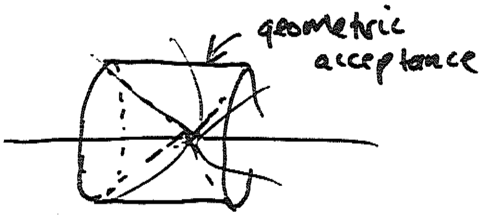
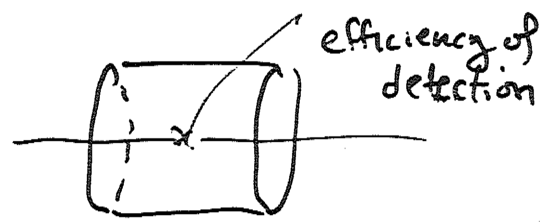
[redacted]

Detector Simulations and Modelling

Typical problems in the design / analysis of HEP experiments

- How well will/does a detector perform?
  - Acceptance and efficiency of the device
  - Resolution (energy, momentum, TOF, etc.)





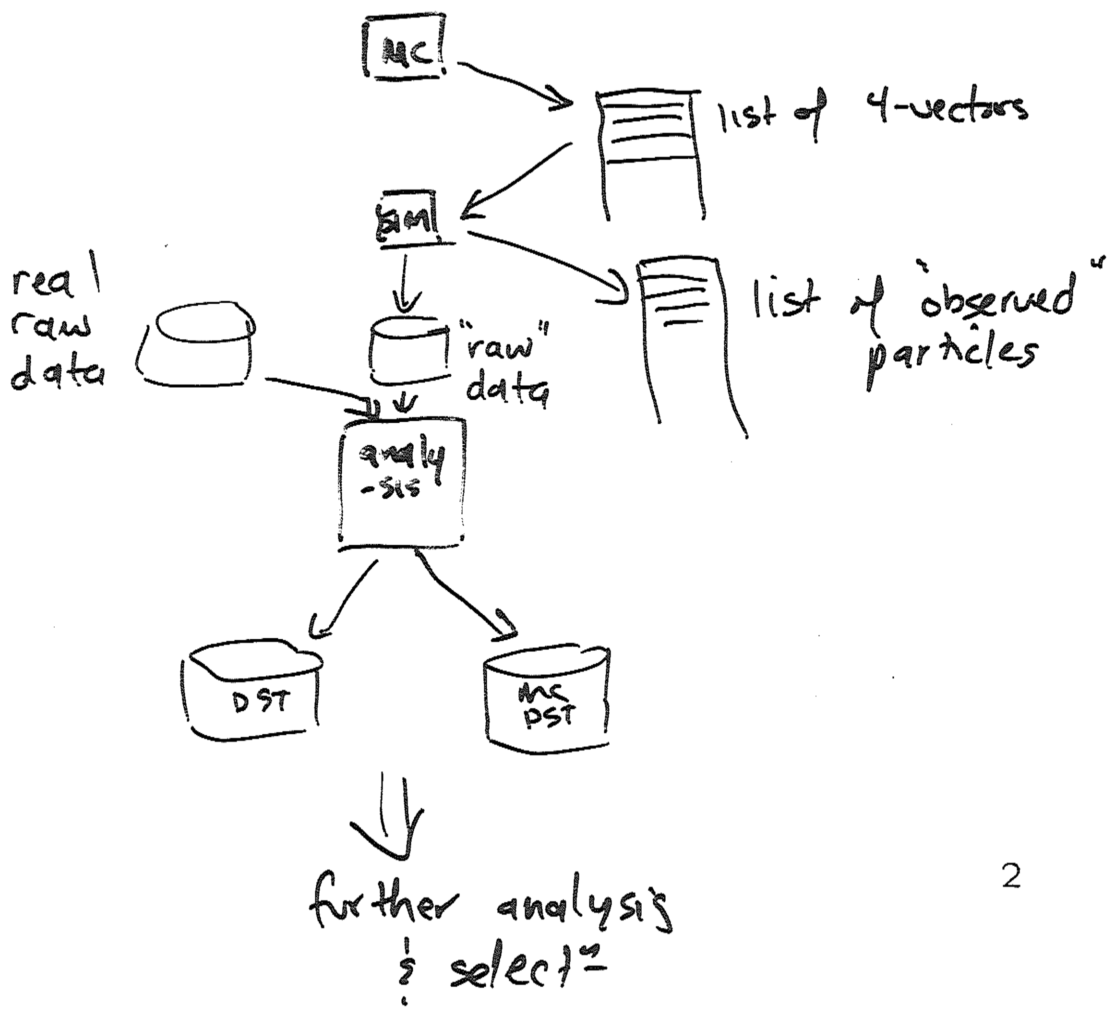
- What can be done to improve or optimize design?
- How do I correct "observed data" to compare with models?
- Can I make a given measurement?
  - What running time is required?
  - What would be needed?

[redacted]

General Strategy

The general strategy is to take an integrated approach

- Use MC Generator to create 4-vectors
- Use detector simulation to model response of detector to particles
- Produce "raw data" record identical in structure to real data
- Process as real data



Review of Simple Principles

Must first understand "back-of-the-envelope" calculations

- Should be able to calculate basic performance without resorting to huge "black box"
- Also necessary tool to validate full-blown detector simulation

For example, tracking chamber momentum resolution

- Gluckstern, NIM **24**, 381 (1963).
- Calculate uncertainty in curvature k

$$\delta k_{res} \simeq \frac{\epsilon}{L^2}\sqrt{\frac{720}{N+4}}$$

$k \doteq \frac{1}{R}$

- Good approximation to drift chamber performance

Check for CDF:

$L = 100$ cm
$N = 84$
$\varepsilon = 200\ \mu$

$\delta k_{res} = ?$

Calorimeter Resolution

Response of calorimeter to high energy showers is

$$\delta E \simeq F\sqrt{E}$$

- Determine missing energy resolution of hermetic calorimeter
- Treat as

$$\not{E}_{Tx} = E_{Ti} \cos\phi_i \quad \text{and} \quad \not{E}_{Ty} = E_{Ti} \sin\phi_i$$

- Results in $\sigma(\not{E}_T) \simeq F\sqrt{\sum E_{Ti}}$ (CHECK!)

