Linear Collider Detectors

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- Many open issues for LC detectors
- Physics goals involve low event rates with relatively low backgrounds
  - opportunity for very efficient and precise approaches

The "next" Linear Collider

The "next" Linear Collider proposals include plans to deliver **a <u>few hundred</u>** <u>fb</u>$^{-1}$ of integrated lum. per year

		TESLA	JLC-C	NLC/JLC-X *
		(DESY–Germany)	(Japan)	(SLAC/KEK–Japan)
$\mathcal{L}_{design}$	(10^{34})	3.4 → 5.8	0.43	2.2 → 3.4
E_{CM}	(GeV)	500 → 800	500	500 → 1000
Eff. Gradient	(MV/m)	23.4 → 35	34	70
RF freq.	(GHz)	1.3	5.7	11.4
Δt_{bunch}	(ns)	337 → 176	2.8	1.4
#bunch/train		2820 → 4886	72	190
Beamstrahlung	(%)	3.2 → 4.4		4.6 → 8.8

* US and Japanese X-band R&D cooperation, but machine parameters may differ

Physics Requirements

- The Linear Collider physics program includes a broad range of goals from discovery to high precision, ranging from $E_{CM} \sim M_Z$ to ~ 1 TeV
  - Higgs studies
  - Supersymmetry
  - Strong WW scattering
  - Top physics
  - Precision Z^0

Detector Requirements

There is perception that Linear Collider Detectors are trivial

Not true!

The detector R&D devoted to the challenges of the LHC are helpful but not sufficient

The LC requirements differ from hadron collider requirements

hadron collider: large cross sections and large backgrounds

linear collider: smaller event rates and smaller (though not negligible) backgrounds

The LC requires a different optimization

Detector Comparisons

Tracker thickness:

CMS	0.30 X_0
ATLAS	0.28 X_0
LC	0.05 X_0

Vertex Detector layer thickness:

CMS	1.7 % X_0
ATLAS	1.7 % X_0
LC	0.06% X_0

Vertex Detector granularity:

CMS	39 Mpixels
ATLAS	100 Mpixels
LC (Telsa)	800 Mpixels

ECAL granularity (detector elements):

CMS	76×10^3
ATLAS	120×10^3
LC(Tesla)	32×10^6

Detector Requirements

Unburdened by high radiation and high event rate,
the LC can use
$\Downarrow$

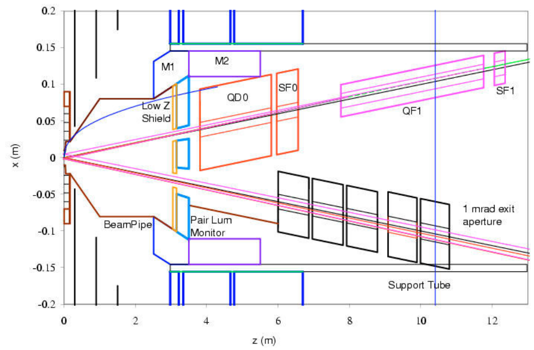
- vxd 3-6 times closer to IP
- 35 times smaller pixels and 30 times thinner vxd layers
- 6 times less material in tracker
- 10 times better track momentum resolution
- > 200 times higher ECAL granularity (if it's affordable)

But to capitalize on this opportunity,
we must begin the R&D now

Prominent R&D Goals

Develop advanced CCD vertex detector
Simulate and prototype superb energy flow calorimeter
Understand limitations of tracking options and develop them
Develop beamline instrumentation (E, pol, lum spectrum, …)
Refine and certify background estimates
Develop high-field solenoid
Develop cost reduction strategies
    eg. integrated cal readout
        digital cal

<u>We don’t have these capabilities now</u>



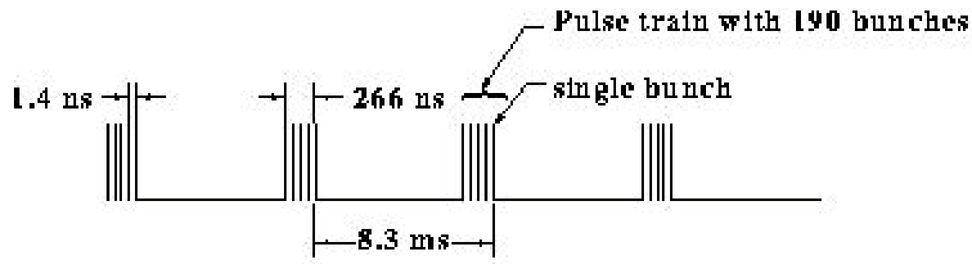
Beamline Issues

- Bunch structure
- IR layout and masks
- Small spot size issues
- Beam-beam interactions

IR Issues

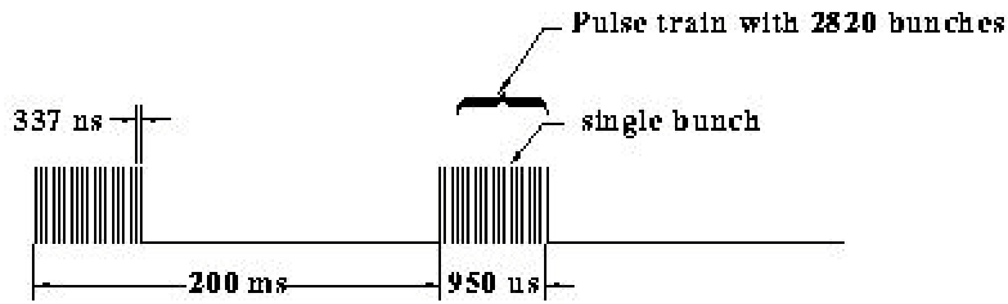
Time structure

NLC (JLC)



a. NLC/JLC 120 pulse trains/sec

Tesla



b. TESLA 5 pulse trains/sec

IR Issues

NLC (JLC)

190 bunches/train ⇒ 1.4 ns bunch spacing

⇒ 0.27 μsec long train

might want to time-stamp within train?

⇒ crossing angle (20 mrad) - (8 mrad for JLC)

Tesla

2820 bunches/train ⇒ 950 μsec long

much higher duty cycle (how to handle?)

no crossing angle, but could have one

IR Issues

Solenoid effects

transverse component of solenoid must be compensated - straight forward

NLC - L Detector

IR Layout

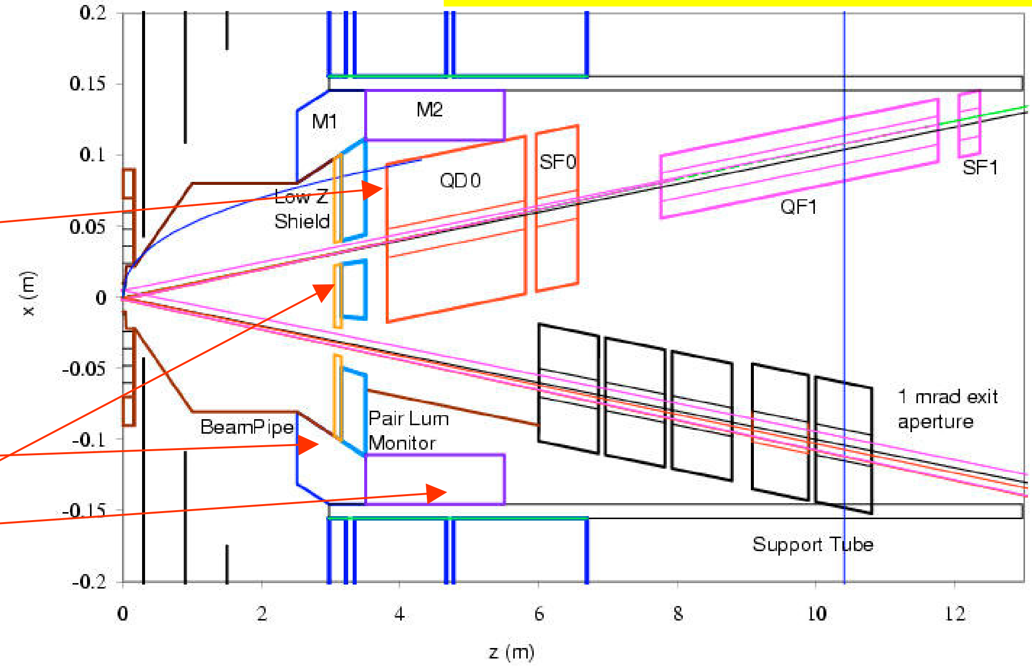
$L^* = 3.8$ m

Masks

M1 - W/Si

M2 - W

Low-Z



IR Issues

Small spot size issues

nm vertical stability required

⇒ permanent magnets for QD0 and QF1

passive compliance + active suppression

15 ns response within bunch train (NLC)

Beam-beam interaction

broadening of energy distribution (beamstrahlung)

