Scintillator-based Hadron Calorimetry for the ILC/SiD

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International Linear Collider Workshops
Snowmass, 14-27 Aug, 2005

Why (not) scintillators?

- Tested and true, well understood & optimized,
- New developments in cell fabrication & photo-detection help meet ILC/PFA demands
  - Fine segmentation at a reasonable cost
  - Photodetection and digitization inside detector $\Rightarrow$min. signal loss/distortion, superior hermeticity
- Can operate in both analog and digital modes
  - Measures energy, unlike RPC & GEM that only offer hit-counting ("tracking" or "imaging" calorimetry)
  - Remains a viable option if digital PFA fails to deliver.

Design Considerations: PFA

- Need $\lesssim$10 cm^2 lateral segmentation.
- At least ~35 layers and ~4λ must fit in ~1 m along R.
  - Min. R_{in} driven by tracker performance.
  - Max. R_{out} limited by magnet and material costs.
  - Min. absorber fraction limited by the need for shower containment.
- ⇒2 cm thick absorber layers if SS (less if W).
- ⇒0.6–0.8 cm sensitive layers must respond to MIPs with good efficiency and low noise.

(cont'd...)

Design Considerations: PFA

(…cont'd)

- Good lateral containment of showers is important for minimizing the confusion term.
- W absorber in ECal ⇒ e/π compensation is not built in ⇒ must be achieved in software ⇒ particle id (inside calorimeter by shower shape?) may be important.

Design Considerations: Others

- The technology must be
  - Reliable,
  - Mechanically sound,
  - Operable inside strong (~4.5T) magnetic field,
  - Capable of 15+ years of running,
  - Tolerant to ~5σ fluctuations in T, P, humidity, purity of gas (if any). Monitoring will be necessary if response depends strongly on any of these,
  - Suited for mass-production and assembly of millions of cells in ~40 layers, (cont'd…)

Design Considerations: Others

- The technology must be (…cont'd)
  - Allow hermetic construction (minimum cracks/gaps)
  - Safe (HV, gas, …),
  - Compatible with other subsystems (MDI?),
  - Amenable to periodic calibration,
  - Able to handle the rates (deadtime < 0.1 s?)
  - Cost-effective (including construction, electronics, operation).

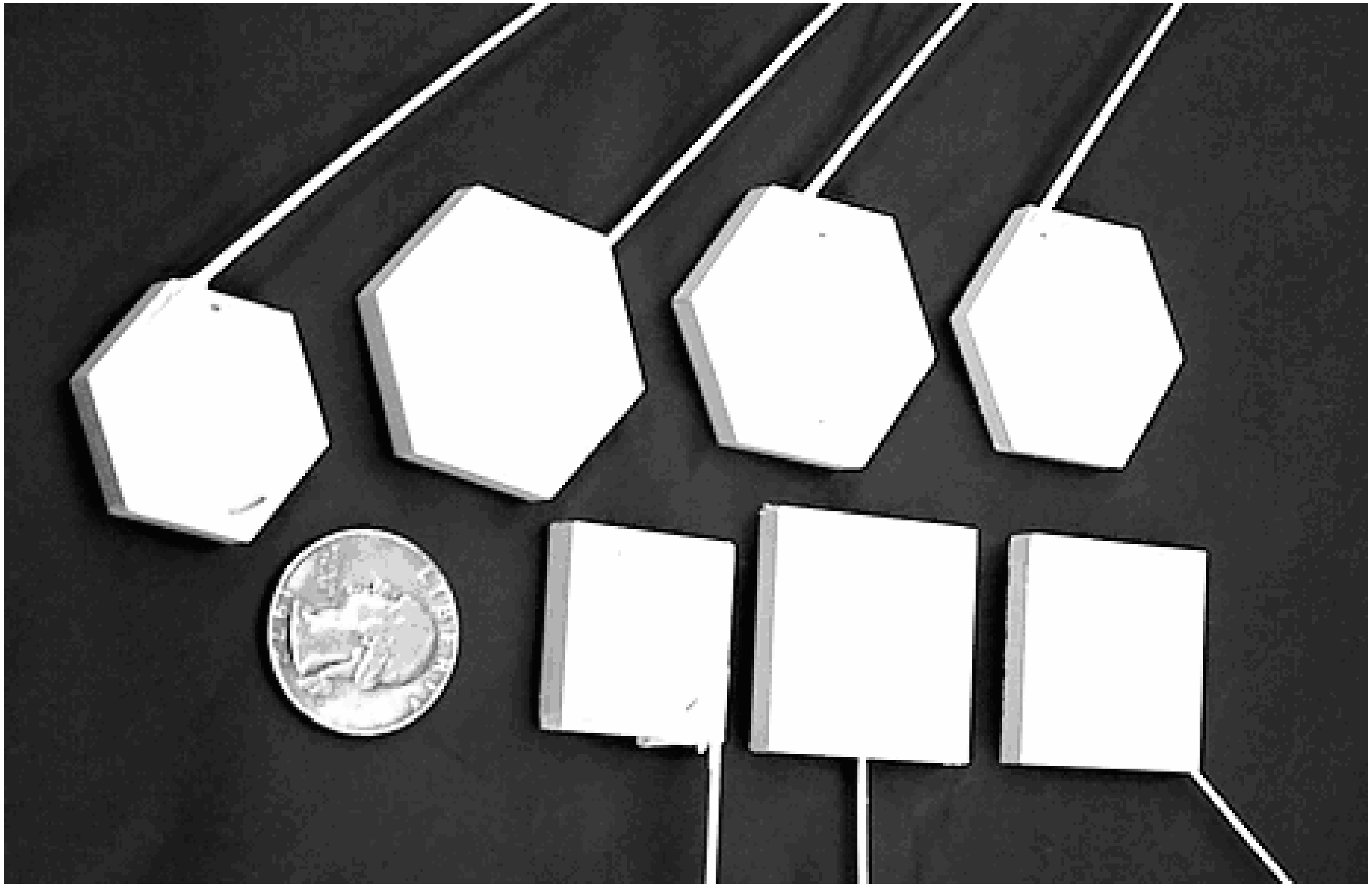
Hardware tests

Cells made of cast (Bicron) and extruded scintillators (NICADD/FNAL) have been extensively tested with many variations of

- Shape (hexagonal, square),
- Size, thickness
- Surface treatment (polishing, coating),
- Fibers (manufacturer, diameter, end-treatment)
- Grooves (σ– shaped, straight)
- Photodetectors (PMT, APD, SiPM, MRS)

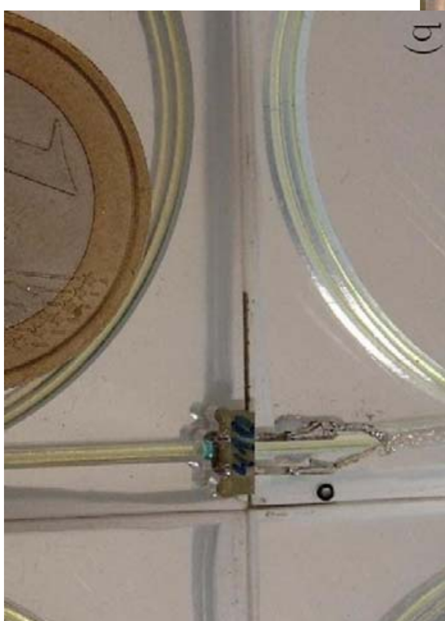
Hardware tests

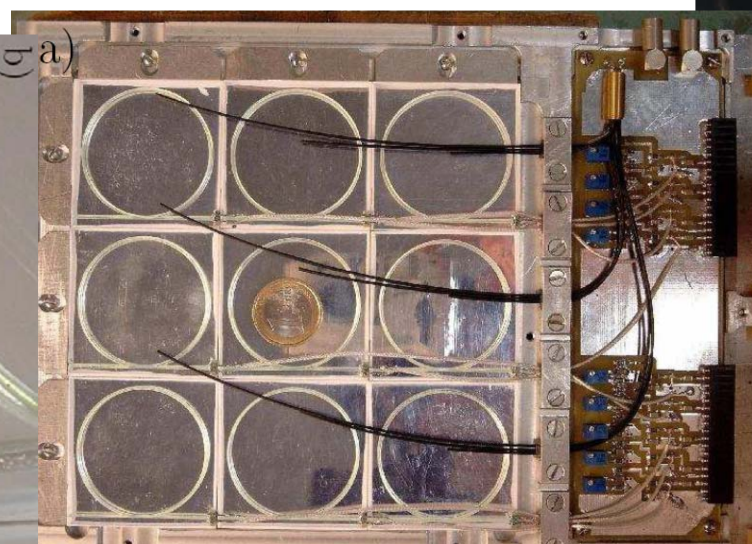
- Different cell and groove shapes with extruded and cast scintillators

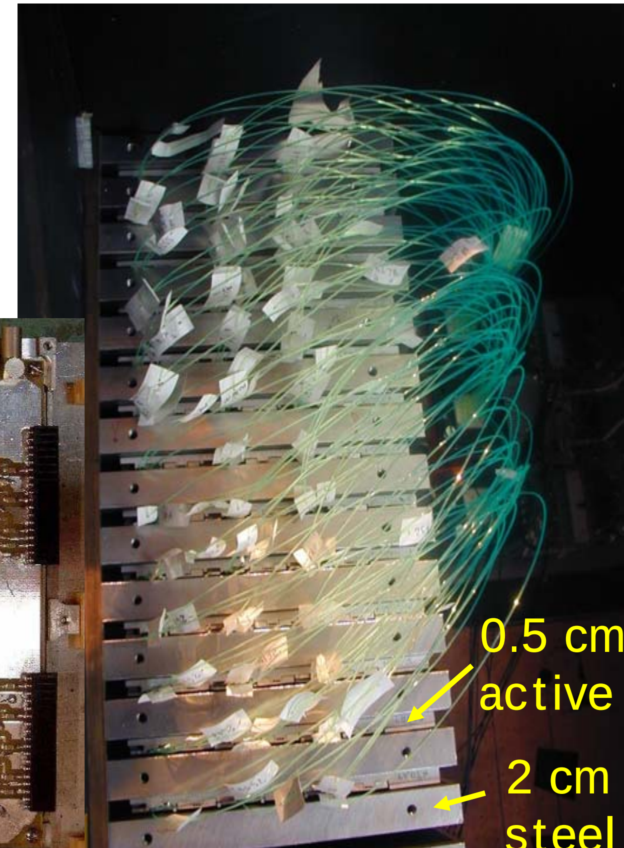


Hardware Prototypes (DESY “MiniCal”)

- DESY 6 GeV e beam 2003-2004
- 108 scintillator tiles (5x5cm)
- Readout with Silicon PMs on tile, APDs or PMTs via fibres