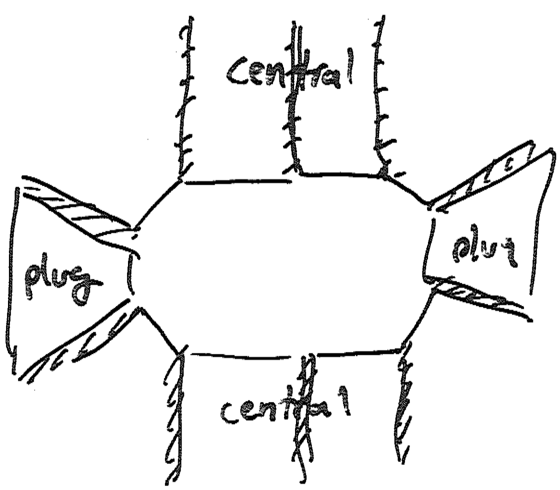
Can use this to determine what the real response should behave as

- But note that for CDF

$$\sigma\not{E}_T \simeq 1.4\sqrt{\sum E_T}$$

but $F \simeq 1.1$

- Other effects that must be considered



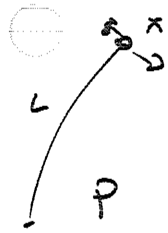
cracks!!

More on Back-of-the-Envelope Calculations

Make use of variety of parametrisations

- Shielding calculations
- Multiple scattering formula δx
- $dEdx$
- particle lifetimes and production properties

L



With this arsenal, can make reasonable approximations

- SDC Letter of Intent based on such calculations
- Backed up in specific cases with more detailed modelling

$$\boxed{\delta\theta = \frac{.015\sqrt{L}}{P}}$$

SDC cal parameters

Table 3-1
A summary of the parameters of the baseline SDC calorimeter which have been assumed in the subsequent analyses. The calorimeter depth is quoted in interaction lengths (λ).

Parameter	Barrel	Endcap	Forward
Coverage	$\lvert\eta\rvert < 1.4$	$1.4 < \lvert\eta\rvert < 3.0$	$3.0 < \lvert\eta\rvert < 6.0$
Radius of front face (m)	2.10		
z position of front face (m)		4.47	12.00
Compartment depth			
EM (– Coil)	1.1	0.9	
HAC1	4.1	5.1	13.0
HAC2	4.9	6.0	
EM resolution			
a	0.14	0.17	0.50
b	0.01	0.01	0.05
HAC resolution			
a	0.67	0.73	1.00
b	0.06	0.08	0.10
HAC nonlinearity			
α	1.13	1.16	1.16
β	0.31	0.38	0.38

$\frac{\sigma}{E} = a\sqrt{E} + bE$

the barrel and 4 mm lead plates in the end-[illegible]ng the 4 mm scintillator throughout. The [illegible]nstant term of 0.01 has been retained. We [illegible]e that the electron response is linear, as [illegible]udies have shown that with a massless gap [illegible] for energy deposited just behind the SDC [illegible] possible to achieve a linear response for [illegible]bove roughly 10 GeV (see Chapter 6).

[illegible]ngle particle response for hadrons has [illegible]etrized from CALOR89 simulations. The [illegible] and constant terms are displayed in Ta-[illegible] the reasons outlined above, the hadron [illegible] is noncompensating with a resulting π/e [illegible]atio as a function of energy that is para-[illegible] follows:

beam results indicate that the performance of the actual calorimeter may be slightly better than that given in Table 3-1 (smaller stochastic and constant terms in the resolution and a better π/e response ratio have been observed).

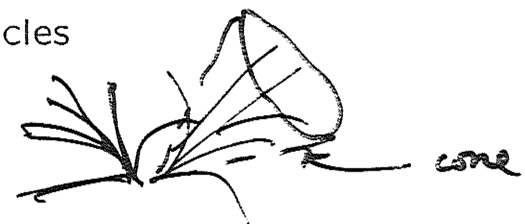
Muon system

The performance of the muon system is described in terms of a momentum resolution that is a function of p_t and η. The parametrization used here is shown in Fig. 3-2 for several values of muon p_t. This resolution has been derived from the covariance matrix for fits to simulated measurement points, ignoring any pattern recognition effects, but including the effects of multiple scattering and misalignments

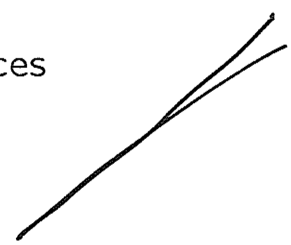
Where Do These Fail?

