SCINTILLATORS

$$\underset{\substack{\uparrow \\ \text{charged} \\ \text{particle}}}{h^{\pm}} + \underset{\substack{\downarrow \\ \text{atom} \\ \text{or} \\ \text{molecule}}}{A} \longrightarrow h^{\pm} + A^{*}$$

$$\hookrightarrow A + \gamma \quad (\sim eV)$$

MECHANISM IS OFTEN A CHAIN OF SEVERAL DECAYS

$$h + A \xrightarrow[\tau]{} h + A^{*}$$

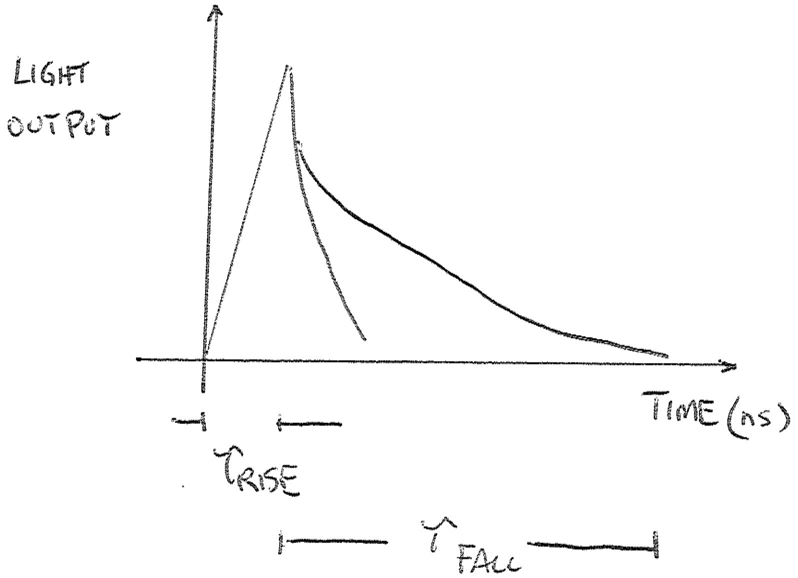
$$A^{*} + B \xrightarrow[\tau]{} A + B^{*}$$

$$B^{*} + C \xrightarrow[\tau]{} B + C^{*}$$

$$\hookrightarrow C + \gamma$$

$\tau \sim ps$

WHOLE CHAIN $\tau \simeq 1 - 10\ nS$



IN PRINCIPLE VERY EFFICIENT

$- 1\ \gamma / 100\ \mathrm{eV}$ DEPOSITED ENERGY

$\Rightarrow 10^4\ \gamma / \mathrm{cm}$ DETECTOR

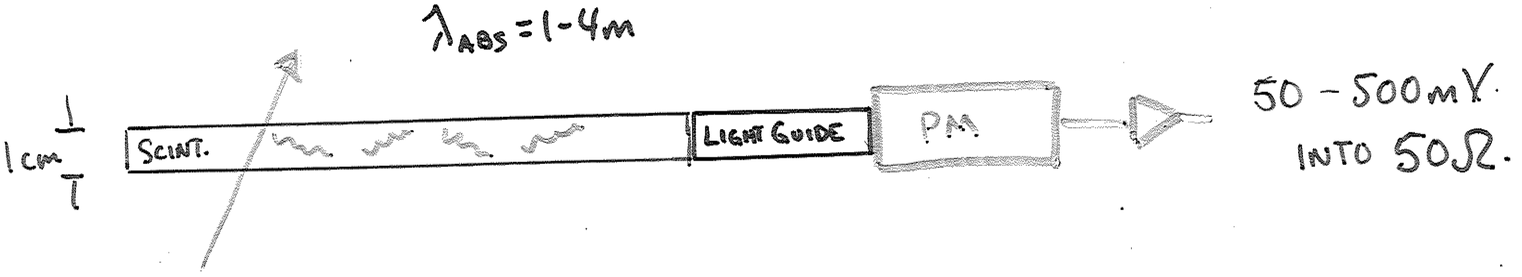
(LIGHT DETECTION EFFICIENCY ~ few %)

$\Rightarrow$ 100 photoelectrons / cm.

