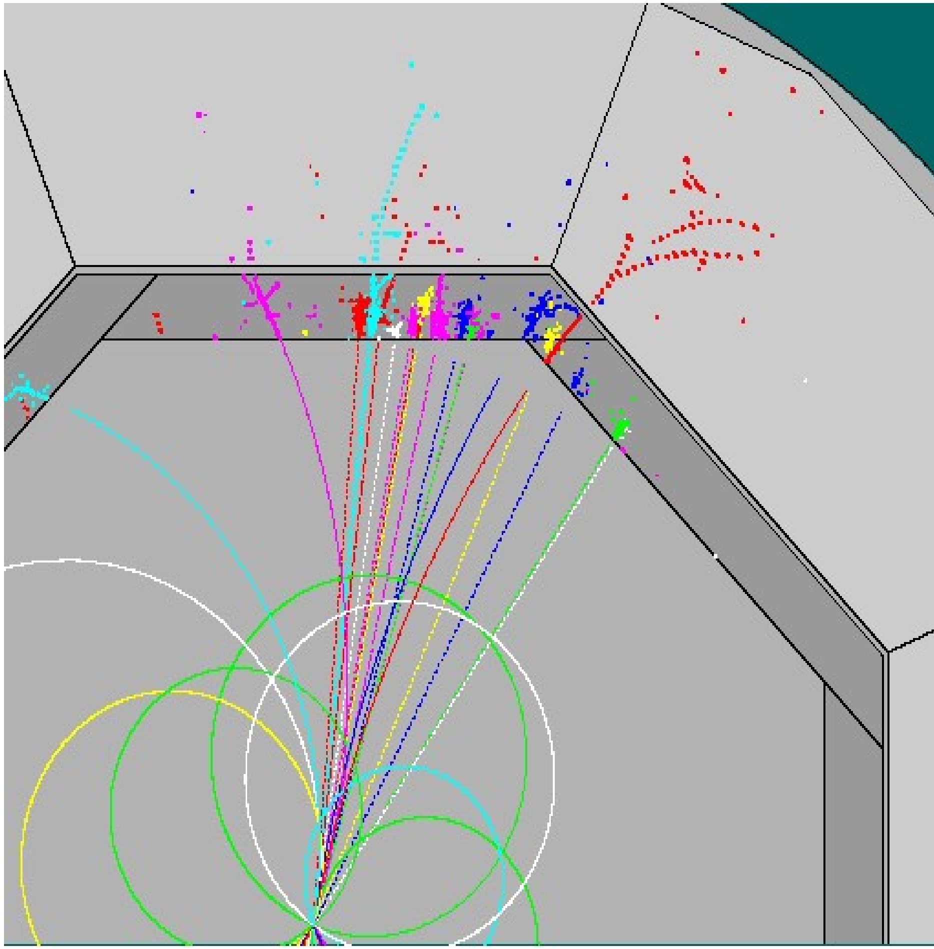
LCDRD ECal R&D

R. Frey, University of Oregon

- Physics goals drive the design
- ECal with scintillator tiles (Project 6.2)
  - Colorado
- ECal design studies (Project 6.10)
  - Kansas
- Development of an silicon-tungsten ECal (Project 6.5)
  - SLAC, <u>Oregon</u>, <u>UC Davis</u>, BNL, Annecy

Hadronic final states and PFA



Complementarity with LHC:

LC should strive to do physics with ***all*** final states.

1. Charged particles in jets more precisely measured in tracker
2. Jet energy 64% charged (typ.)

Separate charged/neutrals in calor.

⇒ The "Particle Flow" paradigm

- ECAL: dense, highly segmented (an "imaging calorimeter")

tau id and polarization

- Analysis of tau final states can provide crucial information on new physics
- Important & broad example: $e^+e^- \longrightarrow \tilde{\tau}_1^+\tilde{\tau}_1^-$, $\tilde{\tau}_1^\pm \longrightarrow \tilde{\chi}_1^0\tau^\pm$
- The SUSY model leaves fingerprint on tau polarization:

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

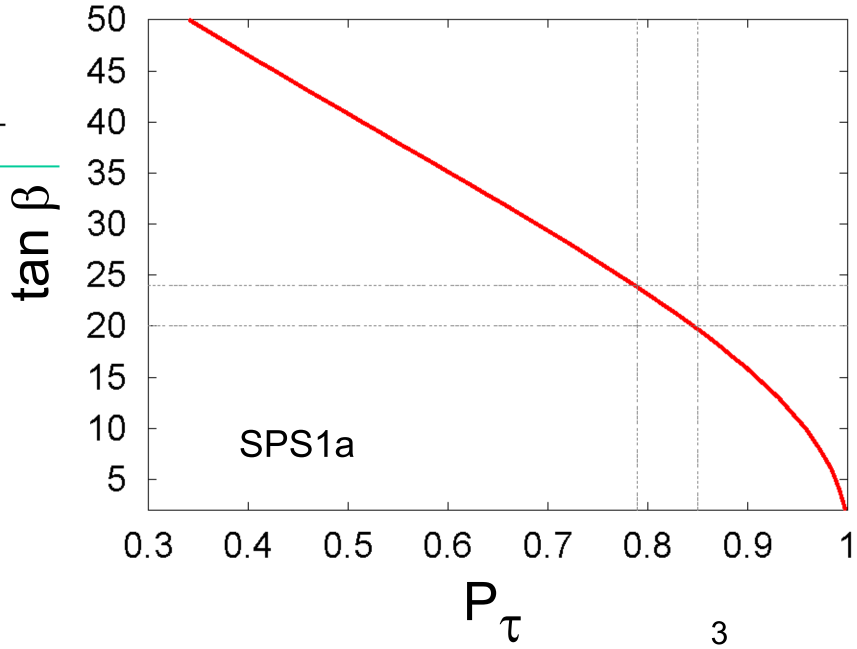
- mSUGRA: $\tilde{\chi}_1 \sim \widetilde{\mathrm{B}} \Rightarrow P_\tau \approx +1$
- non-universal SUGRA: $\tilde{\chi}_1 \sim \tilde{\mathrm{H}} \Rightarrow P_\tau \approx \cos^2\theta_\tau - \sin^2\theta_\tau$
- AMSB: $\tilde{\chi}_1 \sim \widetilde{\mathrm{W}} \Rightarrow P_\tau \approx -1$
- GMSB: $\tilde{\tau}_1^\pm \rightarrow \widetilde{\mathrm{G}}\tau^\pm \Rightarrow P_\tau \approx \sin^2\theta_\tau - \cos^2\theta_\tau$

<u>References</u>:

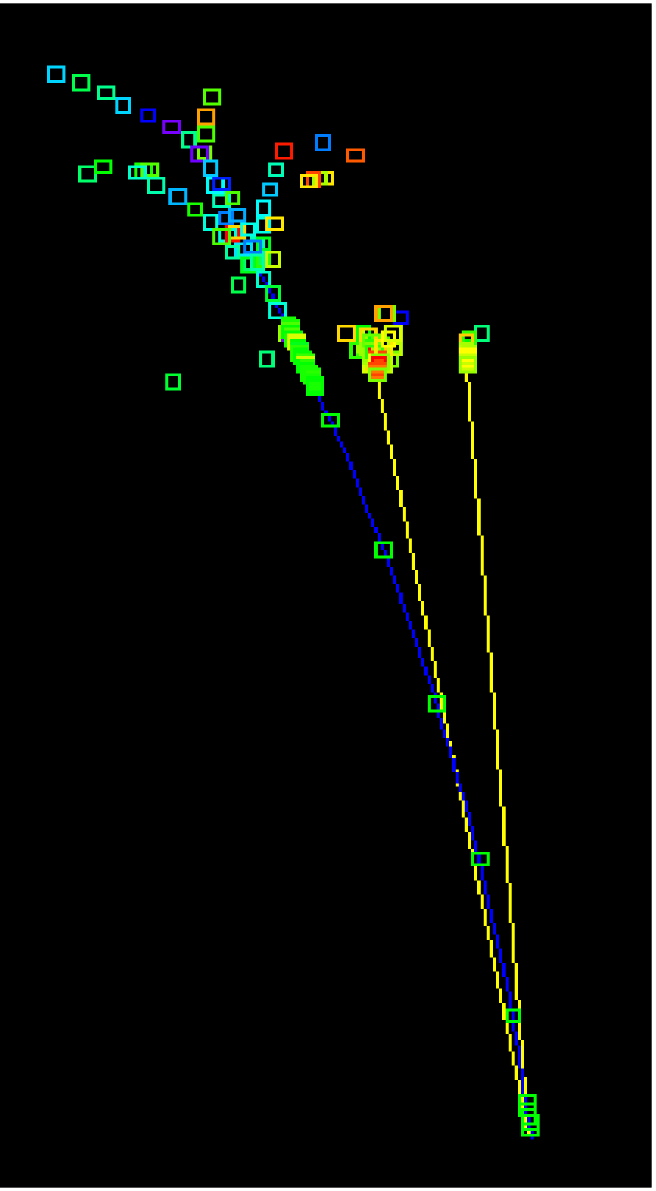
M. Nojiri, PRD 51 (1995)

E. Boos, et al, EPJC 30 (1993) →

Godbole, Guchait, Roy, Phys Lett B (2005)



tau polarization (contd) - measurement



Separate the important decay modes:

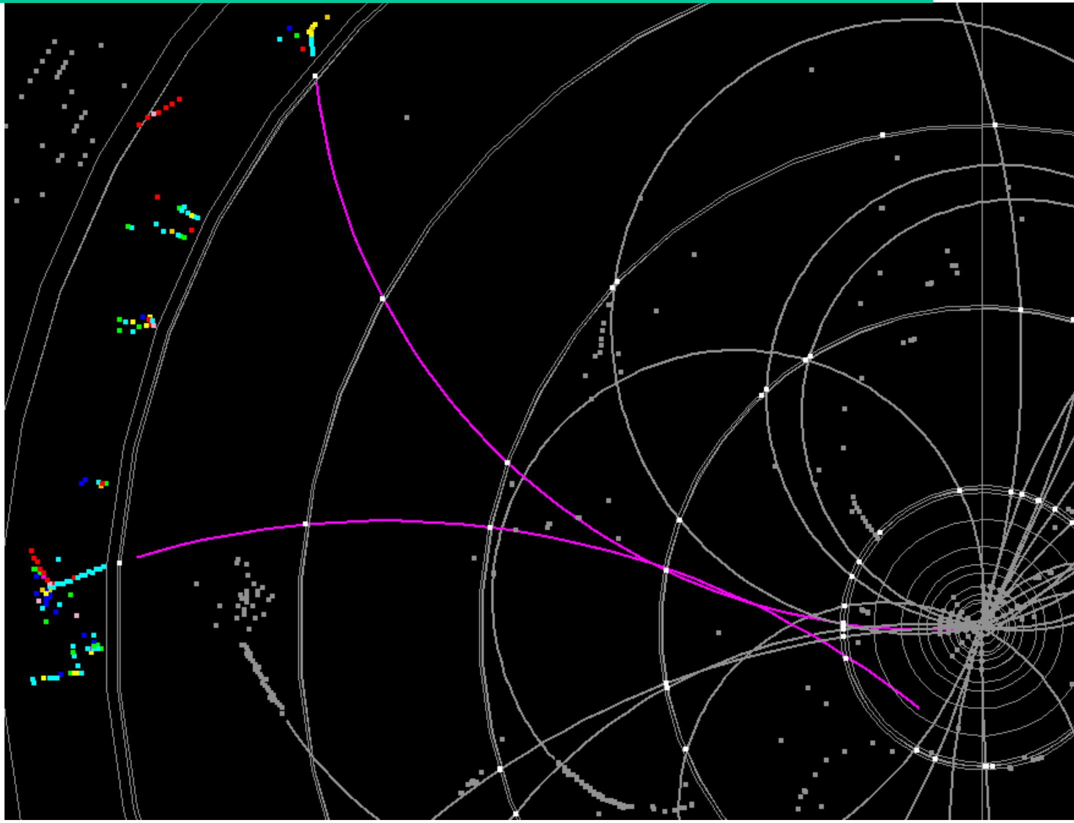
- $\tau^+ \rightarrow \rho^+\nu \quad (\pi^+\pi^o\nu)$
- $\tau^+ \rightarrow \pi^+\nu \quad (\pi^+\nu)$
- $\tau^+ \rightarrow a_1{}^+\nu \quad (\pi^+ \pi^+ \pi^-\nu, \;\; \pi^+\pi^o \pi^o \nu)$

and measure the energy spectrum

as done at LEP (ALEPH best by ~2×)

An important tool to have in the box.

an imaging calorimeter (contd)

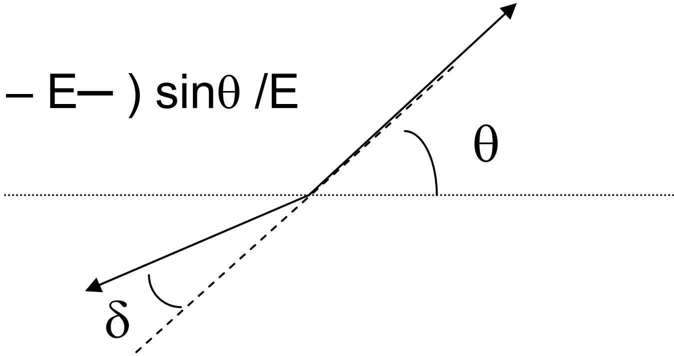


In addition to jets and taus:

- Charged particle tracking, especially V0 recognition in silicon trackers
- id hadrons which begin showering in the ECal
- Photon vertexing
    - (e.g. GMSB SUSY)
- π^o id
    - to improve jet resolution (G. Wilson, Kansas)
    - final state id, eg $\tau \rightarrow \rho\nu$
- electron id in/near jets

- Bhabhas, and acollinearity
- Hermiticity !

