NA31 – the first ε'/ε experiment

Ken Peach

A personal view of the contribution of

Heinrich Wahl

to a classic experiment

What is important? What is interesting?

- There are two basic routes to discovery

1. The High Energy Frontier
   - LEP, HERA, Tevatron, LHC, …
2. The High Precision Frontier
   a) High statistics
   - The 'Factories' (ϕ, τ-c, b, ν, …)

   b) Low systematics
   - Electric Dipole Moments, g-2, rare decays (μ, π, K…), dark matter searches, neutrino oscillations, anti-hydrogen…

   … and ε'/ε

Note: of course, all need high statistics, control of errors etc – but the characteristic feature that leads to discovery is energy, statistics or systematics

In the beginning …

- Ideas for the NA31 experiment formed in 1980/1981, before I joined, to measure ε′/ε to a precision of a few per mille
  - Theoretical expectations were that ε′/ε could be ~2%

- The proposal was approved by CERN in 1982
  - Theoretical expectations were that ε′/ε could be ~0.2% !

- The full Collaboration was

  CERN-Dortmund[1]-Edinburgh-Orsay-Pisa-Siegen

The spokesperson was Heinrich Wahl

1) Later the Dortmund group moved to Mainz.

ε′/ε and the Double Ratio Technique

- ε′/ε excites the theorists
  - Relates to fundamental (quark-level) processes
- experiment measures something different

$$|\eta_{+-}|^2 = \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)}$$

CP violating

CP conserving

$$\eta_{+-} = \varepsilon + \varepsilon'$$

$$\eta_{00} = \varepsilon - 2\varepsilon'$$

$$R_\eta = |\eta_{00}/\eta_{+-}|^2 = 1 - 6\Re(\varepsilon'/\varepsilon)$$

Experimental considerations

$$R_\eta = \frac{N(K_L \rightarrow \pi^0\pi^0)}{N(K_S \rightarrow \pi^0\pi^0)} \; \frac{N(K_S \rightarrow \pi^+\pi^-)}{N(K_L \rightarrow \pi^+\pi^-)}$$

$$\Gamma^{xy} \approx N^{xy} / [F^{xy} \times A^{xy} \times (1 + C^{xy})]$$

Events — Flux — Acceptance — Corrections

- In order for R to be simply related to the quad ratio of the event numbers

F, A and C must cancel either between K_L and K_S or between $2\pi^0$ and $\pi^+\pi^-$

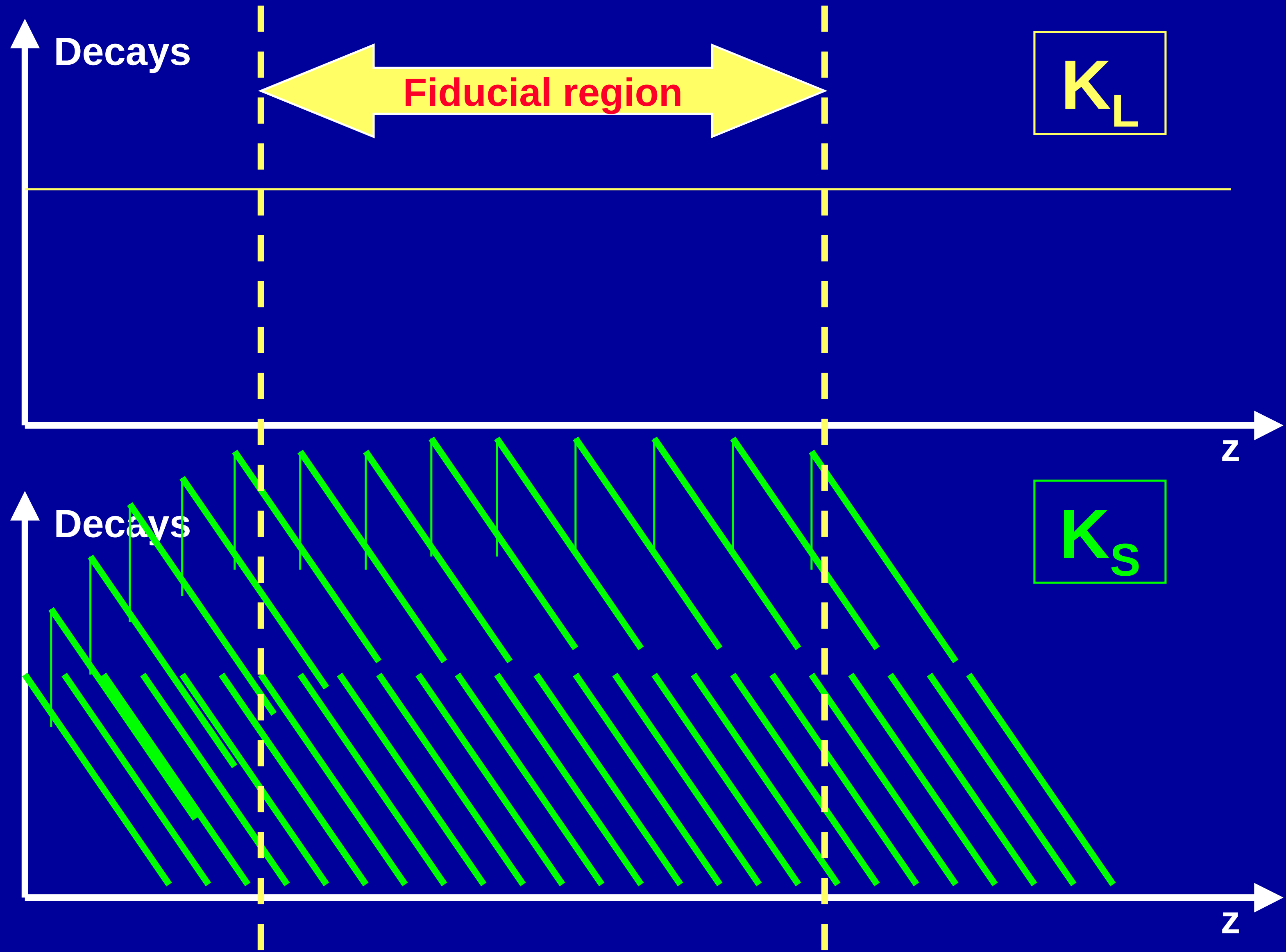
Principles of the Experiment

- Concurrent detection of $2\pi^0$ and $\pi^+\pi^-$
  - Flux cancels
- 'Symmetrical' cuts against additional activity
  - Accidental effects cancel
- Reduction of backgrounds
  - and estimate remaining backgrounds from data
- Reduction of reliance on Monte Carlo simulation
  - Acceptance
    - The Acceptance is a strong function of Energy & Vertex

