Aspects of the SiD detector design for the International Linear Collider

David Strom – University of Oregon, for the SiD Collaboration

- Physics Motivation for the International Linear Collider
- Introduction to the SiD design study
- The SiD electromagnetic calorimeter
  (Annecy, BNL, SLAC, UC-Davis, Oregon)
- The Chronopixel option for the vertex detector
  (Yale, Oregon)

Physics Motivation

Within a year, we anticipate the start of results from the LHC, possible LHC discoveries include:

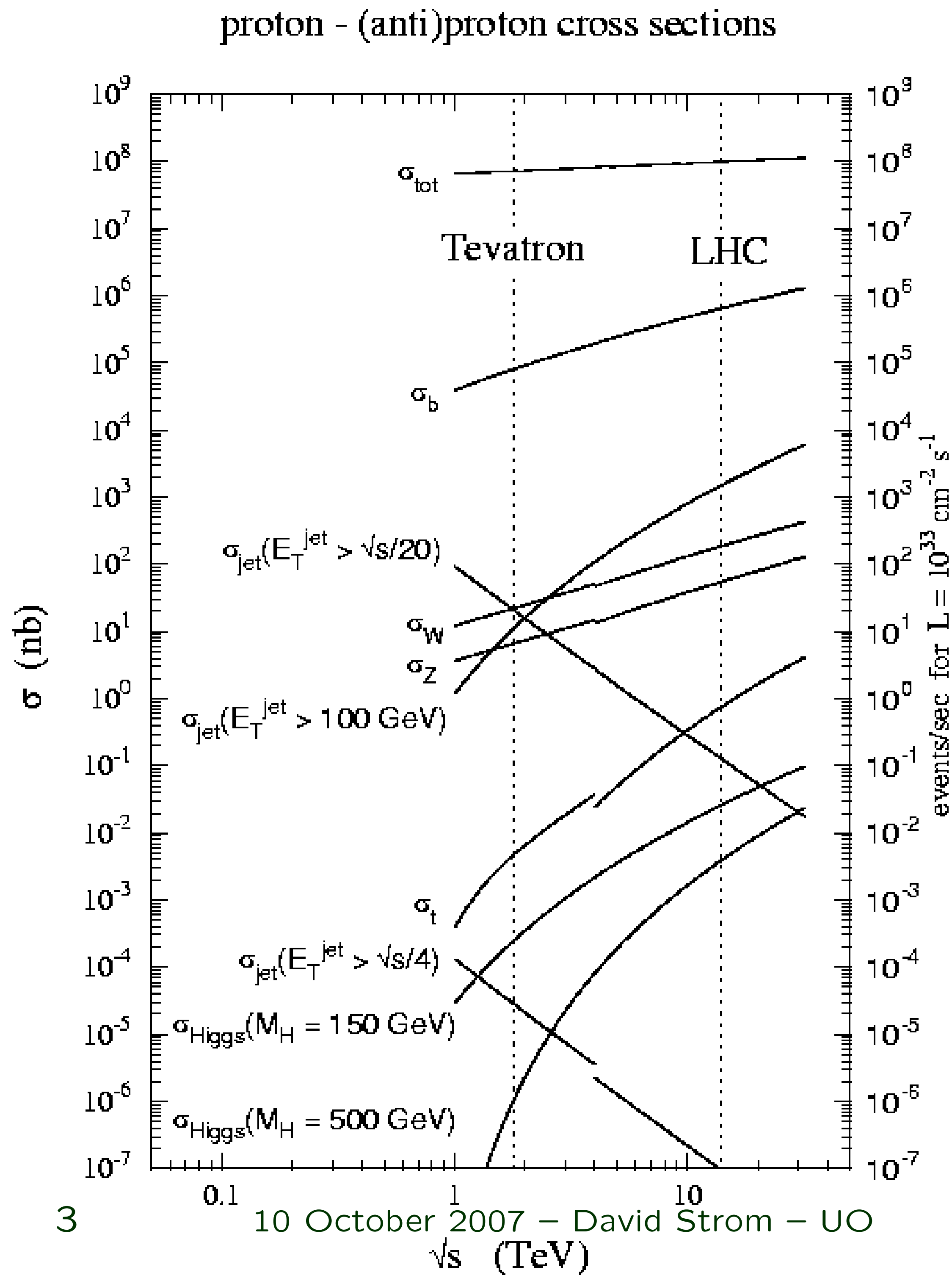
- Higgs boson
- Extra gauge bosons (for example, Z', W', extra dimensions)
- Events with missing energy, for example Supersymmetry
- Massive objects that decay democratically, for example black holes + extra dimensions
- **Stuff no theorist has thought of yet...**

$\Rightarrow$ **Why have a linear collider?**

At the LHC we will only be able to record about 100 of the 40 million beam crossings produced each second.

LHC detector builders and software developers are very clever*, but it may be hard to isolate every event of interest

(* For example see posters on LHC triggers)



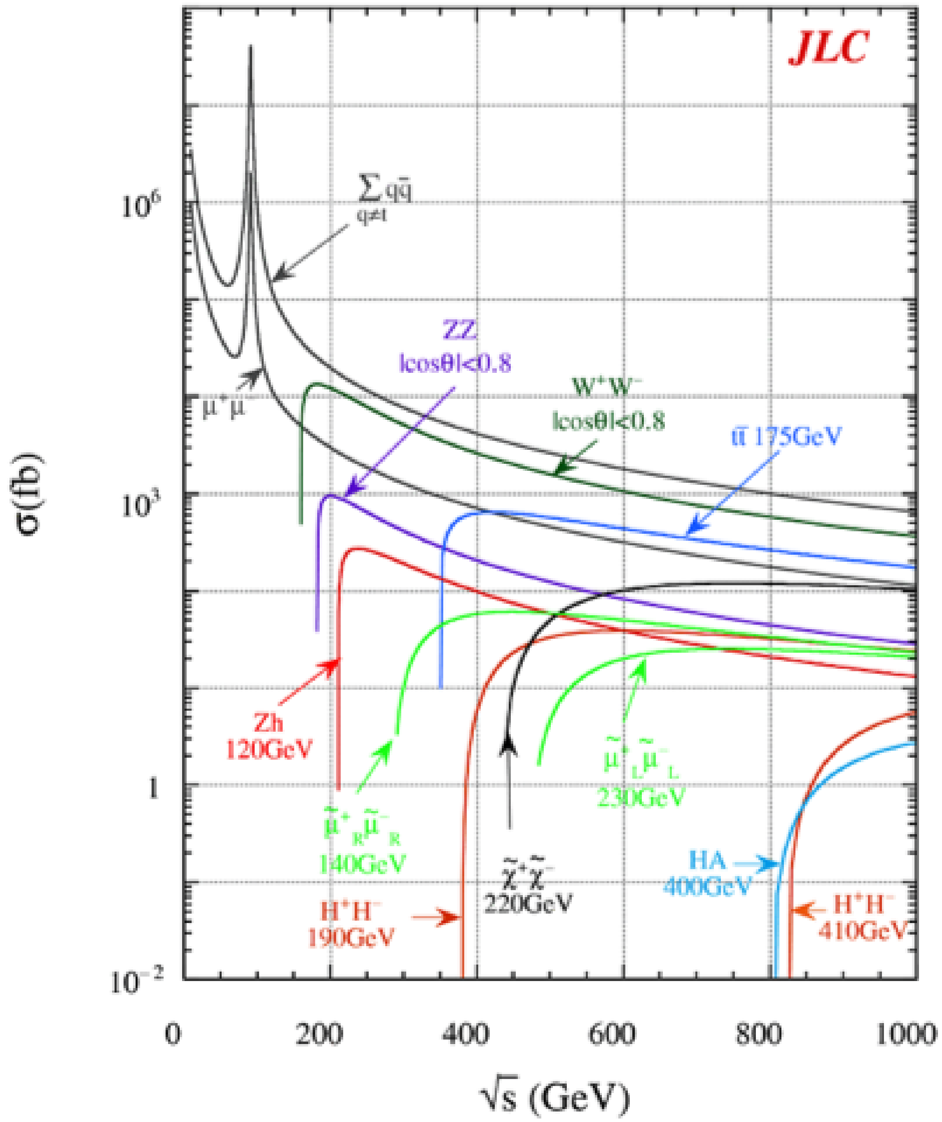
Possible outcome of first few years of the LHC:

– 120 GeV particle decaying to two photons
(Evidence for the Higgs mechanism?)

–events with missing energy and jets
(Evidence for Dark Matter?)

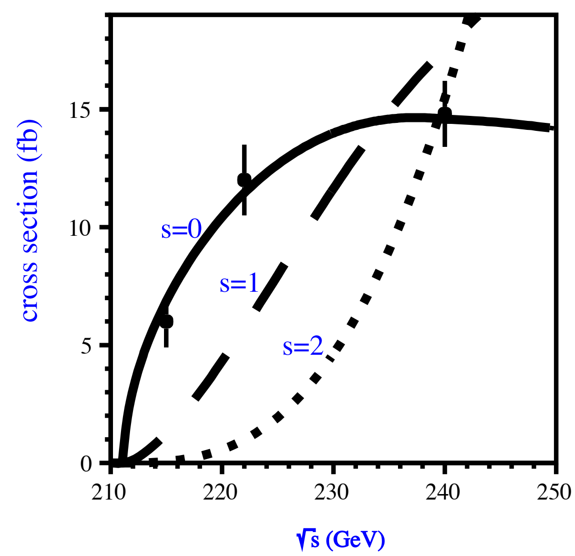
Can the ILC (International Linear Collider) help?

Processes can be studied in e^+e^- physics with much less background, experiments can save every event!



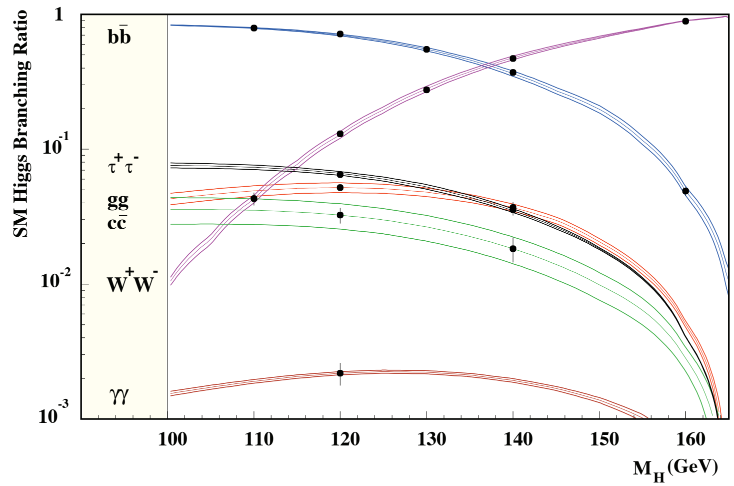
The ILC can help tell us if the "Higgs" is a Standard Model one:

Measure cross section turn-on



hep-ph/0511332

Measure branching ratios

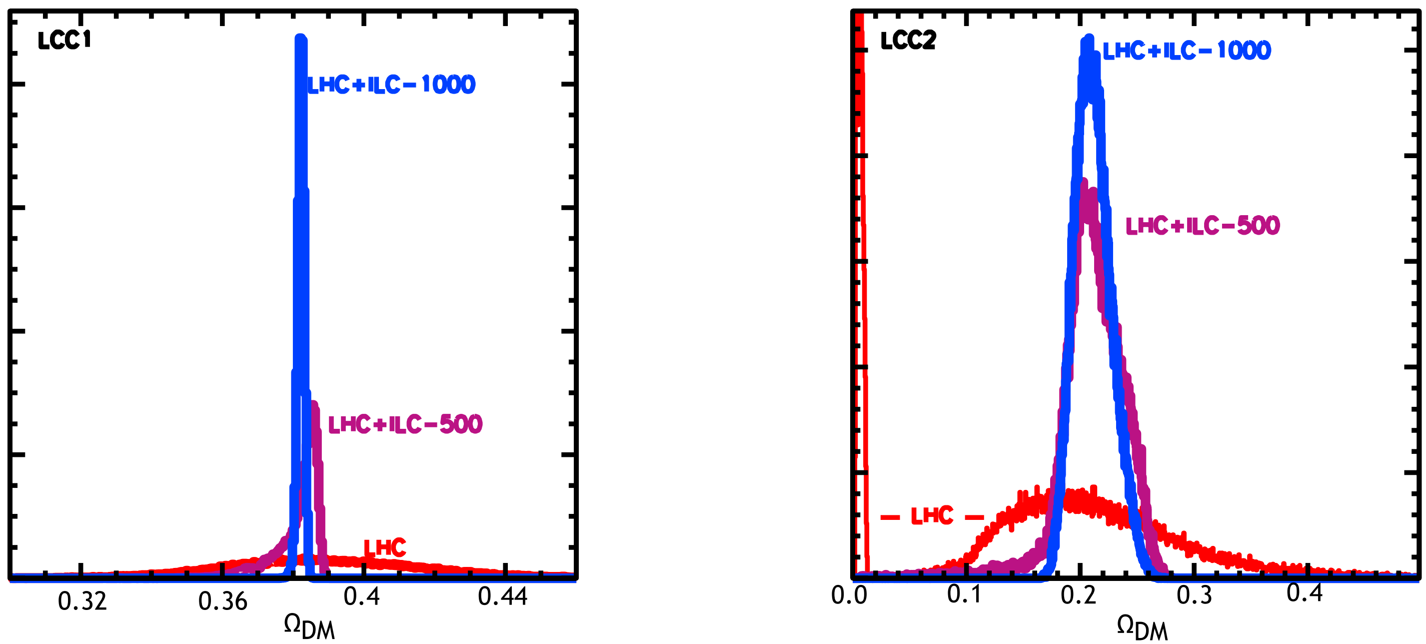


TESLA TDR, errors show expected precision

N.B. in minimal SUSY there is a large parameter space where the light Higgs is subtly different from the SM one and the heavier Higgs are hard to see at the LHC. see Carena, et al., Phys. Rev. D. 65 (2002) 055005.

Many other Higgs ILC studies possible, e.g. ZZh, tth, hhh, $\mu\mu$

The ILC can tell us if the SUSY is the explanation for Dark Matter:



Study by Baltz, Battaglia, Peskin, and Wizansky shows that the gain possible from a linear collider in predicting the mass density of the universe due to dark matter.

