

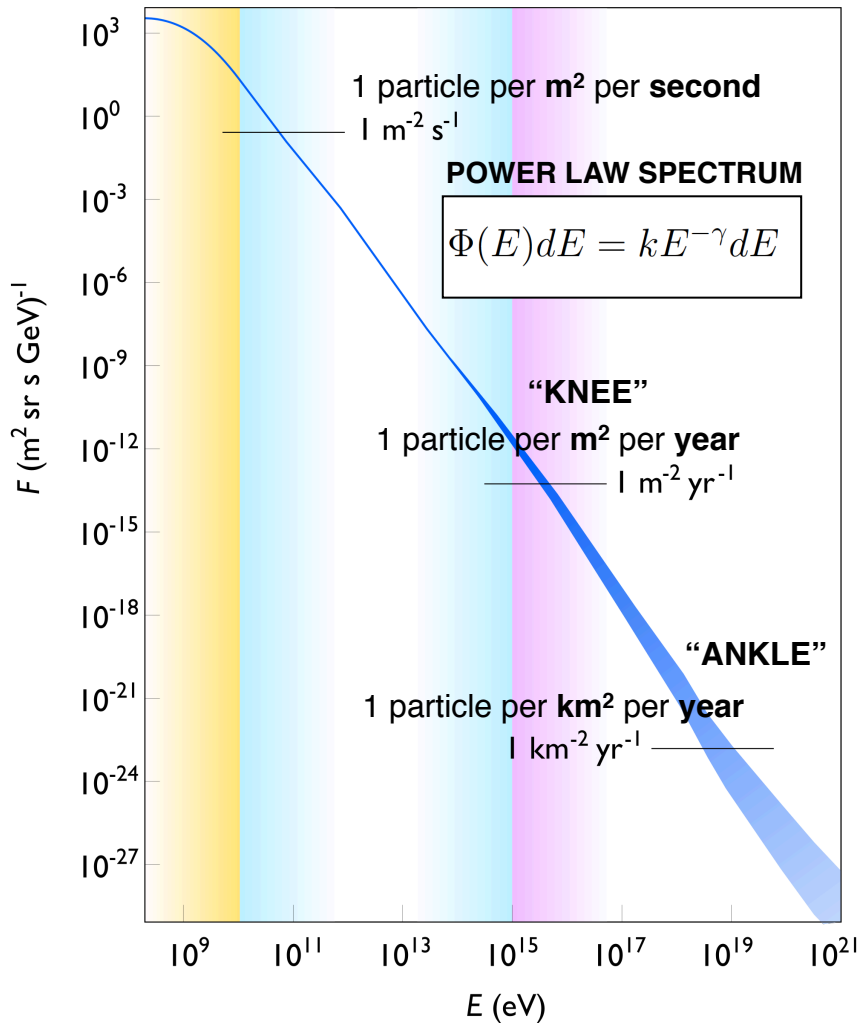
Lecture 19 111219

- Il pdf delle lezioni puo' essere scaricato da
- http://www.fisgeo.unipg.it/~fiandrin/didattica_fisica/cosmic_rays1920/

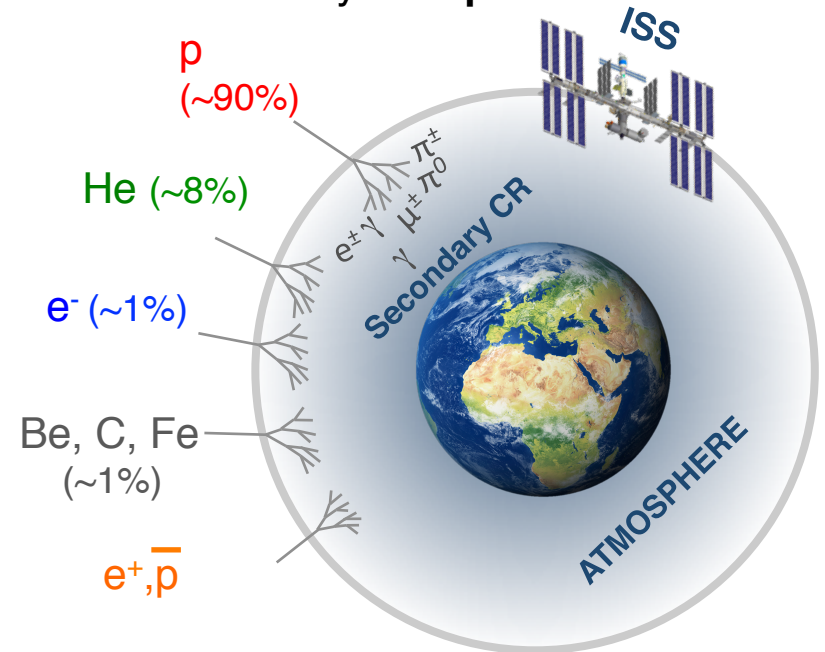
Experimental detection of cosmic rays

Cosmic Rays

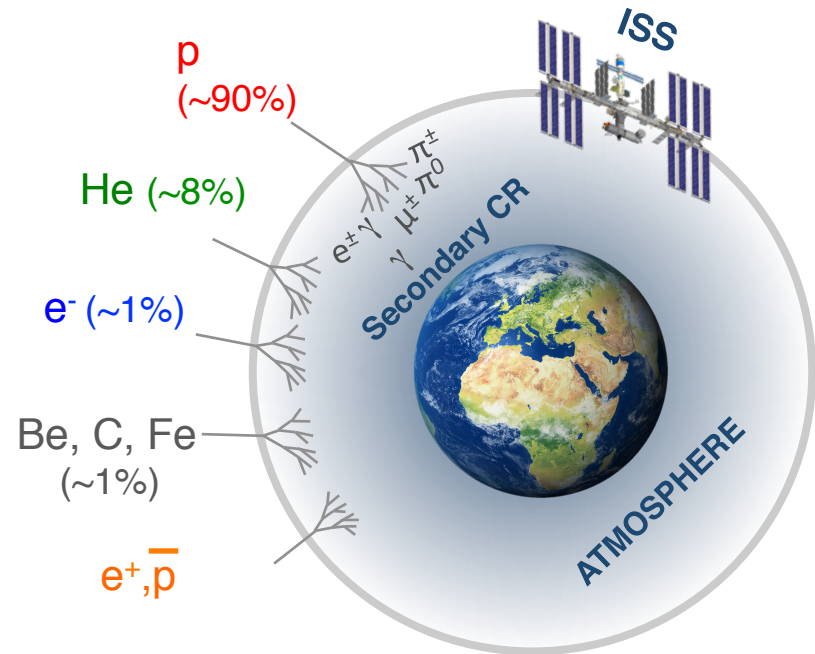
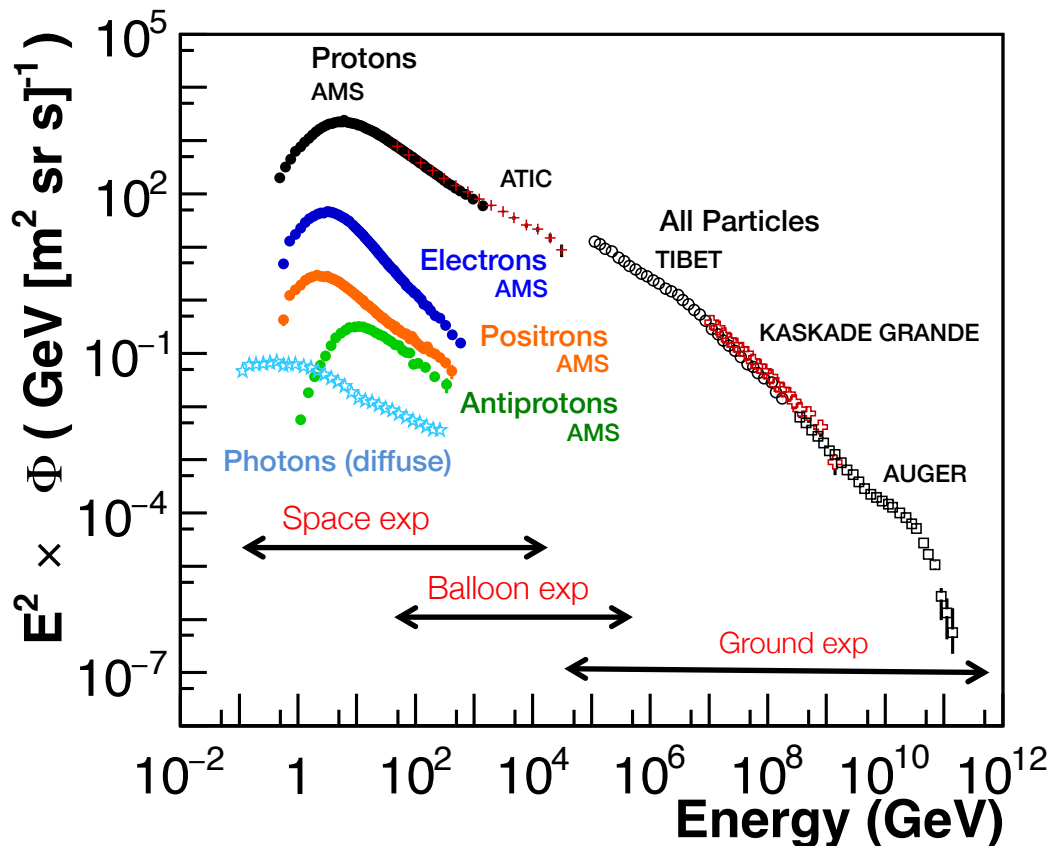
Cosmic ray flux at Earth



- Cosmic ray Flux: Intensity of CR in space per **unit of area, solid angle, time and energy**
- Energy range up to **10^{20} eV**
- Intensities spanning **30 orders of magnitude**
- Most of cosmic rays are **protons and nuclei**



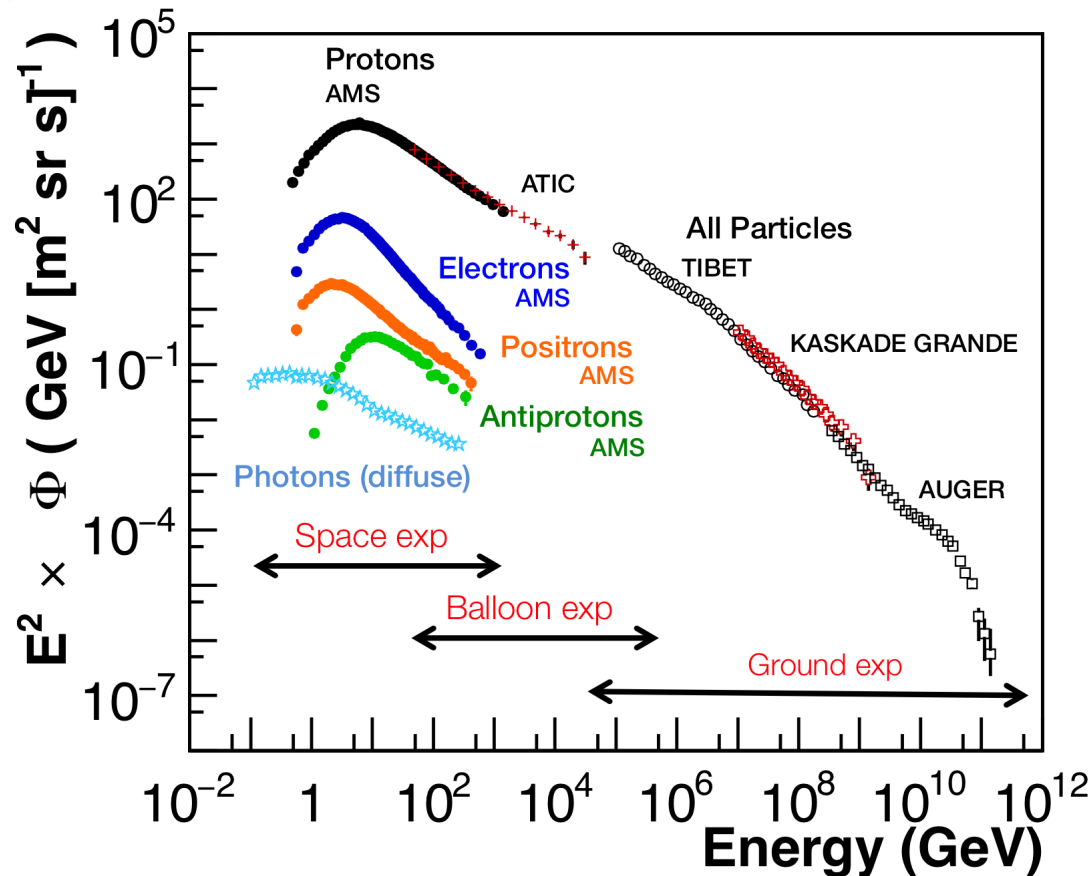
Experimental detection



- Primary cosmic rays interact with atmosphere. Only secondary CRs from interactions reach the ground.
- Flux steeply falling as function of energy. Need large collection areas

