Tracking at the ILC: Why Silicon Tracking is Best, and How it Might Be Optimized

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SCIPP & UC Santa Cruz

STD6 “AbeFest”

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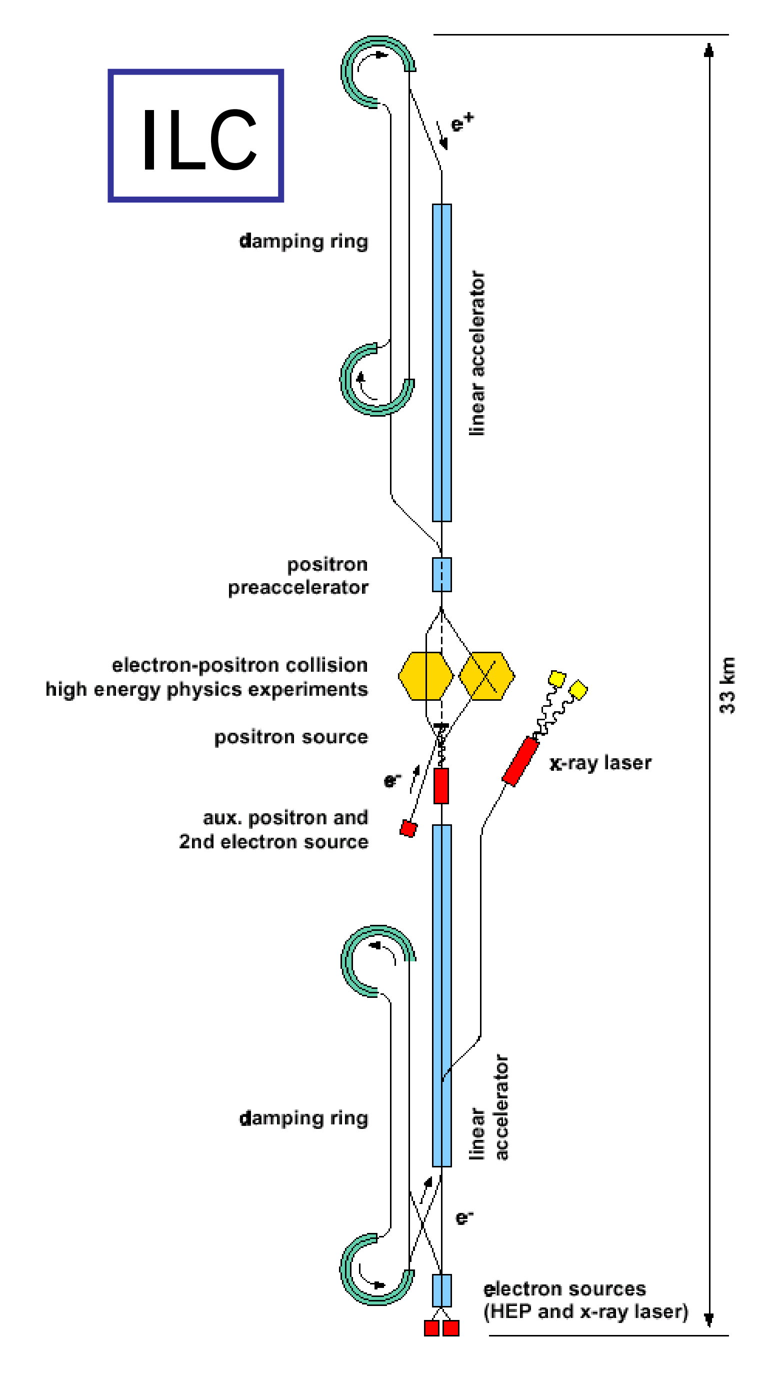


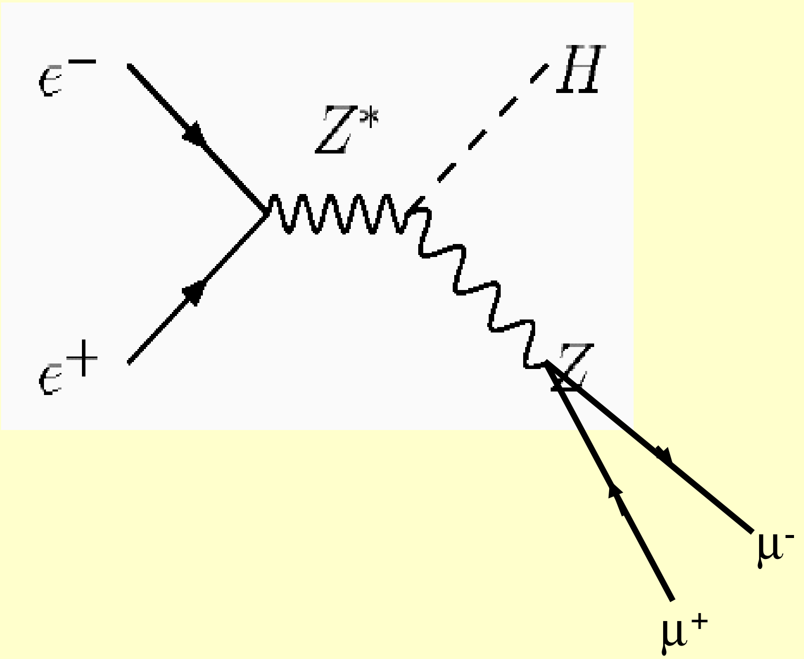
ILC Basics

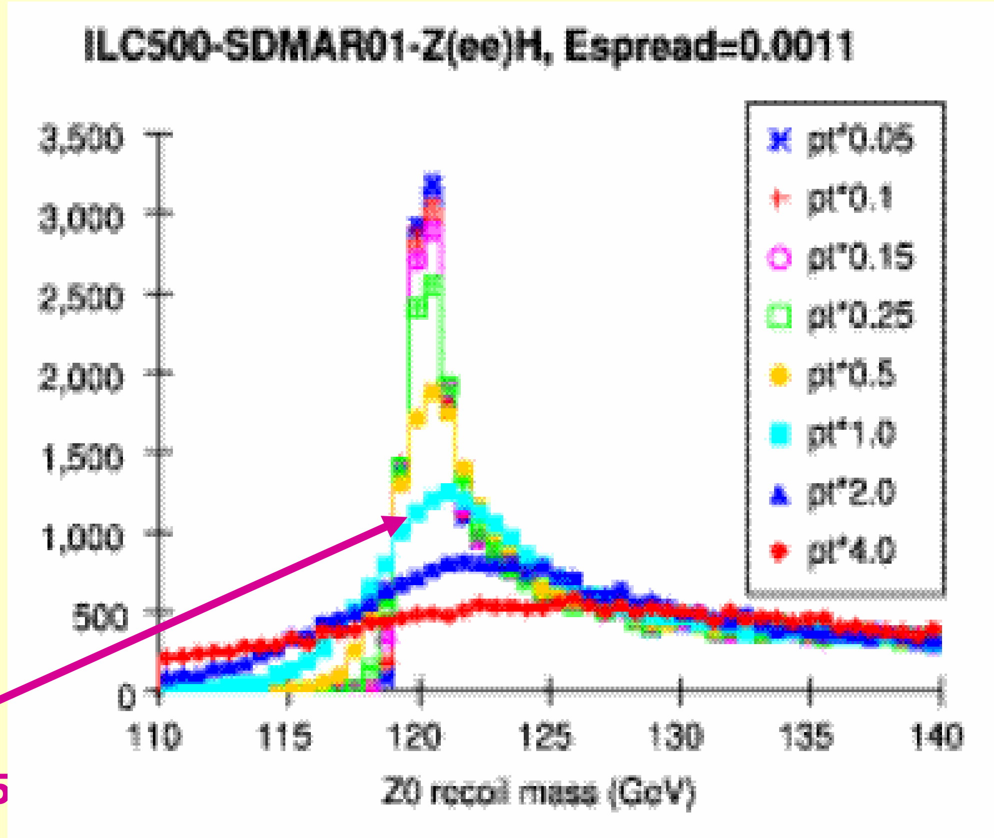
Pulse every ~350 ns for ~1 ms; repeated 5 times/s (0.5% Duty Cycle)

