CALORIMETERS

- BLOCK OF MATTER "INTERCEPTING" A PRIMARY PARTICLE OF SUFFICIENT THICKNESS TO CAUSE IT TO INTERACT AND DEPOSIT ALL OF ITS ENERGY INSIDE THE DETECTOR VOLUME. MUST MEASURE ALL PARTICLES IN THE SUBSEQUENT "SHOWER" OF LOWER ENERGY PARTICLES.

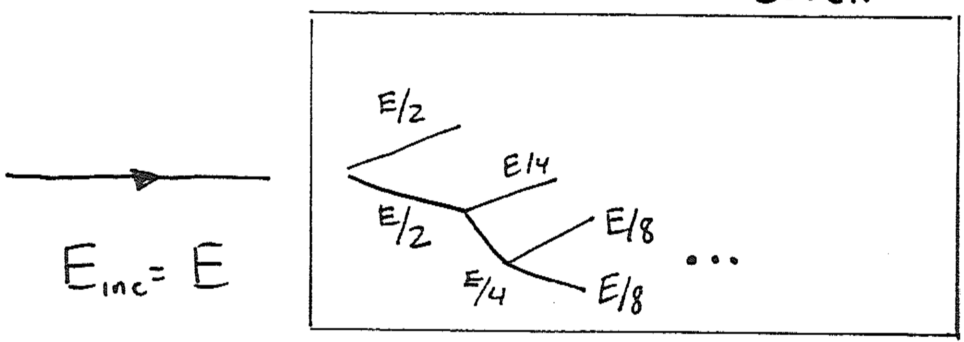
DETERMINE THE ENERGY FROM TOTAL ABSORPTION OF CHARGED OR NEUTRAL PARTICLES.

- A FRACTION OF THE DEPOSITED ENERGY IS DETECTABLE IN THE FORM OF:

SCINTILLATION LIGHT (NaI, BGO, ...)
ĈERENKOV RADIATION ($PbSO_4$, ...)
IONIZATION (LiAr, MWPCs, Si-DET)
(OR HEAT)

THIS FRACTION SHOULD BE PROPORTIONAL TO INCIDENT ENERGY.

CALORIMETER "BLOCK"



$E_{DEP} = E_{VIS} + E_{INVIS}$ ← e.g. BELOW THRESHOLD TO TO IONIZE

$E_{VIS} = K\, E_{INC}$

- DIFFERENT ABSORPTION PROCESSES FOR e, γ AND HADRONS $(p, n, K, \pi, \ldots)$

<u>e, γ</u> : $e^{\pm}: E_0 \rightarrow \frac{E_0}{e}$ $(e \equiv 2.718)$ IN $1\, X_0$ RADIATION LENGTH

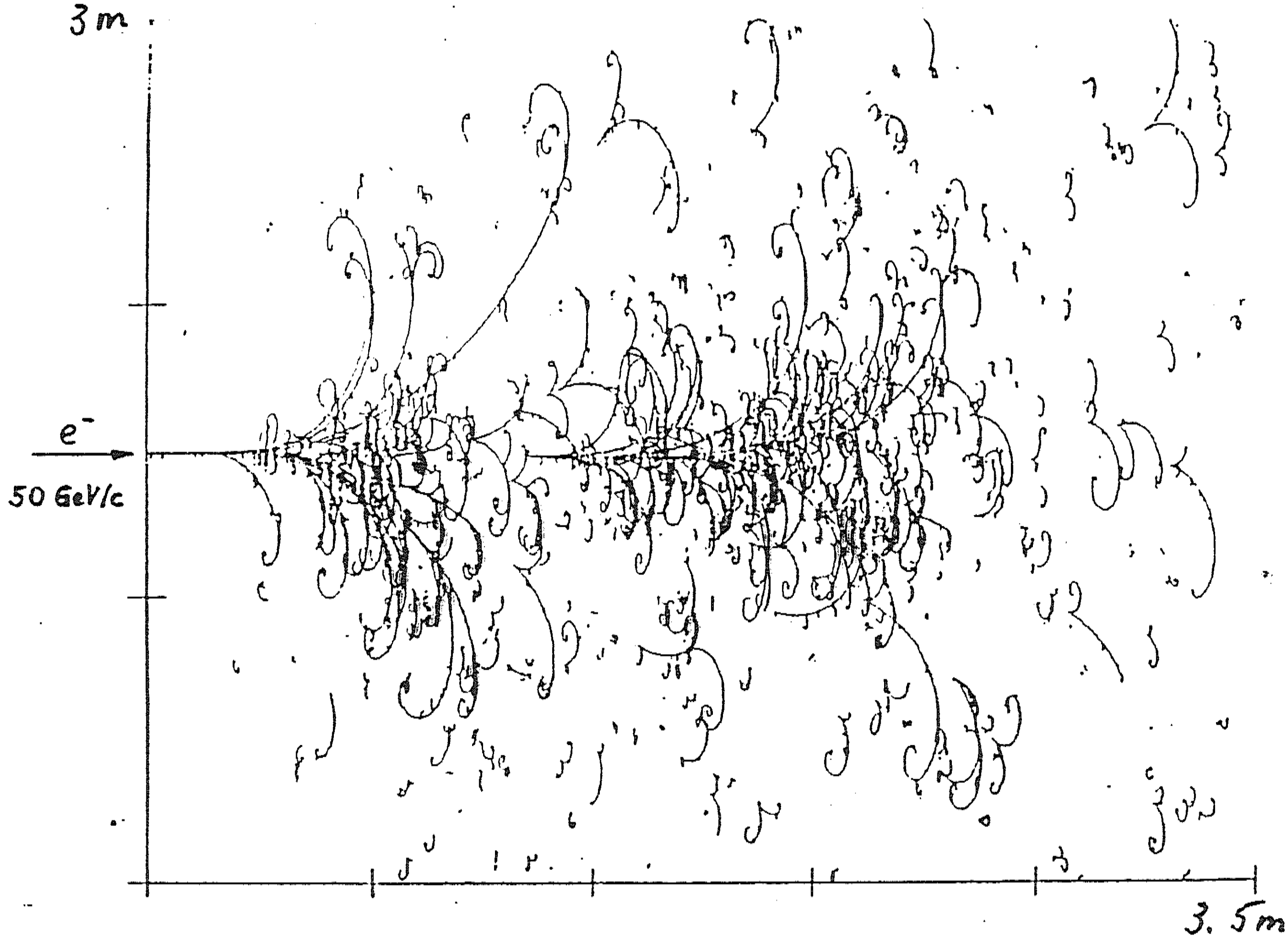
$E = E_0 e^{-x/X_0}$

MOSTLY BREMSSTRAHLUNG

γ : $\gamma \rightarrow e^+e^-$ PAIR PRODUCTION

$I = I_0\, e^{-7x/9X_0}$ (~54% %)

Ex. : E.M. SHOWER



BEBC , Ne/H_2 (70/30%) , B = 3T

ELECTROMAGNETIC SHOWER DEVEL.

EXAMPLE OF A HOMOGENEOUS CALORIMETER ⇒ ALL ENERGY DEPOSITED IN ACTIVE MEDIUM

⇏ ALL ENERGY DETECTED.

h: CHARACTERISED BY NUCLEAR ABSORPTION LENGTH : λ

λ IS MEAN FREE PATH BETWEEN <u>IN</u>ELASTIC NUCLEAR REACTIONS (HADRONS ON NUCLEUS

"TOTAL ABSORPTION" REQUIRES:

$$L^{EM} \simeq 21\ X_0$$

DEPENDS SLIGHTLY ON ENERGY AND MATERIAL (SEE LATER)

$$L^{had} \simeq 6\ \lambda$$

MATERIAL	X_0 (cm)	λ (cm)	ρ_m (cm)	E_{CRIT} (MeV
NaI	2.6	41	4.4	13
BGO	1.1	23	2.3	7
Lead Glass	1.7-2.5			12-16
Fe	1.76	17	1.8	28
Pb	0.56	17	1.6	9.5
U	0.32	10.5	1.0	9

BGO = $Bi_4\,Ge_3\,O_{12}$

Lead Glass PbO / SiO_4

(50-70 → 40-60 %)

CAPABILITIES OF CALORIMETERS

- SENSITIVE TO CHARGED PARTICLES AND TO NEUTRALS ($\pi^0 \to \gamma\gamma$, $\gamma \to e^+e^-$ etc., $n \to p$ NUCLEAR CHARGE EXCHANGE)

- DEVELOPMENT OF SHOWER IS A STATISTICAL PROCESS (LAW OF LARGE NUMBERS)

  AVERAGE NUMBER OF SECONDARIES $\langle N \rangle$ PROPORTIONAL TO ENERGY $\propto E$

- UNCERTAINTY ON ENERGY (IN LIMIT OF LARGE N) $\longrightarrow$ $\sqrt{N} \Rightarrow \sqrt{E}$

$$\Rightarrow \boxed{\sigma_E / E \sim \frac{1}{\sqrt{\langle N \rangle}} \sim \frac{1}{\sqrt{E}}}$$

- AS ENERGY OF SECONDARIES IS DEGRADED

  $\sim 1/2$ OF THEM WILL BE IN LAST STEP OF SHOWER DEVELOPMENT

  $\Rightarrow$ SHOWER LENGTH $\sim \ln(E)$

- CAN SAMPLE SHOWER DEVELOPMENT RADIALLY AND LONGITUDINALLY TO MEASURE

  POSITION AND DIRECTION OF INCIDENT PARTICLE

  (OFTEN USE EXTRA FINE POSITION SAMPLING DETECTOR AT SHOWER MAX)

- DETECTOR RESPONSE DIFFERENT TO $e, \mu, \nu,$ Hadrons

  $\Rightarrow$ PARTICLE ID.

- TYPICAL CALORIMETER SENSITIVE MEDIA ARE "FASTER" THAN TRACKING DETECTORS (ESPECIALLY DRIFT CHAMBERS) eg. SCINTILLATORS, LIQUID ARGON

  $\Rightarrow$ CAN BE USED ON-LINE TO MAKE FAST DECISIONS ABOUT EVENT TOPOLOGIES

  (i.e TRIGGER).

ENERGY LOSS MECHANISMS

RADIATIVE MECHANISMS DOMINATE AT HIGH ENERGY

$\sim \gamma^2$ $\quad (\gamma \gtrsim 100)$

$\hookrightarrow \frac{1}{(1-\beta^2)}$

↳ ONLY FOR ELECTRONS OR VERY HIGH ENERGY MUONS.

THUS BREMSSTRALUNG > IONIZATION (ELECTRONS)

PHOTO ELECTRIC EFFECT
COMPTON SCATTERING (PHOTONS)
PAIR PRODUCTION

↳ DOMINANT PROCESS ABOVE CRITICAL PHOTON ENERGY.

FOR DETAILS ON Q.E.D. PROCESSES INVOLVED SEE:

- PARTICLE DATA REVIEW (LONG LISTINGS)
- D. BAILEY'S NOTES FROM 2405 LAST YEAR.