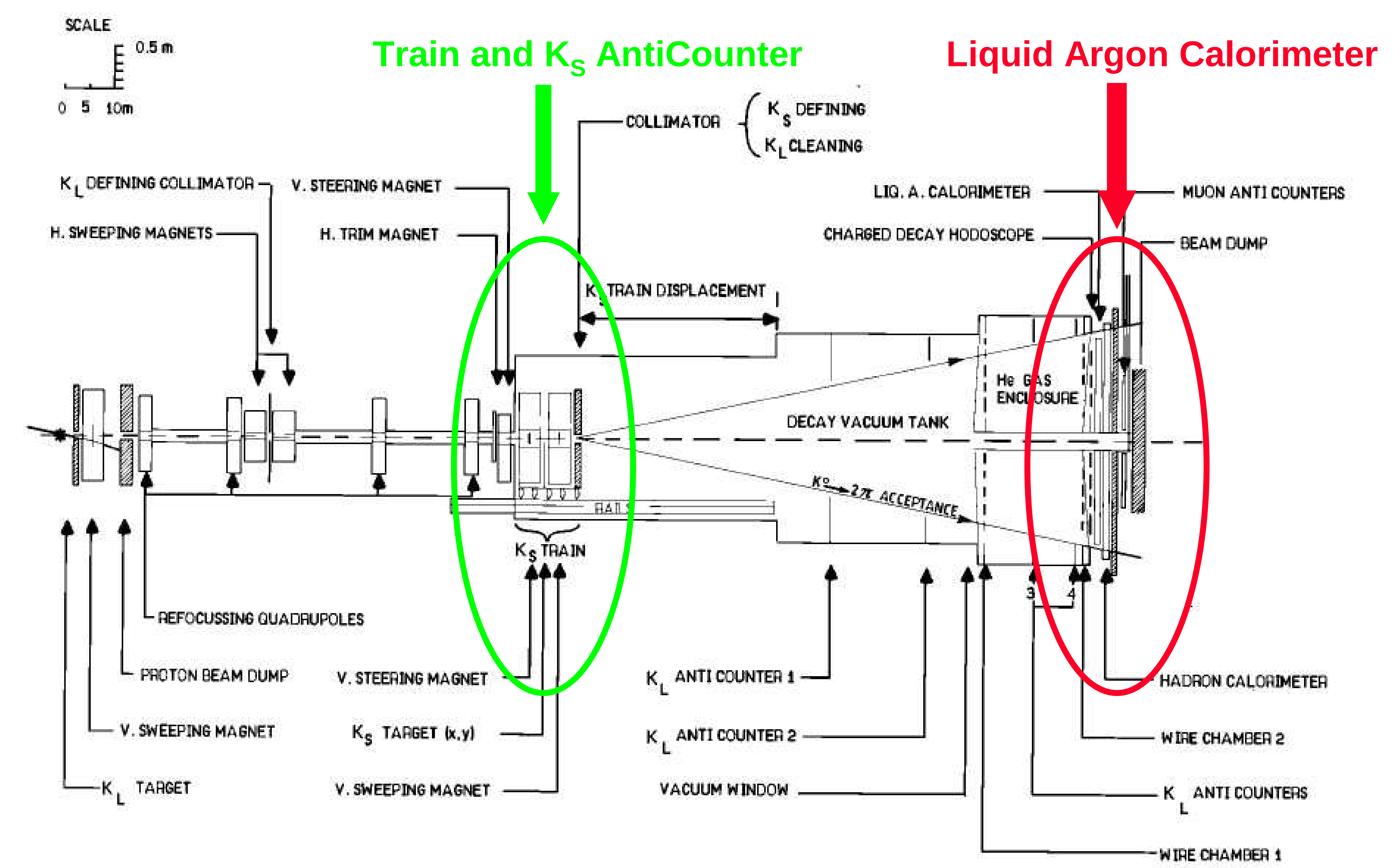
Analyse the data in energy ranges so that residual spectral differences between K_L and K_S are small

Make the K_L and K_S vertex distributions similar, and analyse in vertex ranges so that residual differences are small

'How to make a K_S decay with the K_L lifetime'



The conceptual design



…the target train

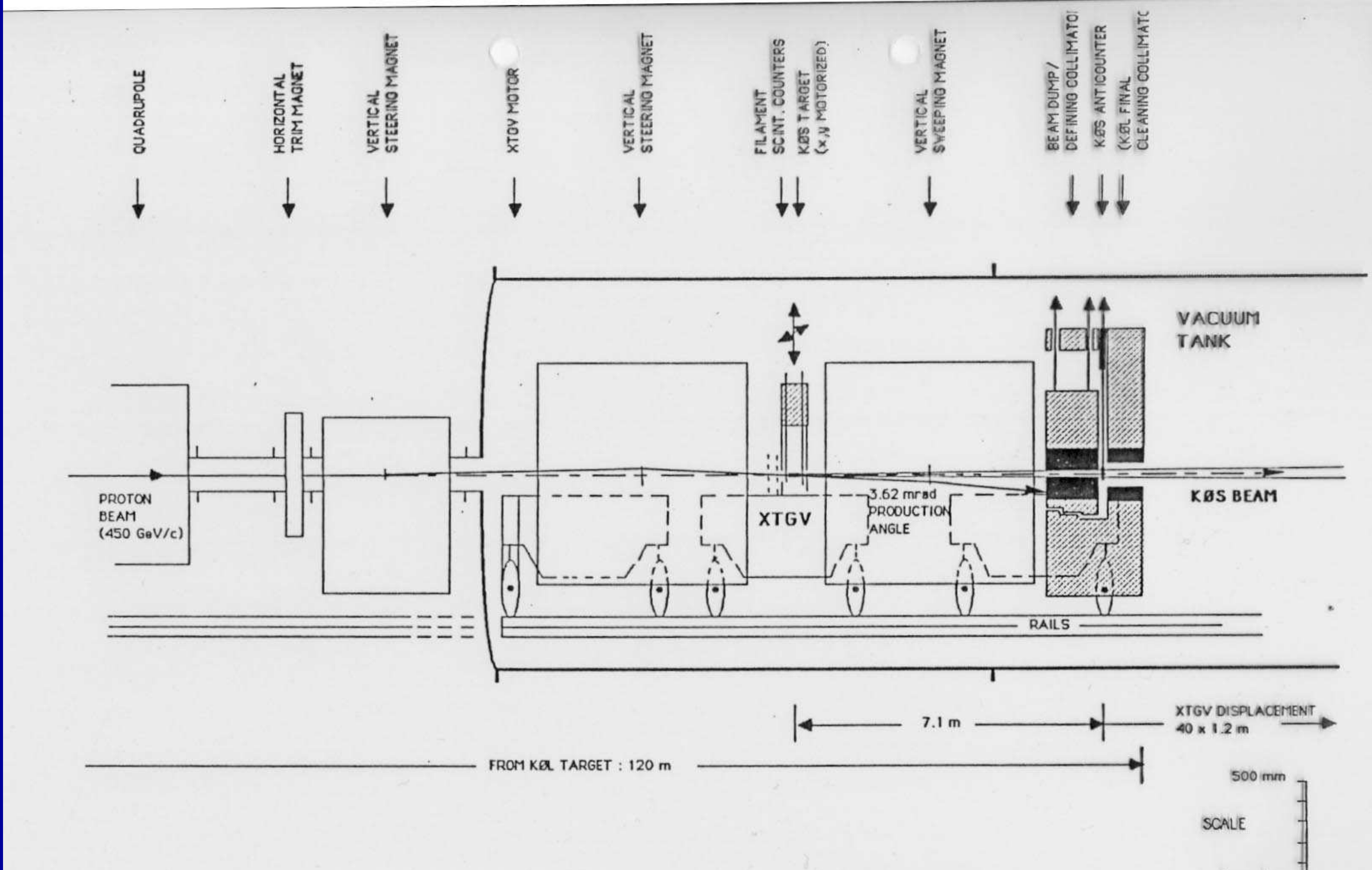
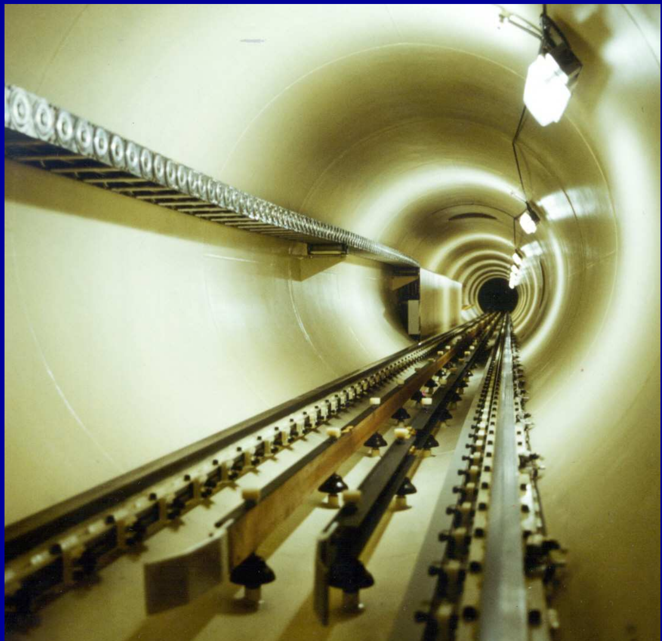
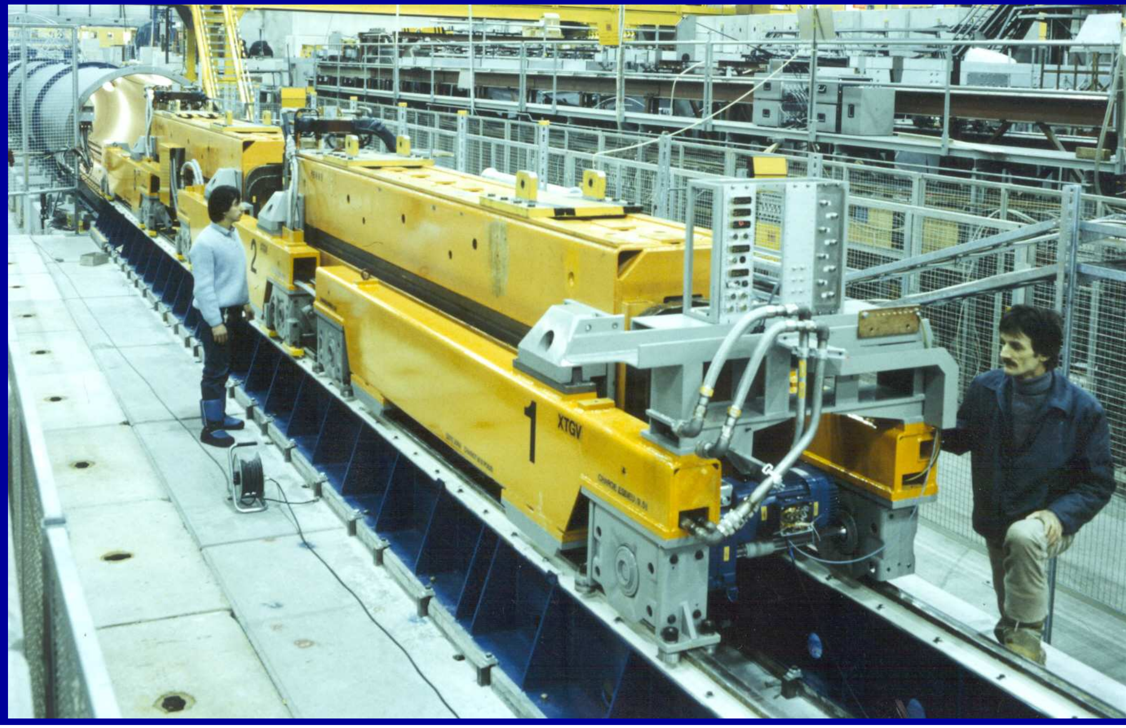


