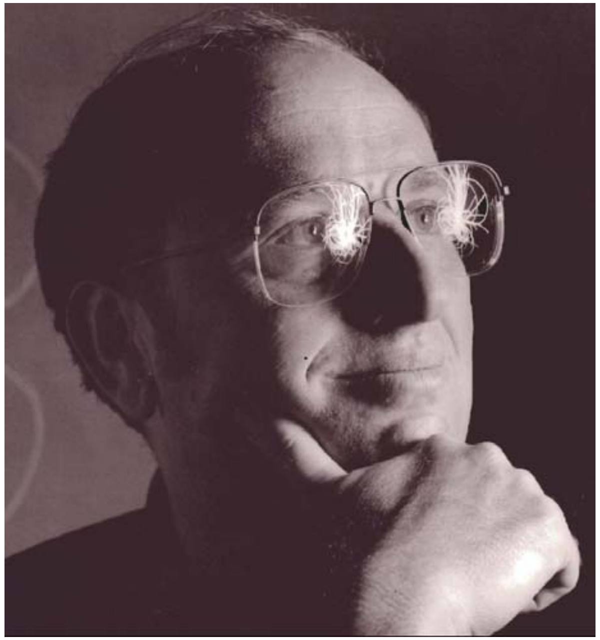
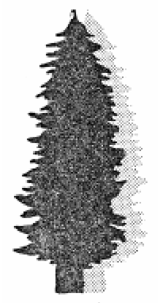
Lessons Learned with the Mark II Drift Chamber
and
Some Early work on Supercollider Tracking
and
LIMEs

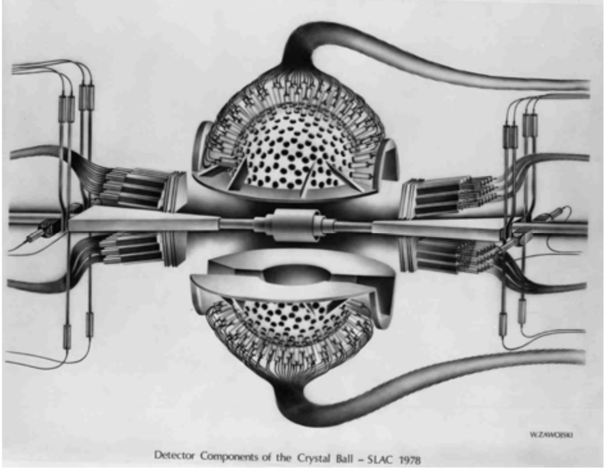


Alan Weinstein, Caltech

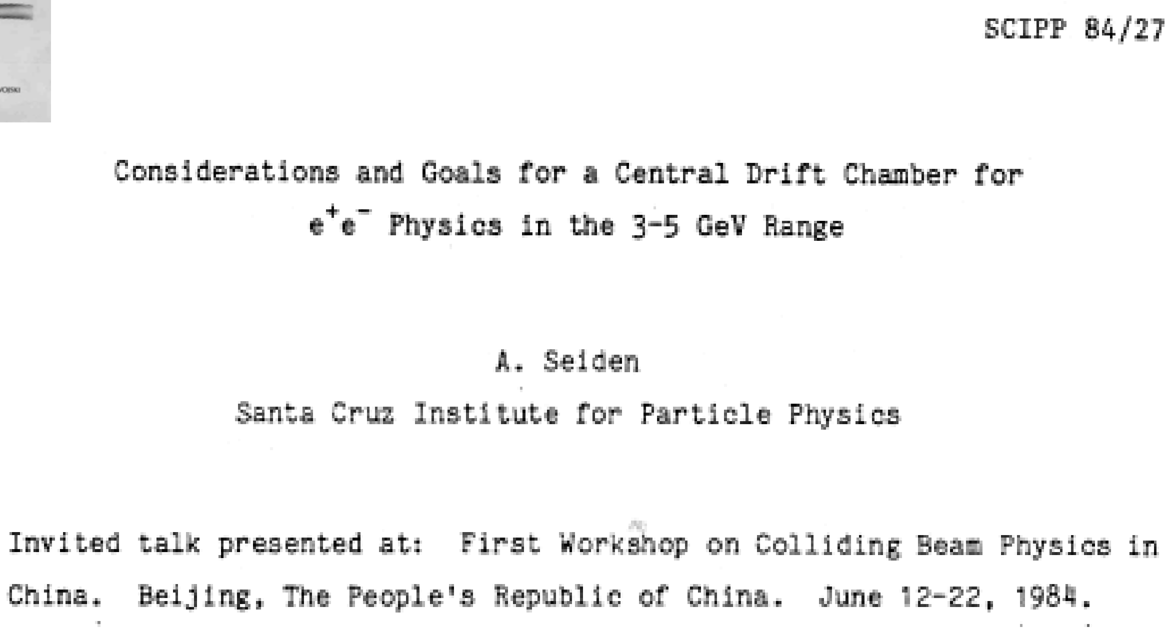


ABEFEST
STD6, Carmel, CA
September 11, 2006

Learning about the design of drift chambers for collider physics



Detector Components of the Crystal Ball – SLAC 1978



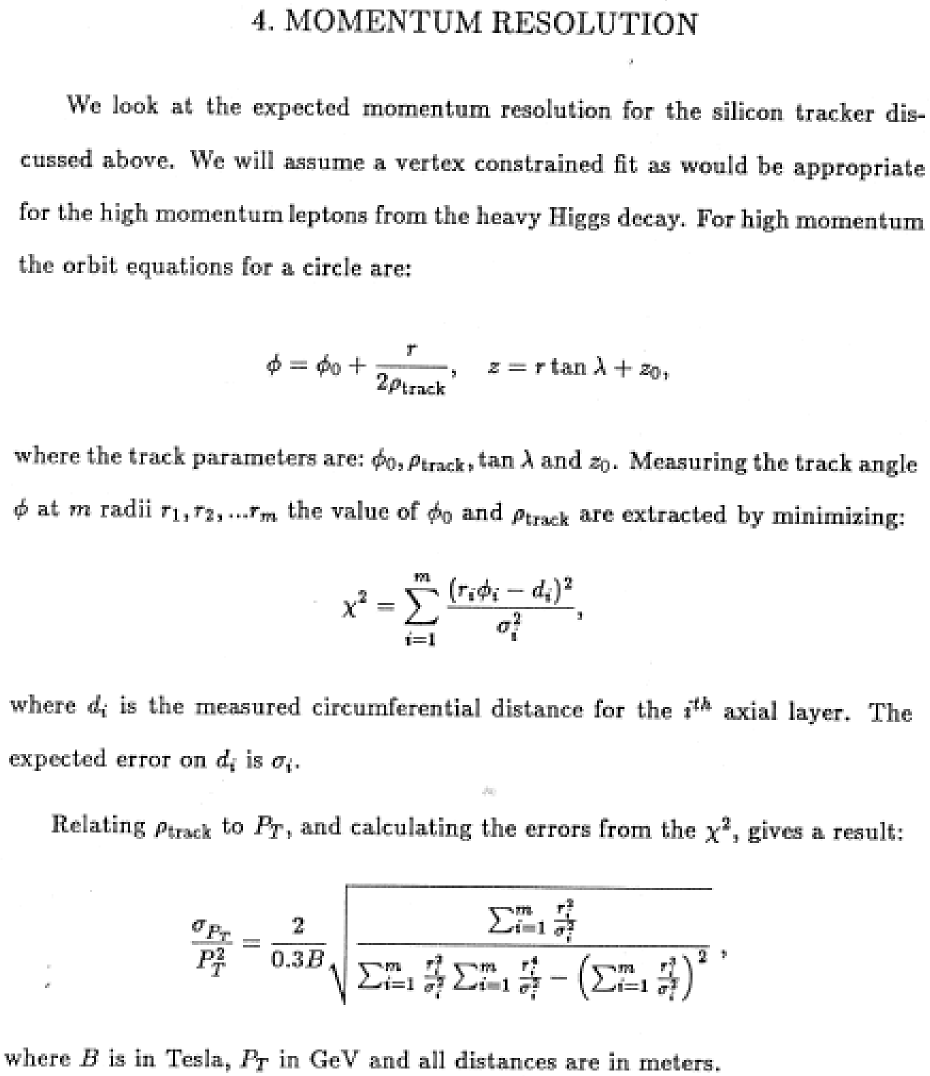
SCIPP 84/27

Considerations and Goals for a Central Drift Chamber for
e^+e^- Physics in the 3-5 GeV Range

A. Seiden
Santa Cruz Institute for Particle Physics

Invited talk presented at: First Workshop on Colliding Beam Physics in China. Beijing, The People's Republic of China. June 12-22, 1984.

Abe’s simple and powerful scaling rules



4. MOMENTUM RESOLUTION

We look at the expected momentum resolution for the silicon tracker discussed above. We will assume a vertex constrained fit as would be appropriate for the high momentum leptons from the heavy Higgs decay. For high momentum the orbit equations for a circle are:

$$\phi = \phi_0 + \frac{r}{2\rho_{\text{track}}}, \qquad z = r\tan\lambda + z_0,$$

where the track parameters are: $\phi_0, \rho_{\text{track}}, \tan\lambda$ and z_0. Measuring the track angle ϕ at m radii $r_1, r_2, \ldots r_m$ the value of ϕ_0 and ρ_{track} are extracted by minimizing:

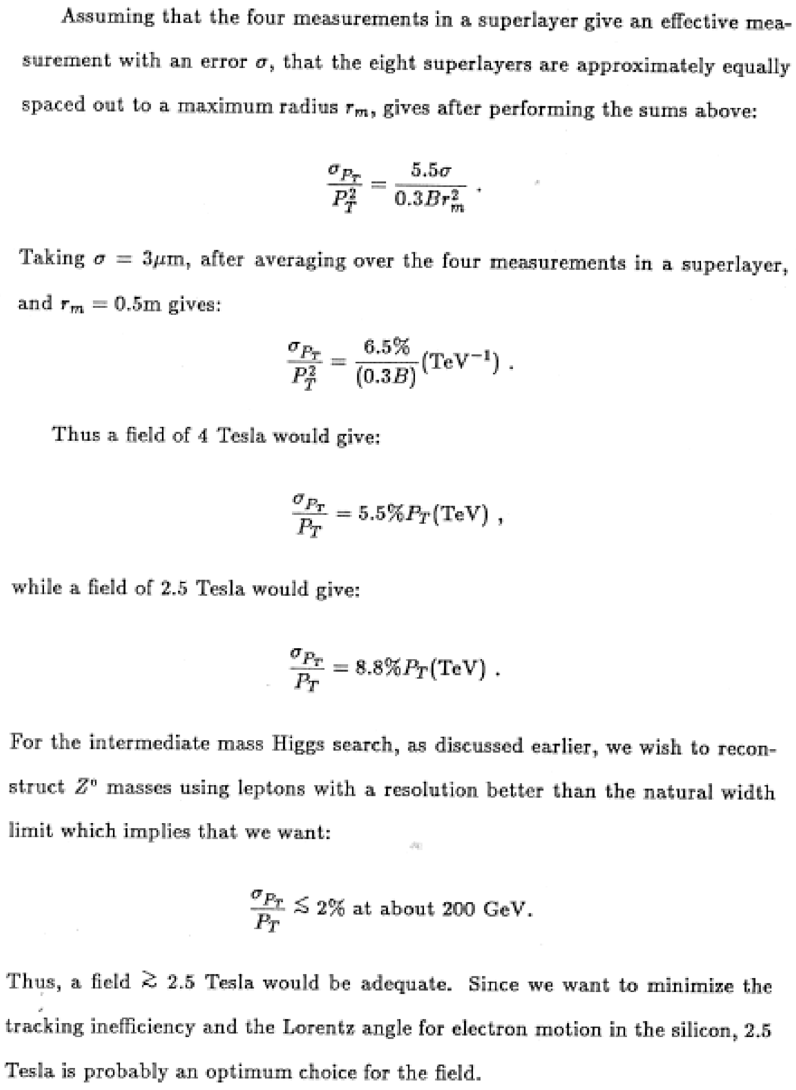
$$\chi^2 = \sum_{i=1}^{m} \frac{(r_i\phi_i - d_i)^2}{\sigma_i^2},$$

where d_i is the measured circumferential distance for the i^{th} axial layer. The expected error on d_i is σ_i.

Relating ρ_{track} to P_T, and calculating the errors from the χ^2, gives a result:

$$\frac{\sigma_{P_T}}{P_T^2} = \frac{2}{0.3B}\sqrt{\frac{\sum_{i=1}^{m}\frac{r_i^2}{\sigma_i^2}}{\sum_{i=1}^{m}\frac{r_i^2}{\sigma_i^2}\sum_{i=1}^{m}\frac{r_i^4}{\sigma_i^2} - \left(\sum_{i=1}^{m}\frac{r_i^3}{\sigma_i^2}\right)^2}},$$

where B is in Tesla, P_T in GeV and all distances are in meters.



Assuming that the four measurements in a superlayer give an effective measurement with an error σ, that the eight superlayers are approximately equally spaced out to a maximum radius r_m, gives after performing the sums above:

$$\frac{\sigma_{P_T}}{P_T^2} = \frac{5.5\sigma}{0.3Br_m^2}.$$

Taking $\sigma = 3\mu$m, after averaging over the four measurements in a superlayer, and $r_m = 0.5$m gives:

$$\frac{\sigma_{P_T}}{P_T^2} = \frac{6.5\%}{(0.3B)}(\text{TeV}^{-1}).$$

Thus a field of 4 Tesla would give:

$$\frac{\sigma_{P_T}}{P_T} = 5.5\% P_T(\text{TeV}),$$

while a field of 2.5 Tesla would give:

$$\frac{\sigma_{P_T}}{P_T} = 8.8\% P_T(\text{TeV}).$$

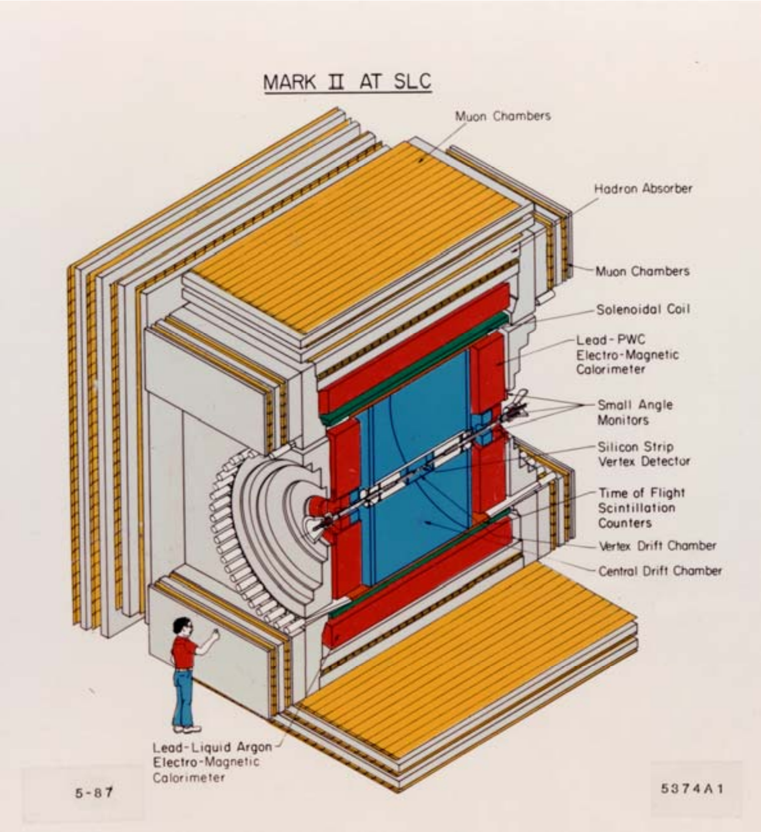
For the intermediate mass Higgs search, as discussed earlier, we wish to reconstruct Z^o masses using leptons with a resolution better than the natural width limit which implies that we want:

$$\frac{\sigma_{P_T}}{P_T} \lesssim 2\% \text{ at about 200 GeV}.$$

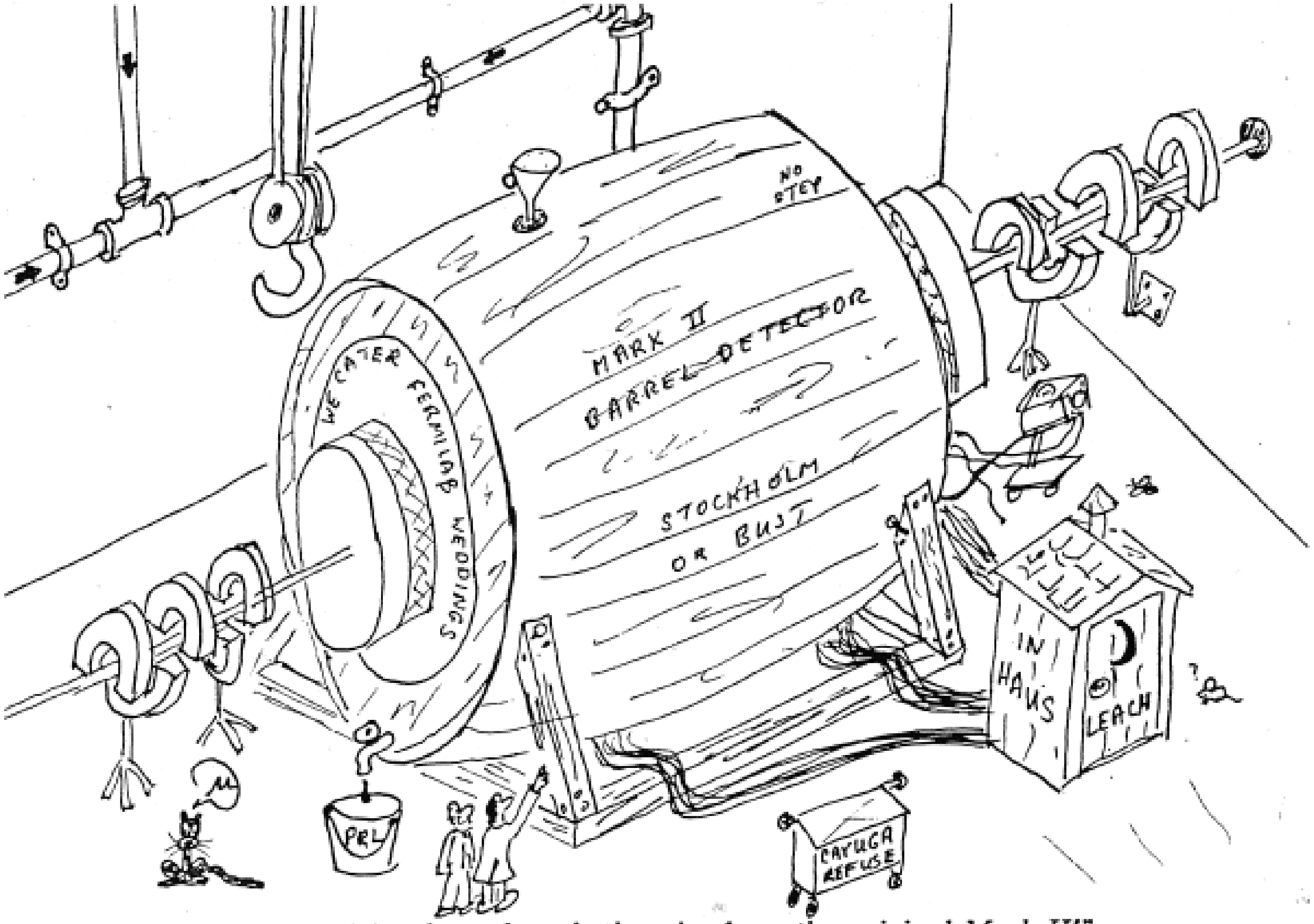
Thus, a field $\gtrsim$ 2.5 Tesla would be adequate. Since we want to minimize the tracking inefficiency and the Lorentz angle for electron motion in the silicon, 2.5 Tesla is probably an optimum choice for the field.

Storied history of the Mark II

- 1977 - Installed at SPEAR
  detailed studies of charmonium and charm (later, Crystal Ball and Mark III)
- 1979 - Moved to PEP
  at beginning of PEP program (29 GeV; search for top; jets and gluons; B mesons…)
- 1982 - Selected to be first detector at SLC
- 1985 - Upgraded and returned to PEP for testing
- 1987 - Rolled onto the SLC beamline
- 1990 – Replaced by SLD



Mark II at SLC
was a substantial rebuild



". . . and right about there is the wire from the original Mark II!"

