SDC-92-278

SDC
SOLENOIDAL DETECTOR NOTES

SDC PRESENTATION AT THE FIRST EAST ASIAN/PACIFIC-USA SYMPOSIUM ON SSC PHYICS, EXPERIMENTS AND TECHNOLOGY AT BEIJING, PRC

May 22, 1992

Takahiko Kondo
KEK

S D C

Solenoidal Detector Collaboration

May 22, 1992

Takahiko Kondo (KEK)

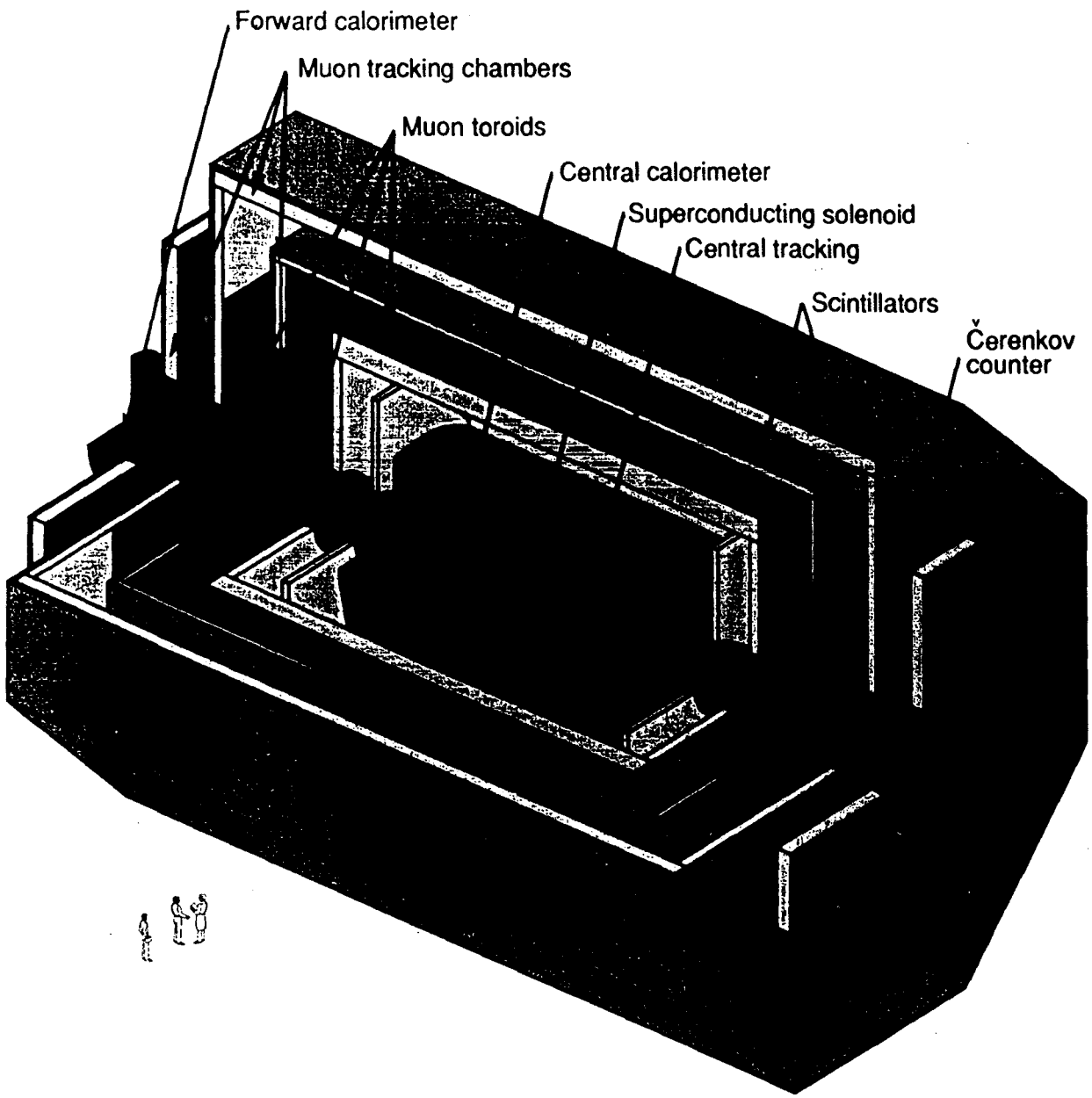
Presented at the First East Asian/Pacific-U.S.A. Symposium on SSC Physics, Experiments, and Technology at Beijing, PRC, May 21-24, 1992.

SDC Collaboration

country	institutions	collaborators
U.S.A.	53	561
Canada	7	26
Japan	17	101
France	1	21
Italy	3	27
U.K.	4	15
C.I.S.	9	106
PRC	2	35
Israel	1	2
Eastern Europe	4	12
Brazil	1	5
(EoI)	(73)	(500)
(LoI)	(84)	(647)
TDR	102	911

History

• before 1989	Design activities at LBL, ANL, FNAL, Universities Design activities in Japan and Europe
• 1989 September	Formation of a single collaboration
• 1989 December	1st collaboration meeting Established governance document
• 1990 March	Selection of spokesperson/technical manager
• 1990 May	Submission of Expression of Interest (EoI)
• 1990 November	Submission of Letter of Intent (LoI)
• 1991 January	Approved to proceed to develop a full technical design
• 1992 April	Submission of Technical Design Report (TDR)
• 1992 May	PAC review of SDC


Forward calorimeter
Muon tracking chambers
Muon toroids
Central calorimeter
Superconducting solenoid
Central tracking
Scintillators
Čerenkov counter

Motivation of SDC detector

- General purpose detector
  for redundant identification of interesting processes
  for new unexpected phenomena

- Balanced combination of tracking, calorimetry and muon system

- Measurement of multiple independent quantities
  - e/μ identification
  - isolation measurement
  - sign of charge and energy measurement of leptons
  - isolated photons
  - jet energy and direction
  - detection of secondary vertices
  - charged particle multiplicity
  - detection on non-interacting neutrals via p_T balance

- Past experience with collider detectors has demonstrated that a detector with multiple independent measurements is far better thanthe sum of subsystems

- Successful CDF experience

- Benefits of a Solenoidal Detector

  - The momentum information makes the detector a fine exploratory tool for the study of a wide range of physics at all p_t and at wide range of luminosities.
  - Determination of ~~electron~~ muon signs up to at least p_t =1 TeV is provided.
  - Momentum/calorimetry provides effective electron ID.
  - Momentum information is necessary to interpret vertex detector measurements.
  - Momentum measurement helps provide in-situ monitoring of calorimetry.
  - Muon momenta can be precisely measured.
  - Jet fragmentation at high p_t can be studied.
  - Charged particle multiplicity for tracks of p_t above a fixed value can be useful for removal of some background.

Requirements on SDC detector

- Challenging experimental environment :

  relative to the Tevatron
  <u>20-fold</u> increase in energy
  <u>~ 1000-fold</u> increase in luminosity

$$\frac{S}{N} \sim \frac{\sigma_{Higgs} \cdot BR}{\sigma_{inel}} \sim \frac{1}{10000000000000}$$

- It requires unprecedented demands on

  - speed-of-response
  - pattern recognition capability
  - excellent momentum resolution
  - segmentation to identify fine structures

- The detector must be sufficiently <u>robust</u> and <u>resistant to radiation for many years of operation</u>

- Operational potentiality for luminosity increase beyond 10^{33} $cm^{-2}s^{-1}$ and sufficient functionality up to 10^{34} $cm^{-2}s^{-1}$

- Cost / performance optimization

- Upgrade capability

  However exceptions that have NO upgrade capabilities are

  - central tracking volume
  - iron toroid thickness
  - calorimeter depth

  Their reductions would lead to unacceptable technical and performance risks

Decision on Tracking Volume (August,1991)

- One of fundamental detector parameters
  Pressure from cost reduction

- Comparison : (radius, half length) = (170 cm, 400cm)
  (150 cm, 300cm)

- Shrinking the tracking volume will
  - substantially reduces the space available for <u>intermediate tracking</u> and makes track triggering difficult in that area
  - increases neutron fluences by ~2 in tracking cavity
  - increases radiation doses in calorimetry near η=3
  - <u>significantly reduces the radial region for straw tracker</u>
  - reduces rapidity range covered by outer barrel tracker
  - degrade momentum resolution by <u>30%</u>
  - reduce cost by approximately $21M

- Decision was made to keep the tracking radius at 170 cm

Technological choices

- Technology choices have been made through extensive reviews by selection committees based on

  - technical feasibility
  - adequacy of performance
  - survivability
  - acceptable technical risk
  - affordable cost
  - strong interest of SDC members

- R&D programs sponsored by SSCL as well as R&D abroad provided significant influences on the SDC technology choices

- Decision process in most cases:
  1. definition of requirements
  2. preparation of conceptual design reports
  3. oral presentations
  4. recommendations by ad-hoc review committee
  5. review and recommendations by the Technical Board
  6. ratification by the Executive Board

Technological choices (cont.)

- Solenoid magnet styles

  type-S (short coil / non-magnetic returns)
  type-I (short coil / iron endcap)
  type-L (long coil / non-magnetic endplug)

  $\xrightarrow{\text{Sep.1990}}$ type-(SI)

- Central calorimetry

  scintillating tile calorimeter with waveshifting bar readout
  scintillating tile calorimeter with waveshifting fiber readout
  scintillating fibers embedded in the absorber ("spaghetti")
  liquid argon ionization calorimeter
  warm liquid ionization calorimeter

  $\Downarrow$ Nov. 1990

  tile fiber calorimeter
  liquid argon calorimeter

  $\Downarrow$ Sep. 1991

  tile fiber calorimeter

Technological Choices (cont.)

- Time digitizer for straw chamber

  TVC/AMU
  TMC $\xrightarrow{\text{Sep. 1991}}$ TMC

- Central outer tracking devices

  modular straws
  hybrid tracker with straws/fibers
  scintillating fibers
  } $\xrightarrow{\text{Nov.1991}}$ { straw system
  fiber system

- Absorber material of calorimeter

  EM/Had : Pb/Pb
  EM/Had : Pb/Fe $\xrightarrow{\text{Nov. 1991}}$ Pb/Fe

Technological Choices (cont.)

- Forward calorimetry

  liquid argon calorimeter
  warm liquid calorimeter
  liquid scintillation calorimeter
  high pressure gas calorimeter

  → Jan.1992 → liquid scintillator / high pressure gas

- Barrel muon chambers

  octagonal tube
  round tube without field shaping
  round tube with field shaping
  oval tube with field shaping
  jet cell chamber

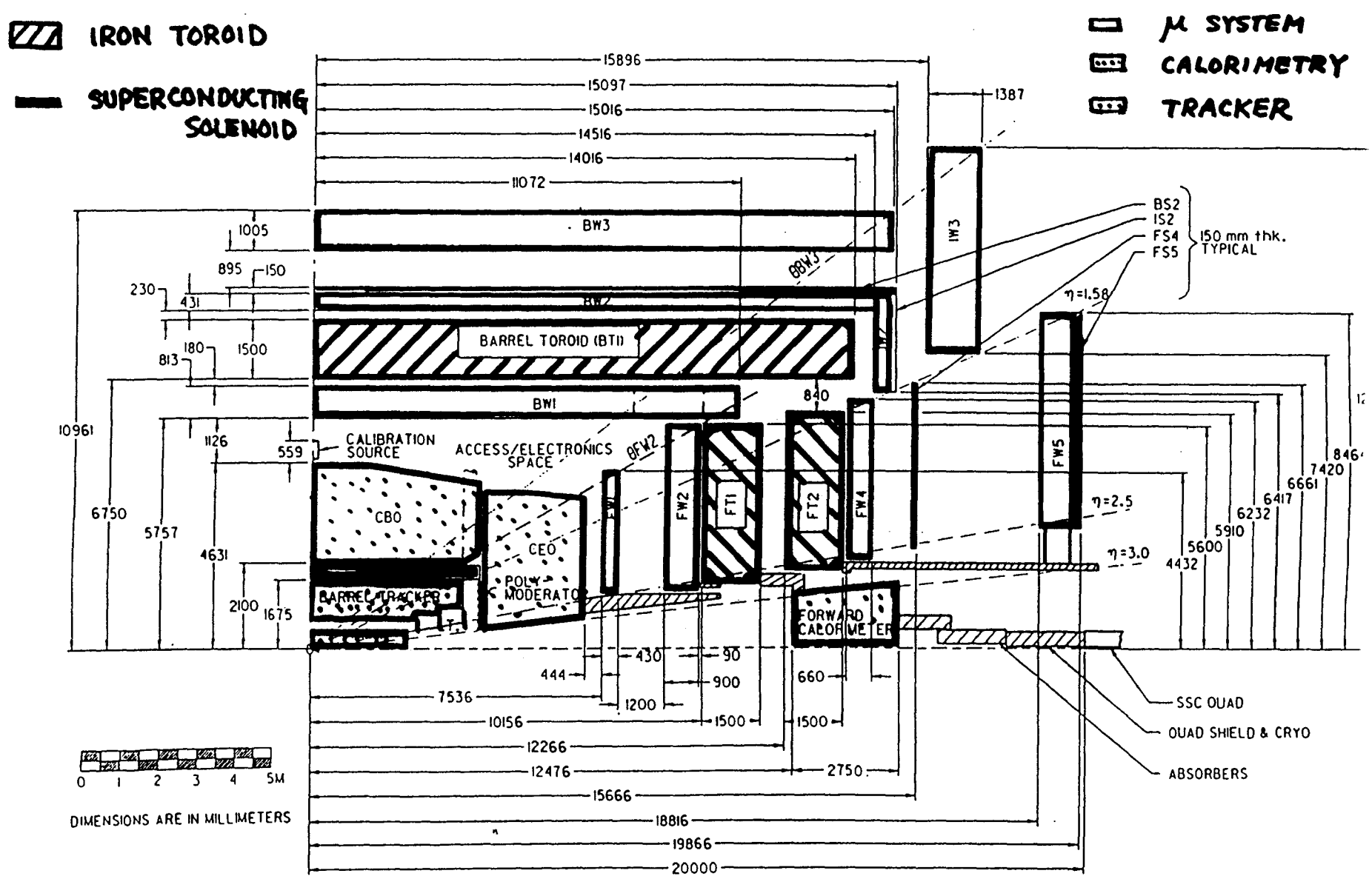
  → Feb. 1992 → round tube with field shaping

- Selections to be done in near future

  outer tracking technology
  forward calorimetry technology
  readout electronics for central calorimetry

SDC Detector Summary

Solenoid magnet:	- 2 Tesla - tracking volume : 3.4 m diameter x 8.6 m long
Central tracking & vertex detection :	- inner silicon systems (covering $\|\eta\| < 2.5$) - outer straw-tube or scintillating-fiber system in barrel region - outer gas-microstrip or scintillating-fiber for intermediate-angle region
Precision hermetic calorimetry :	- scintillating tile with fiber readout with Pb(EM) Fe(Had.) absorber - high spatial resolution EM shower max scintillation detector
Forward calorimetry :	- covering $3 < \|\eta\| < 6$
Muon system :	- iron magnetic toroids - tracking chambers and scintillation counters


IRON TOROID
SUPERCONDUCTING SOLENOID
μ SYSTEM
CALORIMETRY
TRACKER
BW3
BW2
BW1
BARREL TOROID (BT1)
IW3
BS2
IS2
FS4
FS5
150 mm thk. TYPICAL
η=1.58
η=2.5
η=3.0
CALIBRATION SOURCE
ACCESS/ELECTRONICS SPACE
CBO
CEO
POLY-MODERATOR
BARREL TRACKER
FW1
FW2
FT1
FT2
FW4
FW5
FORWARD CALORIMETER
SSC QUAD
QUAD SHIELD & CRYO
ABSORBERS
DIMENSIONS ARE IN MILLIMETERS
0 1 2 3 4 5M

Expected Performance of SDC Detector

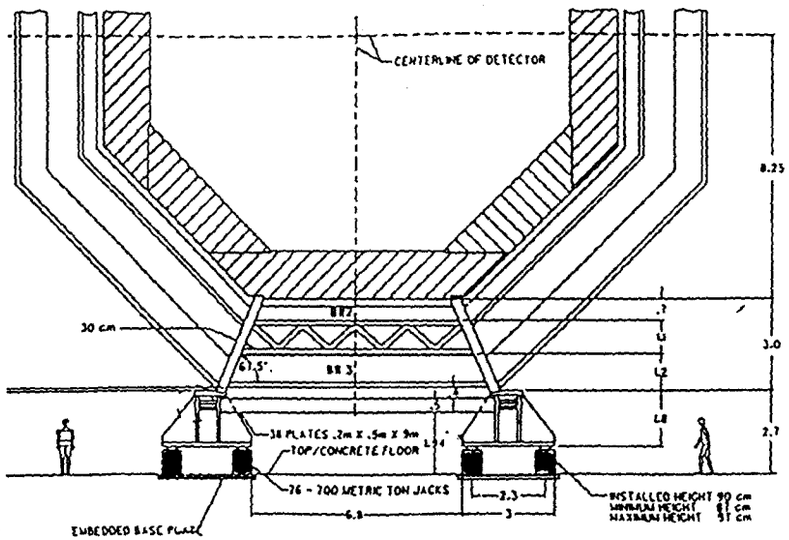
$\frac{\Delta p_t}{p_t}$ @ 1 TeV	$\eta = 0$	16 %	charged particle
	$\eta = 2.5$	60 %	charged particle
$\frac{\Delta p_t}{p_t}$ @ 1 TeV	$\eta = 0$	11 %	muon
	$\eta = 2.5$	18 %	muon
$\frac{\Delta E_t}{E_t}$ (EM)	$\lvert\eta\rvert < 3$	$\sim \frac{14\ \%}{\sqrt{E_t}} \oplus 0.01$	
$\frac{\Delta E_t}{E_t}$ (Had)	$\lvert\eta\rvert < 3$	$\sim \frac{60\ \%}{\sqrt{E_t}} \oplus 0.04$	(single π)
$\frac{\Delta E}{E}$ (Had)	$3 < \lvert\eta\rvert < 5.5$	$\sim \frac{100\ \%}{\sqrt{E}} \oplus 0.08$	

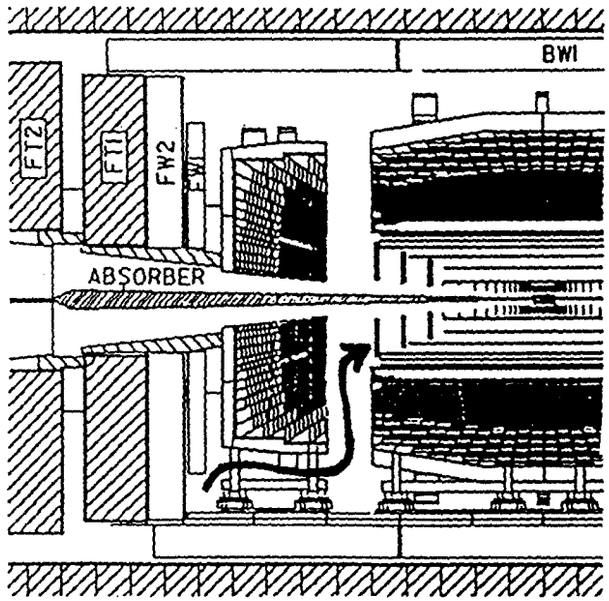
SDC Capabilities

Electron ID	E/P method (EM energy / track momentum) hadronic / EM response transverse shape at shower max detector
Muon ID	traversal of > 14λ double measurement of momentum calorimeter tower pulse height
Tau ID	low multiplicity jet, proper kinematics
Neutrinos	transverse energy unbalance in hermetic calorimeter
Quarks and gluons	jets of hadrons in calorimeter and tracking system
B quarks	displaced vertices measured in silicon system
Pattern recognition in complex events	high resolution and excellent two-track separation of silicon tracker

SDC Detector Integration

- stability of the barrel toroid against floor motion is maintained by the <u>distributed hydraulic jacking system</u>
- <u>access</u> capability to the back of calorimeter
- <u>access</u> to inner trackers by retracting endcap calorimeter, FW1 and absorber





SDC MANAGEMENT
(May 4, 1992)

Spokesperson:	G. Trilling (LBL)
Proj. Manager/Co-Spokesp.:	T. Kirk (SSCL)
Deputy Spokespersons:	G. Bellettini (Pisa)
	D. Green (Fermilab)
	T. Kondo (KEK)
Act. Proj./Tech. Manager:	M. Gilchriese (LBL/SSCL)
Chair, Inst. Board:	A. Goshaw (Duke)

SDC Executive Board

R. Amendolia (Pisa)	J. Elias (Fermilab)
S. Errede (Illinois)	G. Feldman (Harvard)
E. Gabathuler (Liverpool)	K. Kondo (Tsukuba)
A. Maki (KEK)	S. Mori (Tsukuba)
Y. Nagashima (Osaka)	T. Ohsugi (Hiroshima)
R. Orr (Toronto)	L. Price (ANL)
R. Ruchti (Notre Dame)	A. Seiden (U.C.S.C.)
J. Siegrist (SSCL)	M. Strovink (LBL)
R. Thun (Michigan)	N. Tyurin (Protvino)

Notes: T. Kirk is replacing M. Gilchriese as Project Manager. The Exec. Board will be expanded by 3 members in the next month: 2 from U.S./Canadian universities and one from the former Soviet Union.

SDC Technical Board
(May 4, 1992)

K. Amako (KEK)
G. Bellettini (Pisa)
D. Bintinger (SSCL)
M. Edwards (RAL)
J. Elias (Fermilab)
G. Feldman (Harvard)
W. Frisken (York)
M. Gilchriese (LBL/SSCL)
R. Hubbard (Saclay)
T. Kirk (SSCL)
V. Kubarovsky (Protvino)
A. Maki (KEK)
T. Ohsugi (Hiroshima)
J. Proudfoot (ANL)
J. Siegrist (SSCL)
Y. Takaiwa (KEK)
T. Thurston (SSCL)
Y. Watase (KEK)
A. Yamamoto (KEK)

A. D. Baden (Maryland)
J. Bensinger (Brandeis/SSCL)
M. Campbell (Michigan)
K. Einsweiler (LBL)
D. Etherton (SSCL)
W. Ford (Colorado)
I. Gaines (Fermilab)
D. Green (Fermilab)
R. Kephart (Fermilab)
T. Kondo (KEK)
A. Lankford (U.C.I.)
S. Mori (Tsukuba)
L. Price (ANL)
A. Seiden (U.C.S.C.)
W. Smith (Wisconsin)
R. Thun (Michigan)
G. Trilling (LBL)
H. Williams (Pennsylvania)

Physics Requirements for Tracking

- Rapidity coverage <u>up to at least $|\eta| = 2.5$</u>

  for efficiency ($H \rightarrow 4$ charged leptons) > 60%

- Momentum precision = <u>20% @ 1TeV/c</u>
  for Z mass reconstruction and
  for sign-of-charge determination (Z', $W_L W_L$...)

- Reconstruction efficiency > 97% for isolated high p_t tracks from Higgs, top, etc, especially for e, μ

  $\rightarrow$ tracking material <u>< 15% X_0</u>
  <u>< 7% X_0 inside 50cm</u>

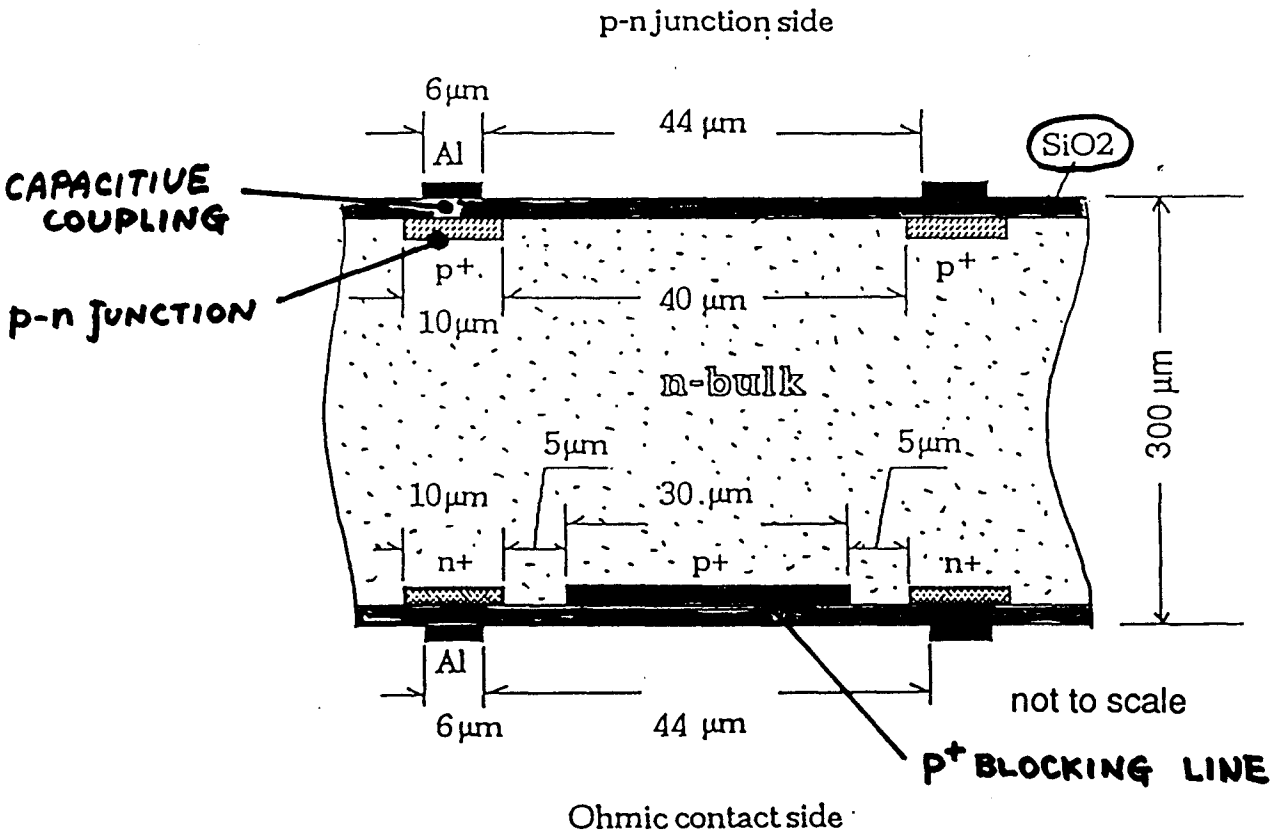
- Effective <u>b quark</u> and τ <u>tagging</u>
  t quark physics, charged Higgs search etc

Silicon Tracker

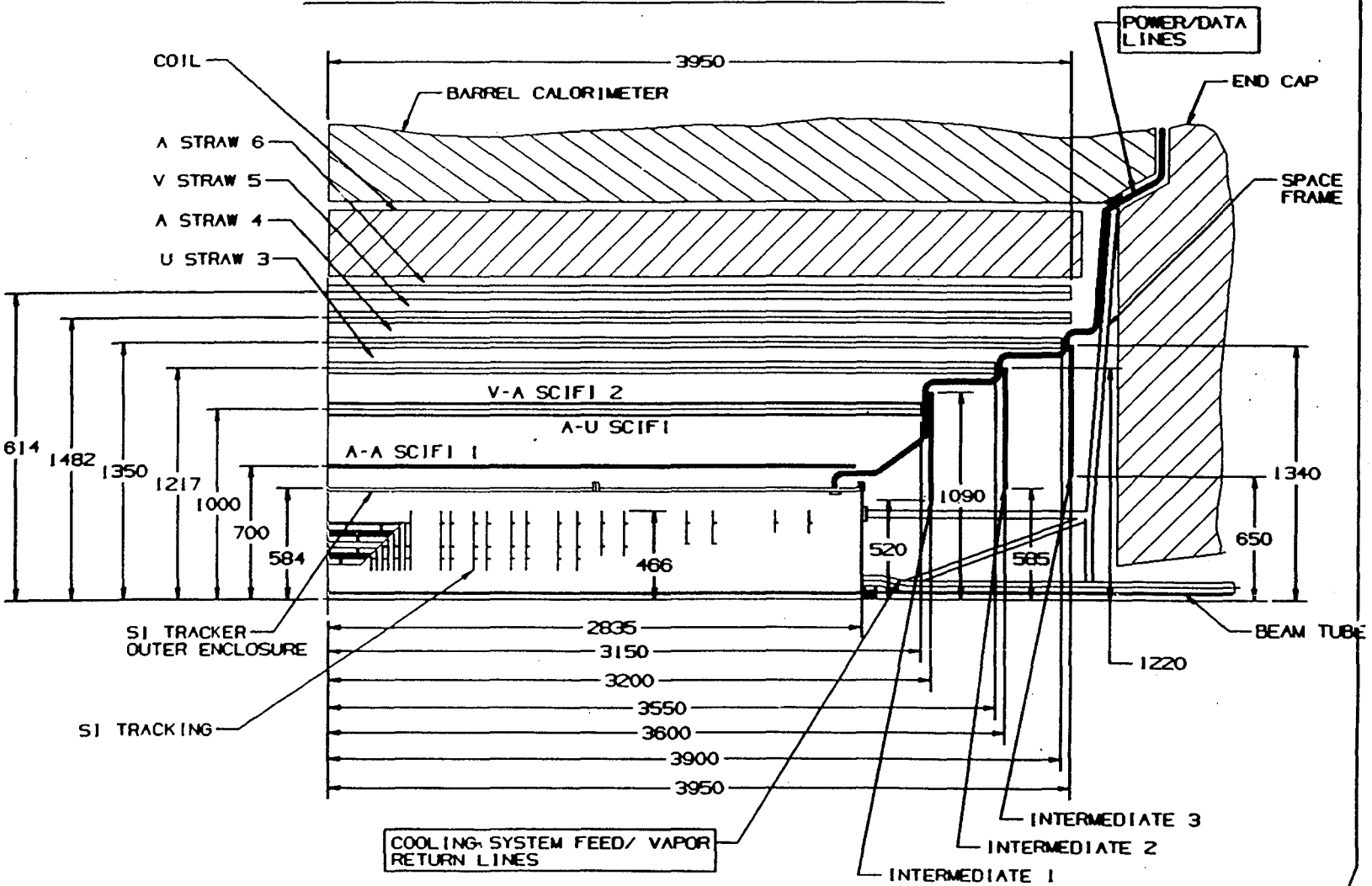
Functions :
- pattern recognition inside jets
- b tagging via 2-ndary vertex finding
- track triggering (2nd level)

