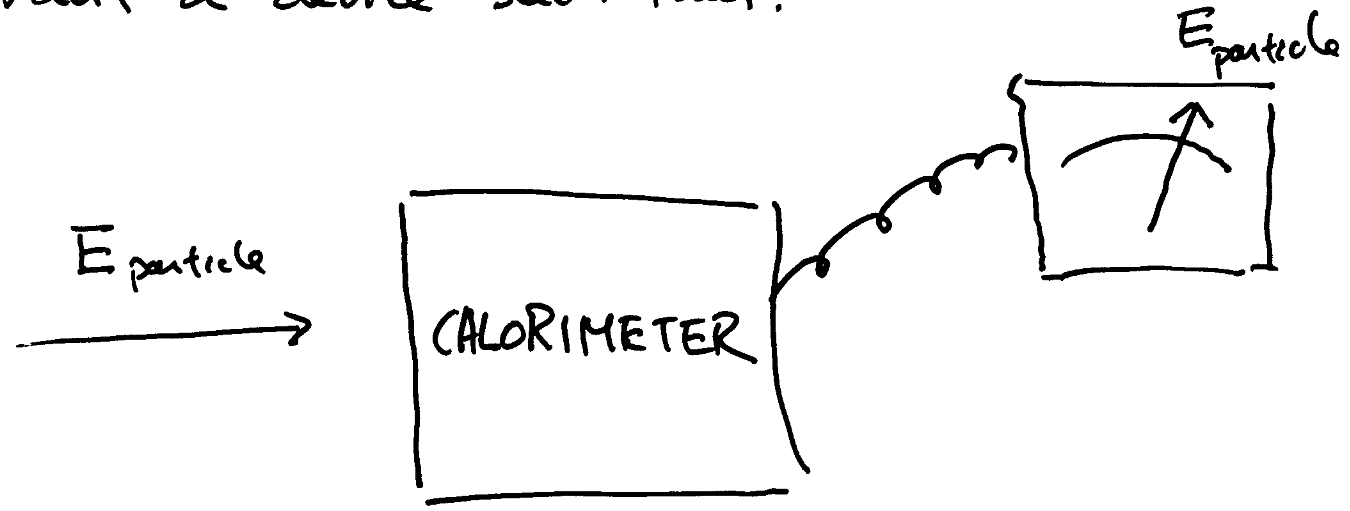
R. Yoshida
ANL
ZEUS ~~meeting~~ "lecture"

Introduction to Calorimetry
& The ZEUS Calorimeter

Want a device such that:



What actually happens in such a device is a **VERY** complicated business!
(Even for EM showers)

To learn the **REAL** story ⇒
look up review article, book ($\gtrsim$ 1990)

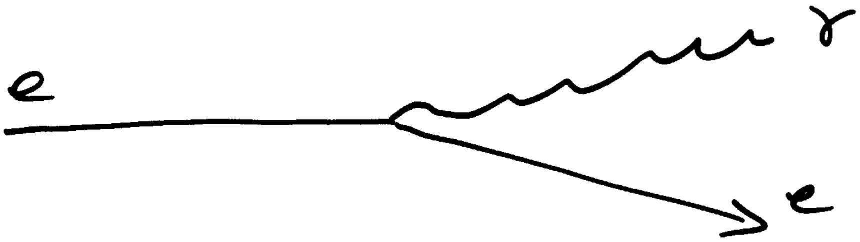
A ~~10~~ 15 min intro. to Calorimetry

⇒

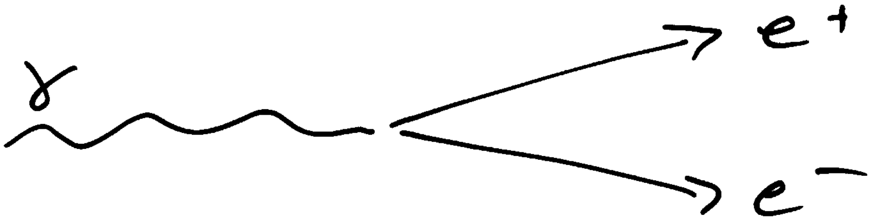
Electro-magnetic calorimetry

⇒ measure energy of **electron, γ**

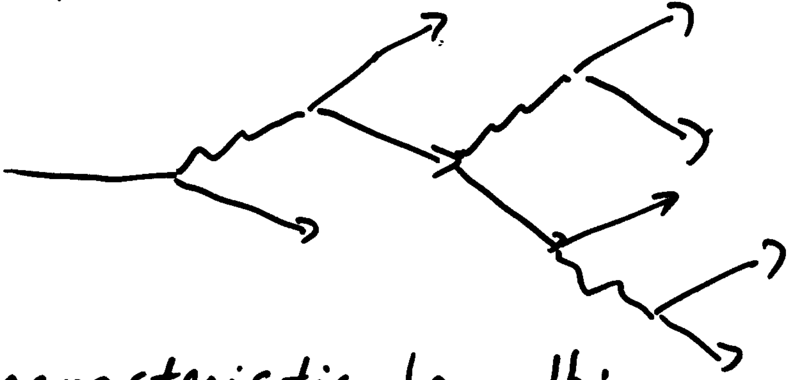
"High energy" ($\gtrsim$ 20 MeV) **electrons** "lose" energy mostly via bremsstrahlung.



γ via pair production



EM shower:



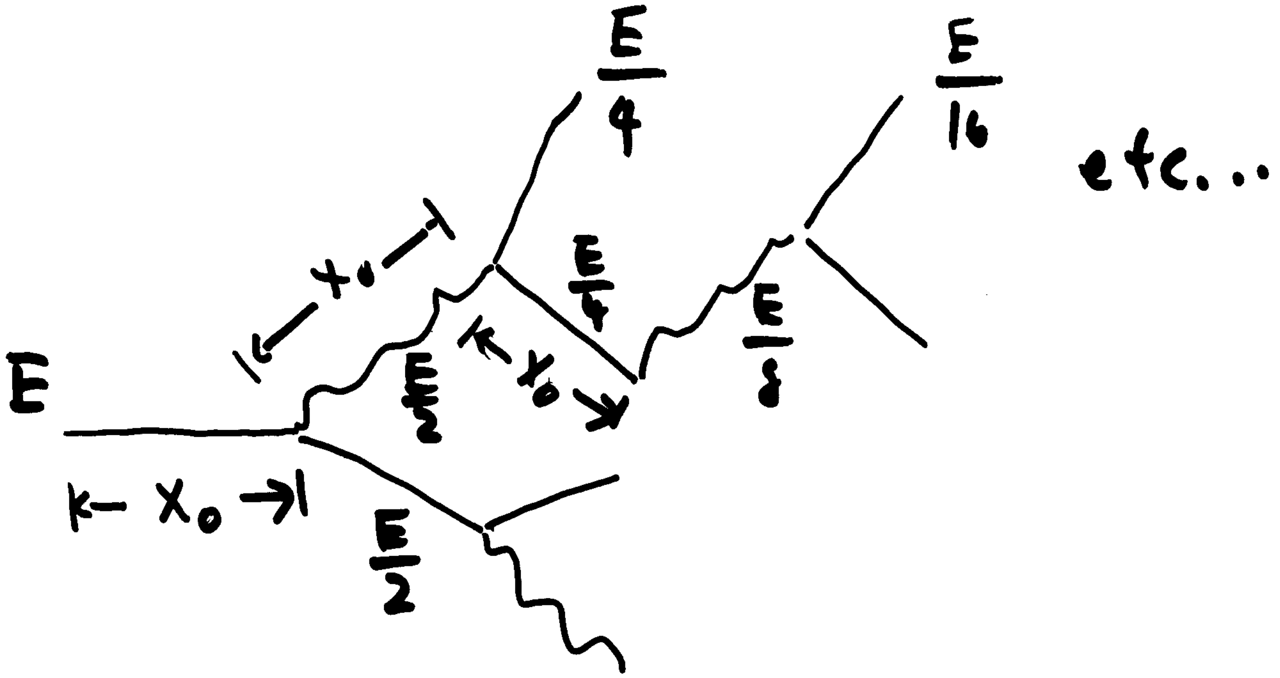
etc.

Characteristic length:

"Radiation Length" X_0 electron loses $\frac{1}{e}$ of E via Brems.

To gain some insight:

A simple model (Rossi 1952)



After t steps there are:

2^t particles of energy $\frac{E}{2^t}$

The shower stops at t_{max}

$$\frac{E}{2^{t_{max}}} = E_c$$

Where E_c = "critical energy"

Too low for Brems. & pair prod.

$$t_{max} = \frac{1}{\ln 2} \ln\left(\frac{E}{E_c}\right)$$

The long. size of shower

$$\sim \ln E.$$

What about the energy measurement:

Say we measure the ionization

$\Rightarrow$ same as counting charged particles.

$$N_{all} = \sum_{0}^{t_{max}} 2^t = 2 \cdot 2^{t_{max}} - 1 \simeq \frac{2E}{E_c}$$

$$N_{e^+e^-} = \cancel{\frac{3}{4}}\frac{4}{3}\frac{E}{E_c}$$

The measured energy $\propto E$

Particle multiplication statistical $\Rightarrow$

Then the **Resolution** of the meas.