Fig. 5 SHEMATIC LAYOUT OF K_S^0 - BEAM TRAIN ("XTGV")

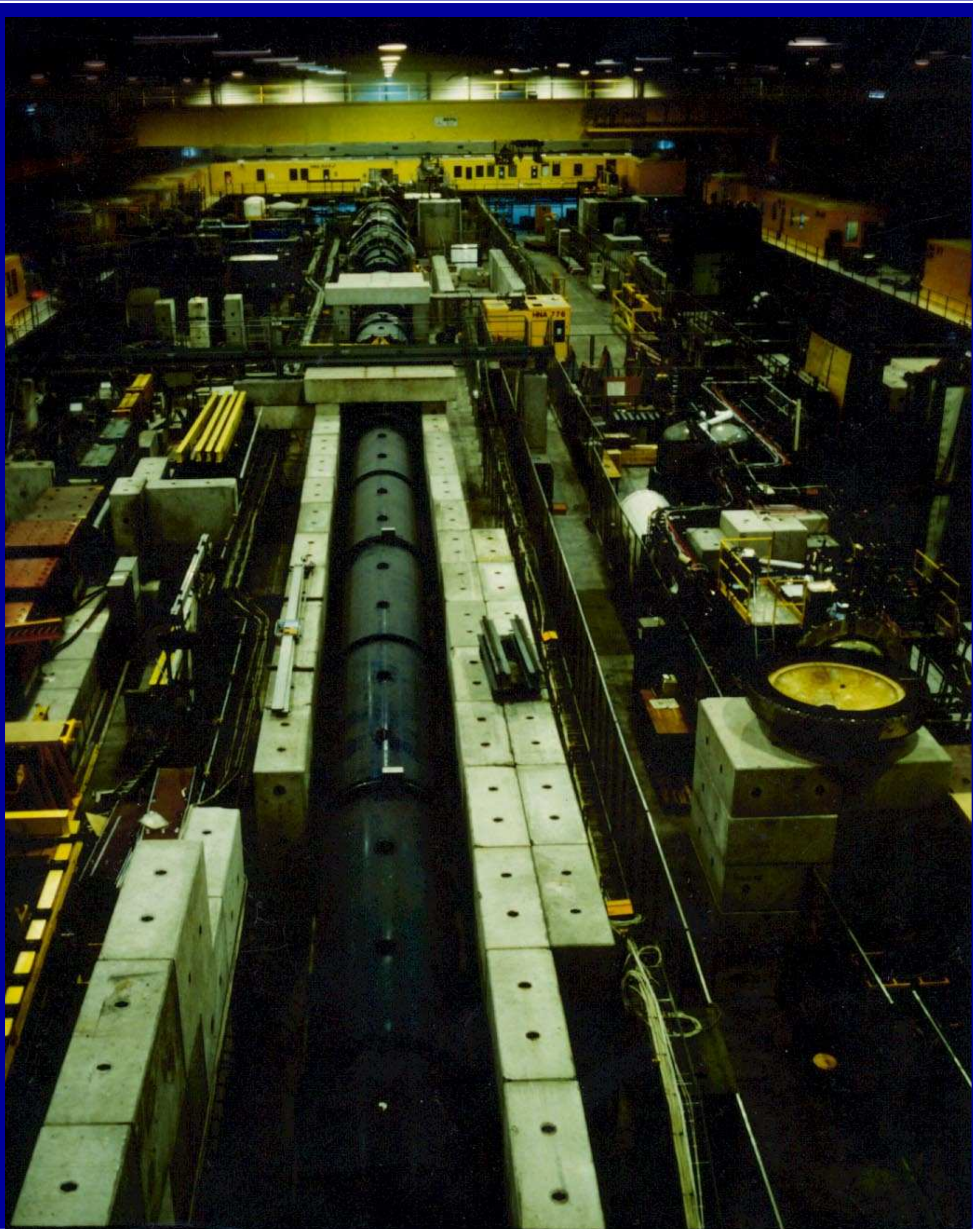
VERTICAL SECTION

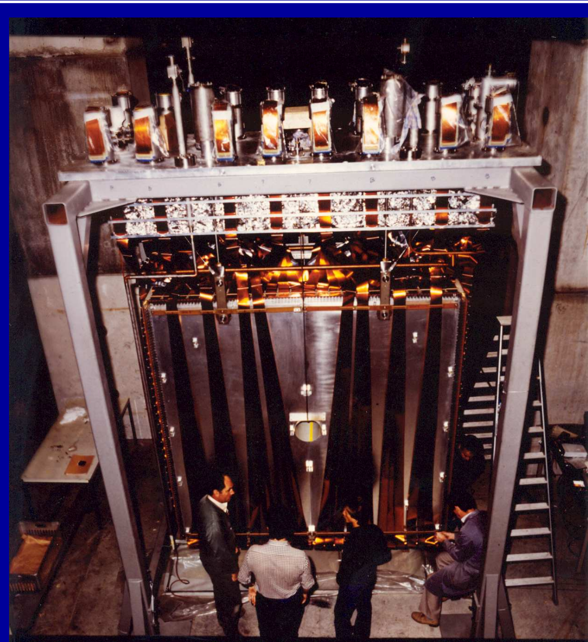
The target train …



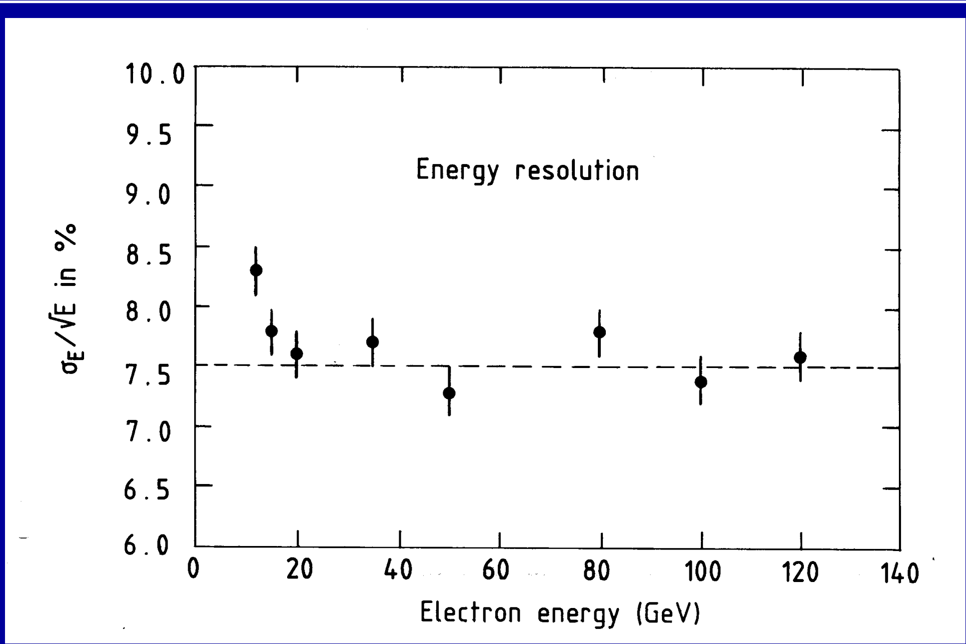


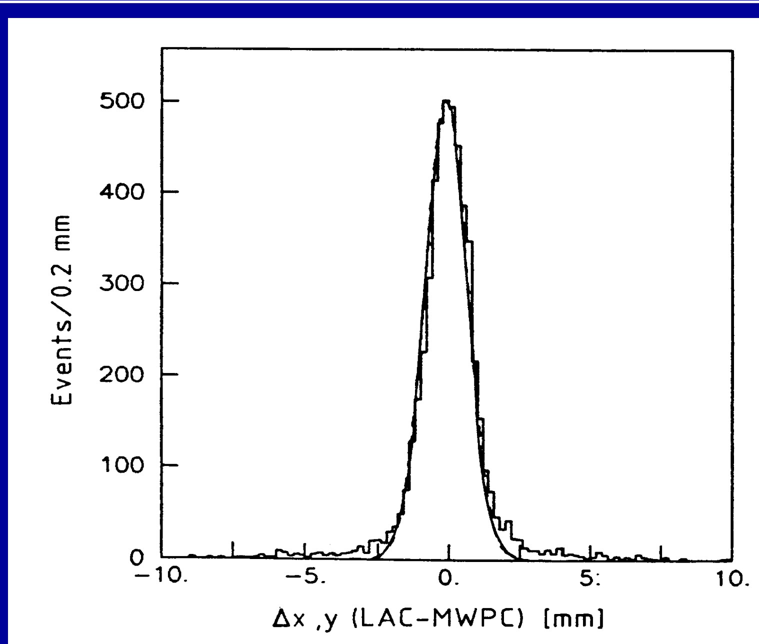
… and the detector

