PHYS 6610: Graduate Nuclear and Particle Physics I

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I. Tools

3. Detectors

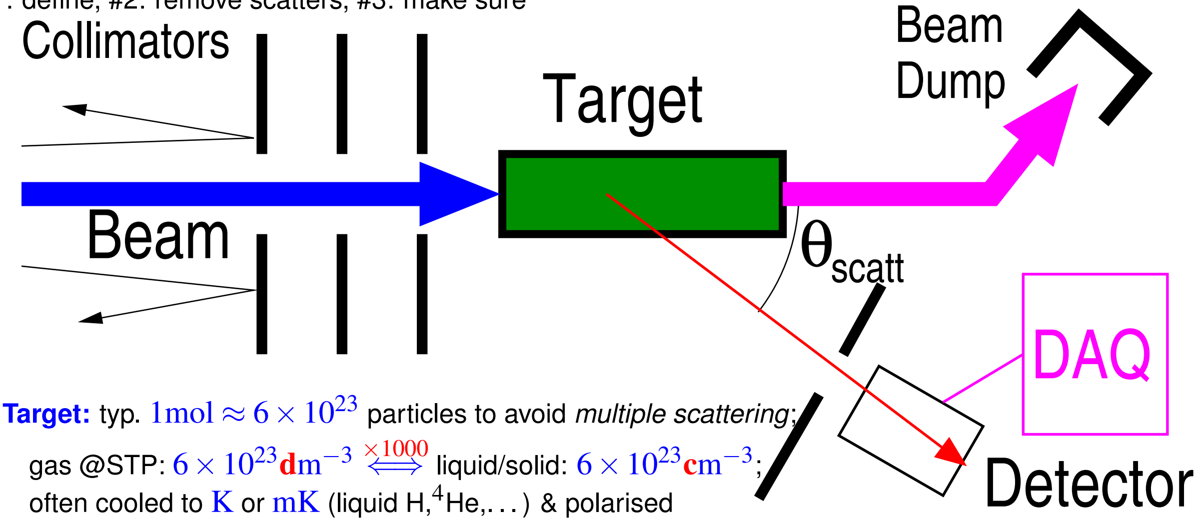
Or: How You Measure What You Measure

References: [HG 3,4; PDG 34-36]

(a) What An Experiment Really Is (Ideally)

Beam Cleanup: remove charged undesireds by $\vec{B}$
Collimators: make sure *all* beam hits target
eliminate “beam halo” (cotravelling undesireds)
#1: define, #2: remove scatters, #3: make sure

Charged-Beam Dump: use Cu; after bend to reduce backscatter; measure charged-beam flux by Faraday cup; often most radioactive piece during run



Target: typ. $1\,\mathrm{mol} \approx 6\times10^{23}$ particles to avoid *multiple scattering*;
gas @STP: $6\times10^{23}\,\mathbf{dm}^{-3} \overset{\times 1000}{\Longleftrightarrow}$ liquid/solid: $6\times10^{23}\,\mathbf{cm}^{-3}$;
often cooled to K or mK (liquid H,^{4}He,...) & polarised

If you are a beam, everything looks like a target:
Nature cannot separate between **signal (good)** and **noise (bad)**:
contaminations: scatter from wrong reaction, atomic e^-,
container, impurities/stabilising compounds (e.g. $NaPO_3$ for P),
collimators, beam dump; environment: concrete, cosmics,...

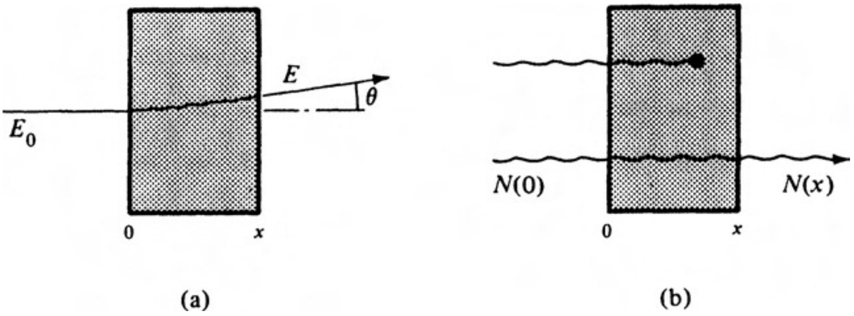
Detector:
collimator often defines angle

Data Acquisition:
hardware/software filters,
event recording,...

$\Longrightarrow$ **student** $\Longrightarrow$ **paper**

(b) Interaction of Particles With Matter $< 10\,\mathrm{GeV}$ [HG 3; Per 11.5]

Atomic Physics Dominates. Two extremes: real world in-between, mixed.



(a)

(b)

[HG 3.1]

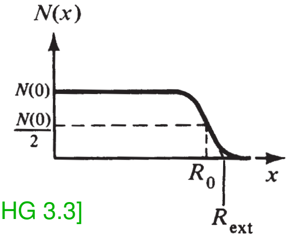
Multiple Scattering (e.g. electron)

usually small E loss, small angle

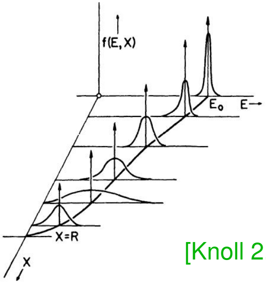
energy & angle spread

R_0: mean range

energy profile gets smeared with penetration



[HG 3.3]



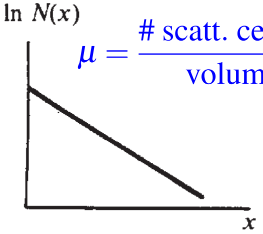
[Knoll 2.4]

Absorption (e.g. photon)

“all or nothing”

$N(x) = N_0\, \mathrm{e}^{-\mu x}$ with

attenuation (absorption) **coefficient**



$$\mu = \frac{\#\ \text{scatt. centres}}{\text{volume}} \times \sigma$$ cross section

$$X_0 = \frac{1}{\mu}$$ mean free path

[HG 3.4]

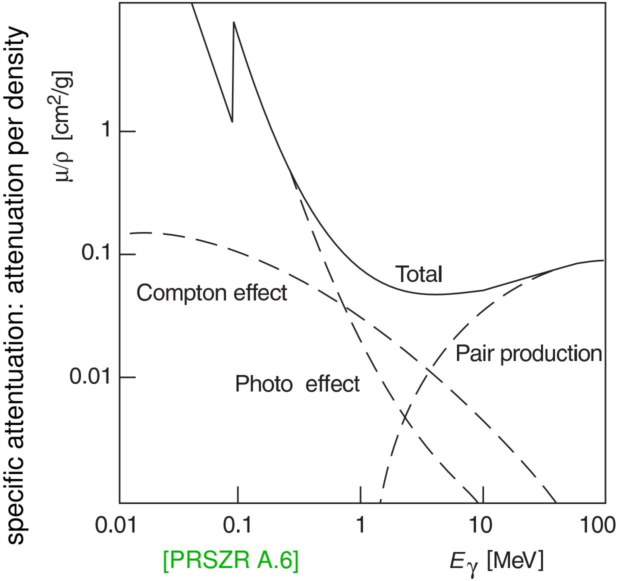
Photons in Matter

Photoelectric effect (with edges from atomic shells; γ absorbed) $\propto Z^{4.5}/E^3$

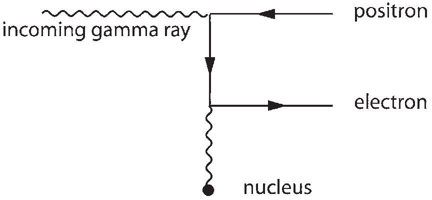
+ Compton (inelastic) $\gamma Z \to \gamma e Z'$: multi-scatt. with large energy loss $\Longrightarrow$ quasi-attenuation $\propto Z \times \ln E/E$

+ Pair Production $\gamma \to e^+ e^-$ at $\geq 1\,\mathrm{MeV}$, in Coulomb of heavy nucleus, coherent $\propto Z^2 \ln E$