Expect Ω_{DM} to be known from microwave measurements to a few % in the future

The ILC can help illuminate the mechanism underlying SUSY

- Stau production at the ILC

$$\begin{aligned} e^+e^- &\rightarrow \tilde{\tau_1}^+ + \tilde{\tau_1}^- \\ &\rightarrow \tau^+\tilde{\chi}_1^0 + \tau^-\tilde{\chi}_1^0 \end{aligned}$$

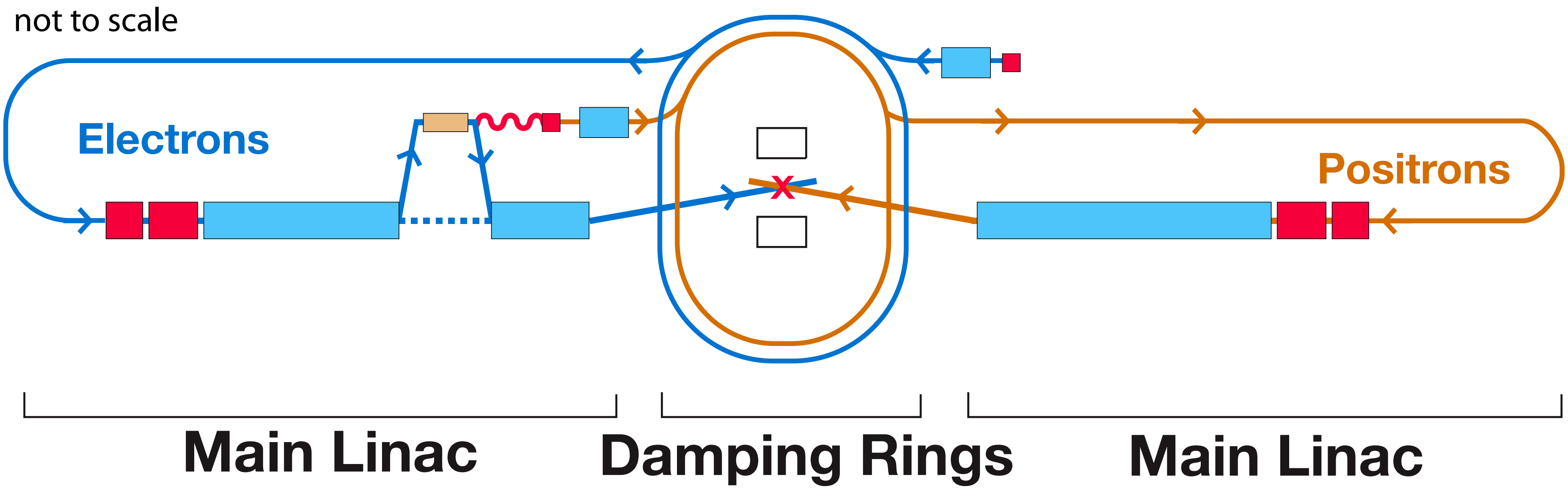
- SUSY model gives tau polarization (Godbole, Guchait, Roy, Phys Lett B (2005))

$\tilde{\chi_1} = N_{11}\tilde{B} + N_{12}\tilde{W} + N_{13}\tilde{H}_1 + N_{14}\tilde{H}_2$

mSUGRA:	$\tilde{\chi_1} \sim \tilde{B} \rightarrow P_\tau \approx +1$
non-universal SUGRA	$\tilde{\chi_1} \sim \tilde{H} \rightarrow P_\tau \approx \cos^2\theta_\tau - \sin^2\theta_\tau$
AMSB:	$\tilde{\chi_1} \sim \tilde{W} \rightarrow P_\tau \approx -1$
$GMSB$	$\tilde{\chi_1} \sim \tilde{H} \rightarrow P_\tau \approx \cos^2\theta_\tau - \sin^2\theta_\tau$

- $\tau^- \rightarrow \rho^-\nu_\tau$ is especially useful for polarization measurement

The ILC Machine: Essentials



- CM energy is 500-1000 GeV
  - superconducting r-f cavities
  - initially 30km
- Very small (nm) beam spot

(600 nm × 5.7 nm) $\mathcal{L} = 2 \cdot 10^{34} cm^{-2} s^{-1}$

- Electron polarization to 80%
- Push-pull interaction region

- Intense Global Design Effort (GDE)
- Site to be selected:
  - virtual organization until then
- Construction could start as early as five years from now

Detectors at the ILC

• Much $R\&D$ has been done in individual groups or in generic working groups like the Calice group for calorimetry

see for example, http://polywww.in2p3.fr/activites/physique/flc/calice.html

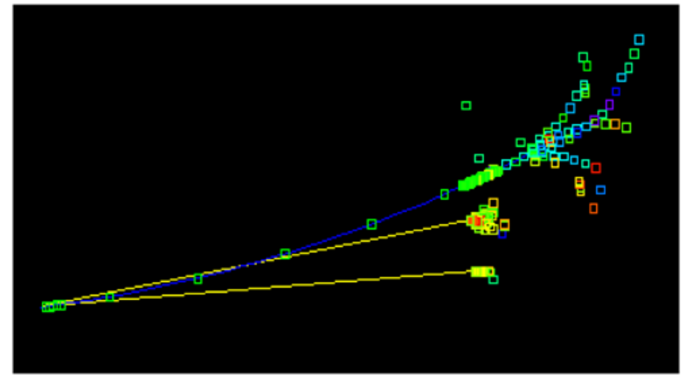
• Detector level studies have been preformed in groups called concepts
⇒ I will report on work from the SiD (Silicon Detector) group

• With in the next year the concept groups will evolve into collaborations that will prepare **letters of intent**
⇒ Two groups will be selected to prepare Engineering Design Reports
– organized by newly appointed Research Director Sakue Yamada

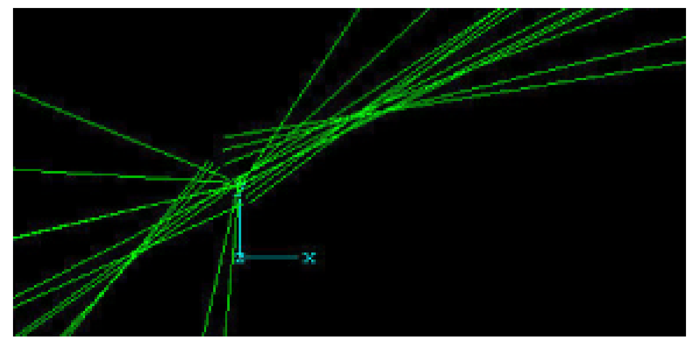
What drives the detector design;

Why isn't this just another LEP detector?

- Excellent calorimeter granularity needed for energy reconstruction and tau polarization ($\sim 2 - 3\times$ better than LEP)
Reduce di-jet mass resolution to order of Z and W boson widths



- Precise vertex detector needed for separation of b, c and light hadrons, event reconstruction, etc. ($\sim 3\times$ better than SLD)
$\Rightarrow$ Inner radius of the beam pipe proportional to B field because of soft e^+e^- pairs produced in the field of the colliding beams, e.g. 5 T



Jim Brau SLD

- $\sim \sigma_{p_t}/p_t^2 \sim 2 \times 10^{-5}$ ($\sim 10\times$ LEP)

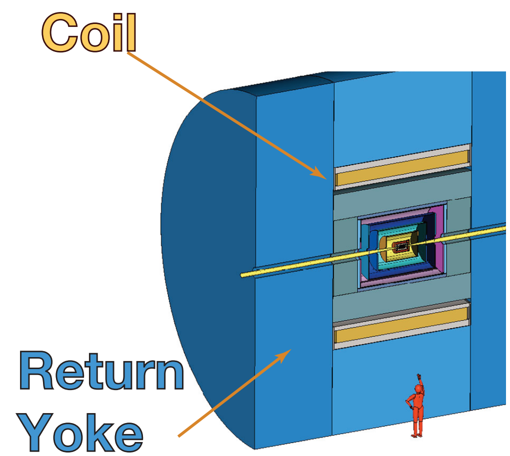
Practical considerations

- 5T magnets are thick

⇒ a∼1.0 interaction length

⇒ all calorimeters must go inside of the coil

- Iron return yoke is used a muon filter



- **Cost, $\propto R^3$, implies that calorimeters must be as dense and compact as possible.**

- SLC experience argues for a detector that is robust against machine background.

⇒ **Silicon is an excellent choice**

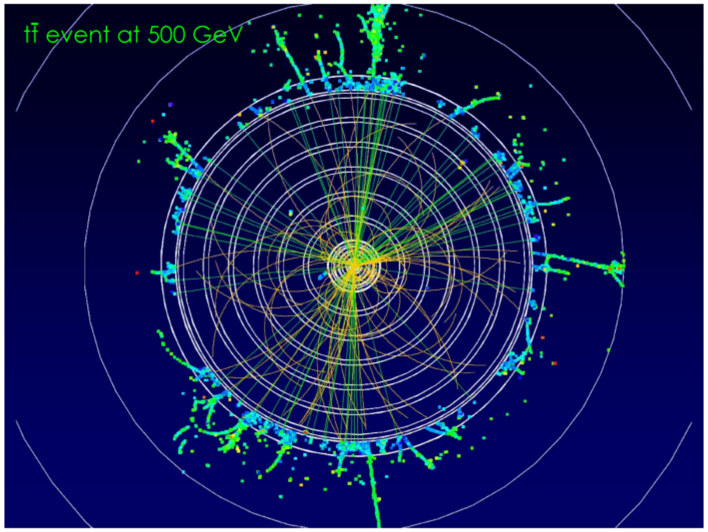
Should we rely on compensating calorimetry?

(i.e. should response of calorimeters be equal for hadrons and electrons)

• LEP experience shows that shows that both transverse and longitudinal granularity is needed for τ polarization, b-jet tagging with leptons, etc.

• Magnetic field bends tracks before they reach the calorimeter, calorimeter measures wrong particle direction

• Best jet finders are not based on cones



Steve McGill

• Particle flow idea – measure charged particles in tracker, photons in the ECAL and neutral hadrons (neutrons and K-longs) in the HCAL
$\Rightarrow$ Must identify depositions from charged particles so they can be thrown away

3-4% energy resolution for jets possible

Features of SiD (Silicon Detector)

- Pixel vertex detector

– many options, consider chronopixels

- Silicon tracking detector

- Silicon-Tungsten EM Calorimeter

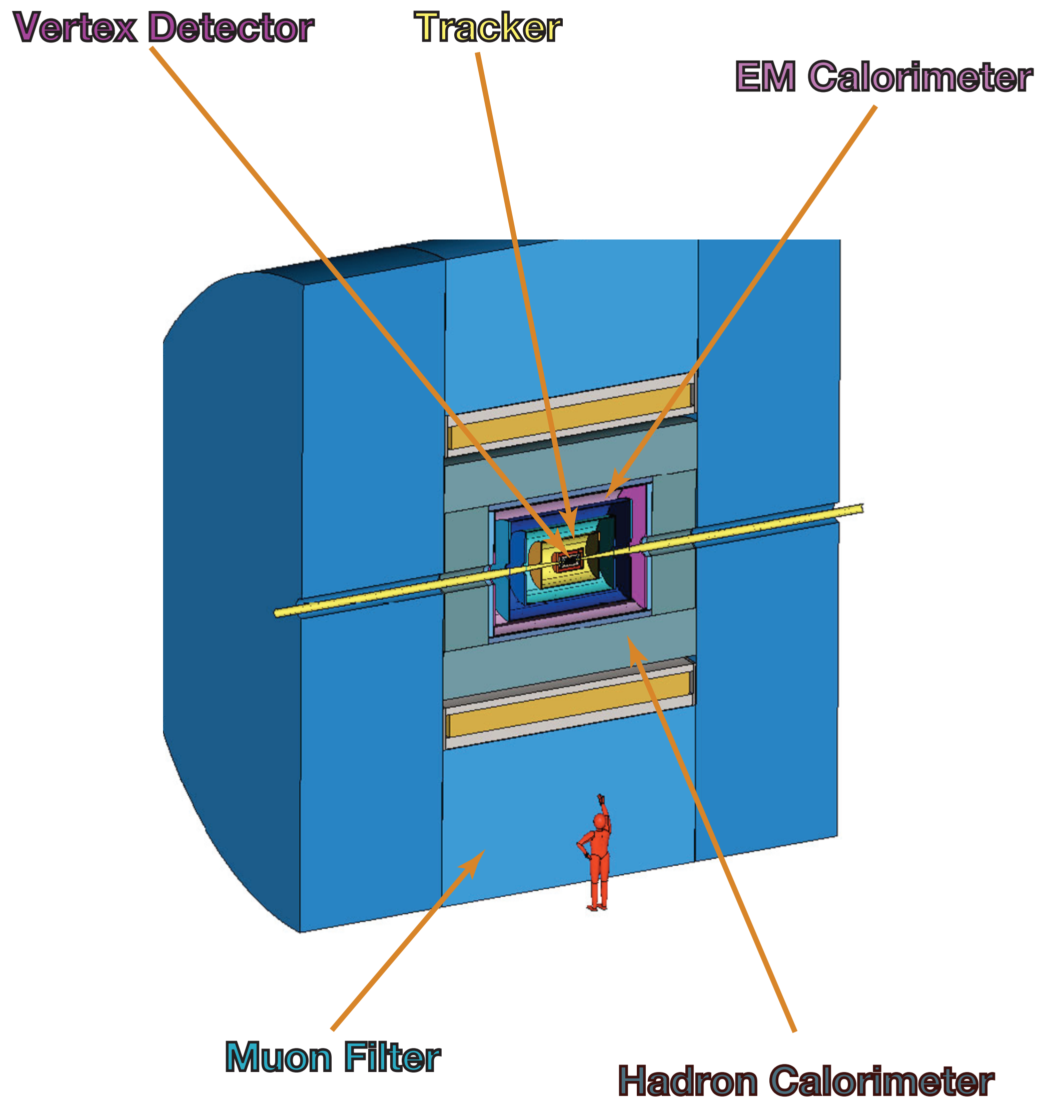
–Consider SiD design

see Calice for another approach

- Granular Hadron Calorimeter.

(Steel+RPCs, Steel+GEM, or Tile Scint.)

- Muon filter (RPCs?) outside coil



Motivation for Silicon Tungsten Electromagnetic Calorimeter*

- A silicon tungsten calorimeter is well matched to particle flow algorithms currently proposed for hadronic event reconstruction

- High granularity is desirable for other physics, e.g. τ from SUSY

- Silicon prices have declined:

  – Large scale production of CMOS $\sim 5\$/\text{cm}^2$ $\sim$ 50 proc. steps
  – Silicon solar cells $\sim 0.1\$/\text{cm}^2$
  $\Rightarrow$ Expect price for large scale production of simple high-resistivity sensors to be in-between

- **Possibility of integrated electronics simplifies detector construction and allows for a compact detector**

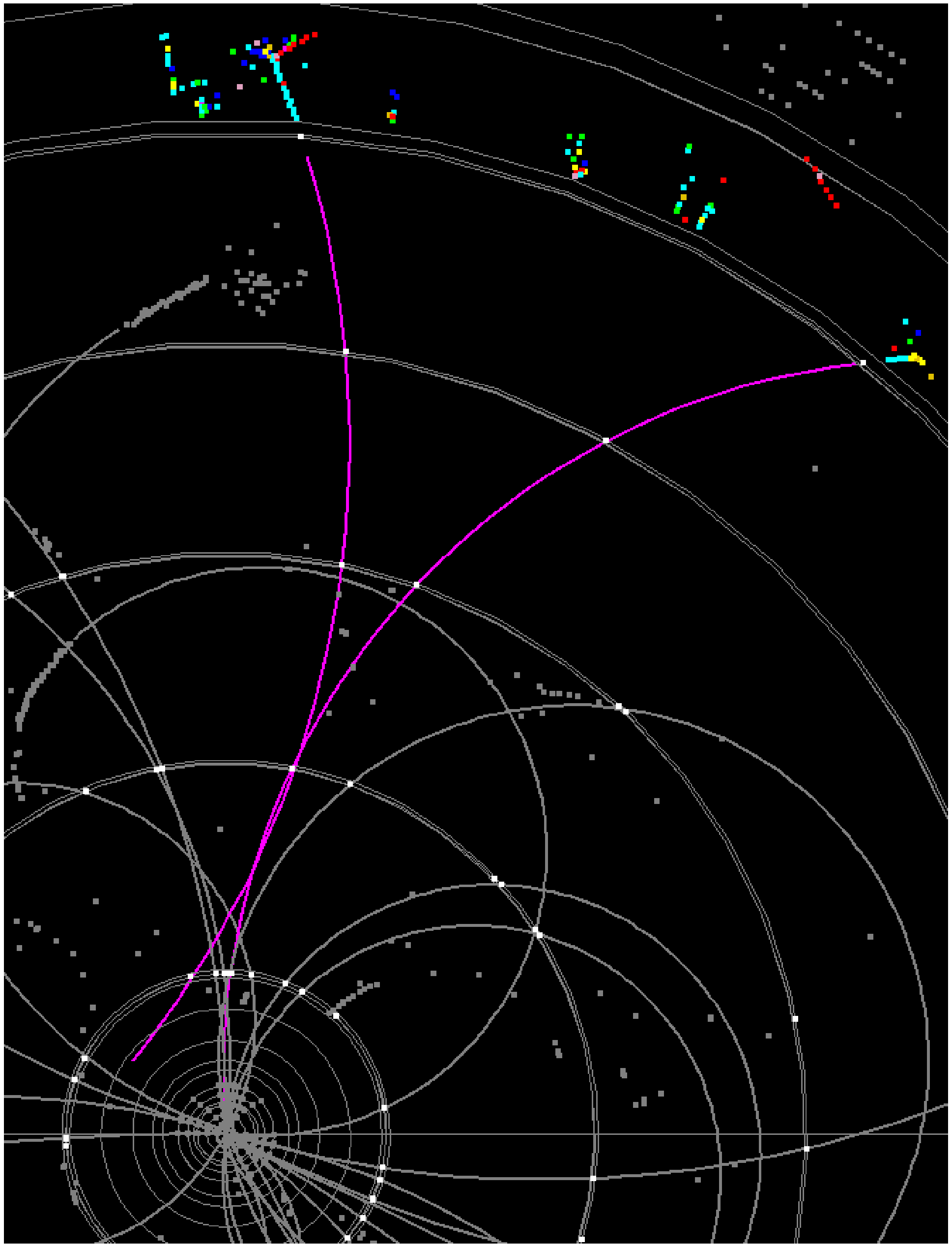
* Si-W detector first proposed in the context of a linear collider in 1996: (Brau, et al., Snowmass 1996)

Secondary Advantages of Silicon Tungsten:

- Granular detector can aid in tracking K_0, backscatters, etc.

