Il Charm e le Camere a Bolle

Simposio in Onore di Romano Bizzarri

10 febbraio 2004

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Summary

- **The European Hybrid Spectrometer (EHS)**
- **The LExan Bubble Chamber (LEBC)**
- **NA13.The first tests**
- **NA16. The first experiment**
- **NA27. The last experiment**

The EHS proposal

In the mid 70's beam energies of several hundreds GeV were becoming available in the CERN NA from the SPS

A number of European groups joined together to study and design a general purpose apparatus with a rapid cycling bubble chamber as an imaging vertex detector (as opposed to a very large bubble chamber). It was called European Hybrid Spectrometer.

It has been clear since the beginning that, even if magnetic analysis of the secondaries was to be provided by the high magnetic field (3T) on the bubble chamber, a full fledged magnetic spectrometer was needed for the high momentum secondaries.

Further basic elements were the **gamma detectors**, and **particle identification**

We, in Padova, joined forces with Oxford and RAL, leading the design and building of

RAL	the bubble chamber
Oxford	ISIS, a large drift volume with a single horizontal sense wires plane providing images and ionisation of the tracks
Padova	with Rome, Trieste and Genova; the Forward Gamma Detector, a Pb glass wall, measuring energy and directions of the photon showers

Oxford, Padova, RAL and Trieste, submitted a physics proposal based on a 350 GeV π^- beam. Its scopes were very broad and did non include yet charm physics

The EHS proposal

Advantages of a rapid cycling bubble chamber discussed by W. Allison et al. CERN/SPSC 74-45; CERN/SPSC 75-15

Part A. W. Allison et al. CERN/SPSC 76-43

Part B. W. Allison et al. CERN/SPSC 78-91: CERN/EP/EHS/PH 78-10

Part C. G.A. Akopjianov et al., CERN/SPSC 78-91

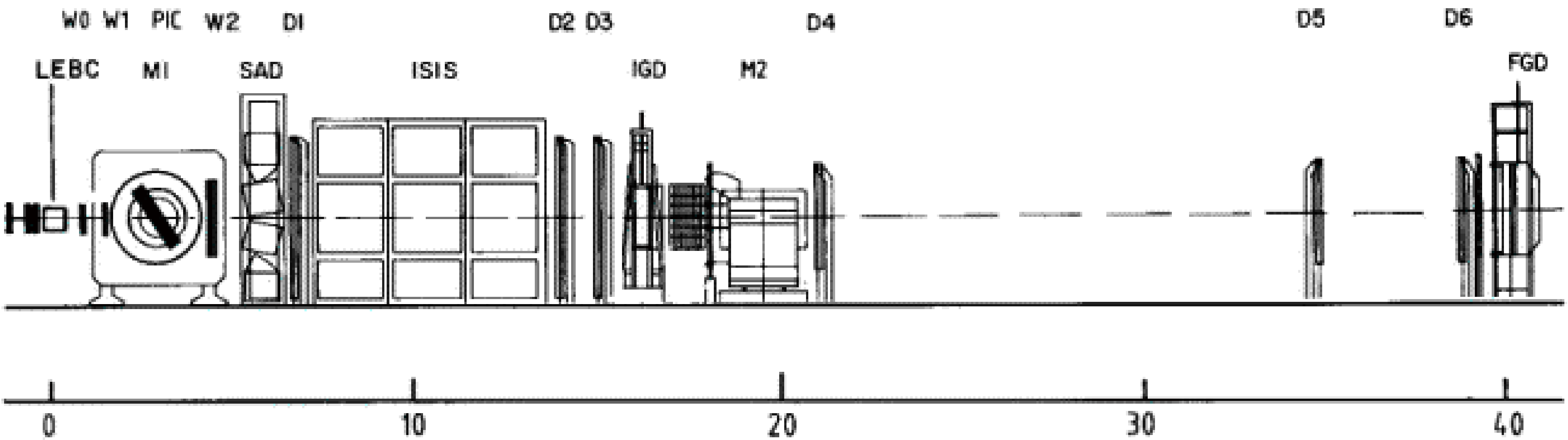


Fig. 1. The European Hybrid Spectrometer as used for the NA27 π^- exposure

The EHS as used by NA27 in 1983 with LEBC and PIC (A. Bettini et al. Proc. Conf. on Miniaturisation in high energy physics (Pisa 1980)) in the magnet originally foreseen for the bubble chamber

Charm from neutrinos. 1979

In the summer of 1979 A. Zichichi organised in Geneva the EHS International Conference on High Energy Physics

Marcello Conversi summarised the status of "Lifetime of charged hadrons produced in neutrino interactions"

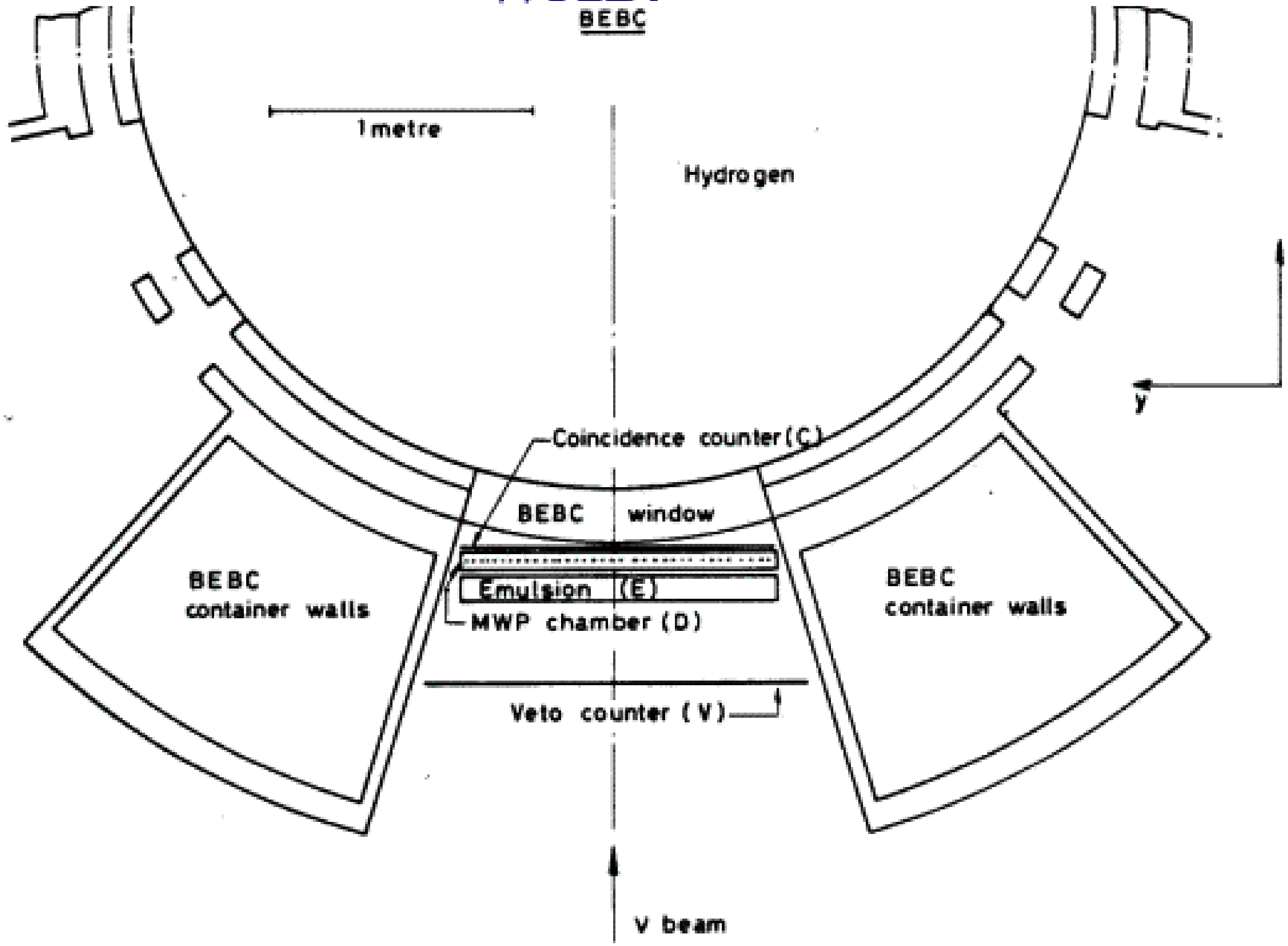
In the **Introduction** Conversi writes:

"Until recently rather conflicting results have been reported from experiments based on different techniques, concerning the lifetime τ_c of charmed particles. Thus, some three years after these new states of hadronic matter were found as predicted by the "GIM mechanism", no conclusive answer could be given to the fundamental question of whether or not the decay rate of charmed hadrons is governed basically by the Fermi weak constant as expected."

"The theoretical prediction is that charged particles all have lifetimes of the same order of magnitude, essentially determined by the rate of the charmed quark β decay. Including first order gluon effects and correction for the finite mass of the s-quark the value of $\tau_c = 5 \times 10^{-13}$ has recently been reported (N. Cabibbo, G. Corbo and L. Maiani: in press)"

Conversi describes 3 experiments (his own WA17 at CERN and 2 at FNAL)

WA17



BEBC pictures are visually scanned searching for secondaries originated in the emulsion stack, which is both the target and the vertex detector. BEBC, in a 3.5 T field acts as a large acceptance spectrometer

Charm 1979

WA17

Hybrid BEBC + emulsions

Charge	Nature	Decay time (10^{-13} s)
+	?	0.5-1.2
+	Λ_c^+	7.3±0.1
+	?	1.6-5.3
0	meson	0.2-4.2
0	?	0.4-2.5

E-546. 15' bubble chamber

D^+ ?? $\quad \tau = \left(2.5^{+3.5}_{-1.5}\right) \times 10^{-13} s$

D^0 ?? $\quad \tau = \left(3.5^{+3.5}_{-1.5}\right) \times 10^{-13} s$

E-553. 15' hybrid spectrometer + emulsions

no candidate

Our conclusions

- E546 confirmed that the spatial resolution of traditional bubble chambers is not sufficient
- emulsion resolution OK, but statistics, for traditional techniques, are marginal
- wide acceptance spectrometer, with full magnetic analysis of charged tracks, gamma detectors (energy and position) and particle ID are needed
- We were building the EHS hybrid spectrometer, we had built automatic film measurement devices (at Oxford, Padova and CERN)

We needed a high resolution, at least 30 μm, high rate imaging vertex detector!

LEBC. The idea

A bubble chamber might be the solution, provided

•we would be able to take images of bubbles as small as 20-30 μm with a high enough contrast

•we would be able to reach a high enough bubble density along the tracks

•how close can we approach the foam limit, while keeping stable operation conditions?

•we would be able to cycle the chamber at high rate (30-50 Hz) for several millions of cycles

Heinrich Leutz and his group, with the experience of BEBC, the large H2 bubble chamber, had the idea that lead us to the success: the Lexan Bubble Chamber.

LEXAN is a clean thermoplastic polycarbonate previously used in the BEBC Track Sensitive Target

The first LEBC was used in NA13 without the spectrometer.