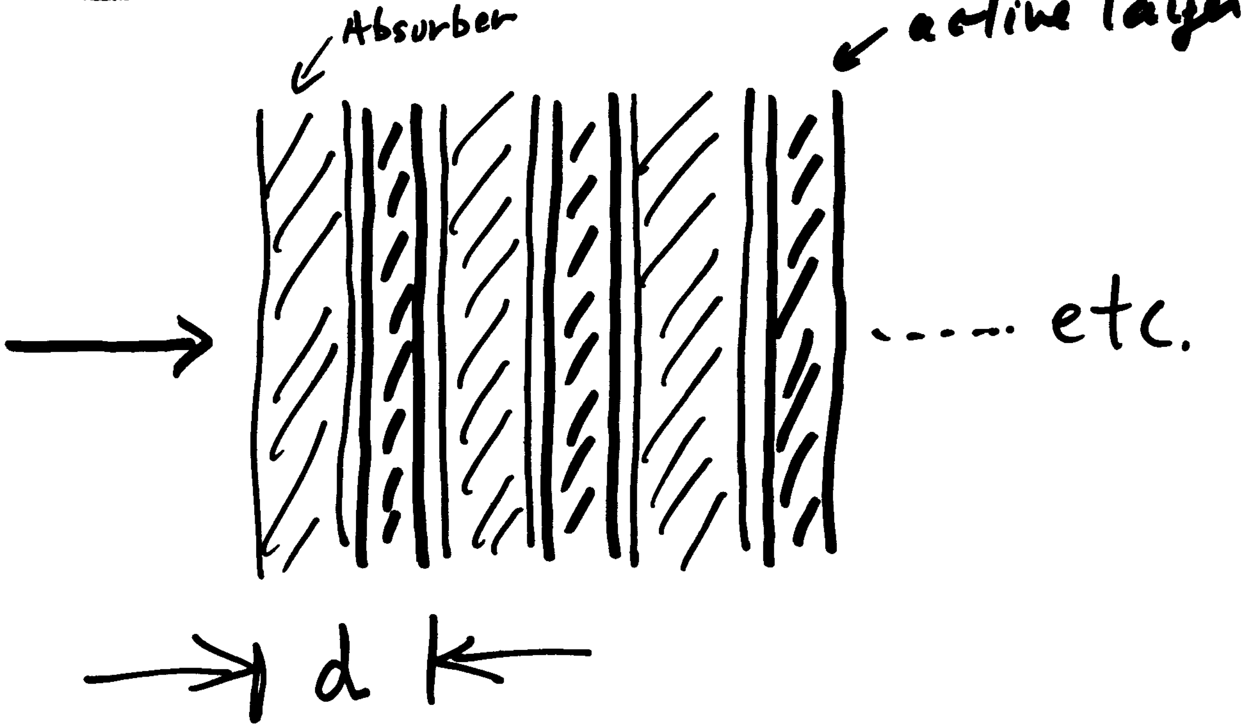
$$\frac{\sigma(E)}{E} = \frac{1}{\sqrt{N_{e^+e^-}}} = \frac{\sqrt{E_c 3}}{2} \Big/ \sqrt{E}$$

The resolution $\propto 1/\sqrt{E}$

if $E_c = 0.7$ MeV

$$\frac{\sigma(E)}{E} = 2.3\% \Big/ \sqrt{E\,[\text{GeV}]}$$

Sampling Calorimeter



In the Rossi model:

The number of particles you see: N_{sample}

$$N_{sample} \propto \frac{N_{e^+e^-}}{d\,[X_0]}$$

so the sampling fluctuation ⇒

$$\frac{\sigma_{sample}}{E} \propto \frac{1}{\sqrt{N_{sample}}} \propto \sqrt{d} \Big/ \sqrt{E}$$

i.e. more you sample better (as $\sqrt{\ }$) your resolution.

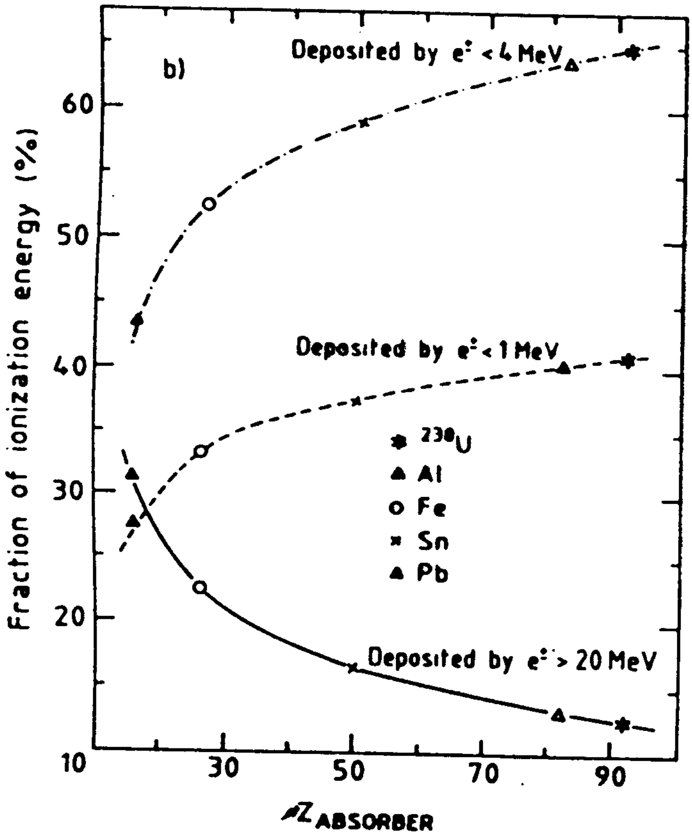
Final note ⇒

The Rossi Model is COMPLETILY WRONG!

(As a microscopic model)

10 GeV electron

Fraction of $E_{dep.}$ by...



60% ← $e^{\pm}$ (< 4 MeV)

40% ← $e^{\pm}$ (< 1 MeV)

← $e^{\pm}$ (> 20 MeV)

Z absorber

So most energy is deposited by <u>low</u> energy $e^{\pm}$'s.

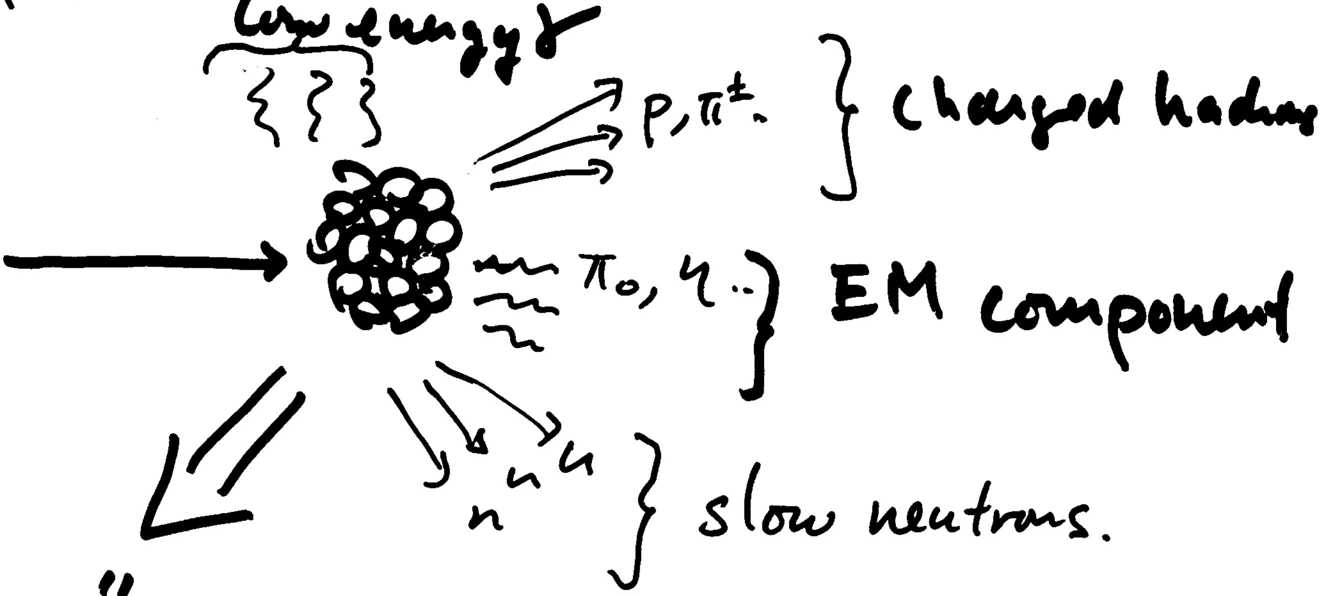
HOMEWORK: WHY DOES THE ROSSI MODEL WORK?

Hadronic Calorimetry

(and compensation)

A much more complicated story... than EM.

A hadron strikes a nucleus ...



"lost" nuclear binding, ν

~20 - 30% large fluctuation.

⇒ one reason for worse resolution of hadronic calorimeter..

Another ⇒ EM component.

