Linear Collider Detector R&D Issues

Jim Brau
SLUO Annual Meeting
July 15, 1998

Our goal is to be prepared to submit a detailed technical proposal for an experiment in a few years (when the accelerator proposal is ready.)

- What do we need to develop or demonstrate?
  subsystem by subsystem
  some of the R&D will be more advanced than others.
- How do some detector choices constrain other aspects of the detector choices?
- How do we integrate subsystem issues into full detector constraints?

Desirable Detector Features
(Conclusions from Prior Studies)

Principal Measurement Goals:

- Missing Energy
- Jet-jet reconstruction
- Lepton ID
- b, c, τ vertices

Linear Collider Detector will benefit from good:

- Hermeticity
- Charged track momentum resolution
- Charged track impact parameter resolution
- Electromagnetic & hadronic calorimeter energy resolution
- Granularity (calorimeter segmentation, 2-track separation)
- Electron / muon identification

Special needs of the Linear Collider Detector:

- Very high B field to curl up beam-induced pairs
- Accurate differential luminosity measurement
- Subdetectors that correctly handle 90 bunches / train at 2.8 ns separation

Special constraint:

- Final focus quads (2 meters from I.P.) that must be anchored to bedrock

Reminder (again) of the NLC Beam Parameters

E_{cm} = 0.5 Tev ($L \approx 5\times10^{33}$)
E_{cm} = 1 - 1.5 Tev ($L \geq 10^{34}$)

90 bunches per train (bunch spacing 2.8 nsec)
120 - 180 trains/second

$P(e^-) \geq 80\%$ ($\Rightarrow$ 90%)

Backgrounds:

- muons - < 1 μ / train
- synchrotron rad. - collimation controlled
- e^+e^- pairs - potential problem -> large B field
- mini-jets ($\gamma\gamma\rightarrow$hadrons) few jets per train @ 1 TeV
  - $\Rightarrow$ timing to 1 nsec useful

Beam spot size:

- tiny ($\sigma_X \sim 0.3\ \mu m$, $\sigma_Y \sim 0.006\ \mu m$)
- know to: $\sigma_{XY} \sim 4\ \mu m$, $\sigma_Z \sim 10\ \mu m$

Beamstrahlung:

- $\langle\delta E\rangle \approx$ 3% @ 0.5 TeV
- $\langle\delta E\rangle \approx$ 12% @ 1.0 TeV

Caveats for this presentation:

Best technological choices are coupled:

overall configuration choice

cheaper (read smaller or compact) is better

unless it doesn't do the physics

so A big question is :

Can Compact Detector Perform As Needed?

References:

Zeroeth-order Design Report for the NLC, SLAC Report 474
Physics and Technology of the NLC, SLAC Report 485
Snowmass 96, New Directions for HEP, DPF/DPB of APS
JLC Physics (www-jlc.kek.jp)
DESY 1997-048, Concept. Design Report for a 500 GEV e^+e^- LC.....
2nd Joint ECFA/DESY Study, Orsay (April, 1998), www.desy.de

Outline of Talk

Example of an R&D Program on one subdetector
- CCD Vertex Detector Development:
  - current state-of-the-art
  - desirable improvements
  - plan for R&D to achieve improvements

Some comments on the R&D issues on other subsystems
- tracking
- particle id?
- calorimetry
  - electromagnetic
  - hadronic
- muon detection
- trigger/DAQ
- luminosity measurement
- polarization measurement
- simulation
- backgrounds

Conclusions

Three Detector Configurations Have Been Studied

JLC Detector

- diameter = 16 m
- CCD vertex detector
- Central Drift Chamber
- Lead/plastic Calorimeter -> EM resolution = $15\%/\sqrt{E} \oplus 1\%$

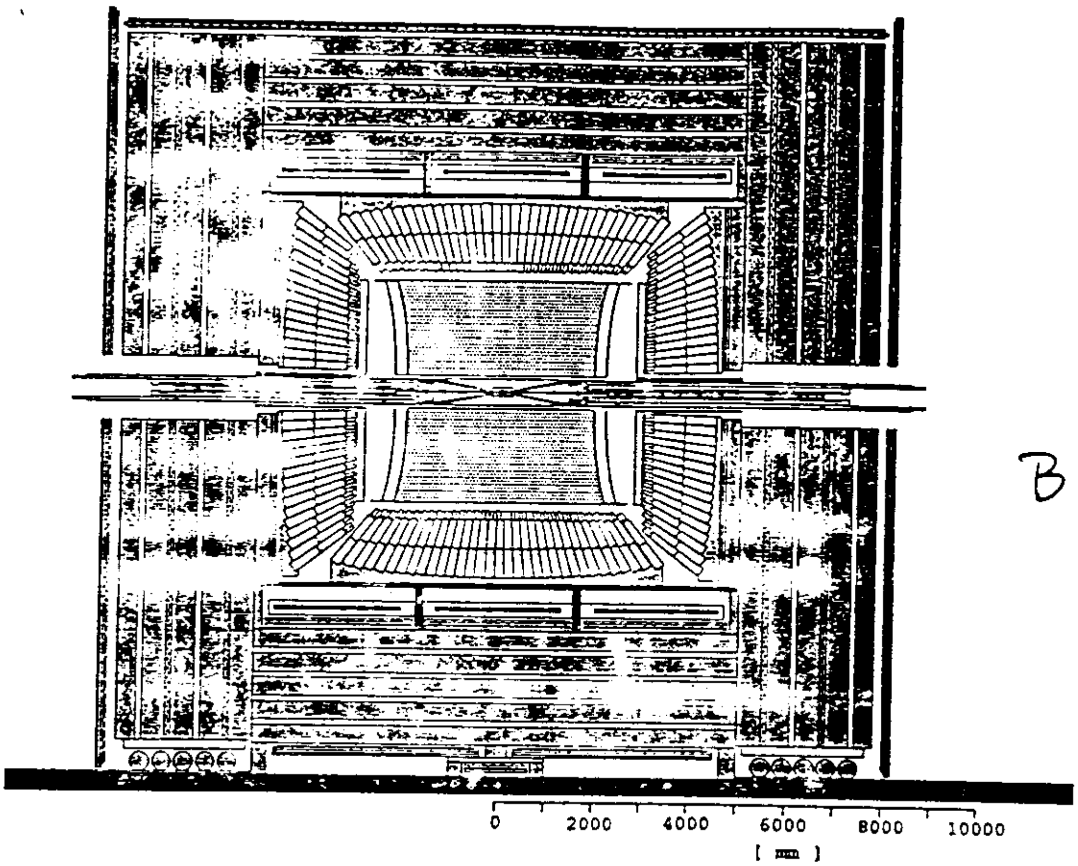
ECFA Detector

- diameter = 13 meters
- B = 3 Tesla (to contain e+e- pairs)
  $\Rightarrow$ coil inner radius = 3 meters
- CCD or APS Vertex Detector
- TPC Tracker
- Shashlik Calorimeter (lead/fiber EM)

Snowmass/NLC Detector

- diameter = 7 meters
- B = 4 Tesla (to contain e+e- pairs)
  $\Rightarrow$ coil inner radius = 0.7 meters
- CCD Vertex Detector
- silicon strip tracking
- Finely segmented EM calorimeter
  (silicon pads/W, inside coil)

NOTE all three of these are conventional e^+e^- detectors:
Solenoidal field with standard layout of subdetectors covering nearly 4π



B = 2 Tesla

Figure 3.1: Schematical drawing of the JLC detector

DETECTOR	TYPE	CONFIGURATION	PERFORMANCE
VTX (Vertex Detector)	Silicon CCD	Pixel Size ; 25 μm Number of Layers ; 2 layers Layer Position ; r=2.5cm & 7.5cm Thickness ; 500 μm / layer $\lvert \cos\theta \rvert < 0.95$	Position Resolution ; $\sigma = 7.2\ \mu$m Impact Parameter Resolution δ [μm]: $\delta^2 = 11.4^2 + (28.8/p)^2 / \sin^3\theta$
CDC (Central Drift Chamber)	Small-cell Jet Chamber	Radius ; r = 0.3 - 2.3 m Length ; l = 4.6 m Number of Sampling = 100 $\lvert \cos\theta \rvert < 0.70$ (full sampling) $\lvert \cos\theta \rvert < 0.95$ (20 samplings)	Position Resolution ; $\sigma_x = 100\ \mu$m (/ axial wire) $\sigma_z = 2$ mm (/ stereo wire) Momentum Resolution ; $\sigma_{Pt} / Pt = 1.1\times10^{-4} Pt \oplus 0.1\%$ $\sigma_{Pt} / Pt = 5\times10^{-5} Pt \oplus 0.1\%$ (with vertex constraint)
CAL	Lead + Plastic Scintillator Sandwitch (Compensated)	EM part ; thickness = 29 Xo cell size = 10cm x 10cm HAD part ; thickness = 5.6 λo cell size = 20cm x 20cm Si Pad ; pad size = 1cm x 1cm $\lvert \cos\theta \rvert < 0.99$	Energy Resolution ; $\sigma_E / \sqrt{E} = 15\% / \sqrt{E} \oplus 1\%$ (e & γ) $\sigma_E / \sqrt{E} = 40\% / \sqrt{E} \oplus 2\%$ (hadron) Si Pad Position Resolution ; $\sigma = 3$ mm Si Pad e/π Rejection = 1/50
MUON	Single Cell Drift Chamber	Number of Superlayers ; 6 $\lvert \cos\theta \rvert < 0.99$	Position Resolution ; $\sigma = 500\ \mu$m Pt > 3.5 GeV (barrel)

* All momentum and energy are expressed in [GeV].

