomeron interactions, and the pomerons are believed to have primarily a gluon content. Current data do appear to indicate evidence for glueballs. The other topic is that of relativistic heavy-ion collisions with the emphasis on strange production: **WA85**, **WA94** and **WA97**. The data show changes in strange-production ratios compatible with the existence of a quark–gluon plasma, in support of evidence in other reactions.

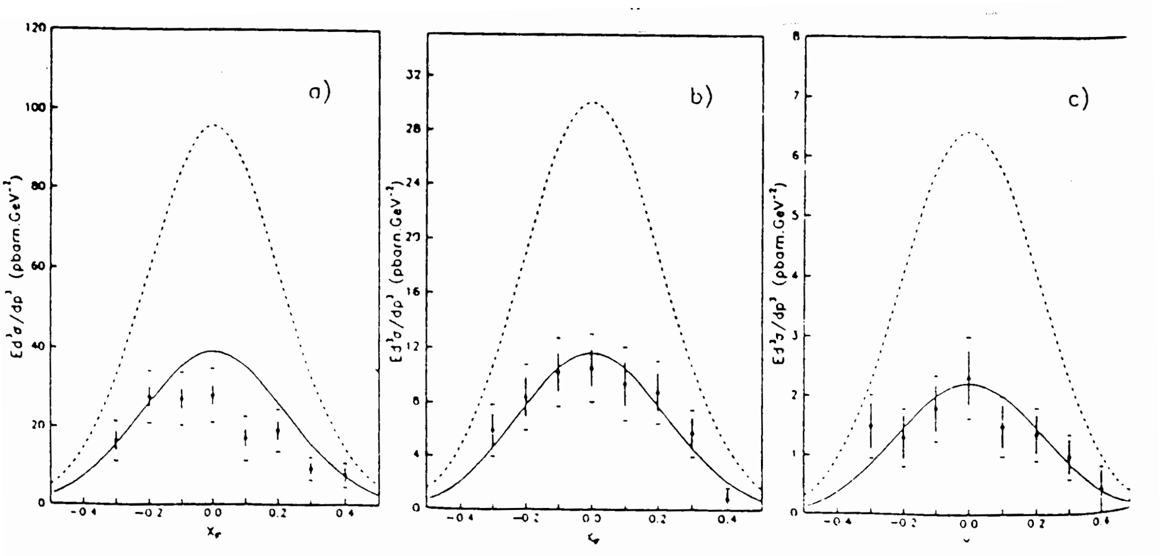

Fig. 3.5: a–c) Invariant cross-sections from **WA70** for pp → γ X for $4.0 < p_T < 4.5$, $4.5 < p_T < 5.0$ and $5.0 < p_T < 6.0$ GeV respectively. The curves are as in Fig. 3.4.