Counting rate

- Il goal di tutti gli esperimenti di raggi cosmici e' di determinare il flusso di particelle di una data specie in uno specifico intervallo di energia/momento/rigidita'/velocita'/...
- Per farlo occorre identificare, contare le particelle che attraversano l'apparato sperimentale con un'energia/momento/rigidita' X fra X e $X + \Delta X$
- Identificare una particella significa determinarne massa e carica elettrica con il segno



The flux intensity determines the experimental technique to be used to determine the CR flux

Two class of detection techniques:

- direct detection
- indirect detection

At low energy the atmosphere screens the CR flux → need to go in space, outside atmosphere or in stratosphere where few residual atmosphere is present above the apparatus → Direct measurement

At very high energy, the flux is low, direct detection is not feasible → use atmosphere as active medium and detect the secondary (charged and/or photons CR that reach ground → Indirect measurement

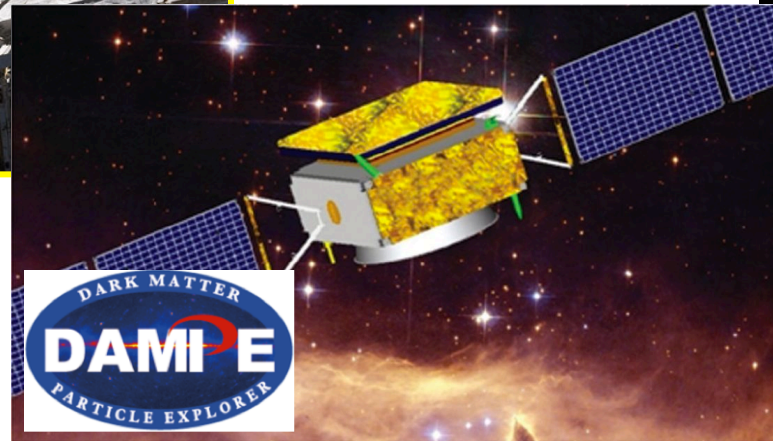
Counting rate

- What is measured in any CR experiment is the **counting rate dN_i/dt** , not the flux J_i
- Practically, in any experiment, data are collected for a time T during which N_i particles of the specie i (crossing the detector volume and interacting with its active materials) are identified and counted
- The relationship between dN_i/dt and J_i must be found, i.e. the Instrument Response Function (IRF) must be known

Direct measurement

- Direct measurements means that primary CR enter the detector without any interaction with spurious material (i.e. atmosphere) before they enter the detector volume
- Allow for a complete identification of the particle at low energy (spectrometric + calorimetric measurement) and partial id for intermediate energies below the knee (calorimetric only)

Space Borne experiments



- ✓ Direct measurements outside atmosphere
- ✓ Continuous duty cycles, typically many years of lifetime
- ✓ Field of view covering the whole sky
- ✗ Smaller acceptances
- ✗ Operation in space and communications not trivial
- ✗ "Use once and destroy"



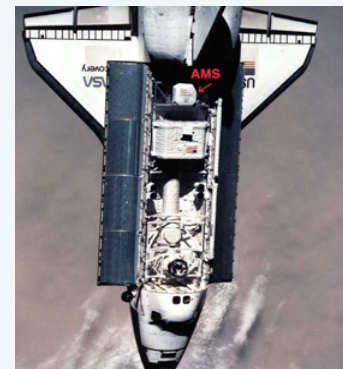
Long missions (years)
Small payloads
Low energies..

IMP series < GeV/n
 ACE-CRIS/SIS $E_{kin} < \text{GeV/n}$
 VOYAGER-HET/CRS < 100 MeV/n
 ULYSSES-HET (nuclei) < 100 MeV/n
 ULYSSES-KET (electrons) < 10 GeV
 CRRES/ONR < (nuclei) 600 MeV/n
HEAO3-C2 (nuclei) < 40 GeV/n

Short missions (days)/ Larger payloads



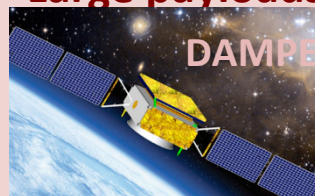
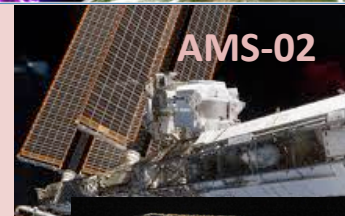
CRN on Challenger
 (3.5 days 1985)



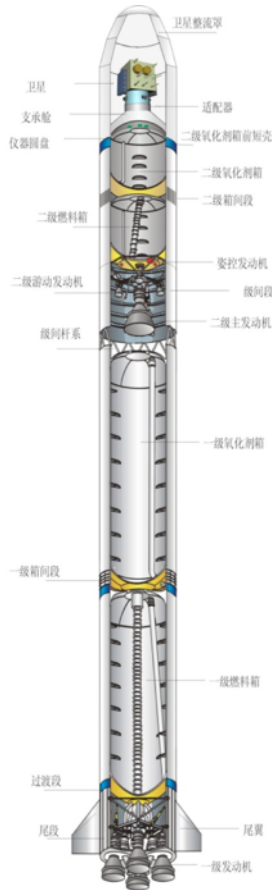
AMS-01 on Discovery
 (8 days, 1998)



Long missions
Large payloads



Operations in Space

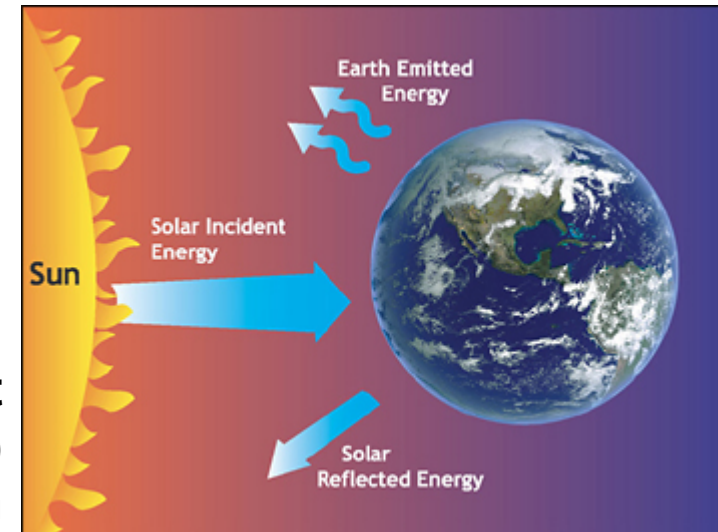


Mechanical stress at launch:

- Static acceleration
- Random vibration
- Sinusoidal vibration
- Pyroshock

Life in space:

- Thermal stresses due to Sun-light (seasonal / day-night effects)
- Vacuum



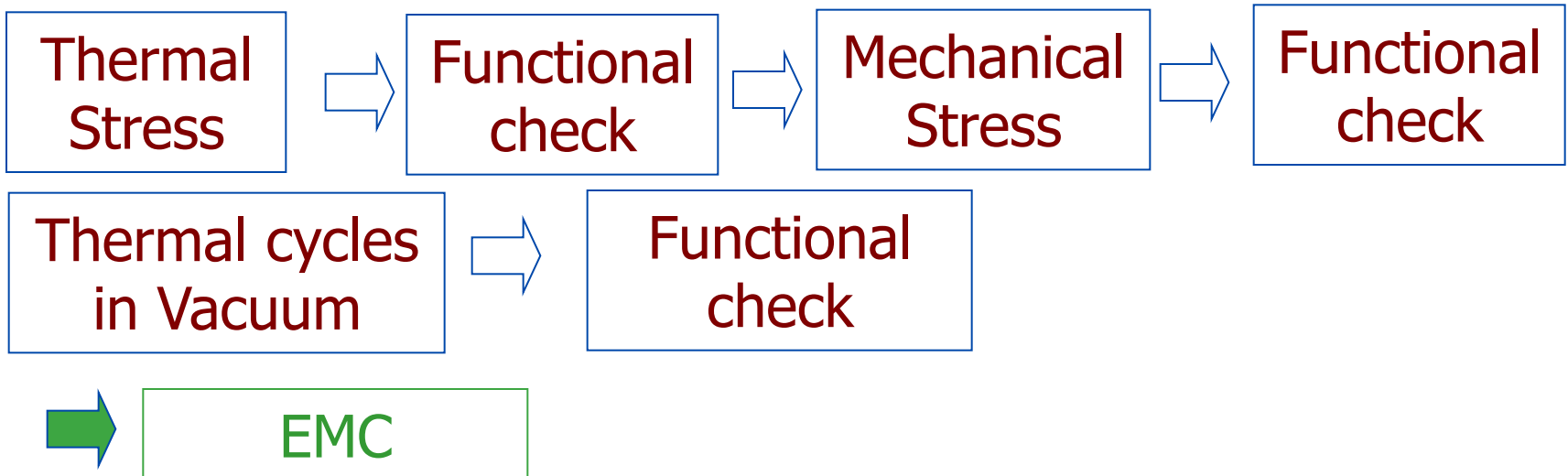
Careful Design, Model validation
and Qualification are needed to
ensure *highest possible reliability*

Operations in Space

Space is a harsh environment

Full space qualification sequence before launch:

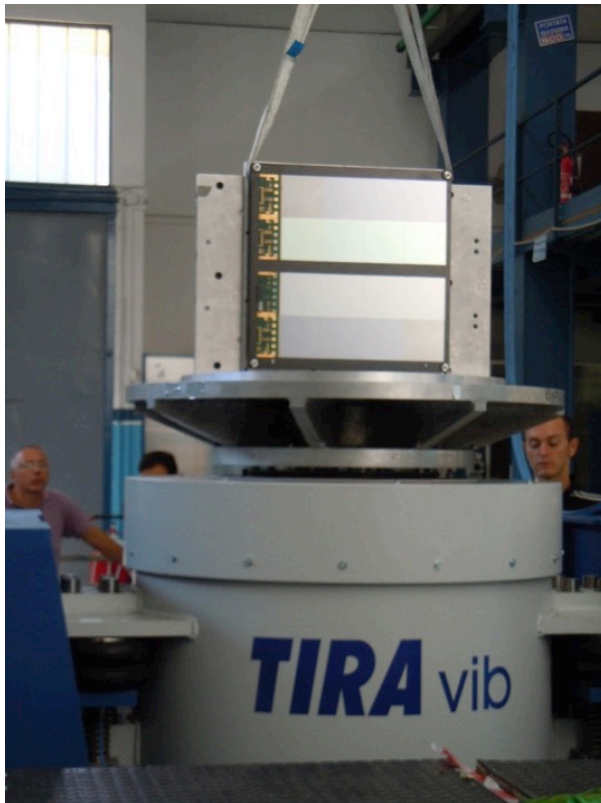
- Operational tests after stress
- Verification of dynamical behaviour
- Verification of thermal model



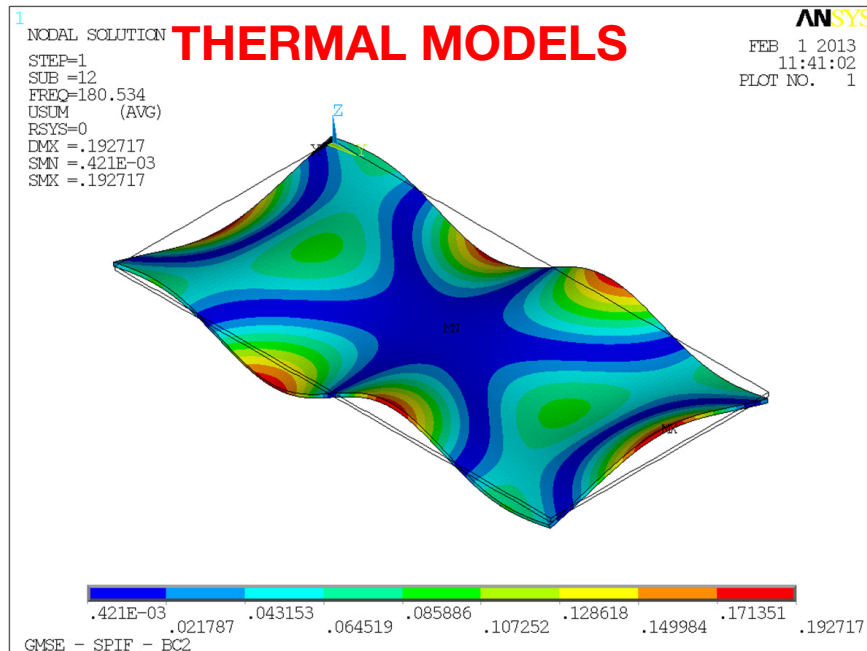
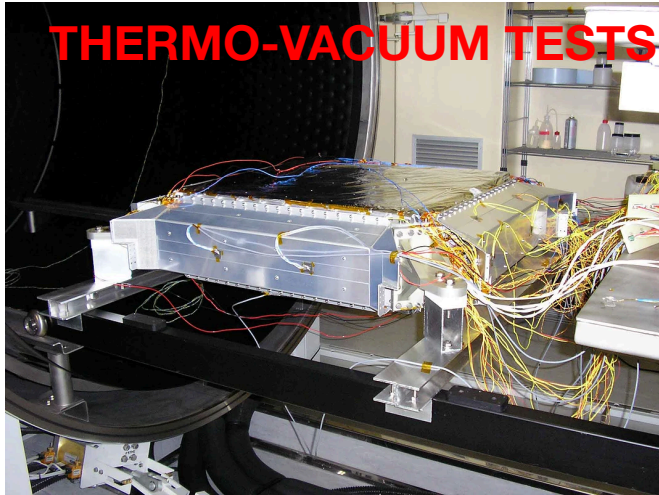
Operations in Space