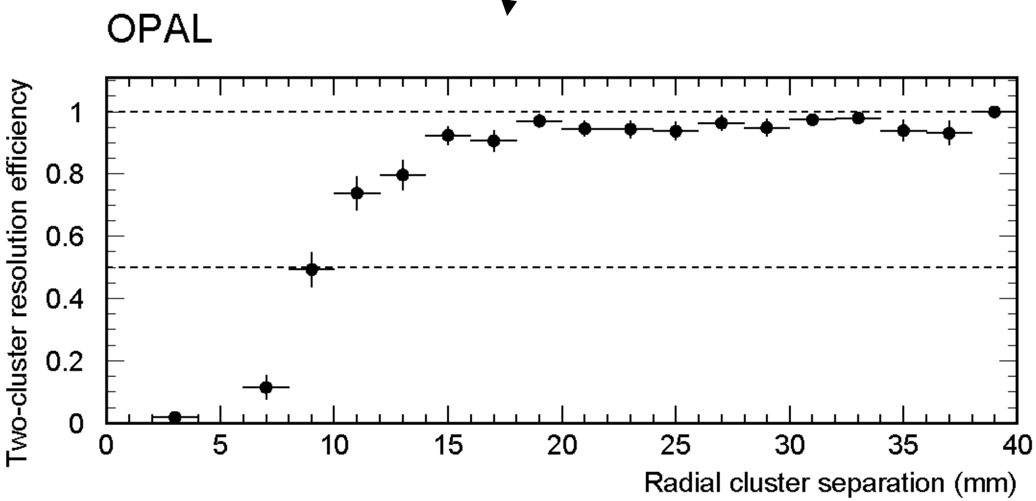
$\delta \propto (E+ - E-)\sin\theta / E$



Segmentation requirement

- In general, we wish to resolve individual photons from jets, tau decays, etc.
- The resolving power depends on Moliere radius and segmentation.
- We want segmentation significantly smaller than R_m

Two EM-shower separability in LEP data with the OPAL Si-W LumCal (David Strom) :

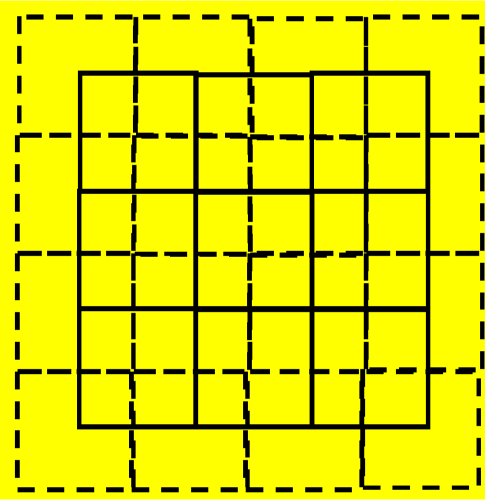


$$f_E \simeq \frac{R_{cal}}{\sqrt{R_M^2 + (4d_{pad})^2}}$$

$$d = 2.5\text{mm} \;,\; R_M \sim 17\text{mm}$$

U. Of Colorado R&D (Project 6.2)

- Offset scintillator tiles to improve spatial resolution
  - Proof of principle in simulation with single particles
  - Requires studies of jet reconstruction

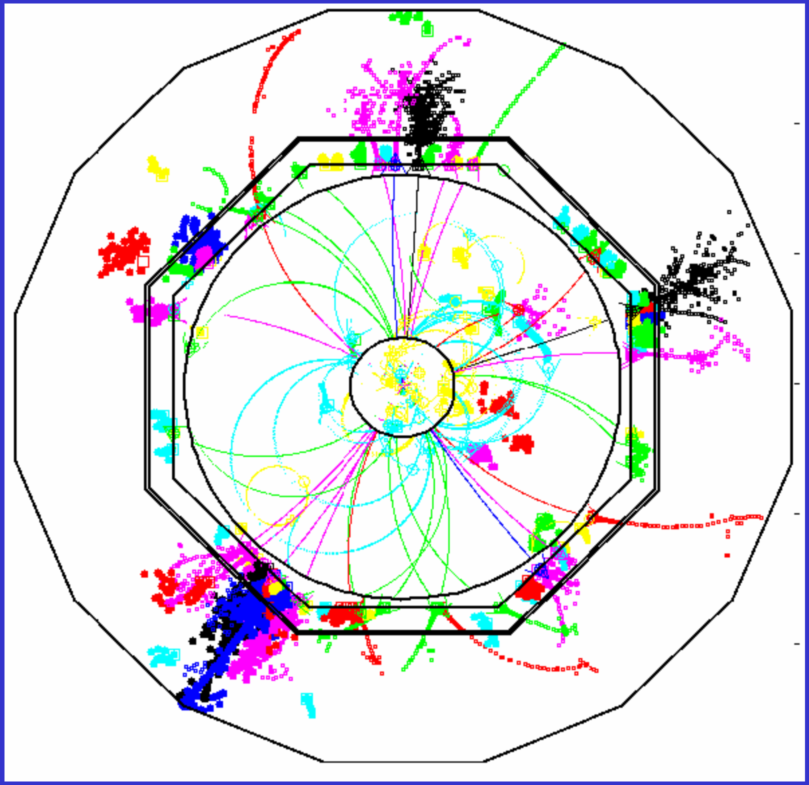


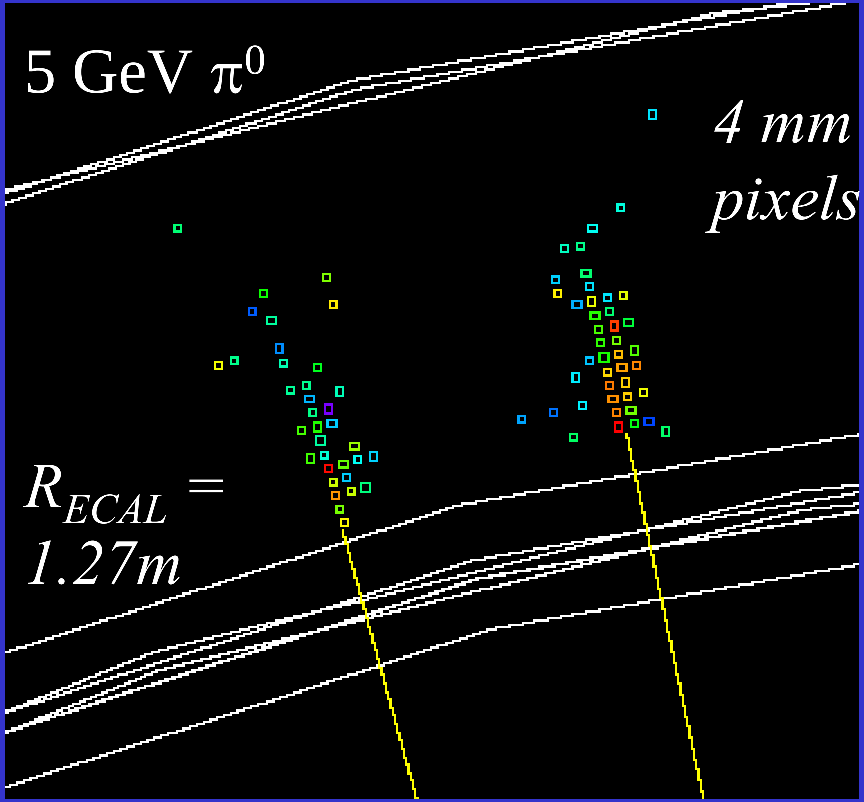
→ **For application now to scintillator HCal**

- SiPM development for scintillator options

- Simulation studies for forward calorimetry
  - SUSY and SUSY background

Investigation of ECAL Concepts Designed for Particle Flow





Project 6.10, PI Graham W. Wilson, University of Kansas

ILC Detector R&D Review, Argonne, June 2007

For more details : see talks at LCWS07 (Calorimetry R&D Review and Sim/Reco)

Overview

- Physics-driven ILC detector designs push the calorimetry in new directions.
- Physics needs:
  - Hermeticity
    - Neutrinos, SUSY particles etc
  - Jet energy measurement
    - Reconstruct W, Z, h, …
  - General-purpose performance
    - Prepare for the unexpected
    - Retain reasonable EM resolution, timing resolution.
- Particle-Flow approach has many open questions and opportunities for innovation
  - ECAL is where showers start, is a big cost driver, and is at the heart of understanding how to design a detector

- Assuming an excellent tracker, current PFA approaches indicate E_{jet} resolution has 3 major contributions
- 1. Confusion (double counting).
- 2. Intrinsic hadronic energy resolution.
- 3. Intrinsic EM energy resolution.

- This project focusses on investigating approaches which can address these limiting factors.
- 1. Larger detector (GLD/LDC like)
  - Cost effective ECAL
  - Investigate ECALs with Si and Scint
- 3. High granularity ECAL for precision photon measurement
  - Use π^0 mass constraint to improve σ_E
  - Only use Si near the front of the ECAL?
- 1,2. Precision timing to resolve confusion/reconstruct K^0_L,n using TOF

Example detector model

A radially staggered buildable analog EM calorimeter.

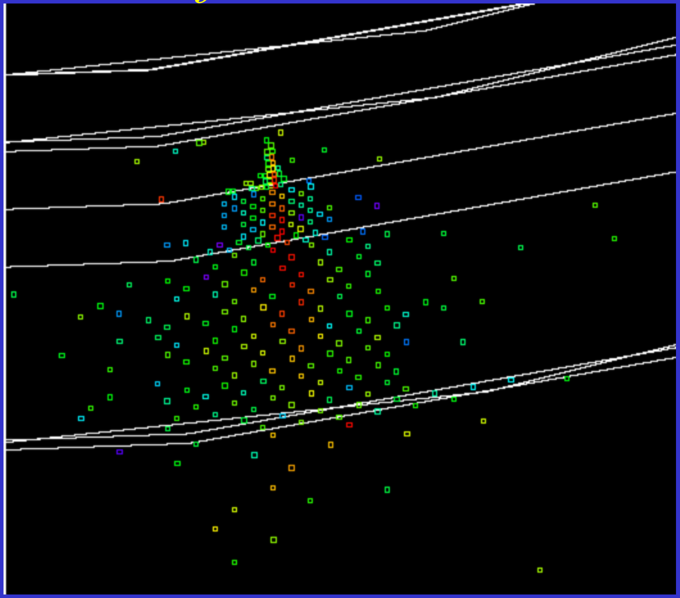
High granularity, Tungsten absorber, B = 3T.

	R(m)	Nlayers	X0	Active	Cell-size (mm)
EM Barrel 1:	2.10	10	0.5	Si	2.5 × 2.5 × 0.32
EM Barrel 2:	2.13	10	0.5	Si	10 × 10 × 0.32
EM Barrel 3:	2.16	20	0.5	Sc	20 × 20 × 2

Choices made based on 2005 R&D work, driven by making a sensible, robust design with aggressive performance and minimizing Silicon area in a GLD-scale detector.

Expect: $\sigma_E/E = 11\%/\sqrt{E}$ at low energy

frankyaug05, with N. Graf, M. Thomson

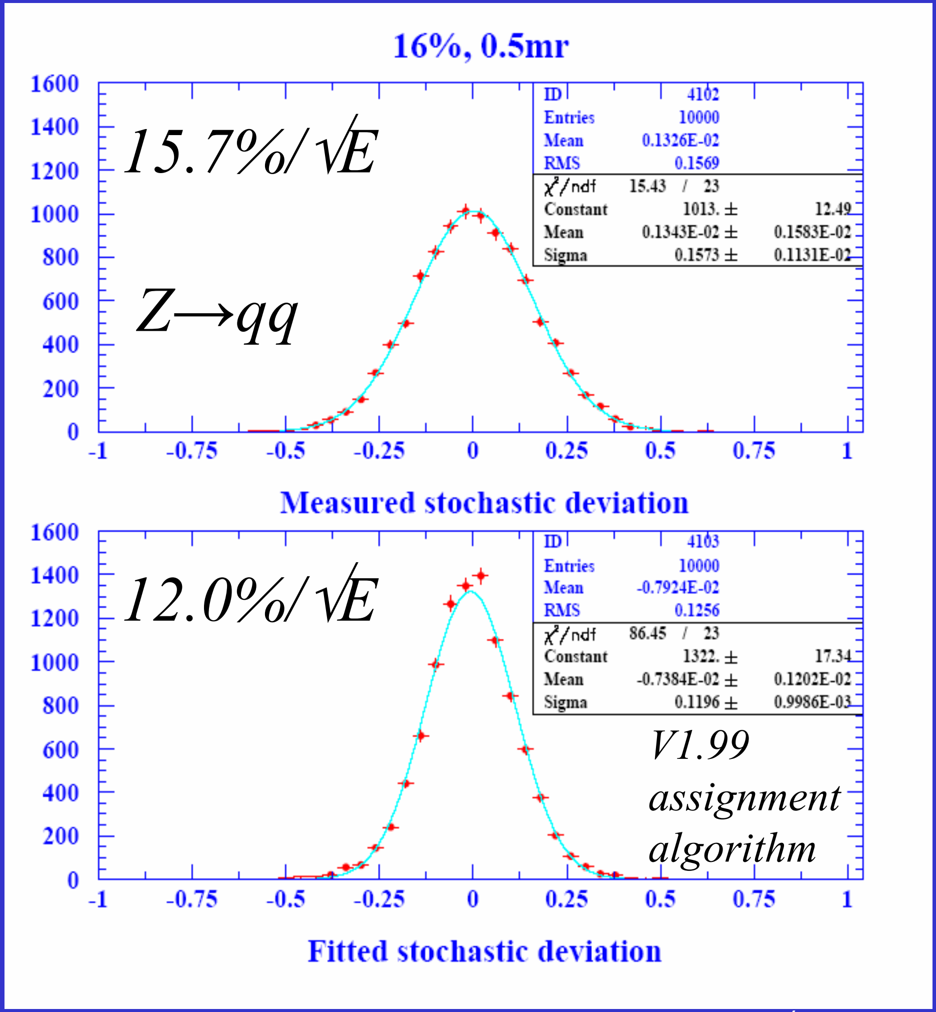


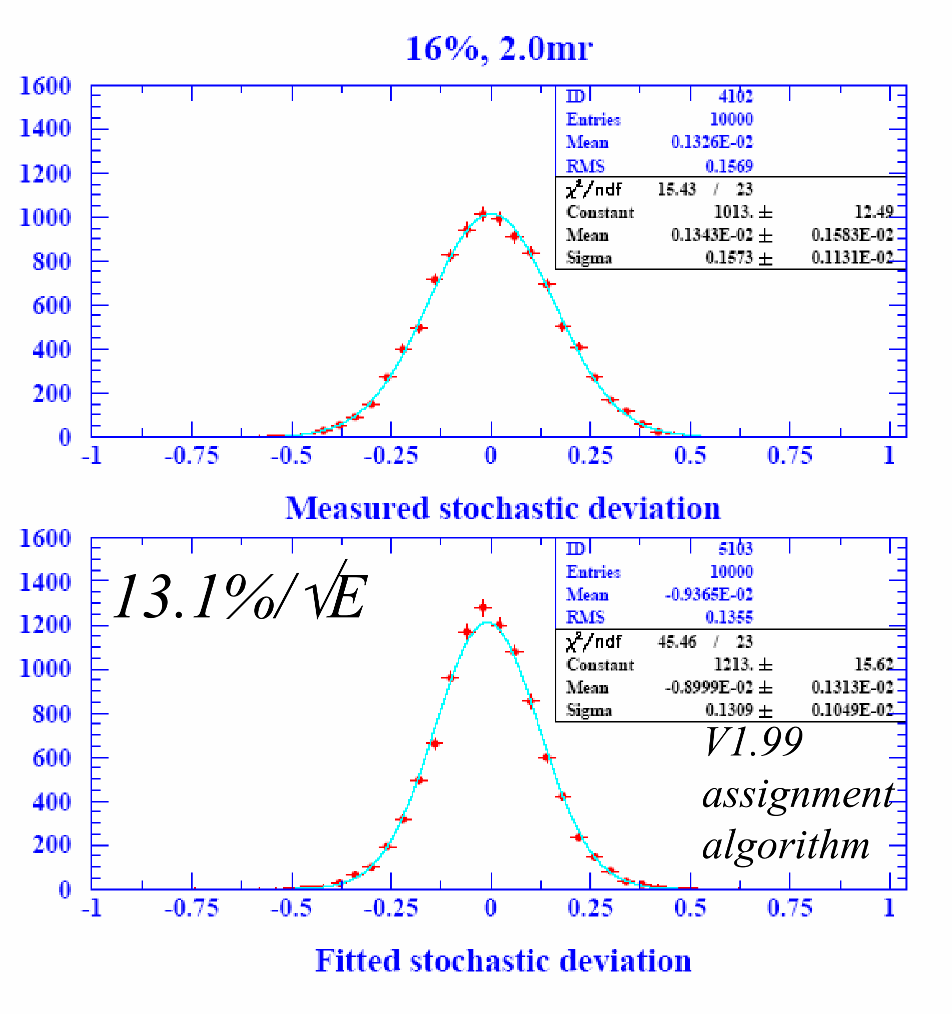
50 GeV photon

Using π^0 mass constraint to improve energy resolution of prompt EM component of jets

With aggressive design, have demonstrated that 300 μm position resolution is achievable for a 1 GeV photon.