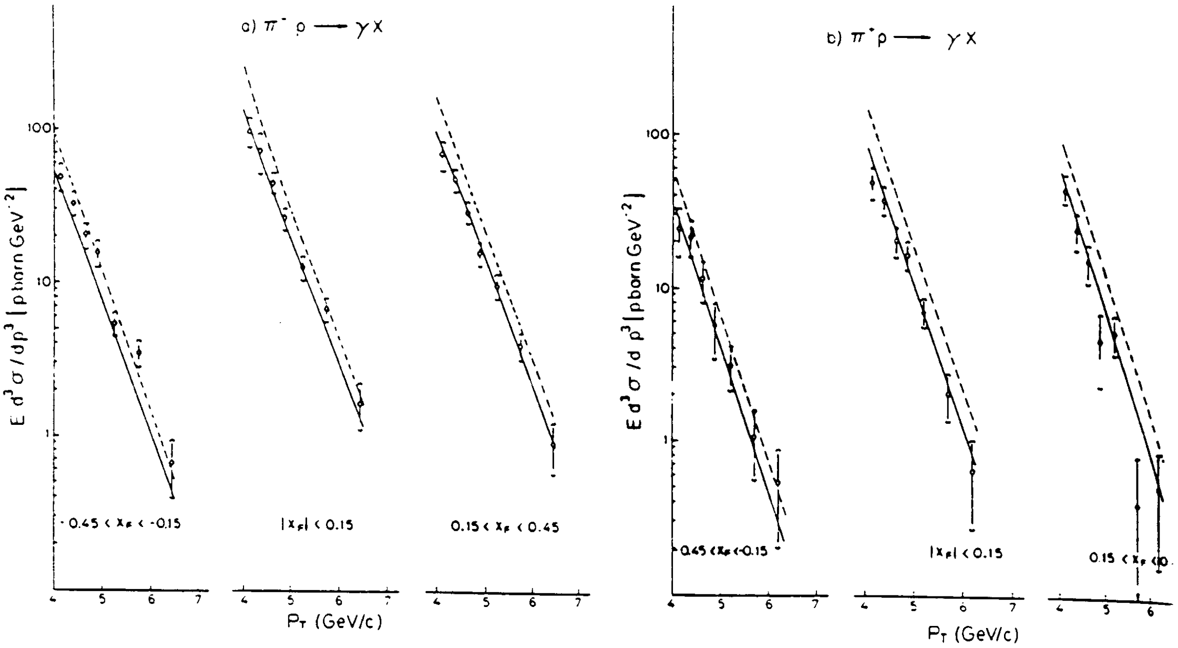

Fig. 3.6: a, b) Invariant cross-sections from **WA70** for π^- p → γ X and π^+ p → γ X for the three ranges $-0.45 < x_F < -0.15$, $-0.15 < x_F < 0.15$ and $0.15 < x_F < 0.45$. The curves are as in Fig. 3.4.

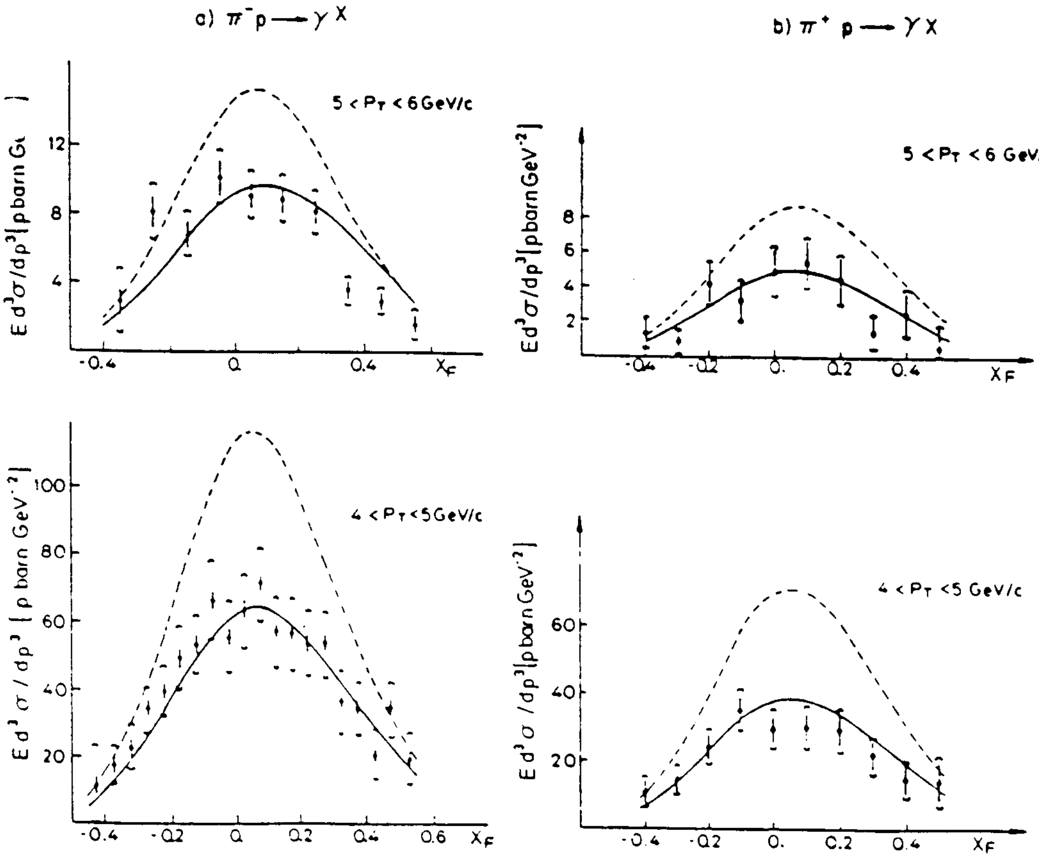

Fig. 3.7: a, b) Invariant cross-sections from **WA70** for $\pi^- p \rightarrow \gamma X$ and $\pi^+ p \rightarrow \gamma X$ for $4.0 < p_T < 5.0$ GeV and $5.0 < p_T < 6.0$ GeV. The curves are as in Fig. 3.4.

