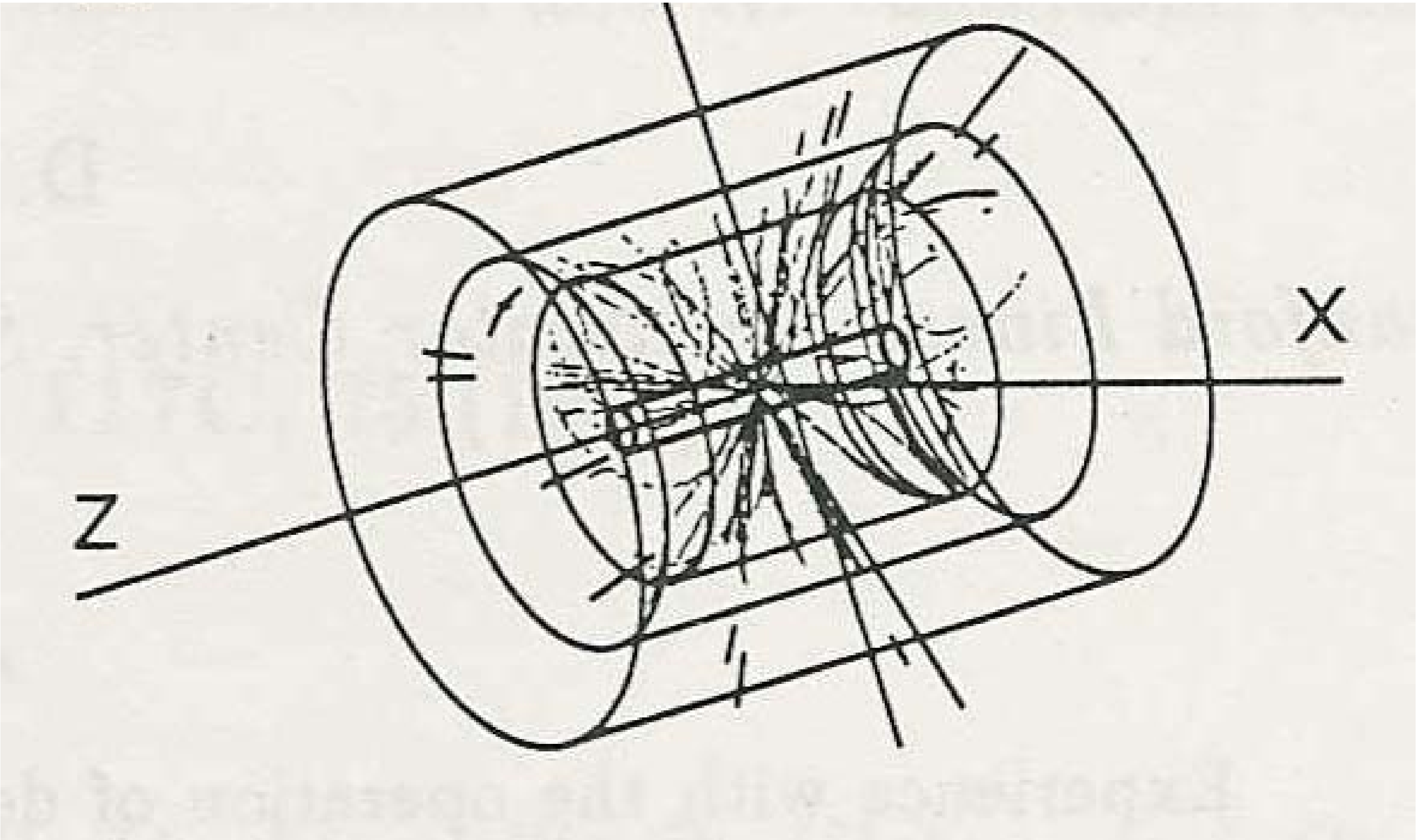
Vertex Detectors and the Linear Collider

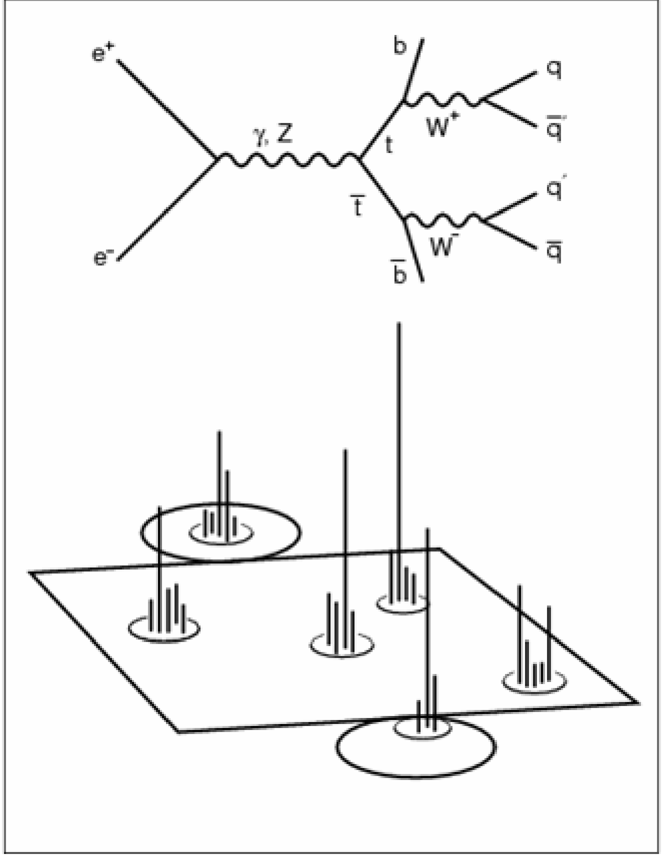
Chris Damerell
Rutherford Appleton Lab

- **What is their purpose?** *(still somewhat contentious, long after LCWS 1991!)*
- **General principles of vertex detector design, and prospects for ILC**
- **What specific technology to use?**
- **How not to be blown away by 10^9 pixels – electromagnetic interference, signal sampling, and other issues**
- **How can we get to ILC physics, from where we are now?**

What are vertex detectors for?



- Dave Burke, LCWS 1991
- Particle flow *almost* reveals the underlying Feynman diagram …



- **Vertex detector will *tag b and c jets and tau leptons* with high efficiency (reducing background, both combinatoric and from other multi-jet processes)**

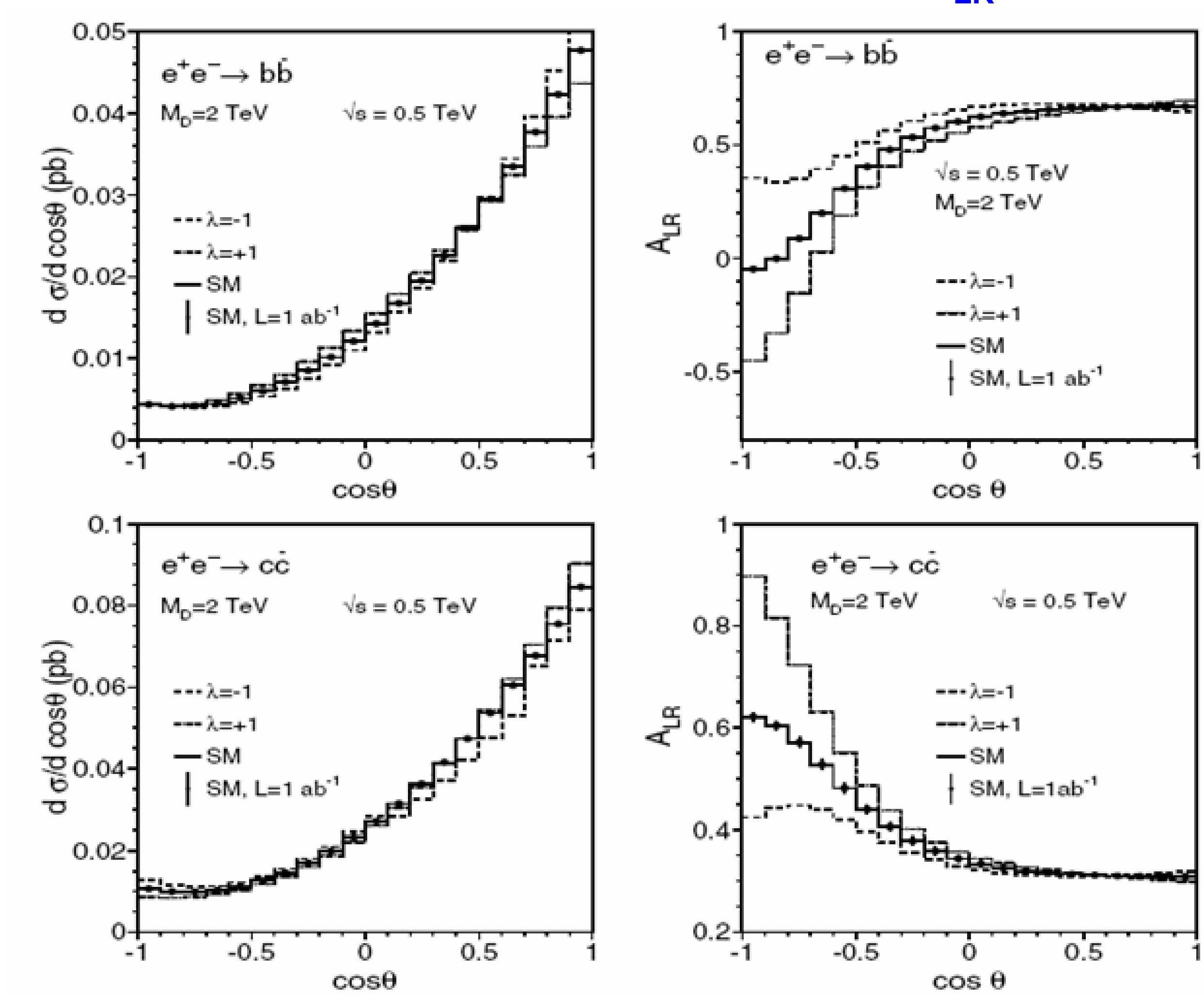
- **Will also efficiently perform *heavy quark sign selection,* via measurement of the *vertex charge* (net charge of 'displaced vertex') – new from SLD**

$e^+e^- \to q\bar{q}$ at max $\sqrt{s}$

- **e+e- → q qbar differential cross-sections for L and R-polarised electrons at max sqrt(s), as probe of BSM processes**
- **Sabine Riemann, 'Fermion-pair production at a linear collider – a sensitive tool for new physics searches' [LC-TH-2001-007]**
- **Sensitive to Z', leptoquarks, R-parity violating scalar particles, and extra spatial dimensions**
- **Requires efficient quark charge sign-selection out to large |cos theta|**