Online ~10 yrs after LHC → Precision is key

Reconstructing Higgsstrahlung

Haijun Yang, Michigan



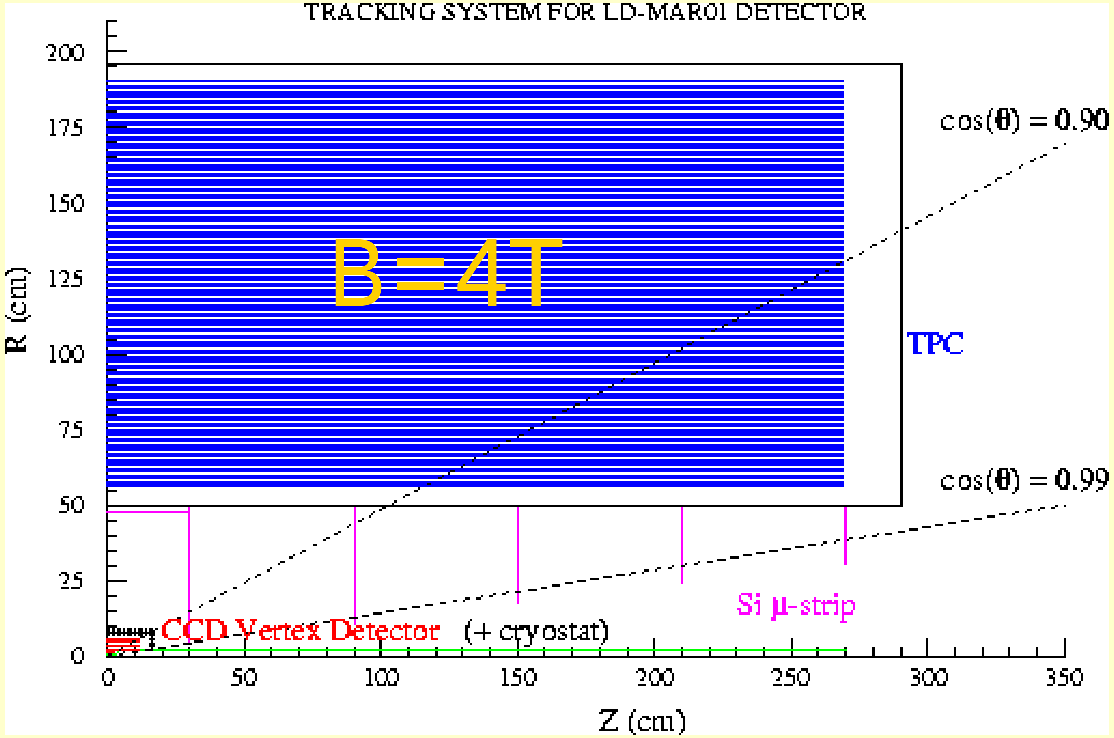


$M_{\mu\mu}$ for

$\delta p_\perp / p_\perp^2 = 2x10^{-5}$

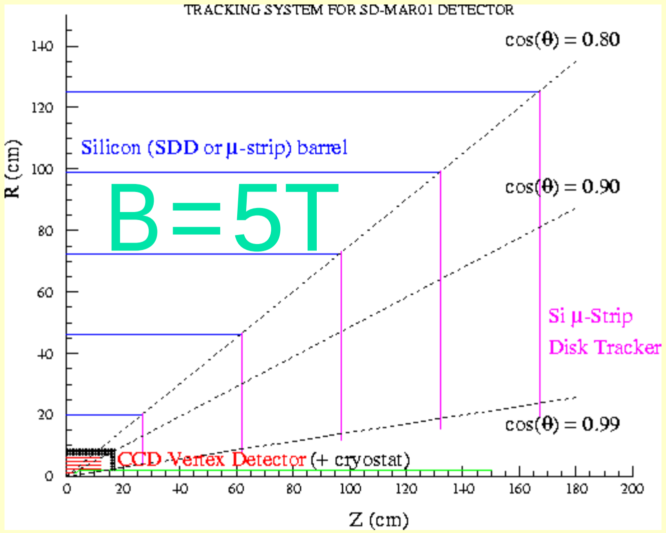
The Trackers

Gaseous (GLD, LDC, ...)

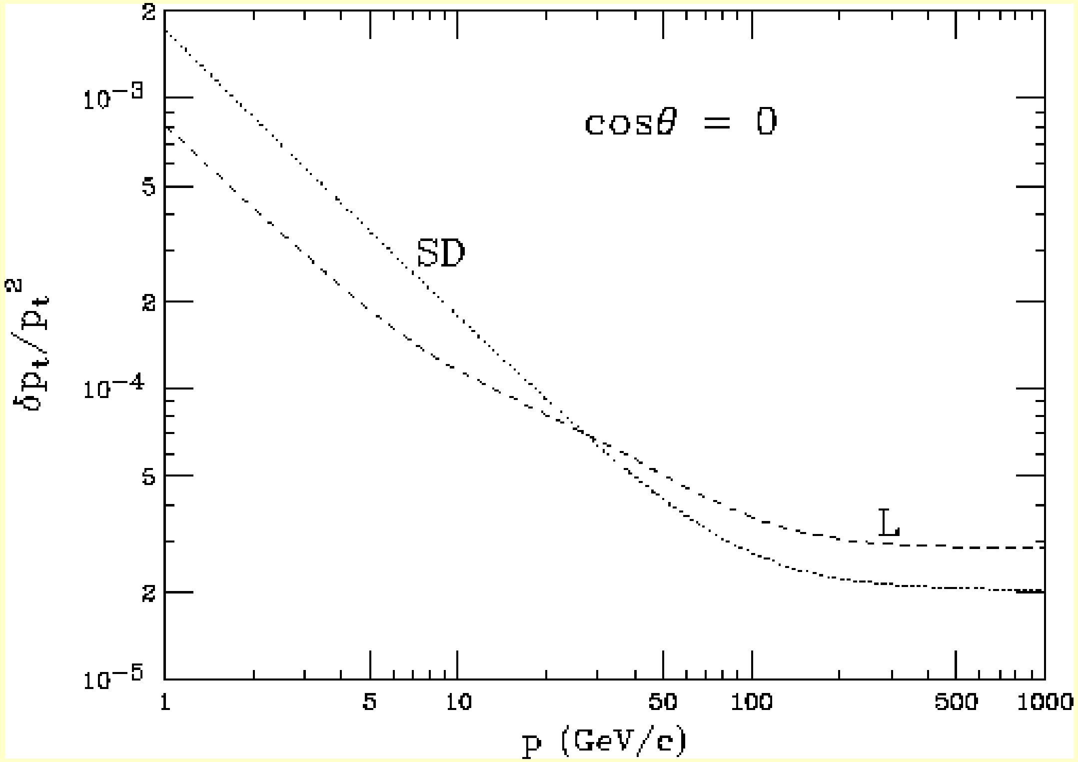


Solid-State (SD, SiD, ...)