In the following years more improved versions of LEBC were built by CERN

A. Hervé, et al. Proc. Conf. on Miniaturisation in high energy physics (Pisa 1980)

LEBC

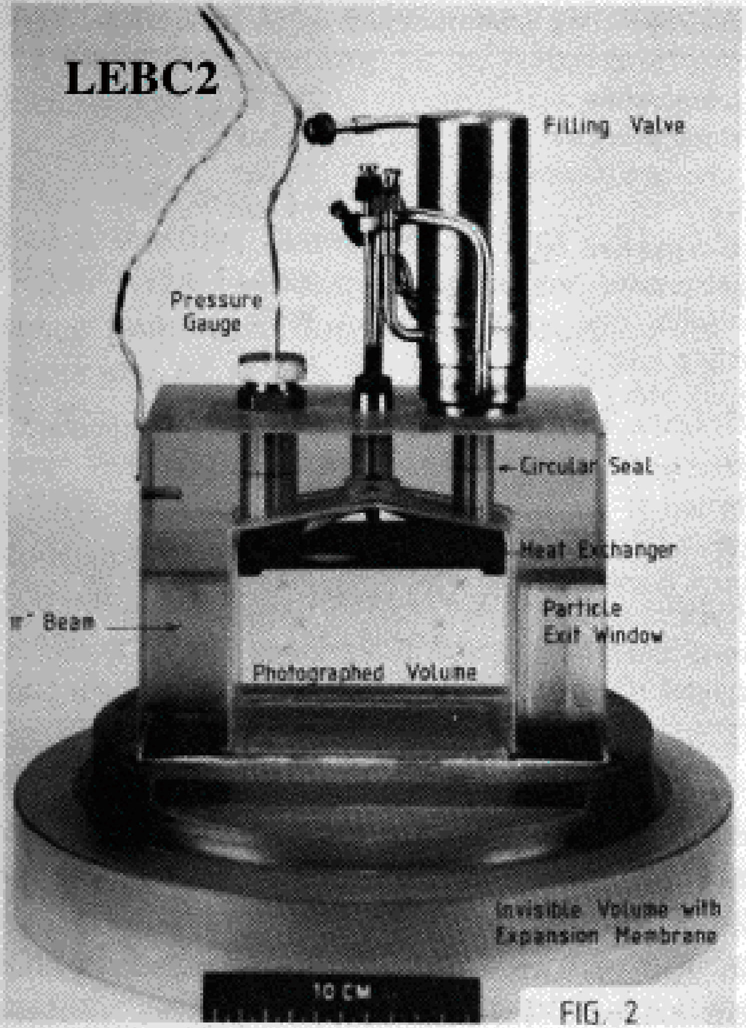


FIG. 2

Fig. 2. The chamber body of LEBC, fabricated from LEXAN. Within the upper part of the rectangular frame the metallic circular seals for valve, gauge and heat-exchanger are visible

The first (NA13) configuration

Volume = 1 litre , Ø= 20 cm, depth = 4 cm

Axis: horizontal, perpendicular to the beam

No **B** field

Illumination: bright field

Lens: f = 180 mm @ F/11

diffraction limited @ **30 μm**

field depth ≈ **2-3 mm**

Lateral magnification = 1/3.25

Slow spill beam with 1.2 s flat top

Beam section @ LEBC: 2 mm (H) x 80 mm (V)

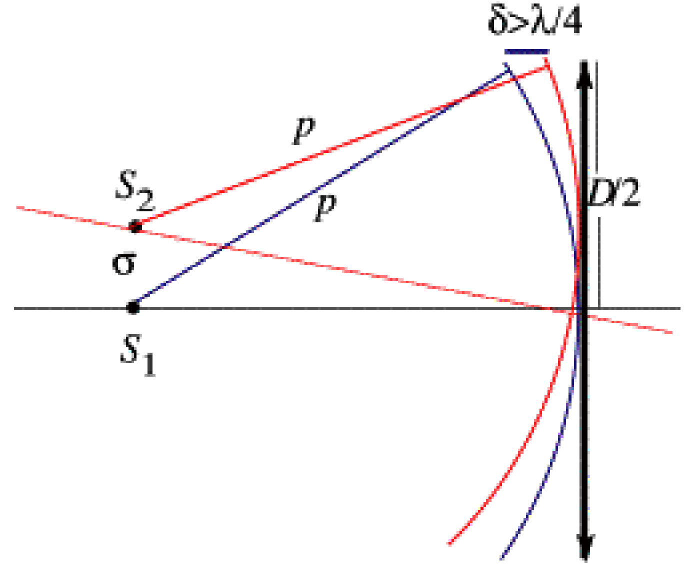
Expansion Δp = 4.1 bar (from static 7.4 bar)

Flash delay = 200 μs for 40-50 μm bubble diameters **<u>and</u>** high (≈70/cm) bubble density

Depth of focus and resolving power

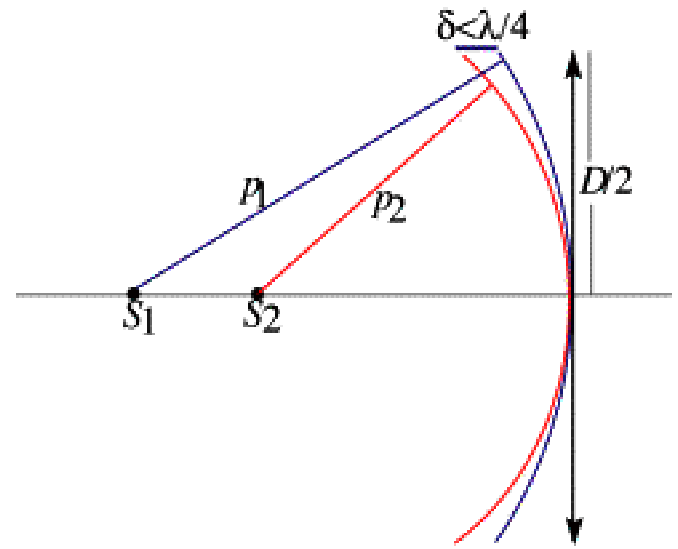
To distinguish to point sources (bubbles), the two wave fronts they produce must differ **at least by $\lambda/4$** @ the lens

$$\sigma \approx 1.22\frac{\lambda p}{D}$$



To have both point sources (bubbles) in focus the two wave fronts must not differ by **more than $\lambda/4$** @ the lens

$$\Delta p \approx \frac{p^2}{D^2}2\lambda$$



High resolving power ⇒ small depth of field

NA13. LEBC is working

NA13. An extension of the π^- proposal by Brussel, CERN, Oxford, Rome, RAL, Trieste

June-July 1979. First run of LEBC. One view only. $\pi^- p$ @ 340 GeV

Exposure: 2.5 events/μb (48 000 events)

Simple interaction trigger, requesting outgoing multiplicity ≥ 2

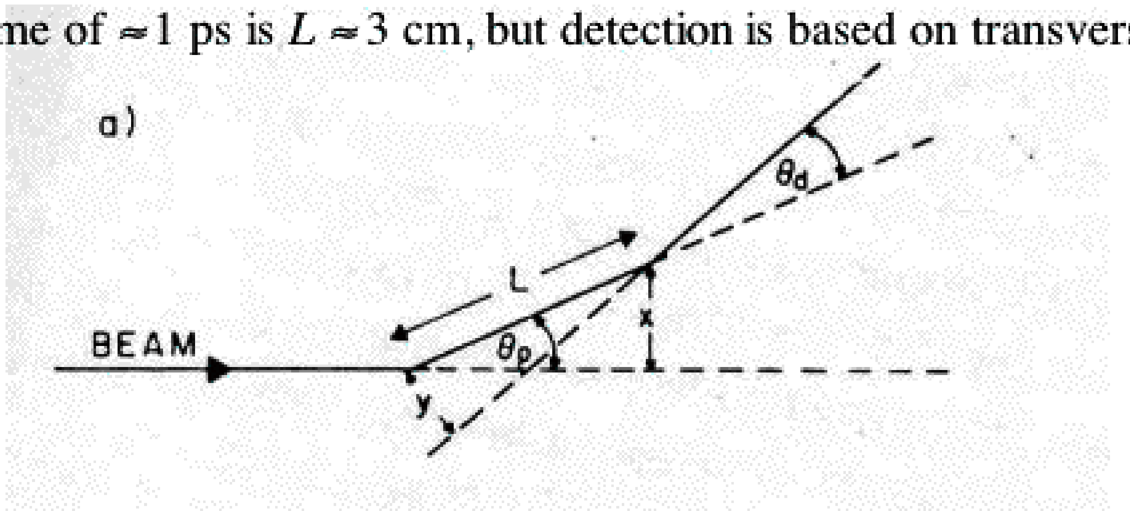
LH2 as target liquid important to minimise background from secondary interactions and gamma conversion

Remaining expected main topological background from strange particles decays

Detection of charm production via topological signal by scanning (twice) the pictures

Expected decay lengths for a lifetime of ≈ 1 ps is $L \approx 3$ cm, but detection is based on transverse distances such as x and y