~5% of power at 500 GeV

backgrounds

e^+e^- pairs

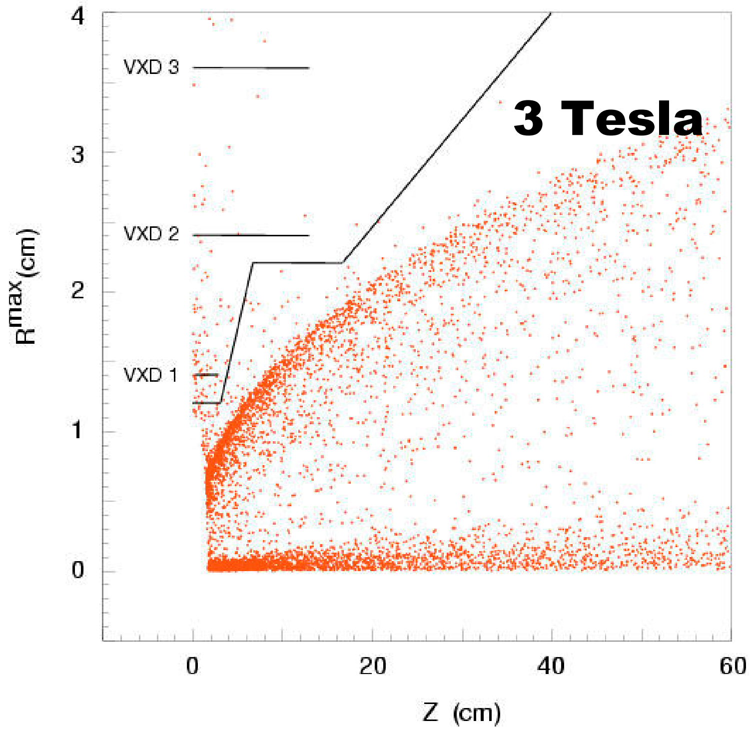
radiative Bhabhas

low energ tail of disrupted beam

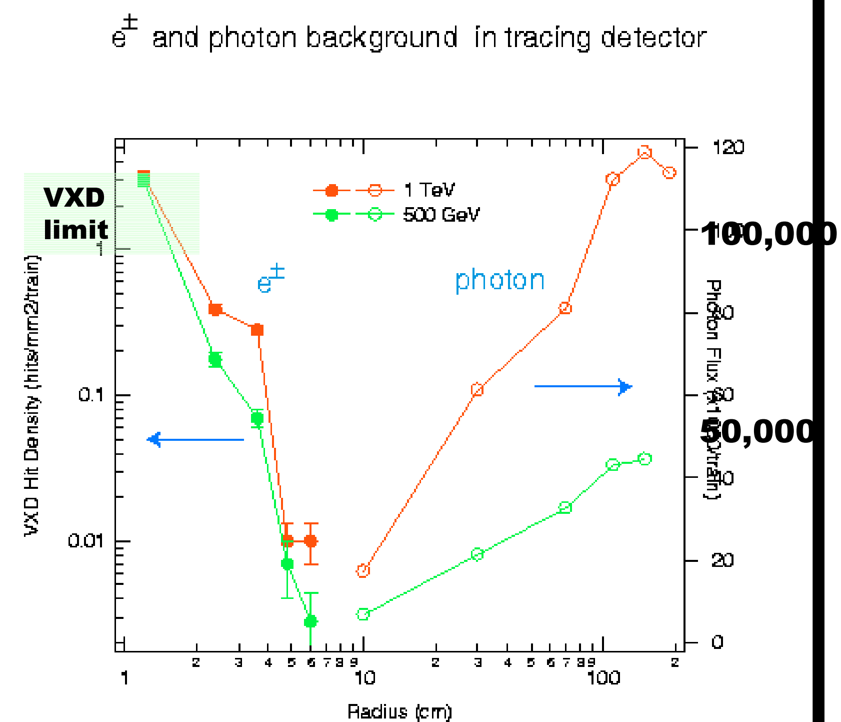
neutron "back-shine" from dump

hadrons from gamma-gamma

IR Issues

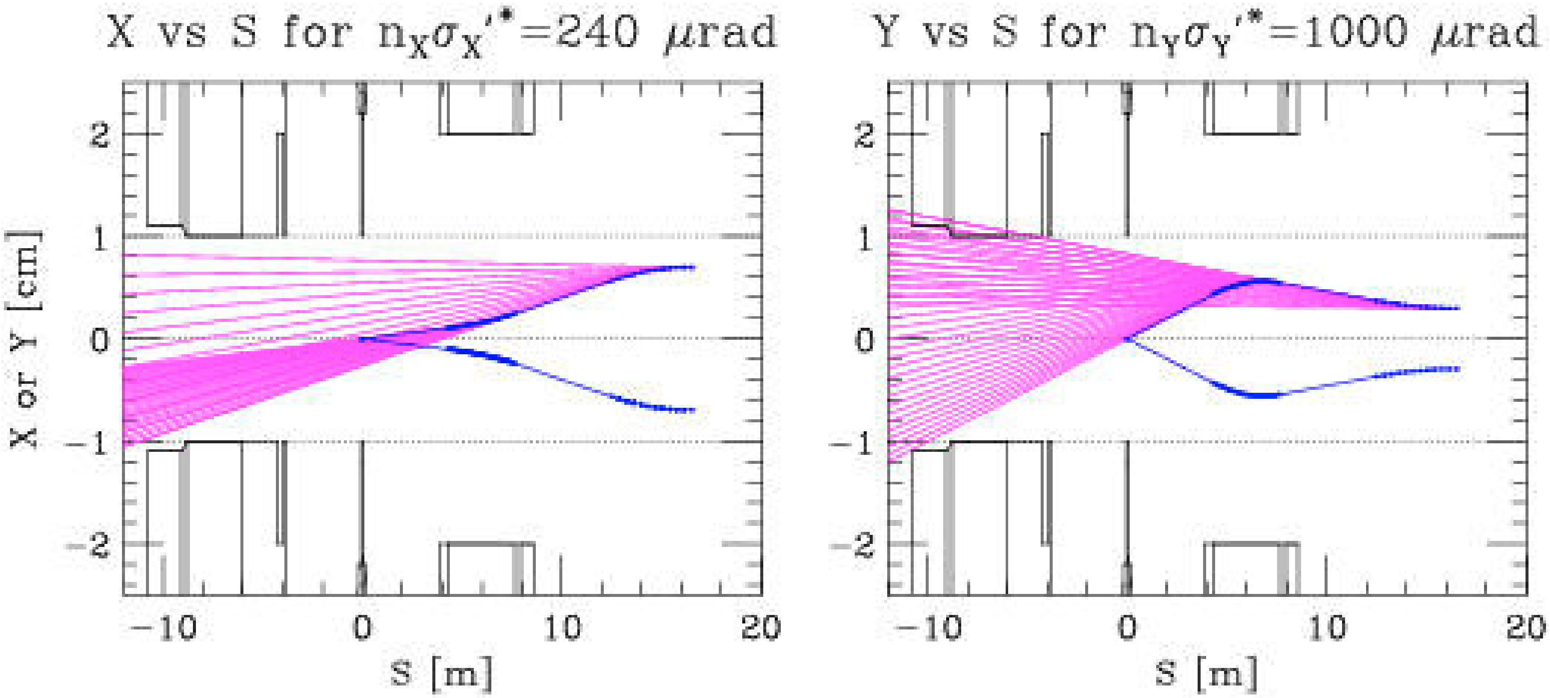


e^+e^- pairs



Hits/bunch train/mm² in VXD, and photons/train in TPC

IR Issues

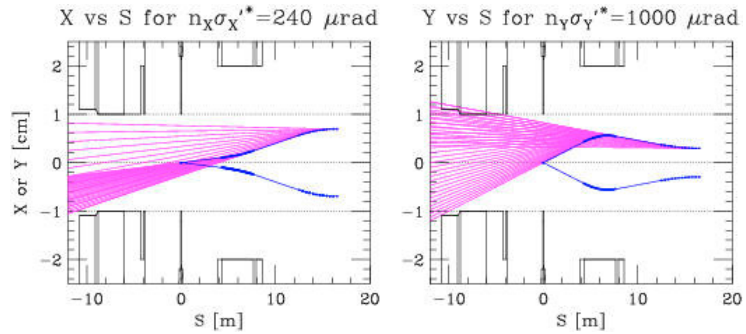


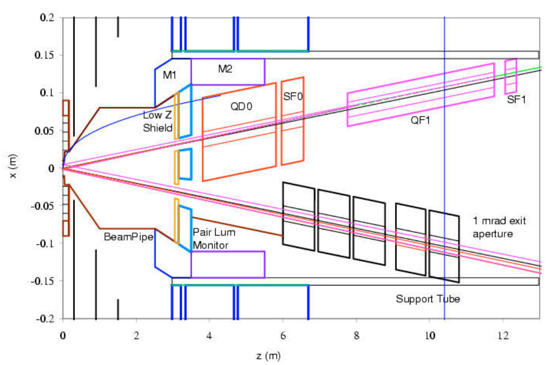
Synchrotron radiation photons from beam halo in the final doublet

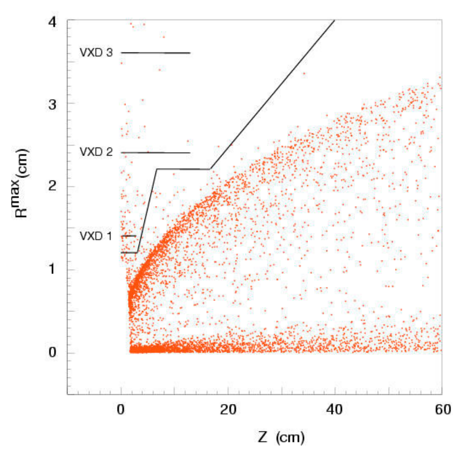
halo limited by collimation system

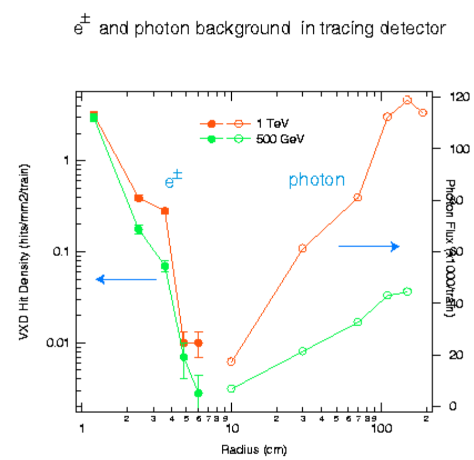
IR Issues

The experimenters (us) must pay attention to these issues, work with the accelerator physicists to minimize them, and prepare to live with what's left