Detector :

- high resistivity (4~8kΩ) n-type silicon
- double sided : axial +10mrad stereo
  p^+ blocking line for isolation on ohmic side
- unit detector
  barrel : 3.4cm x 6cm x 300μm
  disk : 7cm(max)x 6cm x 300μm
- strip pitch : 50μm



BASELINE CENTRAL TRACKER CONCEPT

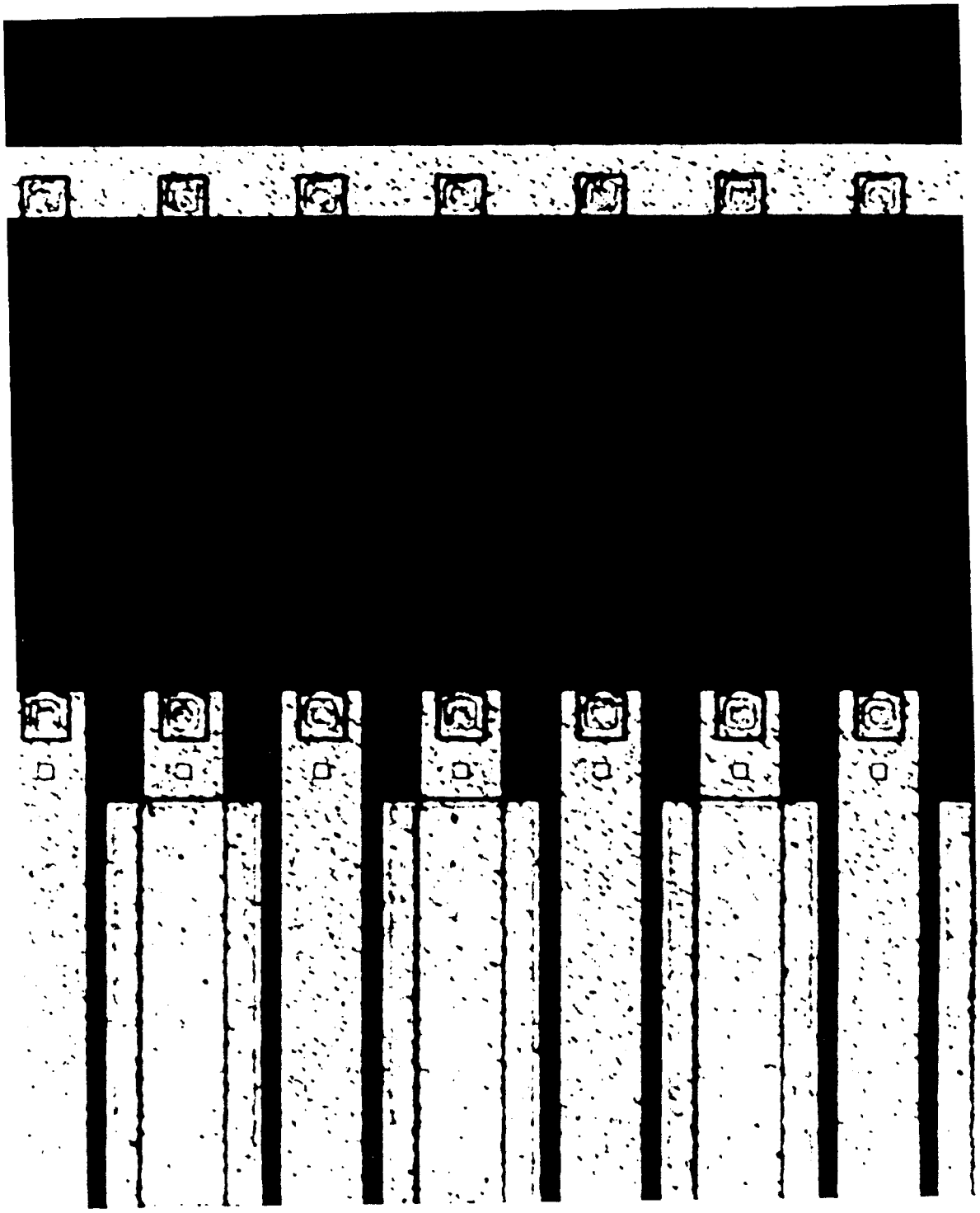


NOTE: ALL DIMENSIONS ARE IN MILLIMETERS

LOS ALAMOS

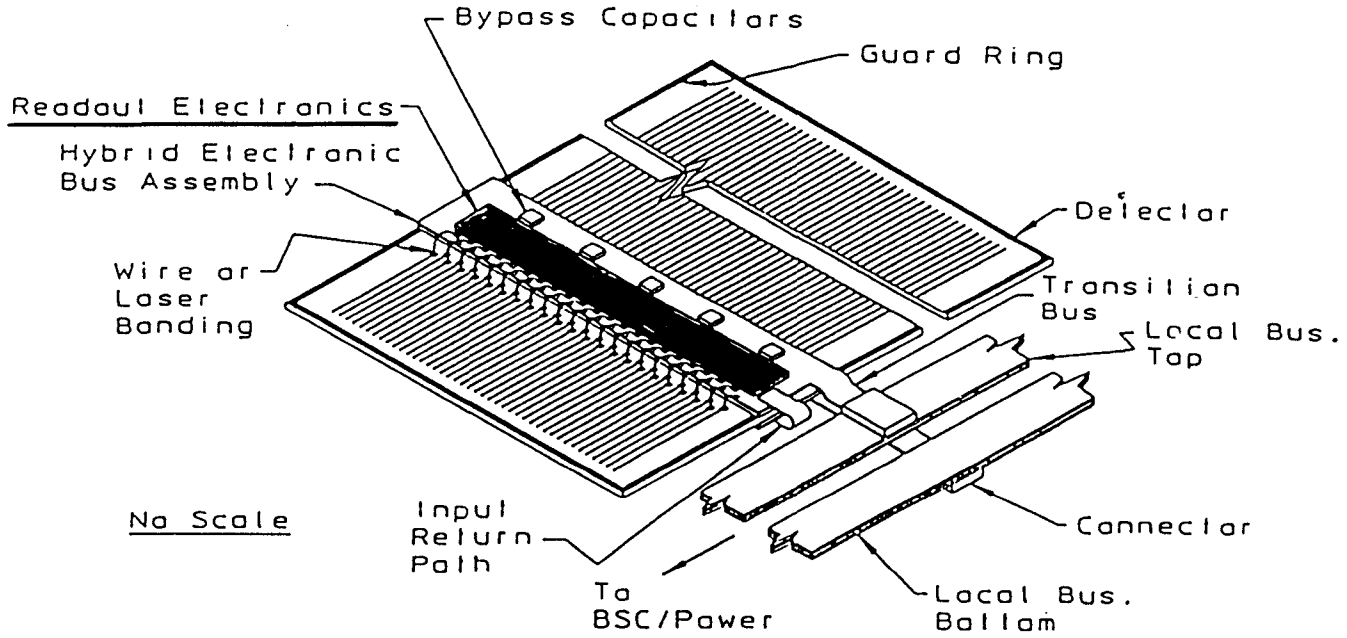
MEE-12
MECHANICAL AND ELECTRONIC ENGINEERING DIVISION

SIL-V8-JM-001 5-24-91



Silicon Readout Electronics

- preamp/shaper/discri bipolar chip (620μW/ch)
- CMOS data driven buffering (200μW/ch)
- hit/no-hit only, no analog information
- chips bonded directly to silicon detectors
- electronic channels : 6,481,920 !!
- total power dissipation : 6.6 kW
- aluminum/Kapton ribbon cables or optical fiber
- most critical issues : cross-talk
  material thickness



Silicon Detector Configurations

- detector layers : 8 barrels +13 disks
- 2 detectors/readout , 4 detectors/module
- detector area : 6.78 m^2+ 10.16 m^2 ~ 17 m^2
- kept at ~0°C by evaporation of liquid butane
- mounted on a space frame made of Mg-MMC
- gas enclosure : 5.16m long 0.93 m dia.
- position accuracy 5 μm

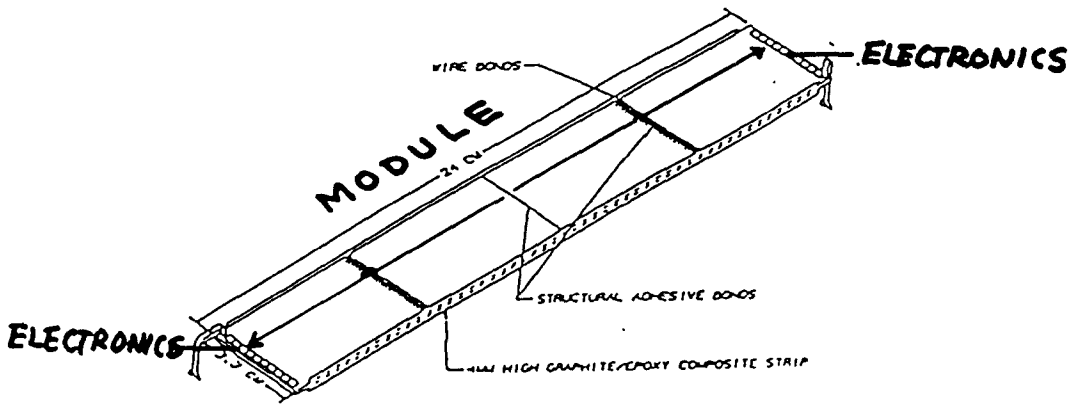


Fig. 50. Silicon wafer assembly with wire and adhesive bonds and graphite/epoxy composite edge-strip reinforcement.

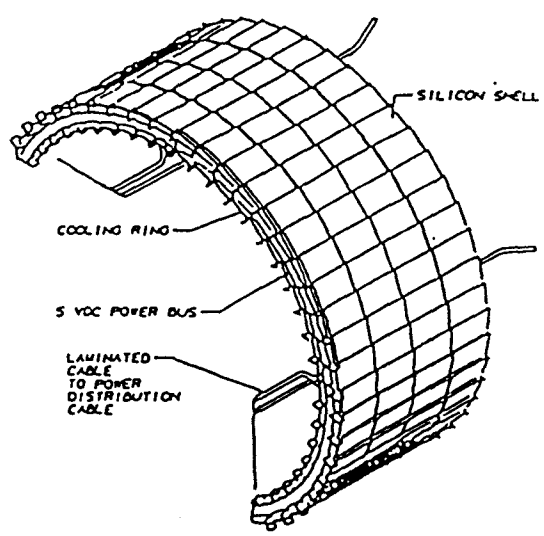


Fig. 51. Silicon wafer shell assembly.

GEANT Simulation of an $t\bar{t} \rightarrow e\,\mu\,\nu\,\bar{\nu}\,b\,\bar{b}$ event

RECONSTRUCTED EVENT

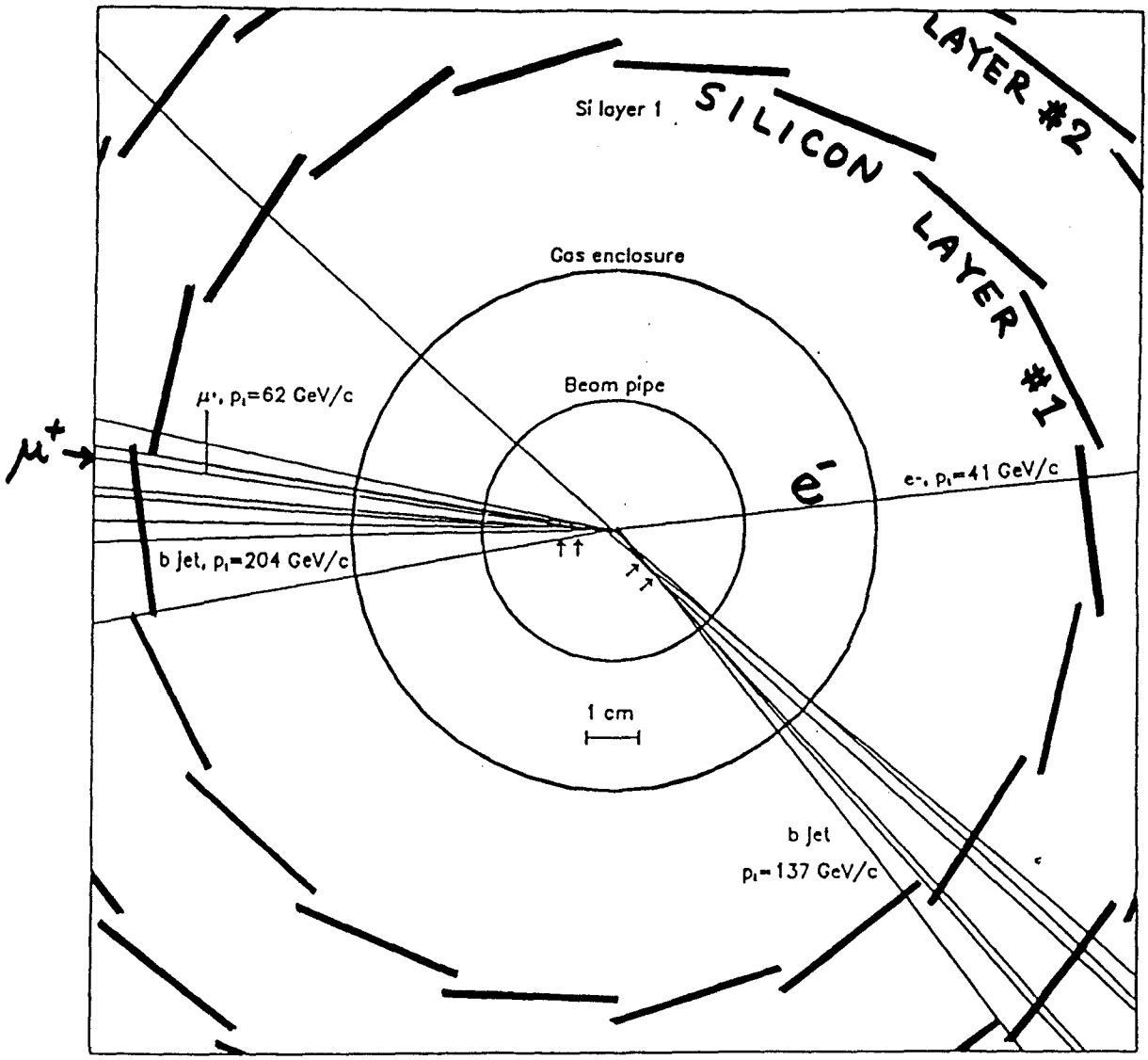


FIG. 4-13. GEANT simulation of an Isajet $t\bar{t} \rightarrow e\mu\nu\nu b\bar{b}$ event with $M_{top} = 150$ GeV/c^2, showing the beam pipe, inner tracking gas enclosure, and first barrel silicon layer at 80% of actual size. Tracks reconstructed using data from the silicon and straw systems with $p_t > 2$ GeV/c and $|\eta| < 2.5$ are plotted. Charged leptons and b jets from the $t\bar{t}$ decay are indicated with their generated momenta; the muon is actually inside one of the b jets. Arrows indicate the true decay vertices of the b and c mesons within the b jets. The secondary vertices are visible by eye from the reconstructed tracks.

THE SECONDARY VERTICES ARE VISIBLE !

Silicon Detector Performance

- very low occupancy
- coordinate measurement 12μm in rφ
  1.5 mm in z
- uniform coverage to $\eta = 2.5$
- nearly 100% reconstruction efficiency
- 20-40% efficiency of b-tagging efficiency

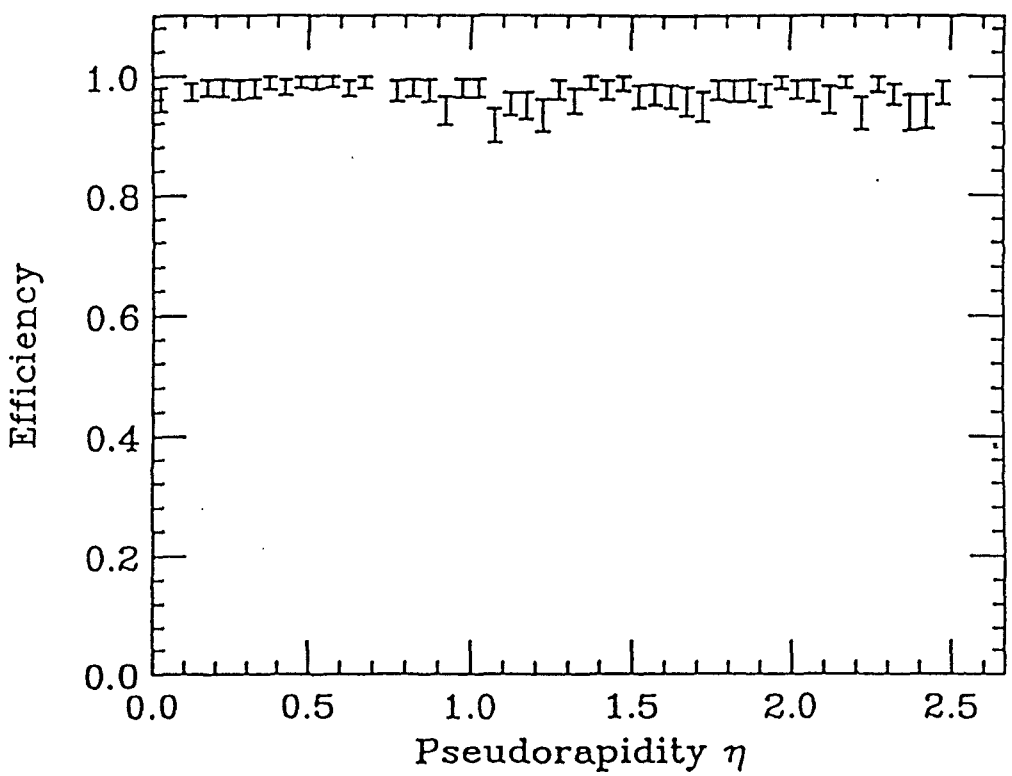
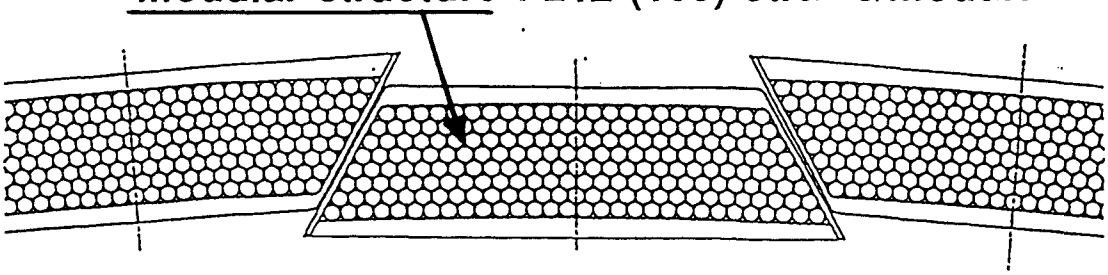


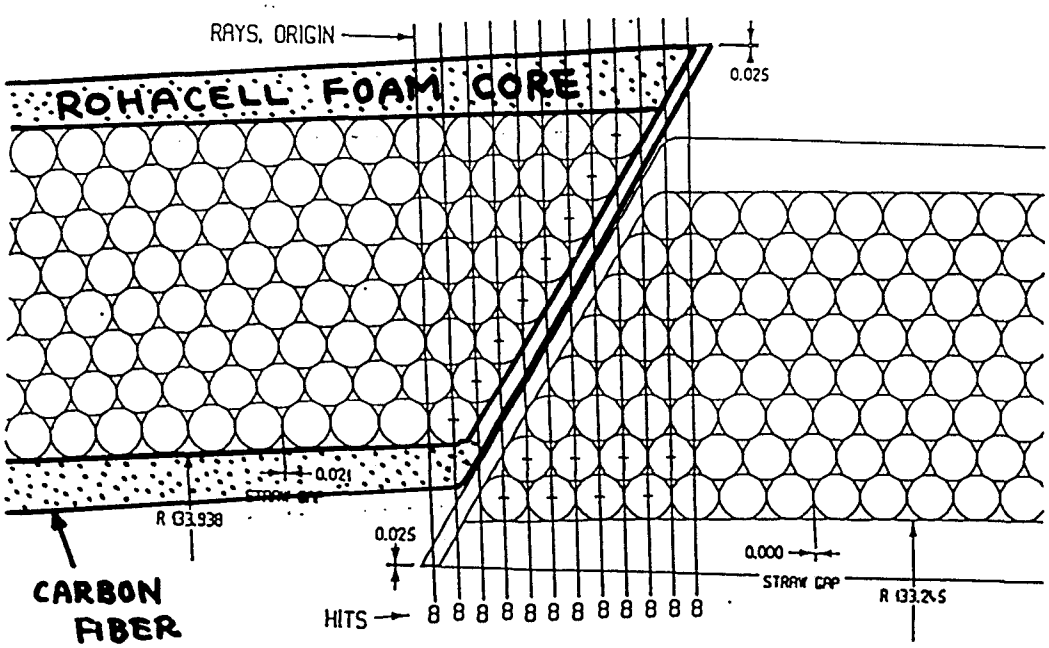
FIG. 4-9. Efficiency of single tracks with $p_t > 1$ GeV/c in Higgs events as a function of pseudorapidity.

Straw Tracker

Detector Element

- straw : 4mm dia.
- length : 4m, wire support at every 80 cm
- anode : wire 38μm dia. gold plated W
  cathode : 0.15 mm thick copper(17.5Ω/m)
- fast gas : CF_4/Isobutane (80/20), V_d =105μm/ns
  max drift time = 29 ns @ B= 2T
- attenuation : 44% / 4m
- modular structure : 212 (159) straws/module

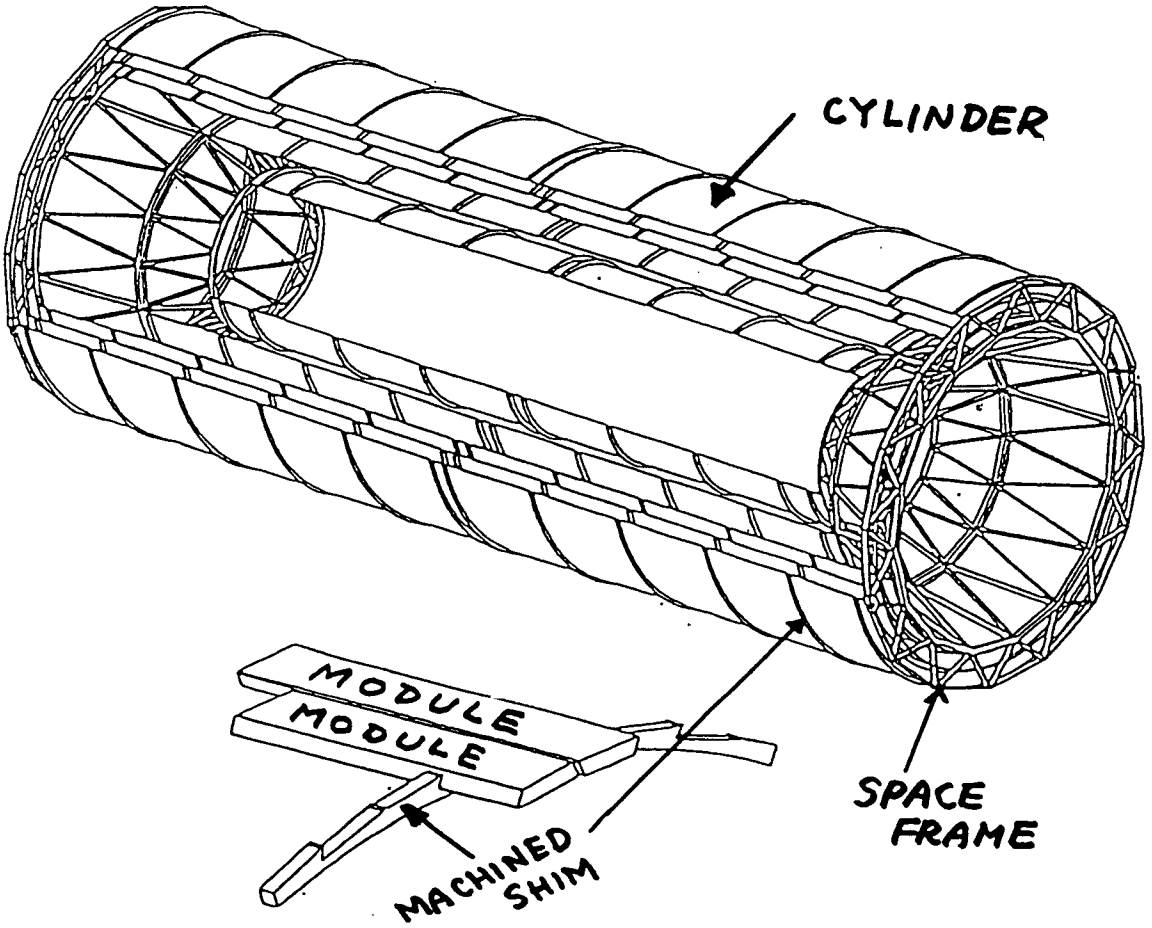




Straw Tracker Configurations

- 5 superlayers: 3 axial + 2 stereo (±3°)
- total number of straws : 137,164 channels
- straw modules mounted on machined shim rings
- shim rings on graphite composite cylinders
- cylinders supported by graphite space frames

MATERIAL : GRAPHITE FIBER + CYANATE ESTERS (RESIN)

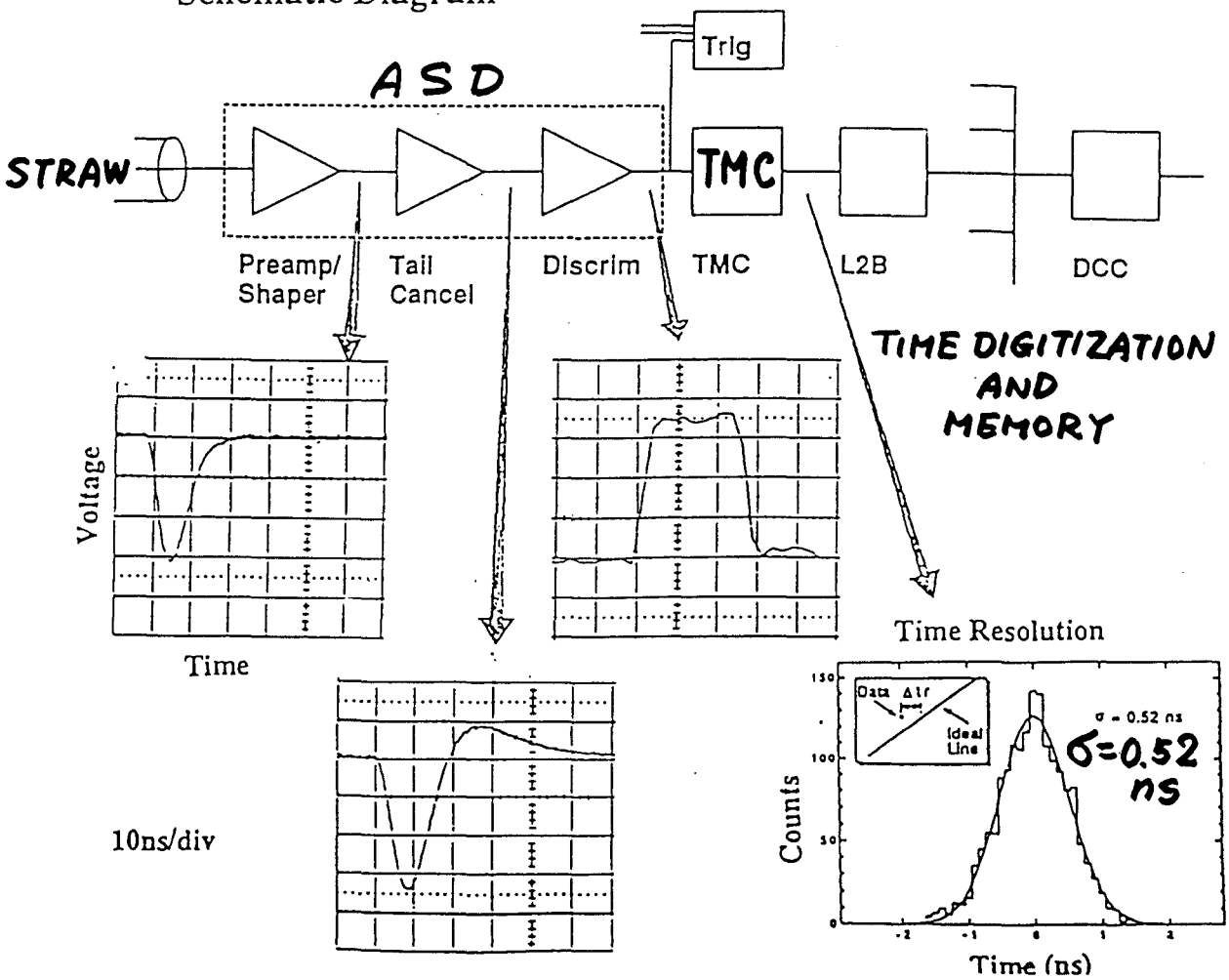


Wire Chamber Readout

Specifications

* Minimum Detectable Charge	≈ 1 fC
* Time Resolution	< 0.75 ns
* Peaking Time	5-7 ns
* Double Pulse Resolution	20 - 30 ns
* Power Dissipation	< 20 - 25 mW