The SD-MAR01 Tracker



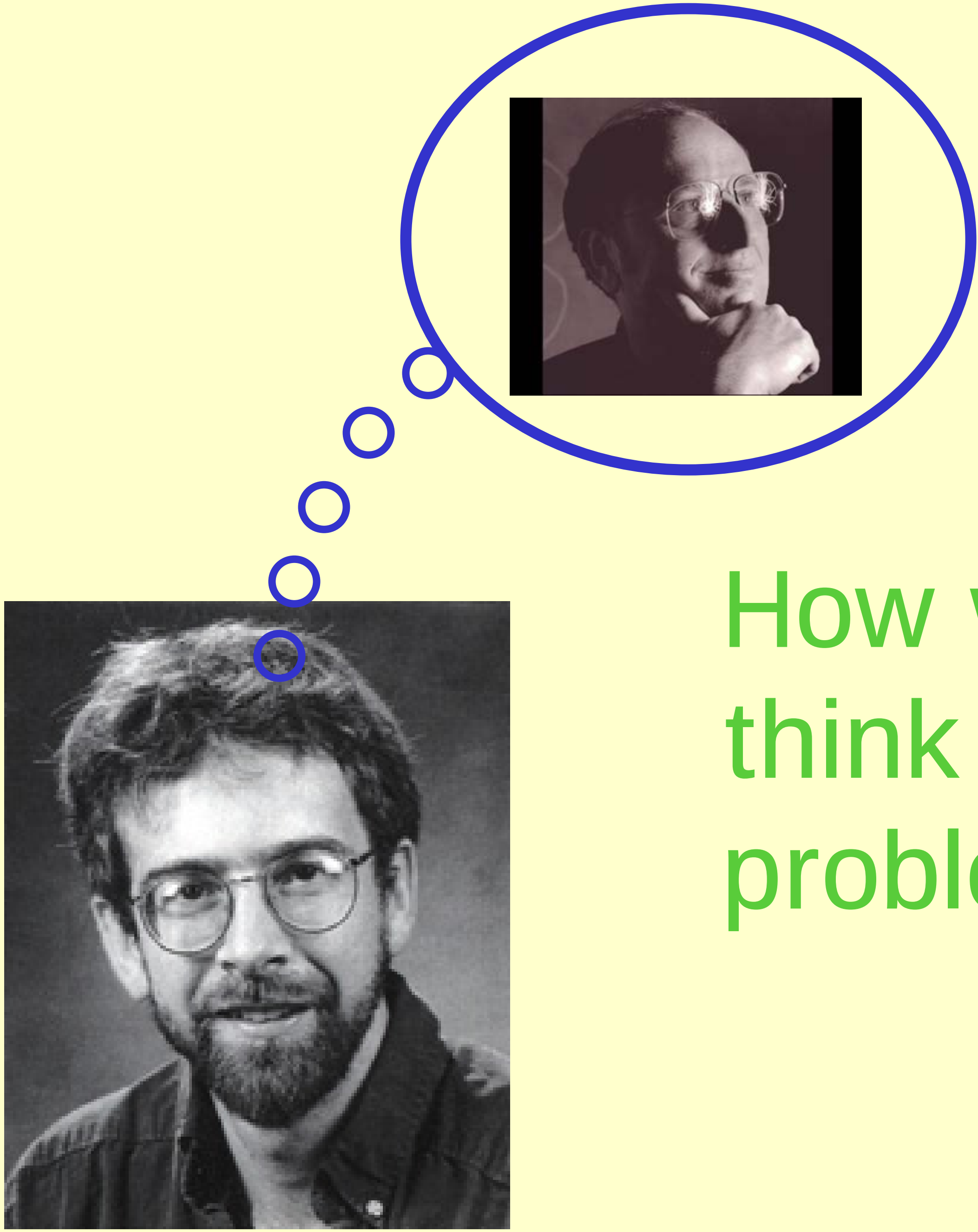
... and Their Performance



Error in radius of curvature ρ is proportional to error in $1/p_\perp$, or $\delta p_\perp / p_\perp^2$.

This is very generic; details and updates in a moment!

Code: http://www.slac.stanford.edu/~schumm/lcdtrk.tar.gz



How would Abe think about this problem?

Some "facts" that one might question upon further reflection

1. Gaseous tracking is natural for lower-field, large-radius tracking

In fact, both TPC's and microstrip trackers can be built as large or small as you please. The calorimeter appears to be the cost driver.

High-field/Low-field is a trade-off between vertex reconstruction (higher field channels backgrounds and allows you to get closer in) and energy-flow into the calorimeter (limitations in magnet technology restricts volume for higher field). The assignment of gaseous vs solid state tracking to either is arbitrary.

② Gaseous tracking provides more information per radiation length than solid-state tracking

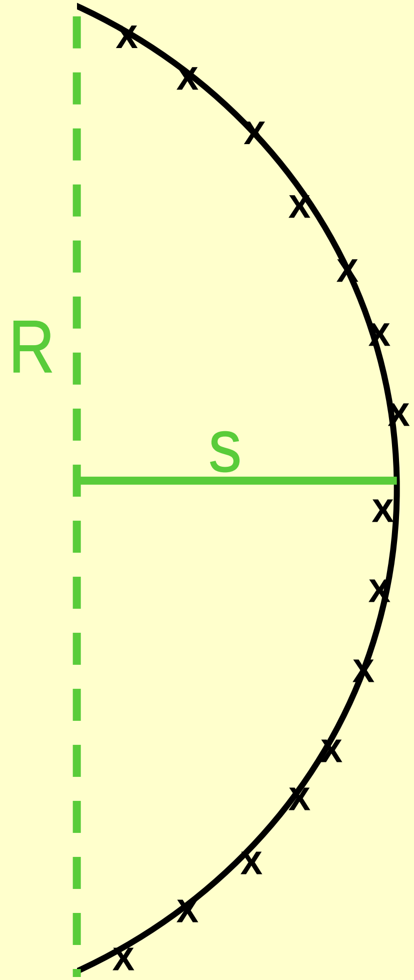
For a given track $p_\perp$ and tracker radius R, error on sagitta s determines $p_\perp$ resolution

Figure of merit is $\eta = \sigma_{point}/\sqrt{N_{hit}}$.

Gaseous detector: Of order 200 hits at σ_{point}=100 µm ➔ η = 7.1 µm

Solid-state: 8 layers at σ_{point}=7µm ➔ η = 2.5µm

Also, Si information very localized, so can better exploit the full radius R.



For gaseous tracking, you need only about 1% X_0 for those 200 measurements (gas gain!!)

For solid-state tracking, you need 8x(0.3mm) = 2.6% X_0 of silicon (signal-to-noise), so 2.5 times the multiple scattering burden.

BUT: to get to similar accuracy with gas, would need $(7.1/2.5)^2$ = 8 times more hits, and so substantially more gas. Might be able to increase density of hits somewhat, but would need a factor of 3 to match solid-state tracking.

Solid-state tracking intrinsically more efficient (we'll confirm this soon), but you can only make layers so thin due to amp noise ➔ material still an issue.

③ Calibration is more demanding for solid-state tracking

The figure-of-merit η sets the scale for calibration systematics, and is certainly more demanding for Si tracker (2.5 vs. 7.1 μm).

But, η is also the figure-of-merit for $p_\perp$ resolution.

For equal-performing trackers of similar radius, calibration scale is independent of tracking technology.

Calibrating a gaseous detector to similar accuracy of a solid-state detector could prove challenging.

4 All Other Things Equal, Gaseous Tracking Provides Better Pattern Recognition

It's difficult to challenge this notion. TPC's provide a surfeit of relative precise 3d space-points for pattern recognition.

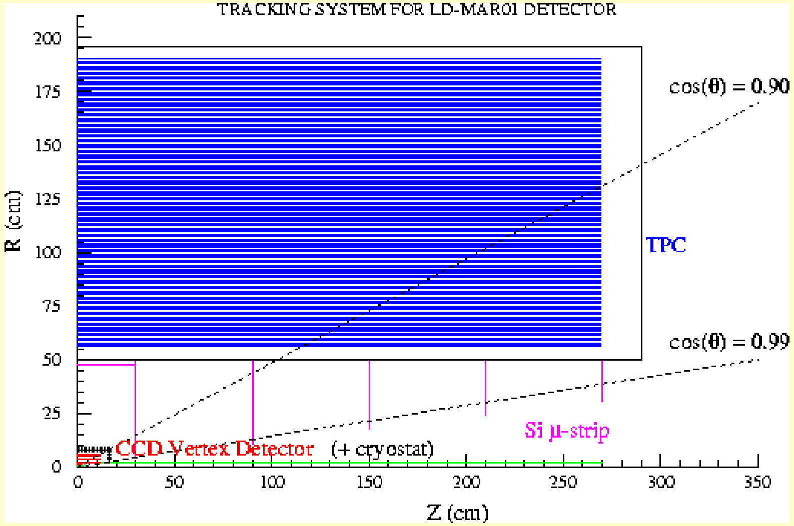
They do suffer a bit in terms of track separation resolution: 2mm is typical, vs 150 μm for solid-state tracking. Impact of this not yet explored (vertexing, energy flow into calorimeter).