TYPICALLY THESE DETECTORS ARE ~ COARSE
(few cm DETECTOR ELEMENTS)

$\Rightarrow$ RESOLUTIONS NOT BETTER THAN
SEVERAL mm.

OVERVIEW OF SIGNAL



$\frac{dE}{dx} \simeq 2\ \mathrm{MeV/cm}$

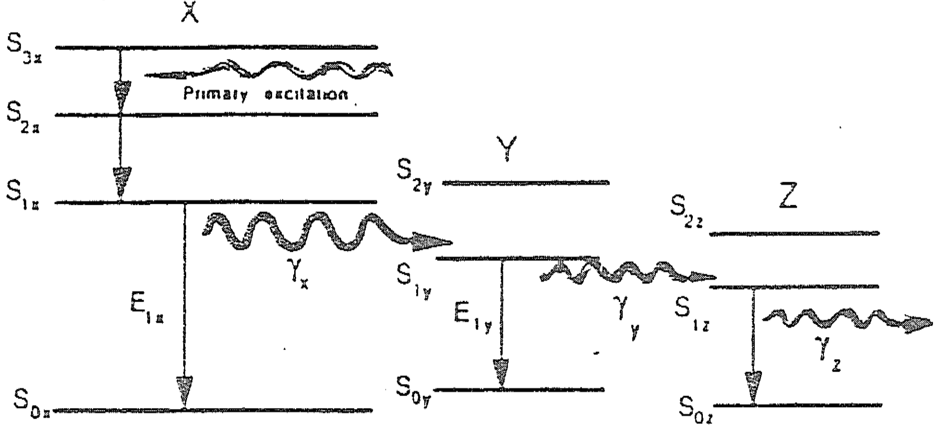
$\Rightarrow 2\times10^4\ \gamma$ PRIMARY $\simeq 200\ \gamma \rightarrow$ PM

$2\times10^3\ \gamma \rightarrow$ LIGHT GUIDE $\simeq 50$ p.e. $* \ G = 10^7$.

WAVELENGTH SHIFTING

PRIMARY SCINTILLATION MAY BE MORE EFFICIENT AT AN "UNDETECTABLE WAVELENGTH.

OPTICAL TRANSPORT PROPERTIES OF OVERALL DETECTOR SYSTEM (i.e. TOTAL INTERNAL REFLECTION) MAY BE BETTER AT LONGER WAVELENGTH.