Space is a harsh environment

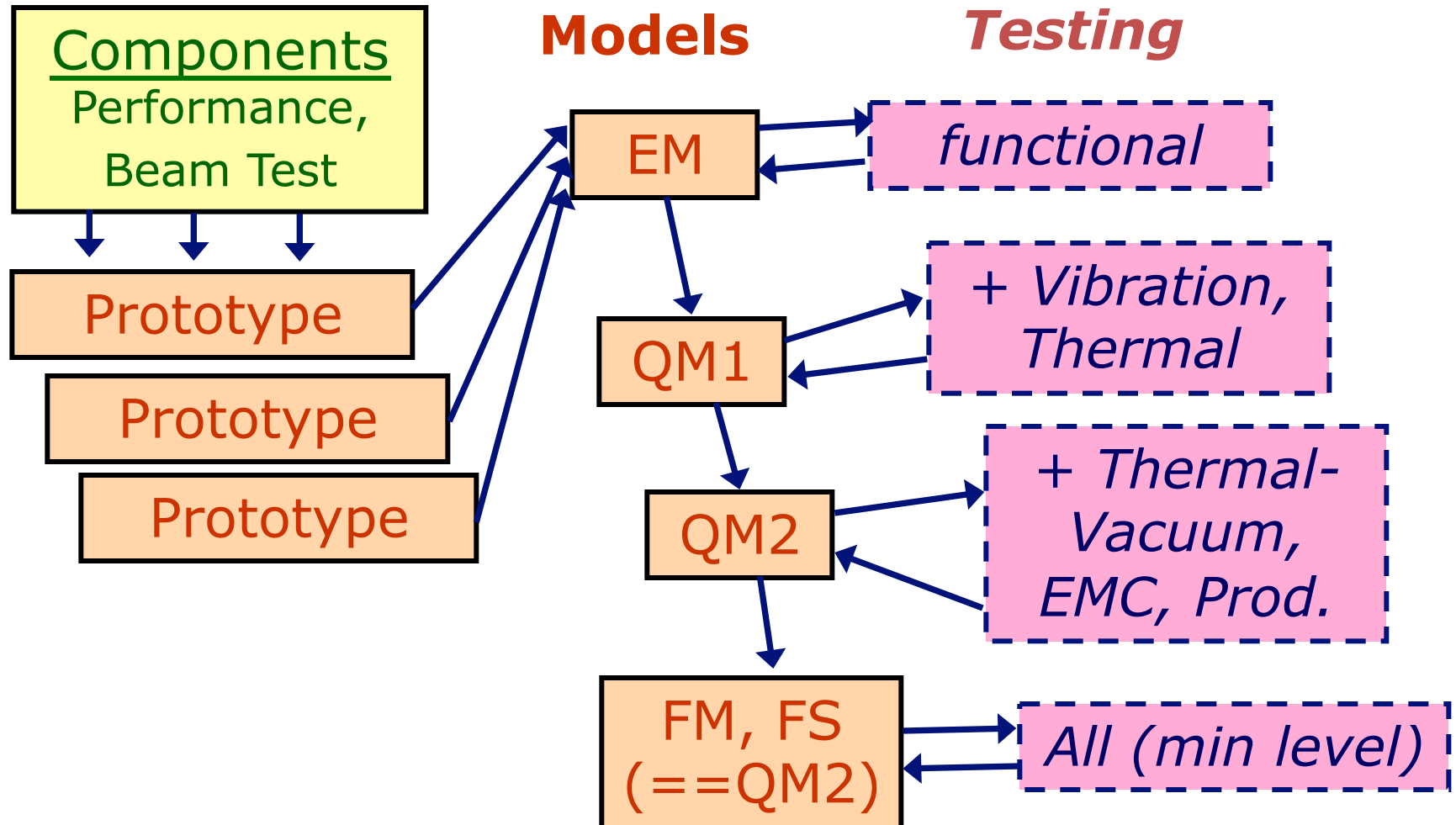
Typically 3 step for test procedure:
Thermal, Vibration, Thermo-Vacuum



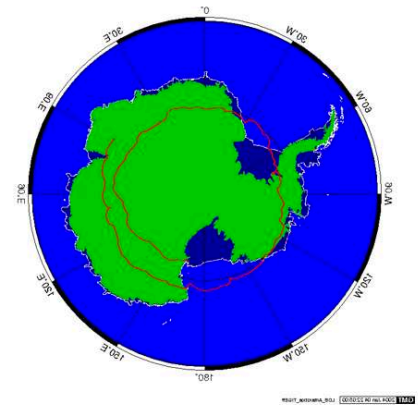
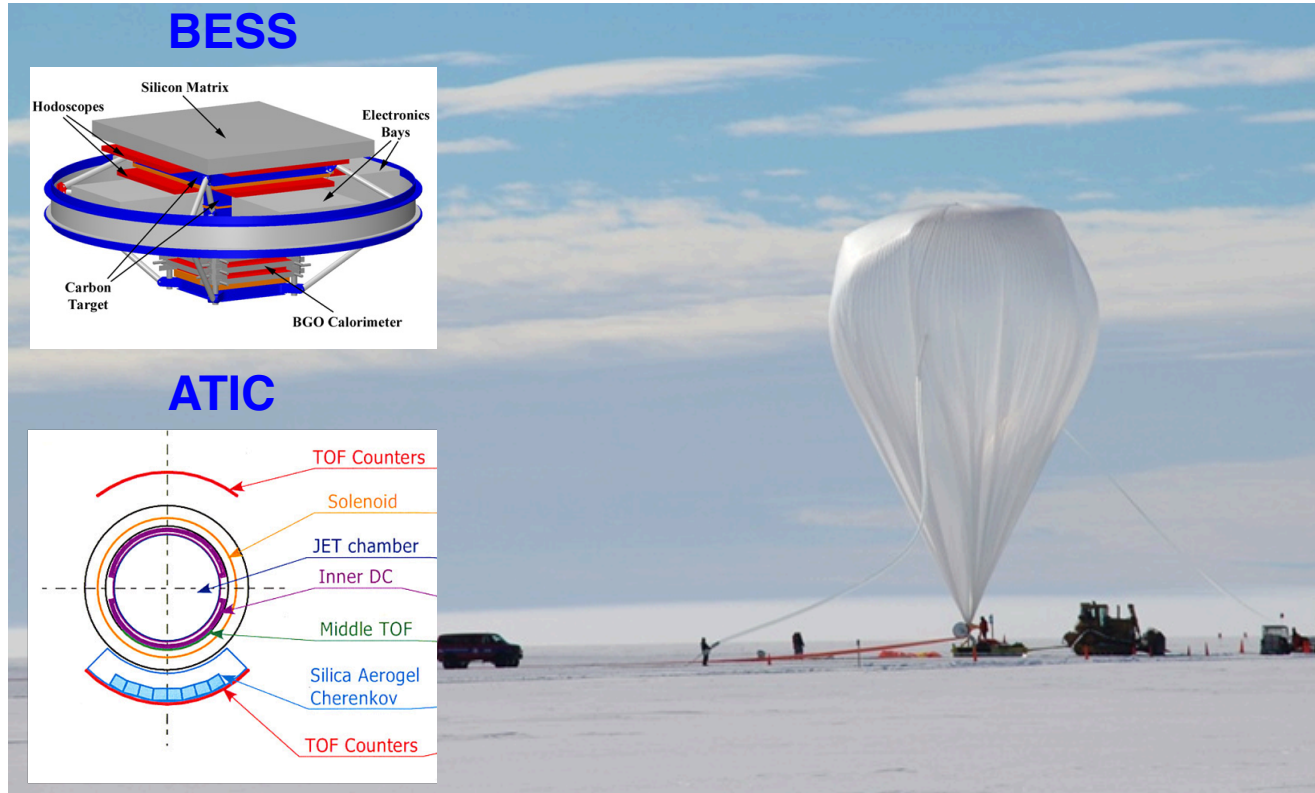
Operations in Space



The long process to fly....



Balloon experiments



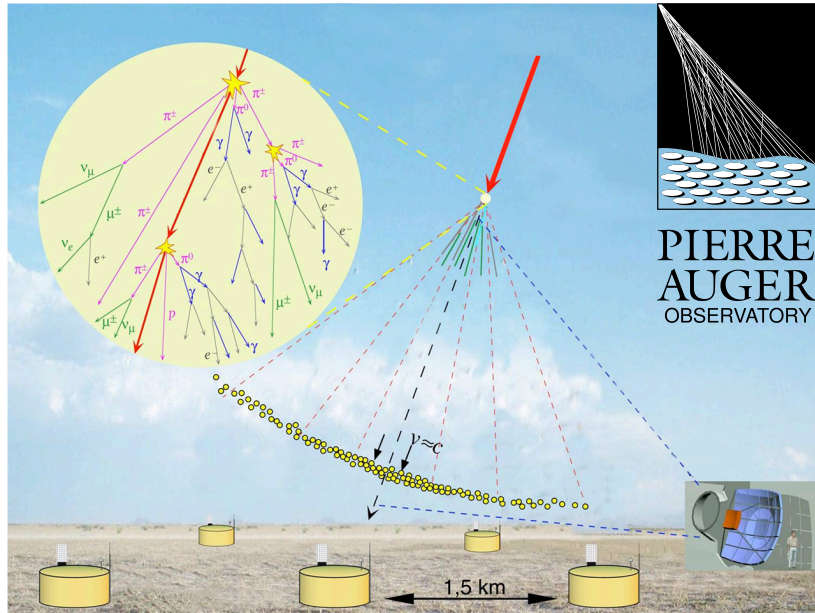
- ✓ Larger acceptances than space borne experiments
- ✓ Direct measurements
- ✗ Orbit limited at North poles for maximum 1 month
- ✗ Residual atmosphere above the payload

Indirect measurement

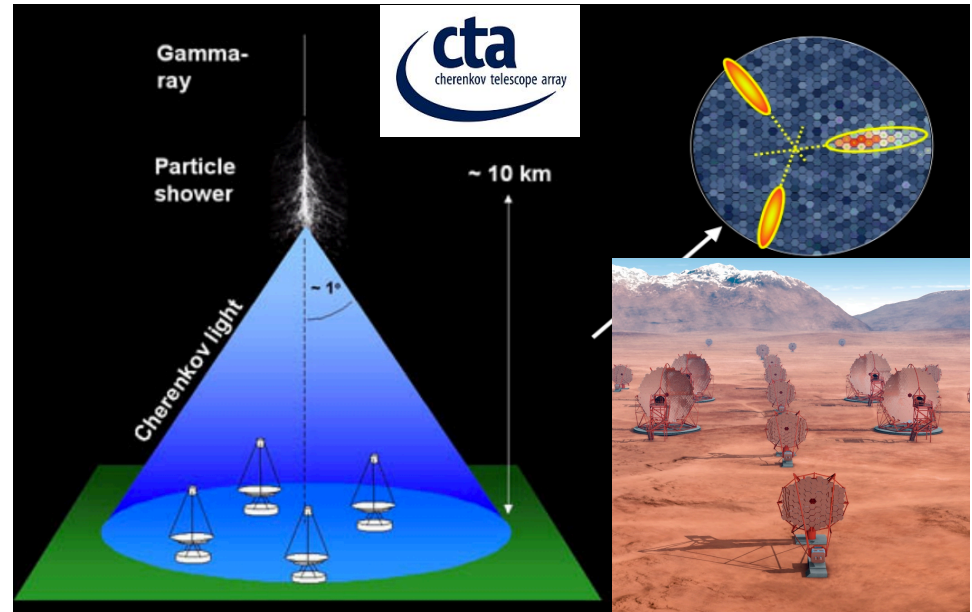
- Indirect measurements means that primary CR interact with the atmosphere producing shower of particles that partly reach the ground, where they are collected by arrays of detectors.
- Do not allow for the identification of the particle and heavily rely on MonteCarlo simulation of the interactions of primaries with atmosphere