Radiation Processes

Compton Scattering

~~Compton scattering~~

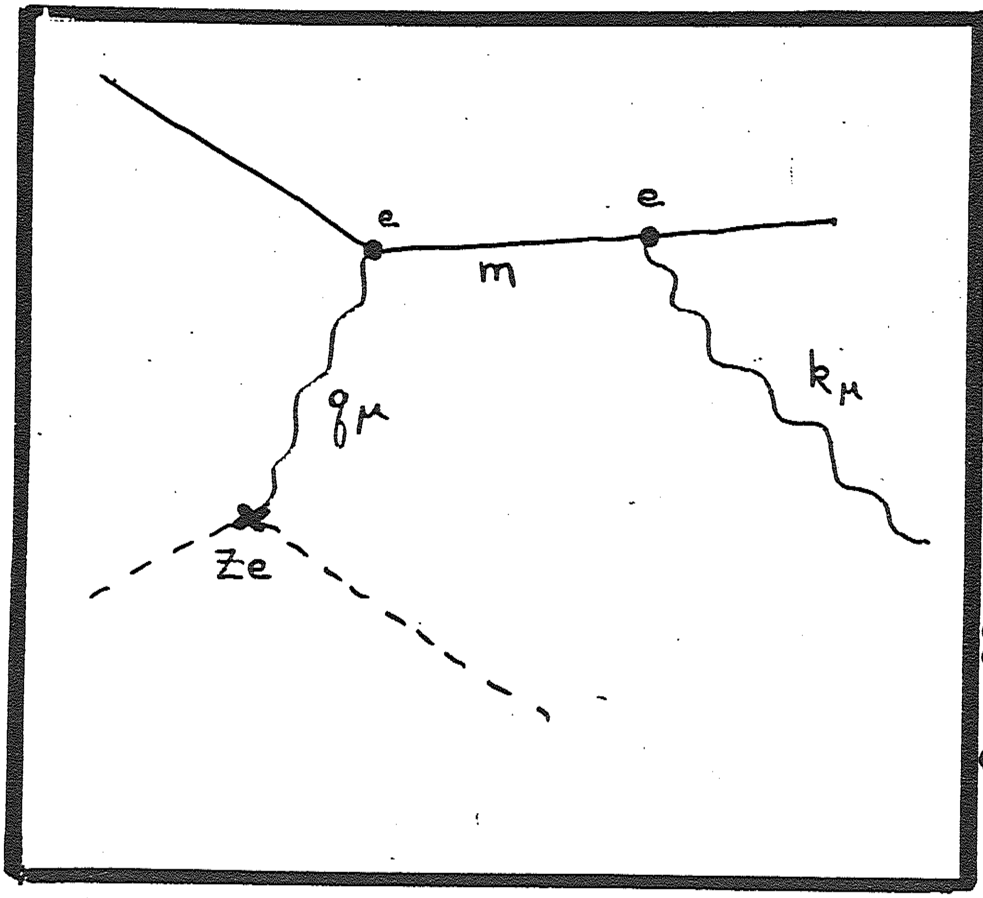
$$\sigma = \pi \frac{\alpha^2}{m^2}\left[\frac{1}{\gamma^3}\ln(1+2\gamma) + \frac{2(1+\gamma)(2\gamma^2-2\gamma-1)}{\gamma^2(1+2\gamma)} + \frac{8\gamma^2}{3(1+2\gamma)^3}\right]$$

Photo Electric Effect

Positron annihilation

$$\sigma = \pi \frac{\alpha^2}{m^2}\frac{1}{\gamma+1}\left[\frac{\gamma^2+4\gamma+1}{\gamma^2-1}\ln\left(\gamma+\sqrt{\gamma^2-1}\right) - \frac{\gamma+3}{\sqrt{\gamma^2-1}}\right]$$

$\gamma = E_{e^+}/m_e$



PAIR PRODUCTION

~~Pair Production~~

$$\frac{d\sigma}{dk} = Z\alpha\frac{\alpha^2}{m^2}\frac{4}{k}\left[\left(w_+^2+w_-^2+\tfrac{2}{3}w_+w_-\right)\ln\left(\frac{183}{Z^{1/3}}\right) - \frac{1}{9}w_+w_-\right] \quad \sigma\sim$$

$w_\pm = E_\pm/k$, $E_+E_- >> km$

Bremsstrahlung

$$\frac{d\sigma}{dk} = Z^2\frac{\alpha^2}{m^2}\frac{4}{k}\left[\left(1+w^2-\tfrac{2}{3}w\right)\ln\frac{183}{Z^{1/3}} + \frac{w}{9}\right] \quad \sigma$$

$w = E_f/E_i$, $E_i >> m$

$\alpha E_i >> m$ $\qquad \sigma = Z\alpha\frac{\alpha^2}{m^2}\left[\ln\left(183\,Z^{-1/3}\right) + \frac{1}{18}\right.$

~~Synchrotron radiation~~

ALL OF THESE RADIATIVE EFFECTS $\propto Z^2$ AND DENSITY OF MATERIAL

CAN CHARACTERISE ANY MATERIAL BY ITS RADIATION LENGTH

$$E = E_0 \, e^{-x/X_0}$$

$$X_0 \left[{}^{gr}/_{cm^2} \right] \simeq 180 \frac{A}{Z^2}$$

e.g.

$X_0(U) = 3.2$ mm

$X_0(Pb) = 5.6$ mm

$X_0(Fe) = 18$ mm

X_0 (Scintillator) $=$ 424 mm

X_0 (Air) $= 3 \times 10^5$ mm.

PROCESS OF "LOSING" $1/e$ OF ENERGY EVERY X_0 CONTINUES UNTIL SHOWER ELEMENTS FALL BELOW "CRITICAL ENERGY", ϵ.

THIS IS THE ENERGY LOST IN COLLISIONS (IONISATION) PER X_0

$$\epsilon\ (\mathrm{MeV}) \simeq 550/Z$$

THIS IS THE DEMARKATION ENERGY BETWEEN SECONDARY PRODUCTION (SHOWER GROWING) THROUGH RADIATIVE EFFECTS

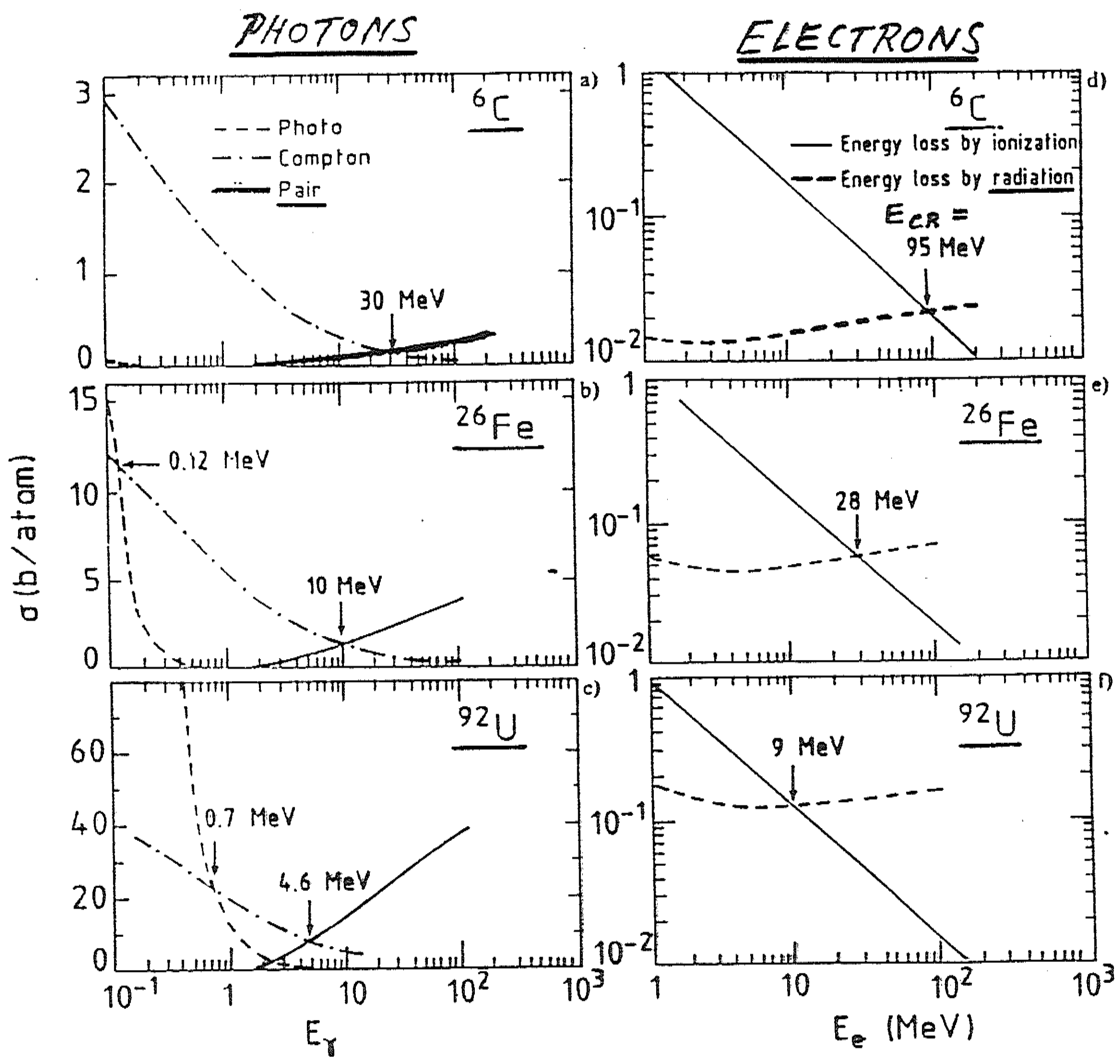
&

THE FINAL DISSIPATION OF THE LAST GENERATION OF SHOWER PARTICLES IN IONIZATION

$\epsilon_{Cu} = 9$ MeV $\qquad \epsilon_{SCINT} = 87$ MeV

$\epsilon_{Fe} = 21$ MeV $\qquad \epsilon_{L\text{-}Ar} = 30$ MeV.

ENERGY LOSS AS FUNCTION OF ABSORBER



- E. Storm, H.J. Israel, Nucl. Data Tables 7 ('70), 565;
- L. Pages et al., Atomic Data 4 ('72), 1.

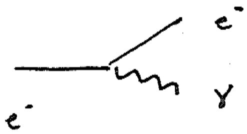
Comp. by C.W. Fabjan, R. Wigmans; CERN-EP/89-64

also Fig. on p. 3-6

LONGITUDINAL SHOWER PROFILE

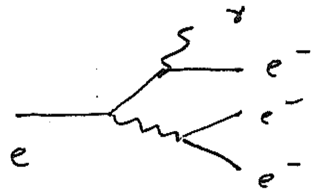
SIMPLE MINDED APPROACH:

$1X^0$



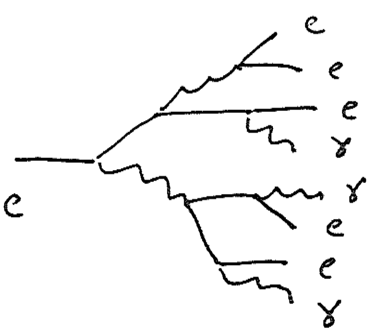
$e^- \rightarrow e^-$ γ

$2X$



$e^- \rightarrow 3e^-$ γ

$3X^0$



$e^- \rightarrow 5e^-$ 3γ

1% — 99%   1‰ 99.

$$N_{\text{secondary}} = 2^t \qquad t = x/X_0$$

$$E_{sec} = E_0 / 2^t$$

$$\Rightarrow t(E) = \frac{\ln(E_0/E)}{\ln 2}$$

A MORE SOPHISTICATED PARAMETRISATION

ANSATZ => $$\frac{dE}{dt} = N \, t^{\alpha} \, e^{-\beta t}$$

- N: Normalisation
- t^{α}: GROWS OVER SHORT x/X_0
- $e^{-\beta t}$: DECAYS FOR LARGE $\frac{x}{X_0}$

What is N?

$$E_{inc} = \int_0^{\infty} dE = N \int_0^{\infty} t^{\alpha} e^{-\beta t} \, dt$$

$$= N \frac{\Gamma(\alpha+1)}{\beta^{\alpha+1}}$$

$$\Rightarrow \quad \frac{dE}{dt} = \boxed{E_{inc} \frac{\beta^{\alpha+1}}{\Gamma(\alpha+1)}} \, t^{\alpha} e^{-\beta t}$$

CAN TAKE MOMENTS OF THIS FUNCTION TO LEARN MORE ABOUT α, β IN TERMS OF SHOWER OBSERVABLES.