Simple calculations fail for a variety of reasons

1. Have to estimate competing effects, eg.
   - jet response
     - intrinsic response
     - out-of-cone corrections
     - overlap with other particles



   - tracking
     - two-track separation
     - correlation with several devices
     - unusual detector geometries



2. Complex final states or interactions
   - correlated effects
   - inability to deal with complexity
     - trackfinding in dense jets
     - particle ID in cluttered environment

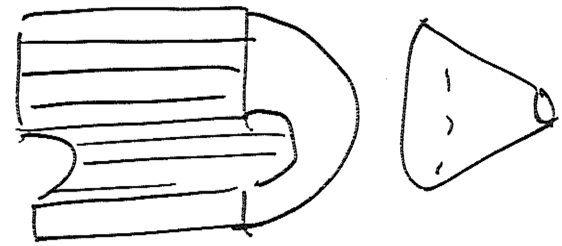
$t\bar{t} \to W^+W^- b\bar{b}$
↳ jj
↳ $\ell\nu_\ell$

3. Detector response difficult to parametrise, eg.
   - shower leakage through calorimeter cracks

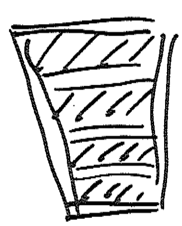
Implementation of Typical Detector Simulati

First must incorporate a description of detector geometry

- Must include definitions of volumes
  - define active regions
  - usually heirarchical



- Composition of volumes
  - amount of material
  - radiation lengths and absorption lengths

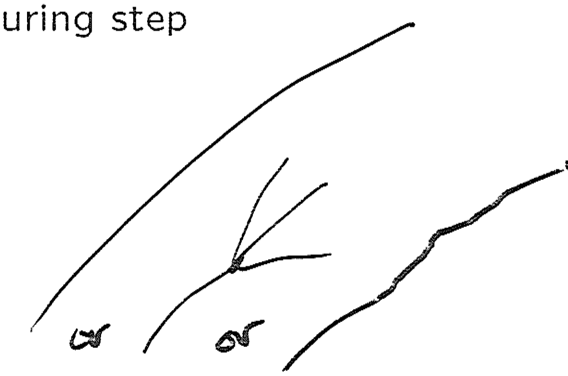


- Requires a "database" that is efficiently accessed
  - GEANT is a good example of this approach
  - given $(x, y, z) \to$ volume

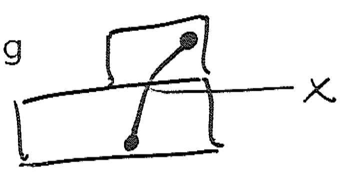
Perform Stochastic Simulation

Step each generated particle through the detector

- "swim" the particle through B field using RK
- incorporate step size commensurate with features of detector
- At each step:
  1. Determine if particle interacts during step
     - decays
     - suffers a nuclear interation
     - multiple scatters



  2. Incorporate energy loss in material
  3. Check to see if a volume boundary crossed
     - If so, cut step to find exit point
     - Perform whatever bookkeepping



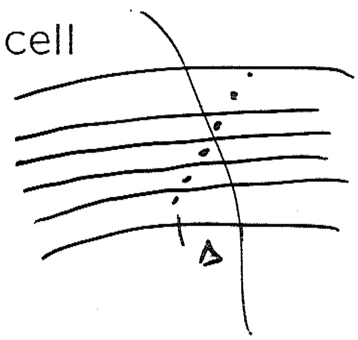
  4. Check to see if passing through active detector
     - simulate detector response

Continue till particle exists detector

Examples of Detector Response

For tracking detector (eg, Drift Chamber)

- determine cell of detector
- determine exact point in sense cell
- "smear" measured point
- convert to a TDC count
- include inefficiency



Calorimeter response can be done in a number of ways

1. parametrise response of calorimeter cell to shower
   - typically quite fast
   - requires good model of shower response
2. Use detailed shower MC
   - EGS typical for EM showers
   - GEISHA favourite model for hadronic showers

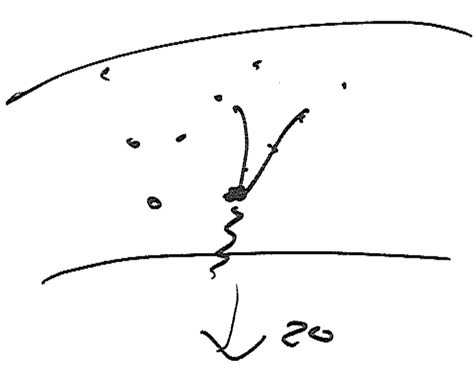
Tuning Simulations

Largest effort is involved in validating simulations

- Have to ensure that simulation is accurate
  - volumes correctly defined
  - detector response correctly modelled
  - consistent with operation of detector
- Have to understand time dependence of detector response
  - Calibration constants for detector should take into account variations
  - Have to ensure this!

Typically done by using test beam data first

- Next steps require studying data and comparing with detector simulation
- Use specific channels to test understanding
- Feedback into both simulation and data analysis



Case Study: Dijet Balancing at CDF

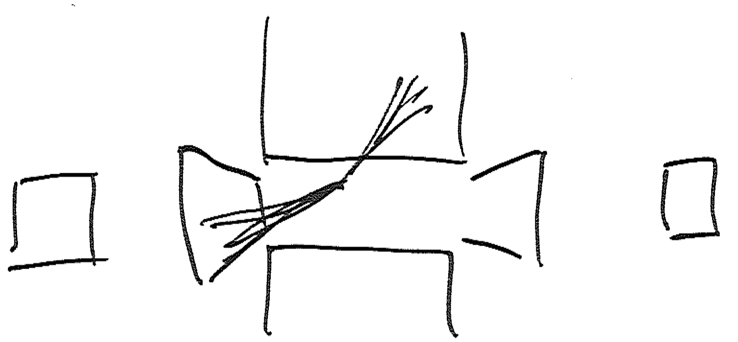
CDF has studied calorimeter response by using

