SPEAR Magnetic Detector (Mark I)

(Mark I)

Bob Hollebeek Grad Student 1970-1974

Postdoc Columbia, CERN Dec 1974-dec 1978

SLAC Assistant Professor 1979-1986

PENN Associate and Full Professor 1986 –

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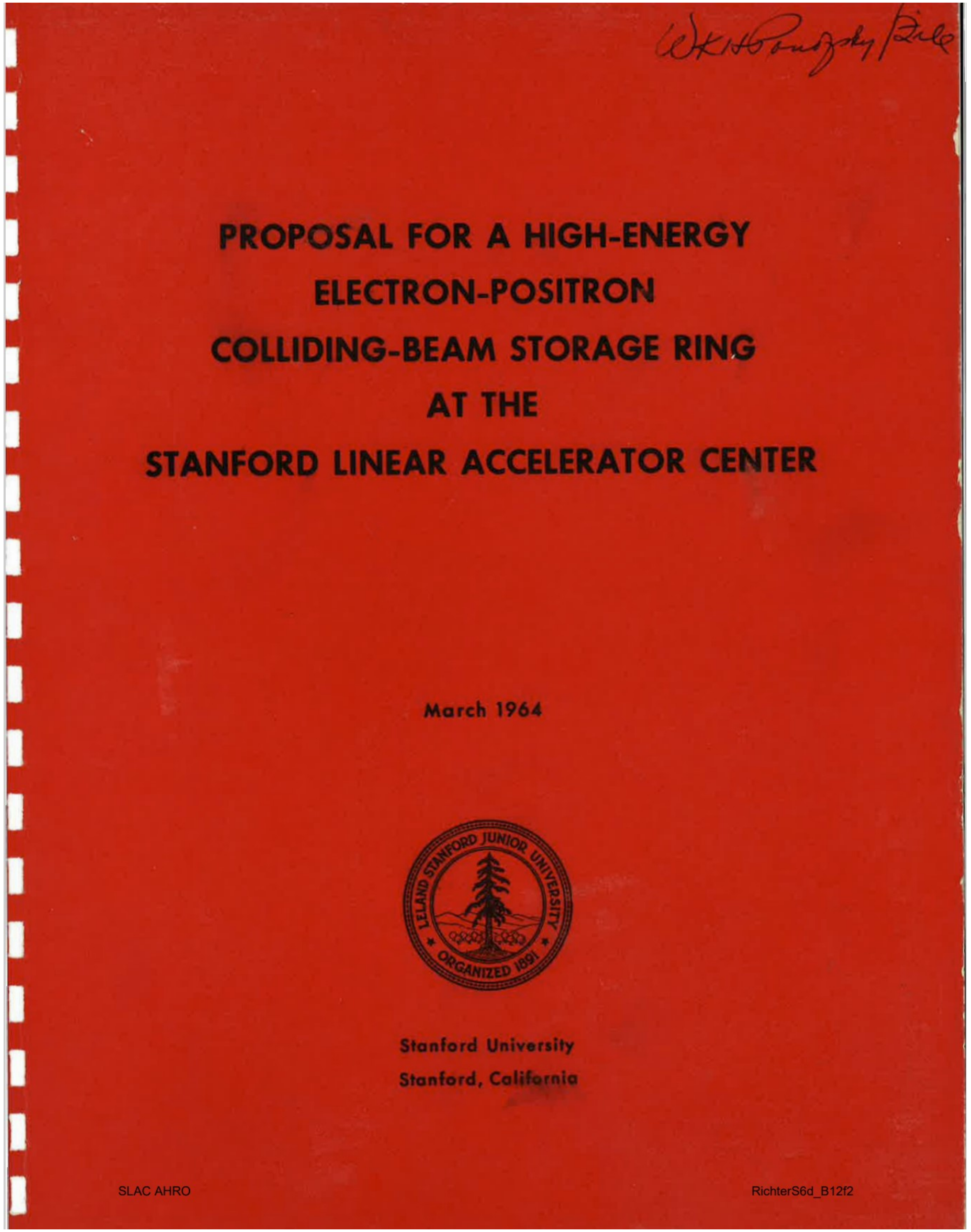
215-498-5277