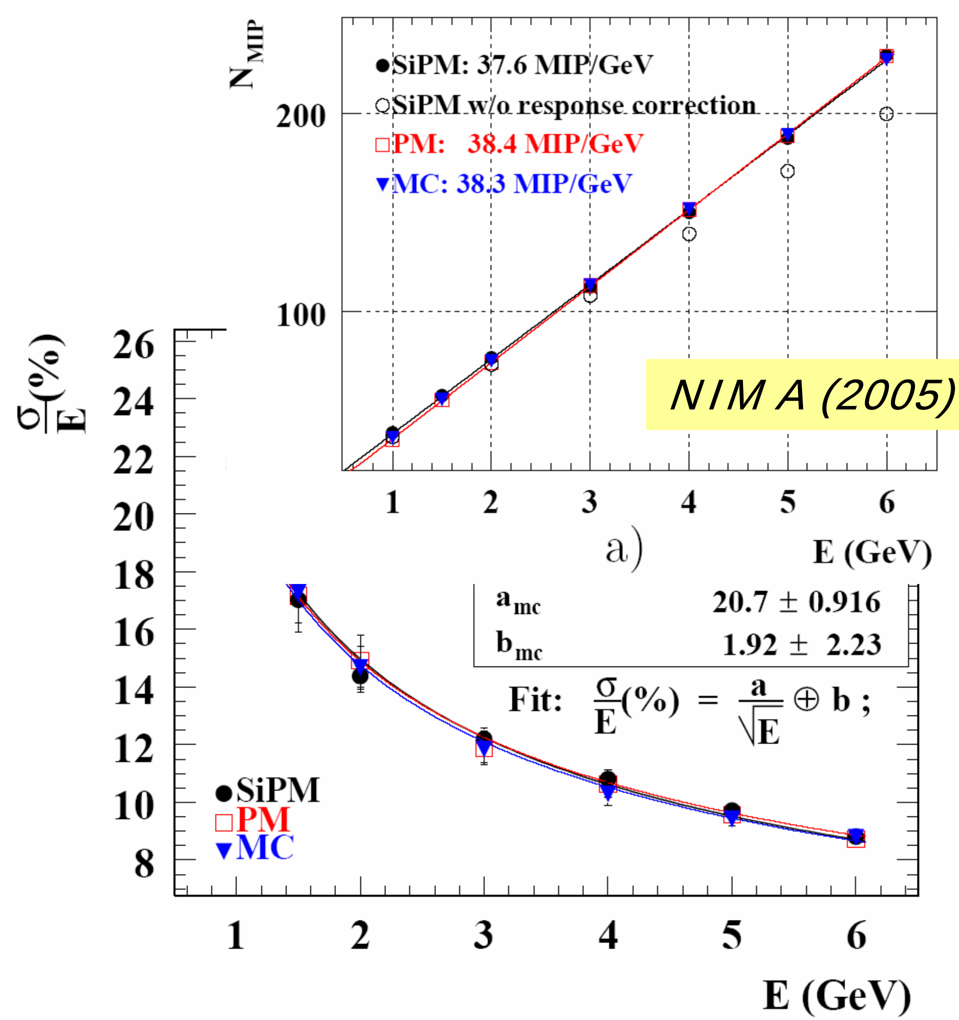




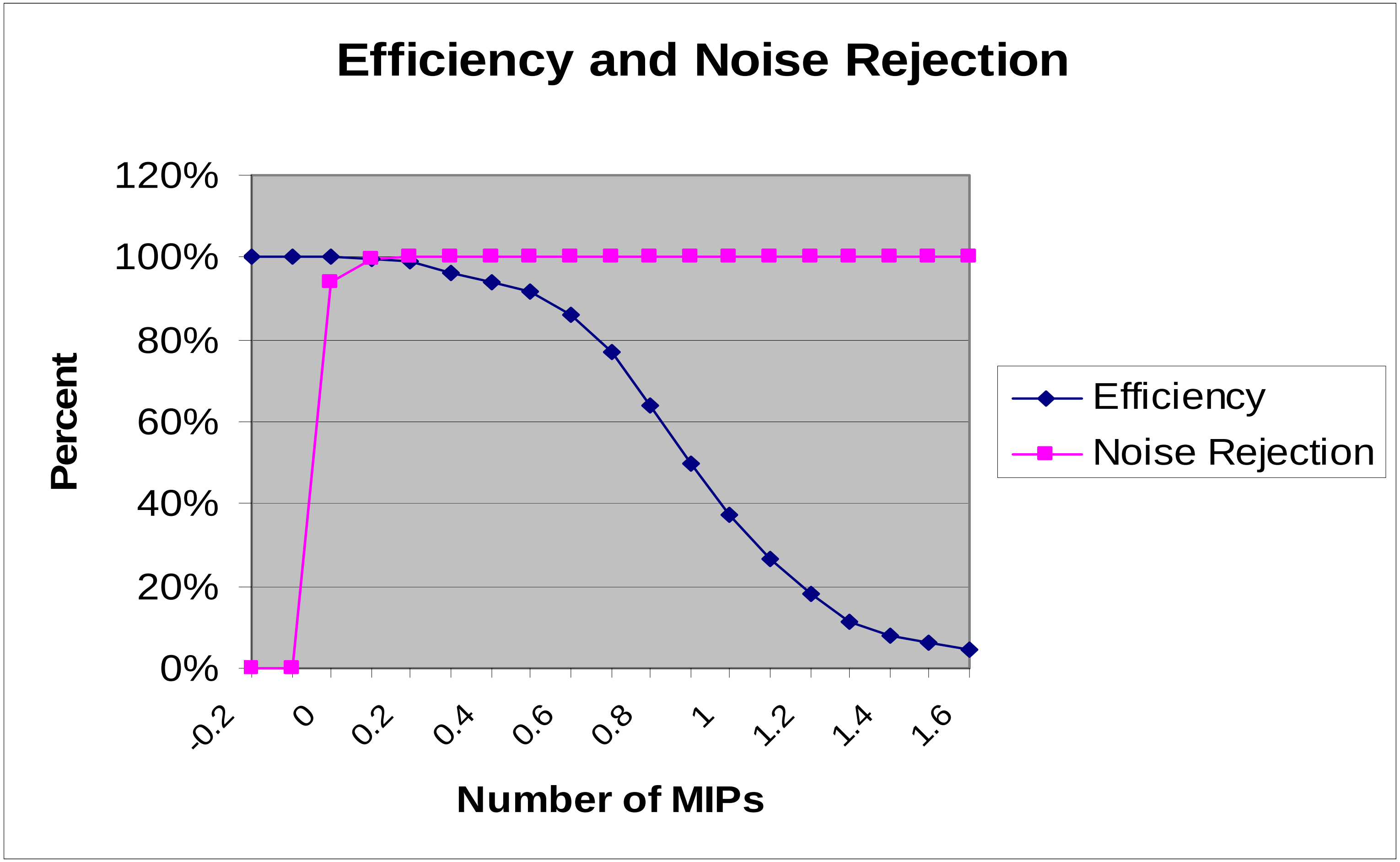
DESY, Hamburg U, ITEP, LPI, MEPHI, Prague

DESY "MiniCal" Test Beam results

- Resolution as good as with PM or APD*
- Non-linearity can be corrected (at tile level)
  - Does not deteriorate resolution
  - Need to observe single photon signals for calibration
- Well understood in MC
- Stability not yet challenged



Choosing the Optimum Threshold



0.25 MIP threshold: efficient, quiet

Miscellaneous Measurements

Response ratios between types, glues, fibers,…

- Scintillator type: extruded/cast ≈ 0.7
- Optical glue: EJ500/BC600 ≈ 1.0
- Fiber: Y11/BCF92 ≈ 3.2
  - Y11 = 1 mm round Kuraray,
  - BCF92 = 0.8 mm square Bicron

Extruded/cast (cost) ≈ 0.05

Optimum parameters

- Shape: Hexagonal or Square
- Thickness: 5 mm
- Lateral area: 4 – 9 cm^2
- Groove: straight
- Fiber: Kuraray 1 mm round (or similar)
- Fiber glued, surface painted
- Scintillator type: Extruded

Based on what we have learnt so far

But a bigger question is the photodetector:

PMTs are costly, bulky, won't operate in B field.

We have been investigating APDs, MRS, Si-PM…

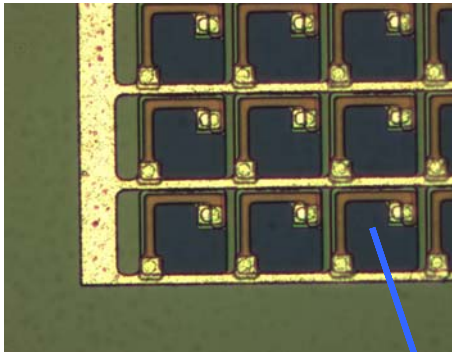
The Metal/Resistor/ Semiconductor Photodiode (MRS)

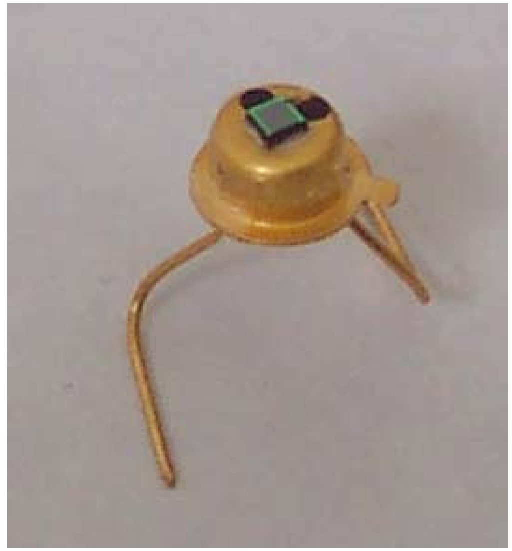
- From the Center of Perspective Technologies & Apparatus (CPTA),
- Multi-pixel APDs with every pixel operating in the limited Geiger multiplication mode & sensitive to single photon,
- 1000+ pixels on 1 mm x 1 mm sensor,
- Avalanche quenching achieved by resistive layer on sensor,
- Detective QE of up to 25% at 500 nm,
- Good linearity (within 5% up to 2200 photons)
- Immune to magnetic field,
- Radiation-tolerant.

Study of MRS/SiPM

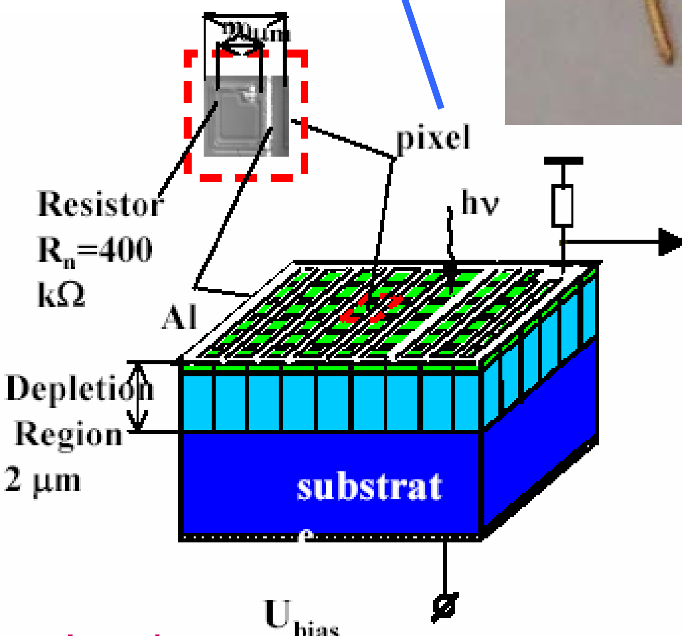
- Determination of Working point:
  - bias voltage,
  - threshold,
  - temperature
- Linearity of response
- Stress tests: magnetic field, exposure to radiation.
- Tests with scintillator using cosmic rays and radioactive source.

Metal Resistive Semiconductors (MRS)

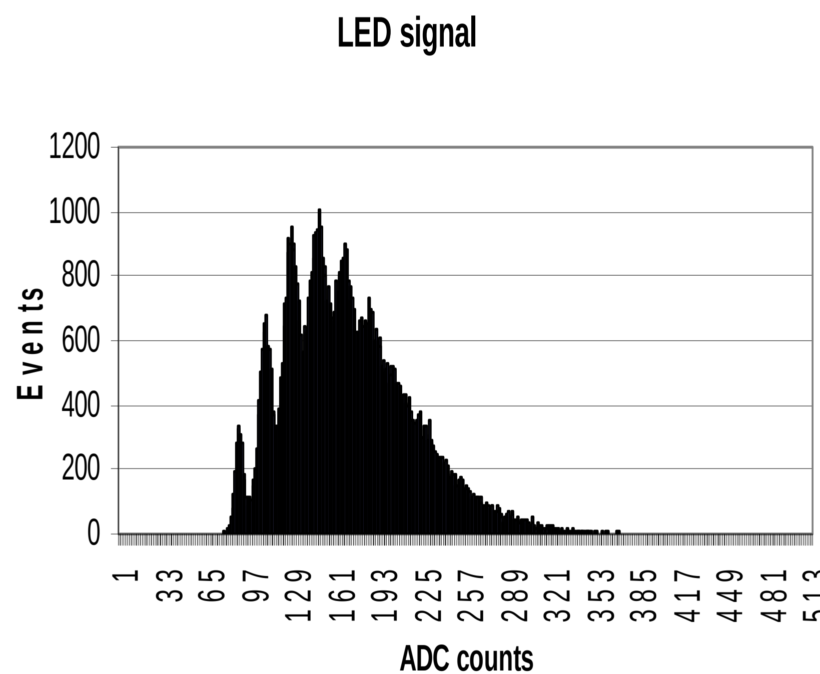




Poduced by the
Center of Perspective
Technologies &
Apparatus (CPTA)



Typical pulseheight spectrum



B. Dolgoshein

SiPM Summary

We have conducted a set of measurements to illustrate the potential use of Si photodetectors in High Energy Collider experiments in general, and for hadron calorimetry at the ILC in particular.

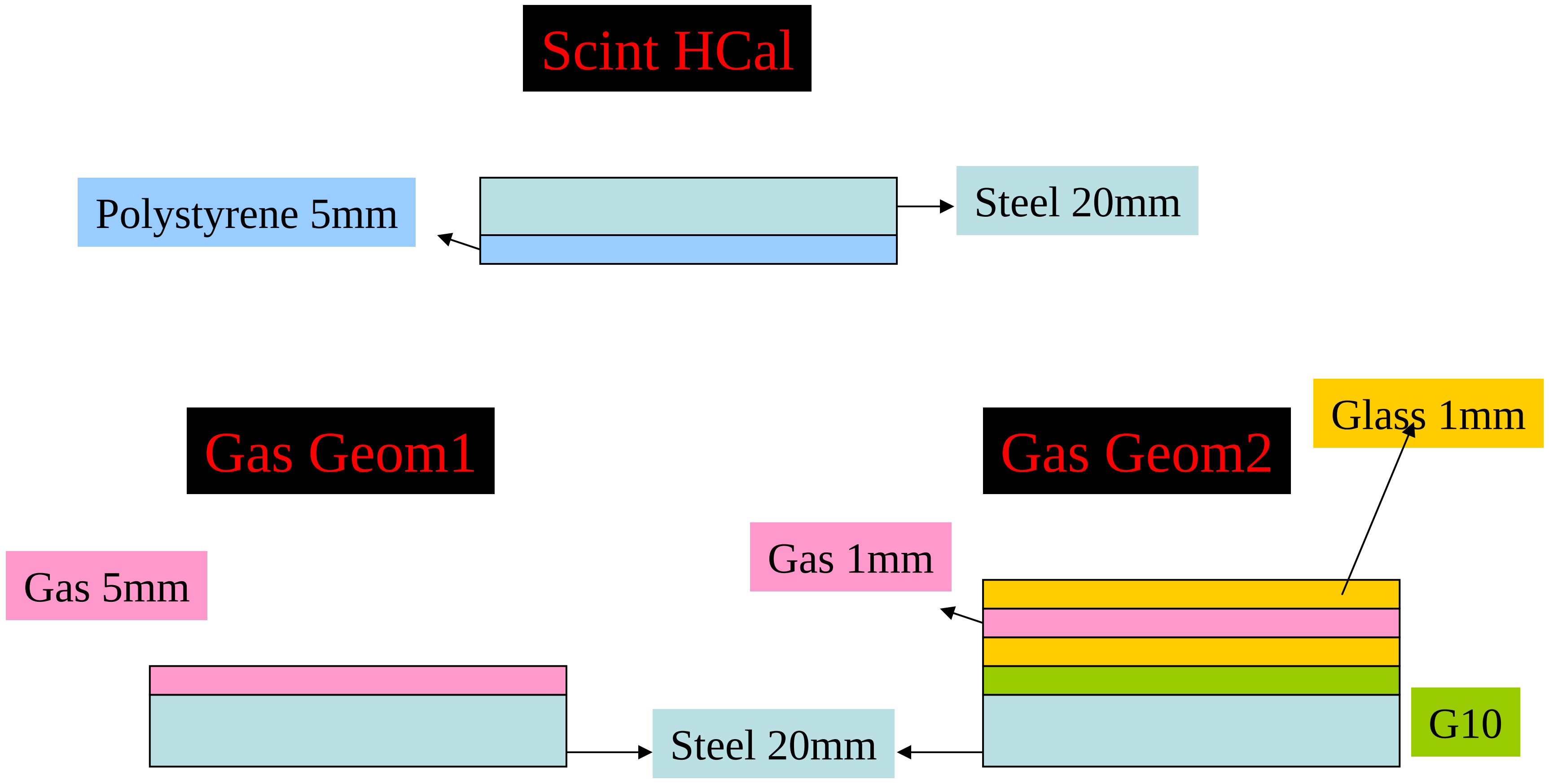
- Good MIP sensitivity, strong signal (gain ~O(10^6)),
- Fast: Rise time $\approx$ 8 ns, Fall time $<$ 50 ns, FWHM $\approx$ 12 ns (w/ amp)
- Very compact, simple operation (HV, T, B,...),
- Each sensor requires determination of optimal working point,
- Noise is dominated by single photoelectron: a threshold to reject 1 PE reduces the noise by a factor of ~2500,
- The devices operate satisfactorily at room temperature (~22 $^\circ$C). Cooling reduces noise and improves gain,
- Not affected by magnetic field (tested in up to 4.4 T + quench),
- No deterioration of performance from 1 Mrad of γ irradiation.