1) 1^{ST} MOMENT : $\int_0^\infty t^0 \left(\frac{dE}{dt}\right) dt = E_{INC}$

BY DEF'N

2) 2^{nd} MOMENT: $\int_0^\infty t \left(\frac{dE}{dt}\right) dt = \frac{\alpha+1}{\beta} = \bar{t}$

→ ENERGY WEIGHTED <u>AVERAGE DEPTH</u>
(1/2 ENERGY DEPOSITED $t < \frac{\alpha+1}{\beta}$; 1/2 AFTERWARDS)

3) 3^{rd} MOMENT $\int_0^\infty (t-\bar{t})^2 \left(\frac{dE}{dt}\right) dt = \sigma(t)$

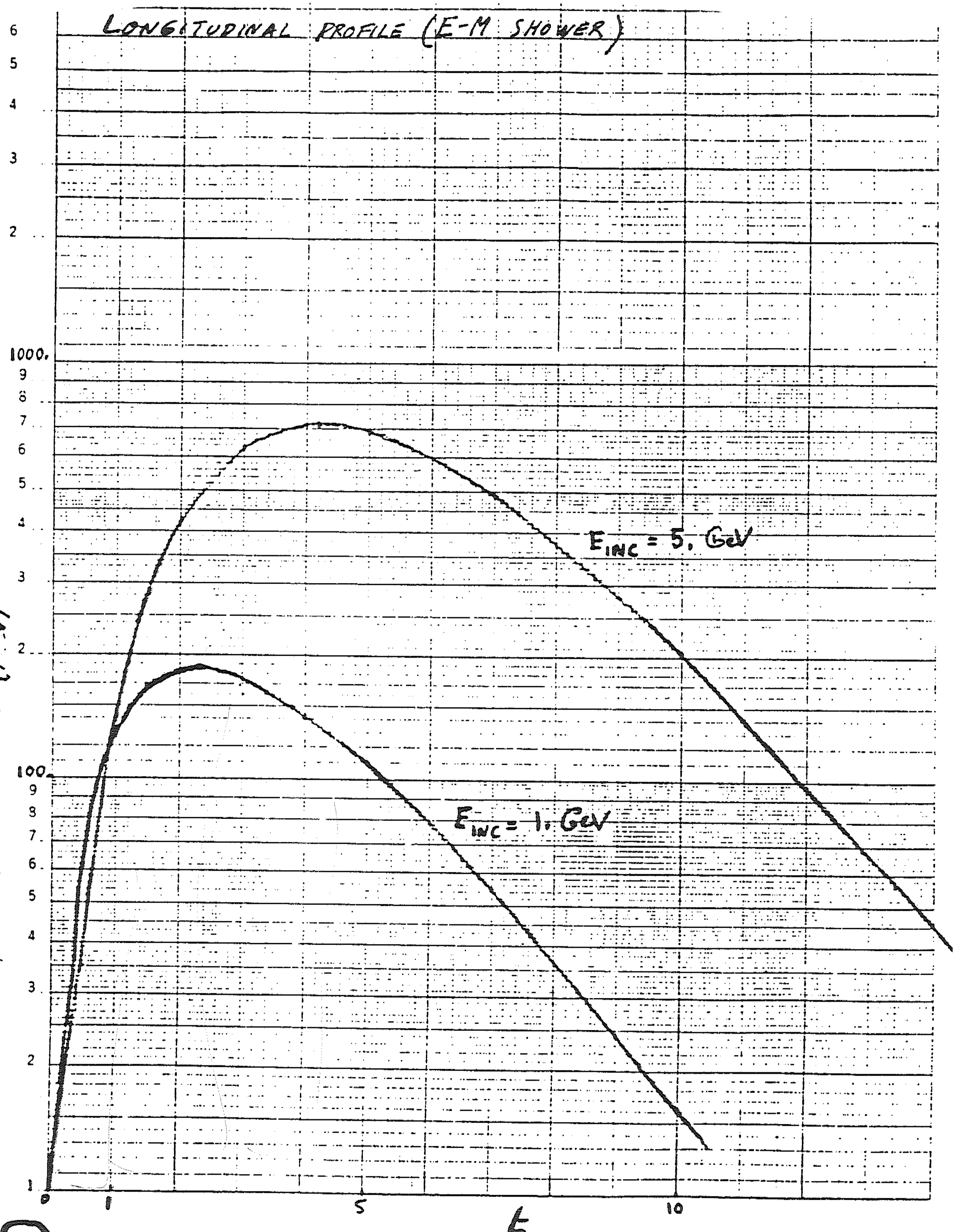
GIVES <u>LONGITUDINAL SPREAD OF SHOWER</u>

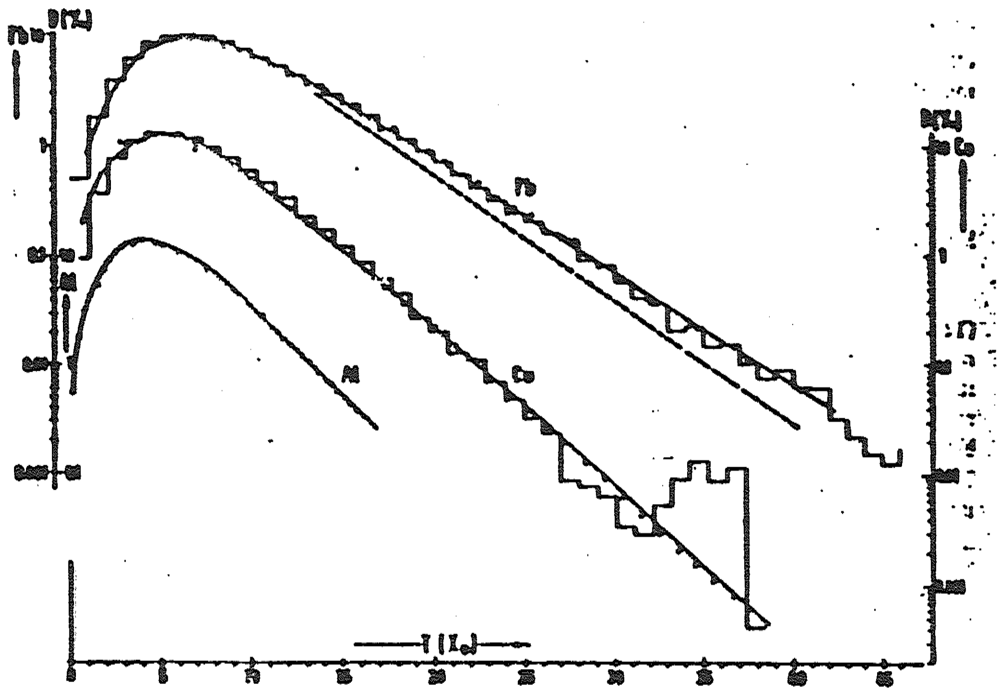
R.M.S.

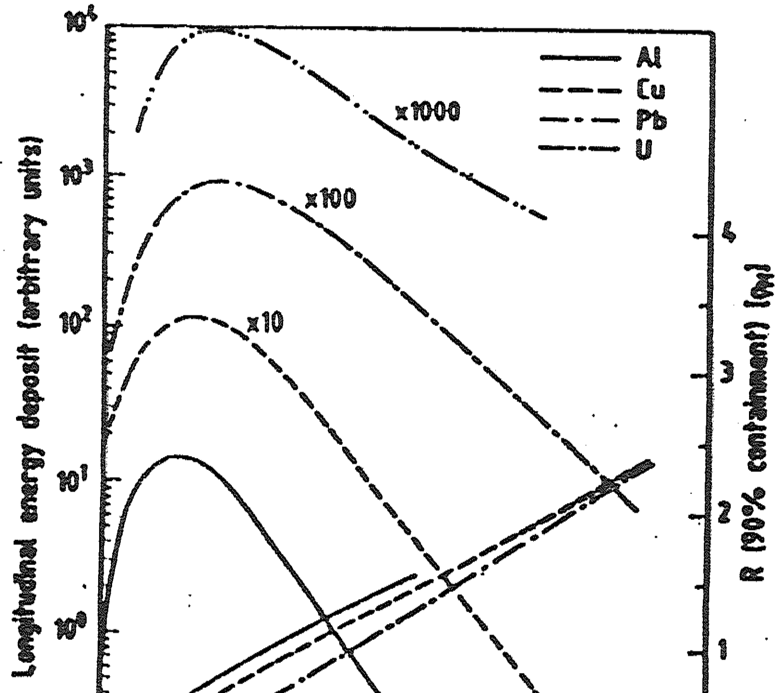
$$\sigma(t) = \pm \frac{\sqrt{\alpha+1}}{\beta}$$

4) <u>SHOWER MAXIMUM</u> $\frac{d}{dt}\left(\frac{dE}{dt}\right)\Big|_{t_{max}} = 0$

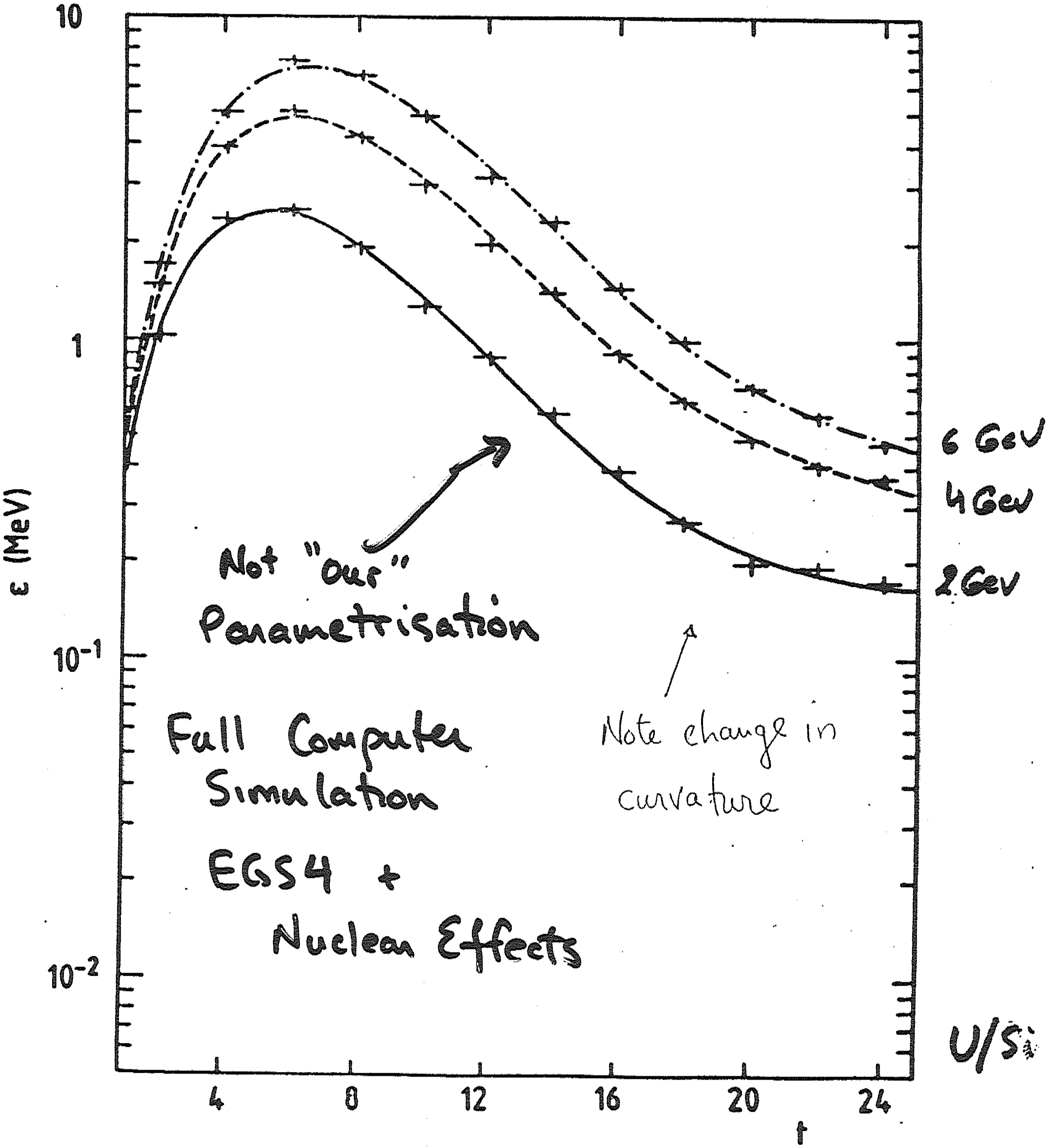
$$\rightarrow t_{max} = \alpha/\beta$$


LONGITUDINAL PROFILE (E-M SHOWER)
E_INC = 5. GeV
E_INC = 1. GeV
1000.
100.
0
1
5
10
t


Pb
Cu
Al
t (X₀)


Al
Cu
Pb
U
x1000
x100
x10
Longitudinal energy deposit (arbitrary units)
R (90% containment) (ρ_M)
Depth (X_0)

Uranium + Scintillator.