1964 Proposal

Not approved –
accelerator studies proceed


PROPOSAL FOR A HIGH-ENERGY
ELECTRON-POSITRON
COLLIDING-BEAM STORAGE RING
AT THE
STANFORD LINEAR ACCELERATOR CENTER

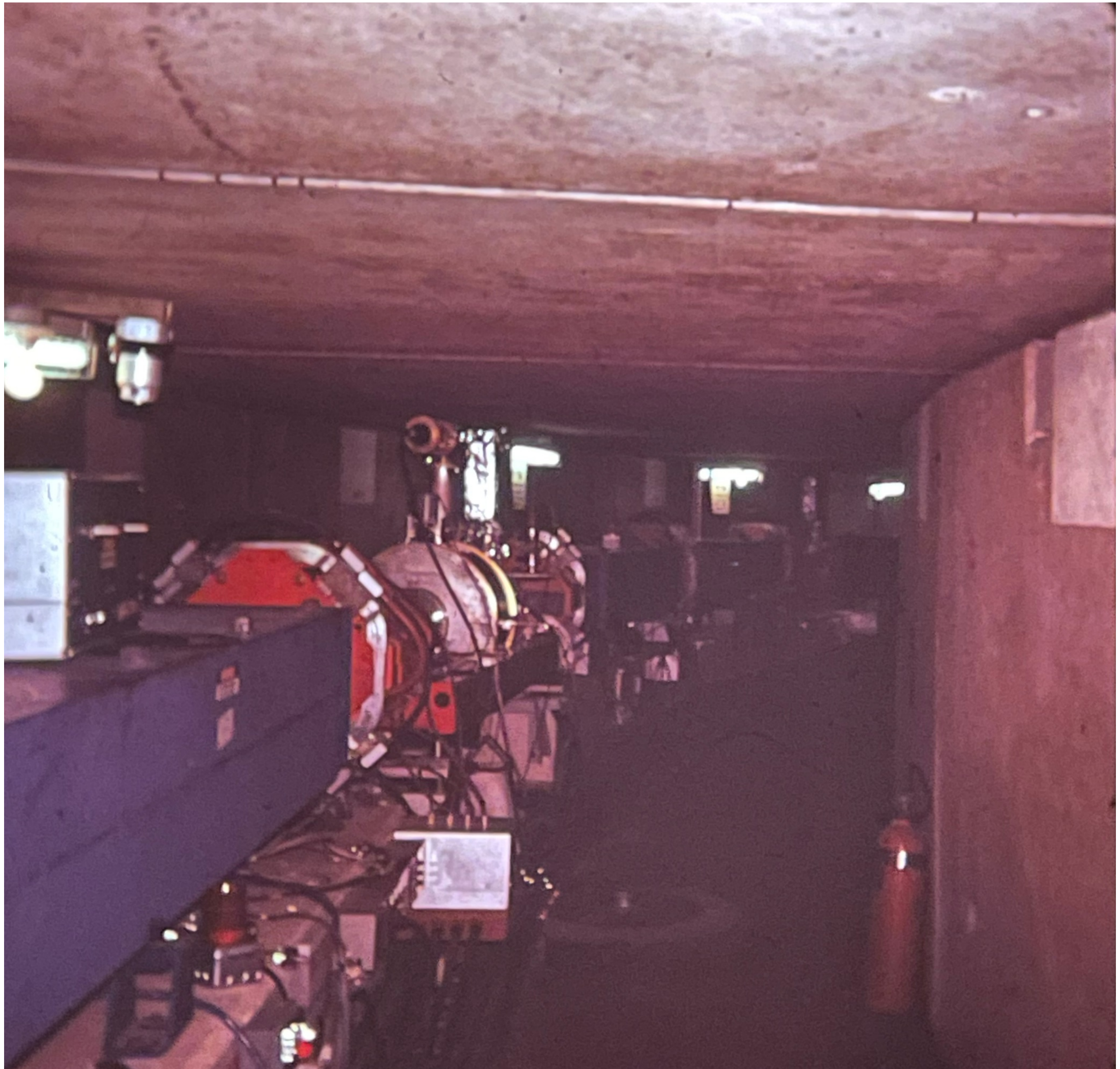
March 1964

Stanford University
Stanford, California

SLAC AHRO

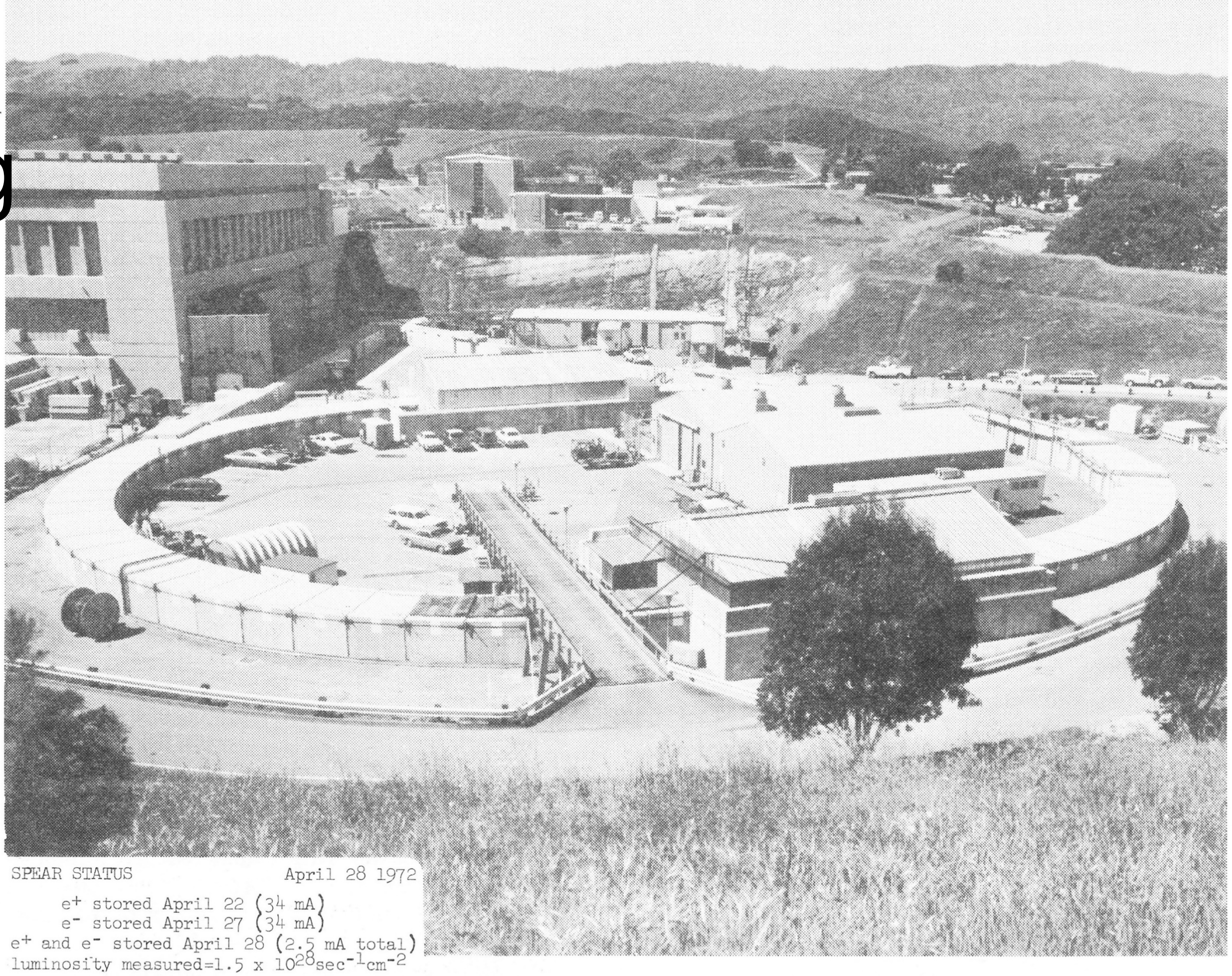
RichterS6d_B12f2

SPEAR Ring 1972



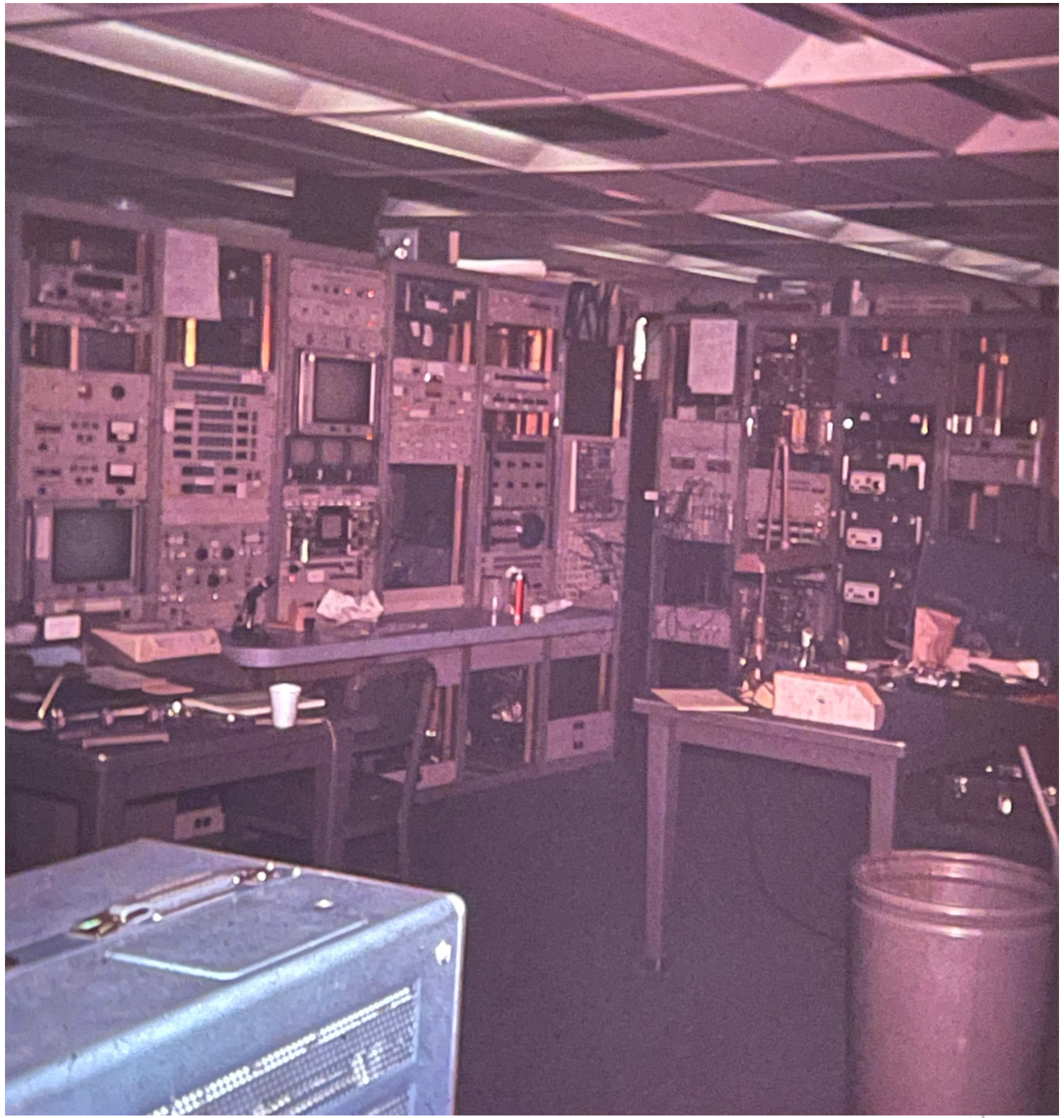
Bending Magnet, Quadrapole, RF

SPEAR Ring



SPEAR — 1972. *This photo of the first storage ring at SLAC was proudly completed with typed-on performance figures. The view is from the east end of the site looking over the Research Yard.*

Control Room (1972)



Positron Source (1964)

The positron beam at SLAC will be produced by the method developed by Pine and Yount at the Stanford Mark III linear accelerator.[1] Electrons are accelerated to some relatively high energy and then hit a thick radiator inserted in the machine. The radiator thickness (several radiation lengths, typically) is chosen to be that at which the maximum number of charged particles exists in the shower induced by the incident electron. That part of the accelerator downstream of the radiator is adjusted to accelerate positrons. At shower maximum in the radiator most of the positrons have energies near the critical energy in the material. Mark III experiments have shown that in tantalum most of the positron energies lie between zero and 20 MeV. This whole energy bin is accelerated to a high energy; the positrons have the same absolute energy spread at any final energy.

The present conversion efficiency f measured at Mark III for 500 MeV electrons incident on a 3.2 radiation length target is[2]

$$f = 2 \times 10^{-4} \; e^+/e^-$$

for a positron energy spread of 20 MeV, within the phase-space acceptance of the accelerator. This measurement was made by comparing the current of positrons accelerated to 500 MeV, within a 20 MeV spread, with the electron current incident on the radiator.

The conversion efficiency is approximately proportional to the energy of the electron incident on the radiator, and hence we can simply scale the efficiency measured at Mark III in order to compute the positron beam intensity expected at SLAC. The number of positrons per pulse within the storage ring acceptance is given by

$$N_+ = f \times \frac{E}{500} \times \frac{\Delta E_s}{20} \times N_-$$

---

[1] D. Yount and J. Pine, Nucl. Instr. and Methods 15, 45 (1962).

[2] A. Browman, private communication.

Magnetic Detector Proposal team

December 27 1971

1. Title of Experiment: Proposal for a Magnetic Detector for SPEAR

2. Spokesman: Rudolf R. Larsen

Experimenters:

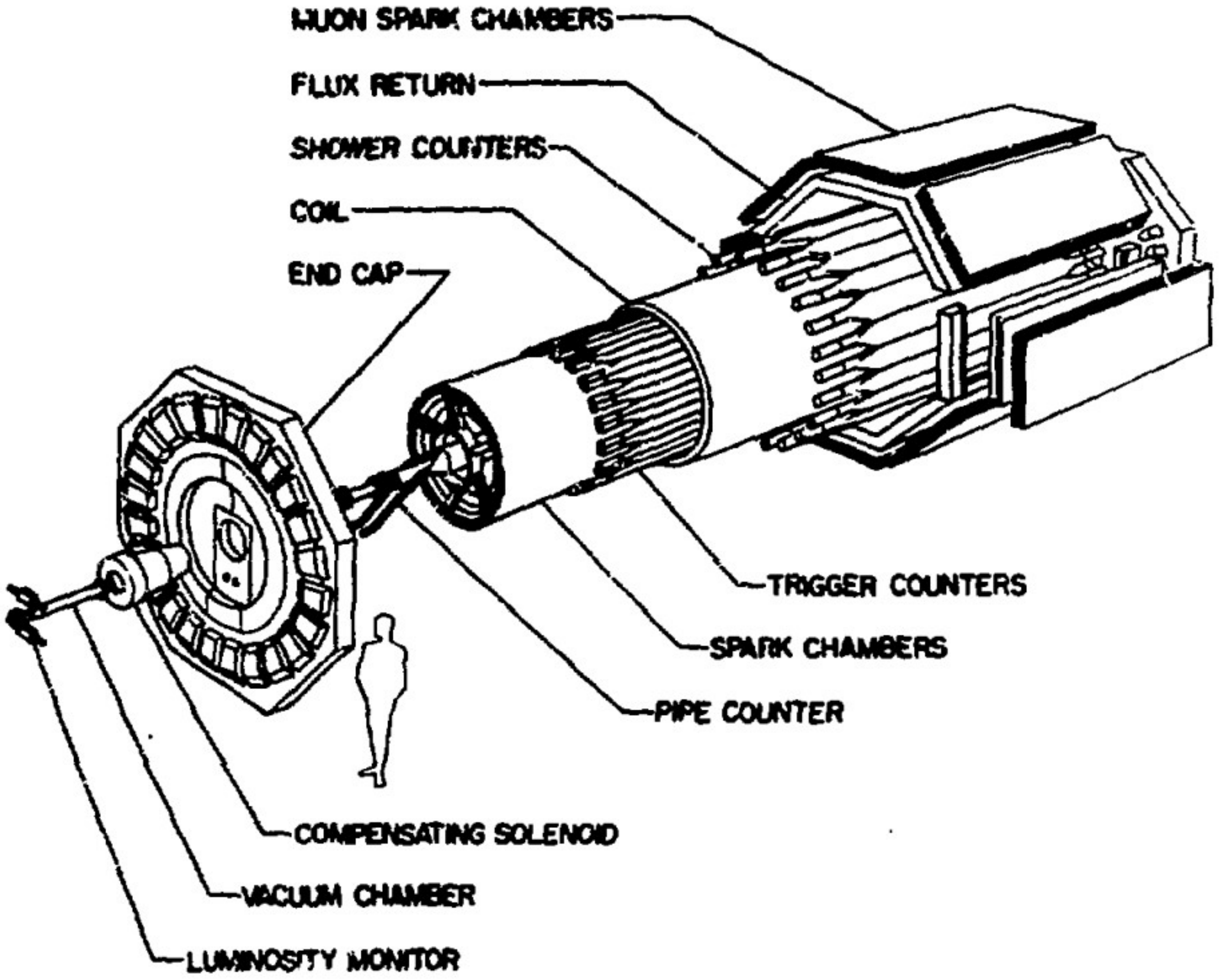
Name	Group and Distribution
A. M. Boyarski	Group C - SLAC
J. Dakin	Group E - SLAC
G. Feldman	Group E - SLAC
G. E. Fischer	Group C - SLAC
D. Fryberger	Group EFD - SLAC
Rudolf R. Larsen	Group C - SLAC
H. L. Lynch	Group C - SLAC
F. Martin	Group E - SLAC
M. L. Perl	Group E - SLAC
J. R. Rees	Group C - SLAC
B. Richter	Group C - SLAC
R. F. Schwitters	Group C - SLAC
G. S. Abrams	LBL - UC Berkeley
W. Chinowsky	LBL - UC Berkeley
C. E. Friedberg	LBL - UC Berkeley
G. Goldhaber	LBL - UC Berkeley
R. J. Hollebeck	LBL - UC Berkeley
J. A. Kadyk	LBL - UC Berkeley
G. H. Trilling	LBL - UC Berkeley
J. S. Whitaker	LBL - UC Berkeley
J. Zipse	LBL - UC Berkeley

Thesis Acknowledgments

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the contributions of the many members of the SLAC-LBL Magnetic Detector Group and also to thank the SPEAR staff and operators for the successful construction and operation of the storage ring which made this experiment possible. I would also like to thank my advisor, W. Chinowsky, for making my graduate experience a pleasant one and for his many discussions and suggestions during the course of this work. I am pleased also to acknowledge the contribution of B. Richter who kept track of my work at SLAC and several times initiated the discussions which got the analysis moving again after difficulties had slowed it down. I must also thank M. Breidenbach, A. Boyarski, C. Morehouse, R. Schwitters, and H. Lynch for countless discussions both of the physics results and the day-to-day problems of the analysis. Finally, to Jeanne Miller, who had to type this, my apologies.