$$gg \rightarrow gg$$

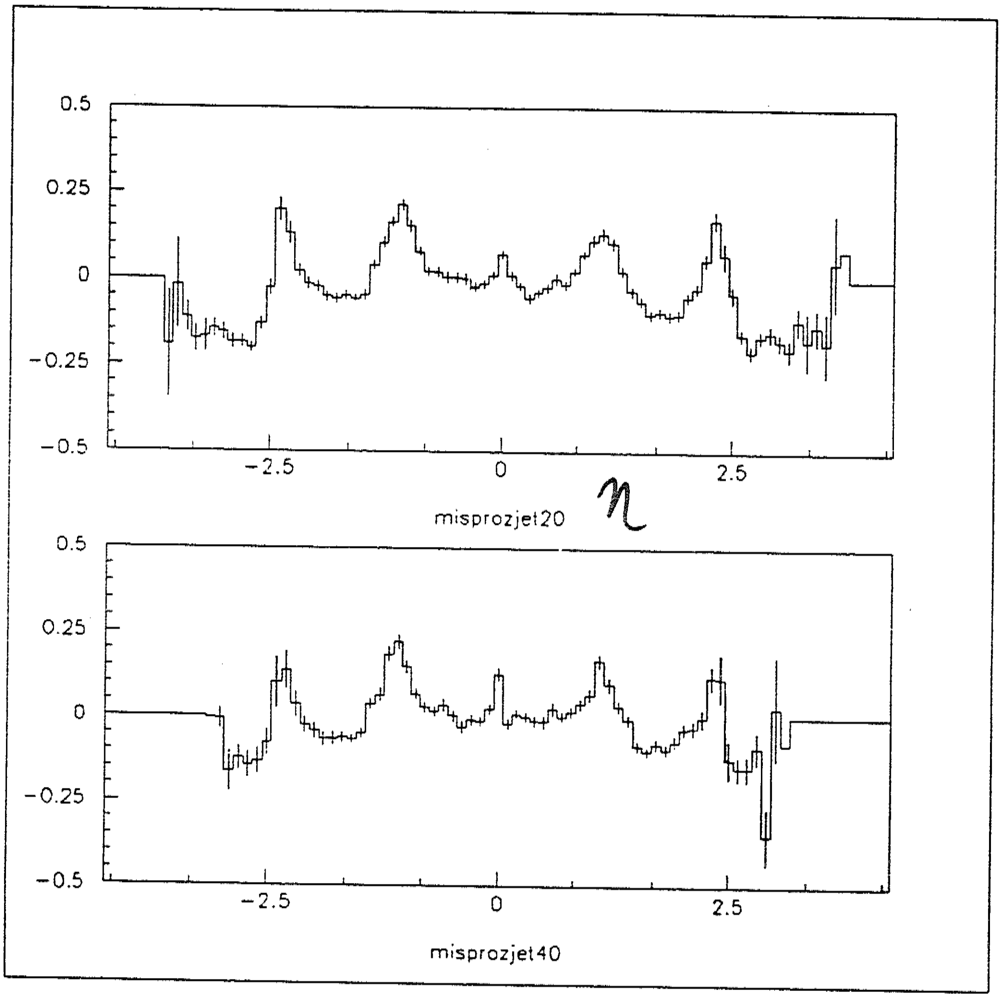
ggg

which generates two equally balanced jets in calorimeter

- Look for two clusters of energy
- Compare average energy of one jet with the energy of the jet in central calorimeter



- Calibrate central calorimeter response
  - Use test beam data
  - Use single particle response
- Use this to develop a correction function
  - Also in "fast" detector simulation



$\frac{\Delta(\text{CEM} - \text{other})}{\text{CEM}}$

Figure 1: MPF vs. η from data a) $50 < \Sigma P_t < 100$ GeV/c, b) $100 < \Sigma P_t < 130$ GeV/c.

Limitations of Detector Simulations

Detector simulations are limited in various ways

- Only as good as the accuracy of the modelling
  - Have to really understand detector
  - Have to make sure physics process is correctly described

- have to know MC is correct!

- Always limitations in approximations
  - Depends on what you are looking at
  - Closer you look, generally find more problems

CDF → don't understand tracking .... @ 10μ level!

- Things that are not checked are probably wrong
  - Just depends on the level
- Sometimes difficult to get the right information
  - Too much information at times

GEANT

CERN has developed a general-purpose simulation package: GEANT

- Provides tools for defining volumes
- All standard algorithms for incorporating particle interactions
- Provides graphical detector display
- User supplies volume description and response of active components
    - define volumes
    - loop over particles
      propagate
    - generate output

Has wide-spread acceptance

- But it is slow and cumbersome at times
- Avoids reinventing much of the wheel so very useful place to start

Detector Readout and Data Acquisition Systems

Organisation of "typical" HEP appartus

- Detector
- Front End Electronics
- Data Collection
- Data Acquisition
- Trigger System
- Alarms and Limits / Controls / Monitoring / Slow Control
- Online Computing and Software

Will look at each of these components in more detail

The Detector

Any HEP Detector is composed of many subdetectors

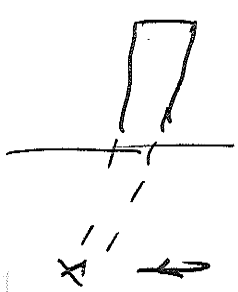
- tracking
- calorimetry
- particle ID
- lepton and hadron identification

Each subdector works by detecting particles using the interaction of particles with material

1. ionisation
2. radiation (synchroton, Cerenkov, x-ray, scintillation)

Typically detectors are segmented in some manner

- SILICON STRIP DETECTORS ($10^5 - 10^8$ cells)
- ionisation counters – electrostatic cells (10^4 cells)
- calorimeters – cells or towers ($10^3 - 10^4$ towers)
- scintillators – divided into "paddles" ($10^2 - 10^3$)