All results here include the combinatoric issues.



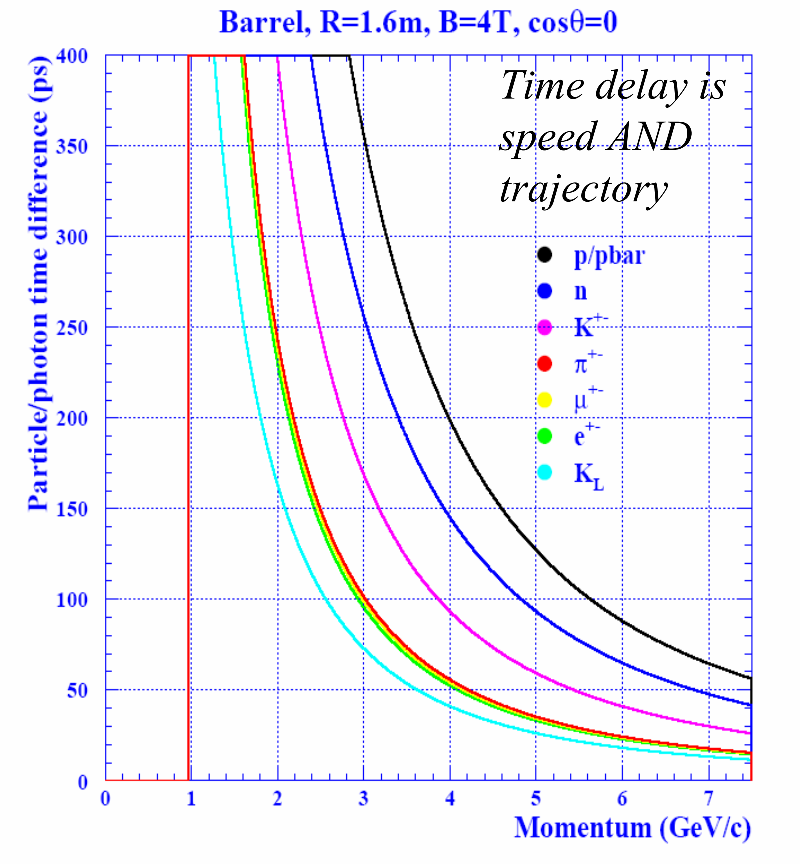


Perfect pairing → 9.4%/√E

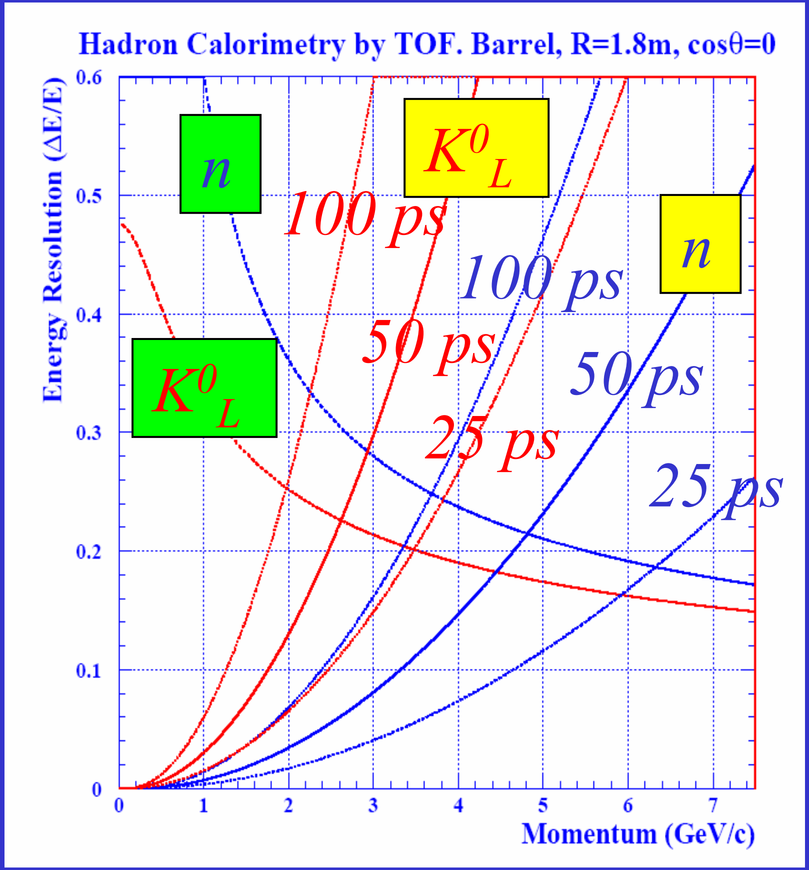
Fast Timing / Temporal Calorimetry

Idea: time resolution at below the 100 ps level is now easily achievable with dedicated detectors. Can it be applied in a useful way in an ILC detector ?

Can TOF help measure neutral hadrons at low p ?



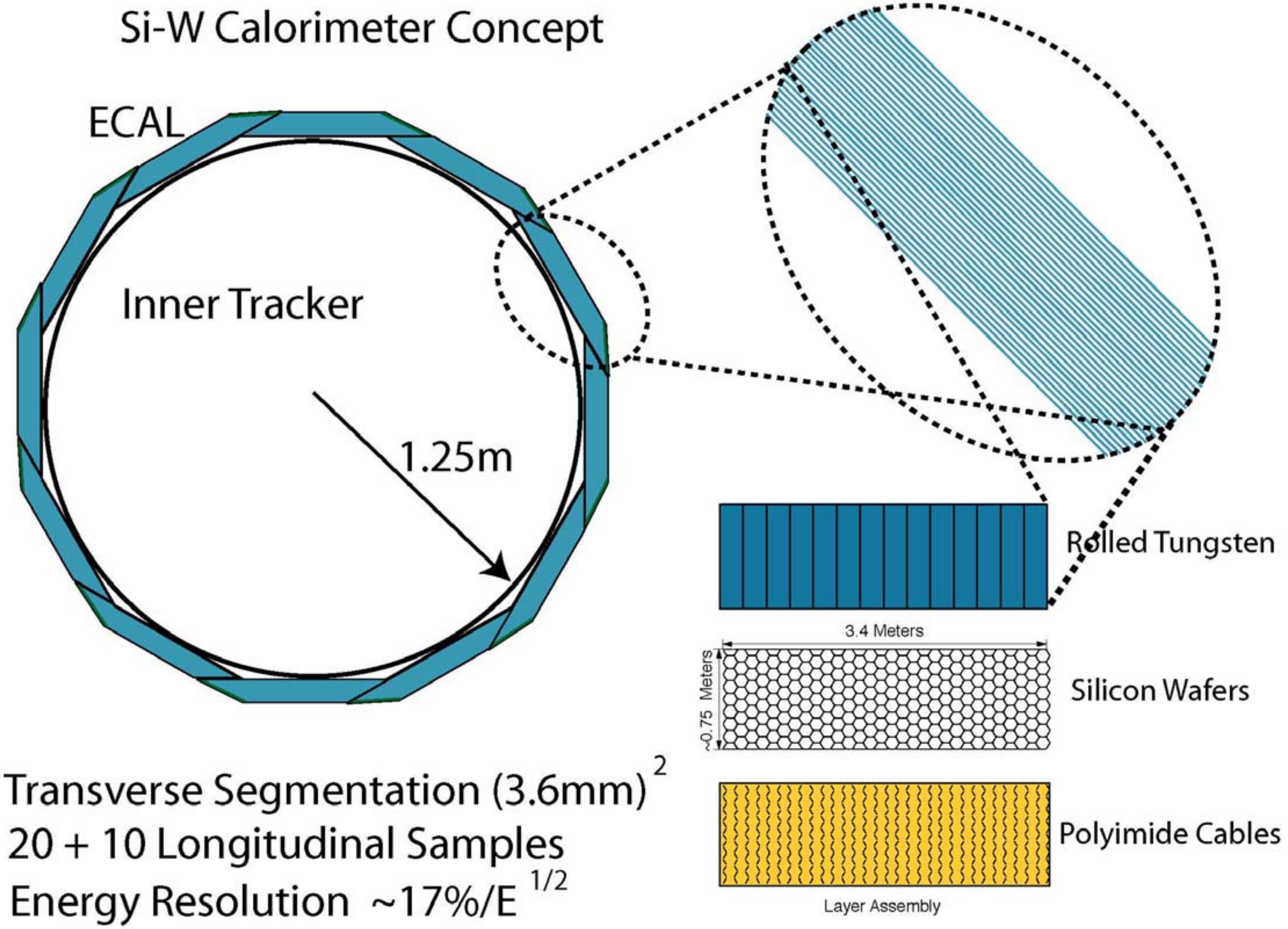
Time delay is speed AND trajectory



Can help resolving $\gamma/\pi^{\pm}$. (PID by TOF possible – but redundant with dE/dx in a TPC-based detector). ***Resolve confusion.***

HCAL (LDC DOD) TOF

A Silicon-Tungsten ECal with Integrated Electronics for the ILC (Project 6.5)



<u>Baseline configuration:</u>

- transverse seg.: 13 mm^2 pixels
- longitudinal: (20 x 5/7 X_0) + (10 x 10/7 X_0) $\Rightarrow$ 17%/sqrt(E)
- 1 mm readout gaps $\Rightarrow$ 13 mm effective Moliere radius

Currently optimized for the SiD concept

Si/W ECal R&D Collaboration

M. Breidenbach, D. Freytag, N. Graf,
R. Herbst, G. Haller, J. Jaros
Stanford Linear Accelerator Center

- KPiX readout chip
- downstream readout
- mechanical design and integration

J. Brau, R. Frey, D. Strom,
undergraduates
U. Oregon

- detector development
- readout electronics

V. Radeka
Brookhaven National Lab

- readout electronics

B. Holbrook, R. Lander, M. Tripathi
UC Davis

- cable development
- bump bonding

S. Adloff, F. Cadoux, J. Jacquemier,
Y. Karyotakis
LAPP Annecy

- mechanical design and integration

Goals of the R&D

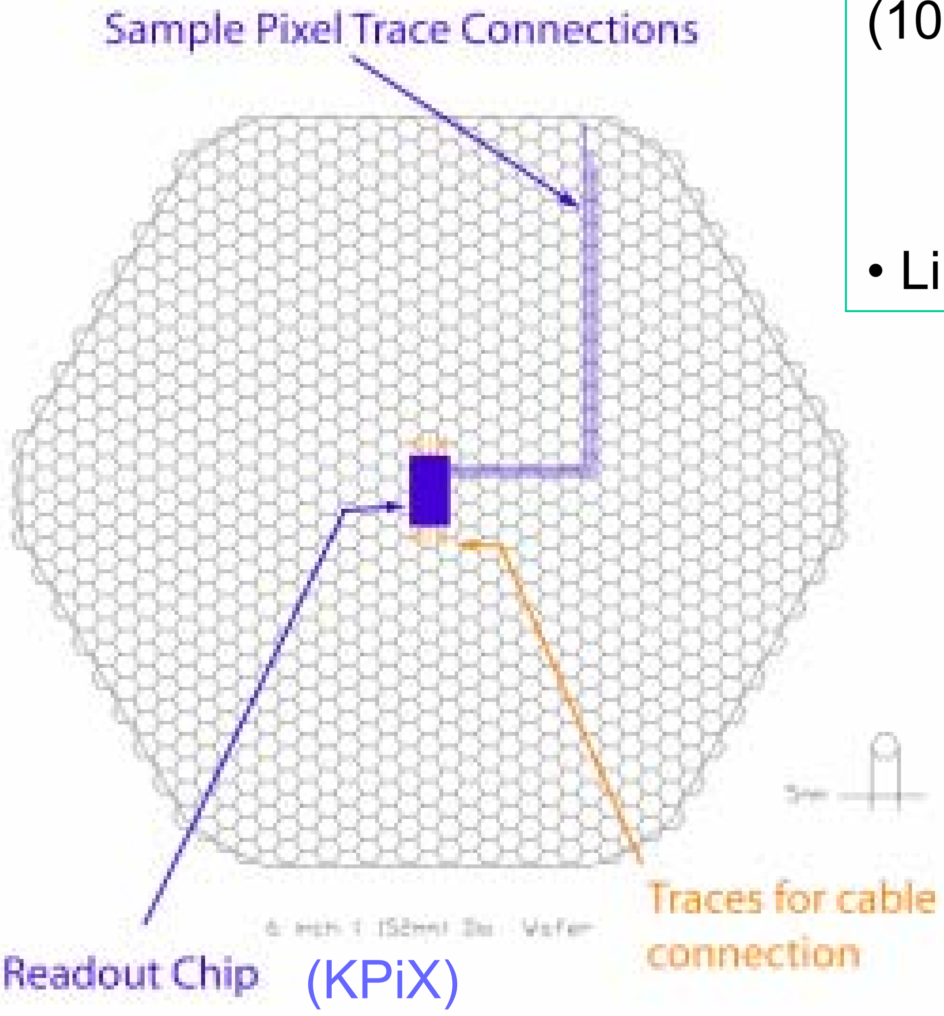
Design a practical ECal which (1) meets (or exceeds) the stringent ILC physics requirements (2) with a technology that would actually work at the ILC.