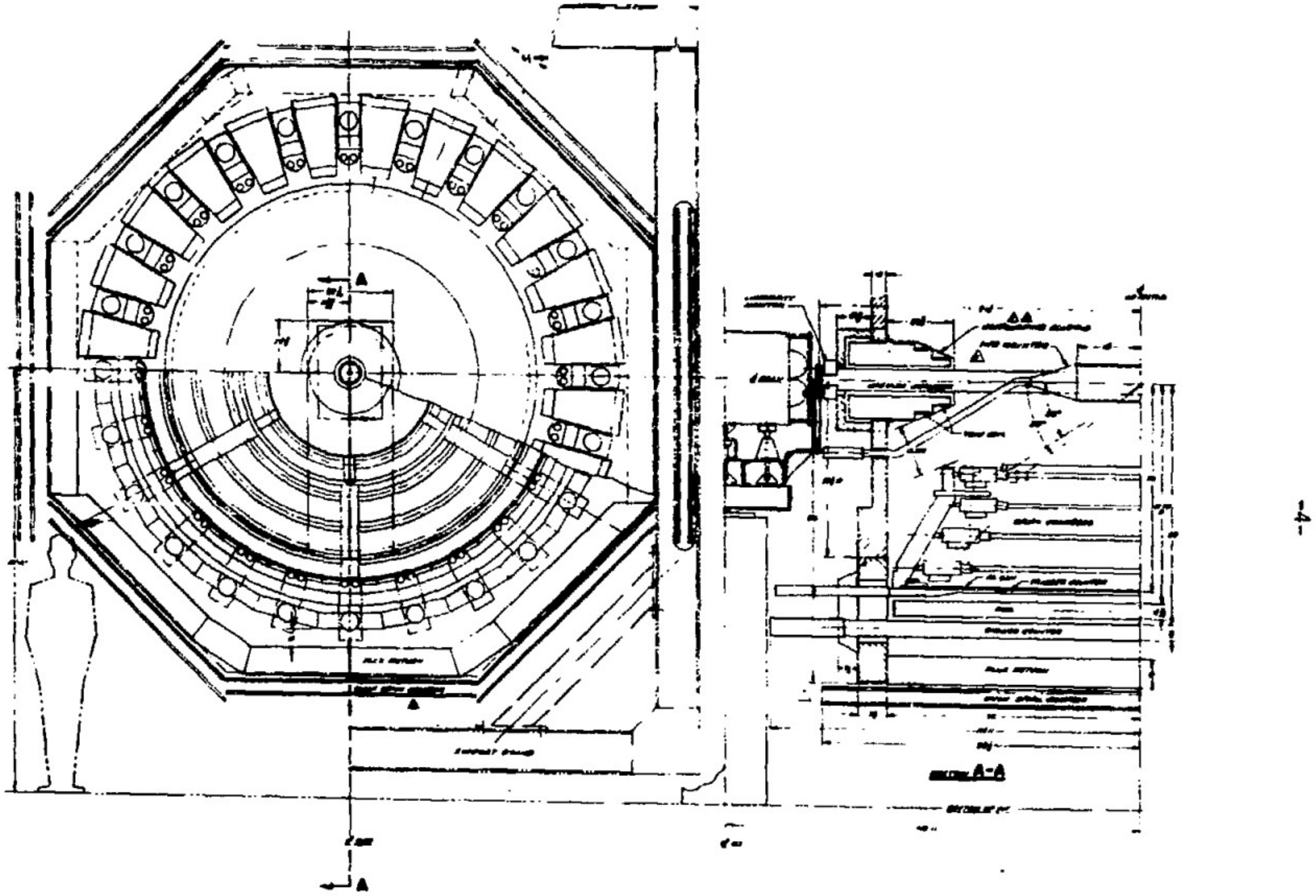
Detector



XBL 753-404

Fig. 1

Thesis Detector -z



XBL 753-405

Detector -xy

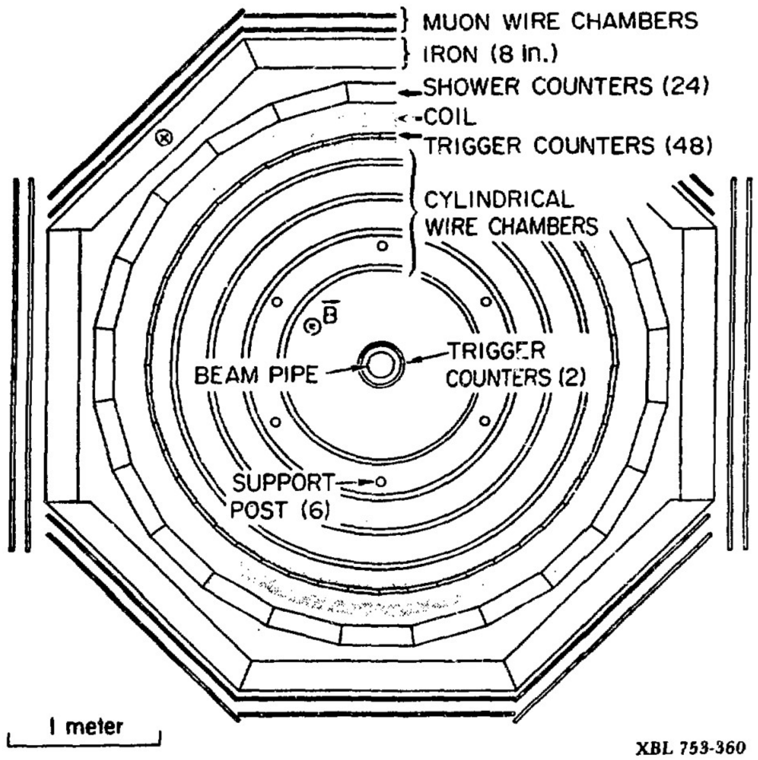


Fig. 3

Stories

Wiring with Scott

Scott and I, travelling daily from Berkeley in an LBL car, were given the job (by Marty) of connecting said, the TDCs . Seemed simple enough, so we got to work. The cables were 4ns Lemo and went from the discriminators to the TDC via 4ns LEMO cables. There were a lot of cables sand a crate full of camac module so we carefully checked everything and went back to Berkeley in the evening rush. There were a lot of cables completely covering the crate, so we were quite proud of our work.

and Marty

When we returned the next morning , we were surprised at what we saw. The cables had been completely redone by Marty. They were neatly bundles and bound with cable ties. The face of the modules were no longer covered. Instead, it was easy to extract a module and be reasonably sure that only the few cables removed were to be plugged back in. (required a special tool).

High Voltage with Rudy

I was on the night shift with Rudy Larson. One experienced physicist and one grad student. When the beam crashed and the klystron needed to be reset, we headed out the side door of the control room to the klystron cabinet. We needed a tall ladder and a hook to ground the top of the unit. Just before heading up, Rudy turned to me and said, “do you know CPR ”. I said no and held the ladder tight. (Later at CERN I learned CPR, fire fighting, and putting out electrical fires.)

(Rudolf Reinhold Larsen, 94 – The Glenn County Observer)

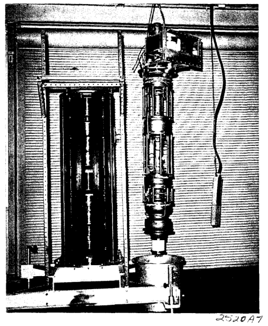


FIG. 7--Photograph of a SPEAR II, 125-kW cw klystron.

More stories

Choice of running energies

I don't know who I asked, but when it was decided to start at 3.0,3.8,4.8 for high statistics and scan in 100 MeV intervals, I asked why it was as large as 100 MeV. The answer had something to do with the scale of strong interactions at high energies.

Strike and energy setting

In the middle of the runs, there was a strike by the operators, so the machine was run instead by physicists. The energy was set by a n oscillator in the control room .

You needed to be sure that you did not cross any resonances of which there were many.

Tracking names -> Pearl

The original names of the tracking routines were Marsha, Elsie, Doreen, and Pearl, but eventually it was just Pearl – another story.

Vertex finding and fitting Circe and dumpdup and Boojum and Snark

I was also writing code to find vertices and to combine that with better recalculations of the track momenta.. This led to circe, dumpdup, boojum, and Snark. Those of you familiar with Alice might see something here and the code was full of quotes from CS Lewis.

Burt and tracking/leaving/returning

I went to SLAC almost daily during the runs, and while there often met with Burt – he was really interested in the tracking and often had very good suggestions.

Computer systems November 1972

Sigma 5 CPU with 48k 32-bit words

1.17 megahertz Sigma 5

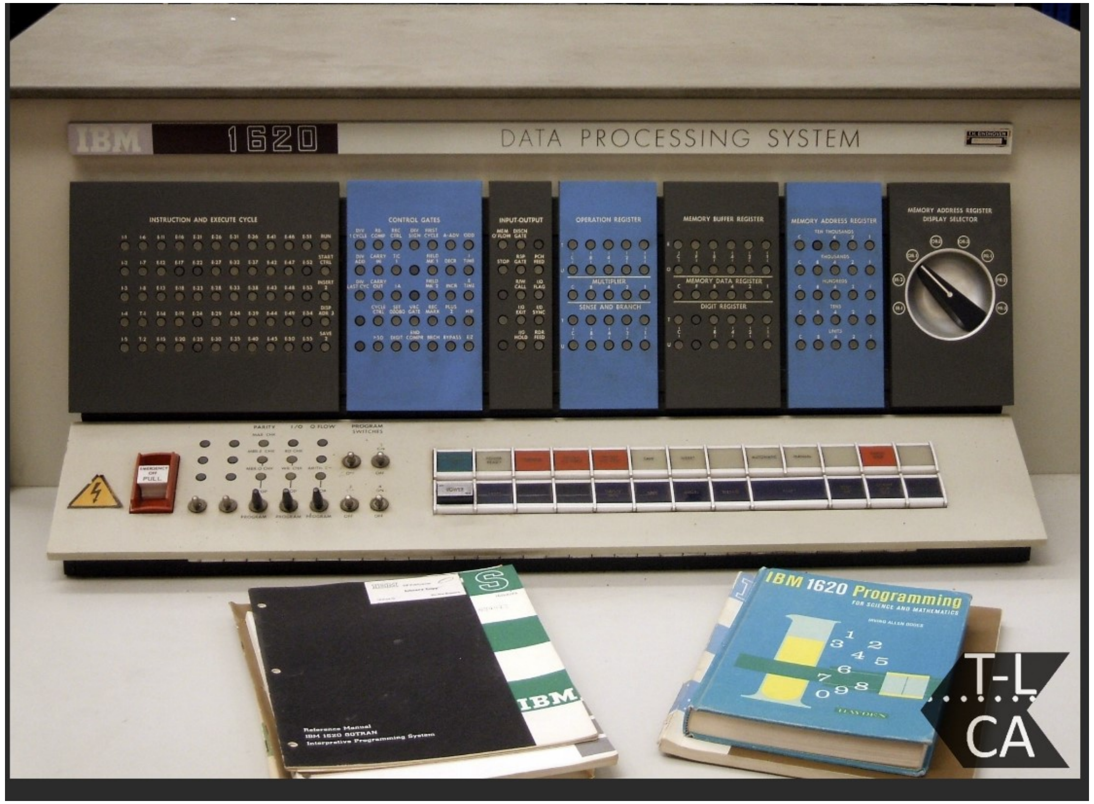
Fortran

Display 1024x1024 (8”x8”)

IBM 1620 Arizona State University 1964

Learning to Program on the IBM1620
at ASU while in high school
(sophomore)