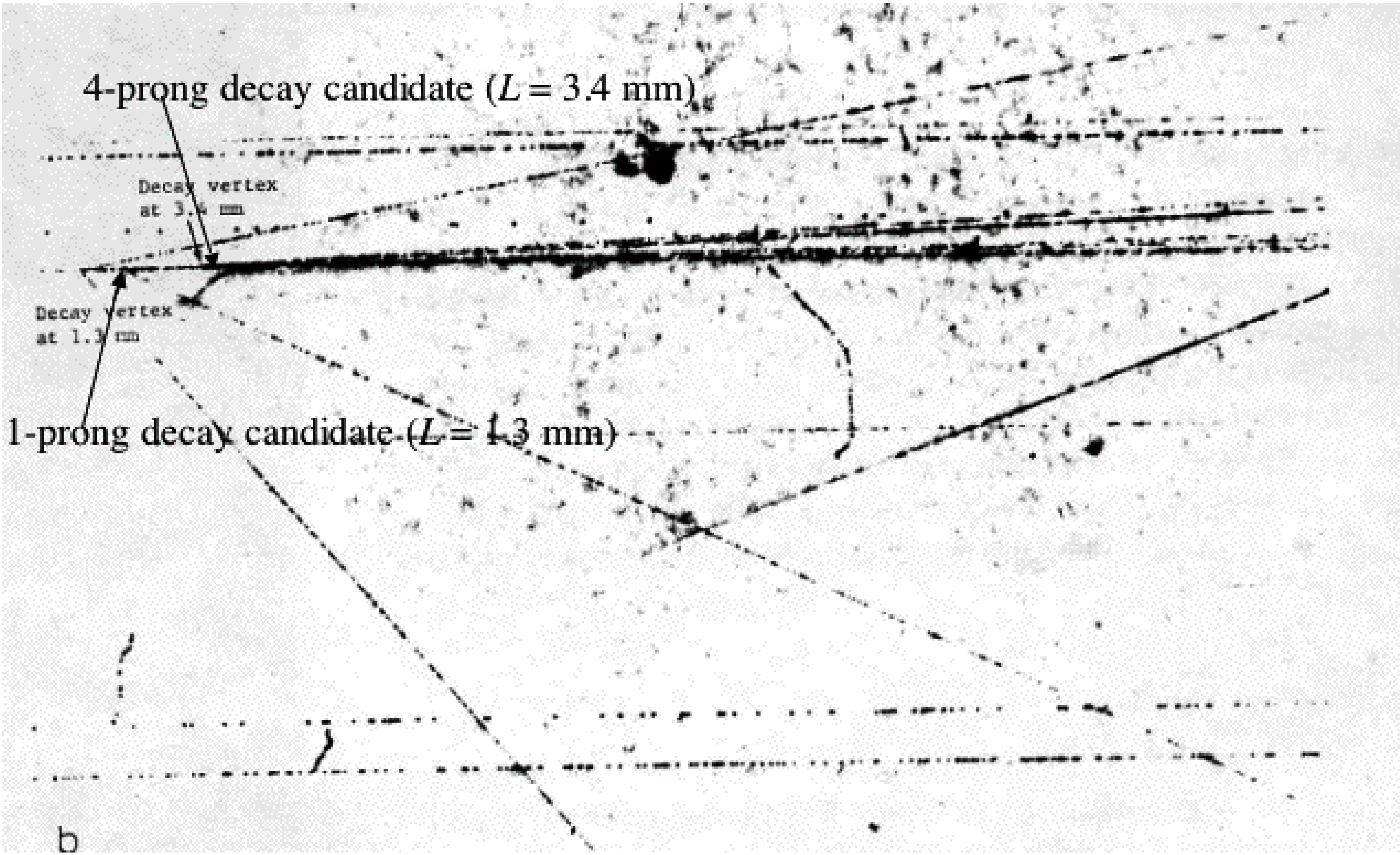
$$x = \frac{p_T}{m} tc$$



Expected x = 60μm for t = 0.1 ps, even if L =several mm

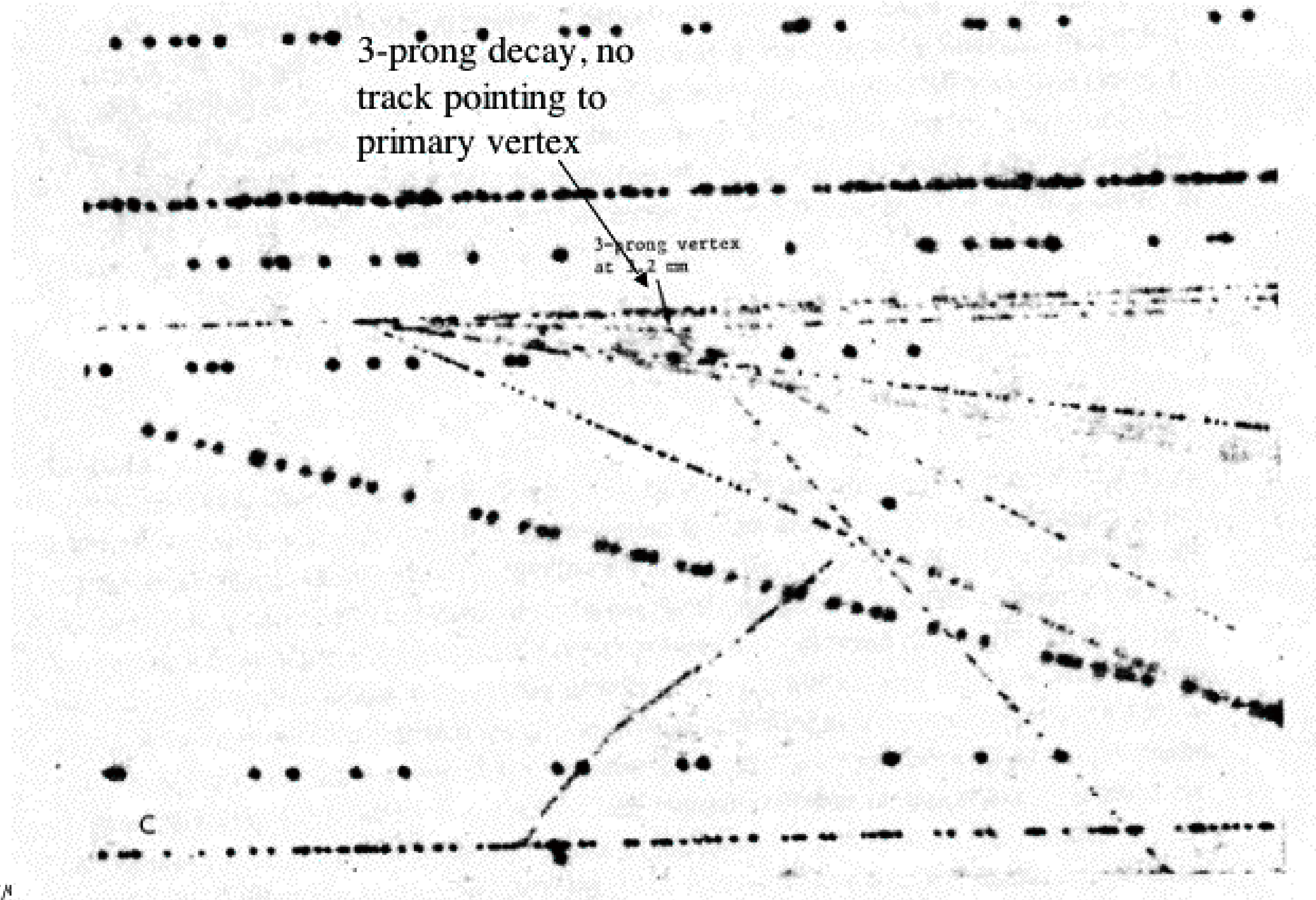
W. Allison et al. Phys. Lett. **93B** (1980) 509

NA13. Example of associated production



NA13. A golden C3 event

Small background in C3 topology (strange *V*° charged track from primary vertex overlap)



NA13. Topologies, signals and backgrounds

Careful study of the statistical properties of the strange (longer lifetime) background in than pair production candidate events

Evidence for signal in the *a priori* defined "charm region ($L < 3$ cm, $x < 60\ \mu$m)"

ev. type	observed pairs	calc. backgr.	signal
All	20	8.2	11.8
CC	5	0.8	4.2
CV	10	4.0	6.0
VV	5	3.4	1.6

Significant evidence of charm pair production by hadrons ($\sigma \approx 40\ \mu$b)

Significant signal in 3-prong topology ($\sigma_D{}^{\pm} \approx 35\ \mu$b, $\tau = 10^{-12}$ s)

We had a working vertex detector, LEBC, with the requested spatial resolution, bubble density, rate and trigger ability

we had, as expected, backgrounds, but they looked manageable

We needed the EHS spectrometer immediately

NA16. LEBC + EHS

LEBC

- 2 stereo views. Spatial resolution = 40 μm
- Kicker magnet in the beam to suppress earlier tracks

PIC

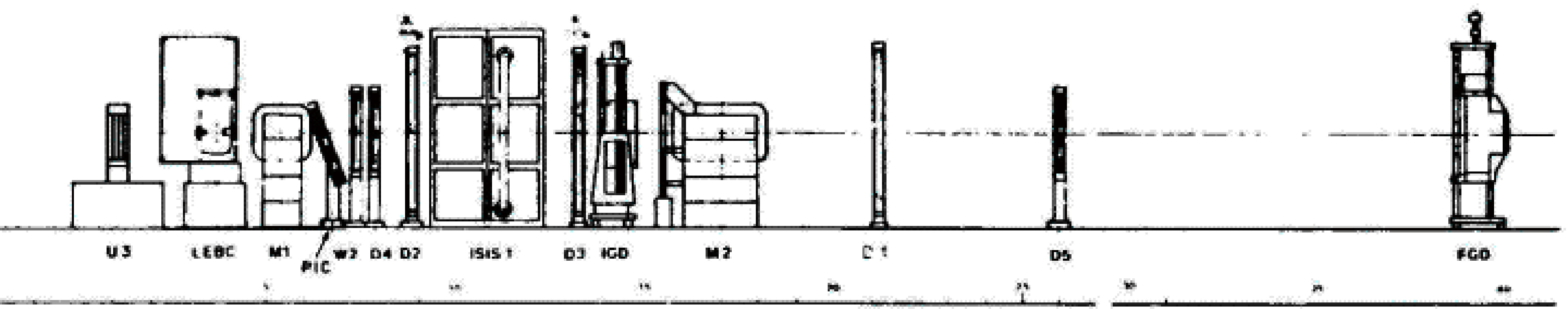
- Matching between LEBC and spectrometer resolution. Proportional Inclined Chamber (100 μm spatial resolution, 300 μm two track resolution, track element angle $\pm 1.5^\circ$)

EHS (partial)

- momentum analysis spectrum. [$\Delta p/p = 2.2 \times 10^{-4} p$ (1st lever arm), $0.4 \times 10^{-4} p$ (2nd lever arm)]
- gamma detectors [$\Delta E/E = 10\%/\sqrt{E} + 2\%$; $\Delta m(\pi^\circ) = 20$ MeV]
- pictorial drift chamber ISIS1 giving ionisation data (first module)

Exposure. June 1980

- 360 GeV beams: π^- (7.8 μb^{-1}) and p (7.3 μb^{-1})



NA16 V2 V4 atypical event

Phys. Lett. **102B** (1981) 2285

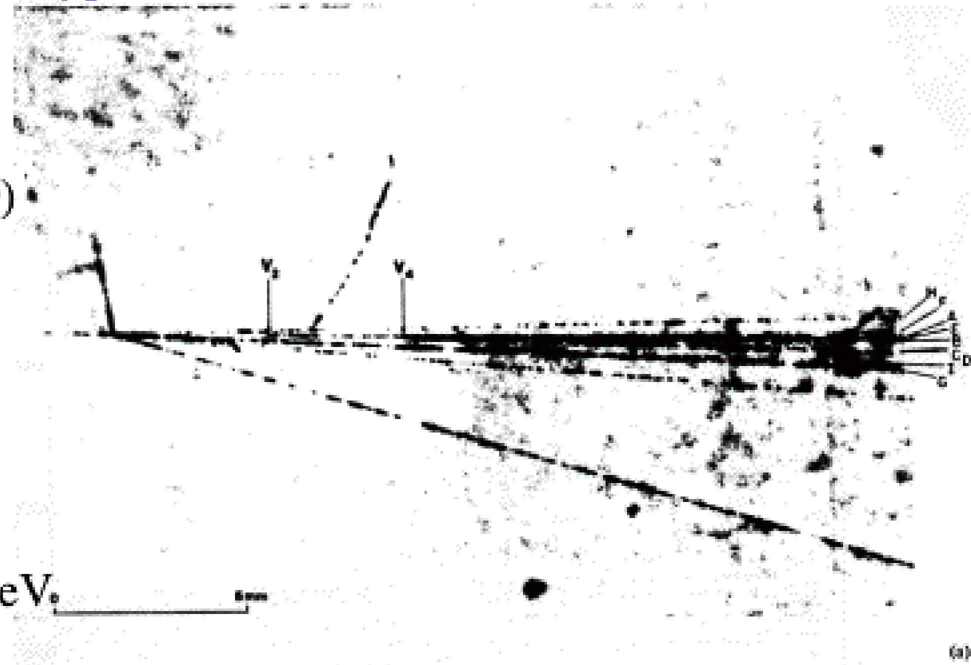
Independently measured in three laboratories

Six tracks fully analysed in the spectrometer

Particle ID in ISIS1 (only 60 sense wires on 320)

6 γ detected in the calorimeters (energy and positions); 3 and only 3 π^0's reconstructed