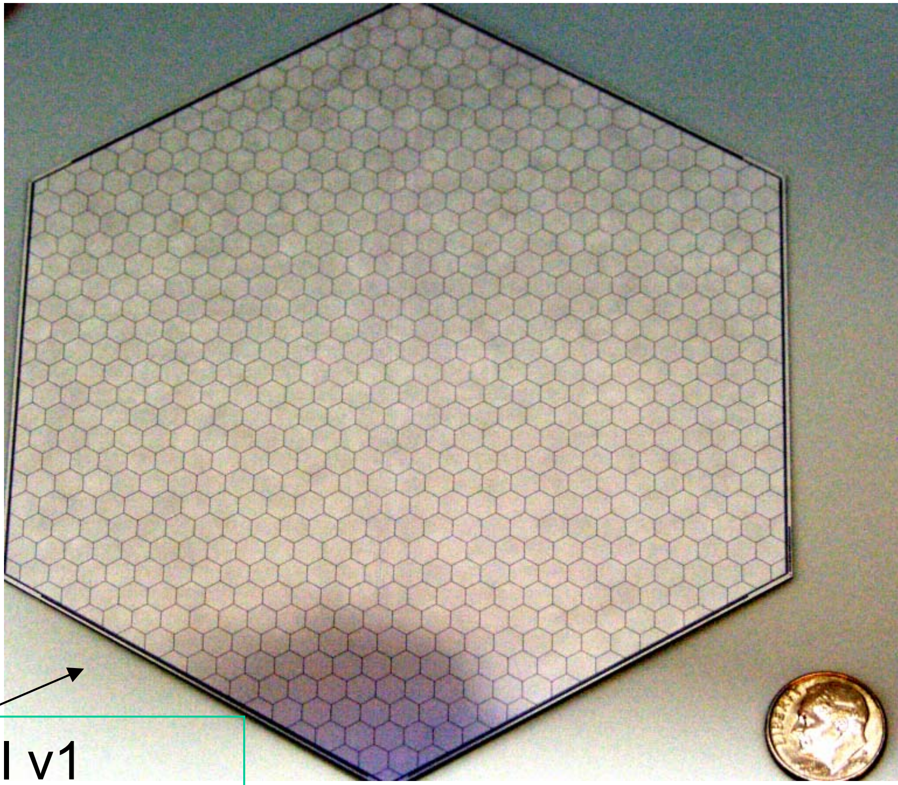
- The physics case calls for a dense (small R_m), highly segmented "imaging calorimeter" with modest EM energy resolution

  $\Rightarrow$ W-Si pixel sampling calorimeter
- The key to making this practical is a highly integrated electronic readout:
  - readout channel count = pixel count /$\sim$1000
  - cost $\approx$ independent of trans. segmentation for seg. > 2-3 mm
    - 3.6 mm is current default
  - allows for a small readout gap (1 mm) $\Rightarrow$ small effective R_m (13 mm)
  - low power budget (passive cooling)
  - handles the large dynamic range of energy depositions (few thousand)
- This takes some time to develop (getting close).

Silicon detector layout and segmentation

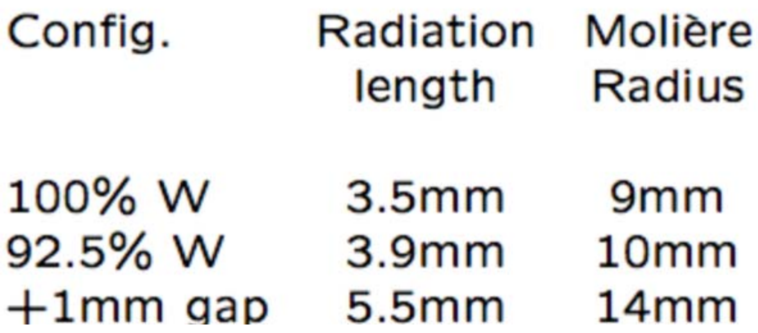
- One KPiX readout chip for the sensor (1024 pixels, 6 inch wafer)
    - KPiX also being considered for Si tracker and DHCal with GEMs
- Limit on seg. from chip power (≈2 mm^2)





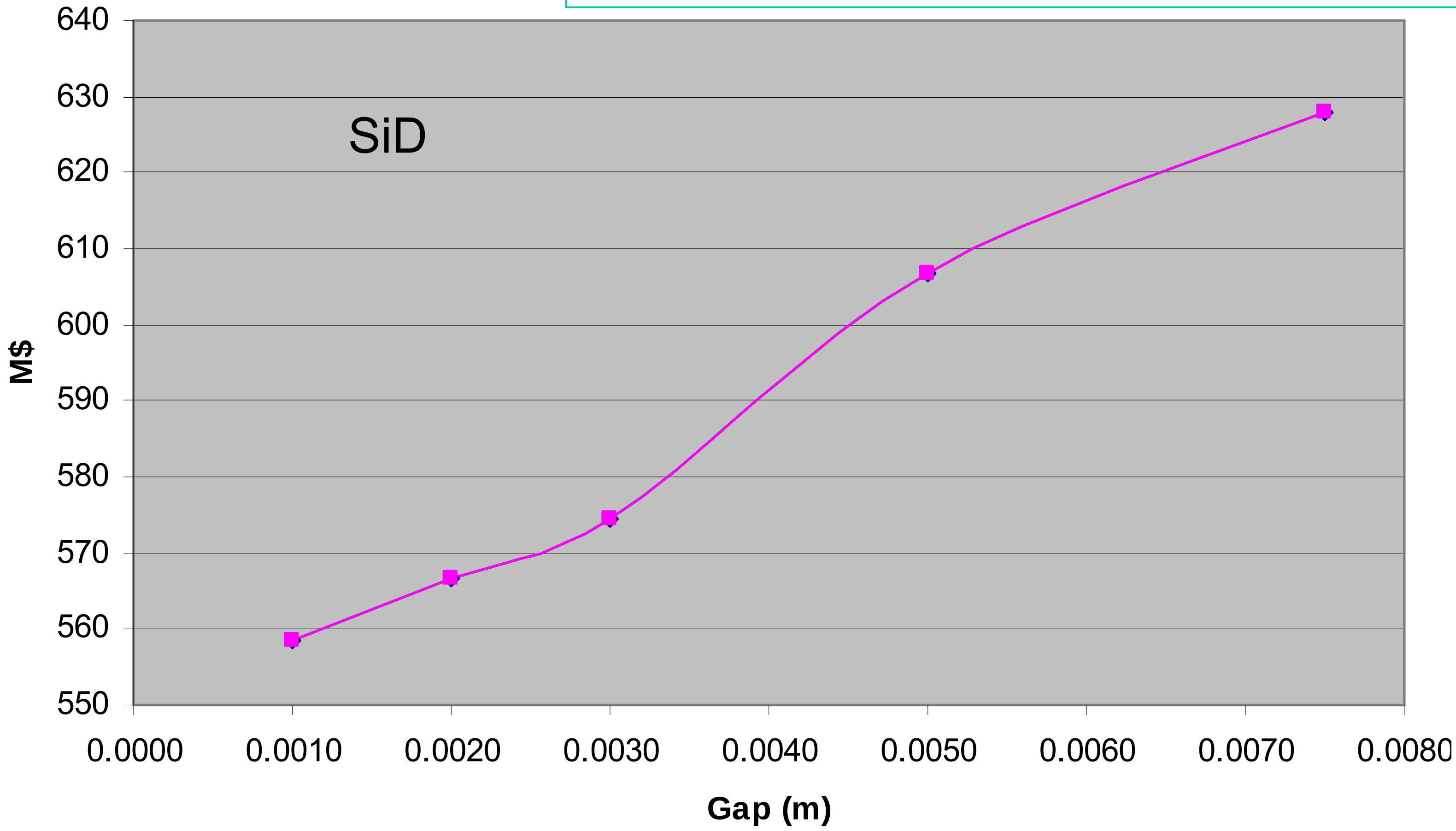
Fully functional v1 prototype (Hamamatsu)

Critical design parameter is the gap between layers

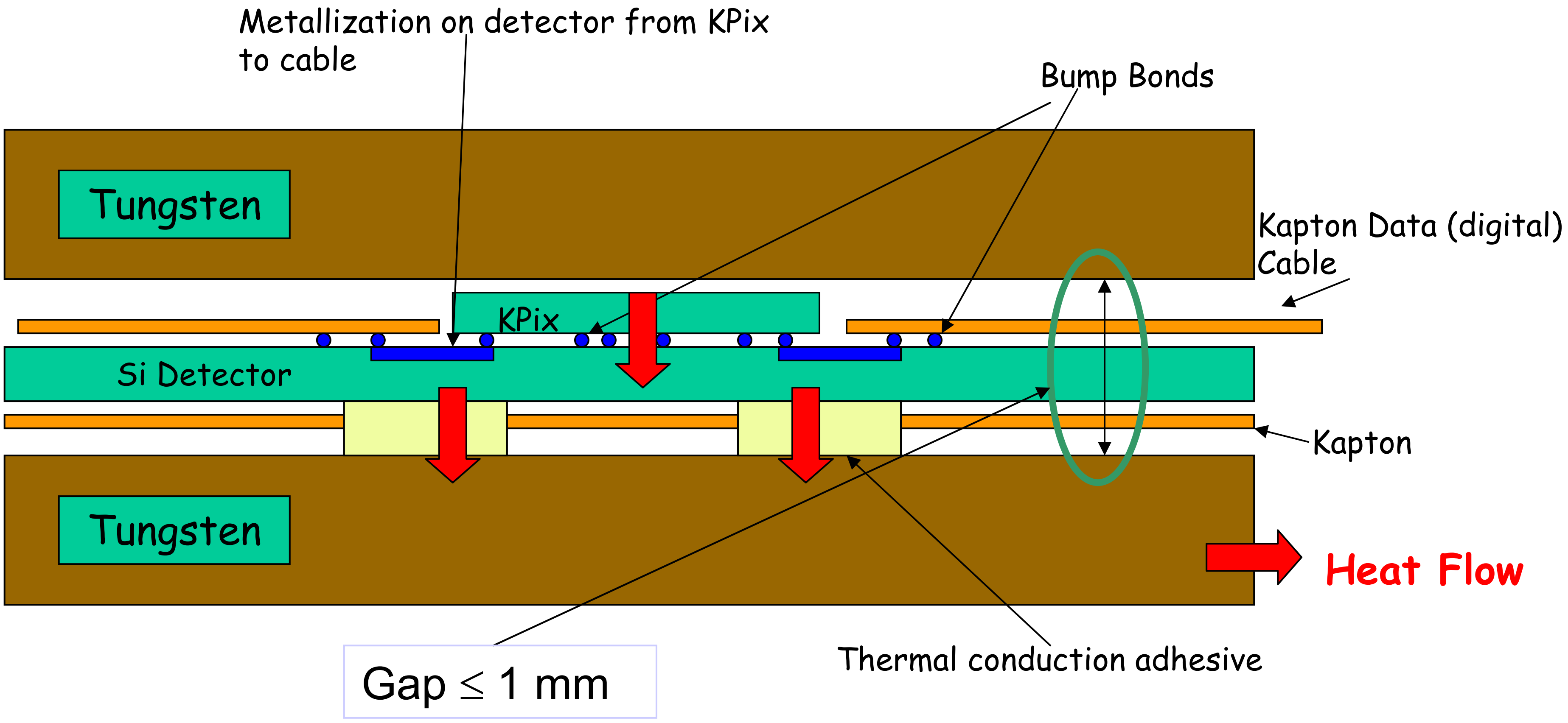


Config.	Radiation length	Molière Radius
100% W	3.5mm	9mm
92.5% W	3.9mm	10mm
+1mm gap	5.5mm	14mm

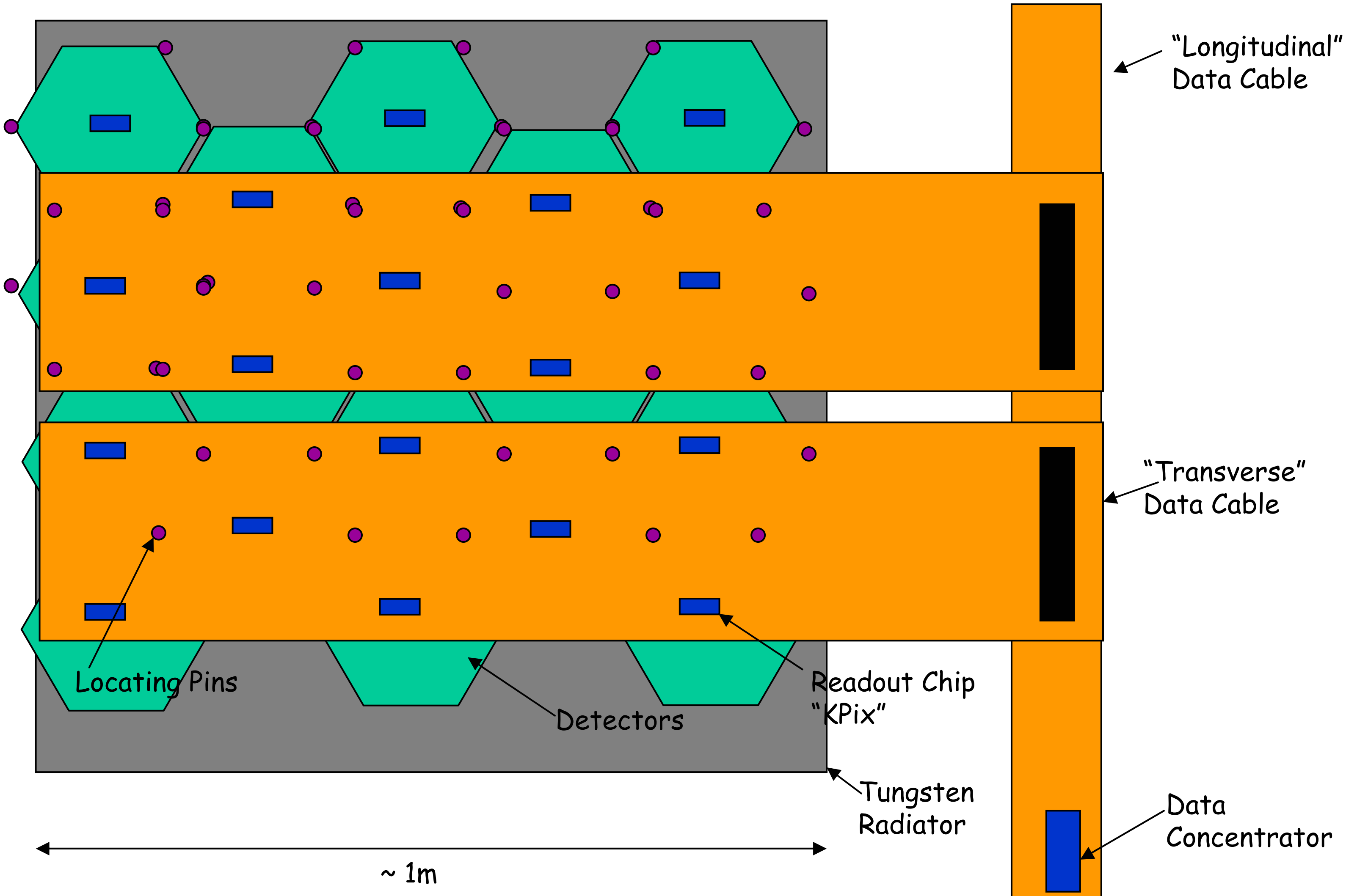
- Small gap maintains small Moliere radius
- Larger Rm ⇒ larger detector to maintain shower separability ⇒ cost !
- Small gap makes a cost-controlled compact detector practical