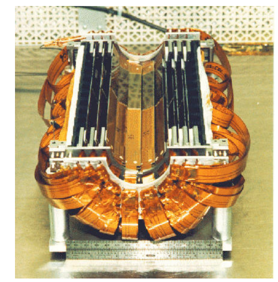




Detector Requirements

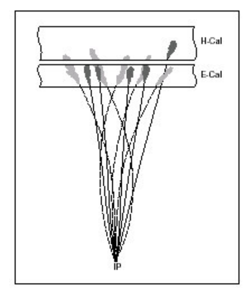
Vertex Detector

physics motivates excellent efficiency and purity
large pair background from beamstrahlung
→ large solenoidal field (≥ 3 Tesla)
pixelated detector [(20 μm)^2 → 2500 pixels/mm^2]
min. inner radius (< 1.5 cm), ~5 barrels, < 4 μm resol,
thickness < 0.2 % X_0

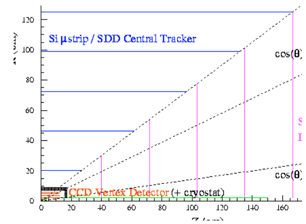


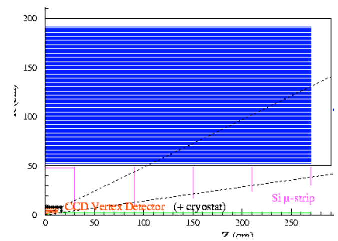
Calorimetry

excellent jet reconstruction
eg. W/Z separation
use energy flow for best resolution
(calorimetry and tracking work together)
fine granularity and minimal Moliere radius
charge/neutral separation → large BR^2



Detector Requirements





<u>Tracking</u>

robust in Linear Collider environment
isolated particles (e charge, μ momentum)
charged particle component of jets
    jet energy flow measurements
assists vertex detector with heavy quark tagging
forward tracking (susy and lum measurement)

<u>Muon system</u>

<u>high efficiency</u> with small backgrounds
secondary role in calorimetry ("tail catcher")

<u>Particle ID</u>

dedicated system <u>not</u> needed for primary HE physics goals
particle ID built into other subsystems (eg. dE/dx in TPC)

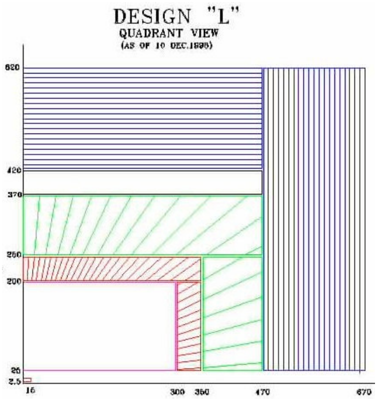
Beamline requirements

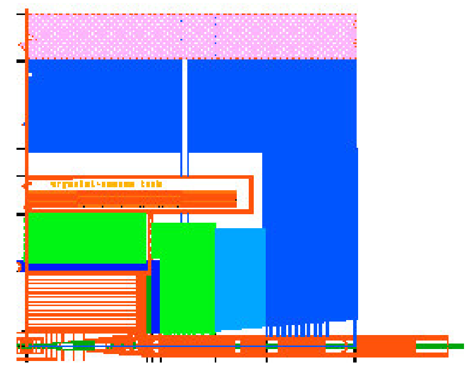
Beam energy measurement

- Need 50-100 MeV (10^{-4}) precision
  - SLD WISRD technique is probably adequate (needs work)
  - TESLA plans BPM measurement pre-IP (needs work)
- Luminosity spectrum
  - acolinearity of Bhabhas
  - question - can it be extracted from WISRD?
- What about effect of beam disruption

Polarization measurement

- SLD achieved 0.5% - same technique at NLC should give 0.25%
- TESLA plans only before IP (is this okay? NLC bias says no)
- Positron polarization helps dramatically





LC Detectors

several strawman detectors are under study

LC Detectors

Tesla TDR Detector

American (2 High Energy and 1 Low Energy)
- Snowmass LC Resource Book

1.) L
conventional large detector based on the early American L (Sitges/Fermilab LCWS studies)

2.) SD (silicon detector)
motivated by energy flow measurement

3.) P (low budget, trimmed-down version)

JLC Detector
3 Tesla detector

References: Particle Physics Experiments at JLC, hep-ph/.0109166; and http://acfahep.kek.jp
TESLA TDR, DESY 2001-011, hep-ph/0106315
Linear Collider Resource Book for Snowmass 2001, hep-ex/0106055-58

LC Detectors

TESLA TDR

- "pixel" vertex detector
- silicon/W EM calorimeter (energy-flow)
- 4 T coil

TESLA TDR, DESY 2001-011, hep-ph/0106315

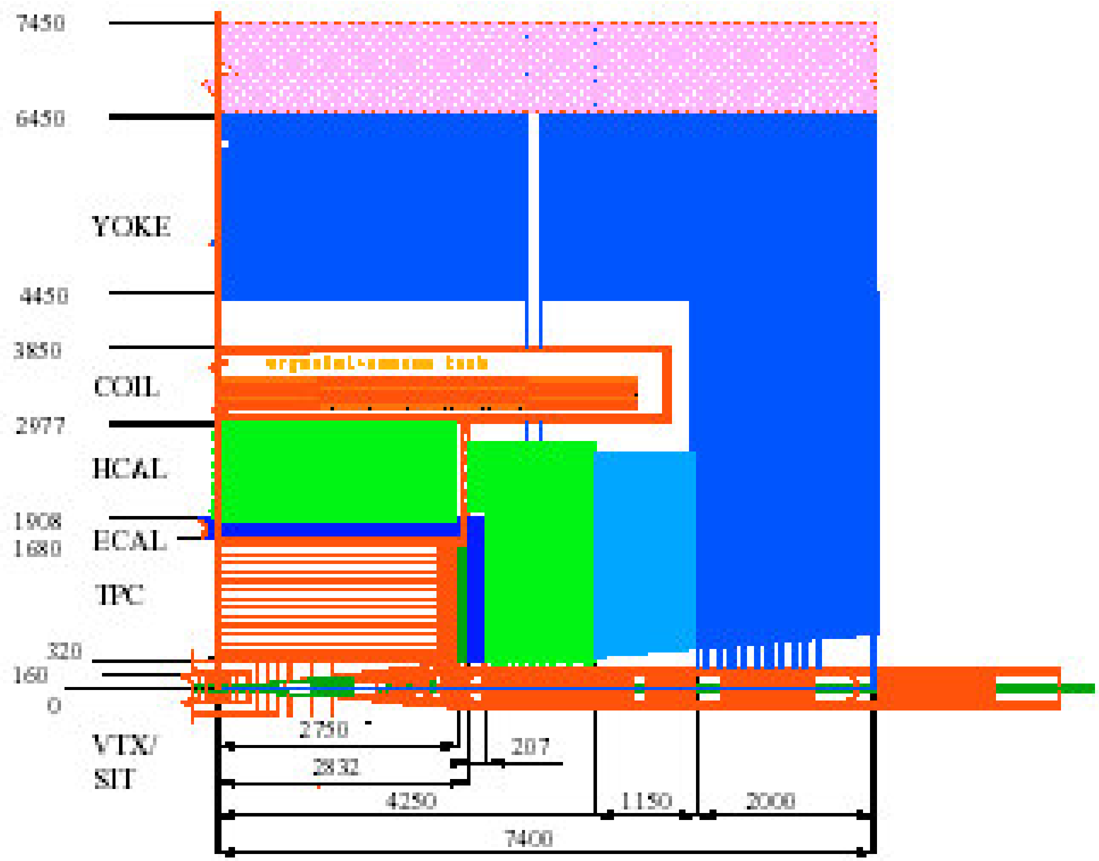
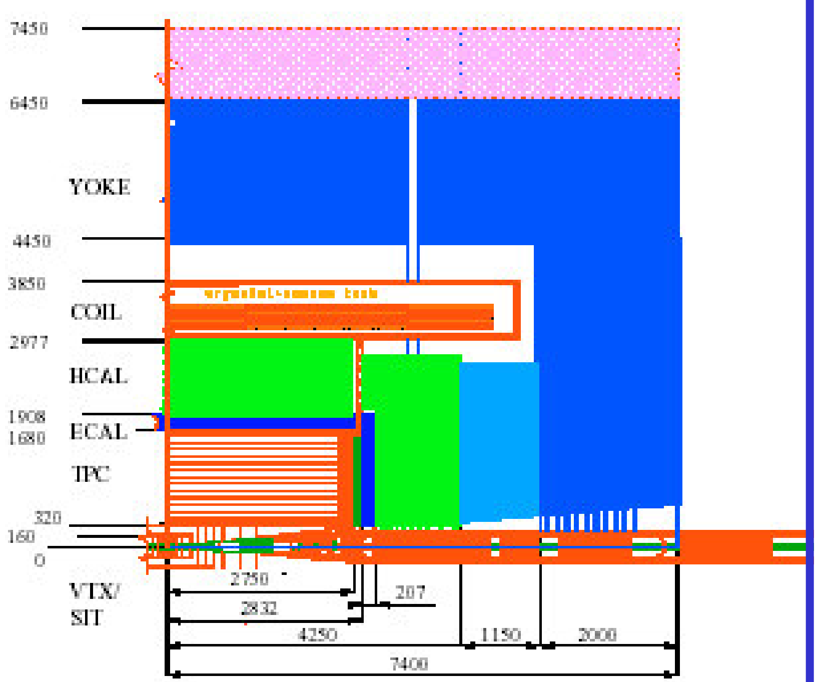


Figure 1.1.1: *View of one quadrant of the TESLA Detector. Dimensions are in mm.*