Ground based experiments

Charged CRs



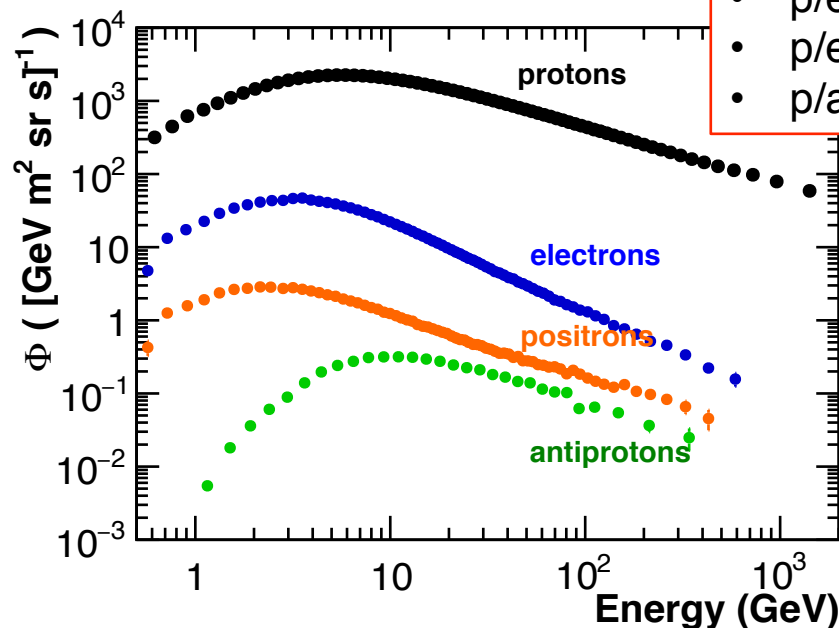
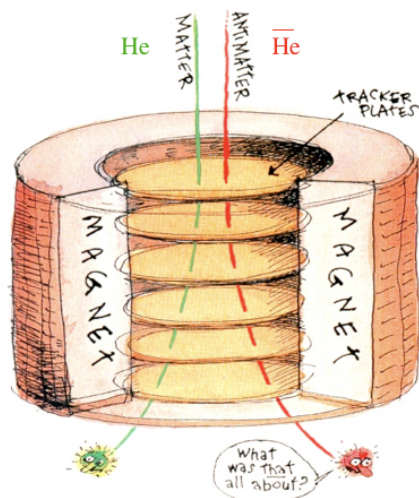
Gamma Rays



- ✓ Large collection areas $\rightarrow$ probe CR energies TeV –Eev ranges
- ✗ Indirect measurements
 - Primary CR identified via the analysis of shower shapes and composition at ground (highly rely on MonteCarlo simulations)
 - Main systematics are the parametrization of X-sections at very high energies

Particle Identification (in space)

- Direct identification of the cosmic rays via measurement of their
 - **Velocity** (Time of Flight systems, Cherenkov Radiation detectors)
 - **Charge** (dE/dX detectors, Cherenkov Radiation detectors)
 - **Energy or Rigidity** (Calorimeters, Spectrometers)
 - **Sign of the charge** (Spectrometers)
 - **Peculiar Interactions** (TR detectors, Calorimeters, Neutron detectors, ...)
 - **Incoming Direction** (Tracking detectors)



- $p/e^- \sim 10^2$
- $p/e^+ \sim 10^3$
- $p/\text{antip} \sim 10^4$

Particle identification is fundamental for antimatter measurements

Particle Identification

- Particles are uniquely identified by their **velocity**, **momentum** and **sign of the charge** combining the information from several subdetectors
- Curvature in magnetic field $\rho \propto R = \frac{p}{Ze}$
- Velocity after time of flight measurements $\beta \propto \frac{1}{\Delta T}$
- Ionization losses $\frac{dE}{dX} = f(z, \beta)$
- Calorimetric measurements $E_{kin} = (\gamma - 1)mc^2$
- Cherenkov and Transition Radiation
- Typically, measurements are more than the number of searched parameters $\rightarrow$ multiple measurements used to over-constrain the values and to crosscheck systematic effects
- NB: at high energies ($\beta \rightarrow 1$), the sensitivity of velocity measurements decreases. Complementary techniques used to infer the particle energy.

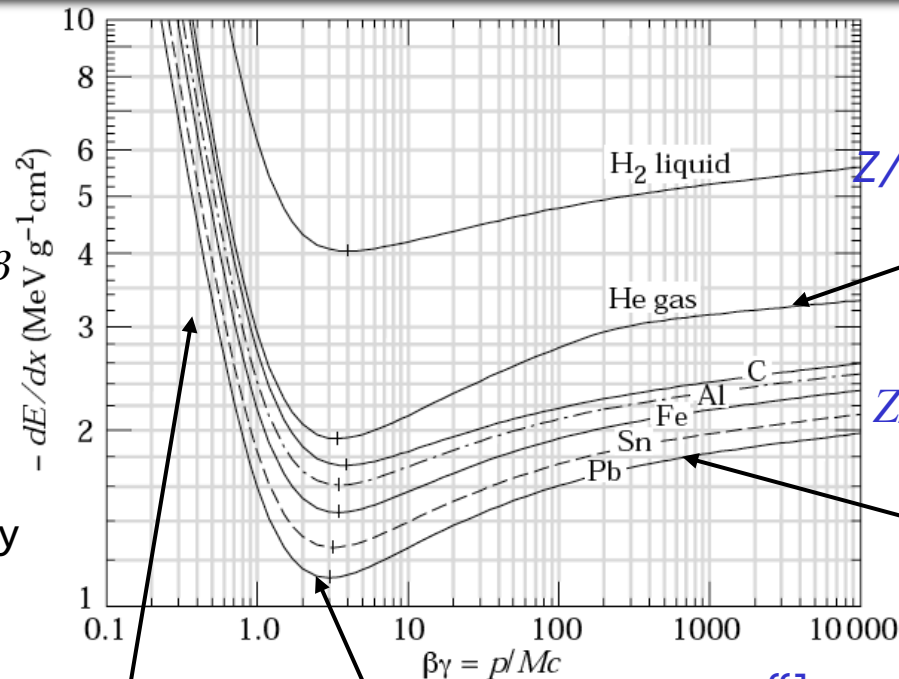
Bethe Bloch

Specific energy loss expressed in terms of grammage $X = \rho x$

0.31 MeV g⁻¹ cm²

$$-\frac{dE}{dX} = 4\pi N_A r_e^2 m_e c^2 Z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \gamma^2 \beta^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2} \right]$$

- Only valid for “heavy” particles ($m \geq m_\mu$) i.e. not electrons
- For a given material, dE/dX depends only on β – independent of mass of particle and z of incident particle
- First approximation: medium characterized by electron density $\sim Z/A$



$Z/A = 1$

“Fermi plateau”
at large γ

$Z/A \sim 0.5$

$$\frac{dE}{dX} \propto \ln \gamma^2$$

$$\frac{dE}{dX} \propto \frac{1}{\beta^2}$$

“kinematical term”

$\beta\gamma \approx 3-4$ ($v \approx 0.96c$)

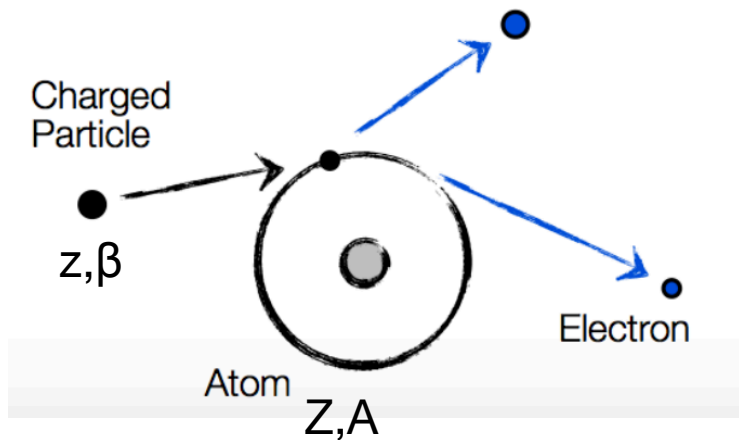
Minimum ionizing particles, MIPs

$$\frac{dE'}{dX}_{\min} \sim 1-2 \text{ MeV g}^{-1} \text{ cm}^2$$

“log relativistic rise”

True for all particles with same charge

Ionization energy losses



Main effect of energy loss in materials:
continuous energy losses by ionization from scattering off atomic electrons

Scattering off electrons: high energy losses, small trajectory deviation

Scattering off nuclei: small energy losses, high scattering angles (multiple scattering)

Bethe-Block formula: energy loss per unit of grammage $X = \rho x$

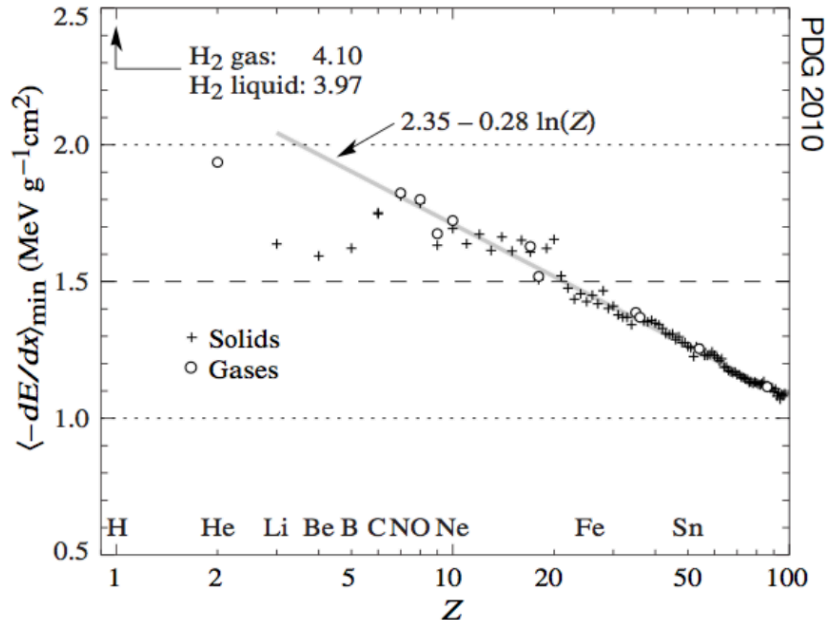
$$\frac{dE}{dX} = 0.31 \text{ MeV}/(\text{g}/\text{cm}^2) z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \log(f(\beta)) - \beta^2 - \delta(\beta\gamma) \right]$$

Energy loss depends on particle and medium properties.

$$\frac{dE}{dX} \propto z^2 \quad \text{proportionality to particle charge used to identify heavy nuclei}$$

Minimum Ionizing particles

MIP dependence on chemical species



$$\left. \frac{dE}{dX} \right|_{\min} \approx 1.5 \div 2 \text{ MeV}/(\text{g}/\text{cm}^2)$$

Below minimum: higher energy losses $\sim 1/\beta^2$

Above minimum: energy loss approx. constant (relativistic rise)

At very high energies (above the “critical energy”) radiative energy losses dominates.