Sabine Riemann: one example for large ED, sqrt(s) = 0.5 TeV

e_L 1 ab^{-1} A_{LR}

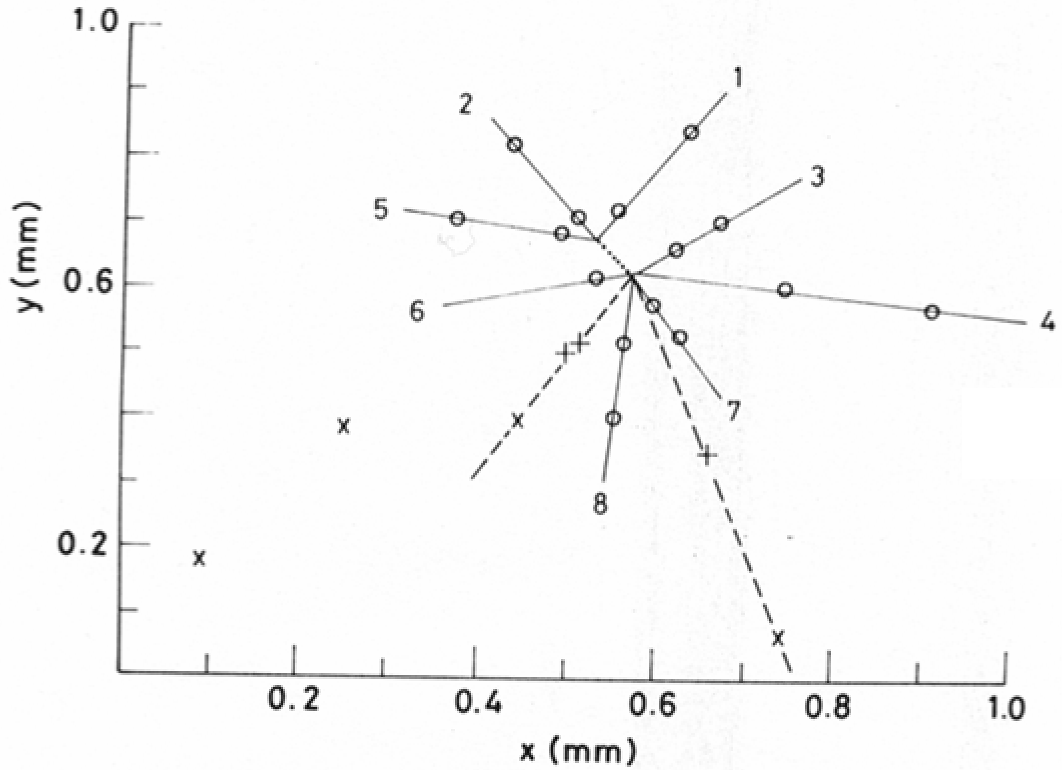


$e^+e^- \to b\bar{b}$

$e^+e^- \to c\bar{c}$

For these channels, sensitivity extends to M_D around 5 TeV
For muon pairs, effects are much weaker (not measurable even with 1 ab^{-1} of data)

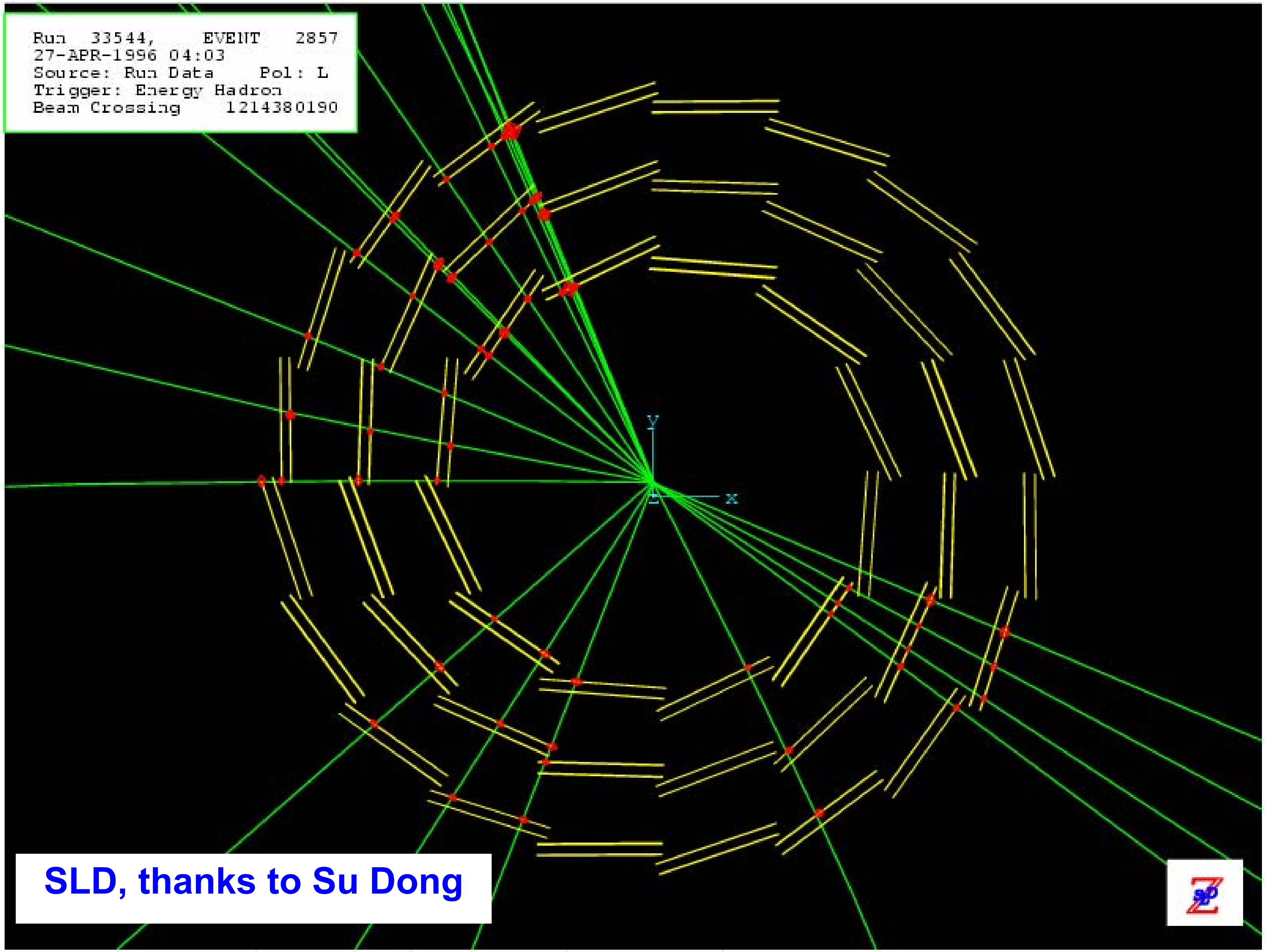
General design principles

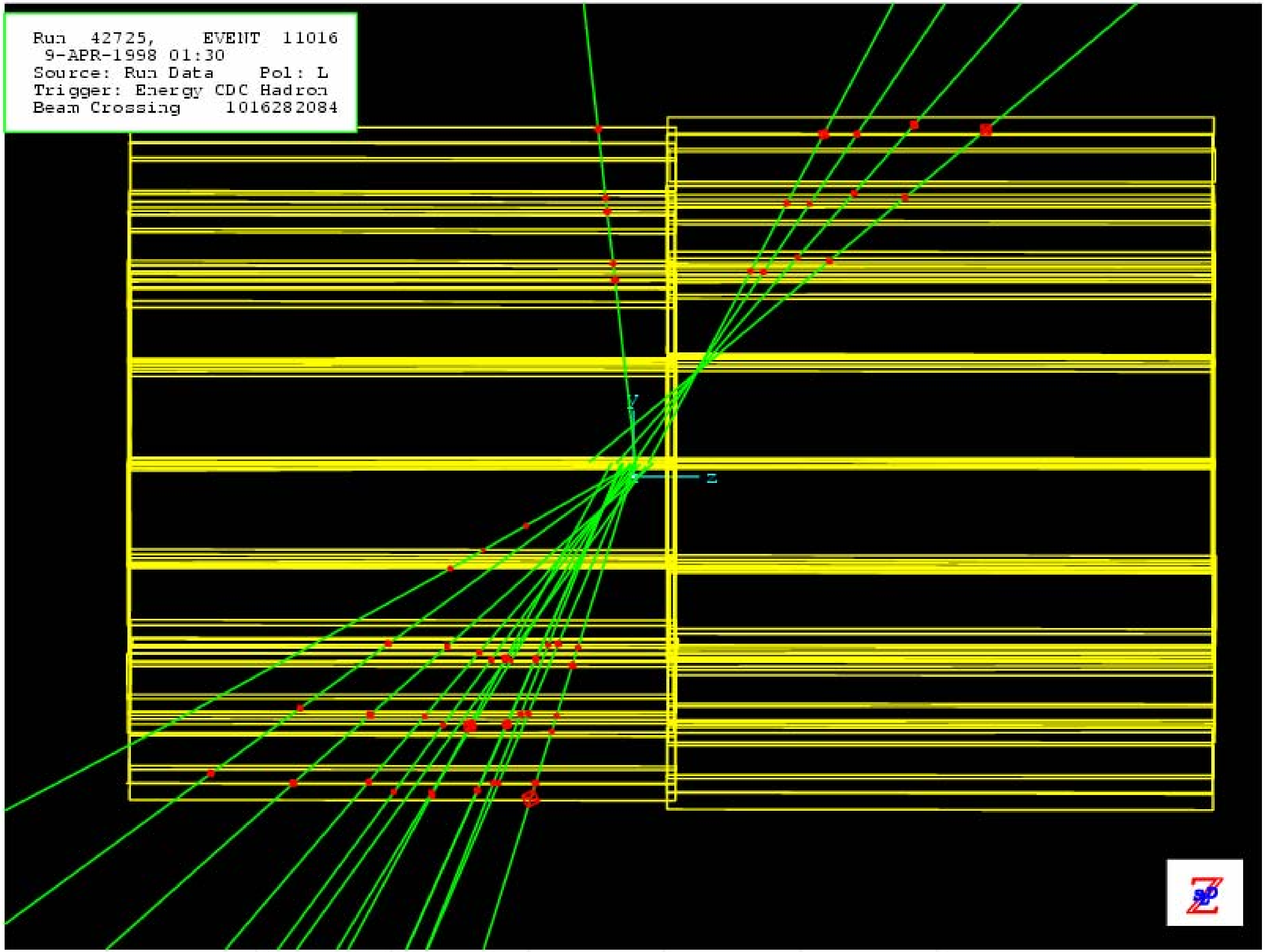


NA32, 1985

- Fixed target experiments were much easier!

- For the collider environment, the 'adequate' vertex detector has yet to be built – hence numerous options and constant upgrades


Run 33544, EVENT 2857
27-APR-1996 04:03
Source: Run Data Pol: L
Trigger: Energy Hadron
Beam Crossing 1214380190
y
x
SLD, thanks to Su Dong


Run 42725, EVENT 11016
9-APR-1998 01:30
Source: Run Data Pol: L
Trigger: Energy CDC Hadron
Beam Crossing 1016282084
Y
Z

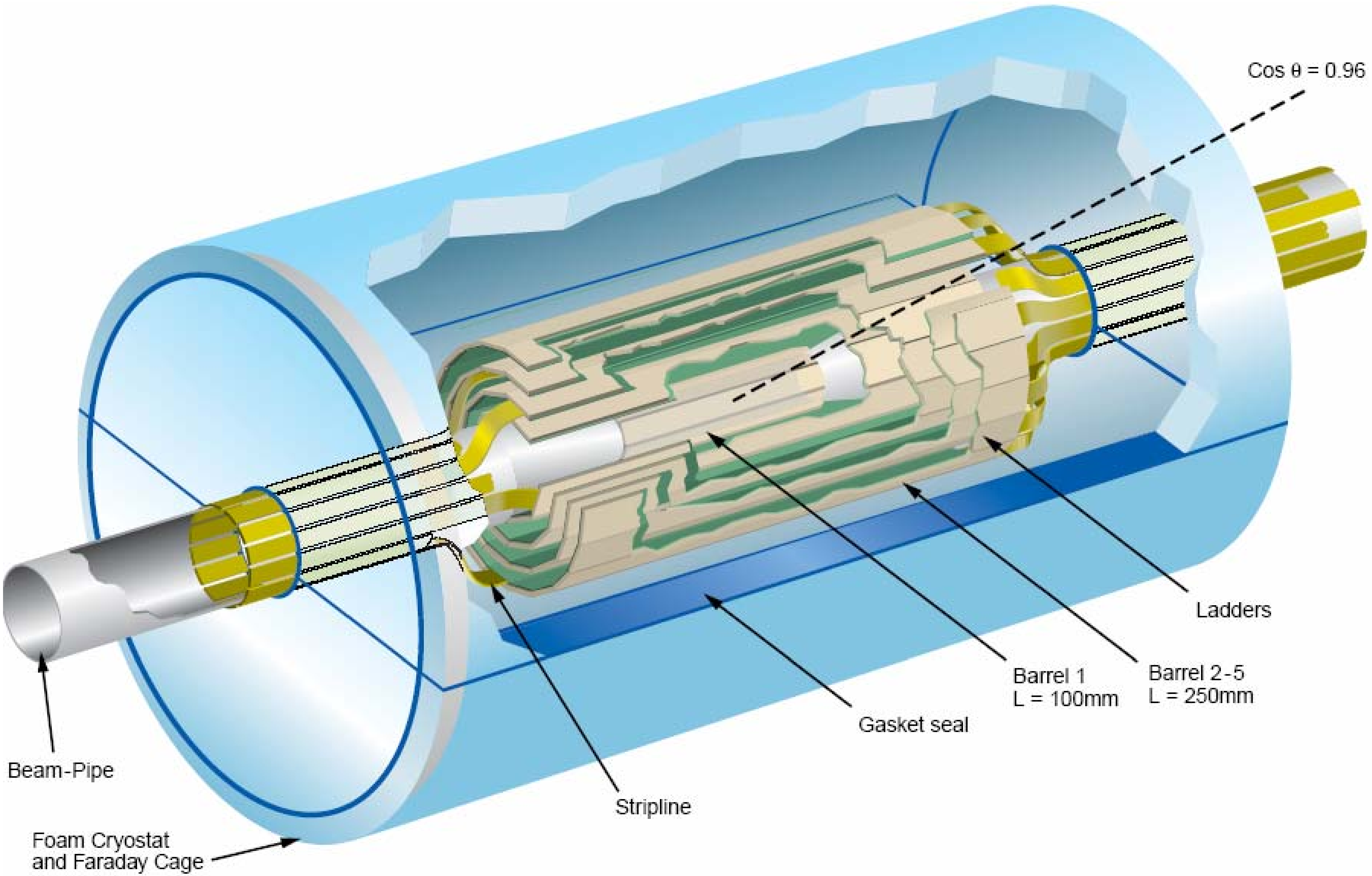
- **For the ILC, we can certainly do much better:**
- **R_{bp} 12-15 mm, cf 25 mm at SLD**
- **Layer thickness 0.05-0.1% X_0 , cf 0.4% X_0 at SLD [20 μm of Si is 0.02% X_0]**
- **Point measurement precision at least as good as at SLD (approx 3 μm)**
- **Resulting impact parameter precision will be** $\sigma_{r\phi} \approx \sigma_{rz} = 3.9 \oplus 7.8/(p\sin^{3/2}\theta)$ μm
- **Compared with, at SLD:**