Schematic Diagram

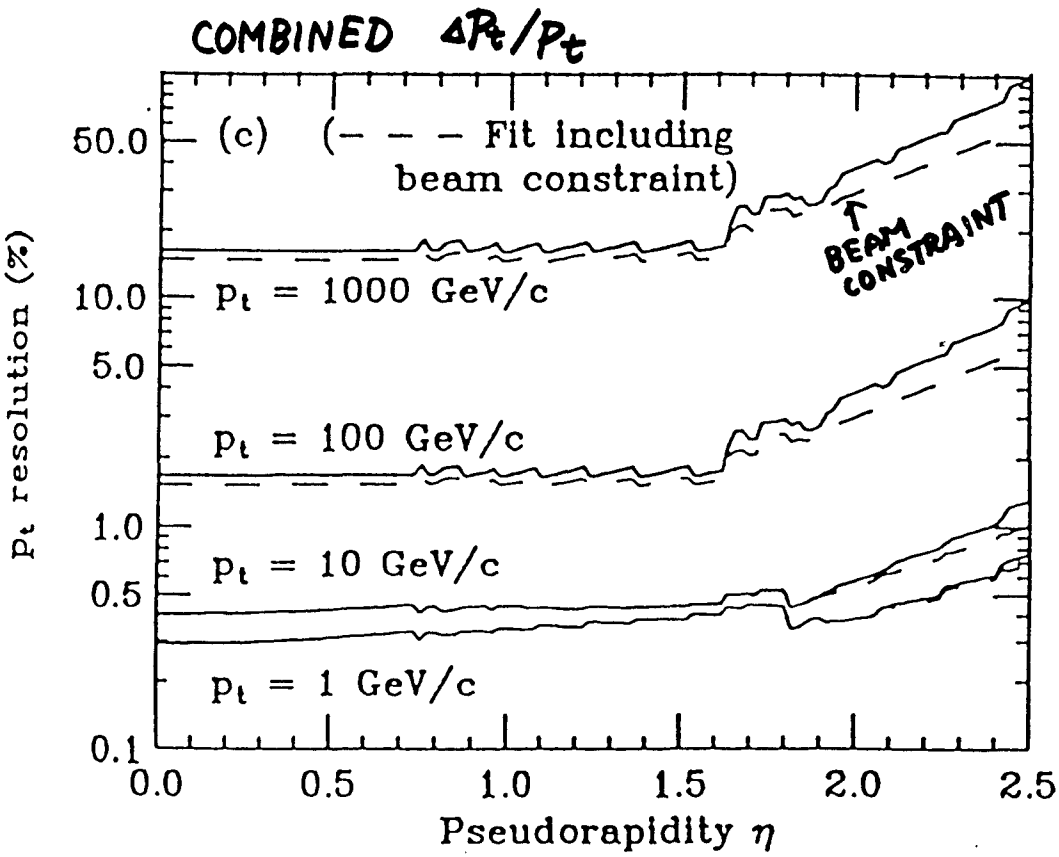


Straw Tracker Performance

- position resolution : ~100μm in rϕ (measured)
- rapidity coverage up to η = 1.8
- occupancy : 9.6% (inner)- 2.6% (outer) @ 10^{33}
- total charge : < 0.2C/cm/10years @10^{33}
- momentum resolution in conjunction with inner silicon tracker

  $\Delta p_t/p_t$ = 17% (at 1 TeV/c, no BC)

  $\Delta\phi_0$ = 0.066mr, Δb = 13μm, Δz_0 = 0.77mm



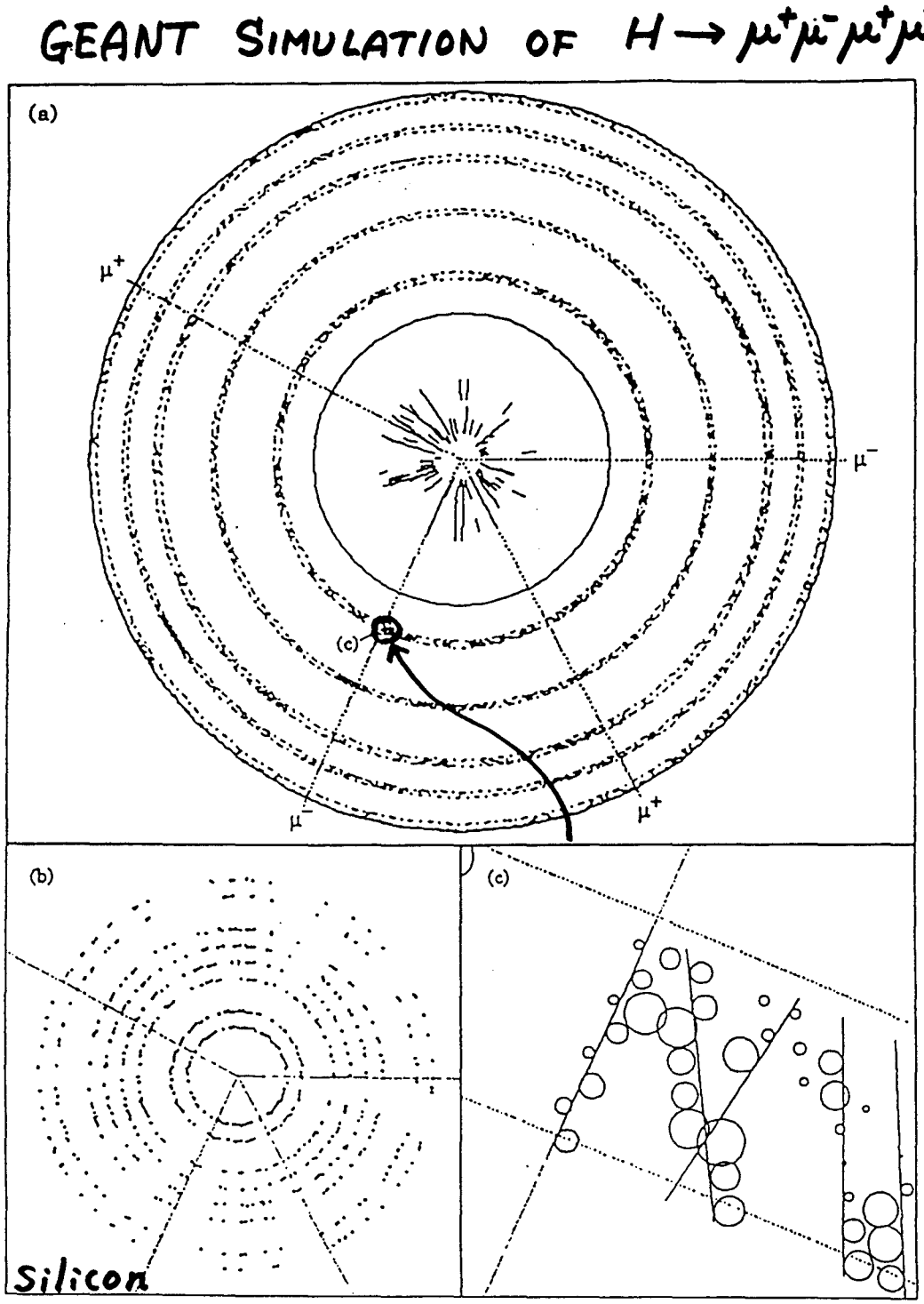
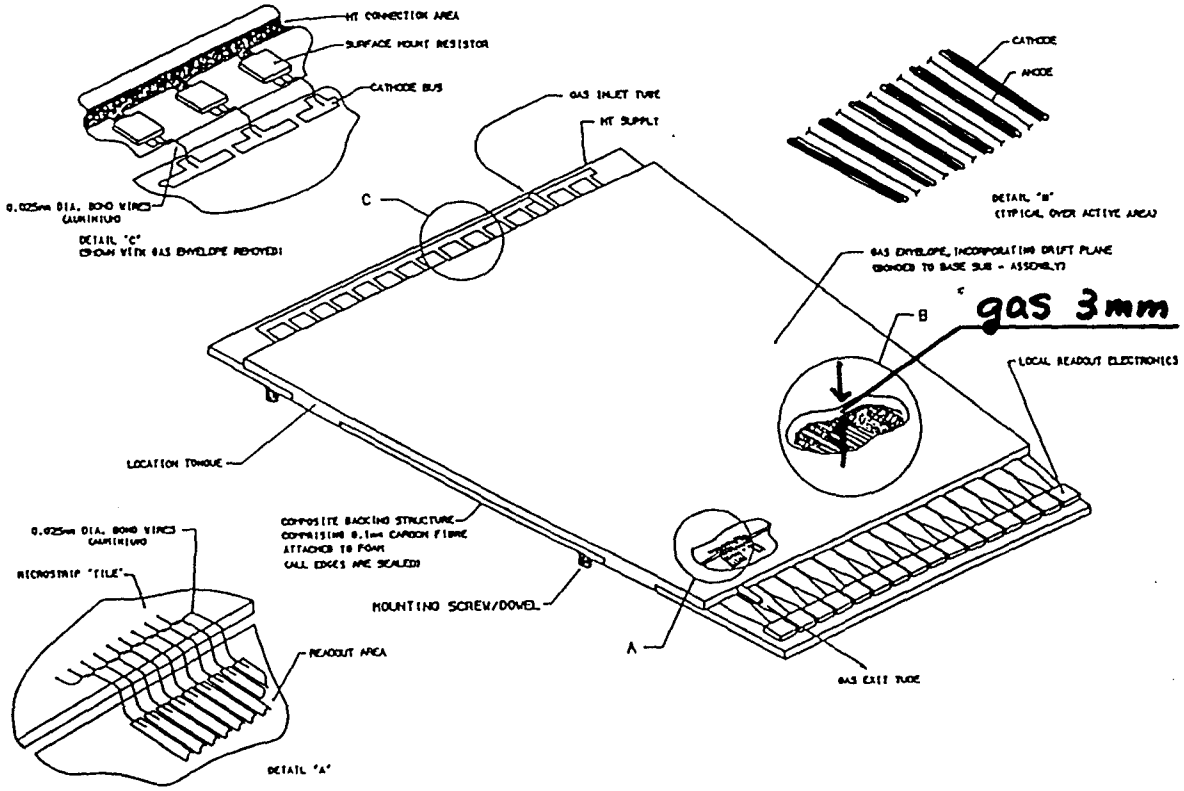


FIG. 4-8. a) The barrel region of the central tracker for a leptonic Higgs event at design luminosity, showing the reconstructed muon tracks from the Higgs decay, the raw data for the outer tracks and reconstructed track segments from the silicon tracker. b) Close-up of the barrel region of the silicon tracker, showing reconstructed space points. c) Close-up of the inner straw superlayer corresponding to the marked region in a). Straw tube hits are represented by circles with radius proportional to drift time. Short lines represent locally reconstructed track segments, and the long line is a fully reconstructed high transverse momentum track.

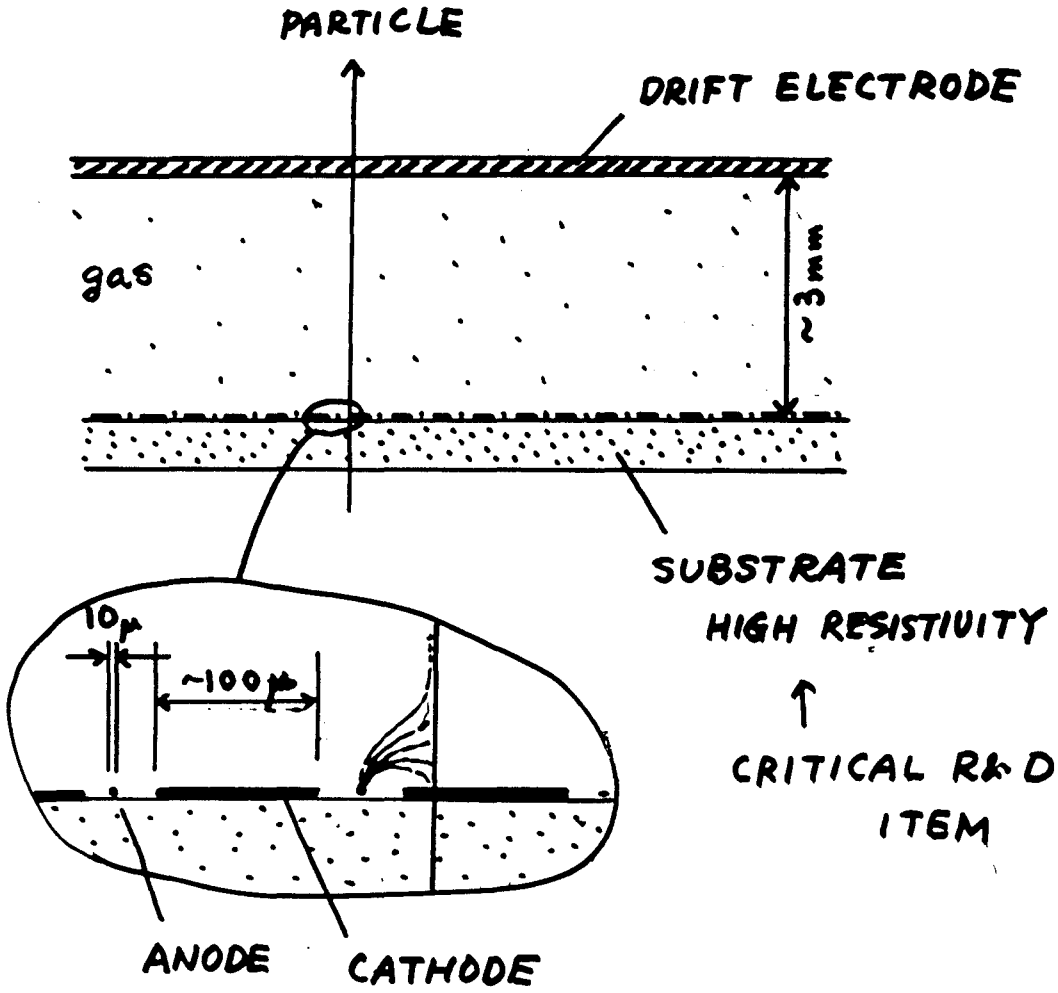
Gas Microstrip Tracker

Detector Element

- tile size : 270mm max x 180 mm
- keystoned cathode : 70~134μm in width
- anode : ~10μm strip, anode pitch : ~200μm
- <u>3mm</u> ionization path
- gas : Xe/DME/CO_2 or CF_4 based gas
- gas gain ~ 5×10^3

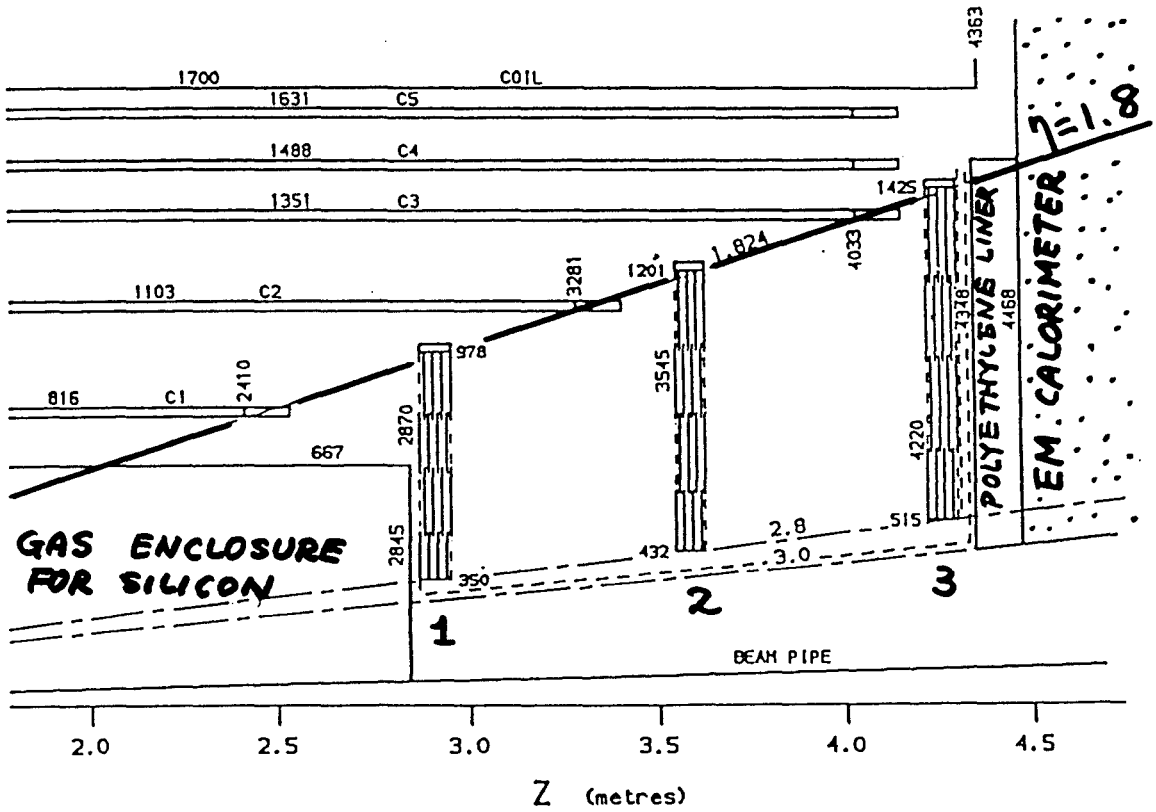


GAS MICROSTRIP DETECTOR



Gas Microstrip Detector Configurations

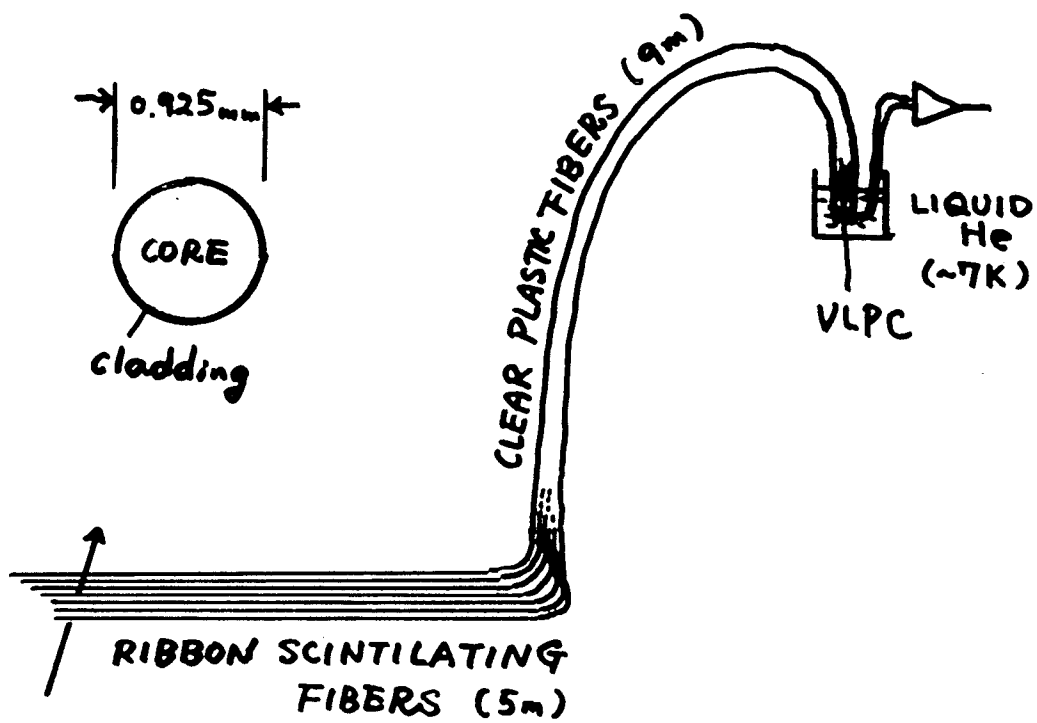
- 3 superlayer / side
- 2 radial + 2 small angle stereo /superlayer
- 3120 tiles, 1.36 x 10^6 channels
- occupancy = 4 x 10^{-3} @ 10^{33}
- rapidity coverage : $1.8 < |\eta| < 2.8$
- provide Level 1 trigger by measuring $\Delta\phi/\Delta z$



Scintillating Fiber Tracker (option)

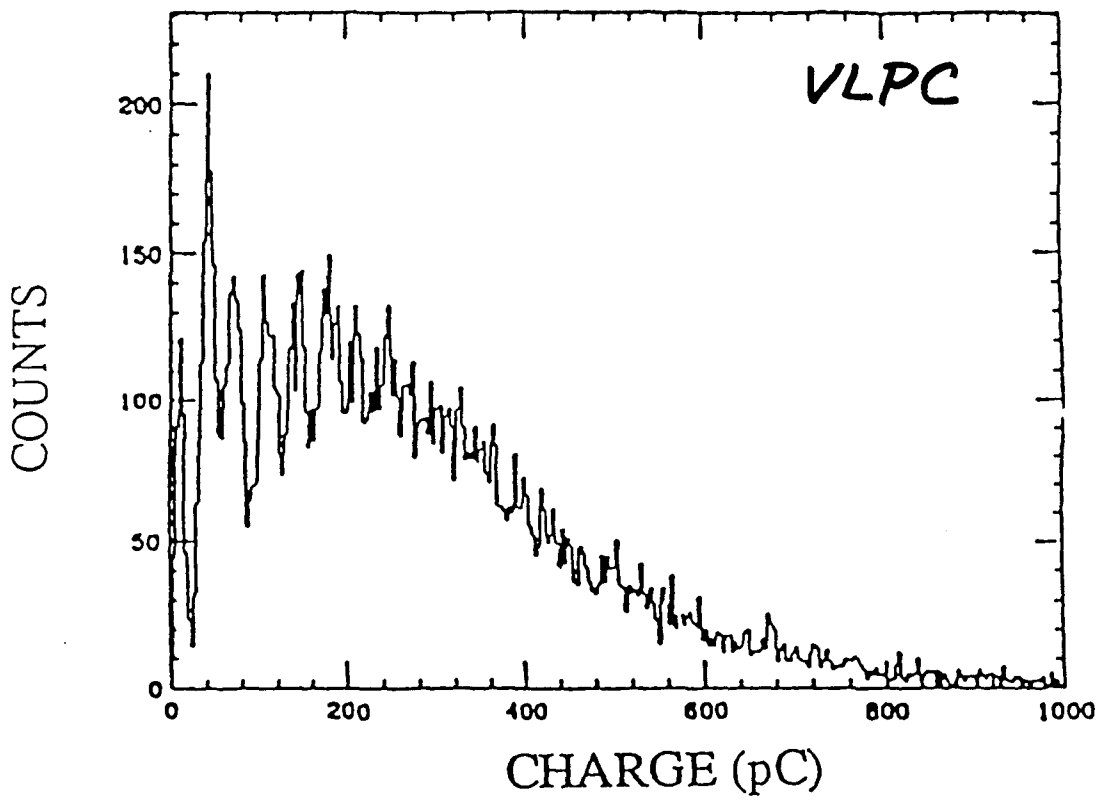
Detector Elements

- scintillating fiber : 0.925 mm dia.
  core : polystyrene+PTP+3HF
  cladding : polymethylmethacrylate (PMMA)
- optically coupled to clear fiber of 1mm dia.
- wavelength peak at $\lambda \sim 530$ nm (yellow-green)
  - optimum optical transmission
  - less radiation damage
- photo-electron yield ~ 5 demonstrated with 3.5m sci-fi (0.83mm dia.) + 3m clear fiber



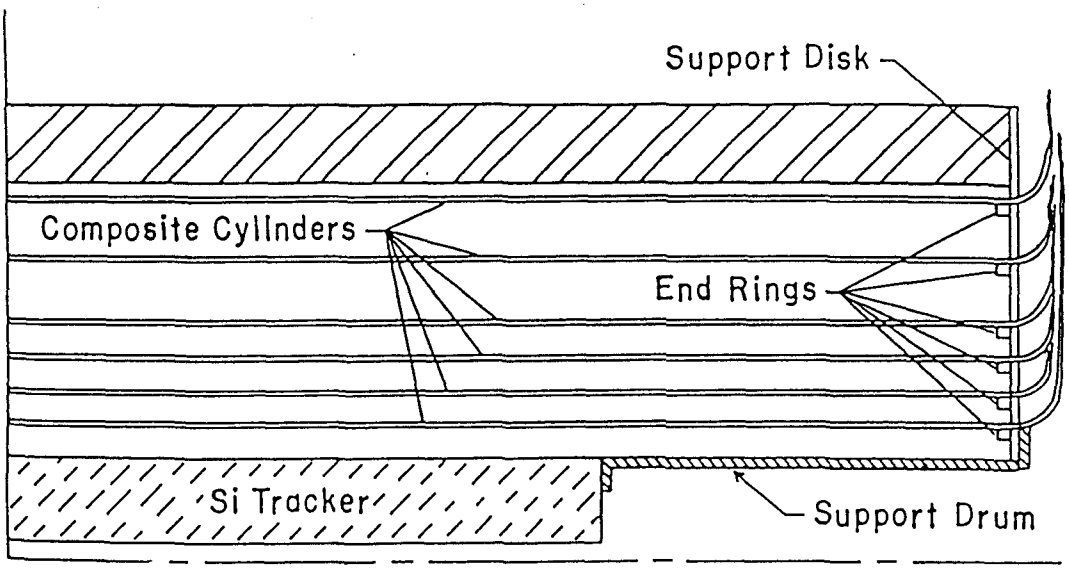
Photon Detector

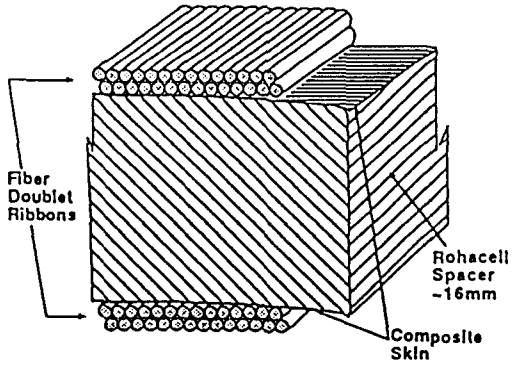
- VPLC (visible light photon counter) developed by Rockwell International Science Center
- original device: SSPM for infrared sensor, but infrared response must be reduced to clear military restrictions.
- quantum efficiency >75% at $\lambda \sim 565$nm and low infrared efficiency (<1%) has been achieved.
- must be operated at 6-7K (liq-He temperature)
- room temperature preamplifiers can meet the S/N requirements



Detector Configurations

- total number of fibers : 475K channels
- 6 superlayers
  - 2 for axial + small angle stereo (±6°)
  - 4 for axial only
- two doublets / superlayer
- 64 VLPC cassette/cryostat assembly at the back of barrel calorimeter