Energy loss fluctuations

La perdita di energia dE/dx (Bethe Block) descrive la perdita media di energia per una particella nell'attraversare uno spessore dX di materiale. Cio' significa che in un fascio, una particella in media perde $\langle dE/dx \rangle$

$$\left\langle -\frac{dE}{dx} \right\rangle = \rho K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\ln \frac{2mc^2 \beta^2 \gamma^2}{I} - \beta^2 - \frac{\delta(\gamma)}{2} \right]$$

In un mezzo omogeneo, dalla BB si ha $\langle dE \rangle \propto X$ $\langle dE \rangle \approx \rho K z^2 \frac{Z}{A} \frac{1}{\beta^2} X$

Se fissiamo l'attenzione su una singola particella, in generale

$-\frac{dE}{dx} \neq \left\langle -\frac{dE}{dx} \right\rangle$ ovvero la perdita totale in uno spessore ΔX , $\Delta E \neq \langle \Delta E \rangle$

a causa delle fluttuazioni statistiche che avvengono

i. nel numero di collisioni con gli elettroni del mezzo

ii. nella perdita di energia nelle singole collisioni

$$\Delta E = \sum_{n=1}^N \delta E_n$$

N : number of collisions

δE : energy loss in a single collision

δE distribuite statisticamente



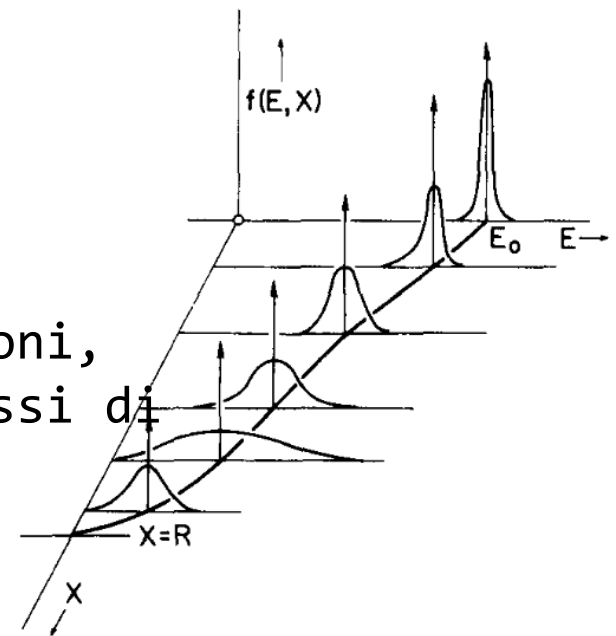
Energy loss fluctuations for $R \ll L$

Un fascio di particelle monoenergetiche con $E = E_0$ mostrerà uno sparpagliamento σ intorno a $E = E_0 - \langle dE \rangle$, dopo aver attraversato un spessore (costante) di materiale e non sarà più monoenergetico (una delta di Dirac) con $E = E_0 - \langle dE \rangle$, ma mostrerà una distribuzione di perdite intorno a quella media.

La forma della distribuzione dipende dallo spessore attraversato

Nel trattare il problema delle fluttuazioni, tradizionalmente si hanno due grandi classi di assorbitori:

1. assorbitori spessi
2. assorbitori sottili



Energy loss fluctuations for $R \ll L$

- La distinzione tra assorbitori spessi e sottili non è netta.
- L'assorbitore diventa spesso quando il # di collisioni $N \rightarrow \infty$ ma nella pratica è sempre finito e non è facile distinguere sempre bene i due casi (anche perché siamo nell'ipotesi che la particella perda una frazione piccola dell'energia, cioè $R \ll L$)

thick and thin absorbers

Roughly, for a MIP the energy loss in a thickness X g/cm² of absorber is $\Delta E = \langle dE/dX \rangle X$ and also $\Delta E = \sum_0^N \delta E_i$

The δE_i are distributed statistically according to their probability between $\delta E_{\min}$ and $\delta E_{\max}$

If $N \rightarrow \infty$, $\Delta E \gg \delta E_i$, for any i and thus also for the max cinematically allowed $\delta E_{\max}$: $\Delta E \gg \delta E_{\max}$

$$\langle dE/dX \rangle X \gg \delta E_{\max}$$

Therefore a detector can be said “thick” if

$$X \gg \delta E_{\max} / \langle dE/dX \rangle$$

In other words, the detector is thick if single collisions with large energy transfers are not important for the AVERAGE total energy loss

- Is a 1 cm scintillator thick or thin for 1 GeV muon?

1 GeV μ

$$W_{\max} = 2m_e c^2 \beta^2 \gamma^2$$

$$\beta = p/E \quad \gamma = E/m \quad E^2 = p^2 + m^2$$

$$E^2 = 1^2 + (.105)^2 \Rightarrow E = 1.0055$$

$$\beta = 1/1.0055 = .9945$$

$$\gamma = 1.0055/.105 = 9.576$$

$$W_{\max} = \frac{2(.511)}{e^2} \cdot e^2 \cdot (.9945)^2 (9.576)^2$$

$$= 92.69 \text{ MeV}$$

$$\Delta E = (dE/dX)(\rho x)$$

$$= 1.956 \cdot 1.032 \cdot 1 = 2 \text{ MeV}$$

$$W_{\max} \gg \Delta E$$

So 1 cm plastic scintillator
is NOT thick

Actually, even 1 cm of Pb is not thick
since $DE = (dE/dX)(\rho x) = 1.1 \cdot 11.35 \cdot 1 = 12.5 \text{ MeV!!}$

Energy loss probability

- Trascurando lo spin dell'e- (ie scattering di Coulomb), la probabilita' di espellere un e- di energia fra E ed E + dE e' :

$$P(E)dE = k \frac{X}{E^2} dE \quad \text{where} \quad k = 2\pi N_A r_e^2 m_e c^2 Z^2 \frac{1}{A \beta^2} \quad (1)$$

Si ricordi la distribuzione del # di e- espulsi con E fra E ed E+dE in una collisione $n(E) = -\frac{dN}{dE dx} = \pi N_e \left(\frac{e^4 Z^2}{8\pi^2 \epsilon_0^2 m_e v^2} \right) \frac{1}{E^2}$

E di fatto e' la probabilita' che un e- venga emesso con energia fra E ed E+dE entro l'intervallo di energie permesse, a meno di una normalizzazione $\int n(E)dE = 1$:

E_{min} e' dell'ordine di I il potenziale di ionizzazione

E_{max} e' dato dalla max energia trasferibile in un urto

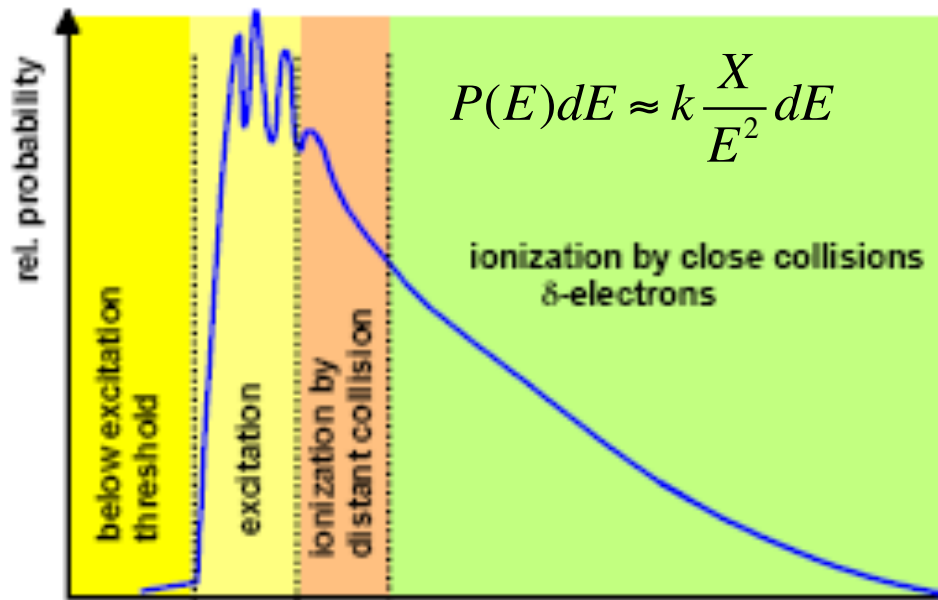
La distribuzioni esatta per elettroni e' $P(E)dE = k \frac{X}{E^2} (1 - \beta^2 \frac{E}{E_{\max}}) dE$

La distribuzioni esatta per particelle pesanti di spin ½ e'

$$P(E)dE = k \frac{X}{E^2} (1 - \beta^2 \frac{E}{E_{\max}} + \frac{1}{2} \frac{E}{E + mc^2}) dE$$

La probabilita' di emissione (cosi' come lo spettro) e' limitata dalla cinematica fra $E_{\min} < E < E_{\max}$

Energy loss probability



Andamento schematico della probabilita' di perdere un'energia W in una collisione.

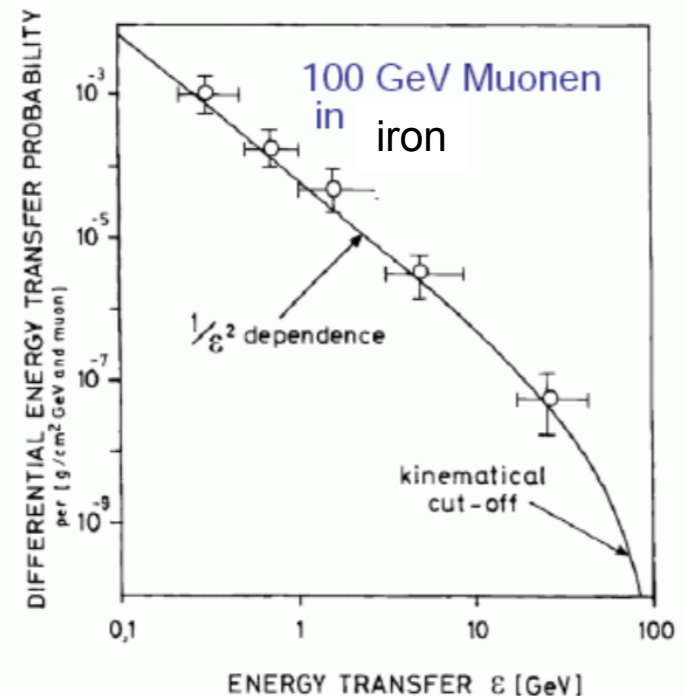
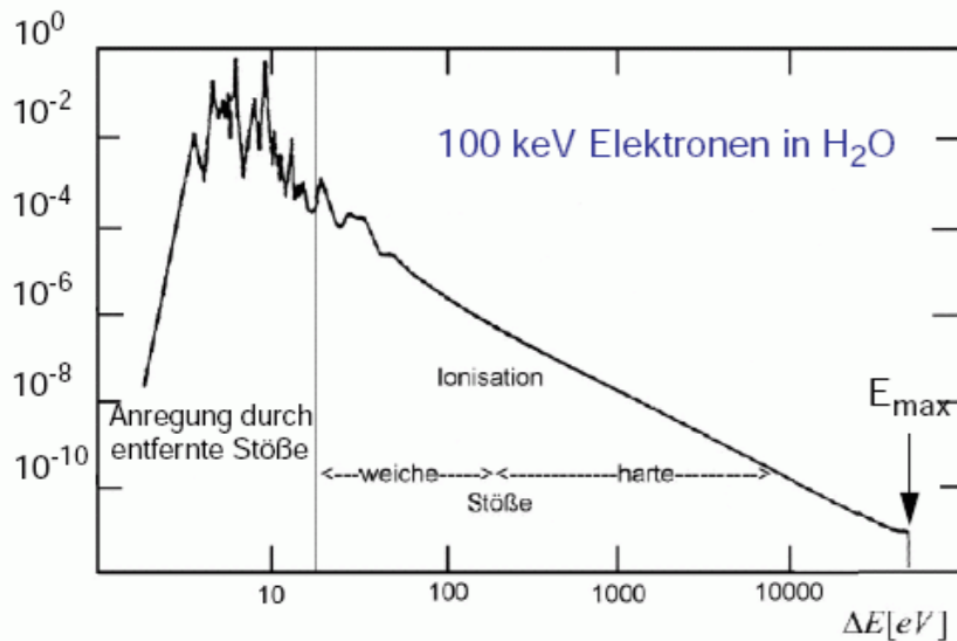
La distribuzione descrive bene la probabilita' finche' il trasferimento di energia e' grande rispetto all'energia di legame atomico (regione verde).

A basse energie (es. per collisioni distanti) entrano in gioco altri effetti (screening/polarizzazione del mezzo, eccitazione di elettroni atomici, oscillazioni atomiche).

δ Electrons

Energy distribution of secondary electrons:

$$\frac{dN^2}{dT dx} = \frac{1}{2} k z^2 \frac{Z}{A} \frac{1}{\beta^2} \frac{F(T)}{T^2}$$

$$F(T) = 1 - \beta^2 T / T_{max} \quad (\text{Spin } 0)$$


Example: 500 MeV pion in 300 μm Si: 5% produce an electron with T > 166 keV
 important background in Cherenkov counter
 Number of δ-electrons proportional z^2/β^2

Energy loss fluctuations for $R \ll L$

Il numero di collisioni nel mezzo determina la distribuzione delle perdite di energia intorno al valore medio $\langle dE \rangle$

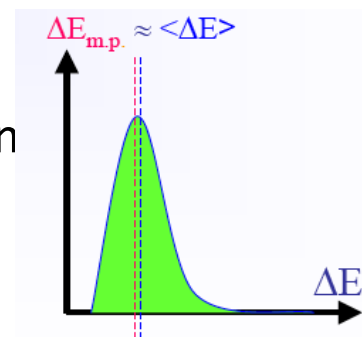
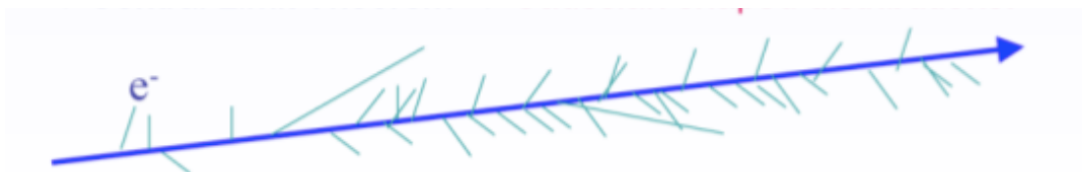
Ciò deriva direttamente dal teorema del limite centrale: la somma di N variabili casuali, che seguono tutte la stessa distribuzione statistica, diventa una gaussiana nel limite di $N \rightarrow \infty$.