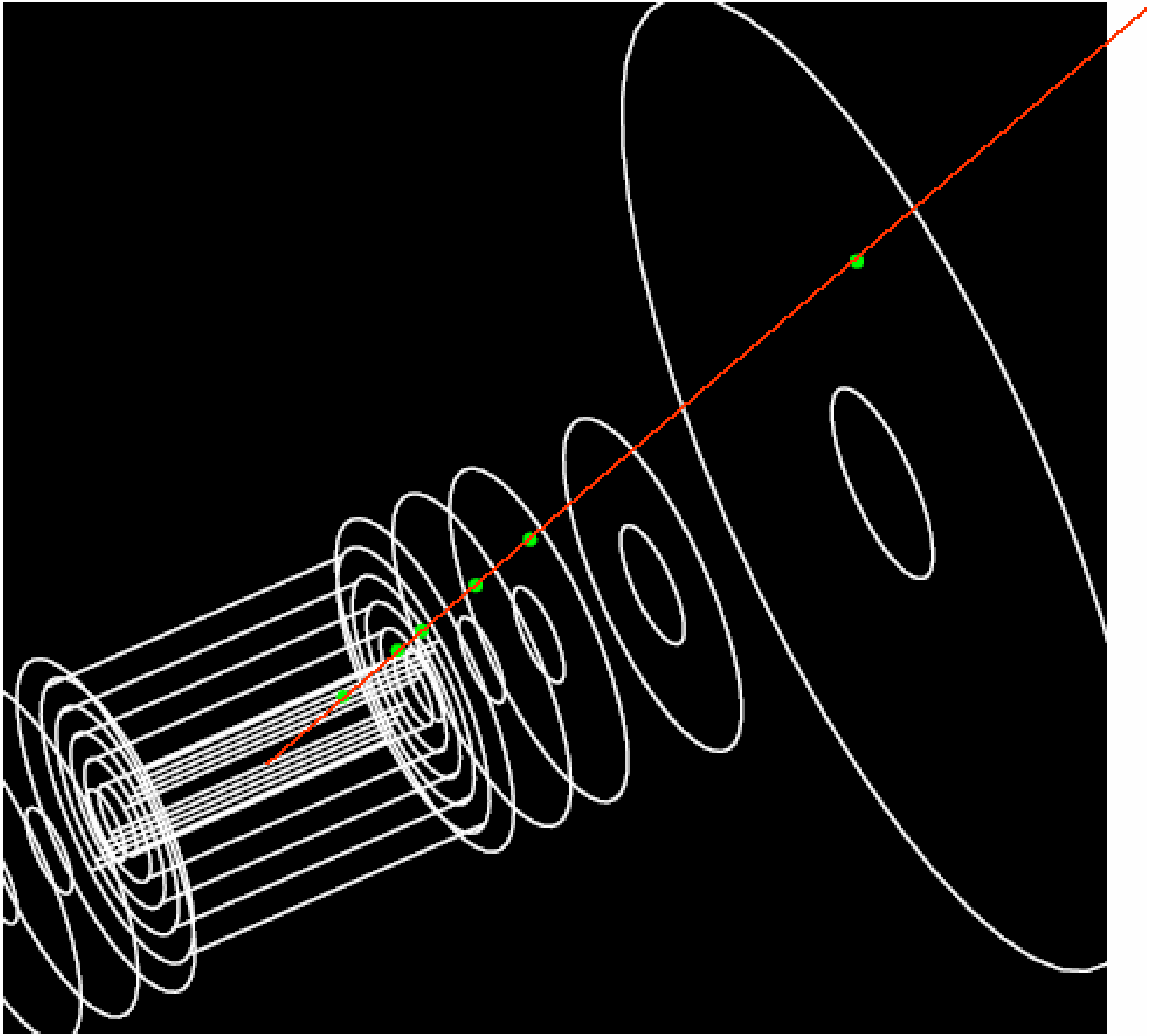
$$\sigma_{r\phi} = 7.7 \oplus 33/(p\sin^{3/2}\theta) \ \ \mu\text{m}$$

$$\sigma_{rz} = 9.6 \oplus 33/(p\sin^{3/2}\theta) \ \ \mu\text{m}$$

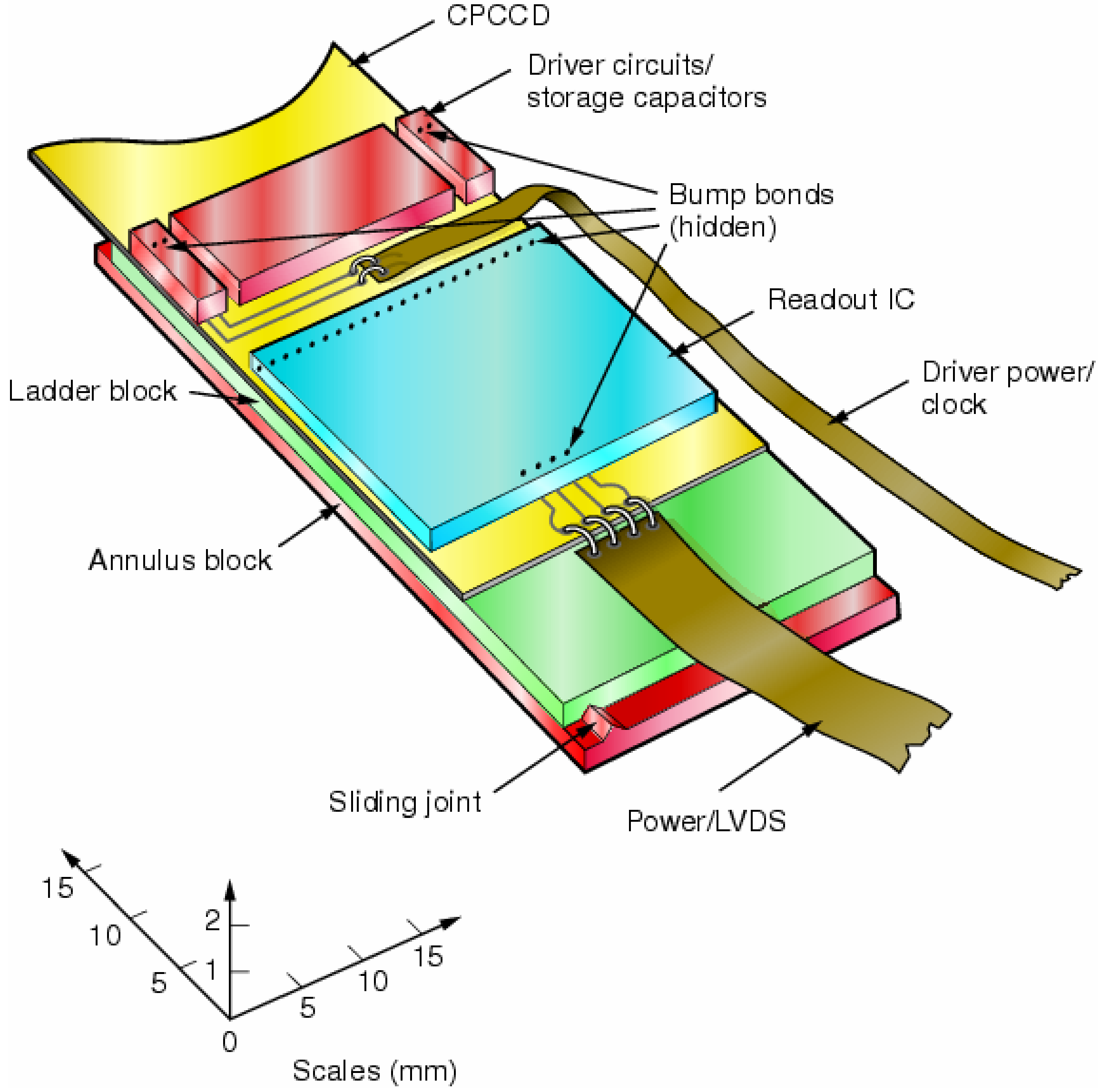
[really helped by more open geometry, with longer lever arm provided by 5 layers compared to 3]

Generic long-barrel detector
(TESLA TDR)