SiPM prospects on the horizon

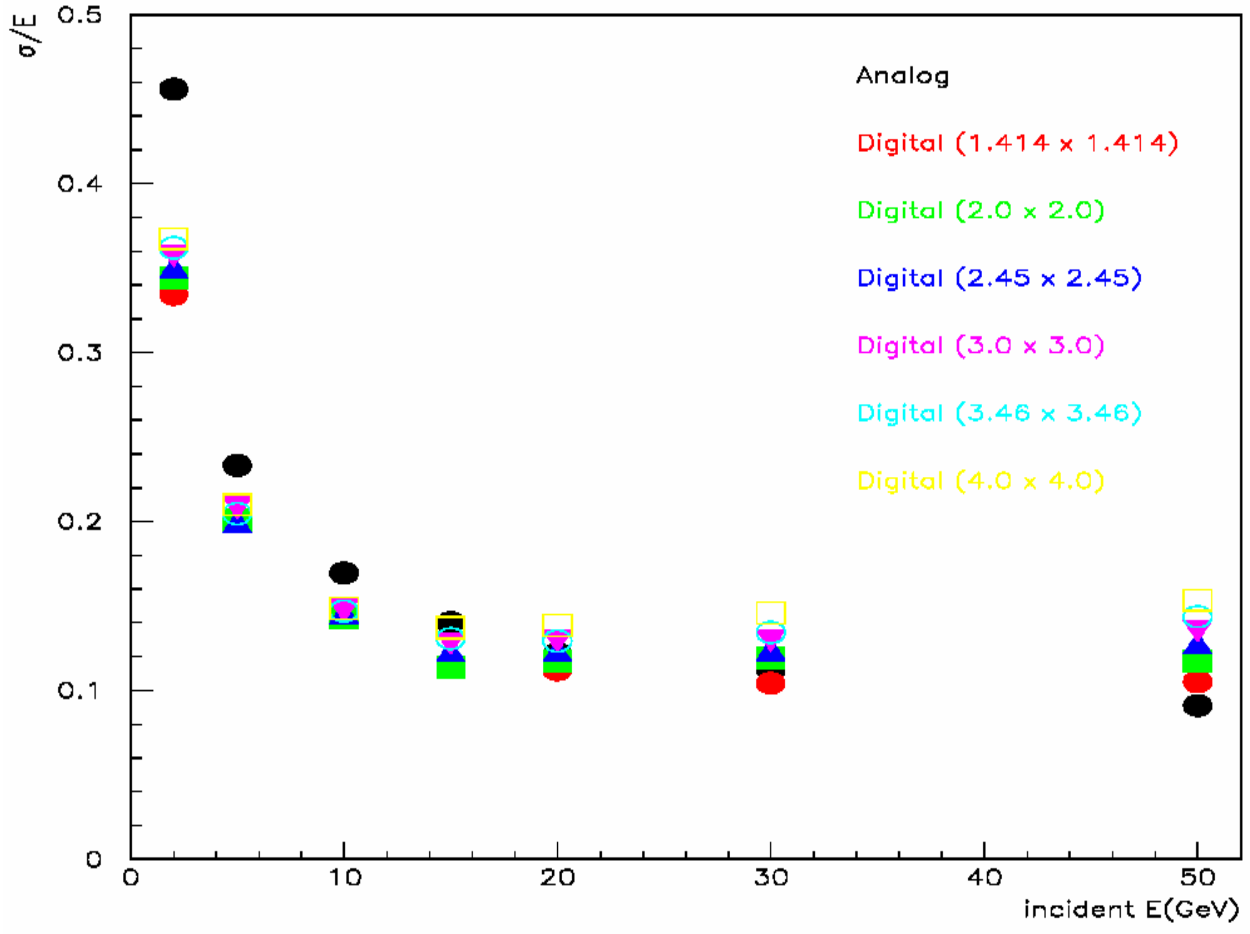
- Bigger SiPMs are under development
  - 3mm x 3mm made, but require cooling to −40 C
  - 5mm x 5mm thought possible
  - cost increase: insignificant (CPTA), linear (H’matsu)?
- 5mm x 5mm may help us eliminate fibers
  - put the SiPM directly on the cells
  - wavelength matching by n−on−p (sensitive to blue scint. light) or WLS film
  - hugely simplifies assembly
- Better uniformity across sample with purer Si.

Simulation Studies

Geometries considered



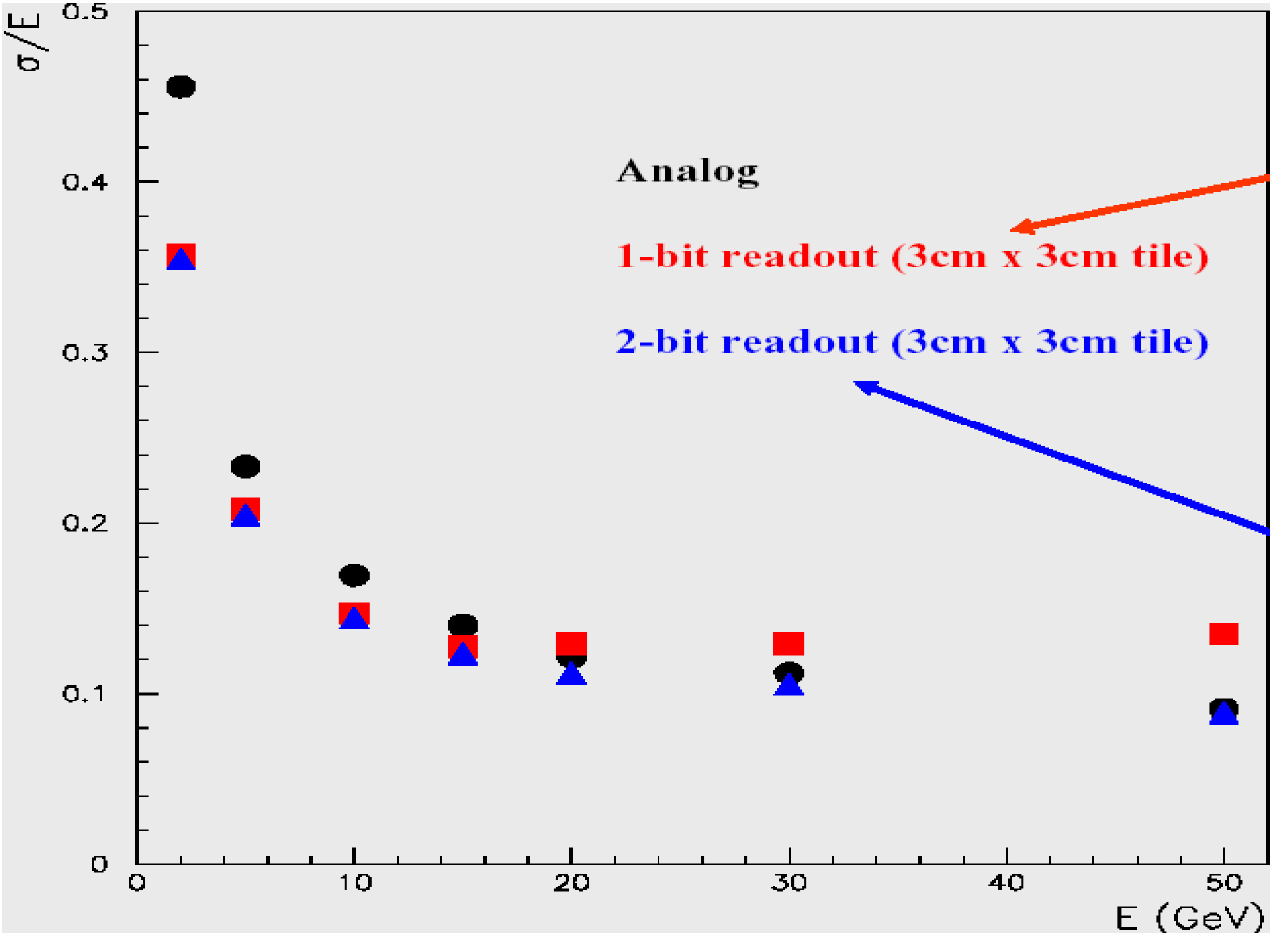
π^+ energy resolution as function of energy for different (linear) cell sizes



Compensation

- Cell counting has its own version of the compensation problem (in scintillators).
- With multiple thresholds this can be overcome by weighting cells differently (according to the thresholds they passed).
- In MC, 3 thresholds seem to be adequate.

π^+ energy resolution vs. energy



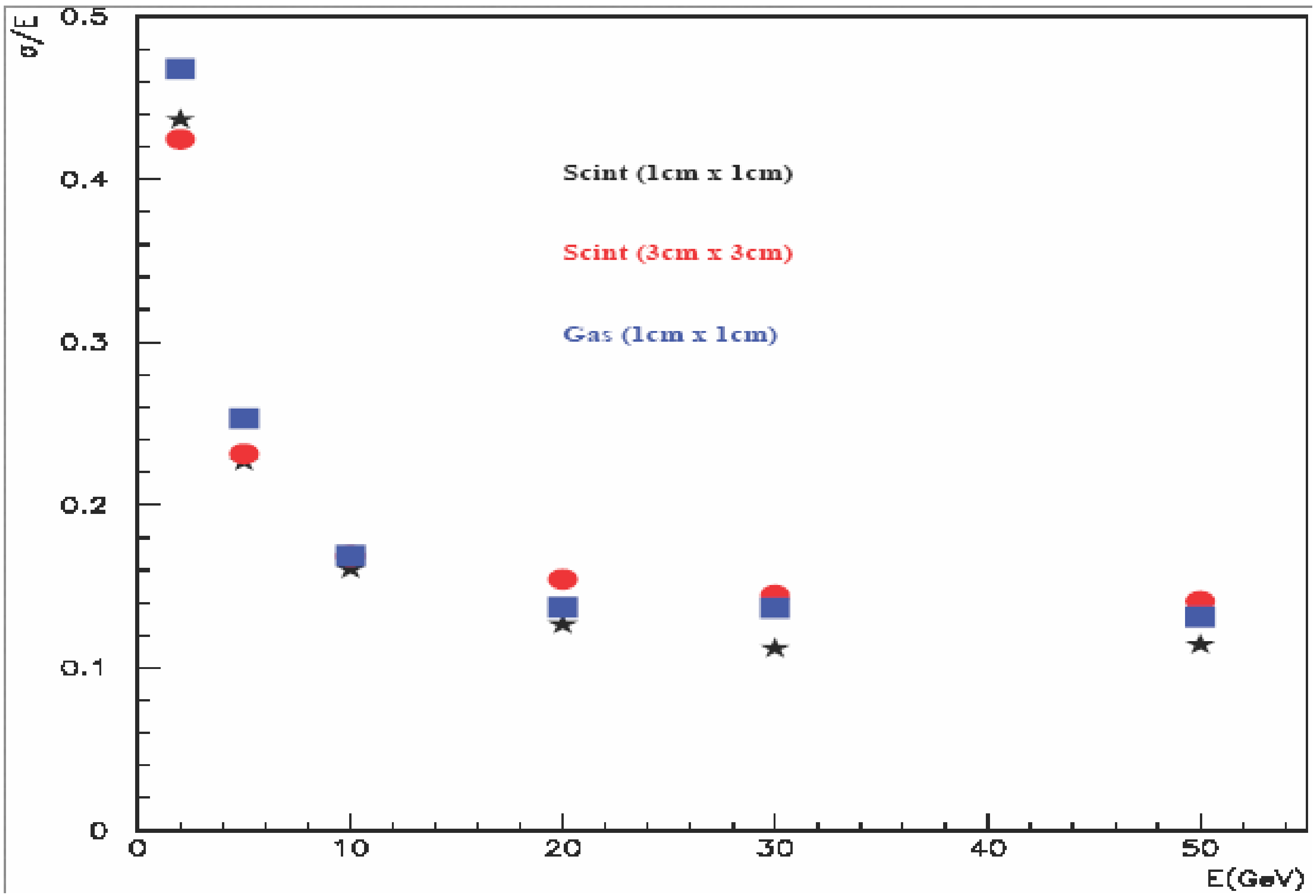
Two-bit ("semi-digital") rendition offers better resolution than analog

Nhit vs. fraction of π^+ E in cells with E>10 MIP: Gas vs. scintillator

2-bit readout affords significant resolution improvement over 1-bit for scintillator, but not for gas