LC Detectors

- TESLA TDR

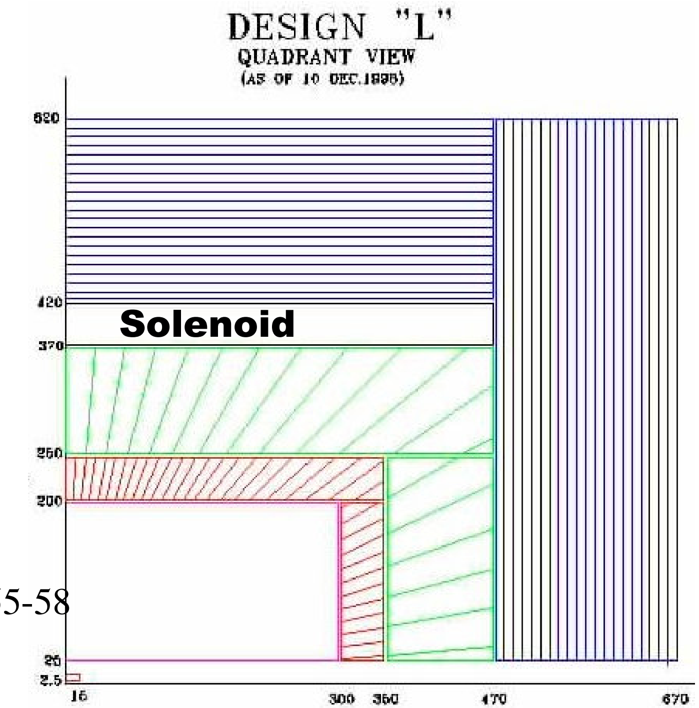


Subdetector	Goal	Technologies
Vertex Detector (VTX)	$\delta(IP_{r\phi,z}) \leq 5\,\mu m \oplus \frac{10\,\mu m\ GeV/c}{p \sin^{3/2}\theta}$	CCD, CMOS, APS
Forward Tracker (FTD)	$\frac{\delta p}{p} < 20\,\%$, $\delta_\theta < 50\,\mu rad$ for p=10-400 GeV/c down to $\theta \sim 100$ mrad	Si-pixel/strip discs
Central Tracker (TPC)	$\delta(1/p_t)_{TPC} < 2 \cdot 10^{-4} (GeV/c)^{-1}$ $\sigma(dE/dx) \leq 5\%$	GEM, Micromegas or wire readout
Intermediate Tracker (SIT)	$\sigma_{point} = 10\,\mu m$ improves $\delta(1/p_t)$ by 30%	Si strips
Forward Chamber(FCH)	$\sigma_{point} = 100\,\mu m$	Straw tubes
Electromag. Calo. (ECAL)	$\frac{\delta E}{E} \leq 0.10 \frac{1}{\sqrt{E(GeV)}} \oplus 0.01$ fine granularity in 3D	Si/W, Shashlik
Hadron Calo. (HCAL)	$\frac{\delta E}{E} \leq 0.50 \frac{1}{\sqrt{E(GeV)}} \oplus 0.04$ fine granularity in 3D	Tiles, Digital
COIL	4 T, uniformity $\leq 10^{-3}$	NbTi technology
Fe Yoke (MUON)	Tail catcher and high efficiency muon tracker	Resistive plate chambers
Low Angle Tagger (LAT)	83.1–27.5 mrad calorimetric coverage	Si/W
Luminosity Calo. (LCAL)	Fast lumi feedback, veto at 4.6–27.5 mrad	Si/W, diamond/W
Tracking Overall	$\delta(\frac{1}{p_t}) \leq 5 \cdot 10^{-5} (GeV/c)^{-1}$ systematics $\leq 10\,\mu m$	
Energy Flow	$\frac{\delta E}{E} \simeq 0.3 \frac{1}{\sqrt{E(GeV)}}$	

Table 1.3.1: *Detector performance goals for physics analyses for $\sqrt{s}$ up to $\sim$ 1 TeV.*

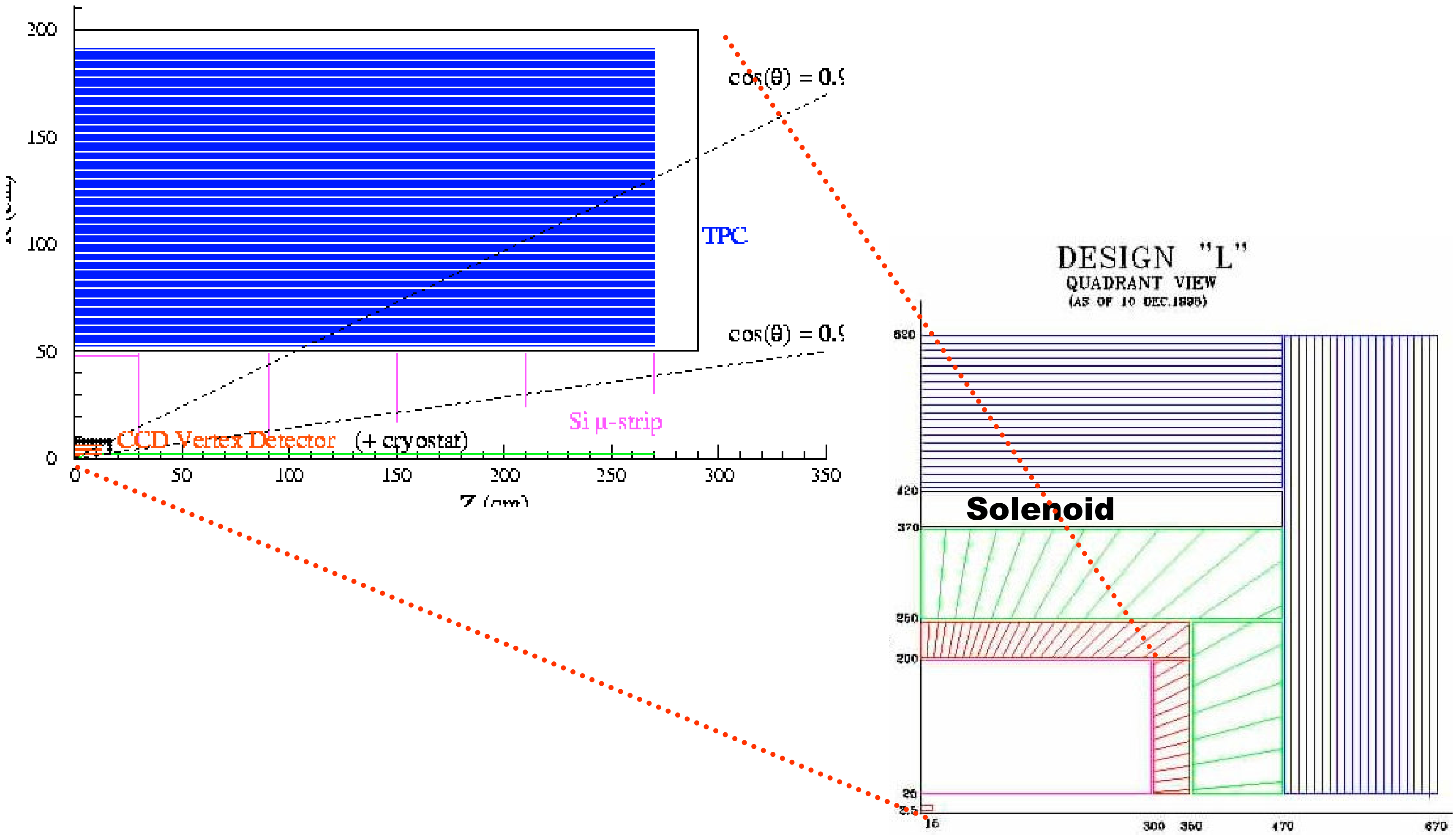
Resource Book L Detector

5 barrel CCD vertex detector
3 Tesla Solenoid
    outside hadron calorimeter
TPC Central Tracking (52 $\rightarrow$ 190 cm)
Intermediate Si strips at R=48 cm
Forward Si discs (5 each)
Pb/scintillator EM and Had calorimeter
    EM   40 x 40 mrad^2
    Had   80 x 80 mrad^2
Muon - 24 5 cm iron plates with gas
    chambers (RPC?)



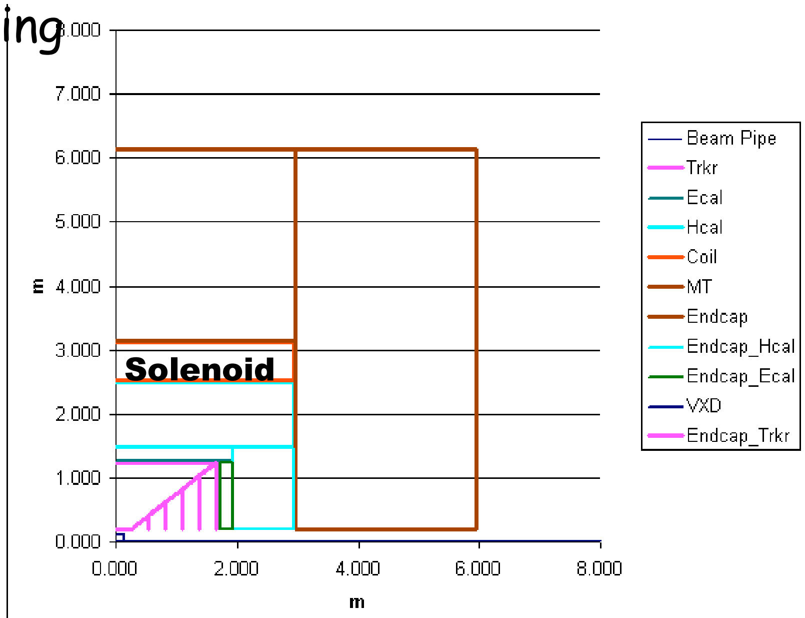
Linear Collider Resource Book for Snowmass 2001, hep-ex/0106055-58