- Robust against beam halo muons

- Dense calorimeter keeps coil small

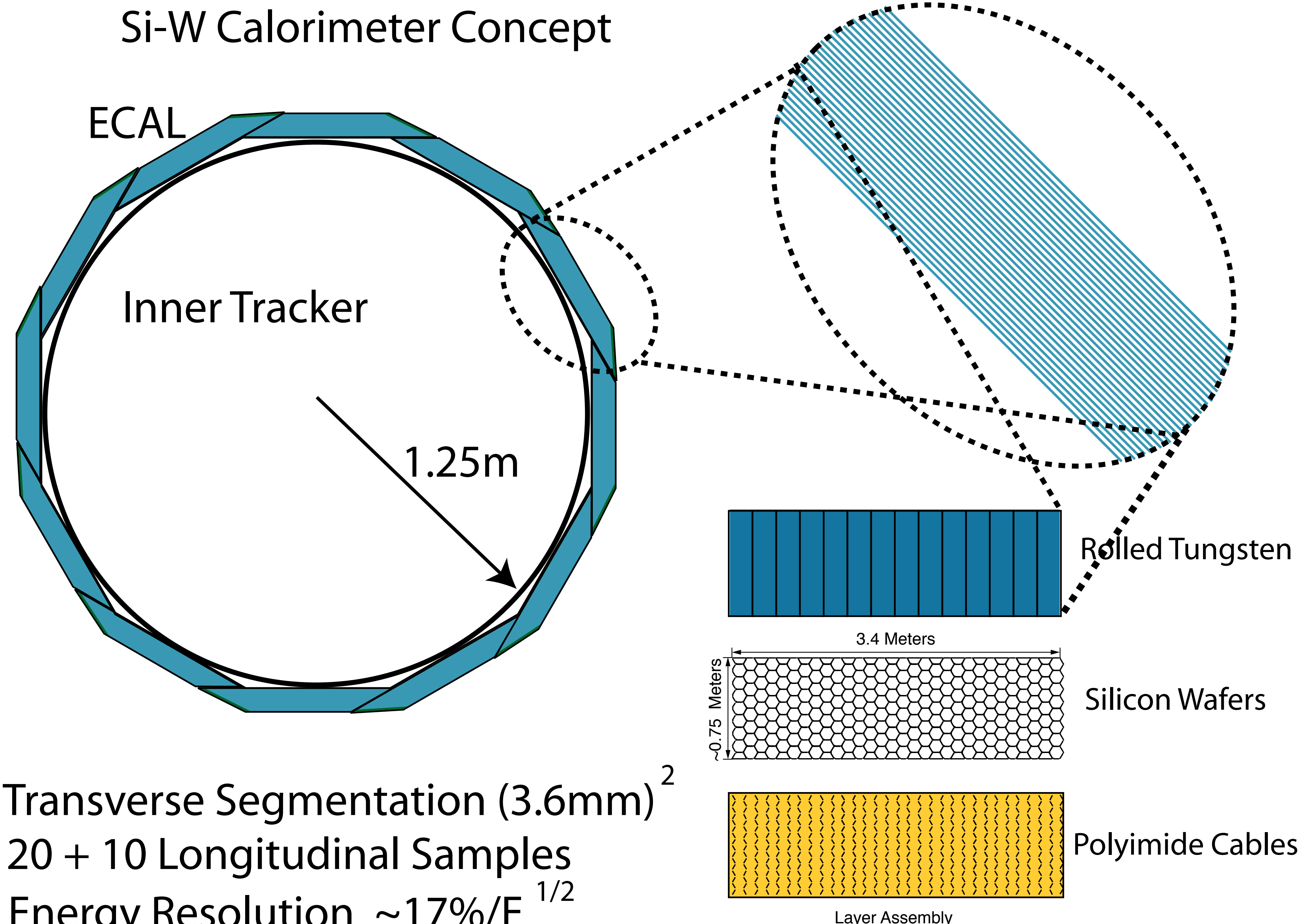


- SiD group working on an ECAL with millimeter sized pads:

Y. Karyotakis	V. Radeka	B. Holbrook R. Lander M. Tripathi	J. Brau R. Frey D. Strom	M. Breidenbach, D. Freytag, N. Graf G. Haller, R. Herbst T. Nelson
Annecy	BNL	UC-Davis	Oregon	SLAC
Mechanics	**Electronics**	**Bump Bonding** **Cabling** Mechanics	**Si Detectors** Mechanics Simulation	**Electronics** Mechanics **Simulation**

SiD also has an active group led by Marcel Stanitzki from the UK that is working on a tera-pixel options – 50μm x 50μm pixels.

Si-W Calorimeter Concept



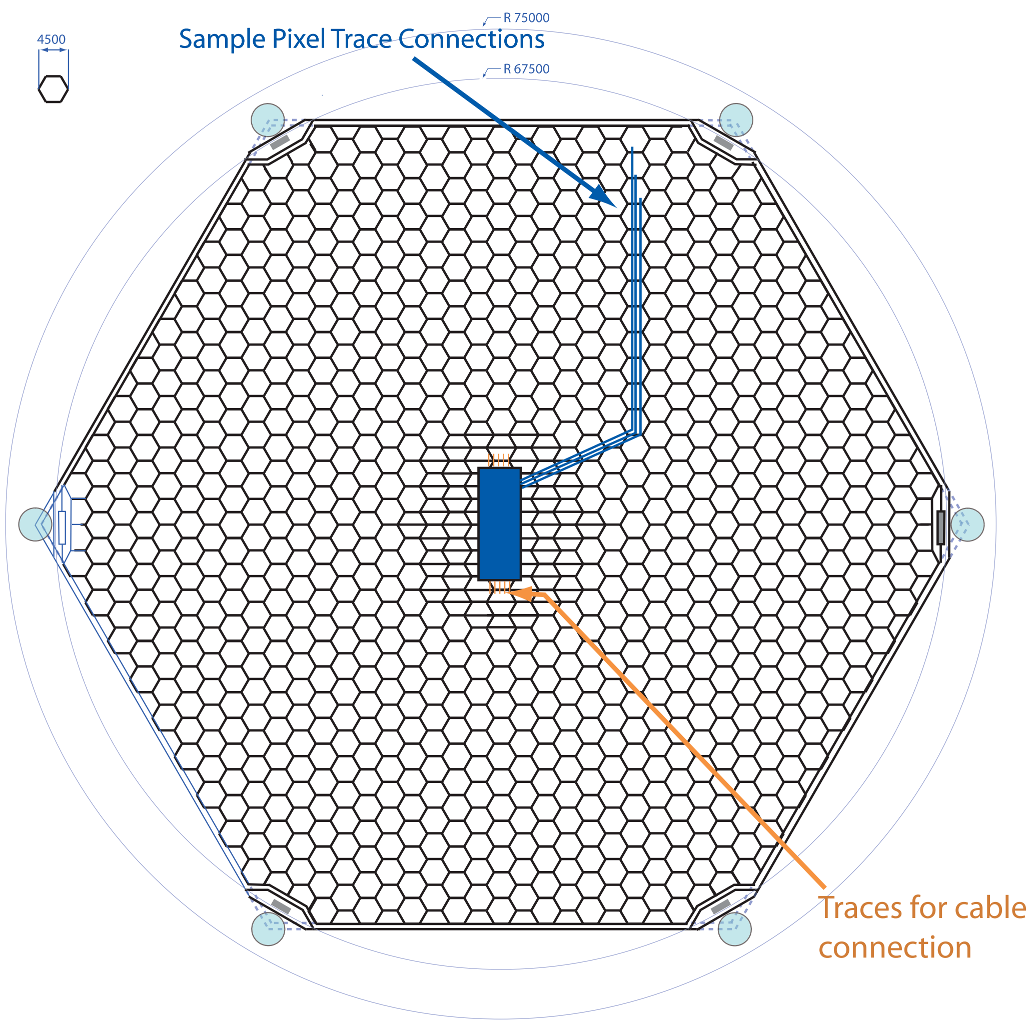
Transverse Segmentation $(3.6\text{mm})^2$

20 + 10 Longitudinal Samples

Energy Resolution $\sim 17\%/E^{1/2}$

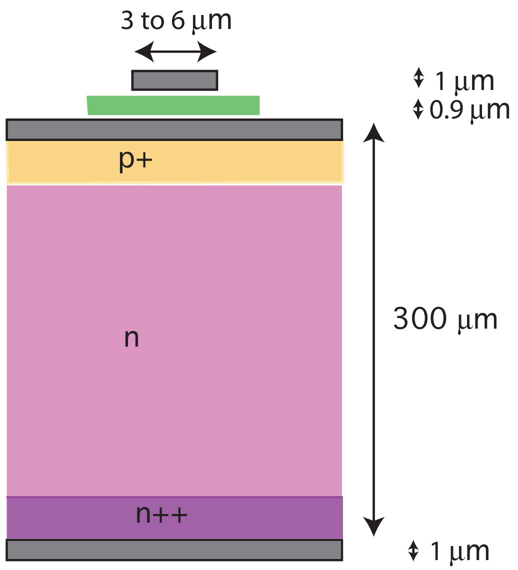
Silicon Concept

- Readout each wafer with a single chip
- Bump bond chip to wafer
- To first order cost independent of pixels /wafer
- Hexagonal shape makes optimal use of Si wafer
- Channel count limited by power consumption and area of readout end chip

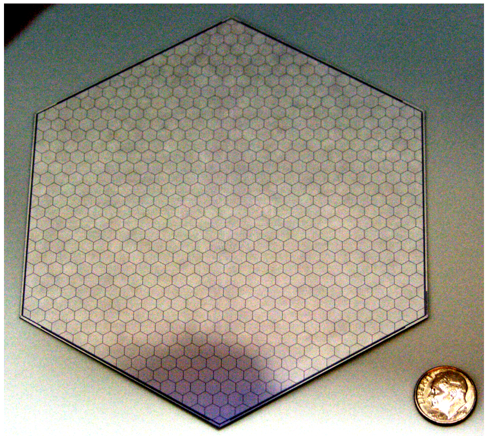


Silicon Detector Design

- DC coupled detectors (avoids bias resistor network)
- Two metal layers
- Si design simple, reduce cost
- Cross talk small when used with KPiX
- Trace capacitances (typical 30pF) are bigger than the 5pF pixel capacitance



Status: Ten version-1 prototypes produced, perform as expected

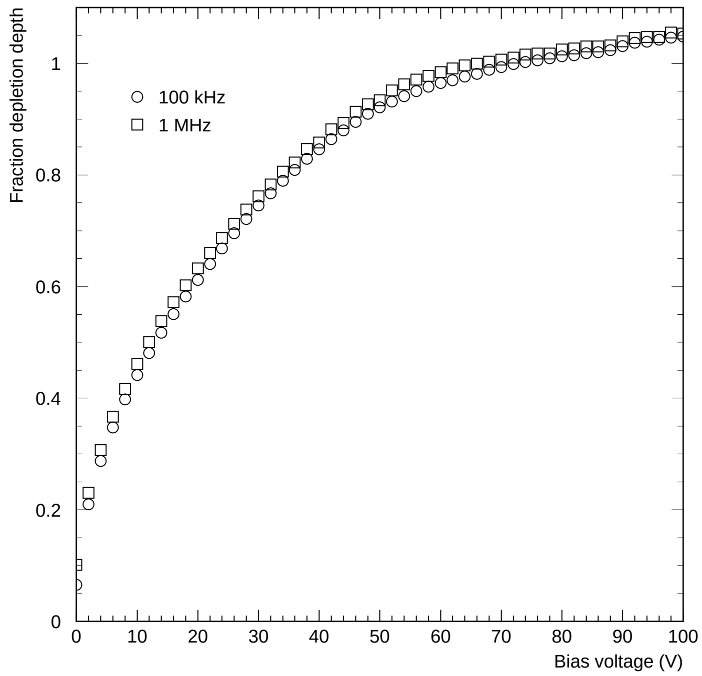


Depletion voltage (as inferred from CV curve) is as expected

Depletion depth is given by

$$d = \sqrt{2k_{Si}\epsilon_0\mu\rho(V + V_{bi})}$$

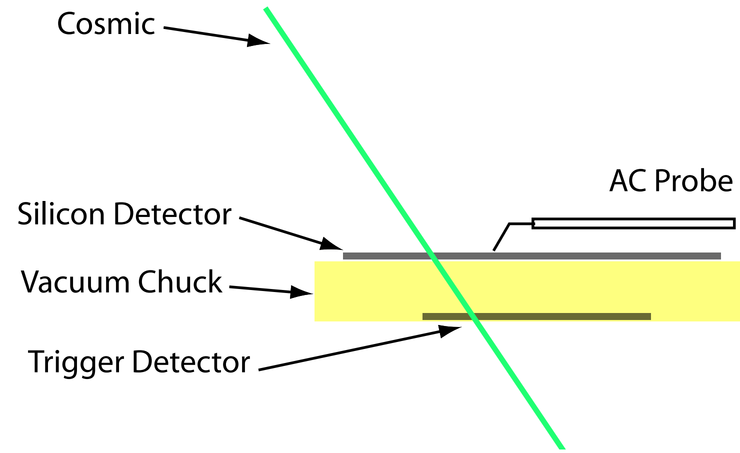
where
μ is the mobility,
ρ is the resistivity,
V is the bias voltage,
V_{bi} is the built in voltage.