Front End Electronics

Each segment must be instrumented with necessary electronics

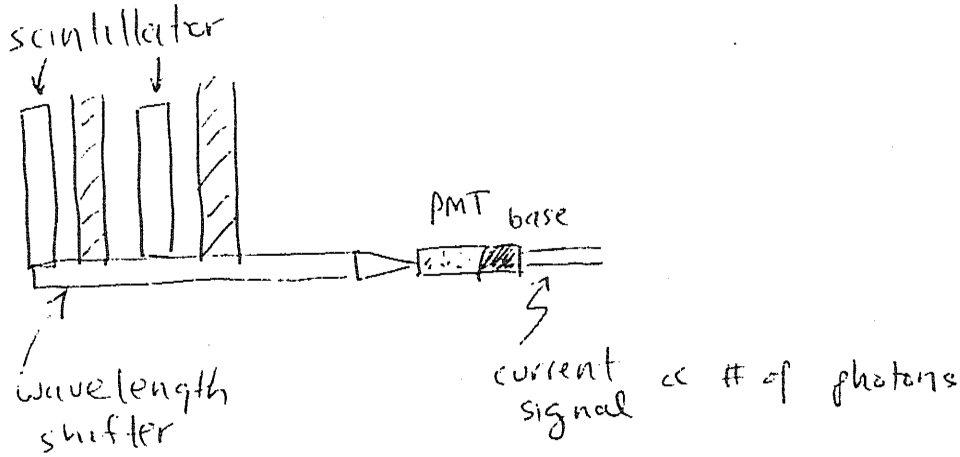
- must have method of amplifying ionisation signals
  - preamplification ("preamps") to generate detectable signal
- detection of charge (using a capacitor) and/or time of arrival of signal, eg.
  - discriminator to detect when collected charge exceeds given threshold
  - total charge could be integrated
    * usually done in a time "window"
    * total charge (analogue) is then digitized using ADC
- Signals are often "shaped" to improve S/N characteristics

Type	Det. Cap.	Peak Time	Charge
	pF	nSec	electrons
Si Pixel	.05-.5	10-30	2 E4
Si Strip	5-10	10-30	2 E4
Wire/Pad	5-50	3-20	1 E4 - 1 E6
Liq. Cal.	500-50,000	100-1000	2 E4 - 2 E8
PMT	1-3	3-5	1 E6 - 1 E7

Visible Light Detectors

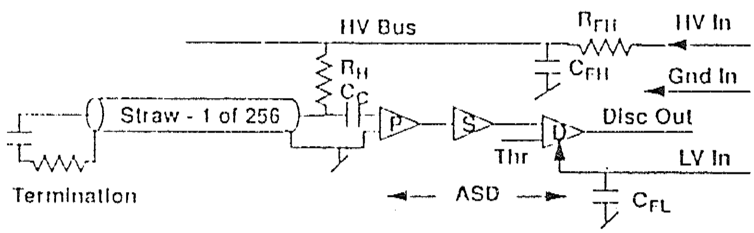
Scintillators (both liquid and solid) generate a number of detectable photons

- Light amplified using photomultipliers
  - Best phototubes can detect single electrons
  - Voltage output is proportional to number of photons via # Photo Electr
- Phototube "base" is a multi-stage amplifier integrated onto tube
- signal can then be discriminated to determine time-of-arrival



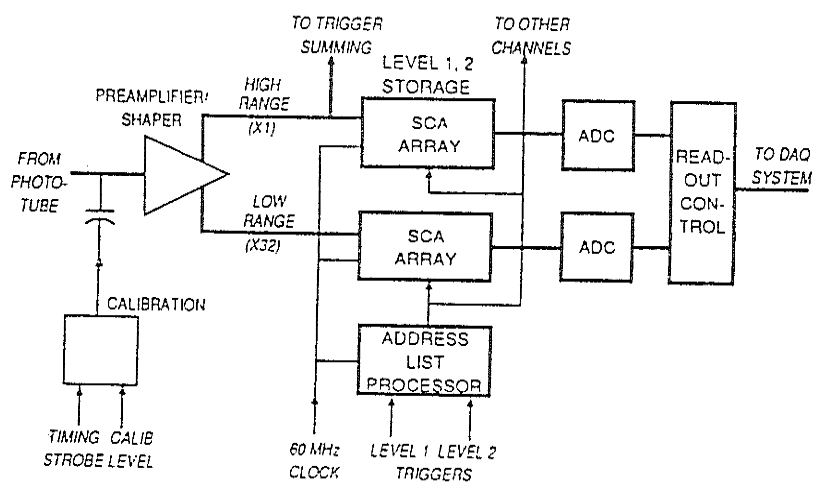
Examples of Readout Systems

Wire Chamber Electronics



ASD:
AMPLIFIER
SHAPER
DISCRIMINATOR

Calorimeter Electronics



SCA:
SWITCHED
CAPACITOR
ARRAY.

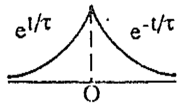
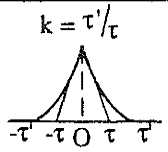
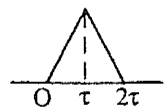
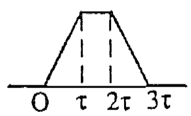
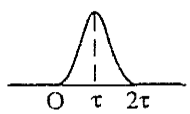
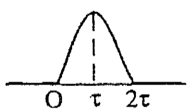
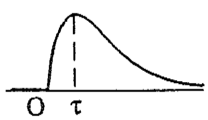
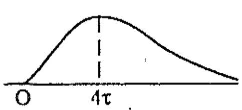
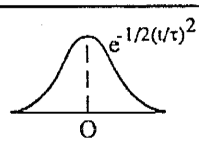
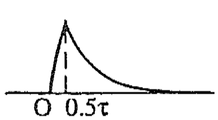
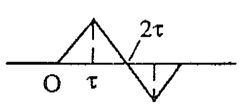
Signal Processing Issues

Usually, must optimise front end electronics to achieve maximum performance

- signals can be "shaped" by employing filters
- can use rapid sampling of signal
  - 60 MHz Flash ADC is commonly used (15ns)
  - expensive and generates lots of data for each signal

Signal Shaping can be done to either improve charge or time resolution

- Important where signal of interest is of a given frequency
- Technology is now quite complex
- Most systems have integrated shaping circuits into front end
- Considered "analogue" electronics – still somewhat of a black art.