π^+ energy resolution vs. energy

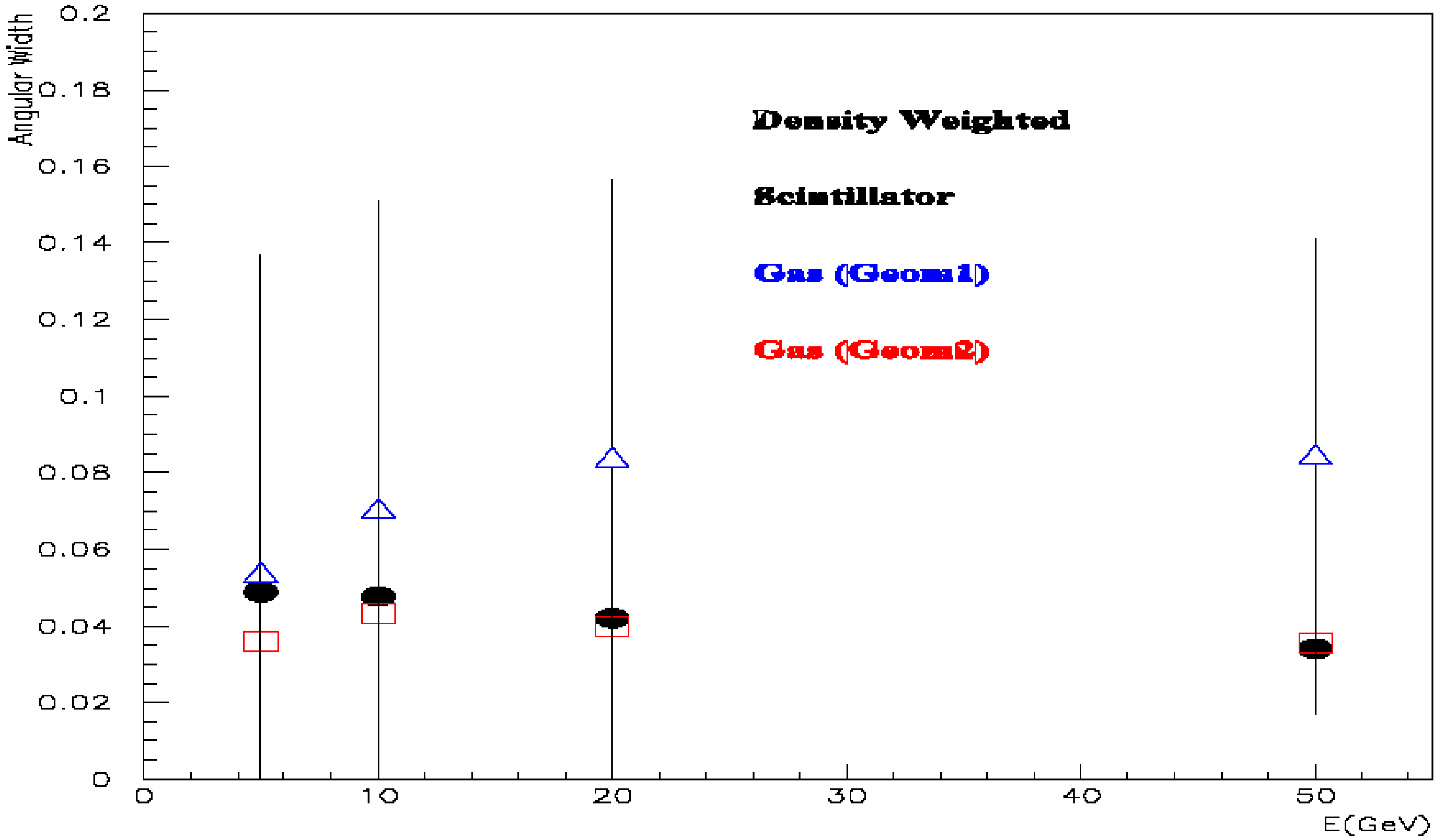
Multiple thresholds not used



Non-linearity

- Nhit/GeV varies with energy.
- This will introduce additional pressure on the "constant" term.
- For scintillator, the non-linearity can be effectively removed by "semi-digital" treatment.

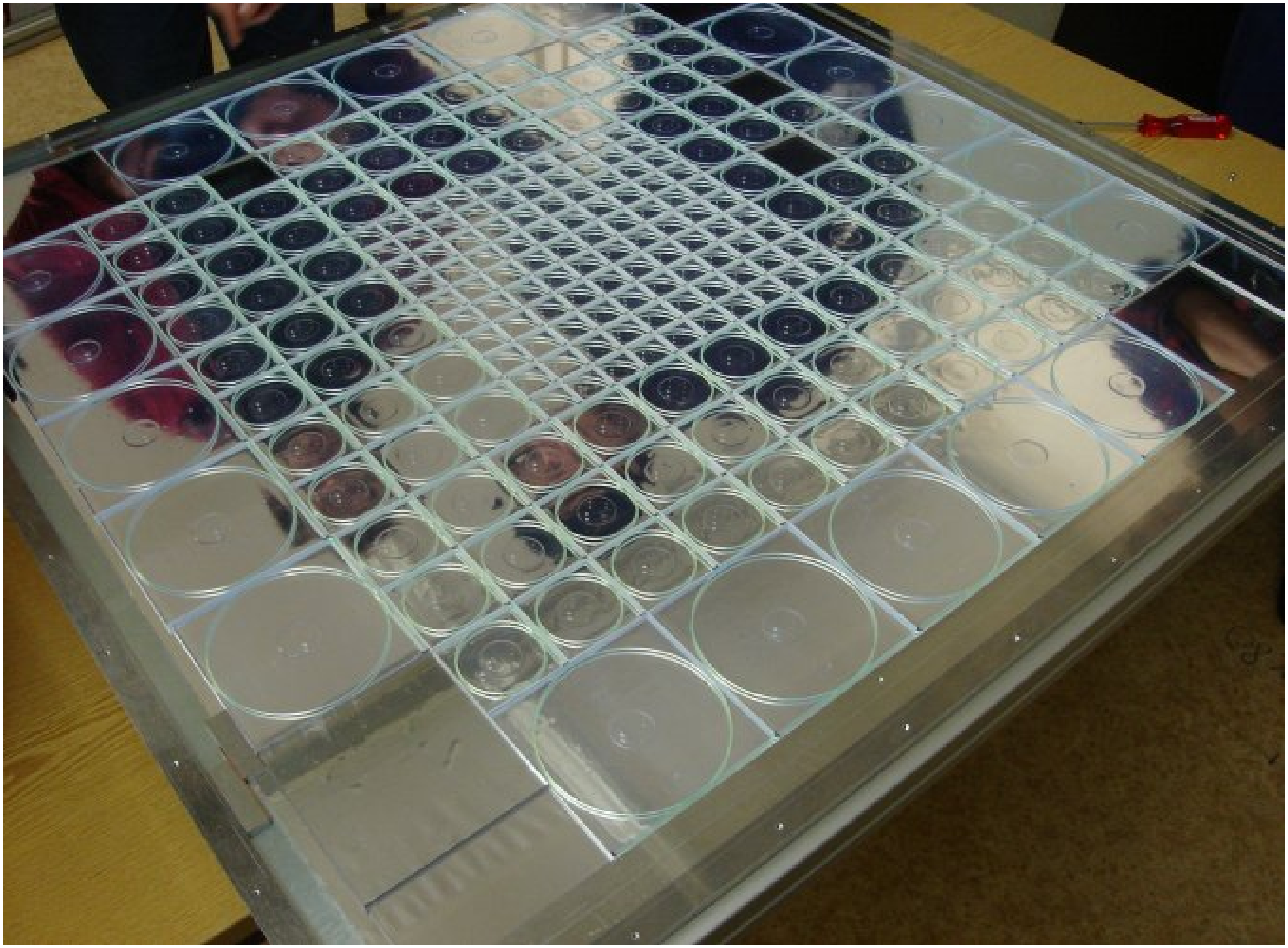
$\pi^{\pm}$ angular width: density weighted



Simulation Summary

- Large parameter space in the nbit–segmentation–medium plane for hadron calorimetry. Optimization through cost–benefit analysis?
- Scintillator and Gas–based ‘digital’ HCals behave differently.
- Need to simulate detector effects (noise, x–talk, non–linearities, etc.)
- Need verification in test–beam data.
- More studies underway.

TB: Scint HCal layer assembly



Summary

- Simulations indicate (semi-) digital approach to be competitive with analog calorimetry
- Prototypes indicate scintillator offers sufficient sensitivity (light x efficiency) & uniformity.
- Now optimizing materials & construction to minimize cost with required sensitivity.
- SiPM and MRS photodetectors look very promising.
- Preparations for Test Beam (Analog tile HCal and Strip tail-catcher/muon tracker) are in full swing.

All-in-all scint looks like a competitive option.

We are moving toward the next prototype.

Thank you!

For further details, see talks given by DC at

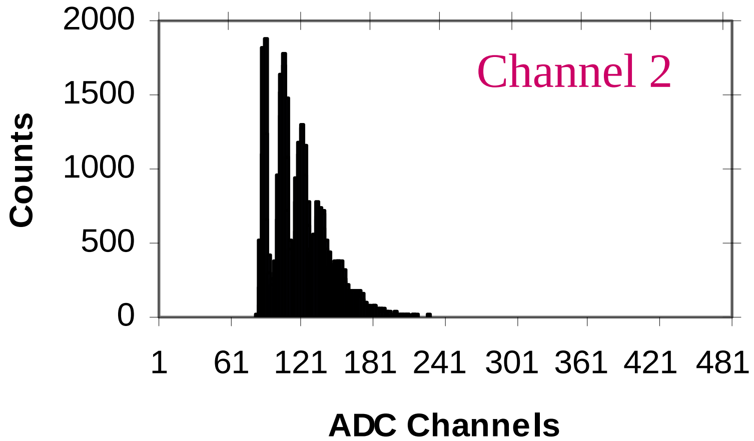
- The LC study group mtg on 26 May ’05,
- The Beaune Photodetection Conference, 19–24 June ’05.

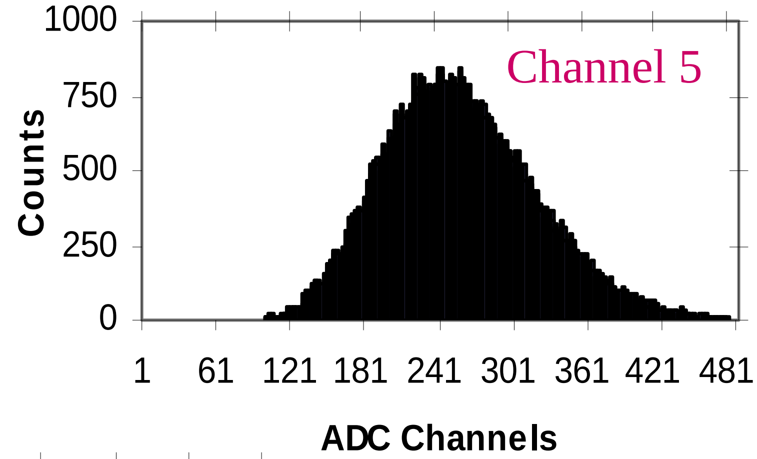
Links at

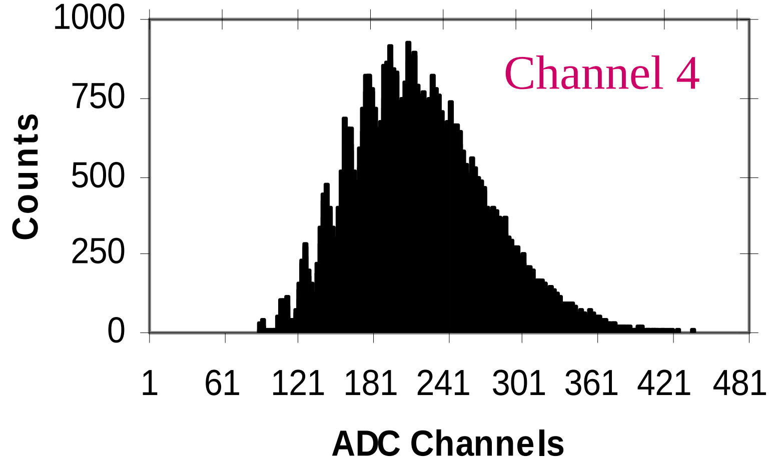
http://www.fnal.gov/~dhiman/talks.html

Backup slides

Working point determination with LED



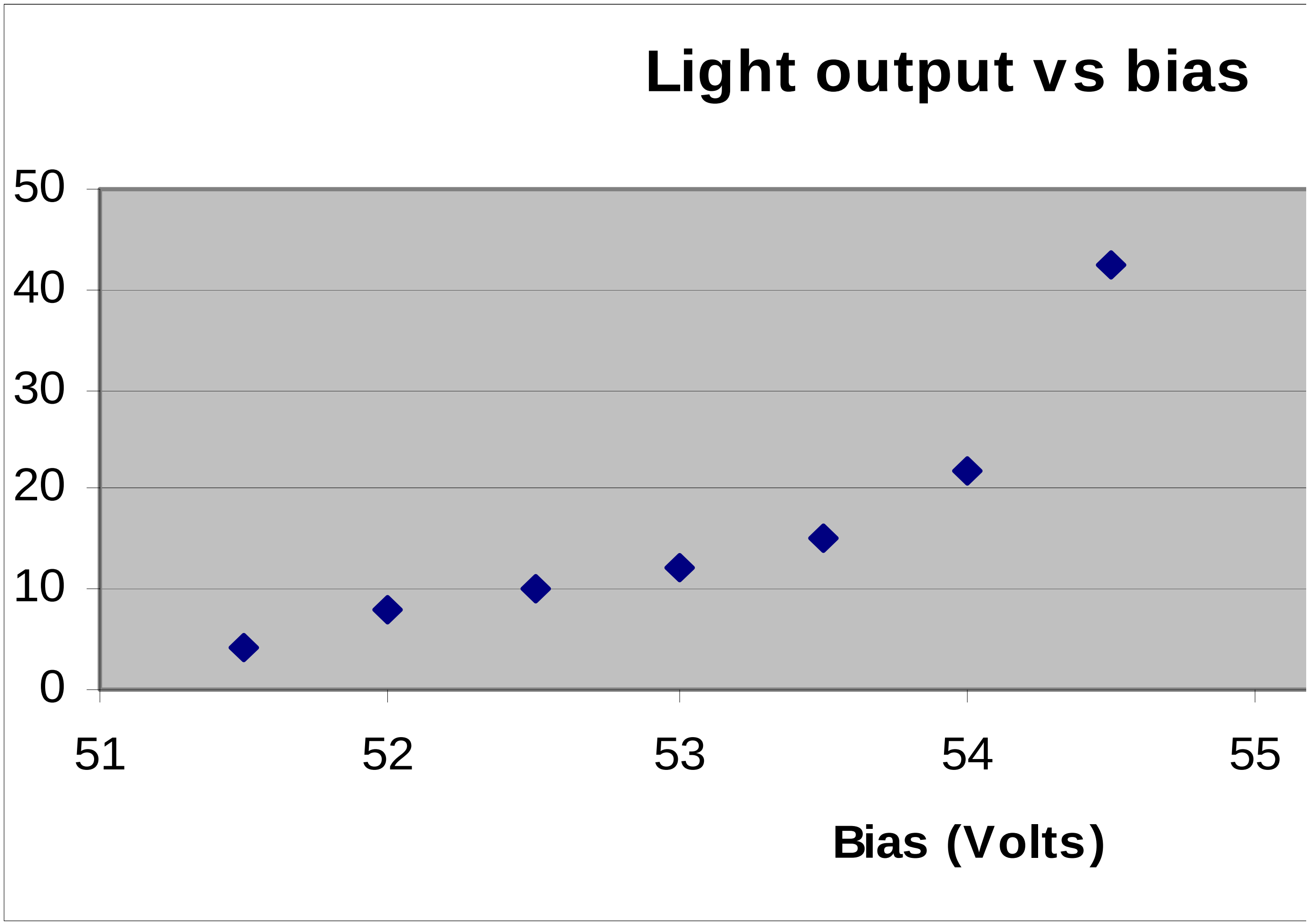




- The MRS is to able to separate single photoelectrons
- Different response under identical setup