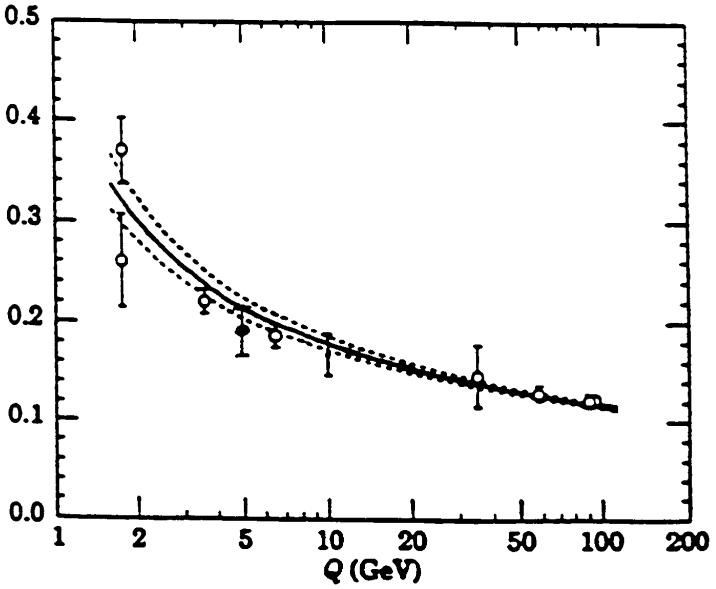

Fig. 3.8: Comparison of α_S from the double prompt photon experiment of **WA70** with the latest summary from the Particle Data Group.

Of the remaining five experiments, four were concerned with charm and/or beauty production: **WA82**, **WA84**, **WA89** and **WA92**. Data samples are by now sufficiently large to enable rare decay modes to be studied with some precision.

WA82

M. Adamovich et al., Phys. Lett. B280 (1992) 163

Measurement of the relative branching fractions of D^0 centreline Cabibbo-suppressed decays

The D^0 sample was produced with a 340 GeV π^- beam, with two-prong and four-prong decays. The dominant decays seen are of course the Cabibbo-allowed $D^0 \rightarrow K^-\pi^+$ (1075 events, of which 441 had RICH identification of the K^-) and $D^0 \rightarrow K^-\pi^-\pi^+\pi^+$. The Cabibbo-suppressed channels observed were $K^- K^+$, $\pi^-\pi^+$ and $\pi^-\pi^-\pi^+\pi^+$. The results are:

$$B(D^0 \rightarrow K^- K^+)/B(D^0 \rightarrow K^-\pi^+)\ 0.107 \pm 0.029 \pm 0.015$$
$$B(D^0 \rightarrow \pi^-\pi^+)/(B(D^0 \rightarrow K^-\pi^+)\ 0.048 \pm 0.013 \pm 0.008$$
$$B(D^0 \rightarrow \pi^-\pi^-\pi^+\pi^+)/B(D^0 \rightarrow K^-\pi^-\pi^+\pi^+)\ \ 0.115 \pm 0.023 \pm 0.016$$

Invariant-mass distributions are shown in Figs. 3.9 and 3.10. From these results, the ratio $B(D^0 \rightarrow K^+ K^-)/B(D^0 \rightarrow \pi^+\pi^-)$ is $2.23 \pm 0.81 \pm 0.46$. If SU(3) flavour symmetry is not broken, then one expects this ratio to be 0.86, and estimates of symmetry-breaking effects increase this only to the range 1.0 to 1.4. This disagreement is part of the ‘charm decay puzzle’ for which many solutions have been proposed.