EM response

fraction of "hadronic" energy

$$\pi^{\pm} = f_{em}\, e + \underset{(1-f_{em})}{f_h}\, h$$

response of CALORIMETER TO $\pi^{\pm}$

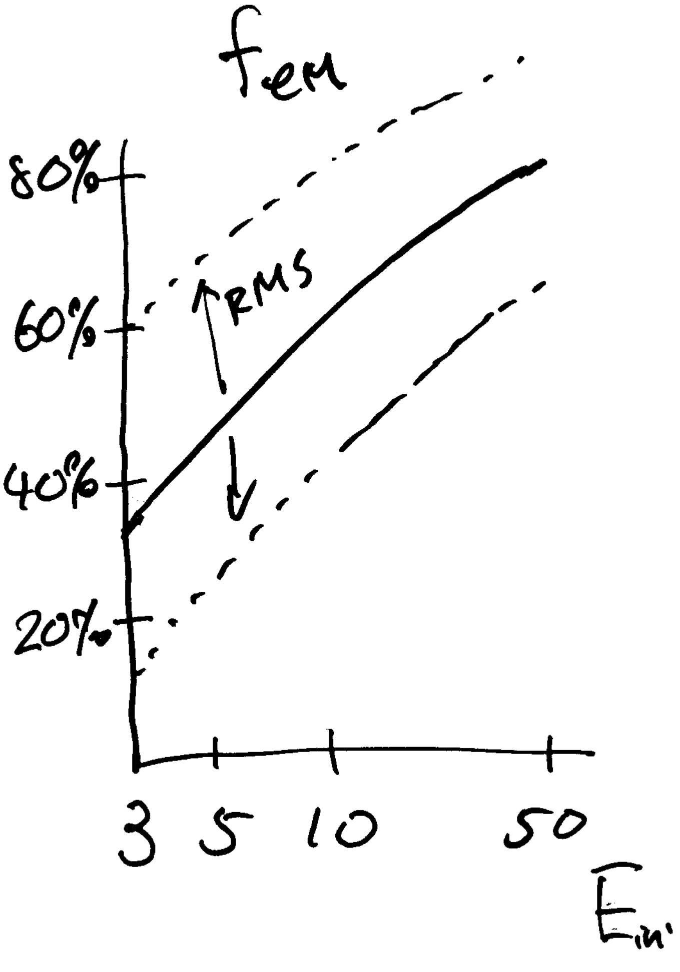
fraction of EM energy

"hadronic" response

"hadronic" means everything in the shower except the "EM comp."

EM fraction f_{em} is:

1. large
2. Fluctuates a lot (non-gaussian)
3. Depends on E_{ini}



So if $\frac{e}{h} \neq 1$ then:

1. Signal for mono-energetic hadron
→ non-gaussian

2. Fluctiation in f_{em} contributes to the energy resolution

3. $\frac{\sigma}{E} \not\propto \frac{1}{\sqrt{E}}$

4. Hadron response non-linear

In general, ... $\frac{e}{h} > 1$ ← binding energy loss
slow neutrons not seen.

But ...... →

In a sampling calorimeter,
we can **TUNE** $\frac{e}{h}$!

We need e ↓ (but not too much!)
We need h ↑

This is possible because

$$\frac{de}{dx} \neq \frac{dh}{dx}$$

x: A property of the sampling calorimeter.

i.e.:
- Material of passive medium
  Fe, Pb, U, ... etc.
- Thickness of passive medium
- Material of active medium LAr, Sci...
- Thickness of active medium

⋮

For example..

Active media **LAr** vs. **Sci.**

⇒ Slow neutrons lose their (kinetic) energy via (elastic) collisions with nuclei.

i.e. Lighter the nuclei, more energy transfered to the active media.

Organic Sci has lots of hydrogen.

Use of Sci. ⇒ $n\uparrow$ (relatively)

Passive media **Pb** vs. U

⇒ U will produce relatively more neutrons via fission. $n\uparrow$

Only helps it sensitive to n ⇒ Sci

not LAr

But... if you wait a long time ($\sim 1\mu s$)

neutron capture will produce γ's

e ↓ with thickness of absorber

How fast depends on Z of the material

Remember - low energy $e^{\pm}, \gamma$

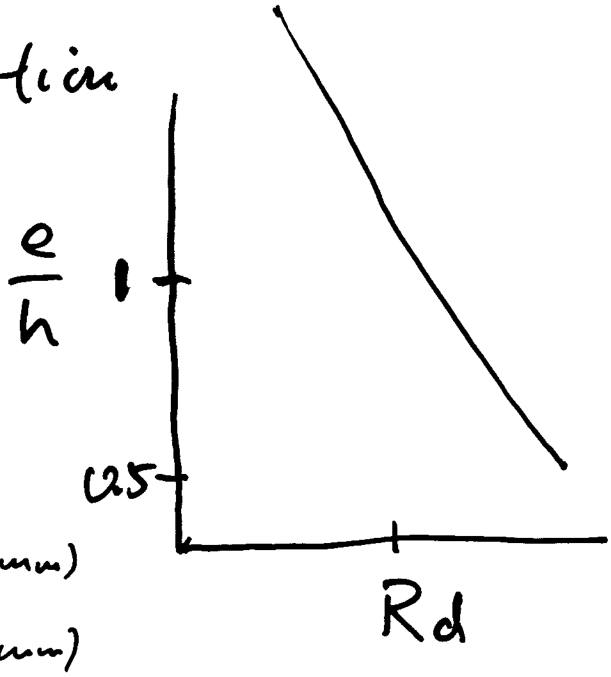
photo electric effect $\sim Z^5$

h relatively insensitive to thickness.

For **Sci** Sandwich calorimeters:

To a first approximation

$$\frac{e}{h}(R_d),$$



$$R_d = \frac{\text{Thickness of Abs. (mm)}}{\text{Thickness of Sci. (mm)}}$$

$R_d^0(U) \simeq 1$

$R_d^0(Pb) \simeq 4$

$$\frac{e}{h}(R_d^0) = 1$$

Practical limit of thinness
of SCIN. PLATE ~ 2-3 mm.

R^{i}_{d} ⇒ fixes the thickness of absorber.

For $\frac{e}{h} = 1$: U ~ 2-3 mm $1 X_0$

Pb ~ 8-12 mm. $5 X_0$

Remember: $\frac{\sigma_{\text{sample}}}{E} \propto \underset{\uparrow}{\sqrt{d}} / \sqrt{E}$

thickness in X_0

sampling fluctuation of Pb-Sci
worse than U-Sci.

Can do better with sci fibers.
(1 mm dia)

	e	**π**
CHORUS SPACAL	$\frac{13\%}{\sqrt{E}}$	$\frac{28\%}{\sqrt{E}}$

Pb-Sci calorimeter

The ZEUS U-Calorimeter

1. Physical description
   - Test beam results

2. Calibration using
   U radioactivity

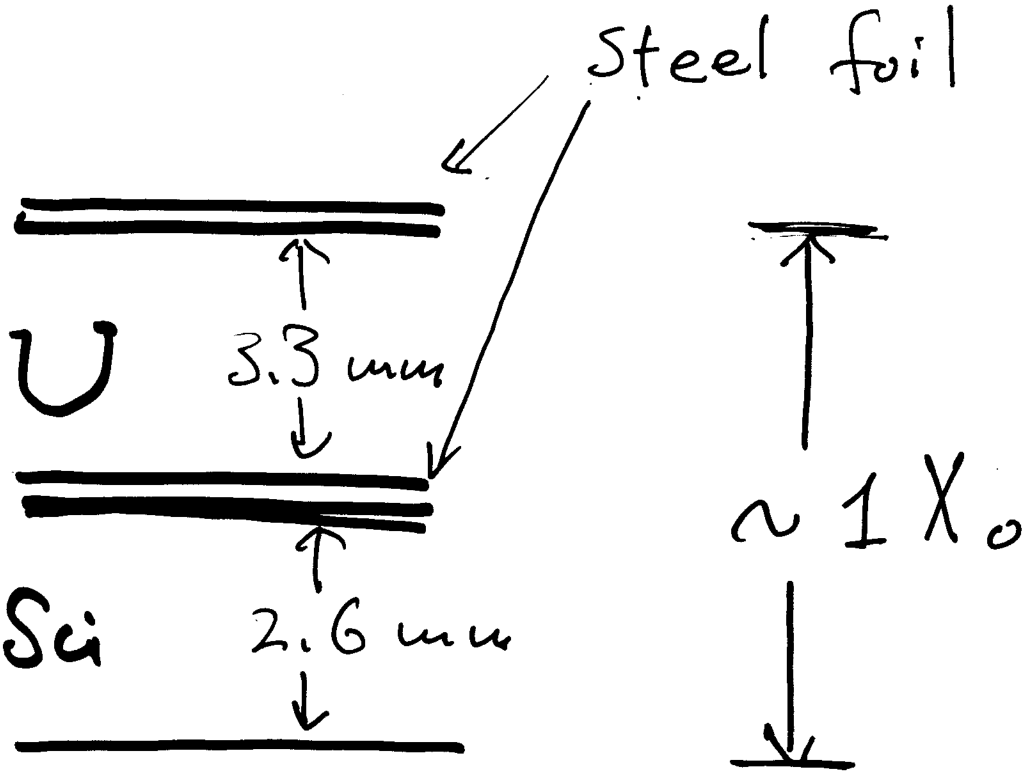
3. Readout & trigger

DESY-92-159
CALOR. 92 conf.

The Uranium Calorimeter

Uranium-Scintillator sandwich

— full intrinsic compensation.