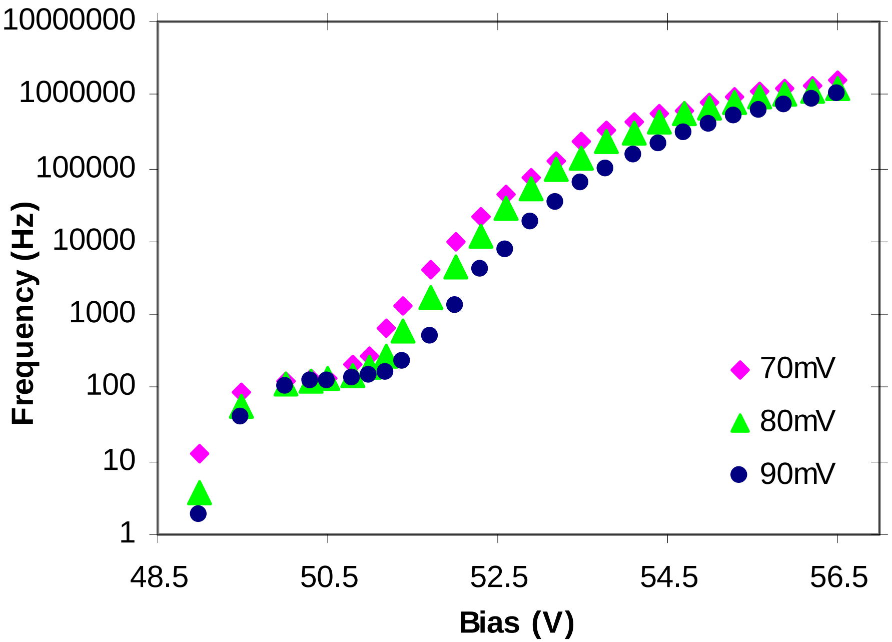
⇒ working point must be determined for each channel individually

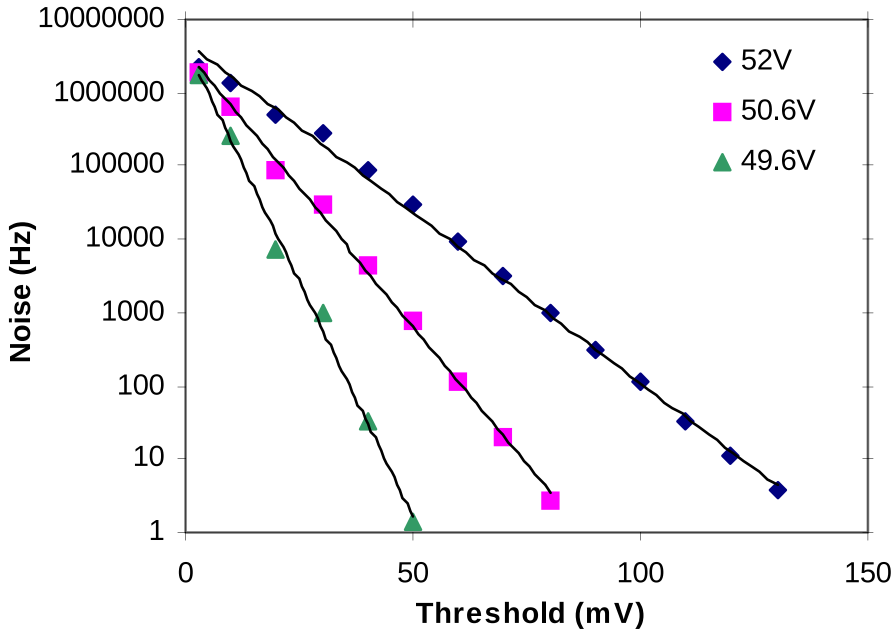
Cosmic MIP detection with SiPM



Comparable to PMT

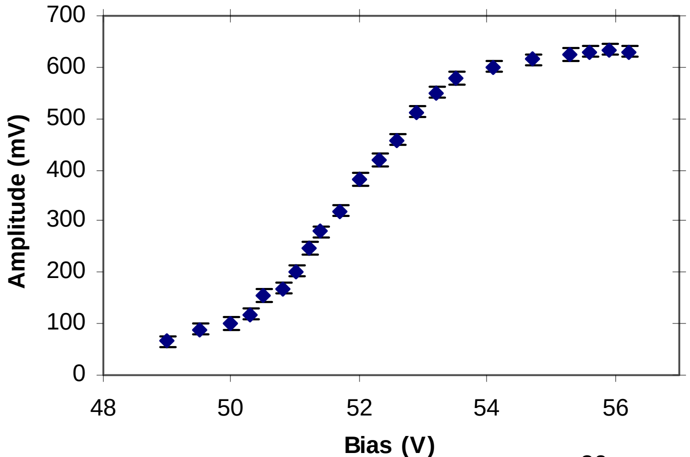
Noise Rate vs. Bias Voltage & Threshold

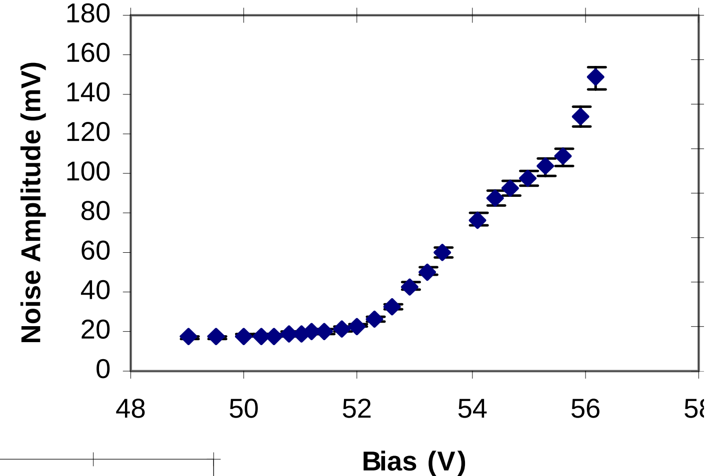


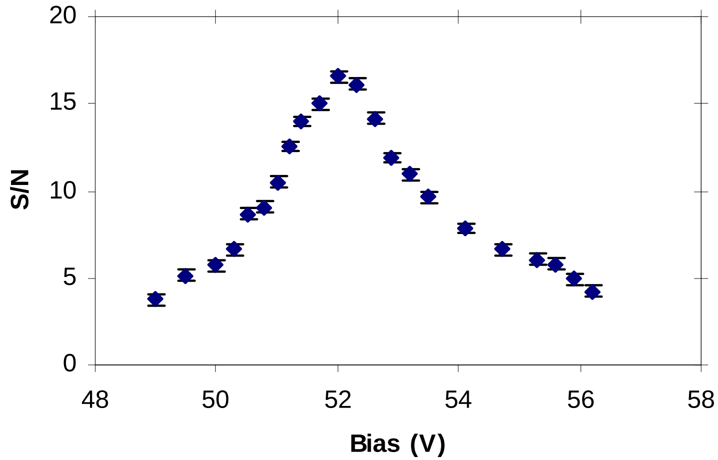


- The right end of the plateau region in the Figure on left is optimal for our purpose.
- For thresholds in the range of 80±10 mV and bias voltage in 50.0±0.5 V, the dark noise is well under control.

Signal & Noise Amplitudes vs. Bias Voltage

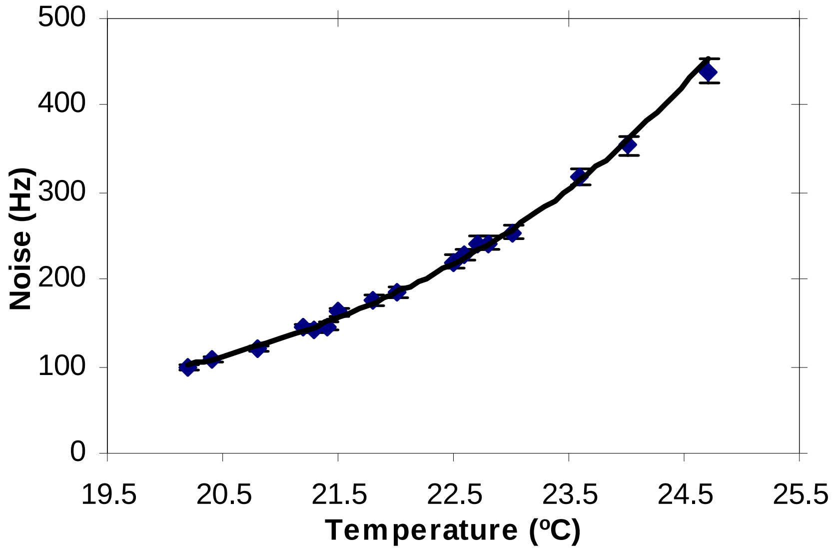


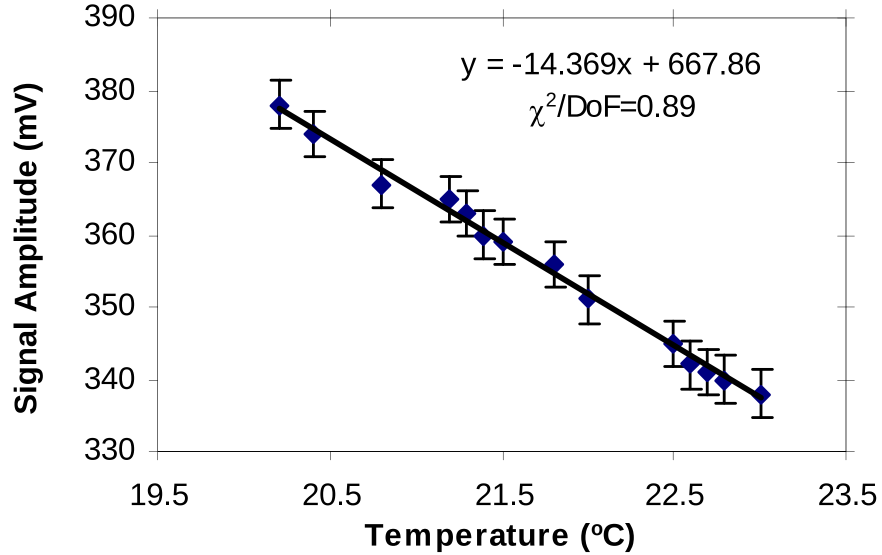




- For this particular device S/N peaks at $V_{bias} \approx 52$ V
- Sharp peaking in S/N⇒ working point must be found for each piece.

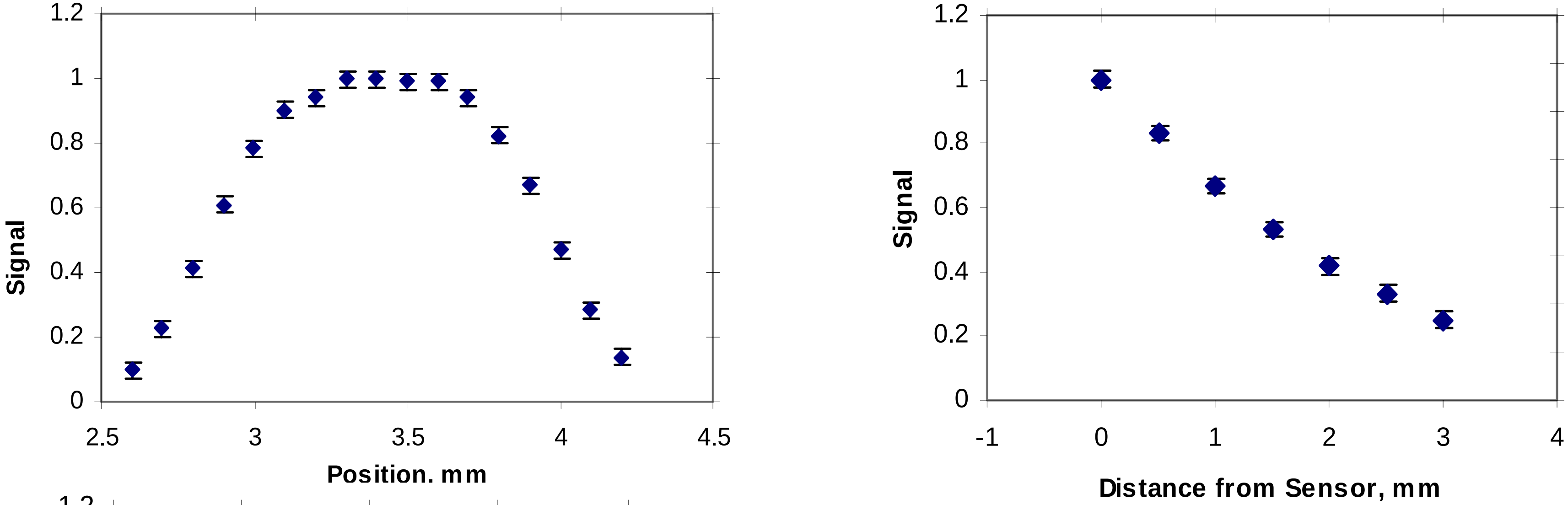
Temperature Dependence

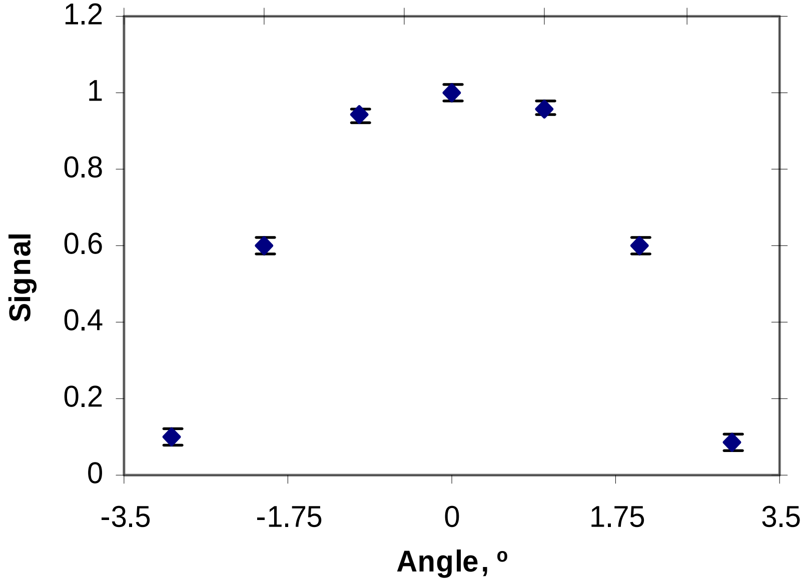




- Bias = 51.3 mV, threshold = 80 mV
- Loss in signal amplitude with increase in T ≈ 3.5%/ °C

Fiber Positioning on MRS





Optimal fiber-sensor mating is crucial.