readout gap cross section -- schematic

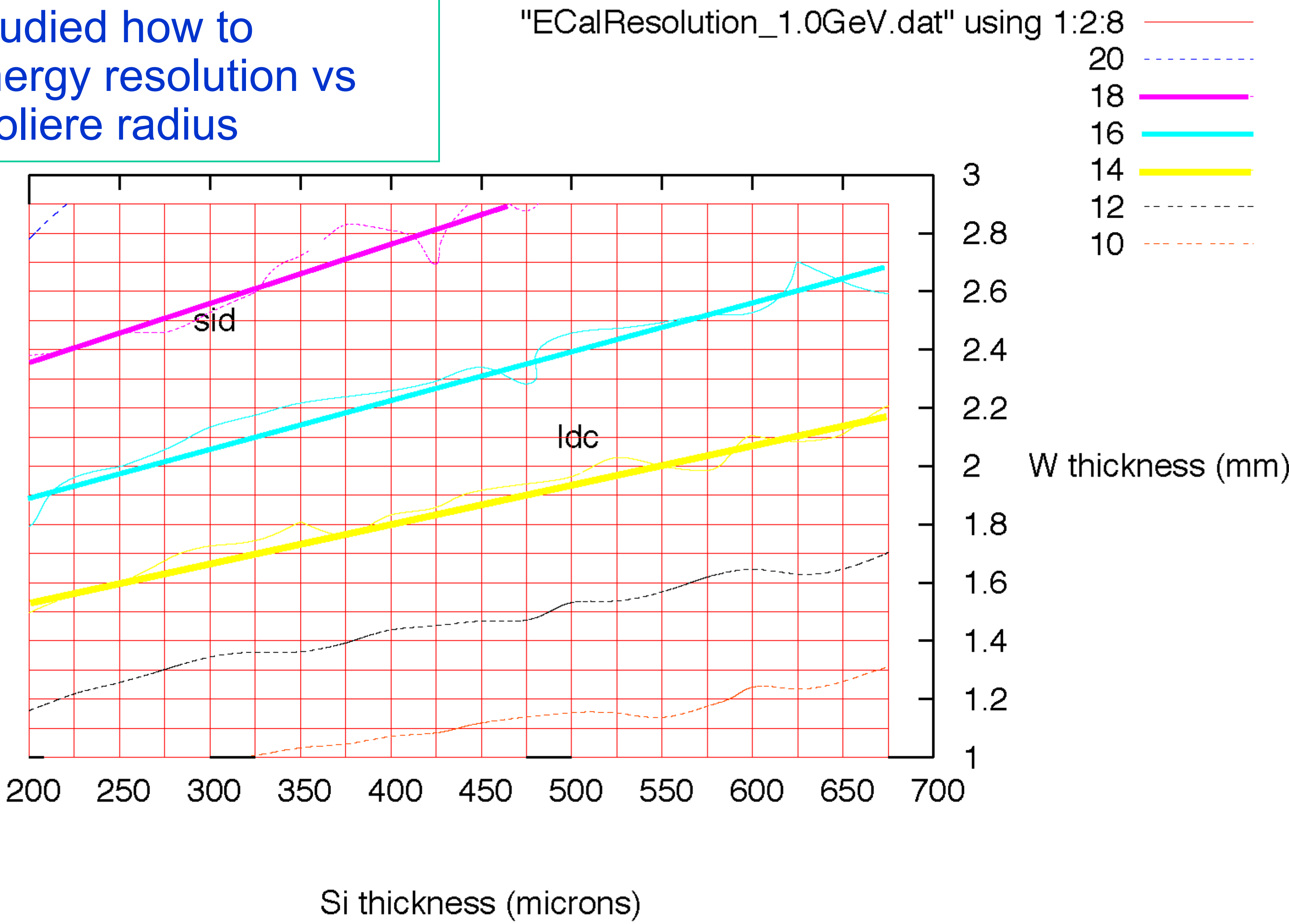


Conceptual Schematic – Not to scale



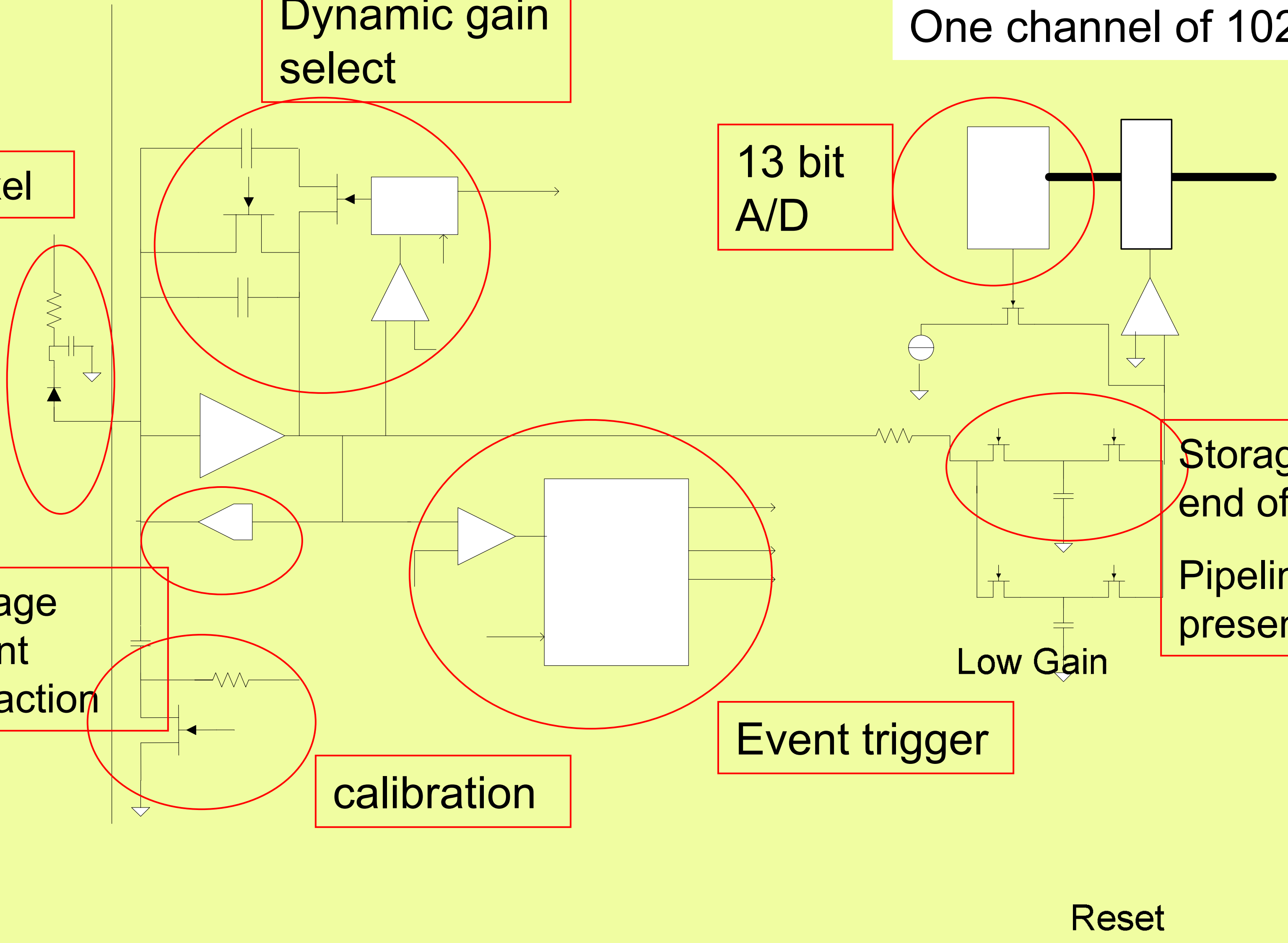
Energy resolution

- No physics case has emerged for EM energy resolution better than ~0.15/√E
- We have studied how to optimize energy resolution vs cost and Moliere radius



KPiX chip

One channel of 1024



Si pixel

Dynamic gain select

13 bit A/D

Storage until end of train.

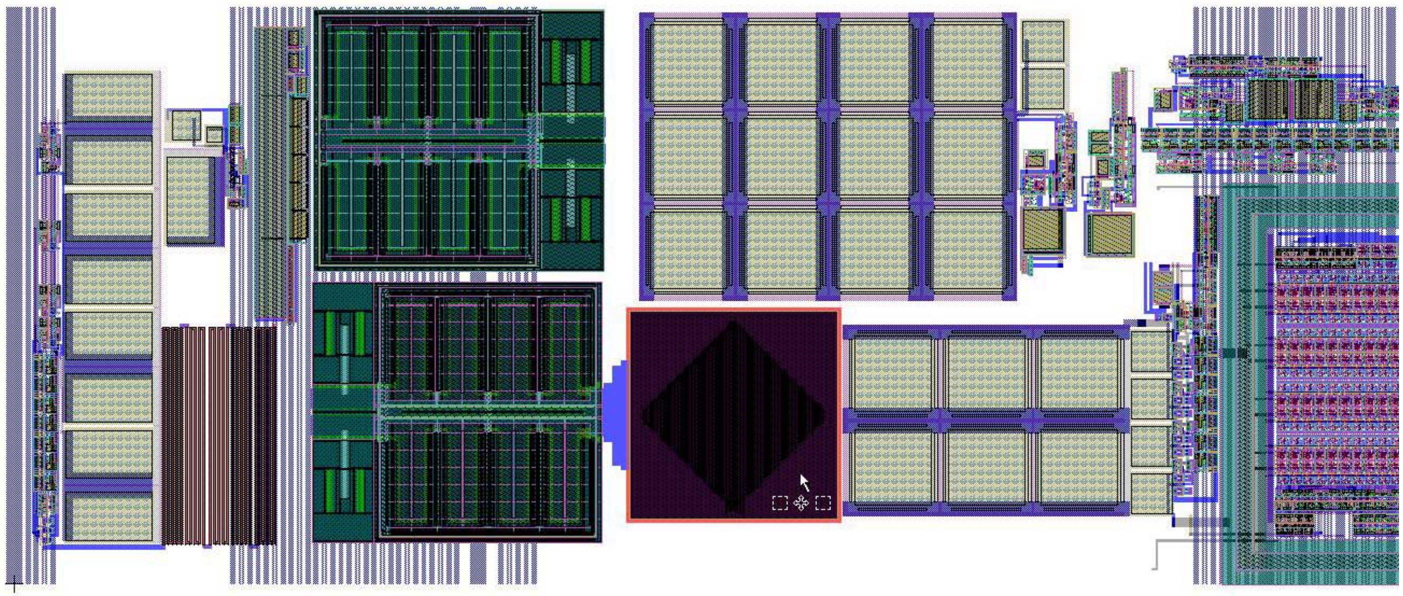
Pipeline depth presently is 4

Leakage current subtraction

calibration

Event trigger

KPiX Cell 1 of 1024



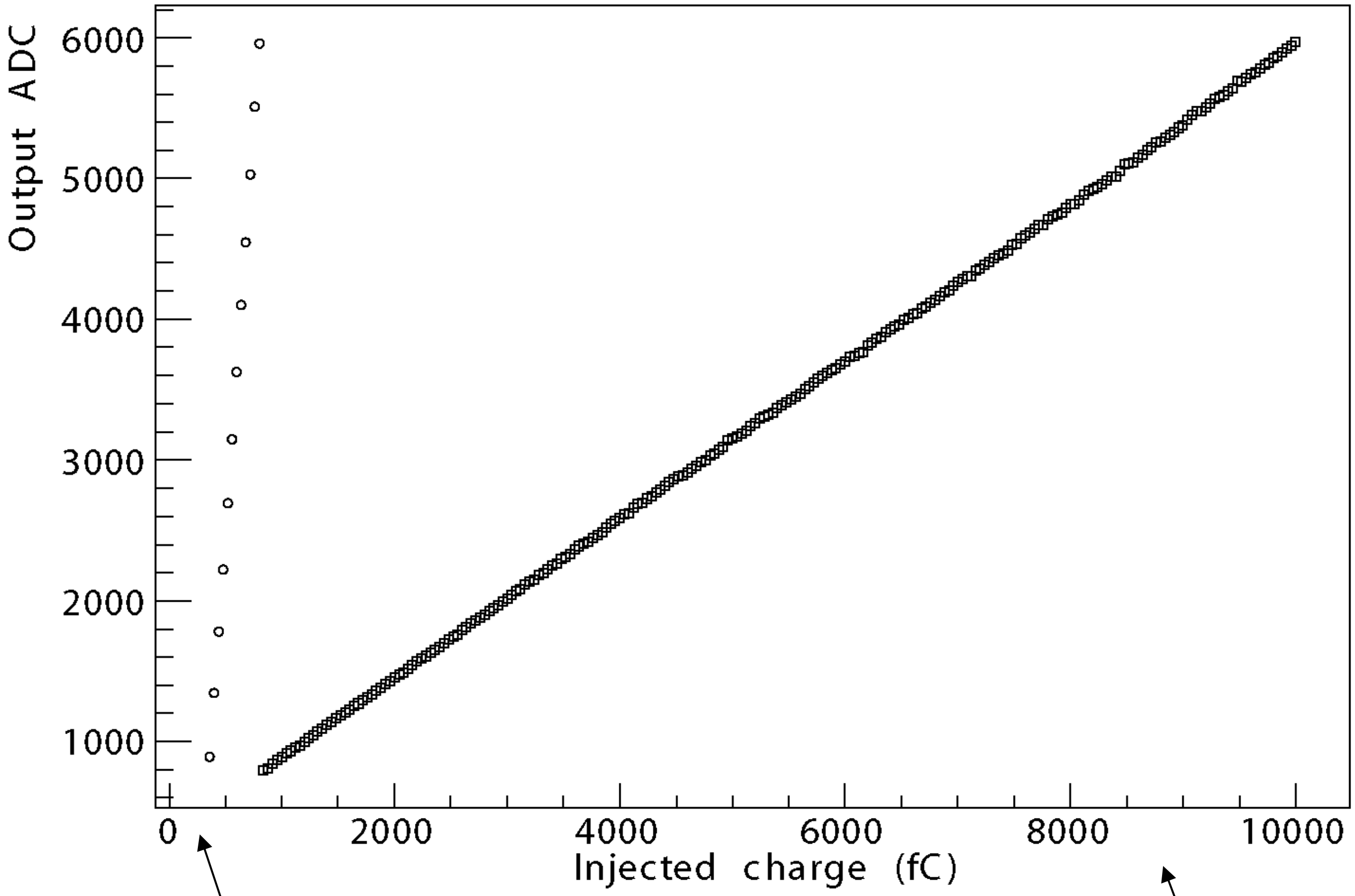
64-channel prototypes:

- v1 delivered March 2006
- v4 currently under test
- v5 submitted (June ’07)

It’s a complicated beast – will need a v6 before going to the full 1024-channel chip

Dynamic Range

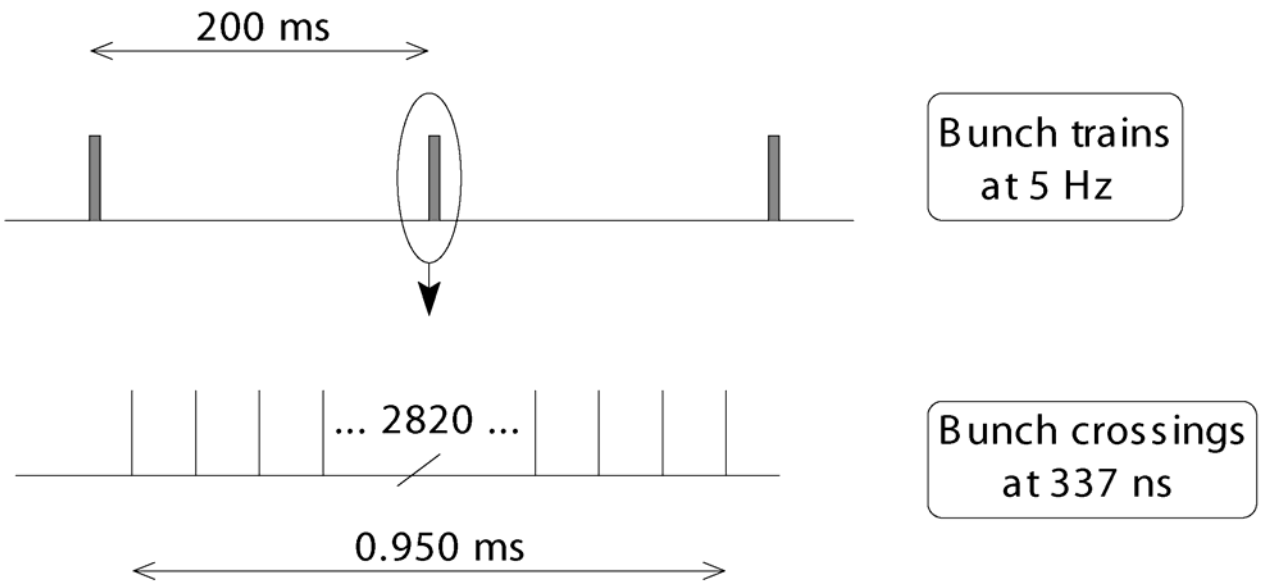
KPiX-2 prototype on the test bench



1 MIP (4 fC)

Max signal: 500 GeV electron

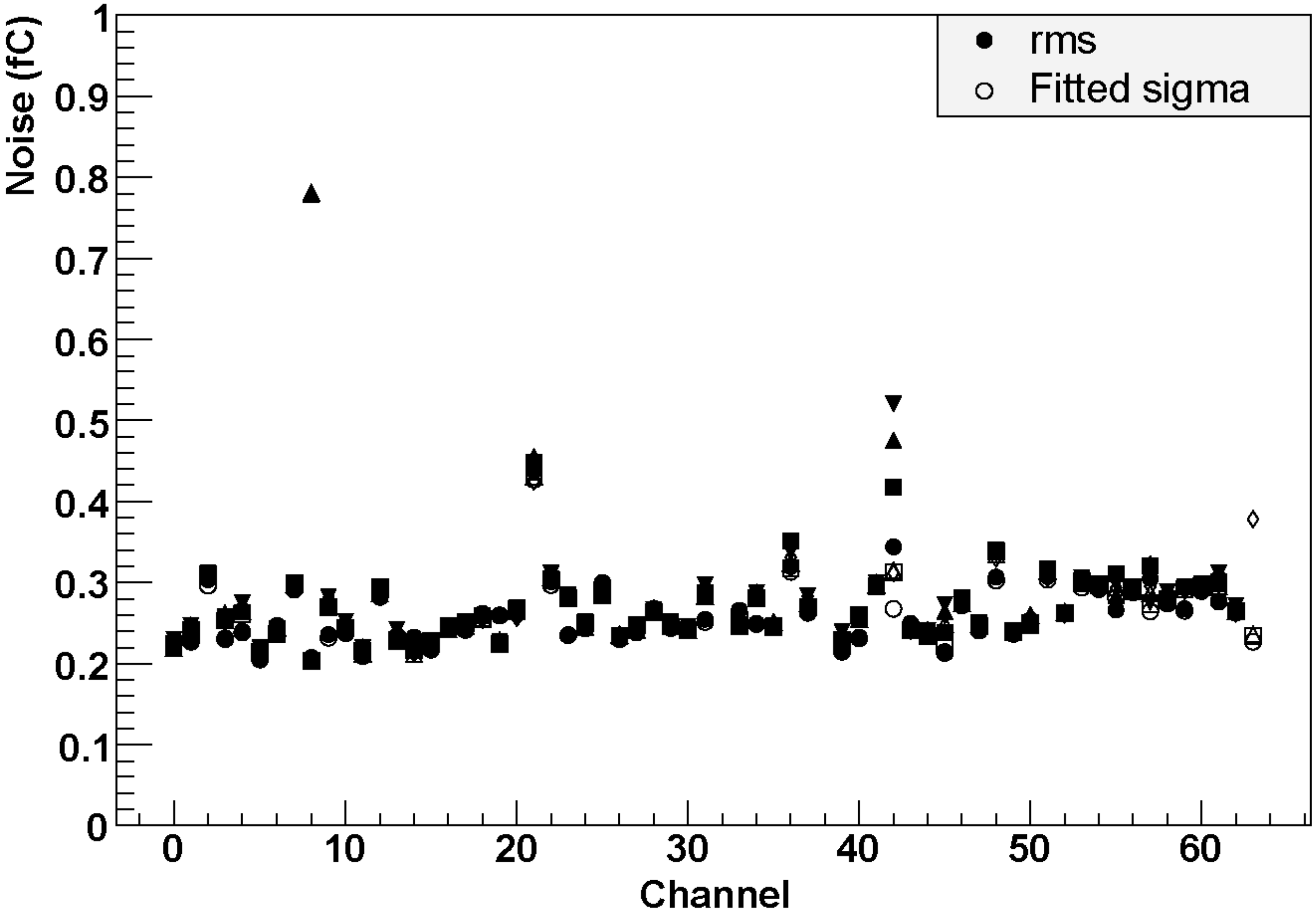
Power



Phase	Current (ma)	Instantaneous Power (mw)	Time begin (us)	Time End (us)	Duty Factor	Average Power (mw)	Comments
All Analog "on"	370.00	930.00	0.00	1,020.00	5.10E-03	4.7	Power ok with current through FET's
Hold "on", charge amp off	85.00	210.00	1,021.00	1,220.00	9.95E-04	0.2	
Analog power down	4.00	10.00	1,020.00	200,000.00	9.95E-01	9.9	
LVDS Receiver, etc		3.00	0.00	200,000.00	1.00E+00	3.0	Receiver always on.
Decode/Program		10.00	1.00	100.00	4.95E-04	0.0	Sequencing is vague!
ADC		100.00	1,021.00	1,220.00	9.95E-04	0.1	
Readout		50.00	1,220.00	3,220.00	1.00E-02	0.5	
Total						18.5	Total power OK

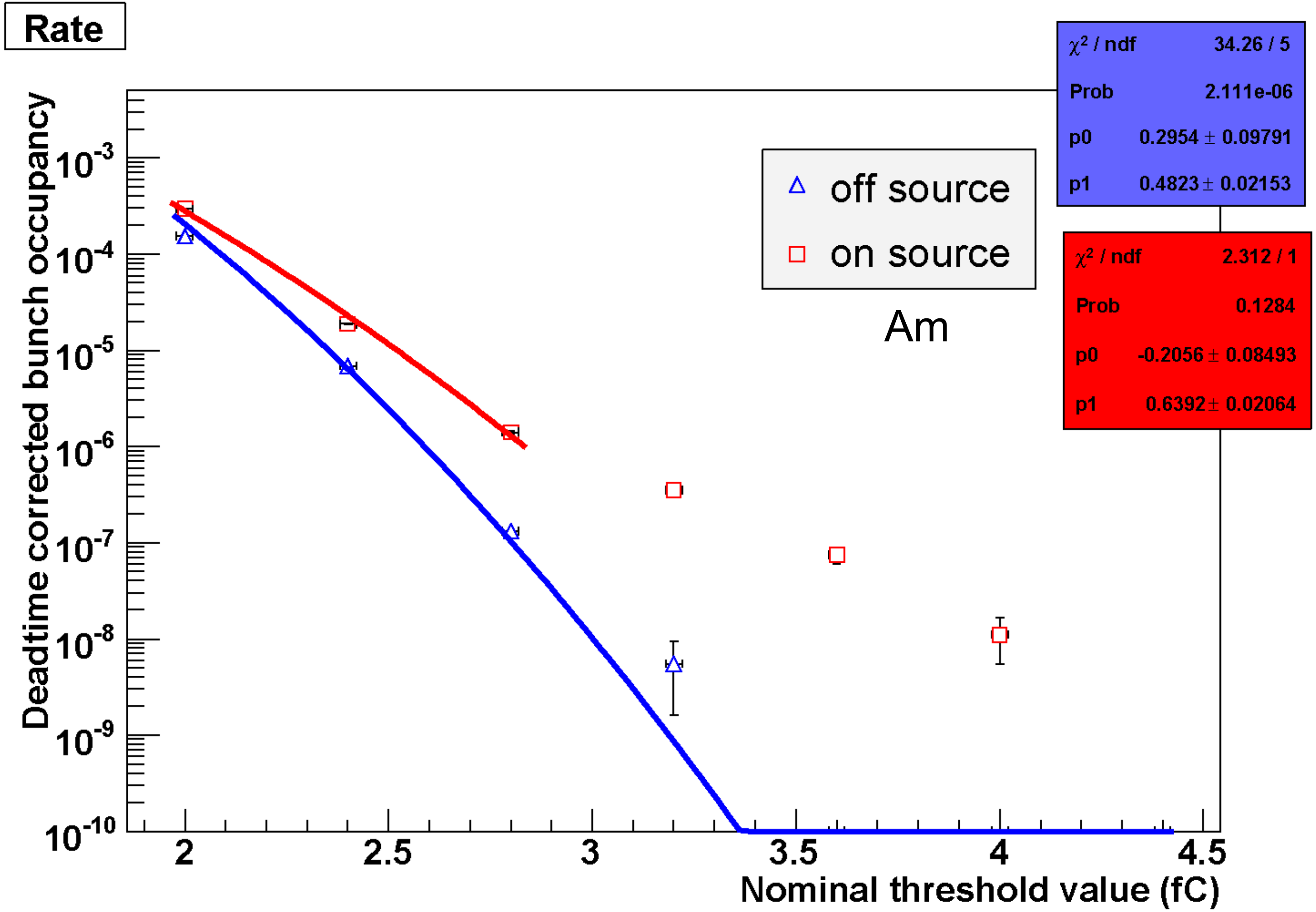
Passive conduction of 20 mW to module end (≈75 cm) via the tungsten radiator results in a few °C temperature increase ⇒ OK !