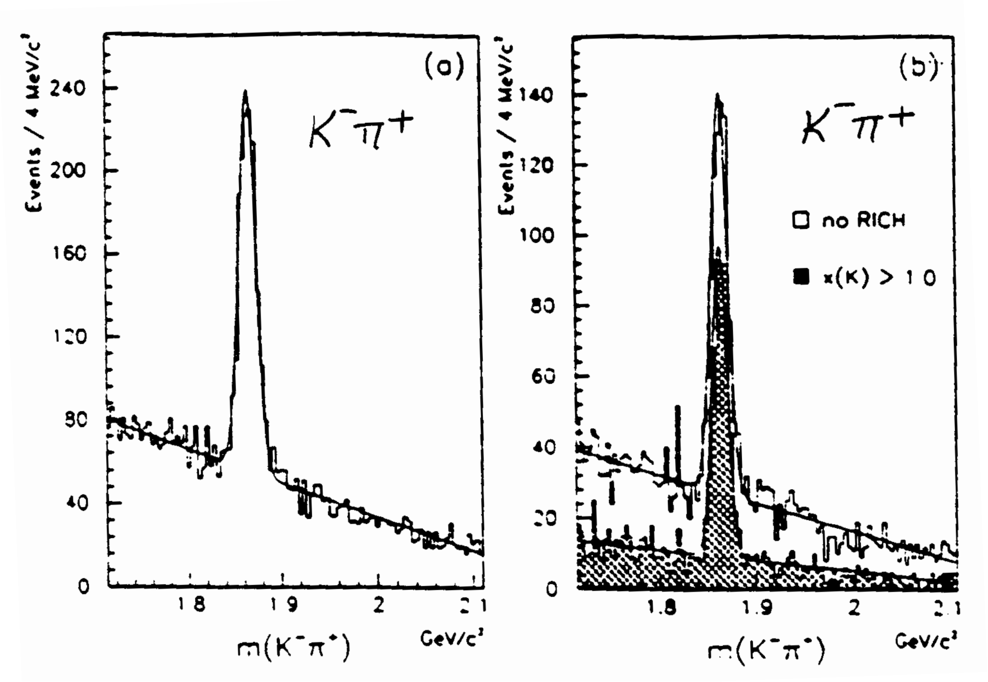

Fig. 3.9: $K^-\pi^+$ invariant-mass distributions from **WA82** (a) without RICH identification and (b) with RICH identification for $x_K > 1.0$.

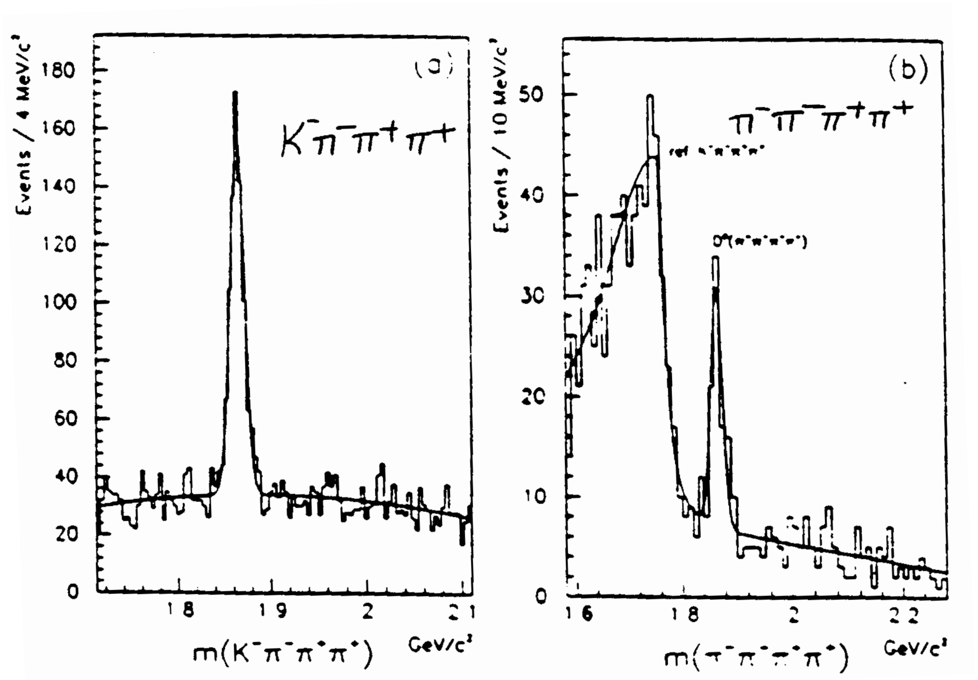

Fig. 3.10: (a) $K^-\pi^-\pi^+\pi^+$ invariant-mass distribution and (b) $\pi^-\pi^-\pi^+\pi^+$ invariant-mass distribution from **WA82**. The latter distribution shows the reflection of the former.