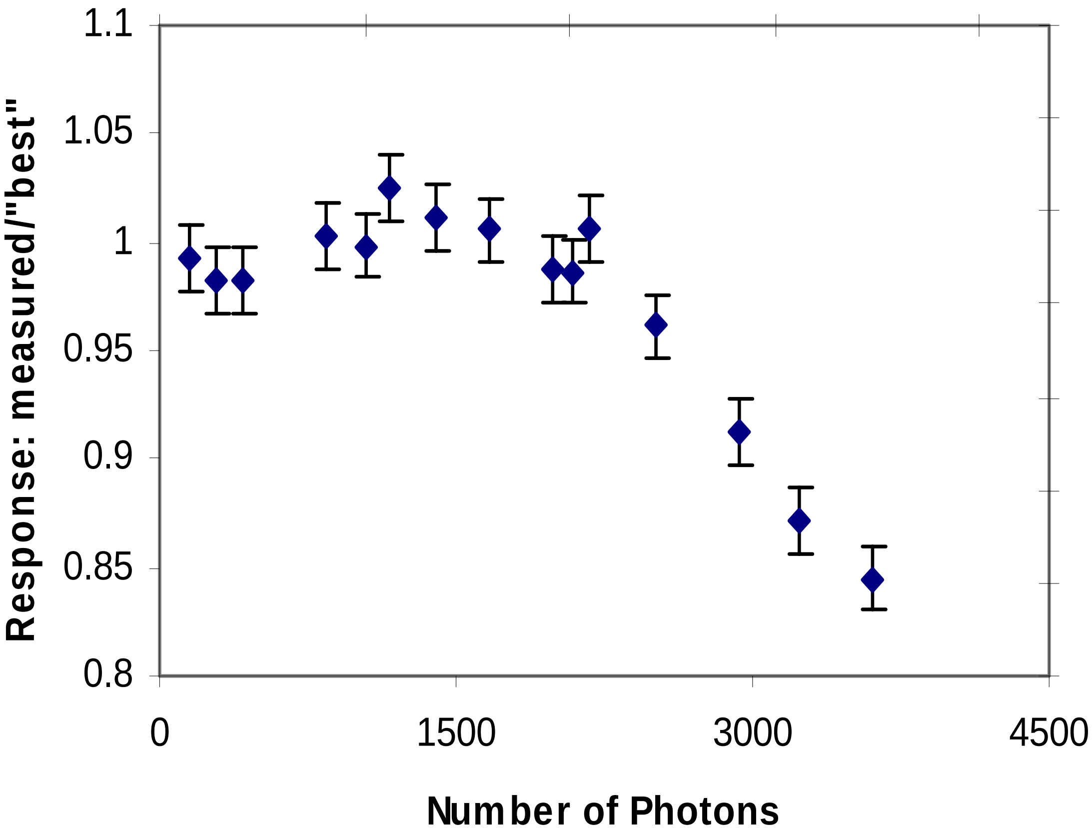
Linearity of Response

Since the response of an individual pixel is not proportional to n_γ, (unless it has had time in between to recover), non-linearity is expected when the detector receives a large number of photons.

Deviation reaches 5% (10%) at $n_\gamma \approx 2200$ (3000) or, $n_{PE} \approx 550$ (750).

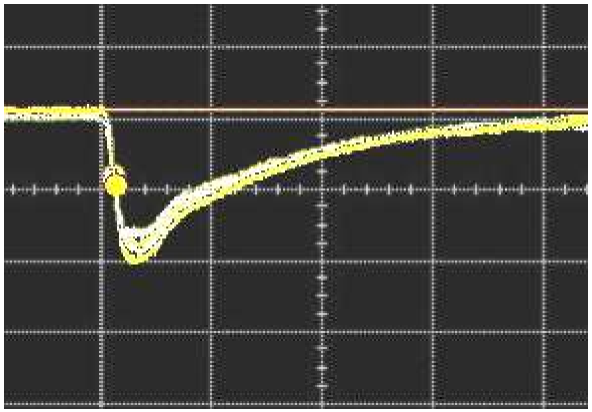
One MIP ≈17 PE

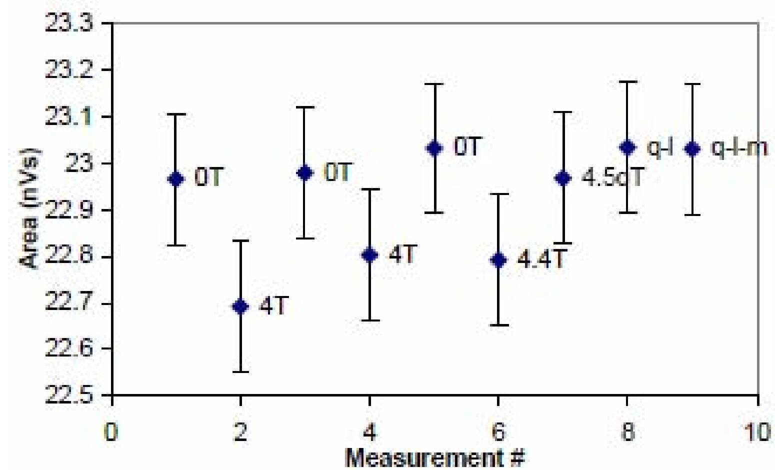
⇒ up to 32 MIPs can be measured within 5% linearity.

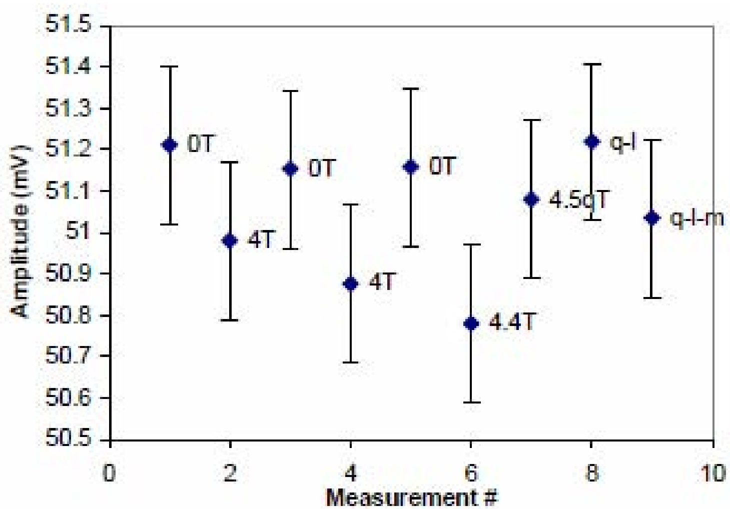


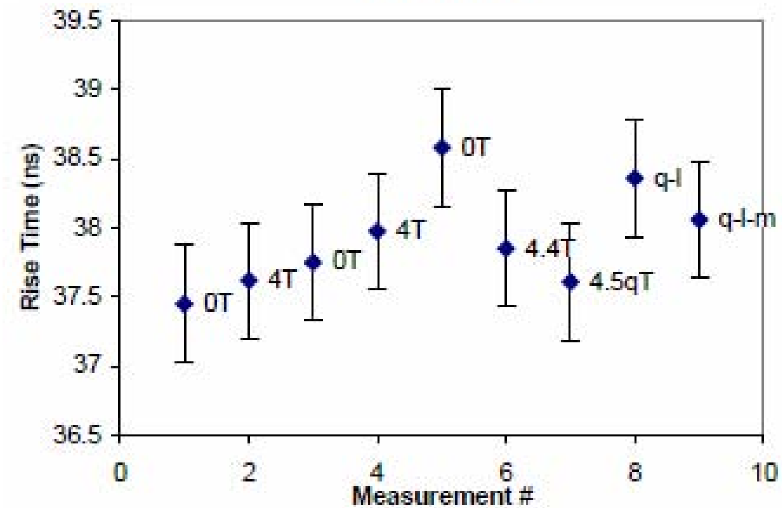
Stress Tests: Effect of Mag. field

No significant effect of fields up to 4.4 T and quenching at 4.5T:



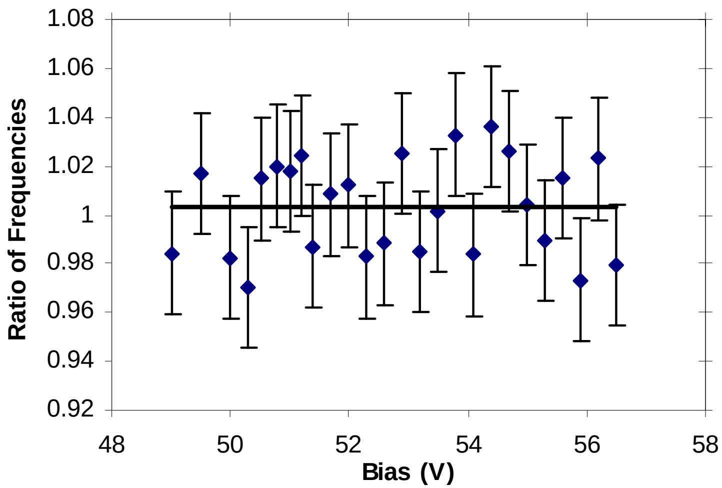


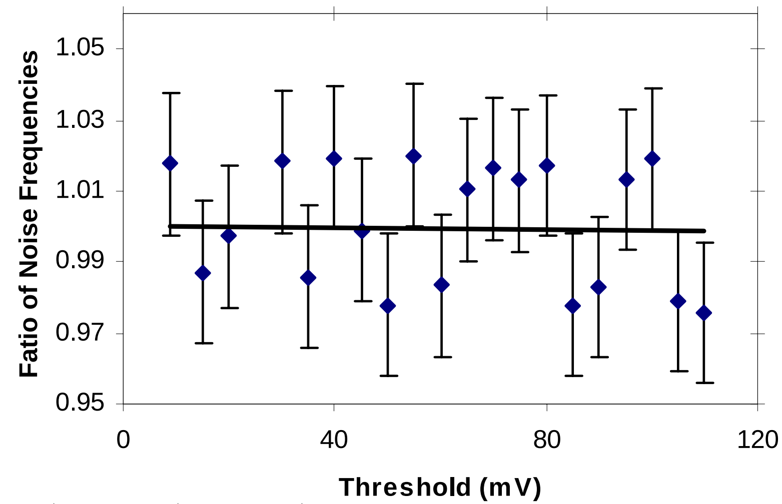


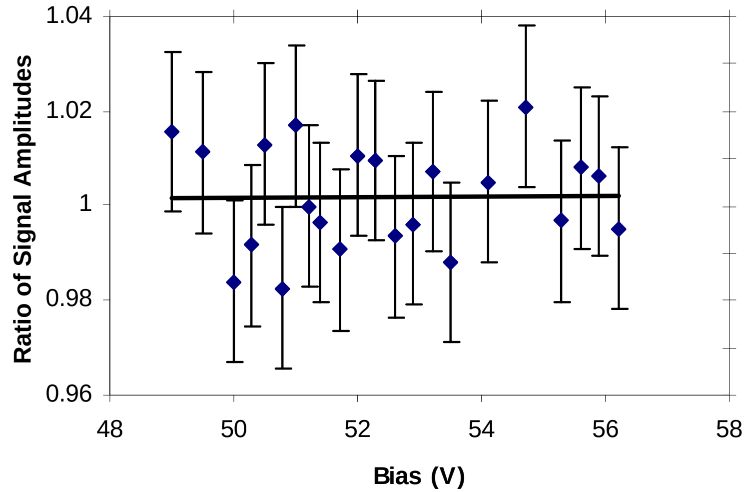


Stress Tests: Effect of Irradiation

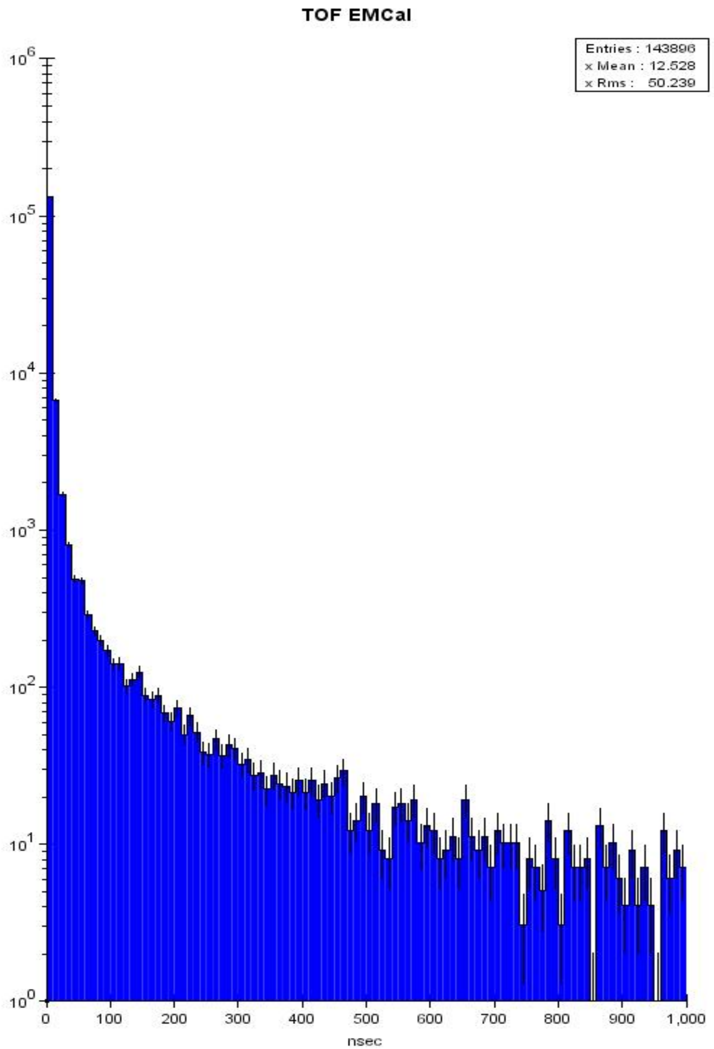
- No detectable damage from 1 Mrad of γ:

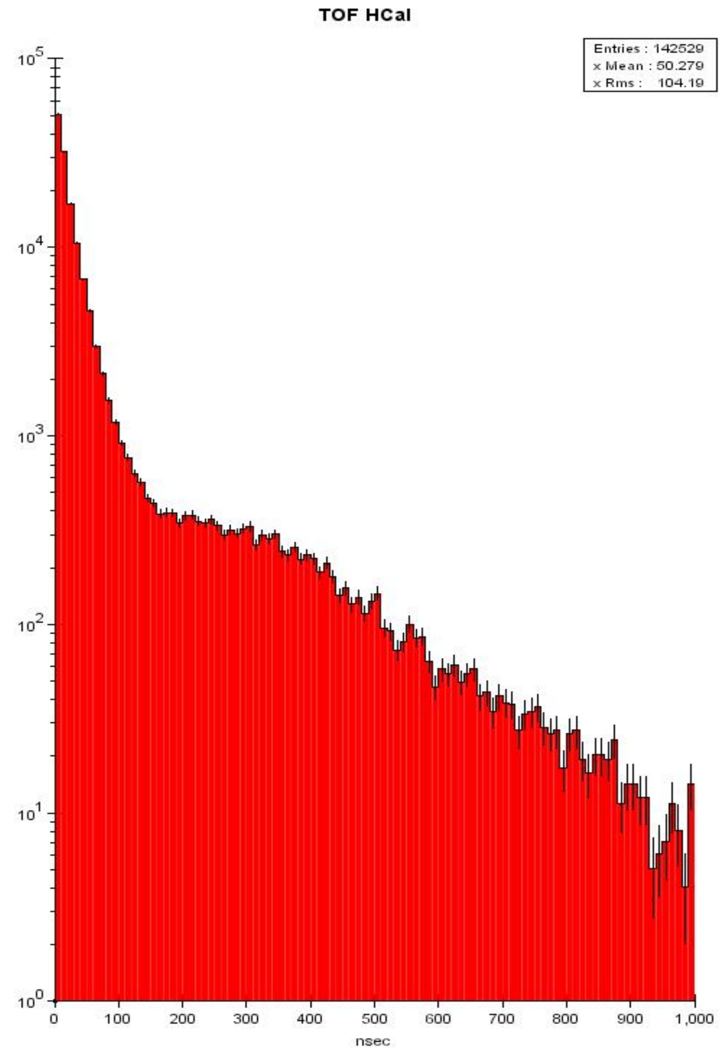




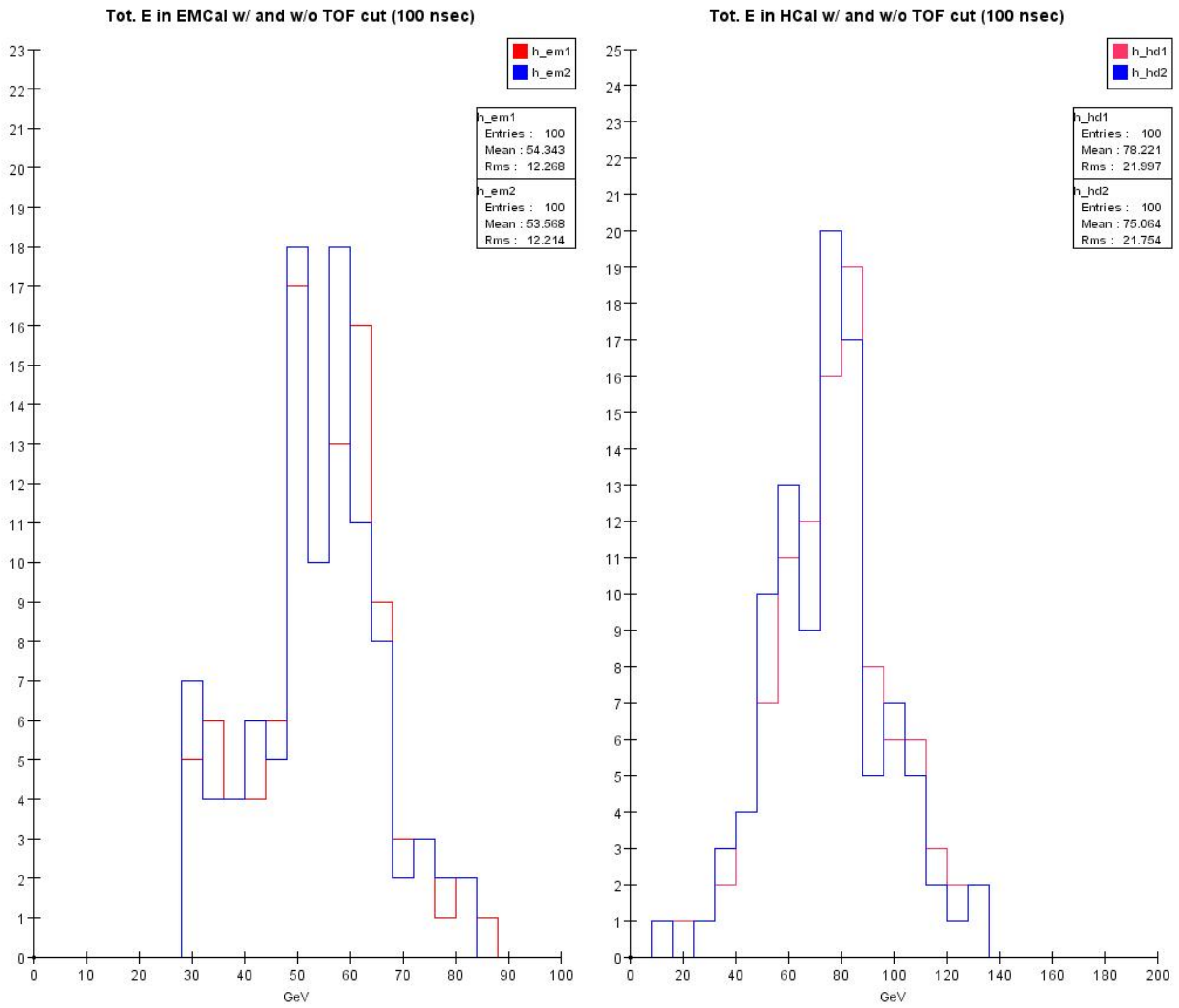


Hit timing

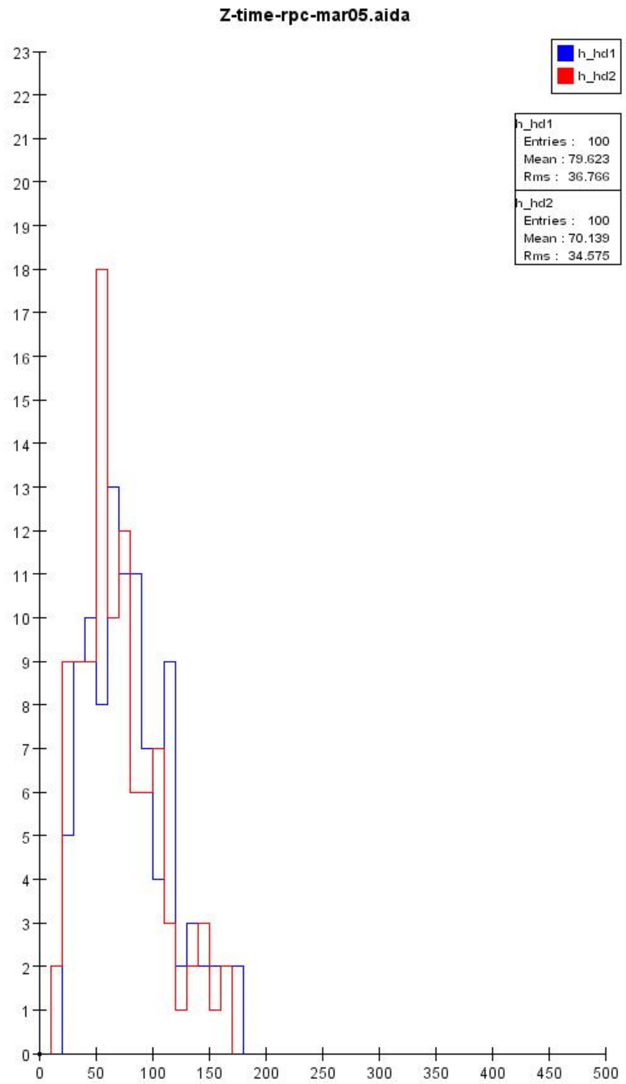

TOF EMCal
Entries : 143896
x Mean : 12.528
x Rms : 50.239
nsec

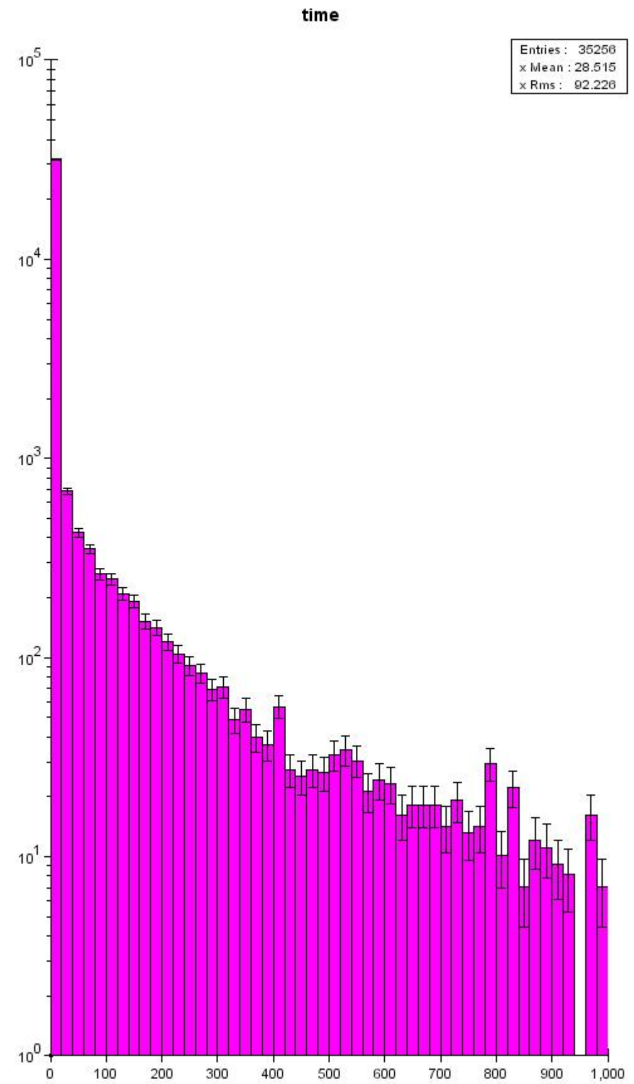

TOF HCal
Entries : 142529
x Mean : 50.279
x Rms : 104.19
nsec

Hit timing (contd.)

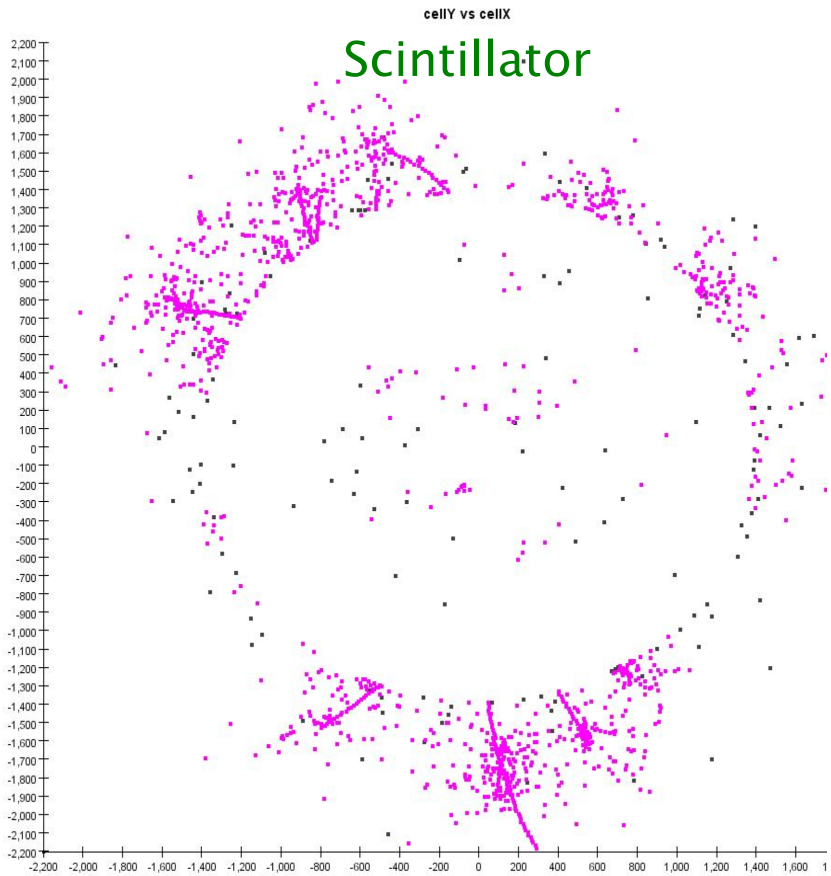


Hit timing (contd.)