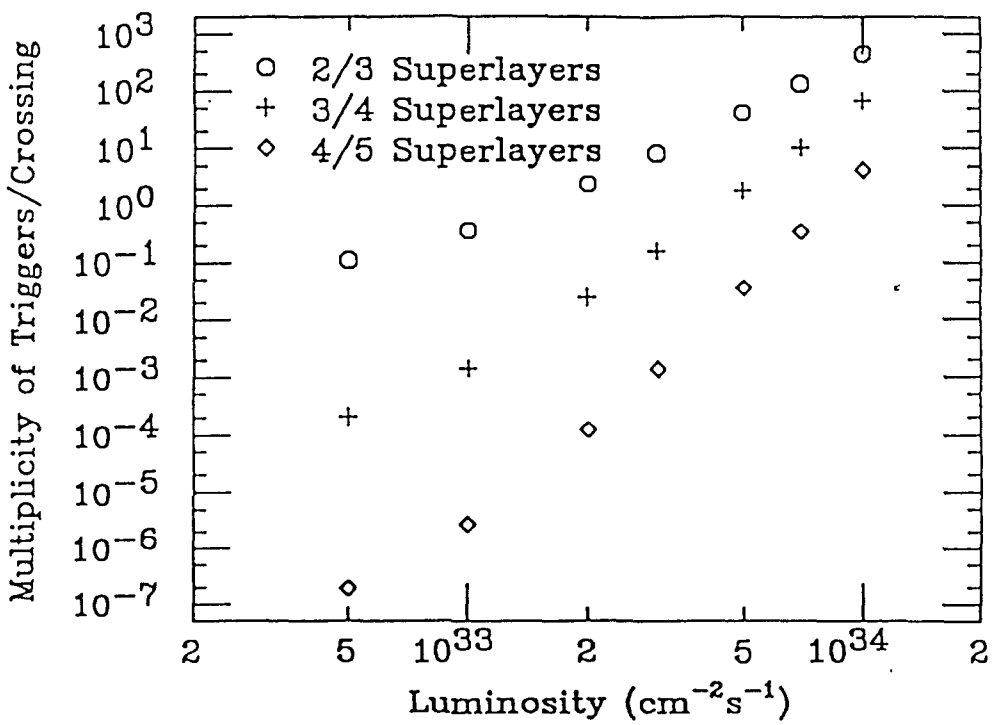




Detector Performance

- occupancy
  1.7% (inner) - 0.2% (outer) @10^{33}

- Level-1 trigger rate
  0.4/crossing upto $|\eta| = 2.3$ @ 10^{33}
  ~5/crossing upto $|\eta| = 1.7$ @10^{34}



Material in the Tracking Volume

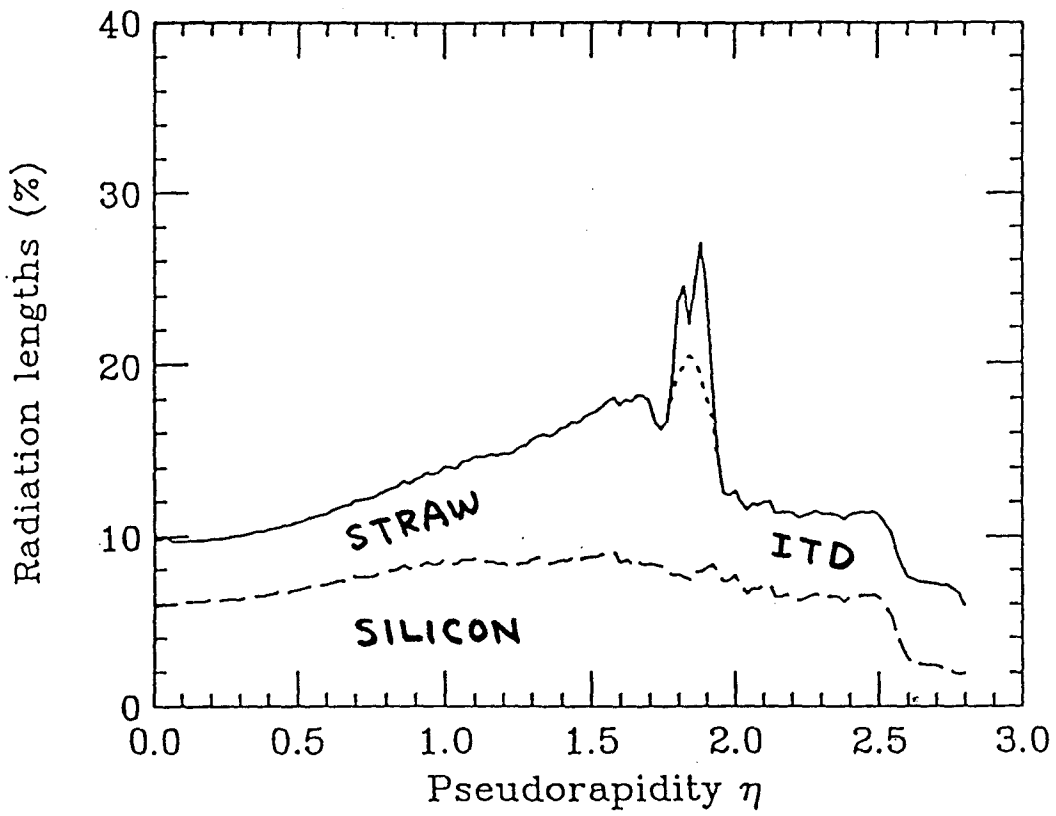


FIG. 4-14. Number of radiation lengths vs. rapidity for the full tracking system (solid curve) and silicon alone (dashed curve).

Physics Requirements on Calorimetry

[1] <u>Rapidity coverage</u> by EM calorimetry:

reconstruction of electrons within $|\eta|<2.5$

$$\frac{N(H\rightarrow 4e,\ |\eta|<2.5)}{N(H\rightarrow 4e,\ |\eta|<1.5)} = 2.5$$

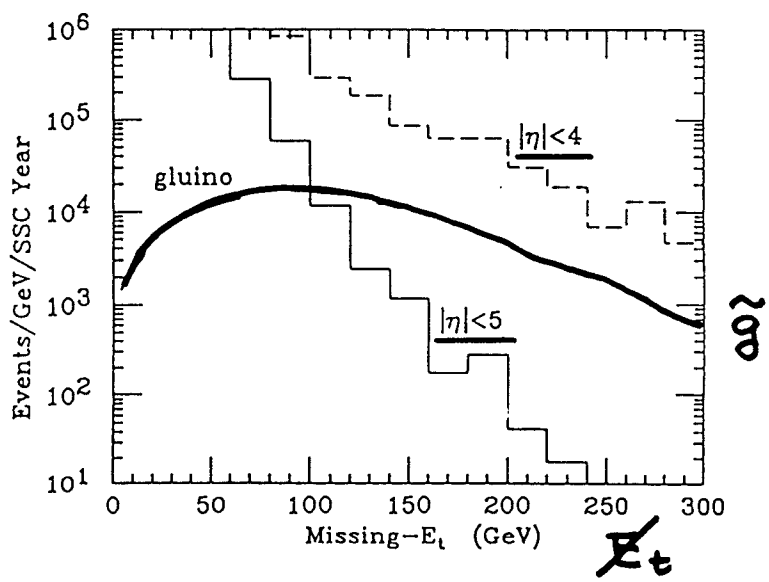
$\rightarrow$ EM calorimeter must <u>extend to $|\eta|<3$.</u>

[2] Missing Et measurement :

300 GeV gluino detection

$\rightarrow$ <u>jet measurement up to $|\eta| < 5.0$</u>

$\rightarrow$ the active area must extend to $|\eta| < 6.0$



[3] EM Energy resolution :

measurement of Z' width and $H\rightarrow\gamma\gamma$ detection

$\rightarrow$ stochastic term $< 15\%/\sqrt{E_t}$

<u>constant term < 1%</u>

[4] EM transverse segmentation

- e, γ ID, isolation requires 0.05 in $\Delta\eta \times \Delta\phi$
- minimize pile-up effect
- separate 2 e's from heavy Higgs$\rightarrow Z \rightarrow e^+e^-$

[5] Hadron transverse segmentation

reconstructed mass of Z, W $\rightarrow$ 2 jets 0.1 × 0.1

[6] Linearity

EM : $< 1\%$ for mass meas. of $H \rightarrow 4e$, $Z' \rightarrow ee$
HAD : single π response at ~5% per TeV for compositeness measurement to 20TeV

[7] Dynamic range : $\sim 2 \times 10^5$

minimum energy = 20 MeV (isolation, μ meas.)
maximum energy ~ 4 TeV ($Z' \rightarrow ee$)

[8] Calorimeter depth

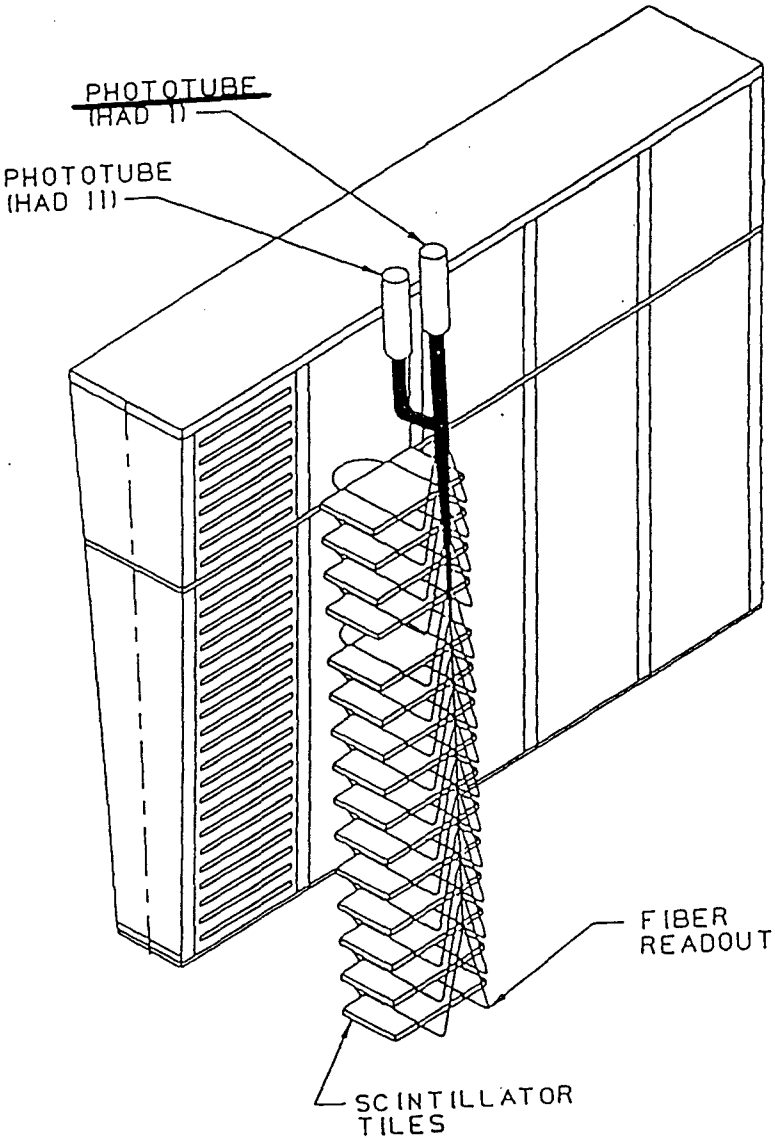
$22X_0$ to keep the EM constant term <0.3%
10λ at $\eta=0$ to have sufficient containment
(example : 10 TeV dijet mass)

Calibration of Calorimeter

- scintillator calorimetry is <u>inherently neither uniform nor stable</u> , unlike ionization detectors.
- three ways of calibration
  1. source calibration (^{57}Co and ^{137}Cs)
  2. optical flasher calibration
  3. in situ calibration
     - ±0.2% calibration in EM by E/P method in one month using W→ev
     - hadron part by $\pi^{\pm}$ and γ-jet balance

EM calorimeter <u>constant term</u> budget.

Source of constant term	Contribution
Calibration tower to tower	0.2%
Leakage	0.3%
→ Transverse uniformity	0.5%
→ Tile-to-tile variations incl. thickness variations and longitudinal masking	0.5%
Absorber thickness variations	0.2%
→ Radiation damage	0.5%
Total (added in quadrature)	< 1.0%

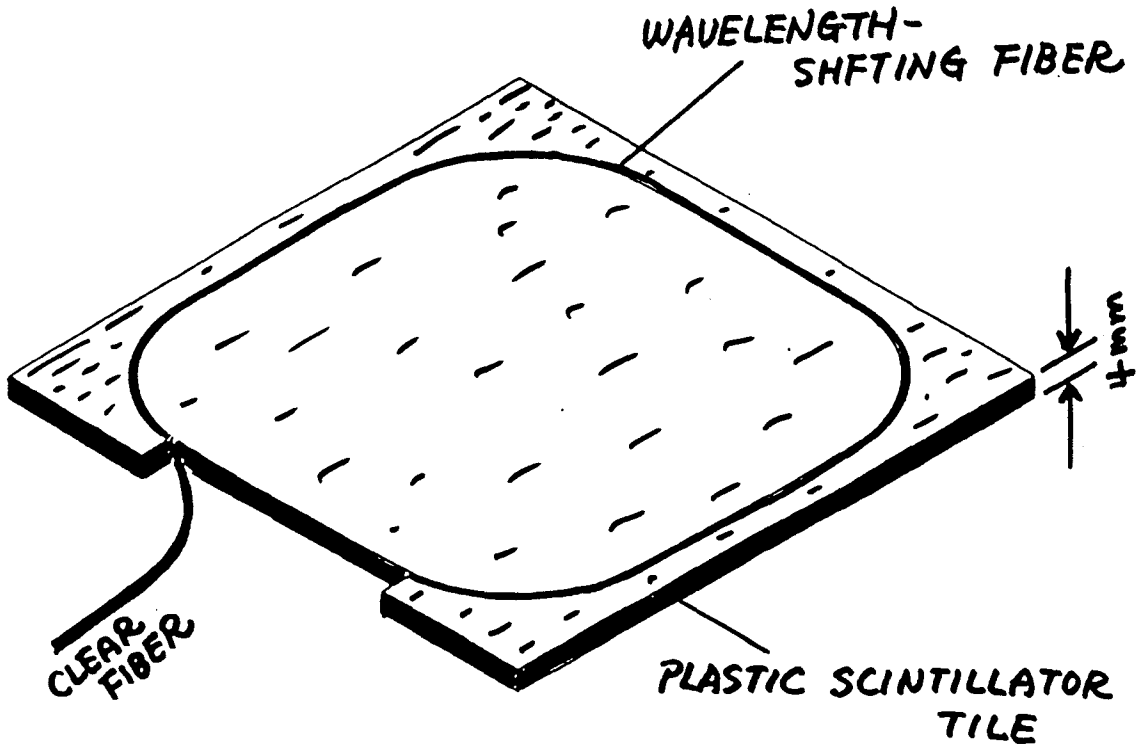

PHOTOTUBE
(HAD I)
PHOTOTUBE
(HAD II)
FIBER
READOUT
SCINTILLATOR
TILES

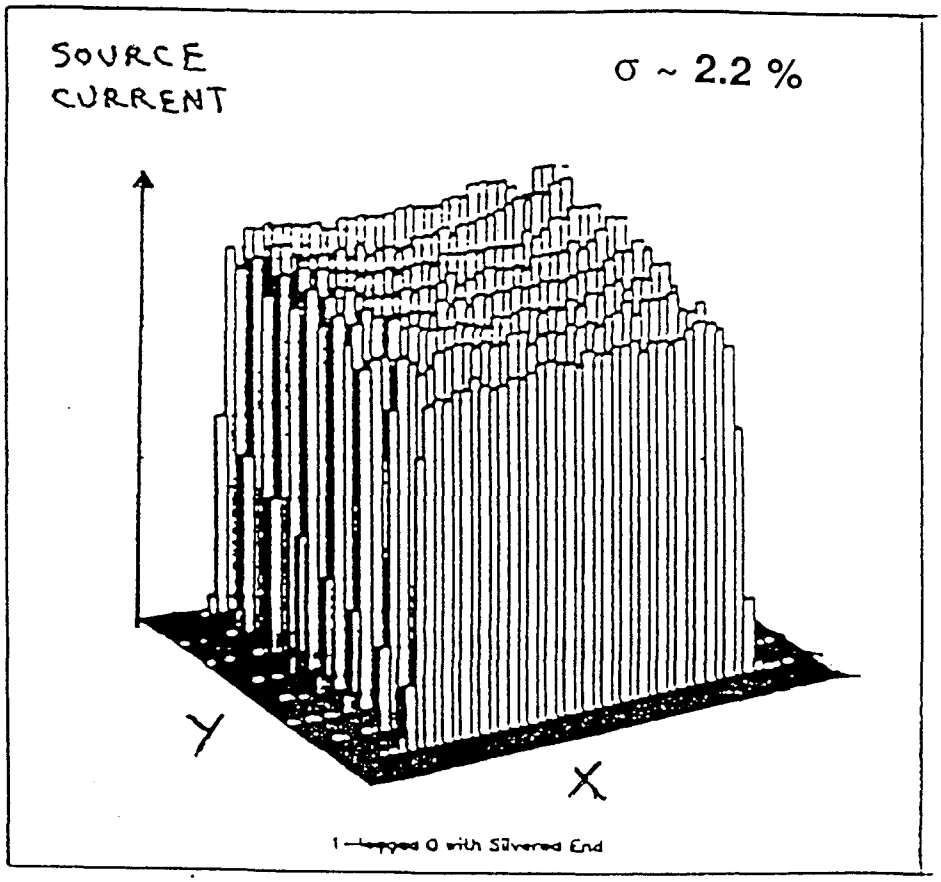
Scintillation Calorimetry

Detector element

- 4mm thick plastic scintillator tiles with wavelength-shifting fiber (Y7, 1mmϕ) readout
- extended-green sensitive phototube
- transverse uniformity of light yield <2%
- longitudinal masking by filter at the phototube face to correct tile-to-tile variation

  < 5% rms for hadron, < 2% rms for EM

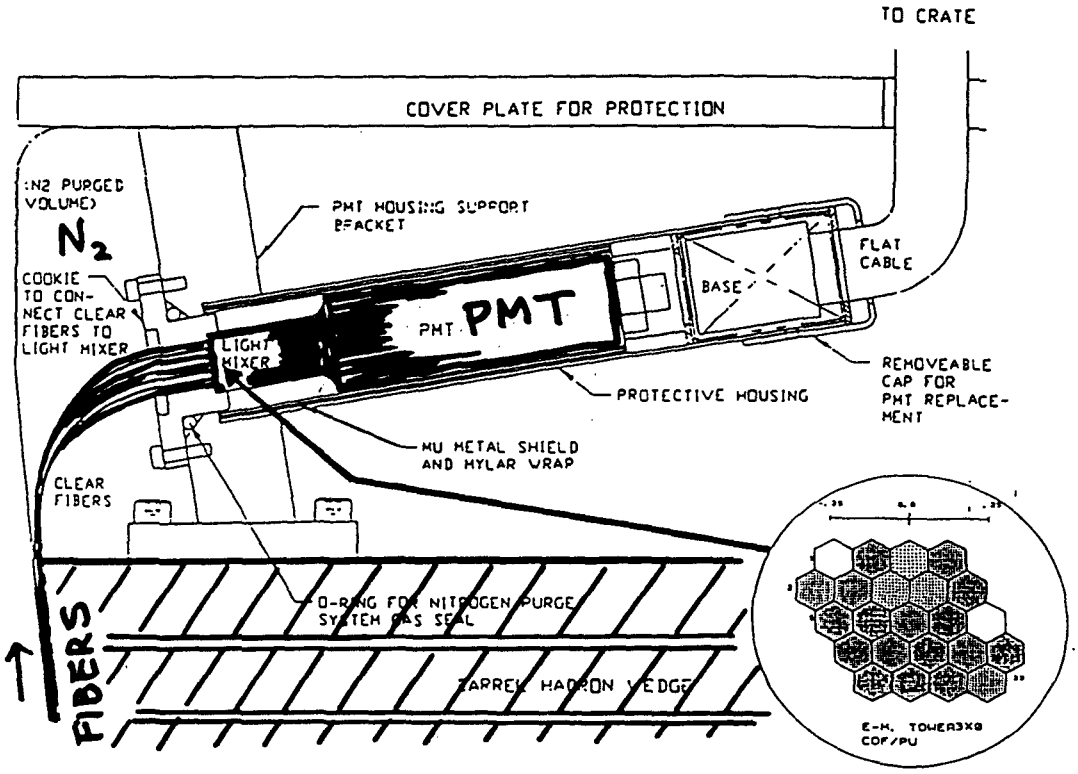




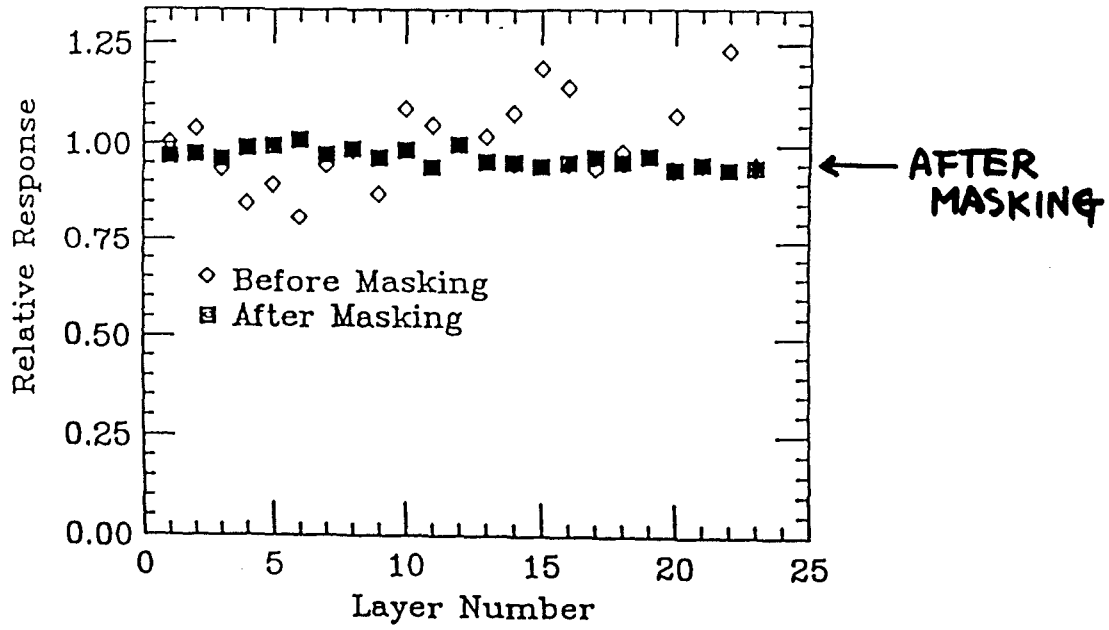
Tile/Fiber Transverse Uniformity

" σ " tile

Longitudinal Uniformity by Masking



neutral density filetr



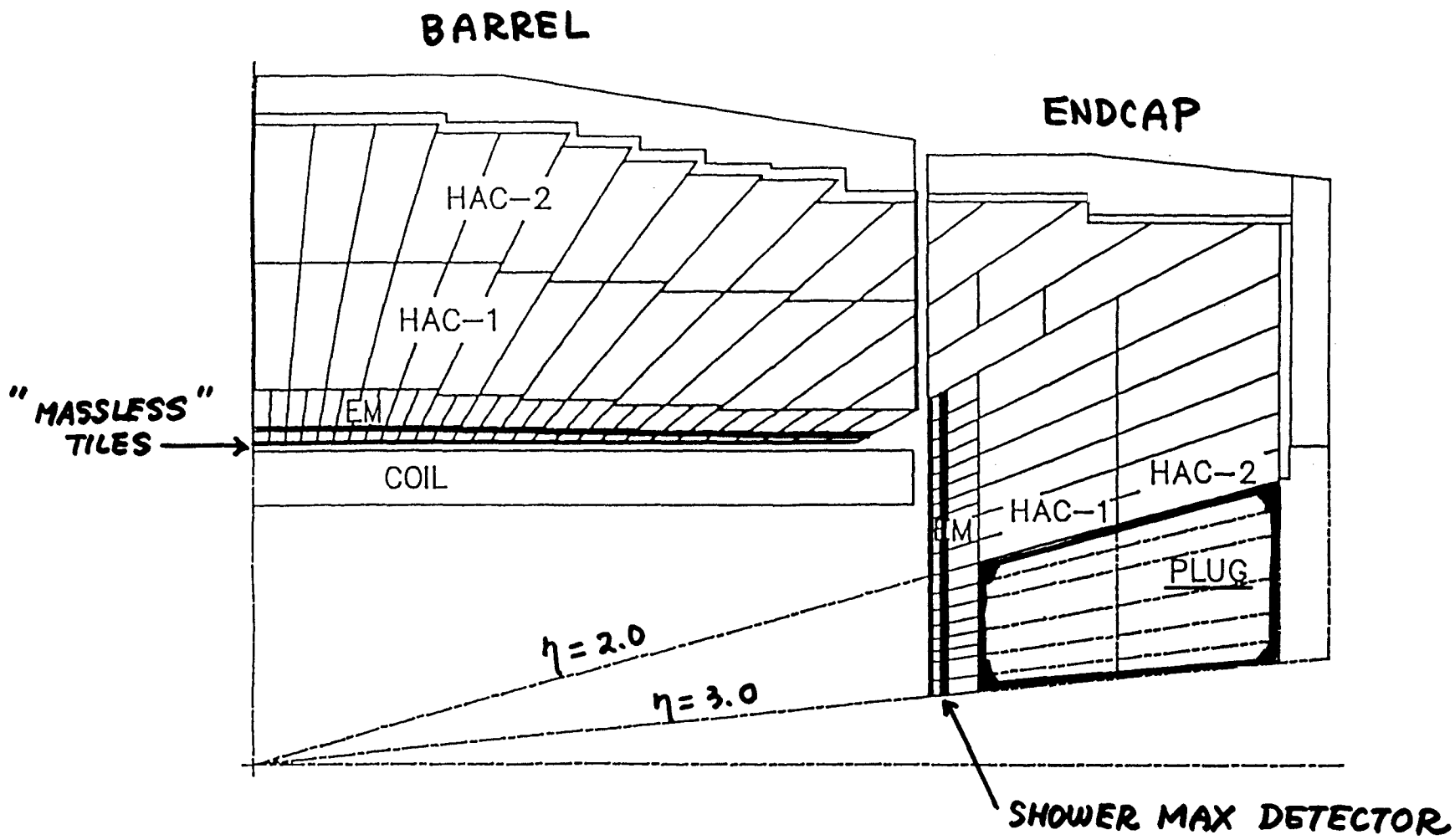
Detector configurations

- Calorimeter absorber
  Pb (4 or 6 mm thick) for EM part
  Fe (24-90 mm thick) for hadronic part :
  - comparable resolution with Pb case
  - better field and less compressive force
  - lower neutron flux in EM and tracker
  - mechanically stable and lower cost

- Segmentation
  - 2 EM longitudinal division in endcap 1 in barrel
    for correcting radiation damage
  - 2 longitudinal division in hadron
    - twice in sampling thickness in 2nd part
    - estimate shower leakage possible
    - can meet resolution in lower cost

- thicker scintillator of pre-radiator tile (massless)
  - correction of energy loss in the solenoid
  - statistical separation of γ and π°

- replacement of EM scintillator is possible endcap
  endplug region ($2<|\eta|<3$) can be replaced


BARREL
ENDCAP
HAC–2
HAC–1
EM
"MASSLESS" TILES
COIL
HAC–2
HAC–1
EM
PLUG
η = 2.0
η = 3.0
SHOWER MAX DETECTOR

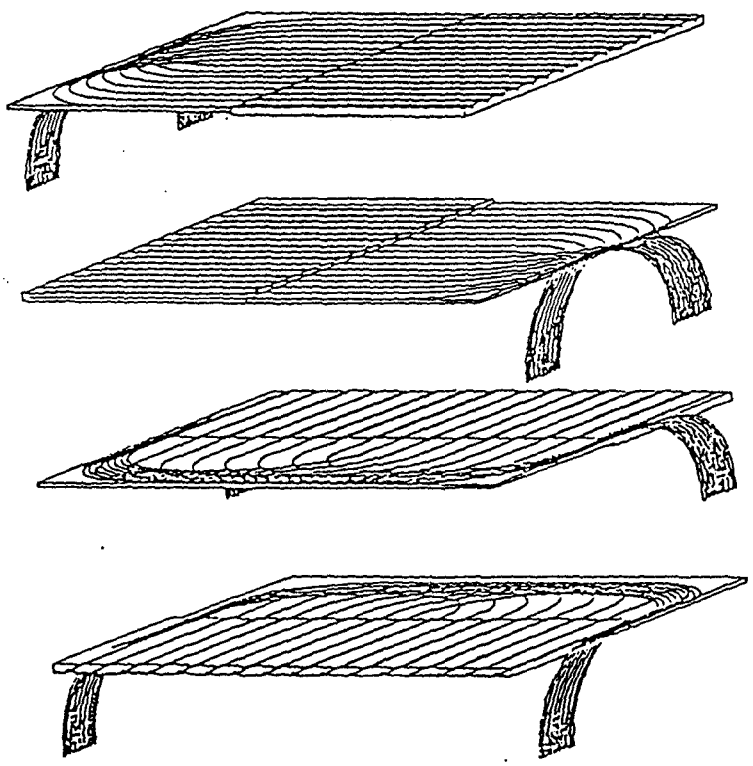
Shower Max Detector

Functions

- measure EM position to 2-3 mm in $r\phi$ and z
- redundant measurement of EM energy