Resource Book L Detector

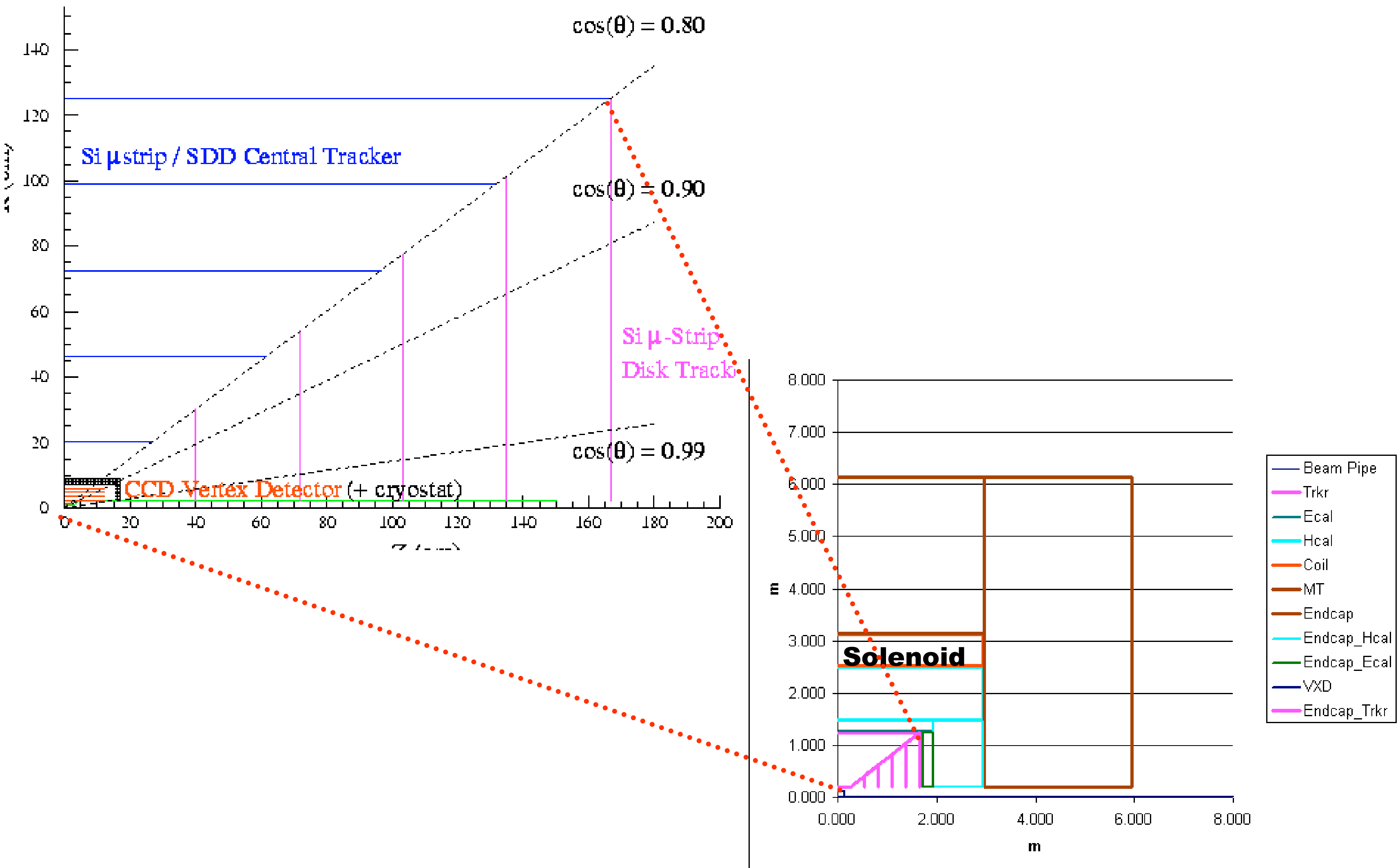


Resource Book SD Detector

5 barrel CCD vertex detector
5 Tesla Solenoid
    outside hadron calorimeter
Silicon strips or drift (20 → 125 cm) 5 layers
Forward Si discs (5 each)
W/silicon EM calorimeter
    0.5 cm pads with 0.7 X_0 sampling
and Cu or Fe Had calorimeter (4 λ)
    80 x 80 $mrad^2$
Muon - 24 5cm iron plates with
    gas chambers (RPC?)



Resource Book SD Detector



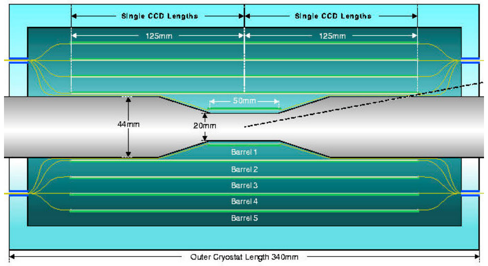
Resource Book High Energy Detector Comparison

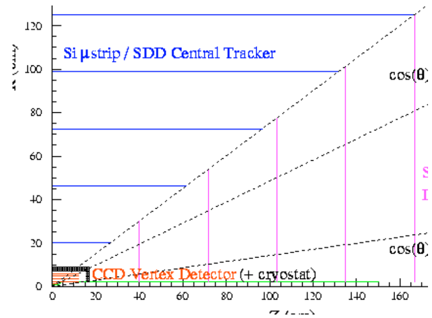
	L	SD
Solenoid	3 T	5 T
R(solenoid)	4.1 m	2.8 m
BR^2 (tracking)	12 m^2T	8 m^2T
R_M (EM cal)	2.1 cm	1.9 cm
trans.seg / R_M	3.8 0.6 (6th layer Si)	0.26
R_{max}(muons)	645 cm	604 cm

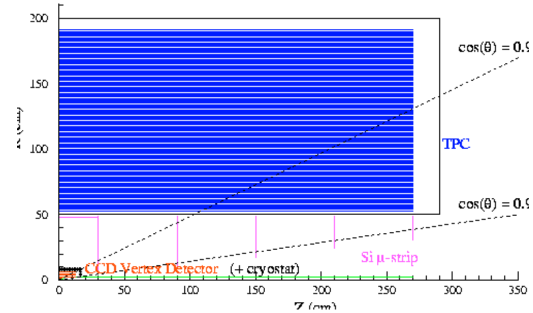
Resource Book P Detector

Designed for a low budget, reduced performance

5 barrel CCD vertex detector
3 Tesla Solenoid
    inside hadron calorimeter
TPC Central Tracking (25 $\rightarrow$ 150 cm)
Pb/scintillator or Liq. Argon EM
  and Hadronic calorimeter
    EM 30 x 30 $mrad^2$
    Had 80 x 80 $mrad^2$
Muon - 10 10cm iron plates w/ gas
    chambers (RPC?)

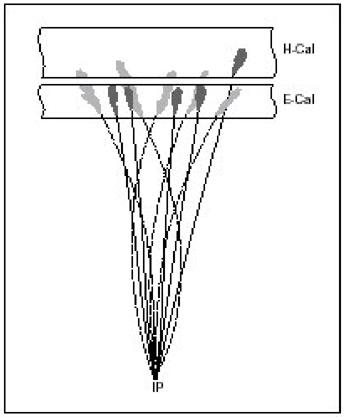






Subsystems

- Vertex Detector
- Tracker
- Calorimeter
- Muon Detector
- Beamline measurements



Vertex Detector

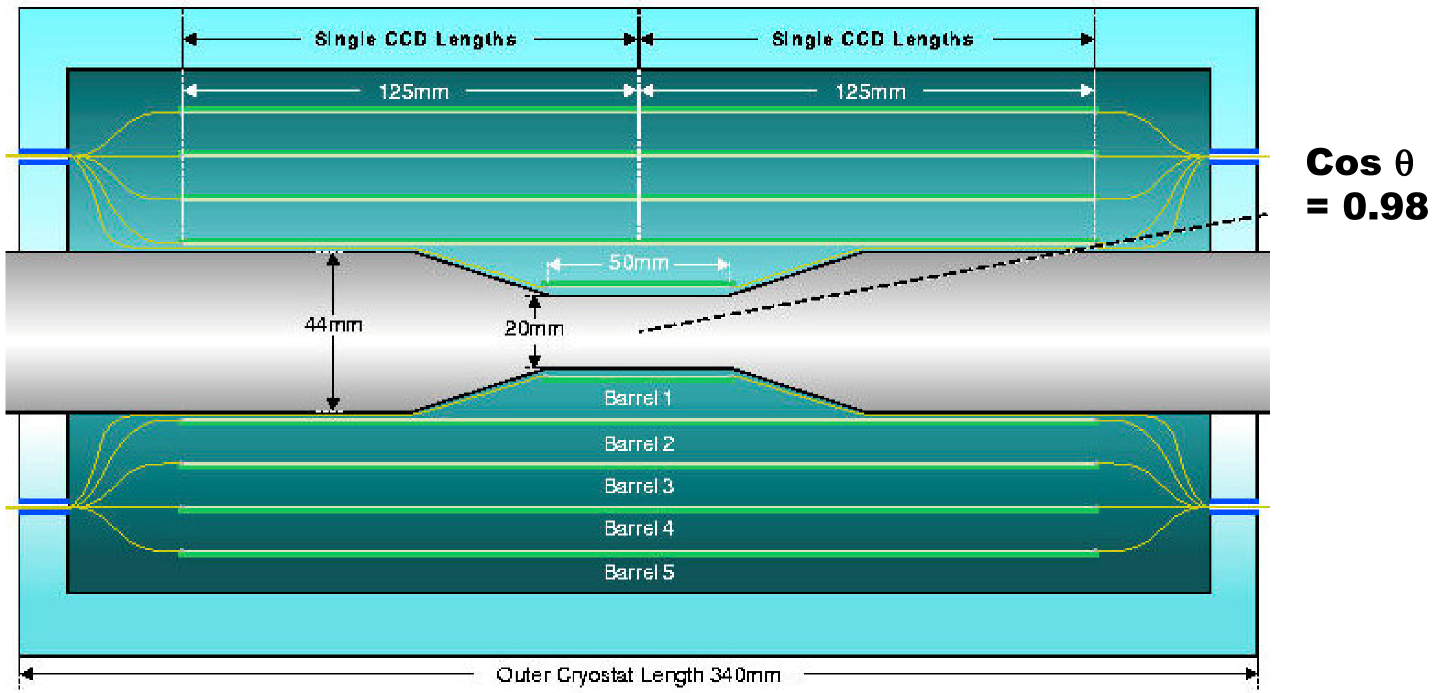
American L, SD, and P detectors assume the same CCD VXD