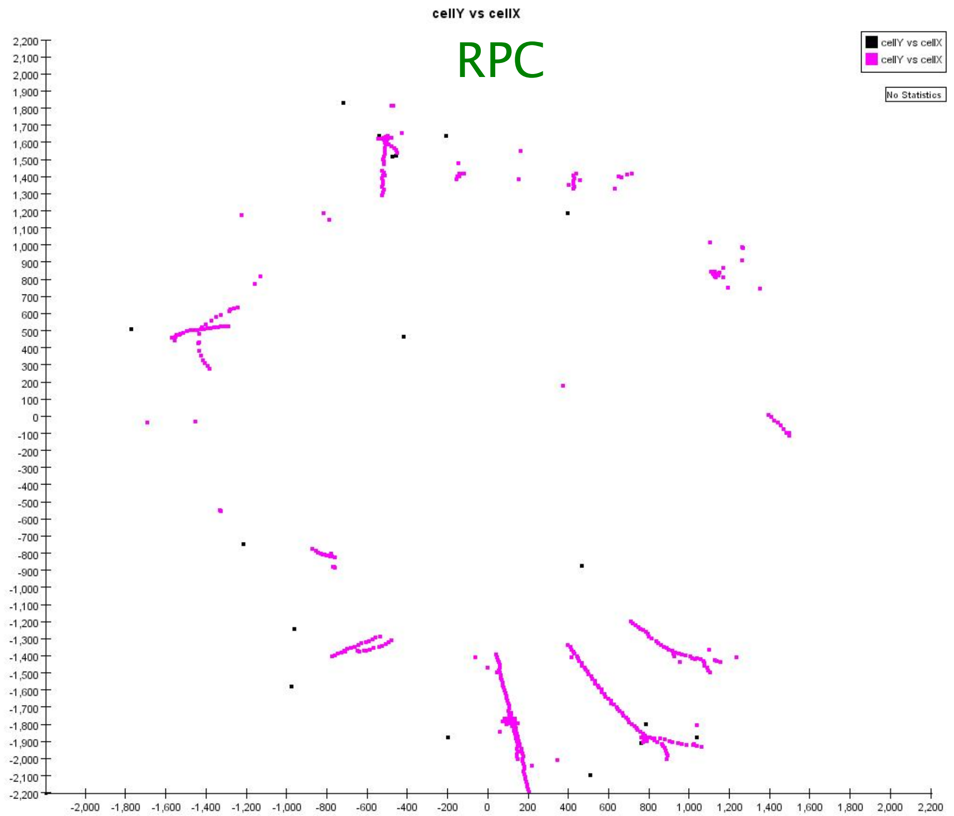




Hit timing (contd.)

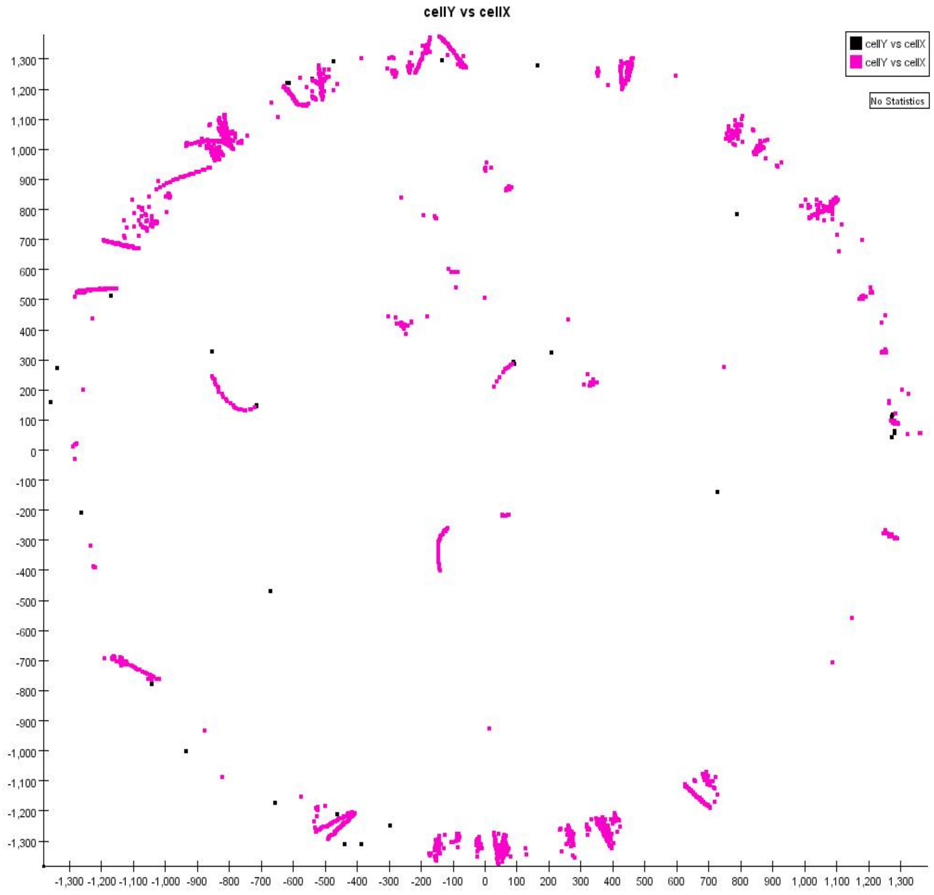


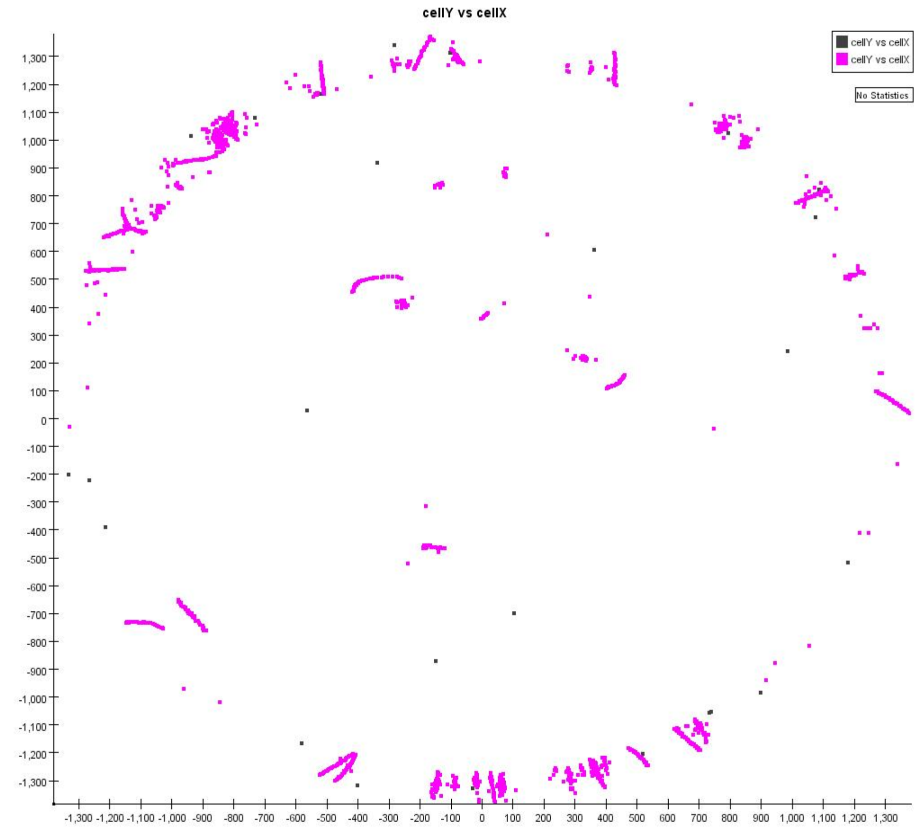
- Same Z→jj event at pole
- Same cell size (1cm x 1 cm)
- Same threshold of 0.25 MIP



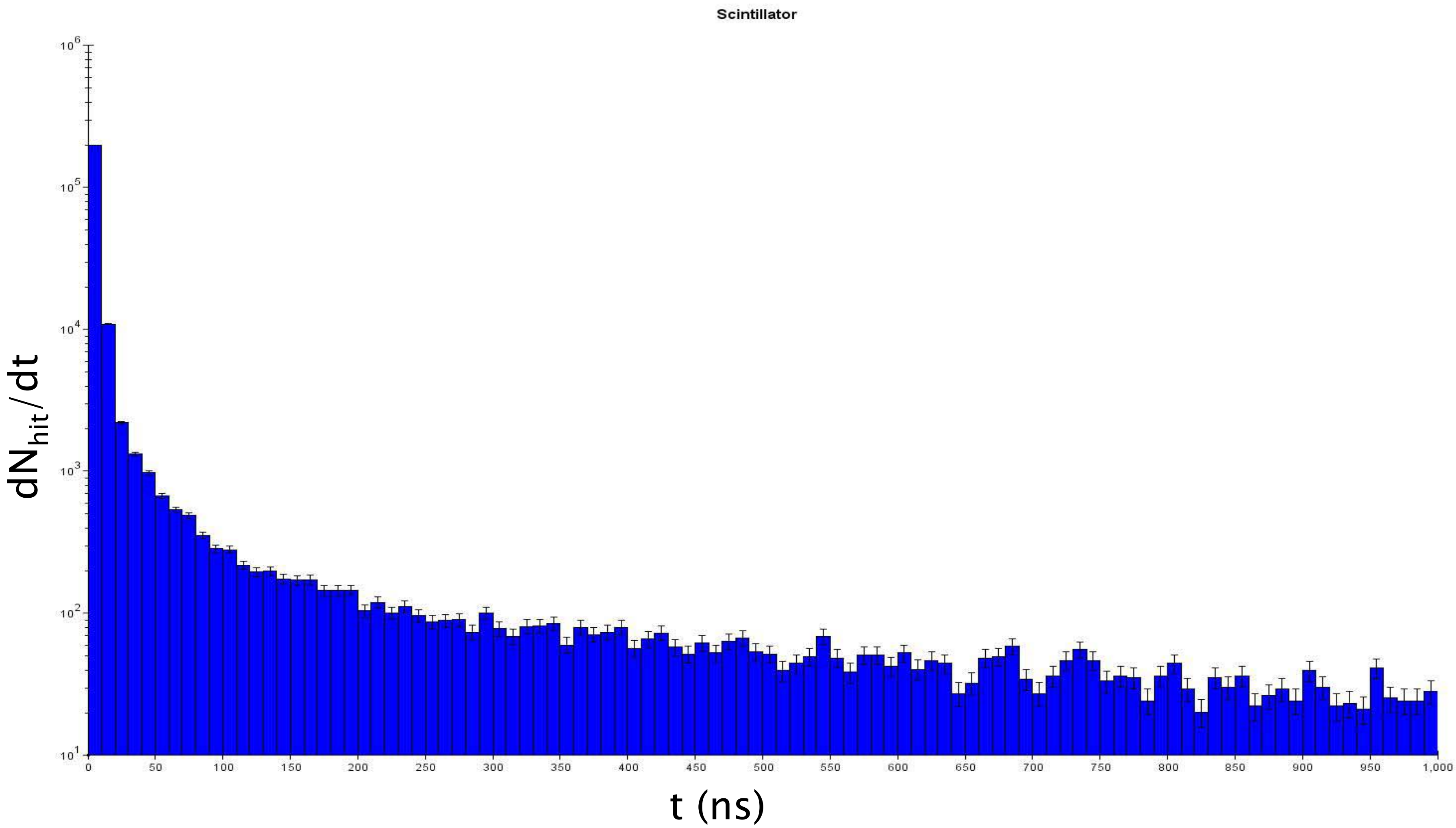
Hit timing (contd.)

ECal hits in the same events as on the last slide

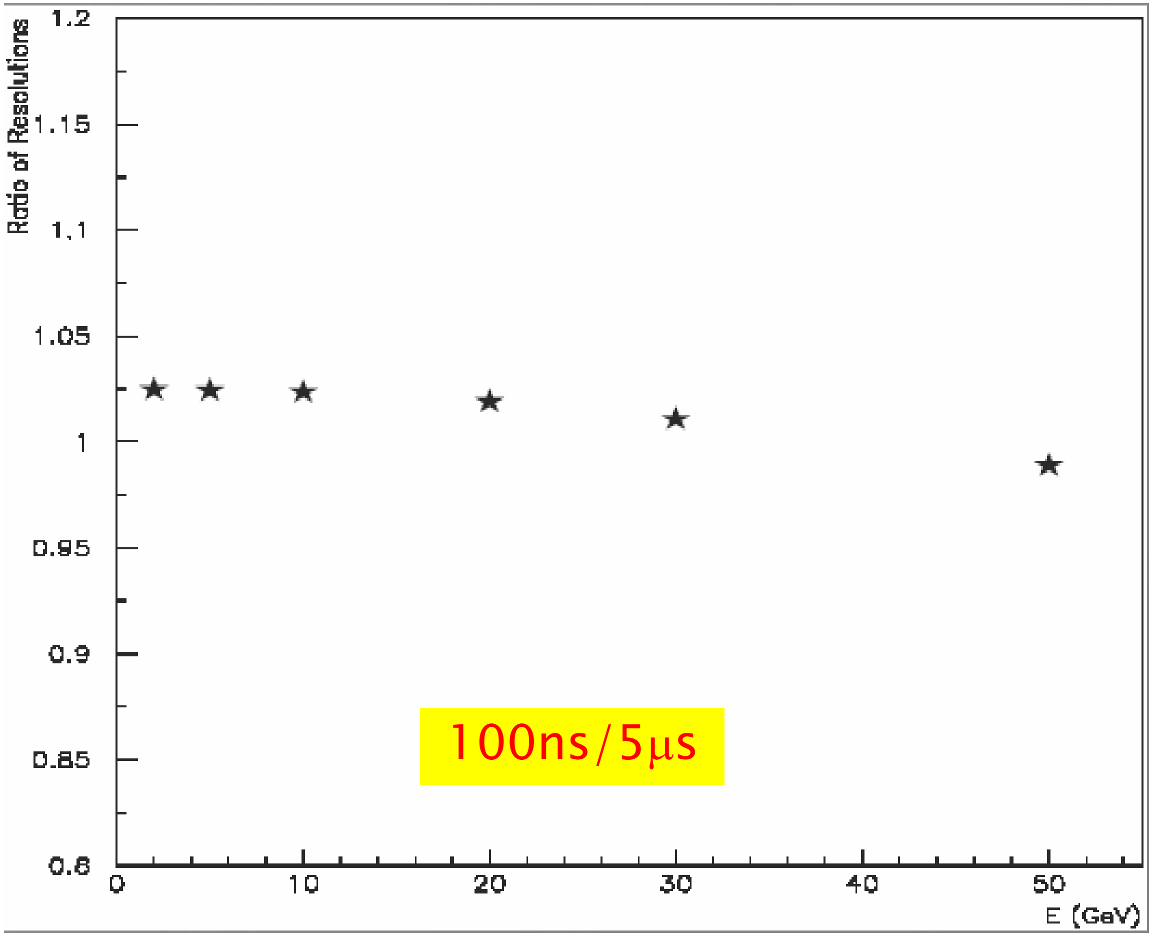




Time of flight



Time-of-flight dependence of resolution



Avalanche Photo-Diodes

Hamamatsu APD gain vs V @ diff wavelengths (T= 18 °C)