For solid-state tracking, still don't know how many layers is "enough" (K^0_S, kinks), but tracking efficiency seems OK evevn with 5 layers (and 5 VTX layers)

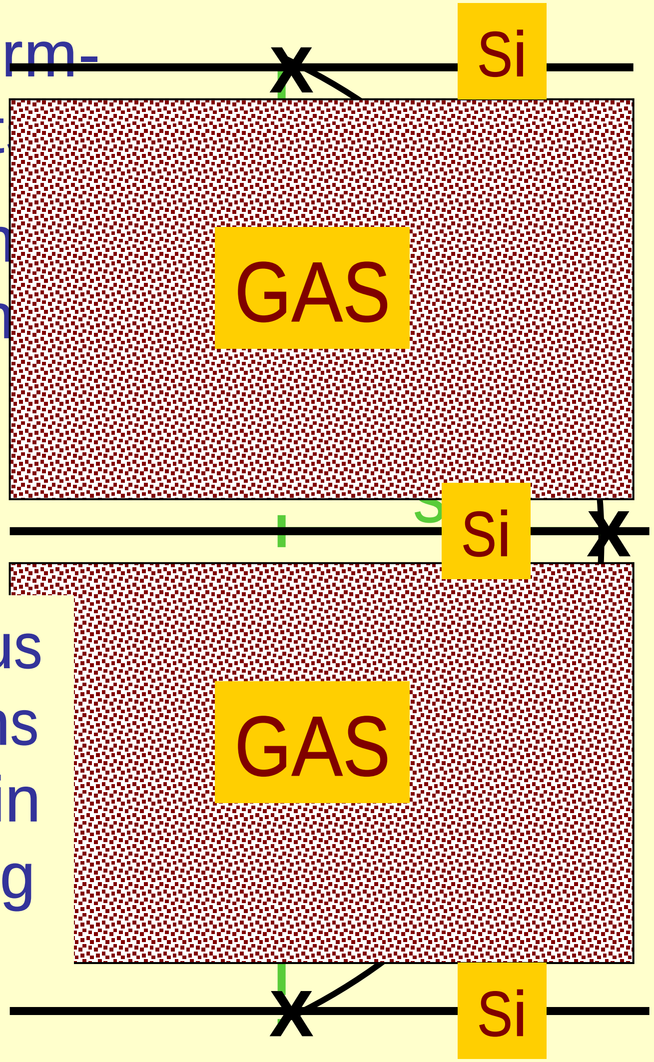
Hybrid Trackers – the Best of Both Worlds?

In an ideal world, momenta would be determ-ined from three arbitrarily precise r/ϕ point

Optimally, you would have Si tracking at th points, with "massless" gaseous tracking in between for robust pattern recognition ➔ Si/TPC/Si/TPC/Si "Club Sandwich".



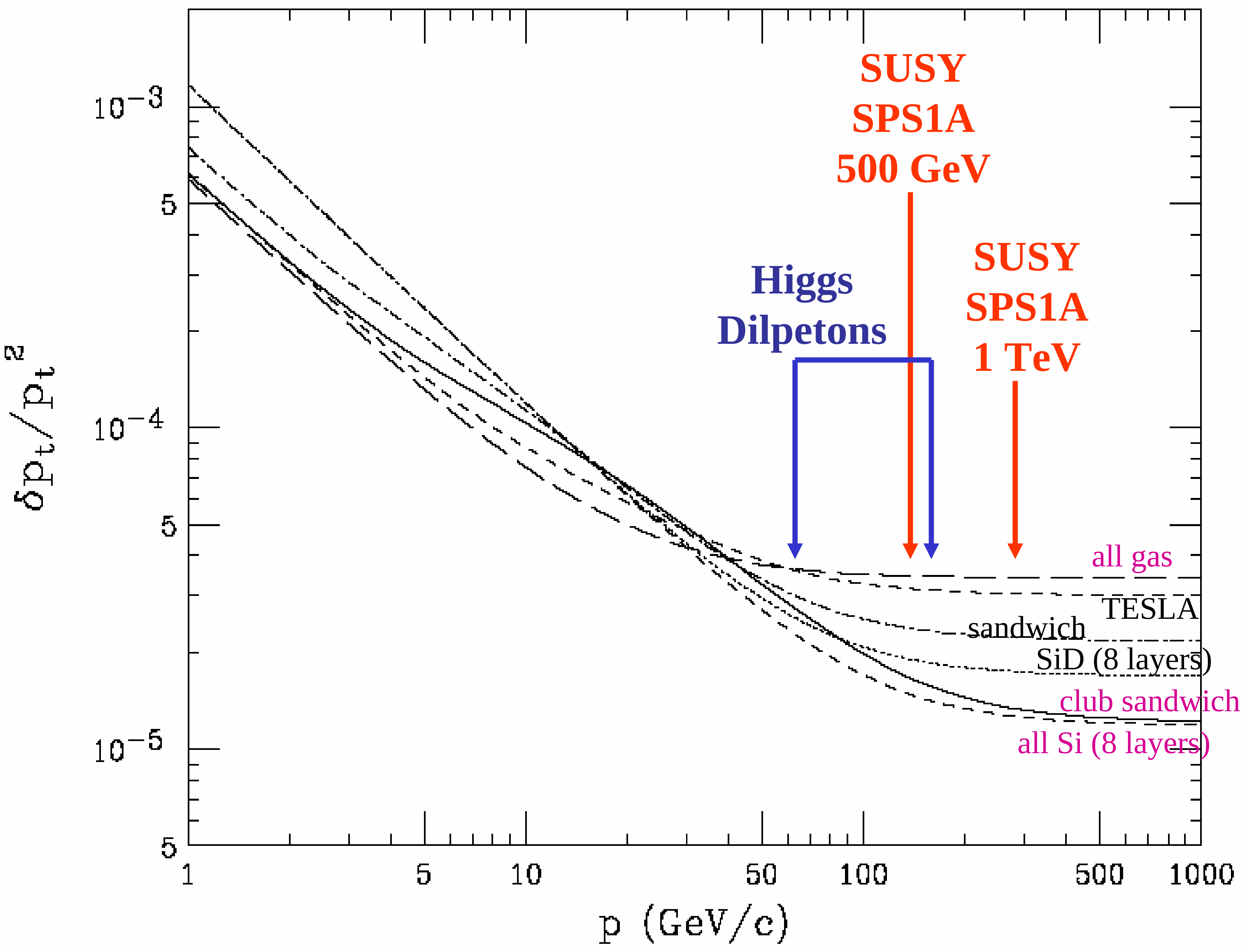
Current gaseous tracking designs recognize this in part (Si tracking to about R/4).



Hybrid Tracker Optimization

Let's try filling the Gaseous Detector volume (R=20cm-170cm) with various things...

- All gas: No Si tracking (vertexer only)
- TESLA: Si out to 33cm, then gas (100 μm resolution)
- Sandwich: Si out to 80cm, and then just inside 170cm
- Club Sand: Si/TPC/Si/TPC/Si with central Si at 80cm
- All Si: Eight evenly-spaced Si layers
- SiD: Smaller (R=125cm) Si design with 8 layers



SUSY
SPS1A
500 GeV
Higgs
Dilpetons
SUSY
SPS1A
1 TeV
all gas
TESLA
sandwich
SiD (8 layers)
club sandwich
all Si (8 layers)
$\delta p_t / p_t^2$
p (GeV/c)

How might you design ILC Silicon μstrip ladders?

Precision → low mass, low noise

- Long modules: less servicing but worse signal-to-noise
- Short modules: Excellent signal-to-noise but more servicing

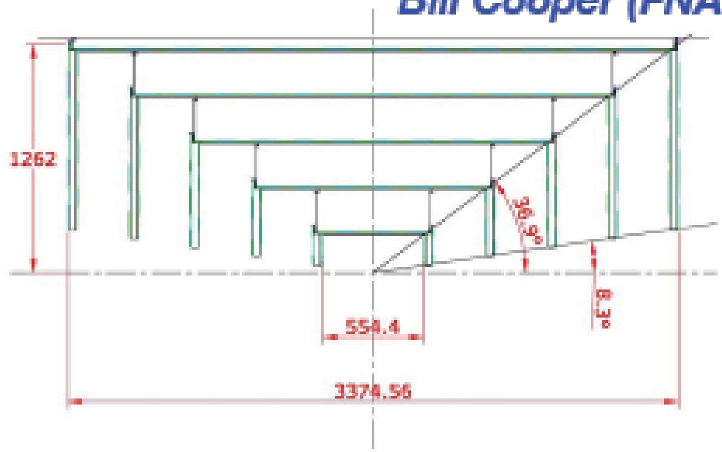
Either way: **cycle power** to avoid cooling tubes (~1msec switch-on)