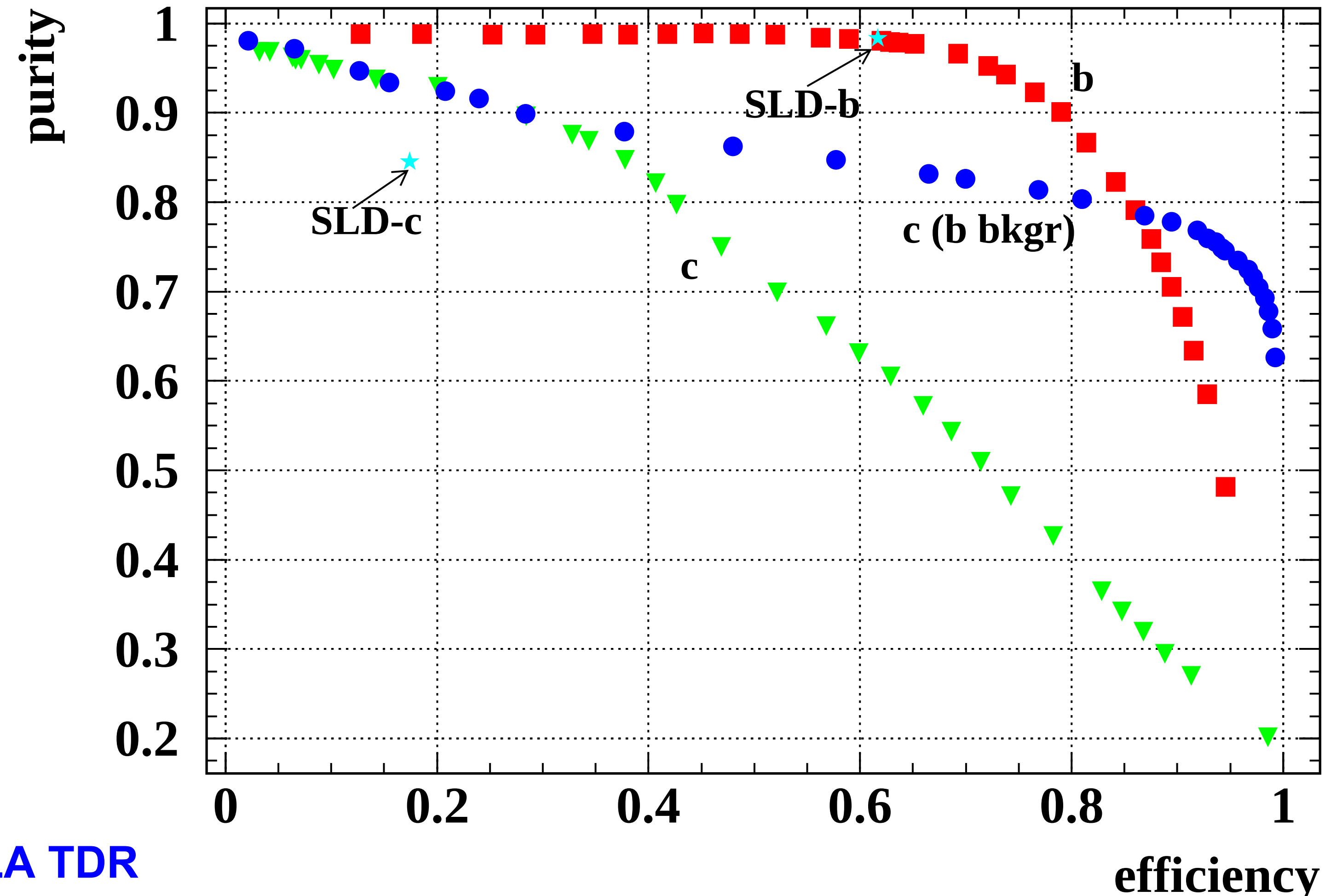




SiD vertex detector design concept – Norm Graf


CPCCD
Driver circuits/
storage capacitors
Bump bonds
(hidden)
Readout IC
Driver power/
clock
Ladder block
Annulus block
Sliding joint
Power/LVDS
15
10
5
2
1
0
5
10
15
Scales (mm)

Measuring flavour ID at ILC

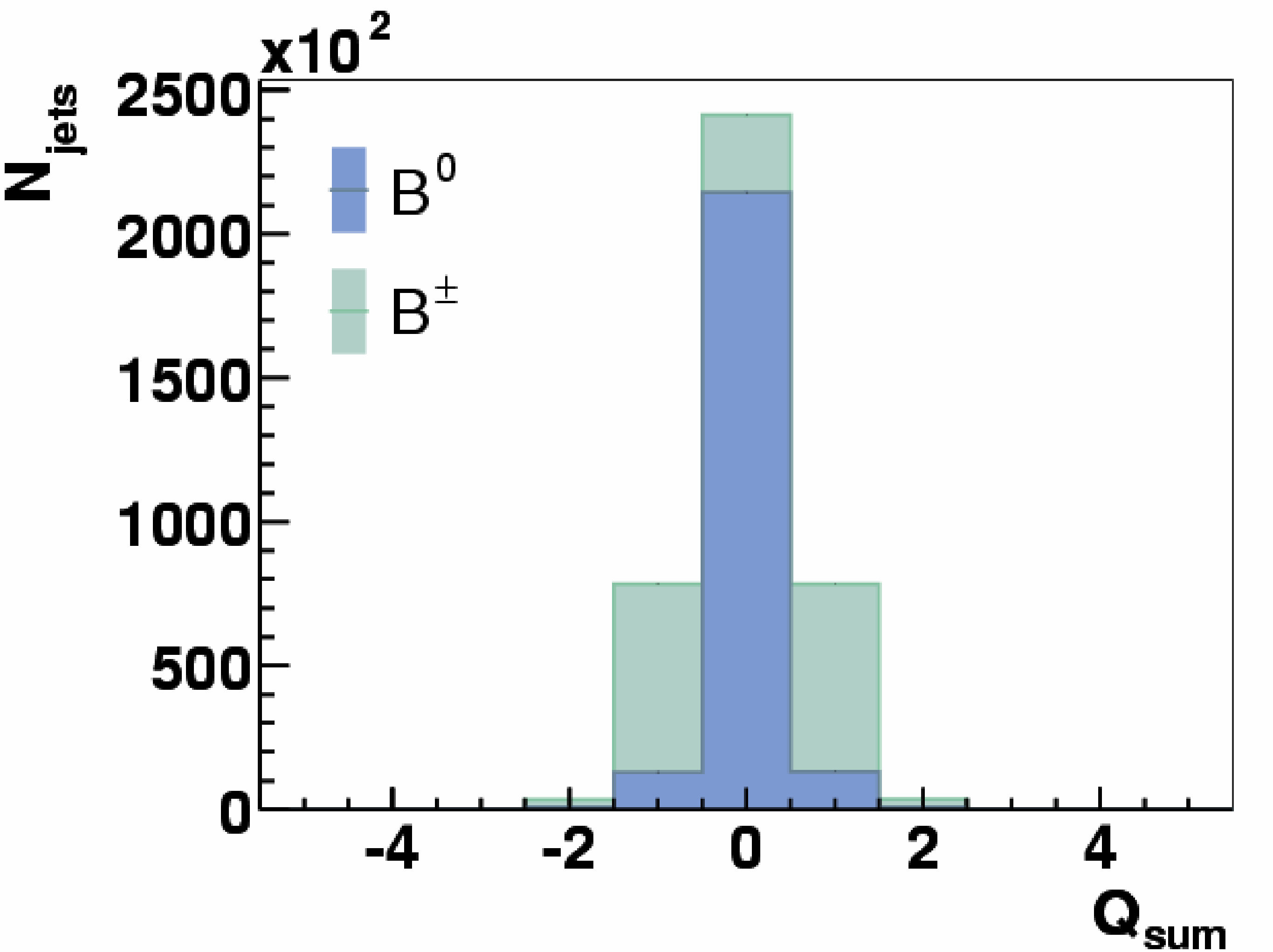


TESLA TDR

‘Purity’ means for quarks from Z^0 decays – it’s only one benchmark

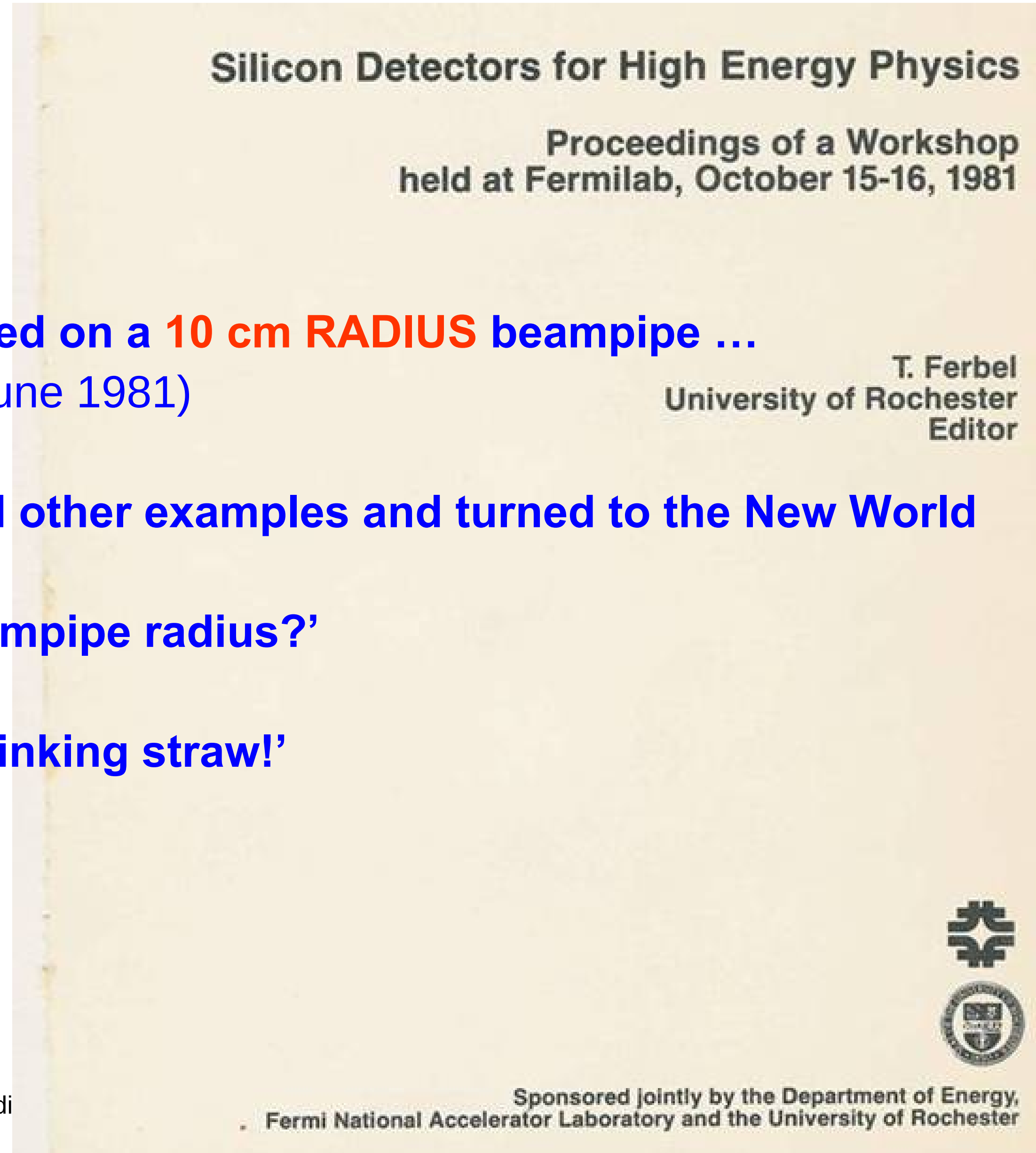
*Case of charm tag with low light-quark background **is** interesting, eg for adding flavour tag to reconstructed Ws, to enable top polarization measurement*

Prospects for vertex charge at ILC



Sonja Hillert, LCFI: **preliminary study – could get better or worse - don't yet believe these figures!**

A vital parameter – the beampipe radius

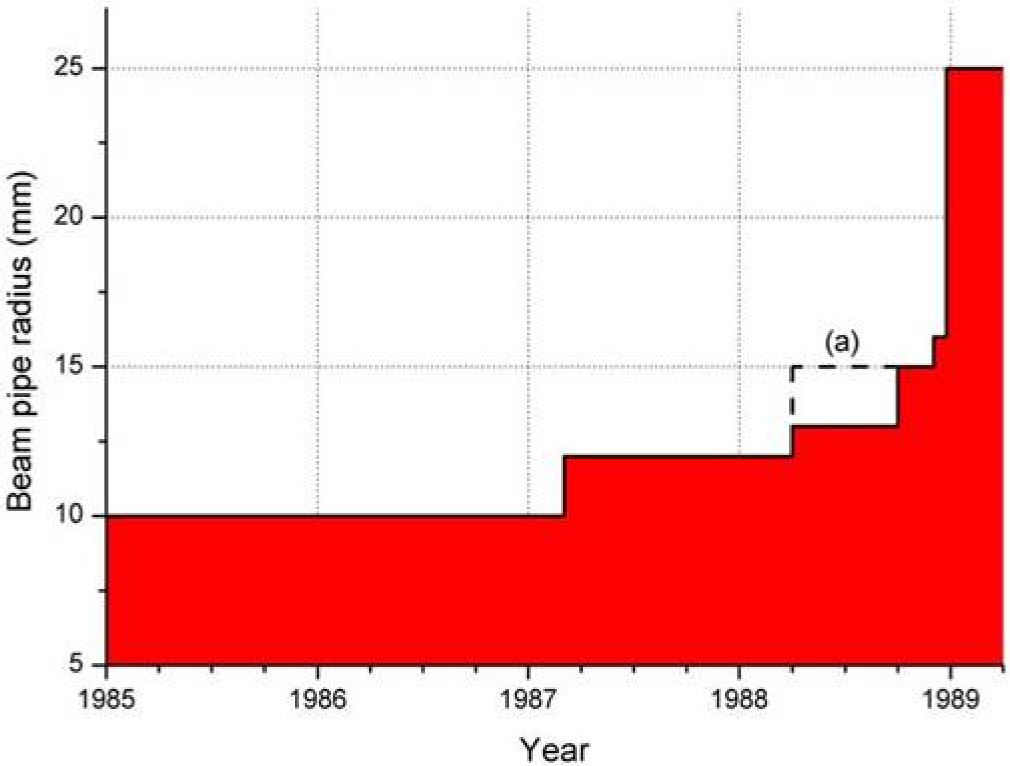

Silicon Detectors for High Energy Physics

Proceedings of a Workshop
held at Fermilab, October 15-16, 1981

T. Ferbel
University of Rochester
Editor

Sponsored jointly by the Department of Energy,
Fermi National Accelerator Laboratory and the University of Rochester

- **In 1981, LEP was fixated on a 10 cm RADIUS beampipe …**
  (Villars workshop 1-7 June 1981)
- **Disappointed, I followed other examples and turned to the New World**
- **'SLC? What's the beampipe radius?'**
- **'About the size of a drinking straw!'**



- Such a time dependence is not inevitable: at LEP it went the other way!
- Their R_bp was *reduced* from 10.6 cm in 1991 to 5.6 cm in 1995
- Maybe the ILC machine design will be a balance between European conservatism, American optimism and Asian realism, hence more stable
- In Europe, Nick Walker (ECFA workshop, Obernai, 1999) promised us a radius of 1.5 cm – but not a millimetre less!
- Don't let him forget this promise!