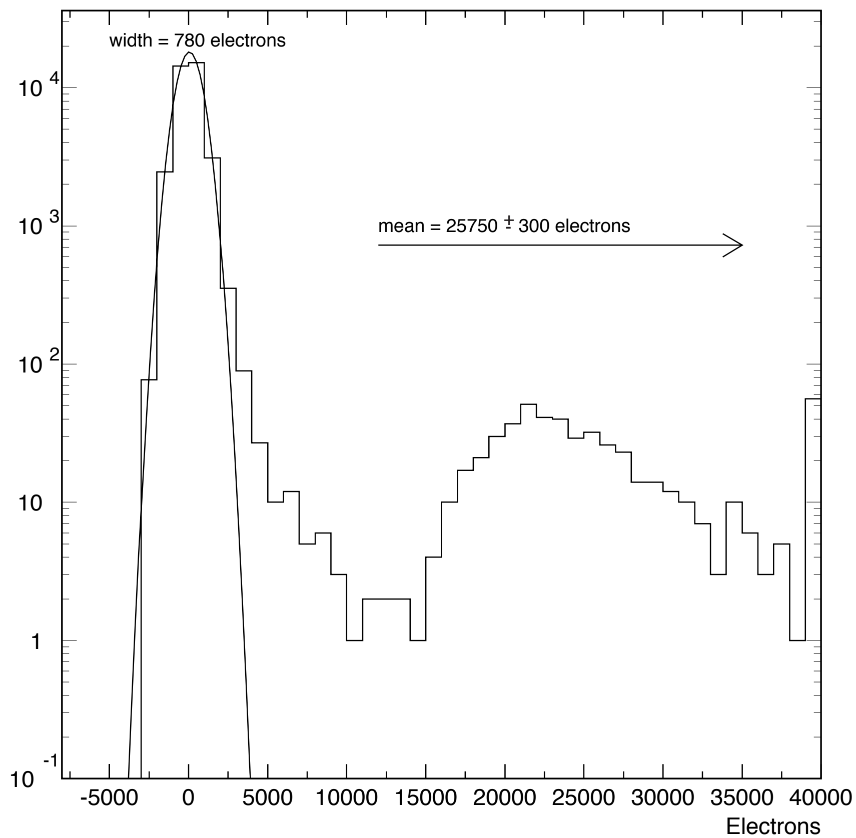


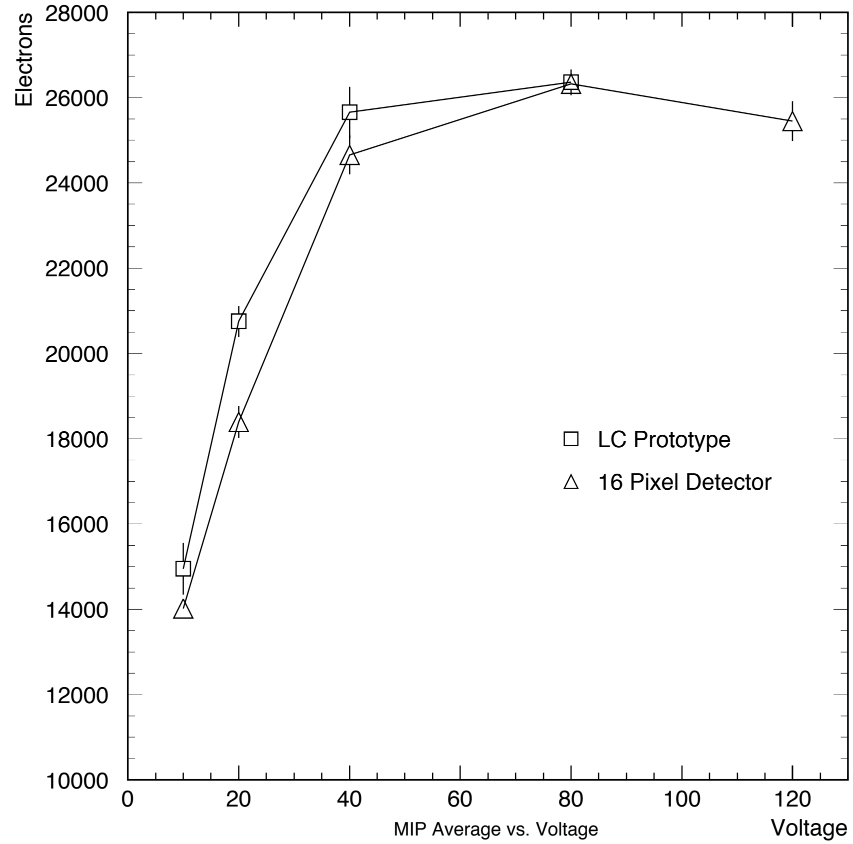
Neighboring pixels were floating – distorts depletion depth at high voltage

• Increasing the detector thickness from 300μm to 500μm could require bias voltages as high as 300 Volts.

Response of detectors to cosmics
(Single 5mm pixel)
Simulate LC electronics
(noise somewhat better)



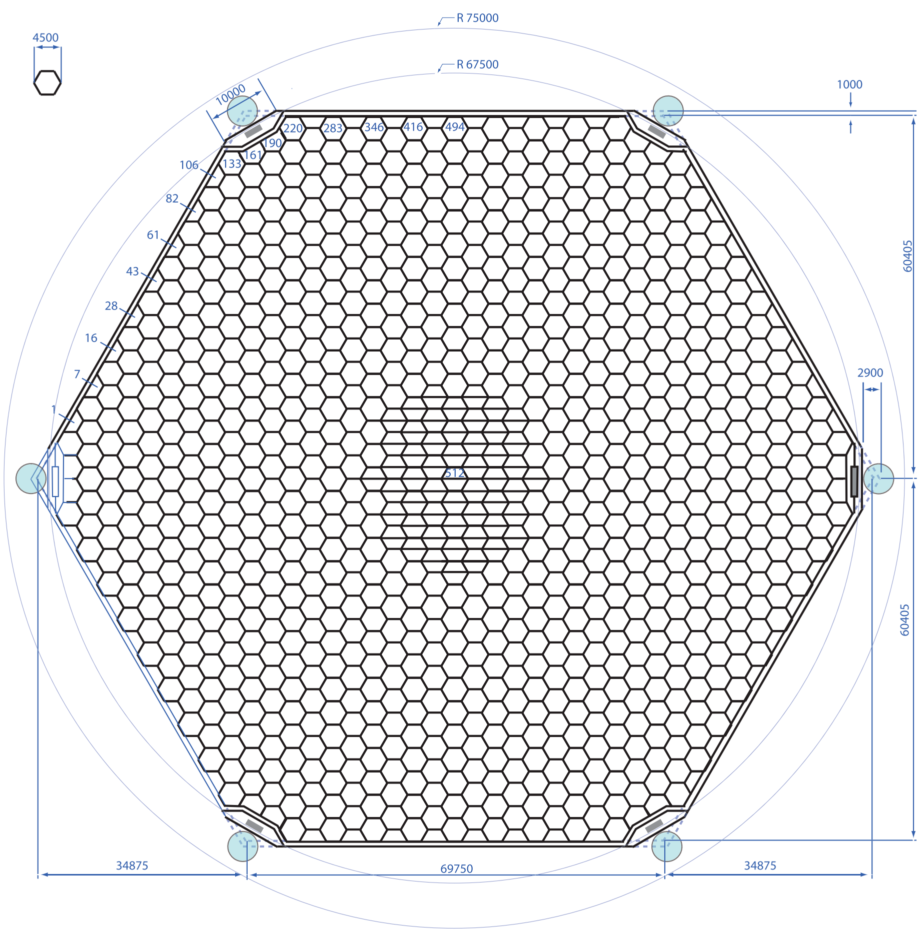




Errors do not include ∼ 10% calibration uncertainty (no source calibration)

Sensor layout for second prototypes

- $973 + 51$ pixels
- Possible top side bias
- Vertices removed to allow for spacers
- Long dimension of the pixel is 4.5 mm
- Pixel area is $(3.63\,\mathrm{mm})^2$
- Maximum radial dimension of active area is $< 67.5\,\mathrm{mm}$



Implication for dead space

- Dead space is dominated by edges

- Hexagonal detectors give lowest possible dead space

$$f_{dead} = \frac{4(w_g + c)}{\sqrt{3}h} \sim 5\%$$

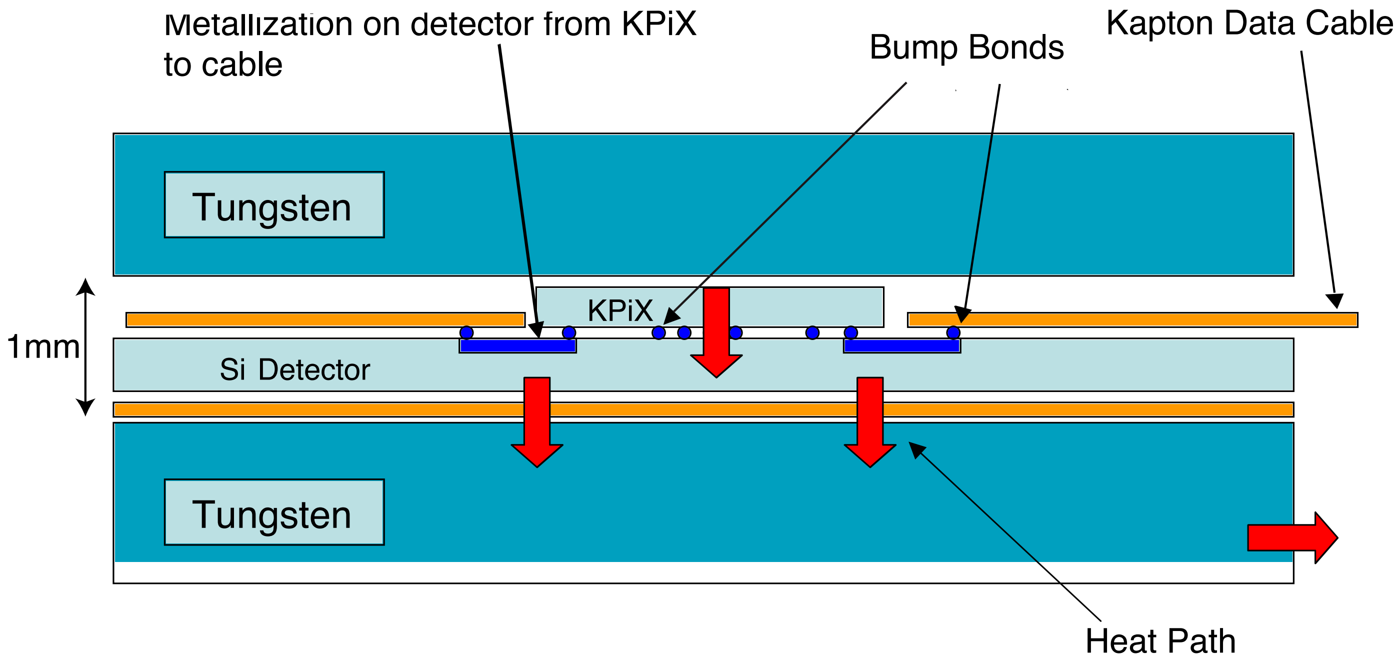
where w_g is the guard ring thickness (1mm) and c is half the clearance between detectors (0.4mm). For proof http://arxiv.org/abs/math.MG/9906042/

- Lost area at vertices is about 0.7%

- Lost area for top side bias is about 1.4%

- Energy resolution goes like $\sqrt{1 - f_{dead}}$ as long gaps are projective

Expect to keep gap between tungsten layers to 1 mm



Watches have thinner movements

0.98 mm movement,

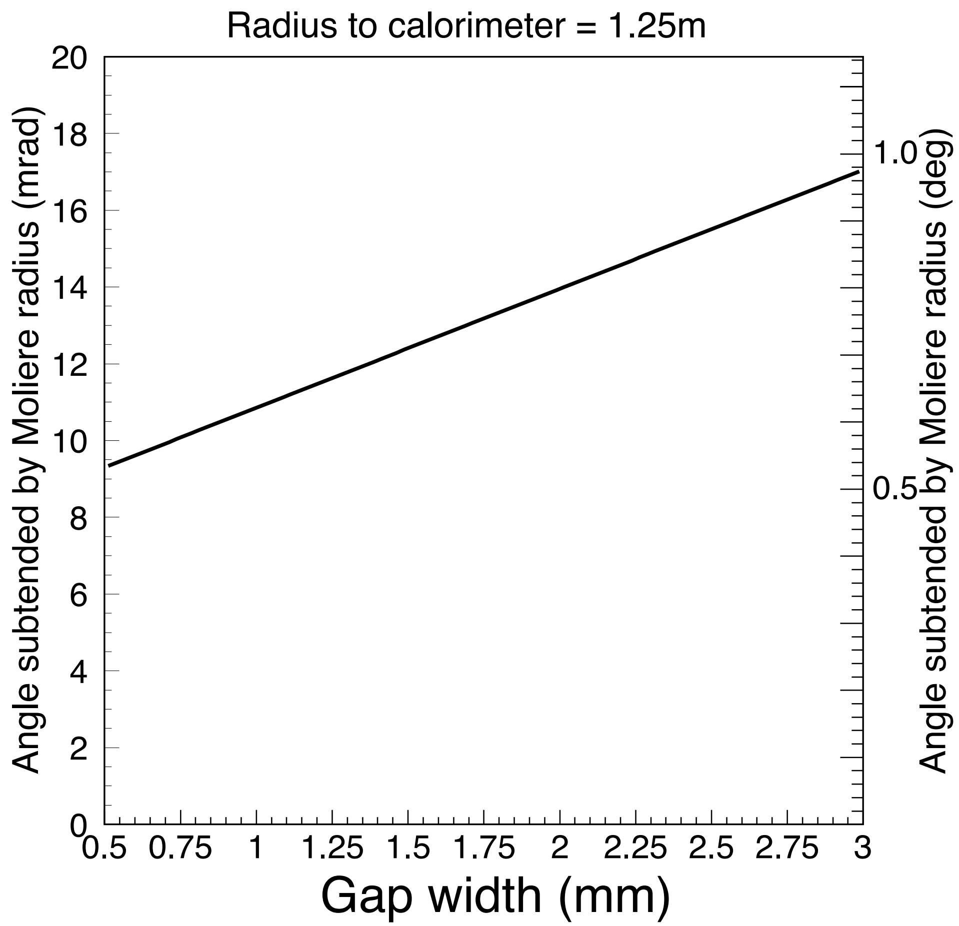
3.50 mm overall

May need to add local capacitors near KPiX

Critical parameter: gap between tungsten layers.

Config.	Radiation length	Molière Radius
100% W	3.5mm	9mm
92.5% W	3.9mm	10mm
+1mm gap	5.5mm	14mm
+1mmCu	6.4mm	17mm

Assumes 2.5mm thick tungsten absorber plates



Need to separate EM clusters so that track-EM cluster association can be performed

Impact of gap on PFAs is not yet quantified with simulations

For unmerged photons, charged and neutral energy can be separated, even if there is some overlap.