Noise in KPiX-4



- 1 MIP = 3.9 fC ⇒ meets ECal S/N spec of 8/1
- outliers probably due to routing issues

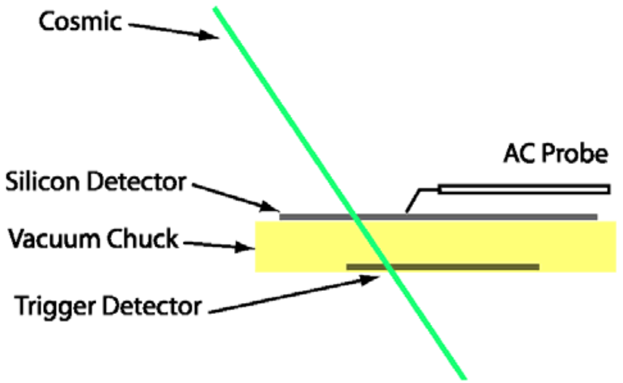
Noise is gaussian



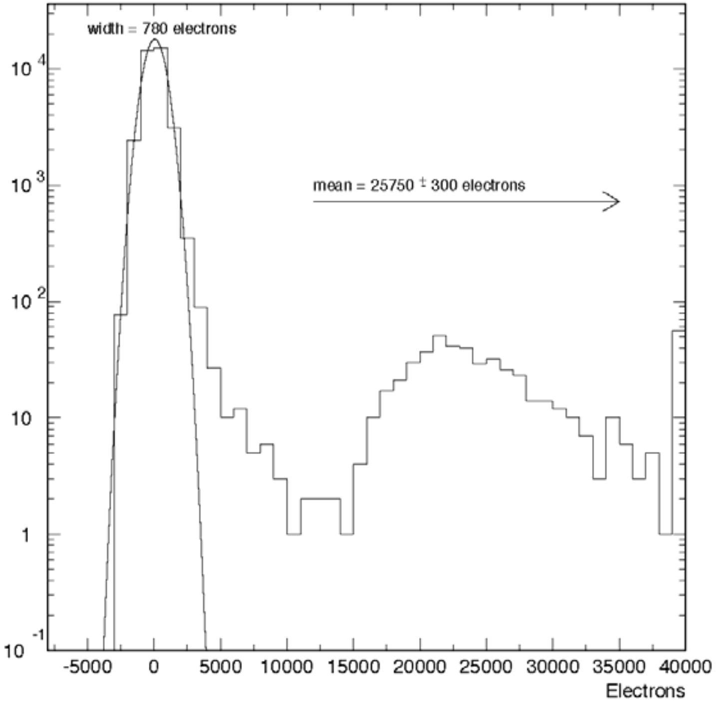
⇒ Can set threshold at ≈ 0.5 MIP

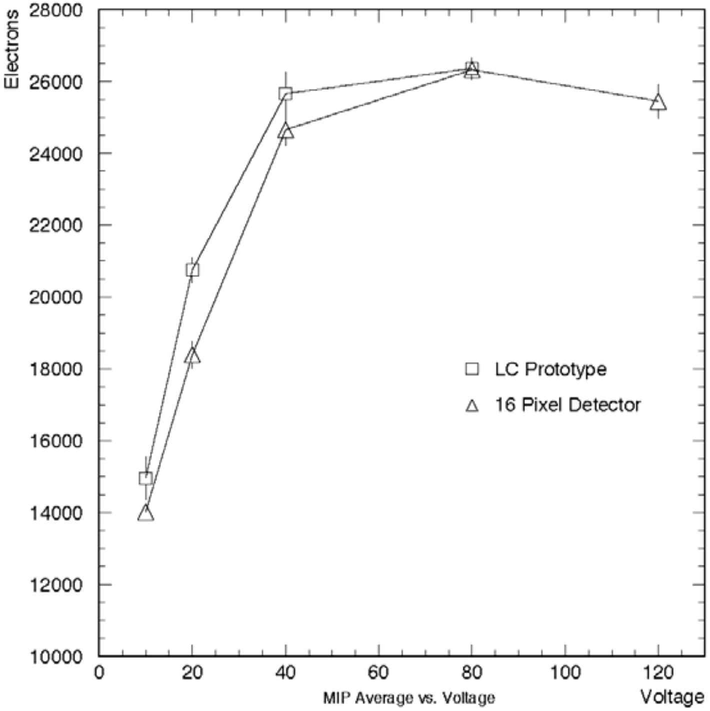
prototype Si detector studies

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



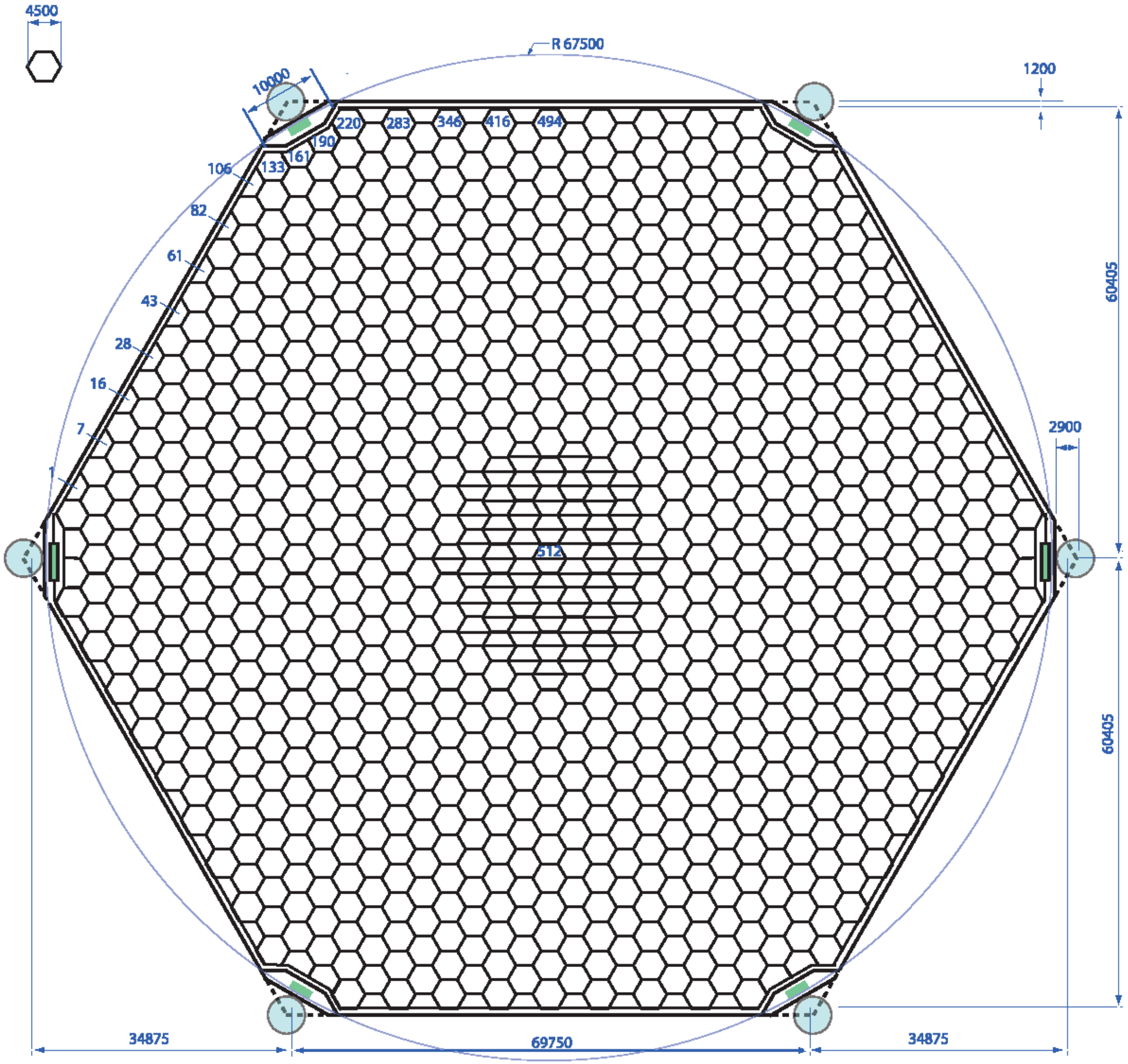
Cosmic
AC Probe
Silicon Detector
Vacuum Chuck
Trigger Detector





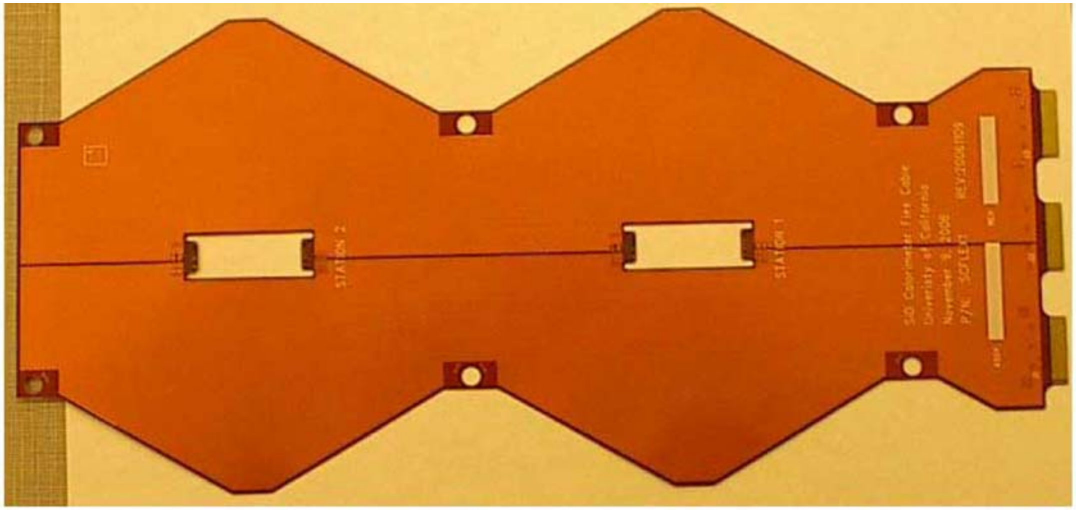
Errors do not include ~ 10% calibration uncertainty (no source calibration)

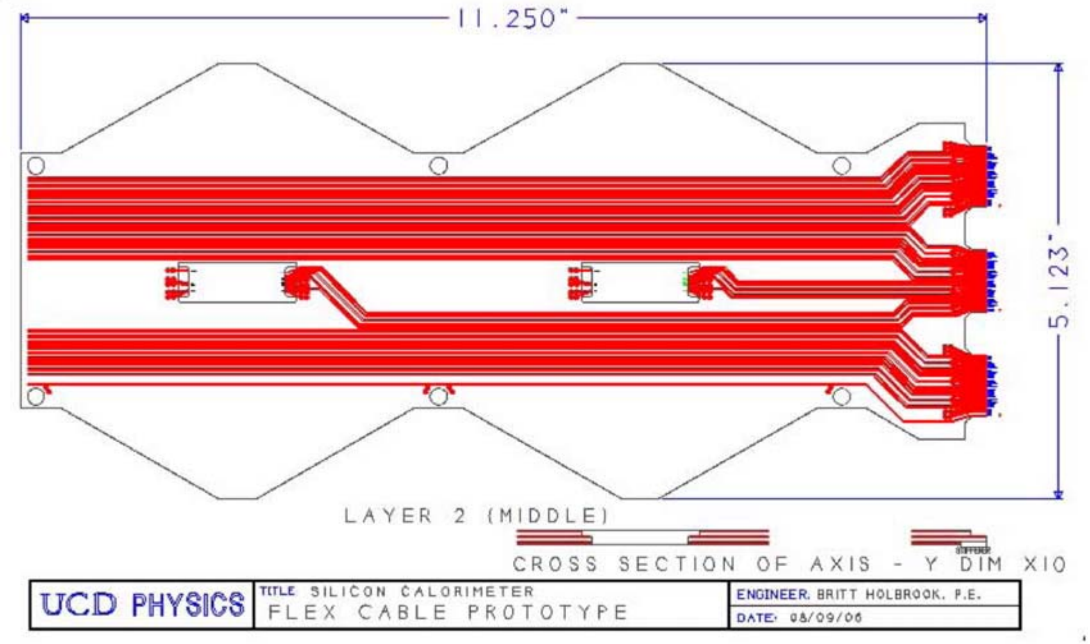
v2 Si detector – for full-depth test module



- 6 inch wafer
- 1024 13 mm^2 pixels
- improved trace layout near KPiX to reduce capacitance
- procurement in progress (it will take 6-12 months to complete the 40-wafer purchase – funding limited)

Readout flex cable (digitized signals, power&control)





- First prototype:
  - 2 stations
  - Buried signal layer between power and ground
  - Wire bond connections
  - No problem for prototypes
- For ECal:
  - ~6 stations: should be OK
  - Would like to determine length limit for next round (vias and multi-layers difficult for ~1m)

on multiple (2) Si-W R&D efforts

- The CALICE collaboration includes a very significant and well-funded Si-W R&D effort
  - Their effort has focused on developing a test beam prototype using non-ILC technology
    - Has collected data at DESY and CERN during the last year
  - More recently they have been developing a generation II design

- We decided to directly develop an ILC design (gen. II)
  - Technology was proven in SLD, ALEPH, OPAL lum. calorimeters
- Many of our design innovations have been incorporated in the CALICE gen. II design
  - Integrated electronics, power pulsing, small gaps, sub-cm transverse segmentation, etc

- This arrangement has been beneficial for developing a viable ILC ECal design with essentially no redundancy (so far)

Si-W (project 6.5) Status Summary

- KPiX readout chip
  - Currently studying v4 prototype (2x32 channels)
  - Submit v5 in next few weeks (4x32 channels)
    - Improved biasing of MOS capacitors; new poser bus for comparators
    - Optimized shaper time constants
  - Expect to submit 1024-channel KPiX in late Fall or Winter
- Silicon sensors
  - v2 prototype submitted to industry (40 sensors)
  - Schedule funding limited – hope to acquire sensors Fall-Winter
- Readout flex cable – short version for first module OK
- Bump bonding – first trials (UC Davis) just starting

→ Combine the above: a full-depth, single-wafer wide module
→ Test in a beam: (1) electrons (2008); (2) hadrons with HCal

The R&D leading to an “ILC-ready” Si-W ECal technology is progressing well

Extra stuff...

Future Si-W Development Milestones

I. Connect (bump bond) prototype KPiX to prototype detector with associated readout cables, etc
  - Would benefit from test beam (SLAC?) - 2007
  - A “technical” test

II. Fabricate a full-depth ECal module with detectors * and KPiX-1024 readout * – functionally ≈equivalent to the real detector
  - Determine EM response in test beam – 2008
  - Ideally a clean 1-30 GeV electron beam (SLAC??)

III. Test with an HCal module in hadron test beam (FNAL?) – 2008-?
  - Test/calibrate the hadron shower simulations; measure response

IV. Pre-assembly tests of actual ECal modules in beam – >2010

V. Develop mechanical design, 2008→

* *pending funding*

R&D Milestones and test beams

I. Connect (bump bond) prototype KPiX to prototype detector with associated readout cables, etc
  - Would benefit from test beam (SLAC?) - 2007
  - A “technical” test

II. Fabricate a full-depth ECal module with detectors and KPiX-1024 readout – functionally ≈equivalent to the real detector
  - Determine EM response in test beam – late 2007-8
  - Ideally a clean 1-30 GeV electron beam (SLAC?)