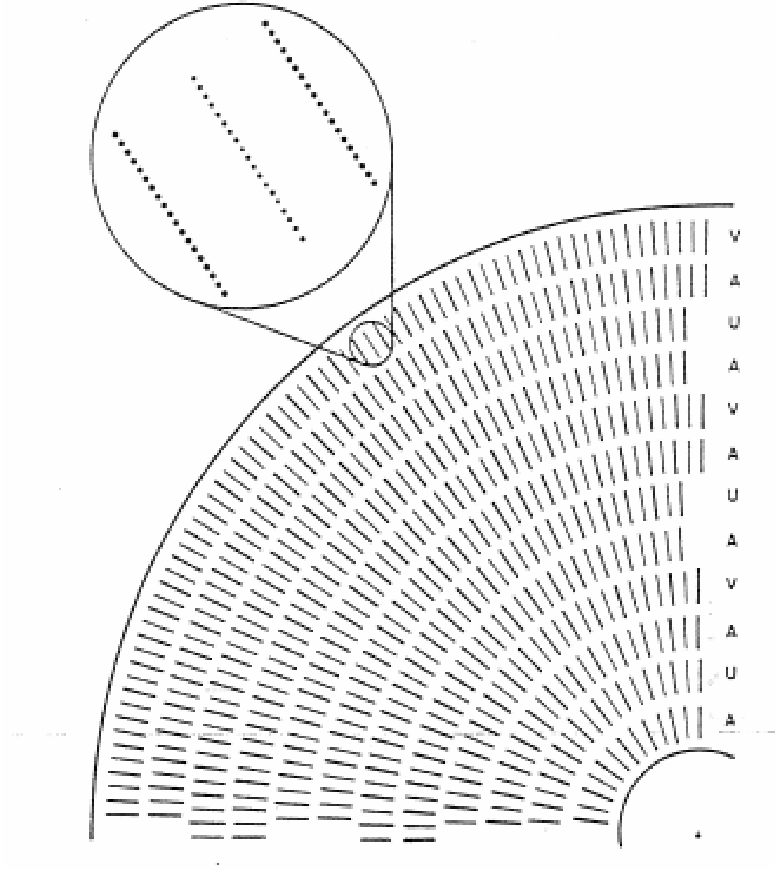
Wish list for drift chambers for tracking at high energy colliders

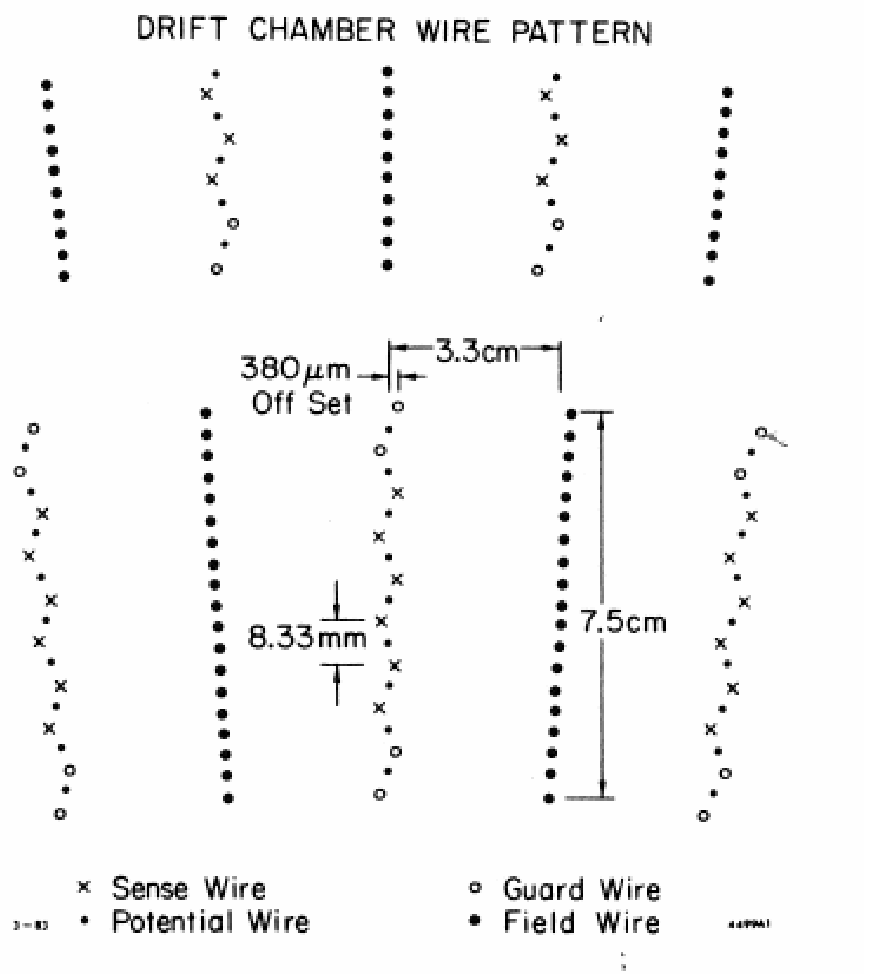
- High spatial resolution to precisely measure curvature of high-pt tracks
- Highly segmented to register hits from closely-spaced tracks in the core of high-p_t jets
- very low mass to minimize multiple scattering, electron bremsstrahlung, inelastic collisions
- high ionization signal to improve dE/dx measurement
- mechanically stable at the micron level
- stable gas to minimize afterpulsing and false hits
- linear drift region to maintain spatial resolution across cells
- small Lorentz angle to permit large cells azimuthally
- high rate capability – to distinguish between tracks from closely-spaced beam crossings
- radiation hard to withstand high rate at small radii
- on-detector pipelined electronics
- provide info for triggering
- low power dissipation
- **Sufficient information to perform pattern recognition robustly**

The importance of pattern recognition

- Finding tracks in the presence of wire inefficiencies,
  hot wires, too few points, etc, was always problematic.
- Track finding failures resulted in missed tracks,
  fake tracks, poorly measured tracks;
  severely degrading the ability to extract physics reliably.
- Needed fine segmentation and robust algorithms,
  to reduce the *purely technical* problem
  of track finding failure to insignificance,
- even in the "extremely jetty" events anticipated at the SLC,
- so that we could concentrate on the more *fundamental*
  problems of single-hit resolution, dE/dx resolution, two-hit
  separation, multiple scattering, etc.

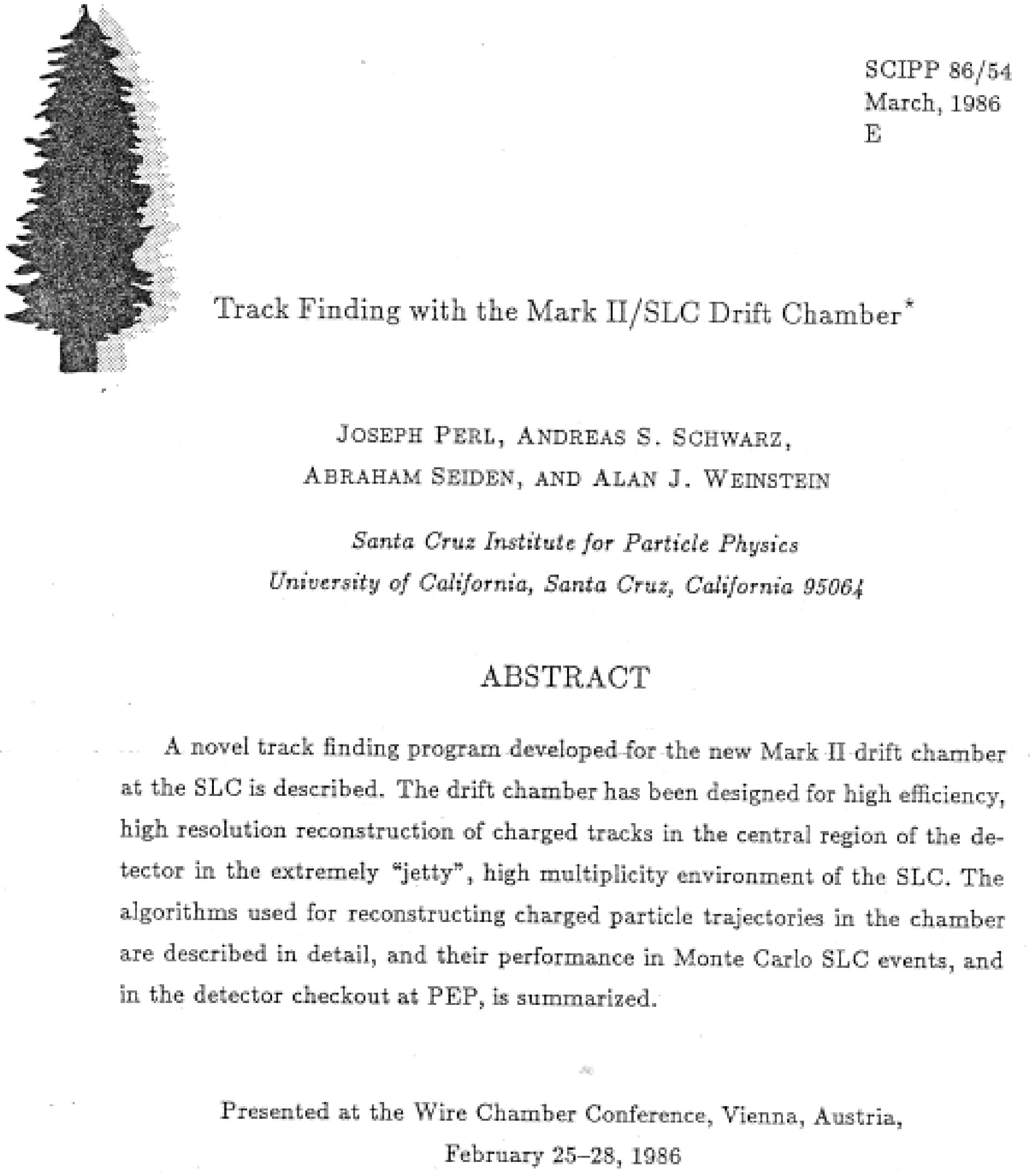
Solution: LOTS of layers, arranged in superlayers, with plenty of stereo





6 axial, 6 stereo (±3.8º) superlayers
each with 6 sense wires, 30 μm dia.
72 drift time and dE/dx measurements
36936 wires. 2.3 m long. R = 0.25-1.44 m

Robust track finding



SCIPP 86/54
March, 1986
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Track Finding with the Mark II/SLC Drift Chamber*

JOSEPH PERL, ANDREAS S. SCHWARZ,
ABRAHAM SEIDEN, AND ALAN J. WEINSTEIN

Santa Cruz Institute for Particle Physics
University of California, Santa Cruz, California 95064

ABSTRACT

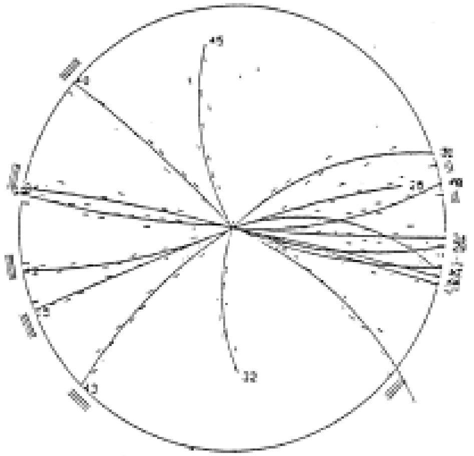
A novel track finding program developed for the new Mark II drift chamber at the SLC is described. The drift chamber has been designed for high efficiency, high resolution reconstruction of charged tracks in the central region of the detector in the extremely "jetty", high multiplicity environment of the SLC. The algorithms used for reconstructing charged particle trajectories in the chamber are described in detail, and their performance in Monte Carlo SLC events, and in the detector checkout at PEP, is summarized.

Presented at the Wire Chamber Conference, Vienna, Austria,
February 25–28, 1986

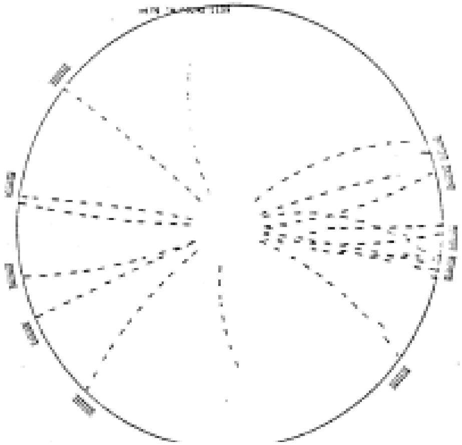
- Local pattern recognition at superlayer level, including L/R ambiguity
- Each superlayer track segment, tangent to helical arc from origin, provides independent measure of curvature κ; φ_0
- Cluster axial segments in κ; φ_0 space and stereo segments in $\tan\lambda$, z_0 space
- Iterative passes through segments and hits to pick up short tracks, etc

$$\kappa = \frac{\frac{-d\phi}{dr}}{\sqrt{1+\left(\frac{\bar{r}\,d\phi}{dr}\right)}}$$

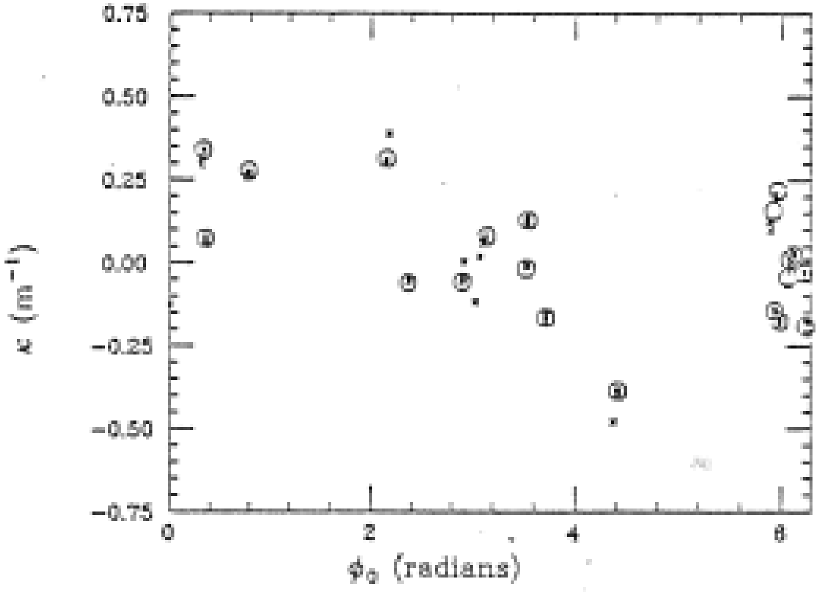
$$\phi_0 = \bar{\phi} + \arcsin \kappa\bar{r}$$



(a)

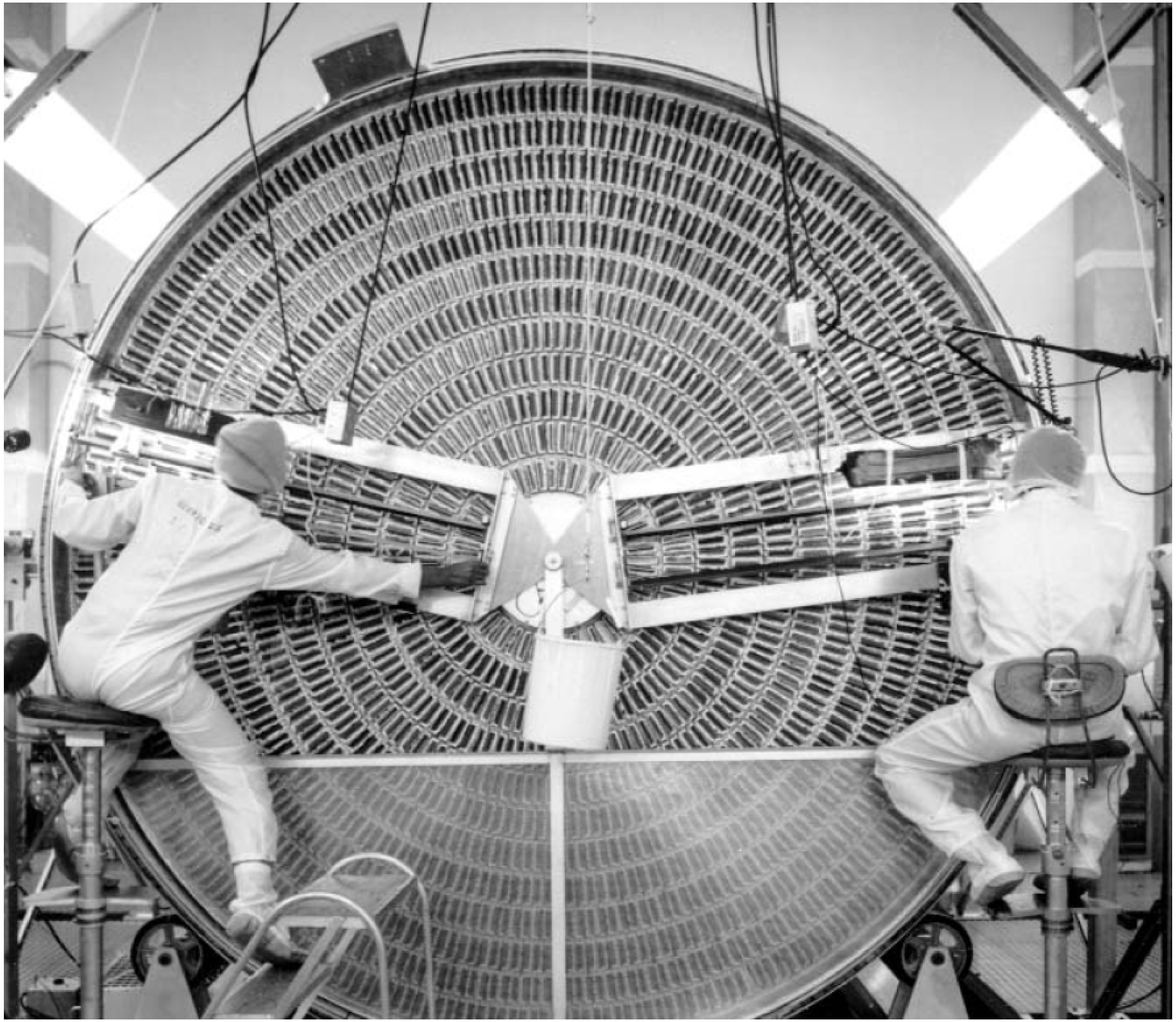


(b)

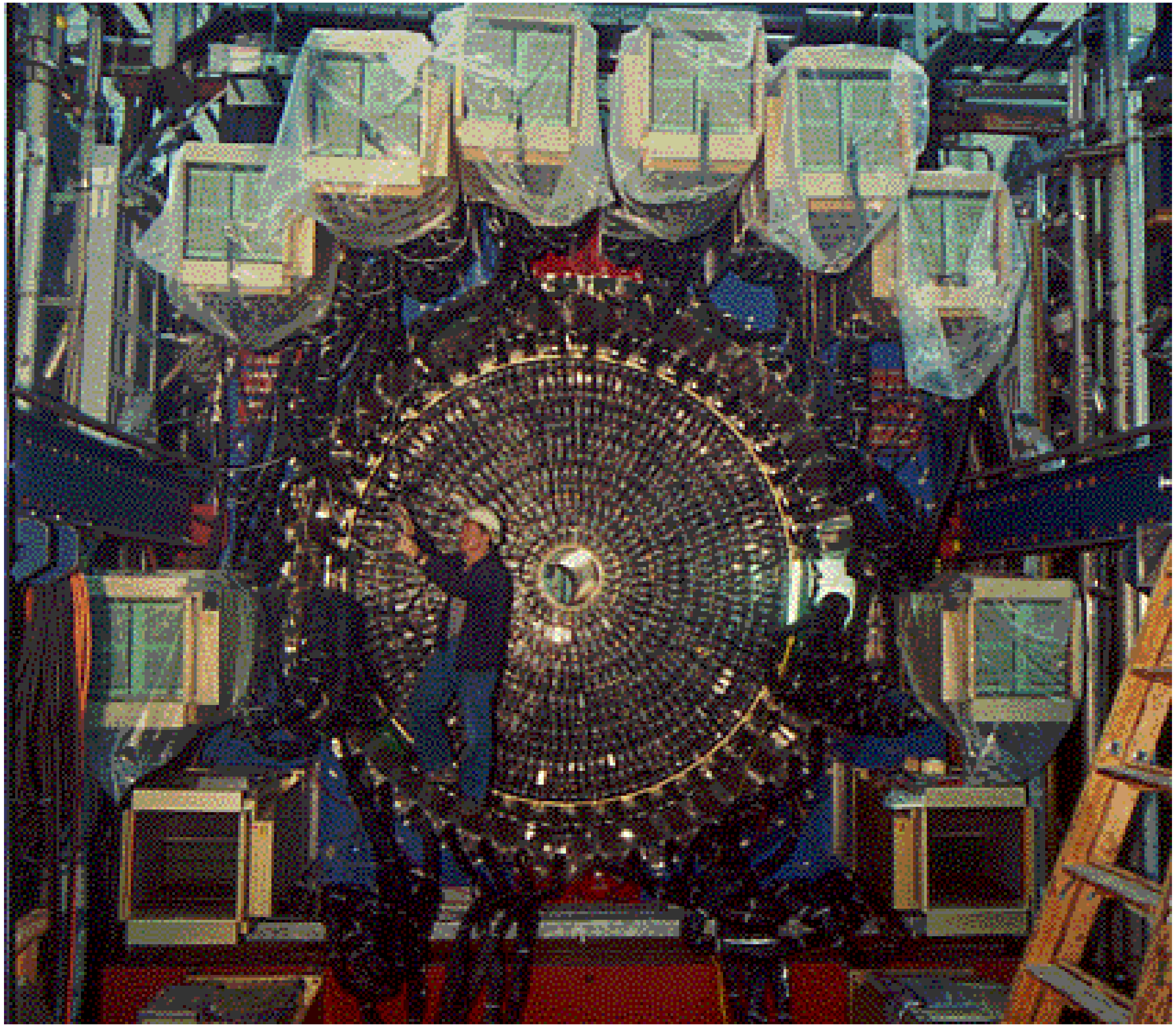


(c)