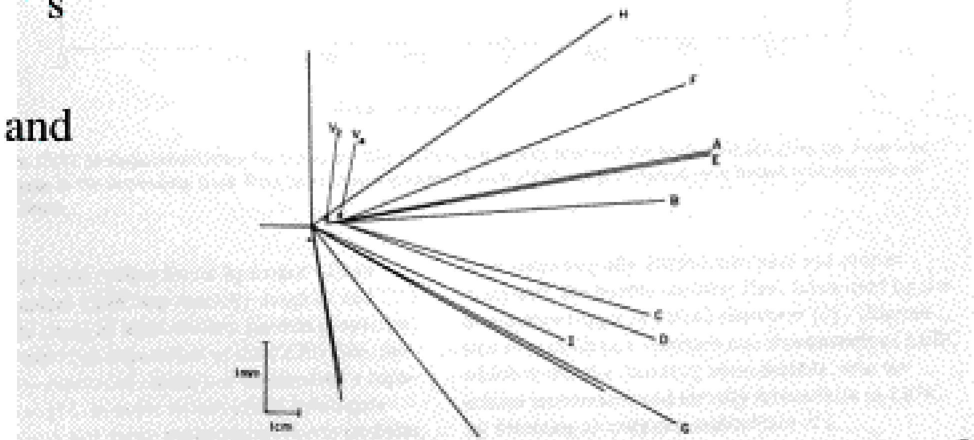
Interpret as associated production of



$$D^0 \to K^-\pi^+\pi^0\pi^0$$
$$m = 1.857 \pm 0.022 \text{ GeV}$$
$$p = 119.0 \pm 0.6 \text{ GeV}$$
$$\tau = (2.1 \pm 0.1) \times 10^{-13} \text{s}$$

$$\overline{D}^0 \to K^+\pi^+\pi^-\pi^-$$
$$m = 1.862 \pm 0.009 \text{ GeV}$$
$$p = 78.5 \pm 0.3 \text{ GeV}$$
$$\tau = (5.9 \pm 0.1) \times 10^{-13} \text{s}$$

Ionisation measured in ISIS1 agrees with the K^+ and K^- assignments



LEBC + EHS work beautifully

***D°* lifetime is small < ps, confirming emulsion experiments**

Adeva et al. Phys. Lett. **102B** (1981) 285

NA16. Main results

Phys. Lett. **122B** (1983) 312

Backgrounds from secondary interactions and gamma conversion negligible (LH2)

Main background from strange decays suppressed taking $x < 60\ \mu$m

77 events containing 60 identified charm decays

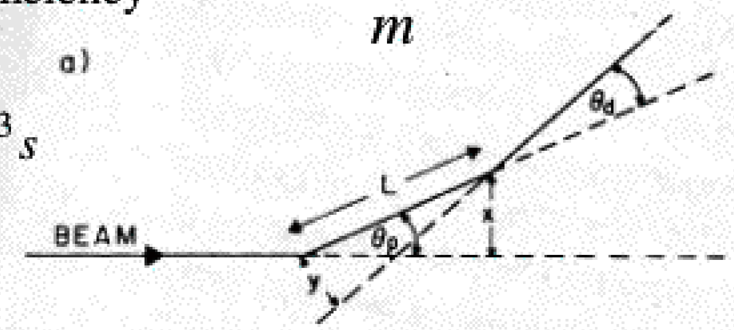
52 of them have a good over constrained (2C and 3C) kinematical fit

$23D^\circ$, $20D^\pm$, 9 D_s, Λ_c, charm ambiguous

Selection of $L > L_{min}$ for reliable calculation of the efficiency

16 D°, $15D^\pm$,

$$x = \frac{p_T}{m} tc$$



$$\tau(D^0) = \left(4.1^{+1.3}_{-0.9}\right)\times 10^{-13}\, s \qquad \tau(D^\pm) = \left(8.4^{+3.5}_{-2.2}\right)\times 10^{-13}\, s$$

$$R = \frac{\tau(D^\pm)}{\tau(D^0)} = 2.1^{+1.4}_{-0.6}$$

Decays of charmed particles had been described in the c quark spectator model.

Comparison with μ decay had lead to an universal lifetime for all charmed particles of $\approx 7\text{x}10^{-13}$ s

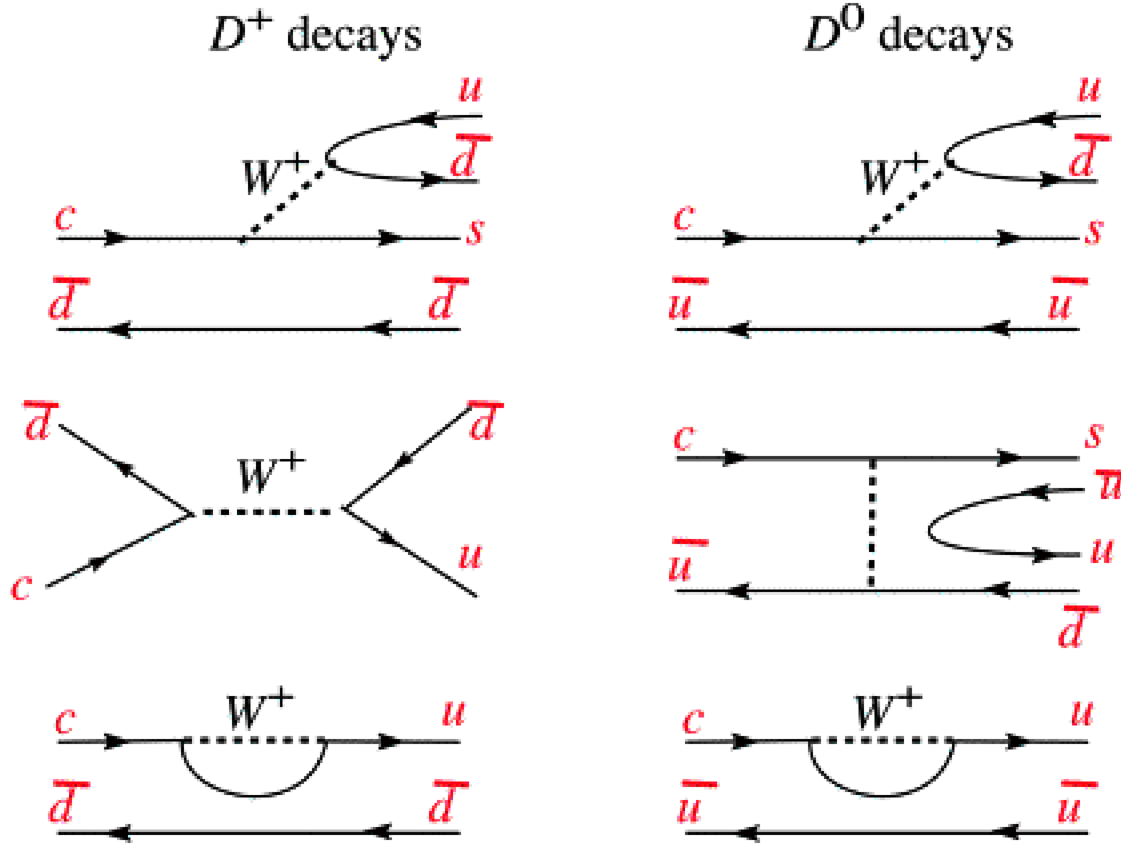
But we found that the lifetimes of charmed mesons are different

γ production in the SLAC bubble chamber with ad hoc high resolution camera (1983) $\tau_{D^\pm} = \left(7.4^{+2.3}_{-2.0}\right)\times 10^{-13}\text{s}$ $\quad \tau_{D^0} = \left(6.8^{+2.3}_{-1.8}\right)\times 10^{-13}\text{s}$

ν beam at FNAL on emulsion + spectrometer (7 D°, $5D^\pm$) $\tau_{D^\pm} = \left(10.3^{+10.5}_{-4.1}\right)\times 10^{-13}\text{s}$ $\quad \tau_{D^0} = \left(1.00^{+0.53}_{-0.31}\right)\times 10^{-13}\text{s}$

Charming lives

Charm decays had been believed to be dominated by the "spectator" graph, hence that lifetimes of all charmed hadrons were nearly identical



Sources of possible differences

Two identical d's in the D^+, not in D° decay (effects of Pauli?)

D^+ and not D° has an annihilation channel open, but it is Cabibbo-suppressed

D° W exchange is suppressed too (helicity and colour)

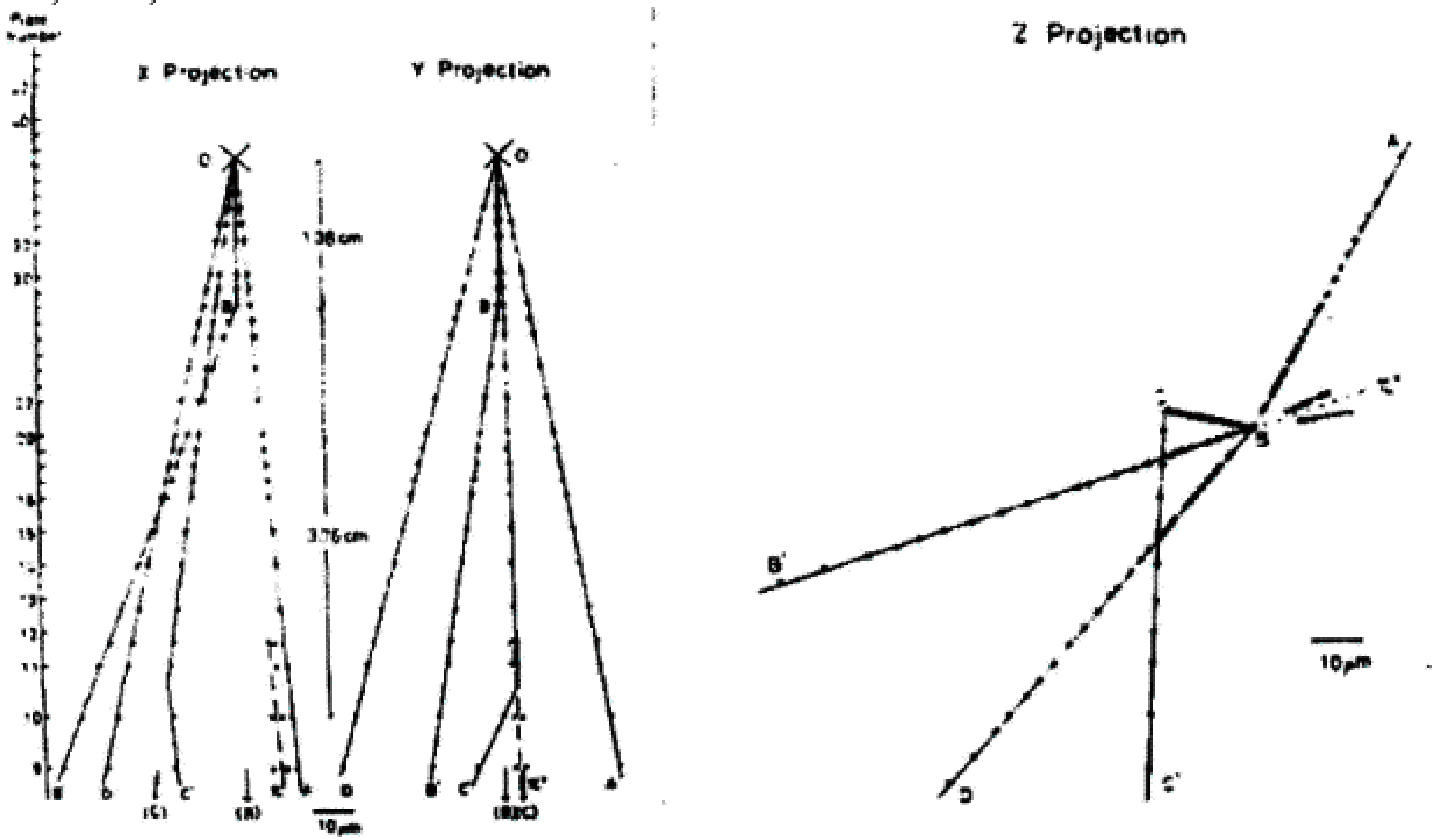
Penguins are Cabibbo, helicity and colour suppressed