M C's   Prototype Tests

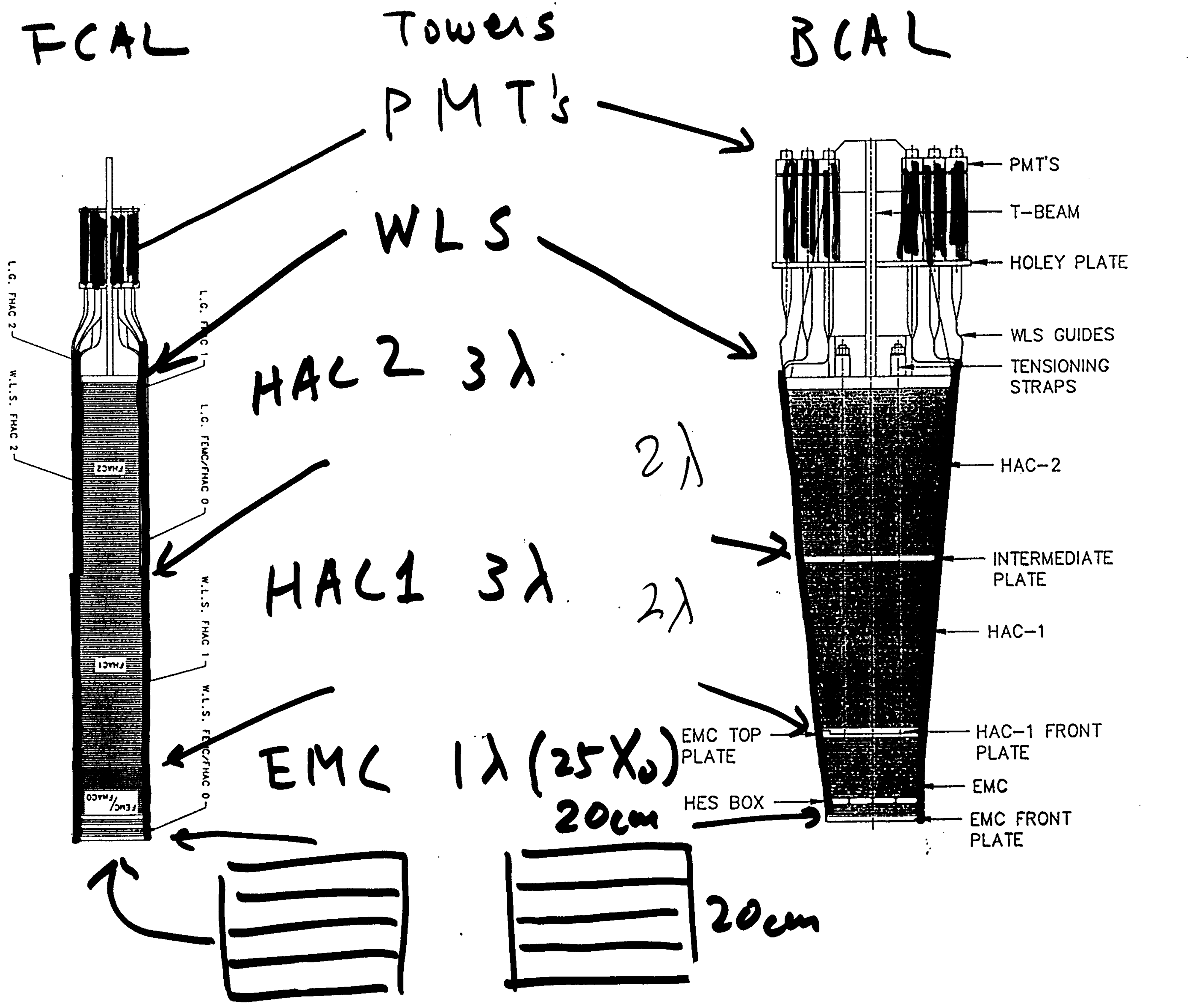
↓

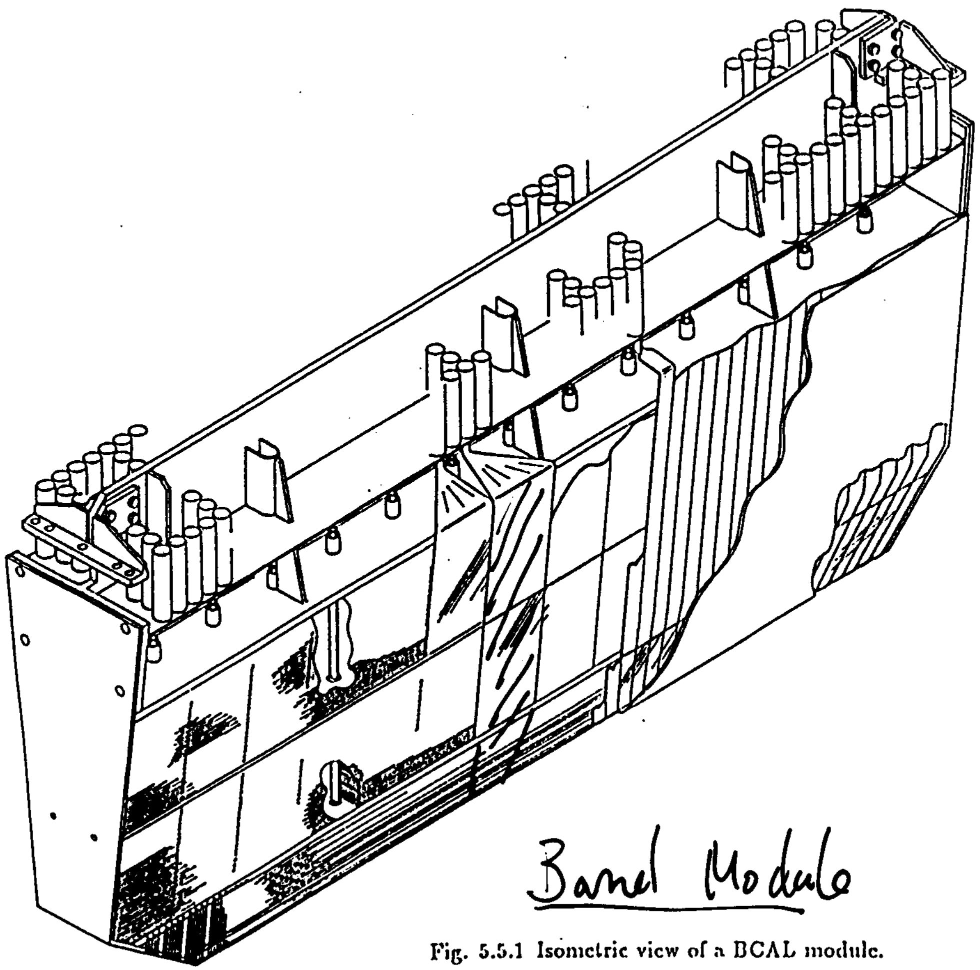
Compensation Mechanism

↓

USE Thickness ratio as tuning parameter

$$\frac{e}{h} = 1$$


FCAL
Towers
BCAL
PMT's
WLS
HAC2 3λ
HAC1 3λ
EMC 1λ (25X0)
2λ
2λ
20cm
20cm
L.G. FHAC 2
W.L.S. FHAC 2
L.G. FHAC 1
L.G. FEMC/FHAC 0
W.L.S. FHAC 1
W.L.S. FEMC/FHAC 0
FHAC2
FHAC1
FEMC/FHAC0
PMT'S
T-BEAM
HOLEY PLATE
WLS GUIDES
TENSIONING STRAPS
HAC-2
INTERMEDIATE PLATE
HAC-1
HAC-1 FRONT PLATE
EMC TOP PLATE
EMC
HES BOX
EMC FRONT PLATE