	Shaping	Function	A_2	$\sqrt{A_1A_3}$	$\frac{A_2}{\sqrt{A_1A_3}}$	A_1	A_3	$\sqrt{\frac{A_1}{A_3}}$
1	indefinite cusp		0.64 $\left(\frac{2}{\pi}\right)$	1	0.64	1	1	1
2	truncated cusp	 k=1 k=2 k=3	0.77 0.70 0.67	1.04 1.01 1	0.74 0.69 0.67	2.16 1.31 1.31	0.51 0.78 0.91	2.06 1.30 1.10
3	triangular		0.88 $\left(\frac{4}{\pi}\ln 2\right)$	1.15 $\left(\frac{2}{\sqrt{3}}\right)$	0.76	2	0.67 $\left(\frac{2}{3}\right)$	1.73
4	trapezoidal		1.38	1.83	0.76	2	1.67	1.09
5	piecewise parabolic		1.15	1.43	0.80	2.67	0.77	1.86
6	sinusoidal lobe		1.22	1.57	0.78	2.47	1	1.57
7	RC-CR		1.18	1.85	0.64	1.85	1.85	1
8	semigaussian (n = 4)		1.04	1.35	0.77	0.51	3.58	0.38
9	gaussian		1	1.26	0.79	0.89	1.77	0.71
10	clipped approximate integrator		0.85	1.34	0.63	2.54	0.71	1.89
11	bipolar triangular		2	2.31	0.87	4	1.33	1.73

← COMP... FO... TRACK...

↑ POWER/NOISE

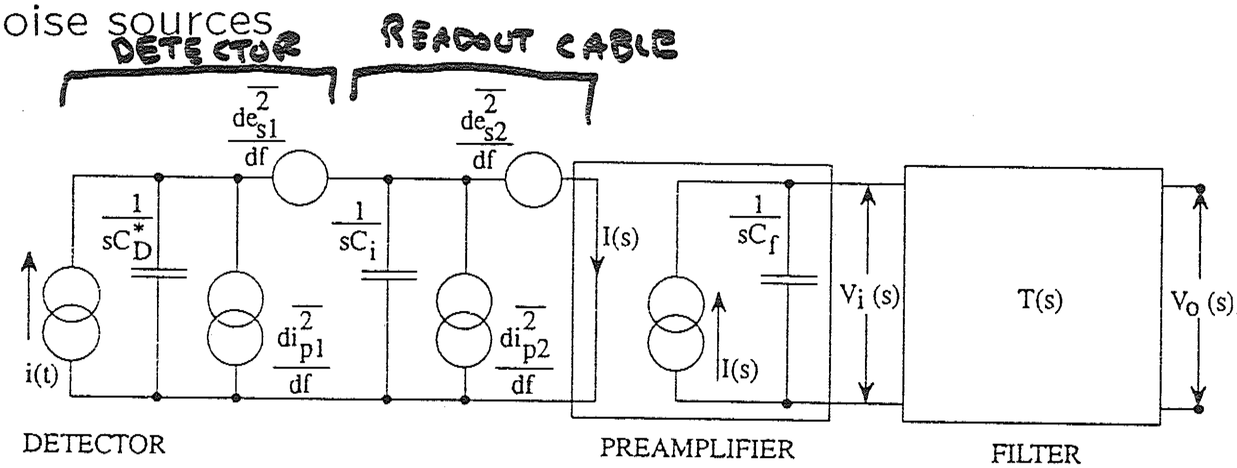
$A_2 \sim$ POWER

$\sqrt{A_1A_3} \sim$ NOISE

 REF?

Understanding Noise

Have to start with a model for circuit elements and noise sources



Make assumptions about DC and AC behaviour of components

- Can find approximate analytical solutions

$$V_o(t) = \int_0^{t_m} i(x) \cdot V_{o,\delta}(t_m - x)\, dx \qquad V_{o,\delta} = \text{impulse response for } T(s)$$

$$\Rightarrow \quad ENC \leq 2(A_W \cdot B_W)^{1/2} \sqrt{A_1 A_3}\,(C_D + C_i)\left[1 + \dots\right]$$

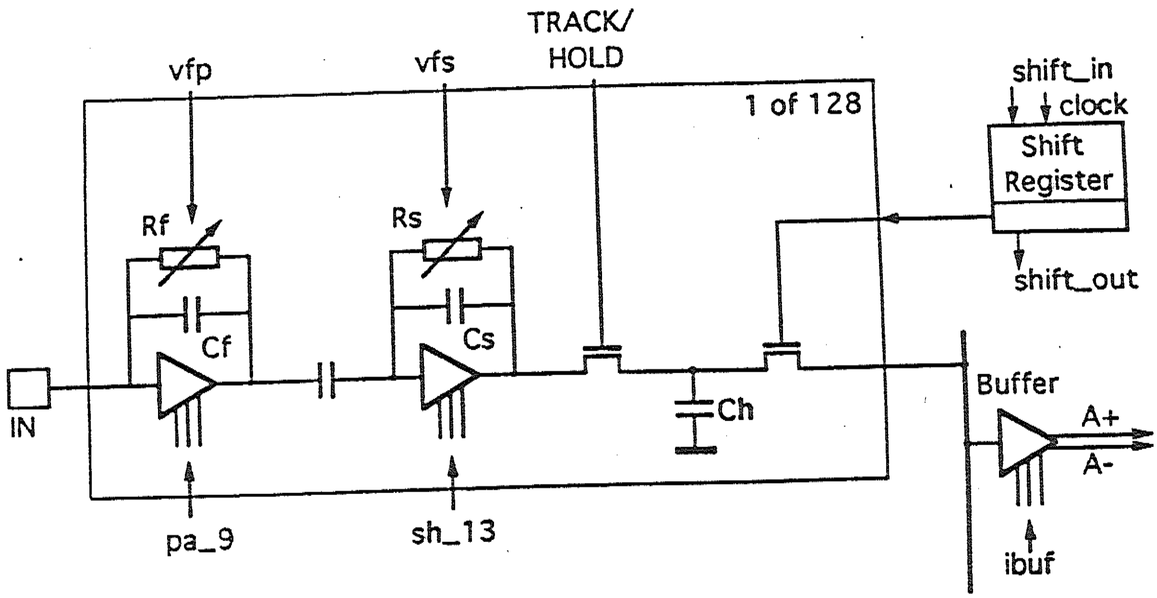
Can also simulate the heck out of the circuit using HSPICE