We were only at the beginning. To disentangle the contributions of the different graphs and their possible interferences, the lifetimes of all charmed hadrons, both mesons and baryons, had to accurately measured. (Achieved in ≈ 2000)

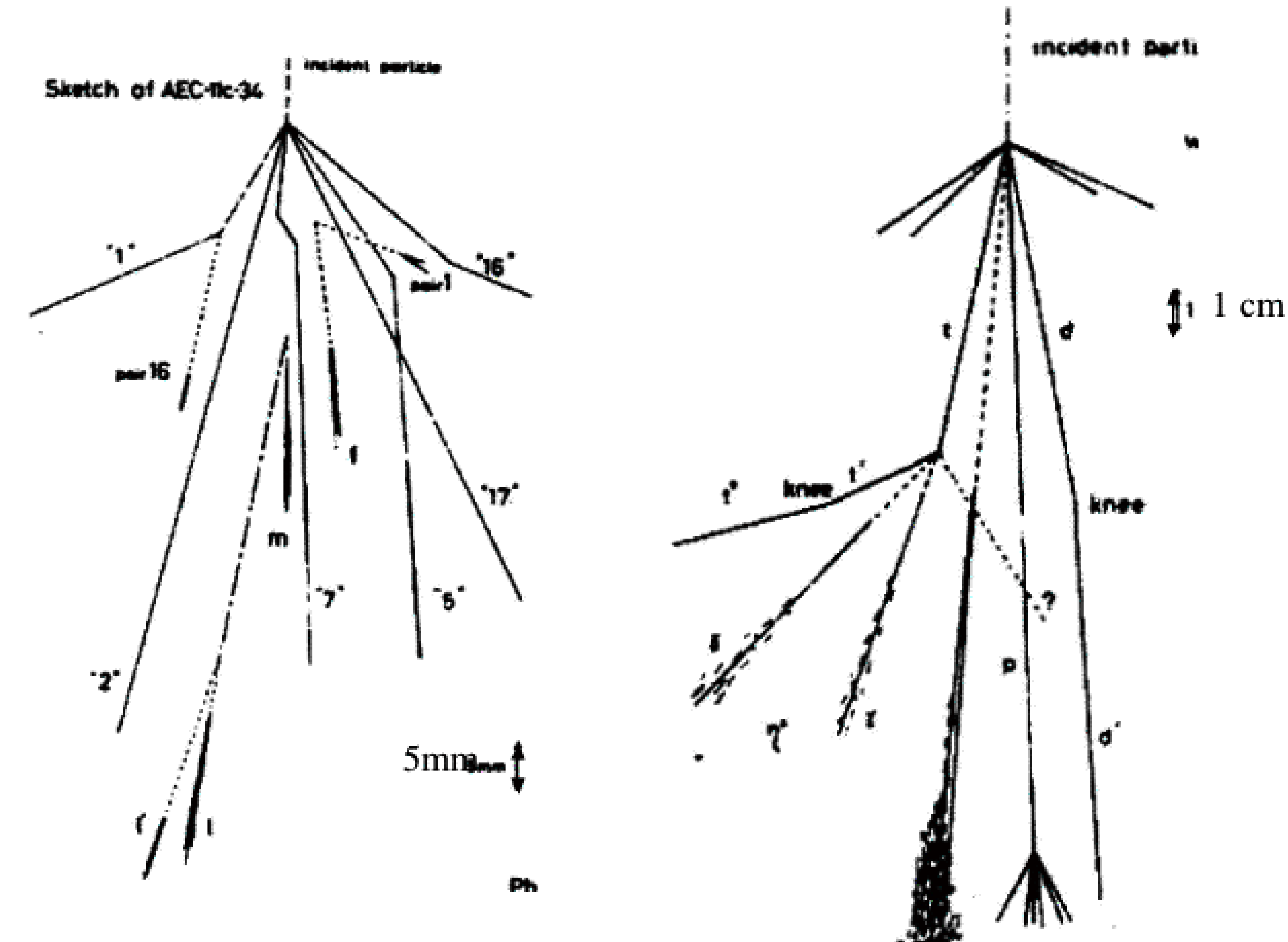
The Nagoya X events. 1971

We did not know that

First evidence for *X* particles by the Nagoya group (K.Niu et al., Prog. Theor. Phys. 46(1971)1644)

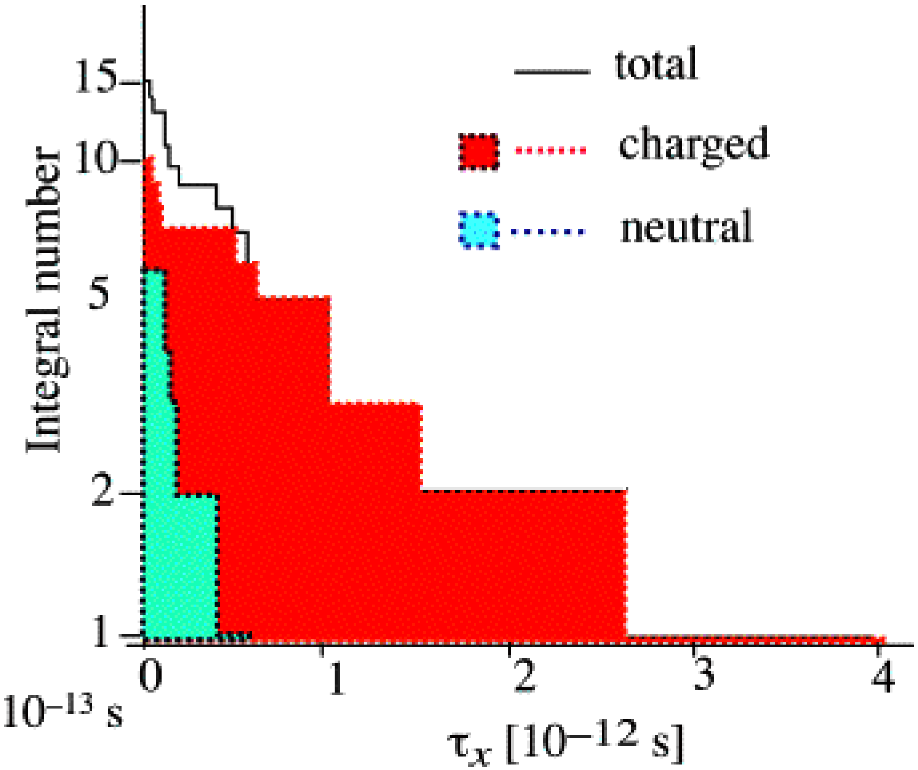


2 multi TeV events



The two lifetimes of X particles

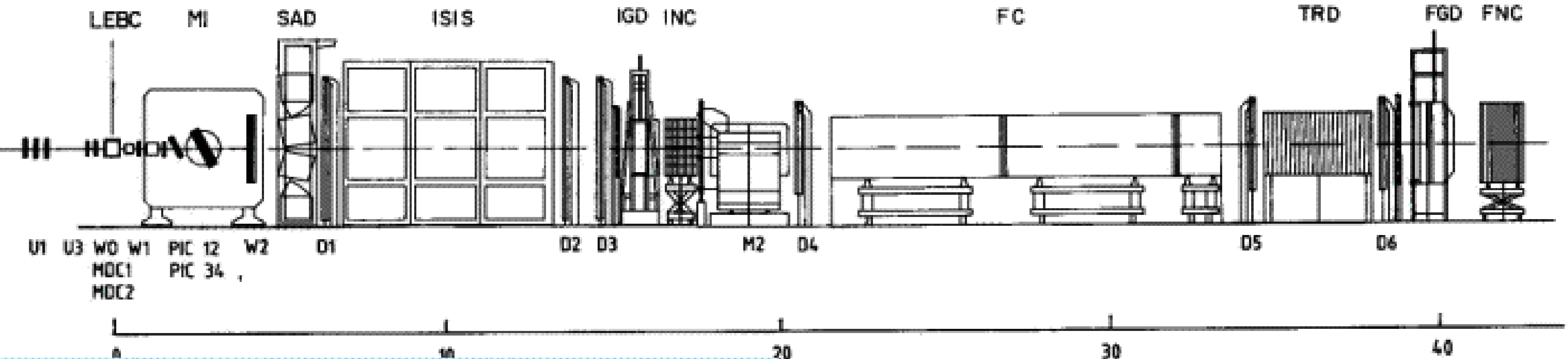
K.Niu, K.Niwa et al.(Nagoya, Tokyo, Yokohama)
14th International Cosmic ray Conference at Munich 1975



τ(charged) $\approx 20 \times 10^{-13}$ s

τ (neutral) $\approx 4 \times 10^{-13}$ s

NA27



Aims

improve precision on charm lifetimes

improve knowledge on hadroporoduction of charm

Production cross-sections, σ, $d\sigma/dp_T$, $d\sigma/dx_F$

Branching ratios

2 different beams

- 360 GeV π^-. 16 ev/μb
- 400 GeV *p*. 38.5 ev/μb

Apparatus

Improved bubble chamber. LEBC2

- bubble diameter 17-22 μm
- depth of focus 1.5 - 2.0 mm
- bubble density 80 cm^{-1} (close to foam limit!)

Improved particle ID

- ISIS2 (320 sense wires)
- Silica Aerogel

Improved trigger

- > 2 hits in W0 and W1 and Fiducial Volume
- Trigger by Rome group

Charm hadroproduction

At the time NA27 was proposed, the size of the hadroproduction cross section of charm particles was a puzzle

At the Stockholm Conference on HEP, L. Montanet recalled the following "history" of $\sigma(pp \rightarrow charm)$ @ $\sqrt{s} \approx 25$ GeV

1976 $\sigma(pp \rightarrow charm) < 1.5\ \mu b$ (@90% c.l.)

1978 $\sigma(pp \rightarrow charm) = 100\text{-}500\ \mu b$

1982 $\sigma(pp \rightarrow charm) = 20\ \mu b$

Beam dump experiments had nuclei as targets. A dependence of σ was unknown

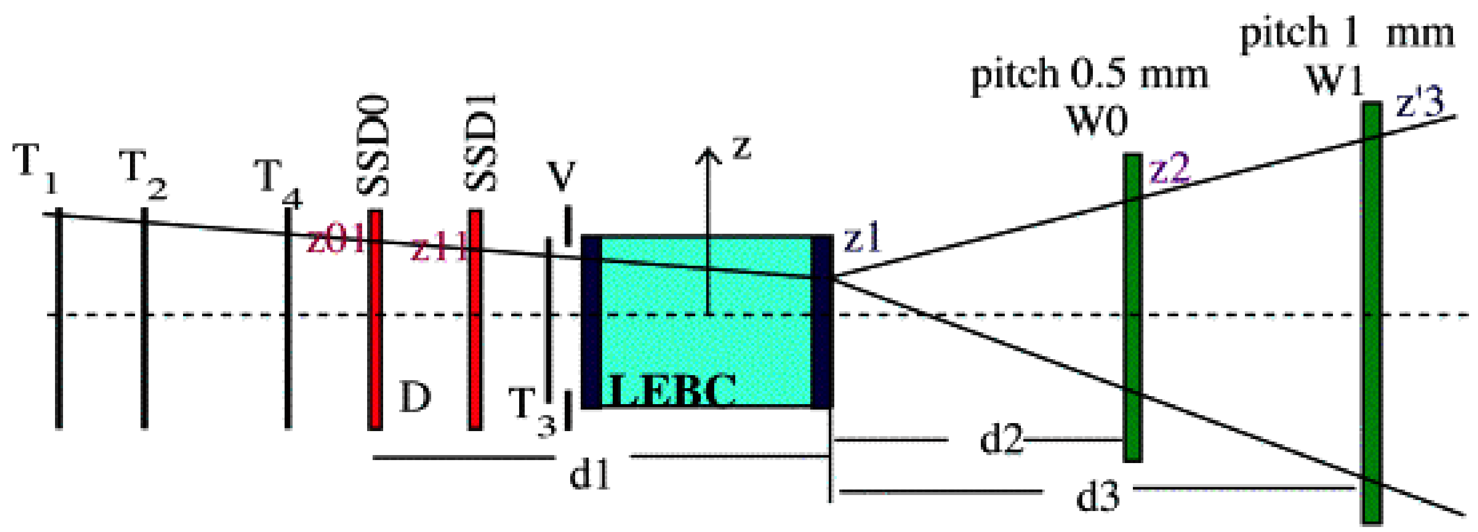
In general measurements were made difficult by