Detector

- crossed narrow scintillator strips at depth $6X_0$
- strip size : 1.2cm x 10cm
  but initially gang four (two) strips together
- total readout : 47,104 channels initially
- multi-channel PMT for baseline readout
  possibilities on APD, APD-MCPMT & VLPC



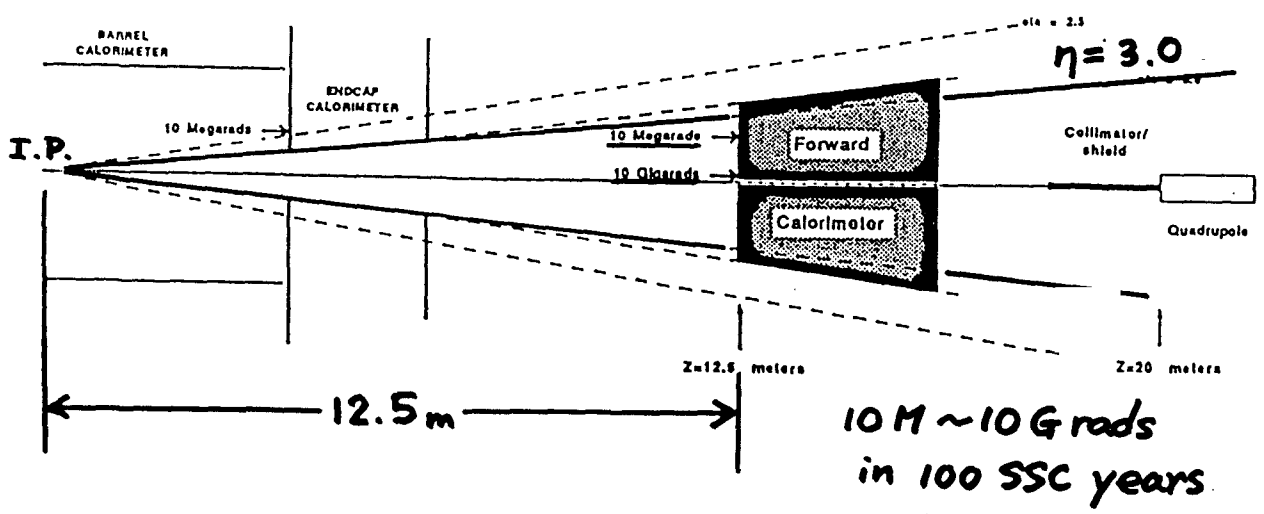
Forward Calorimeter

Functions
- missing Et measurement
- jet tagging for WW/ZZ fusion

Detector Technology
- high pressure gas ionization calorimetry
  - Argon gas + 5% methane at 100 atm
  - unity gain
  - drift velocity : 2ns / mm

or • liquid scintillator in quartz tubes (5mmϕ)

Detector configurations
- Front face of calorimeter at Z = ± 12.5 m
  - granularity matched to the shower size
  - tower occupancy rate reduces
  - reduce radiation damage and neutron albedo
- 0versize radially by one λ



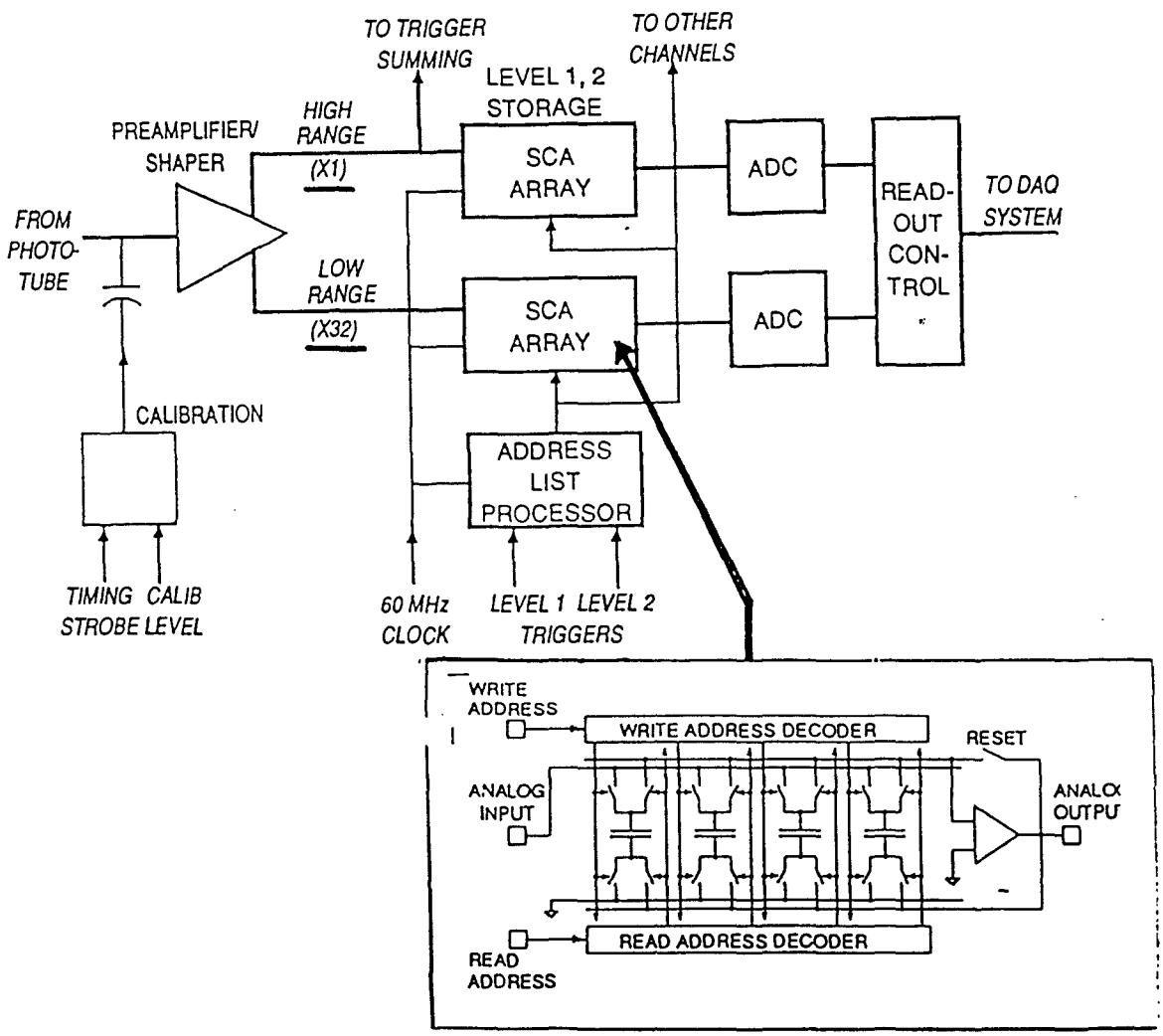
Front-end Electronics for Calorimeter

- dynamic range : 2 x 10^5 (18 bits)
- signal sampling at 60 MHz

Two different architectural approaches

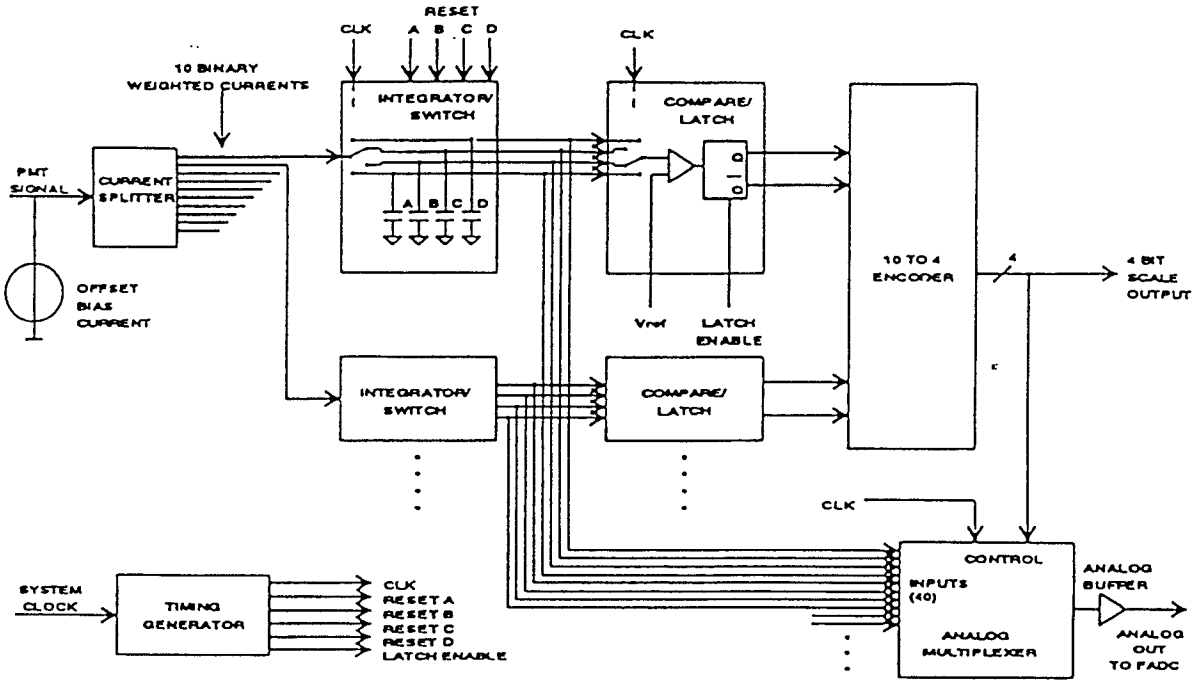
(1) Switched Capacitor Arrays ANALOG

- CMOS sample and hold of analog signals
- divided to two signal amplitude ranges
- A-to-D conversion after Level-2 decision



(2) Digital Phototube Readout DEGITAL

- digitize PMT signals at each PMT base
- 8-9 bit accuracy with 20 bits dynamic range



Muon System

Functions
- muon triggering (adjustable p_t^{TH})
- identification of muons
- improve momentum resolution

Three Components

(1) Magnetized iron toroids (1.8Tesla)

	$\|\eta\|$ range	thickness	kick in θ mr
barrel	<1.4	1.5m	$810/p_t$
forward	1.4 - 2.5	3.0m	$1620\tan\theta/p_t$

(2) Trigger scintillation counters

To define the beam crossing in Level-1 trigger

barrel	single layer	2240 counters
forward	two layers	2256 counters

(3) Wire drift chambers

	drift tube OD	superlayers	tubes
barrel	9.32 cm	3 (BW1-3)	57624
forward	4.5 cm, 6 cm	4 (FW1-5)	32240

Future Options

a. Cerenkov counters in forward region

b. Drift tube layer (FW3) to improve

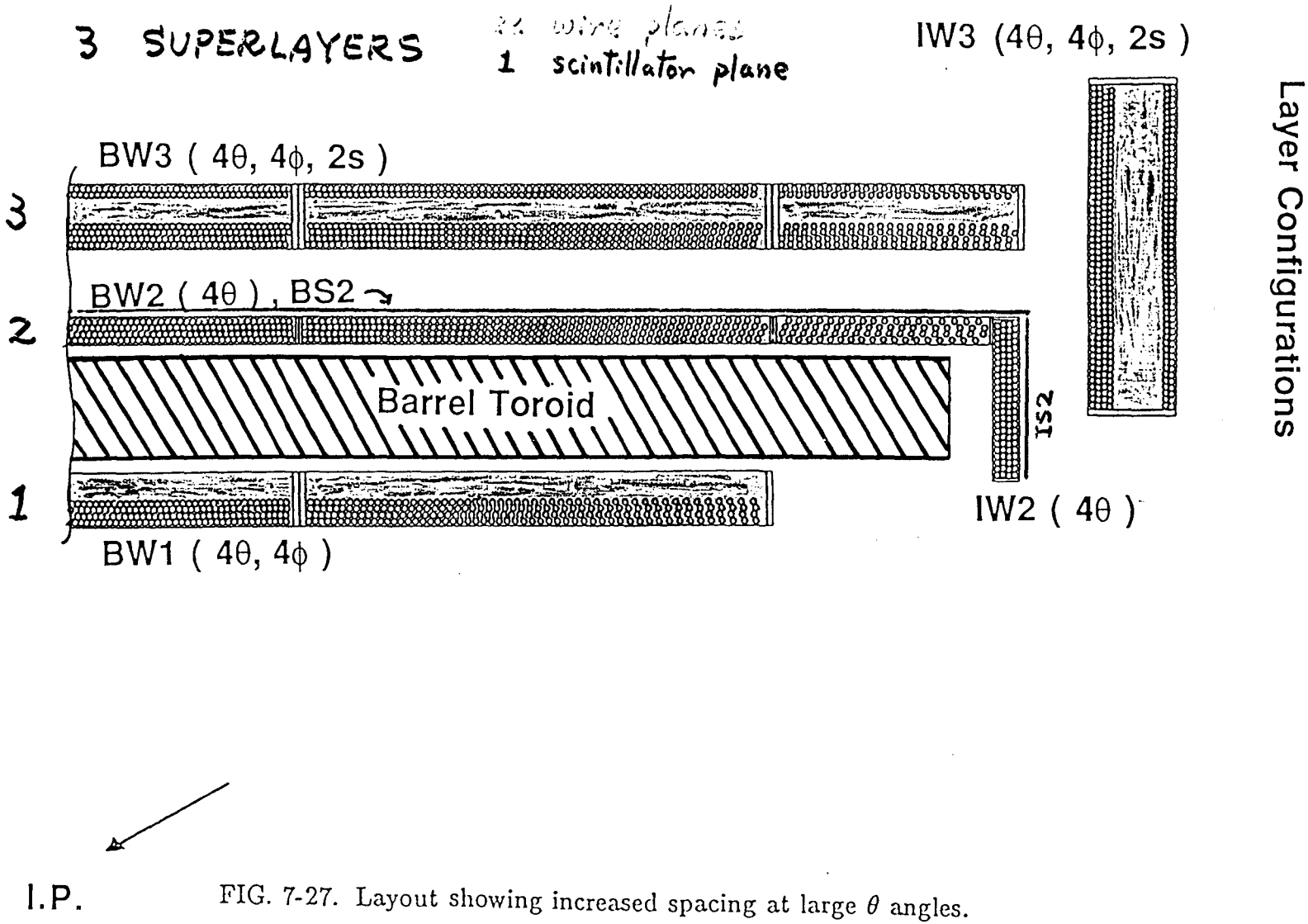
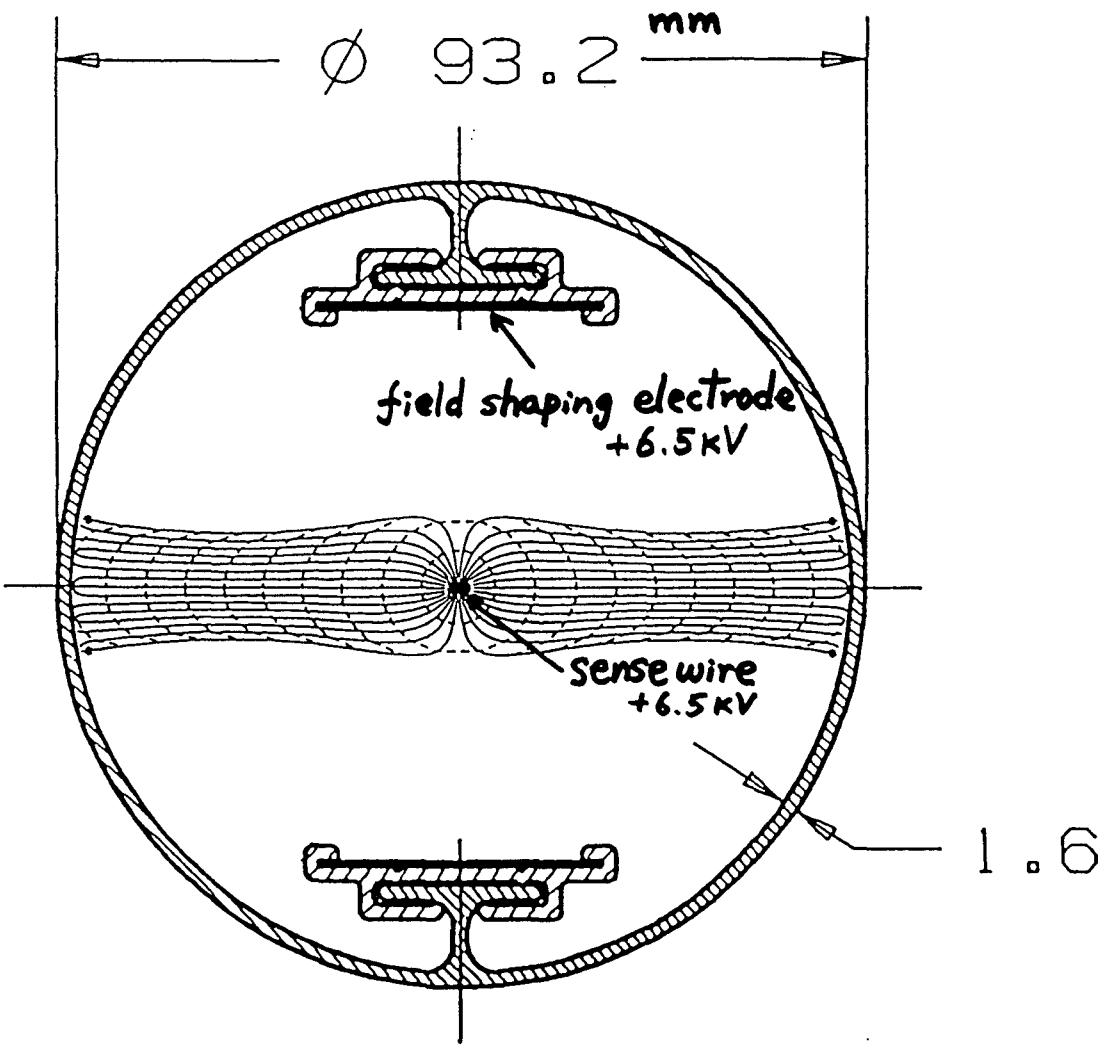


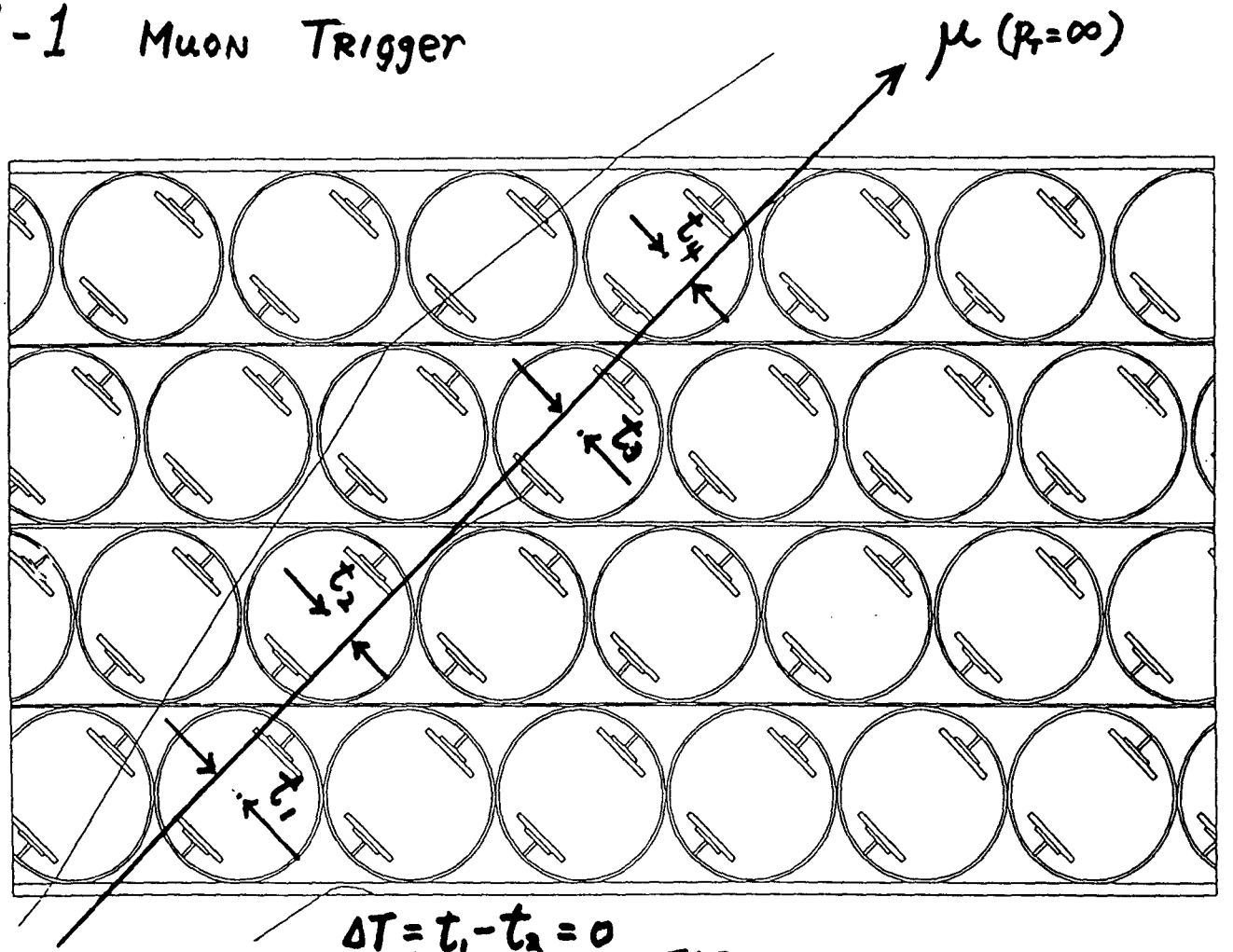
FIG. 7-27. Layout showing increased spacing at large θ angles.

Muon Drift Tube

- inside radius 45 mm
- → field shaping electrode
- anode wire 75 or 90 μm dia. W
- gas Ar-CO_2 (90-10)
- gas gain 10^5
- position resolution 250 μm
- → double track separation 5 mm
- → tubes become also structural units by epoxing