- Really important for the machine people to design the FF system for minimal beampipe radius (though they can't of course reduce the pair background)
- What if 10 mm R_{bp} had been possible at LEP and SLC?
- SLD would very probably have measured the B_s mixing parameter – and we are still waiting for that …
- At LEP, had they been able to flavour-tag every jet cleanly, would have reached a definitive conclusion about a Higgs boson in their mass range, with only a handful of events, on ZERO background
- *As with any microscope, getting close helps. The physics potential has still to be investigated*

What vertex detector technology for the ILC?

Technologies

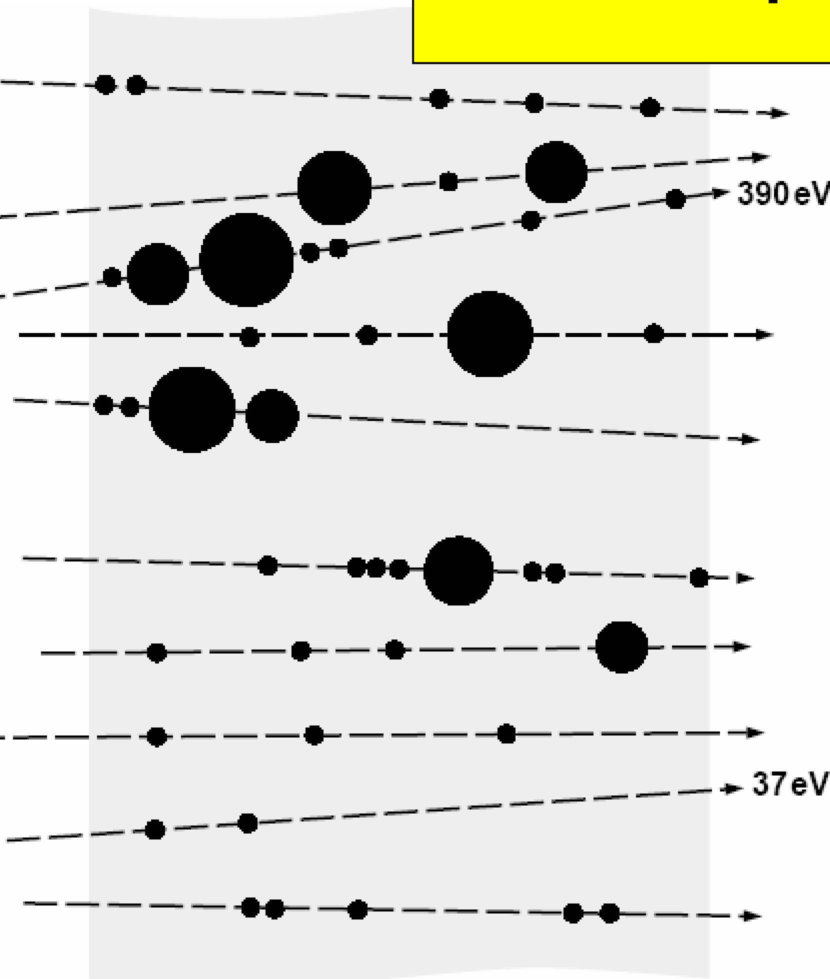
CAP
CPCCD
DEPFET
FAPS
FPCCD
HAPS
ISIS – edge readout
ISIS – distributed readout
MAPS – transverse readout
MAPS-digital
SoI
Macro-pixel/Micro-pixel sandwich

Both lists are probably incomplete – apologies!

Groups

Birmingham U
Bonn U
Bristol U
Brunel U
DESY
Glasgow U
Insubria U
KEK
Lancaster U
LBNL
Liverpool U
Mannheim U
MPI Munich (Halbleiterlabor)
Nijmegen U
NIKHEF (Amsterdam)
Oregon U
Oxford U
PNSensor (Munich)
RAL
SLAC
Strasbourg U
Tohoku Gakuin U
Toyama College of Maritime Tech
AGN-U of Science and Technology, Krakow
Warsaw U
Yale U
U of Hawaii

Sensor operating principles



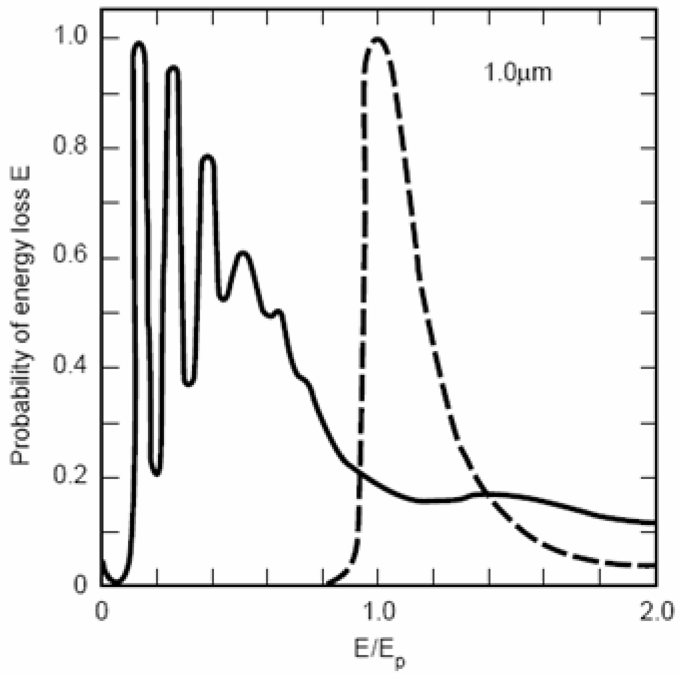
3.2 M-shell plasmons per μm (17 eV)

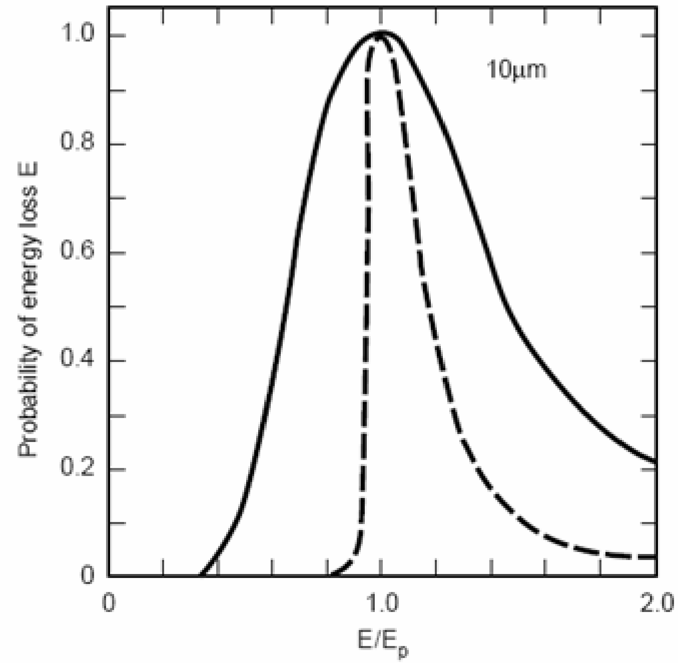
0.6 L-shell plasmons per μm (120 eV)

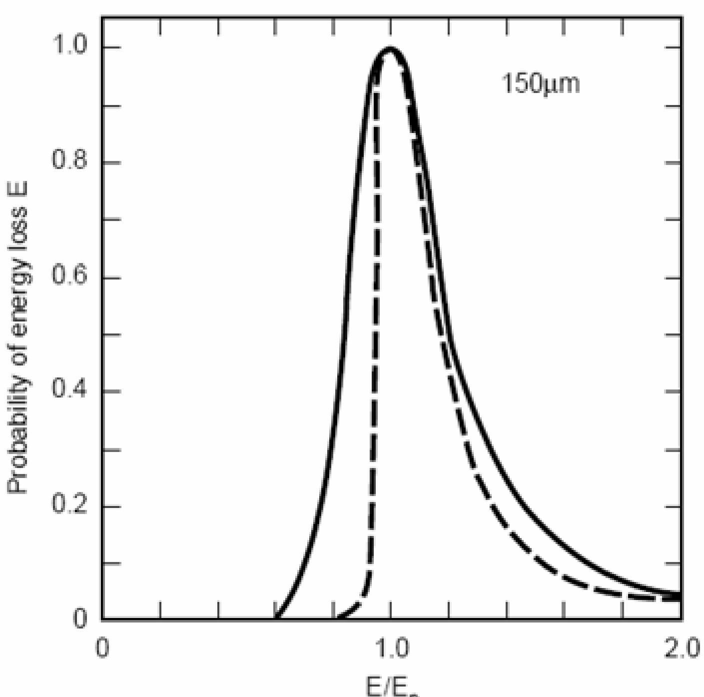
0.01 K-shell plasmons per μm (1.5 keV)

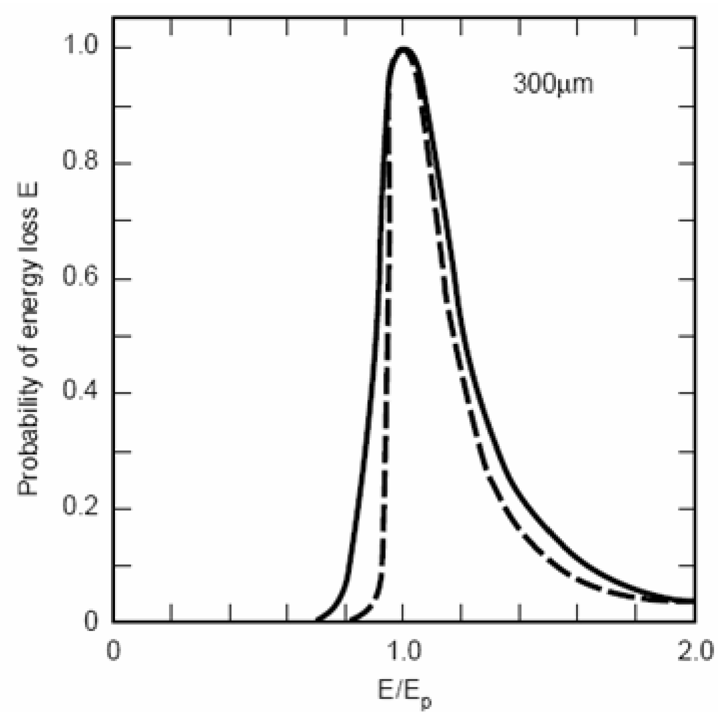
~4 primary collisions/μm with wildly fluctuationg energy loss