- Bottom line is that you still have to build and measure the performance to be sure

Cf. Radeka CERN Academic Training 86/3/10-13

WT has copies

Schematic Diagram of One Channel of VIKING Chip



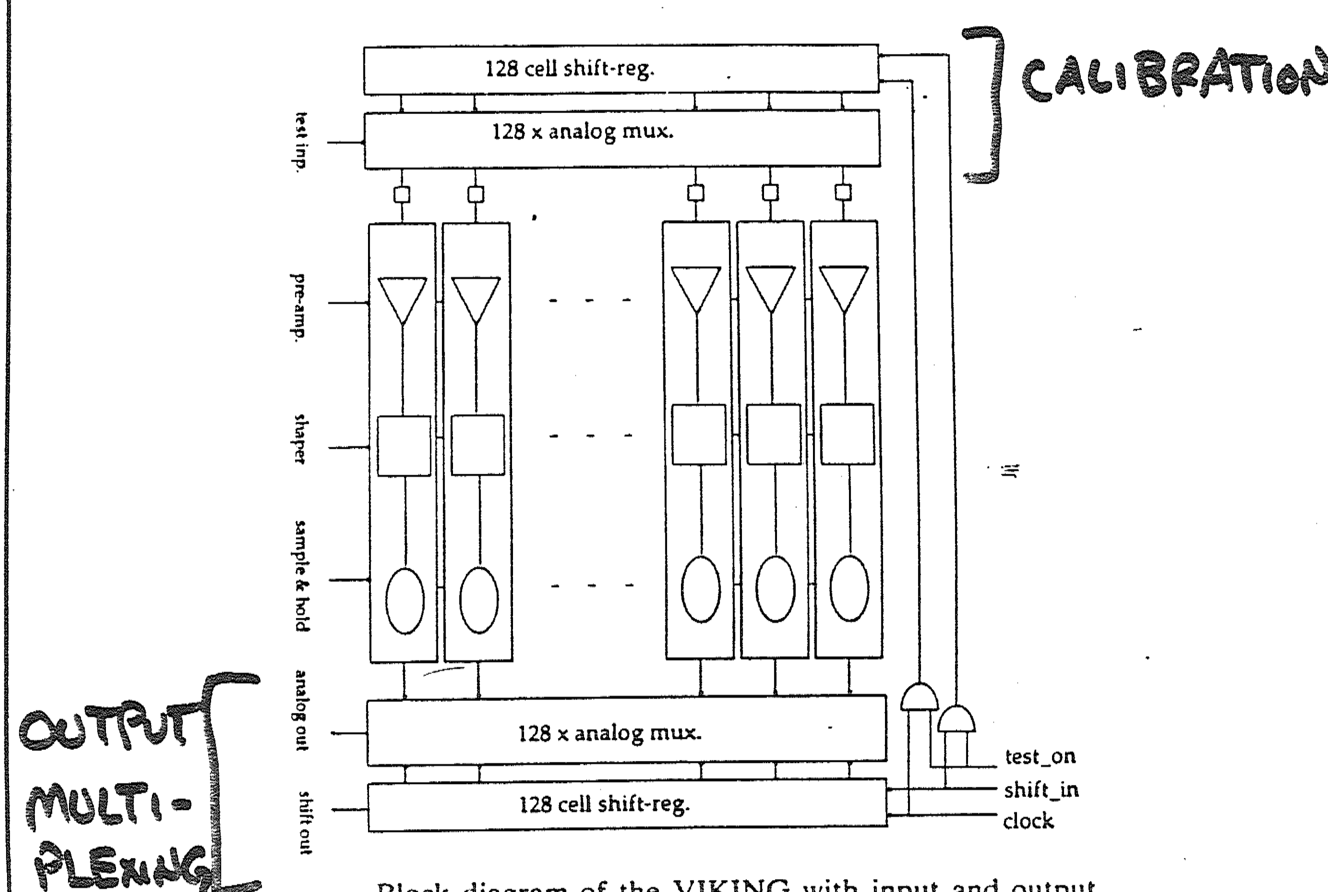
Functional circuit diagram for one of the 128 channels of the Viking-2 chip.

RC - CR shaping

AN EXAMPLE OF SILICON / DIAMOND READOUT CHIP

VIKING / VA1 / VA2 / VA3 ....

Block Diagram for 128-Channel Chip

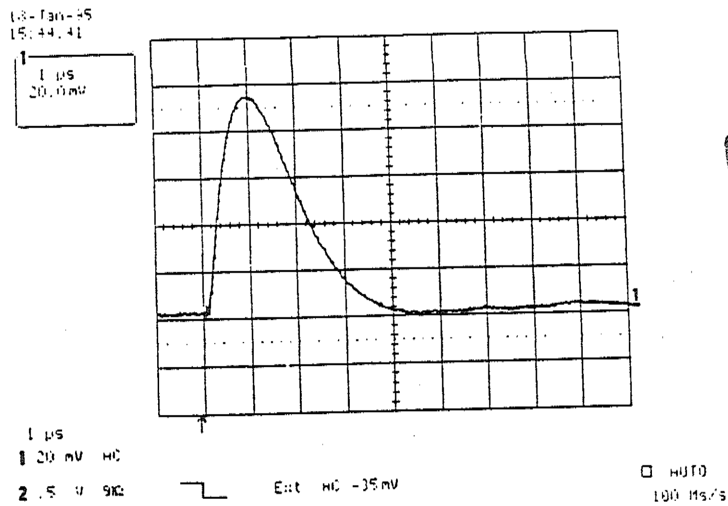


Block diagram of the VIKING with input and output multiplexing.