large hadronic backgrounds

large combinatorial backgrounds

no easy trigger

NA27. The interaction trigger



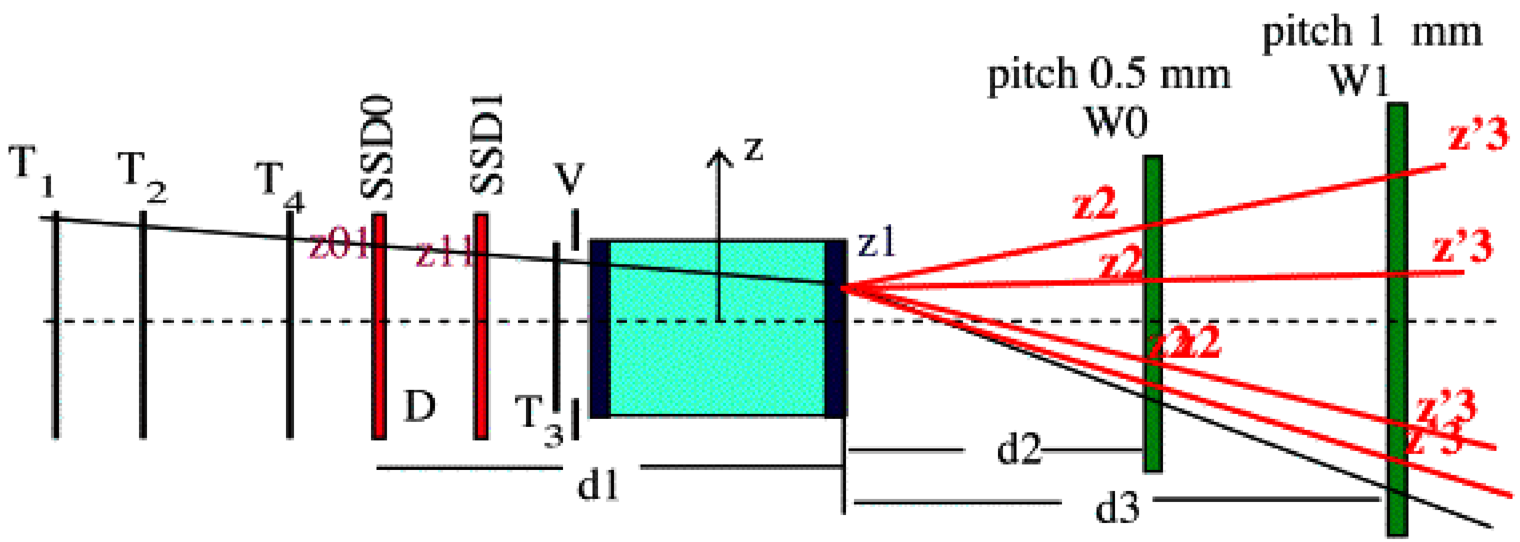
Being the chamber small, about 1/4 of the events happen in the windows

A 2nd level trigger was designed to skip these 1st level triggers

Using the coordinates z01 and z11 measured in the Si μstrip detectors SSD0 and SSD1 the on line fast algorithm calculates the coordinate $z1$ of the vertex, if it was in the exit window (similar for entrance window).

For each hit $z2$ in the wire chamber W0 the algorithm calculates $z'3$ in W1 and looks for matches

NA27. The interaction trigger



MBNIM fast logic reaches the decision stage within 16 μs (the flash delay)

Physics of beauty was a possible next step for the hybrid technique, which we discussed in depth in that period

Increased trigger sophistication and enhanced depth of focus vs.. resolution capability had to be achieved

optical "tricks"

holography

Scanning and data reduction

π^- run (1982)

Pictures with primary interaction	265 000	double scan+check by physicist
with a decay in "charm box"	6368	measure
after measurement and kinem. analysis	276	very precise measure (HPD Strasburg)
final sample	**114 events with 183 charm decays**	

***p* run**

Pictures with primary interaction	1 015 000	double scan+check by physicist
with a decay in "charm box"	5000	measure
after measurement and kinem. analysis	720	very precise measure (HPD Strasburg)
final sample	**324 events with 557 charm decays**	

geometrical reconstruction & kinematical fit

associate π° if any

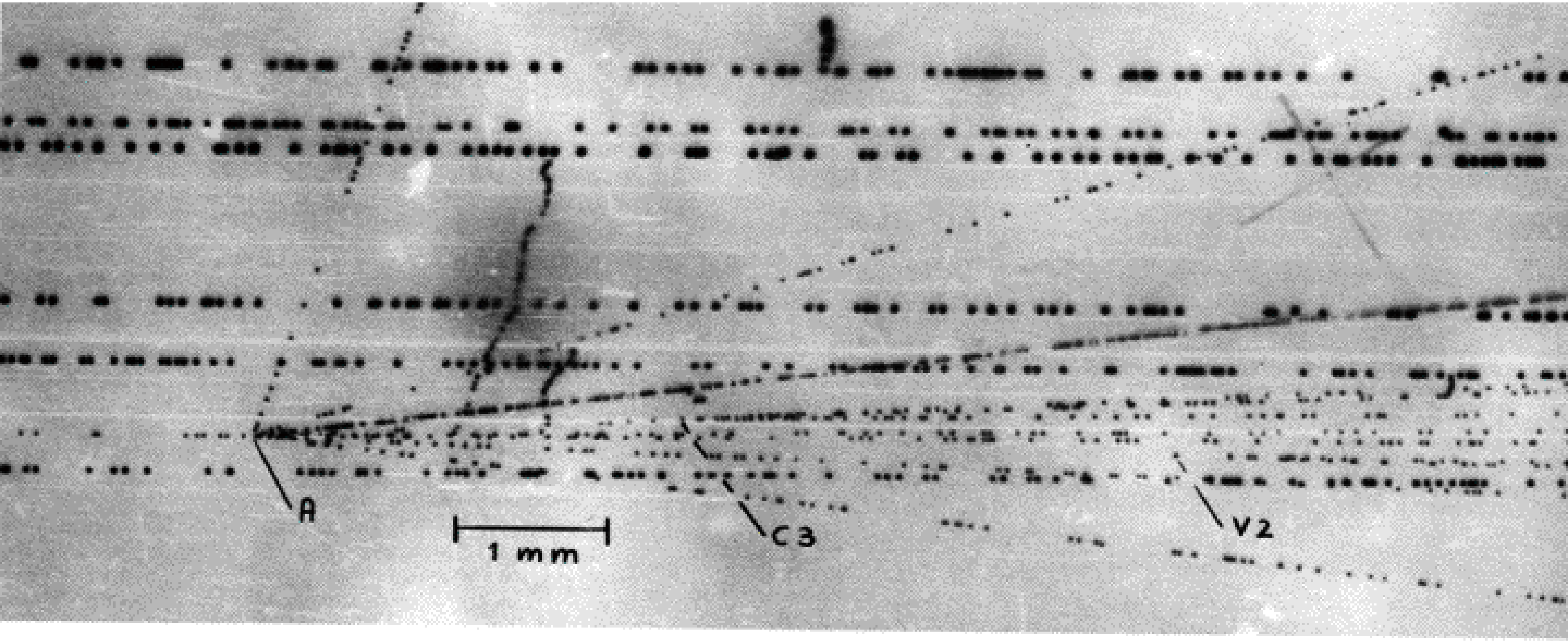
add information from ionisation measurement (probability to be π, K or p)

Only relevant background: strange decays

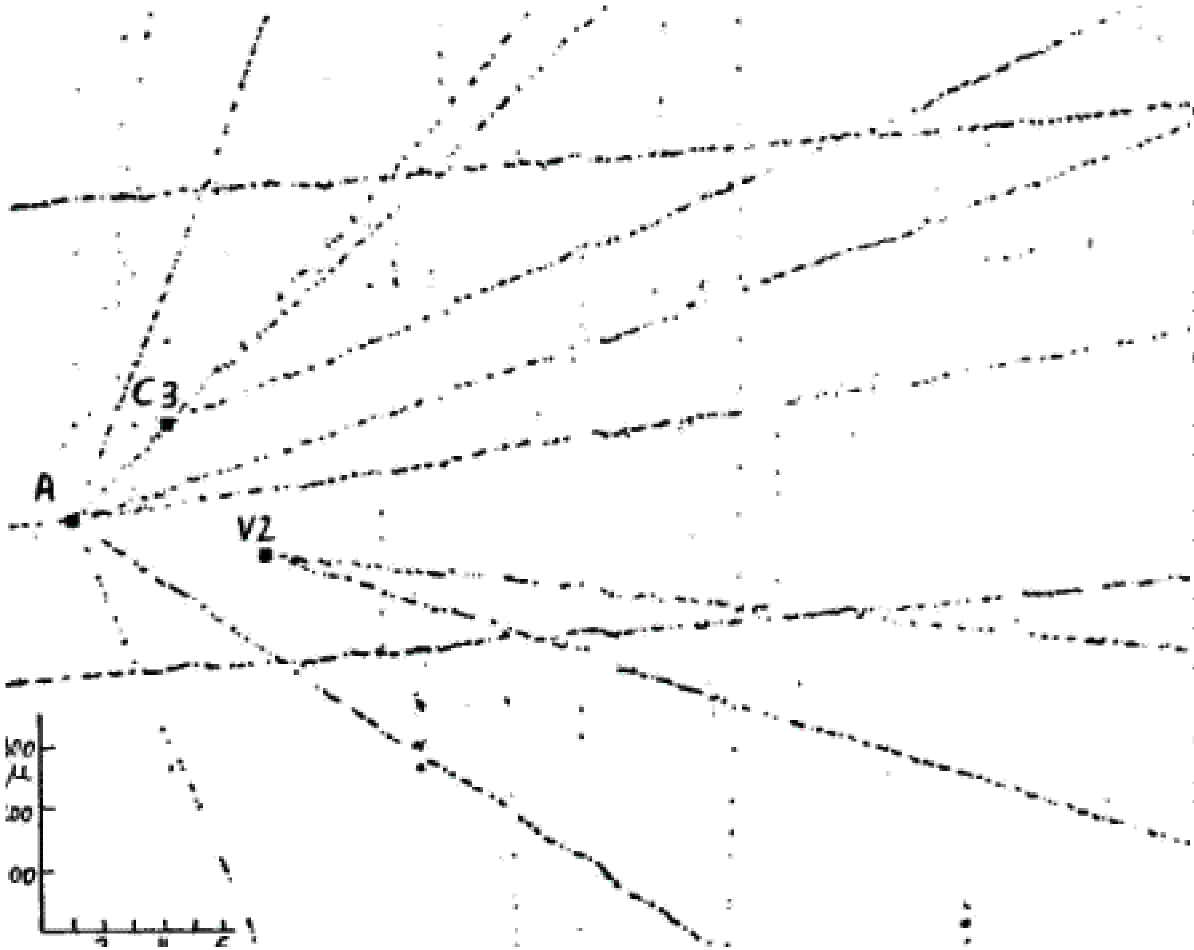
C3, V4 and C5 topologies are background free