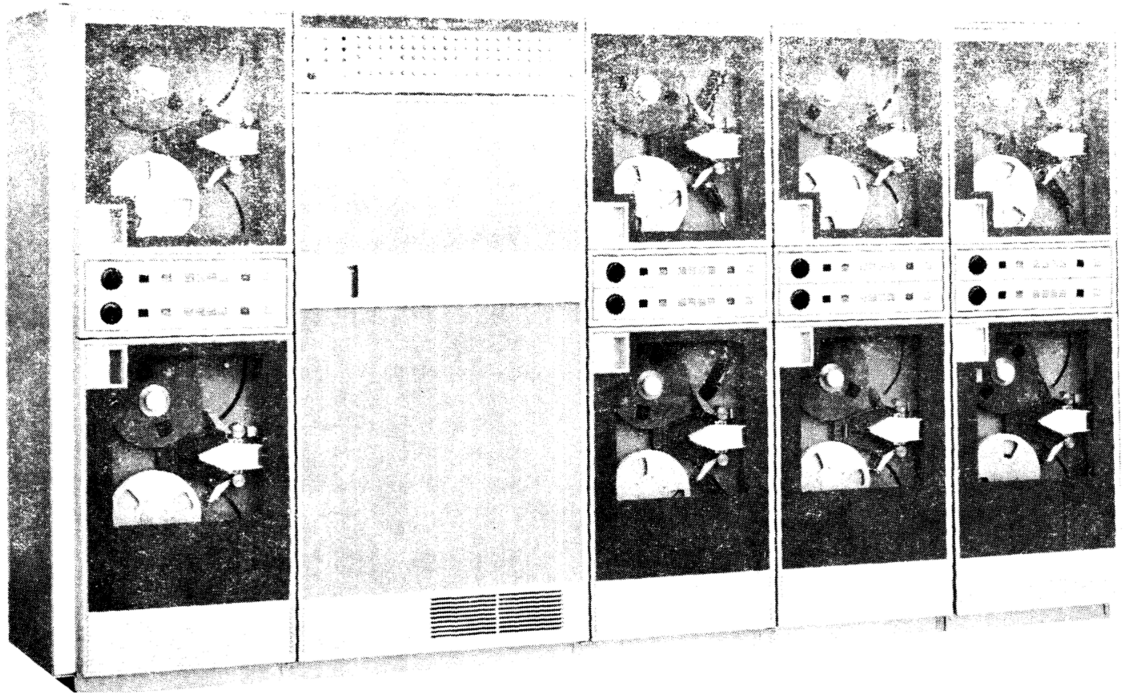
Course for HS students at
Arizona State University (ASU)
to teach programming in Fortran



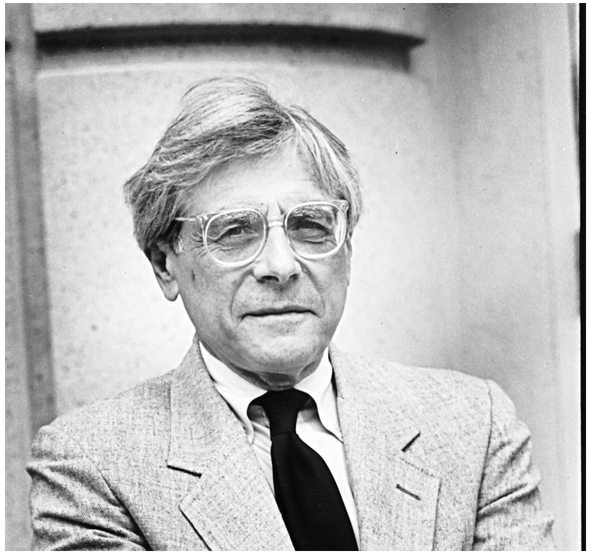
ASU (Tempe Arizona)) computing (Fortran)

Evenings at ASU – prime numbers (Junior year)

GE-225   Phoenix was GE computing home
ASU 1965



Willy Chinowsky



Digital PDP8

Joined Willy Chinowsky in Segre-Chamberland group at LBL

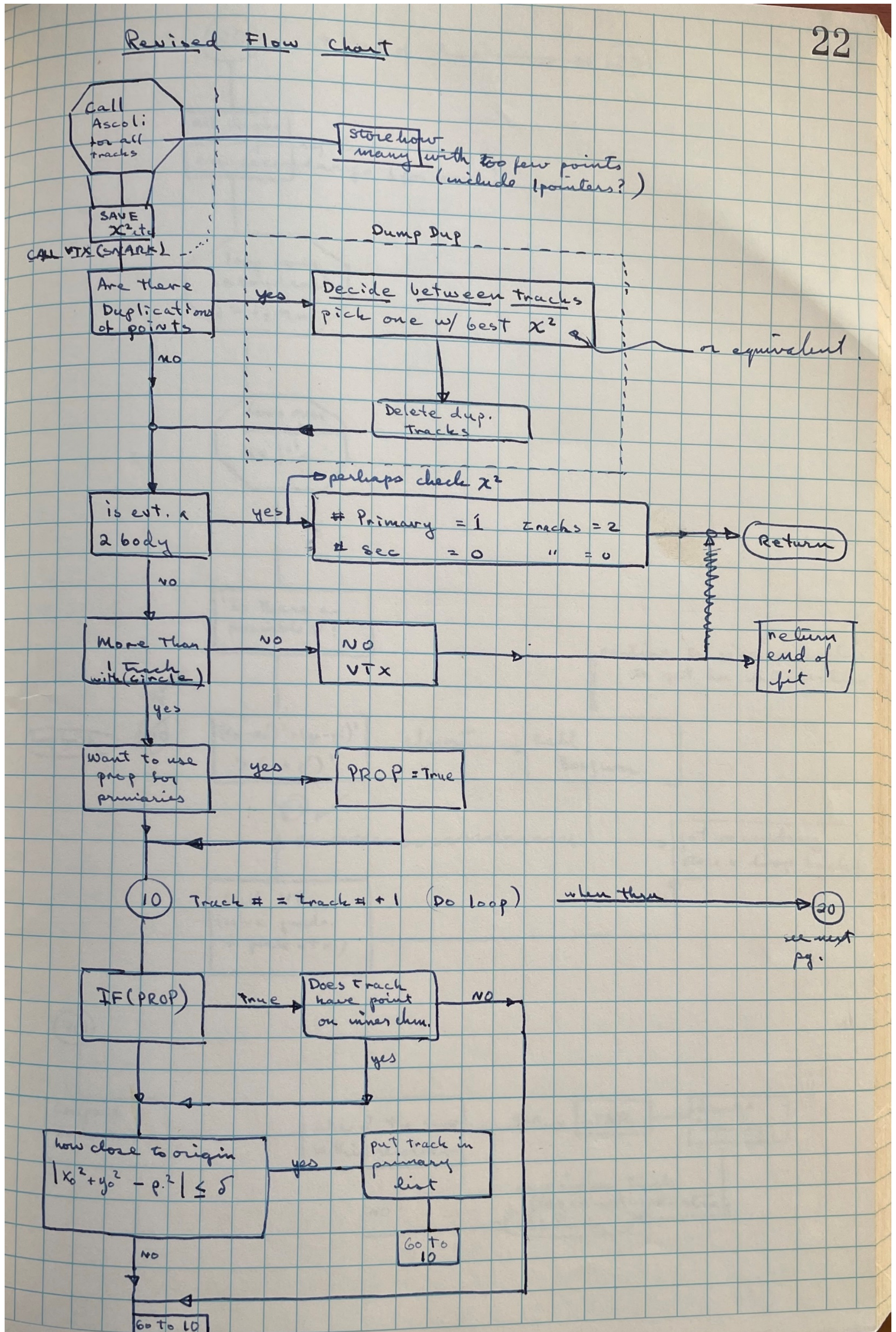
First Assignment
Bevatron tests of shower modules and scintillator
Paper tape input program
Machine Language

My focus: tracking and fitting, vertex finding

Early Flow diagram
Outside to inner layer Tracking
Duplicate removal
Vertex finding and fitting

Check with simulations
Write display routines

Check results on simulations



First Problem

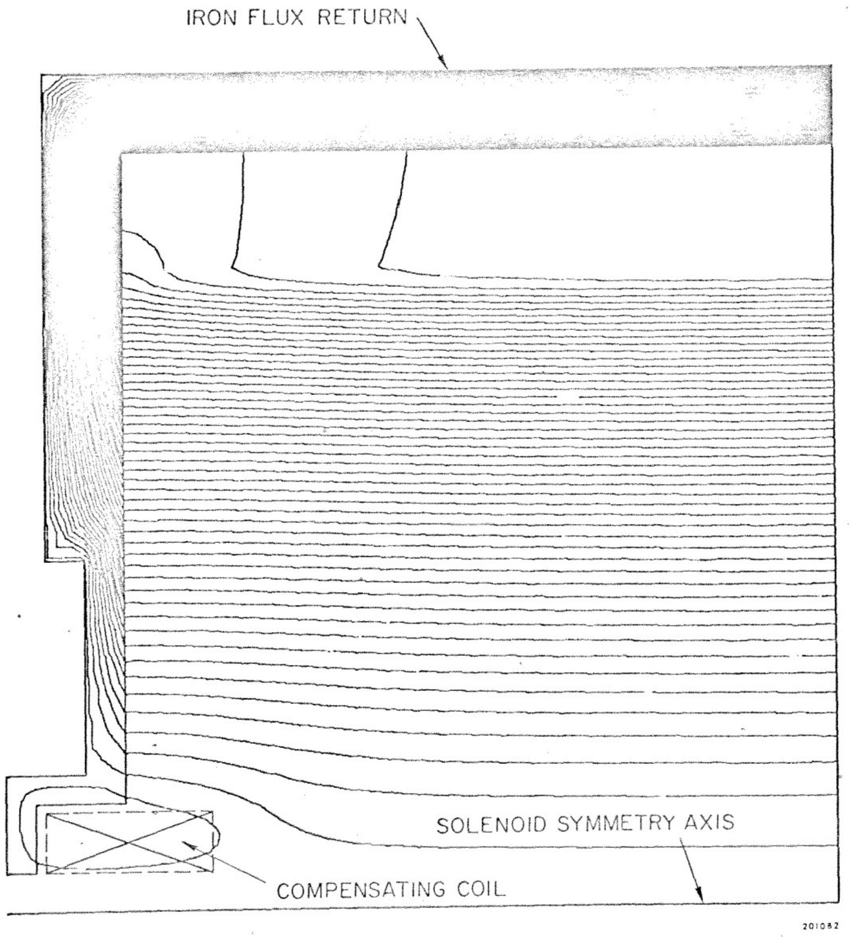
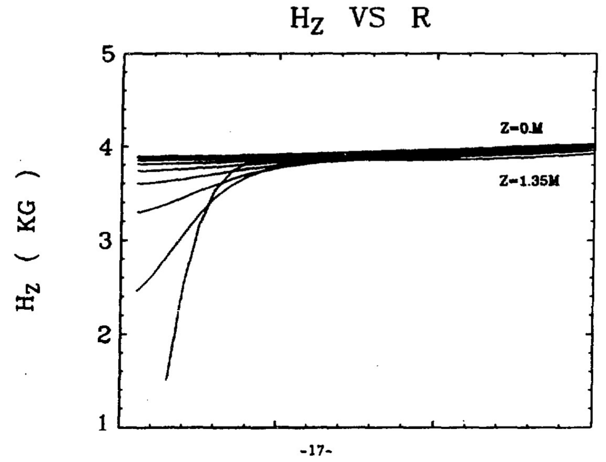


FIGURE 3

Thesis
hz vs r



hz vs z

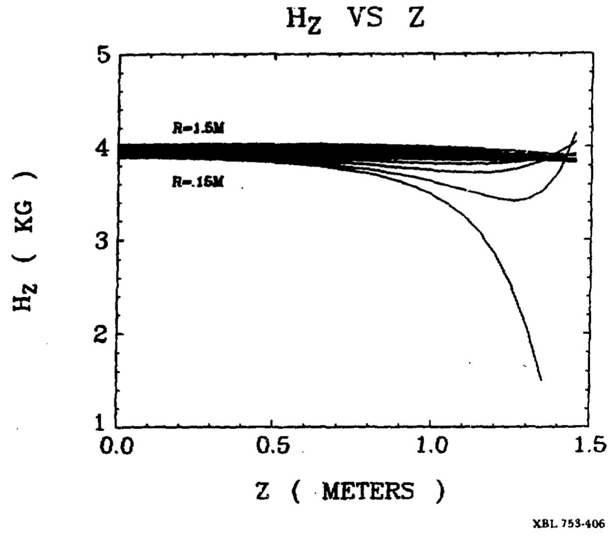


Fig. 5

hr vs z

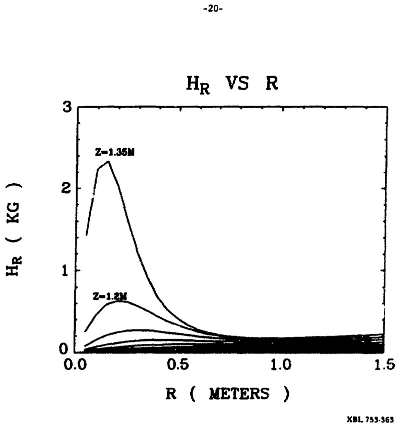


Fig. 8

Second Problem
Wire chamber radii (missing inner measurements)