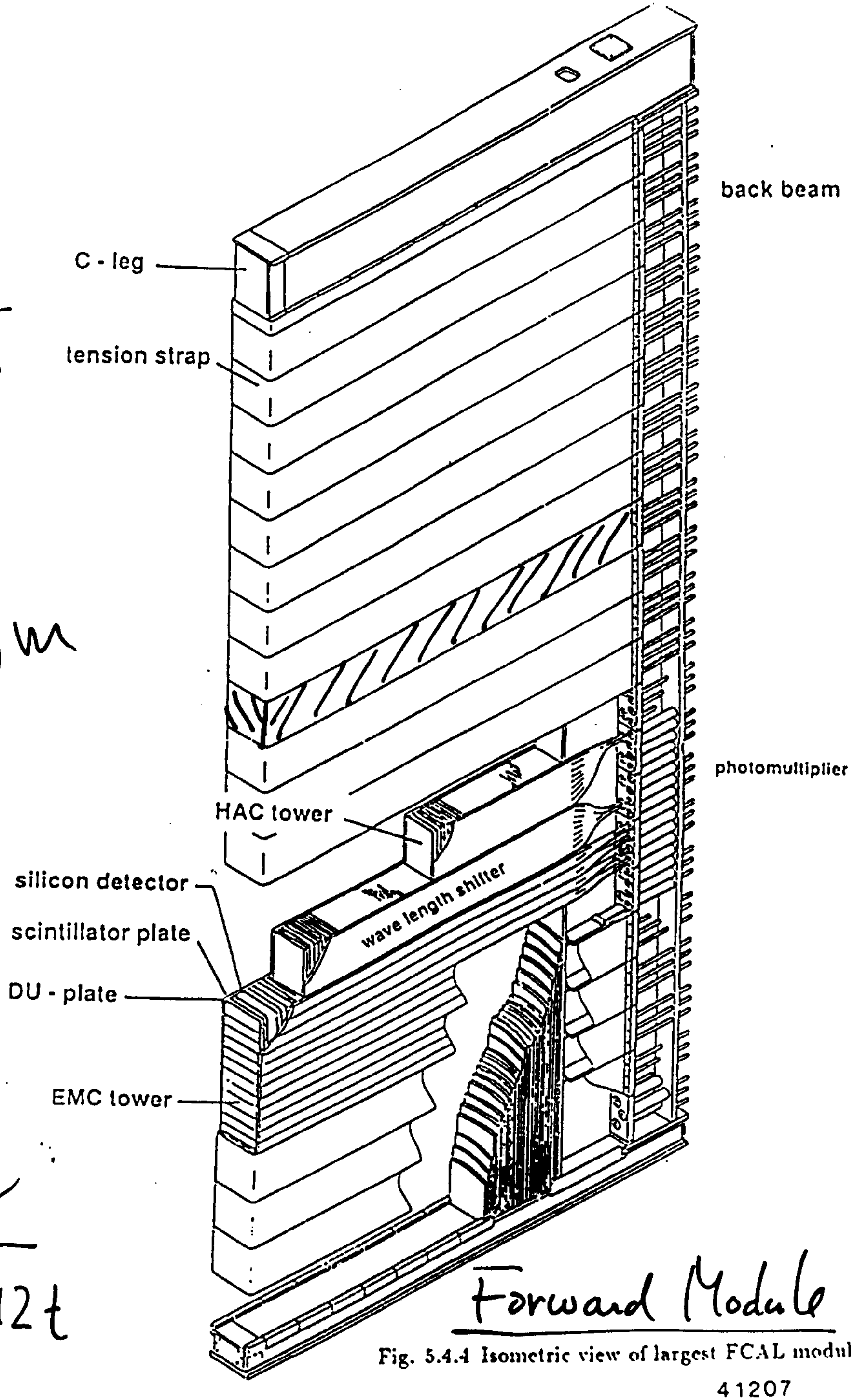


Barrel Module

Fig. 5.5.1 Isometric view of a BCAL module.

4.6m

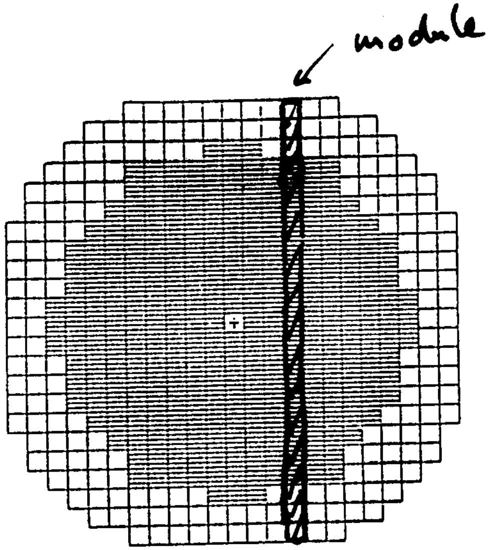
~12t



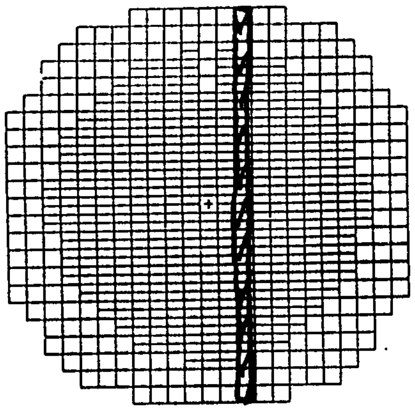
Forward Module

Fig. 5.4.4 Isometric view of largest FCAL module.