$\Longrightarrow$ describe all three by attenuation $\mu = \mu_{\text{photo}} + \mu_{\text{Compton}} + \mu_{\text{pair}}$

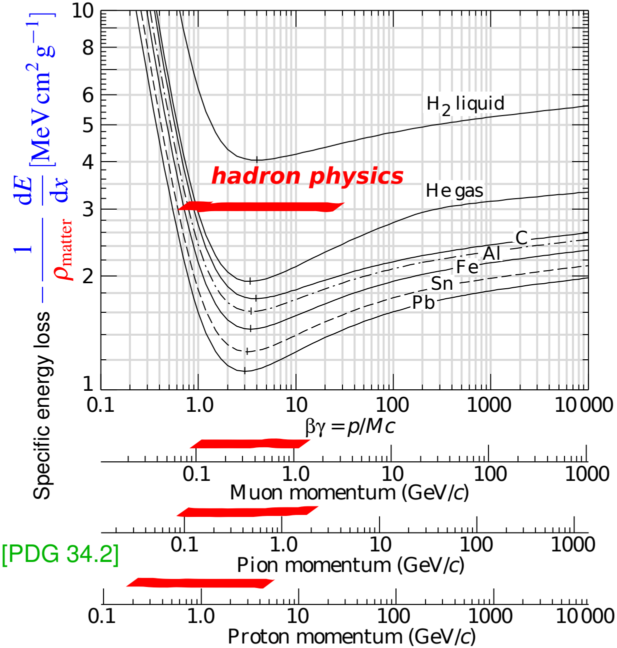


[PRSZR A.6]



Heavy Charged Particles: $E \lesssim m$

Loss mostly by **Coulomb with bound electrons**: avg. ionisation energy $I \implies$ multiple scattering process



[PDG 34.2]

material: the more electrons, the quicker loss
(here normalised to ρ_{material}!)

particle: Rutherford-σ depends only on $\beta\gamma = \frac{p}{m}$!
at given p: for $m \nearrow$, momentum transfer $\searrow$

small E (non-relativistic): $\propto 1/E \propto 1/\beta^2$
long passage time $\implies$ long interaction time

minimum at $\beta\gamma \approx 3$: Hadron Physics problem

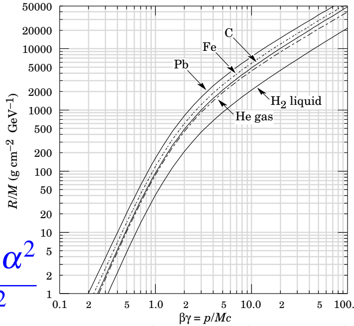
above: relativistic rise $\propto -\ln[1-\beta^2]$
moving $\vec{E}$ Lorentz contracted $\implies$ wider range

eventual saturation (Fermi plateau):
surrounding charges screen

Specific range

$$R = \int_{E_{\text{in,kin}}}^{0} \frac{dE_{\text{kin}}}{dE/dx}$$

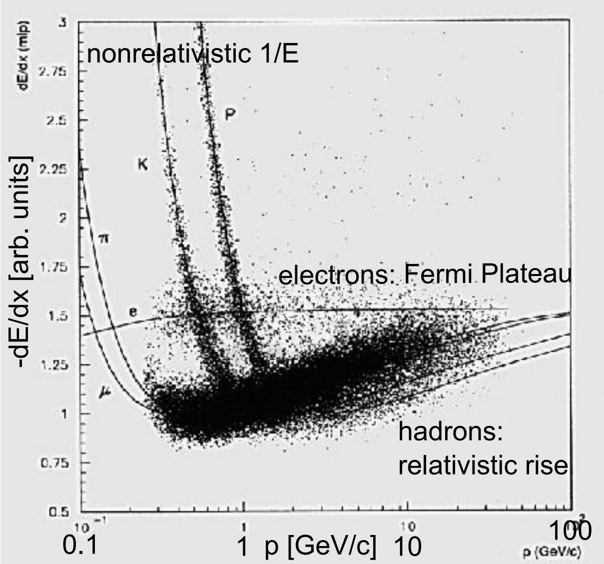
[PDG 34.4]



Modelled up to few % by **Bethe formula** in relativistic QM at
$0.1 \lesssim \beta\gamma \lesssim 1000$ & I: avg. excitation pot. of material [derivation: Per]

$$-\frac{1}{\rho}\frac{dE}{dx} \approx \frac{4\pi Z_{\text{particle}}^2 \alpha^2}{m_e}\,\frac{n_e}{\beta^2}\left[\ln\frac{2m_e\beta^2\gamma^2}{I \approx 16 Z_{\text{mat}}^{0.9}\,\text{eV}} - \beta^2\right] \overset{\text{low}\beta}{\approx} \frac{2\,\text{MeV}}{\text{g/cm}^2}\,\frac{Z_{\text{part}}^2\alpha^2}{\beta^2}$$

Electron vs. Heavier Particles at Same Energy/Momentum



– electron: relativistic even for MeV; Fermi plateau at $1\ \mathrm{GeV}$

– proton $E \lesssim 50\ \mathrm{MeV}$: non-relativistic $\Longrightarrow$ photoeffect; stopping $\gg$ electron for same p: smaller β

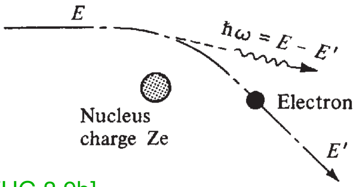
– proton $E \sim 5\ \mathrm{GeV}$: minimum between Photo/Compton and Bremsstrahlung

– proton $E \gtrsim 10\ \mathrm{GeV}$: e^+e^- pair production $+$ hadronic reactions, rise to Fermi plateau.

Energy loss at low-E: proton $\gg$ electron $\Longleftrightarrow$ at high-E: proton $\ll$ electron $\Longrightarrow$ Discriminate!

Electrons & Positrons in Matter: Charged but $E \gg m$ [Edyn RadSys 42]

Atomic Ionisation & Excitation (like heavy particle)



[HG 3.9b]

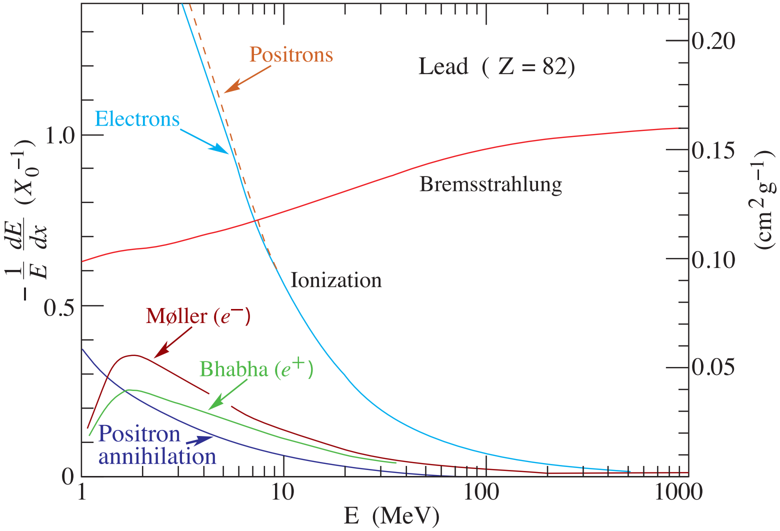
small mass more easily deflected

+ Bremsstrahlung $e^\pm Z \to e^\pm Z\gamma$: dominant above $E \approx \dfrac{600\mathrm{MeV}}{Z}$:

direction change in Coulomb field of heavy nucleus (Larmor)

$\Longrightarrow$ radiation: $-\dfrac{\mathrm{d}E}{\mathrm{d}x} \propto \dfrac{Z^2\, E}{m^2}$: suppressed for all but electrons

+ pair-production from secondary photon $\gg 1\mathrm{MeV}$ $\Longrightarrow$ shower



e^- energy loss in lead

[PDG 34.11]

Nuclear Reactions

[Tav 2.5]