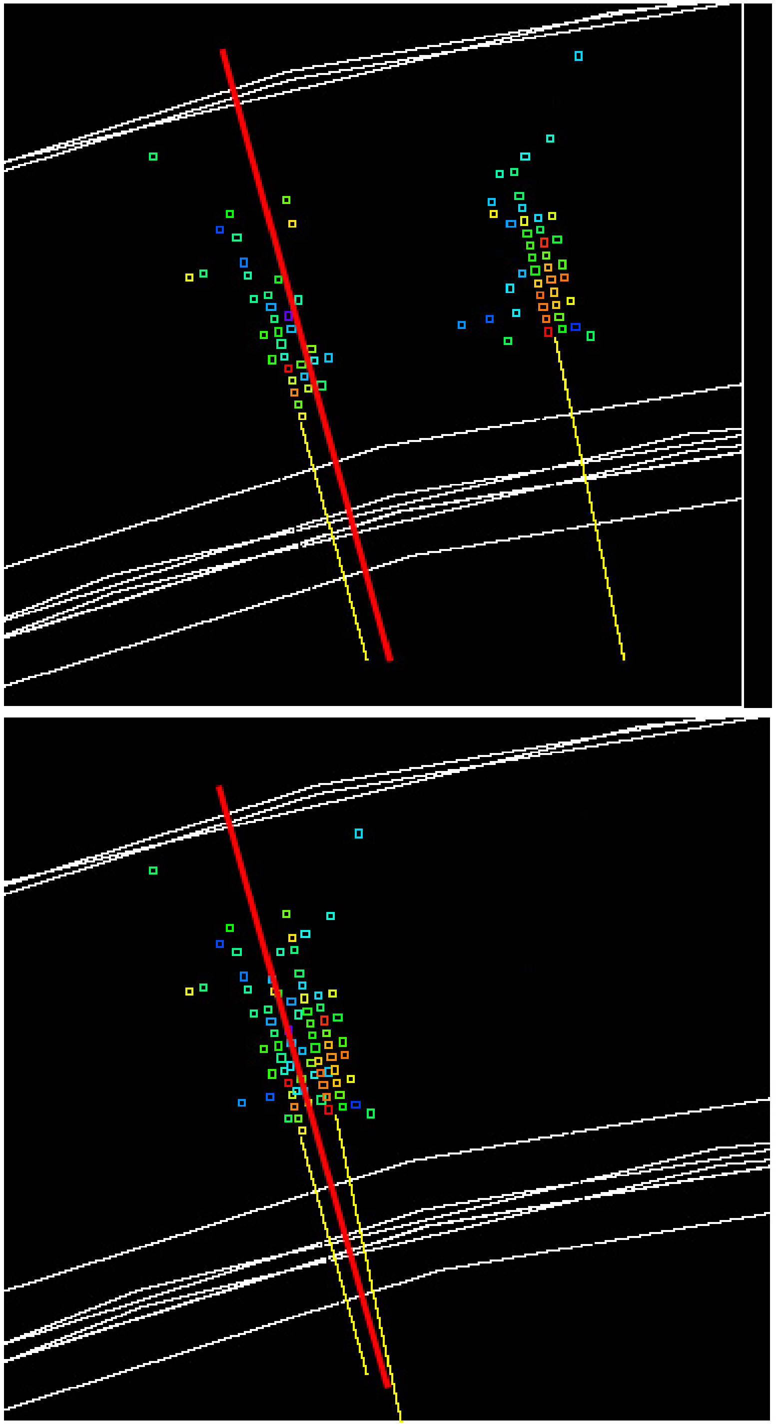
Compare EM shower centroid with track.

ECAL photon-photon separation is an important figure of merit.

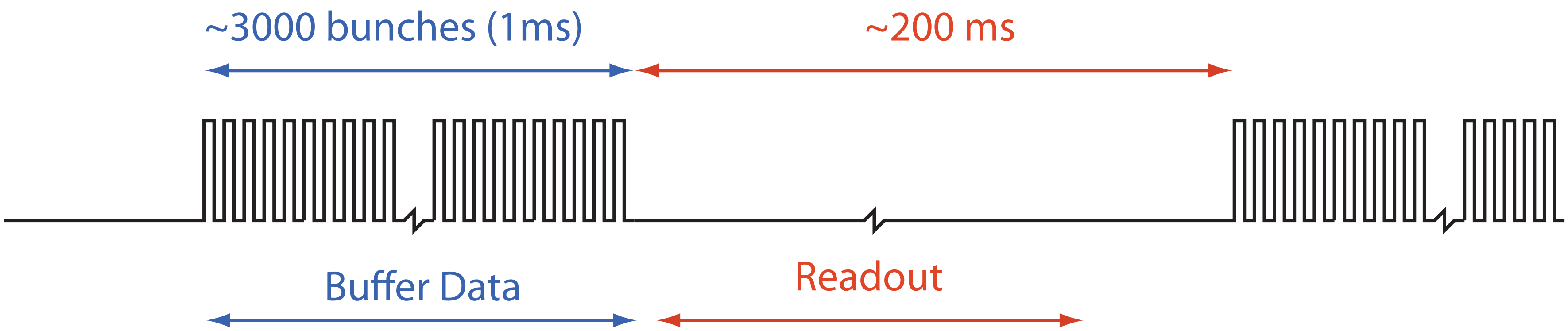
Sophisticated shower finding needed

Segmentation well below the Molière radius is useful.

Segmentation is not decisive for particle flow, could be for τ physics



Electronics: Bunch Structure at the ILC



- Duty cycle of bunches is low, $\sim 1/200$

$\Rightarrow$ Only provide high current to front end during bunch train

Reduces power

- In the high granular SiD concept, occupancy is low

$\Rightarrow$ Buffer data during the bunch train

Only 4 buffers are needed for $> 1\%$ dead time everywhere in the ECAL

Minimizes digital interference to analog signals

Power requirement – Can we get the heat out?

Back of the envelope calculation of Δ temperature in ECAL

Thermal Conductivity:

- W alloy 120W/(K-m)
- Cu 400W/(K-m)

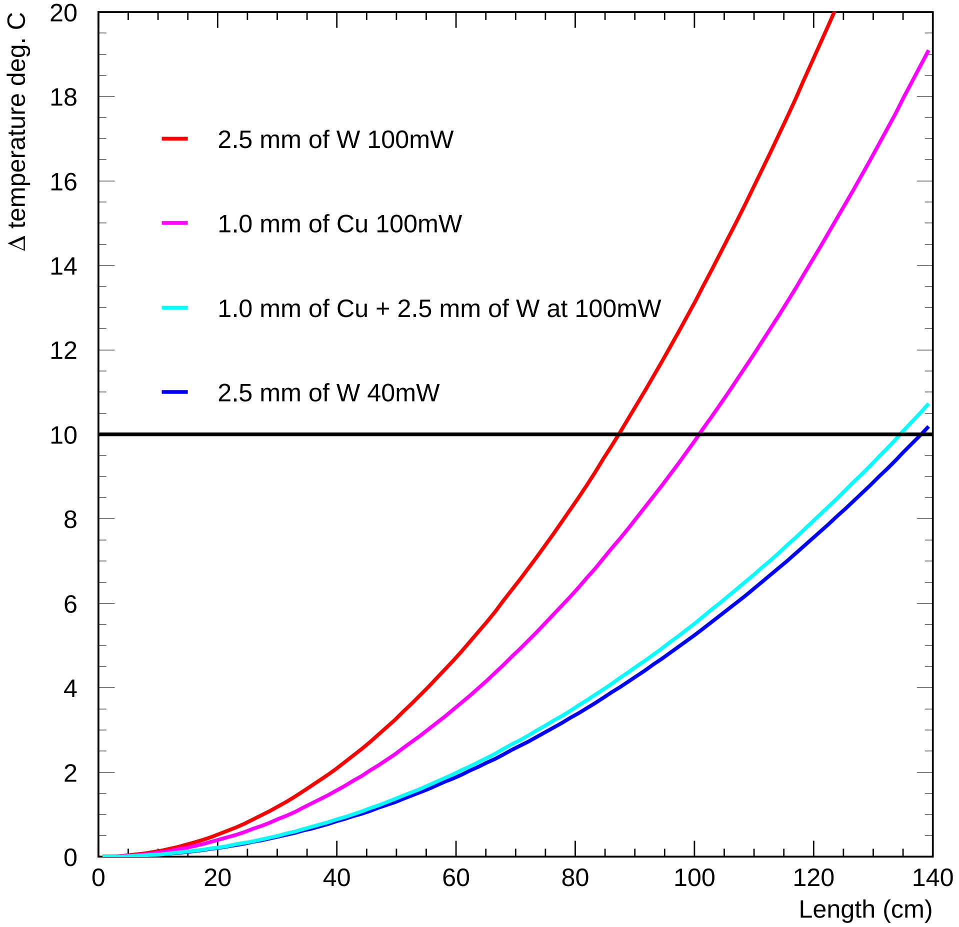
Need to reduce heat to below 100mW/wafer (∼ 1mW/cm^2).

- HCAL will be easier

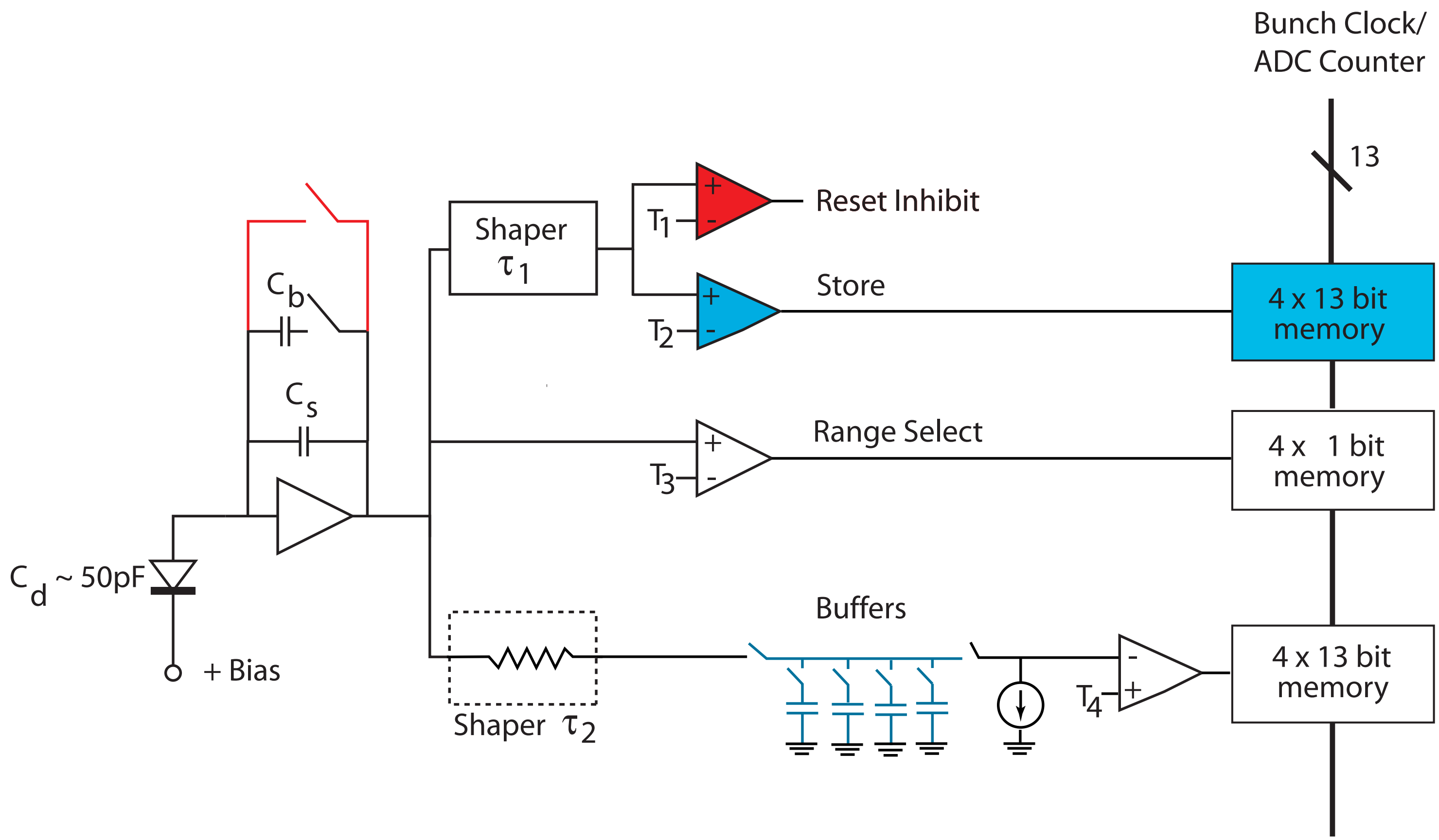
⇒ lower channel density

⇒ thicker absorber

Present design ∼ 20 mW
Consistent with prototype measurements

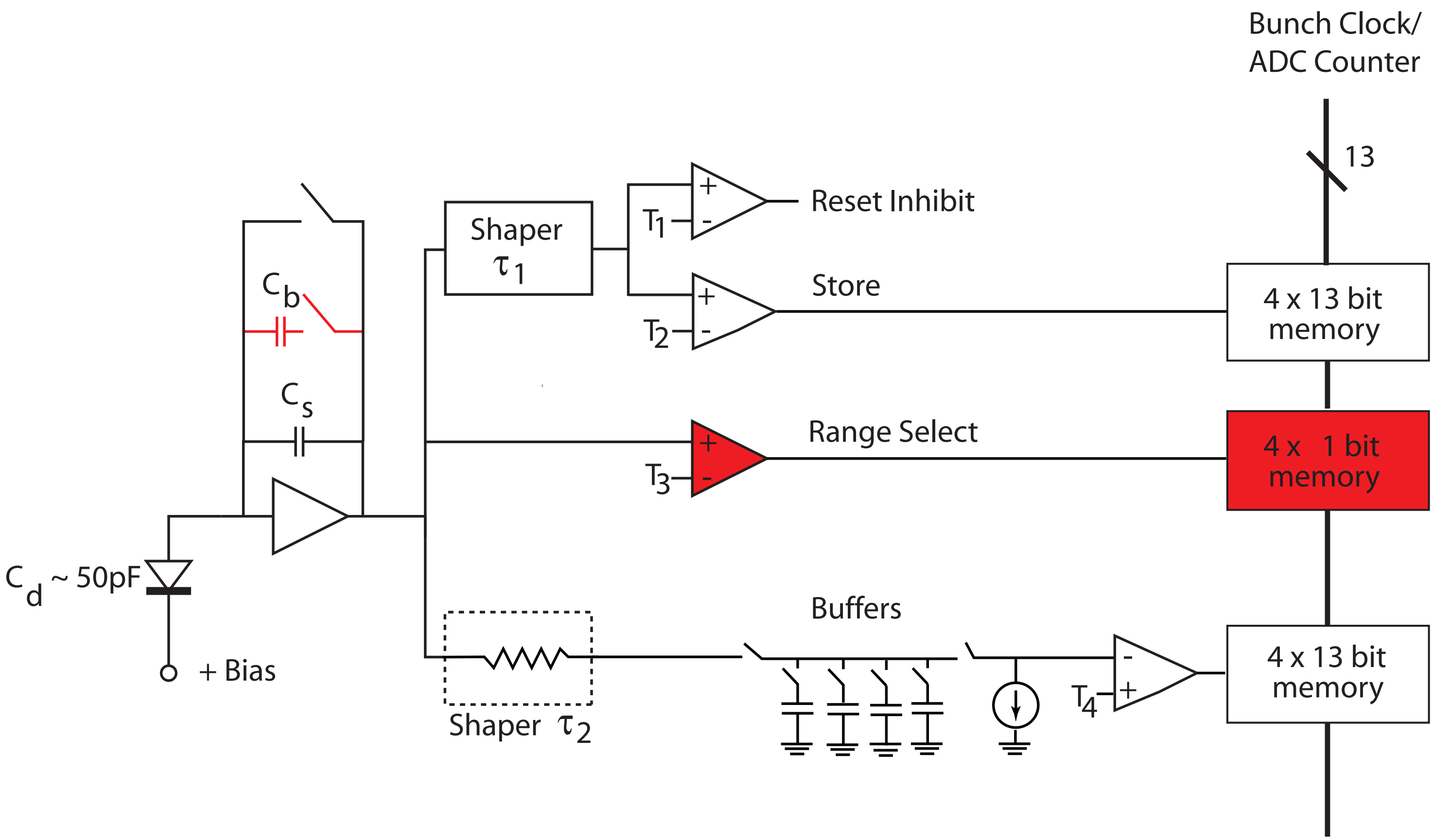


KPiX Concept – saves up to 4 samples from each train



- Threshold T_1 is used to inhibit resets (set at 2 × noise)
- Threshold T_2 is used to enable data storage (set at 4 × noise)
- Bunch clock (time) is stored in SRAM (13 bit precision)
- Analog charge is stored on capacitors (13 bit precision)