41207

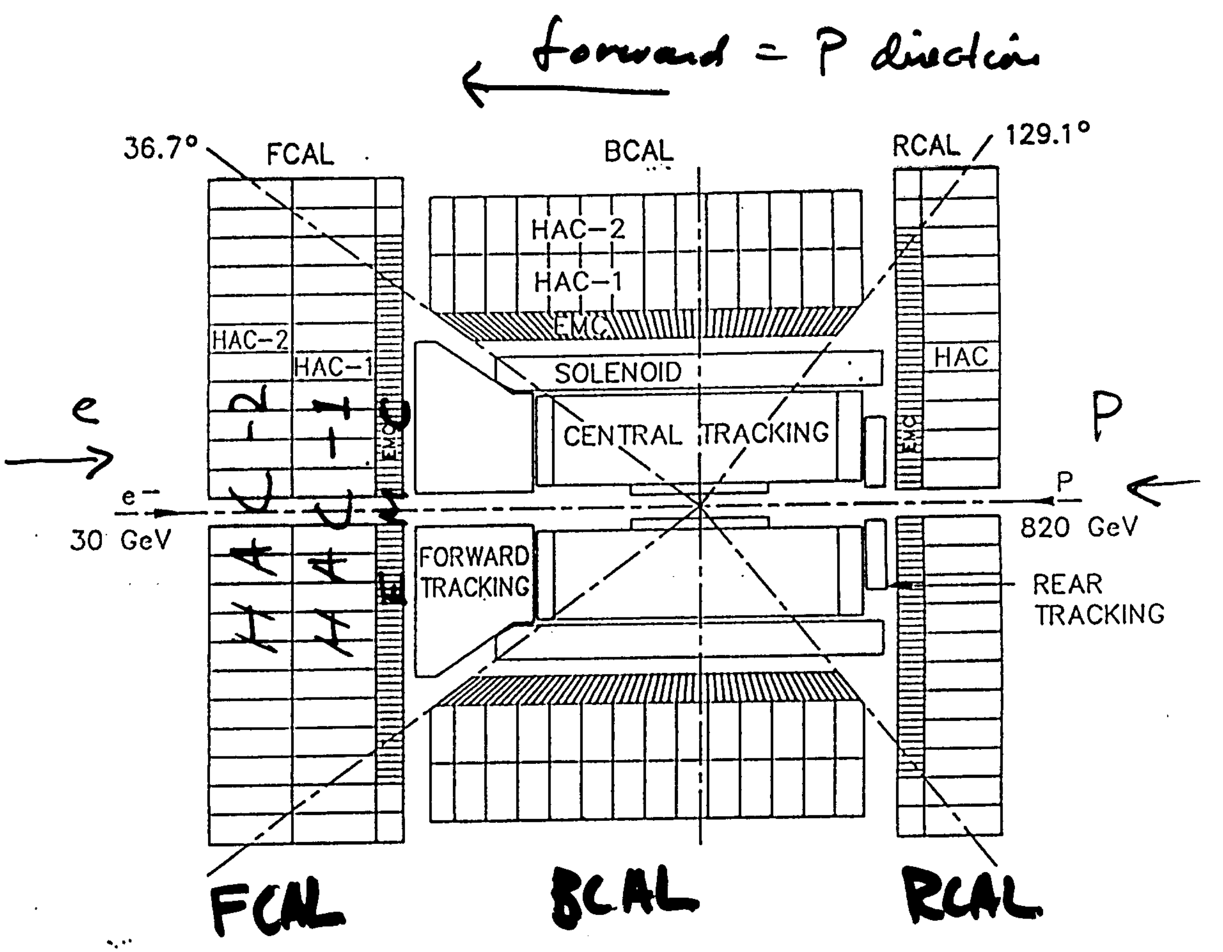


FCAL FCAL front view



RCAL front view

RCAL

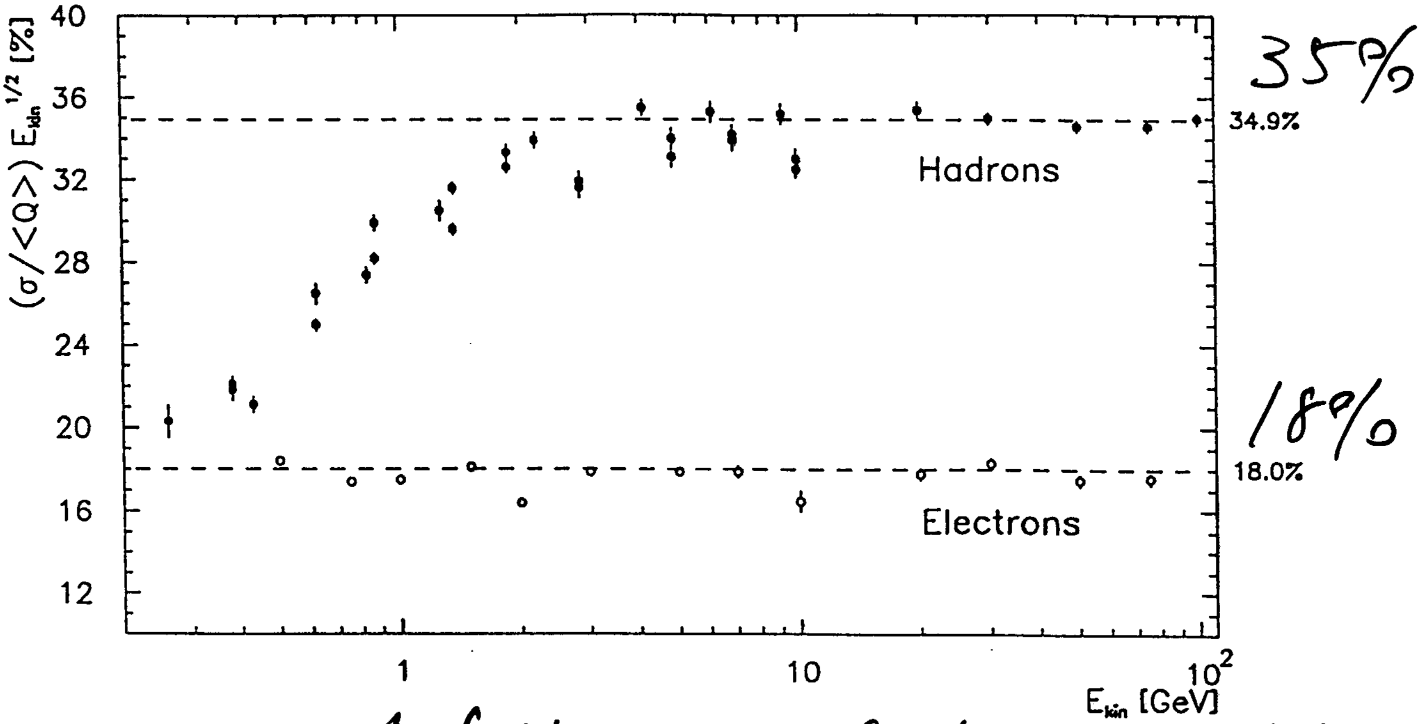


Coverage: 99.8% forward hemisphere
99.5% backward hemisphere.

~12k channels
~6k cells

Energy Resolution

Prototype test



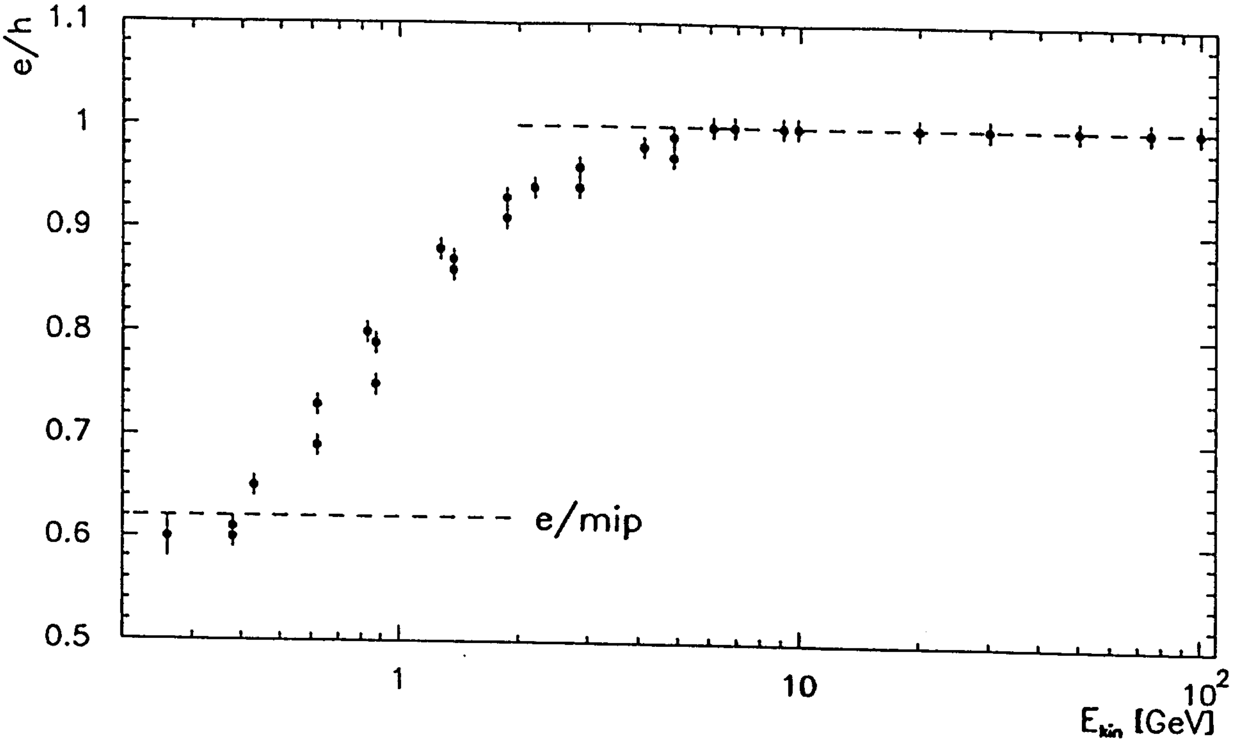
1 GeV 10 GeV 100 GeV

E_{kin}

F/RCAL module test

17.5%/$\sqrt{E}$ at 47 GeV electron

e/h, FCAL prototype.



1 GeV 10 GeV 100 GeV

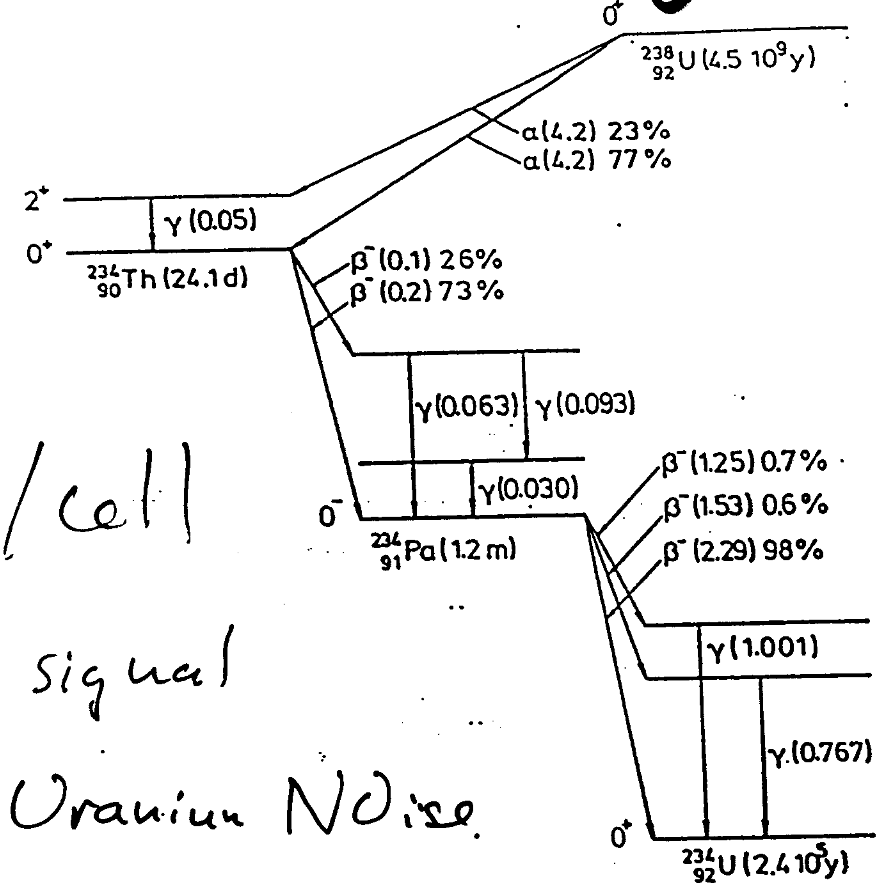
E_{kin}

Approach e/mip at lower energies

⇒ Hadrons lose their energies through ionization, at low energies

Calibration:

^{238}U:



^{238}U decay

$\geq$ 1 decay/us/cell

Integrate this signal

I_{UNO} ← Uranium NOise

Prop. to gain (up to + PMT)

monitor gain → Plot

Cell to Cell Calibration → Plot

Good to 1 – 1.5%

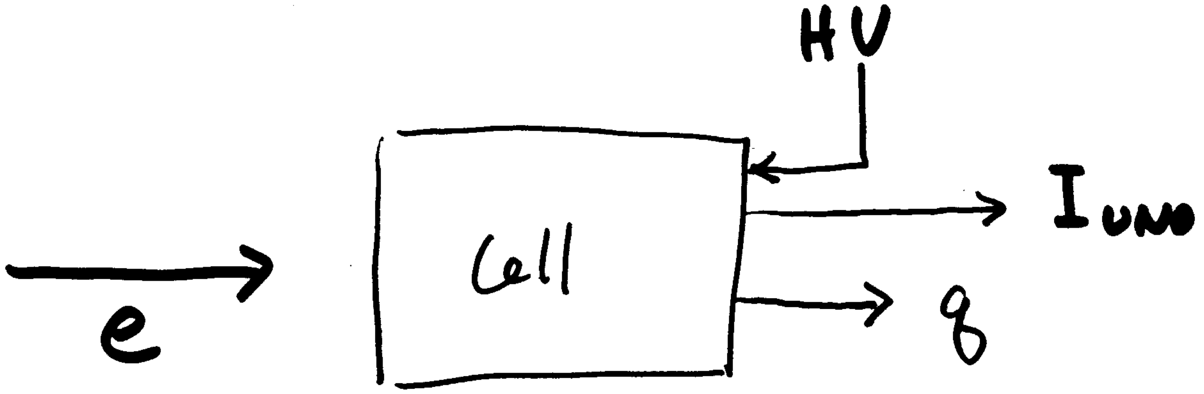
Absolute calibration at test beam.