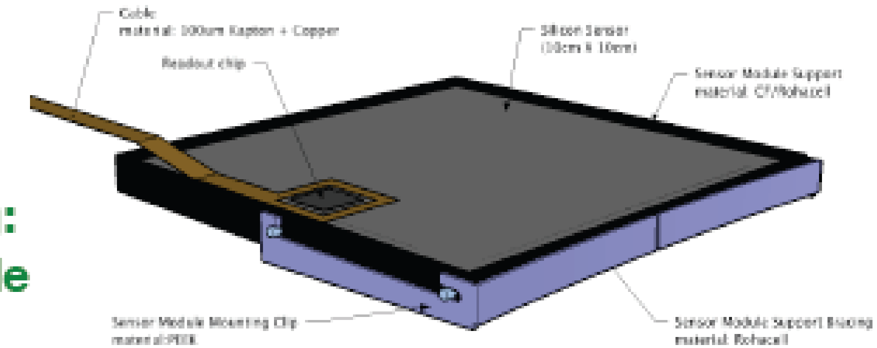
Tim Nelson, SLAC

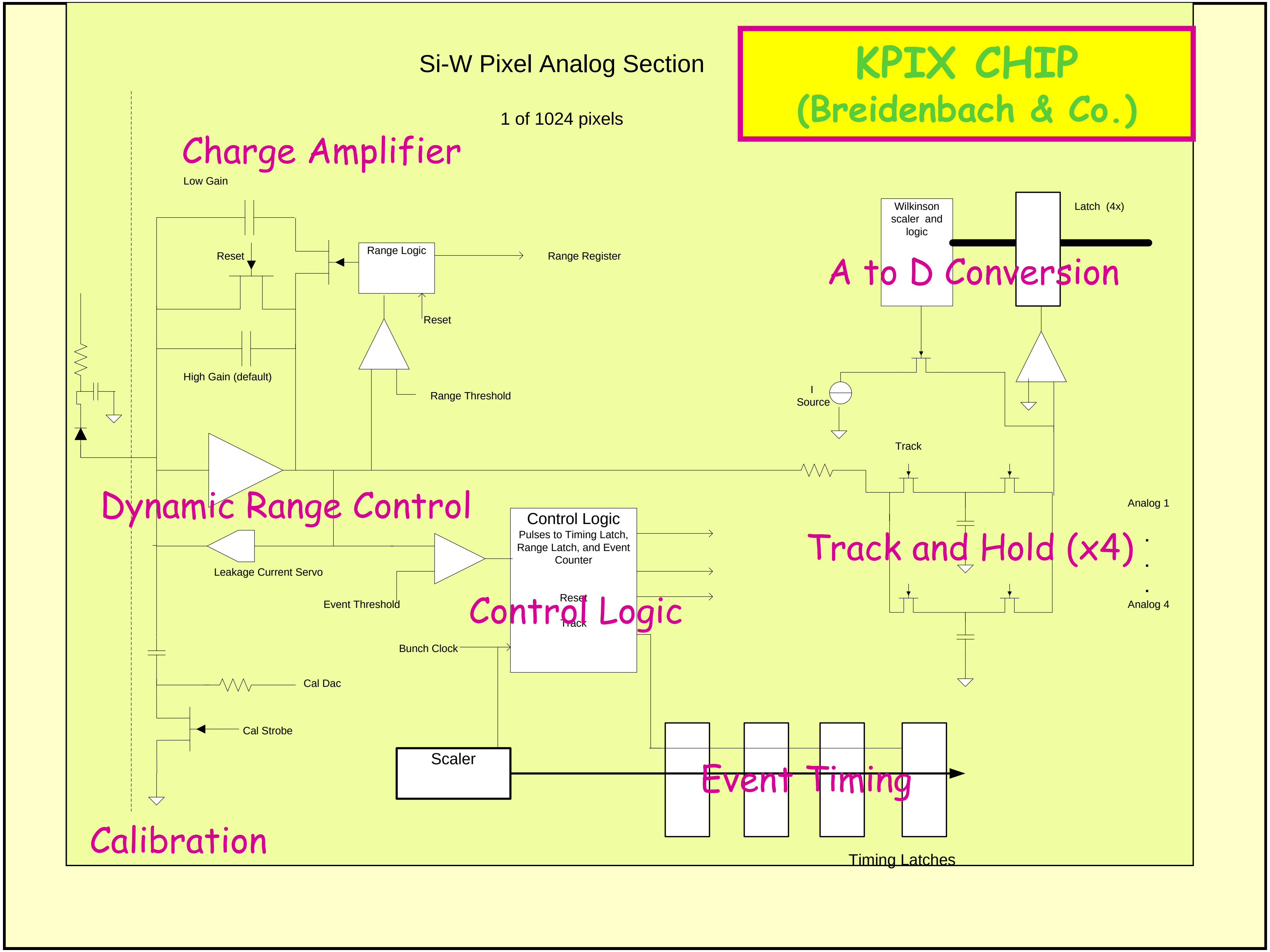
Alternative: Small Modules

Bill Cooper (FNAL)

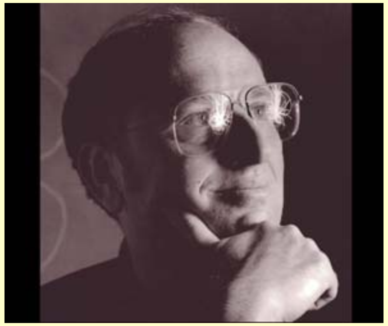
- *Shift responsibility for rigid/robust support onto underlying structure:* **Nested, closed carbon-fiber / Rohacell cylinders (a la D0 CFT, Atlas SCT)**
- *Tile cylinders with small, simple modules, each with own readout*
  - **Very high S/N (~20)**
  - **Simple, low-risk assembly**
  - **"One hand" installation/handling: even in-situ replacement possible**






Si-W Pixel Analog Section
1 of 1024 pixels
KPIX CHIP
(Breidenbach & Co.)
Charge Amplifier
Low Gain
Reset
Range Logic
Range Register
Reset
High Gain (default)
Range Threshold
Wilkinson scaler and logic
Latch (4x)
A to D Conversion
I Source
Track
Analog 1
Track and Hold (x4)
Analog 4
Dynamic Range Control
Leakage Current Servo
Event Threshold
Control Logic
Pulses to Timing Latch, Range Latch, and Event Counter
Reset
Track
Control Logic
Bunch Clock
Cal Dac
Cal Strobe
Scaler
Event Timing
Timing Latches
Calibration