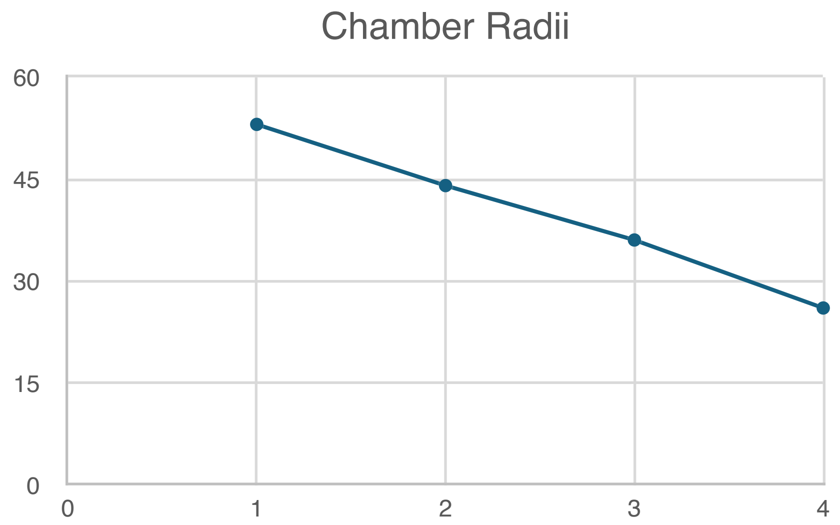


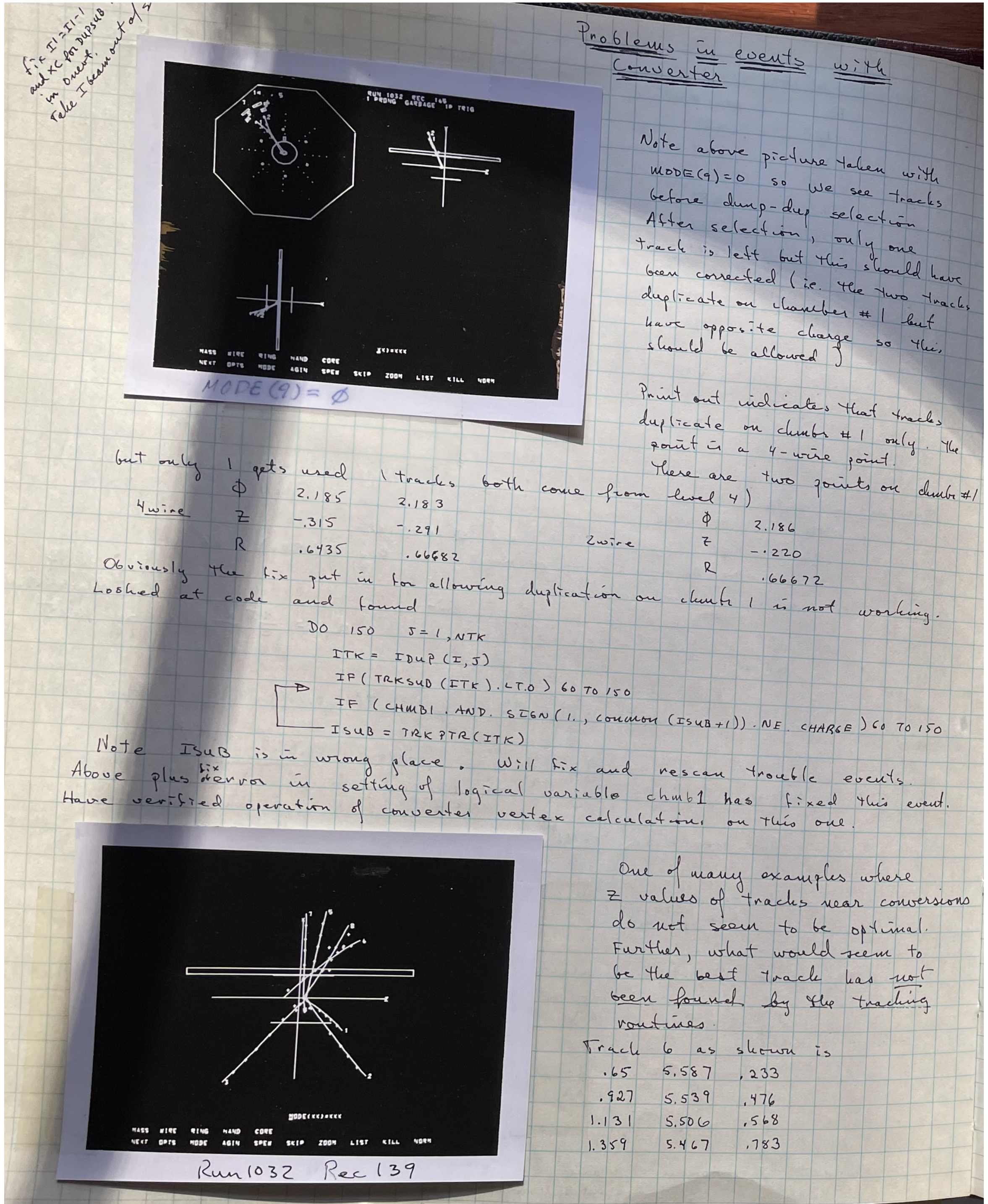
Table 1.

Chamber #	R	L	Wire Spacing	Approx. # of Wires	# of Wands
1	53"	106"	1/24"	31900	16
2	44"	95.6"	1/24"	26500	24
3	36"	86.4"	1/24"	21700	28
4	26"	86.7"	1/24"	15700	32

Table 1

My Logs – real data – scans

Corrections
Conversions
Posts
Z information



fix I'=I1-1 and XC for DUPSUB in ONEVT. Take I beam out of 4

RUN 1032 REC 145
1 PRONG GARBAGE 1P TRIG

MASS WIRE RING HAND CORE
NEXT OPTS MODE AGIN SPEW SKIP ZOOM LIST KILL NORM

MODE(9) = ∅

Problems in events with Converter

Note above picture taken with MODE(9)=0 so we see tracks before dump-dup selection. After selection, only one track is left but this should have been corrected (i.e. the two tracks duplicate on chamber #1 but have opposite charge so this should be allowed)

Print out indicates that tracks duplicate on chmbr #1 only. The point is a 4-wire point. There are two points on chmbr #1 but only 1 gets used (tracks both come from level 4)

4wire	Φ	2.185	2.183	2wire	Φ	2.186
	Z	-.315	-.291		Z	-.220
	R	.6435	.66682		R	.66672

Obviously the fix put in for allowing duplication on chmbr 1 is not working.
Looked at code and found

```
      DO 150  J=1,NTK
      ITK = IDUP(I,J)
      IF (TRKSUD(ITK).LT.0) GO TO 150
      IF (CHMB1 .AND. SIGN(1.,common(ISUB+1)).NE.CHARGE) GO TO 150
      ISUB = TRKPTR(ITK)
```

Note ISUB is in wrong place. Will fix and rescan trouble events.
Above plus ~~error~~ fix in setting of logical variable chmb1 has fixed this event.
Have verified operation of converter vertex calculation on this one.

MODE(XX)=XXX

MASS WIRE RING HAND CORE
NEXT OPTS MODE AGIN SPEW SKIP ZOOM LIST KILL NORM

Run 1032 Rec 139

One of many examples where Z values of tracks near conversions do not seem to be optimal. Further, what would seem to be the best track has not been found by the tracking routines.

Track 6 as shown is

.65	5.587	.233
.927	5.539	.476
1.131	5.506	.568
1.359	5.467	.783

Tape format (DST)

Similar to object oriented
Event on tape with Pointers to data, tracks, vertices, …
Had to work on SLAC and Berkeley computers

Event Classes

Table 6. Event Classes

Event Code	Subtype
0 Garbage	0 No vertex found
	1 <2 tracks not hitting posts
	2 illegal trigger
1 Cosmic	0 2-prong, cosmic timing
	1 2p, no TDC information
	2 >2p with a cosmic pair
2 Wall	0 2p, vertex at vacuum chamber
	1 >2p, vertex at vacuum chamber
	2 1p, vertex at vacuum chamber
	3 vertex outside Z cut
	4 vertex outside radial cut
3 QED, EE	0 2p, large showers, good TDC
	1 2p, large showers, bad TDC
	2 >2p, with collinear EE pair
	3 2p, one large shower
4 Mu Pair	0 collinear 2p, low pulse height, good timing
	1 $\mu\pi$ or non-collinear $\mu\mu$ candidates
5 Hadron	0 >2p
	1 2p non-coplanar
	2 2p charge ± 2
6 Unknown	0 vertex fit failure
	1 1p from $4 < R < 6$ cm
	2 2p, non-coplanar, $4 < R < 6$ cm
	3 vertex lies at $R > 10$ cm
	4 ≥3p, $4 < R < 6$ cm
	5 2p, coplanar, $4 < R < 6$ cm
	6 collinear pair with no TDC in a multiprong
	7 collinear or coplanar π pair with $0 < R < 2$ cm

Filter percentages

Filter

Data Sample	NTASH		EARLY TIME		COSMIC		NPTS		NROAD		Total Number of Events	% Survival
3.0 GeV B = 4kg	5	0%	18246	12.3%	75893	51.1%	7741	5.2%	5180	3.5%	148575	27.9%
3.8 GeV B = 4kg	9	0%	42801	15.5%	116556	42.3%	14186	5.2%	10719	3.9%	275357	33.1%
4.8 GeV B = 4kg	149	0%	51712	13.8%	143688	38.3%	11842	3.2%	37440	10.0%	375073	34.7%
4.8 GeV B = 2kg	32	0%	41380	19.8%	66099	31.7%	6368	3.1%	21680	10.4%	208630	35.0%

Table 4. Number of Events Eliminated by Filters

Thesis search

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Inclusive momentum and angular distributions from electron positron annihilation at √s = 3.0, 3.8, and 4.8 GeV

THESIS/DISSERTATION · 09 May 1975

DOI: https://doi.org/10.2172/4182950 · OSTI ID: 4182950

Hollebeek, Robert John [1]

1. Univ. of California, Berkeley, CA (United States)

- Hide Author Affiliations

Inclusive features of multi-hadron final states produced in the annihilations of electrons and positrons are presented.