Range Switching



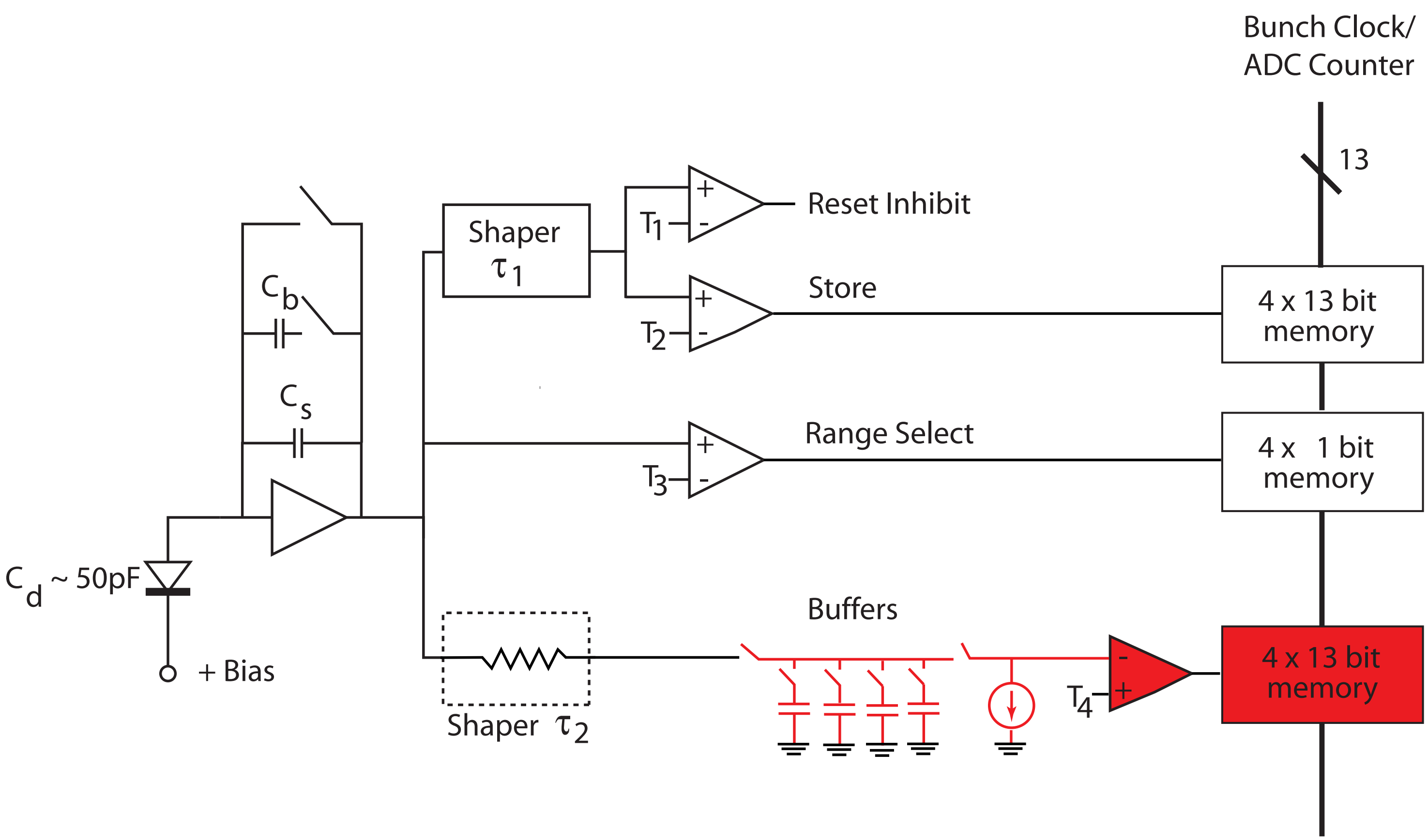
- Dynamic range switching (driven by threshold T_3) selects C_s or $C_b||C_s$

$\Rightarrow$ Feedback capacitor $C_b = 10\,\mathrm{pF}$ stores up to 10 pC

$\Rightarrow$ Feedback capacitor $C_s = 400\,\mathrm{fF}$ (0.3 fC gives 0.7 mV)

N.B. Switches to capacitors closed for several RC times so signals settle

Charge Digitization (between bunch crossings)



- Time needed to discharge each capacitor stored in 13 bit memory
- Time is combined with range bit to correct amplitude • May additional features– calibration, threshold choices, bias servo, polarity selection, external triggers, nearest neighbor logic, etc.

Chip Size

- Chip is implemented in TSMC 0.25μm CMOS
- Single analog channels comfortably fits into 200μm by 500μm cell
- Overall chip size (1024 channels) approximately:

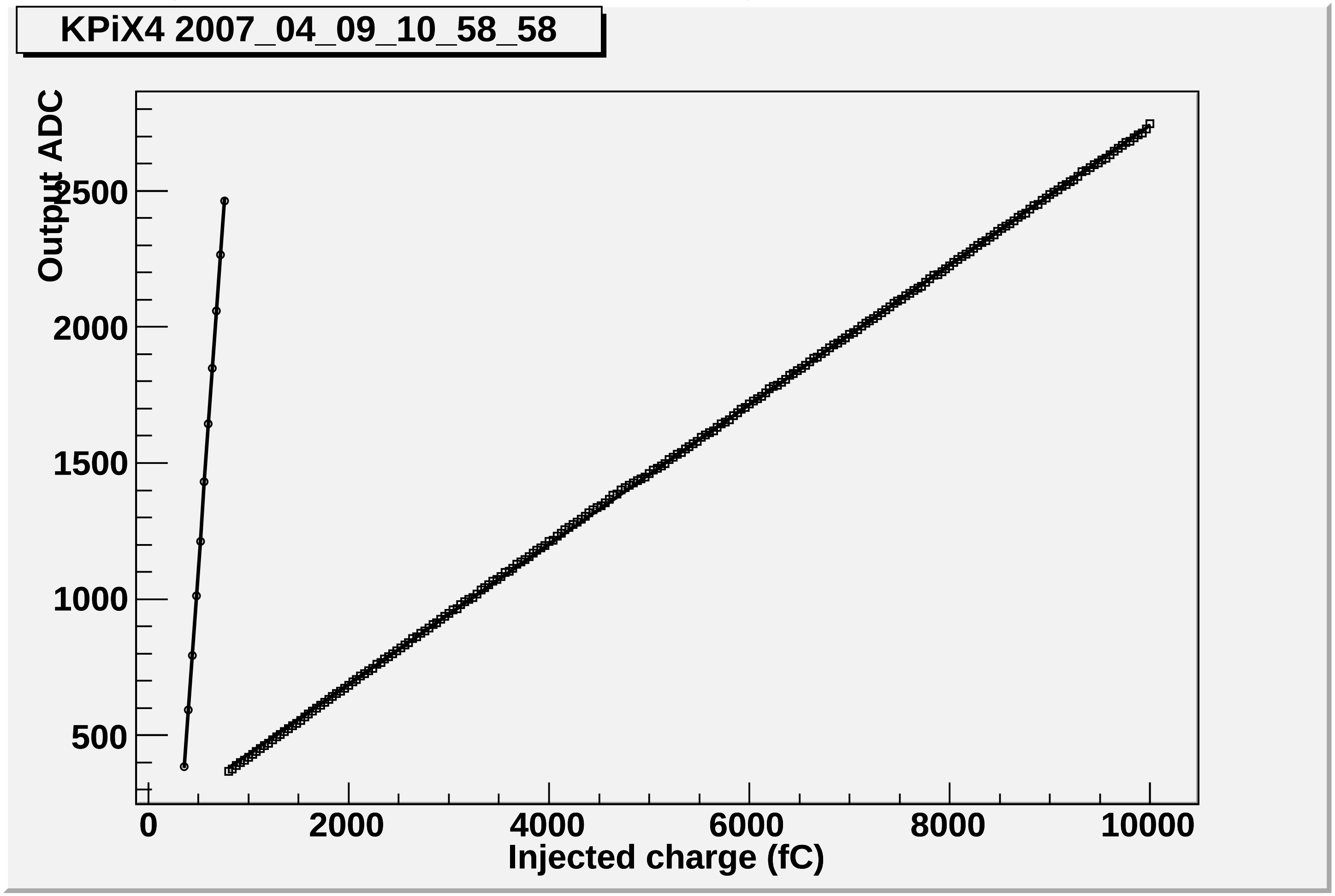
$$18\,\text{mm} \times 6.5\,\text{mm} \sim 1.2\,\text{cm}^2$$

- Aspect ratio helps in routing traces on silicon sensors
- Could not reduce chip size without making bump bounding more difficult

Overall chip size close to optimal

Performance – 64 channel prototype – range switching

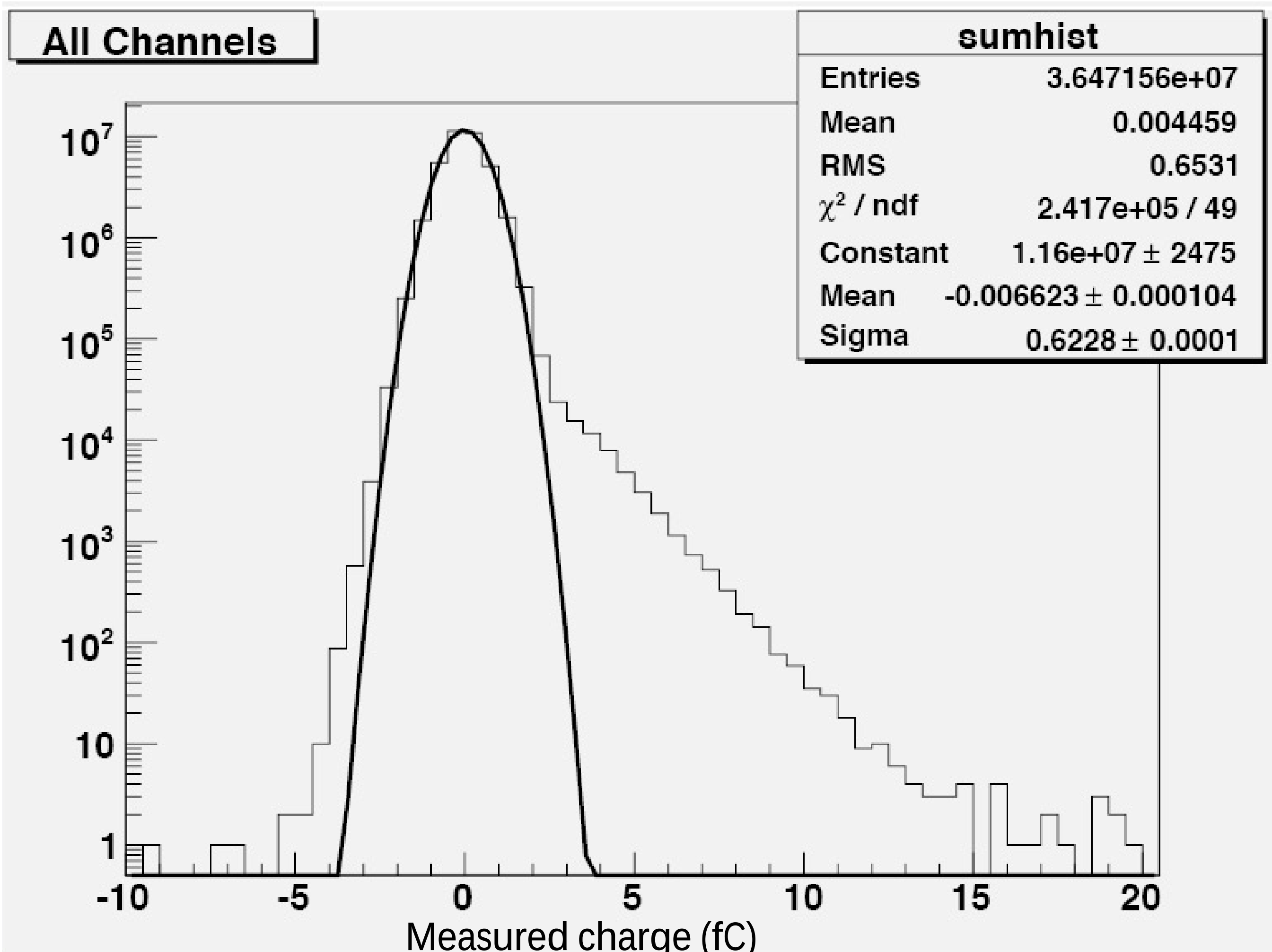
Range switching feature works as designed



Linear behavior extends beyond 10 pC

(Nonlinear behavior extends range by 50% or more)

Performance – test beam with Silicon Strip Detector

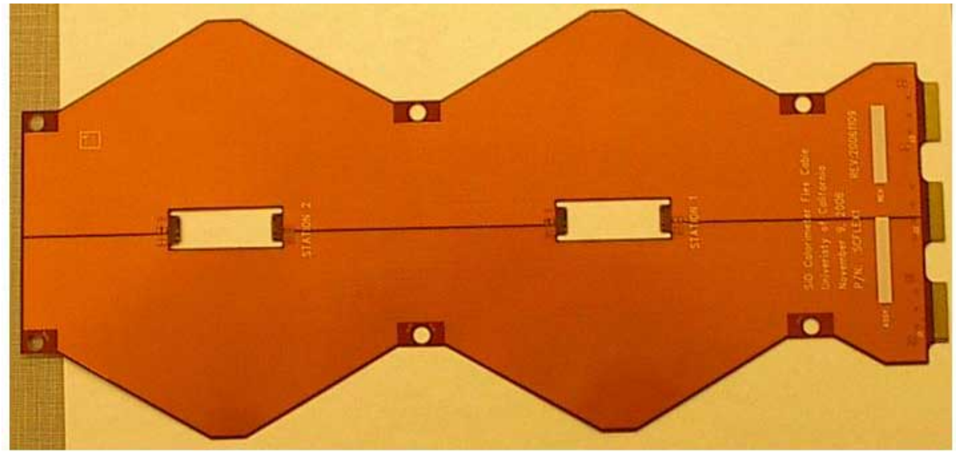


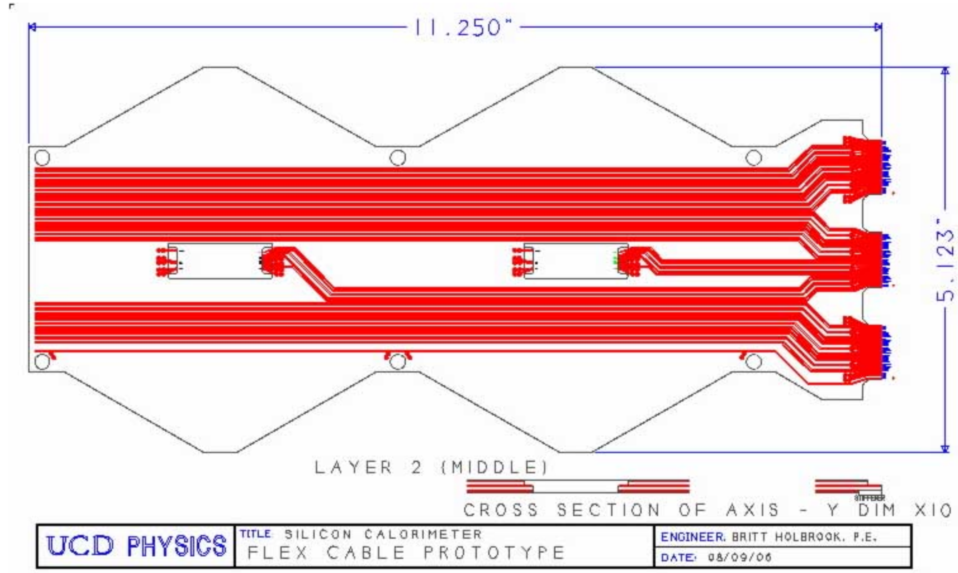
Tim Nelson

Noise of prototype is almost good enough for the calorimeter. Improvements are expected.