IN PRACTICE α, β ARE WEAK FUNCTIONS OF ENERGY IN REALISTIC CALORIMETERS

IN A URANIUM CAL:

$$\alpha = 1.28 + 0.71 \ln(E)$$

$$\beta = 0.56 + 0.009 \ln(E)$$

$$\Rightarrow \quad \bar{t}\,(5\,\text{GeV}) = 5.95\,X_0$$

$$\sigma(t)\,(5\,\text{GeV}) = \pm\, 3.22\,X_0$$

$$t_{max}\,(5\,\text{GeV}) = 4.22\,X_0$$

RADIAL SHOWER SIZE

LATERAL SPREAD COMES FROM TWO SOURCES:

1) PHOTON EMISSION ANGLE IN BREM.

$$\theta_{BREM} \simeq P_e / m_e$$ LARGE BUT BOOSTED

2) MULTIPLE SCATTERING

$$\langle \cos\theta \rangle \sim \cos\left(\frac{21\ \text{MeV}}{\pi \cdot \epsilon_{crit}}\right)$$

DEPENDS ON ϵ_{CRIT} SINCE THE LAST GENERATION OF SHOWER PARTICLES HAS LOWEST MOMENTUM => MOST SCATTERING.

=> SHOWER CONTAINED IN A CYLINDER OF RADIUS:

$$\rho_M = \frac{21\ \text{MeV}}{\epsilon_{CRIT}} \cdot X_0 \simeq \frac{7A}{Z} \left[g/cm^2 \right]$$

MOLIÈRE RADIUS → DESCRIBES AVERAGE LATERAL DEFLECTION OF ELECTRONS OF $E = \epsilon_{CRIT}$ AFTER TRAVERSING $1\,X_0$ OF MATERIAL.

HOMOGENEOUS CALORIMETERS

MATERIAL	σ_E/E	$\rho\ (g/cm^3)$	X_0 (cm)
NaI	$0.3\%/\sqrt{E}$	3.7	2.6
BGO ($Bi_4Ge_3O_{12}$)	$0.4\%/\sqrt{E}$	7.1	1.1
SF6 (Lead Glass)	$3.6\%/\sqrt{E}$	4.1	2.4
SCGI-C (Scintillating Glass)	$2\%/\sqrt{E}$	3.4	4.3

PROBLEMS: 1) VERY EXPENSIVE $2-5\ \$/cm^3$

2) "IDEAL" RESOLUTION NOT USEFUL FOR HADRONIC SHOWERS (FLUCTUATIONS IN SHOWER DEVELOPMENT BIGGER THAN RESOL.

ex. L3 : BGO

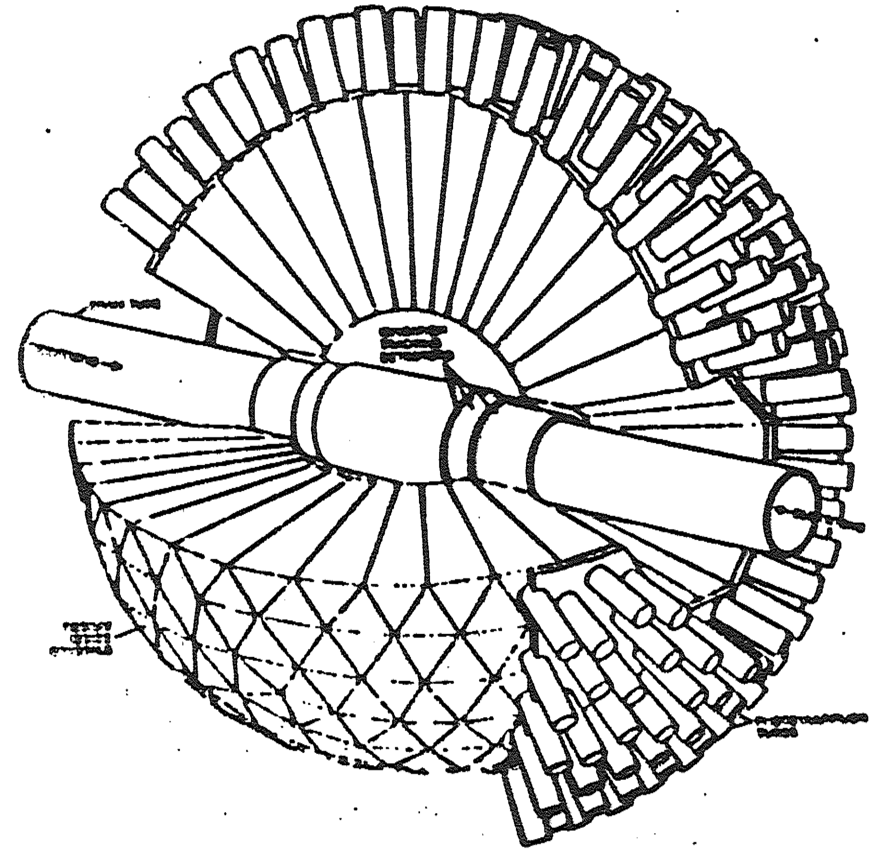
CLEO-1.5 : CsI

CMS : $PbWO_4$

} ← HIGH ENERGY PHOTON MEASUREMEN[T]

$H \to \gamma\gamma$.

CRYSTAL BA~~RREL~~LL

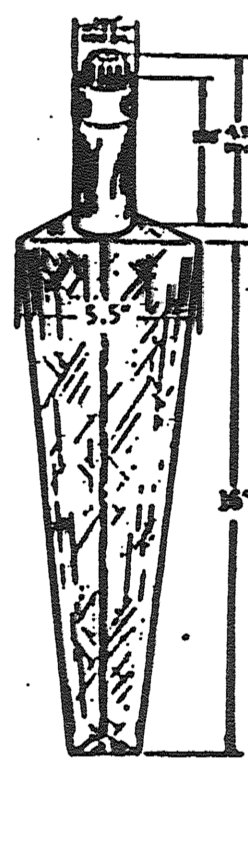


$\pi^0 \rightarrow \gamma\gamma$

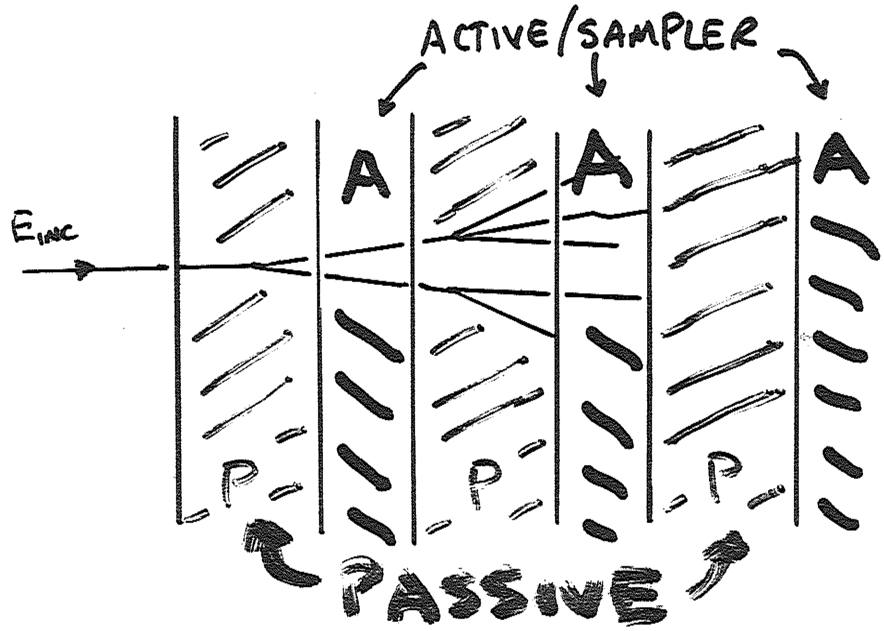
$\eta \rightarrow \gamma\gamma$

$\omega \rightarrow \gamma\gamma\gamma$

+ rare decays.



SAMPLING CALORIMETERS



READ-OUT : SCINTILLATOR, LIQUID ARGON, SILICON, ...

ABSORBER : URANIUM, LEAD, COPPER

WOULD LIKE TO MAKE $\ell_{READOUT}/\ell_{ABSORBER}$ AS LARGE AS POSSIBLE

$\Rightarrow$ SAMPLE AS MANY SECONDARIES AS POSSIBLE

BUT: RADIATION LENGTH OF ACTIVE MATERIAL LONG
(HENCE NEED FOR ABSORBER)

TYPICALLY $\ell_R/\ell_A \sim 1-5\%$

FOR SAMPLING CALORIMETER NEED TO CONSIDER EFFECTIVE QUANTITIES:

EFFECTIVE RADIATION LENGTH:

$$\frac{1}{X_{eff}} = \sum_i \frac{f_i}{X_0^i}$$

$$f_{ACT} = \frac{m_{ACT}}{m_{ACT} + m_{PASS}}$$

$$f_{PASS} = \frac{m_{PASS}}{m_{ACT} + m_{PASS}}$$

EFFECTIVE CRITICAL ENERGY

$$\frac{\epsilon_{eff}}{X_{eff}} = \sum_i f_i \frac{\epsilon_i}{X_0^i}$$

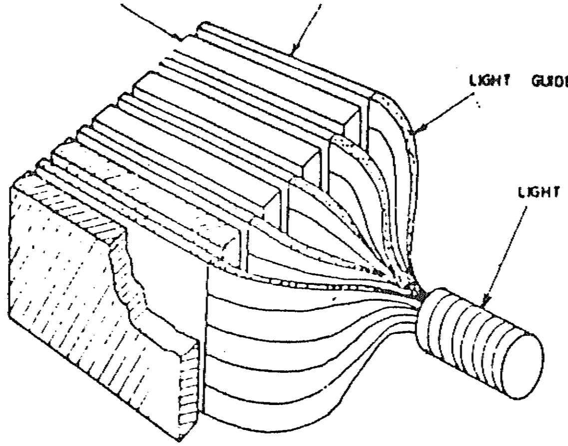
FRACTION OF ENERGY SAMPLED:

$$\eta \equiv \frac{E_{vis}}{E_{INCIDENT}} = f_{ACT} \frac{\epsilon_{ACT}/X_0^{ACT}}{\left(\epsilon_{eff}/X_0^{eff}\right)}$$

(5)