PC/GeV at $I^{nom.}_{UNO}$

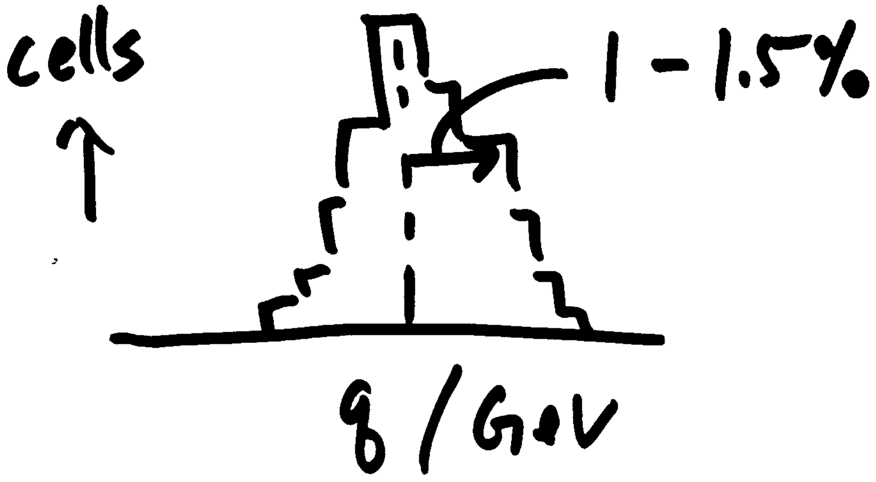
Transport to Experiment.

How to calibrate absolutely (using UNO & testbeam)

1. Build a calorimeter cell.
2. Take to test beam e 1 – 100 GeV, say
3. Adjust HV until $I_{UNO} = I_{UNO}^{nominal}$



4. Take data & determine q/GeV
5. Repeat.

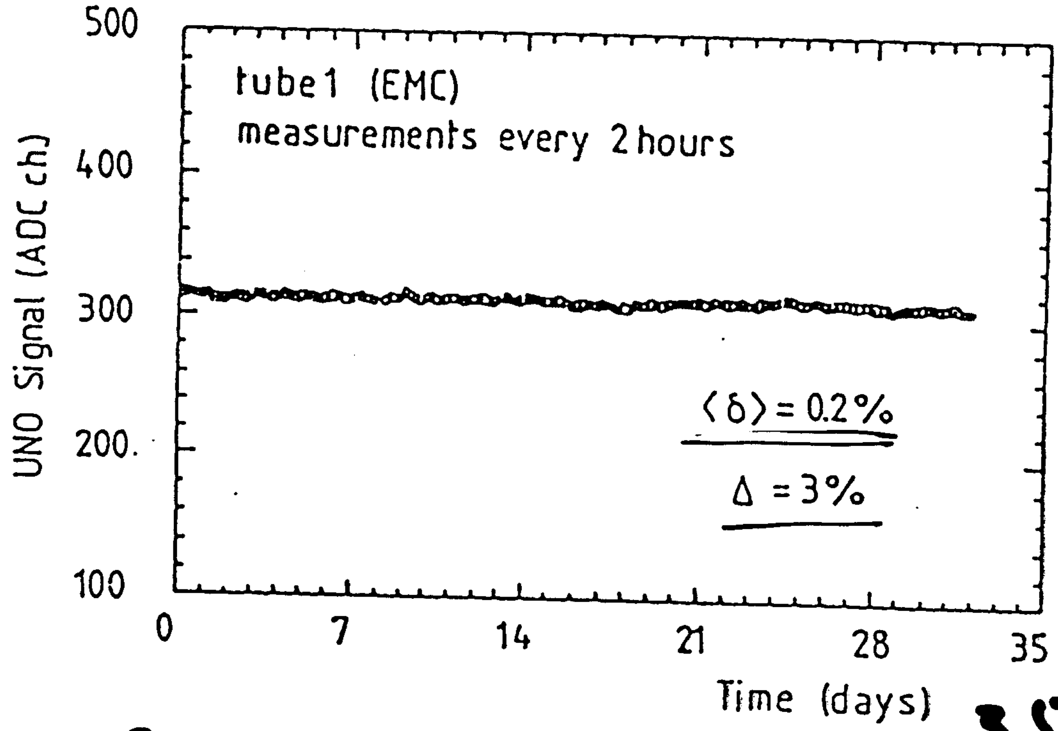


⇒ Bring test beam calibration to ZEUS
pe/GeV & I_{UNO} !

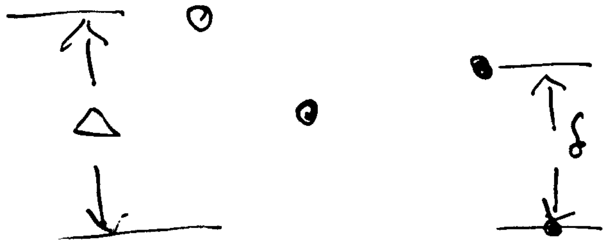
⇒ Don't need to test all cells !

FCAL prototype

Stability of UNO



35 days



Measure I_{UNO} once 8 hours

→ good to 0.5 %

$$q = q_0 \times \frac{I_{UNO}^{nominal}}{I_{UNO}^{measured}}$$

Readout & Trigger

- 12 K channels (6K × 2)
- Buffer until trigger ready (~ few μS)

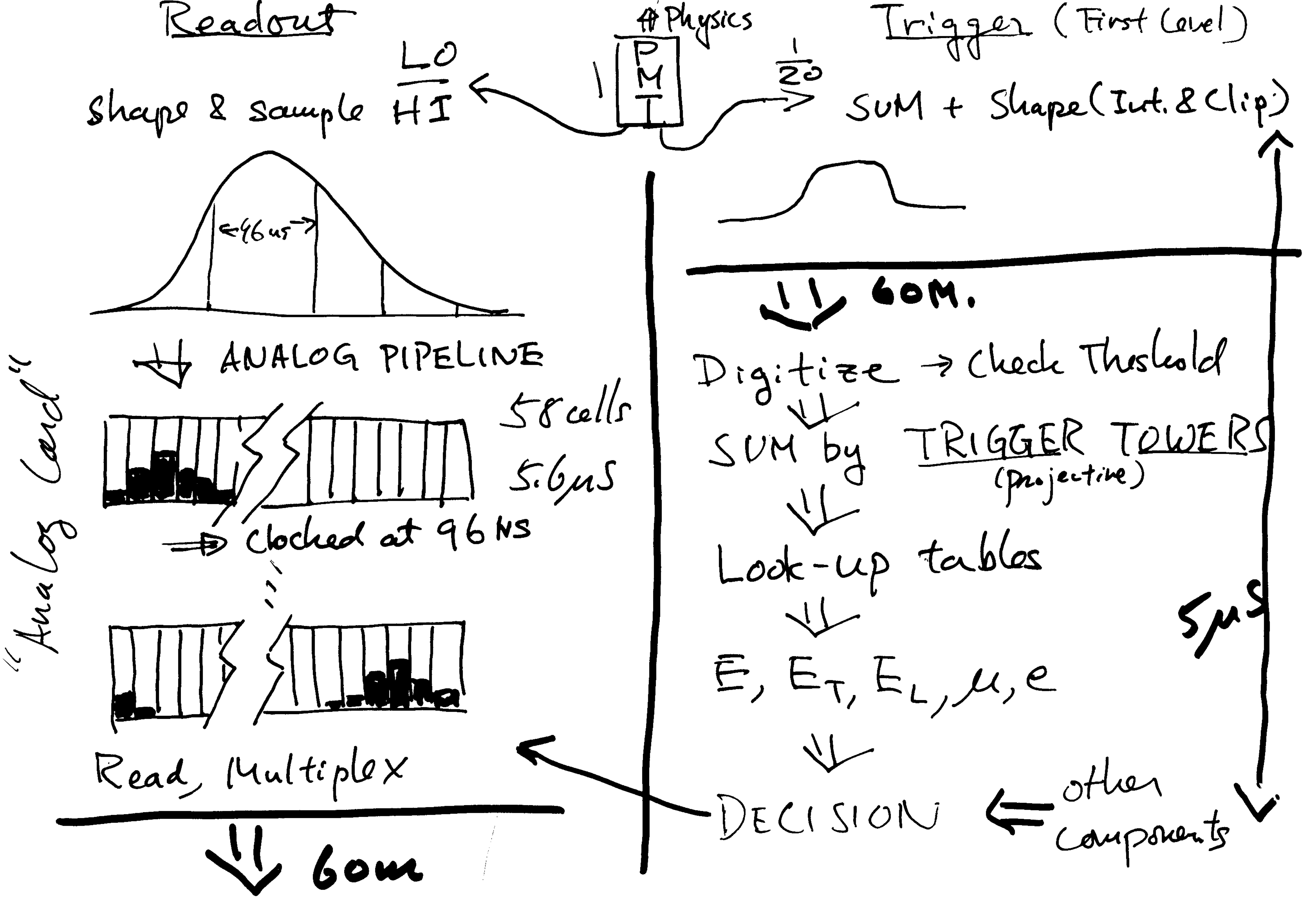
  Avoid pile-up.