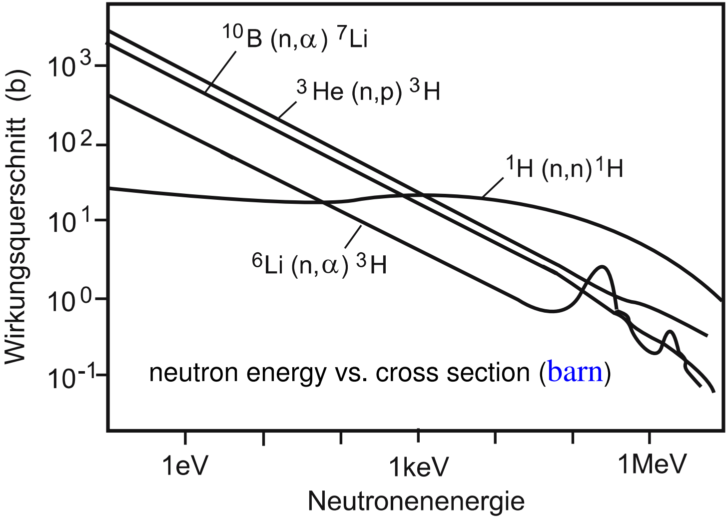
Most important for neutral hadrons at low momenta (neutron,. . .), any hadron at high momenta:

- $\mathrm{eV} - \mathrm{keV}$: fission, capture $\propto 1/$velocity: time in nucleus
- MeV: elastic/inelastic scattering – most E loss when scattering off light/similar-mass partner

  additional enhancement : $\sigma_{np}(1\mathrm{MeV}) \approx 4\pi\, a_{np}^2$ with scatt. length $a_{np} \approx 24\mathrm{fm}$

  $\Longrightarrow$ detect recoil proton & its shower (esp. for neutron)
- $\gtrsim \mathrm{GeV}$: inelastic scattering $\Longrightarrow$ hadron showers (like in cosmic rays)

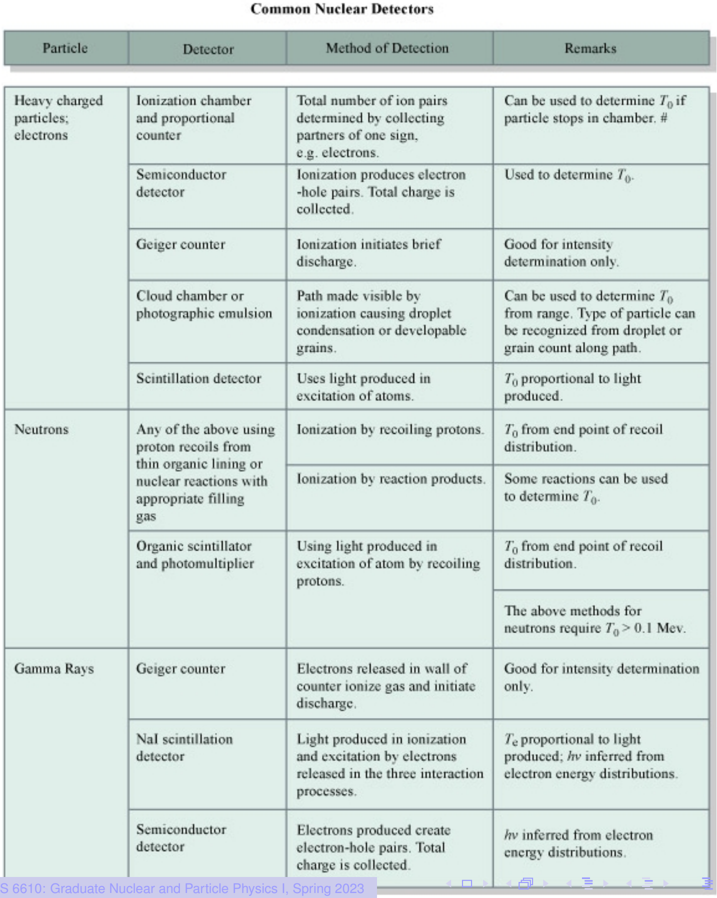
  wins over elmag; large range R_0 $\Longrightarrow$ large penetration length



neutron energy vs. cross section (barn)

[Bethge/Walter/Wiedemann: Kernphysik Fig 5.6]

(c) Detectors



Common Nuclear Detectors

Particle	Detector	Method of Detection	Remarks
Heavy charged particles; electrons	Ionization chamber and proportional counter	Total number of ion pairs determined by collecting partners of one sign, e.g. electrons.	Can be used to determine T_0 if particle stops in chamber. #
	Semiconductor detector	Ionization produces electron -hole pairs. Total charge is collected.	Used to determine T_0.
	Geiger counter	Ionization initiates brief discharge.	Good for intensity determination only.
	Cloud chamber or photographic emulsion	Path made visible by ionization causing droplet condensation or developable grains.	Can be used to determine T_0 from range. Type of particle can be recognized from droplet or grain count along path.
	Scintillation detector	Uses light produced in excitation of atoms.	T_0 proportional to light produced.
Neutrons	Any of the above using proton recoils from thin organic lining or nuclear reactions with appropriate filling gas	Ionization by recoiling protons.	T_0 from end point of recoil distribution.
		Ionization by reaction products.	Some reactions can be used to determine T_0.
	Organic scintillator and photomultiplier	Using light produced in excitation of atom by recoiling protons.	T_0 from end point of recoil distribution.
			The above methods for neutrons require $T_0 > 0.1$ Mev.
Gamma Rays	Geiger counter	Electrons released in wall of counter ionize gas and initiate discharge.	Good for intensity determination only.
	NaI scintillation detector	Light produced in ionization and excitation by electrons released in the three interaction processes.	T_e proportional to light produced; $h\nu$ inferred from electron energy distributions.
	Semiconductor detector	Electrons produced create electron-hole pairs. Total charge is collected.	$h\nu$ inferred from electron energy distributions.

Usually needed:

– $\theta_{\text{scatt}} \rightarrow$ position detectors

– particle ID: charge, mass

interaction characteristics

$\Longrightarrow$ measure two of E, p, β:

$$E = \sqrt{p^2 + m^2} = \gamma\, m$$

$$p = \beta \gamma\, m$$

No detector can do all,

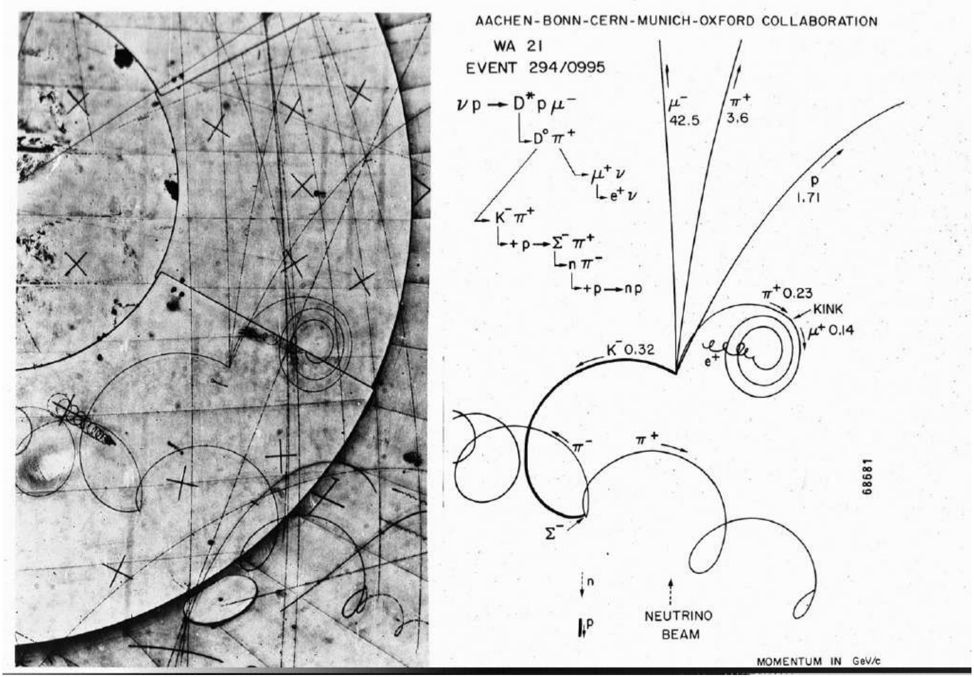
but most are multifunctional.