Flex Cable Development (UC Davis):

- First prototype with 2 chip stations has been fabricated.
- Each cut-out has inner lips which can be used for either wire-bonding or other technology.
- The layout has a buried layer for signals, sandwiched between power and ground layers.



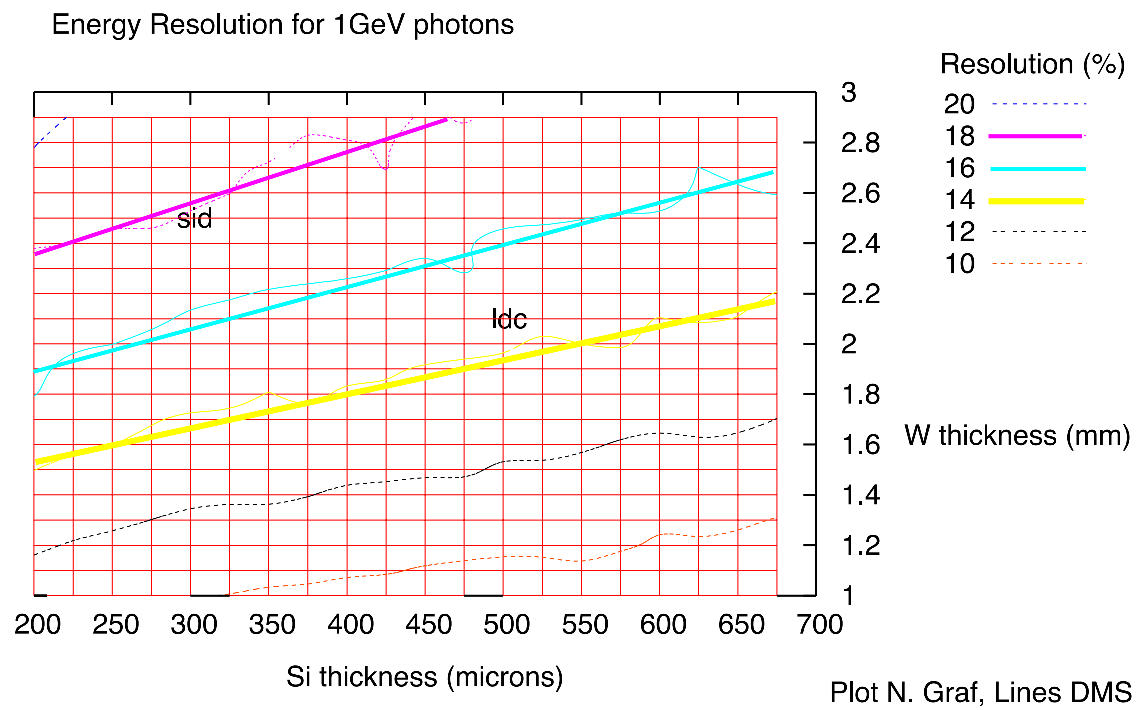


Gold Stud bump-bonding trials with prototype KPiX also underway

Energy Resolution

Resolution depends on

- Tungsten thickness
- Silicon thickness
- Detector depth



- Baseline is 300μm thick Silicon and 2.5 mm thick Tungsten, $\sim$ 17%$/\sqrt{E}$
- Ecal energy resolution does not drive jet energy resolution
- $\Rightarrow$ We are studying physics processes sensitive to ECAL resolution.

Vertex Detector Motivation

- Reconstruct long lived b and c hadrons
- Measure track parameters close to the interaction region: less silicon area, cheaper

The Chronopixel Project:

J. Brau, N. B. Sinev, D. Strom
University of Oregon

C. Baltay, H. Neal, D. Rabinowitz
Yale University

EE work is contracted to Sarnoff Corporation

The Chronopixel project is only one of about 20 different vertex detector efforts in the world.

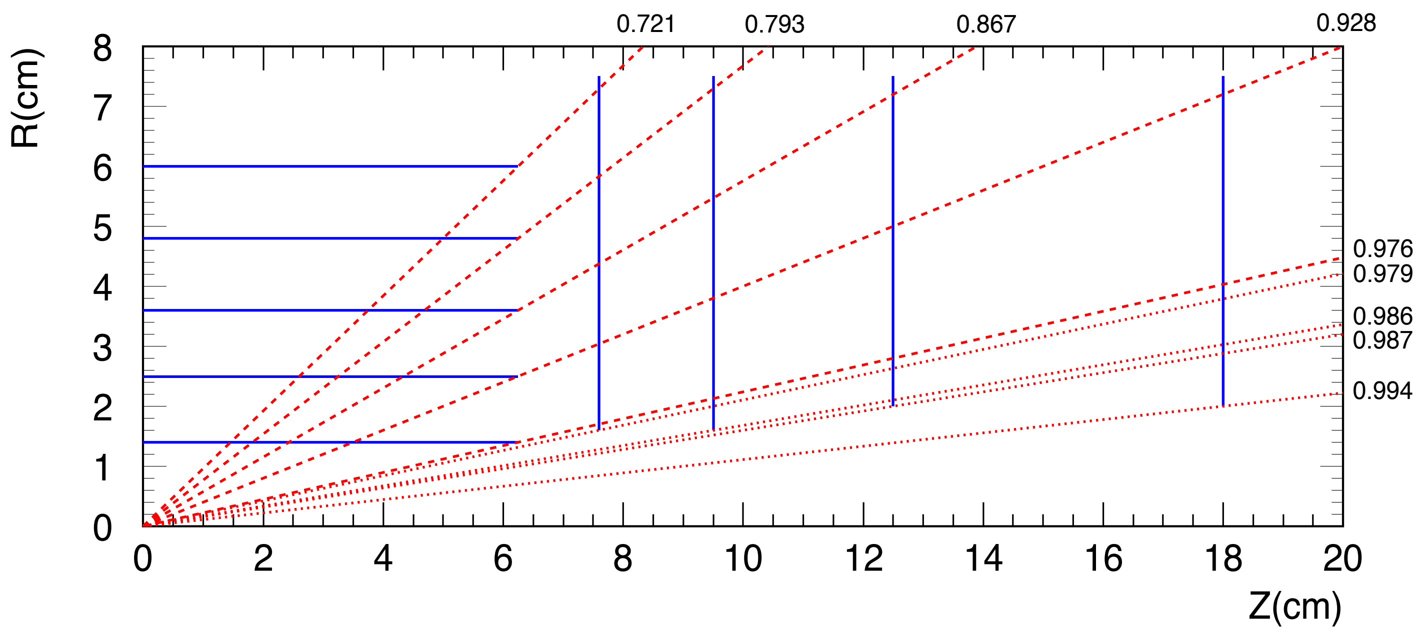
Highest risk, last on the critical path

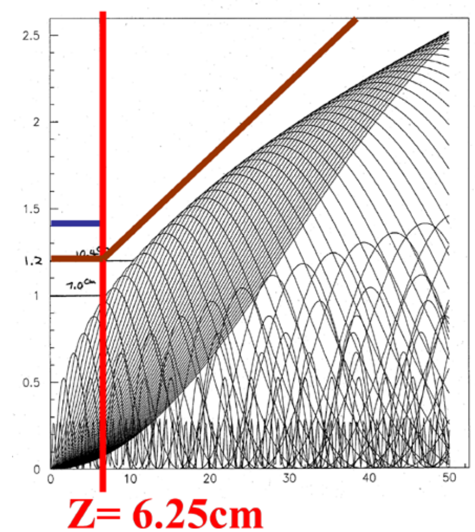
Vertex Detector Requirements

- Good angular coverage with many layers close to vertex
- Efficient detector of particles with a granularity of 20μm $\times$ 20μm $\times$ 20μm or better
- Sufficient time resolution to obtain occupancies of 10^{-4} or better (SLD experience)
- $\sim 0.001X_0$ radiation lengths per layer (c.f. LHC total material $>$ $1.0X_0$)
- Modest average power consumption $<$ 50W
- Plausible peak currents? (2500A if delivered at 2V)!

$\Rightarrow$ Should have $\sigma_{d0} < 5.0\mu$m at high p.

Vertex Detector Configuration in SiD

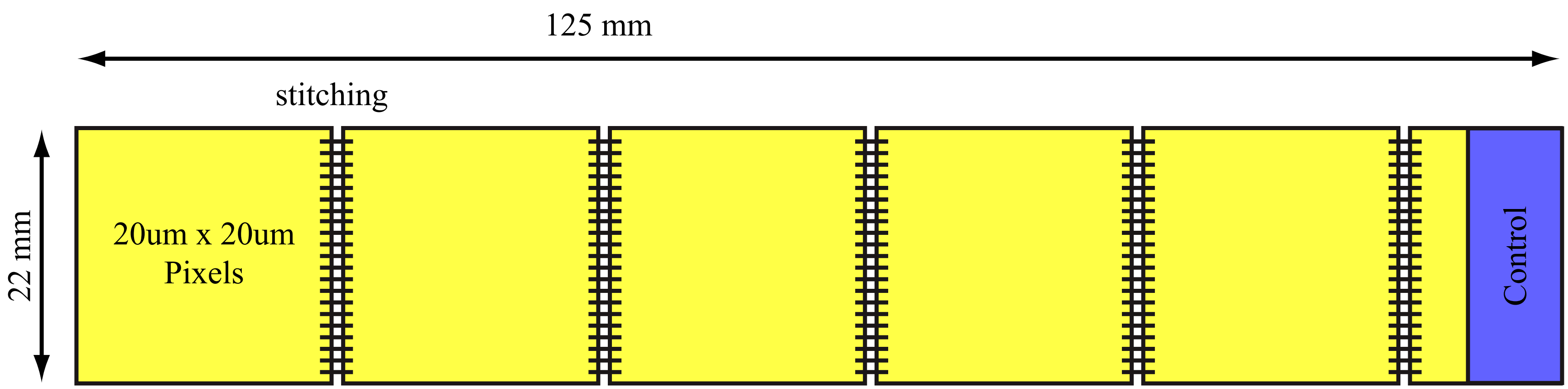




Pair trajectory

Red lines show $\cos\theta$ acceptance

Possible barrel ladder layout:



- Basic pixel unit fits in a single reticle

- Sarnoff stitching technique used to connect pixels buses to control logic

- Power and readout from one end of ladder ($\sim$ 100 conections)

Occupancy

• Baseline occupancy 0.03 hit-clusters/mm^2/bunch, but could be higher for some configurations of the ILC.

• Ideal situation is to have a bunch-by-bunch time tag for each pixel:

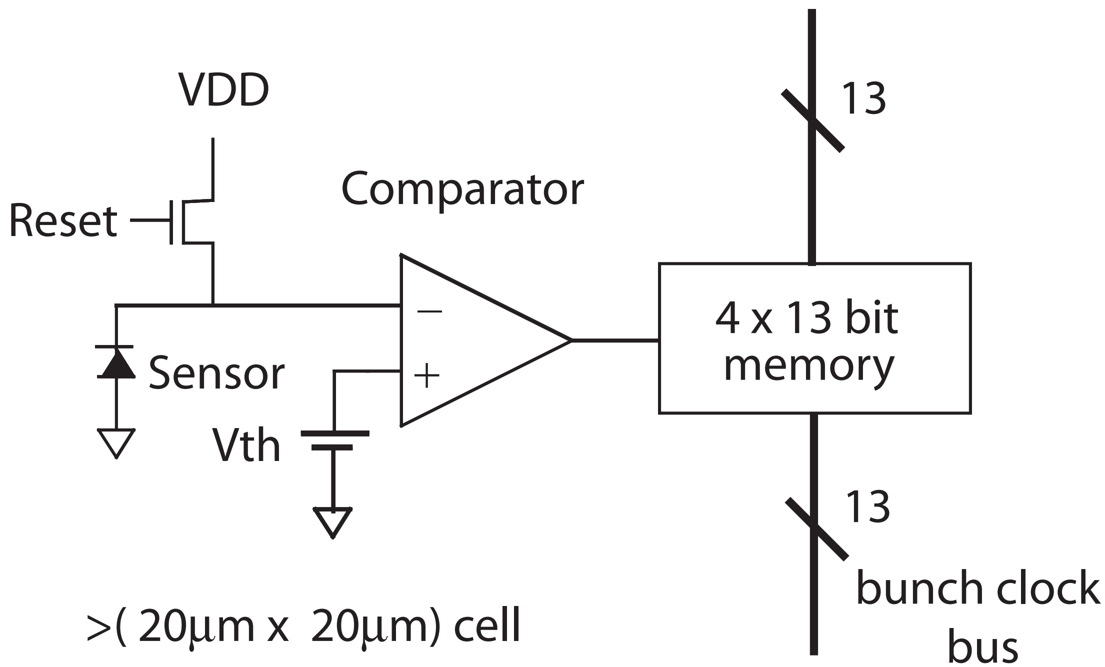
$\Rightarrow$ For 20μm $\times$ 20μm pixels the baseline gives an occupancy of

$$\sim 1.2 \times 10^{-5}/\text{bunch}.$$

N.B. from the point of view occupancy, the pixels could be larger. For 50μm $\times$ 50μm pixels the occupancy is

$$\sim 7.5 \times 10^{-5}/\text{bunch}.$$

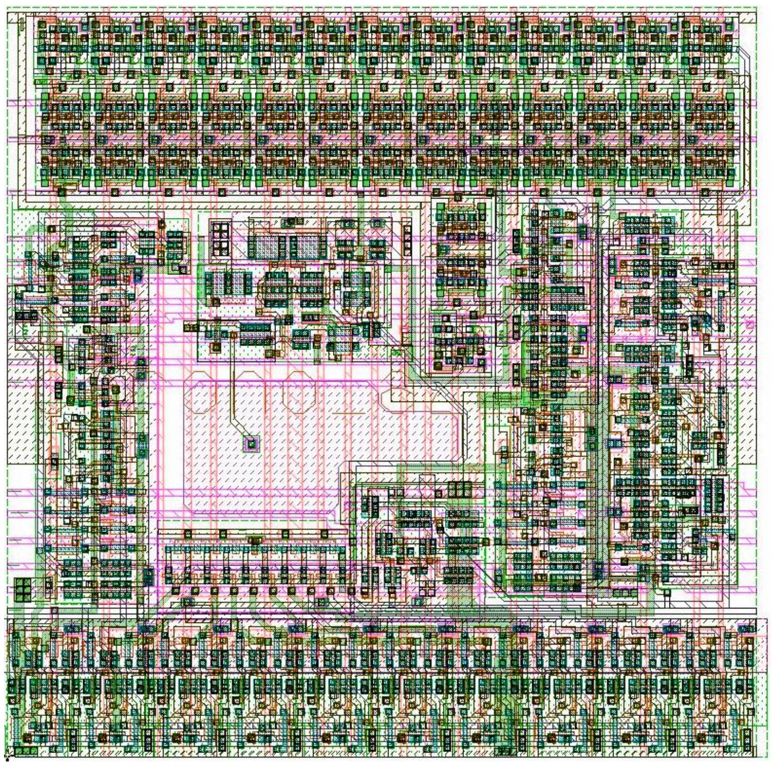
Simplified chronopixel schematic – similar to KPiX, but much less functionality needed–assume digital information is sufficient