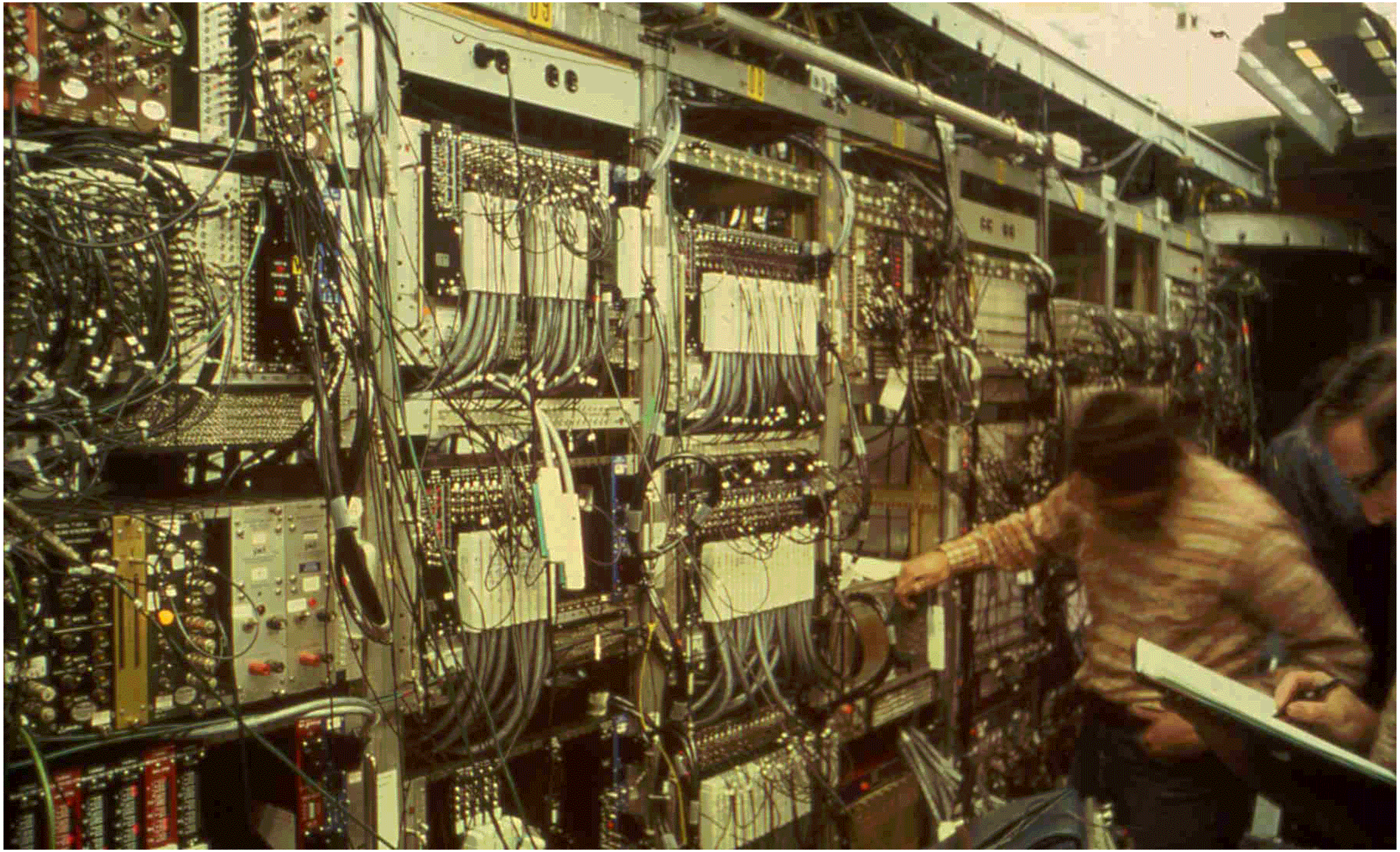
Stringing 37,000 wires



Rolled in to the SLC beamline



Racks of FASTBUS electronics

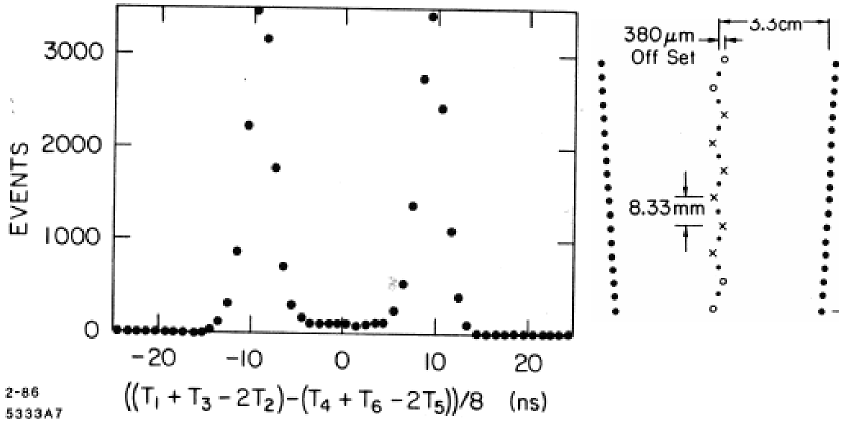


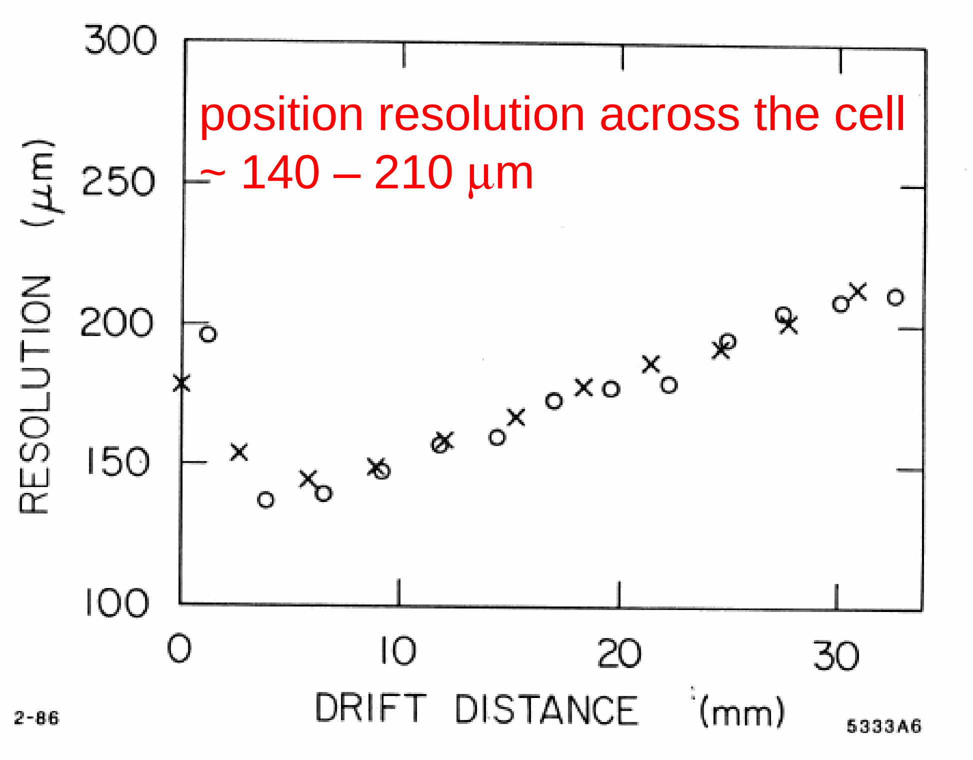
96-ch LeCroy FASTBUS multihit TDCs, 16-ch SLAC FASTBUS 100 MHz 6-bit FADCs

Performance of the Mark II DC

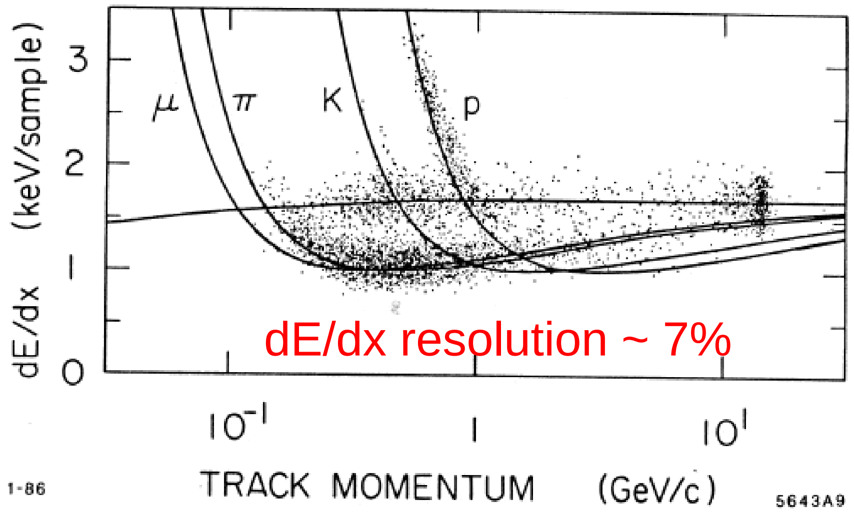
Bfield = 0.45 Tesla
HRS gas: 89% argon, 10% CO_2, 1% methane
drift field ~ 900 V/cm
sense wire gain ~ 2 $\times 10^4$
drift velocity ~ 50 μm/ns

L/R ambiguity resolution



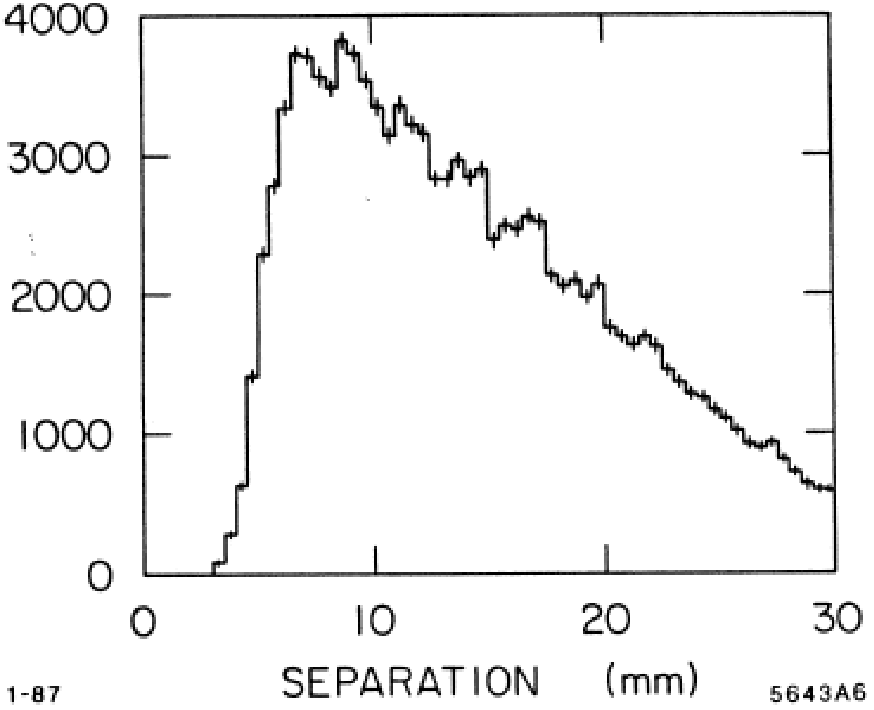


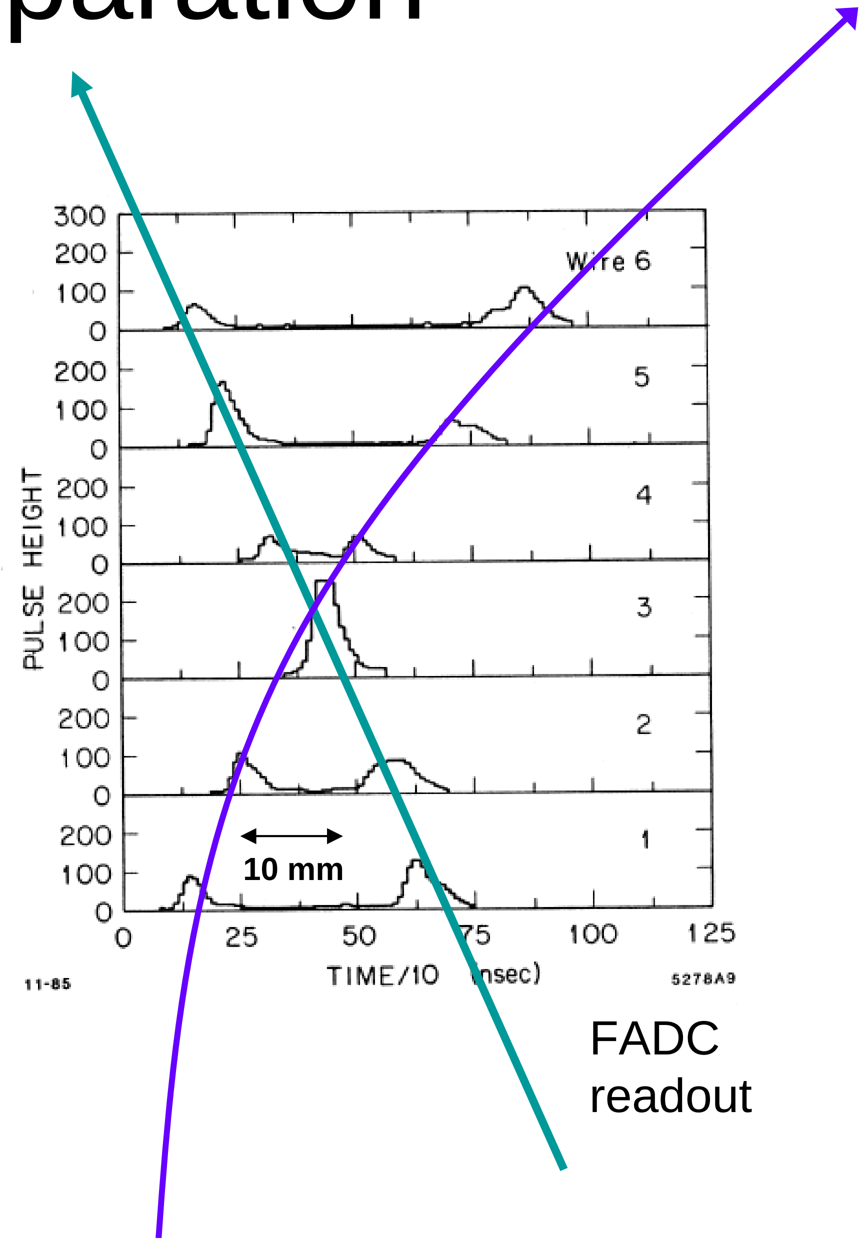
position resolution across the cell
~ 140 – 210 μm



dE/dx resolution ~ 7%

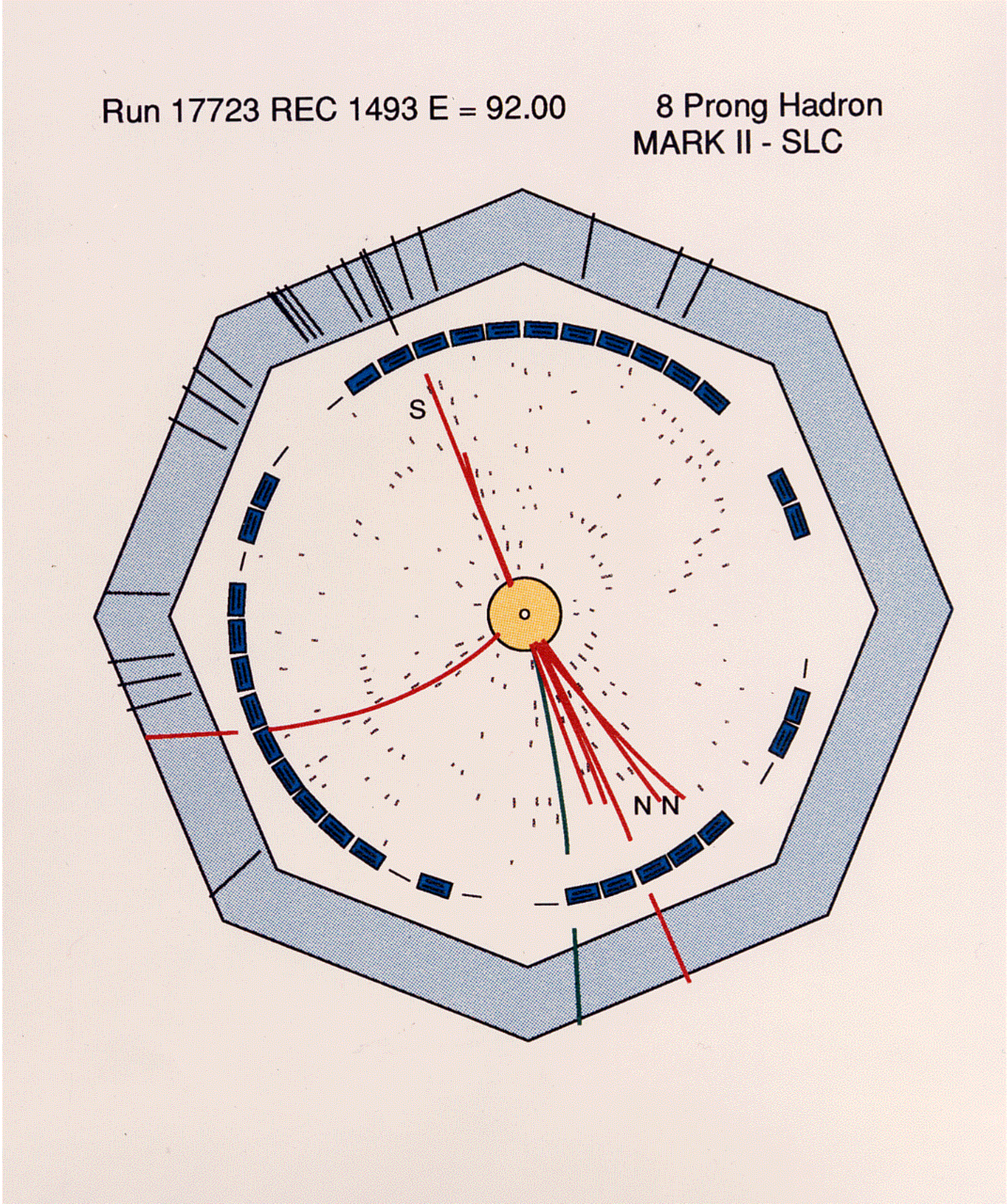
Two-hit separation

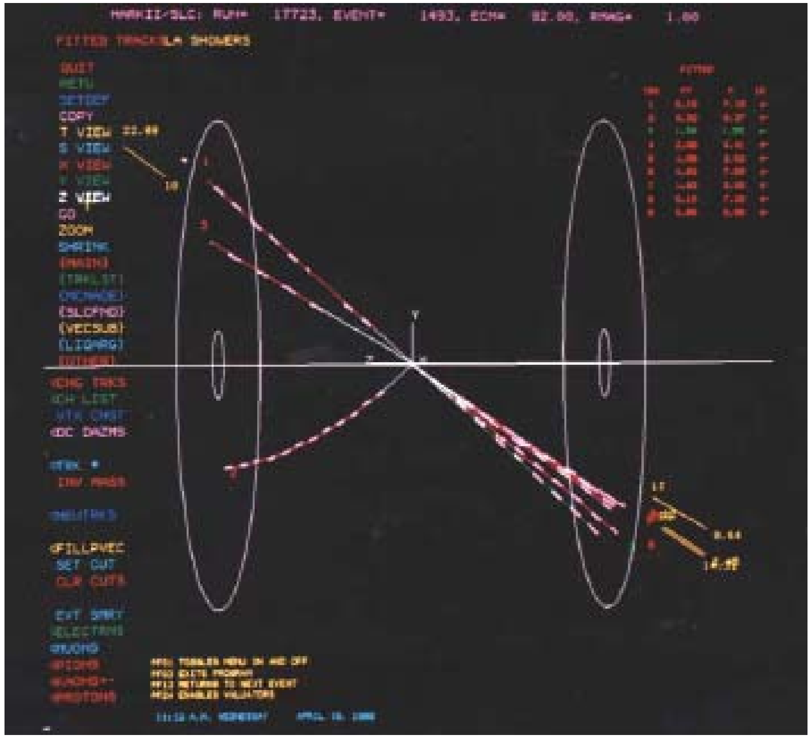




FADC
readout

The first hadronic Z decay!