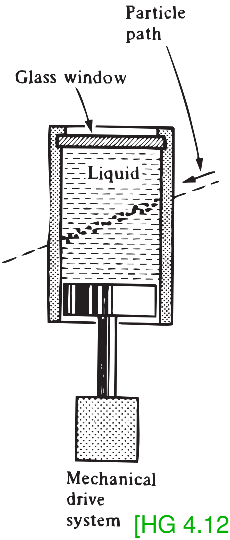
$\Longrightarrow$ **Compromise!**

Efficiencies always $< 100\%$.

Here: only talk about some popular ones.

Multipurpose Example: Bubble Chamber with Magnetic Field





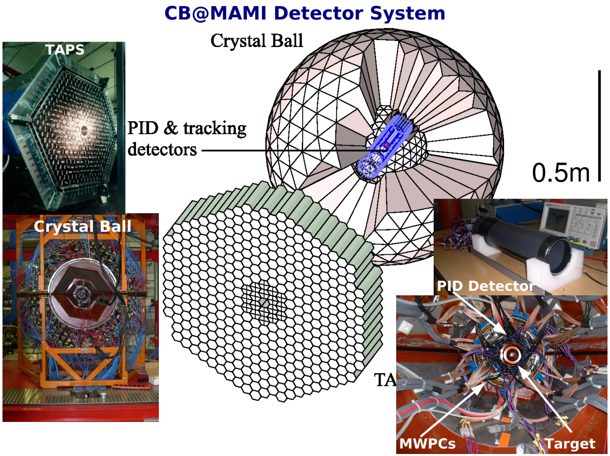
[HG 4.12]

ionisation in superheated medium $\Longrightarrow$ nucleus (i.e. seed) for a bubble $\Longrightarrow$ track $\Longrightarrow$ position(s)

identify: charge Q; momentum $p[\mathrm{GeV}] \approx 0.3\,|Q[e]|\,B[T]\,R[\mathrm{GeV}^{-1}]$; track thickness $\Longrightarrow$ particle ID

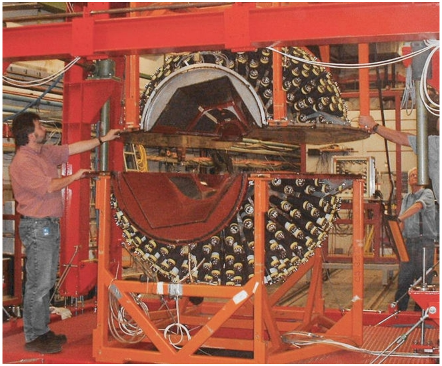
repetition rate $1\ \mathrm{s}^{-1}$ very slow, but nowadays CCD cameras, automated track recognition, rare processes

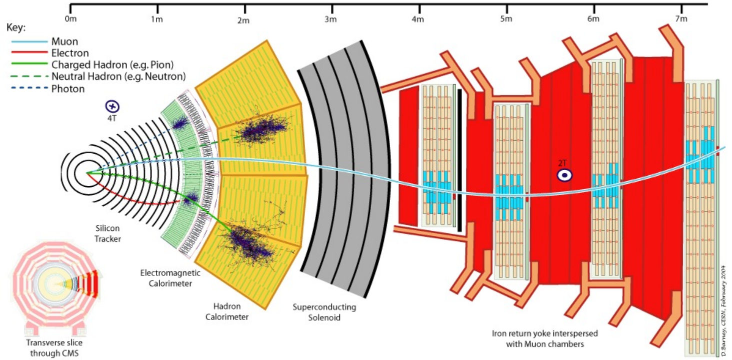
Detector Systems Depend on Purpose, Beam & Energy Briscoe, Downie



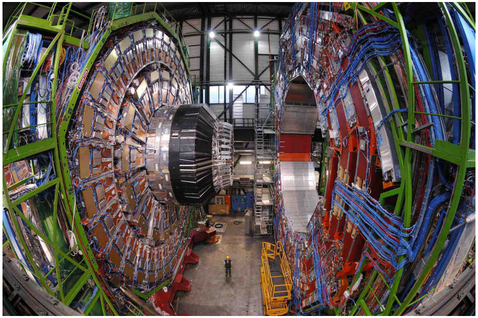
Crystal Ball at MAMI (former SLAC & DESY)

$\lesssim$ GeV; "4π detector": 93% of solid angle





CMS (LHC@CERN; URL): TeV



Spectrometer: Momentum Selector

θ_{scatt} by entrance collimator; $B \approx 1 - 2\ \text{T}$, sophisticated focussing & field mapping, position detector

Example MAMI-A1 (URL): electron scattering for nucleon form factors,. . .

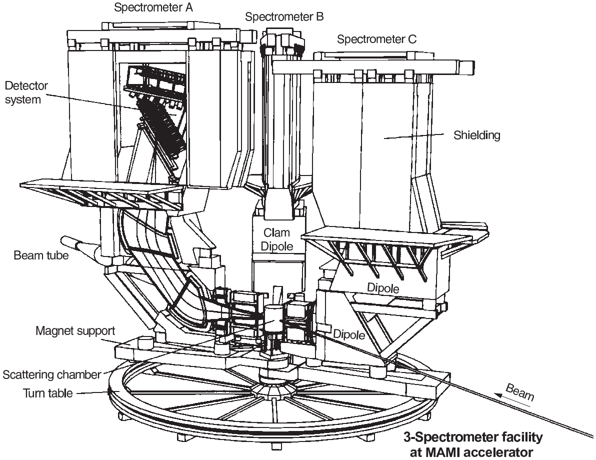


Fig. 5.4. Experimental set-up for the measurement of electron scattering off protons and nuclei at the electron accelerator MAMI-B (Mainzer Microtron). The maximum energy available is 820 MeV. The figure shows three magnetic spectrometers. They can be used individually to detect elastic scattering or in coincidence for a detailed study of inelastic channels. Spectrometer A is shown in cutaway view. The scattered electrons are analysed according to their momentum by two dipole magnets supplemented by a system of detectors made up of wire chambers and scintillation counters. The diameter of the rotating ring is approximately 12 m. (*Courtesy of Arnd P. Liesenfeld (Mainz), who produced this picture*) [PRSZR]

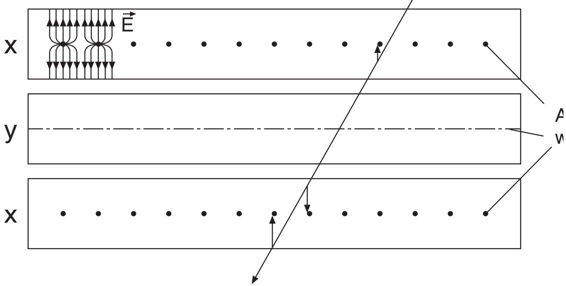
Some Position Detectors

Gas Filled Chambers: cheap, large, robust against radiation – but fragile; $E_{\text{ionisation}} \approx 30\,\text{eV}$

Principle: particle ionises $\Longrightarrow$ accelerate electrons (ions) in $E \gtrsim \text{kV}/\text{cm}$ field $\Longrightarrow$ more ionisation

$\Longrightarrow$ avalanche accelerated to anode ($1:10^{>4}!$) $\Longrightarrow$ detect, resolution $\Delta x \gtrsim 100\,\mu\text{m}$

Multiwire Proportional Chamber MWPC



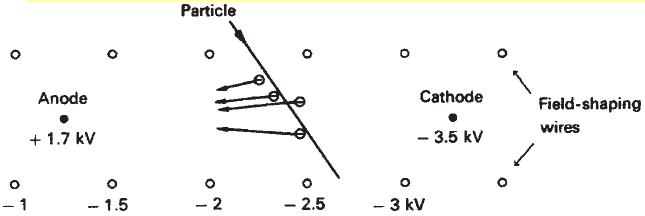
typ. wire-distance $\gtrsim 200\mu\text{m} \sim \Delta x$ [PRSZR A.7]