Table 3.1: Parameters and performances of the JLC

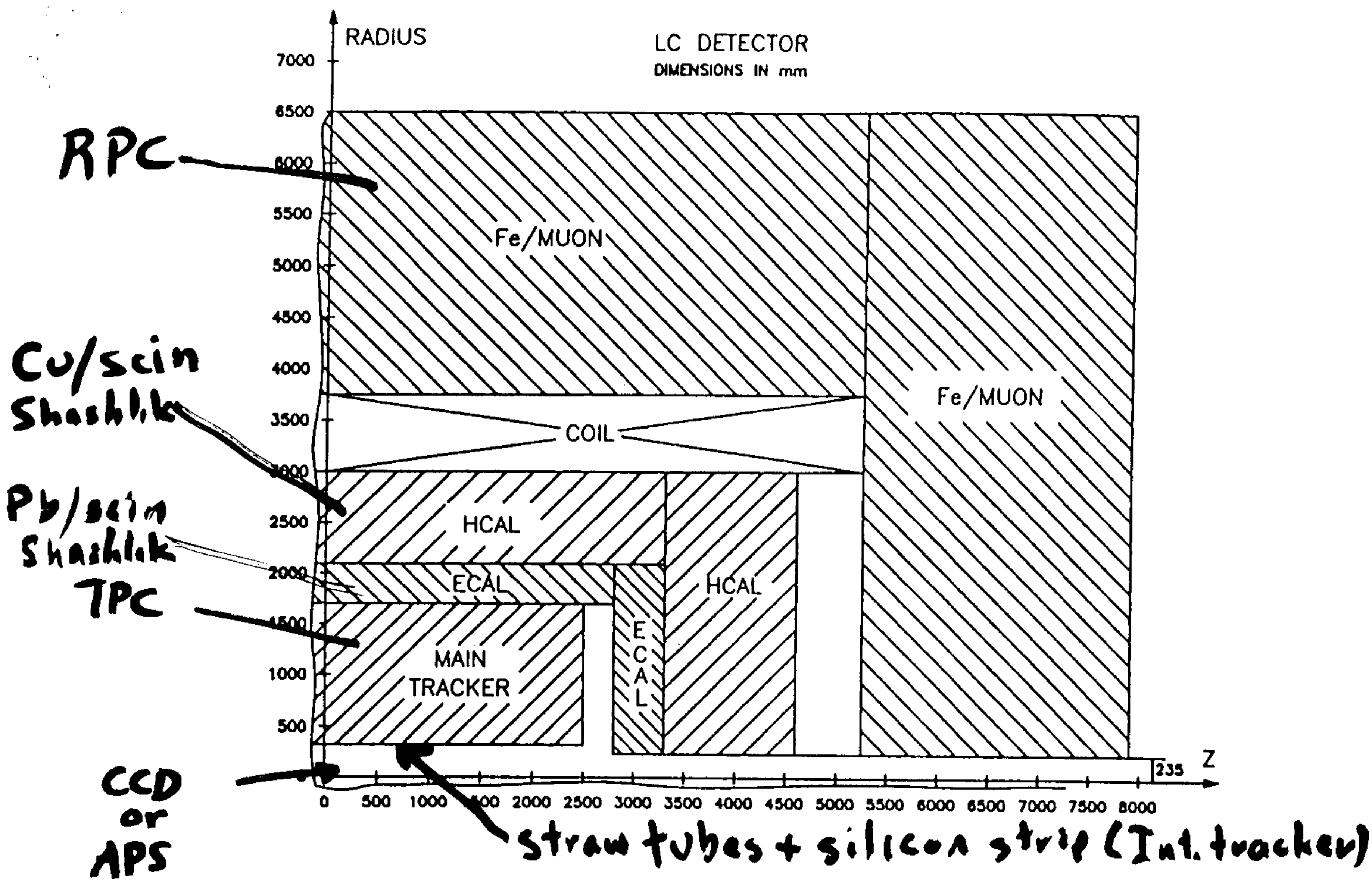


Figure 2.1.1: *Schematical layout of one quadrant of the LC Detector.*

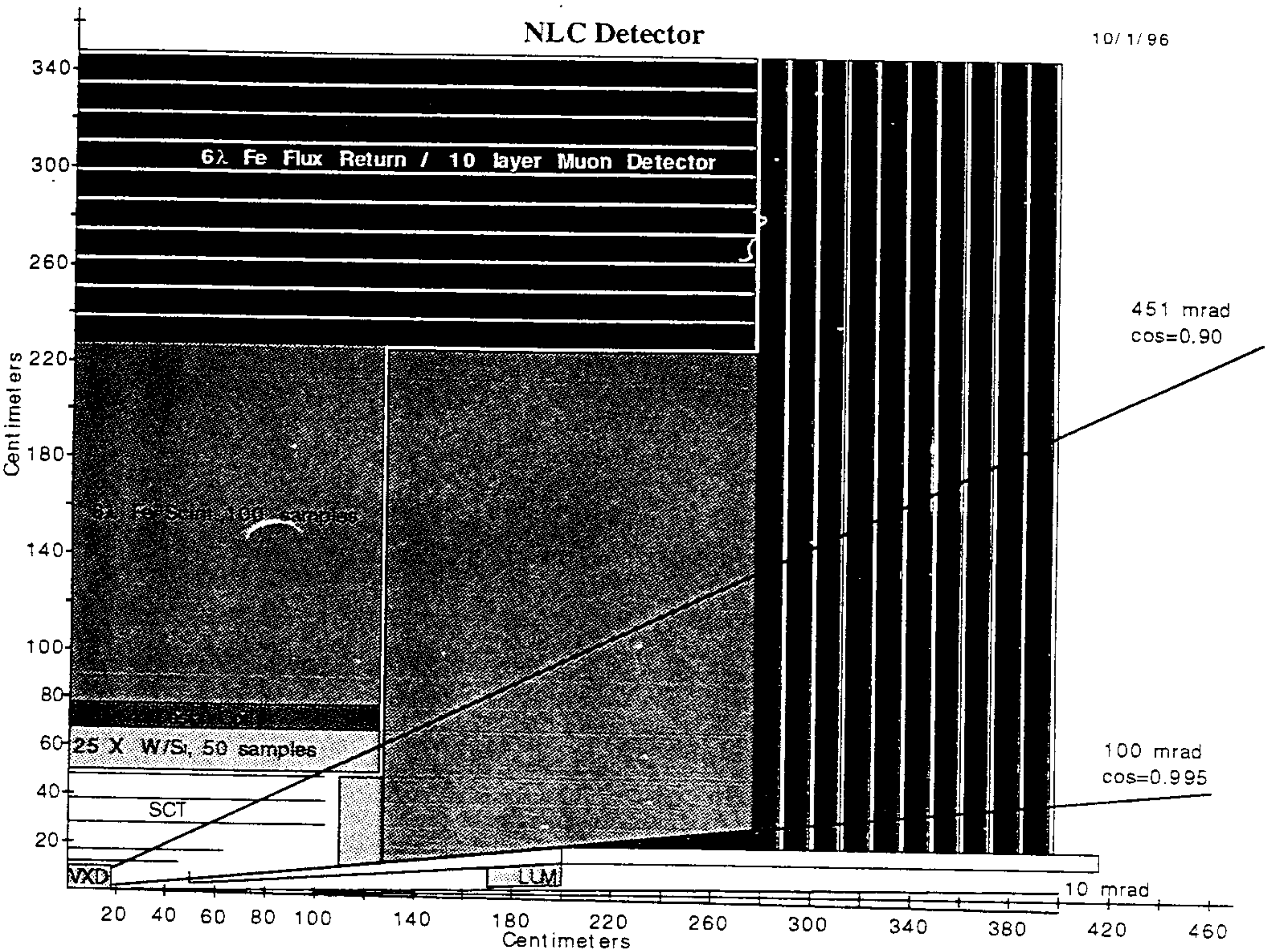


Fig. 2 Cross-section (quadrant view) of overall NLC Detector design

$e^+e^- \to Z H$ (4 jet topology) at 500 GeV w/ 10 fb^{-1}

$Z \to q\bar{q}$, $H \to b\bar{b}$

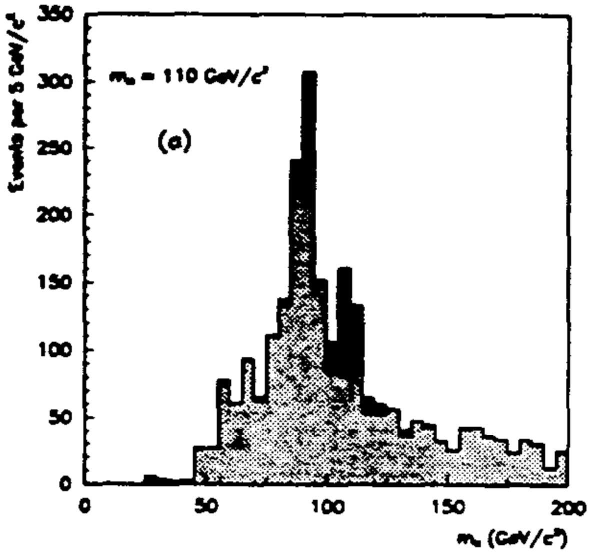
($\sim \frac{1}{5}$ NLC yr)

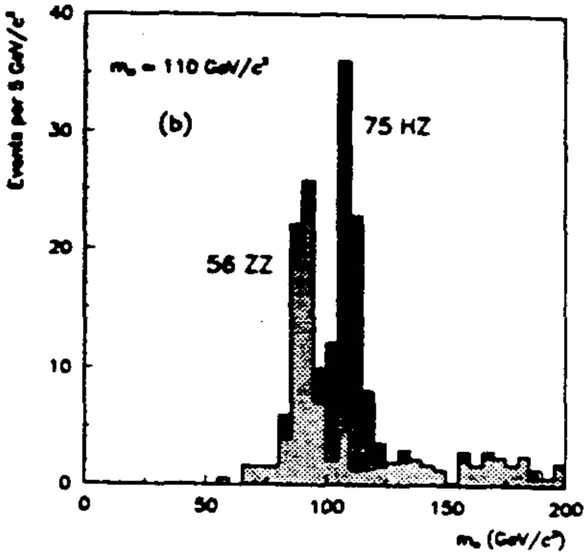
1. ≥ 4 jets w/ $M_{jet} < 45$ GeV ($e^+e^- \not\to q\bar{q}$)
2. $E_{tot} > 0.7\sqrt{s}$ ($t\bar{t}$)
3. $\chi^2_{WW} > 5$ (fit) (WW)
4. $M_{jj} \sim M_Z$ (80-125 GeV)

no b tag

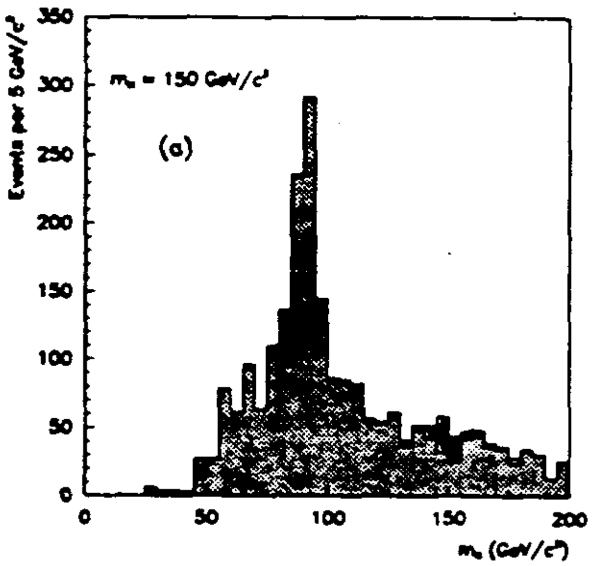
$b\bar{b}$ tag

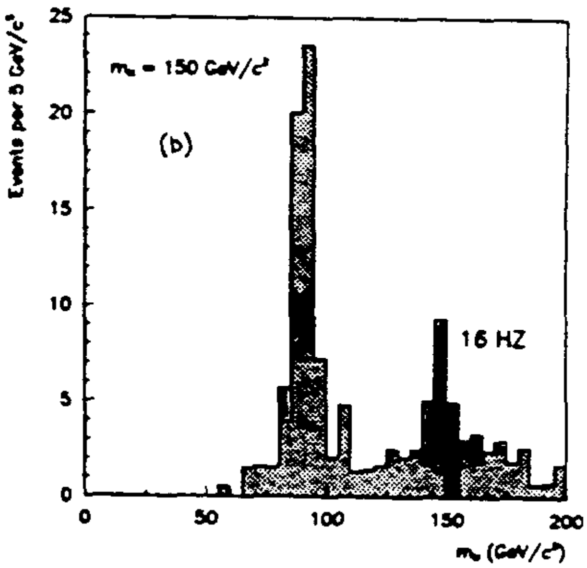
$M_H = 110$ GeV/c^2 →





$M_H = 150$ GeV/c^2 →

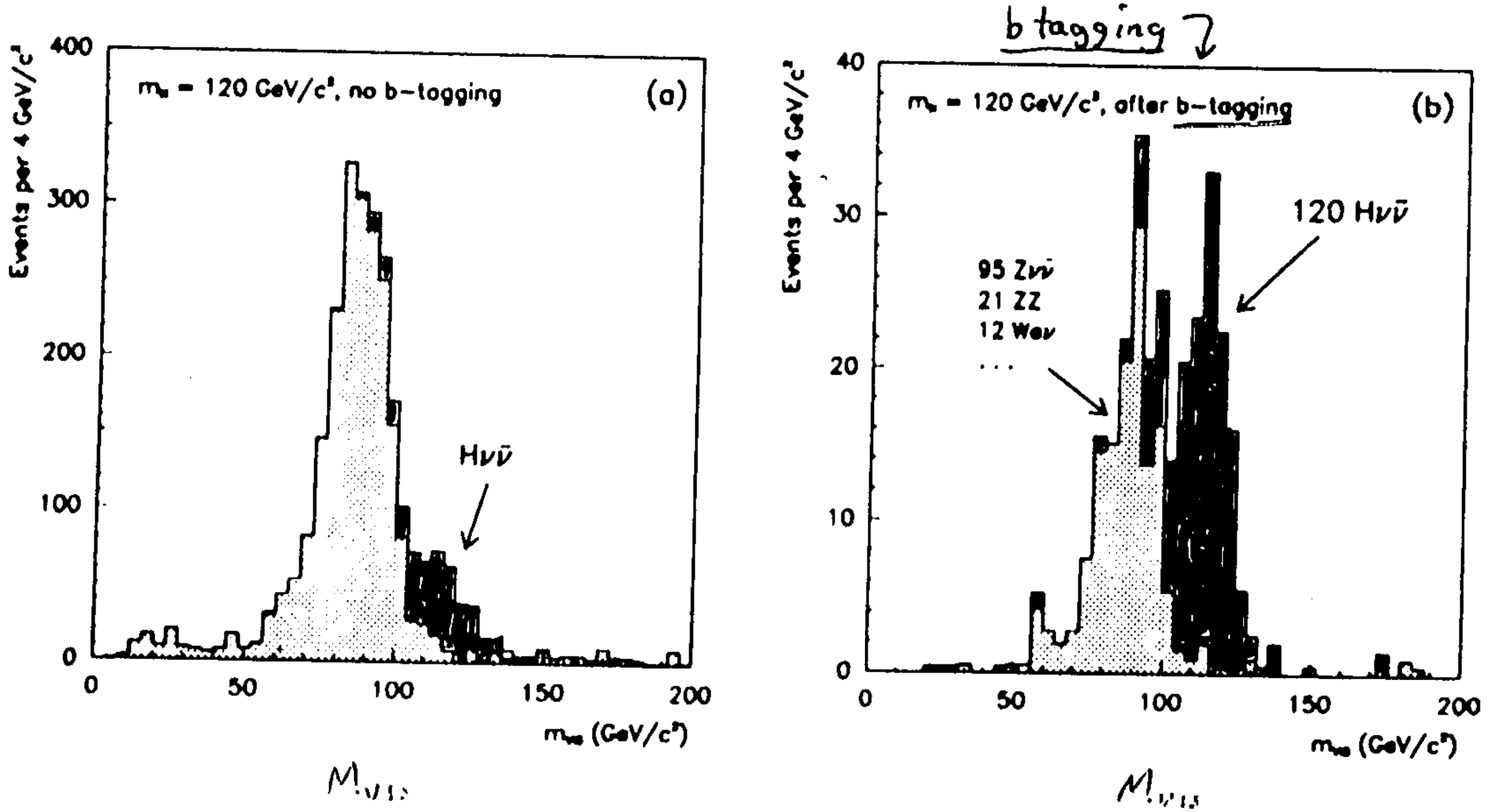




1. $E_{miss} > \sqrt{s}/2$
2. $\not{p}_T > 40$ GeV/c
3. MM > 200 GeV/c²
4. $\theta_{prod} > 25°$
5. $\theta_{acopl.} < 150°$
6. veto isolated leptons

hermeticity

dijet mass resolution



Janot

Example of an R&D Program on one subdetector:

CCD Vertex Detector Development

Physics of Linear Collider demands the best possible vertex detector performance

⇒ clean separation of b, c, and udsg jets, and τ's

Vertexing provides:

* background suppression
* combinatorial reduction within events
* measurement of key branching ratios
  - $H \to b\bar{b}$
  - $H \to c\bar{c}$
  - $H \to$ light quarks and gluons

Optimizing flavor tag:

⇒ track resolution
  * determined by technology: CCDs, active pixels, ??