An early 3D, interactive event display.
We were exploring our colorful side

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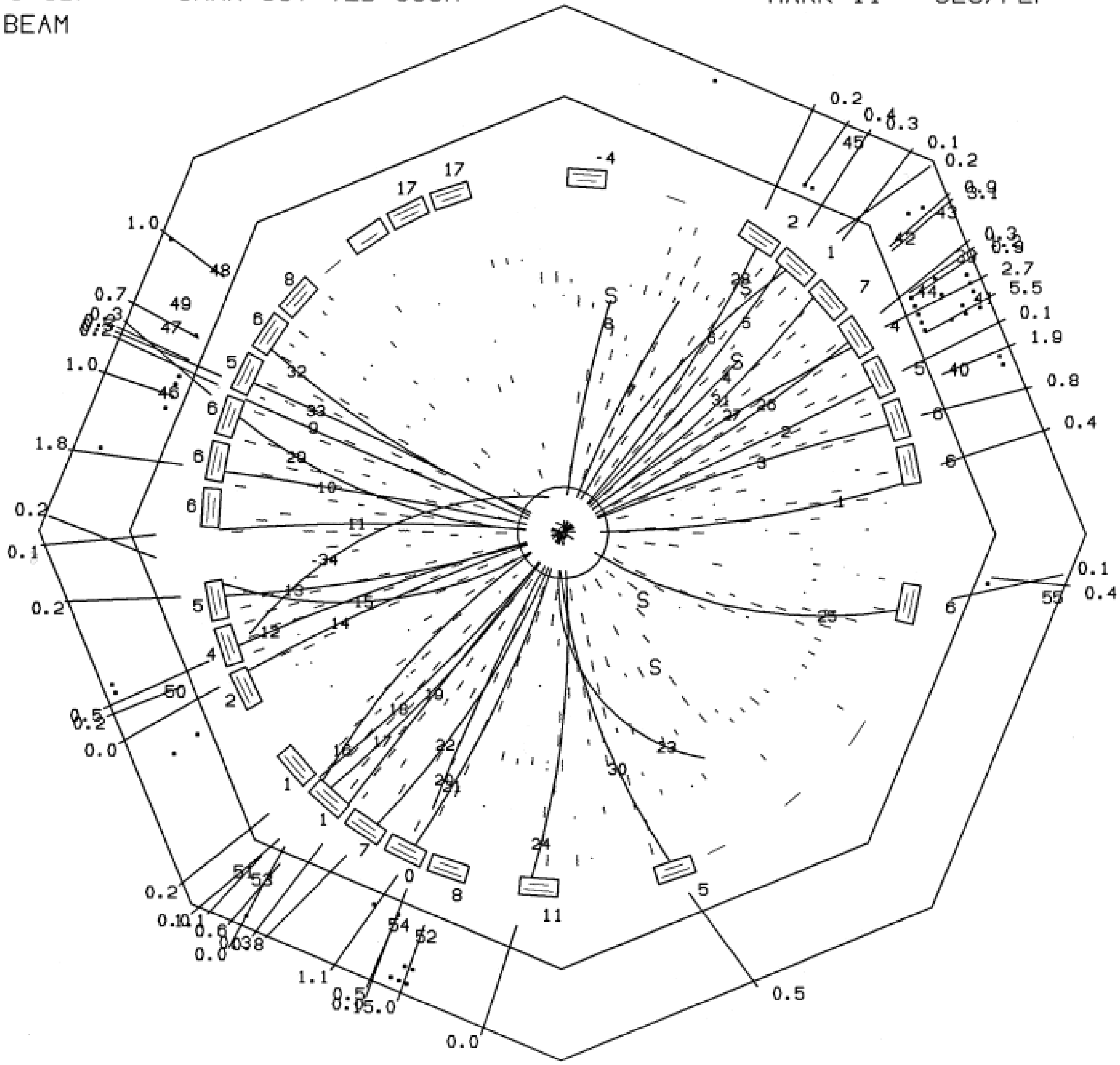
            RUN 18091 REC 2501 E= 90.60    30 PRONG HADRON           (5-0)
            TRIGGER 0 ODF      CHAR SST TED COSM              MARK II - SLC/PEP
                        BEAM
TRK P   ELATOT ID
 1  0.8   0.4 PI-
 2  4.5   0.1 PI-
 3  1.8   0.8 PI+
 4  3.6       PI-
 5  1.3   0.3 PI-
 6  0.5   0.2 PI+
 7  1.2       PI+
 8  1.2   1.1 PI+
 9  3.0   0.2 MU+
10  3.0   1.8 PI-
11  1.4   0.1 PI-
12  1.4   0.5 PI-
13  0.8   0.2 PI+
14  1.4   0.0 PI-
15  0.2   0.2 PI+
16  0.5   0.0 PI-
17  1.1   0.0 PI+
18  1.4   0.2 PI+
19  8.8   0.3 PI-
20  2.2   0.0 PI-
21  0.8   1.1 PI+
22  0.7   0.8 PI+
23  0.2       PI-
24  0.6   0.0 P+
25  0.3   0.1 PI-
26  1.2   0.3 PI-
27  1.5   2.7 PI+
28  0.9   0.2 PI-
29  0.4   0.3 PI+
30  0.4   0.5 PI-
31  0.9   0.1 PI-
32  0.6       PI+
33  2.2   0.5 PI-
34  0.3       PI-
```



Basic Particle Created in Test Of Accelerator

U.S. Physicists Gain in Race With Europeans

By JOHN NOBLE WILFORD

In the first successful test of a new type of atom smasher, American physicists have produced the elusive Z particle, an elementary particle considered to be a key to understanding the fundamental forces of nature. The Americans thus won the first lap in a race with their European counterparts to create the particle in bulk for further research.

Officials of the Stanford Linear Accelerator Center in Palo Alto, Calif., announced the achievement yesterday. They said "unmistakable fragments of a massive Z" particle were detected in an analysis of data from high-energy collisions generated by the accelerator on Tuesday.

In their announcement, the officials said the event was "greeted with relief and guarded optimism" because of the accelerator's novel design and development problems.

Burton Richter, director of the research center, cautioned that "many months of hard work lie ahead before we can bring this first-of-a-kind accelerator to its design performance."

More Particles Needed

Leon M. Lederman, director of the rival Fermi National Accelerator Laboratory at Batavia, Ill., said in a telephone interview that he was "delighted" with the success of the new

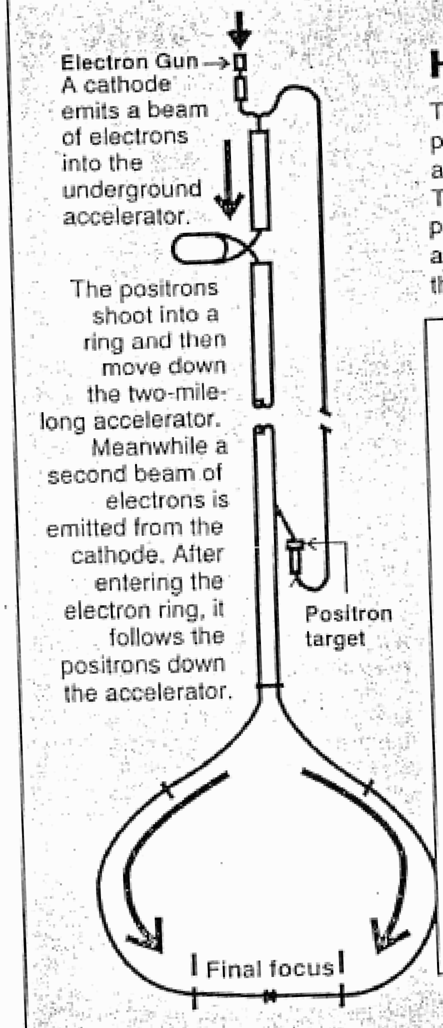
over the Europeans. The Europeans' $1 billion Large Electron-Positron collider, built near Geneva by a 14-nation consortium called CERN (the French acronym for European Center for Nuclear Research), is expected to go into

ough analysis of their behavior might lead to a unifying theory that would explain how all the forces of the universe are related to each other. The other forces, besides the weak force and elec-

head on they annihilate one another, and their vast energy of motion creates new particles. The Z particle decayed almost instanteously, but left a distinctive trace in the collison data

How the Z Particle Was Produced

The Stanford Linear Collider, depicted at left, shoots beams of positrons and electrons down a two-mile straightway to curved arms, where the electrons move clockwise around the other arm. The two beams collide with great violence, producing many new particles, including the elusive Z particle whose creation was announced yesterday. The Z particle is one of the several particles that carry the primary forces of nature, as described in the table below.



Known Force-Carrying Particles

Particle	Force	Role In Universe
Photon	Electro-magnetic	Has been isolated and studied for 80 years. Determines structures of atoms, molecules, solids and liquids
Z and W	Weak	Recently discovered, isolated and studied. Determines stability of atomic nuclei; fuels sun and stars.
Gluon	Strong	Existence proven indirectly but probably cannot be isolated. Holds together protons and neutrons with quarks, the fundamental building blocks of nuclear matter.
Unknown	Gravitation	Quantum mechanics predicts there should be a particle. Usually called a graviton, it has not been discovered.

Source: Stanford Linear Accelerater Center; "The Material World", Oxford University Press