$\Longrightarrow$ needs very small structure

Drift Chamber

measure drift time to anode for 2-dim resolution

Scintillator needed to set trigger for arrival of particle



typ. wire distance $\sim 2\text{cm} \gg \Delta x$ [Per 11.8]

needs constant drift velocity (i.e. const. $\vec{E}$-field)

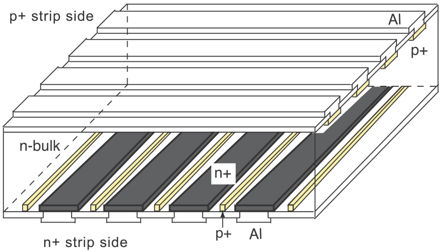
Semiconductor Strips:

$E_{\text{ion}} \approx 3\,\text{eV} \Longrightarrow$ shower $\nearrow$, fluctuation $\searrow$

$\Longrightarrow$ great energy resolution

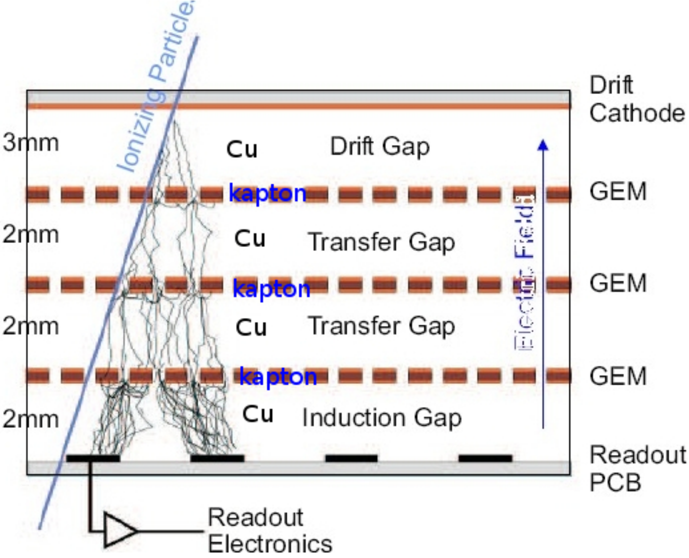
$\Delta x \gtrsim 2\dots5\mu\text{m}$ (etching) $\Longrightarrow$ close to target

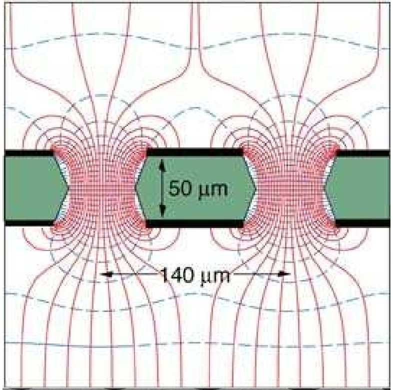
but prone to radiation damage, expensive

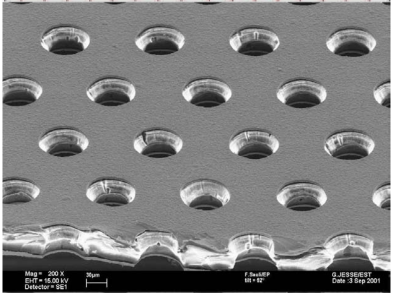


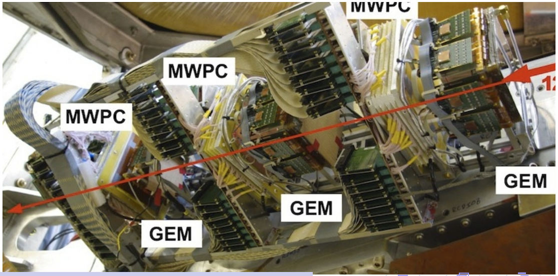
Example of New Develoment: Gas Electron Multiplier GEM [Tav, Downie]

Cu-layer-sandwiched kapton (insulator) foil with micro-holes: strong $\vec{E}$ in hole $\Longrightarrow$ accelerate, shower





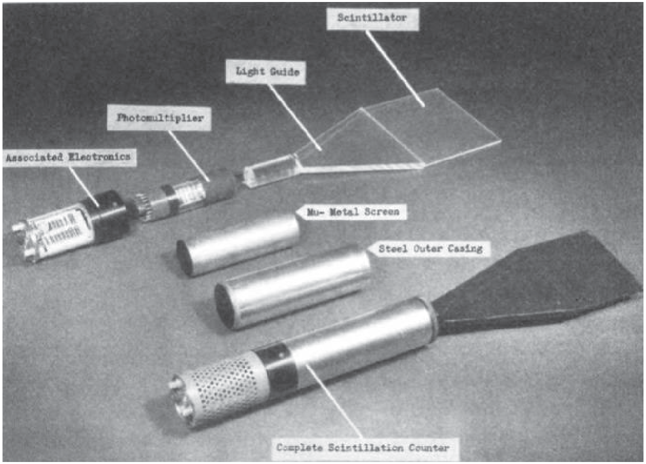




- resolution $\gtrsim 70\,\mu\text{m}$; efficiency $\sim 95\%$
- very stable operation, robust
- large & small structures; “cheap”

More Position Detectors: Scintillators

particle excites/ionises $\Longrightarrow$ visible/UV light by de-excitations, augment by PhotoMultiplier Tube PMT



[Per 9.11]

very fast ($200\,\mathrm{ps}$), robust, simple

$\Longrightarrow$ **Workhorses:**

– position at spectrometer-end

– trigger/timing:

set acceptance window for detectors & DAQ

– veto (cosmic,. . .)

– time-of-flight $\Longrightarrow$ β to find m from p or E,

$$\text{but } \frac{\Delta m}{m} \sim \gamma^2 \Delta t$$

Materials:

– inorganic crystals (NaI, glass,. . .)

– organic: plastic, liquid

– semiconductor: very thin

Calorimeters: Scintillators as Shower Detectors

HW Spectrometer: $\frac{\Delta p}{p} \sim p$: deflection angle $\to 0$ for $p \nearrow$ $\Longrightarrow$ measure E for $E = \sqrt{p^2 + m^2} \approx p$

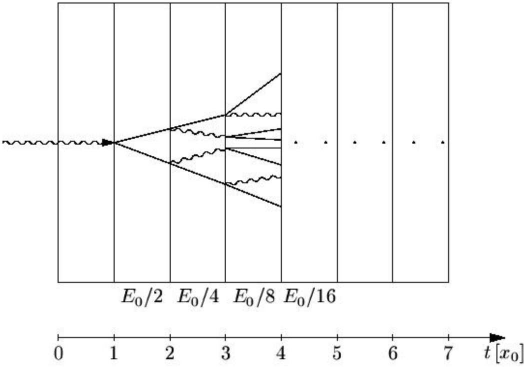
$\Longrightarrow$ total energy by stopping/destroying particle $\Longrightarrow$ length $\propto \ln E =$ many interaction lengths $R_0,\ X_0$

Poisson: $\frac{\Delta E}{E} \propto \frac{1}{\sqrt{E}}$; position & time resolution possible

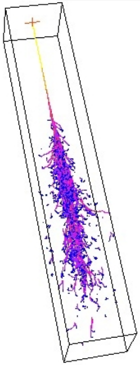
Electromagnetic Calorimeter tuned to $\gamma, e^{\pm}$ detection:

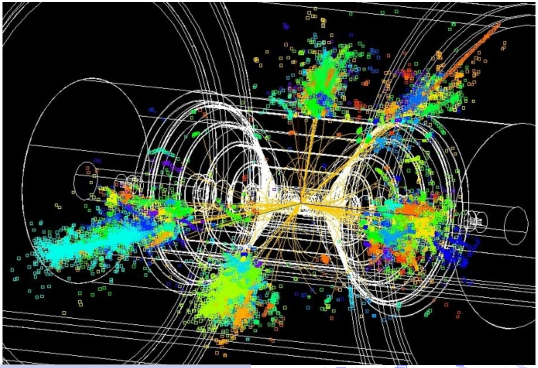
Shower $\propto Z^2$, small X_0, narrow ($\sigma_{\text{Rutherford}} \propto \frac{1}{\sin^4 \theta/2}$)

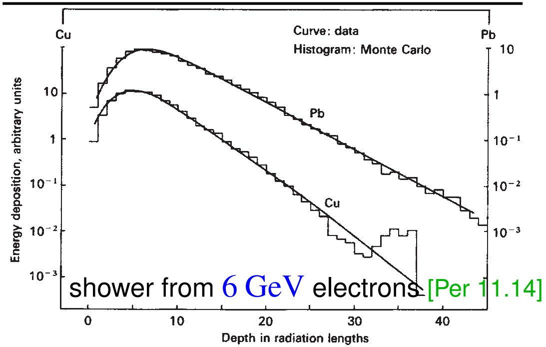
[Per] discusses a **simple shower model**, but. . .