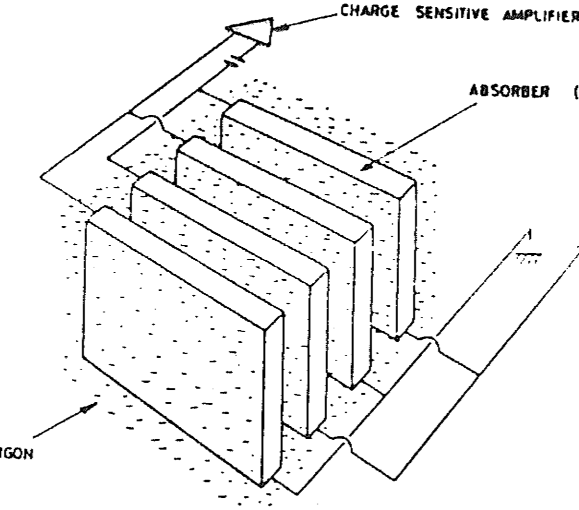
EXAMPLES OF READOUT FOR SAMPLING CALORIMETERS

SCINTILLATOR + ABSORBER TILES

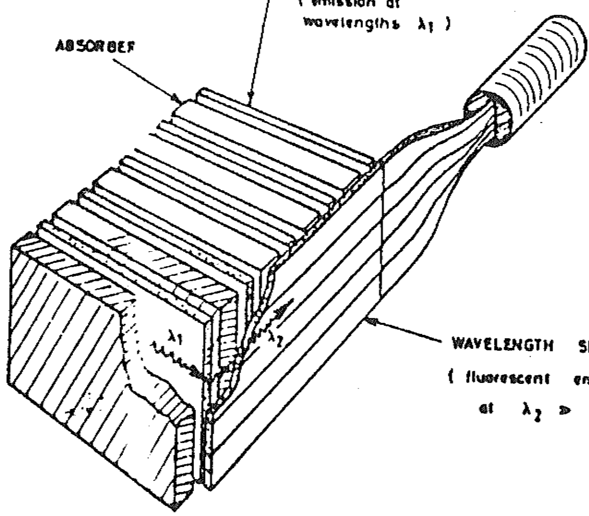


a)

LIQUID ARGON + TILES

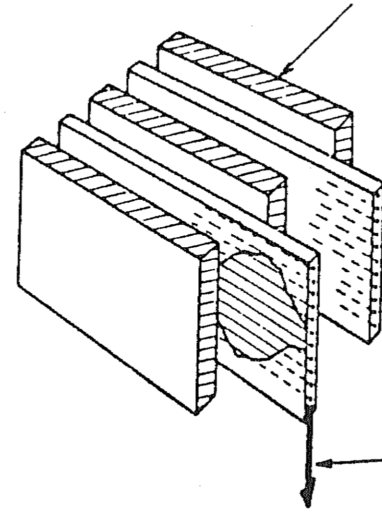


c)



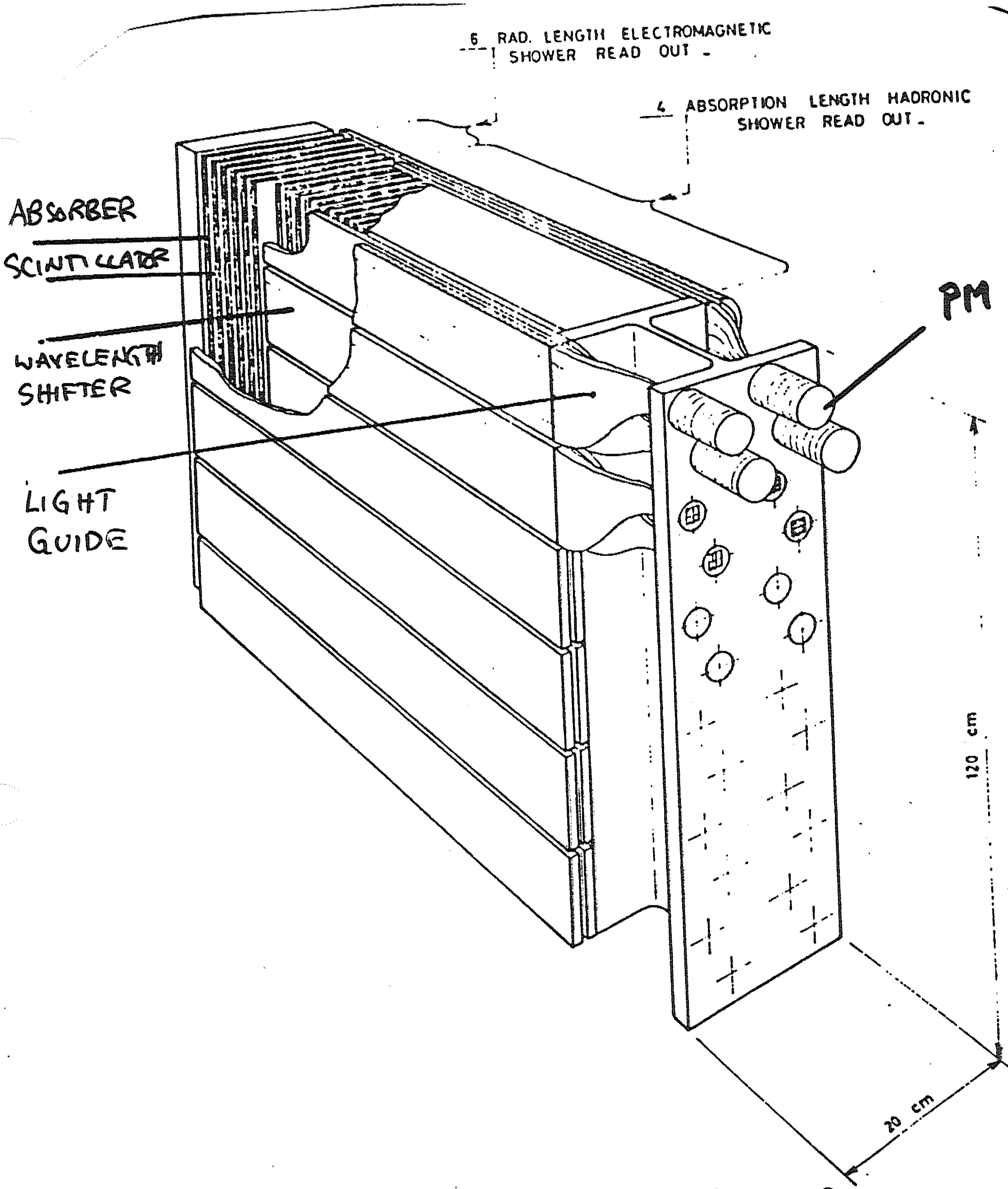
b)

SCINTILLATOR + WAVELENGTH



d)

MWPC + TILES.

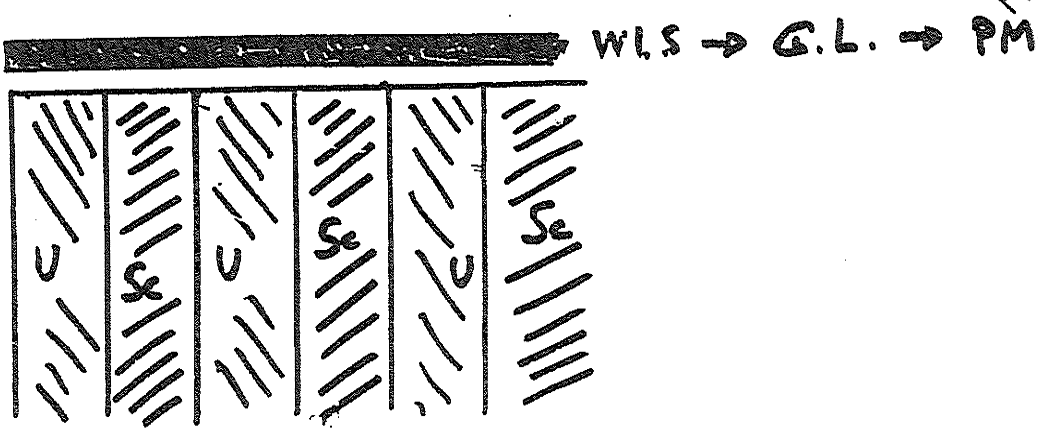


HELIOS

U - Scint

SAMPLING

CALORIMETER



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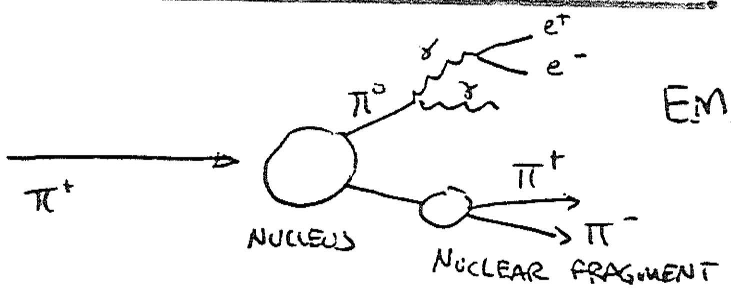
4/11/96

HADRON CALORIMETERS



E.M. COMPONENT

HADRONIC COMPONENT

IN GENERAL SHOWER PROCESS IS UNCALCULABLE (STRONG VS. EM INTERACTIONS)

IN PRACTICE ALMOST UN-SIMULABLE (GEISHA)

USEUAL USE DETECTOR SPECIFIC PARAMETRISATIONS

σ/E ALWAYS MUCH WORSE :

- SAMPLING NECESSARY SINCE λ_{INT} VERY LONG
- LOTS OF "INVISIBLE" ENERGY LOSS MODES:
  NUCLEAR FRAGMENTATION
  NUCLEAR EXCITATION
  THERMAL NEUTRONS
  NEUTRINOS ...
- RESPONSE TO E.M. ($1/3$) AND HADRONIC ($2/3$) COMPONENTS NOT EQUAL

→ LARGE FLUCTUATIONS IN $\#\pi^0$ PRODUCED (CAN IMPROVE IF $e/h = 1$ SEE BELOW

TYPICAL CALORIMETER RESOLUTIONS

HOMOGENEOUS EM CAL $\frac{0.5\%}{\sqrt{E}} - \frac{3\%}{\sqrt{E}} \oplus 0.5\%$

e.g. CLEO, Crystal Ball etc.

SAMPLING EM CAL $\frac{8\%}{\sqrt{E}} - \frac{15\%}{\sqrt{E}} \oplus 1\%$

eg. CDF, ZEUS, ALEPH, ...

COMPENSATED HAD. CAL $\frac{35\%}{\sqrt{E}} \oplus 1\%$ For ISOL $\pi^{\pm}$ etc.

eg. ZEUS, ...

NON-COMPENSATED HAD. CAL $\frac{70\%}{\sqrt{E}} - \frac{110\%}{\sqrt{E}}$

eg. CDF, ATLAS, LEP dets., ...