Pitch : ~ 47 μm

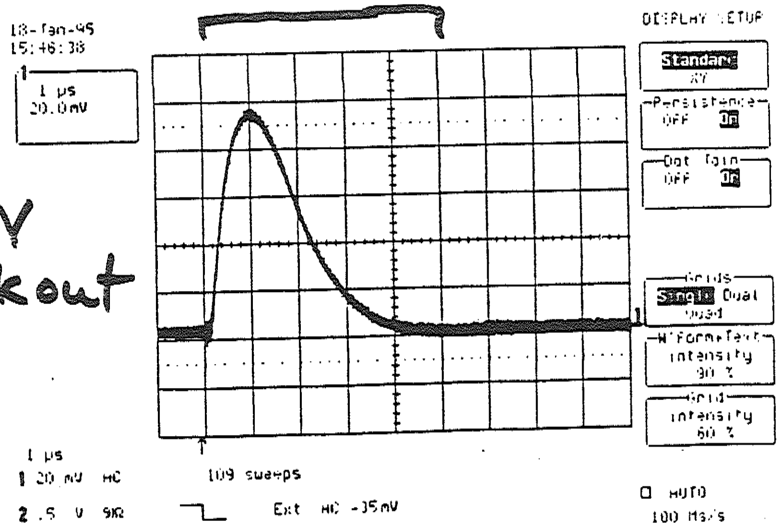
Output Pulse Shape of VA2

$T_p = 1\ \mu sec$



1 sweep

5 μs total time.



~100 mV peak out

Δ= 30K ELECTR @ t=0

109 sweeps

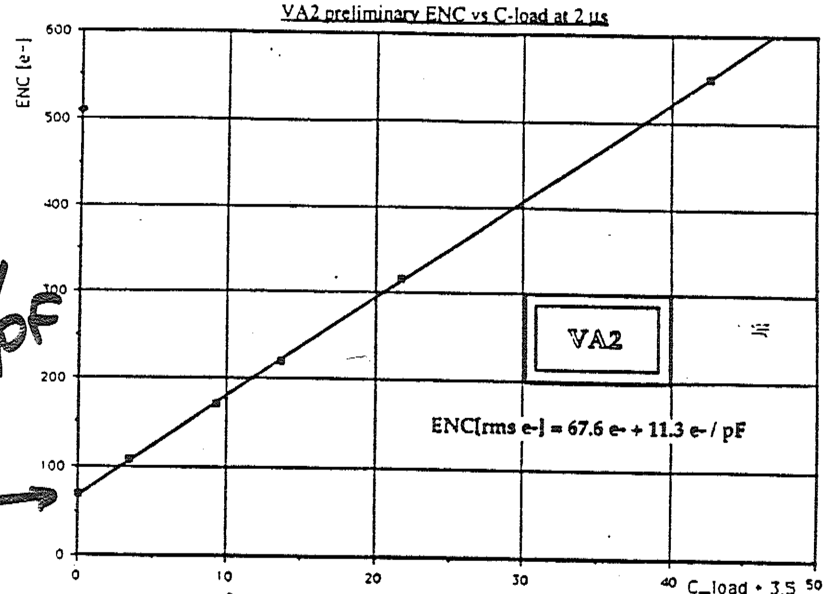
Noise Versus Capacitance for VA2

$\boxed{T_p = 2\ \mu s}$

ENC:

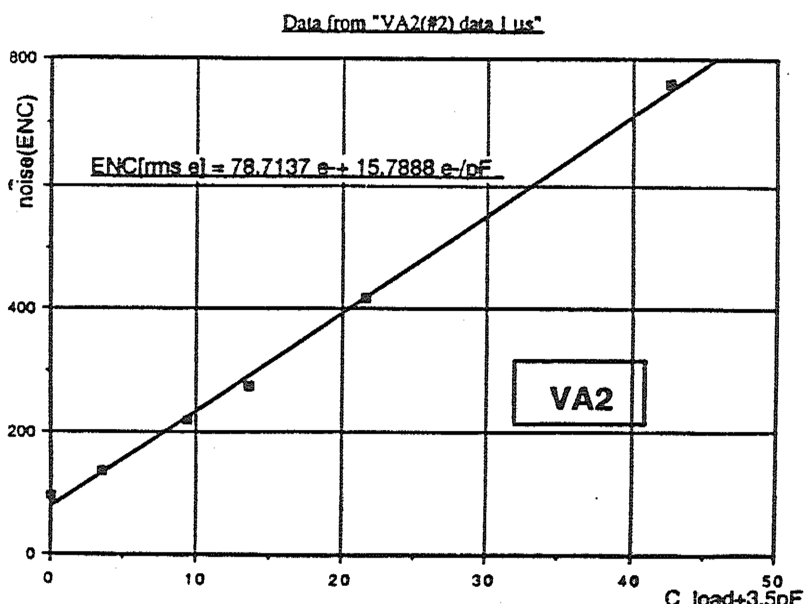
70 + 11/pF

70 →



$\underbrace{\qquad}$ 10-20pF typical of Silicon detectors

$T_p = 1\ \mu s$



ENC = 80 + 16/pF

↑

Scales $\simeq \sqrt{\tau}$.