TABLE OF CONTENTS

Fit to tracks (thesis)

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a) Circle Fit

The equations for a least-square fit to a circle are

$$\chi^2 = \sum_i (r_i - \rho)^2 \qquad r_i = [(X_i - X_0)^2 + (Y_i - Y_0)^2]^{1/2}$$

$$\frac{\partial \chi^2}{\partial \rho} = 0, \quad \frac{\partial \chi^2}{\partial X_0} = 0, \quad \frac{\partial \chi^2}{\partial Y_0} = 0$$

$$\rho = \frac{\sum r_i}{N}, \quad X_0 = \frac{\sum_i}{N} - \frac{\rho}{N}\sum \frac{X_i - X_0}{r_i}, \quad Y_0 = \frac{\sum Y_i}{N} - \frac{\rho}{N}\sum \frac{Y_i - Y_0}{r_i}$$

The equations are highly coupled, and there is no convenient way to iterate them. The problem of fitting points to a circle has been solved by Ascoli. The method consists of minimizing

$$\chi_A^2 = \sum_i \left[\frac{r_i^2 - \rho^2}{2\rho}\right]^2$$

$$= \sum_i (r_i - \rho)^2 \left(\frac{r_i + \rho}{2\rho}\right)^2$$

$$= \sum_i (r_i - \rho)^2 \left[1 + \frac{r_i - \rho}{2\rho}\right]^2$$

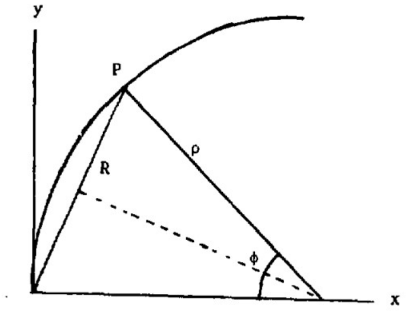
$$\approx \sum_i (r_i - \rho)^2 \left[1 + \frac{(r_i - \rho)^2}{4\rho^2}\right]$$

$$\sin\frac{\phi}{2} = \frac{R/2}{\rho} \quad \text{where R is the radius of point P}$$

so that

$$\phi = 2\sin^{-1}\frac{R}{2\rho} + \phi_0$$

$$\phi = \phi_0 + 2\left\{\frac{R}{2\rho} + \frac{1}{3!}\left(\frac{R}{2\rho}\right)^3 + \frac{3}{5!}\left(\frac{R}{2\rho}\right)^5 + \ldots\right\}$$



In cases where $\frac{1}{3!}\left(\frac{R}{2\rho}\right)^2 \ll 1$, the radius of curvature and initial angle of the track can be estimated by using

$$\phi_1 = \phi_0 + \frac{R_1}{\rho}$$

$$\phi_2 = \phi_0 + \frac{R_2}{\rho}$$

$$\left(\phi_1 - \frac{R_1}{\rho}\right) = \left(\phi_2 - \frac{R_2}{\rho}\right)$$

$$\rho = \frac{R_1 - R_2}{\phi_1 - \phi_2}, \quad \phi_0 = \phi_1 - \frac{R_1}{\rho}$$

R_1 and R_2 are approximately 1.4 and 1.1 respectively so that

Thesis pg 36 z fi

to a *helix*. Thus, the fit for Z_0 (the origin in Z) and $\tan\lambda$ (the tangent of the dip angle) uses

$$Z_i = Z_0 + S_i \tan\lambda$$

where

$$S_i = 2\rho \sin^{-1}\left(\frac{L_i}{2\rho}\right)$$

$$L_i = [(X_i - X_0)^2 + (Y_i - Y_0)^2]^{1/2}$$

with X_0, Y_0 ρ determined by the XY fit. The method is to minimize

$$\chi_Z^2 = \sum \frac{[Z_i - (Z_0 + S_i \tan\lambda)]^2}{\sigma_i^2}$$

where σ_i is used to account for the different resolution *on the* 4° and 2° spark gaps. The solutions of the minimization equations are

$$\tan\lambda = \frac{\left(\sum \frac{Z_i S_i}{\sigma_i^2}\right)\left(\sum \frac{1}{\sigma_i^2}\right) - \left(\sum \frac{Z_i}{\sigma_i^2}\right)}{D}$$

$$Z_0 = \frac{\left(\sum \frac{S_i^2}{\sigma_i^2}\right)\left(\sum \frac{Z_i}{\sigma_i^2}\right) - \left(\sum \frac{S_i}{\sigma_i^2}\right)\left(\sum \frac{Z_i S_i}{\sigma_i^2}\right)}{D}$$

where

$$D = \left(\sum \frac{S_i^2}{\sigma_i^2}\right)\left(\sum \frac{1}{\sigma_i^2}\right) - \left(\sum \frac{S_i}{\sigma_i^2}\right)^2 .$$

Thesis contains fits of the data to several models

nothing fits

-114-

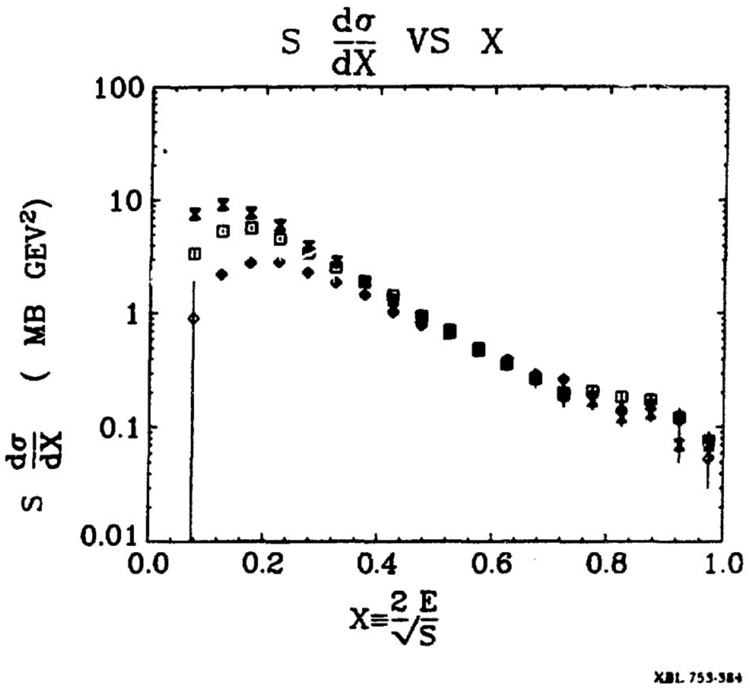
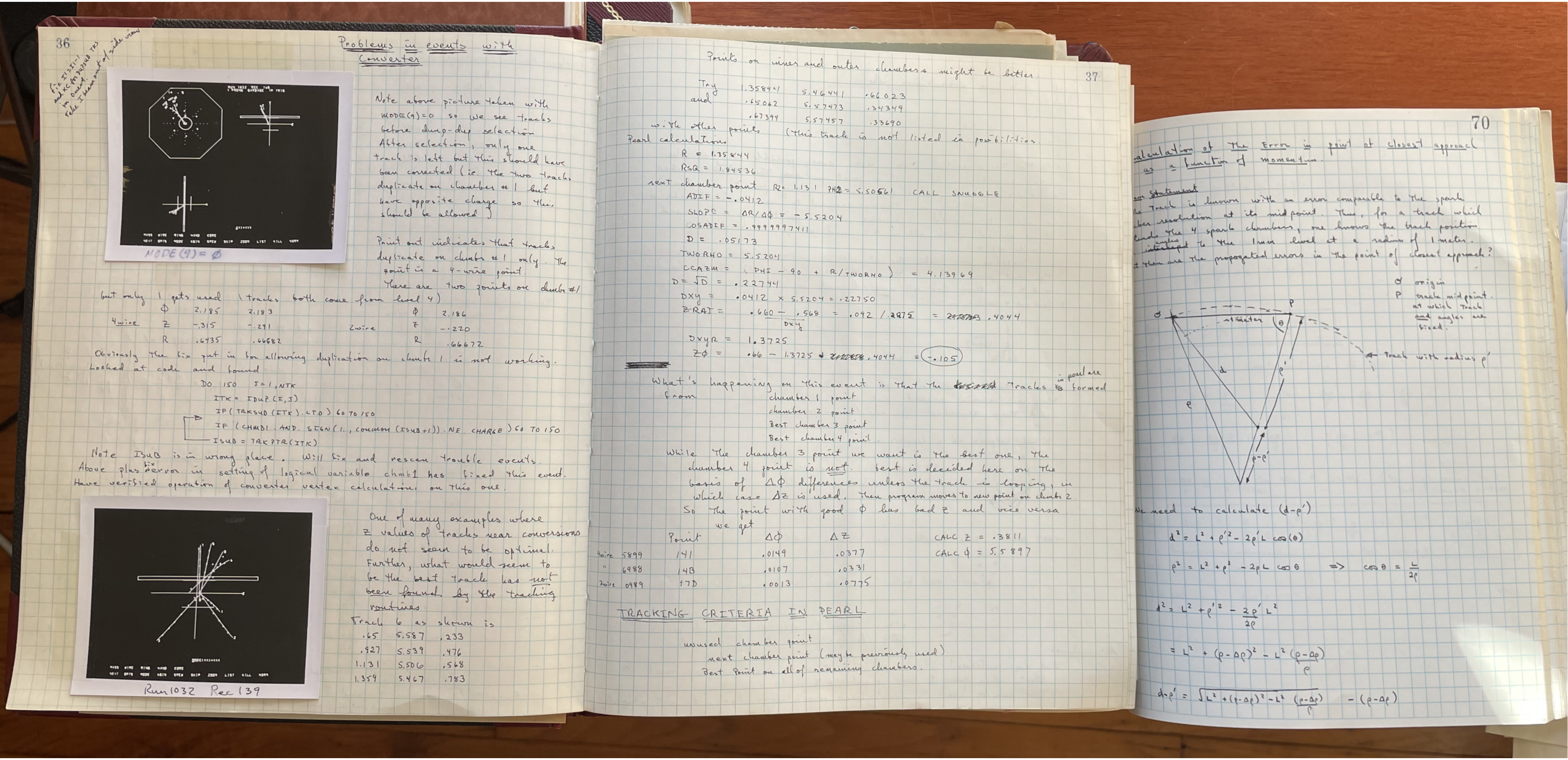