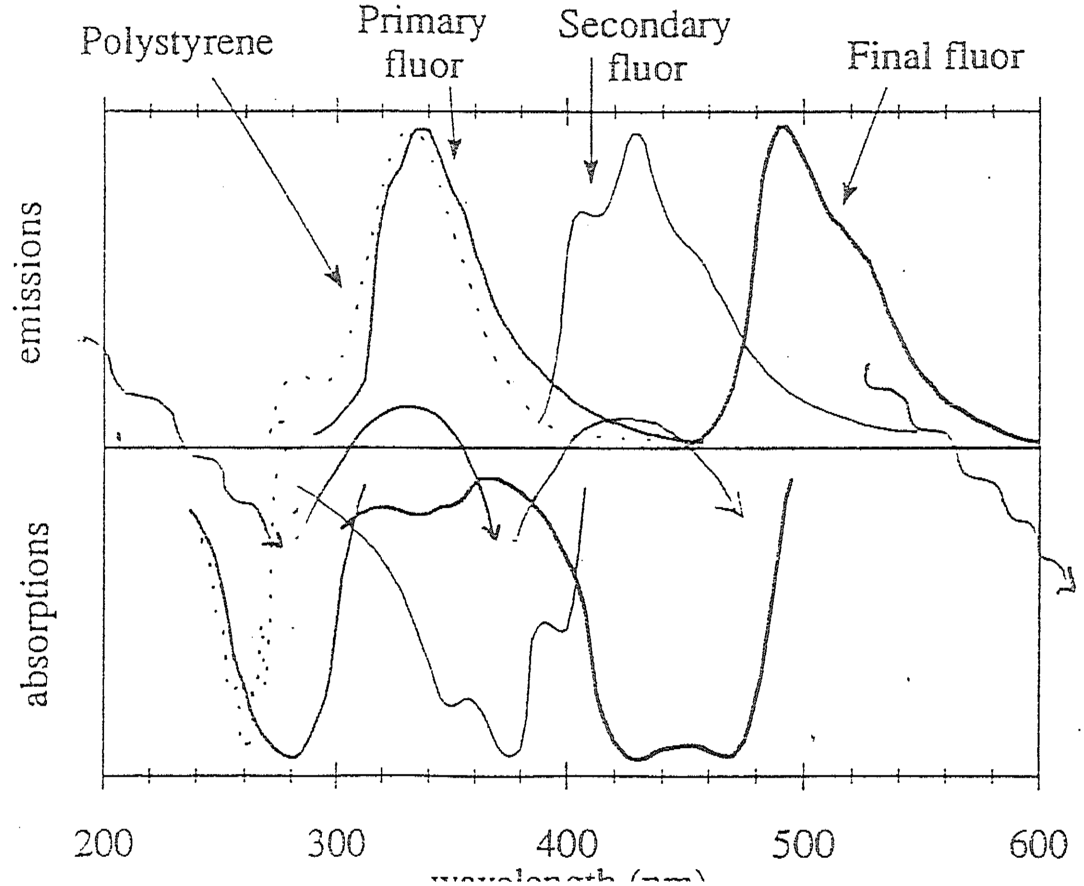
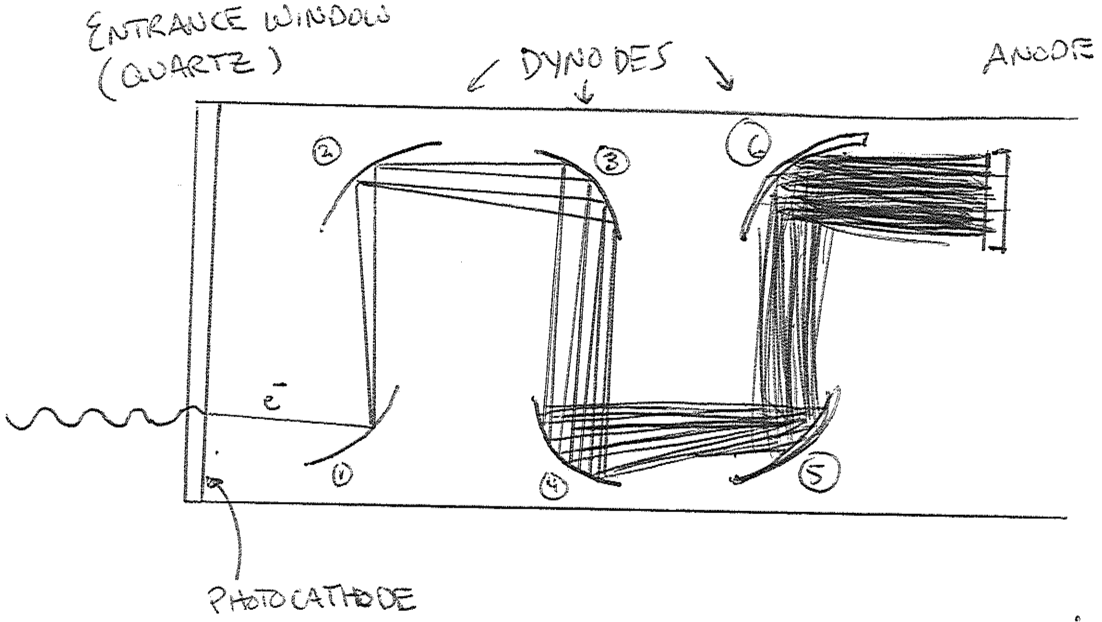
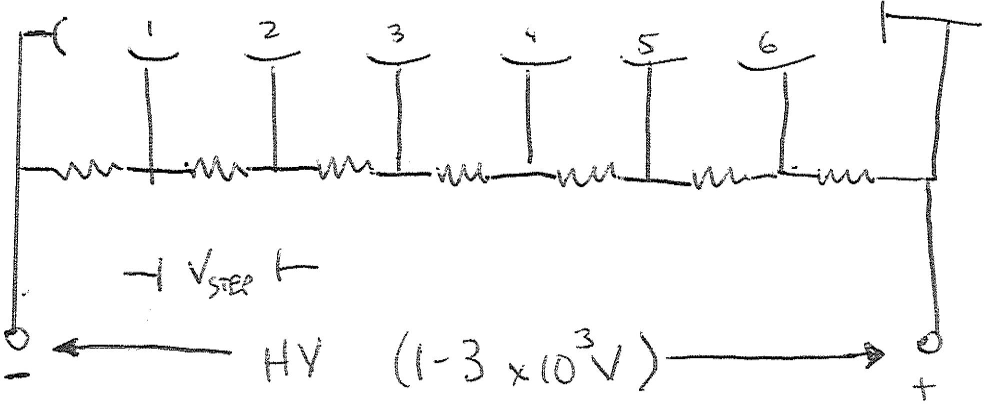