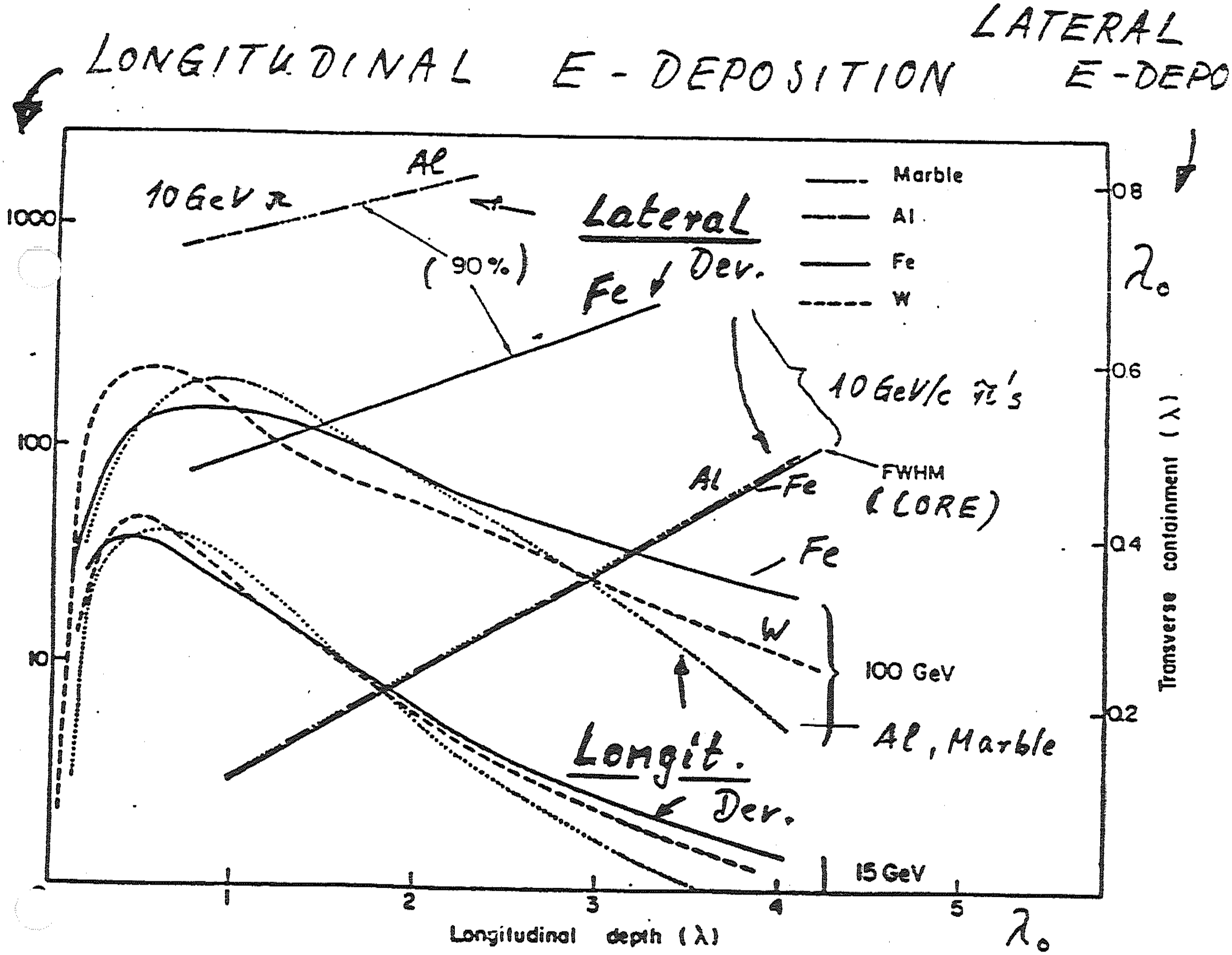
N.B. JET COMPOSITION RESULTS IN FLUCTUATIONS $> \frac{70\%}{\sqrt{E_{jet}}}$

SHOWER CONTAINMENT

LONGITUDINAL $L_{95\%} = 9.4 \ln E + 39$ cm

(E in GeV)

$\simeq 6 \lambda_{INT}$



③

C.W. Fabjan St. Croix Summer School '91
(ed. Ferbel)

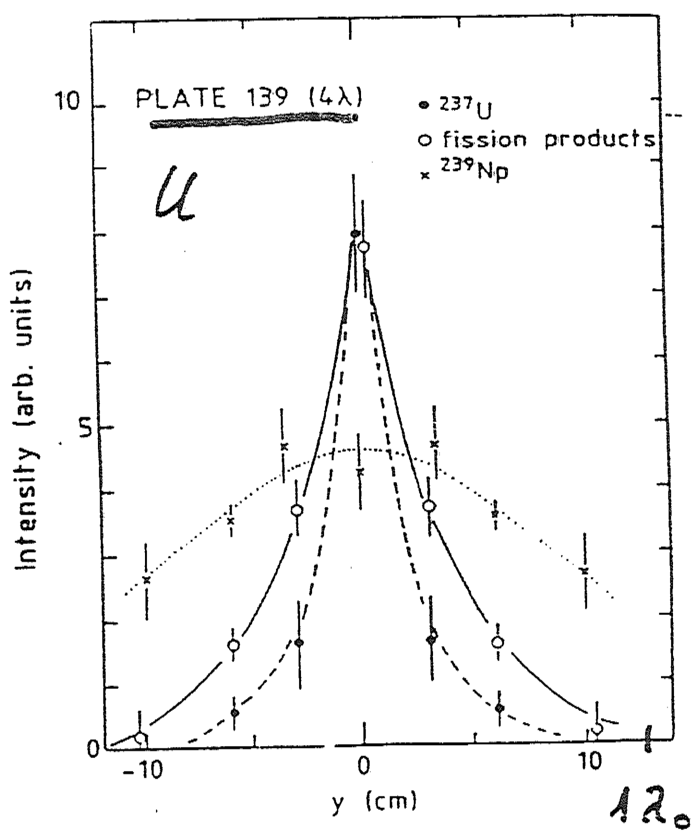
TRANSVERSE CONTAINMENT

$R_{95\%} \simeq 1 \lambda_{INT}$

TESTED WITH 300 GeV π^- → U BLOCK

MEASURE INDUCED RADIOACTIVITY

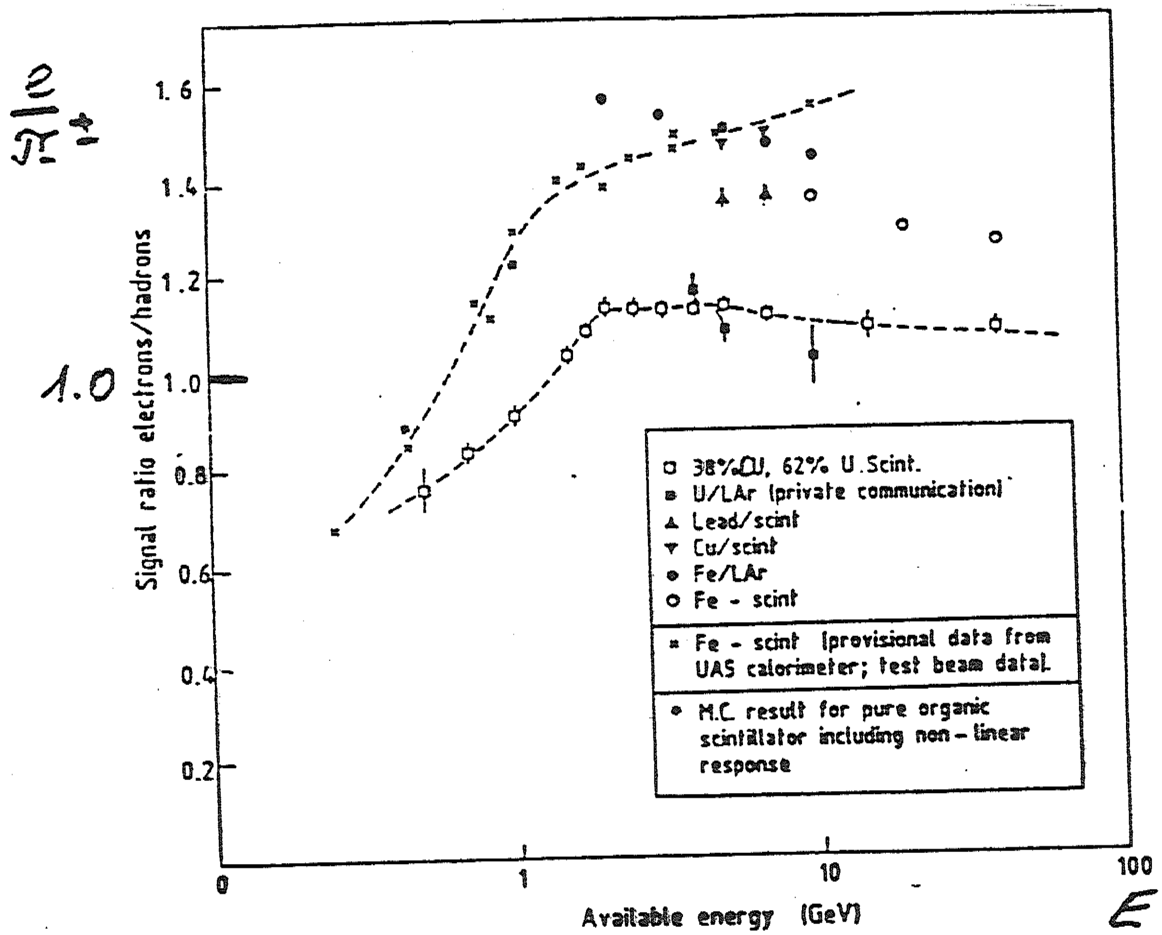
↳ RADIOACTIVE SPECIES INDICATE DIFFERENT COMPONENTS (EM vs. HAD) OF SHOWER.



C. LEROY et al. NIM A252 1986 @CERN by McGILL GROUP.

COMPENSATED HADRON CALORIMETERS ($e/h = 1$)

TYPICALLY RESPONSE TO HADRONS & ELECTRONS/PHOTONS IS DIFFERENT AND VARIES WITH ENERGY:



TO ACHIEVE COMPENSATION:

1) BOOST NON-EM RESPONSE

a) ^{238}U ABSORBER EMITS SOFT γ & n WHICH CAN BE DETECTED IF

b) USE ACTIVE MATERIAL CONTAINING LOTS OF H_2 ⇒ HIGH CAPTURE CROSS-SECTION FOR NEUTRONS.

2) SUPPRESS EM RESPONSE

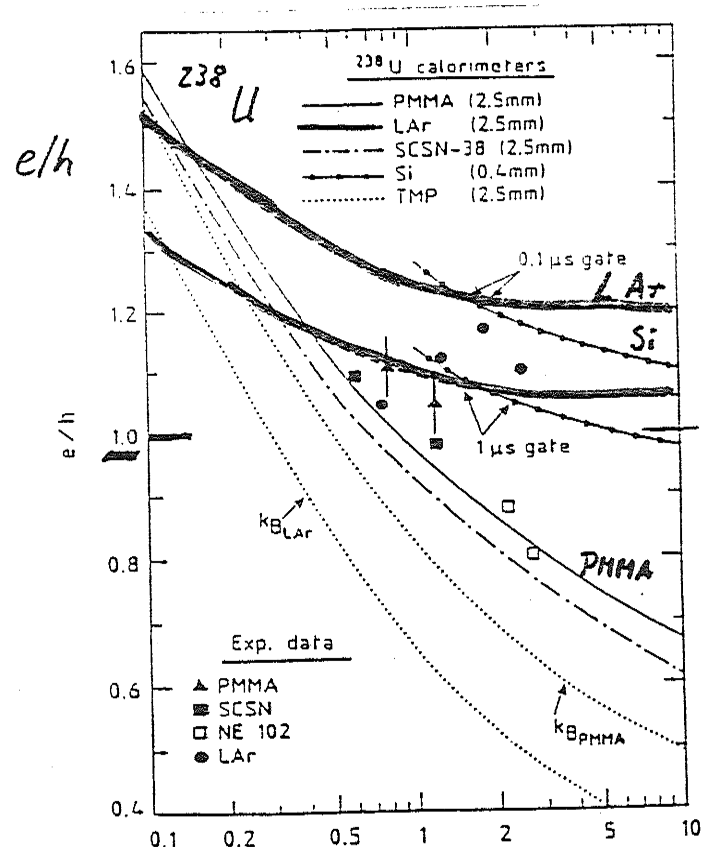
PHOTO-ELECTRIC EFFECT KILLS SHOWERS BELOW CRITICAL ENERGY ($\sim Z^5$). ⇒ USE V. HIGH Z ABSORBER & LOW Z ~~ABS~~ DETECTOR.

U, Scint.

⇒ USE URANIUM ABSORBER

SCINTILLATOR DETECTOR

MUST STILL TWEAK THICKNESS



$R_{TH} = \dfrac{\text{Thickness (Absorber)}}{\text{" (R.O. Layer)}}$

BOTTOM LINE: TRENDY $\sim$ LATE '80's

NOT MUCH OPPORTUNITY TO MEASURE SINGLE HADRON ENERGIES. JETS FLUCTUATE THEIR COMPOSITION ⇒ ADDITIONAL COMPLICATIONS.

OTHER USES OF HADRON CALORIMETERS

ABSORBS ALL PRODUCTS OF JETS EXCEPT:

a) $\mu^{\pm}$: LEAVE MINIMUM IONIZING ENERGY DEPOSITION IN H-CAL.

TYPICALLY LOOKS LIKE FEW GeV
⇒ ADDITIONAL HANDLE TO IDENTIFY MUON.