Fig. 30

My Logbooks   Tracking , Vertex finding, fitting



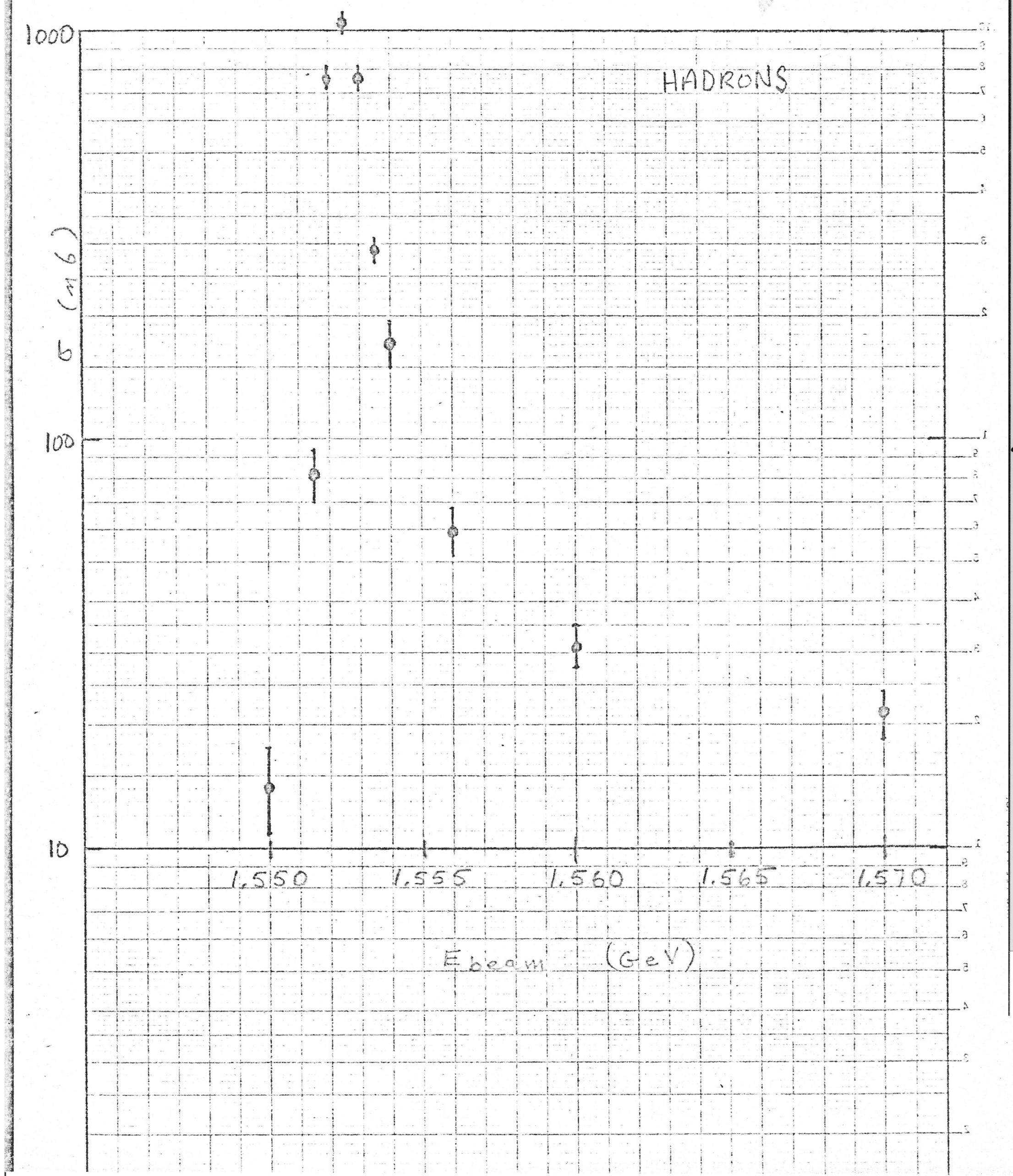
The strike

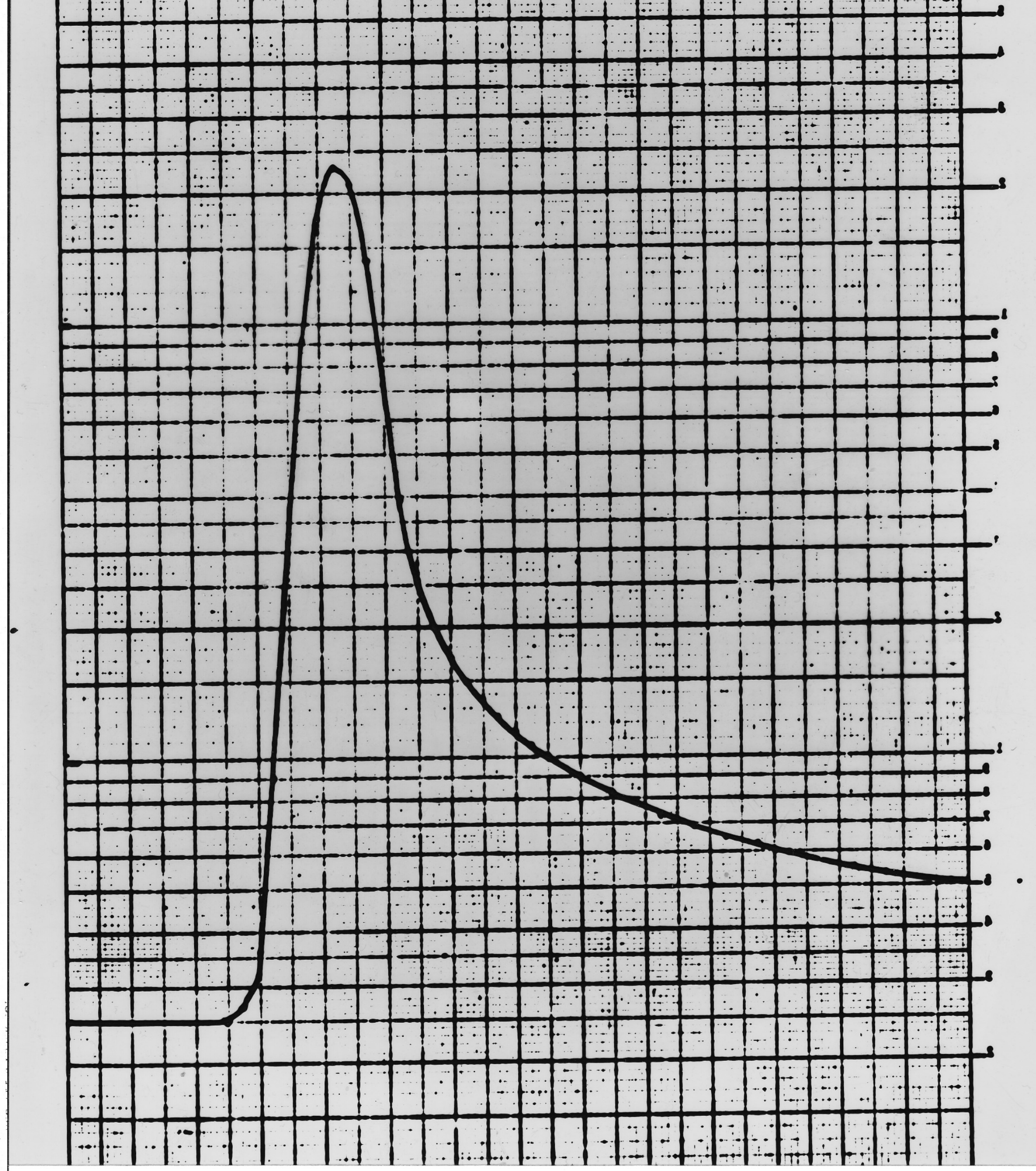
Results from the energy scan

Marty November 11, 1974

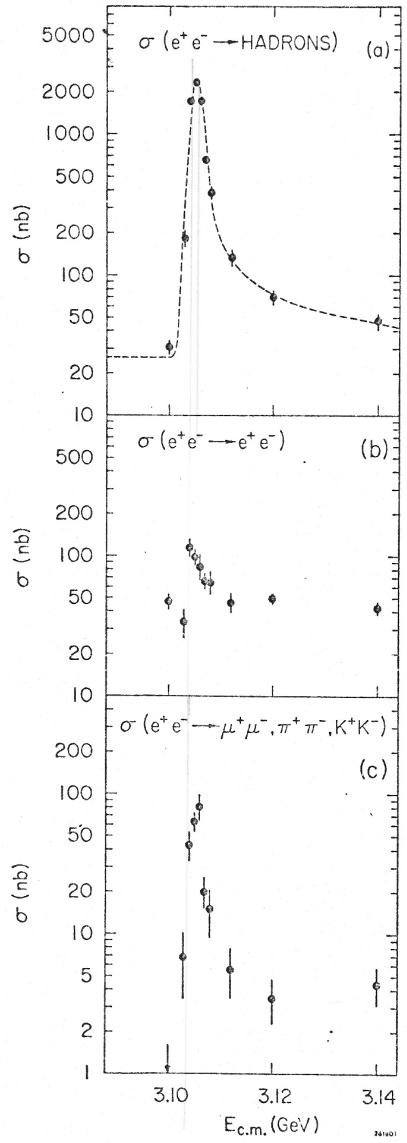
Scan 3100

1000 wasn't big enough !





Discovery papers 3105 and 3.695



)ISCOVERY OF A NARROW RESONANCE IN e^+e^- ANNIHILATION

I.-E. Augustin,[†] A. M. Boyarski, M. Breidenbach, F. Bulos,
Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson,
Jean-Marie,[†] R. R. Larsen, V. Luth, H. L. Lynch, D. Lyon,
Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis,
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;. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg,
;. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu,
;. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse

,awrence Berkeley Laboratory and Department of Physics
University of California, Berkeley, California 94720

ABSTRACT

We have observed a very sharp peak in the cross section
$e^+e^- \to$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-
;s energy of 3.105 $\pm$ 0.003 GeV. The upper limit to the
l width at half maximum is 1.3 MeV.

(Submitted to Phys. Rev. Letters)

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ire de l'Accélérateur Linéaire, Centre d'Orsay de l'Université
, 91 Orsay, France.

23 November 1974

THE DISCOVERY OF A SECOND NARROW RESONANCE
IN e^+e^- ANNIHILATION*

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ABSTRACT

We have observed a second sharp peak in the cross
section for $e^+e^- \to$ hadrons at a center-of-mass energy
of 3.695 $\pm$ 0.004 GeV. The upper limit of the full width
at half maximum is 2.7 MeV.

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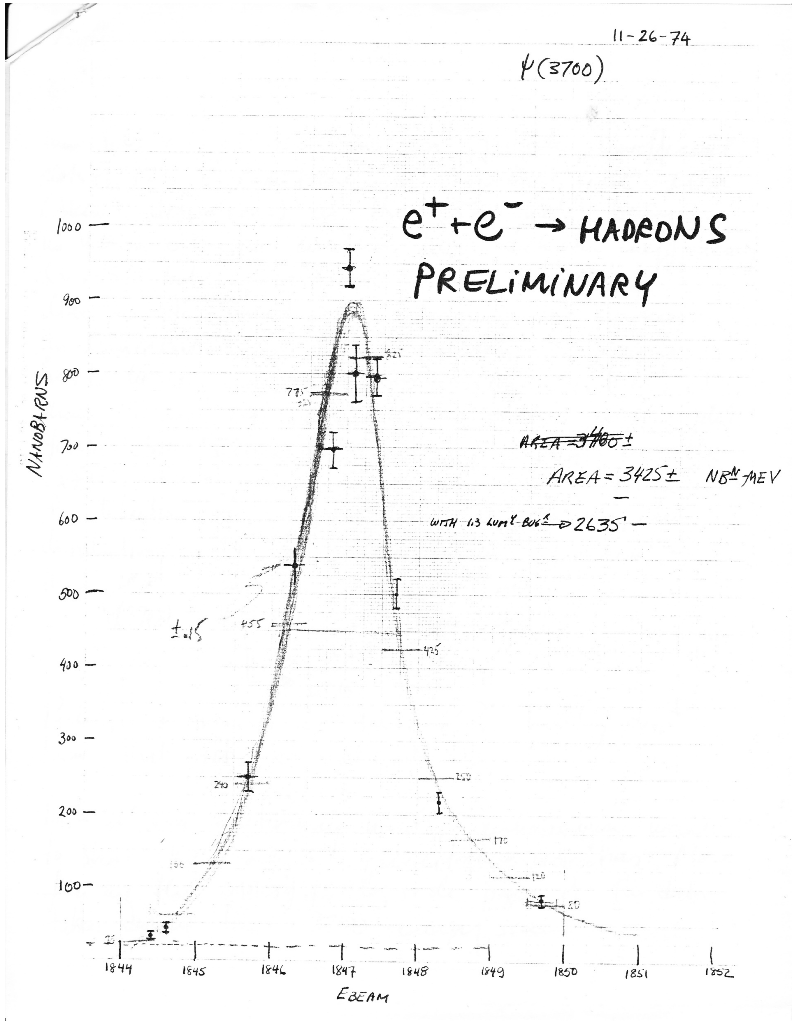
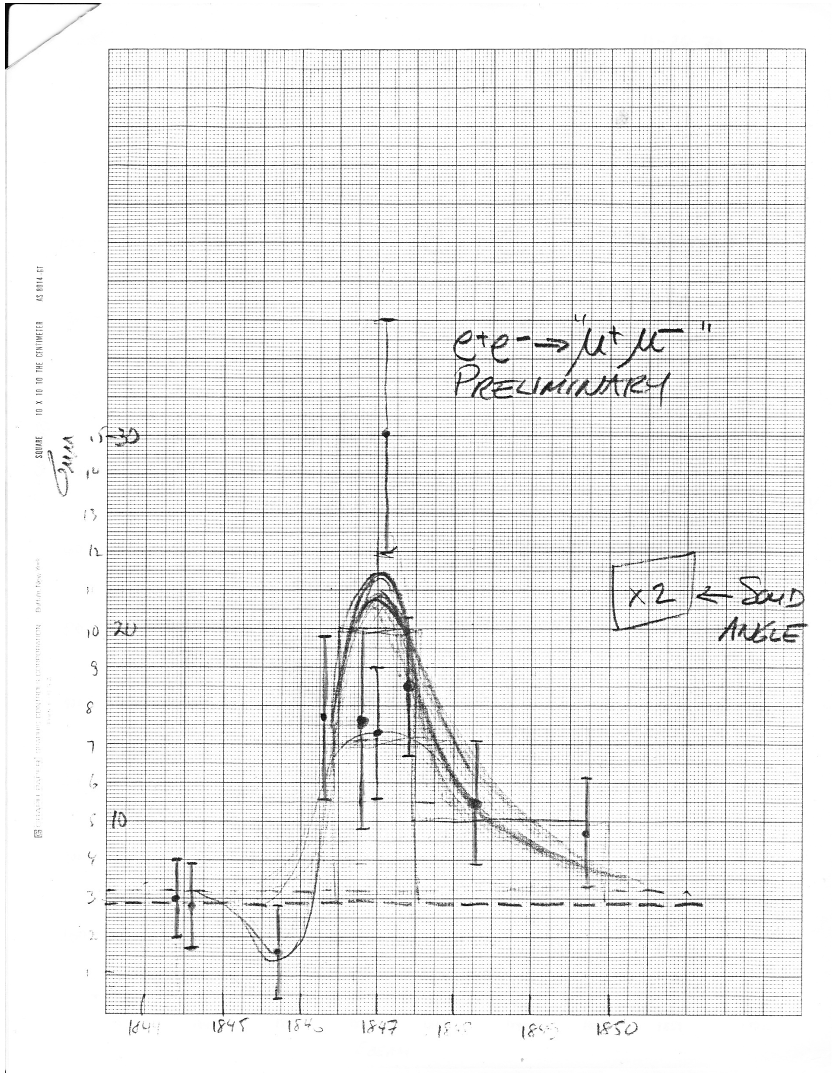
3.695

$e^+e^- \rightarrow$ hadrons



$e^+e^- \rightarrow \mu^+\mu^-$



Phone notes

2RL – 89 – 65

FTS OP 761 – 4250

415 – 843 – 2740 × 5074 ✓

854 – 3300 × 2706

Roy 2369

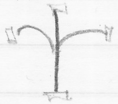
Dec 2 issue of Newsweek

Thursday Dec 5, Roy Schwitters

Plans Run-over old peaks and continue scanning

$3.7 \rightarrow 3.1 + 2\pi$ (soft) often $3.1 \rightarrow e^+e^-$

2 soft pions sharp bump Totology



$3.1 \rightarrow e^+e^-$

have scanned to 4.2 → broad bump but nothing above 100 nb level.

change DACS (Magnet currents) every ~~20 sec~~. 2 min

Width at 3.7 ?