Level-1 Muon Trigger

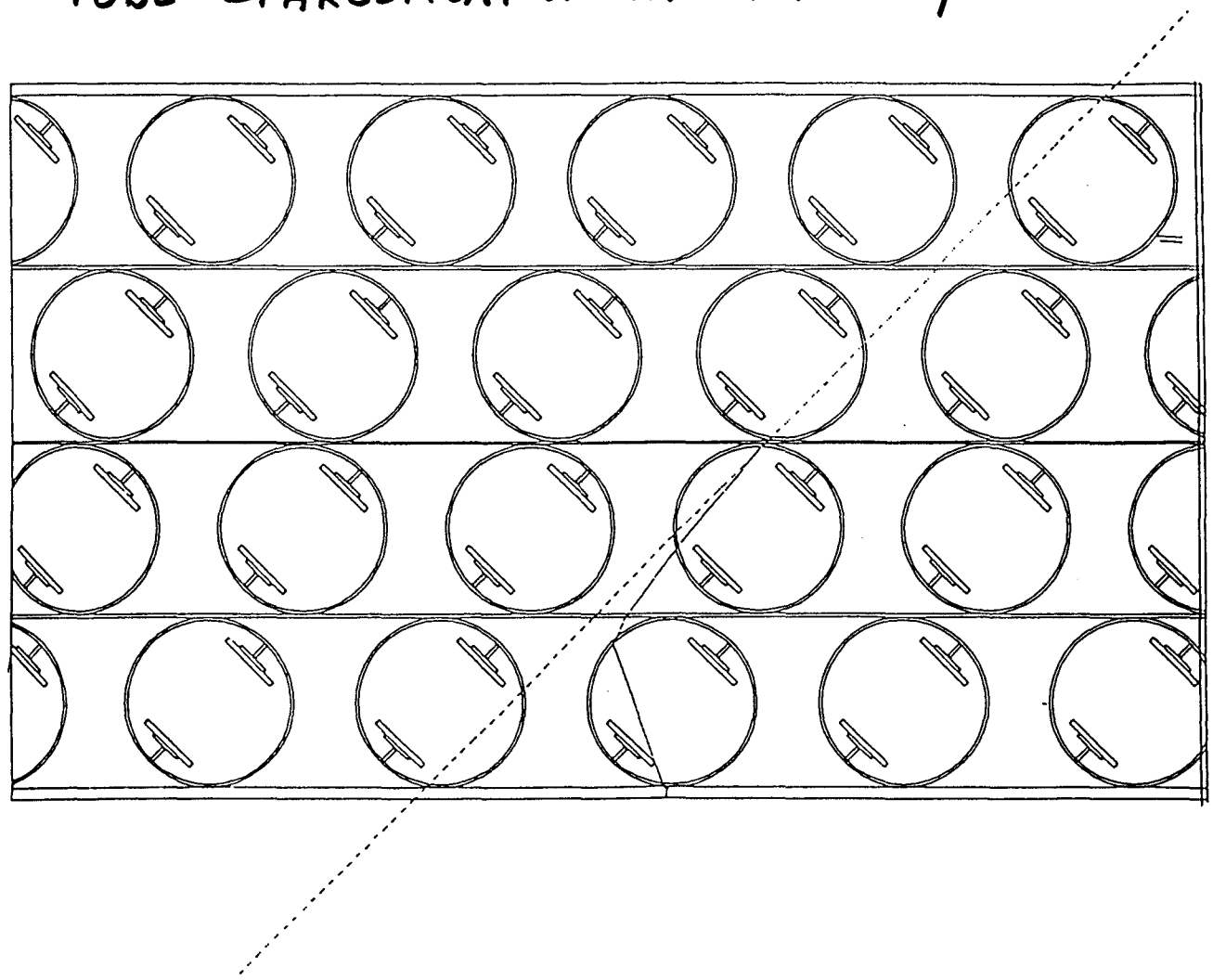


$\Delta T = t_1 - t_3 = 0$

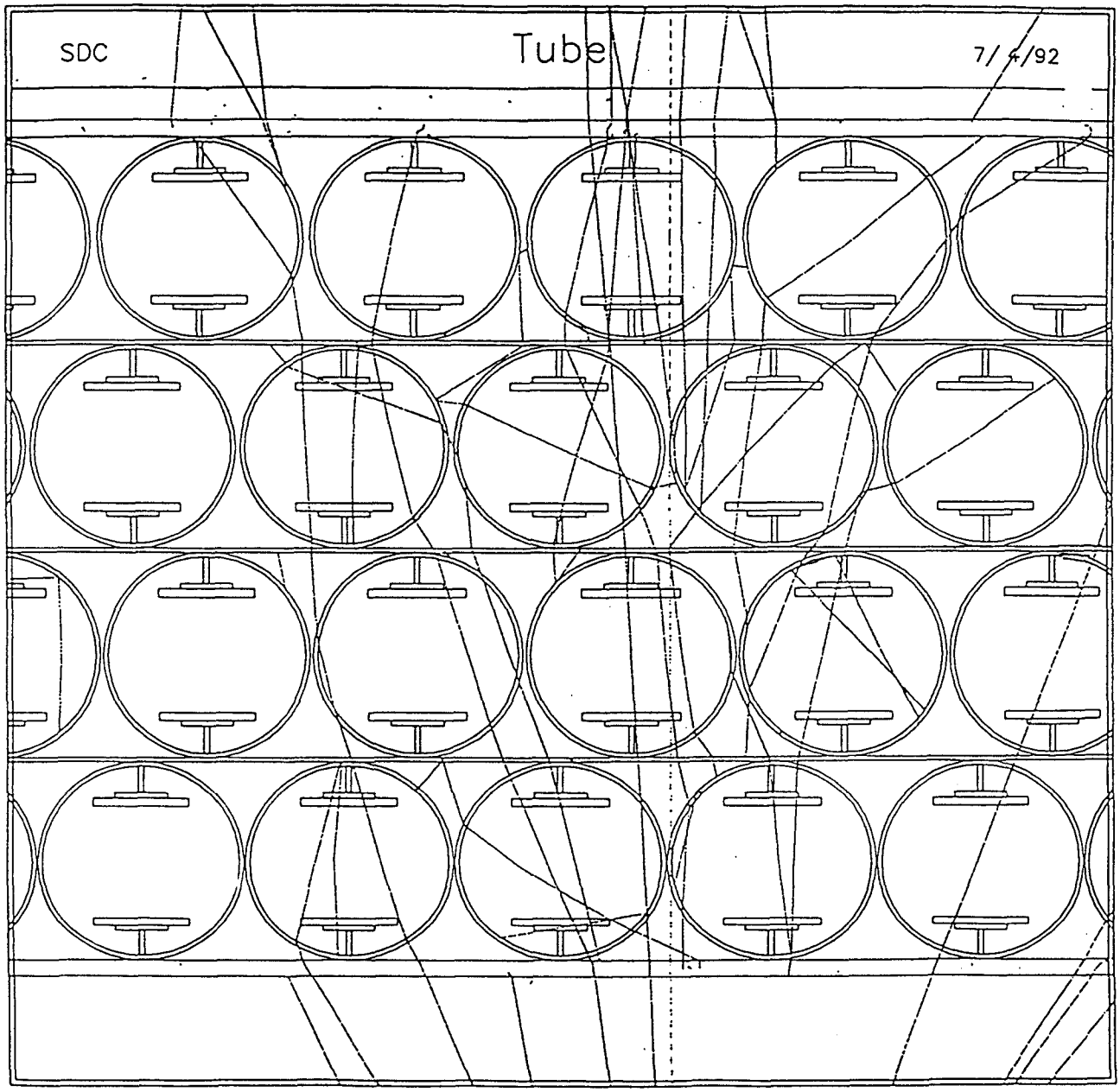
$\Delta T = t_2 - t_4 = 0$

FOR INFINITE MOMENTUM MUONS

TUBE SPARSIFICATION AT HIGHER η



GEANT SIMULATION : 1 TeV μ IN BW2

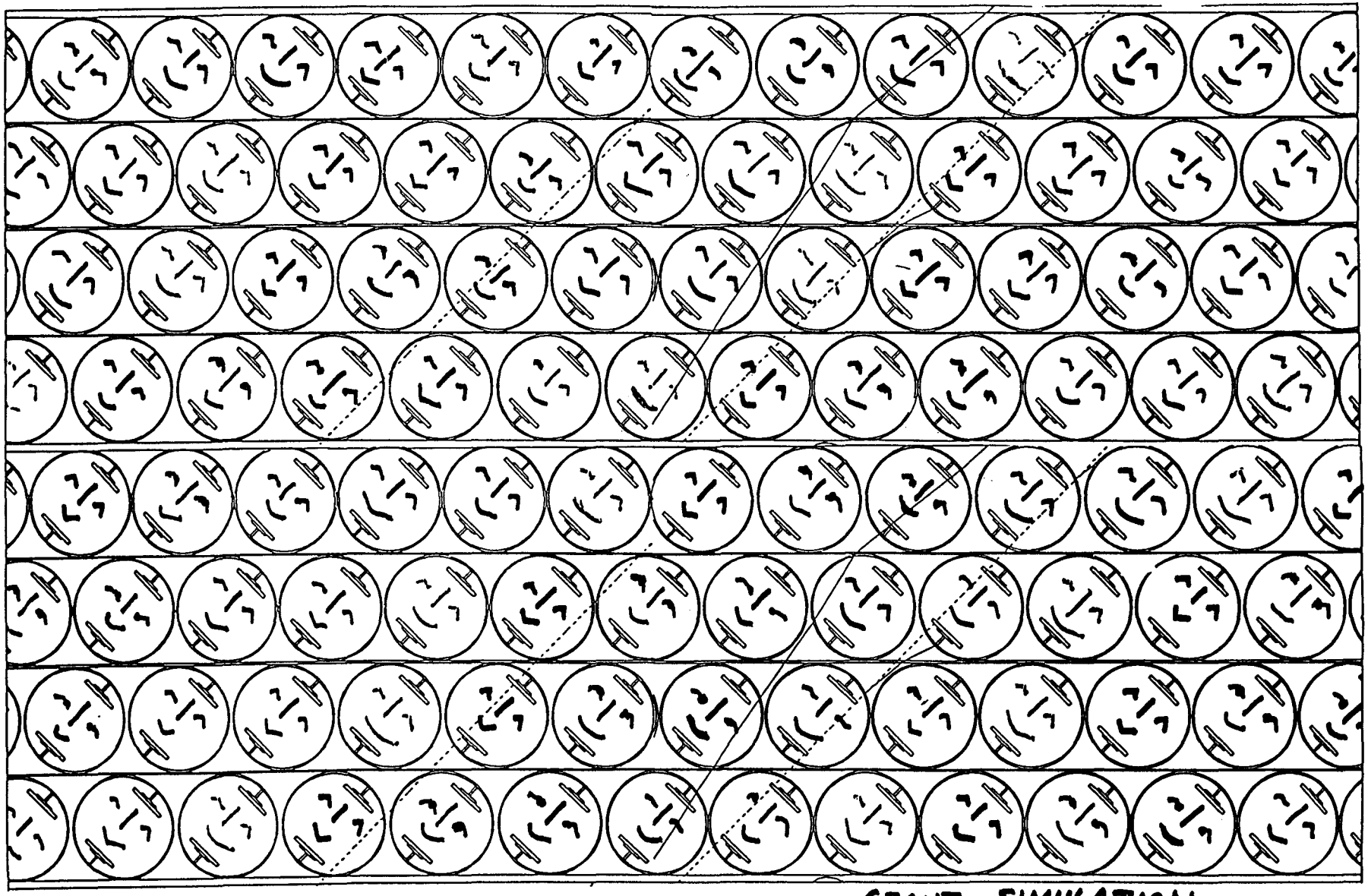


10-20% OF HIGH ENERGY MUONS ARE ASSOCIATED BY LOW ENERGY DEBRIS

1 TeV μ

NEED GOOD 2-TRACK SEPARATION!

SDC Collaboration After the Discovery of Higgs by SDC



GEANT SIMULATION

Trigger

- require ΔT between projective wire pairs
- p_t threshold can be adjusted by Δt intervals
- low p_t fakes be eliminated by ≥ 2 out of 4 pairs

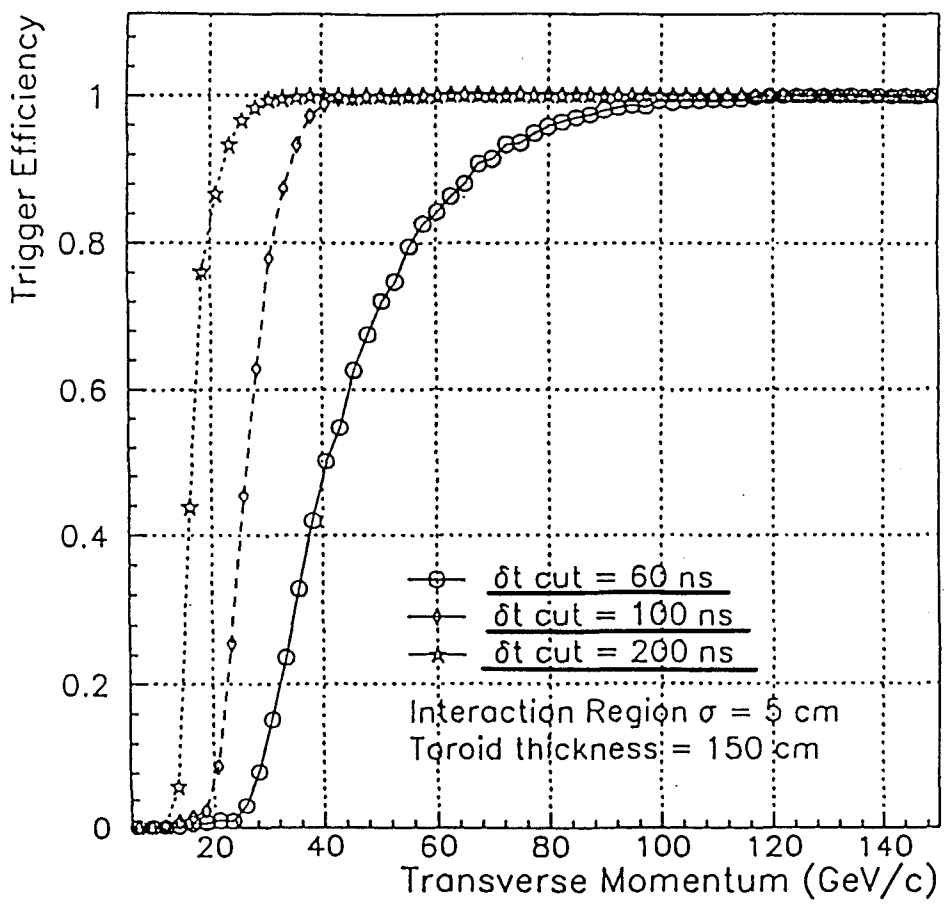


FIG. 7-2. Trigger efficiency versus transverse momentum for three different time difference thresholds.

Momentum Resolution

- combination of ϕ measurements in inner tracker and BW1, BW3 improves p resolution
- stand-alone forward muon system can provide reduced momentum resolution at high *L*.

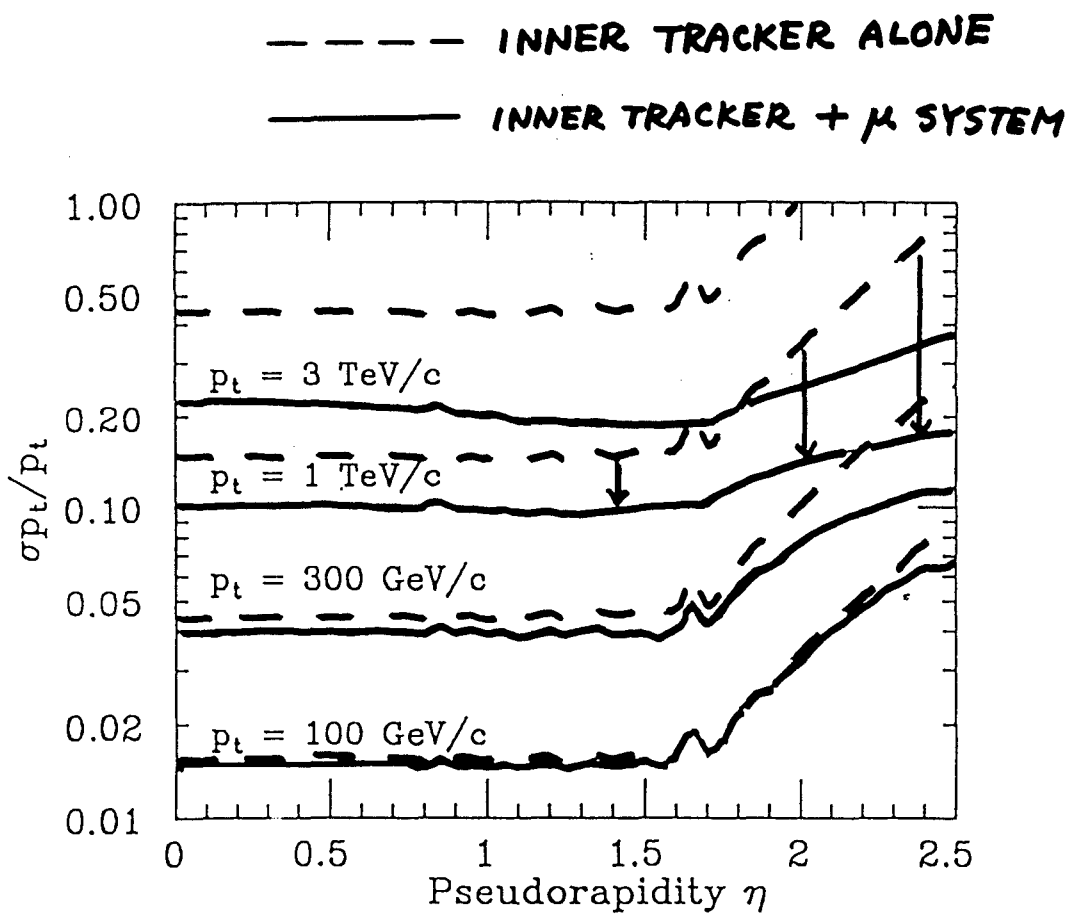


FIG. 7-4. Momentum resolution for muons using combined measurements from the inner tracker and the muon system (solid lines) and from the inner tracker alone (dashed lines).

NEW CHALLENGES
for SSC ELECTRONICS SYSTEMS

~10^7 detector channels for *10^8 interactions/sec*
to *50 - 100 events/sec* of record length *< 1 MByte*
while retaining *all* interesting physics data.

In addition to the problems of extremely high rates and very large numbers of channels, particular challenges arise from:

Time between crossings < Detector response times
Time between crossings < Time of flight
Time between crossings < Trigger decision time

Requires systems with new features:

- "*deadtime-less*" electronics system with simultaneous analog signal processing and digital readout.
- *pipelined* trigger and data systems.

We have developed a conceptual design of electronics systems which address the challenges of event selection and readout of the SDC Experiment at the SSC.

Its chief features are:

- Three-level architecture

- Extensive use of custom IC's for
  - signal processing
  - data storage

  on the detector.

- Event selection based on:
  - local signatures of physics quanta at early levels,
  - complete physics signatures at final level.

- Data acquisition with
  - common front-end protocols
  - extensive use of:
    - parallelism
    - commercial products.

STRATEGY of TRIGGER LEVELS

Level 1:

Identify Physics Objects

$e^{\pm}$, $\mu^{\pm}$, γ, jets, "υ"

and Combinations of Physics Objects

Level 2:

Refine Identification of Physics Objects

e.g.: Sharper p_t, E_t cuts

Reject conversions

Level 3:

Identify Signatures of Physics Processes

With full event data and capability of full analysis

Examples of LEVEL 1 TRIGGER

Trigger	Threshold
Electron	20 GeV
Photon	30 GeV
Muon	20 GeV
Jet (1.6 x 1.6 sum)	140 GeV
Missing E_t	80 GeV
2 electrons	10 GeV
2 photons	20 GeV

ELECTRON TRIGGER

Level 1: Identify electromagnetic shower

Calorimeter trigger towers with E_{em}> Thresh

and E_{hac}/E_{em}< Cut

Reject PMT discharge

Shower max hit within calorimeter tower

Demand track associated with shower

Stiff outer tracker segments

pointing in ϕ to trigger tower and shower max hit

Option: Isolation (Surrounding trigger towers below threshold)

Level 2: Reject γ conversions

By demanding hits in inner silicon layers

Reject $\pi^+ - \pi^0$ overlaps

Spatial match of track with shower max in ϕ

Reject π^+ showers

Loose E/P cut

Option: Isolation (Surrounding trigger towers below threshold)

Level 3: Sharpen E_t measurements

Using full calorimeter segmentation and resolution

Advanced pattern recognition for electron id

With calorimeter and shower max profiles

Refine spatial match between tracks and showers

Using shower max profile and finer tracker resolution

Perform calorimeter energy corrections

For cracks and inert material

Refined rejection of photon conversions

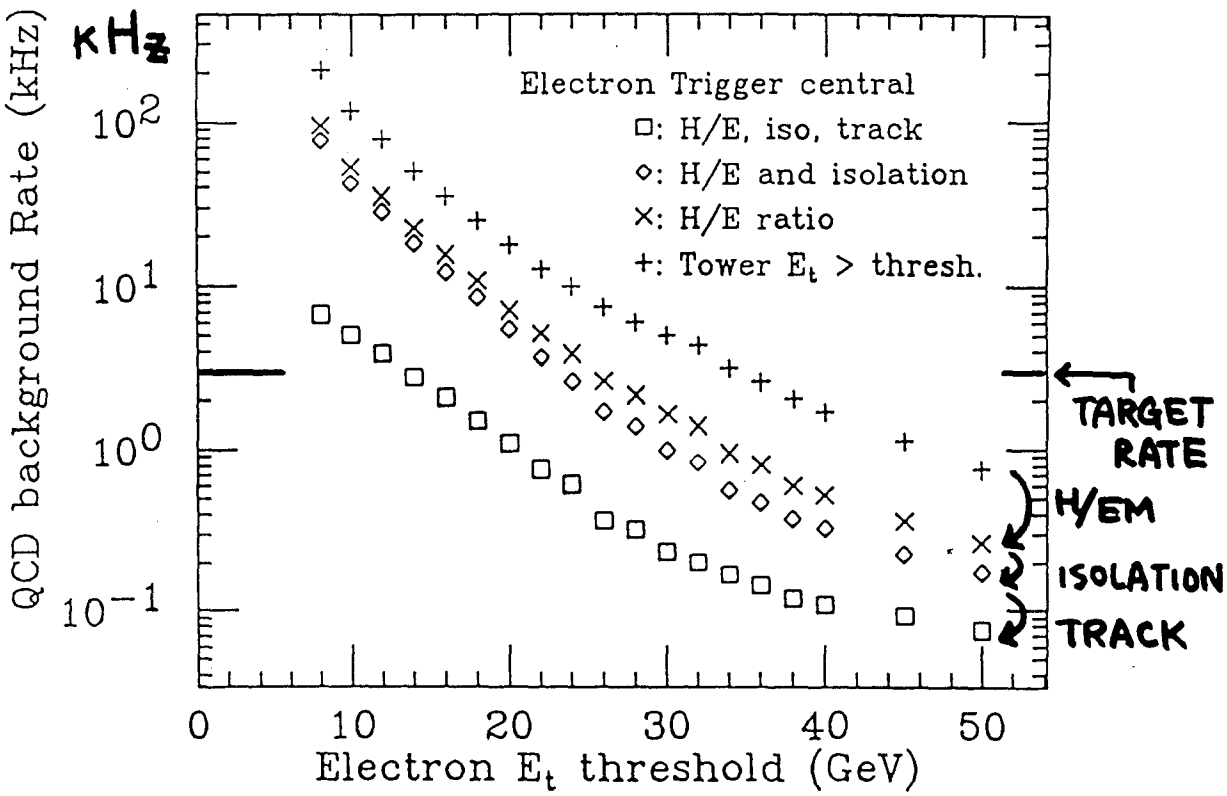
With additional track reconstruction

SDC TRIGGER LEVELS AND RATES

	Avg. Time between Decisions	Average Decision Time	Input Rate (Hz)	Expected Rejection	Output Rate (Hz)
Level 1	16 ns	3 μs	10^8	10^3-10^4	10^4-10^5
Level 2	10-100 μs	50 μs	10^4-10^5	10-10^2	~10^3
Level 3	1 ms	0.5 s	~10^3	10-10^2	10-10^2

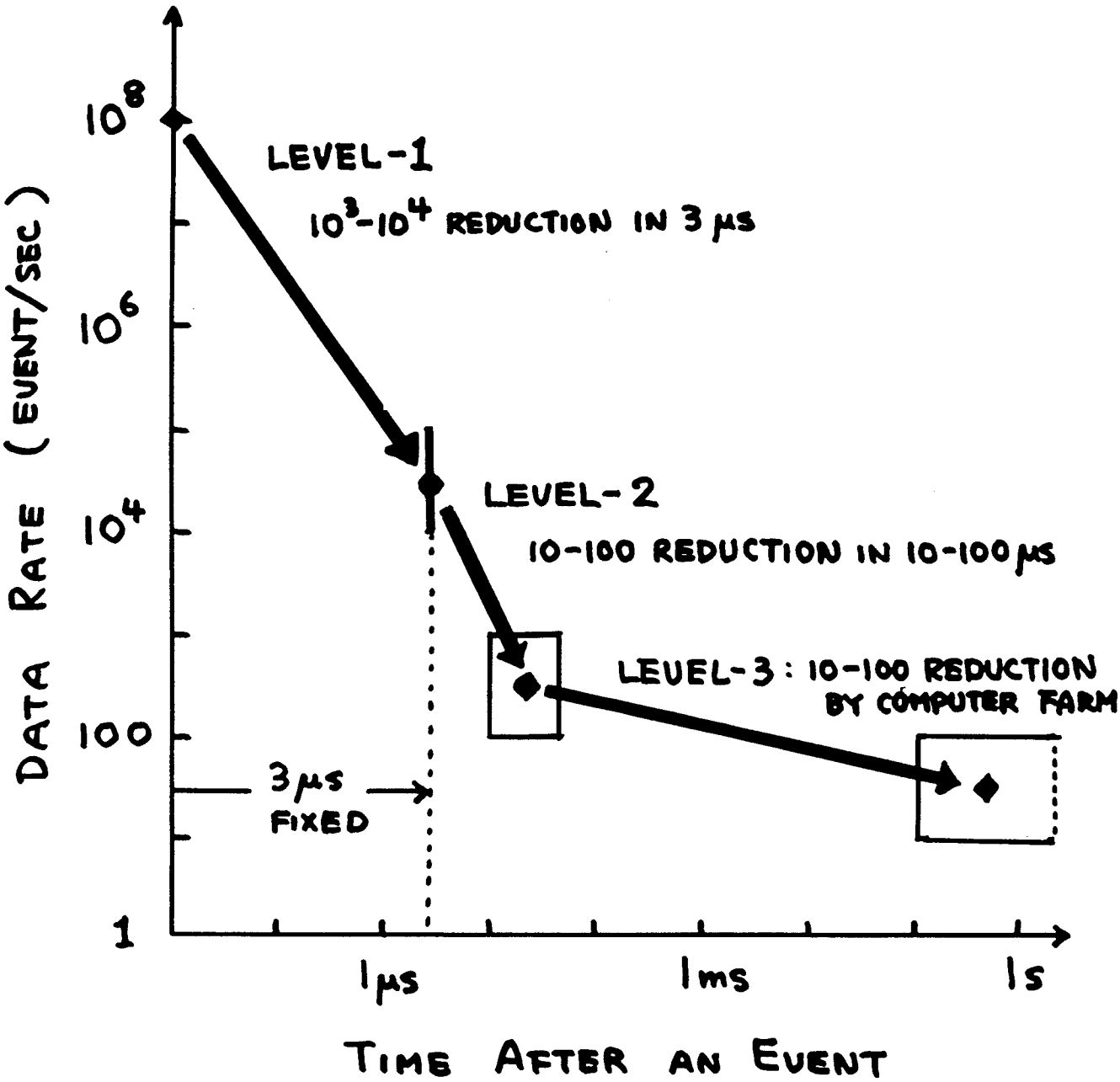
Level 1 ELECTRON TRIGGER

AT 10^{33} $cm^{-2}s^{-1}$

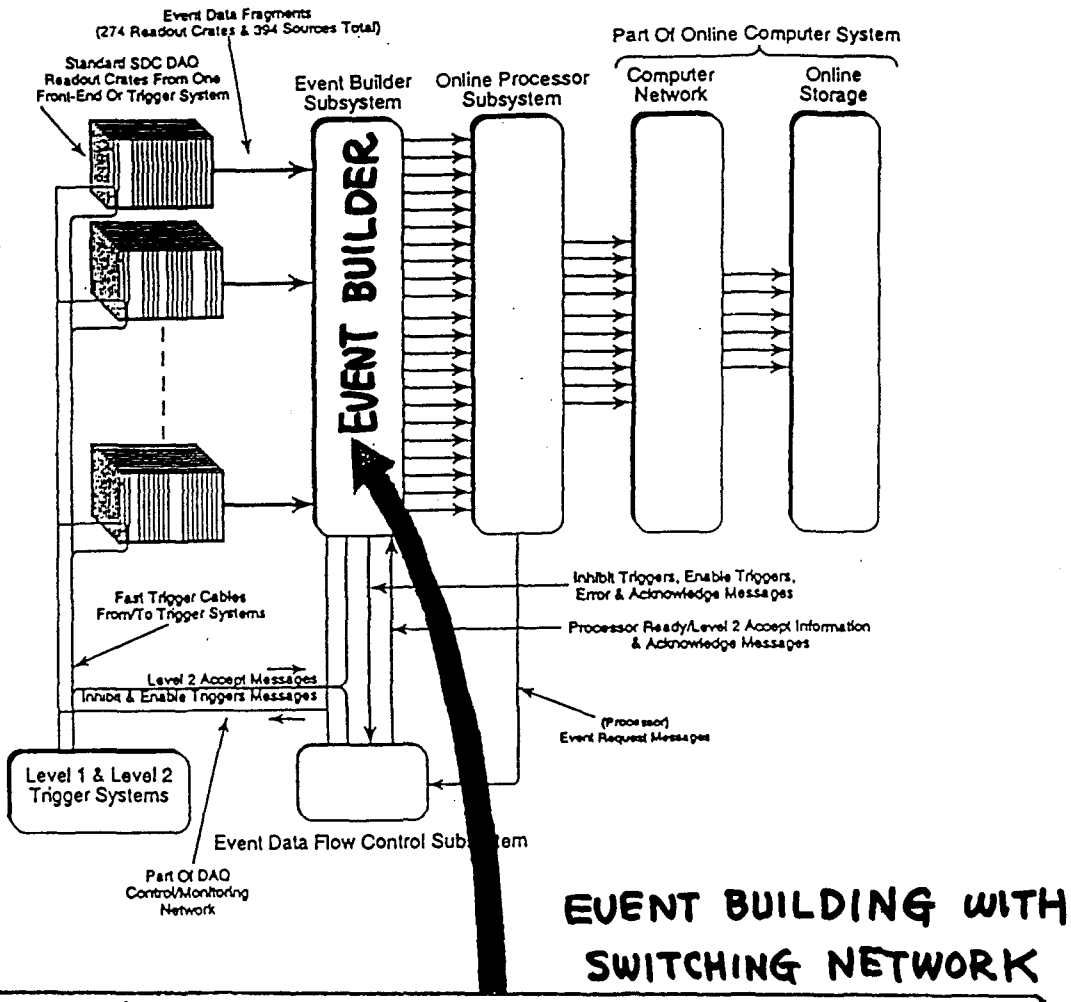


TO REALIZE $E_t^{th} < 20$ GeV FOR ELECTRONS, ALL THREE TRIGGERING REQUIREMENTS HAD/EM, ISOLATION AND TRACKING ARE NEEDED.

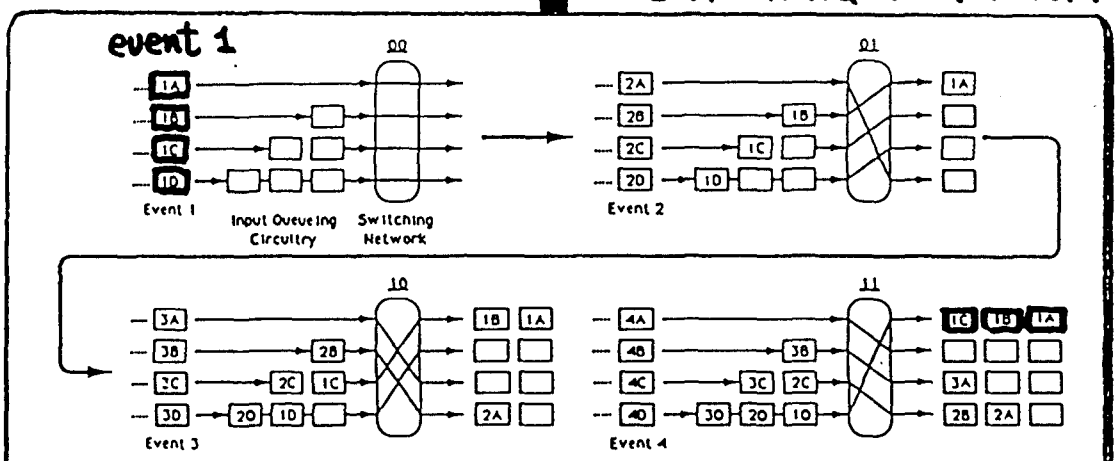
ESTIMATE OF TRIGGER RATES



DATA ACQUISITION BLOCK DIAGRAM



EVENT BUILDING WITH SWITCHING NETWORK



Barrel shift switching network operation.

Superconducting Magnet

- provide an axial magnetic field of 2 Tesla
- thin in X_0 and λ_I for calorimeter performance
- long term stability

Table 5-1
General requirements of SDC solenoid.

Magnet envelope		
Cryostat	Inner radius	1.70 m
	Outer radius	2.05 m
	Total half length	4.389 m
Nominal magnetic field		2 T
Transparency	(η=0)	1.2 X_0
		0.25 λ_I
Cool down time		< 14 days
Quench recovery time		< 4 hr

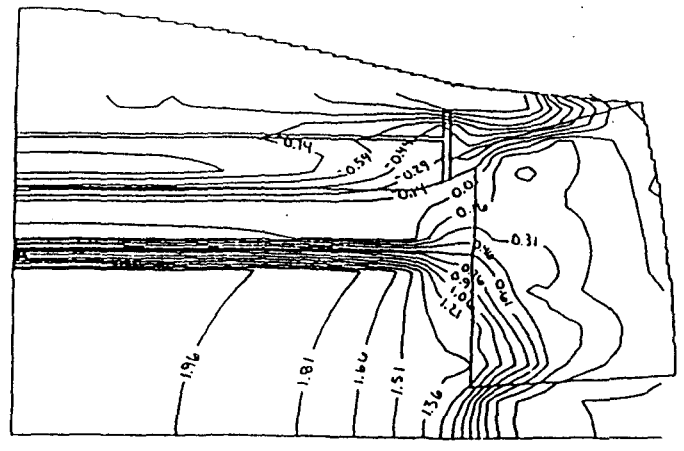


FIG. 5-2. Field contour plot for an axial coil-iron separation of 470 mm. The field is in teslas.