- Trigger 96μs << Processing time

  Deadtime loss design

  decision at 10 MHz

  at First Level



Readout

Physics

PMT

1

$\frac{LO}{HI}$

Shape & sample

←96ns→

ANALOG PIPELINE

58 cells

5.6μS

⇒ Clocked at 96 NS

"Analog Card"

Read, Multiplex

⇓ 60m

Trigger (First Level)

$\frac{1}{20}$

SUM + Shape (Int. & Clip)

⇓ 60M.

Digitize → Check Threshold

⇓

SUM by TRIGGER TOWERS (projective)

⇓

Look-up tables

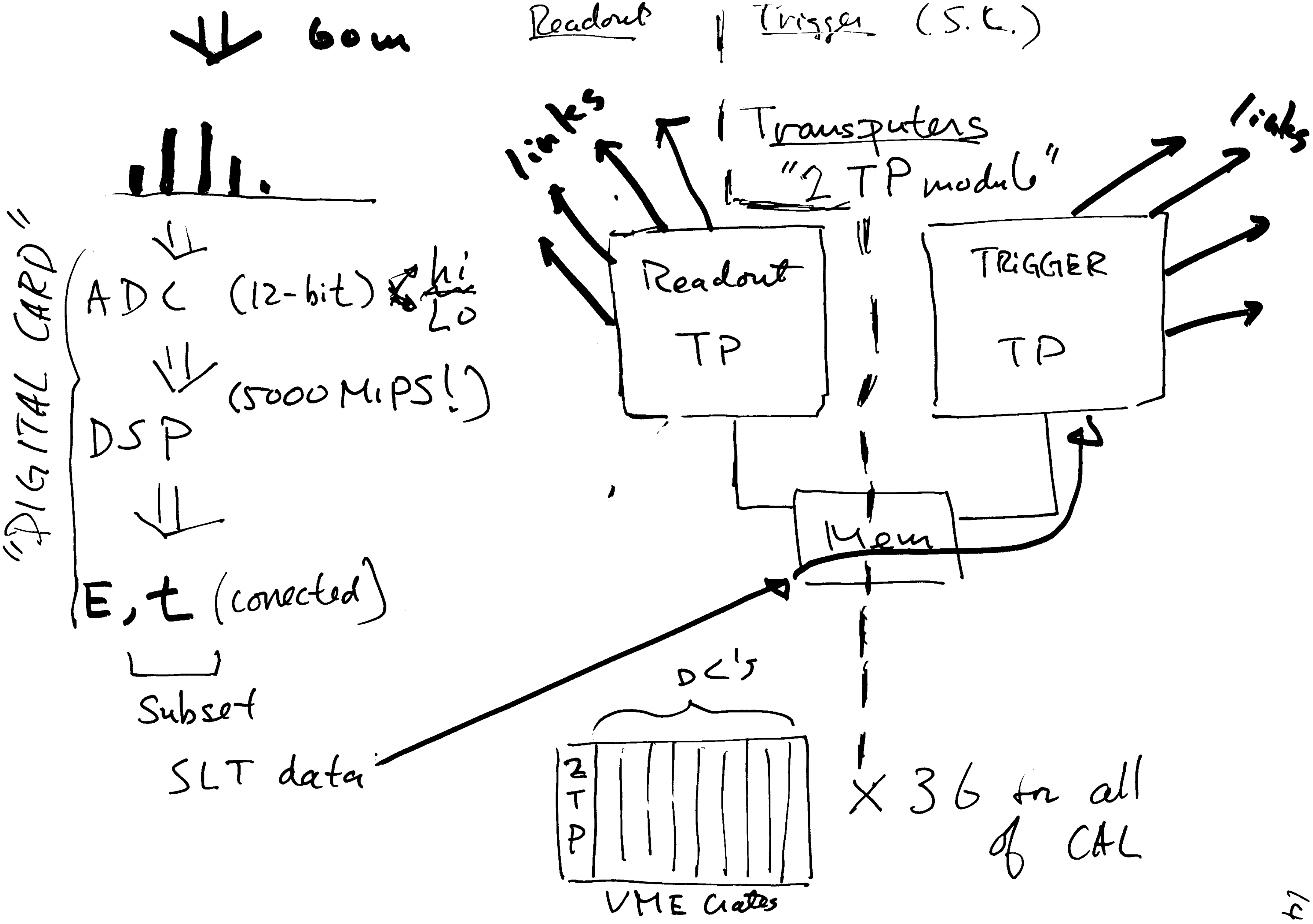
⇓

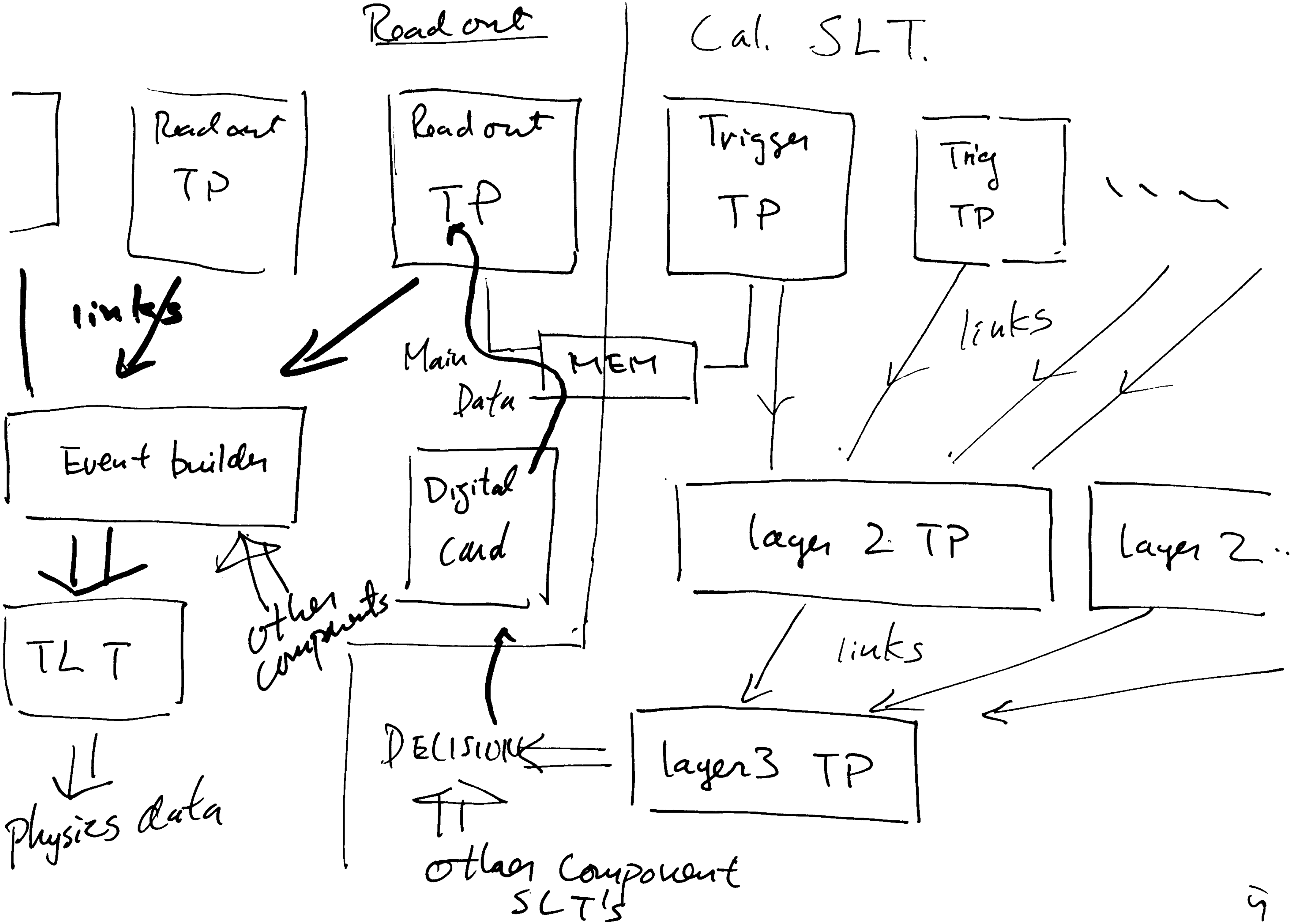
E, E_T, E_L, μ, e

⇓

DECISION ⇐ other components

5μS


60 m
"DIGITAL CARD"
ADC (12-bit) hi Lo
(5000 MIPS!)
DSP
E, t (conected)
Subset
SLT data
Readout | Trigger (S.C.)
Transputers
"2 TP modul"
links
links
Readout TP
TRIGGER TP
Mem
DC's
2TP
VME crates
X 36 for all of CAL


Readout
Cal. SLT.
Readout TP
Readout TP
Trigger TP
Trig TP
links
links
links
MEM
Main Data
Event builder
Digital Card
layer 2 TP
layer 2 ..
layer3 TP
TLT
other components
DECISION
other Component SLT's
physics data

Ref's: (BCAL) NIM A309 (1991) 77
(F/RCAL) NIM A309 (1991) 101
(electronics) NIM A336 (1993) 23

Timing: Z.Note 93-021

Position: Z.Note 94-123
96-093
97-053