Alternatively, step back…

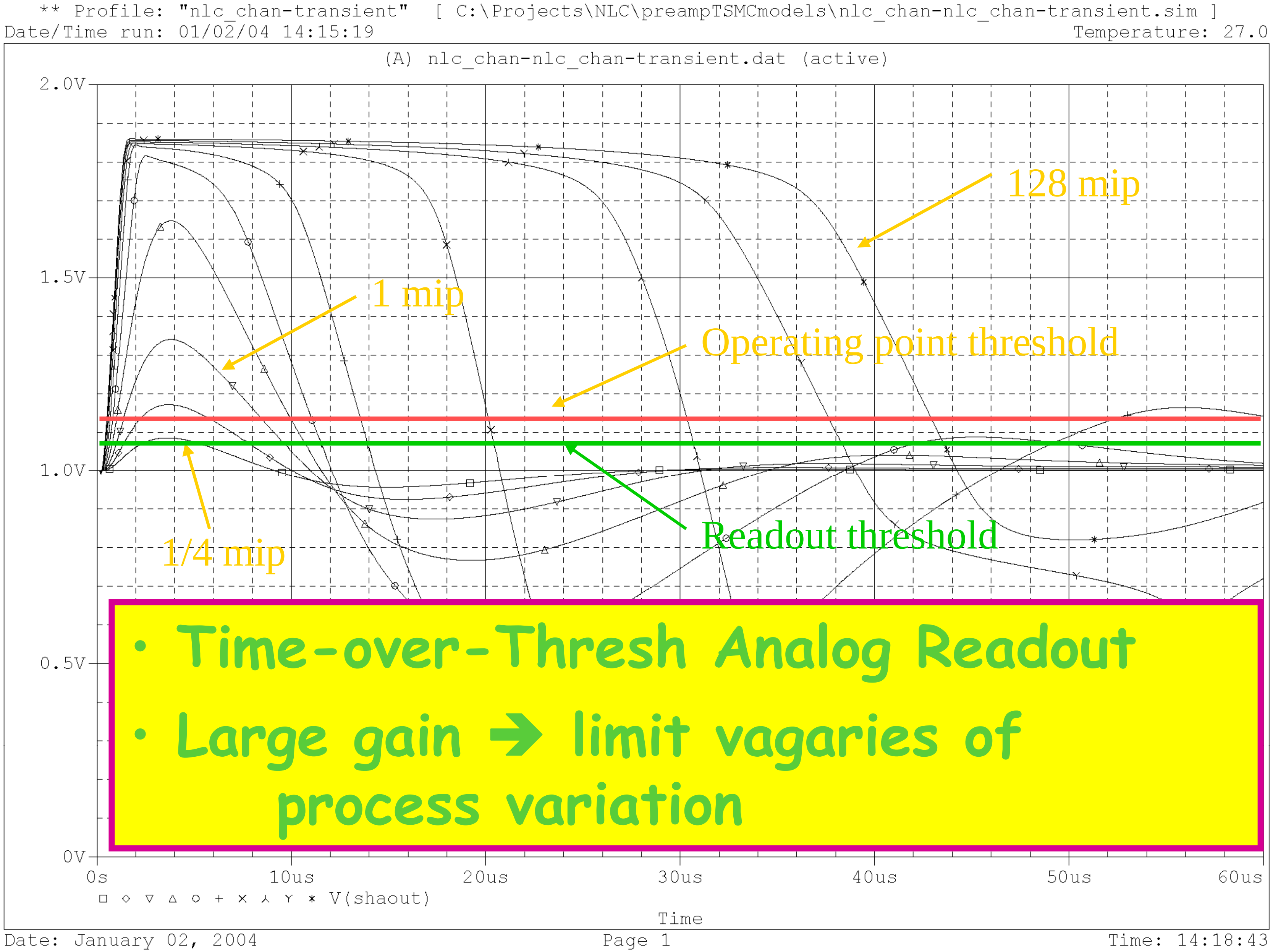


Landau fluctuations large…

• How accurately do you really need to know pulse-heights?

• How much does electronic noise really hurt you?

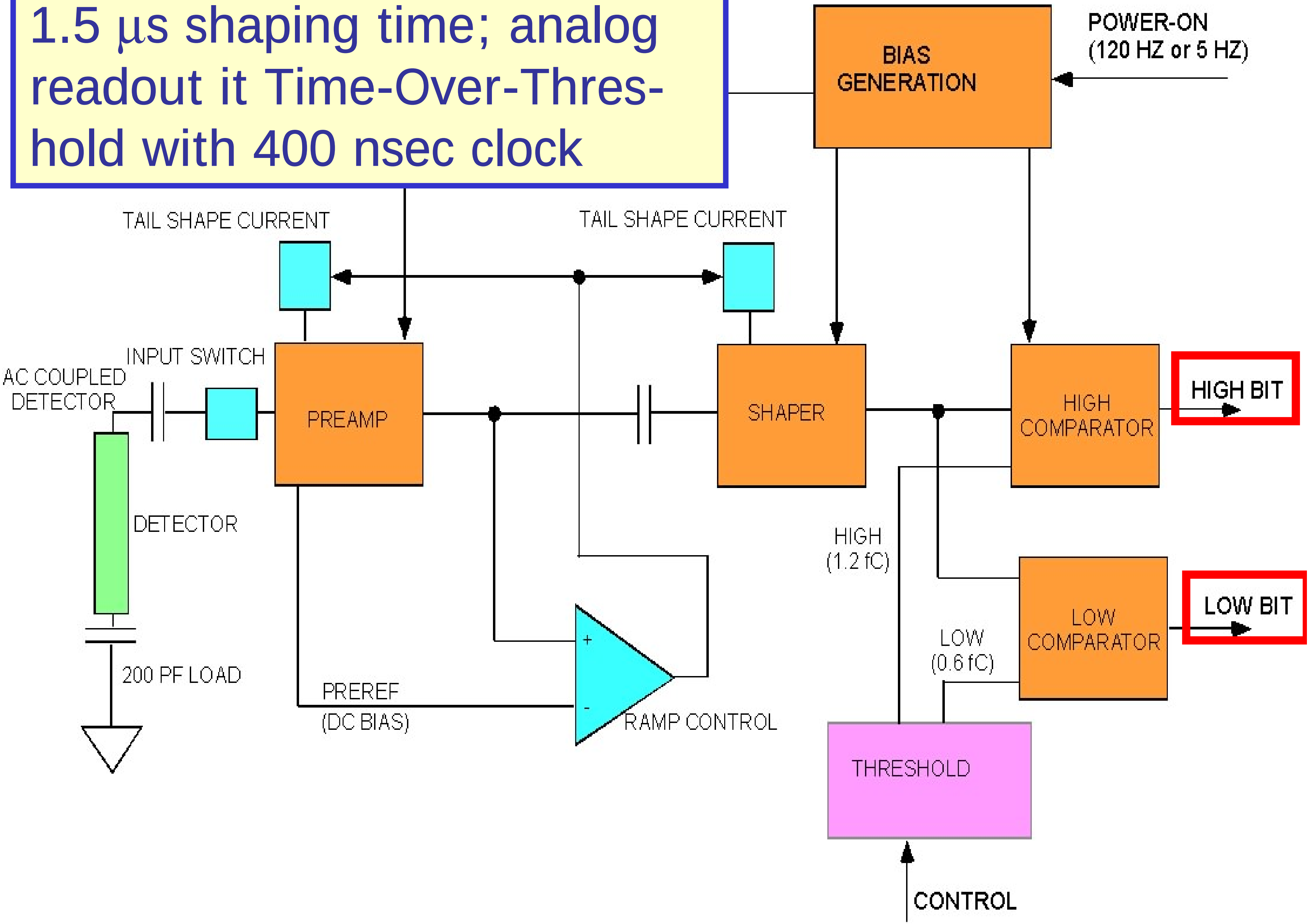
➔ Simulate!



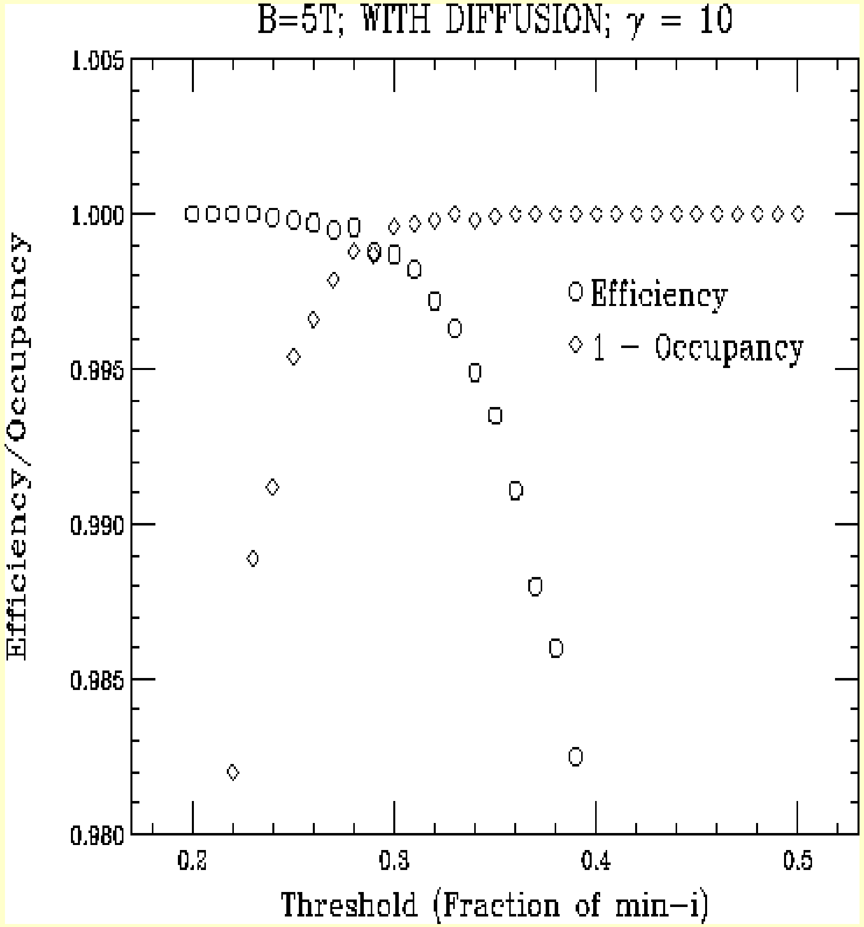
- Time-over-Thresh Analog Readout
- Large gain ➔ limit vagaries of process variation