Se consideriamo come variabile casuale la dE , cioè l'energia persa in una collisione singola, che le collisioni sono statisticamente indipendenti e che in ogni collisione la velocità β del proiettile non è cambiata in maniera apprezzabile in modo che $d\sigma(E)/dE$ è costante $\rightarrow$ l'energia totale persa è la somma di tutte le dE , tutte con la stessa distribuzione ed è quindi gaussiana.

Per assorbitori relativamente spessi la distribuzione della perdita di energia è gaussiana.

Energy loss probability (1)

- Real detector measures the energy ΔE deposited in a layer of finite thickness δx .
- For thick layers and high density materials:
 - Many collisions
 - Central limit theorem: distribution $\rightarrow$ Gaussian



$$P(E)dE = k \frac{X}{E^2} dE \quad \text{con} \quad k = 2\pi N_A r_e^2 m_e c^2 Z^2 \frac{1}{A \beta^2}$$

La probabilità è piccata a piccoli valori di E , cioè per valori $\sim E_{\min}$: la maggior parte delle collisioni comporta piccole perdite di E , ma c'è una probabilità finita che in una singola collisione avvenga una perdita "grande", vicina a $E_{\max}$.

Se N è sufficientemente elevato, in media le perdite di energia saranno simmetriche intorno al valore medio: singole collisioni con alta E sono compensate da tante collisioni a bassa E , in modo che la distribuzione tenda a una gaussiana, in cui il valore medio $\langle dE \rangle$ e la perdita di energia più probabile dE_{mp} coincidono.

Assorbitori spessi: limite gaussiano.

Se il materiale è spesso (ma non troppo) o denso → N è grande quindi vale il **teorema del limite centrale** e la perdita totale di energia E è distribuita secondo una gaussiana

$$f(X, E) \propto \exp\left(-\frac{(E - \bar{E}(X))^2}{2\sigma^2(X)}\right)$$

Con X spessore del materiale, E perdita di energia nell'assorbitore, $\bar{E}$ perdita di energia media = $(dE/dX)X$, e σ la sua deviazione standard.

Assorbitori spessi: limite gaussiano.

Bohr ha calcolato la deviazione standard σ_0 per particelle non relativistiche:

$$\sigma_0^2 = 4\pi Z_{inc}^2 Z_{target} n_a e^4 x = 4\pi r_e^2 N_A (m_e c^2)^2 Z_{inc}^2 \frac{Z_t}{A_t} \rho x = 0.157 Z_{inc}^2 \frac{Z}{A} \rho x [MeV^2]$$

Dove N_A è il numero di Avogadro, r_e il raggio classico dell'elettrone, ρ la densità, A_t il peso atomico (in kg/mol) e Z_t il numero atomico dell'assorbitore.

Estesa a particelle relativistiche diventa:

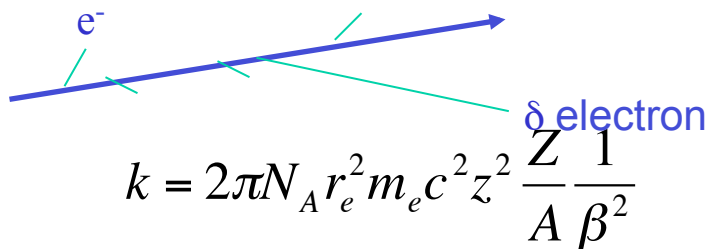
$$\sigma^2 = \sigma_0^2 \frac{(1 - \frac{1}{2}\beta^2)}{1 - \beta^2}$$

- For a Gaussian distribution resulting from N random events the ratio of the width/mean $\propto 1/\sqrt{N}$
- Increasing the thickness of the detector decreases the relative width of the Gaussian peak

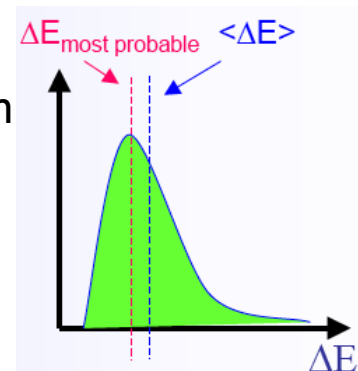
Energy loss probability (2)

■ For thin layers or low density materials:

- Few collisions, some with high energy transfer.
- ⇒ Energy loss distributions show large fluctuation towards high losses
- ⇒ Long Landau tails



$$P(E)dE = k \frac{X}{E^2} dE \quad \text{con} \quad k = 2\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2}$$



La probabilita' e' piccata a piccoli valori di E, cioe' per valori ~ Emin: la maggior parte delle collisioni comporta piccole perdite di E, ma c'e' una probabilita' finita che in una singola collisione avvenga una perdita "grande", vicina a Emax

Se N non e' sufficientemente elevato, singole collisioni con grande E non sono compensate da tante collisioni con piccola E: la distribuzione delle perdite non e' simmetrica intorno al valore medio. Le singole collisioni spostano il valore medio verso alti valori di E, mentre la maggior parte delle perdite e' con piccola E, cioe' il valore piu' probabile rimane piccolo

Energy loss probability

Energy loss distribution differs a lot from a gaussian. Only around the peak the E loss distribution is approximated by a gaussian: the width is large and asymmetric, does not fall as $1/\sqrt{X}$.

This has important consequences from a practical point of view: it makes the average E loss, $\langle dE/dX \rangle$, useless for measuring the energy deposit in the medium: it will fluctuate in a non-gaussian way due high energy deposit fluctuations

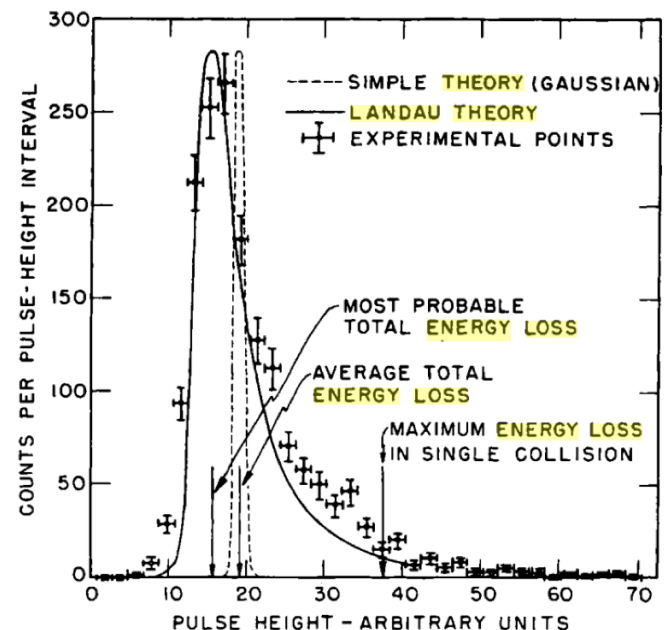
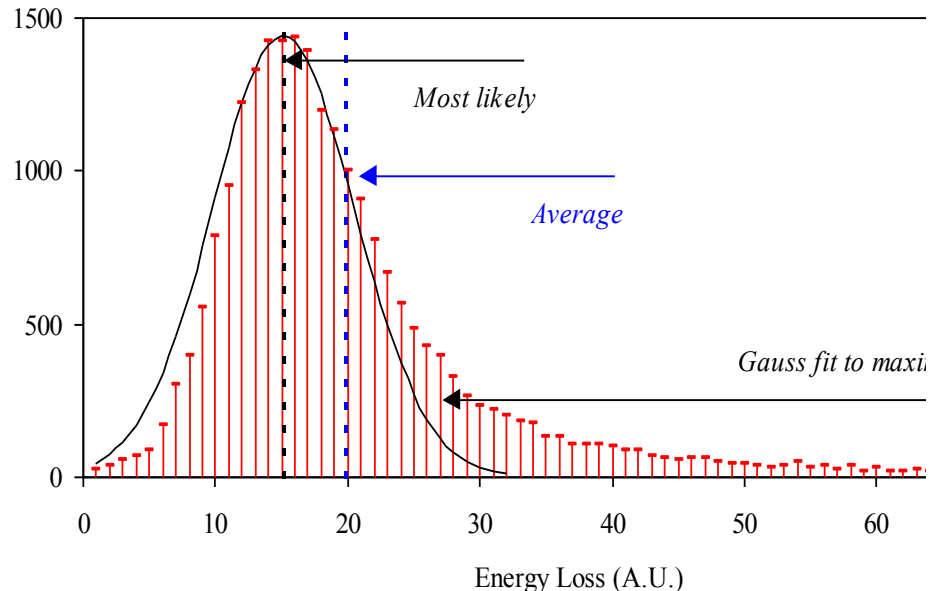


Fig. 2. Frequency distribution of energy losses of 31.5 MeV protons traversing a proportional counter filled with 96% Ar and 4% CO₂. The histogram of experimental points is compared to the theoretical Landau distribution and a gaussian distribution based on ion-electron pair statistics. From Igo *et al.* [3]

Delta rays, most probably energy loss

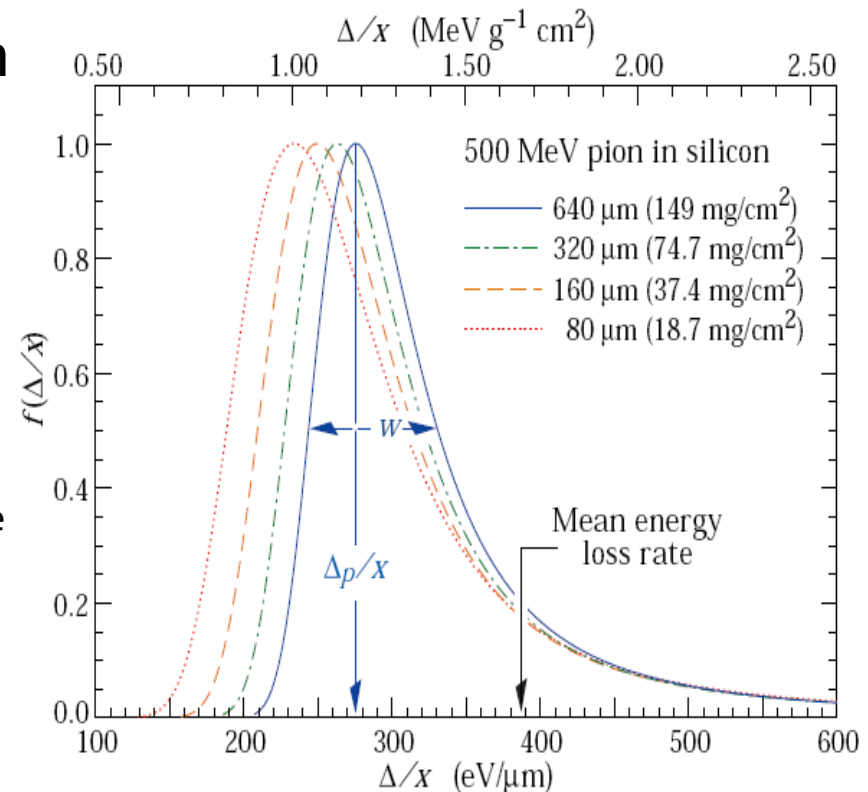
While $\langle dE/dX \rangle$ is affected by fluctuations, peak position (most probable energy loss) is not affected; therefore it is used when sampling dE/dx loss.

- It is important to keep in mind that the m.p. value and the average value do not coincide

Straggling functions in silicon for 500 MeV pions, normalized to unity at the most probable value Δ/x . The width w is the FWHM.

Bibliografia Fernow (Introduction to experimental particle physics)

<http://pdg.lbl.gov>



Assorbitori sottili: teoria di Landau (cenni)

La probabilita' di avere una perdita di energia W dopo aver attraversato uno spessore Δx di materiale puo' essere parametrizzata come segue

$$\chi(W, x) = \frac{1}{\xi} f_L(\lambda)$$

$$\text{con } \lambda = \frac{1}{\xi} \left[W - \bar{W} - \xi \ln \frac{\xi}{\varepsilon'} + 1 - c_E \right];$$

$$\ln \varepsilon' = \ln \frac{(1 - \beta^2) I^2}{2 m v^2} + \beta^2;$$

$$c_E = 0.577 \quad (\text{costante di Eulero})$$

$$\xi = \frac{2\pi z^2 e^4 N_{Av} Z \rho \delta x}{m_e \beta^2 c^2 A} = 153.4 \frac{z^2}{\beta^2} \frac{Z}{A} \rho \delta x \quad \text{keV},$$

$\bar{W}$ e' la perdita media di energia
(dalla bethe -vloch)

ε' è il taglio sulla minima energia trasferibile nel singolo urto, in accordo all'assunzione $\xi/E_{\text{bind}} \gg 1$ (e in modo tale che la perdita media sia quella della bethe-bloch).