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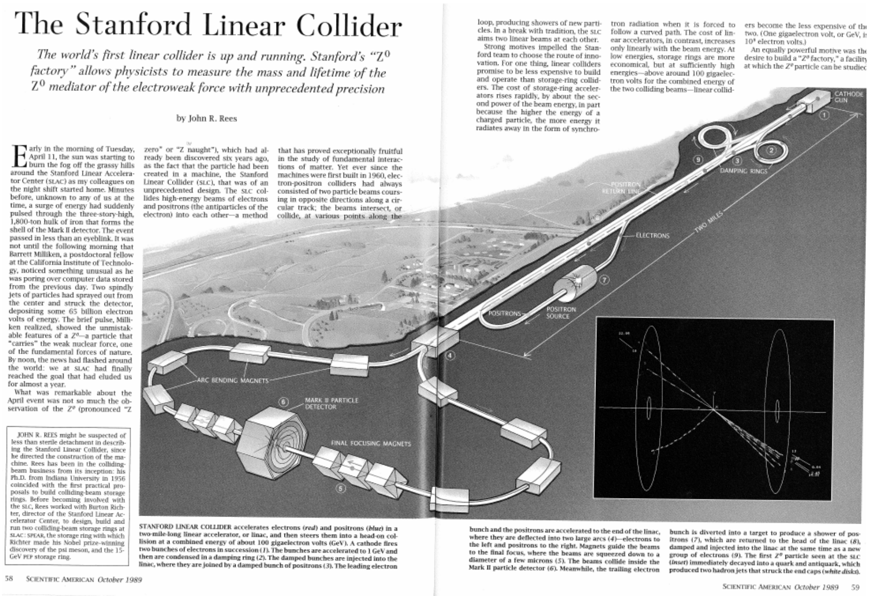
SCIENTIFIC AMERICAN

OCTOBER 1989
$2.95

How to turn technology into industrial competitiveness.
Microscopes that probe the ups and downs of atoms.
Where did the Indo-European languages come from?

Seeing into the heart of matter: *the Mark II detector finds Z^0 particles generated at the Stanford Linear Collider.*

Modern drift chambers:
useful, yes, but also
beautiful things!



The Stanford Linear Collider

The world's first linear collider is up and running. Stanford's "Z^0 factory" allows physicists to measure the mass and lifetime of the Z^0 mediator of the electroweak force with unprecedented precision

by John R. Rees

Early in the morning of Tuesday, April 11, the sun was starting to burn the fog off the grassy hills around the Stanford Linear Accelerator Center (SLAC) as my colleagues on the night shift started home. Minutes before, unknown to any of us at the time, a surge of energy had suddenly pulsed through the three-story-high, 1,800-ton hulk of iron that forms the shell of the Mark II detector. The event passed in less than an eyeblink. It was not until the following morning that Barrett Milliken, a postdoctoral fellow at the California Institute of Technology, noticed something unusual as he was poring over computer data stored from the previous day. Two spindly jets of particles had sprayed out from the center and struck the detector, depositing some 65 billion electron volts of energy. The brief pulse, Milliken realized, showed the unmistakable features of a Z^0—a particle that "carries" the weak nuclear force, one of the fundamental forces of nature. By noon, the news had flashed around the world: we at SLAC had finally reached the goal that had eluded us for almost a year.

What was remarkable about the April event was not so much the observation of the Z^0 (pronounced "Z zero" or "Z naught"), which had already been discovered six years ago, as the fact that the particle had been created in a machine, the Stanford Linear Collider (SLC), that was of an unprecedented design. The SLC collides high-energy beams of electrons and positrons (the antiparticles of the electron) into each other—a method that has proved exceptionally fruitful in the study of fundamental interactions of matter. Yet ever since the machines were first built in 1960, electron-positron colliders had always consisted of two particle beams coursing in opposite directions along a circular track; the beams intersect, or collide, at various points along the loop, producing showers of new particles. In a break with tradition, the SLC aims two linear beams at each other.

Strong motives impelled the Stanford team to choose the route of innovation. For one thing, linear colliders promise to be less expensive to build and operate than storage-ring colliders. The cost of storage-ring accelerators rises rapidly, by about the second power of the beam energy, in part because the higher the energy of a charged particle, the more energy it radiates away in the form of synchrotron radiation when it is forced to follow a curved path. The cost of linear accelerators, in contrast, increases only linearly with the beam energy. At low energies, storage rings are more economical, but at sufficiently high energies—above around 100 gigaelectron volts for the combined energy of the two colliding beams—linear colliders become the less expensive of th two. (One gigaelectron volt, or GeV, i 10^9 electron volts.)

An equally powerful motive was th desire to build a "Z^0 factory," a facilit at which the Z^0 particle can be studie

JOHN R. REES might be suspected of less than sterile detachment in describing the Stanford Linear Collider, since he directed the construction of the machine. Rees has been in the colliding-beam business from its inception: his Ph.D. from Indiana University in 1956 coincided with the first practical proposals to build colliding-beam storage rings. Before becoming involved with the SLC, Rees worked with Burton Richter, director of the Stanford Linear Accelerator Center, to design, build and run two colliding-beam storage rings at SLAC: SPEAR, the storage ring with which Richter made his Nobel prize-winning discovery of the psi meson, and the 15-GeV PEP storage ring.