⇒ outer radius
  * constrained by outer detector compact, conventional, ??

⇒ inner radius
  * limited by LC parameters and detector field
    - ⇒ beam backgrounds
    - ⇒ B-field to constrain

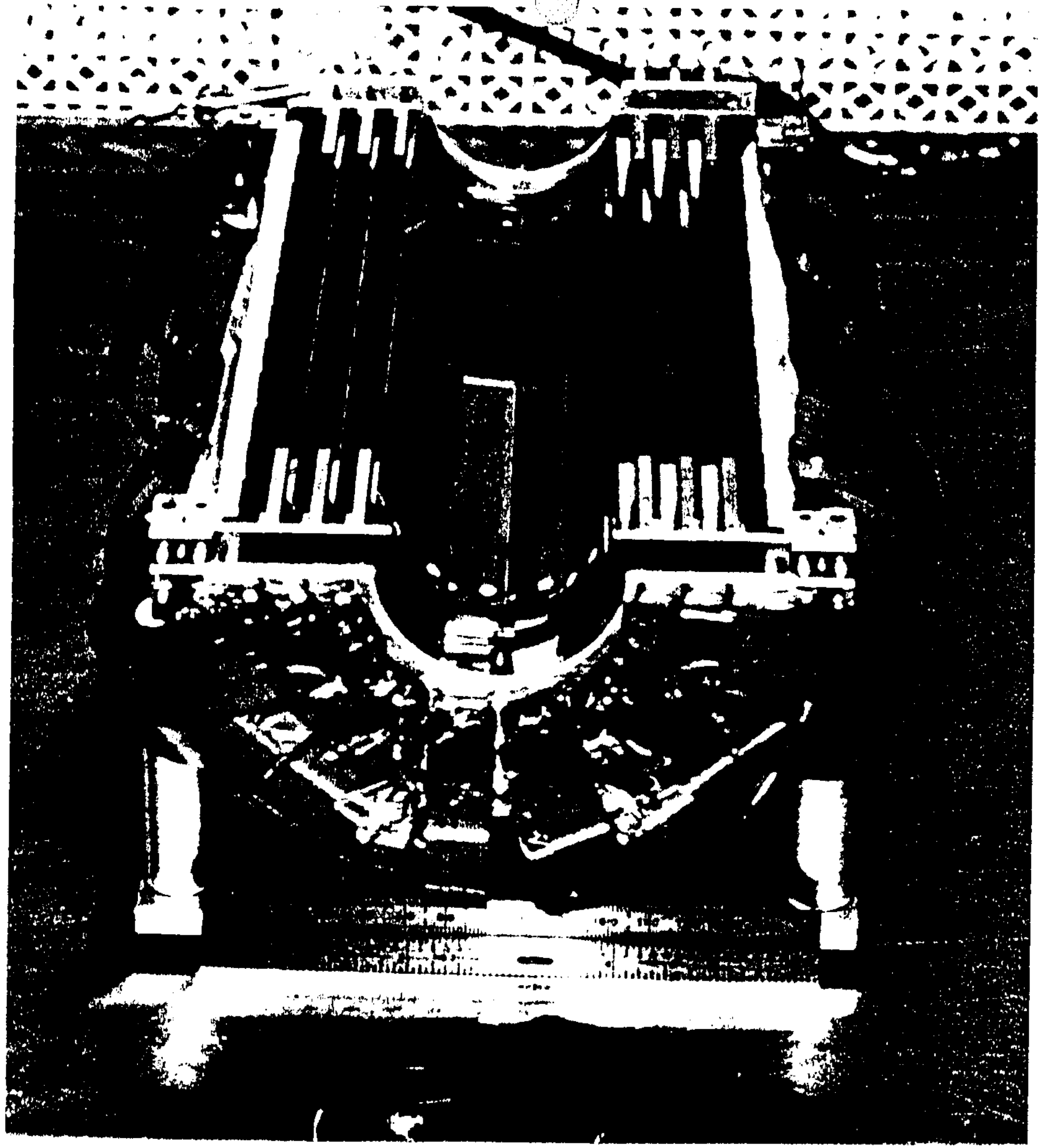
⇒ radiation immunity
  * improve CCDs, or pixels

CCDs current state-of-the-art

- SLD with 307,000,000 pixels
- MHz readout of CCD (5 MHz operational)
- < 5 μm point resolution
- exceptional efficiency and purity

Improvements are needed for Linear Collider

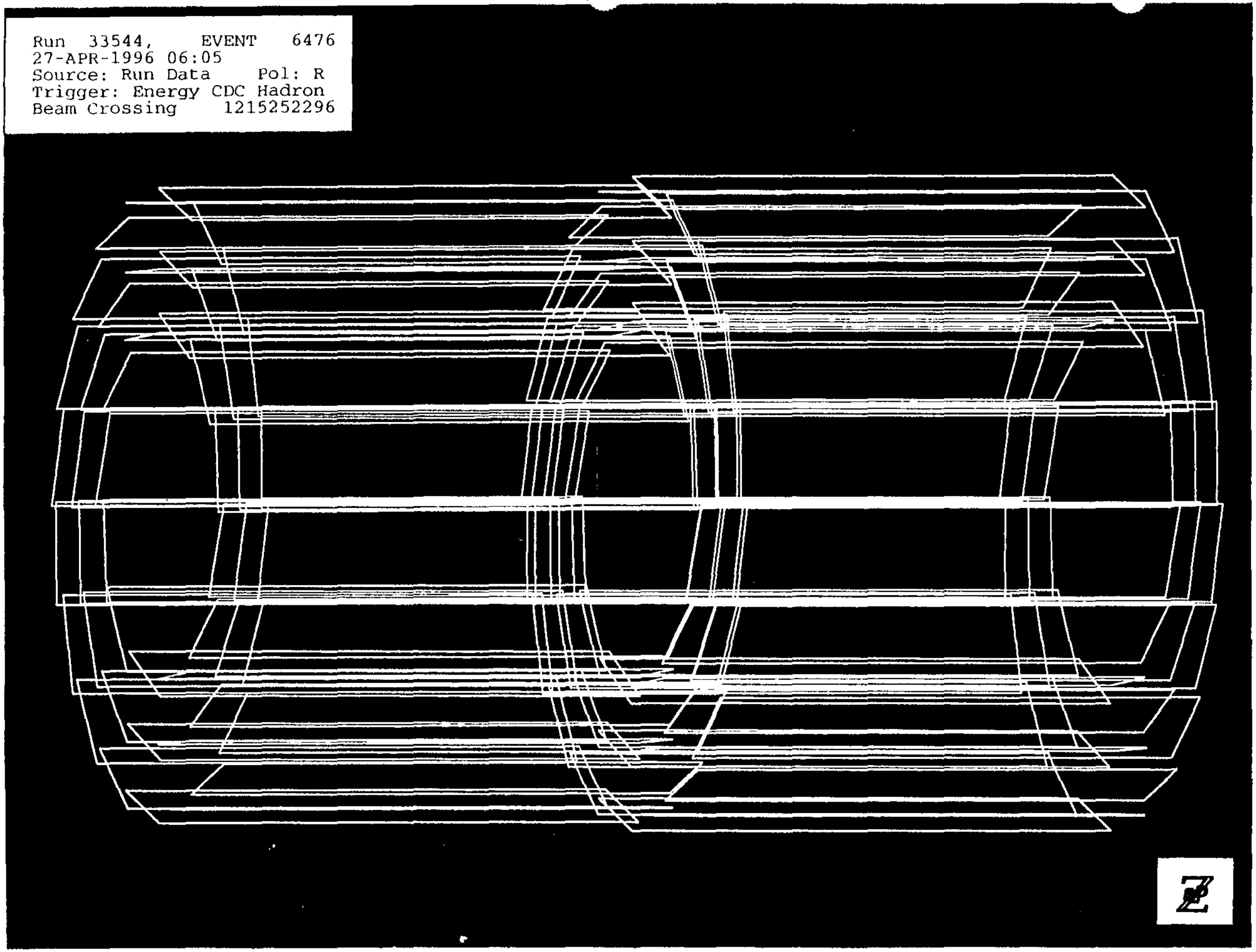
Plan for R&D to achieve improvements has been initiated



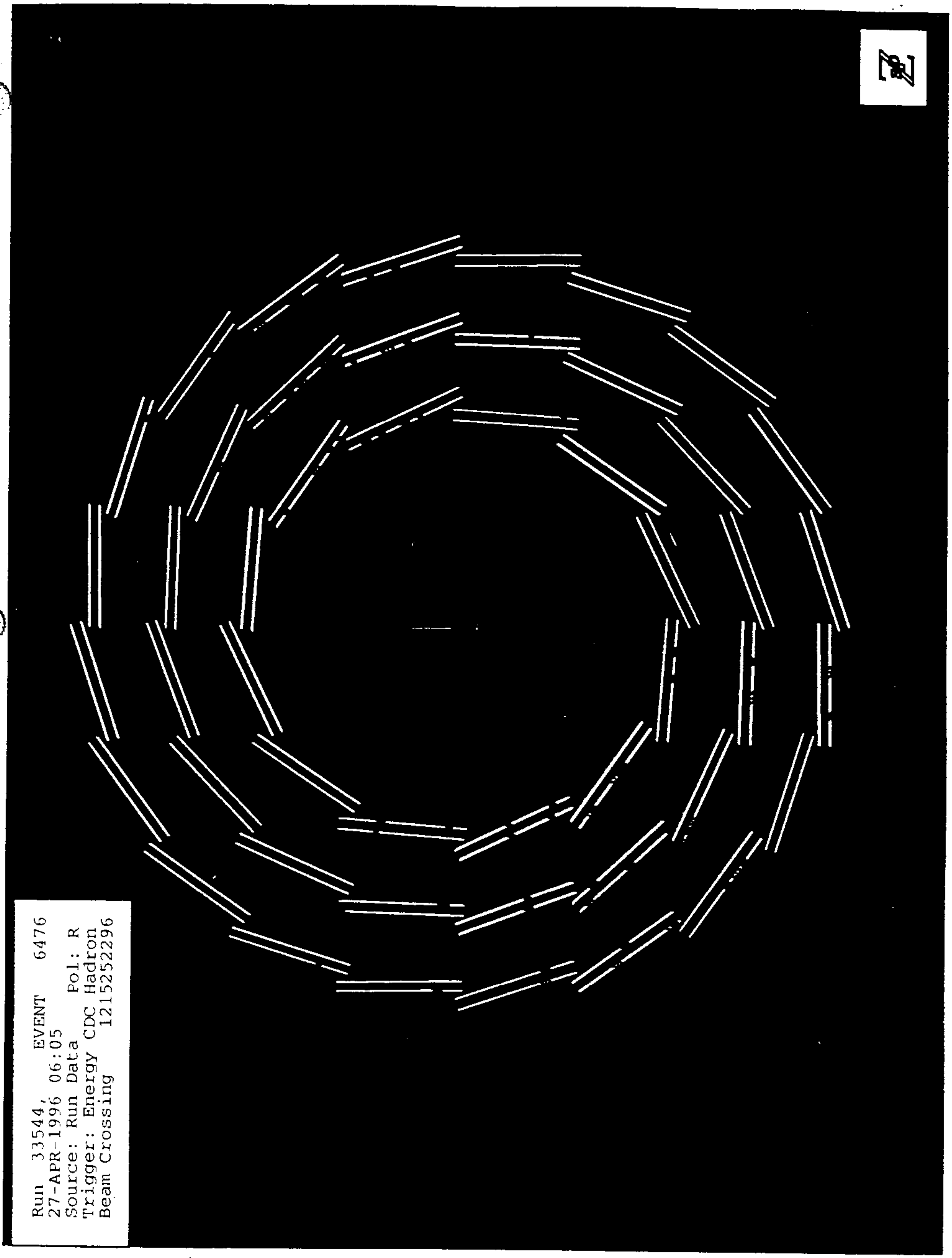
SLD Vertex Detector Upgrade (VXD3)