WA84

M. Adamovich et al., Phys. Lett. B305 (1993) 177

Measurement of the relative branching fraction for

$D^+ \to K^-K^+K^+$ and $D^+_S \to \pi^-\pi^+\pi^+$ decays

These decays cannot be described by simple spectator diagrams, but must involve annihilation sub-processes or final-state rescattering. Furthermore the $D^+ \to K^-K^+K^+$ mode is doubly Cabibbo-suppressed. The 'standard' decay channels used for comparison were $K^-\pi^+\pi^+$ (939 events) and $\phi\pi^+$ (46 events). The results are:

$B(D^+_S \to \pi^-\pi^+\pi^+)/B(D^+_S \to \phi\pi^+)$ 0.33 ± 0.10 ± 0.04

$B(D^+ \to K^-K^+K^+)/B(D^+ \to K^-\pi^+\pi^+)$ 0.057 ± 0.020 ± 0.007

$B(D^+ \to K^-K^+K^+)/B(D^+ \to \phi\pi^+)$ 0.49 ± 0.23 ± 0.06

Invariant-mass distributions for these decays are shown in Figs. 3.11 and 3.12.

WA92 (BEATRICE)

M. Adamovich et al., Phys. Lett. B353 (1995) 563

Search for the decay $D^0 \to \mu^+\mu^-$

This decay is of interest because flavour-changing neutral currents are forbidden at tree level in the Standard Model. At the one-loop level the branching fraction is extremely — indeed too small to be measured — but physics beyond the Standard Model may increase the rate to a value within the capability of future experiments. No candidate compatible with $D^0 \to \mu^+\mu^-$ was found, setting a new upper limit on $B(D^0 \to \mu^+\mu^-)$ of 7.6×10^{-6} at the 90% confidence level.

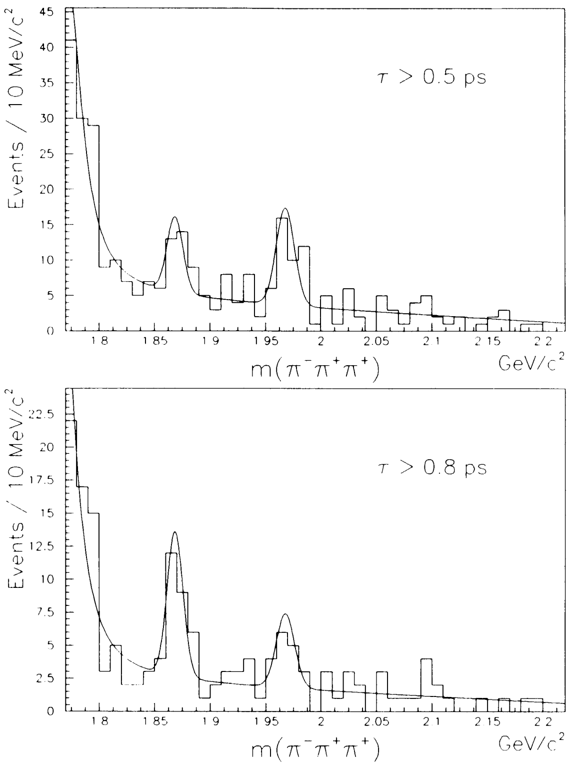

Fig. 3.11: $\pi^-\pi^+\pi^+$ invariant-mass distribution from **WA82** with cuts on proper lifetimes as indicated.