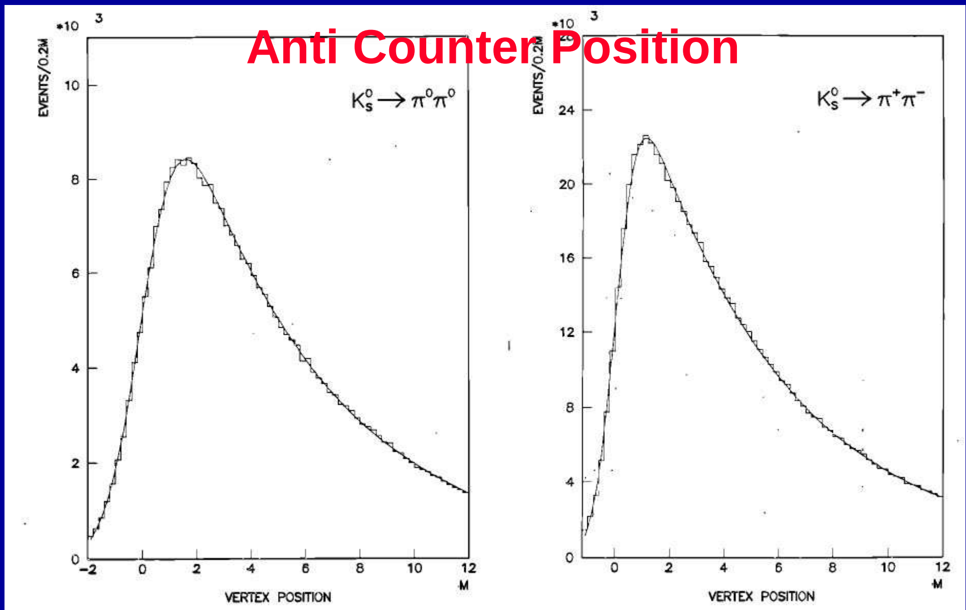


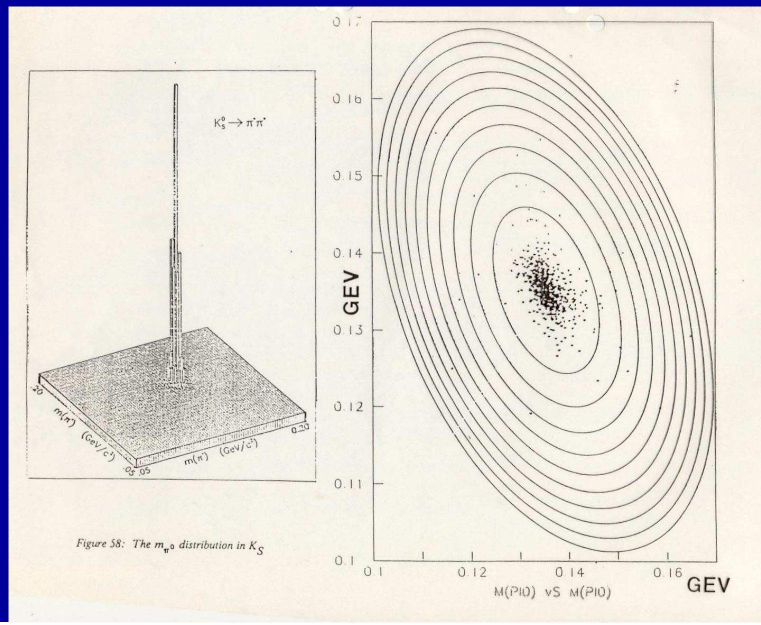


… Calorimeter performance



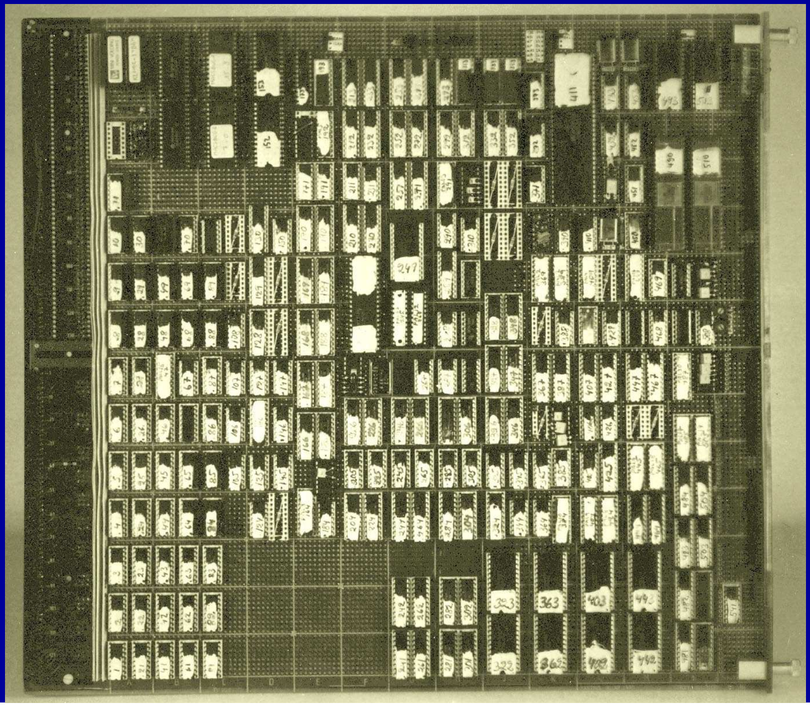




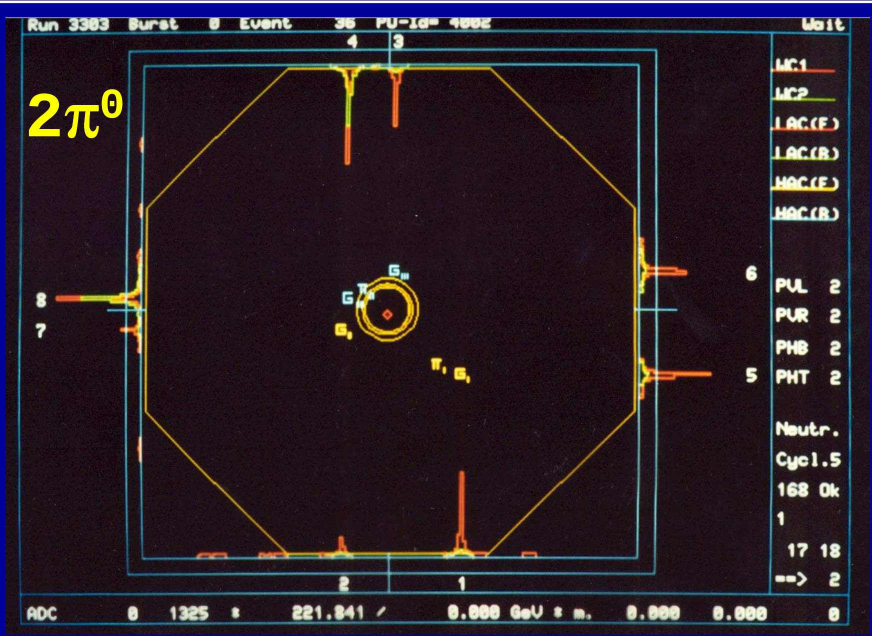


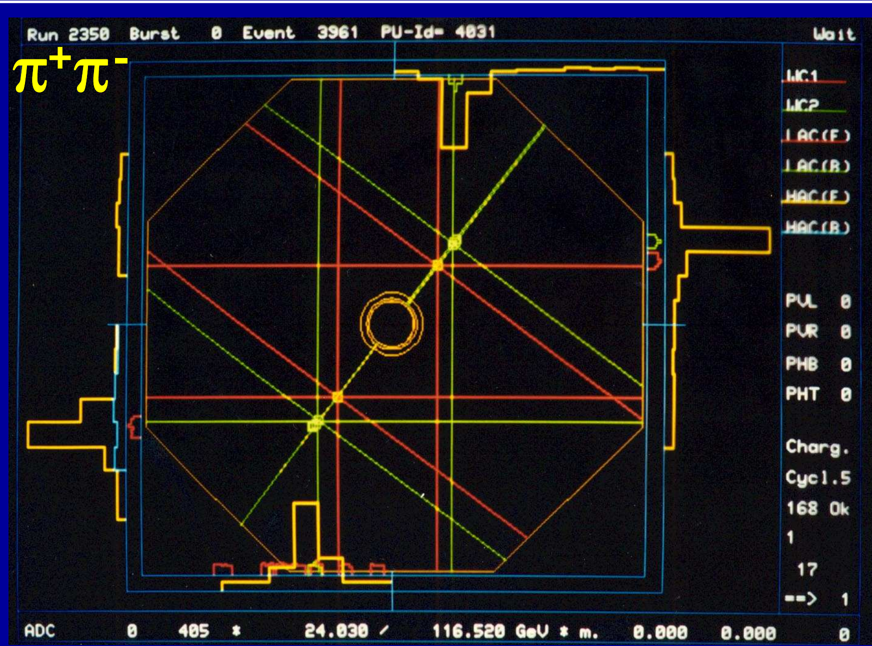
Brave New World

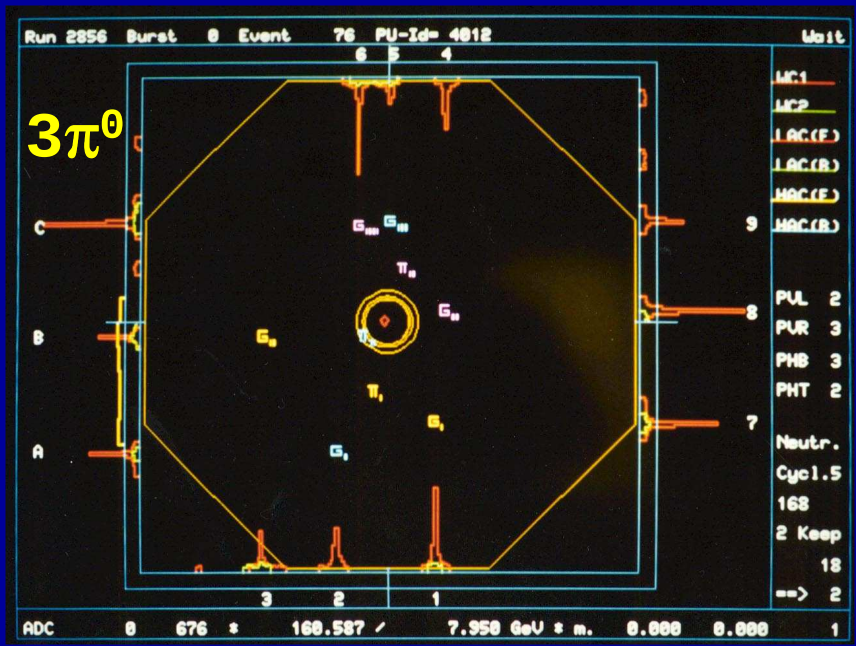
- NA31 (bravely) decided to use Fastbus as its data acquisition technology
  - Adopted by LEP
  - Would mean that we would
    "get a lot of help that we otherwise would not get"
    - Bob Chase remarked (perceptively) that we would
      "need a lot of help that we otherwise would not need"