STANFORD LINEAR COLLIDER accelerates electrons (*red*) and positrons (*blue*) in a two-mile-long linear accelerator, or linac, and then steers them into a head-on collision at a combined energy of about 100 gigaelectron volts (GeV). A cathode fires two bunches of electrons in succession (*1*). The bunches are accelerated to 1 GeV and then are condensed in a damping ring (*2*). The damped bunches are injected into the linac, where they are joined by a damped bunch of positrons (*3*). The leading electron bunch and the positrons are accelerated to the end of the linac, where they are deflected into two large arcs (*4*)—electrons to the left and positrons to the right. Magnets guide the beams to the final focus, where the beams are squeezed down to a diameter of a few microns (*5*). The beams collide inside the Mark II particle detector (*6*). Meanwhile, the trailing electron bunch is diverted into a target to produce a shower of positrons (*7*), which are returned to the head of the linac (*8*), damped and injected into the linac at the same time as a new group of electrons (*9*). The first Z^0 particle seen at the SLC (*inset*) immediately decayed into a quark and antiquark, which produced two hadron jets that struck the end caps (*white disks*).

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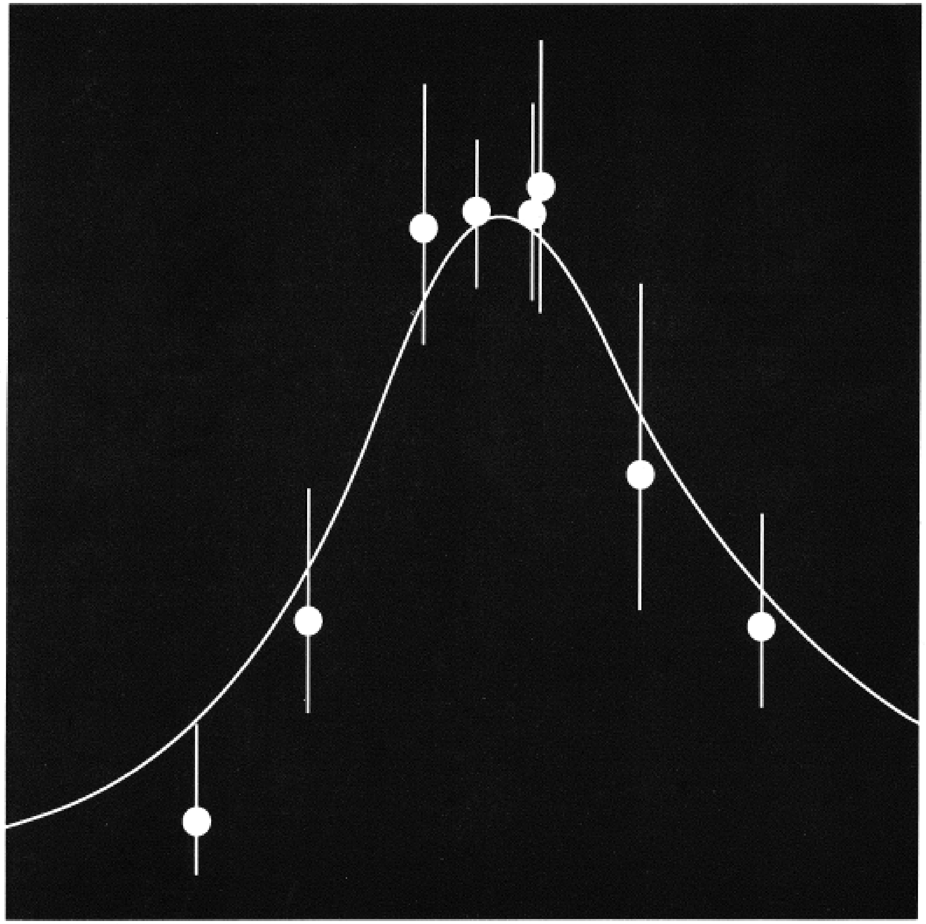
SLAC BEAM LINE

The thing that doesn't fit
is the thing that's most interesting.
— Richard Feynman

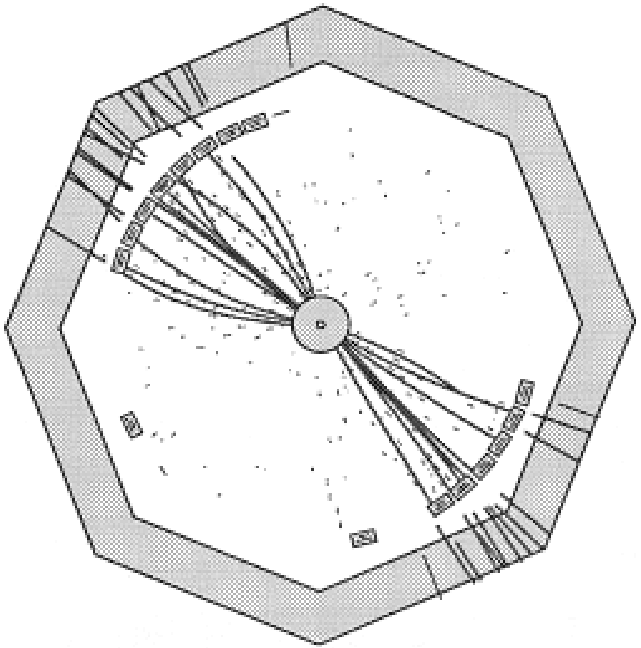
Volume 19, Number 3 *September 1989*



First Results from the SLC

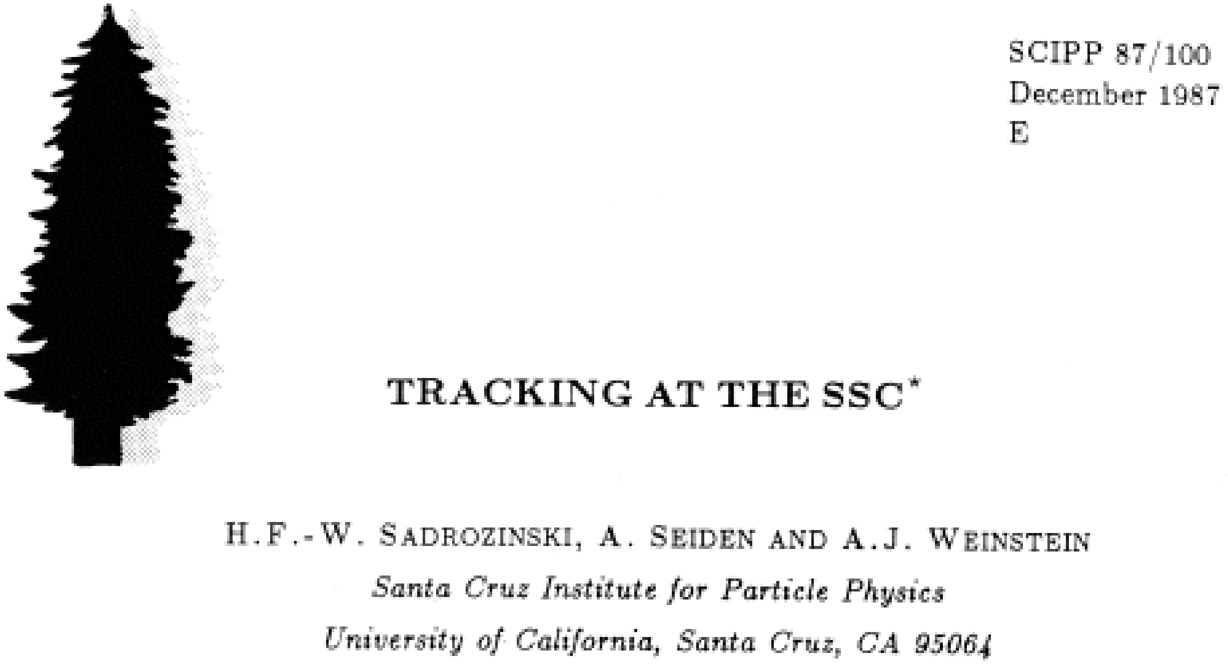
The Mark II Collaboration is a group of about 130 physicists from Cal Tech, Johns Hopkins, the Lawrence Berkeley Laboratory (LBL), SLAC, and the Universities of California (Santa Cruz), Colorado, Hawaii, Indiana and Michigan. They have upgraded the 1800-ton Mark II detector for Z° research (see September 1988 *Beam Line*, p. 3) and installed it surrounding the SLC clashpoint in the Collider Experimental Hall. The SLC began producing Z°'s on April 11 (see April 1989 *Beam Line*, p. 3); by September 1 almost 350 had been observed.

SLAC Beam Line, September 1989



A hadronic Z° decay. The Z° breaks up first into a quark-antiquark pair, which subsequently generates two back-to-back hadron jets.

On to a greater challenge!



SCIPP 87/100
December 1987
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TRACKING AT THE SSC*

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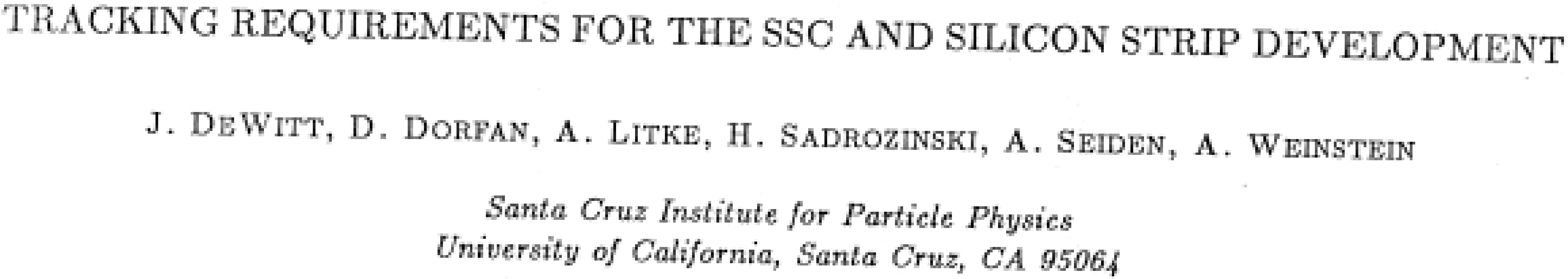

TRACKING REQUIREMENTS FOR THE SSC AND SILICON STRIP DEVELOPMENT

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- The power of Abe’s scaling rules
- The challenge of achieving robust pattern recognition in really dense and jetty events!
- … while minimizing material, cost, size…

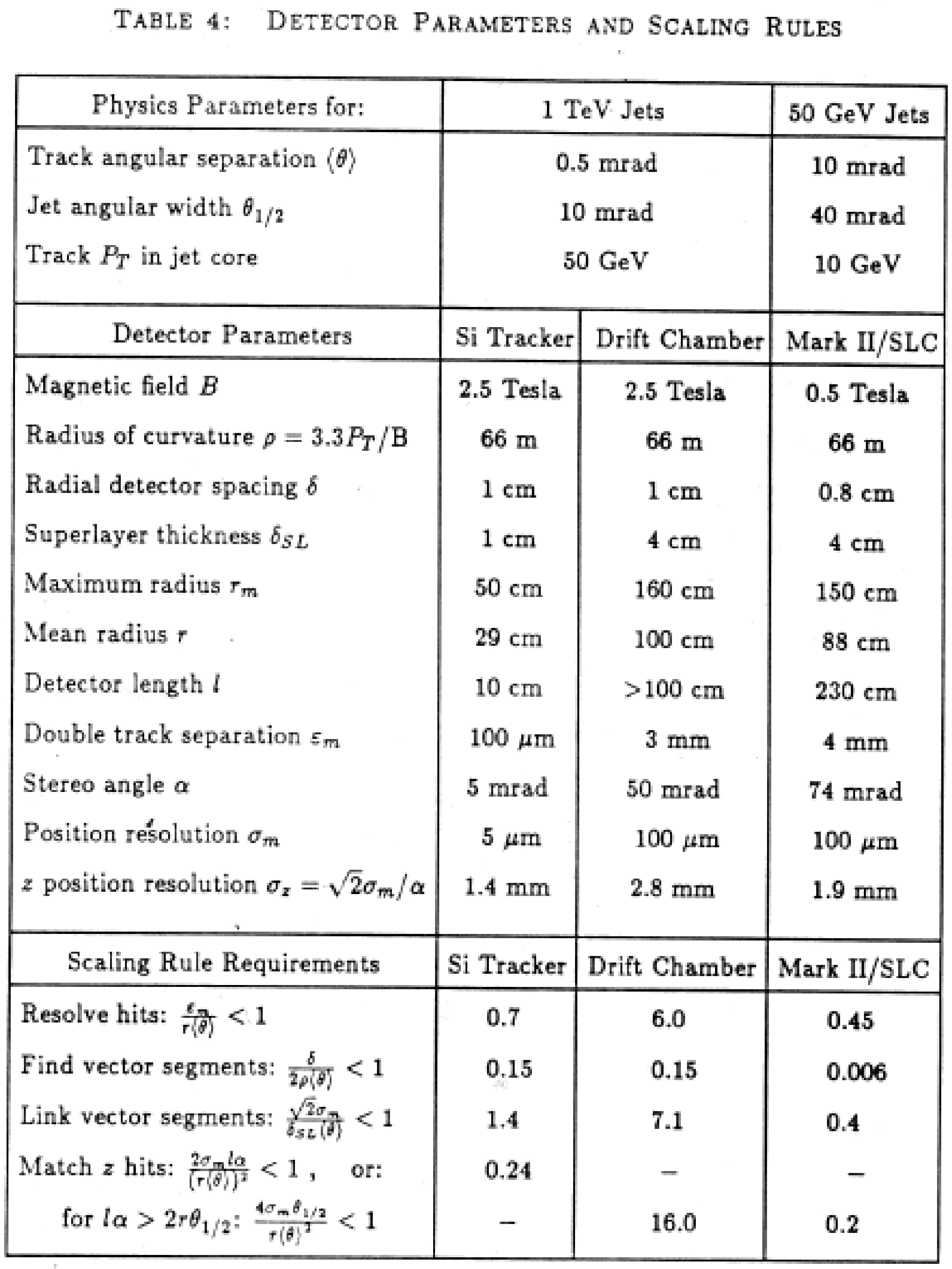
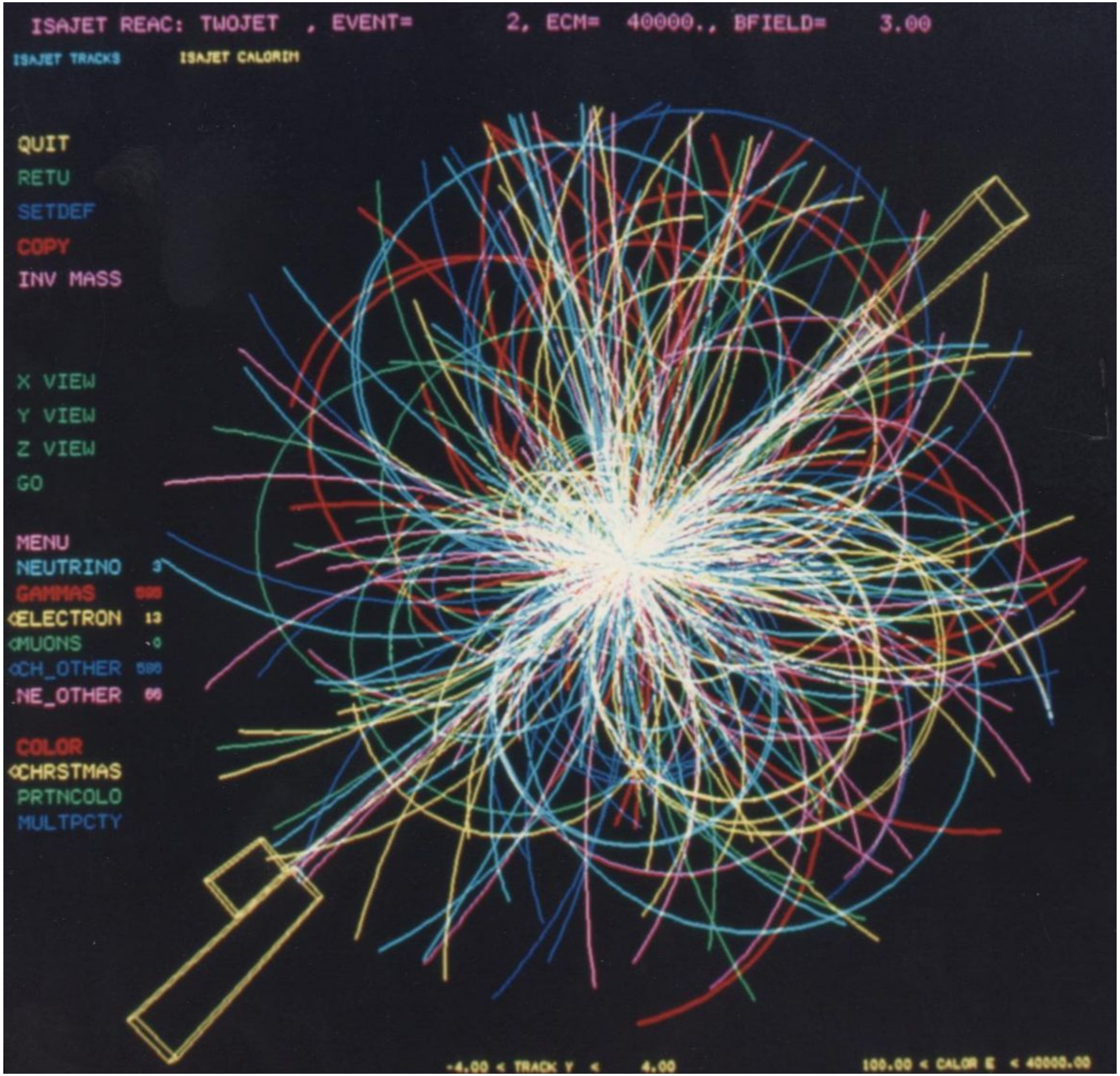


TABLE 4: DETECTOR PARAMETERS AND SCALING RULES

Physics Parameters for:	1 TeV Jets		50 GeV Jets
Track angular separation $\langle\theta\rangle$	0.5 mrad		10 mrad
Jet angular width $\theta_{1/2}$	10 mrad		40 mrad
Track P_T in jet core	50 GeV		10 GeV
Detector Parameters	**Si Tracker**	**Drift Chamber**	**Mark II/SLC**
Magnetic field B	2.5 Tesla	2.5 Tesla	0.5 Tesla
Radius of curvature $\rho = 3.3 P_T/\mathrm{B}$	66 m	66 m	66 m
Radial detector spacing δ	1 cm	1 cm	0.8 cm
Superlayer thickness δ_{SL}	1 cm	4 cm	4 cm
Maximum radius r_m	50 cm	160 cm	150 cm
Mean radius r	29 cm	100 cm	88 cm
Detector length l	10 cm	>100 cm	230 cm
Double track separation ε_m	100 μm	3 mm	4 mm
Stereo angle α	5 mrad	50 mrad	74 mrad
Position resolution σ_m	5 μm	100 μm	100 μm
z position resolution $\sigma_z = \sqrt{2}\sigma_m/\alpha$	1.4 mm	2.8 mm	1.9 mm
Scaling Rule Requirements	**Si Tracker**	**Drift Chamber**	**Mark II/SLC**
Resolve hits: $\frac{\varepsilon_m}{r\langle\theta\rangle} < 1$	0.7	6.0	0.45
Find vector segments: $\frac{\delta}{2\rho\langle\theta\rangle} < 1$	0.15	0.15	0.006