PHOTO MULTIPLIER





GAIN = $(\text{SECONDARY EMISSION FACTOR} - \delta)^N$

N = number of stages $\quad\quad \delta \propto V_{STEP}$

TYPICALLY $\quad G \sim \dfrac{10^7 e^-}{\lesssim 10\,ns} = 1mA$ into 50Ω

$\Rightarrow 50mV/$photo electron.

PHOTO CATHODE QUANTUM EFFICIENCY

SIGNIFICANT CONTRIBUTION TO SCINTILLATOR RESOLUTION IS "INITIAL" # PHOTO ELECTRON FLUCTUATIONS.

IF # PHOTO ELECTRONS IS FEW ($\lesssim$ 3-5) THEN POISSON FLUCTUATIONS WILL BE LARGE.

IF # PHOTO ELECTRONS $\lesssim$ 1 THEN EFFICIENCY WILL BE COMPROMISED.

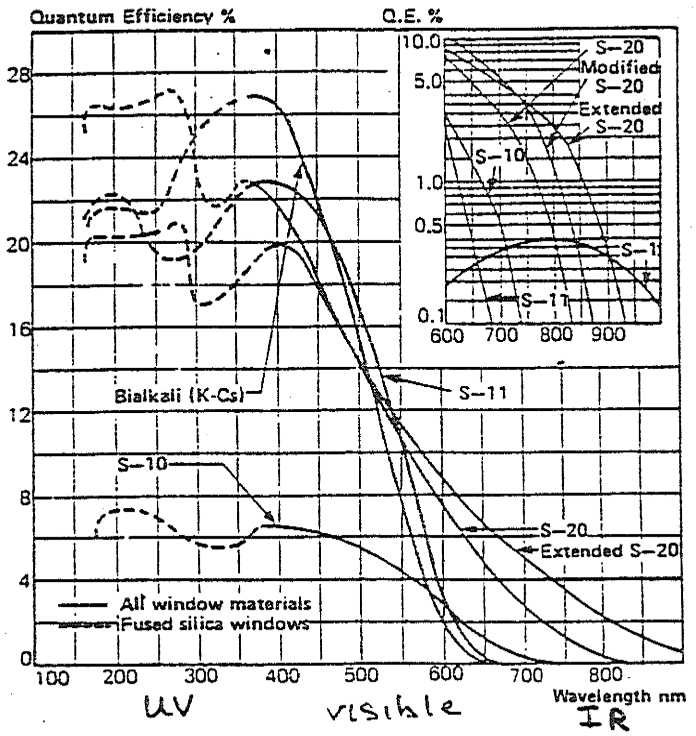


Fig. 8.2. Quantum efficiency of various photocathode materials (from *EMI Catalog* [8.2])