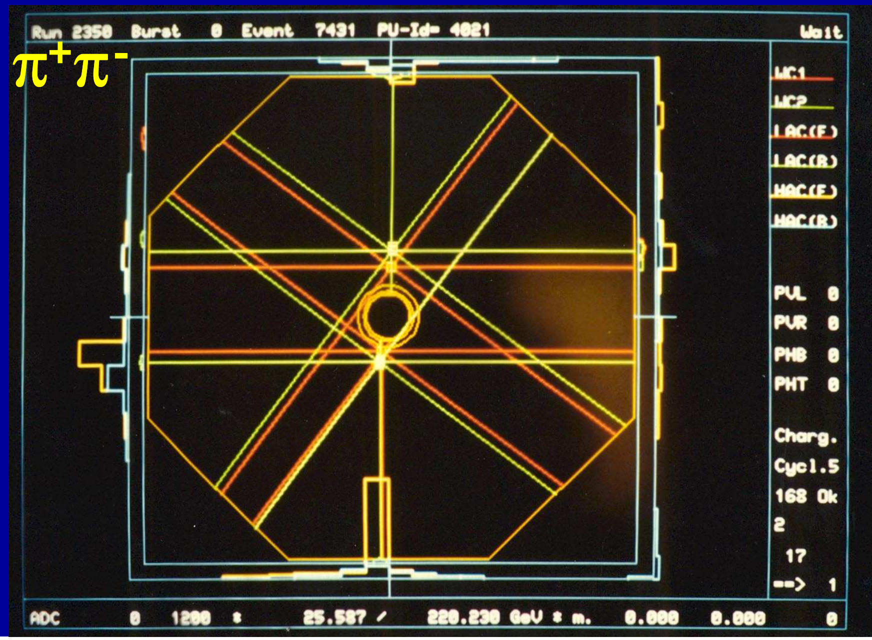


Some events


$2\pi^0$
Run 3303 Burst 0 Event 36 PU-Id= 4002
ADC 0 1325 * 221.841 / 0.000 GeV * m. 0.000 0.000 0


$\pi^+\pi^-$
Run 2350 Burst 0 Event 3961 PU-Id= 4031
ADC 0 405 * 24.030 / 116.520 GeV * m. 0.000 0.000 0


$3\pi^0$
Run 2856 Burst 0 Event 76 PU-Id= 4012
ADC 0 676 * 160.587 / 7.950 GeV * m. 0.000 0.000 1


$\pi^+\pi^-$
Run 2350 Burst 0 Event 7431 PU-Id= 4021
ADC 0 1200 * 25.587 / 220.230 GeV * m. 0.000 0.000 0

Data Taking

- 1982 Test beam work
- 1983 Test beam work
- 1984 First data with full beam (no liquid argon)
- 1985 Full beam and detector, restricted readout
- 1986 First run of the complete experiment
- 1987 Special run to measure phase differences
  - Preliminary result announced in July

$$\varepsilon'/\varepsilon = 0.0033 \pm 0.0011$$

- 1988 More ε'/ε running
- 1989 Final ε'/ε run

From a contemporary seminar

1986 Data

	Events	% Background
$K_L \to 2\pi^0$	109 000	4.0
$K_L \to \pi^+\pi^-$	295 000	0.6
$K_S \to 2\pi^0$	932 000	< 0.1
$K_S \to \pi^+\pi^-$	2 300 000	< 0.1

$$R_\eta = 0.977 \pm 0.004$$

statistical error only

Simple Ratio
0.912
Becomes
0.977
after binning in energy & vertex

Main Systematic Effects on R_η

Effect	%	Improved in 1988/9
Energy Scale	0.3	Yes
$2\pi^0$ background	0.2	Yes
$\pi^+\pi^-$ background	0.2	Yes
Accidental losses/gains	0.2	Yes
All other systematics	<~ 0.2	<~ 0.2

1986 Data
Summary of Corrections to R_η

	Collimator Scattering %	Pretriger Inefficiency %	Trigger Inefficiency %	Accidental Losses&Gains %
$K_L \to 2\pi^0$	< 0.1	0.06 ± 0.06	0.20 ± 0.10	2.6 ± 0.07
$K_L \to \pi^+\pi^-$	< 0.1	0.37 ± 0.07	0.05 ± 0.06	2.6 ± 0.05
$K_S \to 2\pi^0$	0.3	0.04 ± 0.02	0.12 ± 0.03	2.5 ± 0.05
$K_S \to \pi^+\pi^-$	0.3	0.48 ± 0.03	0.01 ± 0.01	2.8 ± 0.05

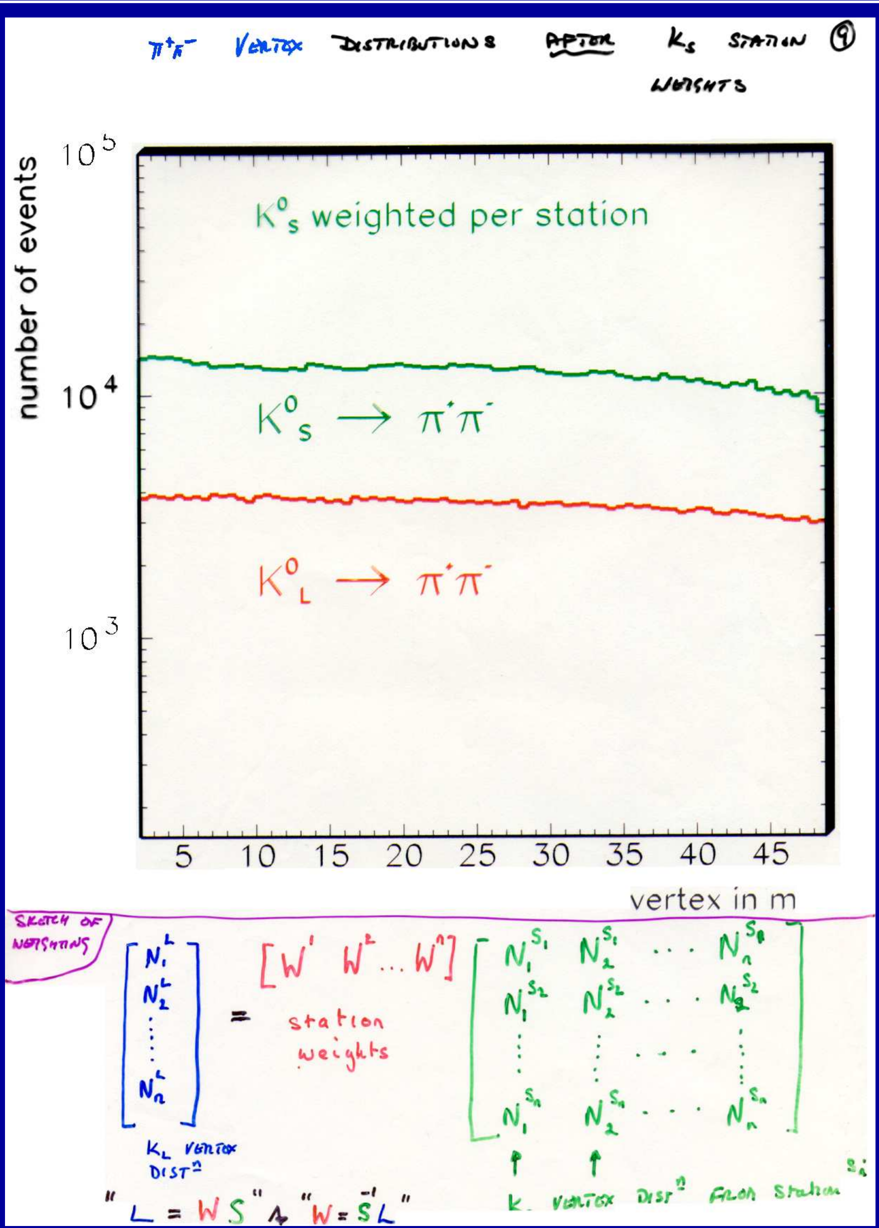
Total effect of $R_\eta \sim 0.2\%$.