307,000,000 pixels

(20μm×20μm×20μm)



Run 33544, EVENT 6476
27-APR-1996 06:05
Source: Run Data Pol: R
Trigger: Energy CDC Hadron
Beam Crossing 1215252296

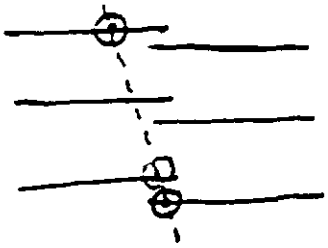


occupancy ~ few x 10^{-5}

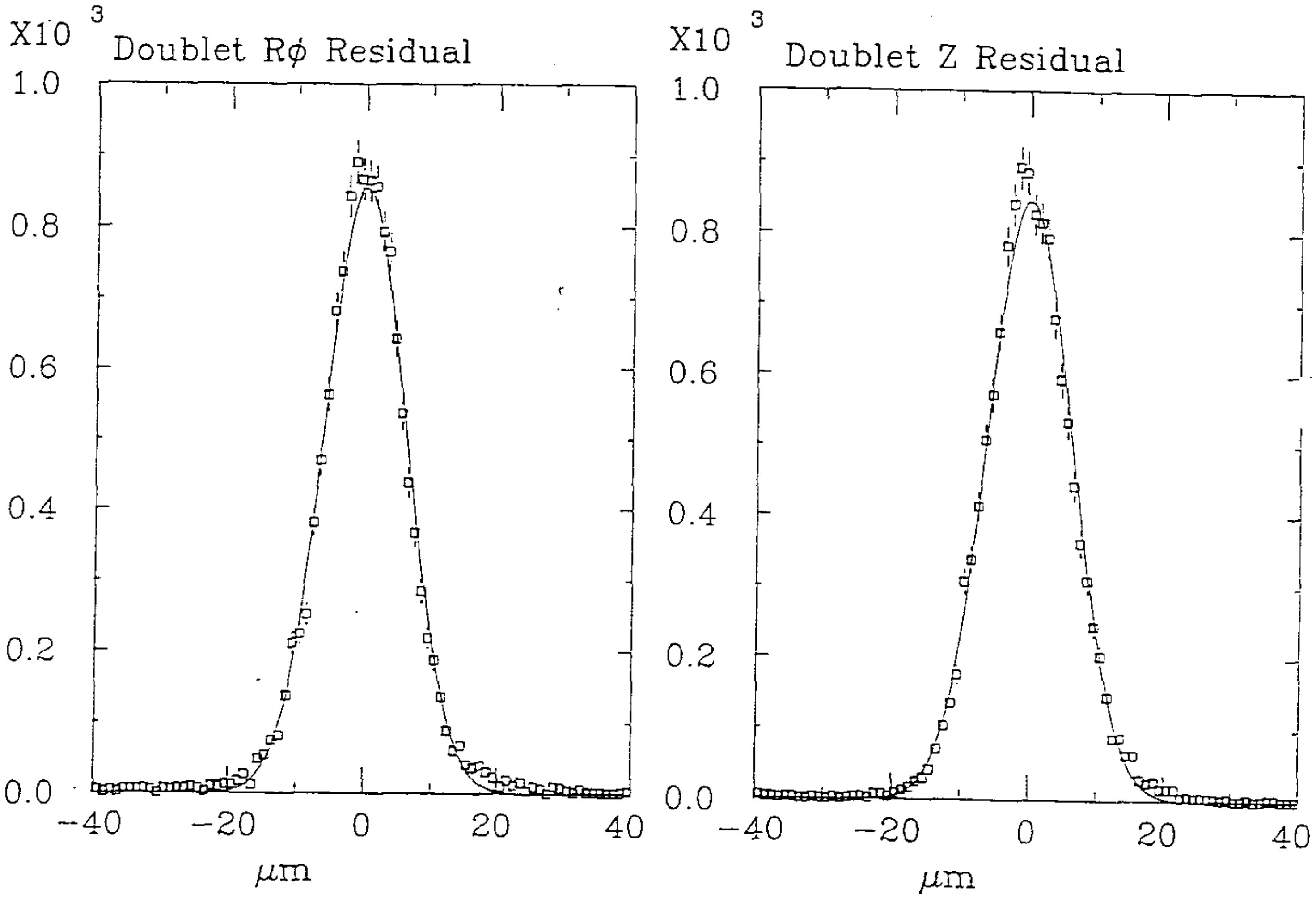
SINGLE HIT RESOLUTION (1997)

use doublets

use separated
hits to make vector
measure residual
at 2nd doublet hit



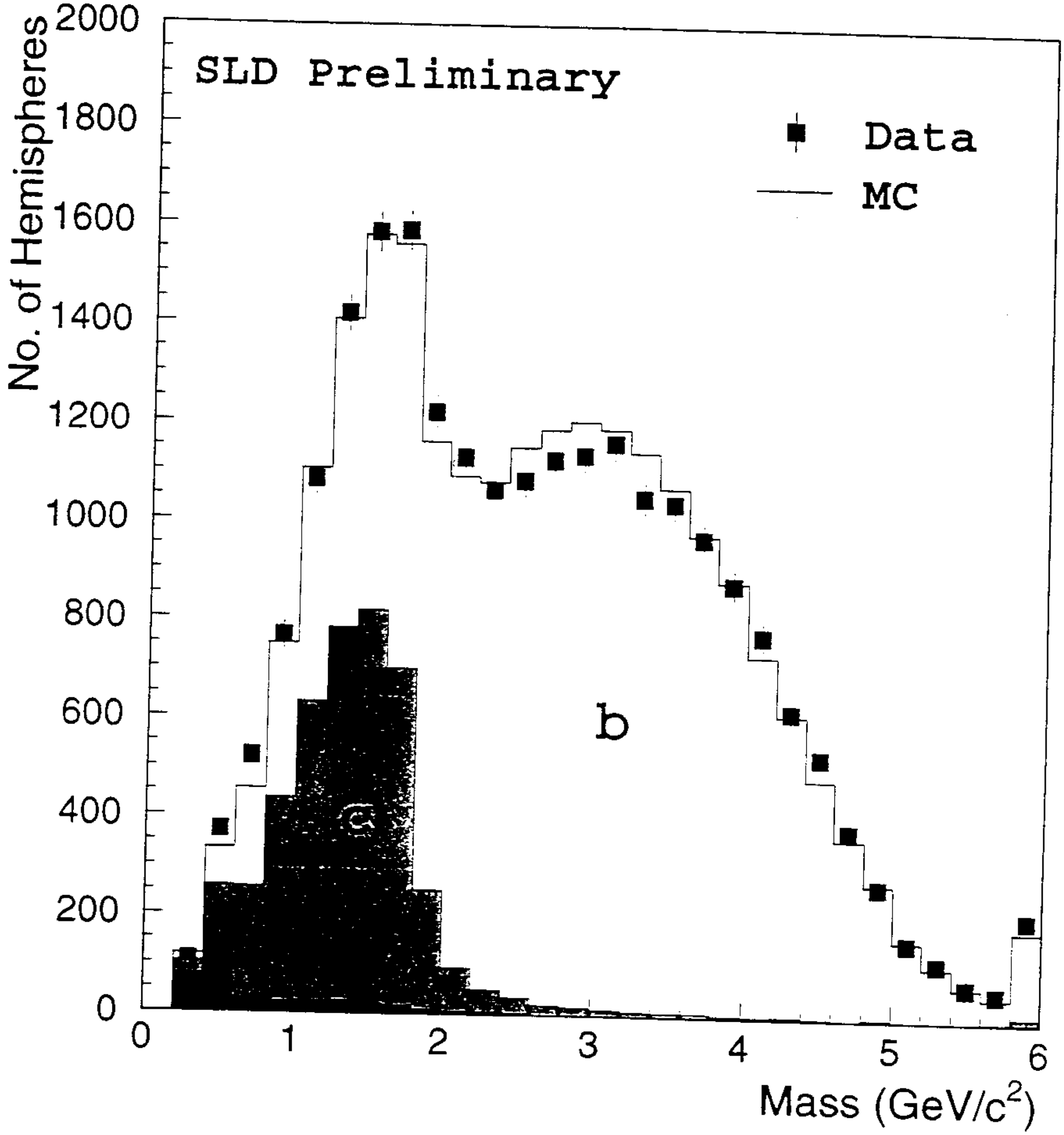
⇒ divide residual by $\sqrt{2}$ ⇒ resolution

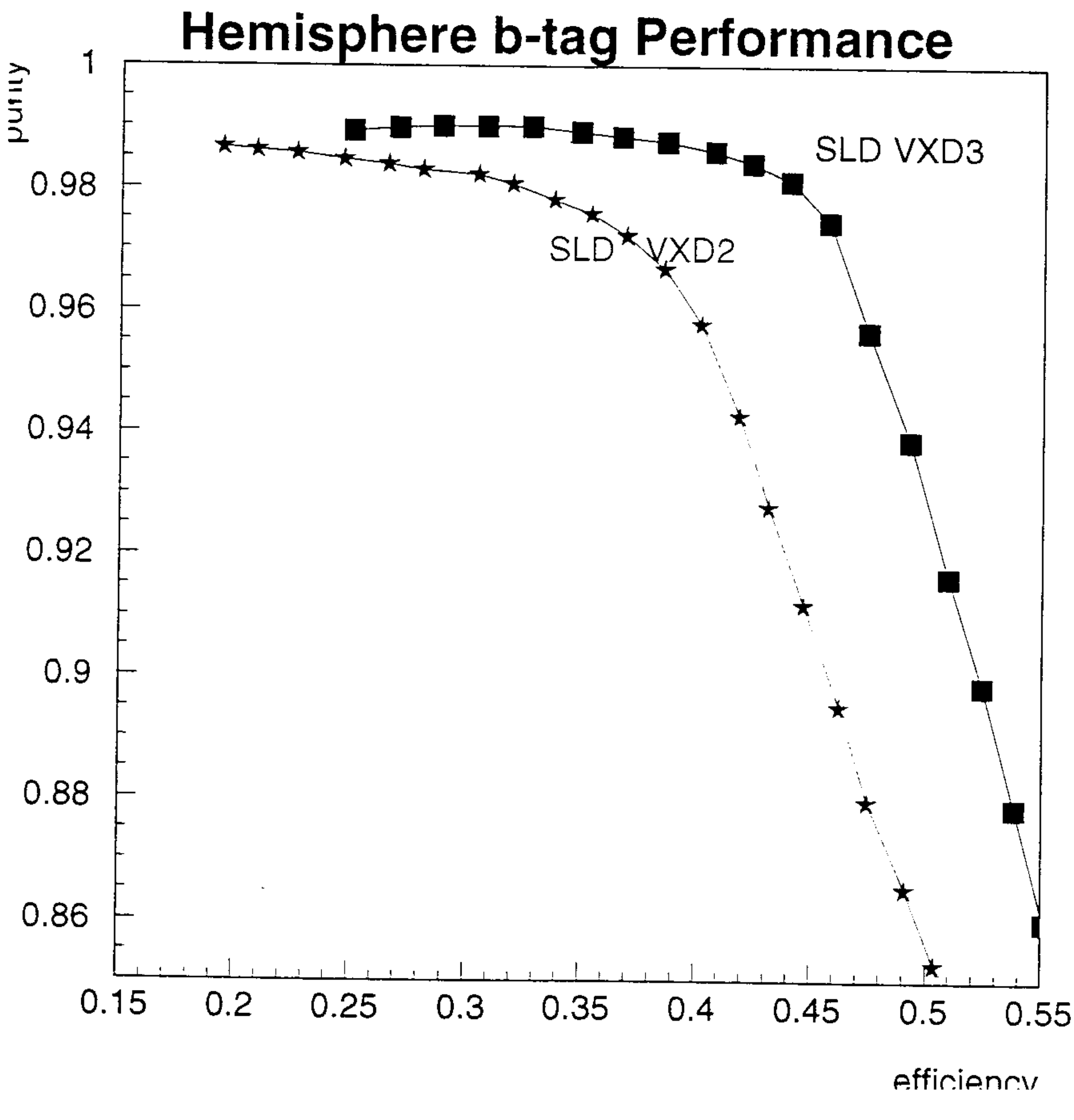


$\sigma_{\text{single hit}}$ = 4.3 μm (rϕ)