Table 8.1. Photocathode characteristics (from RTC catalog [8.3])

Cathode type	Composition	λ at peak response [nm]	Quantum efficiency at peak
S1 (C)	Ag–O–Cs	800	0.36
S4	SbCs	400	16
S11 (A)	SbCs	440	17
Super A	SbCs	440	22
S13 (U)	SbCs	440	17
S20 (T)	SbNa–KCs	420	20
S20R	SbNa–KCs	550	8
TU	SbNa–KCs	420	20
Bialkali	SbRb–Cs	420	26
Bialkali D	Sb–K–Cs	400	26
Bialkali DU	Sb–K–Cs	400	26
SB	Cs–Te	235	10

CHOICES OF SCINTILLATOR

- NOBLE GASES : He, Ne, Ar, Kr
  - fast 1ns
  - UV Photo cathode rare / low efficiency
  - Primary excitation low
    → low density unless liquid/cryogenic

- INORGANIC CRYSTALS NaI, BaF_2, BGO, CsI

high efficiency	$1\gamma / 25eV$
dense	$\rho = 7\,g/cm^3$
high Z	$X_0 \simeq 1-2cm$
slow	$\tau \simeq 100ns$
expensive	

- ORGANIC SCINTILLATORS

fast	1-10ns
cheap	

PLASTICS

flexible geometry ~ build anything

LIQUIDS

even cheaper
~ messy.

CALORIMETER RESOLUTION

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{A_0}{\sqrt{E}}\right)^2 + \left(\frac{A_1}{\sqrt{E}}\right)^2 + (A_2 \ln E)^2 + \left(\frac{A_3\sqrt{N}}{E}\right)^2 + A_4^2$$

$\left(\frac{A_0}{\sqrt{E}}\right)$:

SAMPLING FLUCTUATIONS

CONSIDER ΔE AS ENERGY DEPOSITED IN ONE SAMPLING STEP.

$N = E/\Delta E$ NUMBER OF *POTENTIAL* SAMPLES IN SHOWER.

$$\sigma_E = \sigma_N \, \Delta E = \sqrt{N} \, \Delta E$$

$$\frac{\sigma_E}{E} = \sqrt{N}\,\frac{\Delta E}{E} = \frac{1}{\sqrt{N}} = \frac{\overset{A_0}{\sqrt{\Delta E}}}{\sqrt{E}}$$

RULE OF THUMB $\frac{\sigma_E}{E} = \sqrt{\frac{\Delta E}{E}} = 3.2\% \, \frac{\sqrt{\Delta E\,(\text{MeV})}}{\sqrt{E\,(\text{GeV})}}$

$\frac{A_1}{\sqrt{E}}$: POISSON STATISTICS IN THE DETECTOR SYSTEM

(e.g. STATISTICAL PRECISION ON NUMBER OF PHOTO ELECTRONS)

CONSIDER $N = \bar{n} E$ ($\bar{n}$ IS MEAN NUMBER OF PHOTOELECTRONS PER UNIT INCIDENT ENERGY)

$$\sigma_E = \frac{\sigma_N}{\bar{n}} = \frac{\sqrt{N}}{\bar{n}}$$

$$= \frac{\sqrt{\bar{n} E}}{\bar{n}}$$

$$\frac{\sigma_E}{E} = \frac{1}{\sqrt{\bar{n}}} \frac{1}{\sqrt{E}} \Rightarrow A_1 = \frac{1}{\sqrt{\bar{n}}}$$

ASSUMING $\bar{n} \gg 1$ TO GIVEN GAUSSIAN STATISTICS.