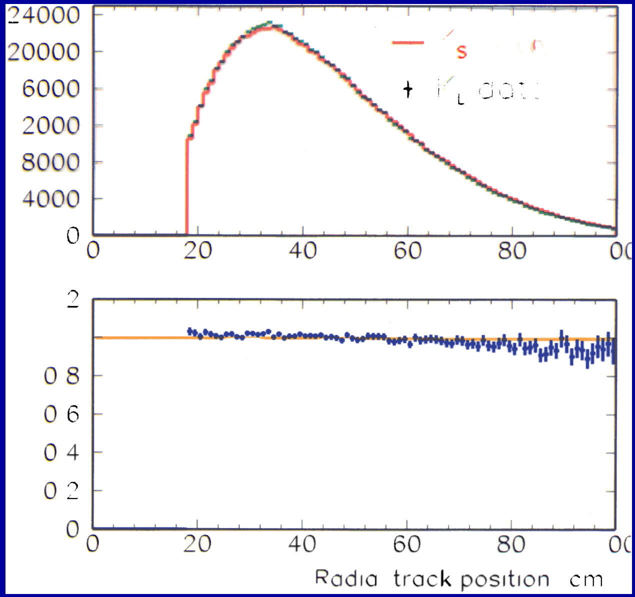
Key points in the analysis

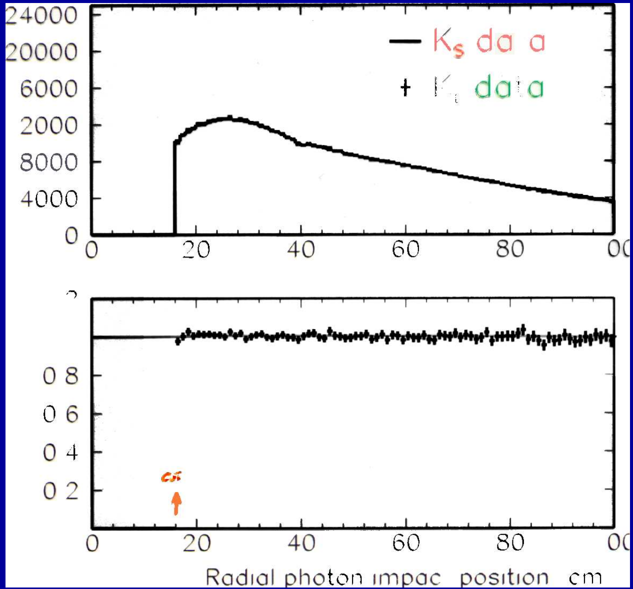
"The devil is in the detail"

- The energy scale
- Statistical analysis
- Accidentals
- Backgrounds
- Trigger efficiencies
- Reconstruction efficiencies
- The acceptance
- Rate effects
- Instrumental effects

Making the cancellation happen







Other physics

1987

First observation of $K_S \to \gamma\gamma$

New measurement of $K_L \to \gamma\gamma$

1988

Search for $K_L \to \pi^0 e^+ e^-$

Measurement of $K_L \to \pi^0 e^+ e^-$

1989

Search for $K_L \to \pi^0 h^0$; $h^0 \to e^+ e^-$

1990

Measurement of the phases ϕ_{+-} and ϕ_{00}, and the phase difference

Measurement of $K_L \to e^+ e^- \gamma$

Observation of $K_L \to \pi^0 \gamma\gamma$

1991

Observation of $K_L \to e^+ e^- e^+ e^-$

1992

Measurement of $K_L \to \pi^0 \gamma\gamma$

1993

New (final) measurement of ε'/ε

$\varepsilon'/\varepsilon = 0.00230 \pm 0.00065$

$\varepsilon'/\varepsilon = 0.0033 \pm 0.0011$ [1987]

Search for $K_S \to \pi^0 e^+ e^-$

1994

Search for $K_L \to \pi^0 \pi^0 \gamma$

1995

Branching Ratios $\Gamma(K_L \to 2\pi^0)/\Gamma(K_L \to \pi^+ \pi^- \pi^0)$ and $\Gamma(K_L \to 3\pi^0)/\Gamma(K_L \to \pi e \nu)$,

Measurement of $K_L \to e^+ e^- e^+ e^-$ & parity of the K_L

Search for $K_L \to \gamma\gamma\gamma$

1997

Measurement of the K lifetime

Measurement of $K_L \to e^+ e^- \gamma\gamma$

[1986] Presentation of the 'Cheque' for 200,000 $K_L \rightarrow 2\pi^0$

… and in action …

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/88-47
6 April 1988

FIRST EVIDENCE FOR DIRECT CP VIOLATION

CERN-Dortmund-Edinburgh-Mainz-Orsay-Pisa-Siegen Collaboration

H. Burkhardt[1], P. Clarke, D. Coward[2], D. Cundy, N. Doble, L. Gatignon, V. Gibson, R. Hagelberg, G. Kesseler, J. van der Lans, I. Mannelli[3], T. Miczaika[4], A.C. Schaffer[5], J. Steinberger, H. Taureg, H. Wahl and C. Youngman[6]

CERN, Geneva, Switzerland

G. Dietrich and W. Heinen[7]

Institut für Physik, Universität Dortmund, Fed. Rep. Germany[a]

R. Black, D.J. Candlin, J. Muir, K.J. Peach, B. Pijlgroms[8], I.P. Shipsey[9] and W. Stephenson

Physics Department, University of Edinburgh, UK

H. Blümer, M. Kasemann, K. Kleinknecht, B. Panzer and B. Renk

Institut für Physik, Universität Mainz, Fed. Rep. Germany[a]

E. Augé, R.L. Chase, M. Corti, D. Fournier, P. Heusse, L. Iconomidou-Fayard, A.M. Lutz and H.G. Sander[1]

Laboratoire de l'Accélérateur Linéaire, Université de Paris-Sud, Orsay, France[b]