V2 topology: cuts to eliminate strange background reduce sample by 40

LEBC V2 C3 event



LEBC V2 C3 event. HPD digitisation



The Strasburg HPD and its graphical interactive facilities was the highest precision and resolution instrument in the collaboration

RMS = 1.8 μm on film (=space)

Detect impact parameter> **7μm**

In 114 charm events of the π run the HPD measurement found the second previously unseen decay in 27 cases

Hadroproduction of charm

NA16 and NA27 gave the first reliable measurements of hadroproduction of charm in the forward direction; no A dependence problem

360 GeV $\pi^- p$ inclusive; $x_F > 0$

NA16 $\sigma(D^0/\overline{D}^0) = 7.7^{+7.2}_{-3.5}\ \mu b$

NA27 $\sigma(D^0/\overline{D}^0) = 10.1 \pm 2.2\ \mu b$

NA27 $\sigma(\Lambda_c) = 4 \pm 4\ \mu b$

NA16 $\sigma(D^\pm) = 4.5^{+2.2}_{-1.4}\ \mu b$

NA27 $\sigma(D^\pm) = 5.7 \pm 1.5\ \mu b$

400 GeV pp inclusive. All x_F . NA27

$$\sigma(D^0) = 10.5 \pm 1.9\ \mu b$$

$$\sigma(\overline{D}^0) = 7.9 \pm 1.7\ \mu b$$

$$\sigma(D^+) = 5.7 \pm 1.1\ \mu b$$

$$\sigma(D^-) = 6.2 \pm 1.1\ \mu b$$

$$\sigma(\Lambda_c)B(\Lambda_c \to pK\pi) = 1.2^{+1.6}_{-0.8}\ \mu b$$

similarity of D production cross-sections by π for x_f>0 and by p at all x_F points to

$$gg \to c\overline{c} \quad \text{rather than} \quad q\overline{q} \to c\overline{c}$$

..... and x_F, p_T distributions, QCD fusion study, branching ratios,. D^*..

$D^{\pm}$ lifetime

NA27 in 1988

149 $D^{\pm}$events

$\tau(D^{\pm})$= 1090+190/–150 fs

PDG 2002 average

$\tau(D^{\pm})$=1051±13 fs

The Si μstrip detector technique developed in the late '70s became by mid '80s the best instrument for charm and beauty lifetimes