$E_\mu \gtrsim$ 200-300 GeV EVEN MUONS

START TO BREMSSTRAHLUNG ⇒ MUCH MORE ENERGY IN CALORIMETER

⇒ PROBLEMS IDENTIFYING VERY HIGH ENERGY MUONS (LHC, ...)

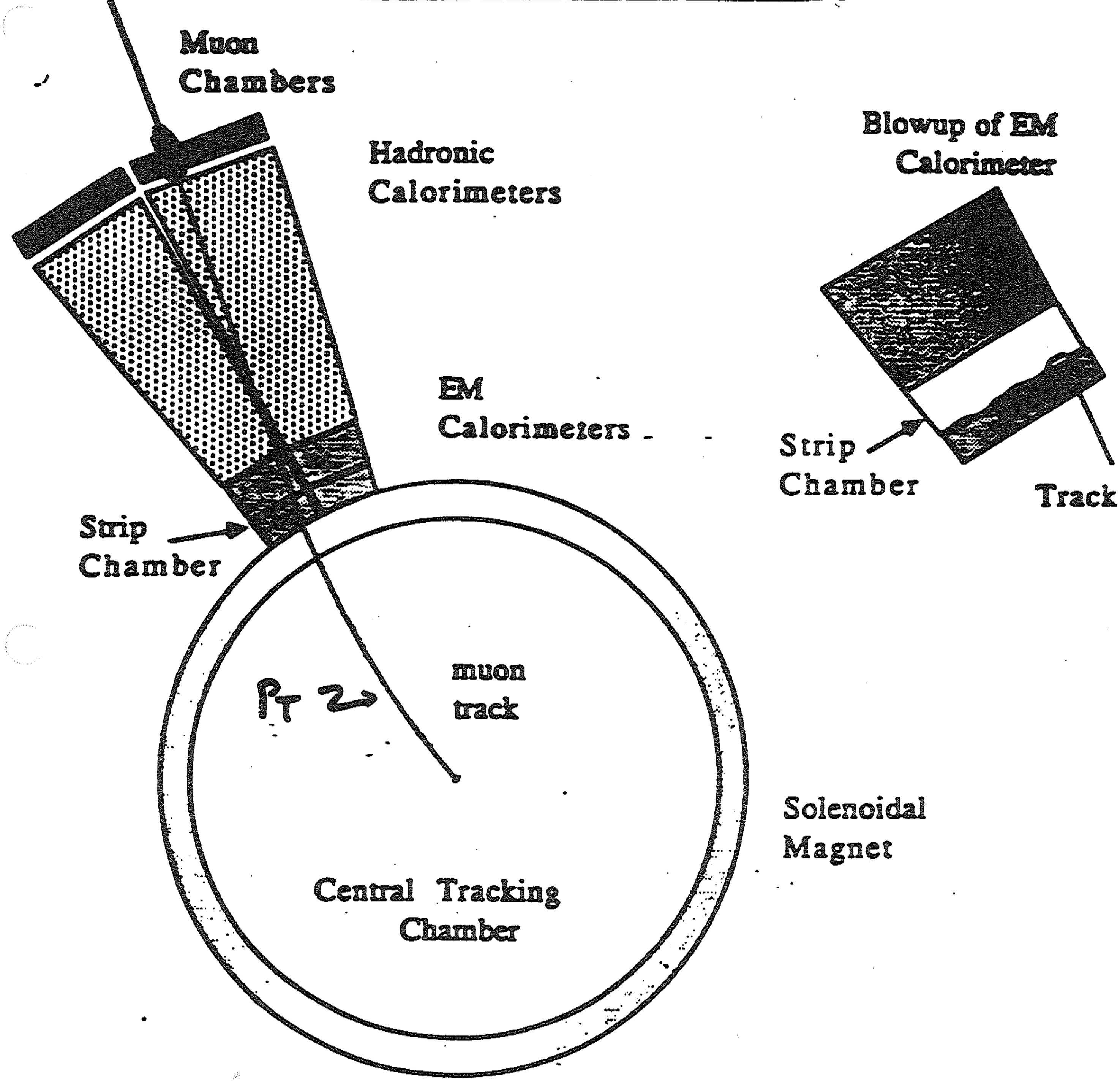
b) ν : LEAVES NO ENERGY AT ALL

σ_ν VERY SMALL : TYPICAL INTERACTION LENGTH 100's OF Km.

⇒ ν LEAVES "MISSING ENERGY" SIGNATURE.

↳ ACTUALLY A MOMENTUM SUM DONE WITH A CALORIMETER.

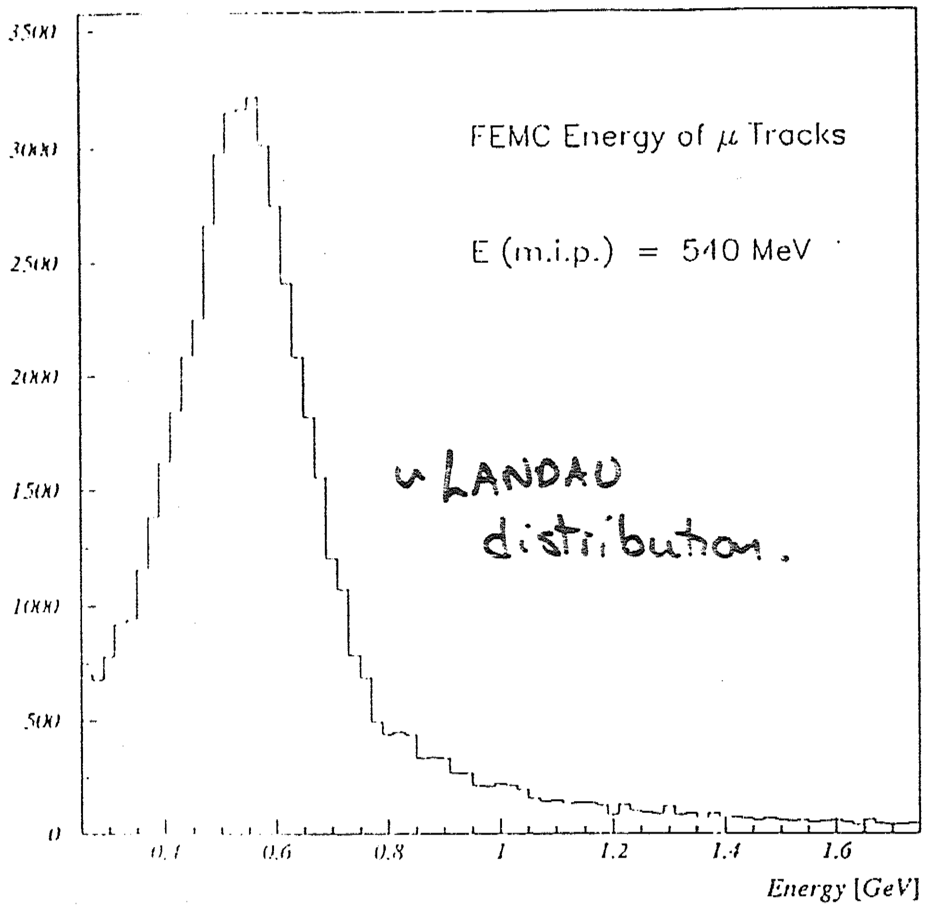
Schematic View of a [redacted] in the CDF Central Calorimeter



CDF Central Muon Variables:

- $P_T > 20; 25$ GeV/c
- EM ≤ 2 GeV
- Had < 6 GeV
- Muon Chamber-Track Match($\delta x, \delta z$) < 1.5 cm
- ~~Slope Match~~
- ~~Isolation~~

+ dijet cut. + "jet" cut



E_μ (E.M.)

DELPHI FWD CALORIMETER

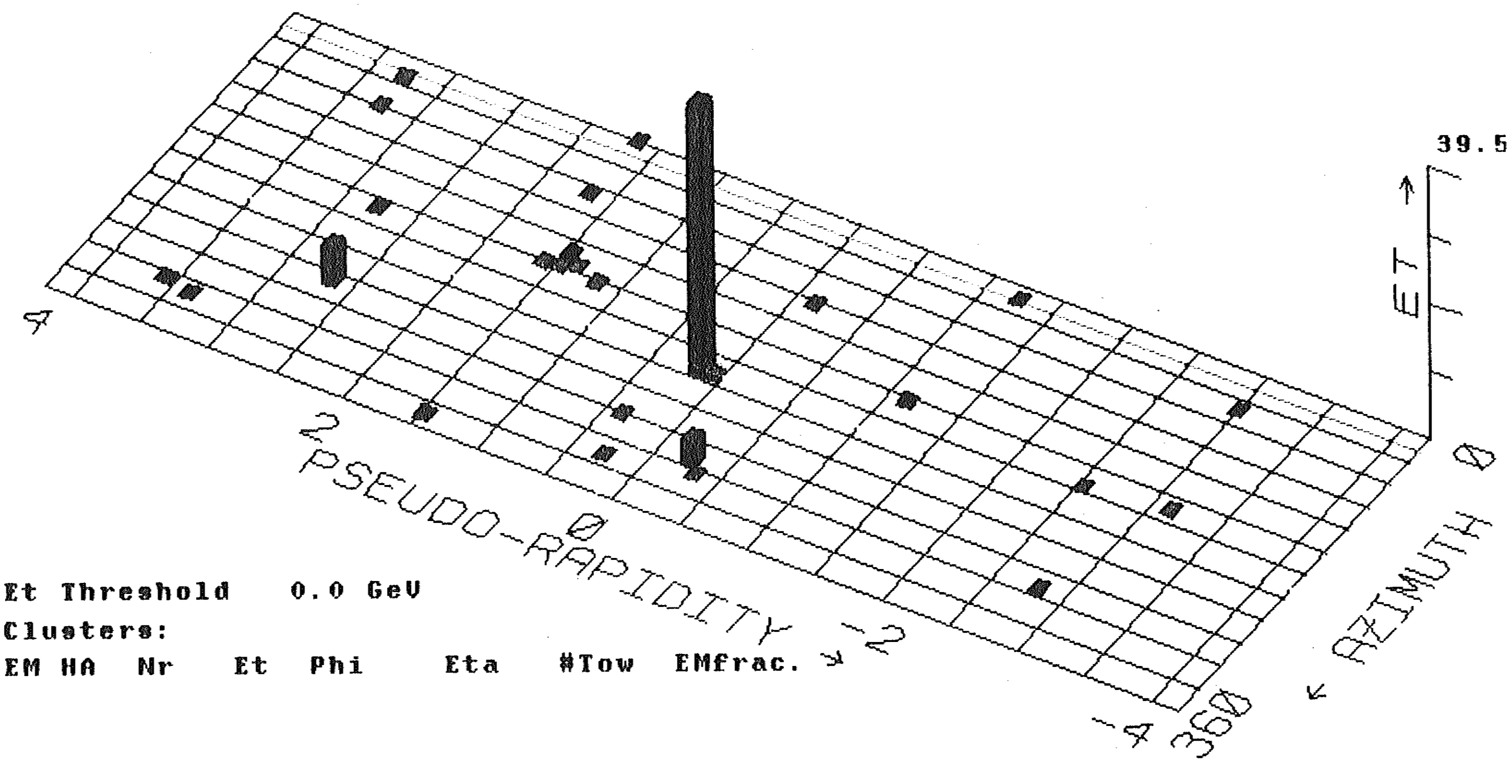
Run 17075 Event 5856 PLATINUM_WS.EVT 17OCT88 8:03:48 21FEB89

DAIS E transverse Eta-Phi LEGO Plot

Max tower E= 39.5 Min tower E= 0.50 N clusters:

METS: Etotal = 293.5 GeV, Et(scaler)= 74.9 (

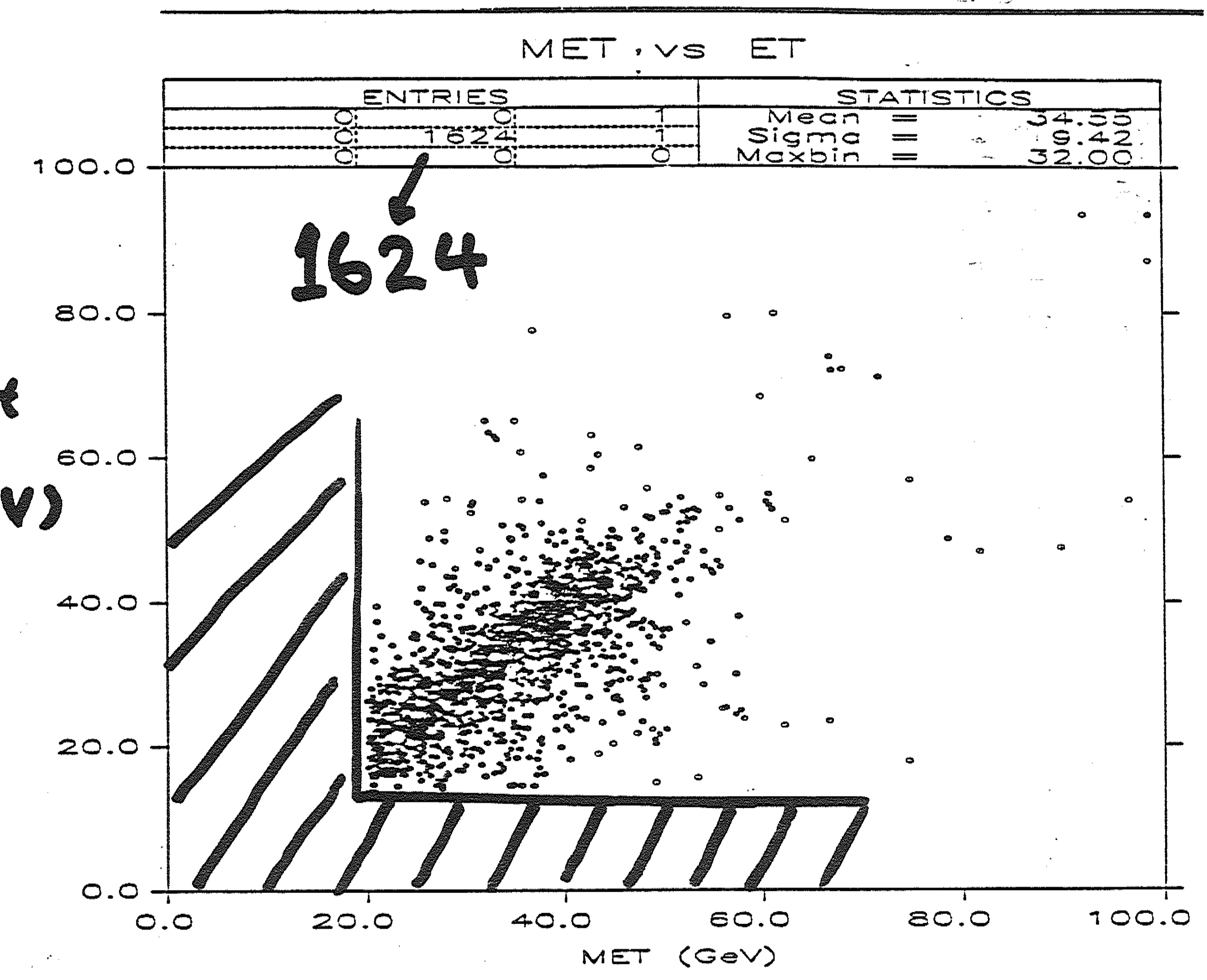
Et(miss)= 36.6 at Phi= 17.1 Deg.



Et Threshold 0.0 GeV

Clusters:

EM HA Nr Et Phi Eta #Tow EMfrac.



≃ 1.8 pb^{-1} CDF Data (Preliminary)

NEED A CALORIMETER WHICH COMPLETELY SURROUNDS INTERACTION REGION.

INNOVATION OF UA1

$W \rightarrow e\nu$ DISCOVERY

↳ MISSING "ENERGY"

RESOLUTION ON "ν" DEPENDS ROUGHLY ON THE TOTAL ENERGY SEEN IN THE CALORIMETER

$$\sigma/E \simeq \frac{a}{\sqrt{E}}$$

$a = 0.5$–0.6 IN CDF HCAL RESOLUTION

$$\Rightarrow \sigma_\nu \simeq a\sqrt{E}$$

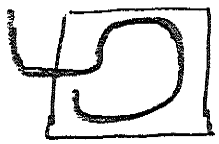
$\Rightarrow$ BEST ν MEASUREMENT MADE WITH LEAST ADDITIONAL ENERGY IN DETECTOR

$\Rightarrow$ LEAST ADDITIONAL PHYSICS ACTIVITY.

INNOVATIONS IN CALORIMETER DESIGN

SOLUTIONS TO THE "CALORIMETER SYSTEM CRACKS" INTRODUCED BY WAVELENGTH SHIFTER BARS:

SCINTILLATING TILES:



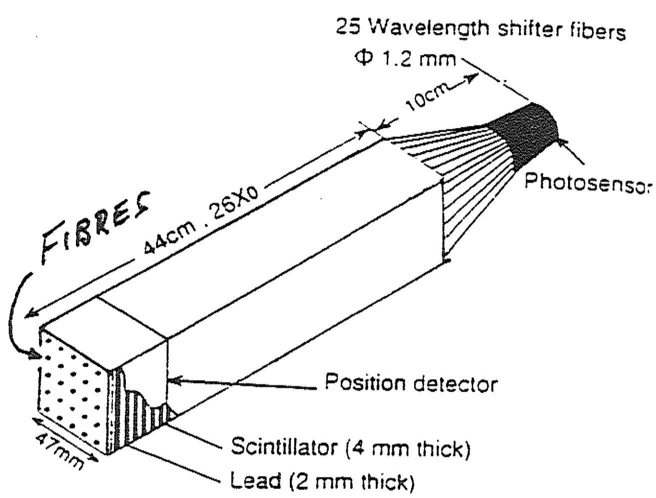
BUNDLE FIBRES TOGETHER FROM MULTIPLE SAMPLES IN A SINGLE "TOWER".

FIBRES EXTRACTED IN SMALL CRACKS

eg. NEW CDF PLUG CALORIMETER

SHISH-KABOB CALORIMETER:

SCINTILLATING FIBRES PENETRATE THE ABORBER PLATES. ADJUST SIZE OF FIBRES TO GET DESIRED SAMPLING FRACTION.



POINT FIBRES "AWAY" FROM INTERACTION POINT. HOT SPOTS

eg. DELPHI LUMINOMITER.

TUNGSTEN + SILICON SAMPLER

eg. ALEPH / OPAL LUMINOMETERS

VERY COMPACT / SMALL MOLIERE RADIUS

=> GOOD BHABHA ELECTRON POSITION / ANGLE DETERMINATION

SILICON STRIPS / PADS PROVIDE VERY PRECISE SHOWER LOCATION

(LUMINOSITY MEASUREMENT @ e^+e^- MACHINES REQUIRE PRECISE ANGLE MEASUREMENT OF e^+e^- with $E_e = E_{beam}$).

LIQUID ARGON CALORIMETRY

→ SOLVES PROBLEMS WITH RADIATION DAMAGE OF SAMPLER MATERIALS (SCINTILLATOR, SILICON etc.) BY RECYCLING ~~ABSORBER~~ ACTIVE MATERIAL

→ TYPICAL PROBLEM IS SIGNAL FORMATION TIME:

a) CHARGE COLLECTION TIMES IN LAr GAPS IS LONG (MANY μs EVEN FOR THIN GAPS)

b) NEED LONG SERIES OF SIGNAL CONNECTIONS

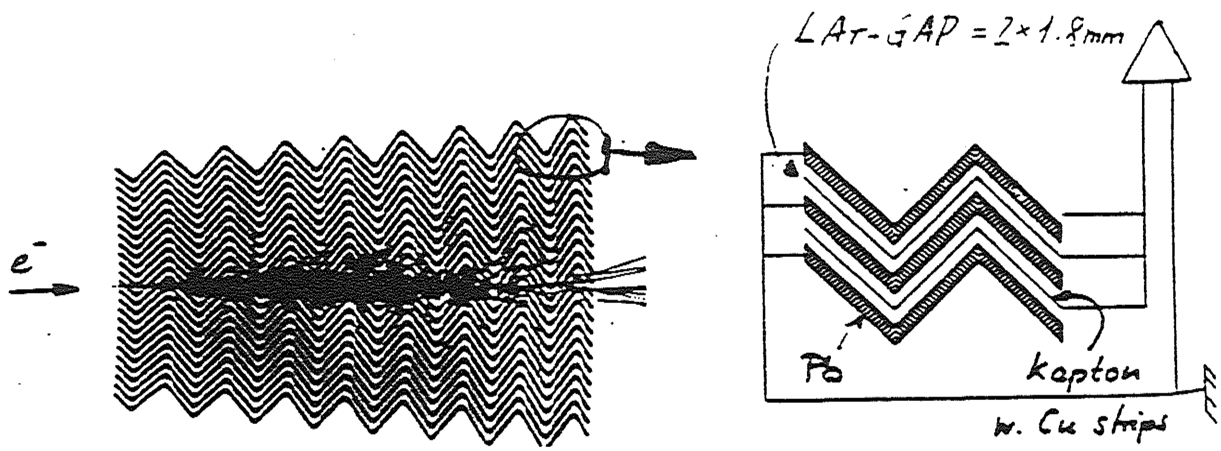
⇒ LARGE CAPACITANCE
" RC TIME CONSTANT.

GAP WIDTH + NUMBER OF GAPS ⇒ LARGE CAPACITANCE. THIS ACTS AS A RESERVOIR OF CHARGE. FLUCTUATIONS ON THIS CHARGE ($\sqrt{N_e}$) CONTRIBUTES TO NOISE OF READOUT

⇒ IMPORTANT CONTRIBUTION TO LOW ENERGY ELECTRON / PHOTON SHOWERS

(eg. ATLAS $H \to \gamma\gamma$ ↳ ~50GeV PHOTONS).

ACCORDIAN CALORIMETER



- NO DEAD REGIONS

  GOOD UNIFORMITY

  HIGH GRANULARITY

  READ ELECTRONICS MOUNTED
  ON CALORIMETER FACE

ONLY NEED ACCORDIAN FOR EM SECTION.

IN OTHER PARTS OF ATLAS USE OTHER "INGENEOUS" SAMPLER GEOMETRIES

e.g. FORWARD CALORIMETER WITH

LAr SHISH-KABOB GEOMETRY,

400 μm GAPS IN W => GOOD CONTAINMENT.

6/11/86

SEMI-QUANTITATIVE LONGITUDINAL HADRONIC SHOWER FORM.

$$\frac{dE}{ds} = E_{inc} \left\{ C \frac{X^{(\alpha_E - 1)} e^{-X}}{\Gamma(\alpha_E)} + \right.$$ EM PART

$$\left. (1-C) \frac{Y^{(\alpha_H - 1)} e^{-Y}}{\Gamma(\alpha_H)} \right\}$$ HAD PART

$$X \equiv \beta_E (S - S_0)/X_0$$

$$Y \equiv \beta_H (S - S_0)/\lambda$$

eg. $\alpha_H = 0.62 + 0.32 \ln E = \alpha_E$

U/Sc Calorimeter: $\beta_H = 0.91 - 0.02 \ln E$

$\beta_E = 0.22$

$C = 0.46$

NB: IN REAL HADRONIC SHOWERS THIS IS ONLY A VERY ROUGH APPROXIMATION

$X(,Y)$ ARE THE NUMBER OF RADIATION (, ABSORPTION) LENGTHS ACCUMULATED SINCE THE BEGINNING OF THE SHOWER (S_0).

$S_0 \neq 0 \Rightarrow$ SIGNIFICANT MATERIAL IN FRONT OF CALORIMETER (eg. MAGNET COIL etc.).