4.4 μm (z)

P_t Corrected Mass (VXD3 97)

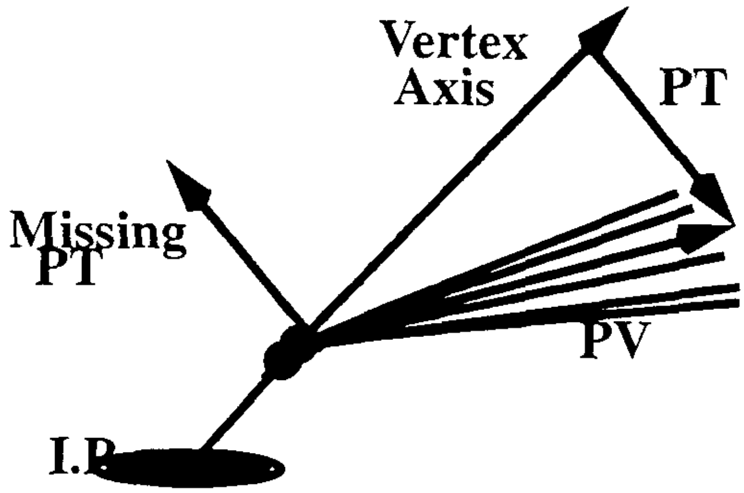




Hemisphere b-tag Performance
purity
1
0.98
0.96
0.94
0.92
0.9
0.88
0.86
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
efficiency
SLD VXD3
SLD VXD2

- Compute M_{raw} mass of tracks in secondary vtx (assign m_π)

- Exploit additional mass information from kinematics :



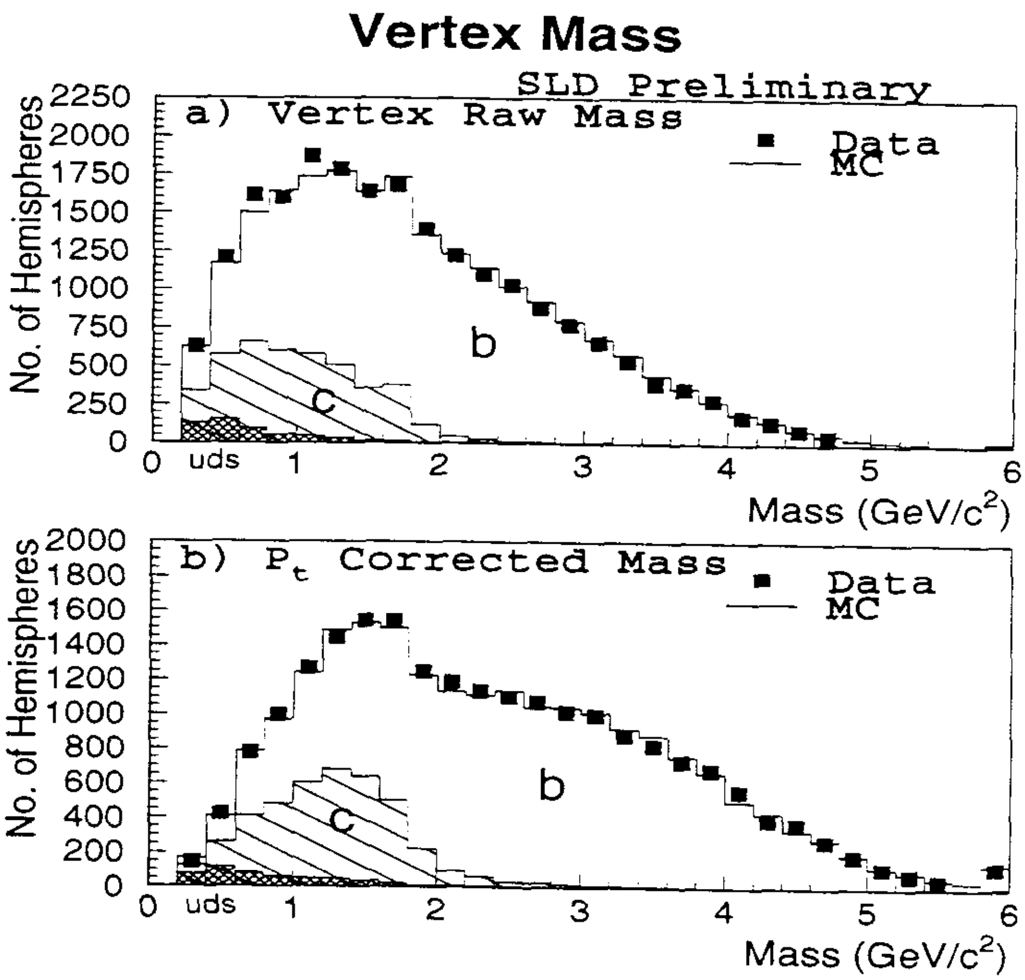
⇒ Define P_T-corrected mass:

$$M = \sqrt{M_{raw}^2 + P_T^2} + P_T$$

Impose :

$M \leq 2\, M_{raw}$

Use smallest P_T allowed by IP and vtx position uncert.



R&D Goals on Vertex Detector:

1. Develop Technology (or Technologies):

   CCDs (and APS active pixel sensors?)

2. Demonstrate technical suitability and select

3. Provide 1 cm beampipe

Imagine 3 pronged approach to R&D:

- physics studies and simulations
- vertex detector design
- vertex detector R&D

Expect this work to be carried out in an international collaboration
(much of this discussion is borrowed from European collaboration - C. Damerell et al)

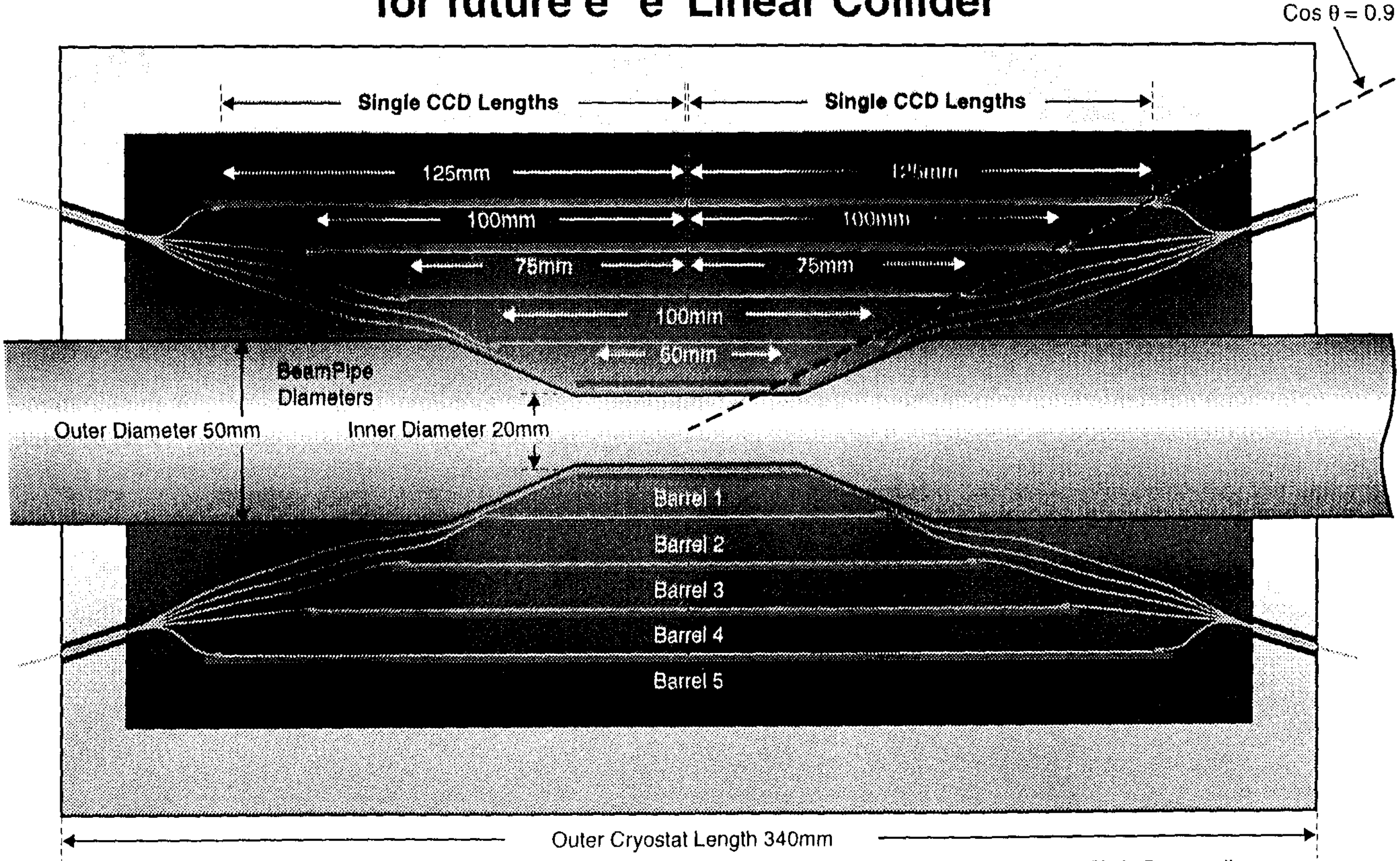
Vertex Detector Design (CCD based parameters)

- Maximum Precision ($< 5\ \mu m$)
- Minimal Layer Thickness
  ($1.2\%\ X_0 \rightarrow 0.4\%\ X_0 \rightarrow 0.12\%\ X_0$)
- Minimal Layer 1 Radius ($28 \rightarrow 12$ mm)
- Polar Angle Coverage ($\cos\theta \sim 0.9$)
- Standalone Track Finding (perfect linking)
- Layer 1 Readout Between Bunch Trains (4.6 msec)
- Deadtimeless Readout (high trigger rate)

Vertex Detector - CCD Detector R&D

- increase readout speed to 50 MHz
- develop thinner ladder ($0.12\%\ X_0$)
- improve radiation hardness (supplementary channels)