Real World: GEANT4 Monte Carlo simulation of shower profile/evolution, efficiency!







shower from $6\ \mathrm{GeV}$ electrons [Per 11.14]

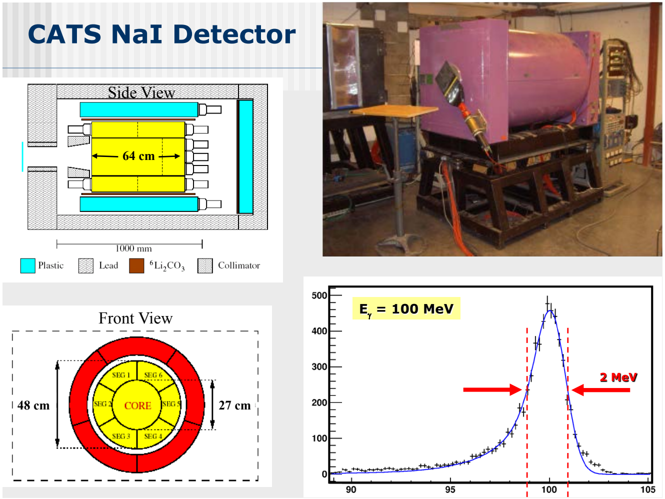
Electromagnetic Calorimeters: Example NaI Crystals

[Briscoe, Downie, Feldman]

radiation length $X_0 = 2.6\ \mathrm{cm} \implies 15\ldots20\ X_0 = 40 - 60\ \mathrm{cm}$: huge mono-crystals

make sure that *all* shower captured: $\dfrac{\Delta E}{E} \sim \dfrac{1\ldots2\%}{\sqrt[2\ldots4]{E\ [\mathrm{GeV}]}}$ [PRSZR]

672 crystals, $15.7\ X_0$ each



1 of 4 largest monocrystals, $24\ X_0$, now at HIγS

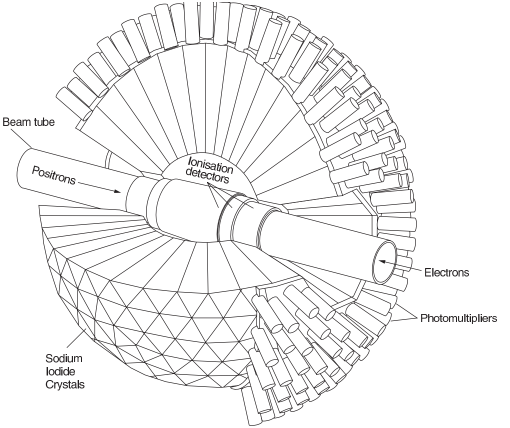


Fig. 13.4. A (crystal ball) detector built out of spherically arranged NaI crystals. High energy photons from electromagnetic $c\bar{c}$ transitions are absorbed by the crystals. This creates a shower of electron-positron pairs which generate many low energy, visible photons. These are then detected by photomultipliers attached to the rear of the crystals. The current measured from the photomultipliers is proportional to the energy of the initial photon (from [Kö86]).

Crystal Ball, now at MAMI (URL) [PRSZR]

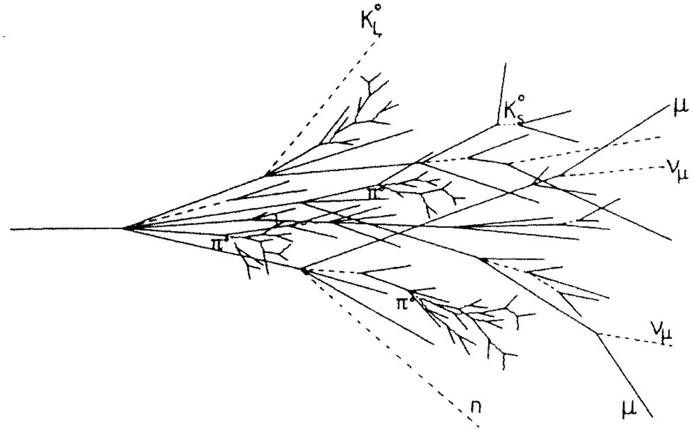
For Compton scattering, meson production, hadron & nuclear spectroscopy, e^+e^- annihilation,. . .

Hadronic Calorimeters

low-E: short shower, cone wide relative to length but narrow absolutely (bowling ball on bowling ball)

high-E: long shower, broad but narrowing as $E \nearrow$: Lorentz boost

elmag. loss & strong interactions $\Longrightarrow$ prefer large A (hard-sphere)



produce other hadrons

with large masses $\Longrightarrow$ fewer particles

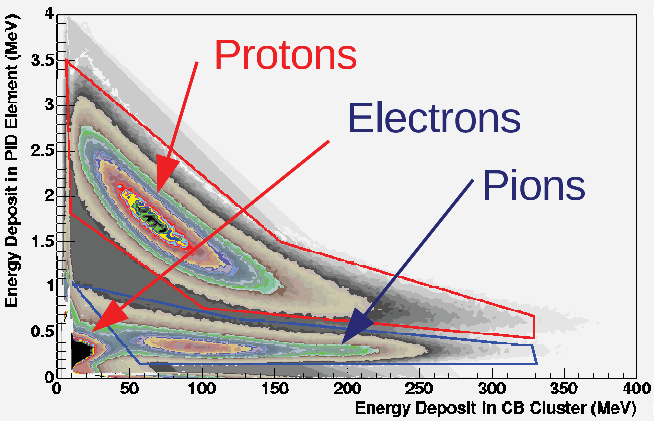
$\lesssim 30\%$ of shower "lost": $\mu,\ \nu,\ \pi^0, \dots$

$$\Longrightarrow \frac{\Delta E}{E} \sim \frac{30\dots80\%}{\sqrt{E\,[\mathrm{GeV}]}}\,!!$$

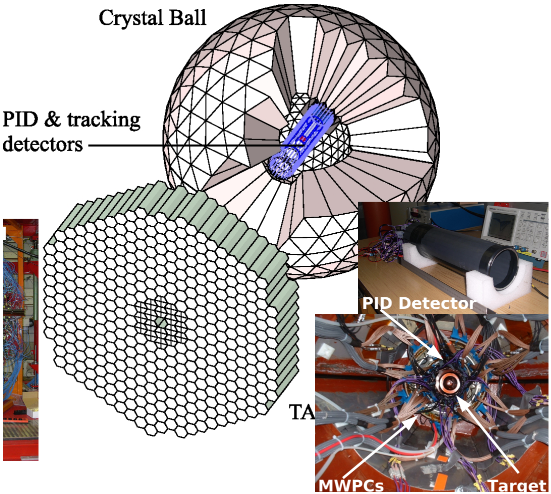
ID often tricky, ambiguous. $\Longrightarrow$ Combine with information from TOF, spectrometer, shower profile,. . .