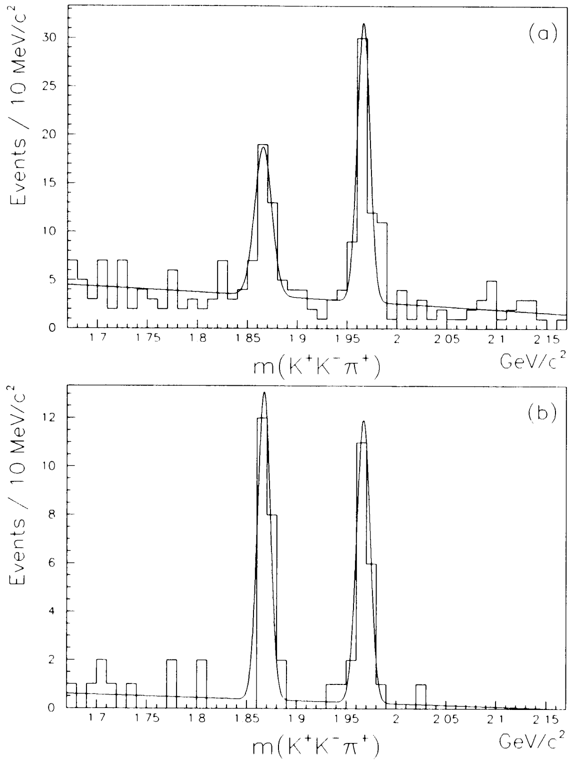

Fig. 3.12: $\phi\pi^+$ invariant-mass distribution from **WA82** (a) without RICH identification and (b) with RICH identification for $x_K > 0.5$.

A by-product of the experiment was excellent data on $D^0(\overline{D}^0) \rightarrow K^{\mp}\pi^{\pm}$ (1406 events). The signal is shown in Fig. 3.13a and the cross-section for $D^0(\overline{D}^0)$, compared with other measurements, is shown in Fig. 3.13b.

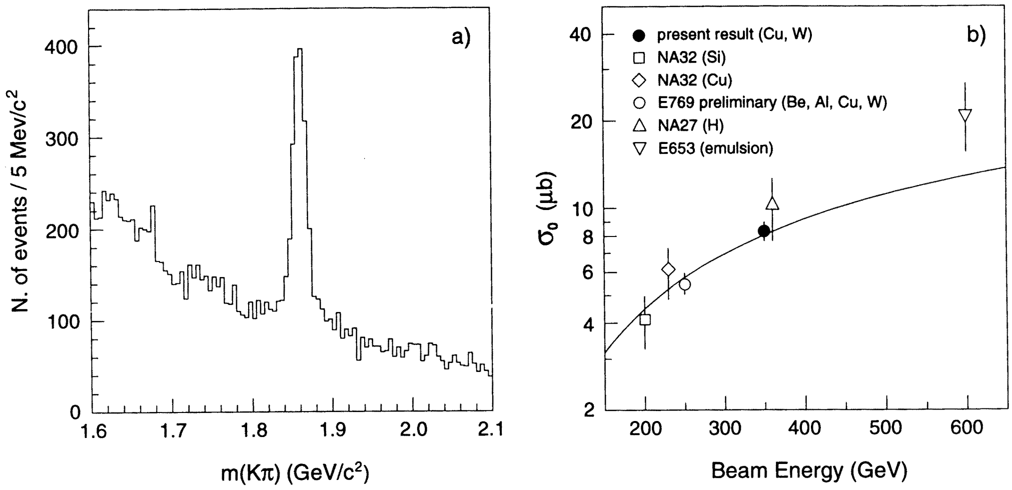

Fig. 3.13: (a) $K\pi$ invariant-mass distribution from **WA92**. As the K is not identified but rather hypothesized, the peak from the $D^0(\overline{D}^0) \rightarrow K^{\mp}\pi^{\pm}$ is superimposed on the physical and combinatorial background. (b) The inclusive D^0 ($\overline{D}^0$) cross-section.

WA89

M.I. Adamovich et al., Phys. Lett. B358 (1995) 151

Measurement of the Ω_C^0 lifetime

This experiment made use of the hyperon beam facility at OMEGA, specifically a 340 GeV Σ^- beam. Three independent samples from two different decay modes were used, giving clean signals for Ω_C^- decaying into $\Xi^-K^-\pi^+\pi^+$ and $\Omega^-\pi^+\pi^-\pi^+$ avoiding topological cuts. The lifetime $\tau = 55^{+13}_{-11}(\text{stat})^{+18}_{-23}(\text{syst})$ fs makes Ω_C the shortest-living weakly decaying particle observed so far, and confirms the predicted pattern of charmed baryon lifetimes. Invariant-mass distributions are shown in Figs. 3.14 and 3.15.