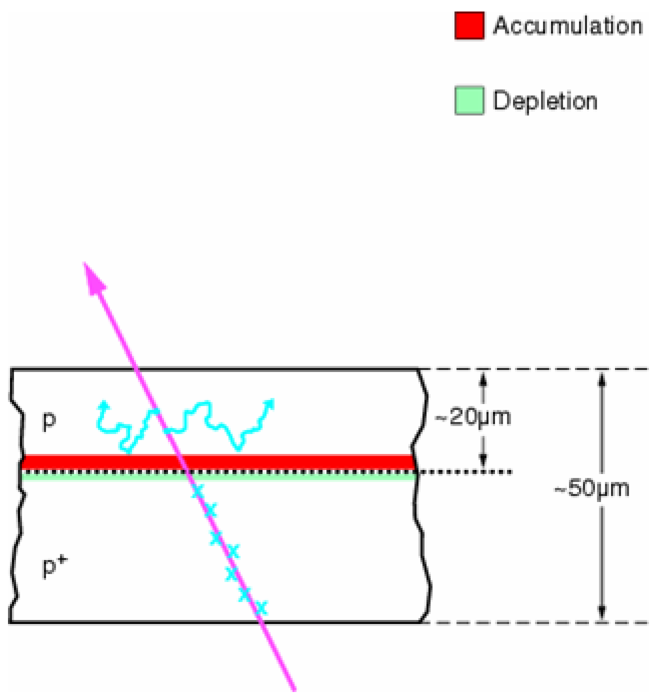
Final thermalisation yields one e-h pair per 3.6 eV deposited


1.0μm
Probability of energy loss E
E/E_p
0
0.2
0.4
0.6
0.8
1.0
1.0
2.0


10μm
Probability of energy loss E
E/E_p
0
0.2
0.4
0.6
0.8
1.0
1.0
2.0


150μm
Probability of energy loss E
E/E_p
0
0.2
0.4
0.6
0.8
1.0
1.0
2.0


300μm
Probability of energy loss E
E/E_p
0
0.2
0.4
0.6
0.8
1.0
1.0
2.0



Minority carrier diffusion length

~ 200 μm

~ 0.1 μm

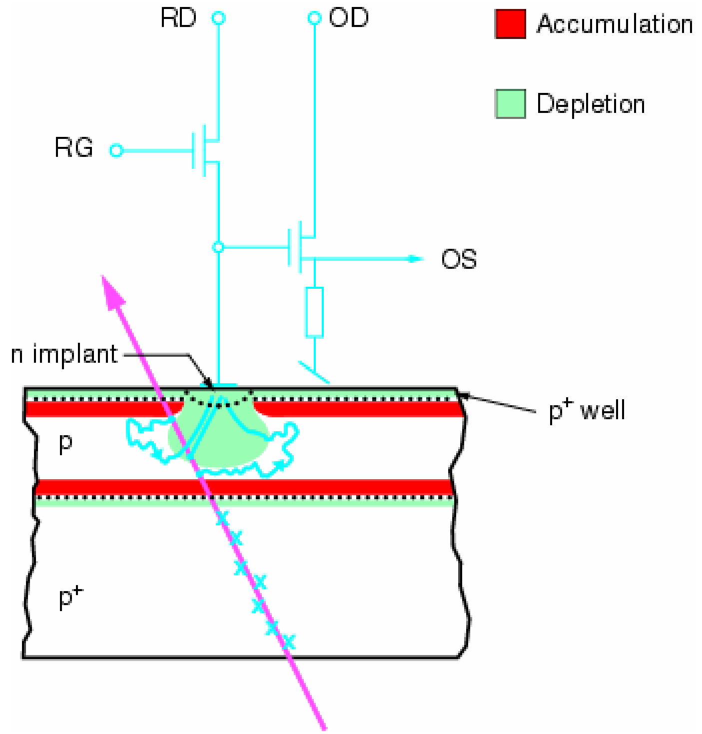
What epi-layer thickness?

Prefer it thin, to avoid losing precision for angled tracks

But not too thin, or lose tracking efficiency

20 μm is 'about right'

- **Imagine p and p+material brought into contact at same potential**
- **Holes pour from p+, leaving a negative space-charge layer (depletion) and forming a positive space charge layer in the p material (accumulation)**
- **This space-charge must of course sum to zero, but it creates a potential difference, which inhibits further diffusion of majority carriers from p+ to p and *incidentally* inhibits diffusion of minority carriers (electrons) from p to p+**
- **This barrier is thermally generated, but the 'penetration coefficient' is temperature independent, and is simply the ratio of dopant concentrations. eg 0.1/1000, so 10^{-4} - this interface is an almost perfect mirror!**



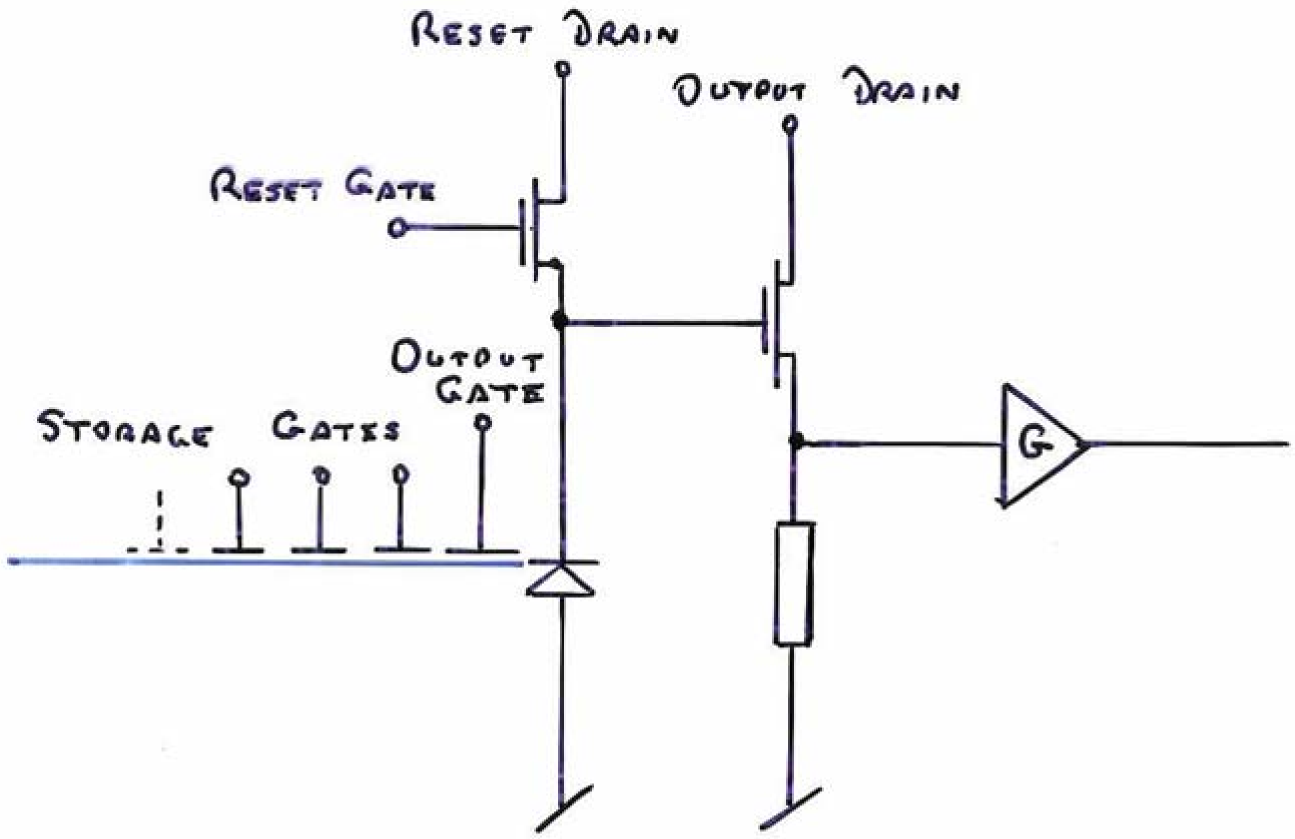
- We can repeat this on the top surface – here the p-well can be used to implant structures (notably n-channel transistors), 'monolithic' with respect to the detector layer below
- Positively biased n implants (reverse-biased diodes) serve to collect the signal charges, partly by diffusion, partly by drift in depleted regions created in the p-type epi layer
- Overlaying dielectric layers, and photolithographically patterned metal layers complete the toolkit for interconnecting the circuit
- Here you have the essentials of a MAPS pixel detector
- To learn about all the beautiful options for ILC vertex detectors, listen to the talks to come in this Symposium, today and Wednesday

How not to be blown away by 10^9 pixels

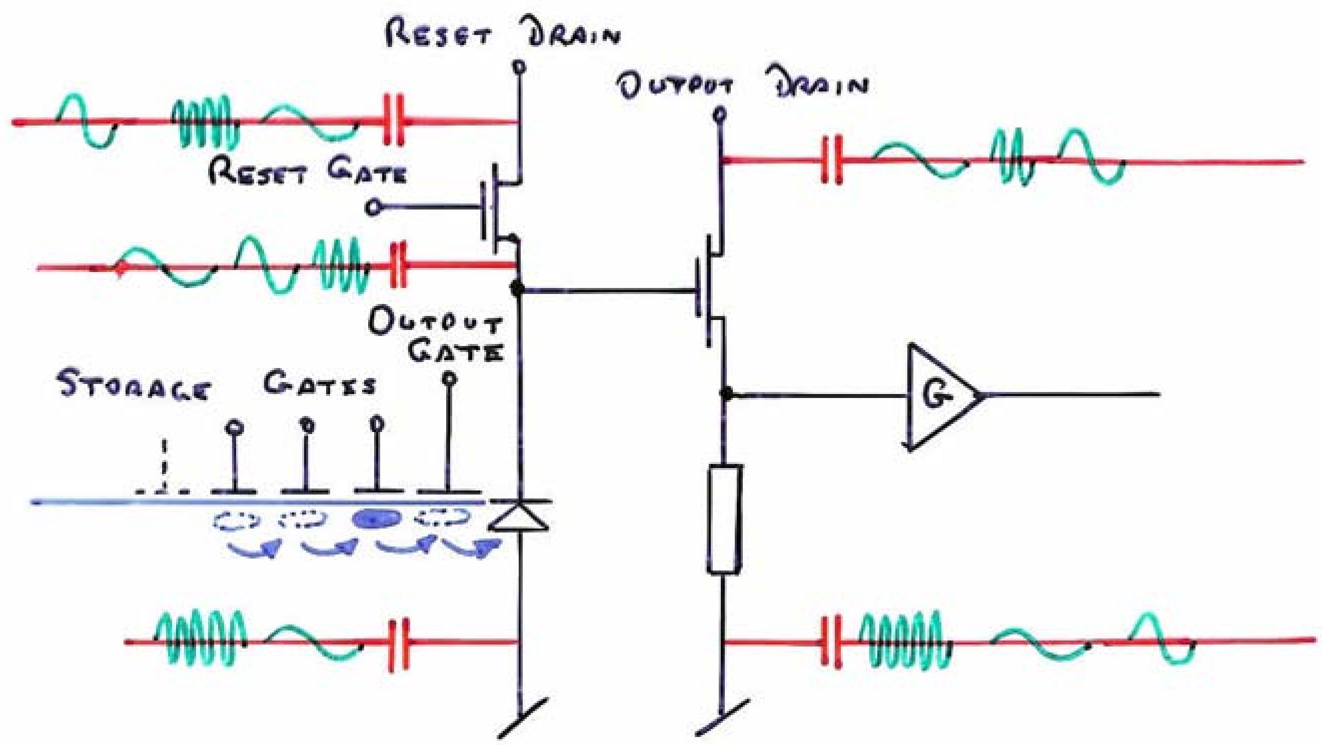
(a) Electromagnetic interference

- **Electron/positron beams traversing the IR radiate massive RF power (wakefields)**
- **Numerous ‘imperfections’ (thin walled sintered Be beampipe, non-welded flanges, ports for BPMs,kicker magnet circuits, beam-size monitors, vac pumps, …) provide leakage paths for RF**
- **A linear collider is intrinsically more hostile in terms of beam-induced RF than storage rings**
- **The vertex detector (in which ~10^9 unamplified signal charges of ~1000 e- are transformed to voltage on the gates of tiny transistors within ~1 mm of the beampipe) is more liable to disturbance by this RF than most detector systems**
- ***Beam-induced pickup disrupted the SLD vertex detector electronics for several μs after each bunch***
- **Dangerous to assume it will be quieter at a machine with 10 times the energy and 10^4 times the luminosity of SLC, needing far more instrumentation to preserve its performance**
- **Problems may not be primarily related to RF from the beam – control systems, such as kicker magnet pulsing circuits active during the train may also be dangerous**