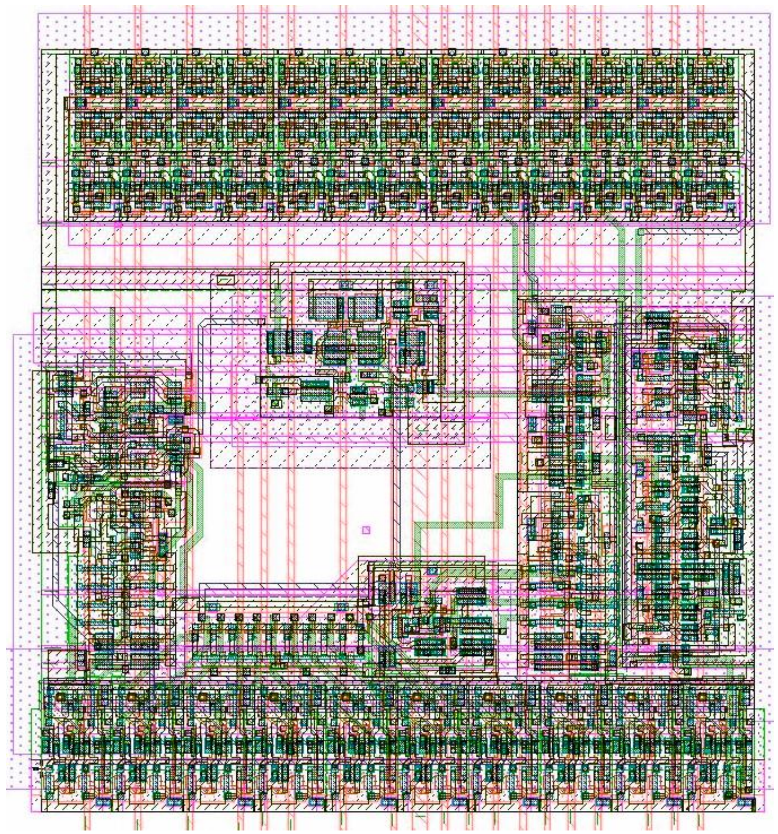
For first prototype target 180 nm CMOS and $50\mu m \times 50\mu m$ pixel for present R&D

Variable threshold is calibrated in each cell (can be done for each bunch train)

Two variations on the pixel circuit have been layout in 180 nm and are ready for fabrication

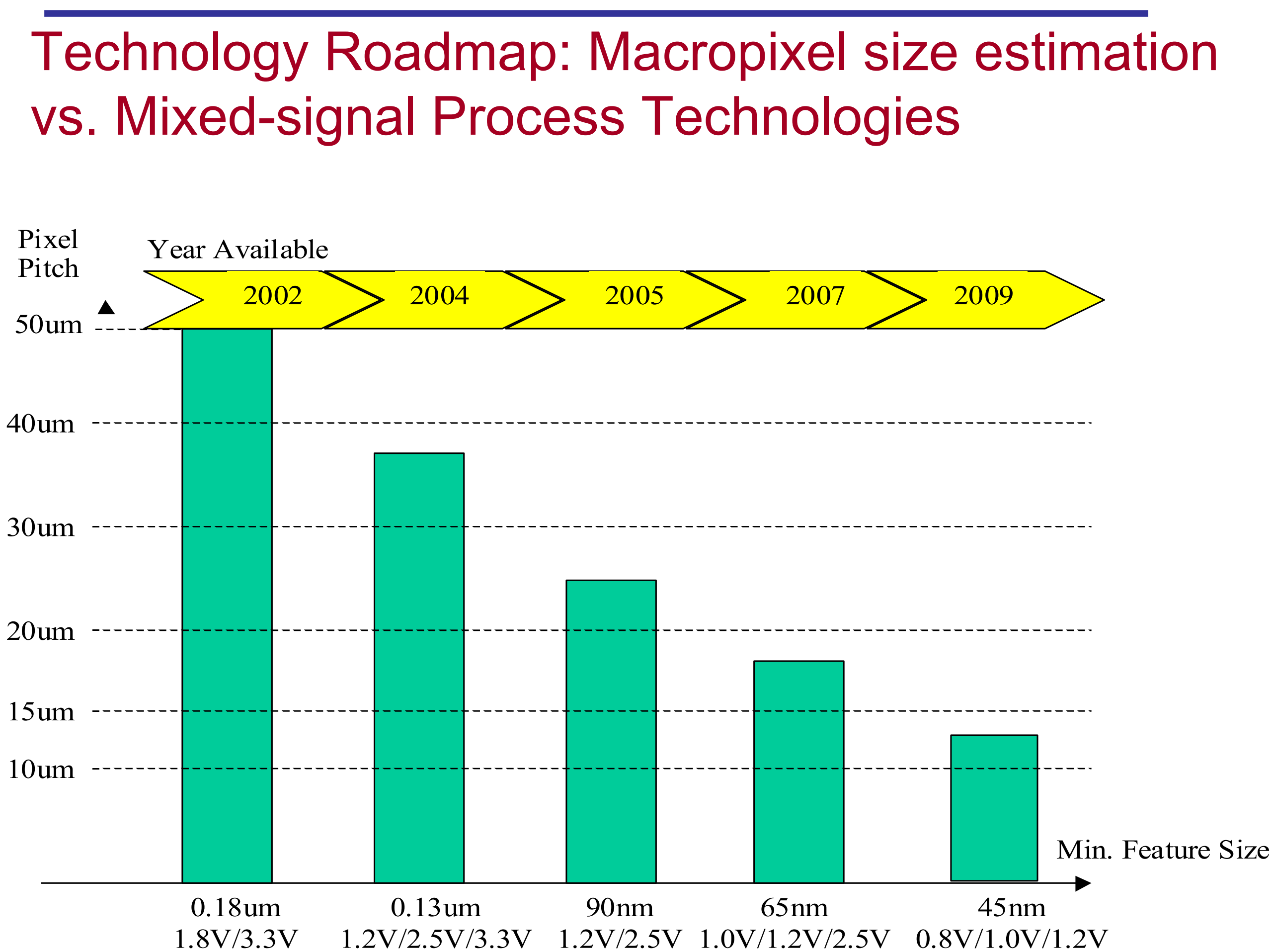


8 step calibrator, 14 x 2 memory



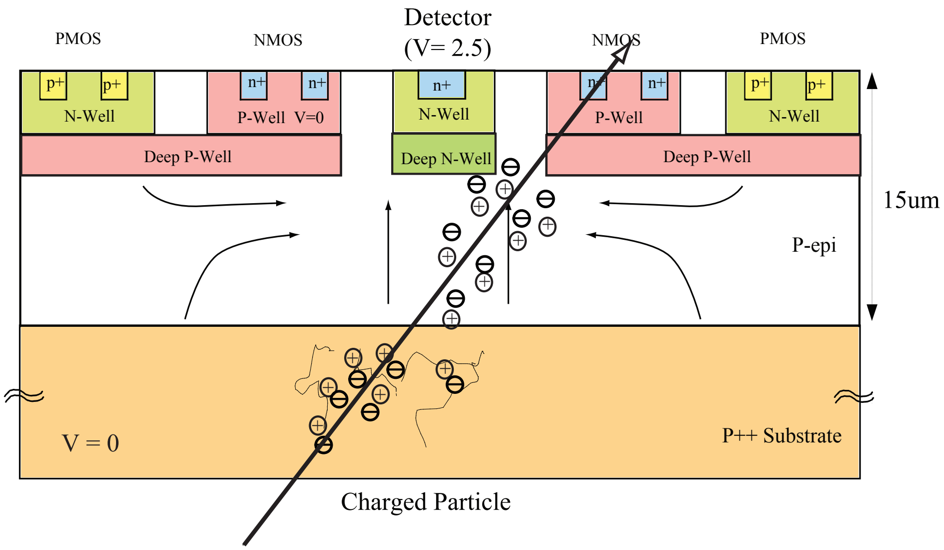
32 step calibrator. 13 x 2 memory

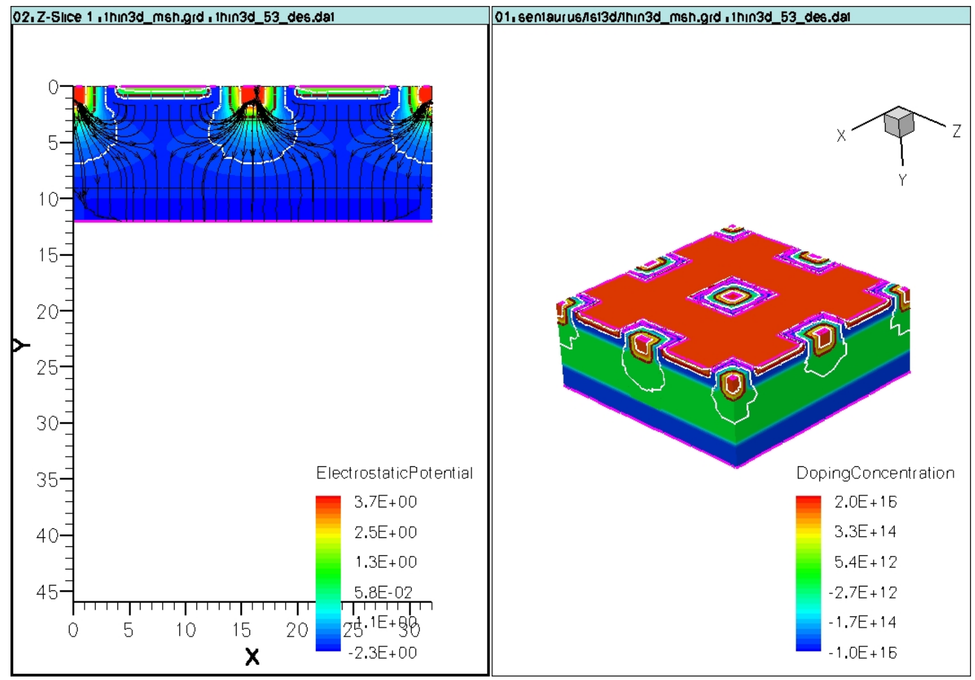
Expect reduction to 20μm $\times$ 20μm pixel with smaller process in future:



Chronopixel is designed with scalable transistors
$\Rightarrow$ no capacitors in signal path

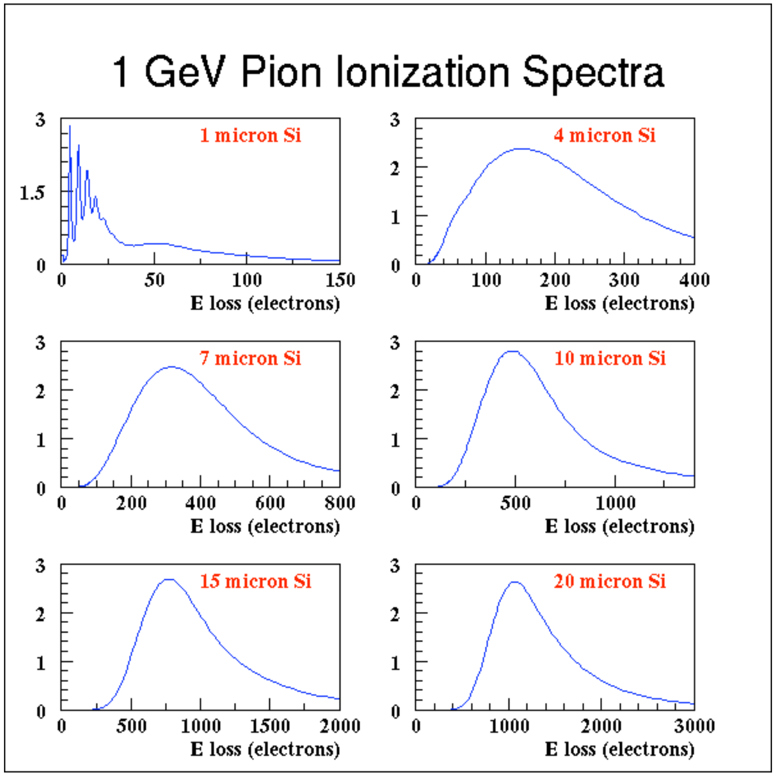
First prototypes do not have deep p-well and will only be active over a small fraction of the pixel. Possible final structure:

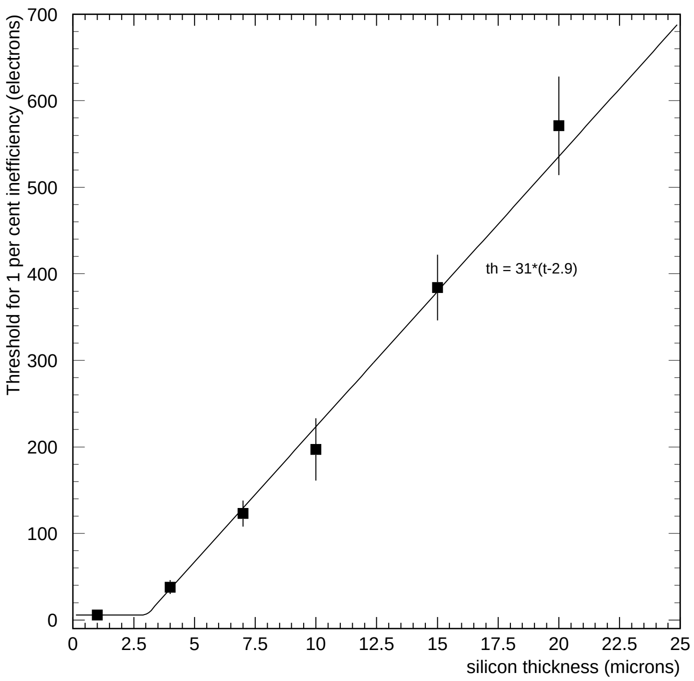




Detailed 3d simulations of the prototype and final device are underway

How thick does the epilayer need to be?





Epilayer Thickness (microns)	Electrons at 99% Efficiency (electrons)	Threshold (electrons)	Acceptable Noise (noise)
4	40	20	4
7	125	63	13
10	250	125	25
15	400	200	40
20	550	275	55

Using a "soft reset" we expect noise well below the 50 electrons expected from $\sqrt{kTC}$ for a hard reset.

Conclusion

- A compact silicon detector is a cost effective viable option for physics at the ILC

- During the next year SiD will define a baseline configuration and produce a Letter of Intent to build one of the two detectors for the ILC

- A Silicon-Tungsten based electromagnetic calorimeter is ideal for particle flow and tau polarization measurements; we are making good progress on showing that this is a realistic option

- The Chronopixel vertex detector option is robust against beam background; it will be challenging to build device that meets all of the requirements of a linear collider