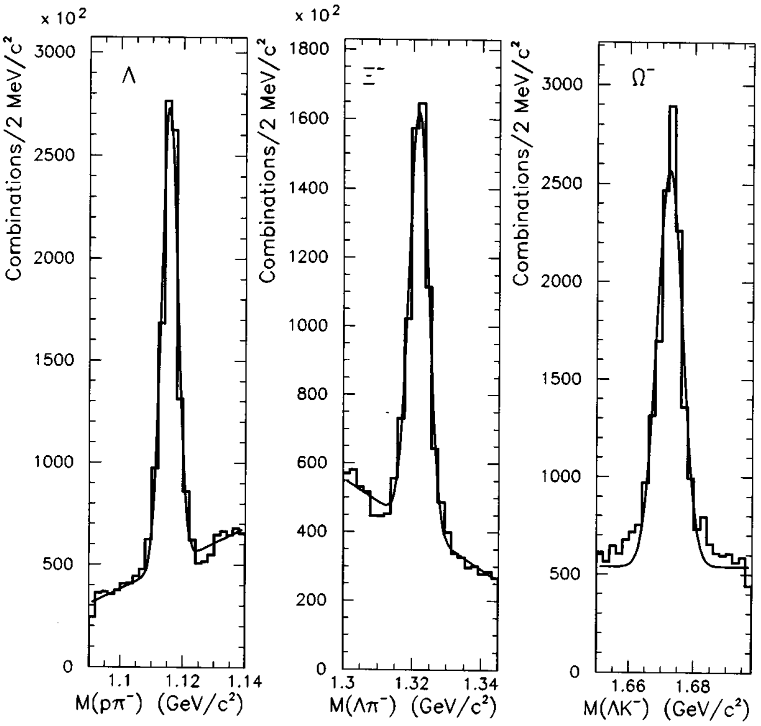

Fig. 3.14: Λ, Ξ^- and Ω^- mass distributions of reconstructed strange particles from **WA89**.

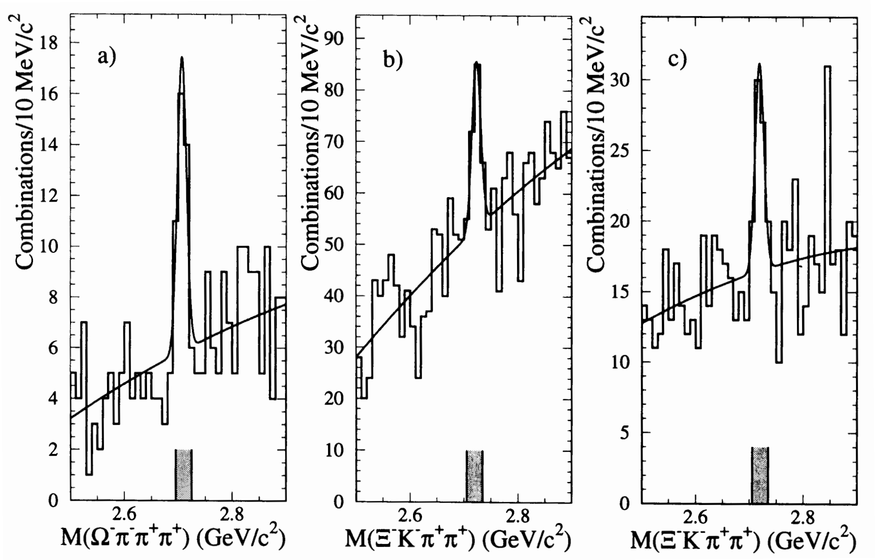

Fig. 3.15: **WA89** mass distributions for the final states: (a) $\Omega^-\pi^-\pi^+\pi^+$, (b) $\Xi^- K^-\pi^+\pi^+$ from carbon, (c) $\Xi^- K^-\pi^+\pi^+$ from all targets with a positively RICH identified kaon.

3.5 End-piece

I hope that this small selection of experiments gives some indication of the range and variety of the OMEGA programme. As I said at the beginning, the story is one of success and the results I have quoted are ample justification of this.

In preparing this historical survey I was reminded vividly of my many friends in the OMEGA community, friends with whom I ran shift, or discussed physics or both. The existence of a well-defined and coherent physics community on OMEGA is one of the reasons for its success. Equally there is OMEGA itself which has proved to be a powerful and flexible facility, and the committed, dedicated and superbly capable in-house team without whom none of this would have been possible.