IF NOT USE POISSON FLUCTUATIONS (c.f. PDG '94 pp 171-172).

A_2: SHOWER LEAKAGE FLUCTUATIONS

$$\frac{\sigma_E}{E} \sim \frac{1}{3} (\text{LEAKAGE})$$

$$\text{LEAKAGE} \sim \ln E$$

A_2 GEOMETRY DEPENDENT (CALORIMETER THICKNESS).

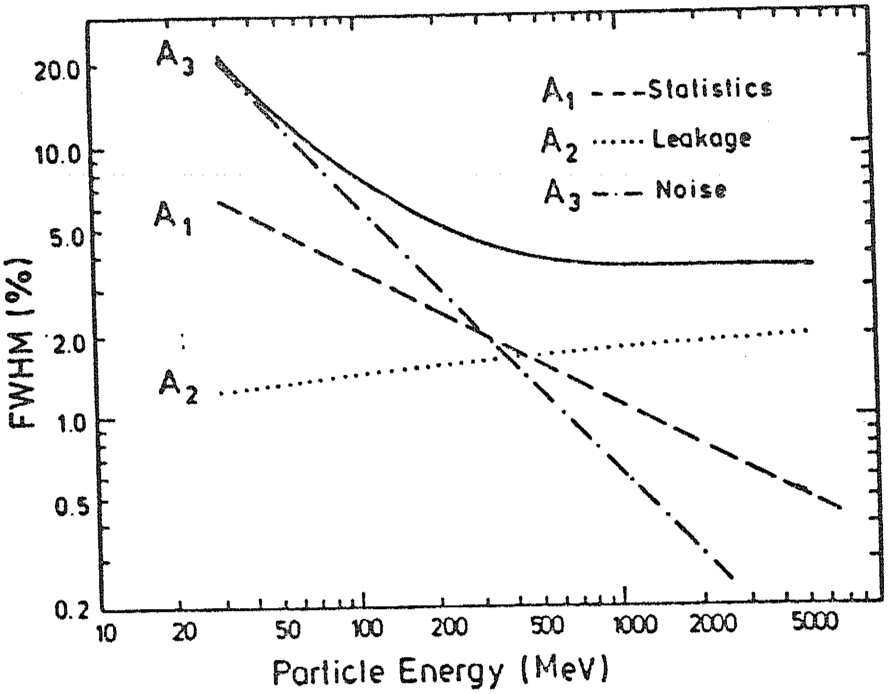
A_3: READOUT NOISE

DEPENDS ON DETECTOR GRANULARITY

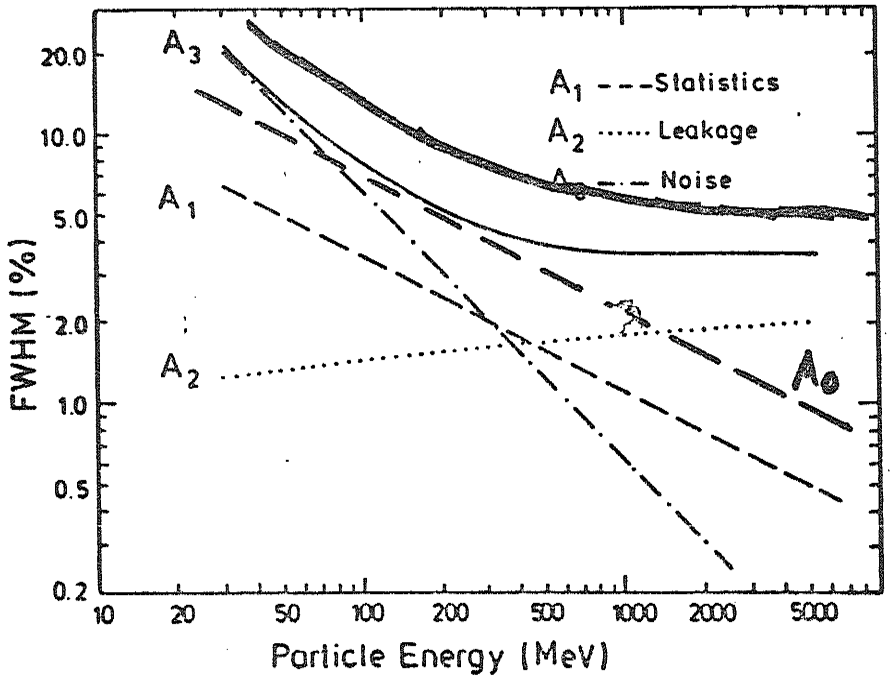
MUST SUM N CHANNELS TO MEASURE ALL INCIDENT ENERGY.