Typical example: ideal CCD



Reality, during the bunch train:



From SLD experience, signal charges stored in buried channel are virtually immune to disturbance by pickup. They were transferred in turn to the output node and sensed as voltages between bunches, when the RF had completely died away

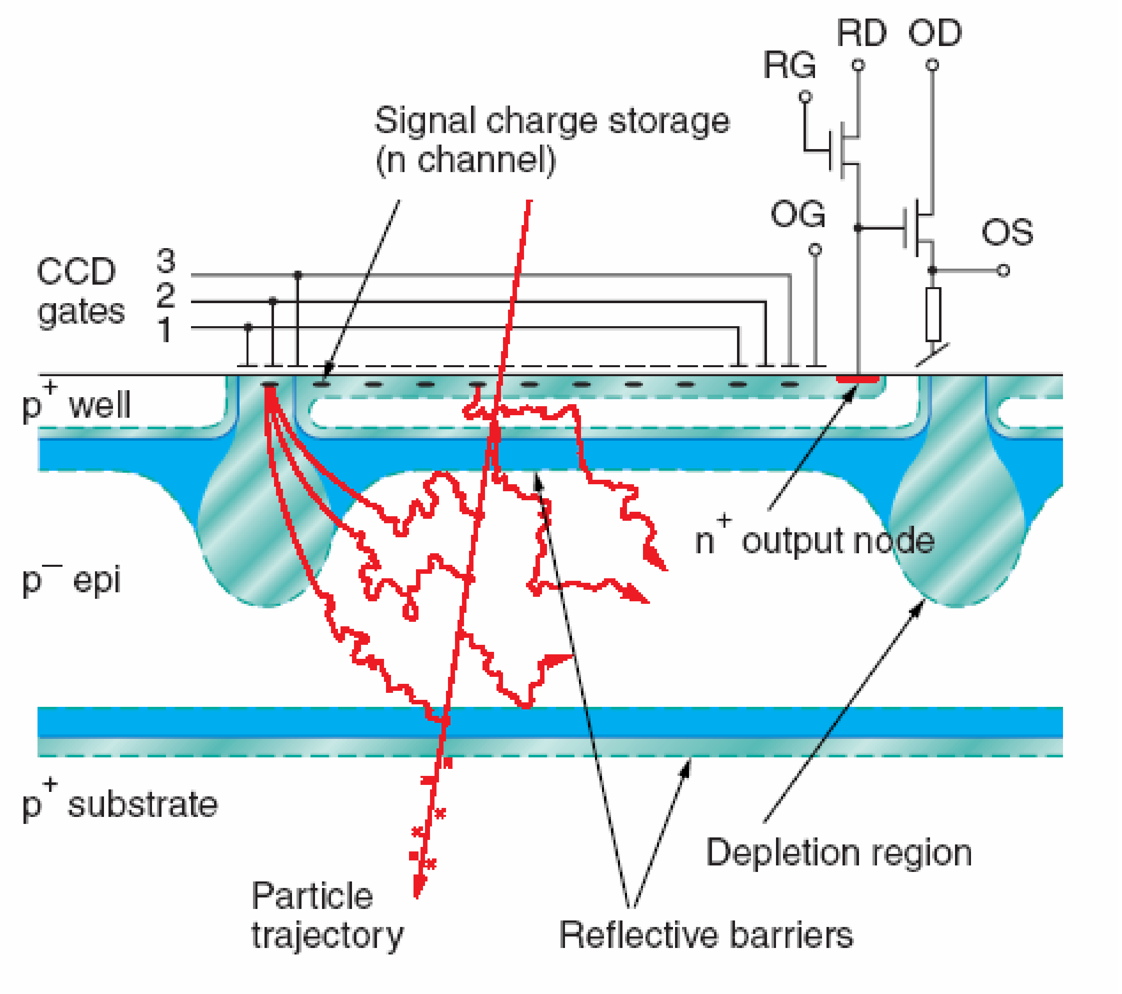
Could this also be done at ILC?

Bunch train: 2820 bunches @ 337 ns, every 200 ms

- **If signals were accumulated throughout a bunch train, background would be totally unacceptable (except maybe for FPCCD of GLC Group)**
- **Seemingly need to read the detector ~20 times during train, at ~50 μs intervals**
- **This may be like trying to hear someone *whisper* on a railway platform while an express train is roaring by. Why not simply wait?**
- **All detector options considered till recently suffered from this problem**
- **At ECFA workshop in Montpellier, November 2003, a good discussion of CDS etc (Marcel Trimpl et al). Afterwards, we came up with a 'new idea'**
- **David Burt of e2V told us 'It's been done!' Even better!**

ISIS: Imaging Sensor with In-situ Storage

- Pioneered by W F Kosonocky et al IEEE SSCC 1996, Digest of Technical Papers, p 182
- Current status: T Goji Etoh et al, IEEE ED 50 (2003) 144
- Frame-burst camera operating up to 1 Mfps, seen here cruising along at a mere 100 kfps – dart bursting a balloon
- Evolution from 4500 fps sensor developed in 1991, which became the de facto standard high speed camera (Kodak HS4540 and Photron FASTCAM)
- International ISIS collaboration now considering evolution to 10^7 – 10^8 fps version!



- **charge collection to photogate from ~20 μm silicon, as in a conventional CCD**
- **signal charge shifted into storage register every 50μs, to provide required time slicing**
- **string of signal charges is stored during bunch train in a buried channel, avoiding charge-voltage conversion**
- **totally noise-free charge storage, ready for readout in 200 ms of calm conditions between trains**
- **'The literature is littered with failed attempts …'**

(b) Correlated Double Sampling

- **CDS is a vital part of the strategy to avoid a data deluge, one which most technologies for the ILC vertex detector claim to employ**

- **Even if reading between trains, fluctuations in transistor noise and detector-related pickup sources will be present, as seen at SLD**

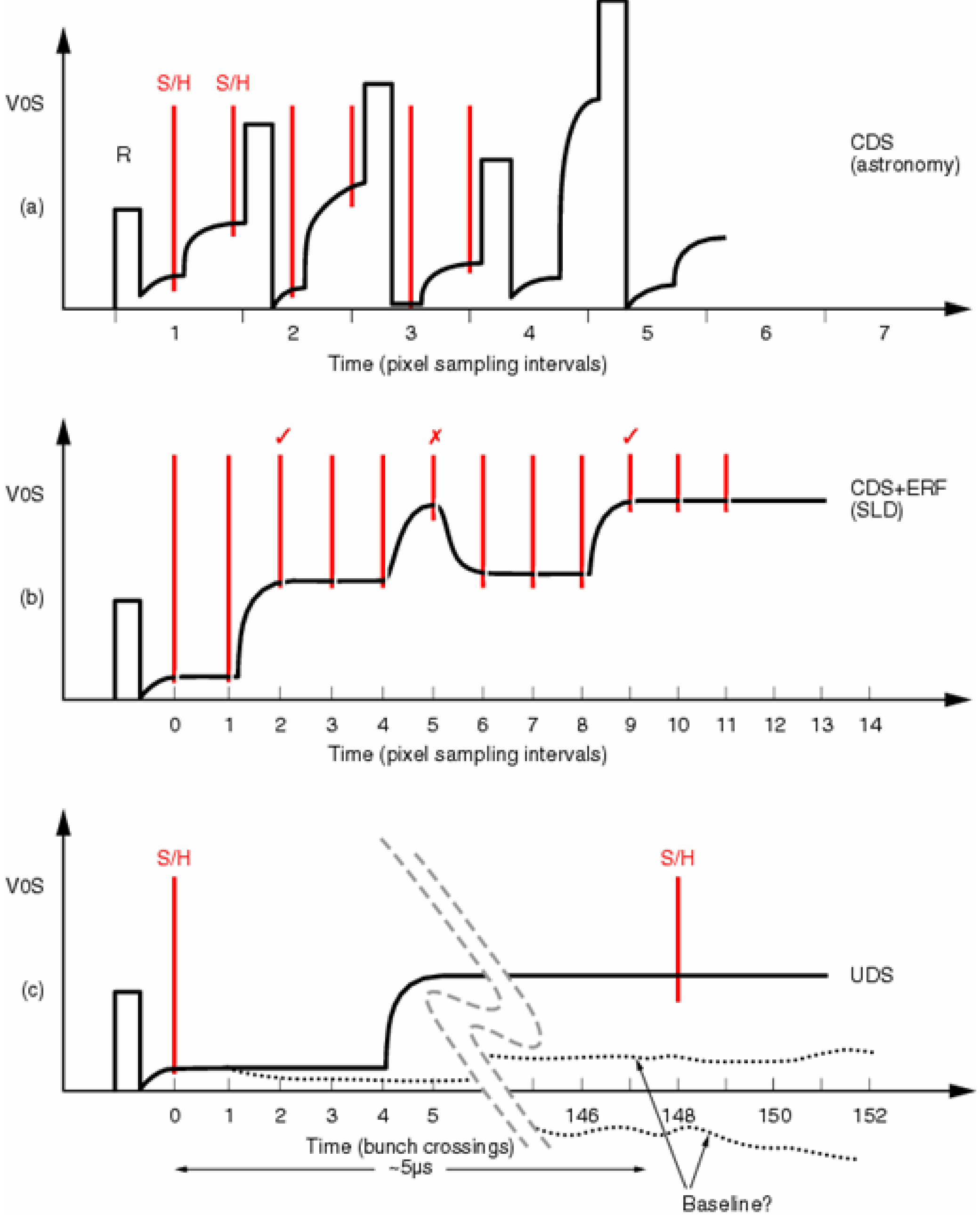
- **CDS - term given in early '70s to pedestal subtraction in CCDs used in astronomy and elsewhere to sense very small signals, where *reset noise and 1/f noise* would otherwise have imposed severe performance restrictions**

- $ENC = \sqrt{kTC_n / 2}$

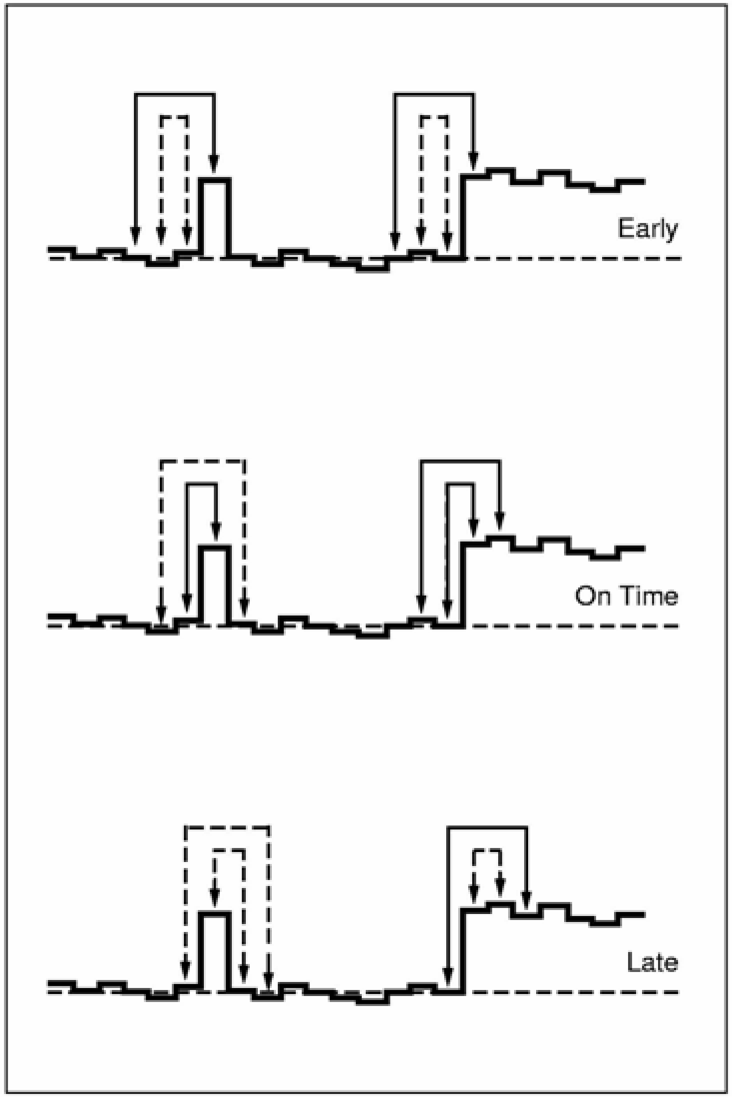
- **Same functionality was achieved in late '70s in CCD-based particle detectors, where the sparse data permitted resetting only between rows, hence faster sampling**