Particle ID at CB-TAPS

[Downie]



Coincidence plot: Show only events in both PID and NaI



$800\,\mathrm{MeV}$ photon beam on hydrogen target

PID $\equiv$ Particle ID: thin plastic scintillator $\Longrightarrow$ particles pass through

Shower discriminant: PID scintillator for “track length”; NaI for calorimetry

neutrals (γ, n): lots in NaI, nothing in PID $\Longrightarrow$ not on this plot

shower profile in NaI: proton signal in 1 crystal only $e^{\pm}$, $\pi^{\pm}$ 2-6 adjacent crystals (wide shower)

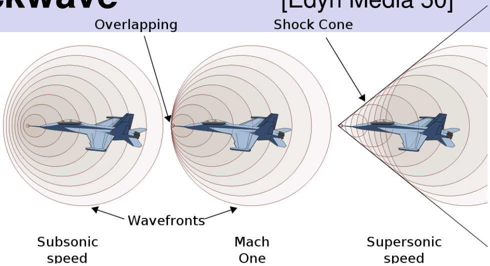
Čerenkov Radiation: Superluminal Shockwave

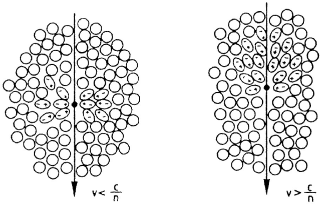
When $\beta > \dfrac{c}{\text{refractive index } n}$ phase velocity of light in medium

$\Longrightarrow$ relaxation along path by shock wave $\Longrightarrow$ light

$\Longrightarrow$ radiation in cone $\cos\theta_C = \dfrac{1}{\beta n}$ depends *only* on β

[Edyn Media 50]

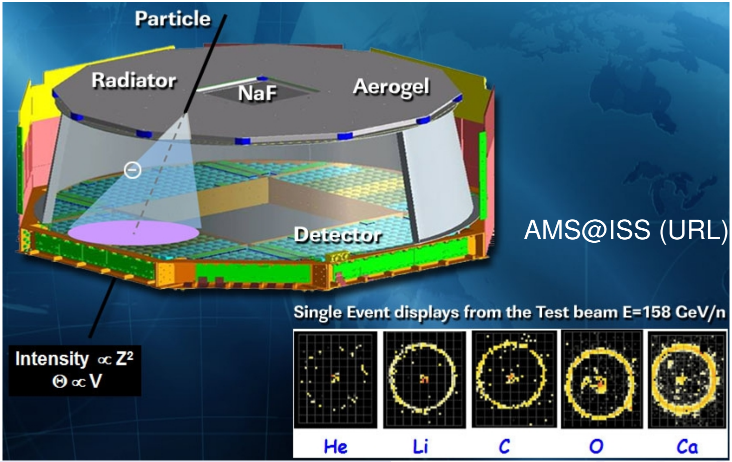




Threshold mode: only detect light $\Longrightarrow \beta_{\text{min}}$ (π^+ vs. K^+ vs. p)

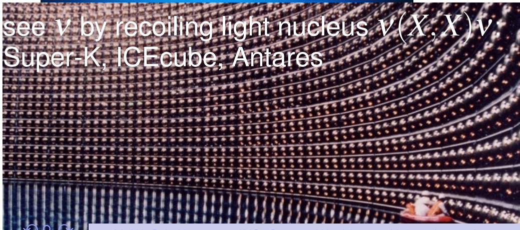
Ring Image Čerenkov RICH: measure $\theta_C \Longrightarrow \beta$

tune material, pressure $\Longrightarrow \gamma \sim 1.2 \cdots > 100$ possible [Per]



AMS@ISS (URL)

“reactor glow”: superluminal $e^{\pm}$



see ν by recoiling light nucleus $\nu(X,X)\nu$: Super-K, ICEcube, Antares

More Special Cases

Short-lived Particles: by decay products (invariant-mass method); e.g. $\pi^0 \to \gamma\gamma$

Neutrons: next-to-no elmag, only strong:

dote scintillators

use proton conversion in low-A material,

${}^6\mathrm{Li}(n,\alpha)^3$He for $E_n > 20\mathrm{MeV}$,…

Muons: if survives tons of shielding but then shows up in elmag calorimeter, it's a muon. (see CMS)

Neutrinos: missing E and p

If it survives kilometres of shielding and then suddenly you see

a recoil nucleus/atom which cannot be explained any other way, it's a neutrino.

– or very special detectors:

chemical conversion (Cl$\longrightarrow$Ar, Ga$\longrightarrow$Ge),

phototubes watching "nothing"

(d) Some General Detector Characteristics

[Grupen/Shwartz 2]
[Leo 5]

Resolutions in energy, momentum, spatial, temporal,. . .

Depend on all variables: particle charge, energy, momentum, hit location, time,. . .

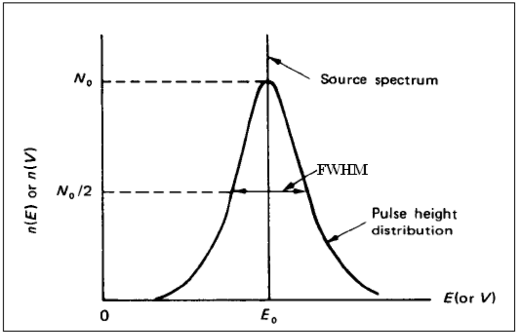
Measurement uncertainties $\pm\sigma_{E/p/x/t/\ldots}$
usually **not Gauß'ian/normal distributed**:

Particle number is discrete, minimal detectable energy,. . .

$\Longrightarrow$ Poisson, Bernoulli, Fano, rare-event statistics,. . .

But often taken as Gauß'ian to make life easier,
if narrowly peaked: "Full Width at Half Maximum concept"

FWHM $= 2\sqrt{2\ln 2}\,\sigma_X \approx 2.355\sigma_X$ (if narrow & Gaußian)



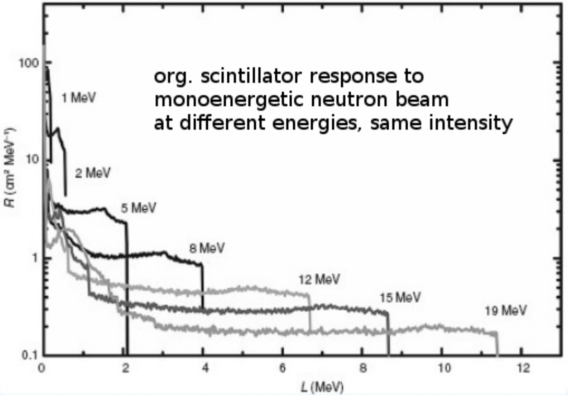
Response dep. on hit charge, E, p, location in detector, time,…

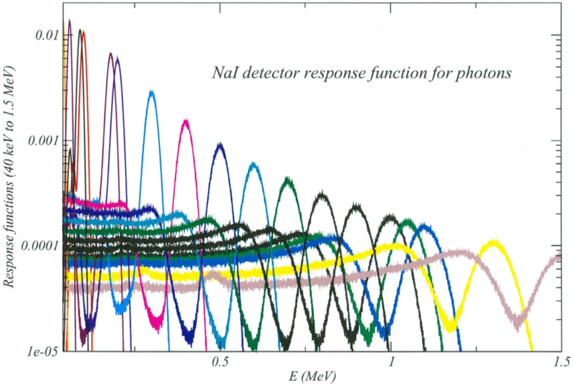
Sensitivity: minimum threshold to trigger signal

Saturation: maximum possible signal (e.g. before radiation damage)

wanted for spatial resolution, **unwanted** for total energy

e.g. energy response function: monoenergetic beam can produce
broad spectrum of deposited energies due to subsequent interaction of recoils & secondaries


org. scintillator response to
monoenergetic neutron beam
at different energies, same intensity


NaI detector response function for photons

Response Function & Pulse Height often highly nonlinear in intensity, energy,…!

Example particle energy: can often not read off accurately simply from peak position.