Superconducting Magnet

- Technical challenges : 1. material transparency ~ $1.2X_0$
  2. compressive force (1700 tonf)

  in addition to predictable and stable operation
  safety against quenches

- Solutions :

[A] $\frac{E(\text{stored energy})}{M(\text{cold mass})}$ = 7.4 kJoule/kg ($\Delta = 0.4X_0$)

~ 5 in past

→ development of high strength aluminum stabilized superconductor

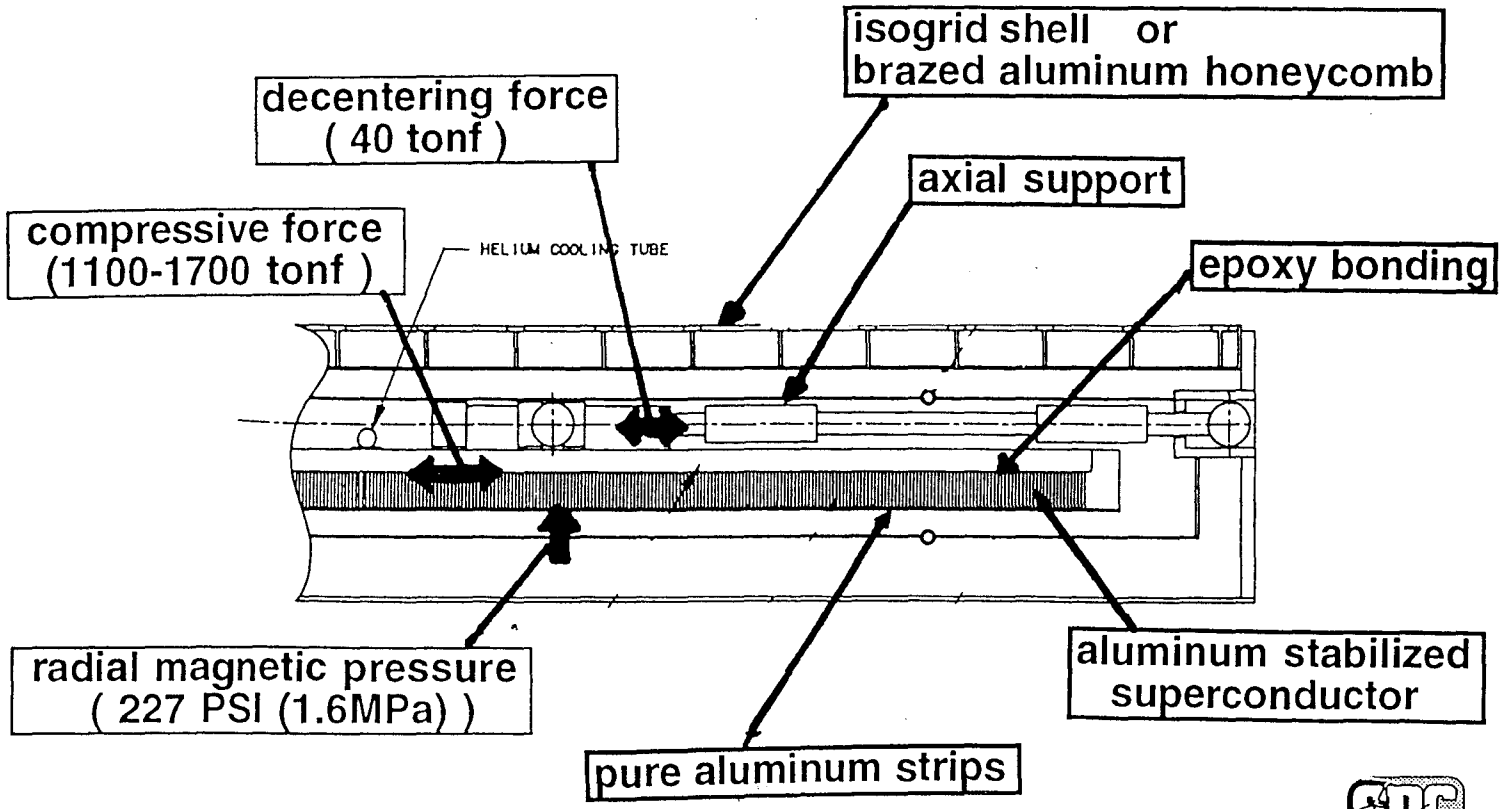
→ increase of quench propagation velocity by pure aluminum strips

[B] lighter material for outer vacuum vessel ($\Delta = 0.2X_0$)

→ isogrid (grid-stiffened) shell or brazed aluminum honeycomb panel

Prototype Superconducting Magnet

- started in 1991 and will be completed in 1993
- one quarter length with a full diameter
- joint work by KEK and FNAL



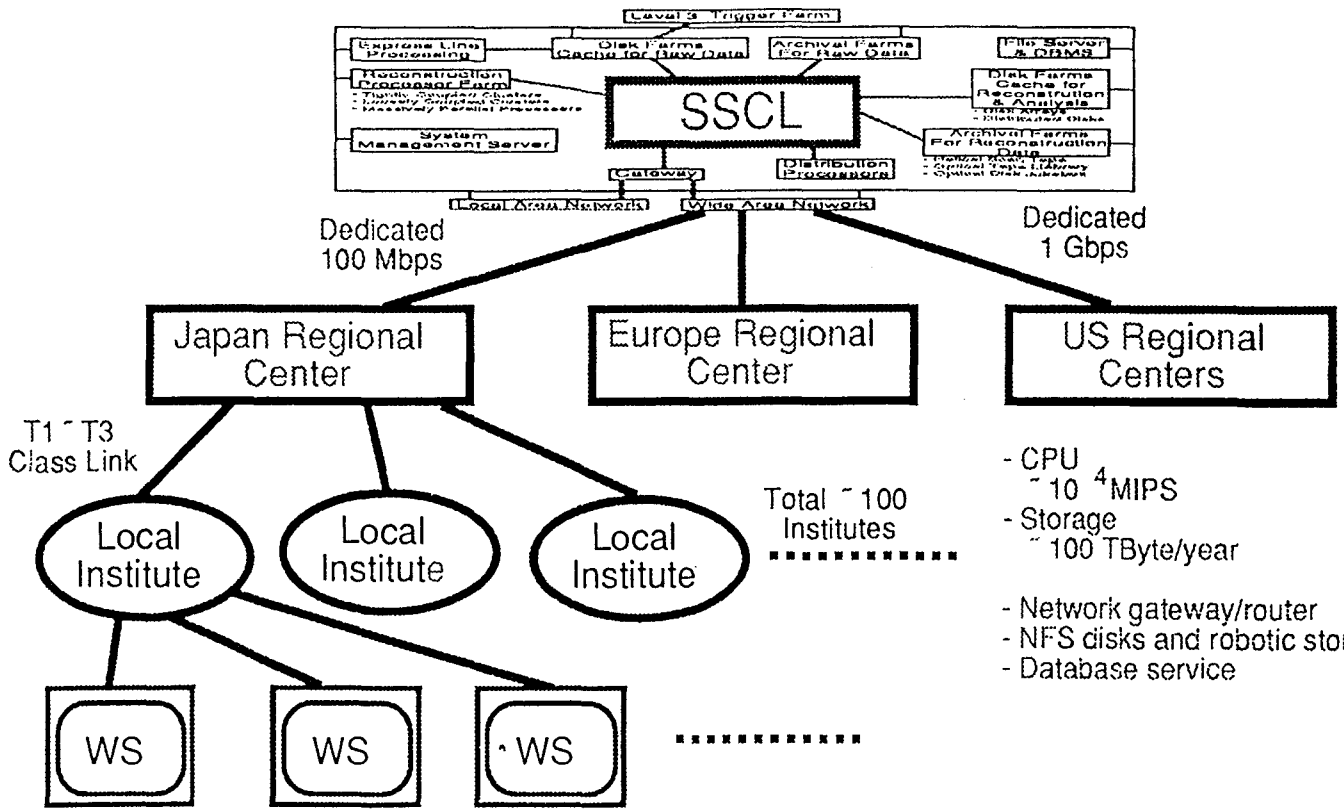
Offline computing

- capabilities for production, analysis and simulation
- processing raw data, storage and data access
- network with high data transfer capability
- regional computing centers

Table 10-2
Design parameters for SDC offline computing.

	Requirement
Data recording rate	100 Hz
Raw data event size (maximum)	1 Mbyte
Live time per year	10^7 sec
Raw plus processed event size	2 Mbyte
Expected DST event size	10^5 bytes
Total number of events per year	10^9
Total raw data size per year	10^{15} bytes
Total processed data size per year	10^{15} bytes

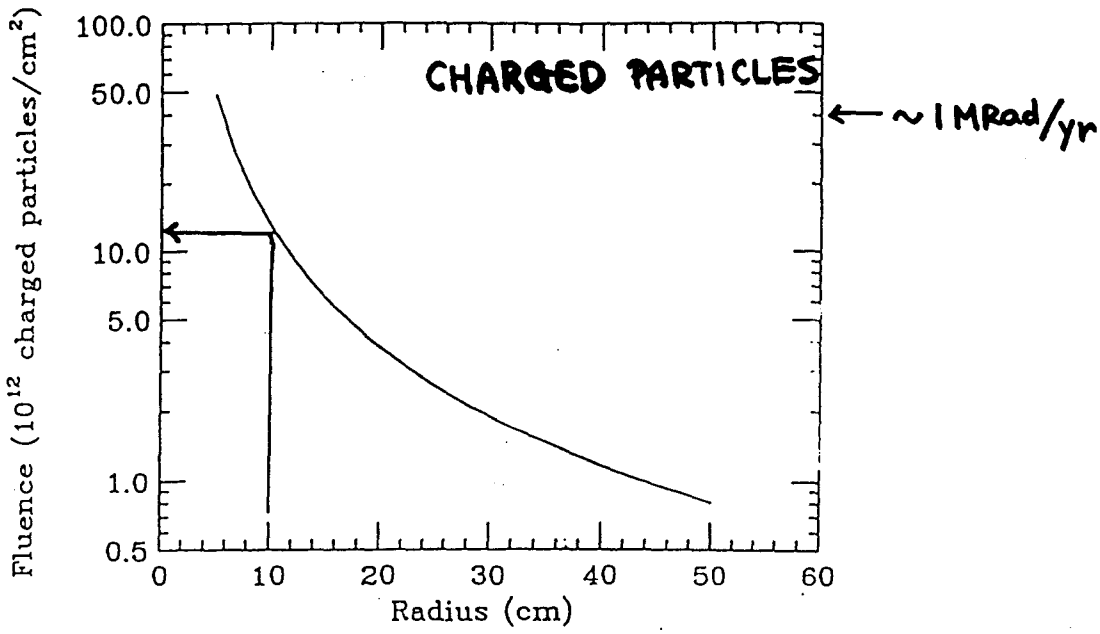
SDC Regional Computer Centers

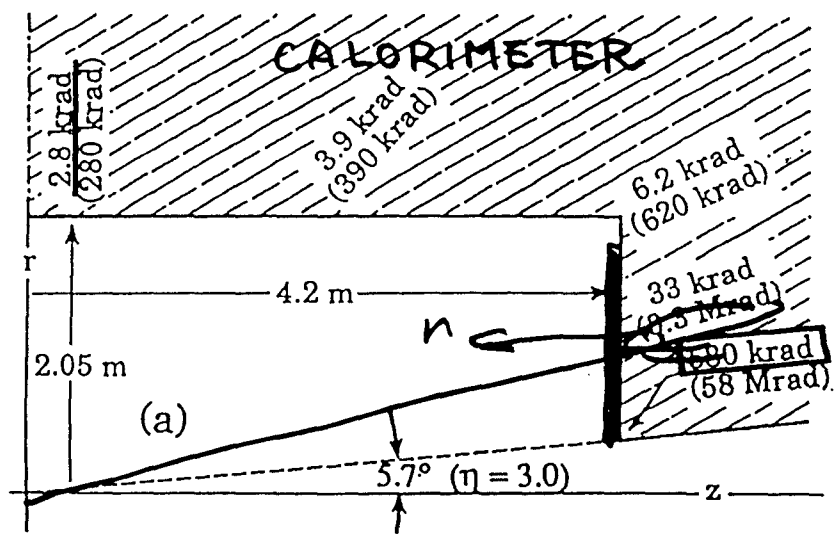


- CPU
  ~ 10^4 MIPS
- Storage
  ~ 100 TByte/year

- Network gateway/router
- NFS disks and robotic storage
- Database service

Radiation Levels @ $L = 10^{33}$ cm^{-2}s^{-1}





Neutron fluences in the tracking volume

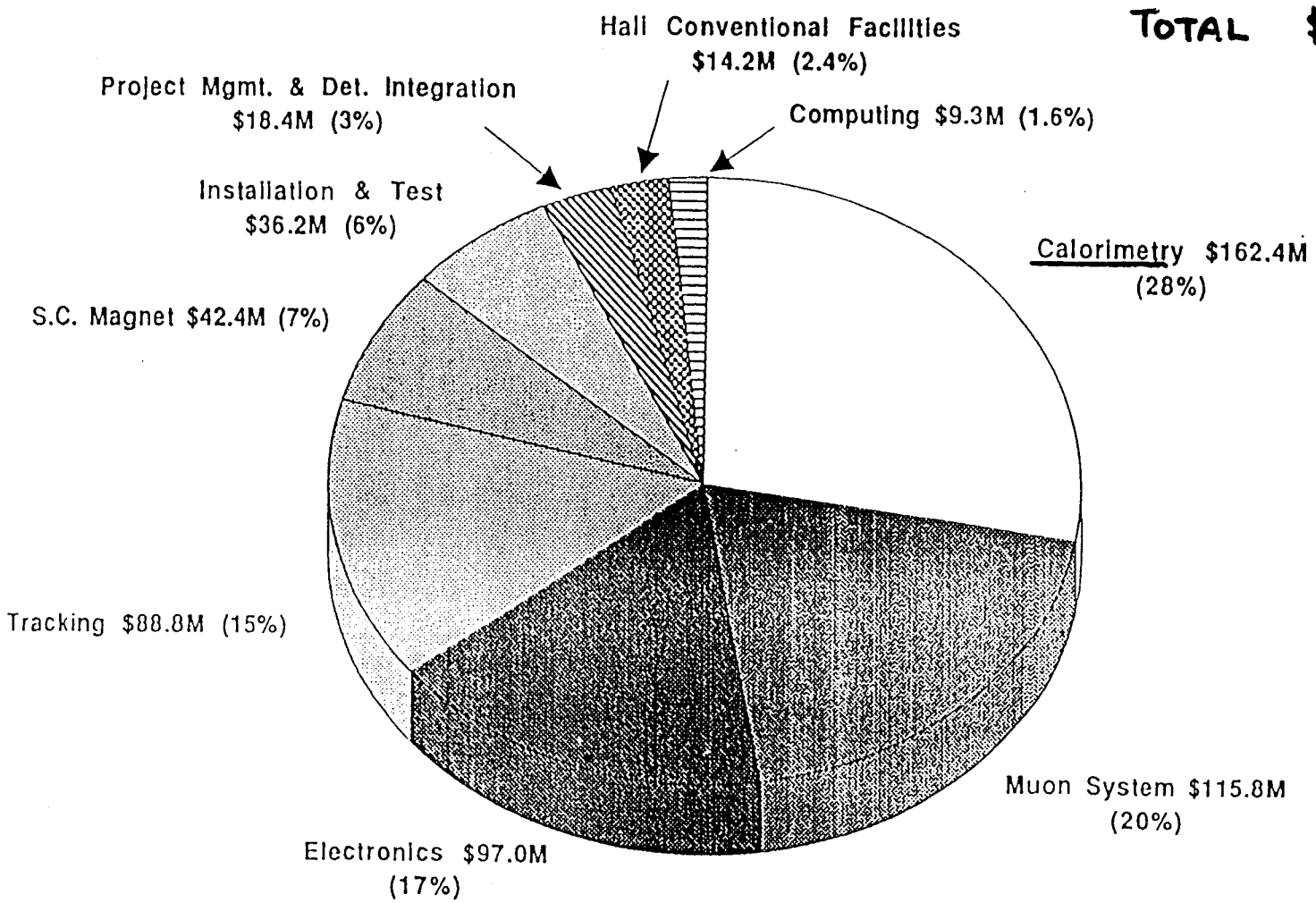
6×10^{11} n /cm^2/year (no liner)
<u>3×10^{11} n /cm^2/year</u> (endcaps lined)

Radiation Effects on Detector Components

Silicon	• dose rate = 10^{12}~10^{13} particles/year at L_0 • polyethylene liners reduces albedo neutrons much • detector tests showed lifetime of ~10-100 years
Straw	• no anode damage to 2C/cm (>100 years) • cathode tested to 0.3C/cm (15-60 years)
Scint fiber	• base material is tested to be radiation tolerant • radiation test of fibers and waveguides is underway
Gas microstrip	• effect on resistive substrate to be investigated
Tile/fiber calorimetry & Shower max	• dose rate = 2.7-570 krad/year at L_0 • extensive tests showed commercially available scintillators are adequate for barrel calorimeter • removable EM endcap with two longit. samplings • removable hadronic endplug at $\lvert\eta\rvert>2$
Forward cal.	• dose rate = 0.1-100 MRad/year at L_0
Front-end electronics	• fast bipolar is intrinsically radiation hard • radiation-hard CMOS exists and looks promising

Summary of SDC Detector U.S. Cost Estimate by Subsystem

TOTAL $584M
(1992 $)



Physics Performance of the SDC Detector

Physics Topics:

1. Electroweak Symmetry Breaking Studies

    a. Standard Model Higgs Searches
    b. Minimal SUSY Higgs Searches
    c. Strongly-coupled Higgs Searches

2. Top Quark Physics

    a. Standard Model Top
    b. Top $\rightarrow H^+ + b$

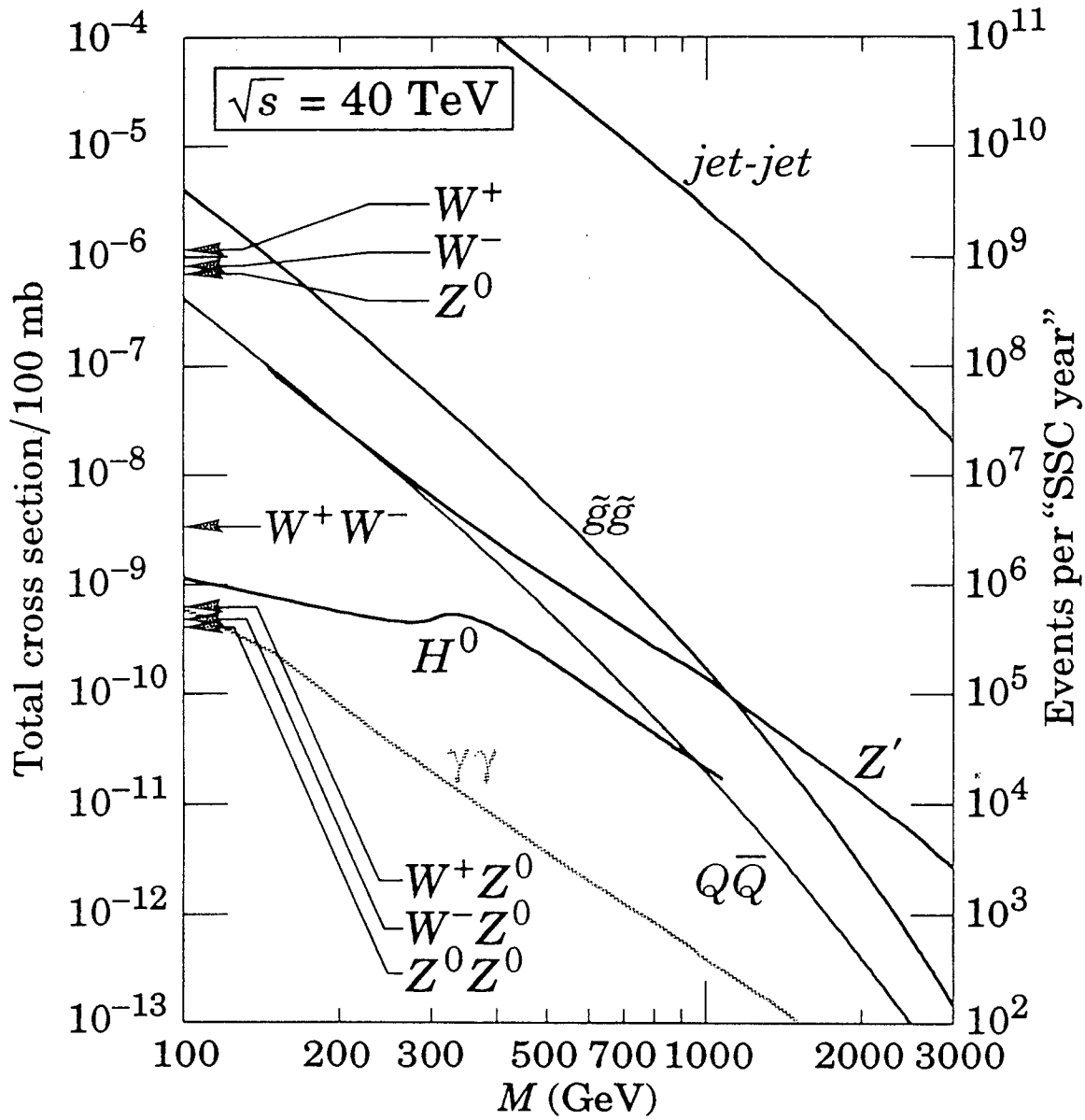
3. Supersymmetry Searches

    a. $\tilde{g}\tilde{g} \rightarrow$ jets + $\not{E}_t$
    b. $\tilde{g}\tilde{g} \rightarrow \ell^{\pm}\ell^{\pm}$ + jets
    c. $\tilde{\chi}\tilde{\chi} \rightarrow \geq 3$ leptons

4. Heavy Gauge Bosons

5. Compositeness Searches

6. QCD Tests


$\sqrt{s}$ = 40 TeV
jet-jet
W^+
W^-
Z^0
W^+W^-
$\tilde{g}\tilde{g}$
H^0
$\gamma\gamma$
Z'
$Q\overline{Q}$
W^+Z^0
W^-Z^0
Z^0Z^0
Total cross section/100 mb
Events per "SSC year"
M (GeV)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
100
200
300
500
700
1000
2000
3000

Physics Simulations

Goals :
- isolate detector requirements
- understand physics capabilities

Detector models :

- η dependent parametrized resolutions for tracking , calorimetry and μ system

- parametrizations for EM and HAD shower shapes

- CALOR89 parametrization for π/e

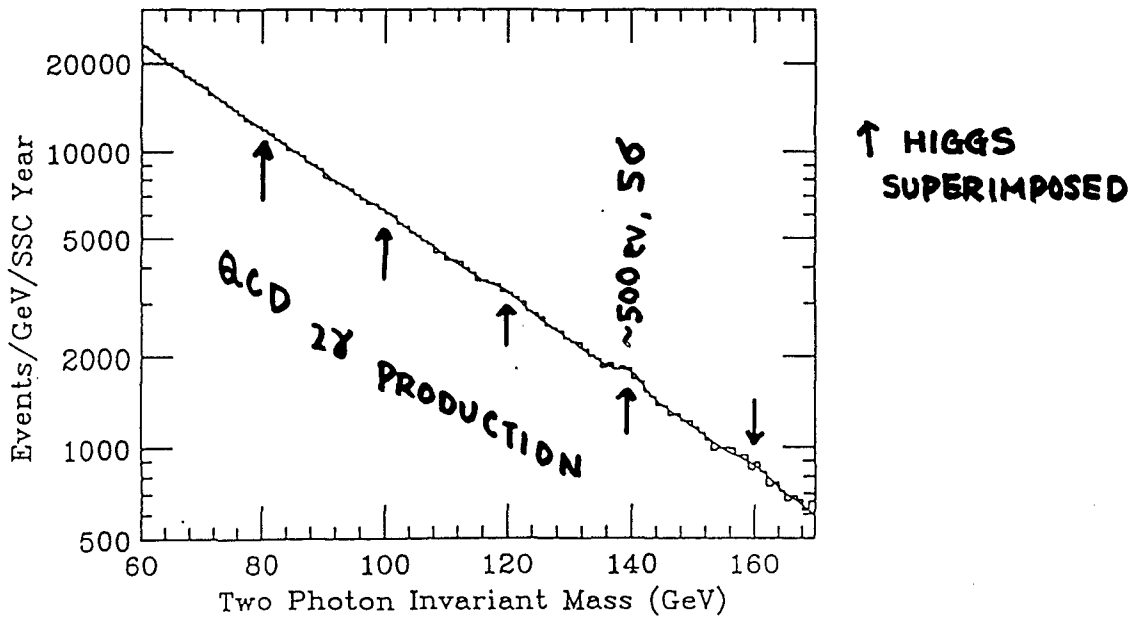
- isolated lepton and γ efficiency = 85%

- CDF estimate for background rejections against backgrounds for γ, e and μ ID
  P(jet faking γ) ~ 5×10^{-4}
- jet reconstruction algorithms based on transverse energy deposition in calorimeter cells

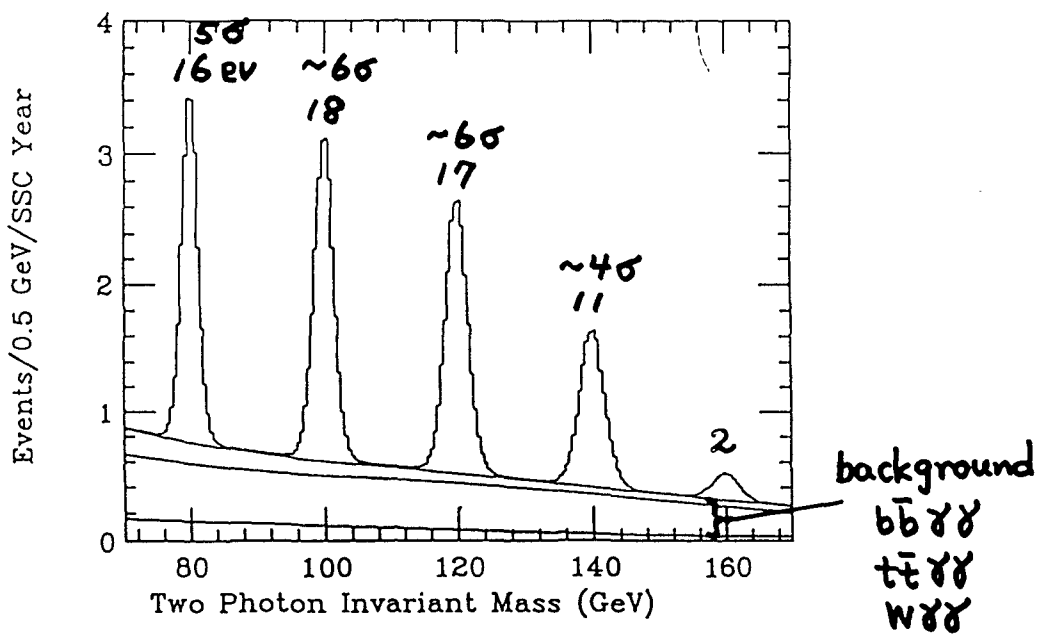
SM Higgs Search

Low Mass Higgs (80 < M < 130 GeV)

(1) Direct production with $H \to \gamma\gamma$:
but signals above backgrounds are marginal.

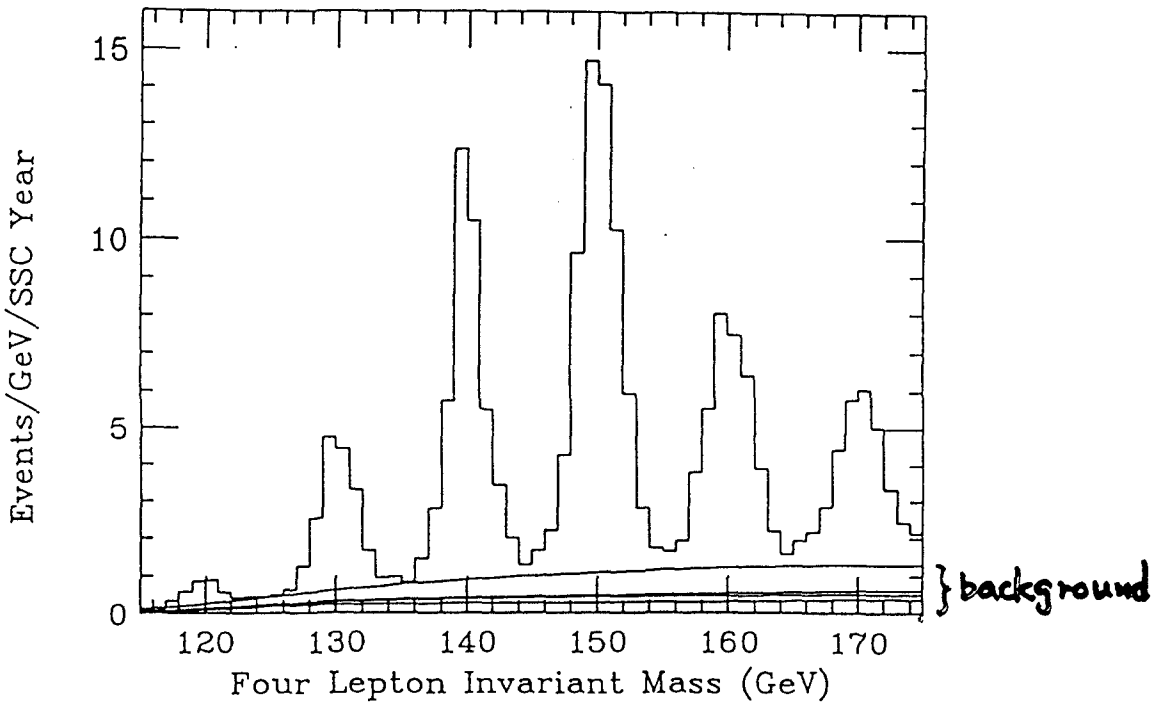


(2) Associated production: WH, ZH, $t\bar{t}H \to \ell\gamma\gamma X$



Intermediate Mass Higgs (130 < M < 180 GeV)

$H \rightarrow Z Z^* \rightarrow 4 \ell$ (4e, 2μ2e, 4μ)



- LEPTON ISOLATION IS IMPORTANT TO REDUCE $t\bar{t}$ DECAYS.