- **ERF - Extended Row Filter, was an important refinement added in SLD**

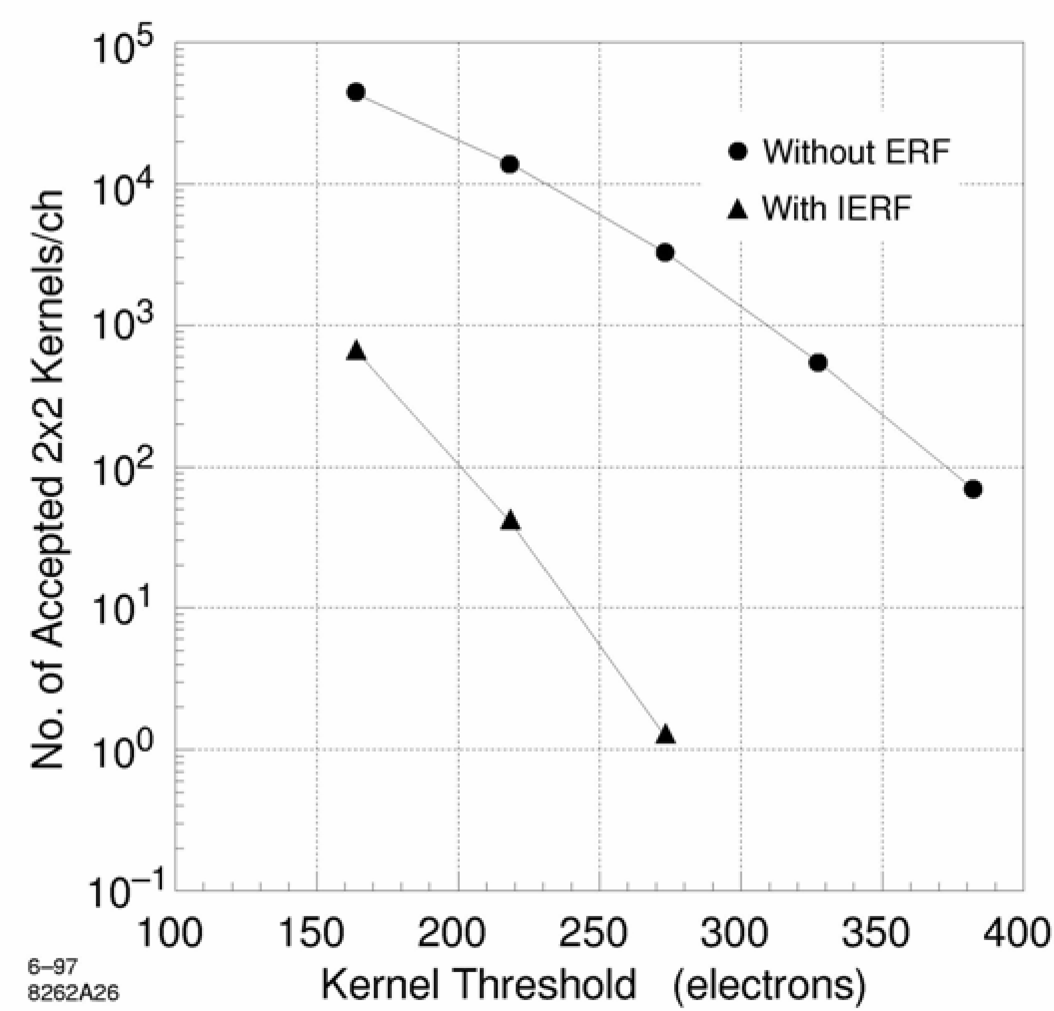
- **'Beware of imitations'**


VoS
S/H S/H
R
(a)
1 2 3 4 5 6 7
Time (pixel sampling intervals)
CDS
(astronomy)
VoS
✓ ✗ ✓
(b)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
Time (pixel sampling intervals)
CDS+ERF
(SLD)
VoS
S/H S/H
(c)
UDS
0 1 2 3 4 5 146 148 150 152
Time (bunch crossings)
~5μs
Baseline?

Extended Row Filter (ERF) suppresses residual noise and pickup:



SLD experience:



Without ERF, rate of trigger pixels would have deluged the DAQ system

Read out at 5 MHz, during 'quiet' inter-bunch periods of 8 ms duration

Origin of the pickup spikes? We have no idea, but not surprising given the electronic activity, reading out other detectors, etc

How can we get to ILC physics, from where we are now?

- Currently many groups are pursuing an expanding range of options for the ILC vertex detector
- All use silicon pixels, but there the similarity ends
- How to converge on (hopefully) two technologies for two large detectors?

Don't believe what any of us claim we can deliver!

- The ILC vertex detector community has informally undertaken to provide working ladders in test beams, circa 2010 (+ δ)
- Some options will drop out sooner: one has recently done so
- Overall detector collaborations should evaluate their results carefully, considering all performance criteria, including efficiency, spatial resolution, material budget at small angles due to mechanical supports and electronics at ends of ladders, robustness wrt EMI, etc

- Only then should they make their technology choices, deciding between long barrels, short barrels plus endcaps, etc etc

- Everyone who has participated in the R&D should be welcome to join one of the ‘winning’ technologies for detailed design, construction, commissioning, and extracting the physics (ideally, a rerun in miniature of the ITRP process)

- [Several ‘losers’ will change direction and find wonderful applications for their technologies, and may gain more than they lose!]

- In the meantime, we should continue building a world-wide community who would all enjoy working together

- Suggest we maintain our inexpensive world-wide phone conferences

[Arlington TX 8 Jan 2003, Mumbai 14 Dec 2003]

- Overall detector collaborations should design for convenient access to the vertex and other small-radius equipment for several reasons, including future upgrades. A ‘losing’ technology, could prove to be a long-term winner (as happened with CCDs at SLC)

- The SLD vertex detector was considered a ‘jewel in the crown’. This may also be true at ILC – the physics potential, combined with particle flow for jet energy measurement, goes far beyond what can be done at LHC

- **Can we be sure that silicon pixels will provide the best solution?**

- **Do you remember the front running technology for SLC in 1982?**

- **CCDs were regarded as a risky outsider.**

- **If you come up with a revolutionary new idea, please do follow it up! Don't be discouraged by the so-called experts!**

- **In the '70s, when most expertise in silicon detectors was in the hands of nuclear science people with string-and-sealing wax production facilities, the construction of semiconductor detectors was more like cookery than science …**

- **To these experts, the concept of CCDs as particle detectors seemed outrageous**

SLC Experiments Workshop 1982

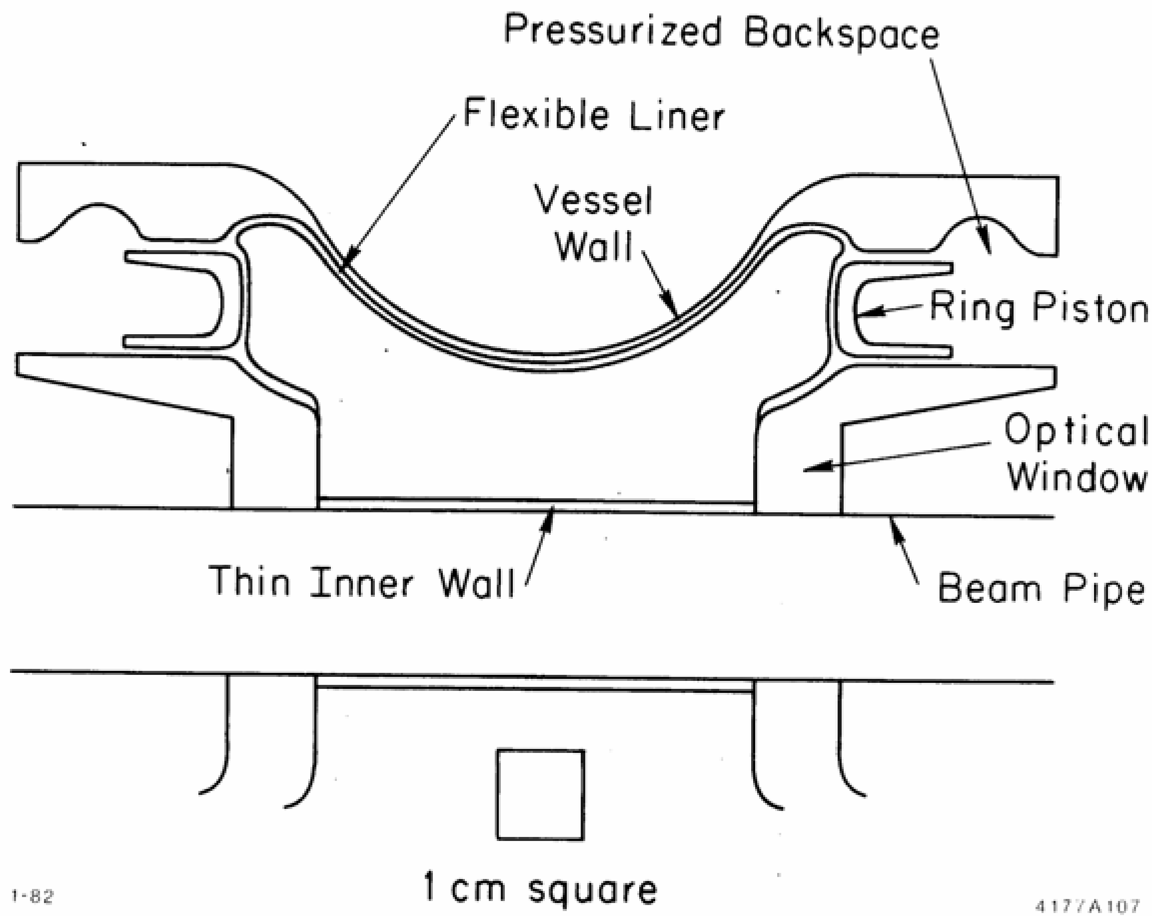


Fig. 7. Conceptual design of a propane bubble chamber vertex detector.

SOME EXPERT OPINIONS IN 1979

"Put such a delicate device in a beam and you will ruin it".

"Will work if you collect holes, not electrons".

"Far too slow to be useful in an experiment".

"It's already been tried; didn't work".

"It will work but only with ≤ 50% efficiency".

"To succeed, you will have to learn to custom-build your own CCDs: investment millions".

"At room temp it would be easy, but given the need to run cold, the cryogenic problems will be insurmountable".

"May work in a lab, but the tiny signals will be lost in the noise (RF pickup etc) in an accelerator environment".

However, Wrangy Kandiah from AERE, Veljko Radeka and Pavel Rehak from BNL, Joe Killiany from NRL, Herb Gursky from Harvard Smithsonian, Emilio Gatti from Milano and a few others were supportive

ILC Detector R&D Topics and Panel

Measurement of luminosity, beam energy and polarisation (LEP)
Vertexing
Tracking (gaseous and silicon)
Calorimetry (ECAL, HCAL, forward region)
Muon tracking
Particle ID
DAQ systems
Electromagnetic interference (EMI)

Areas of interest:

Jean-Claude Brient:	Calorimetry
Chris Damerell:	Vertexing, EMI, PID
Ray Frey:	LEP, MDI, calorimetry
HongJoo Kim	Tracking, calorimetry
Wolfgang Lohmann	LEP, MDI, tracking, calorimetry
Dan Peterson	Tracking, PID
Yasuhiro Sugimoto	Vertexing
Tohru Takeshita	Calorimetry
Harry Weerts	Vertexing, tracking, muon tracking

Schedule: Report end 2005, to be used by GDE in conjunction with the Accelerator R&D report, to secure appropriate funding via FALC etc starting next year.