~700,000,000 pixels [20x20x20 $(\mu m)^3$]

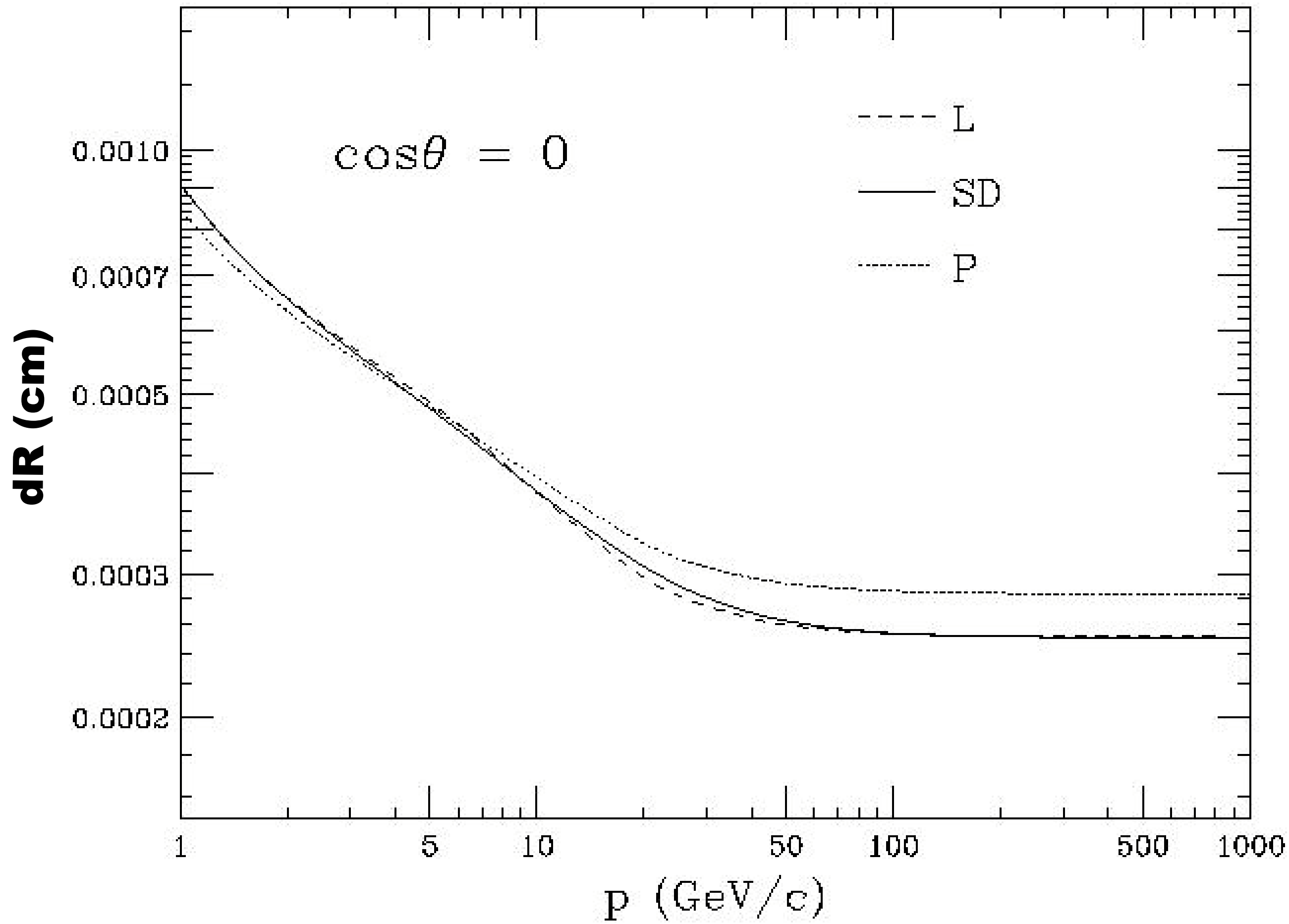
3 μm hit resolution

inner radius = 1.2 cm

5 layer stand-alone tracking

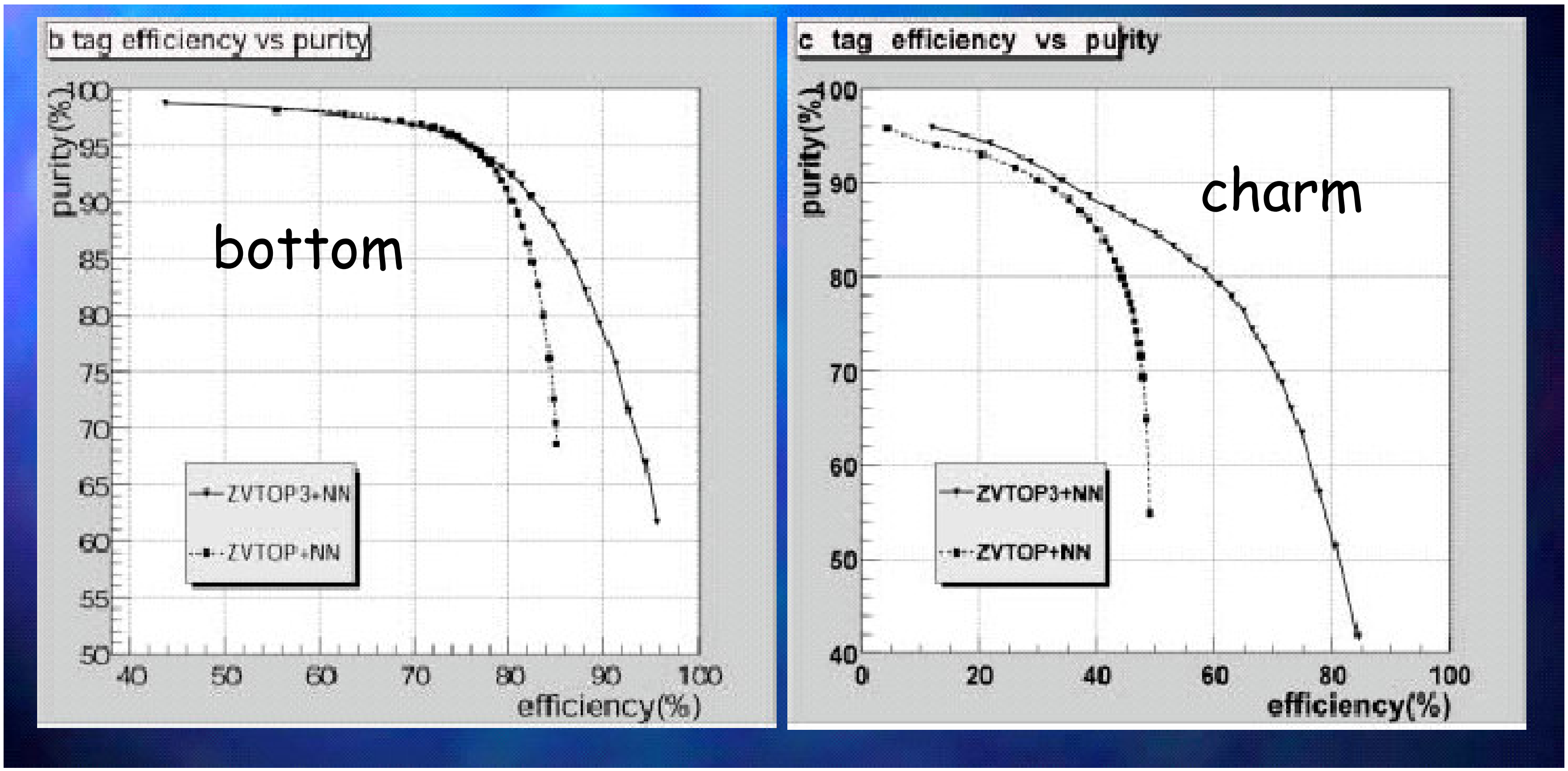


Impact Parameter Resolution



B. Schumm

Flavor Tagging



T. Abe

The R&D Program

Vertex Detector

The R&D program must include the following

resolve discrepancy in Higgs BR studies
understand degradation of flavor tagging with real physics events compared to monojets (as seen in past studies)
understand requirements for inner radius, and other parameters
- **what impact on physics**
- **what impact on collider if minimize inner radius?**