SILICON TRACKER FRONT-END ARCHITECTURE

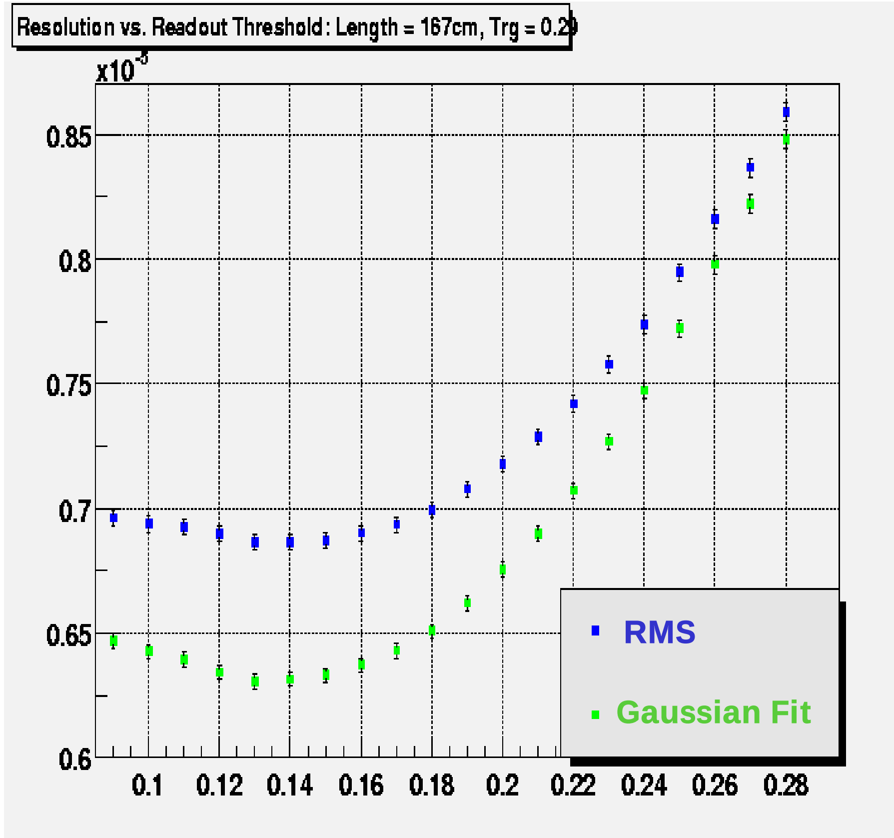
1.5 μs shaping time; analog readout it Time-Over-Threshold with 400 nsec clock



SIMULATED PERFORMANCE FOR 167cm LADDER



Efficiency and Occupancy as a function of high threshold



Resolution as a function of low threshold

Some simulation results

Change from digitized TOT to perfect analog measurement

→ no change in resolution

Eliminate electronic noise

→ resolution improves to 5 μm

Change pitch (had assumed 50 μm)

→ resolution largely unchanged

Prototype and test!

And so...

Surprisingly (?), solid-state tracking is best bang for the "buck" (in the radiation-length economy)

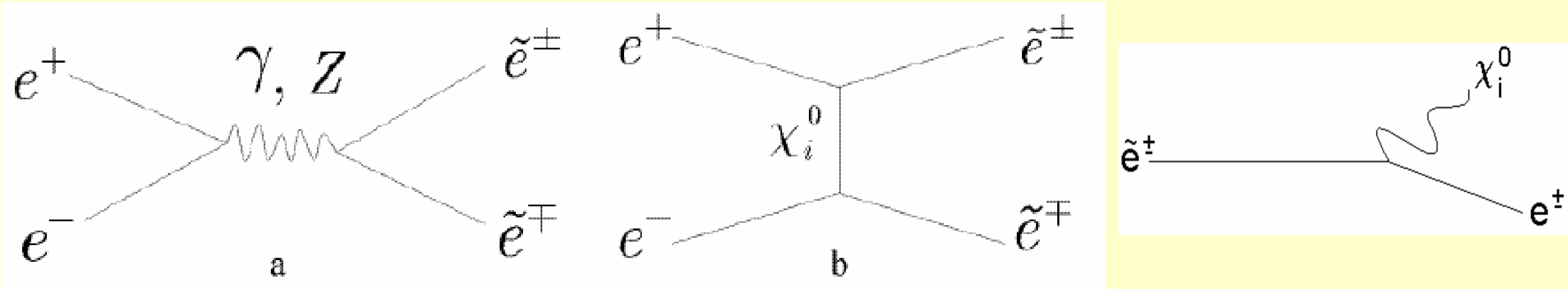
μstrip tracking a must for the ILC

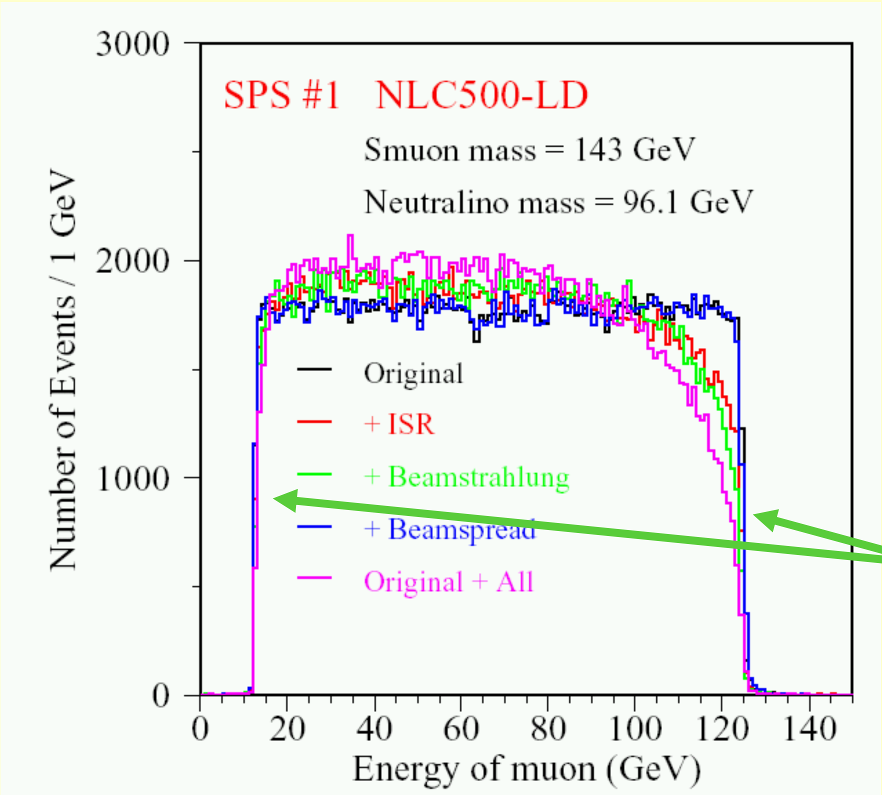
Some conventional wisdom about the relative advantages and disadvantages of gaseous/solid-state tracking are probably not correct.

If ILC settles for one detector, "intentional" **hybrid tracking** may be the way to go.