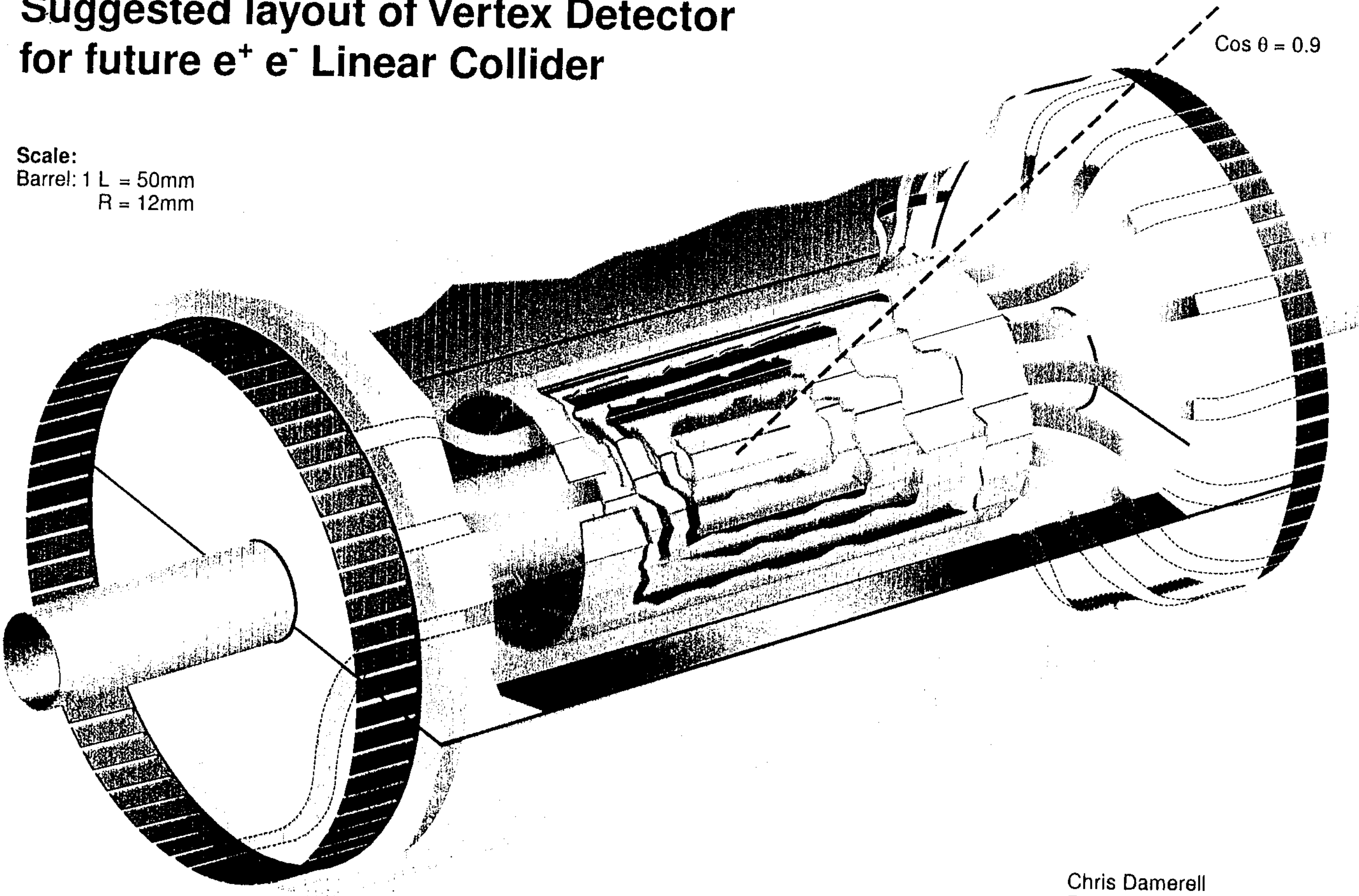
Suggested layout of Vertex Detector for future $e^+ e^-$ Linear Collider



Chris Damerell
Rutherford Appleton Laboratory
May 1996

Suggested layout of Vertex Detector for future $e^+ e^-$ Linear Collider

Scale:
Barrel: 1 L = 50mm
R = 12mm



Chris Damerell
Rutherford Appleton Laboratory
May 1996

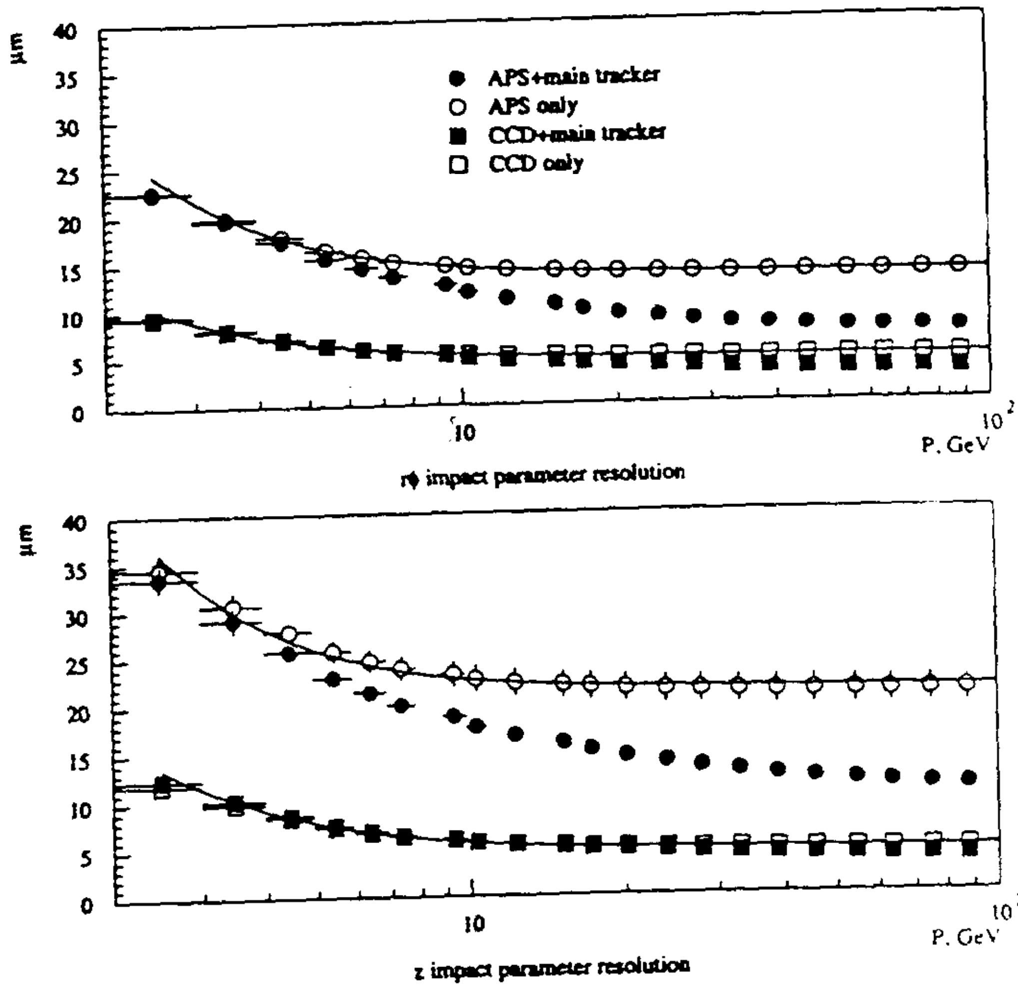


Figure 2.2.8: *Impact parameter resolution for different configurations for vertexing.*

Detector for the Linear Collider ECFA study

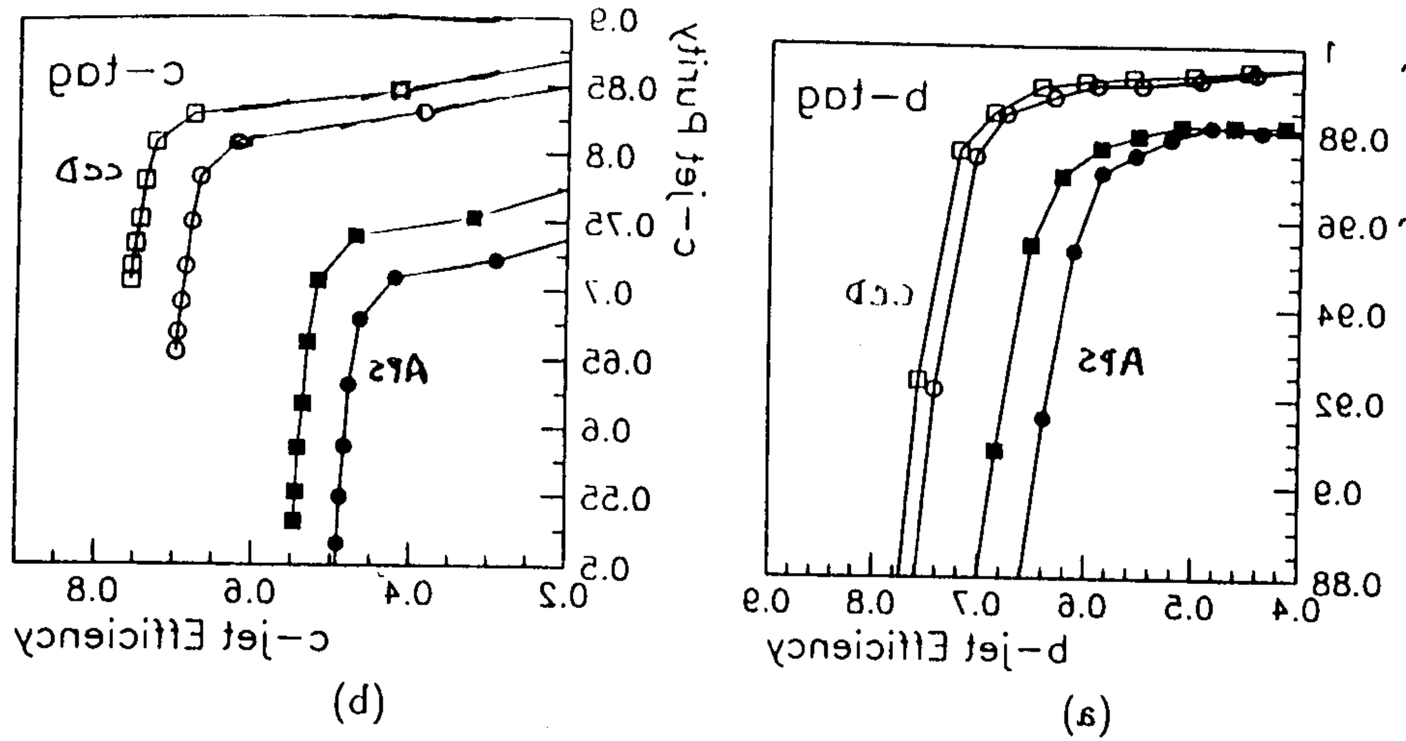


Figure 2.2.2: Purity vs efficiency for (a) beauty and (b) charm identification in 50 GeV jets. Open squares and circles refer to the CCD option, with respectively $r_{beampipe}$ = 10 and 22 mm. The filled squares and circles refer to the APS option for the same $r_{beampipe}$

Damerell + Jackson
SLAC-PUB-7215

Improvements Proposed For NLC - CCD VXD

	VXD3	NLC
Thinner Ladders:		
	0.4%	0.12% thin CCD's nearly to epitaxial layer (~30μm)
Closer to IP:		
R_{bp}=	23.2 mm	10mm
R_{b1}=	28 mm	12mm need 4 Tesla field to constrain e^+e^- pairs
More Layers:		
	3 layers	5 layers inner layer only for link 4 outer tracking layers allows 1 miss / track
Faster Readout:		
	5 MHz	50 MHz more drive pulses to CCD

Simulations (D. Jackson):

$$\sigma_{imp.\ par.}(xy) = \sigma_{imp.\ par.}(rz) = 4.5\mu m \oplus \frac{5.5\mu m}{P \sin^{3/2}\theta} \text{ at IP}$$

Vertex Detector - Physics Studies and Simulations

- Apply heavy quark tag performance to physics channels
- Investigate stand-alone track finding
  - background tolerance
  - layer 1 issues
- Develop detailed CCD signal simulation
  - how can the point resolution be improved even further?
- Create detailed GEANT model of vertex detector and investigate impact of material on overall LC detector performance
- Continue studies of the issues impacting systems outside the vertex detector (machine backgrounds, solenoidal field, etc.)

Plan for International LC Vertex Detector R&D

LC Vertex Detector R&D should be conducted in a "border-less" collaboration

Japan + US + Europe + others?

Share ideas, software, hardware, problems and solutions

⇒ PLAN this effort to maximize yield of R&D and physics capabilities

Rundown on other subdetectors
and "incomplete" list of R&D issues

tracking

Is outer tracking one technology or more?
What technology is it?
- straw tubes (inner?)
- scin fibers (inner?)
- silicon strips ← Snowmass/NLC
- TPC ← ECFA
- Drift ← JLC
  - Note: each of these layouts has
    - $\sigma(1/p_T) \sim 10^{-4}\ GeV^{-1}$ at high p_T,
    - How important is low p_T resolution?
- GEM
- MSGC

Occupancy
Forward Tracking

particle id?