Link vector segments: $\frac{\sqrt{2}\sigma_m}{\delta_{SL}\langle\theta\rangle} < 1$	1.4	7.1	0.4
Match z hits: $\frac{2\sigma_m l\alpha}{(r\langle\theta\rangle)^2} < 1$, or:	0.24	–	–
for $l\alpha > 2r\theta_{1/2}$: $\frac{4\sigma_m\theta_{1/2}}{r\langle\theta\rangle^2} < 1$	–	16.0	0.2



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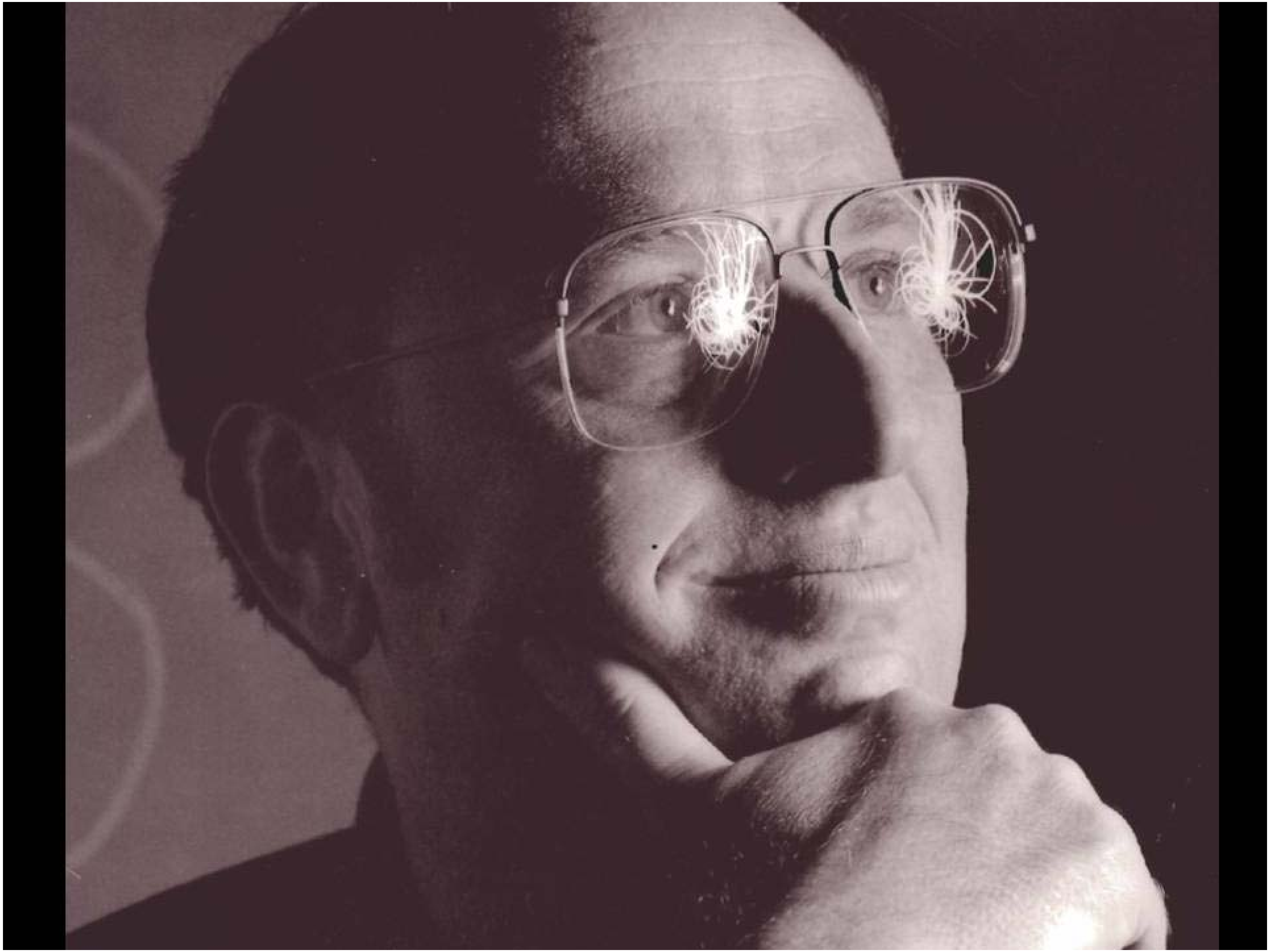

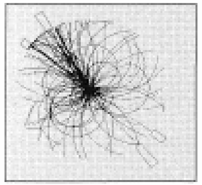
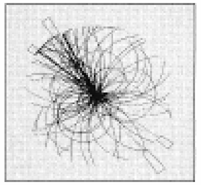
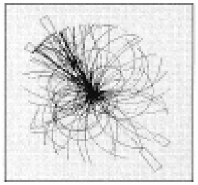
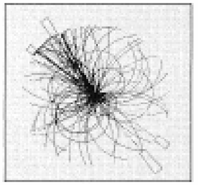
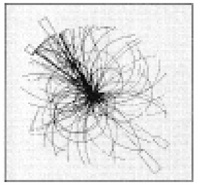
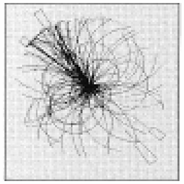
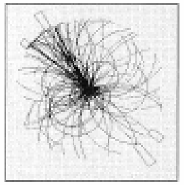
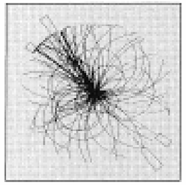
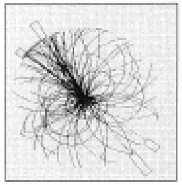
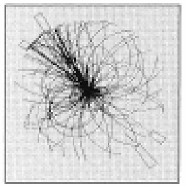
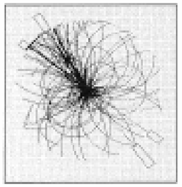
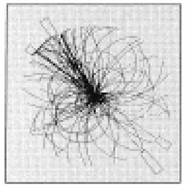
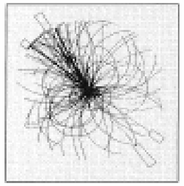
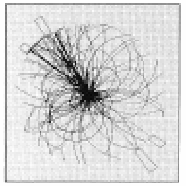
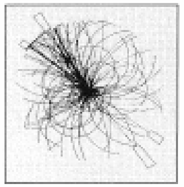

Workshop on Calorimetry for the Superconducting Super Collider

March 13 – 17, 1989

University of Alabama, Tuscaloosa, Alabama

The Workshop will be organized around working groups on

- **requirements for SSC physics**
- **simulations and performance predictions**
- **electronics and triggering**
- **liquid argon calorimetry**
- **room temperature liquid calorimetry**
- **scintillating material calorimetry**
- **silicon calorimetry**
- **gas calorimetry**

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Sponsors

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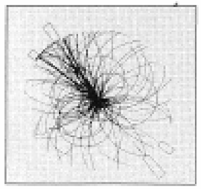
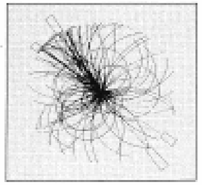
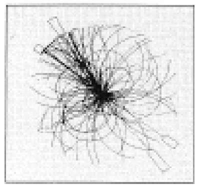
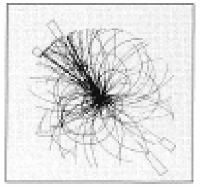
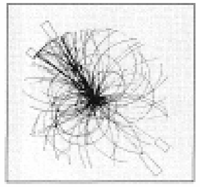
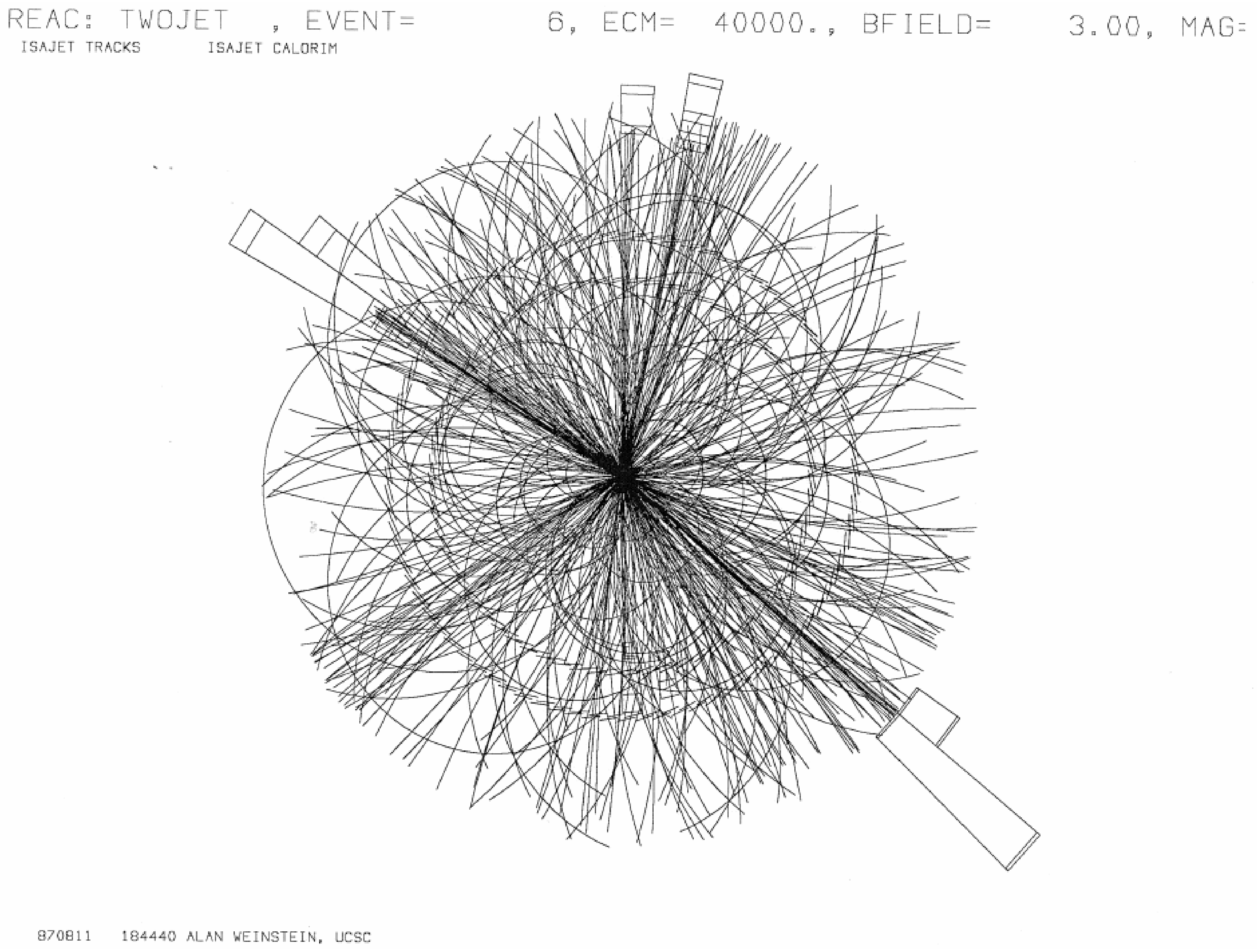
Attendance will be limited to 200. For additional information contact Calorimeter Workshop, Physics Department, University of Alabama, Tuscaloosa, Alabama 35487 (205) 348-3796

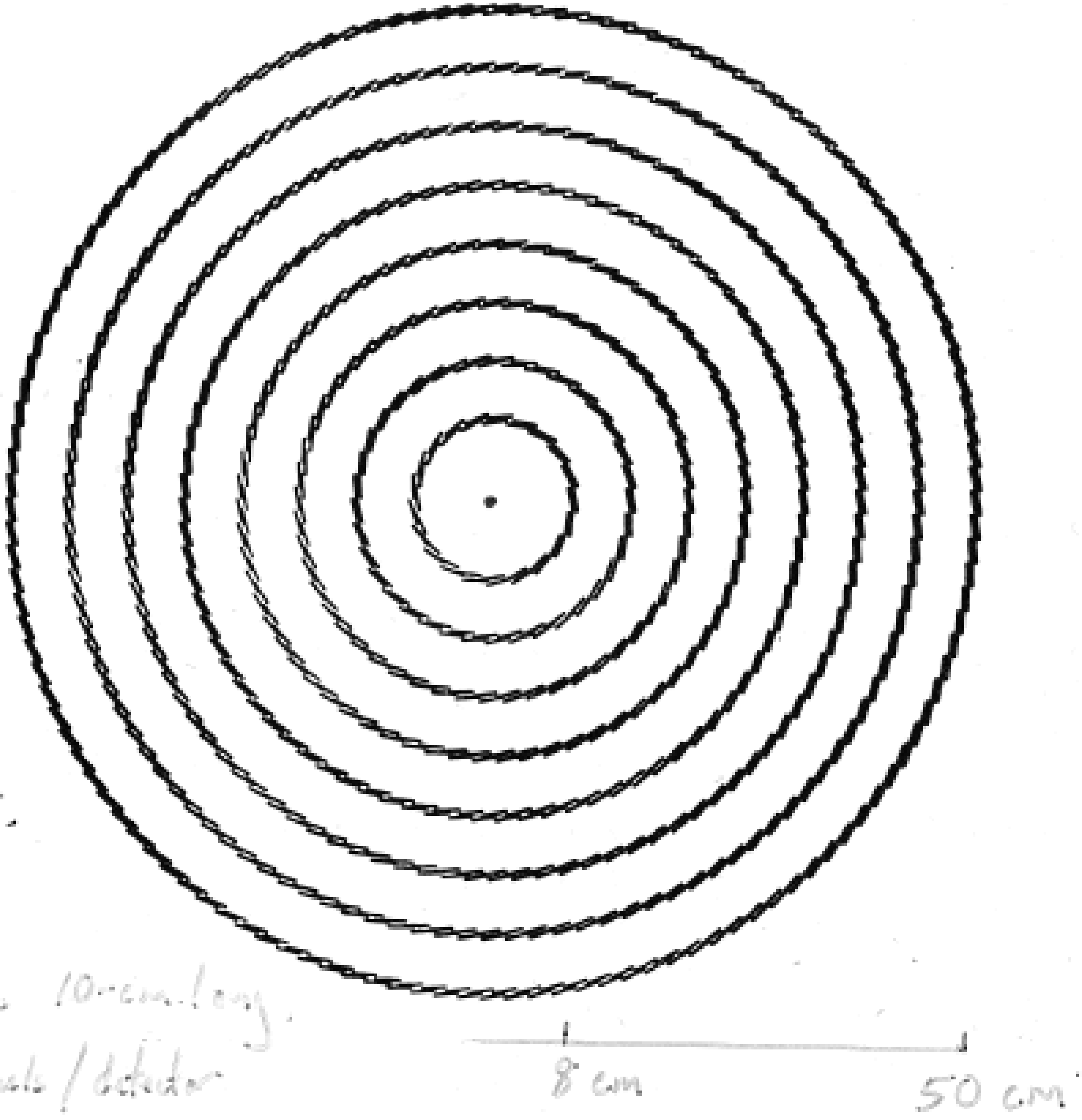






Now these are jetty events!

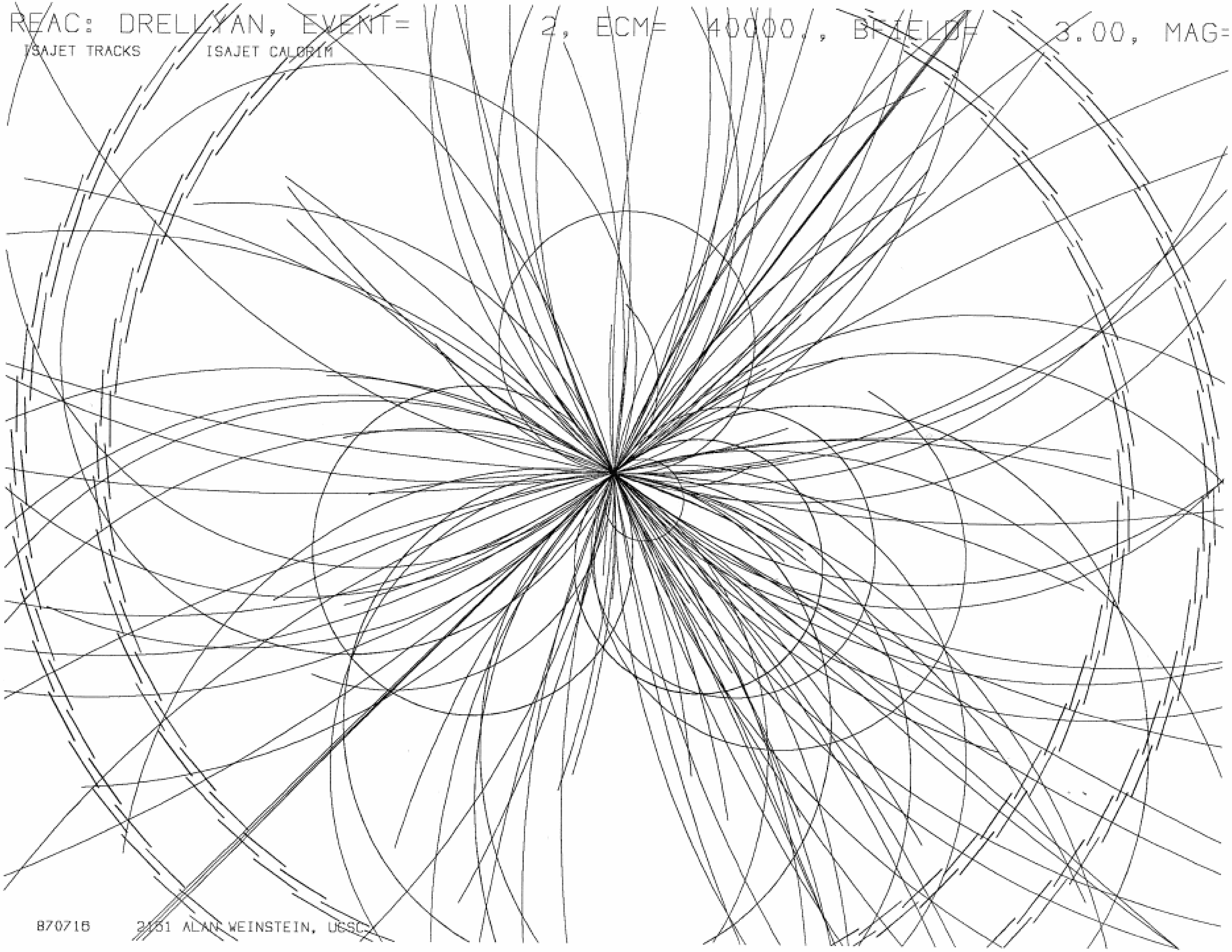


A Silicon Tracking System for SSC Physics

8 double layers of Si μ-strips, with double-sided readout.



20 K detectors, 10-cm long.
2048 channels / detector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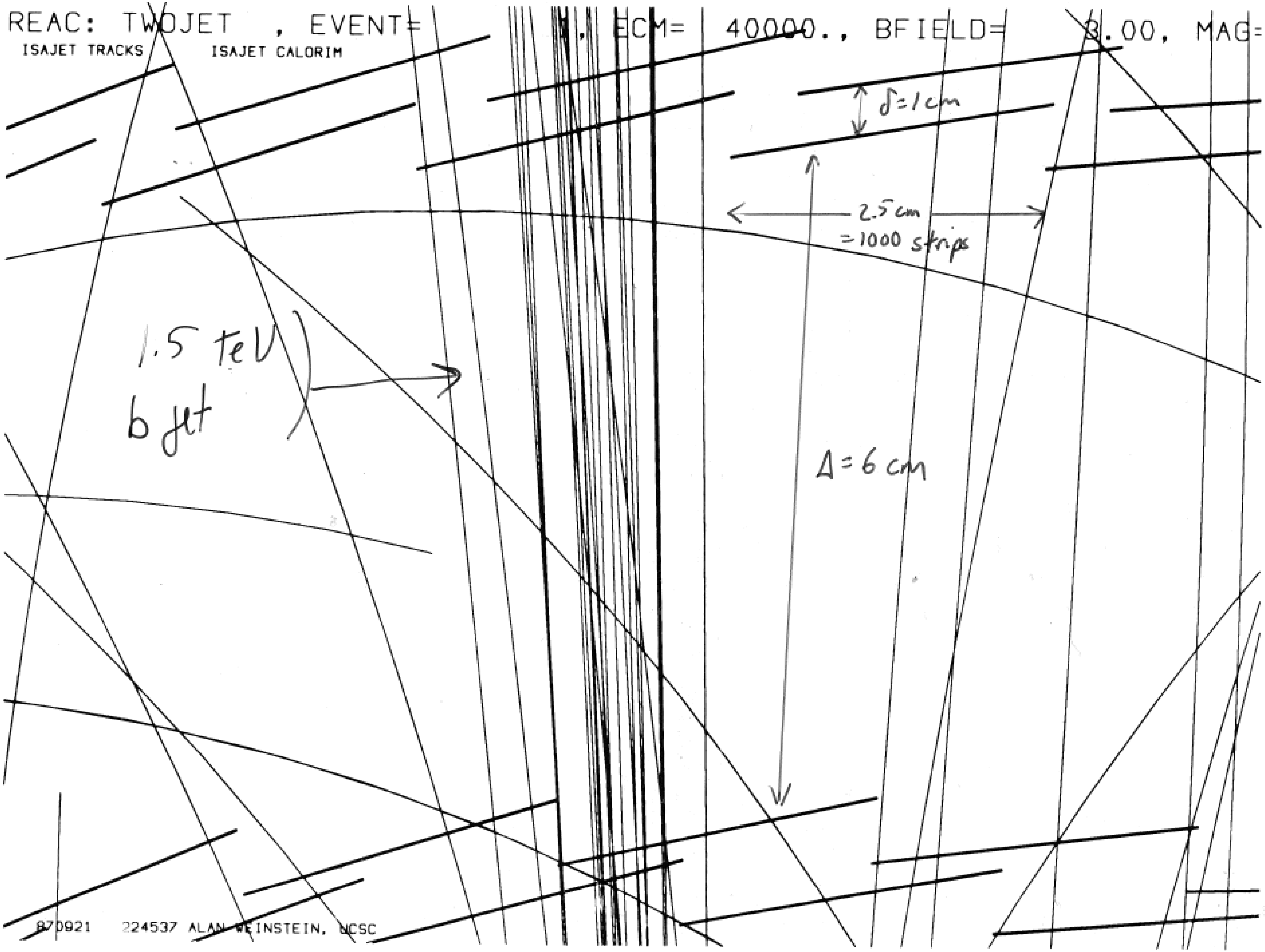
ISAJET CALORIM
870716
2151 ALAN WEINSTEIN, UCSC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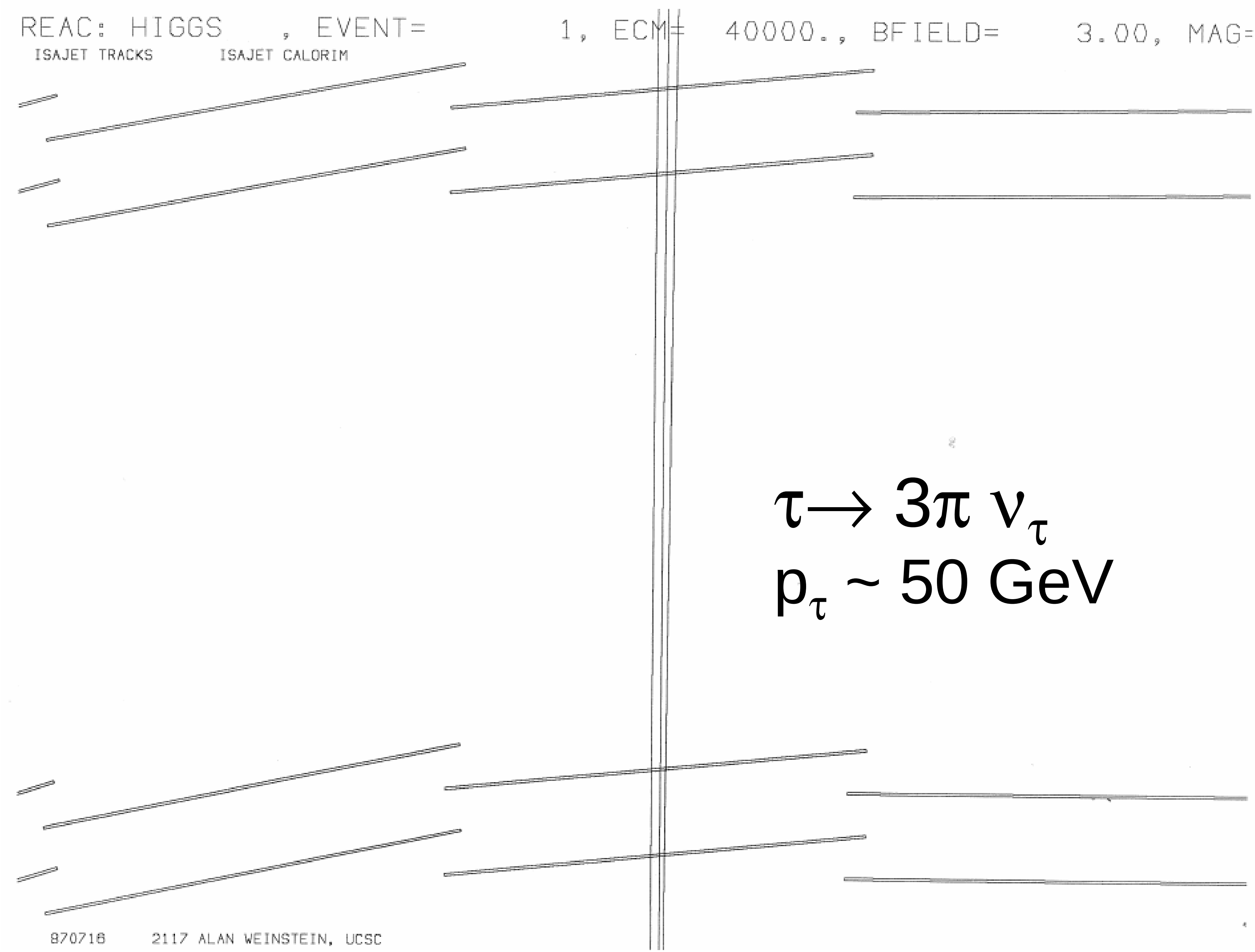
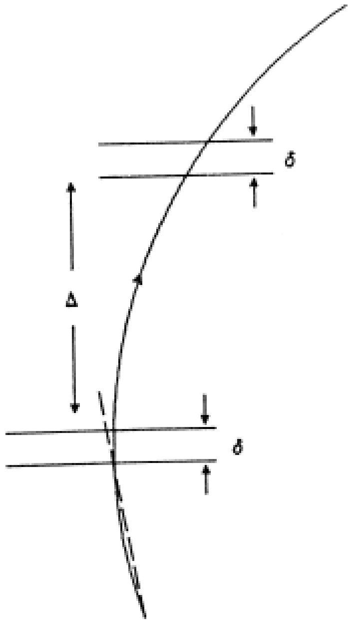
ISAJET TRACKS
ISAJET CALORIM
δ=1cm
2.5 cm
=1000 strips
1.5 teV
b jet
Δ=6 cm
870921 224537 ALAN WEINSTEIN, UCSC



$\tau \rightarrow 3\pi\ \nu_\tau$

p_τ ~ 50 GeV

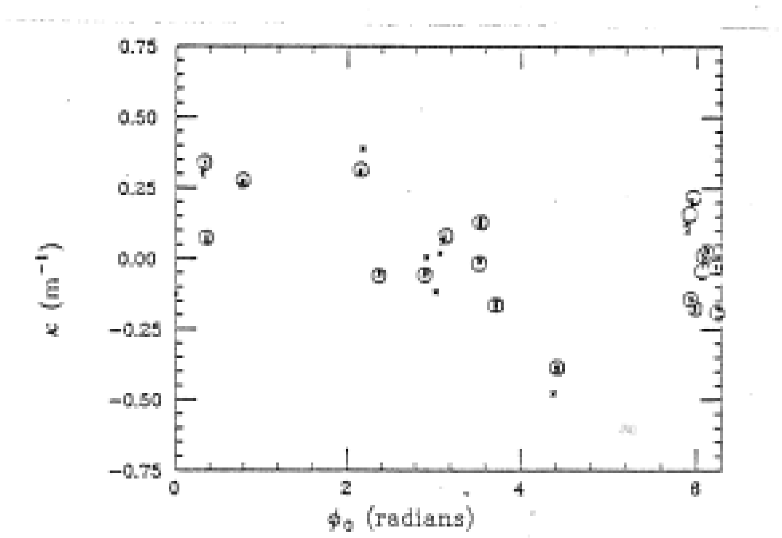
Track segment clustering



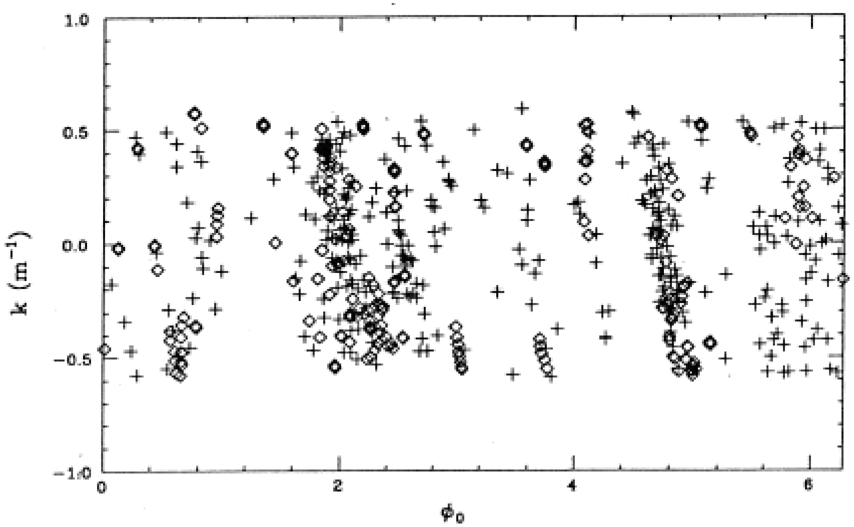
$$\kappa = \frac{\frac{-d\phi}{dr}}{\sqrt{1 + \left(\frac{\bar{r}\, d\phi}{dr}\right)}}$$

$$\phi_0 = \bar{\phi} + \arcsin \kappa \bar{r}$$

at SLC



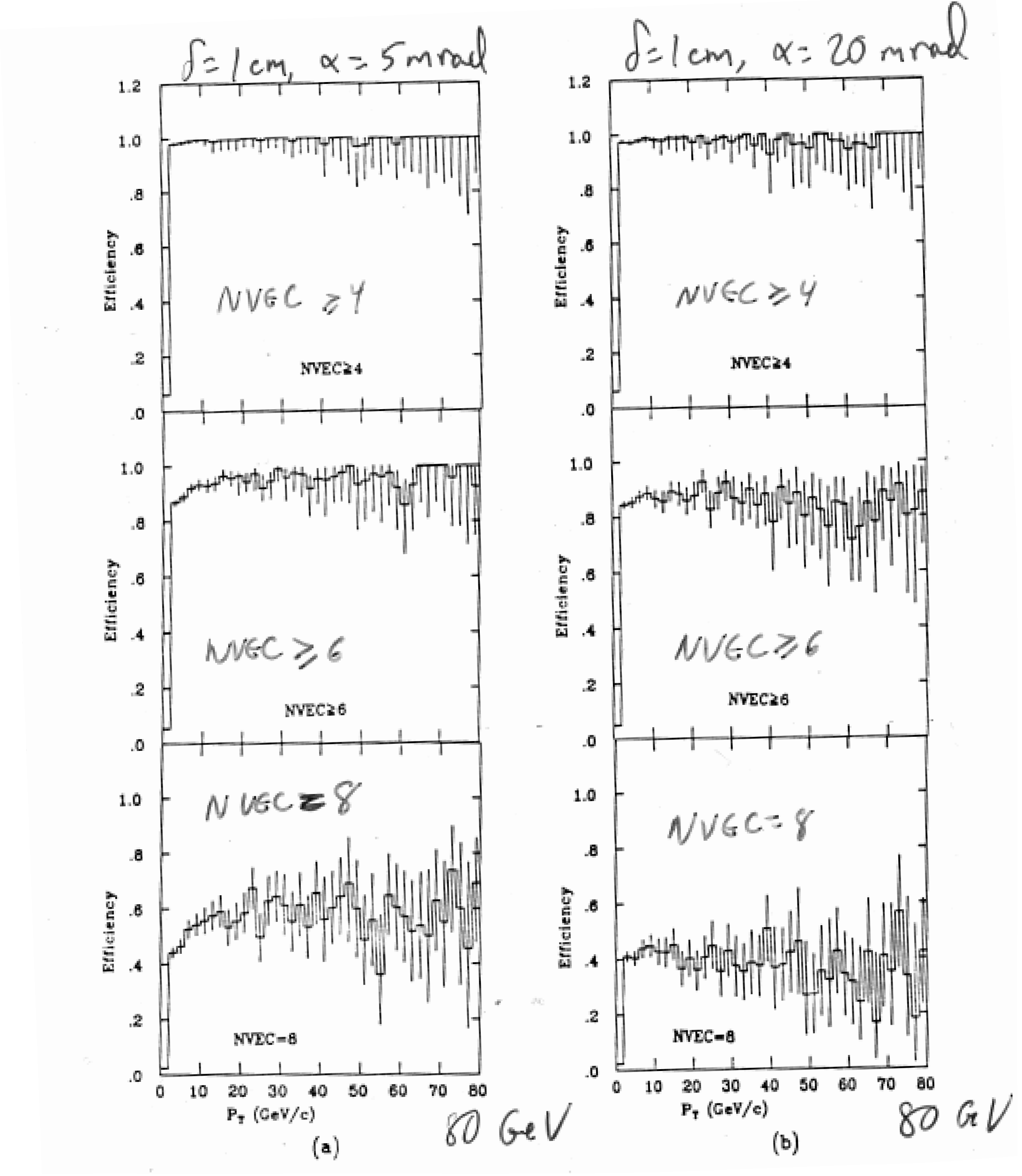
at SSC



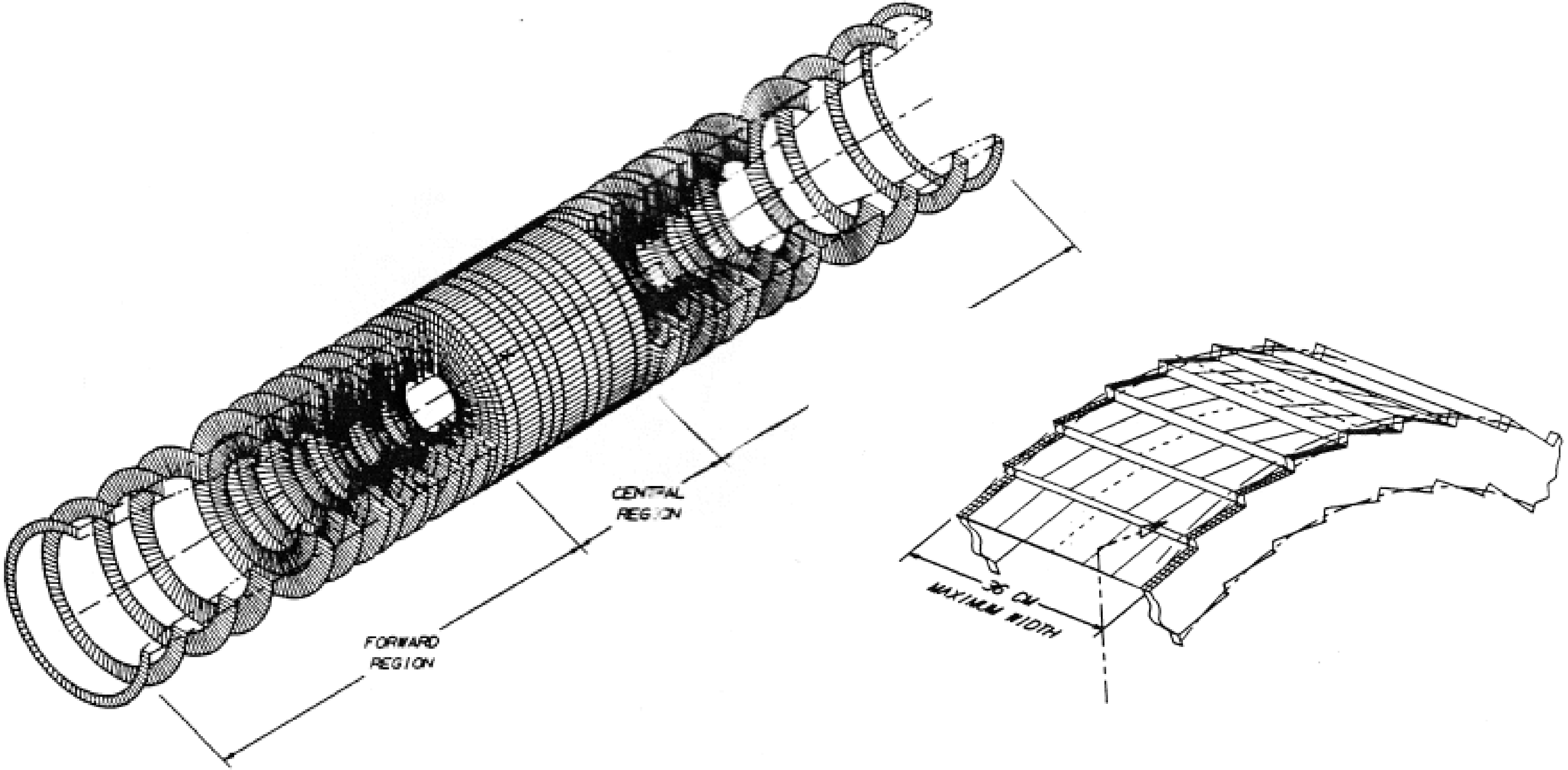
Tracking efficiency

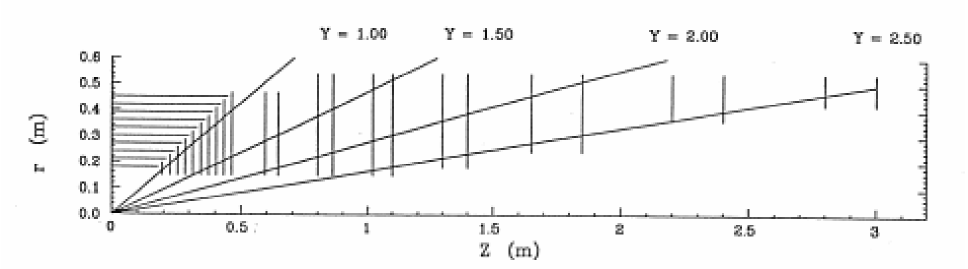
With 8 layers,
4-out-of-8 clustering,
and small-angle
stereo strips,

track finding was
efficient,
even in the core of
high-p_t jets



Silicon tracker for the SSC





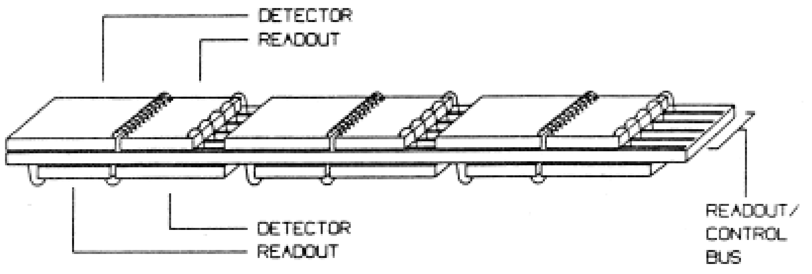


Fig. 14. Schematic arrangement of a short-strip detector ladder using wire bonds.

The SDC at the SSC

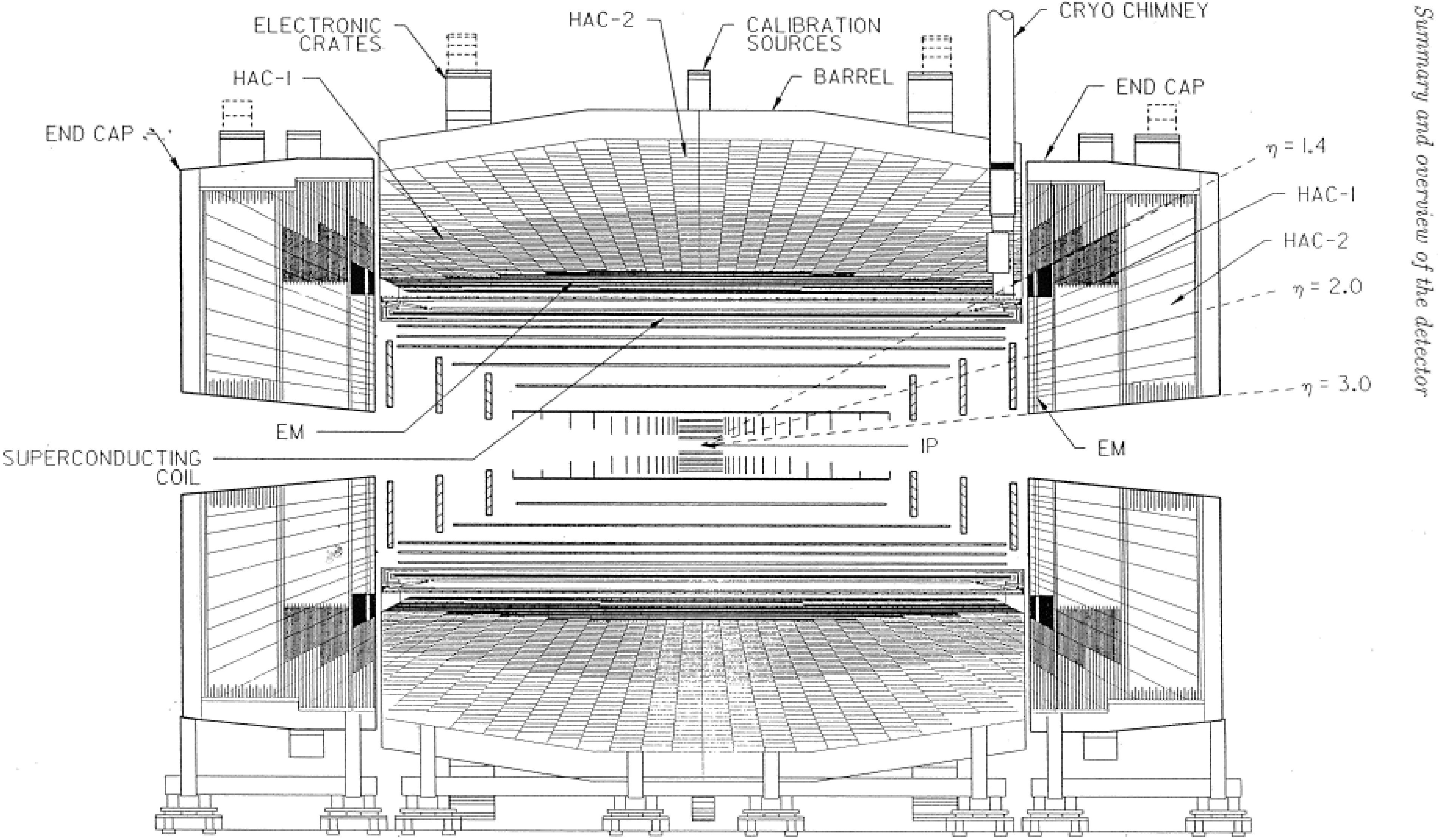
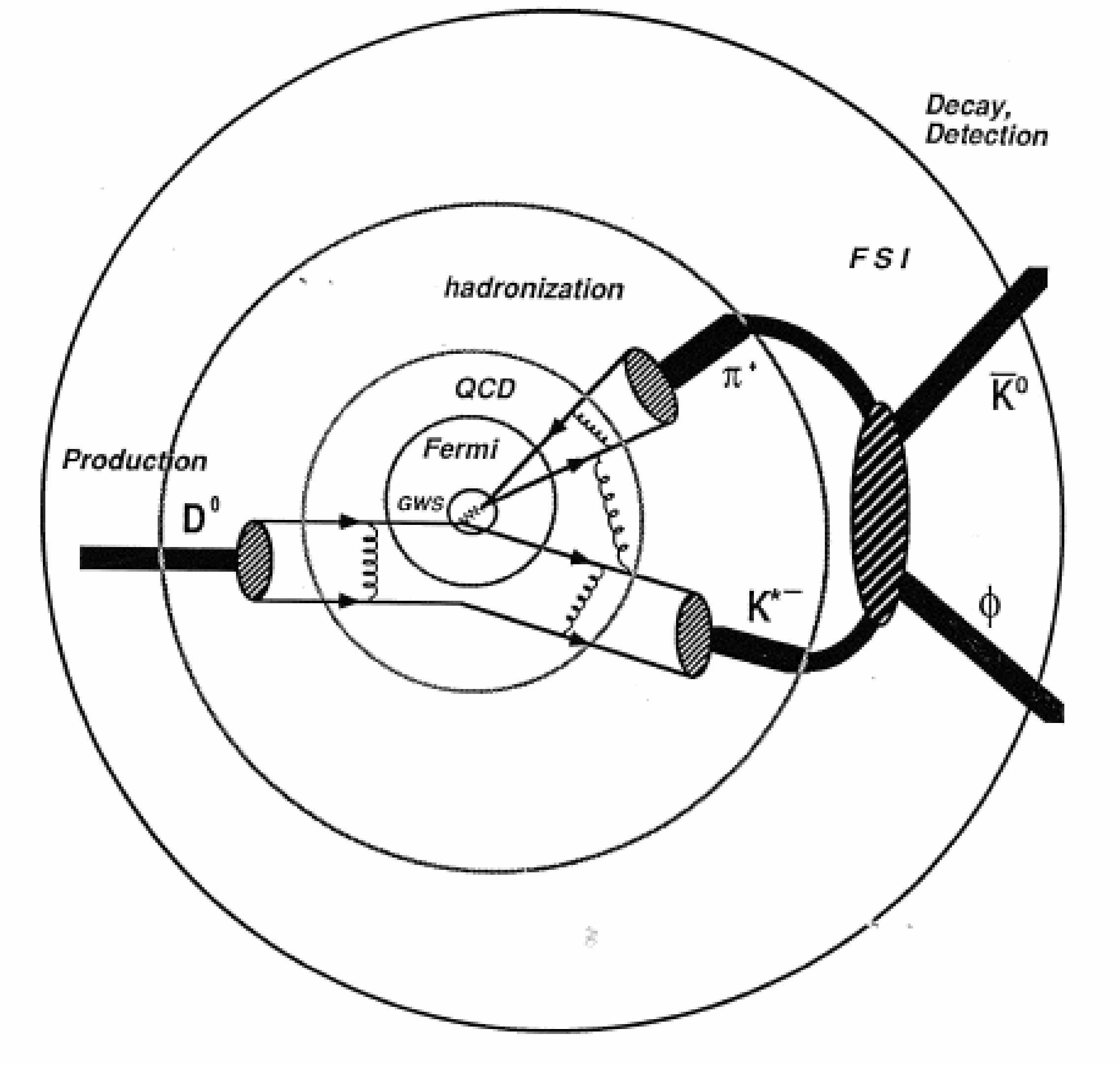
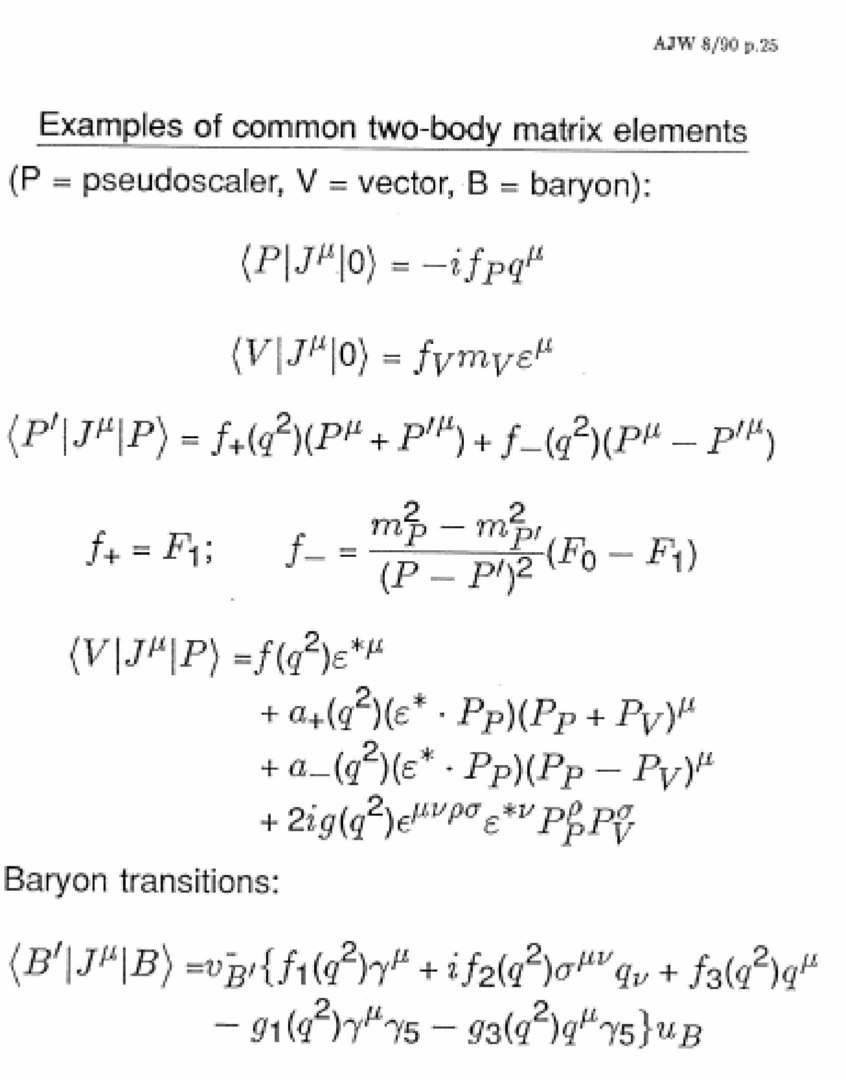


FIG. 2-6. Elevation view of the central calorimeter. The barrel calorimeter displays one line per longitudinal cell (absorber boundary), whereas the endcaps display two lines per cell (which are partly cut away).

Aside: Learning from Abe about Lorentz Invariant Matrix elements



Lots of folks wanted to learn the mysteries; I tried to get it all down



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Examples of common two-body matrix elements

(P = pseudoscaler, V = vector, B = baryon):

$$\langle P|J^\mu|0\rangle = -if_P q^\mu$$

$$\langle V|J^\mu|0\rangle = f_V m_V \varepsilon^\mu$$

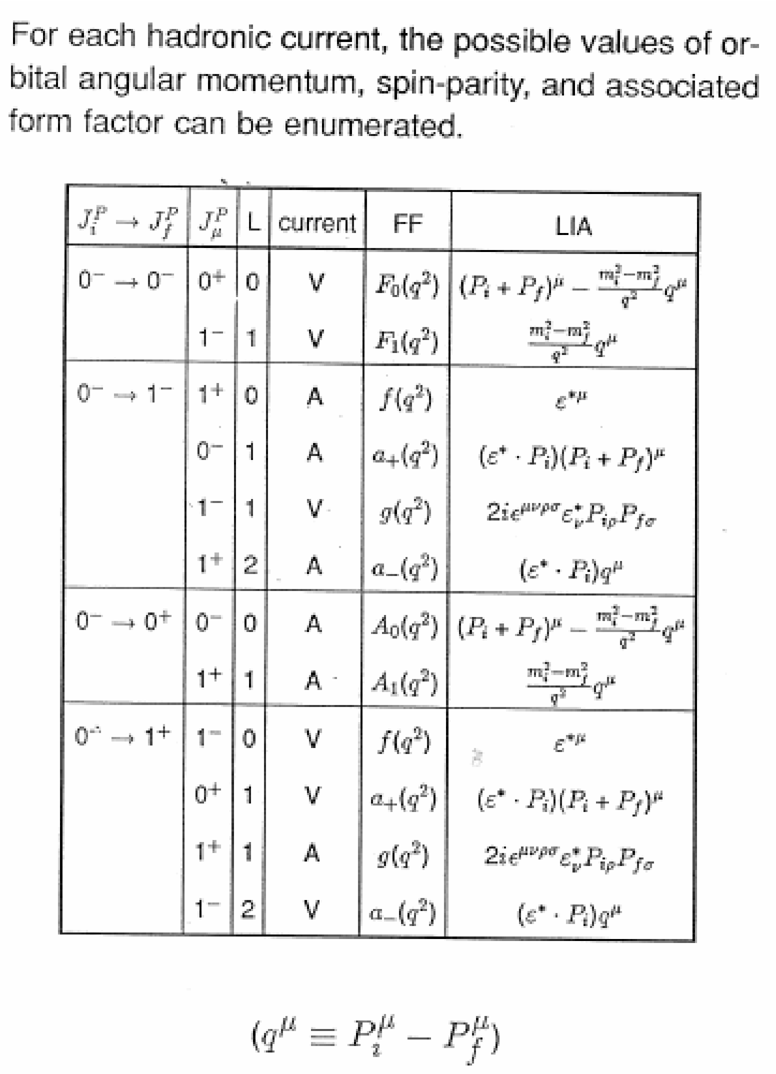