Simulation of pulse development and amplification for ILC Si sensors points to economies that can be exploited, as well as some surprising generalities

Supersymmetry: Slepton Production

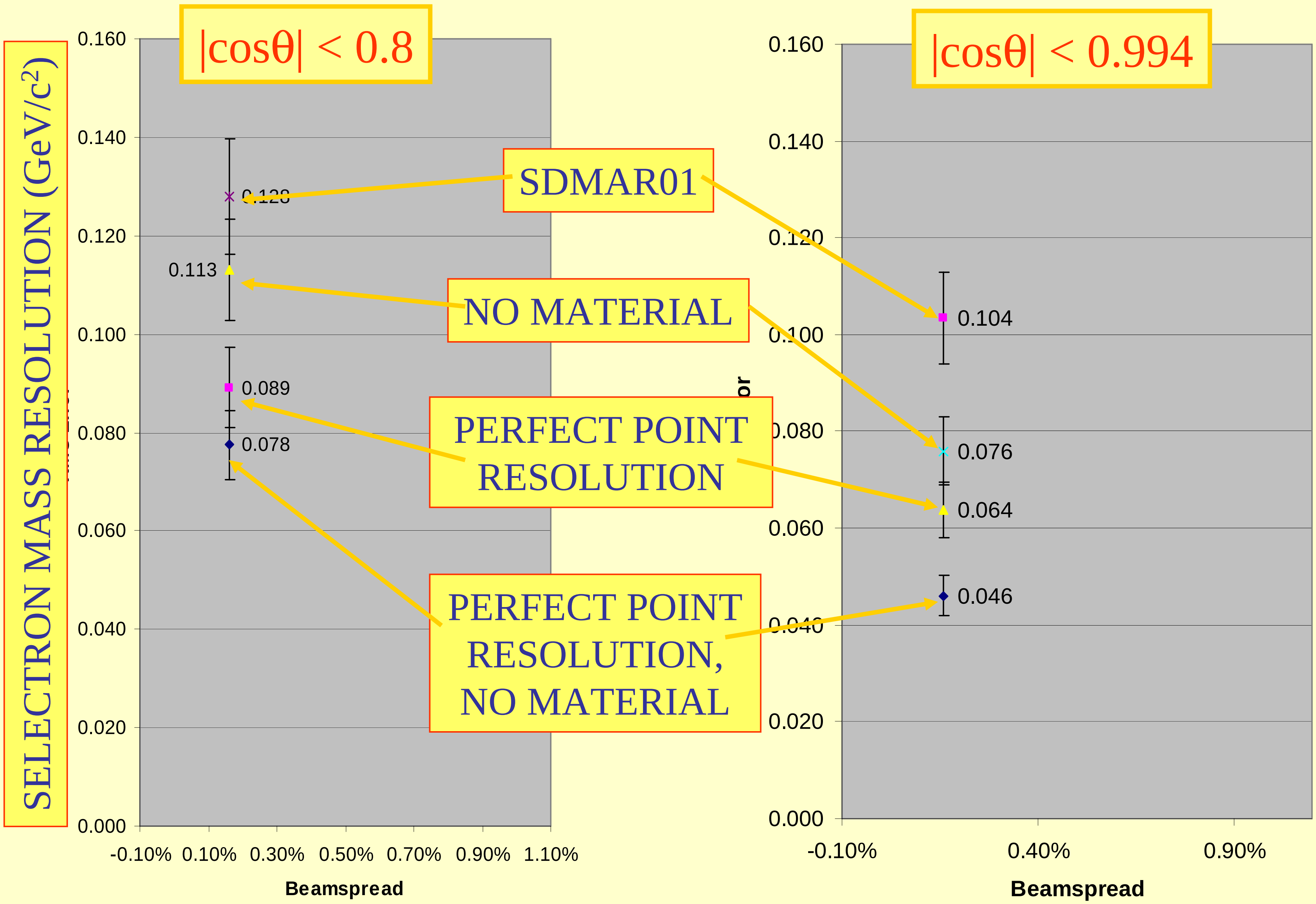




Slepton production followed by decay into corresponding lepton and "LSP" (neutralino)

Endpoints of lepton spectrum determined by slepton, neutralino masses

SUSY Point “SPS1a” at E_{cm}=1TeV



Choice of Tracking Techonolgy (Si, Gas)

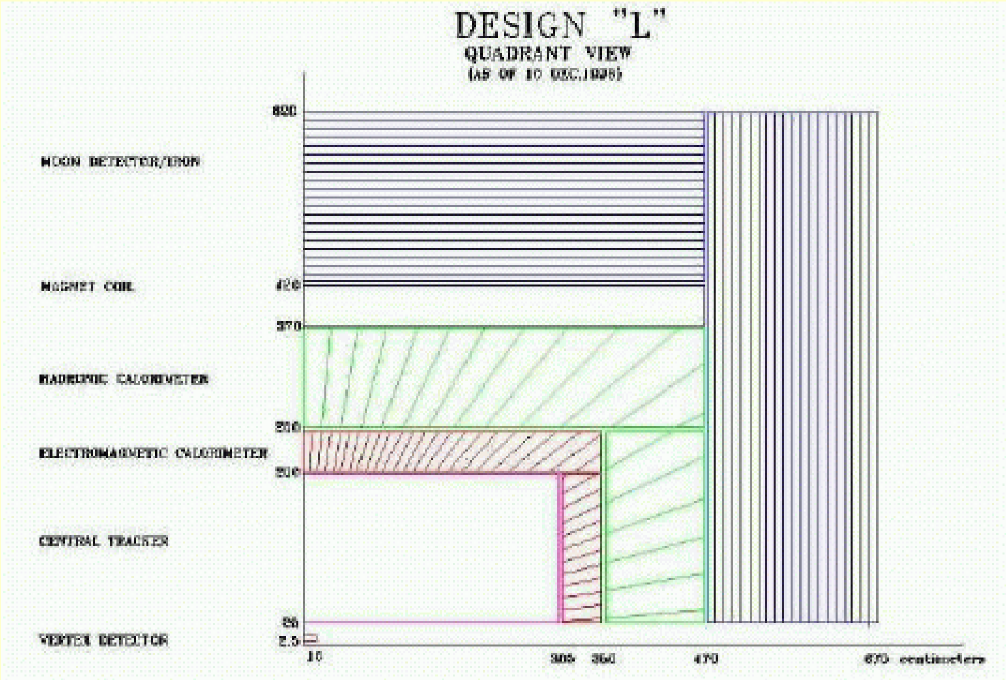
Tracker needs excellent *pattern recognition* capa-bilities, to reconstruct particles in dense jets with high efficiency.

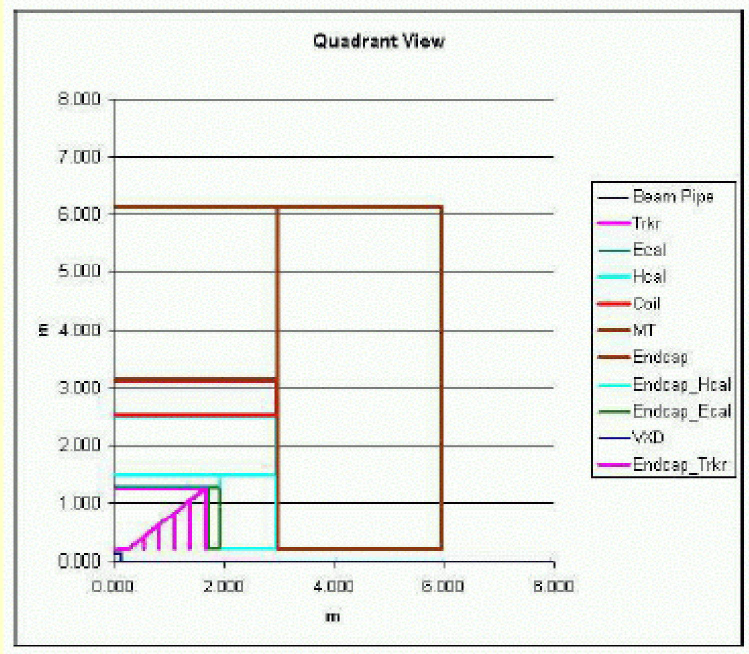
But as we've seen, recent physics studies (low beam-energy spread) also suggest need to push momentum resolution to its limits.

Gaseous (TPC) tracking, with its wealth of 3-d hits, should provide spectacular pattern recognition – but what about momentum resolution? Let's compare.

In some cases, conventional wisdom may not be correct...

Linear Collider Detectors (very approximate)





"L" Design:
- Gaseous Tracking (TPC) R_{max} ~ 170cm
- 4 Tesla Field
- Precise (Si/W) EM Calorimeter

"S" Design:
- Solid-State Tracking R_{max} = 125cm
- 5 Tesla Field
- Precise (Si/W) Calorimeter