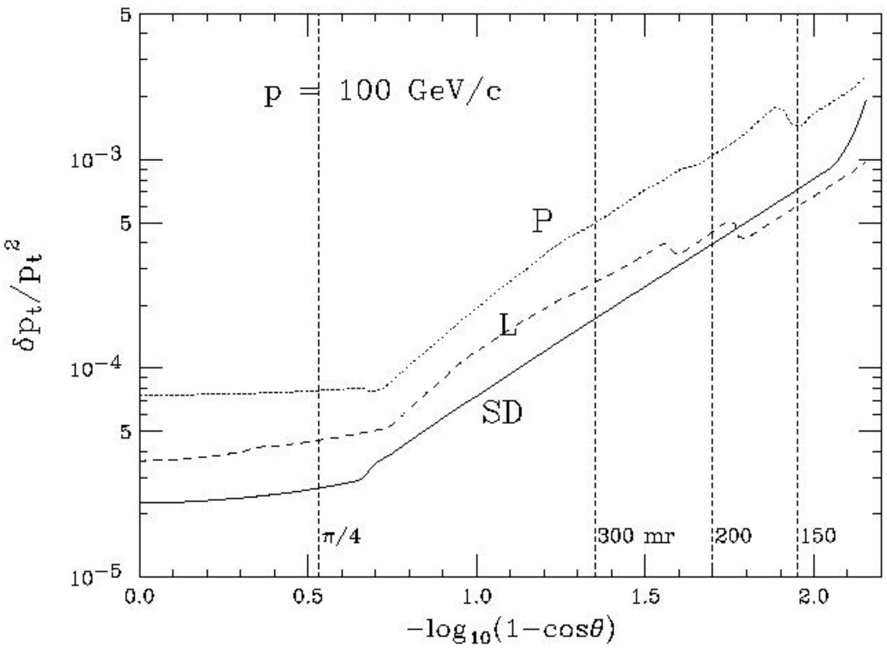
segmentation requirements (two track resolution)
- **500 GeV u,d,s jets**
- **pixel size**

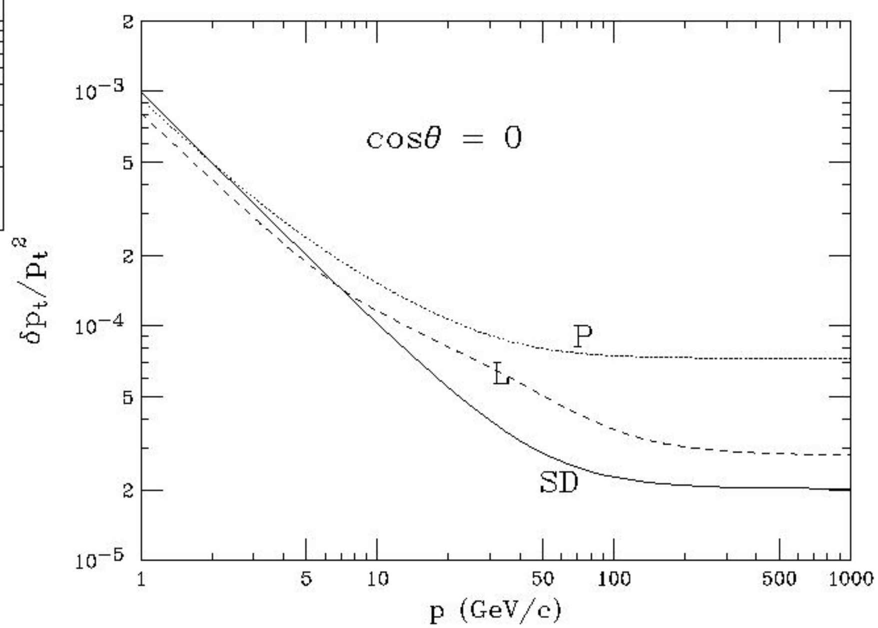
develop hardened CCDs
develop CCD readout, with increased bandwidth
develop very thin CCD layers (eg. stretched)
investigate alternatives to CCDs

Tracking

	L	SD	P
Inner Radius	50 cm	20 cm	25 cm
Outer Radius	200 cm	125 cm	150 cm
Layers	144 TPC	5 Si drift or μstrips	122 TPC
Fwd Disks	5 double-sided Si	5 double-sided Si	5 double-sided Si
B(Tesla)	3	5	3

Tracking Resolution





B. Schumm

The R&D Program

Tracking

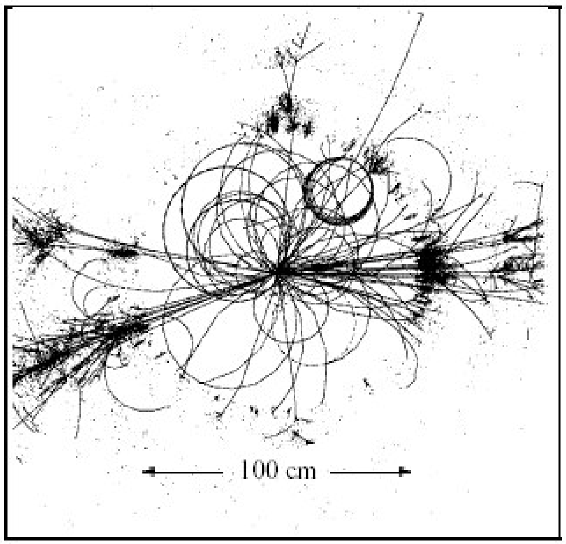
The R&D program must include this list

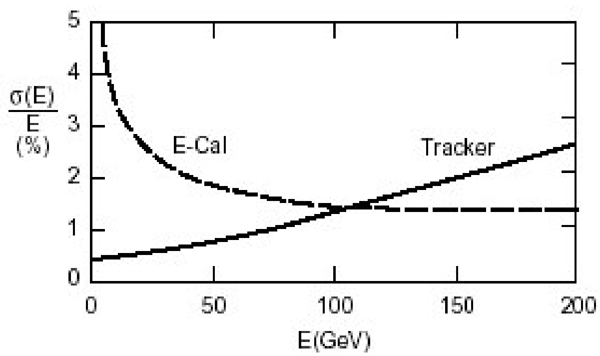
refine the understanding of backgrounds
tolerance of trackers to backgrounds
    will large background be a problem for the TPC (field distortions, etc)
    are ionic space charge effects understood?
study pattern recognition for silicon tracker (include vxd) (2D vs. 3D)
study alignment and stability of silicon tracker
what momentum resolution is required for physics,
    eg. Higgs recoil, slepton mass endpoint, low and high energy
understand tracker material budget on physics
physics motivation for dE/dx (what is it?)
detailed simulation of track reconstruction, especially for a silicon option,
    complete with backgrounds and realistic inefficiencies
    include CCDs (presumably) in track reconstruction
timing resolution
readout differences between Tesla/NLC time structure
role of intermediate layer
tracking errors in energy flow (study with calorimeter)
forward tracking role with TPC
alignment (esp. with regard to luminosity spectrum measurement)
develop thorough understanding of trade-offs in TPC, silicon options
large volume drift chamber (being developed at KEK)
development of large volume TPC (large European/US collaboration at work)
development of silicon microstrip and silicon drift systems
    (being developed in US & Japan)
study optimal geometry of barrel and forward system
two track resolution requirements (esp. at high energy)
    this impacts calorimetry - how much?
study K^0 and Λ efficiencies (impacts calorimetry?)

Calorimeters

	L	SD	P
EM Tech	**Pb/scin (4mm/1mm)x40**	**W/Si (2.5mm/gap)x40**	**Pb/scin (4mm/3mm)x32**
Had Tech	**Pb/scin**	**Cu or Fe/RPC (or Pb)**	**Pb/scin**
Inner Radius	**196 cm**	**127 cm**	**150 cm**
EM-outer Radius	**220 cm**	**142 cm**	**185 cm**
HAD-outer Radius	**365 cm**	**245 cm**	**295 cm**
Solenoid Coil	**outside Had**	**outside Had**	**between EM/Had**
EM trans. seg.	**40 mr**	**4 mr**	**30 mr**
Had trans. seg.	**80 mr**	**80 mr**	**80 mr**

Calorimeters





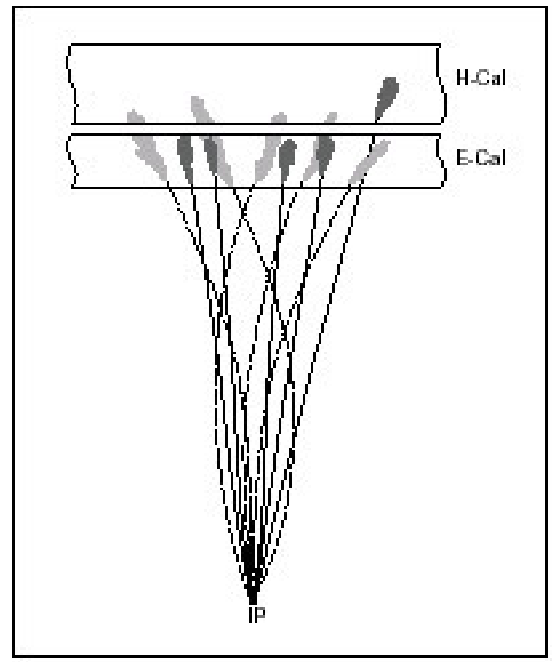
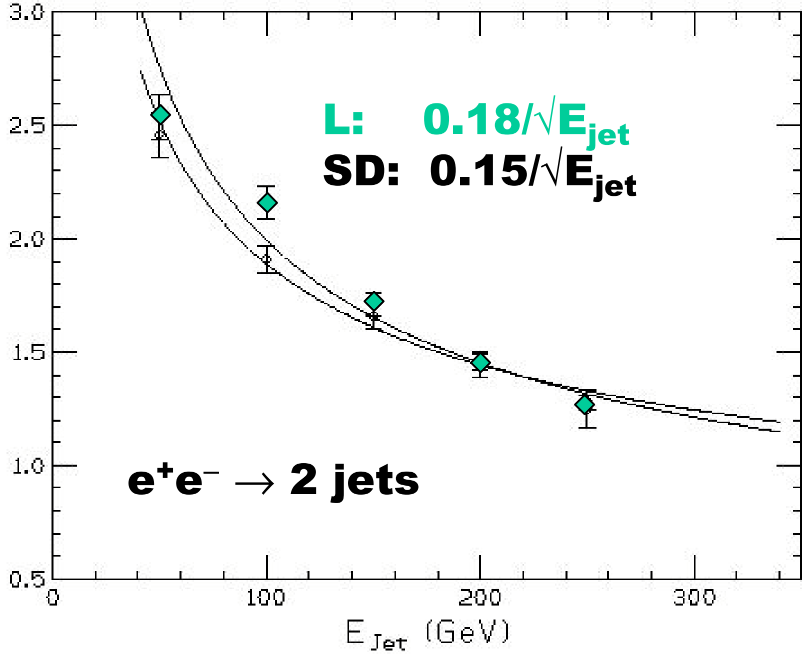