$$\langle P'|J^\mu|P\rangle = f_+(q^2)(P^\mu + P'^\mu) + f_-(q^2)(P^\mu - P'^\mu)$$

$$f_+ = F_1; \qquad f_- = \frac{m_P^2 - m_{P'}^2}{(P-P')^2}(F_0 - F_1)$$

$$\begin{aligned}\langle V|J^\mu|P\rangle =& f(q^2)\varepsilon^{*\mu} \\ &+ a_+(q^2)(\varepsilon^* \cdot P_P)(P_P + P_V)^\mu \\ &+ a_-(q^2)(\varepsilon^* \cdot P_P)(P_P - P_V)^\mu \\ &+ 2ig(q^2)\epsilon^{\mu\nu\rho\sigma}\varepsilon^{*\nu}P_P^\rho P_V^\sigma\end{aligned}$$

Baryon transitions:

$$\begin{aligned}\langle B'|J^\mu|B\rangle =& \bar{v}_{B'}\{f_1(q^2)\gamma^\mu + if_2(q^2)\sigma^{\mu\nu}q_\nu + f_3(q^2)q^\mu \\ &- g_1(q^2)\gamma^\mu\gamma_5 - g_3(q^2)q^\mu\gamma_5\}u_B\end{aligned}$$

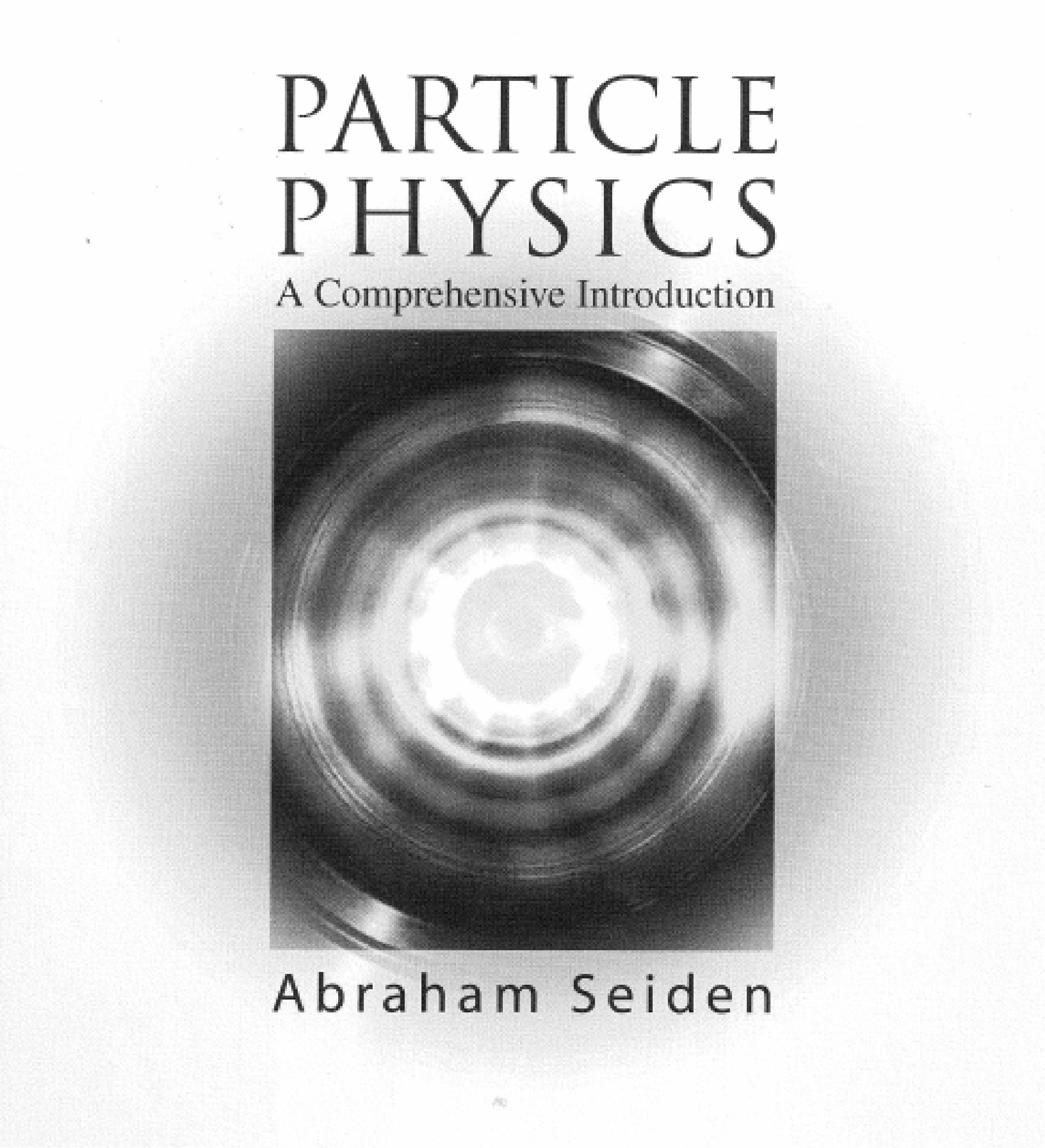


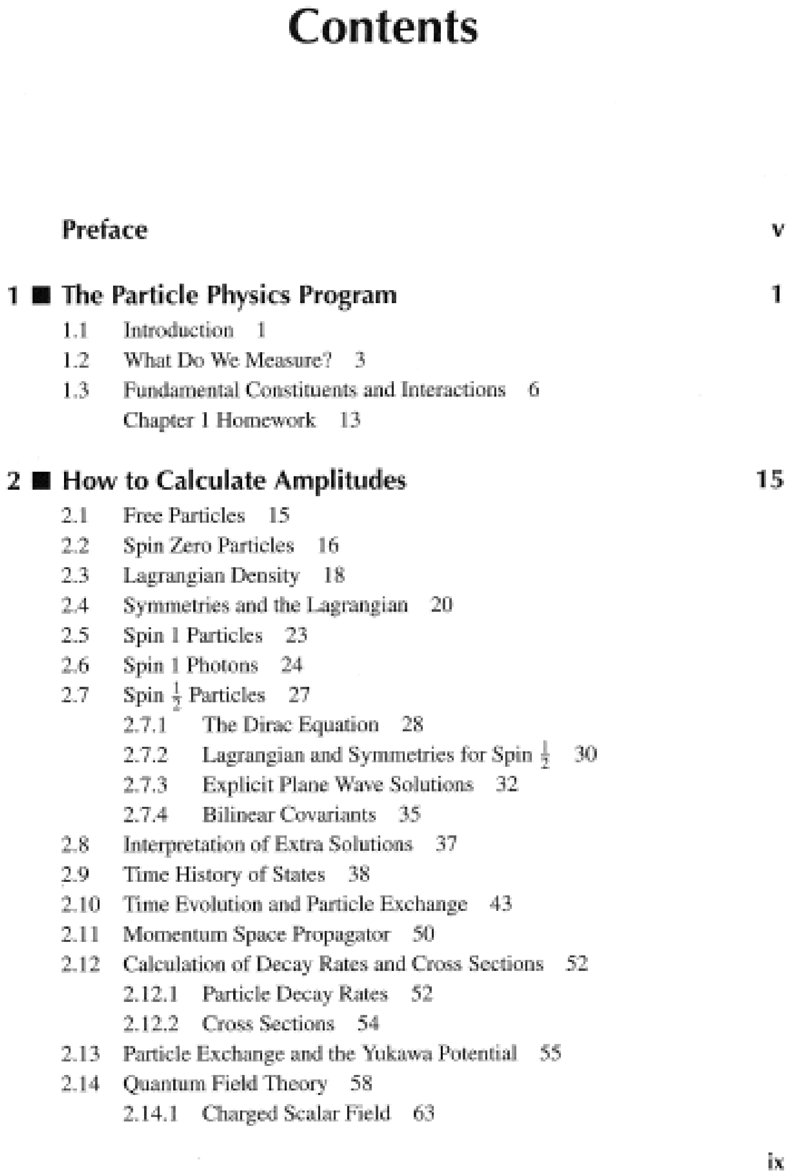
For each hadronic current, the possible values of orbital angular momentum, spin-parity, and associated form factor can be enumerated.

$J_i^P \to J_f^P$	J_μ^P	L	current	FF	LIA
$0^- \to 0^-$	0^+	0	V	$F_0(q^2)$	$(P_i+P_f)^\mu - \frac{m_i^2-m_f^2}{q^2}q^\mu$
	1^-	1	V	$F_1(q^2)$	$\frac{m_i^2-m_f^2}{q^2}q^\mu$
$0^- \to 1^-$	1^+	0	A	$f(q^2)$	$\varepsilon^{*\mu}$
	0^-	1	A	$a_+(q^2)$	$(\varepsilon^* \cdot P_i)(P_i+P_f)^\mu$
	1^-	1	V	$g(q^2)$	$2i\epsilon^{\mu\nu\rho\sigma}\varepsilon_\nu^* P_{i\rho}P_{f\sigma}$
	1^+	2	A	$a_-(q^2)$	$(\varepsilon^* \cdot P_i)q^\mu$
$0^- \to 0^+$	0^-	0	A	$A_0(q^2)$	$(P_i+P_f)^\mu - \frac{m_i^2-m_f^2}{q^2}q^\mu$
	1^+	1	A	$A_1(q^2)$	$\frac{m_i^2-m_f^2}{q^2}q^\mu$
$0^- \to 1^+$	1^-	0	V	$f(q^2)$	$\varepsilon^{*\mu}$
	0^+	1	V	$a_+(q^2)$	$(\varepsilon^* \cdot P_i)(P_i+P_f)^\mu$
	1^+	1	A	$g(q^2)$	$2i\epsilon^{\mu\nu\rho\sigma}\varepsilon_\nu^* P_{i\rho}P_{f\sigma}$
	1^-	2	V	$a_-(q^2)$	$(\varepsilon^* \cdot P_i)q^\mu$

$$(q^\mu \equiv P_i^\mu - P_f^\mu)$$

Finally! From the master himself





Contents

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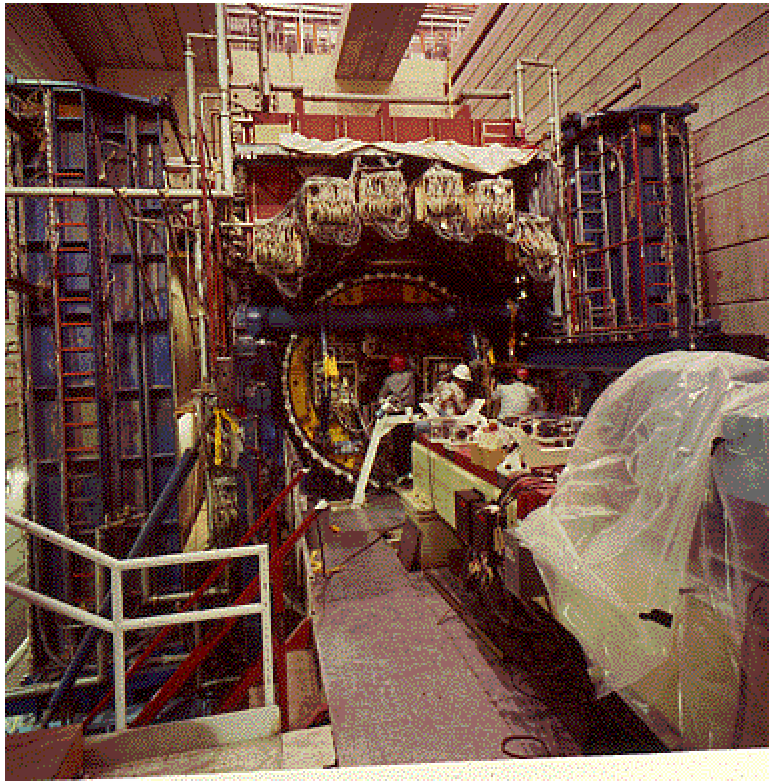
Addison-Wesley, 2005

And in conclusion…

Thank you, Abe, for some of the richest learning experiences, fellowship and fun, and some of the best years of my life at the Santa Cruz Institute for Particle Physics in the 1980’s!



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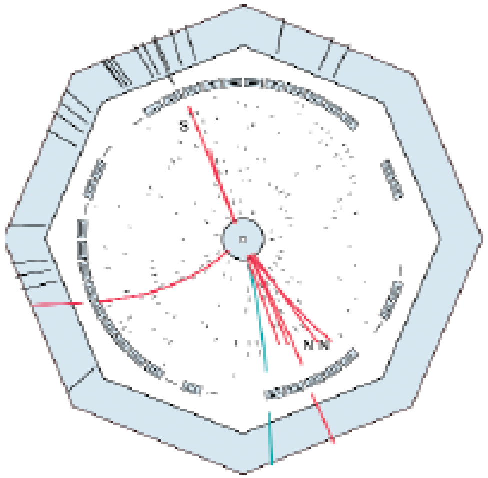

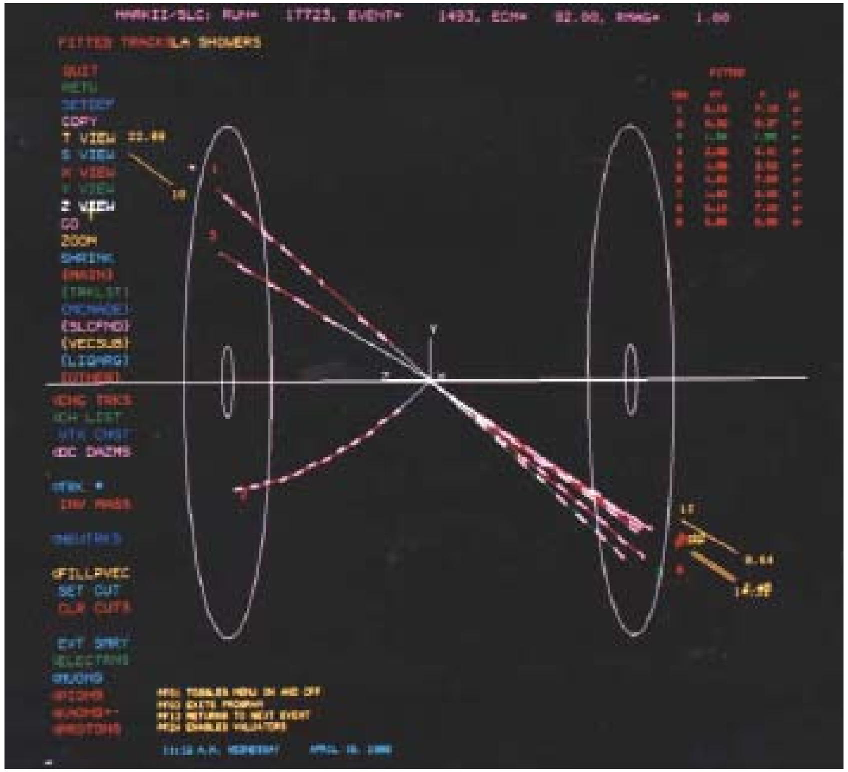

SCIPP 87/78
January 7, 1987
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PERFORMANCE OF THE NEW CENTRAL DRIFT CHAMBER FOR THE MARK II AT SLC*

ALAN J. WEINSTEIN

Santa Cruz Institute for Particle Physics
University of California, Santa Cruz, CA 95064

ABSTRACT

The design and construction of the new central drift chamber for the Mark II detector is described. It has been tested in operation at the PEP storage ring at SLAC in preparation for its installation at the new SLAC Linear Collider (SLC). We present a summary of the chamber performance achieved so far, including its measured position resolution, tracking efficiency, track parameter resolution, and dE/dx resolution.

Talk Presented at the Meeting of the APS Division of Particles and Fields,
Salt Lake City, January, 1987

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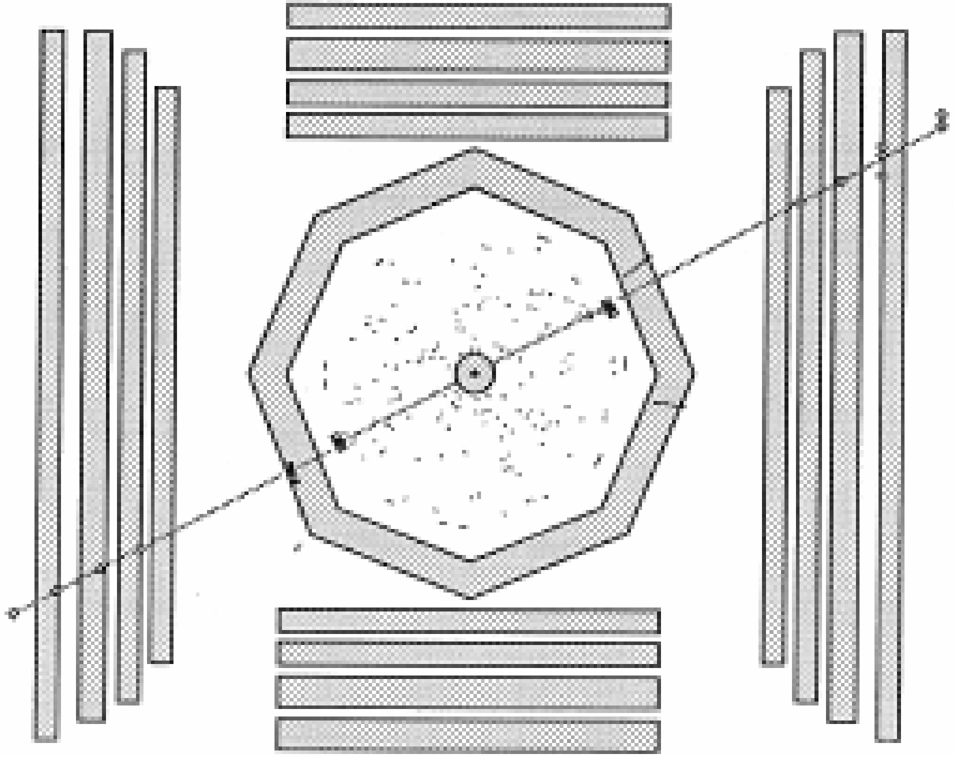
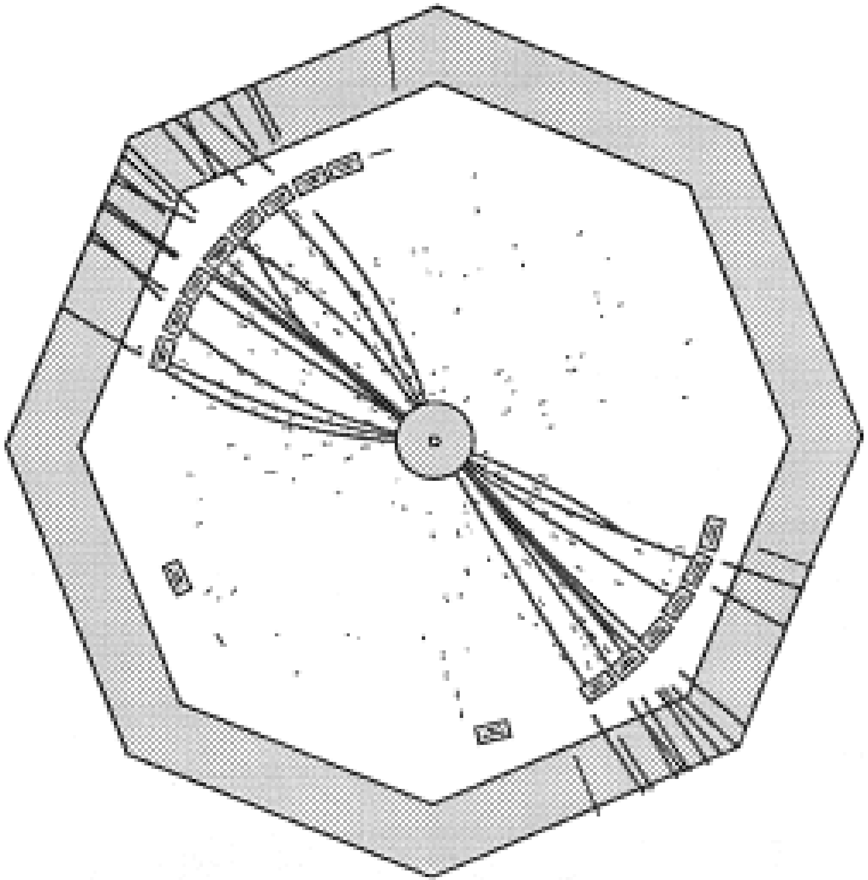
[*] Work supported by the U. S. Department of Energy.

The Mark II Collaboration is a group of about 130 physicists from Cal Tech, Johns Hopkins, the Lawrence Berkeley Laboratory (LBL), SLAC, and the Universities of California (Santa Cruz), Colorado, Hawaii, Indiana and Michigan. They have upgraded the 1800-ton Mark II detector for Z^0 research (see September 1988 *Beam Line*, p. 3) and installed it surrounding the SLC clashpoint in the Collider Experimental Hall. The SLC began producing Z^0's on April 11 (see April 1989 *Beam Line*, p. 3); by September 1 almost 350 had been observed.

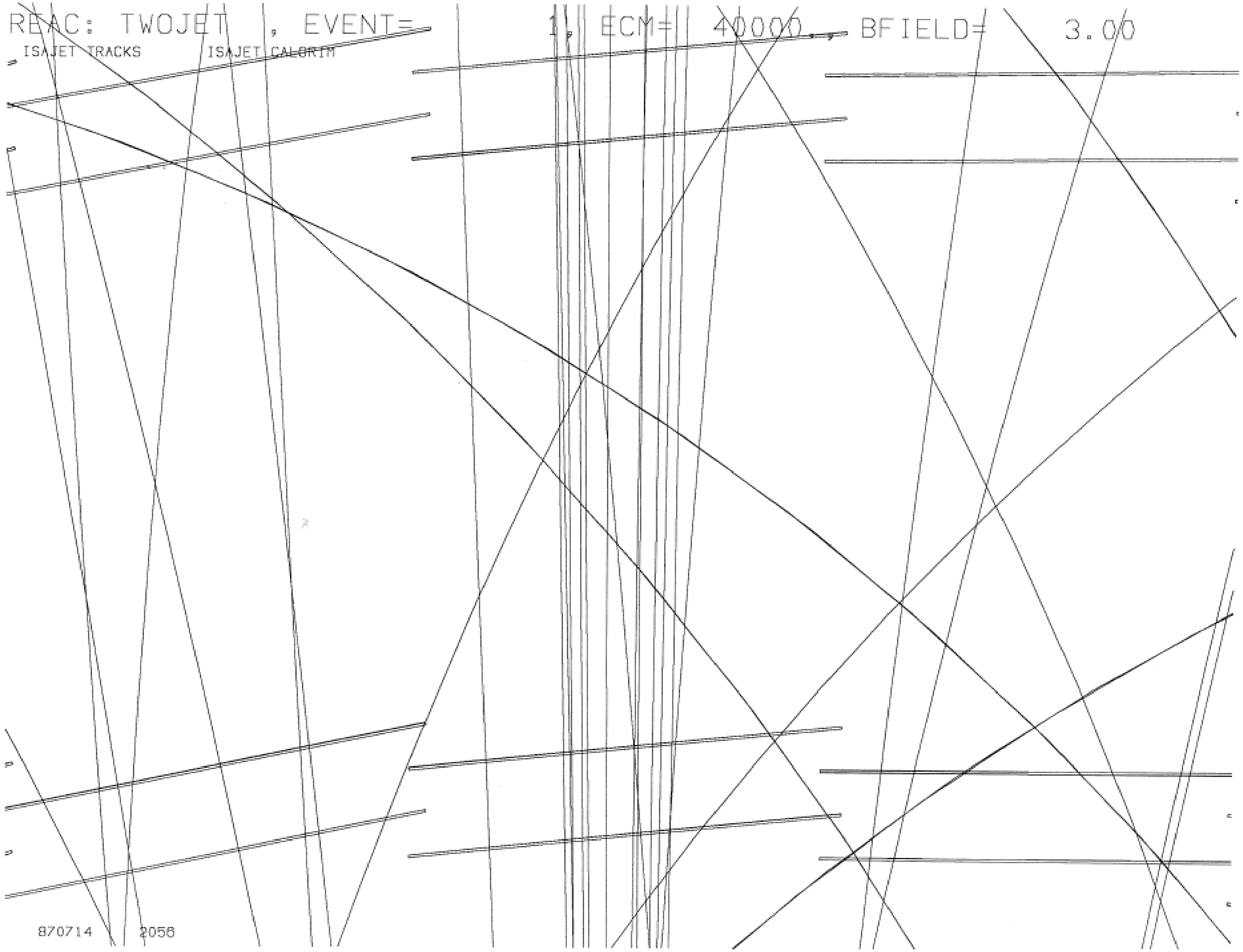


First muon-pair decay of a Z^0 observed at SLC.

SLAC Beam Line, September 1989



A hadronic Z^0 decay. The Z^0 breaks up first into a quark-antiquark pair, which subsequently generates two back-to-back hadron jets.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ISAJET TRACKS
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