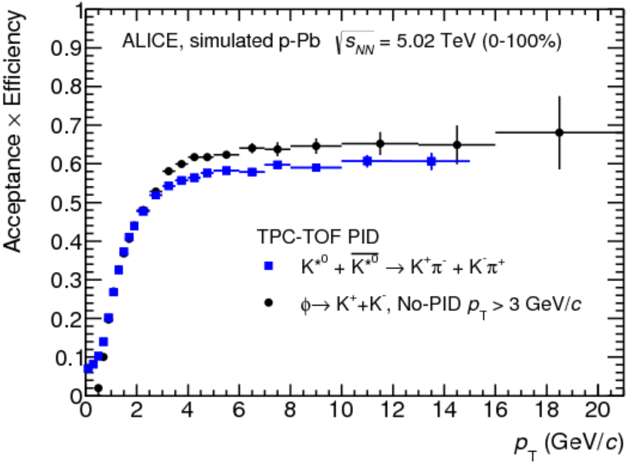
Efficiency dep. on hit charge, E, p, location in detector, time,…

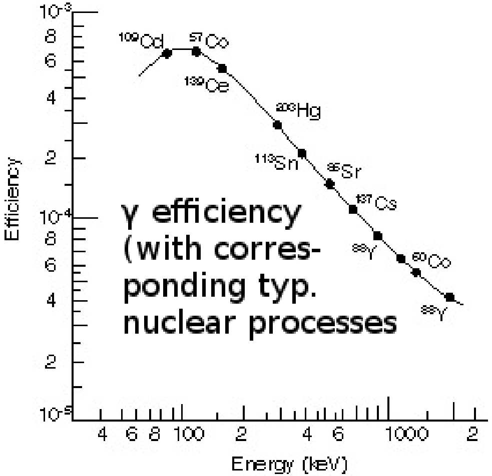
Detector Efficiency $0 \leq \epsilon \leq 1$: probability that particle *actually seen* in detector.

γ-ray in gas counter: few-$\%$; charge in scintillator: $\sim 100\%$; MeV – neutrinos in huge detector: 10^{-18}

$$\text{infer true event number} = \frac{\text{seen events}}{\text{efficiency } \epsilon \pm \sigma_\epsilon} = N_{\text{true}} \pm \sigma_{N\text{true}} \implies \text{Need calibration!}$$

Total/Multiparticle Efficiency: all efficiencies combined.





γ efficiency
(with corres-
ponding typ.
nuclear processes

Time Resolution and Characteristic Times

GW: rare events/high accuracy $\Longrightarrow$ eliminate coincidentals (cosmic, false starts,. . .) by **time-window**:

Trigger: arrival of particle bunch (pulsed beam), signal in other detector,. . .

Sensitive time: allowed window after trigger

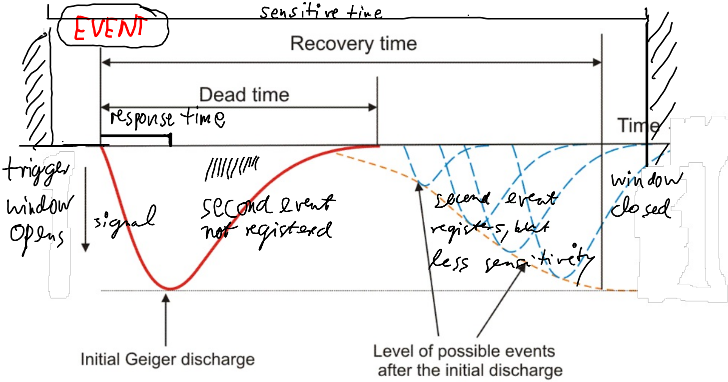
Response time: *form* signal (quick rise!)

Dead time from registration to seeing next event; Čerenkov: 10^{-9}s; Geiger: 10^{-3}s

Event **pile-up** can extend dead-time.

Correction to true events $N_{\text{true}} = \dfrac{N}{1 - N\,\tau_D}$

Recovery time: until *fully* sensitive again



Example: e^- form shower $\longrightarrow$ propagate (next event unseen) $\longrightarrow$ recombine with ions $\longrightarrow$ restore equilibrium

Readout time e.g. into memory: depends on amount of information, writing speed,. . .

Repetition time: minimum between events that can be distinguished by *all* components of experiment.

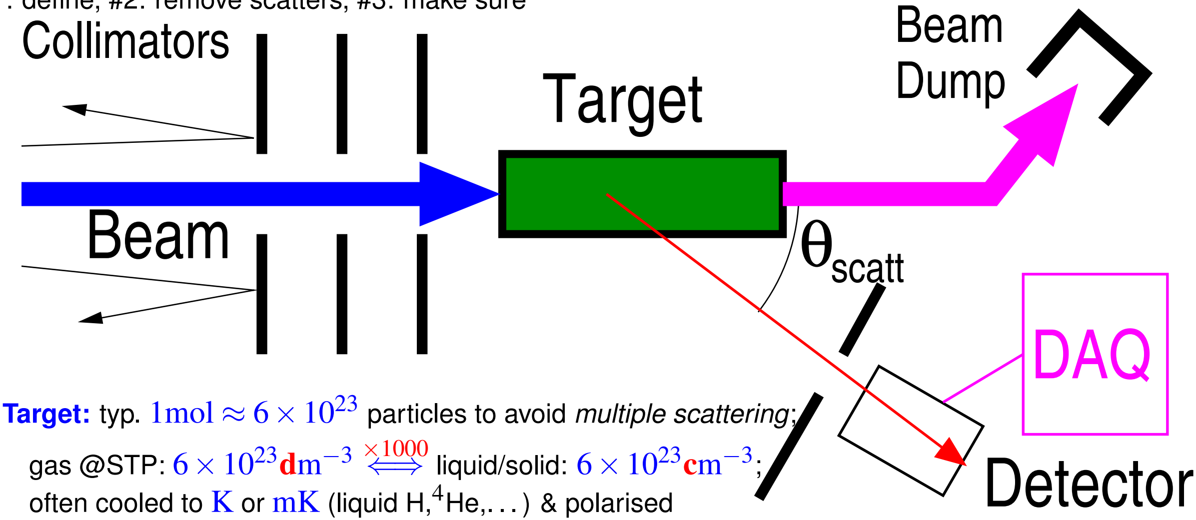
We need repetition time $< \dfrac{1}{\text{event rate}}$, but not $\lll$.

(e) What An Experiment Really Is (Ideally)

Beam Cleanup: remove charged undesireds by $\vec{B}$

Collimators: make sure *all* beam hits target
eliminate “beam halo” (cotravelling undesireds)
#1: define, #2: remove scatters, #3: make sure

Charged-Beam Dump: use Cu; after bend to reduce backscatter; measure charged-beam flux by Faraday cup; often most radioactive piece during run



Target: typ. $1\,\mathrm{mol} \approx 6 \times 10^{23}$ particles to avoid *multiple scattering*;
gas @STP: $6 \times 10^{23}\,\mathbf{dm}^{-3} \overset{\times 1000}{\Longleftrightarrow}$ liquid/solid: $6 \times 10^{23}\,\mathbf{cm}^{-3}$;
often cooled to K or mK (liquid H,^{4}He,…) & polarised

If you are a beam, everything looks like a target:
Nature cannot separate between **signal (good)** and **noise (bad)**:
contaminations: scatter from wrong reaction, atomic e^-,
container, impurities/stabilising compounds (e.g. NaPO$_3$ for P),
collimators, beam dump; environment: concrete, cosmics,…

Detector:
collimator often defines angle

Data Acquisition:
hardware/software filters,
event recording,…

$\Longrightarrow$ **student** $\Longrightarrow$ **paper**

Next: 4. Statistics and Some of Its Pitfalls in 180 Minutes

Familiarise yourself with: [PDG 39/40,

Press/Teukolsky/Vetterlin/Flanery: Numerical Recipes 14/15,

Taylor: Introduction to Error Analysis,

Berendsen: A Student's Guide to Data and Error Analysis,

Andrae/Schulze-Hartung/Melchior: Dos and Don'ts of Reduced Chi-Squared [arXiv:1012.3754 [astro-ph.IM]],

ASA Statement on p-Values: Context, Process and Purpose

Bailey: Not Normal: The Uncertainties of Scientific Measurements, R. Soc. open sci.4:160600]