A_4 : INTERCALIBRATION UNCERTAINTY

- FRACTIONAL CHANNEL-TO-CHANNEL GAIN UNCERTAINTY
- DETECTOR INHOMOGENEITIES
- DEAD SPACE (LEAKAGE $\neq$ SCALING LIKE $\ln E$).
- TEMPERATURE EFFECTS
- RADIATION DAMAGE (ie SAMPLER POISONING



HOMOGENEUS CALORIMETER



SAMPLING CALORIMETER

SHOWER CONTAINMENT

RADIAL SPREAD RECALL $R_m = \frac{E_s}{\epsilon_{CRIT}} X_0$ $E_s \simeq 21\,\mathrm{Me}$

EMPIRICALLY OBSERVE THAT:

$$R_{90\%} = R_m$$

$$R_{95\%} = 2R_m$$

$$R_{98\%} = 3R_m$$

$$R_{99\%} = 4R_m \simeq 4.1\ \mathrm{cm}\ \text{in}\ U$$

FOR EM Shower!

LONGITUDINAL AGAIN EMPIRICALLY OBSERVE THAT:

$$L_{95\%} = \ln(E/\epsilon_{CRIT}) - \alpha + 0.08Z + 9.6$$

(IN UNITS OF X_0)

$\alpha = \frac{1}{2}$ γ

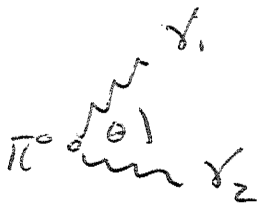
1 $e^{\pm}$

CAN USE X_0^{eff} and ϵ_{CRIT}^{eff} FOR SAMPLING CALORIMETER

CONSIDER A SPECIAL APPLICATION OF RADIAL SHOWER SIZES IN EM CALORIMETER

π^0 IDENTIFICATION

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

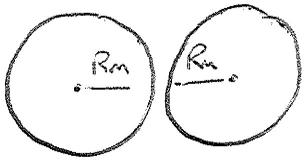


$$m_{\gamma\gamma}^2 = 4 E_1^{\gamma} E_2^{\gamma} \sin^2 \theta/2$$

MINIMUM OPENING ANGLE $\quad \theta_{min} = 2 \dfrac{m_{\pi^0}}{E_{\pi^0}}$

CAN DISTINGUISH 2 γ (FROM π^0) FROM SINGLE γ IF SHOWERS ARE SEPARATED BY

$\simeq 2 R_m$



THUS THE SMALLEST RESOLVABLE ANGLE BETWEEN 2γ IS:

$$\theta_{SMALL} = \frac{2 R_m}{R_{DETECTOR}} \Rightarrow E_{\pi^0} = \frac{m_{\pi^0}}{R_m} R_{DETECTOR}$$

FOR HIGHER ENERGIES π^0's LOOK LIKE SINGLE γ's.