3.7 BB's contaminated by 3.1 decay

4π's + missing neutral strong signal at 3.1, consistent w missing neutral π^0 from MC.

also No γ from Hofst. suggestive of negative G parity

no data at 3.7 for BB's from Hofst. but they have the resolution and more 3.7 data to come this weekend

JD Jackson Psi (3.1

J. D. Jackson Nov 12/74 1

Summary of Key Numbers, Assumptions & Results
(after a check with Roy Schwitters at 11:15 am)

$\Delta W = 1.3$ MeV $W = 3.105 \pm 0.003$ GeV

$\Gamma_{obs} = 1.25 \pm 0.2$ MeV $\therefore$ consistent with very small Γ.
Upper limit: $\Gamma \leq 0.67$ MeV.

$(\sigma_{\mu\mu})_{QED} = 9.03$ nb

Bars on top of quantities means folded with resolution function, ie observed quantities.

$(\overline{\sigma_{total}})_{max} = (2300 \pm 200) \times \underbrace{1.39}_{\text{correction for radiative tail}} = 3200 \pm 280$ nb

$(\Delta\overline{\sigma_{\mu\mu}})_{max} = 80 \pm 20$ nb [This is 2-body, coplanar, not electrons, events – assumed to be $\mu^+\mu^-$ in what follows.]

$(\overline{\sigma_{\mu\mu}})_{max} = (80 \pm 20) \times 1.39 \times \frac{1}{0.55} = 200 \pm 50$ nb

$\overline{r}_{max} = (\overline{\sigma_{\mu\mu}})_{max} / (\sigma_{\mu\mu})_{QED} = 22 \pm 5.5$

<u>Assumptions</u> (1) $J=1$ resonance
(2) Neglect interference at peak
(3) Resolution function is Breit-Wigner with FWHM $= \Delta W$.

Then $\overline{(\sigma_{ab})}_{max} = \frac{12\pi}{W^2} \frac{\Gamma_a \Gamma_b}{\Gamma(\Gamma + \Delta W)}$, $\overline{(\sigma_{total})}_{max} = \frac{12\pi}{W^2} \frac{\Gamma_e}{(\Gamma + \Delta W)}$

With $W = 3.105$ GeV, $\frac{12\pi}{W^2} = 1.521 \times 10^6$ nb

From $(\overline{\sigma_{total}})_{max} = 3200 \pm 280$ nb, $\frac{\Gamma_e}{\Gamma + \Delta W} = (2.1 \pm 0.2) \times 10^{-3}$

If $\Gamma \ll \Delta W$ (see below), $\Gamma_e = (2.7 \pm 0.3)$ keV

(4) Assume $\Gamma_e = \Gamma_\mu$.
Then from $(\overline{\sigma_{\mu\mu}})_{max} = 200 \pm 50$ nb, $\frac{\Gamma + \Delta W}{\Gamma} = 28 \pm 8$
Thus $\Gamma \ll \Delta W$ is confirmed and $\Gamma = \frac{1.3 \times 10^3}{28 \pm 8} = 46 \pm ^{19}_{10}$ keV

$\frac{\Gamma_e}{\Gamma} \simeq 0.06$ (in agreement with $\frac{(\overline{\sigma_{\mu\mu}})_{max}}{(\overline{\sigma_{total}})_{max}} = \frac{200}{3200} = 0.063$)

JD Jackson
Psi´(3.695)

J. D. Jackson 30-11-74 1

Notes on the decay $\psi(3695) \to \psi(3105)\pi^+\pi^-$

The decay of $\psi' \to \psi\,\pi^+\pi^-$ is apparently a significant fraction of the hadronic decays of the $\psi(3695)$, called ψ' here. There is a signal in the 4 prongs of $(e^+e^-)\pi^+\pi^-$, as well as the strong peak at $M \simeq 3.1$ GeV in the mass spectrum recoiling against the $\pi^+\pi^-$ (but not $\pi^+\pi^+$) pair.

I. Assumptions

1. If this decay mode is an appreciable fraction of the ψ' decays, it argues strongly for the ψ and ψ' having some new quantum number in common, a quantum number that inhibits decay directly into ordinary hadrons. We thus assume that ψ' and ψ are $C=-1$, $J=1^-$, $I=0$ objects with color or charmishness. [If Han-Nambu scheme, then color octet and ordinary SU(3) singlets. If charm, then $(\bar{c}c)$ states, analogous to the $\phi(1020)$ as a $(\bar{\lambda}\lambda)$ state.]
2. With $I=0$ for both, single pion emission is forbidden by isospin. Then 2-pion decay with $I=0$ (s-wave) is most likely.
3. The effective interaction is assumed to be

$$H_{int} = g\,(\psi_\mu \psi'^\mu)\,\varphi_{\pi^+}\varphi_{\pi^-}$$

where ψ_μ, ψ'_μ are the vector fields describing the ψ and ψ' particles and g is a dimensionless coupling constant.

II. Kinematics

Define the masses as follows (all in MeV):

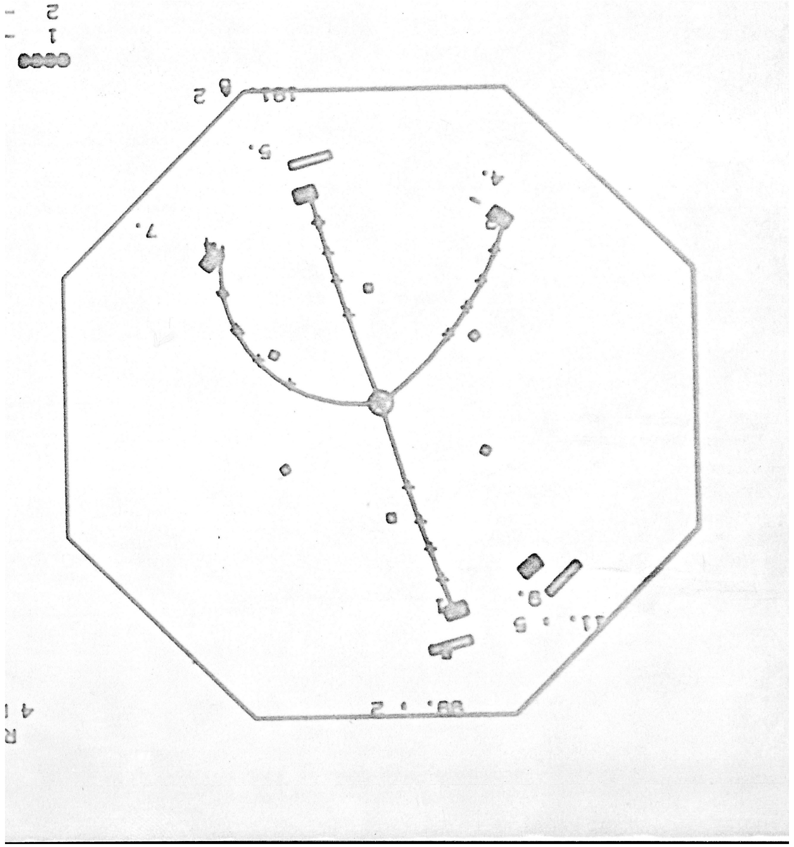
$M = 3695$, $m = 3105$, $\mu = 140$

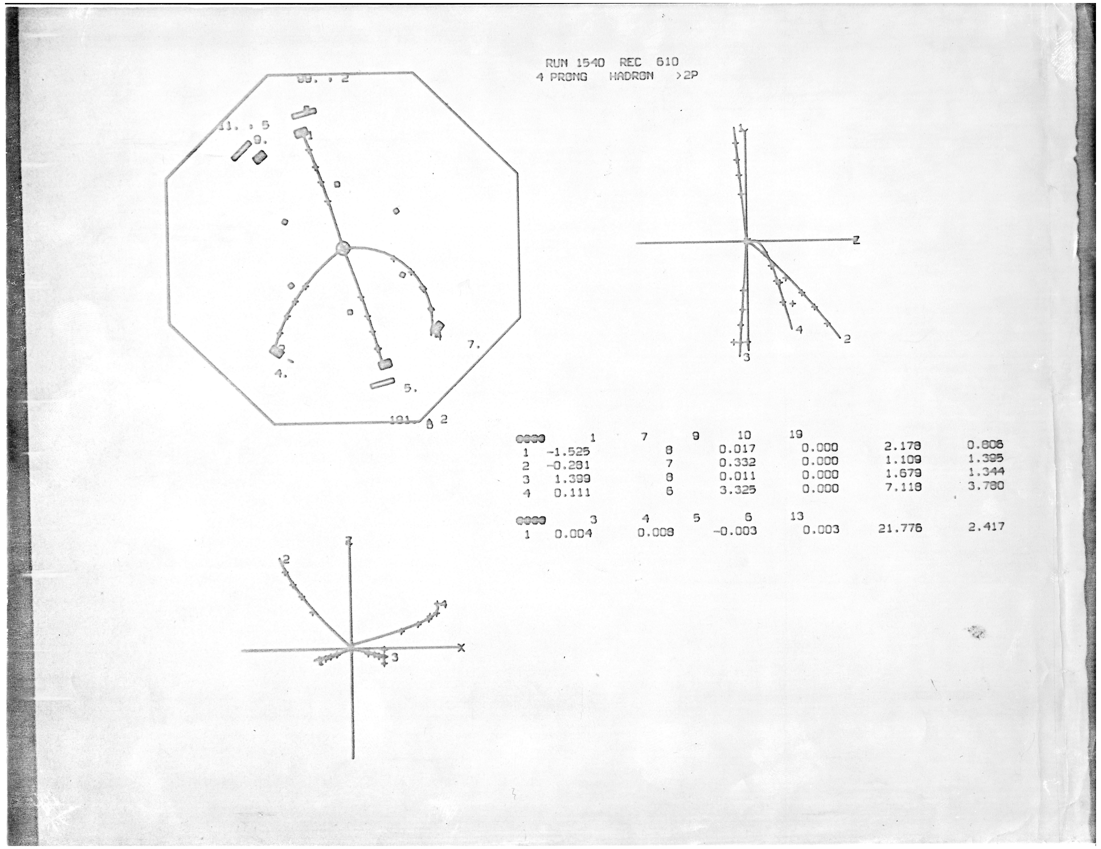
The mass difference is $\Delta M = 590$ MeV.

Richter in Control Room

Richter Nobel

PSI

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4 PRONG HADRON >2P
0000 1 7 9 10 19
1 -1.525 8 0.017 0.000 2.178 0.806
2 -0.281 7 0.332 0.000 1.109 1.395
3 1.399 8 0.011 0.000 1.679 1.344
4 0.111 6 3.325 0.000 7.118 3.780
0000 3 4 5 6 13
1 0.004 0.008 -0.003 0.003 21.776 2.417