Is there any?
If so, what?
Presampler?

calorimetry

Goals:

electron and gamma measurements

jet measurements

missing energy measurement

Strategy for jet measurement

energy flow analysis

tracking + E_{EM} (E_{HAD} correction)

→ "Aleph"

E_{EM} + E_{HAD} (tracking correction)

→ "Zeus/H1"

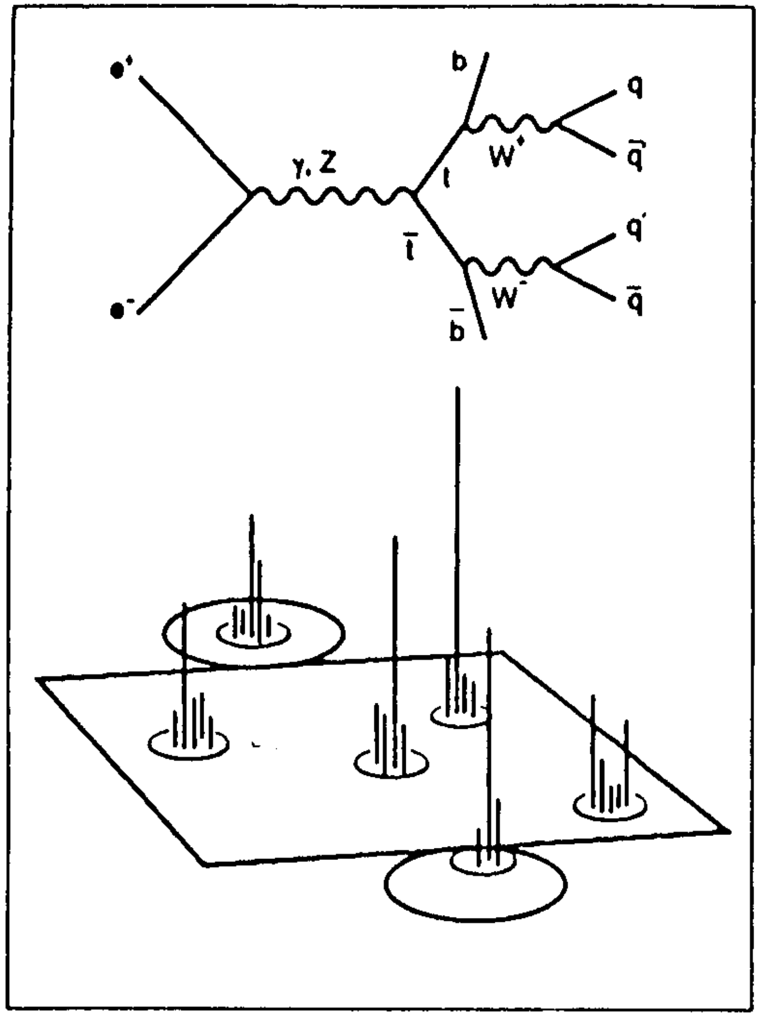


Fig. 1 (based on [2]). Close connection between Feynman diagram and energy flow (unfolded barrel and endcaps).

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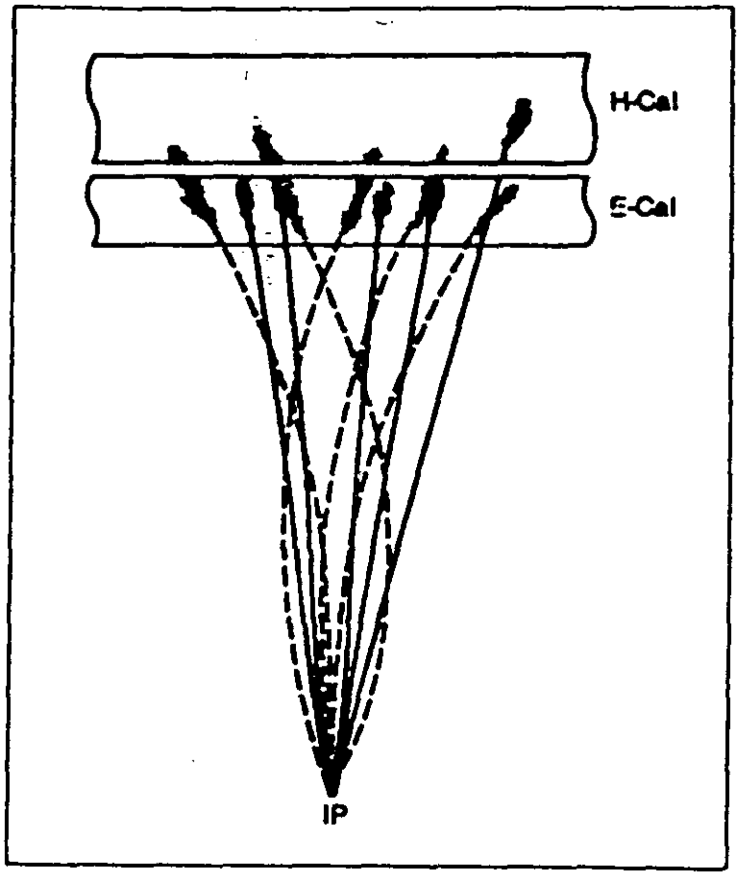


Fig. 3 Separation of charged and neutral particles in calorimeters

Damerell et al
Snowmass '96

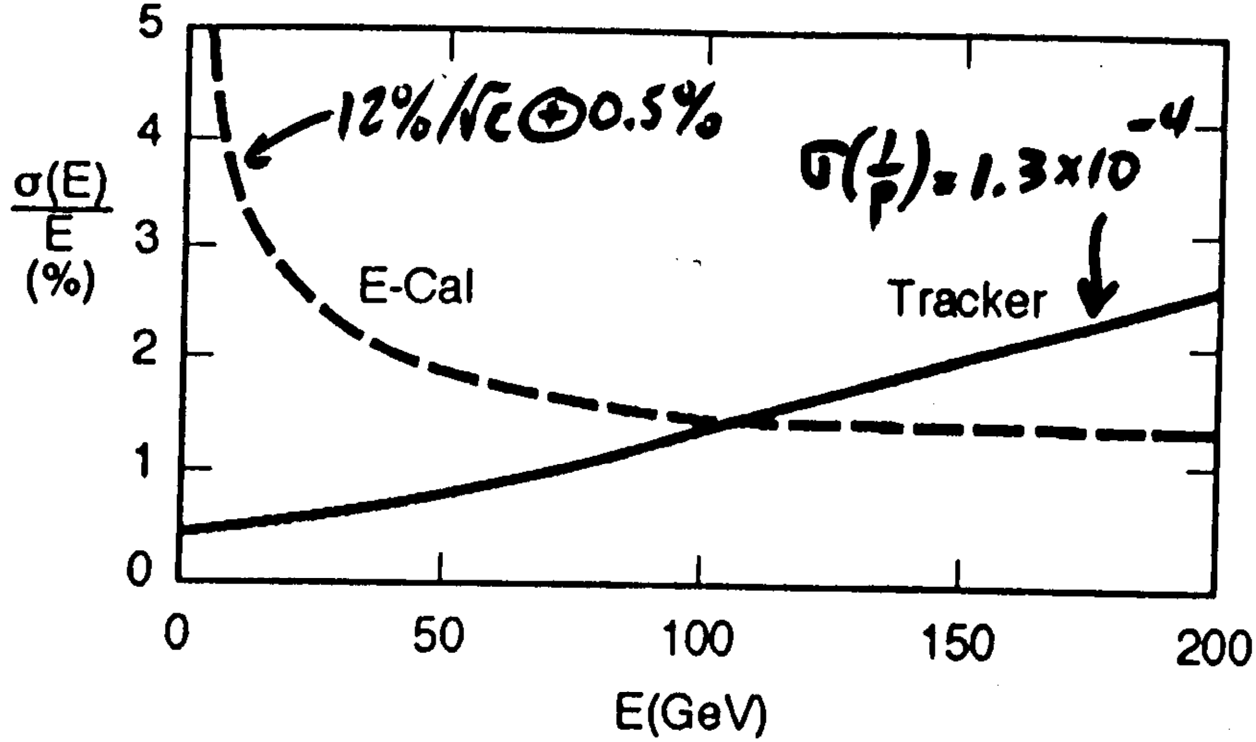


Fig. 5 Energy resolution of SCT and E-cal for single particles.

Damerell et al

JET ENERGY MEASUREMENTS

CALORIMETRIC MEASUREMENTS REQUIRE

- LOW B FIELD
- COMPENSATED RESPONSE

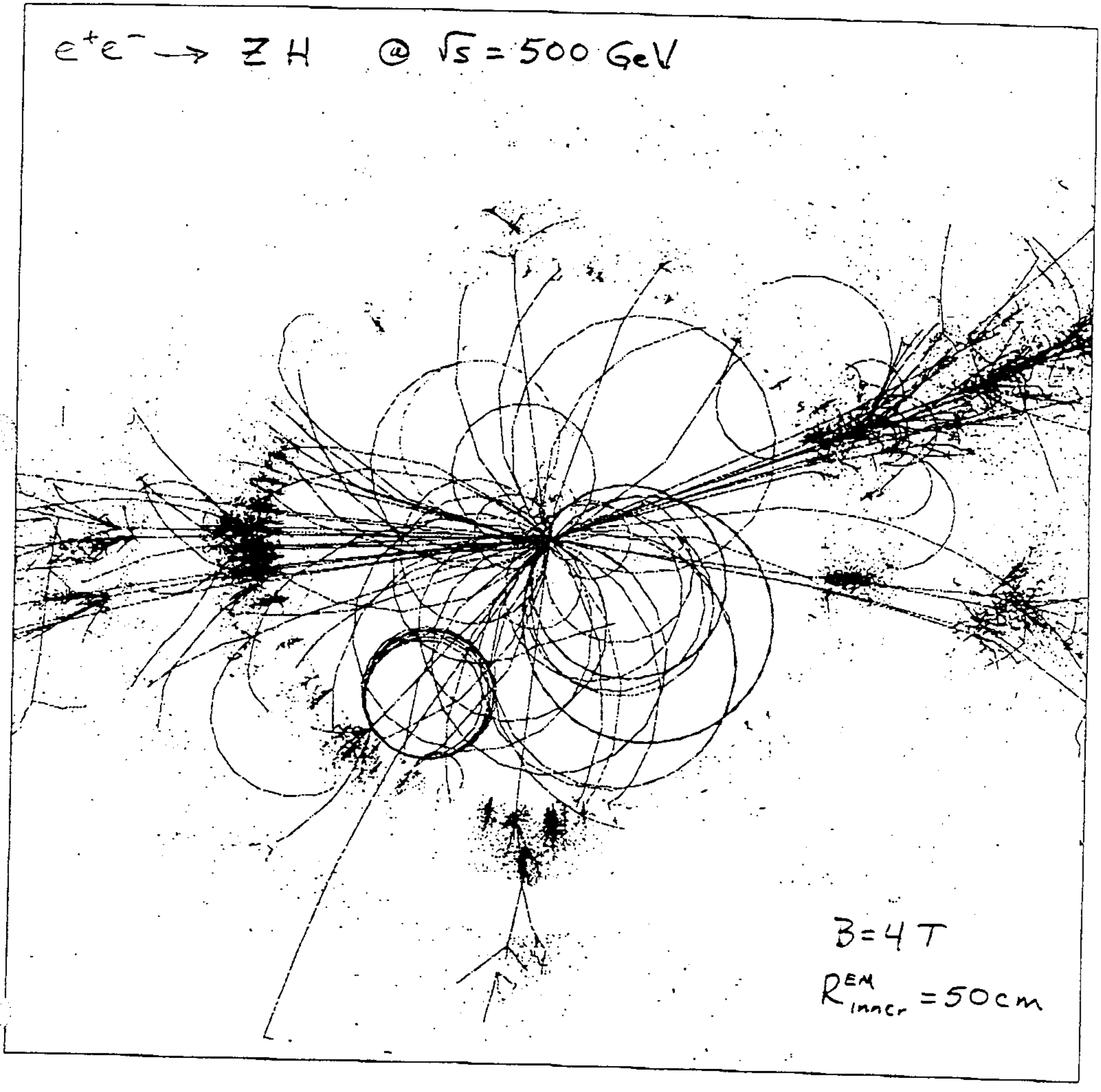
ALTERNATIVE:

TRACKER + CALORIMETER (FOR NEUTRALS)

- HIGH B FIELD
- GRANULARITY IN CALORIMETER TO SEPARATE NEUTRALS FROM CHARGED

(ONLY NEUTRINOS ESCAPE DETECTION)

B. Barakat



calorimetry (cont.)

key issues:
- energy resolution
- granularity
- Moliere radius
- longitudinal segmentation

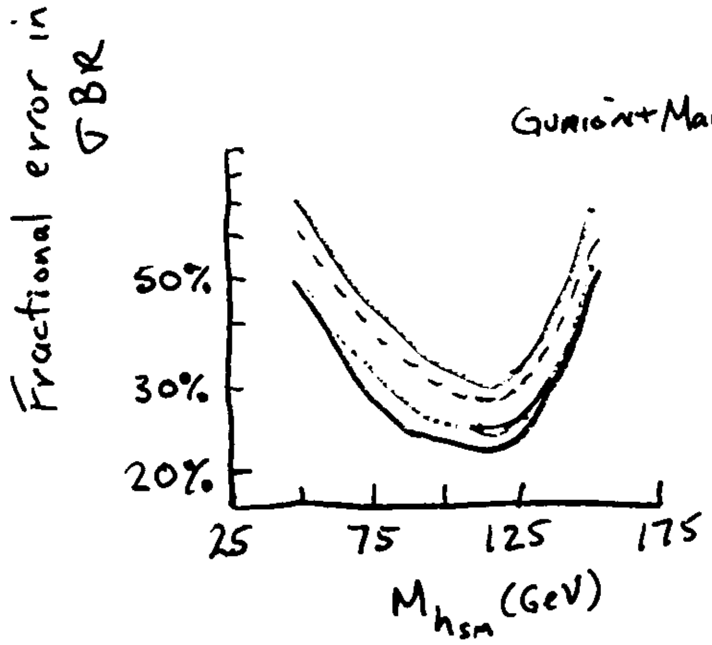
requirements
- granularity
- resolution
  - high energy
  - $H \rightarrow \gamma\gamma$
- tolerance to high magnetic field
- cost containment

electromagnetic technology candidates:
- silicon-tungsten
- Pb-scintillator
- crystals

hadronic

A BIG issue for calorimeter group:
there are many options with different advantages
need to define relative importance of parameters,
and how each choice would satisfy them