Fermilab Tagged Photon Beam + Si μstrip vertex detector

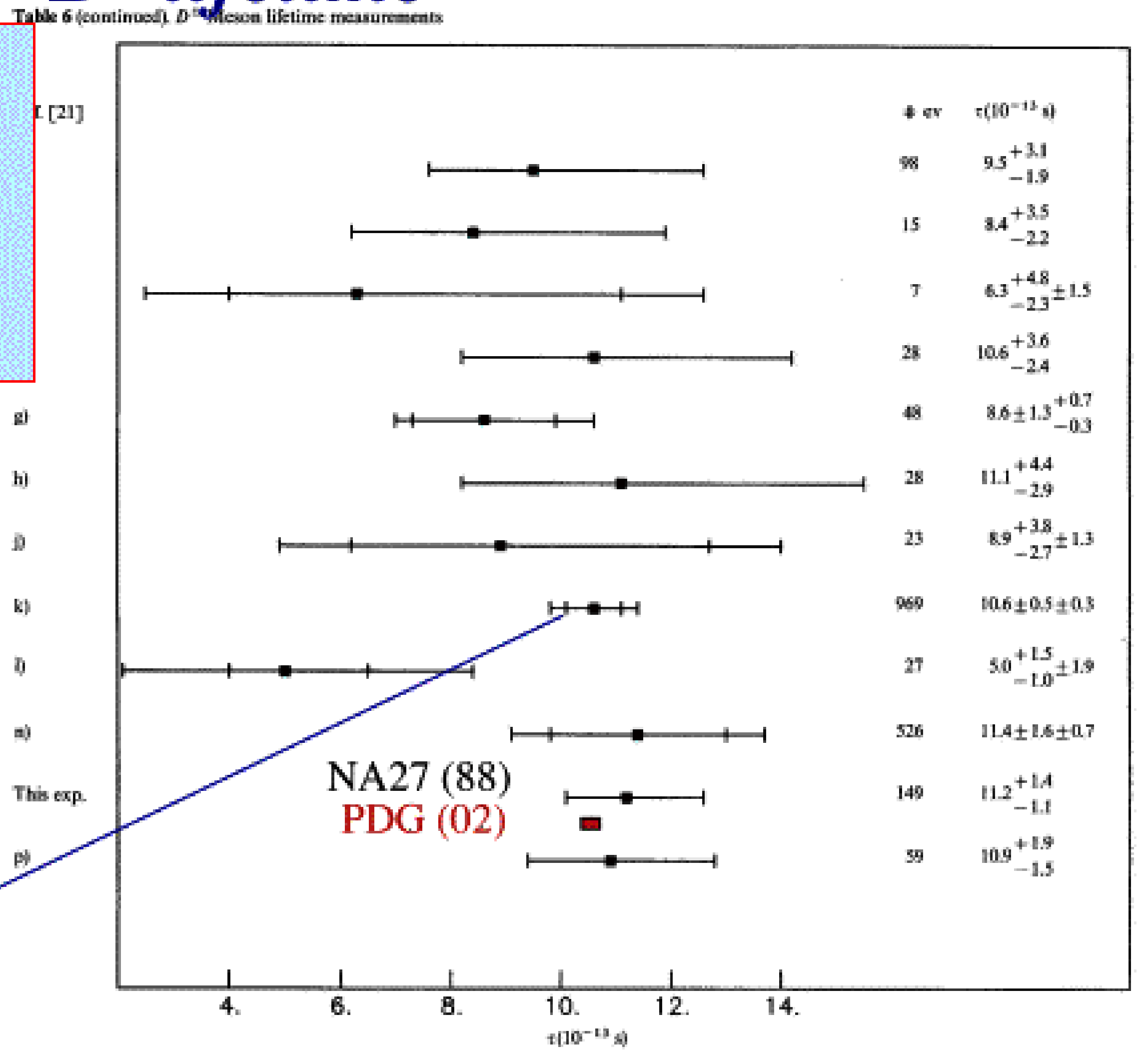
1987

969 $D^{\pm}$, 1360 D°

$\tau_{D\pm}$=(1060±50±30) fs

$\tau_{D^{\circ}}$=(435±15±12) fs

$\tau_{D\pm}/\ \tau_{D^{\circ}}$=2.44±0.14±0.08



Anjos et al. Phys Rev Lett **58** (1987) 311

$D°$ lifetime

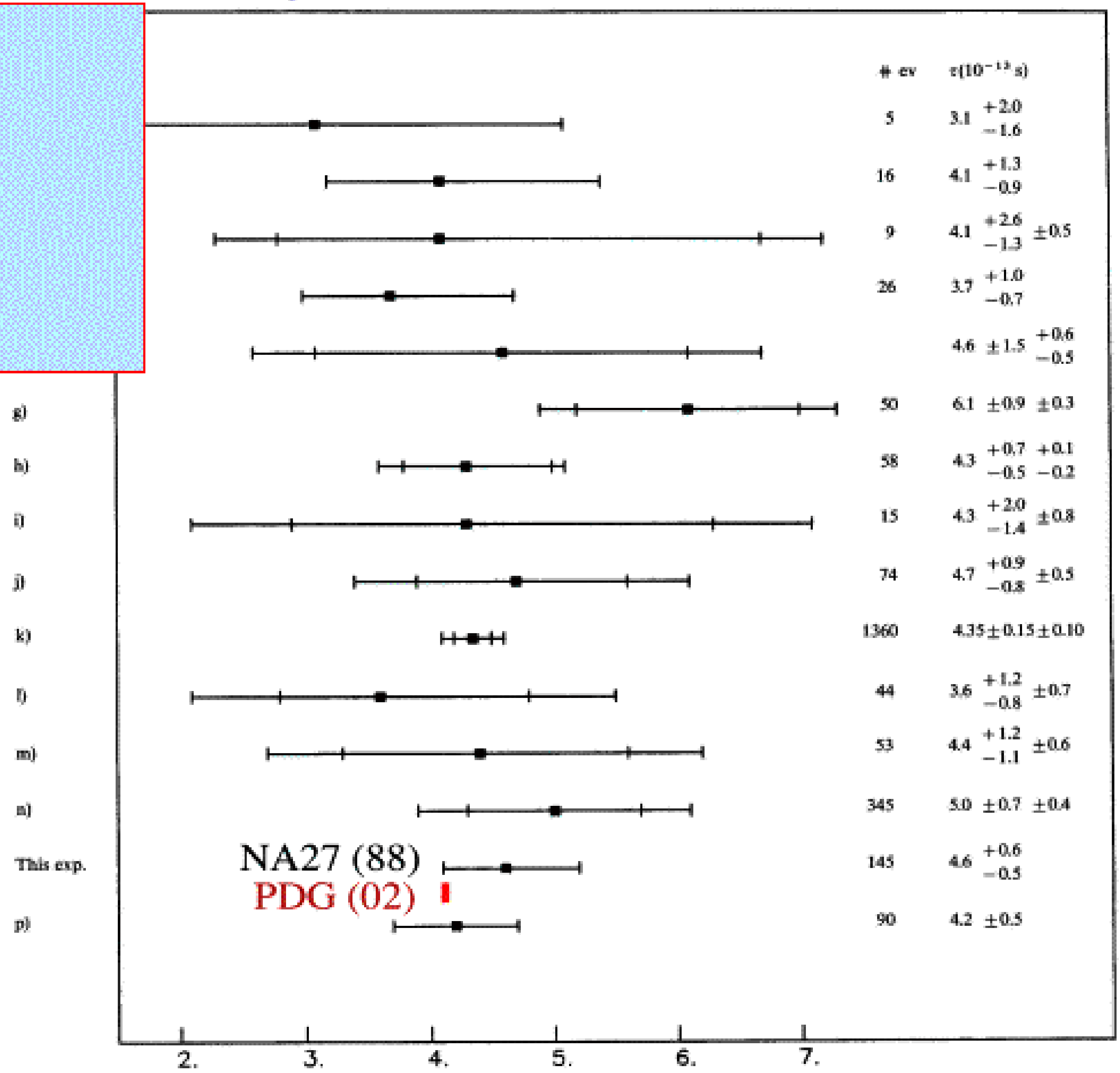
NA27 in 1988

145 $D°$ events

$\tau(D°)$= 460+60/–50 fs

PDG 2002 average

$\tau(D°)$=411.7±2.7 fs



NA27 in 1988

5 Λ_c events

$M(\Lambda_c)$=2284.7±2.3±0.5 MeV

PDG 2002 average

$M(\Lambda_c)$=2284.9±0.6 MeV

Λ_c mass

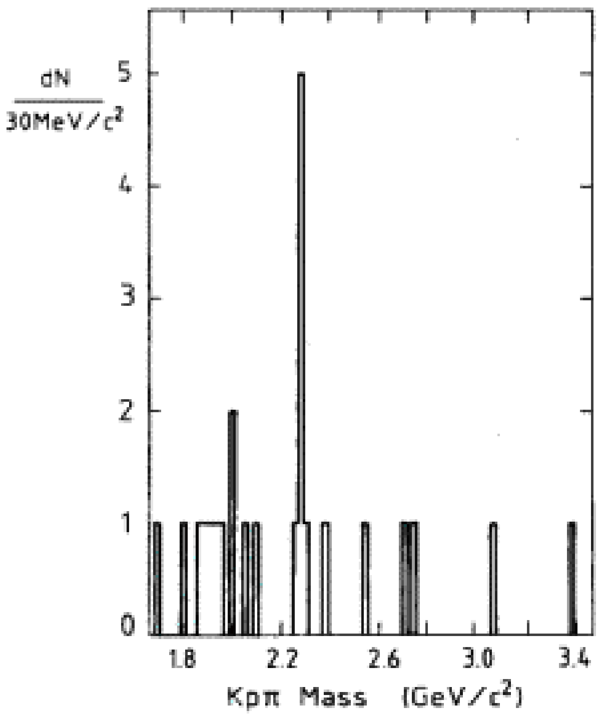
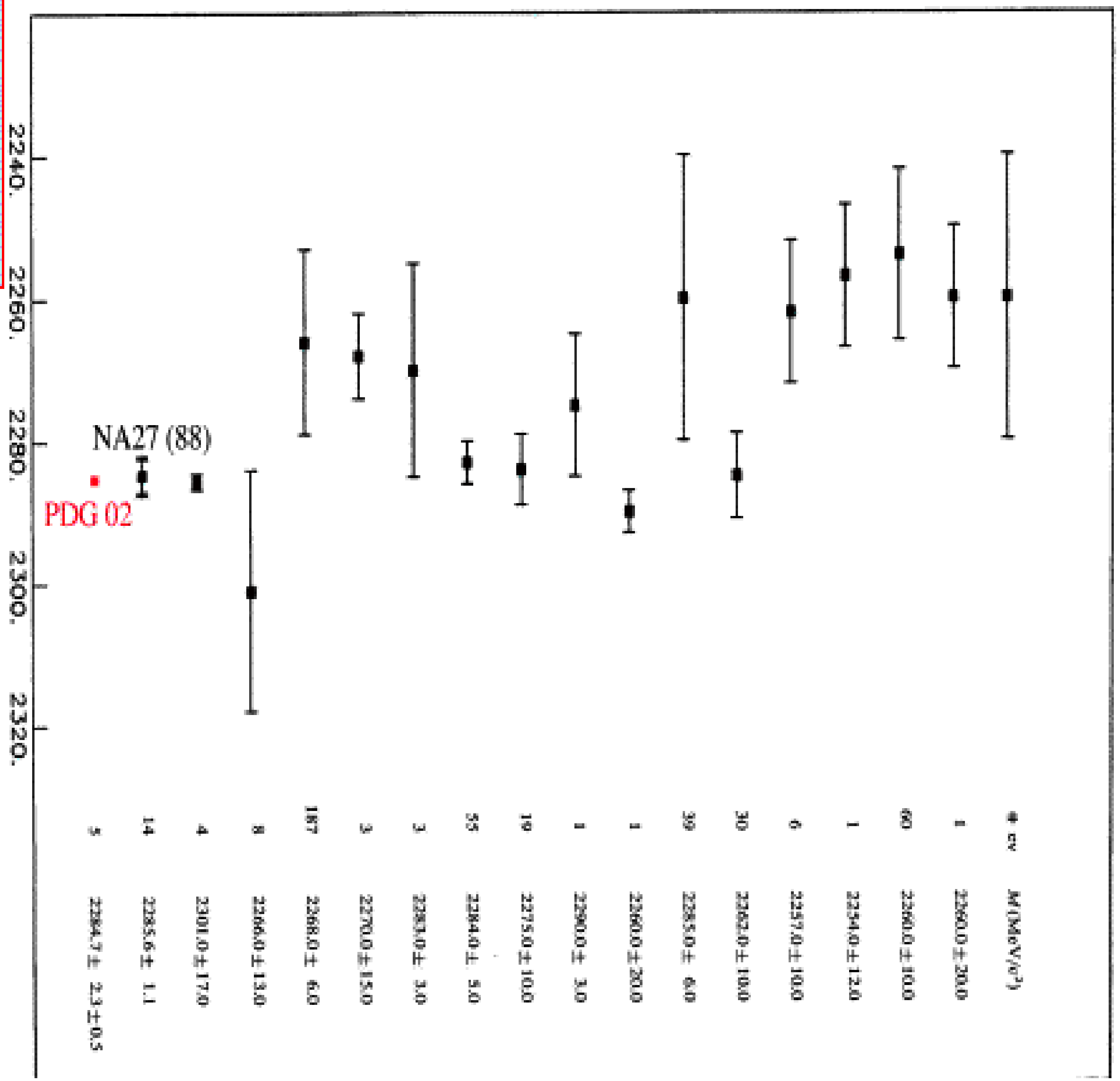


Fig. 2. pKπ invariant mass for the three-prong decays with an average impact parameter ⟨y⟩ smaller than 60 μm.



Λ_c *lifetime*

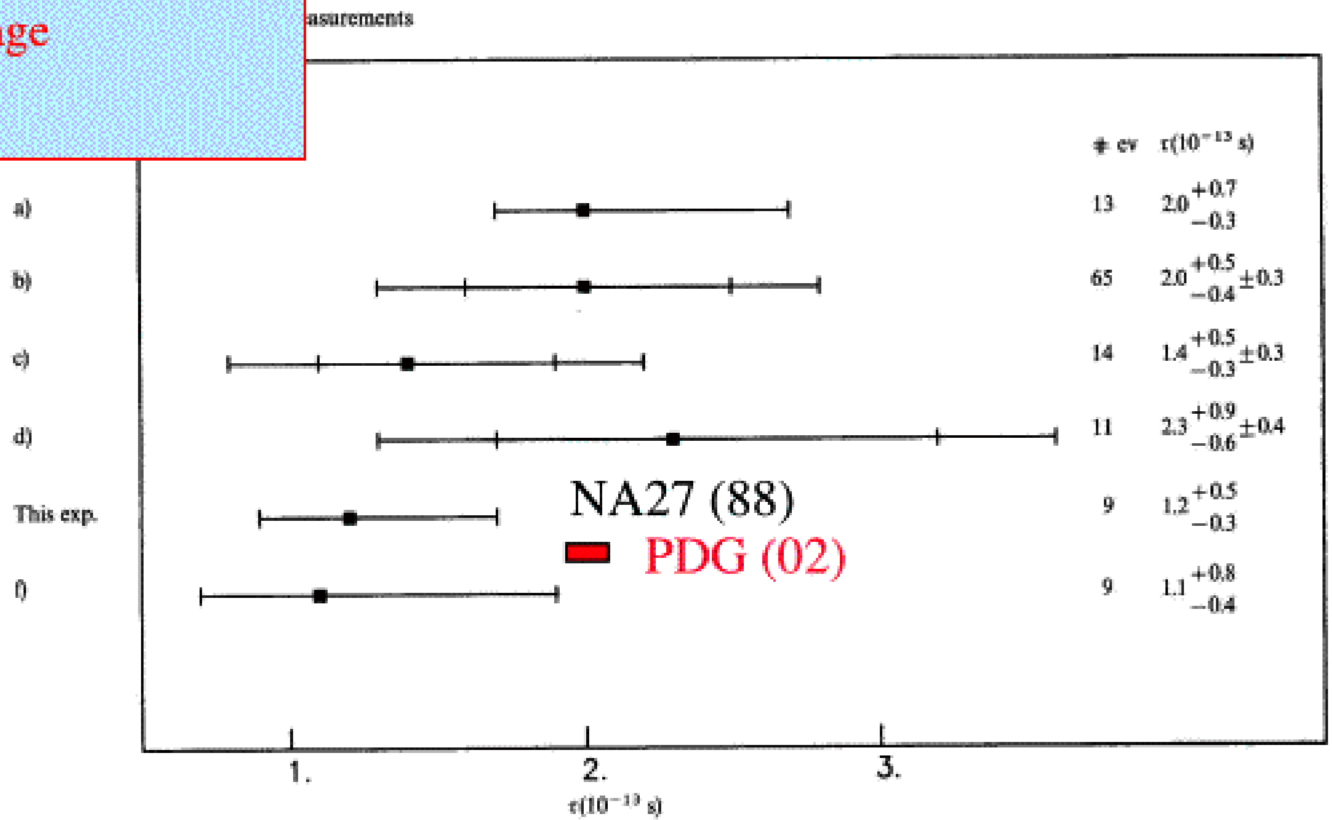
NA27 in 1988

5 Λ_c events

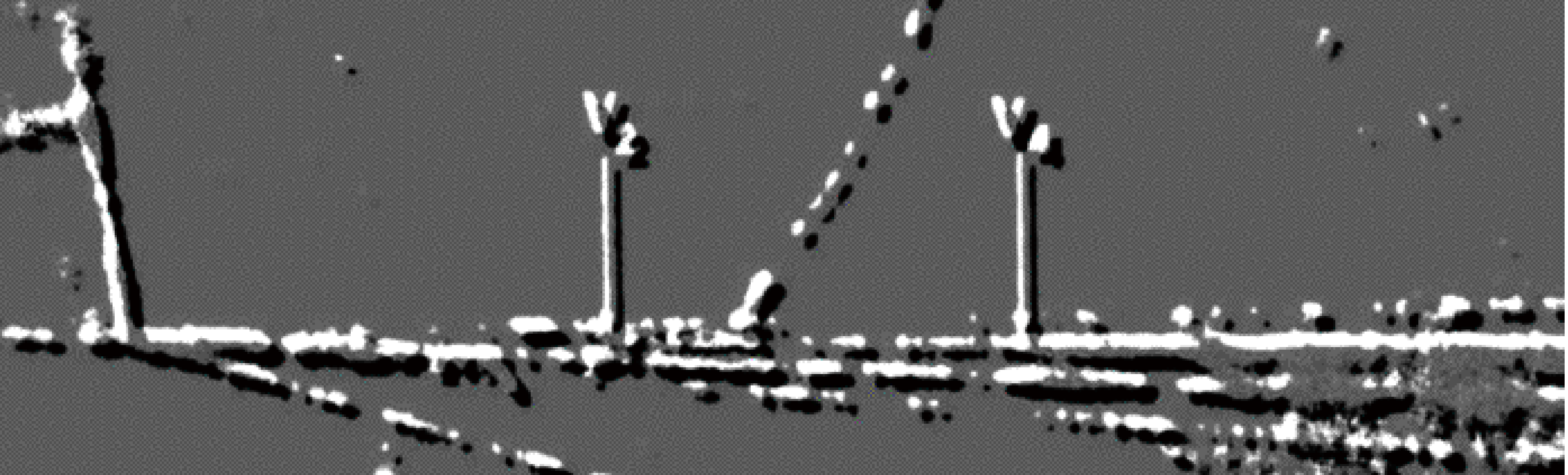
$\tau(\Lambda_c)$=120+50/–30 ps

PDG 2002 average

$\tau(\Lambda_c)$=200±6 fs



Conclusions



The measurement of the charm mesons lifetimes and hadroproduction characteristics have been the last important contribution of bubble chambers to physics

The concept of "general purpose" detector was over. But we did not miss the charmed window of opportunity (mid 70's to mid 80's) and developed the novel concept of high resolution BC coupled to a full large acceptance spectrometer

This basically made clear the issue of the charged vs. neutral lifetimes and that of the hadro-production cross sections. Then the Si μstrip technique took over

But concepts such as the fiducial volume trigger and the electronic image chamber contributed to the next generations of detectors