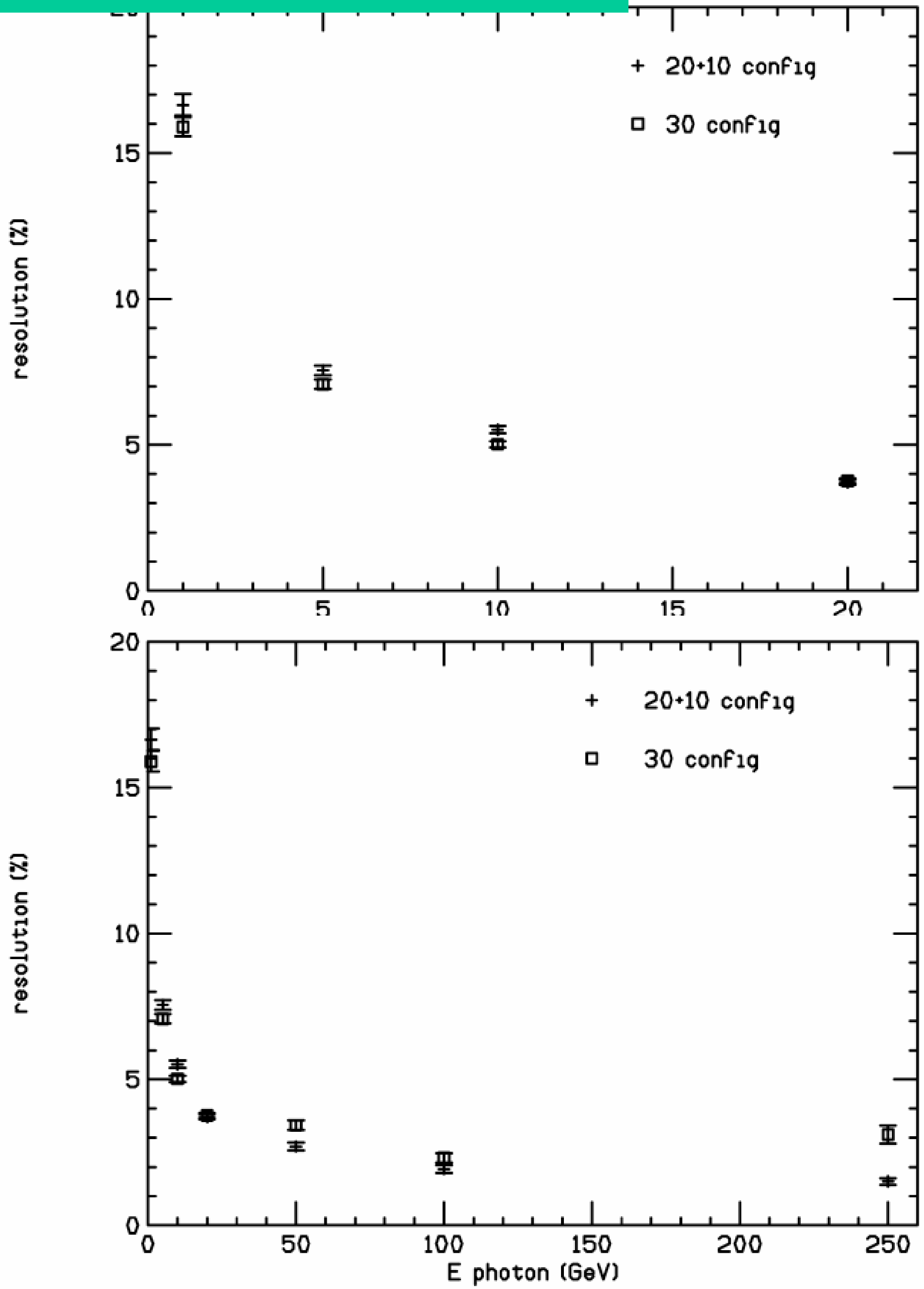
III. Test with an HCal module in a hadron beam (FNAL?) – 2008-?
  - Test/calibrate the hadron shower simulations; measure response

IV. Pre-assembly tests of actual ECal modules in beam – >2010-?

Longitudinal Sampling

Compare two tungsten configurations:

- 30 layers x 5/7 X_0
- (20 x 5/7 X_0) + (10 x 10/7 X_0)

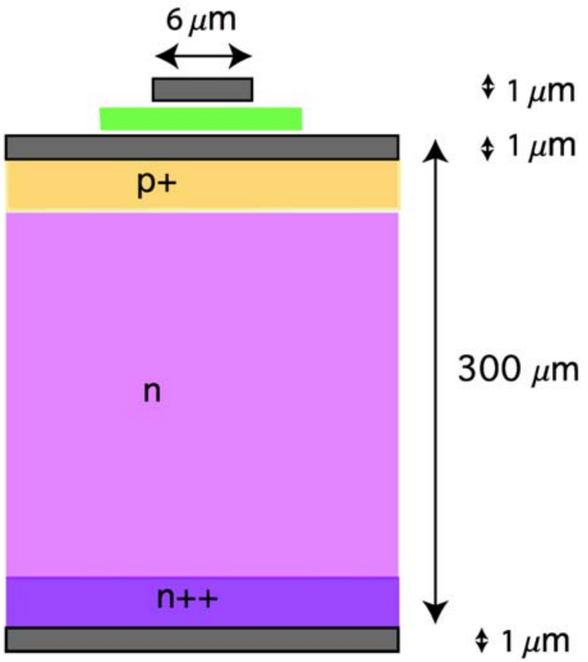


- Resolution is 17% / √E , nearly the same for low energy (photons in jets)
- Better for the 20+10 config. at the highest energies (leakage) ⇒ adopt as baseline

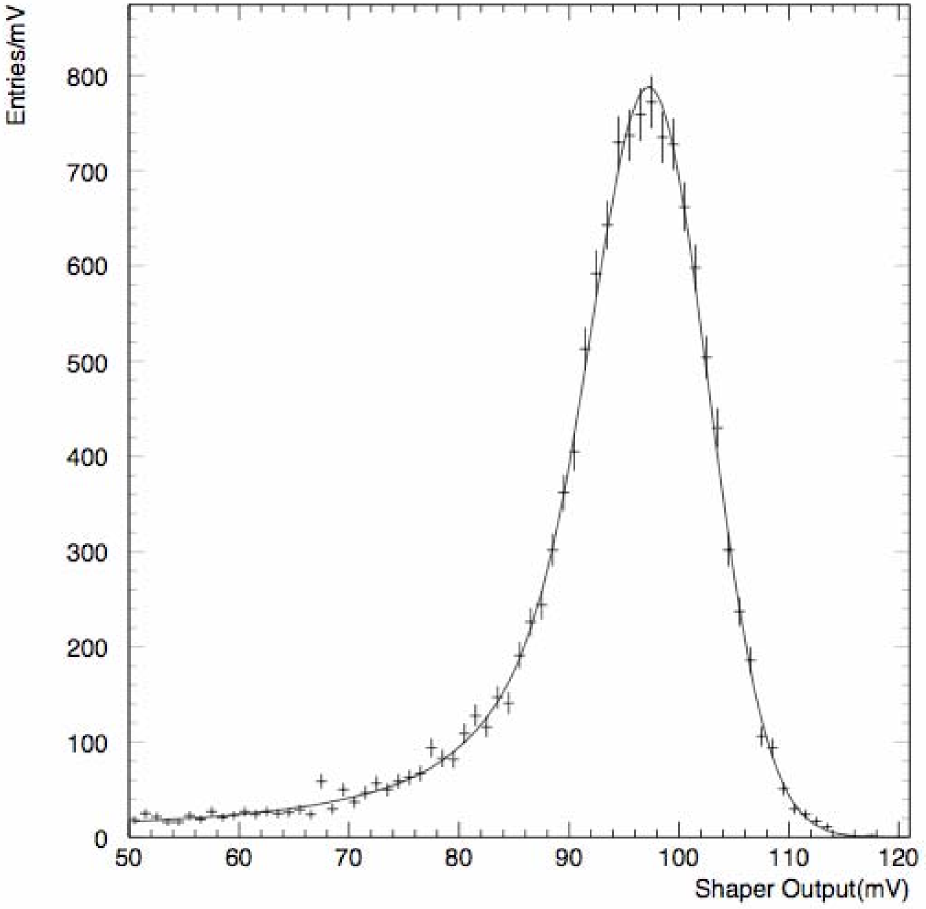
Electronics requirements

- Signals
  - <2000 e noise
  - Require MIPs with S/N > 7
  - Large dynamic range: Max. signal is ≈2500 MIPs (for 5mm pixels)
- Capacitance
  - Pixels: 5.7 pF
  - Traces: ~0.8 pF per pixel crossing
  - Crosstalk: 0.8 pF/Gain x Cin < 1%
- Resistance (traces)
  - 300 ohm max
- Power
  - If < 40 mW/wafer ⇒ allows passive cooling (as long as power is cycled off between bunch trains)
- Provide fully digitized, zero suppressed outputs of charge and bx time on one ASIC for every wafer.

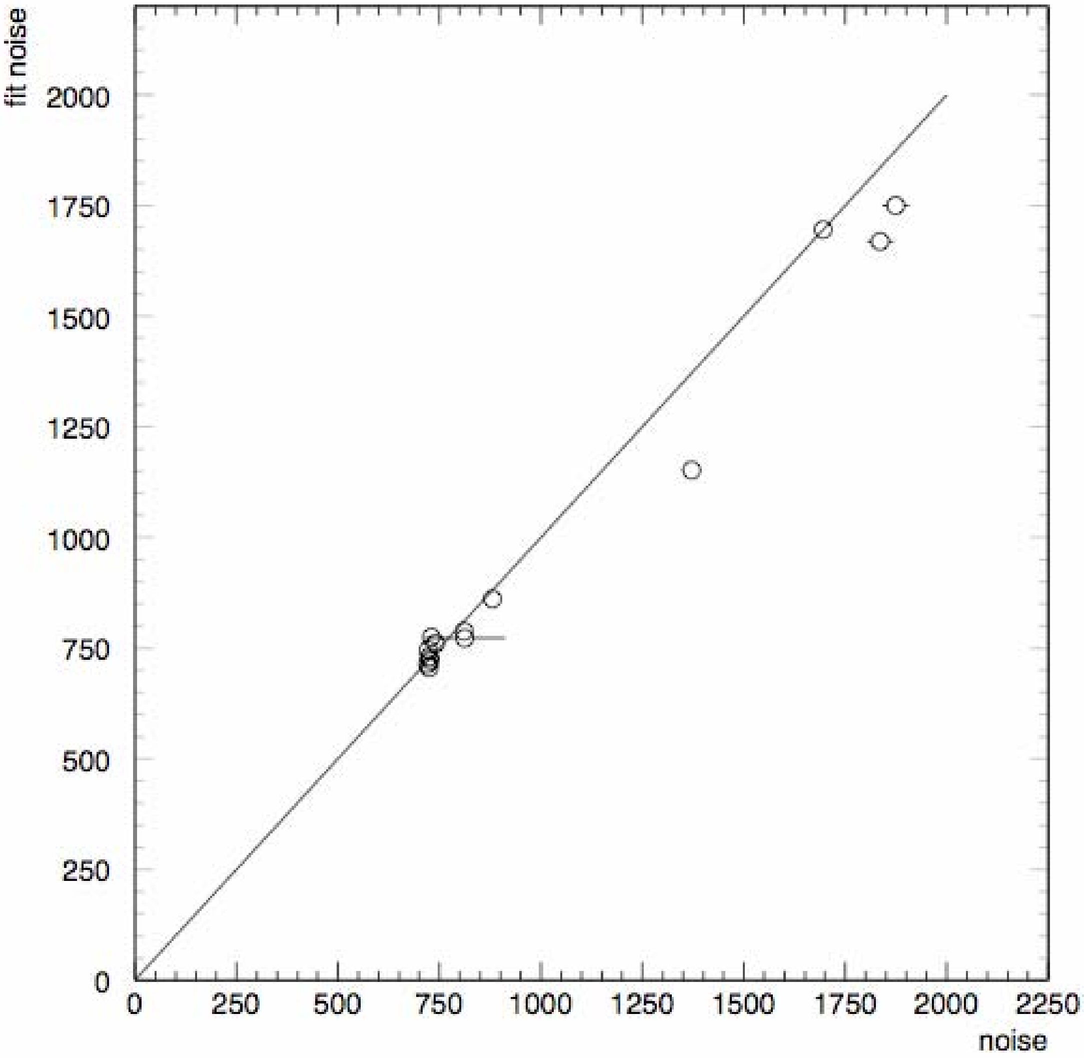
Use DC-coupled detectors: only two metal layers (cost)



Response of Detectors to 60KeV Gamma's from Am^{241}



Possible ~1% wafer-wafer calibration?

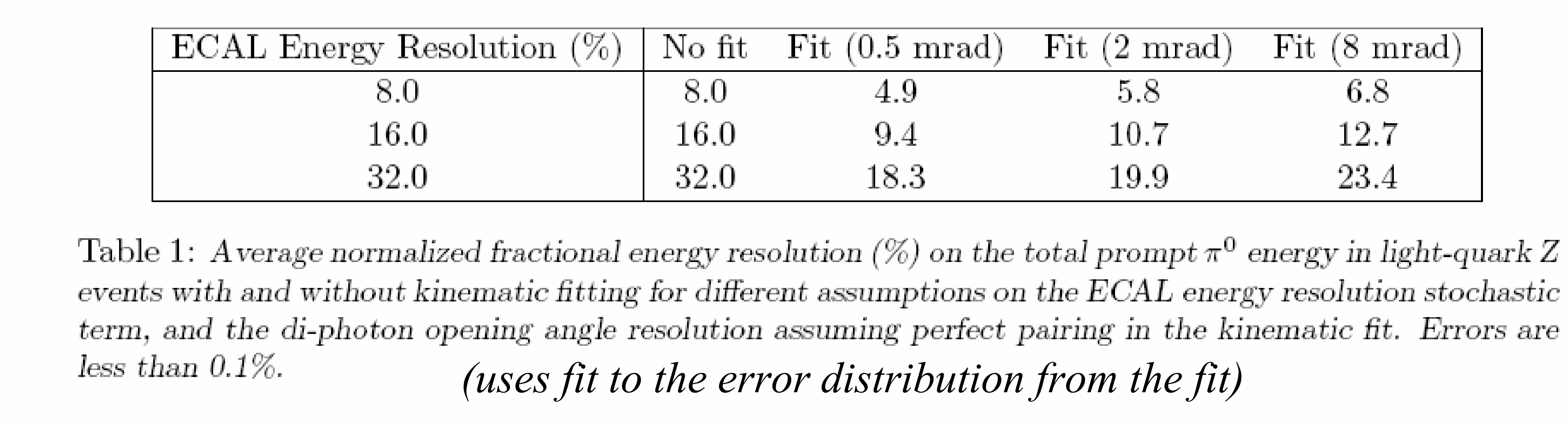


Noise is consistent with expectation from capacitance and series resistance

Backup Slide

Summary on potential of π^0 mass-constraint in hadronic events ($\sqrt{s}=m_Z$)

1. Perfect pairing



ECAL Energy Resolution (%)	No fit	Fit (0.5 mrad)	Fit (2 mrad)	Fit (8 mrad)
8.0	8.0	4.9	5.8	6.8
16.0	16.0	9.4	10.7	12.7
32.0	32.0	18.3	19.9	23.4

Table 1: *Average normalized fractional energy resolution (%) on the total prompt π^0 energy in light-quark Z events with and without kinematic fitting for different assumptions on the ECAL energy resolution stochastic term, and the di-photon opening angle resolution assuming perfect pairing in the kinematic fit. Errors are less than 0.1%.*

(uses fit to the error distribution from the fit)

2. Assignment algorithm 1.99

Using fitted σ of deviation on same 10k events	*7.9*	*6.0*	*6.8*	*7.5*
	15.7	**12.0**	*13.1*	*14.8*
	31.0	*24.9*	*26.1*	*28.7*