$e^+e^- \to Z H$, $H \hookrightarrow \gamma\gamma$



$\int L = 150\, fb^{-1}$

--- NLC detector

$e^+e^- \to Z H$, $H \hookrightarrow \gamma\gamma$ at $\sqrt{s}_{opt}$

BKGND $e^+e^- \to Z \gamma\gamma$

e.g. for $M_h = 120$
$\sqrt{s} = 240$ GeV
17 signal events

calorimeters

$10\%/\sqrt{E} \oplus 1\%$

$5\%/\sqrt{E} \oplus 0.5\%$

$2\%/\sqrt{E} \oplus 0.5\% + 0.2\%$

Note = under investigation by Gunion + Martin
$e^+e^- \to \nu\bar{\nu} H$, $H \hookrightarrow \gamma\gamma$ (smaller background? bigger signal @ 500)

muon detection

volume (cost) driven by inner detector choices

trigger and DAQ

flexibility needed

luminosity measurement

Could be difficult to fit in

polarization measurement

Compton, presumably
Detector location for background immunity
Chromatic effects

backgrounds

simulation

All of the above require detailed simulations to drive the R&D plan (necessary first step)

General issue for all systems: Timing
does an individual subdetector try to keep track of signal times well enough to make its own bunch assignment or does it rely on global pattern recognition to sort things out later?

http://www.slac.stanford.edu/~mpeskin/LC/plan.html

Plans for the North American Linear Collider Detector Simulation Study---draft

At the recent Boulder meeting of the North American interim working group organizers for the linear collider detector project, one of the most important issues was that of how the detector simulation studies would be carried out. In this document, we would like to propose a very specific plan for the studies that will be done between now and the Barcelona international meeting. Our understanding is that this plan implements the decisions that were made in Boulder. Your comments and criticism are welcome.

-- Tim Barklow, Richard Dubois, Michael Peskin

General Structure and Philosophy

In order to formulate a detector configuration for the linear collider experiments, we need to understand how the various choices for the form of the detector affect the quality of the measurements that we will make. To address this question, we plan to choose a number of standard and nonstandard physics processes and to study, for each of these individually, the optimization of the detector. At this stage, the North American working groups do not feel it is important to fix a particular detector design concept or to carry out detailed studies that are specific to a fixed detector or machine design. Rather, we would like to obtain an overview of the merits, problems, and compromises in many possible design schemes. Our goal is not to bring a specific detector design to the Barcelona international meeting, but rather to bring a great deal of data that will make the discussion of design options concrete.

Our plan for accumulating this data is the following: During the summer, Richard will put together the detector simulation software package described below. This package will allow the creation of detectors with fairly arbitrary form, subject to the general constraint that these detectors have cylindical symmetry and uniform solenoidal magnetic fields. (Truly novel detector ideas are welcome, but they fall outside the domain of this package.) The calorimetry in these detectors will be simulated in detail using the GISMO framework. Richard will provide an interface through which the simulated detector will receive high-energy physics events, a collection of generators which write events in the required structure, a simplified simulation of beamstrahlung and other machine-dependent effects compatible with these generators, and a set of specific detector configurations which can be used as examples.

We plan to have these tools ready to introduce to the community at the Keystone meeting at the end of September. We also plan to have one sample physics analysis done by that time, which can be posted as an example.

The work of obtaining an overview of the linear collider physics will be parceled out in manageable chunks to the members of our collaboration. To facilitate this, Michael will discuss with the working group leaders this summer to draw up a list of about twenty specific physics measurements, giving for each a set of specific questions about detector design. We expect that any group submitting an linear collider detector R & D proposal will also contribute manpower to answer one of these sets of questions before the Barcelona meeting.

Physics Questions

With the advice of the interim working group organizers, Michael will prepare a list of about twenty physics processes to study at the linear collider, with a set of questions for each about detector optimization. These reactions will be divided between Standard Model calibration processes and new physics processes. In general, these reactions will involve precision measurements rather than discoveries, since it is those processes that require the most from the detector design. Two examples of these sets of questions are the following:

- In the standard model reaction e+e- -> c cbar, we wish to measure the total cross section and the forward-backward asymmetry. Optimize the detector to improve the efficiency for identifying c cbar in two-jet events and the to improve the quality of these measurements. How are these quantities affected by the vertex detector geometry and resolution? How important is a large tracking chamber with small multiple scattering? Would efficient particle ID improve the efficiency for charm identification?
- In the model of supersymmetry defined by point 3 of the Snowmass study (the ISAJET supersymmetry model with (m0,m1/2,A0,tanbeta,sign mu) = (200,100,0,2,-1)), sneutrino pairs are produced, and the sneutrino can decay by sn -> e- chargino+. The electron energy spectrum is flat, and its endpoints determine the sneutrino and chargino masses. (See the NLC Snowmass report, fig. 2.33.) Optimize the detector to improve the efficiency of the analysis and the determination of these endpoints. What level of hermiticity is required? What isolation cuts must be applied to the electron, and how does this stress the detector parameters? How does the measurement depend on the electromagnetic calorimeter resolution and segmentation?

In carrying out these analyses, one should work at 500 GeV, unless there is a compelling reason to choose a difference center-of-mass energy, and consider for reference an integrated luminosity of 50 fb-1. One may assume any e- polarization (or set of polarizations) which optimizes the analysis.

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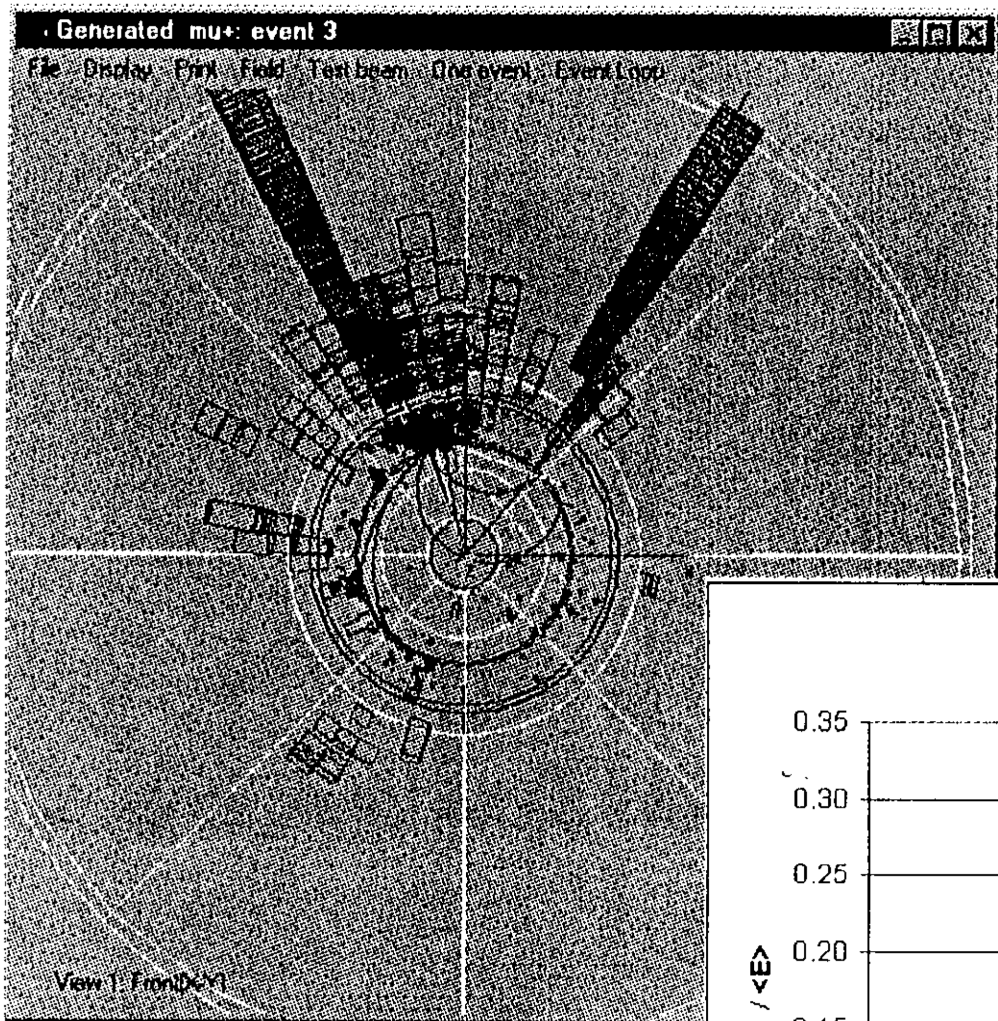
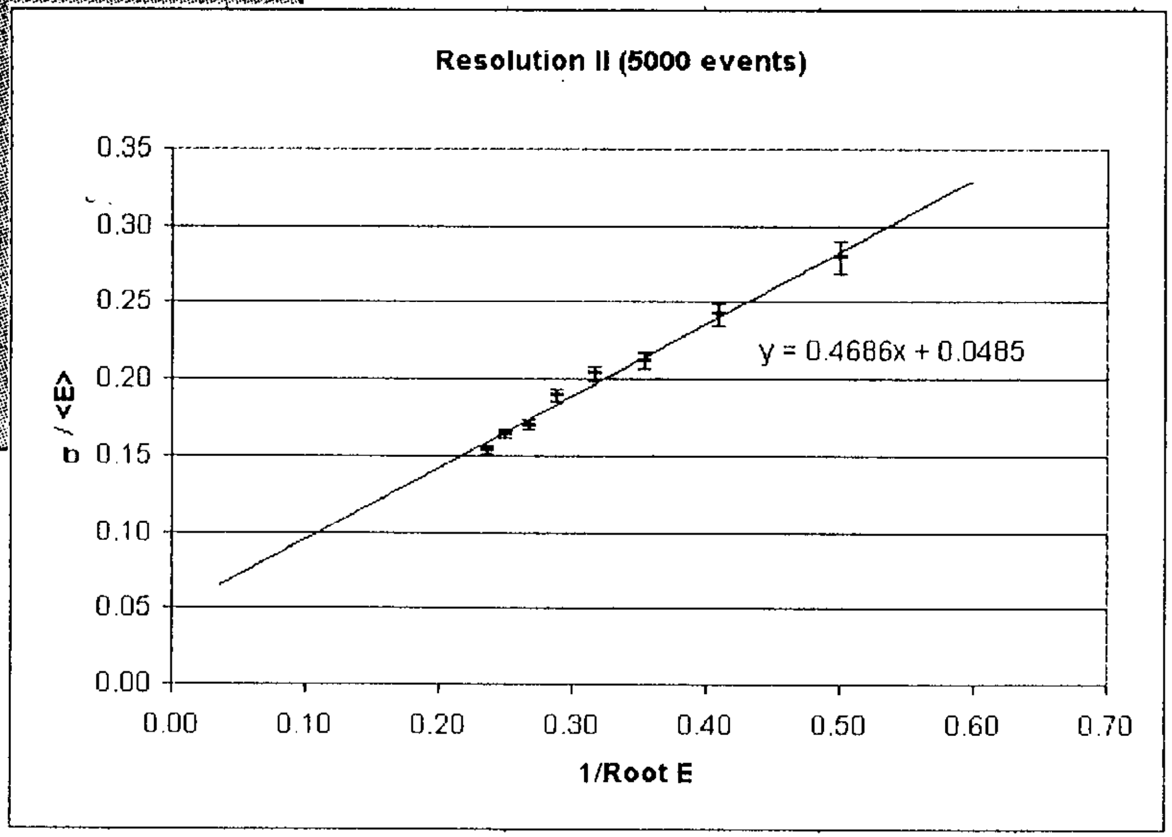


Sample multi-pion simulation

Single π resolution



FLCD Simulations

Conclusion

There are many issues that need to be resolved in order confidently propose an experiment for the Linear Collider.

Now is the time to get on with planning and executing the detector R&D

Simulation will plan a critical role in the near term R&D, as many technical choices depend on detailed performance issues.

Next we need to develop detailed plans covering all subsystems and issues.