A. Bigi, M. Calvetti[10], R. Carosi, R. Casali, C. Cerri, G. Gargani, E. Massa, A. Nappi and G.M. Pierazzini

Dipartimento di Fisica e Sezione INFN, Pisa, Italy

C. Becker[4], D. Heyland[4], M. Holder, G. Quast, M. Rost, W. Weihs and G. Zech

Fachbereich Physik, Universität Siegen, Fed. Rep. Germany[c]

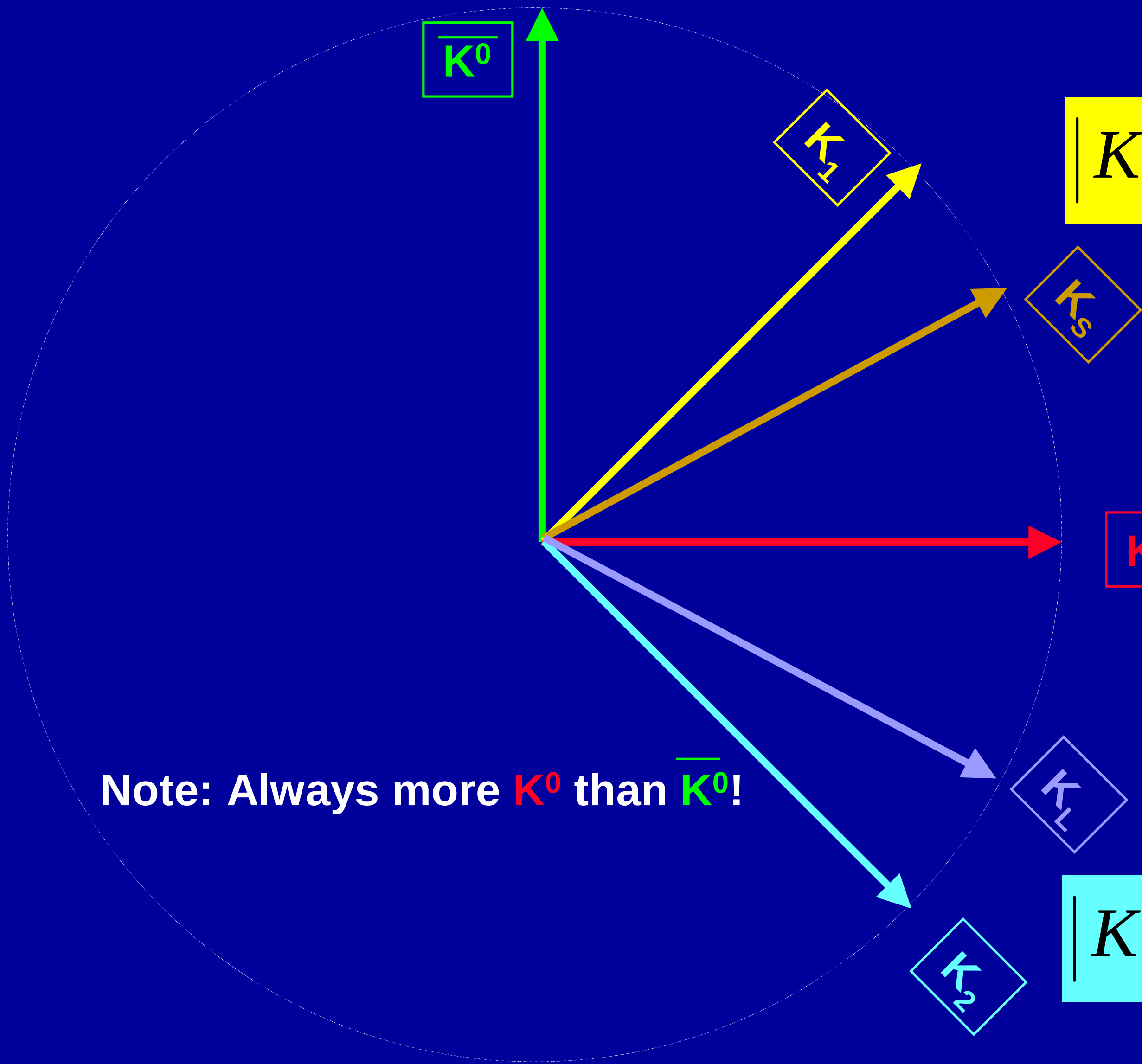
(Submitted to Physics Letters B)

1) Present address: Fachbereich Physik, Universität Siegen, Fed. Rep. Germany.
2) On leave from SLAC, Stanford, Calif., USA (work supported in part by the U.S. Department of Energy contract DE-AC03-765F00515).
3) Present address: Scuola Normale Superiore e Sezione INFN, Pisa, Italy.
4) Present address: DVFLR, Cologne, Fed. Rep. Germany.
5) Present address: LAL, Université Paris-Sud, Orsay, France.
6) Present address: II. Inst. f. Exp. Physik, Universität Hamburg, Fed. Rep. Germany.
7) Present address: IP-Systems, Karlsruhe, Fed. Rep. Germany.
8) Present address: FWI, University of Amsterdam, The Netherlands.
9) Present address: Syracuse University, NY, USA.
10) Present address: Dipartimento di Fisica e Sezione INFN, Perugia, Italy.

a) Funded by the German Federal Minister for Research and Technology (BMFT) under contract 05 4MZ18.
b) Funded by Institut National de Physique des Particules et de Physique Nucléaire, France.
c) Funded by the German Federal Minister for Research and Technology (BMFT) under contract 054 Si74.

	NA31	E731
$K_L \to 2\pi^0$	428 k	410 k
$K_L \to \pi^+\pi^-$	1142 k	327k
$K_S \to 2\pi^0$	2254 k	800k
$K_S \to \pi^+\pi^-$	5541k	1061k
$R_{raw} = \frac{L^{00} S^{+-}}{S^{00} L^{+-}}$	0.9213	1.6629
$\varepsilon'/\varepsilon\|_{fit}$	0.0023	0.0007
Stat.err	0.0004	0.0005
Syst.err	0.0005	0.0003
TOTAL err	0.00065	0.00059

The neutral kaon system



$$|K_1\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle + |\overline{K}^0\rangle\right]$$

$$K_s = \frac{1}{\sqrt{1+|\varepsilon_s|^2}}\left[|K_1\rangle + \varepsilon_s|K_2\rangle\right]$$

$$K_L = \frac{1}{\sqrt{1+|\varepsilon_L|^2}}\left[|K_2\rangle + \varepsilon_L|K_1\rangle\right]$$

$$|K_2\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle - |\overline{K}^0\rangle\right]$$

Note: Always more K^0 than $\overline{K^0}$!

CP conservation

- Since $CP|2\pi\rangle = +|2\pi\rangle$

- CP conservation implies that

1. $\varepsilon_S = \varepsilon_L = 0$

⇒ K_L cannot decay into 2π

! Note that CPT implies

$\varepsilon_S = \varepsilon_L$

ε'/ε

2π **state can be either** $\mathbf{I=0}$ **or** $\mathbf{I=2}$

$\pi^+\pi^-$ **is 2/3 (I=0) and 1/3 (I=2)**

$\pi^0\pi^0$ **is 1/3 (I=0) and 2/3 (I=2)**

$\eta_{+-} = \varepsilon + \varepsilon'$

$\eta_{00} = \varepsilon - 2\varepsilon'$

$$R_\eta = |\eta_{00}/\eta_{+-}|^2 = 1 - 6\Re(\varepsilon'/\varepsilon)$$

$$\varepsilon' = \frac{1}{\sqrt{2}} i e^{i(\delta_2 - \delta_0)} \frac{\Im A_2}{A_0}$$