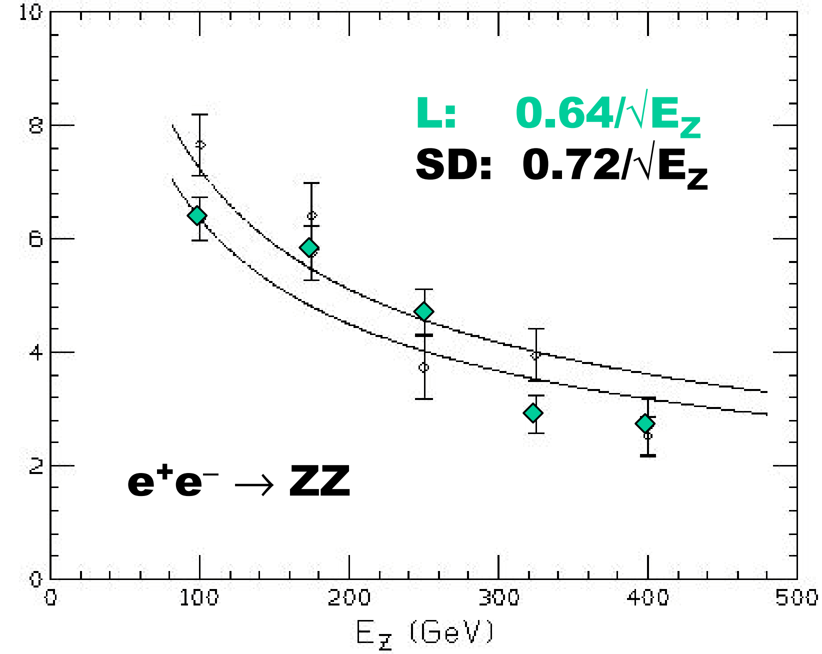
Fig. 3 Separation of charged and neutral particles in calorimeters

Calorimeter Resolution

Jet energy resolution



Di-jet mass resolution



These are idealized studies, and resolutions will be worse.

R. Frey

EM resolution:

L: $\sigma_{EM} / E = (17\% / \sqrt{E}) \oplus (\sim 1\%)$

SD: $\sigma_{EM} / E = (18\% / \sqrt{E}) \oplus (\sim 1\%)$

The R&D Program

Calorimetry

The R&D program must address these issues

energy flow
need detailed simulation
followed by prototype beam test demonstration
further develop physics cases for excellent energy flow
eg. Higgs self-coupling, WW/ZZ at high energy, recon of top and W
for anomalous couplings?, others (SUSY, BR(H>160))
integrate E-flow with flavor tagging
study readout differences for Tesla/NLC
importance of K0/Lambda in energy flow calorimeter
parametrize E-flow for fast simulation
forward tagger requirements
study effect of muons from collimators/beamline
further development of simulation
clustering
tracking in calorimeter
digital calorimeter
study parameter trade-offs (R seg, layers, coil location, transverse seg.)
in terms of general performance parameters
in terms of physics outcome
refine fast-sim parameters from detailed simluation
integrate electronics with silicon detectors in Si/W
reduce silicon detector costs
engineer reduced gaps
mechanical/assembly issues
B = 5 Tesla?
can scintillating tile Ecal compete with Si/W in granularity, etc.?
crystal EM (value/advantages/disadvantages)
barrel/endcap transition (impact and fixes)

Muon Detection

Model L

24×5 cm Fe plates + RPCs

$\sigma_{r\theta} \approx 1$ cm (x 24) $\sigma_z \approx 1$ cm (x 4)

coverage to ~ 50 mrad

Model SD

24×5 cm Fe plates + RPCs

$\sigma_{r\theta} \approx 1$ cm (x 24) $\sigma_z \approx 1$ cm (x 4)

coverage to ~ 50 mrad

Model P

10×10 cm Fe plates + RPCs

$\sigma_{r\theta} \approx 1$ cm (x 10) $\sigma_z \approx 1$ cm (x 2)

coverage to ~ 50 mrad

The R&D Program

The R&D program must include the following

Muons

requirements for purity/efficiency vs. momentum on physics channels
understand role in energy flow (work with calorimetry)
- **detailed simulation**
- **prototype beam tests**

mechanical design of muon system
development of detector options, including scintillator and RPCs

The R&D Program

The R&D program must include the following:

Beamline, etc.

luminosity spectrum measurement
beam energy measurement
polarization measurement
positron polarization
systematics of the Blondel scheme
veto gamma-gamma very forward system

General

is calibration running at Z^0 peak essential/useful/useless?
design a 4-5 Tesla coil

Comment

In general it would be good if more work was done exercising the simulation code that has been put together under the leadership of Norman Graf. Much work has been devoted toward developing a detailed full simulation.

American Linear Collider Physics Group
Working Groups

Detector and Physics Simulations:
Norman Graf/Mike Peskin

Vertex Detector:
Jim Brau /Natalie Roe

Tracking:
Bruce Schumm/Dean Karlen/Keith Riles

Particle I.D.:
Bob Wilson

Calorimetry:
R. Frey/A. Turcot/D. Chakraborty

Muon Detector:
Gene Fisk

DAcq, Magnet, and Infrastructure:

Interaction Regions, Backgrounds:
Tom Markiewicz/Stan Hertzbach

Beamline Instrumentation:
M. Woods /E. Torrence/D. Cinabro

Higgs:
R. Van Kooten/M. Carena/H. Haber

SUSY:
U. Nauenberg/J. Feng /F. Paige

New Physics at the TeV Scale and Beyond:
J. Hewett/D. Strom/S. Tkaczyk

Radiative Corrections (Loopverein):
U. Baur/S. Dawson/D. Wackeroth

Top Physics, QCD, and Two Photon:
Lynn Orr/Dave Gerdes

Precision Electroweak:
Graham Wilson/Bill Marciano

gamma-gamma, e-gamma Options:
Jeff Gronberg/Mayda Velasco

e-e-:
Clem Heusch

LHC/LC Study Group

NLC Cost Estimates

In preparation for Snowmass 2001, the working groups developed an estimate of the expected detector costs

General considerations:

- **Based on past experience**
- **Contingency = ~ 40%**
- **Designs constrained**

High Energy IR

L	**359.0 M$**
SD	**326.2 M$**

Low Energy IR

P	**210.0 M$**

NLC Cost Estimates

	L	SD	P
1.1 Vertex	4.0	4.0	4.0
1.2 Tracking	34.6	19.7	23.4
1.3 Calorimeter	48.9	60.2	40.7
1.3.1 EM	(28.9)	(50.9)	(23.8)
1.3.2 Had	(19.6)	(8.9)	(16.5)
1.3.3 Lum	(0.4)	(0.4)	(0.4)
1.4 Muon	16.0	16.0	8.8
1.5 DAQ	27.4	52.2	28.4
1.6 Magnet & supp	110.8	75.6	30.5
1.7 Installation	7.3	7.4	6.8
1.8 Management	7.4	7.7	7.4
SUBTOTAL	256.4	242.8	150.0
1.9 Contingency	102.6	83.4	60.0
Total	359.0	326.2	210.0

The R&D Program

- There is much work to do - let's get going
- We have identified many of the issues
  - no doubt, this list is incomplete, but strategies are beginning to be formulated to address them,
  - within the ALCPG working groups and the "consortia"
- The report from the International R&D committee reviews the R&D activities
      - http://blueox.uoregon.edu/~jimbrau/LC/LCrandd.ps
  - Please review this draft report (it is a first attempt)
  - send comments to the committee by June 15
  - the report will then be updated

Coming Meetings

- North American
  - June 27-29, UC-Santa Cruz
- Other regions
  - July 10-12, Tokyo, Japan (5th ACFA Workshop)
  - (ECFA/DESY met April 12-15 in St. Malo, France)
- Inter-regional
  - August 26-30, Jeju Is., Korea (LCWS 2002)

Santa Cruz Linear Collider Retreat

June 27th - 29th 2002

- The parallel session on the 28th will include
  - 1.) organize an evaluation of key issues relating to the choice of detector and accelerator technology
  - 2.) coordinate the on-going and proposed R&D efforts; all planned participates are encouraged to give brief reports on their intentions during the parallel sessions at Santa Cruz

Physics and Detector Groups will begin evaluation of

initial and eventual energy reach
integrated luminosity
positron polarization
    how much is needed/useful
gamma-gamma collisions
electron-gamma collisions
electron-electron collisions

energy spectrum
beam bunch structure
other collider parameters

University of California Santa Cruz

Conclusions

The goals for the Linear Collider Detectors will push the state-of-the-art in a number of directions.

eg. finely segmented calorimetry for energy-flow measurement
pixel vertex detectors (approaching a billion pixel system)
integrated readout

Many detector issues remain to be understood and developed.

Please get involved in the effort and help us prepare for the experiments

come to the Santa Cruz LC Retreat, June 27-29