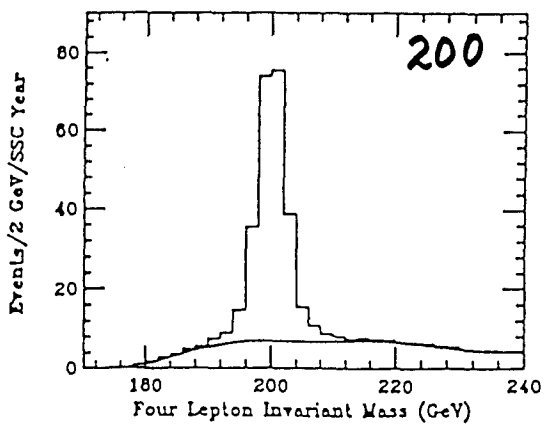
- BACKGROUNDS

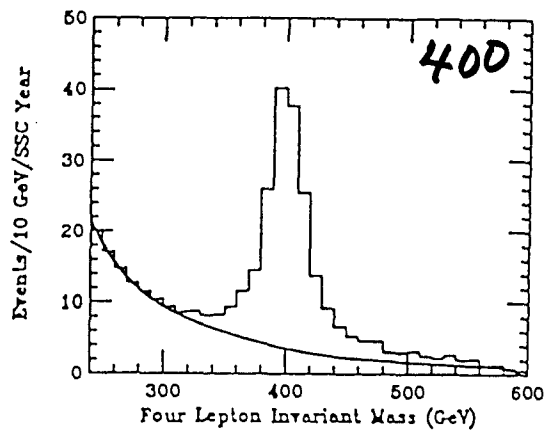
  CONTINUUM ZZ PRODUCTION
  $Z + b\bar{b}$, $Z + t\bar{t}$
  $t\bar{t} \rightarrow 4$ LEPTONS

Heavy Higgs (180 < M < 800 GeV)

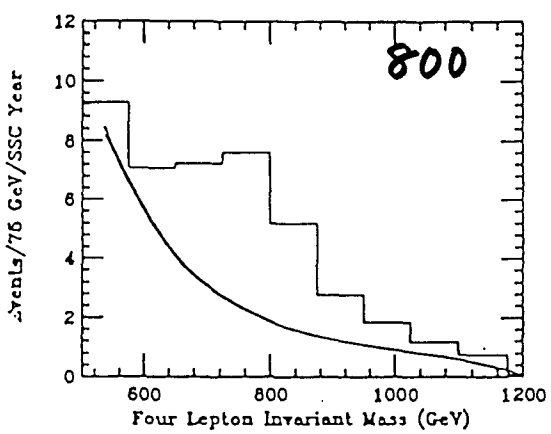
$H \to Z Z \to 4 \ell$

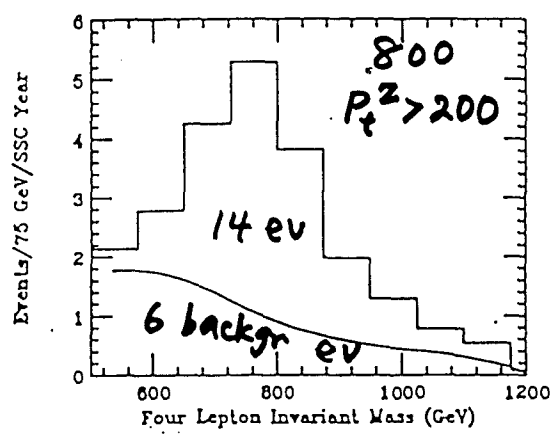
Expected signals for $M_{\text{Higgs}} = 200$, 400 GeV:





Expected signals for $M_{\text{Higgs}} = 800$ GeV:

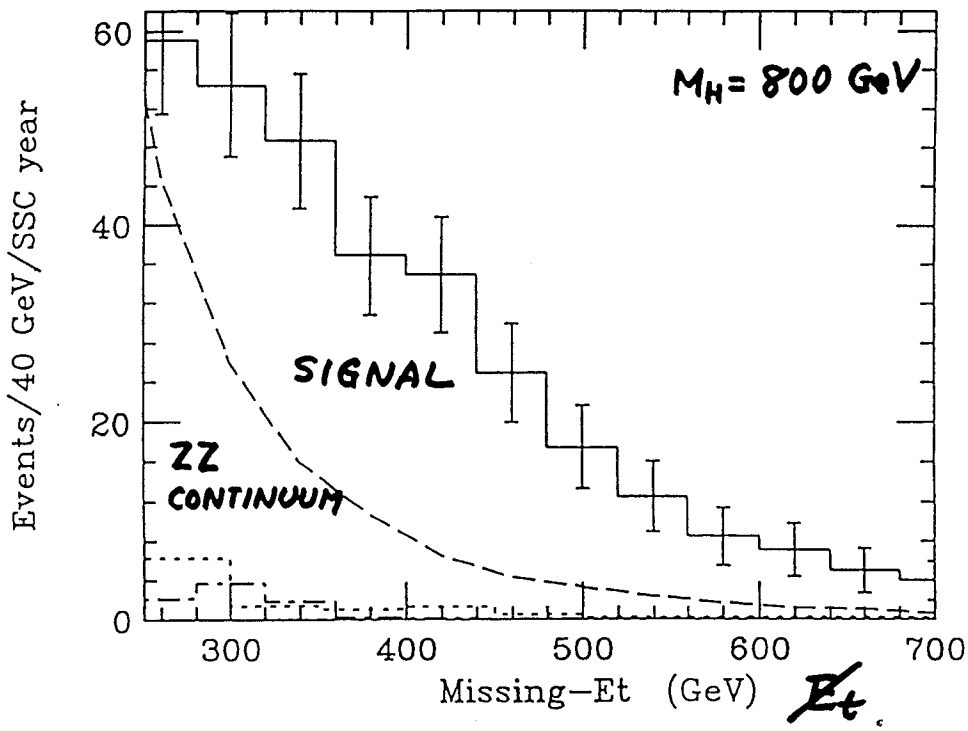




A $p_t(Z) > 200$ GeV requirement reduces the background with little loss of signal. Expect about 14 signal above 6 background in one SSC year.

$H \to ZZ \to 2\ell\, \nu\bar{\nu}$

- 6 TIMES OF $H \to 4\ell$
- need coverage to $|\eta| = 5$



$H \to WW/ZZ \to \ell\nu/\ell\ell$+2jets, with quark tagging

- BR ~ 150 x OF 4ℓ DECAY
- LARGE BACKGROUND FROM W+jets, $t\bar{t}$
- HAD1 SEGMENTATION OF 0.1 x 0.1 NEEDED.

↓

W+jets rejection of ~500
$t\bar{t}$ rejection of ~10^4
S/N ~ 1/5

SUSY Extension to the Higgs Sector

- five physics Higgs bosons : h^0, H^0, A^0, H^+, H^-
- two free parameters : M_A , $\tan\beta$
- production cross sections and BR are modified

RADIATIVE CORRECTIONS → $M_{h^0} \lesssim 110$ GeV

Summary (assuming 3–5 years at SSC design luminosity):

M_A

SMALL
- For small M_A, h^0 observable at LEP-II, $t \to H^{\pm}b$ observable at SSC.

↓

MODERATE
- For moderate M_A and small $\tan\beta$, h^0 observable at LEP-II, $H^0 \to ZZ$ and $t \to H^{\pm}b$ observable at SSC.

↓

LARGE
- For moderate M_A and large $\tan\beta$, none of the Higgs bosons may be observable.
- For large M_A, $h^0 \to \gamma\gamma$ observable at SSC.

These statements are valid for $M_{\text{top}} = 150$ GeV. If the t quark is heavier, the discovery regions are enlarged.

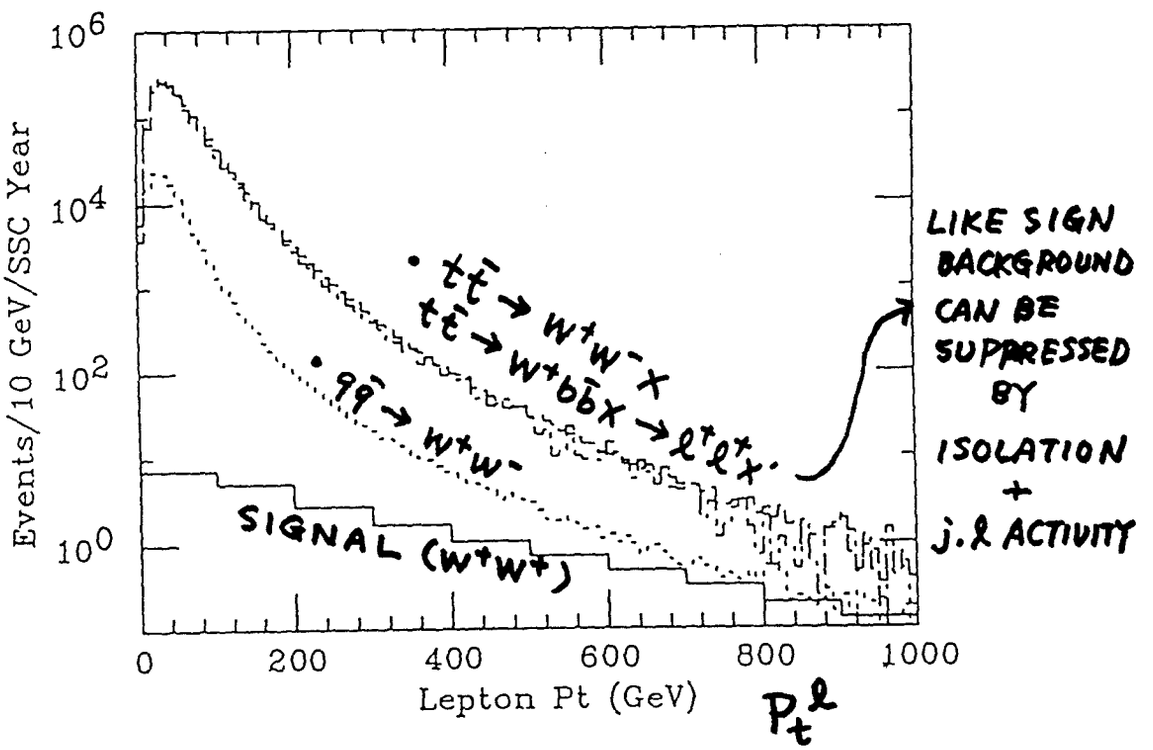
Basic problem is that for large regions of parameter space, Higgs' decay to heavy quarks and are almost unobservable. Searches for $\tau\tau$ decays are promising and may enlarge the regions where minimal SUSY Higgs bosons are observable.

(2) Non-resonant channels : ENHANCEMENTS IN $W_L W_L$, $Z_L Z_L$ SCATTERING AMPL.

detect $W^+W^+ \to \ell^+\ell^+ X$

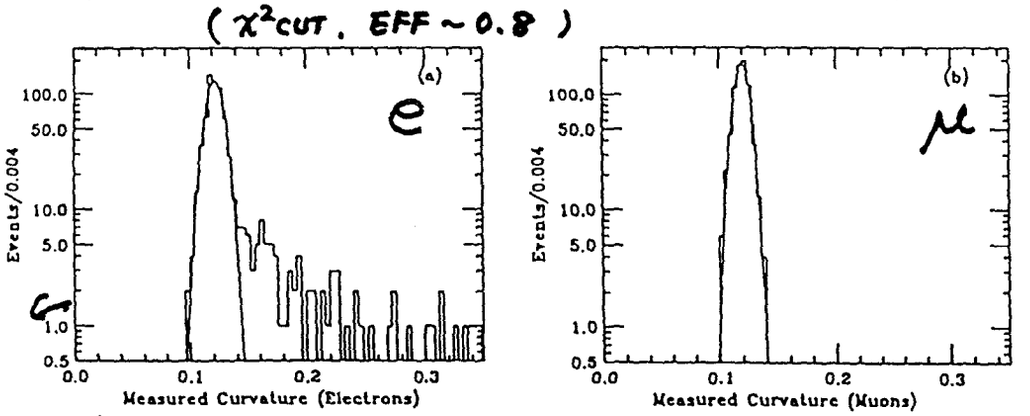
<u>charge measurement is critical</u>

- MISS MEASUREMENT $< 10^{-5}$ ($P_t < 100$)
  $< 10^{-3}$ ($P_t = 500$)



RECONSTRUCTION @ $P_t = 500$ GeV @ 3×10^{33} (17K1.6)

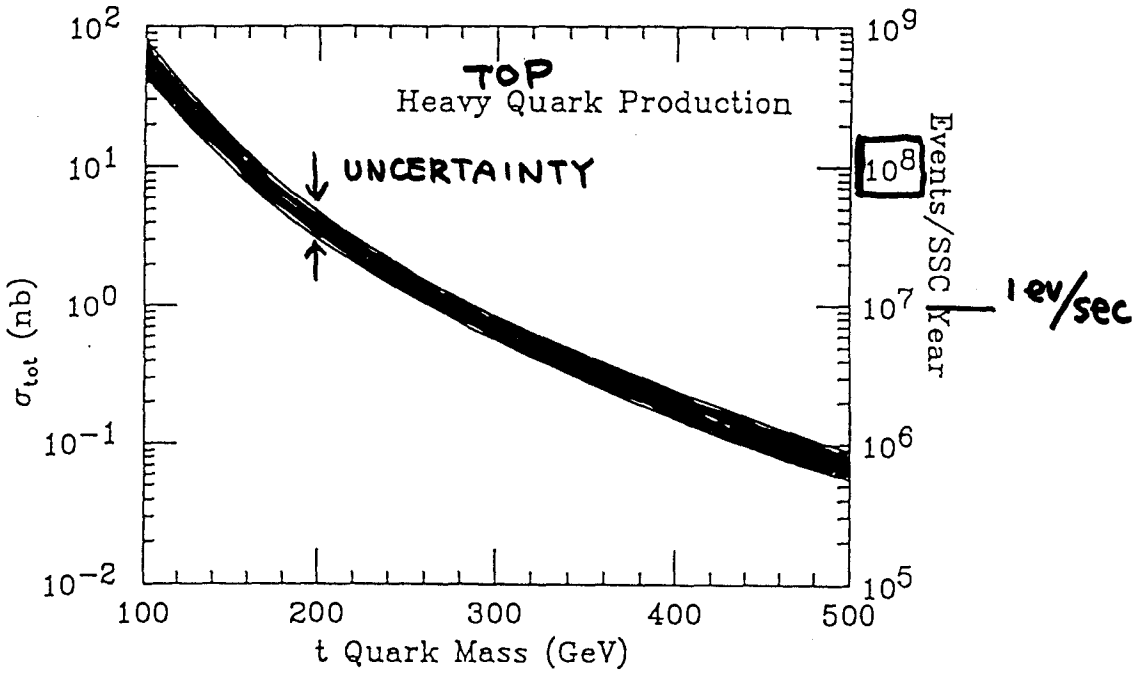
(χ^2 CUT, EFF ~ 0.8)



→ WRONG SIGN PROB $< 10^{-3}$

Top Quark Physics

- Missing piece of the Standard Model
- Huge production cross section:



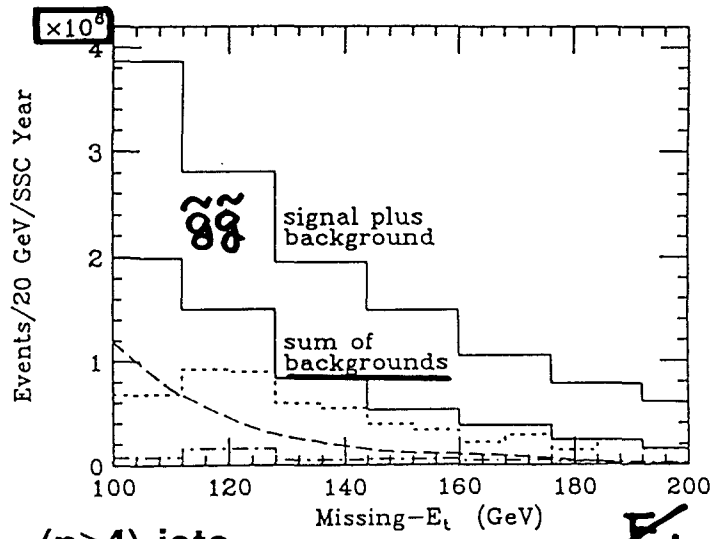
- Possible window onto beyond-the-SM Physics (*e.g.* $t \to H^+ b$)
- Source of Higgs bosons via $pp \to t\bar{t}H$
- Background to rare and exotic phenomena (*e.g.* High energy WW scattering, multilepton final states from WWW or SUSY)

SUSY Particles

a. $\tilde{g}\tilde{g} \rightarrow$ 3 jets + $\not{E}_t$ (case for $m_{\tilde{g}}$= 300GeV)

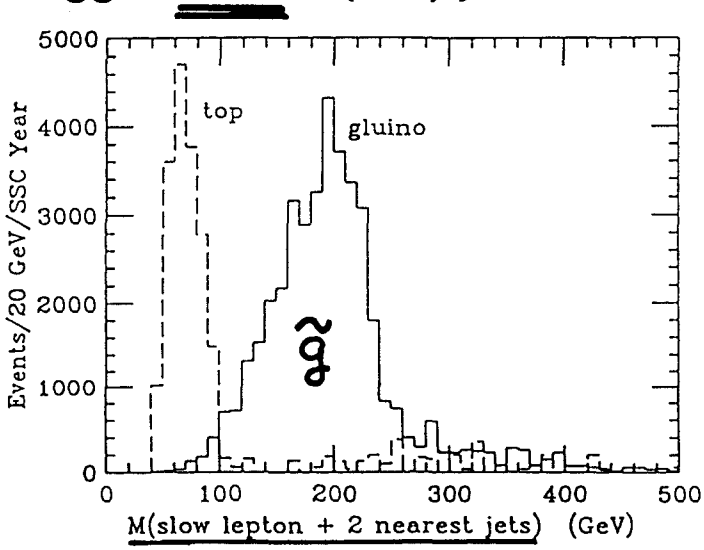
ϕ cut : $\not{E}_t$ points at >20° from a large-p_t jet SUPPRESS MISMEASURE.

~ 10^6 events/yr with $\not{E}_t$ >100GeV



$\not{E}_t$

b. $\tilde{g}\tilde{g} \rightarrow \ell^{\pm}\ell^{\pm}$ + (n≥4) jets



$\tilde{g} \rightarrow \tilde{\chi}^{\pm} q\bar{q}'$ (BR~0.6)

$\hookrightarrow \ell^{\pm}\nu\tilde{\chi}^{0}$ (BR~0.2)

total BR ~ 1%

2×10^6 events/yr ($m_{\tilde{g}} \approx$ 180GeV)

25 events/yr ($m_{\tilde{g}}$ = 2TeV)

c. $\tilde{\chi}\tilde{\chi} \rightarrow \geq$ 3 leptons

SUSY Conclusions

- Gluinos can be discovered and their mass measured in the range $180 < m_{\tilde{g}} < \mathcal{O}(TeV)$ using two independent decay channels

- Weak gauge fermions can be detected in their multi-leptonic decay channel in a large portion of parameter space and for $m_t \geq 150$ GeV

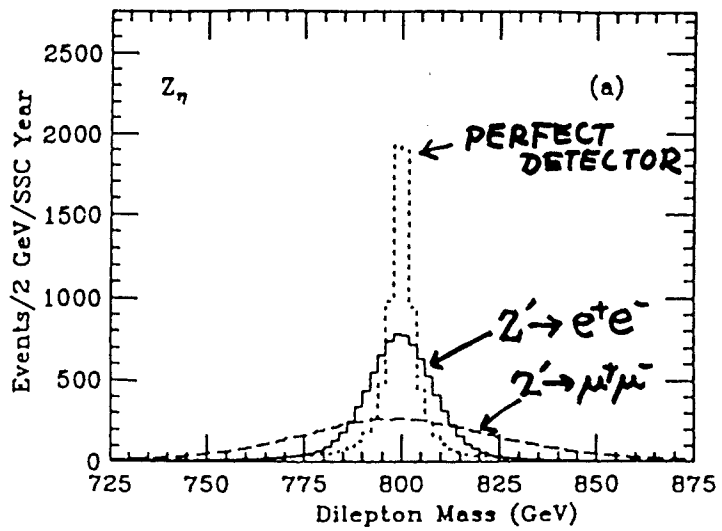
- Supersymmetry will manifest itself in several different phenomena (Higgs properties, *top* decays, $\not{E}_t$, multi-leptons). The coincidence and consistency of the various signals will help selecting the particular model. SDC ability to cover all of these channels will be the key to disentangling the richness of these phenomena into a coherent picture

- More work will be needed to extract additional information from the study of various sources of SUSY signals

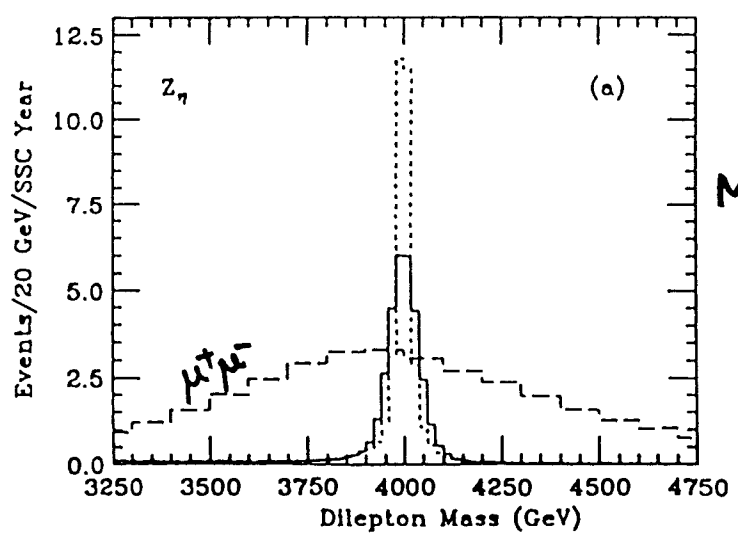
Heavy Gauge Bosons

W' searches : discovery up to 5 TeV

$Z' \to \ell^+\ell^-$: measurement of mass, cross section, F/B asymmetry



$M_{Z'} = 800$ GeV



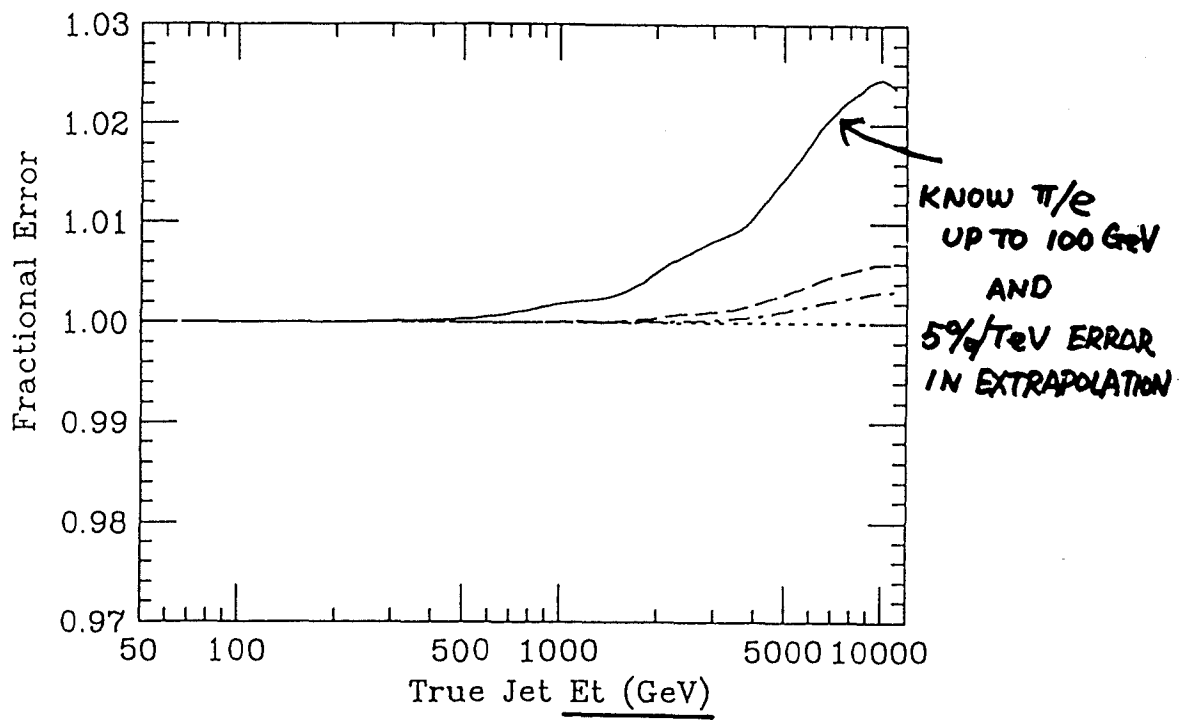
$M_{Z'} = 4$ TeV

Compositeness Searches

- Inclusive jet cross section does not fall as steeply with E_t as QCD predicts

- Statistical limit $\Lambda \geq 30$ TeV after 1 SSC year
  If jet response is perfect below 2 TeV, and wrong by 2% at 5 TeV, the limit is ≥ 25 TeV

- Effect of jet non-linearity due to non-linear single particle response



If calorimeter is properly calibrated, non-linearities do not significantly degrade the capability for compositeness searches.

Physics Performance

Physics Process	Mass Region (GeV)	Physics Signature
Associated Higgs Production		
	80 – 150	$W+H$, $t\bar{t}+H \to \ell\gamma\gamma$
Direct Higgs Production		
	130 – 180	$H \to ZZ^* \to 4\ell$
	180 – 800	$H \to ZZ \to 4\ell$
	500 – 800	$H \to ZZ \to 2\ell 2\nu$
High Mass Boson Pairs		
Requires integrated luminosity of		$Z\gamma \to \ell^+\ell^-\gamma$
at least 50 fb^{-1} for complete studies	1–2 TeV	$W^+Z \to \ell^+\ell^+\ell^-\nu$
		$W^+W^+ \to \ell^+\ell^+$
Discovery of t Quark		
	$\lesssim 1$ TeV	$t\bar{t} \to W^+W^- + X \to e^\pm\mu^\mp + X$
Mass Measurement of t Quark		
Sequential Dilepton Mode	$\lesssim 500$	$t\bar{t}$, one $t \to Wb$; $W \to e\nu$; $b \to \mu + X$
		the other $t \to 3$ Jets
Lepton + Jets + b-tag Mode	$\lesssim 500$	$t\bar{t}$, one $t \to W + X$; $W \to \ell\nu$
		the other $t \to Wb \to b + 2$ Jets
Non-standard t Decays		
Violation of τ Universality	$M_H \lesssim M_{\text{top}} - 15$	$t \to H^\pm b$; $H^\pm \to \tau^\pm\nu$; $\tau^\pm \to \pi^\pm + X$
Peak in 2-Jet Mass Distribution	$M_H \lesssim M_{\text{top}} - 25$	$t \to H^\pm b$; $H^\pm \to c\bar{s}$
Gluino and Squark Searches		
Missing-E_t + Jets	300 – 1000	$\tilde{g}\tilde{g} \to E_t^{\text{miss}}$ + 3–6 Jets
Like-Sign Dileptons	200 – 2000	$\tilde{g}\tilde{g} \to \ell^\pm\ell^\pm$ + 4 Jets
New Z Searches		
Discovery	$\lesssim 4$ TeV	$Z' \to \ell^+\ell^-$
Width and Asymmetry	$\lesssim 2$ TeV	$Z' \to \ell^+\ell^-$
Compositeness		
	$\Lambda \gtrsim 25$ TeV	Inclusive Single Jet Spectrum

Summary

- SDC is a world wide collaboration with >900 collaborators.
- After 2 years of intense efforts on design and R&D by the SDC, a technical design is proposed with most of relevant parameters fixed and with most of detector technologies selected.
- By requiring excellent capabilities in tracking, calorimetry, muon and electronics system, we believe that the proposed detector embodies maximum redundancy for establishing rare new phenomena in an ocean of backgrounds.
- Given adequate support in participating countries, the SDC is prepared to meet the schedule of collider turn-on for physics late 1999.