Assorbitori sottili: teoria di Landau (cenni)

La funzione universale $f_L(\lambda)$ può essere espressa come segue:

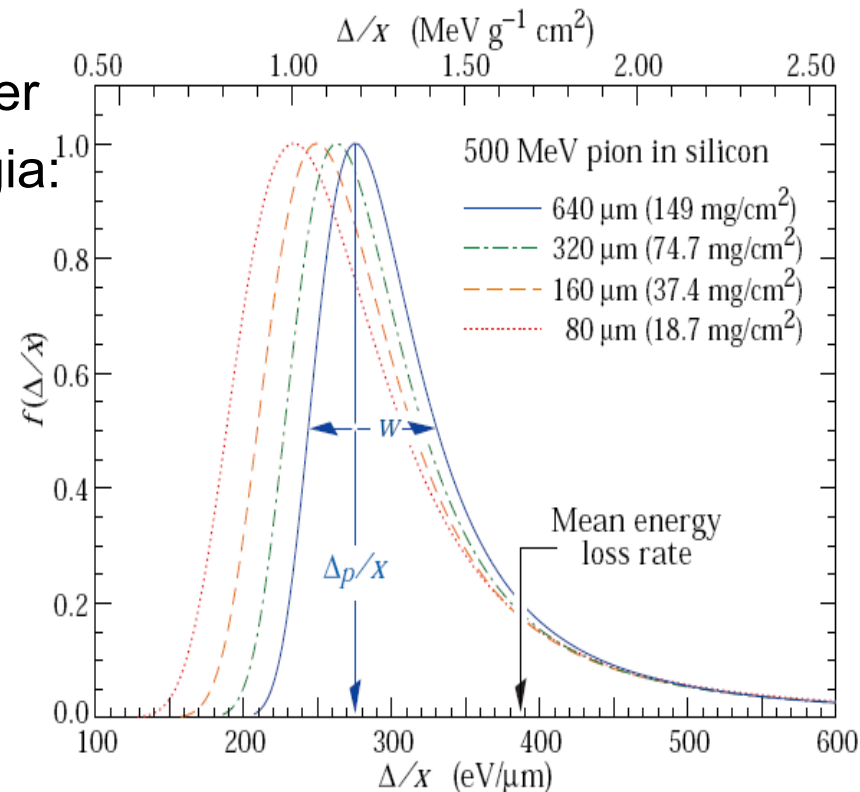
$$f_L(\lambda) = \frac{1}{\pi} \int_0^{\infty} e^{-u(\ln u + \lambda)} \sin(\pi u) du$$

Valutando numericamente $f_L(\lambda)$ si ottiene per il valore più probabile per la perdita di energia:

$$W_{mp} = \xi \left[\ln \frac{\xi}{\epsilon} + 0.198 - \delta \right]$$

δ = correzione per effetto densità
e $\text{FWHM} = 4.02\xi$

$$\xi = \frac{2\pi z^2 e^4 N_{Av} Z \rho \delta x}{m_e \beta^2 c^2 A} = 153.4 \frac{z^2}{\beta^2} \frac{Z}{A} \rho \delta x \quad \text{keV},$$

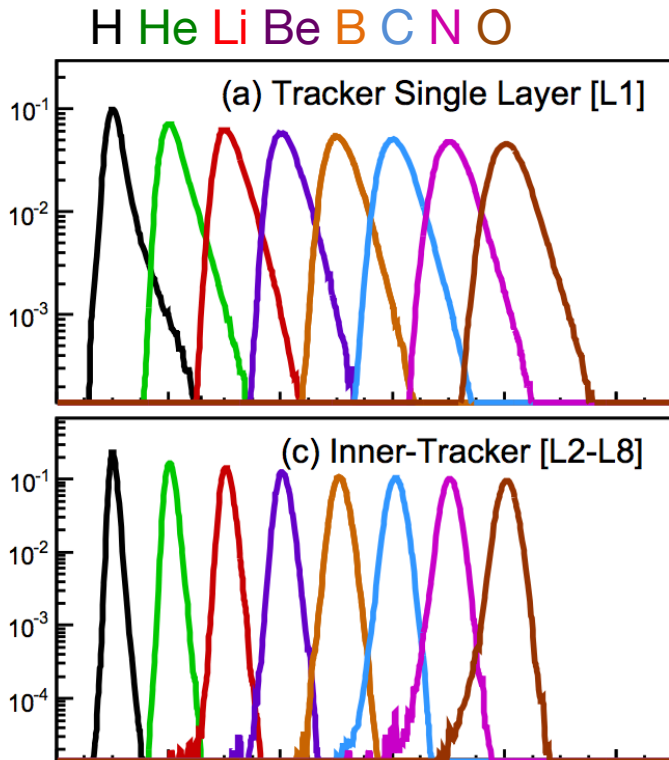


Charge ID

$\frac{dE}{dX} \propto z^2$ charge proportionality used to identify heavy nuclei

Distribution of energy deposits can have long tails

Consequence: multiple measurements of energy deposits are needed to sample the Landau distribution and correctly infer the particle charge



Charge sampled in one layer of silicon
“Landau” distribution, long tails

Charge sampled in seven layer of silicon
Estimator built using mean / truncated mean / likelihood
→ Charge resolution improved

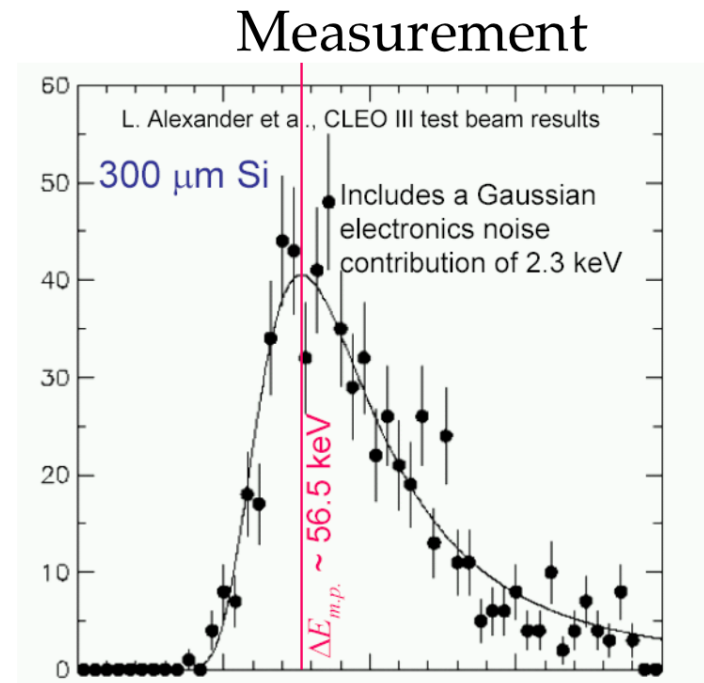
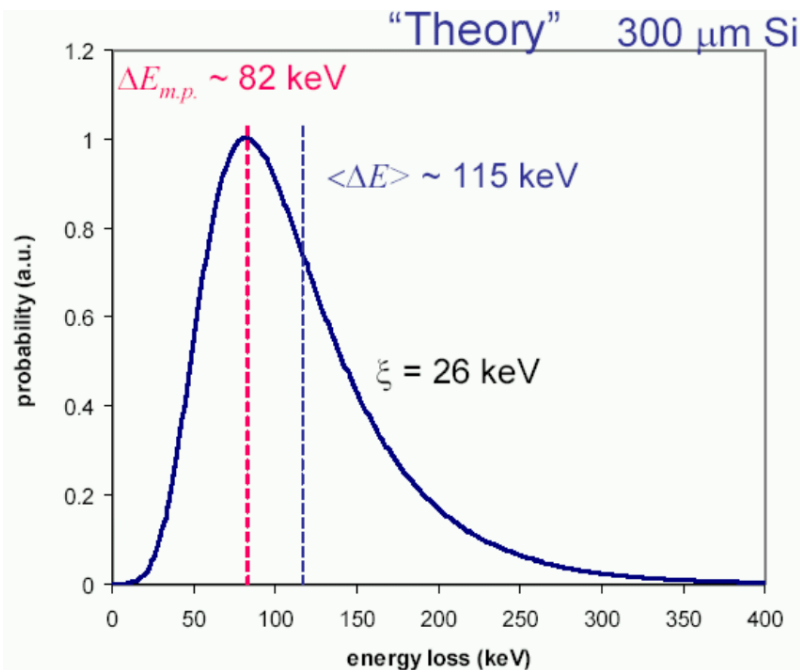
The Landau/Vavilov distribution depends on two parameters:

- ❑ the most probable energy loss W_{mp} and
- ❑ the FWHM of the distribution $\sim \xi$

Typical application of the Landau distribution is the CHARGE Identification of the incident particle, since $W_{mp} = W_{mp}(Z_{inc}, \beta)$ and $\langle W \rangle = W(Z_{inc}, \beta)$

The particle crosses N active layers in which it deposits δE_i , $i=1, \dots, N$ according to the Landau distribution.

Then by a numerical fit, one finds the best parameters W_{mp} , FWHM that describes the measured set of δE_i . Knowing W_{mp} , and the width it is possible to get Z_{inc}

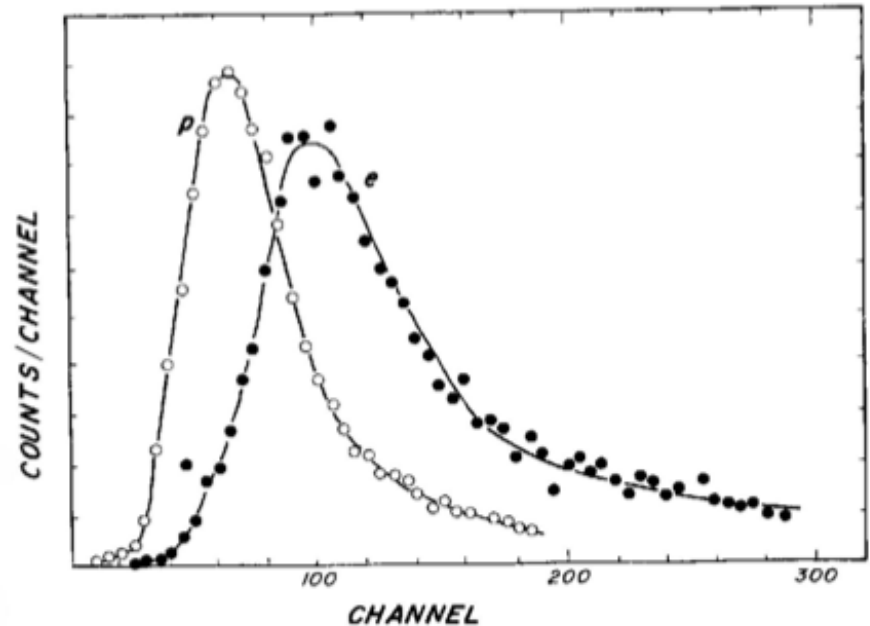


Charge ID

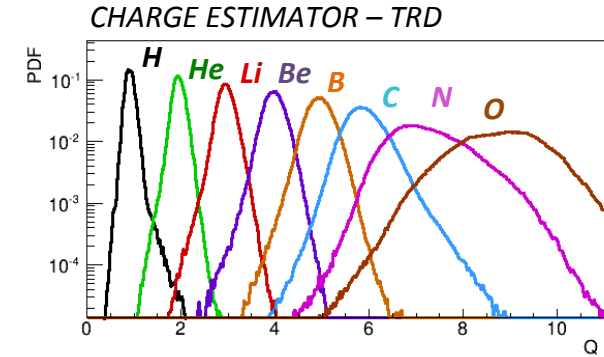
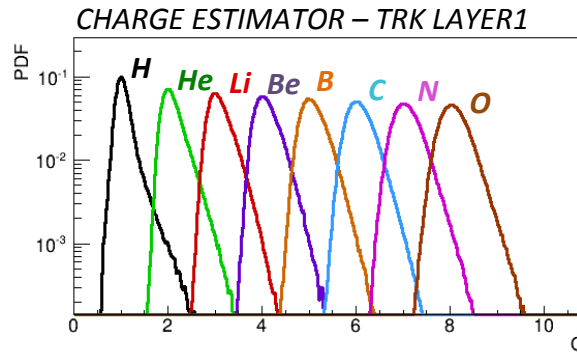
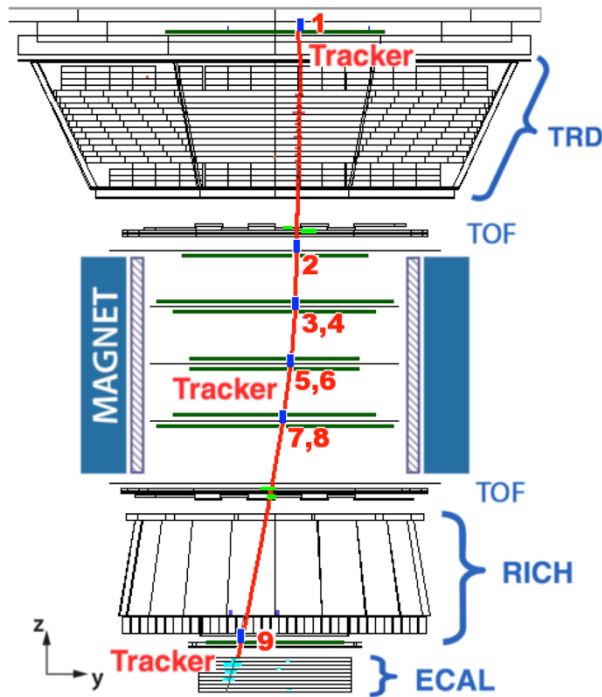
- Conseguenze sperimentali:

- ID di carica fatta tramite la misura del deposito di energia (noto β e/o p): necessita' di avere piu' misure di dE/dX per campionare la distribuzione di Landau/Vavilov da cui ricavare W_{mp} e quindi il valore assoluto della carica dato che $W_{mp} \propto Z_{inc}^2$

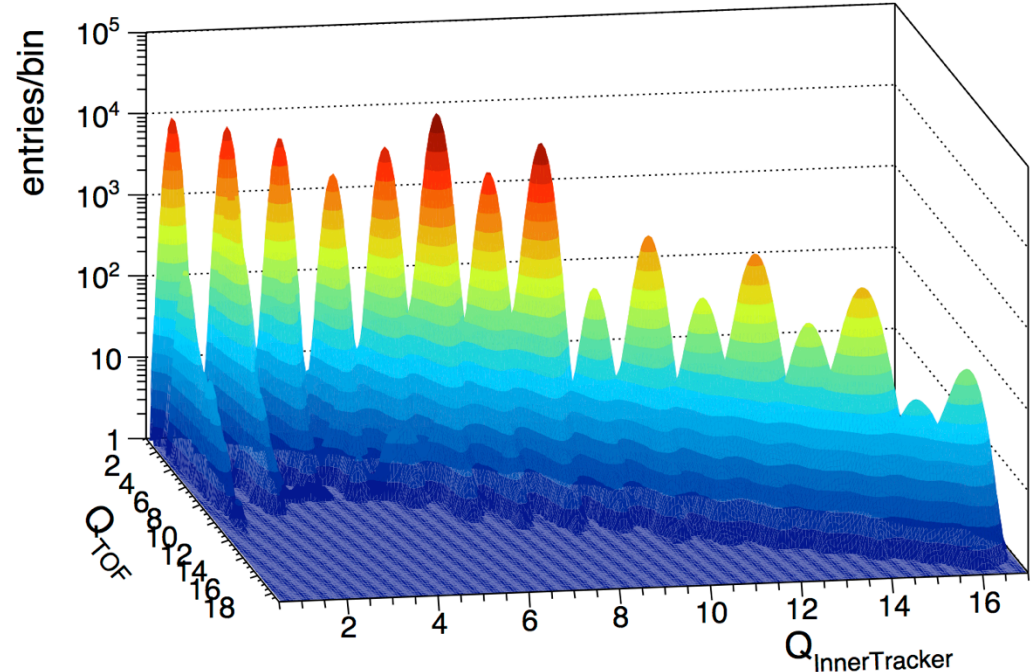
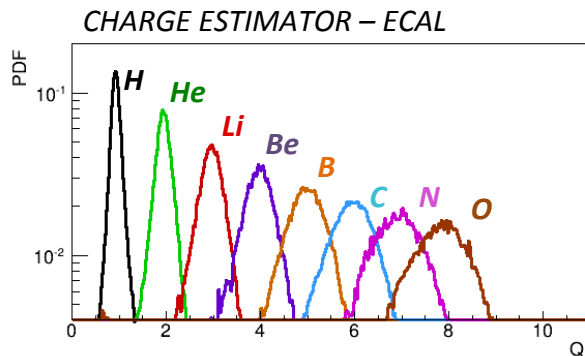
Figure 2.7 Measured pulse height distributions for 3-GeV/c protons and 2-GeV/c electrons in a 90% Ar + 10% CH₄ gas mixture. (After A. Walenta, J. Fischer, H. Okuno, and C. Wang, Nuc. Instr. Meth. 161: 45, 1979.)



Charge ID: Multiple measurements of charge



TOF & TRK charge estimators

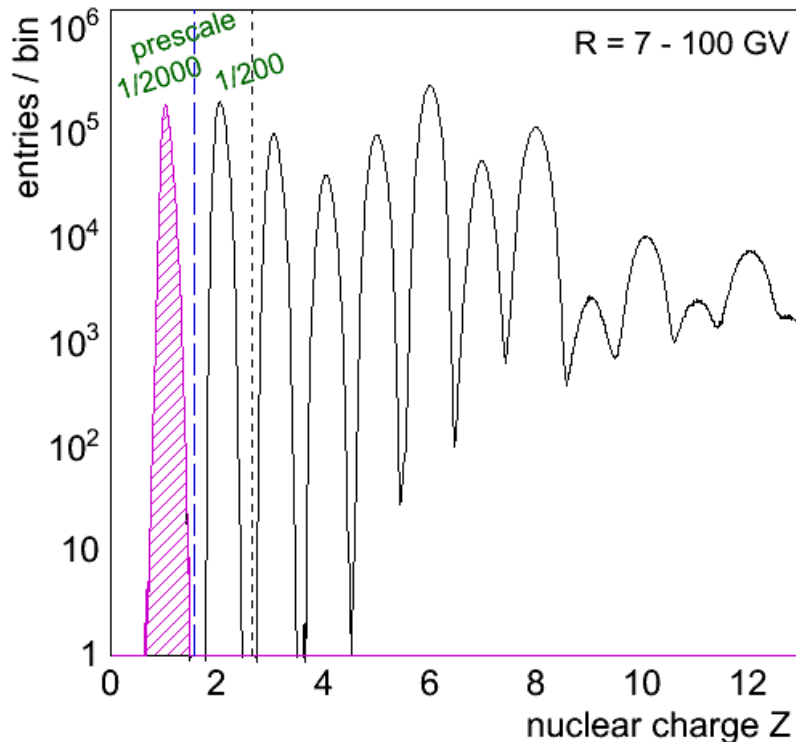


Charge measurement using Tracker

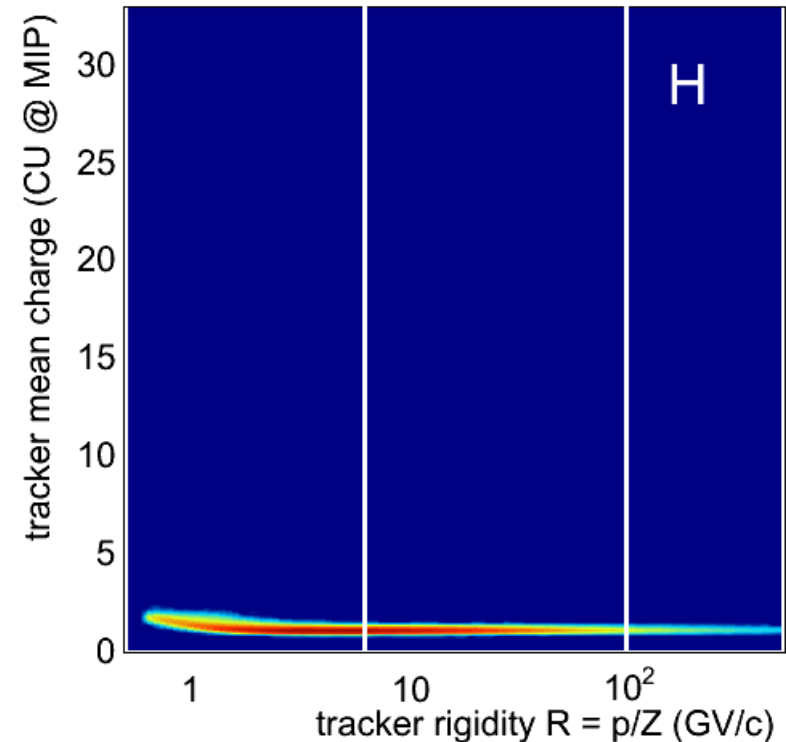
Identification of Light Cosmic Ray Nuclei

with the AMS Silicon Tracker

Selected charge: $Z = 1$ [Hydrogen]

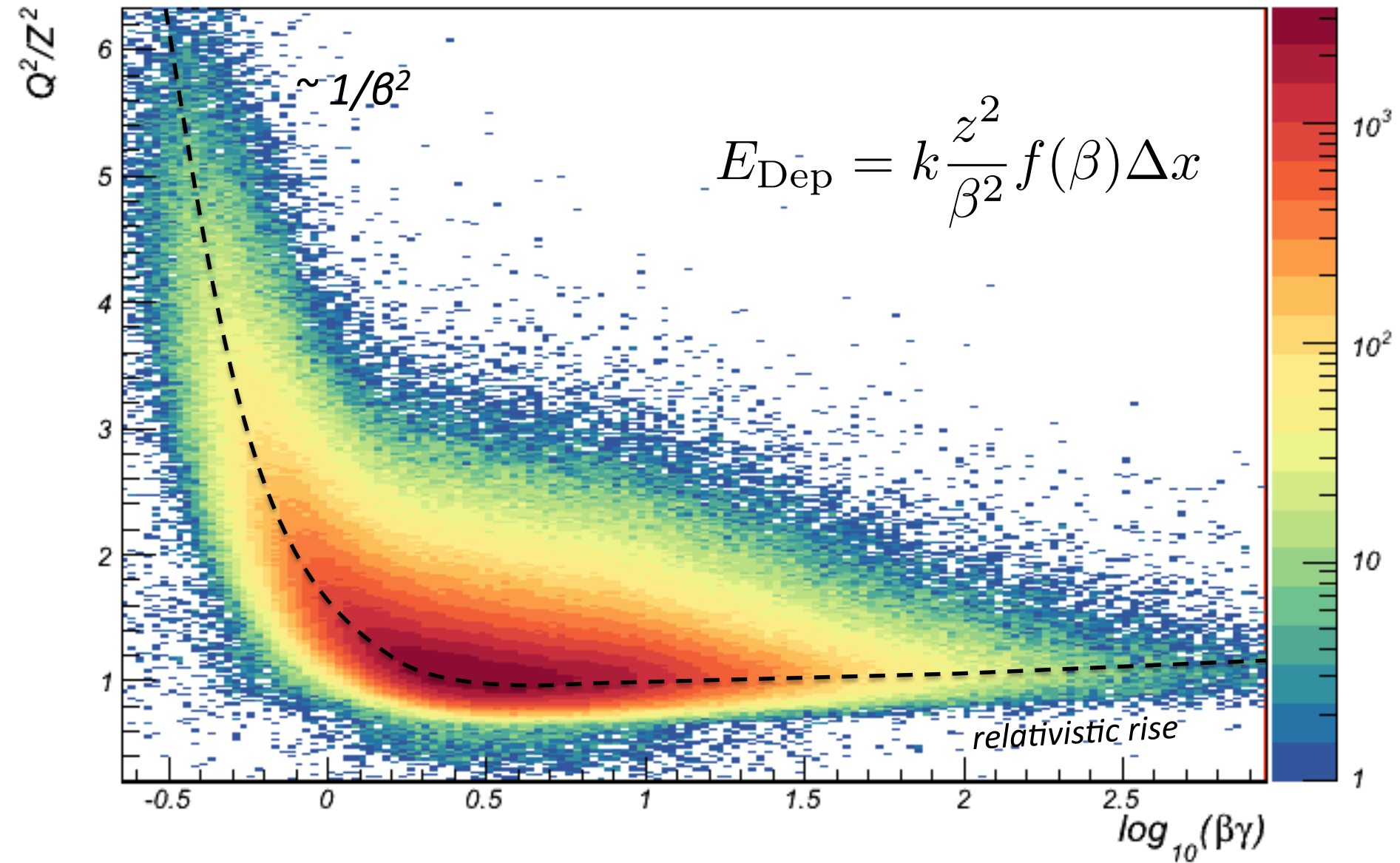


Tracker $\langle dE/dX \rangle$ VS Rigidity



animated slide – set full screen

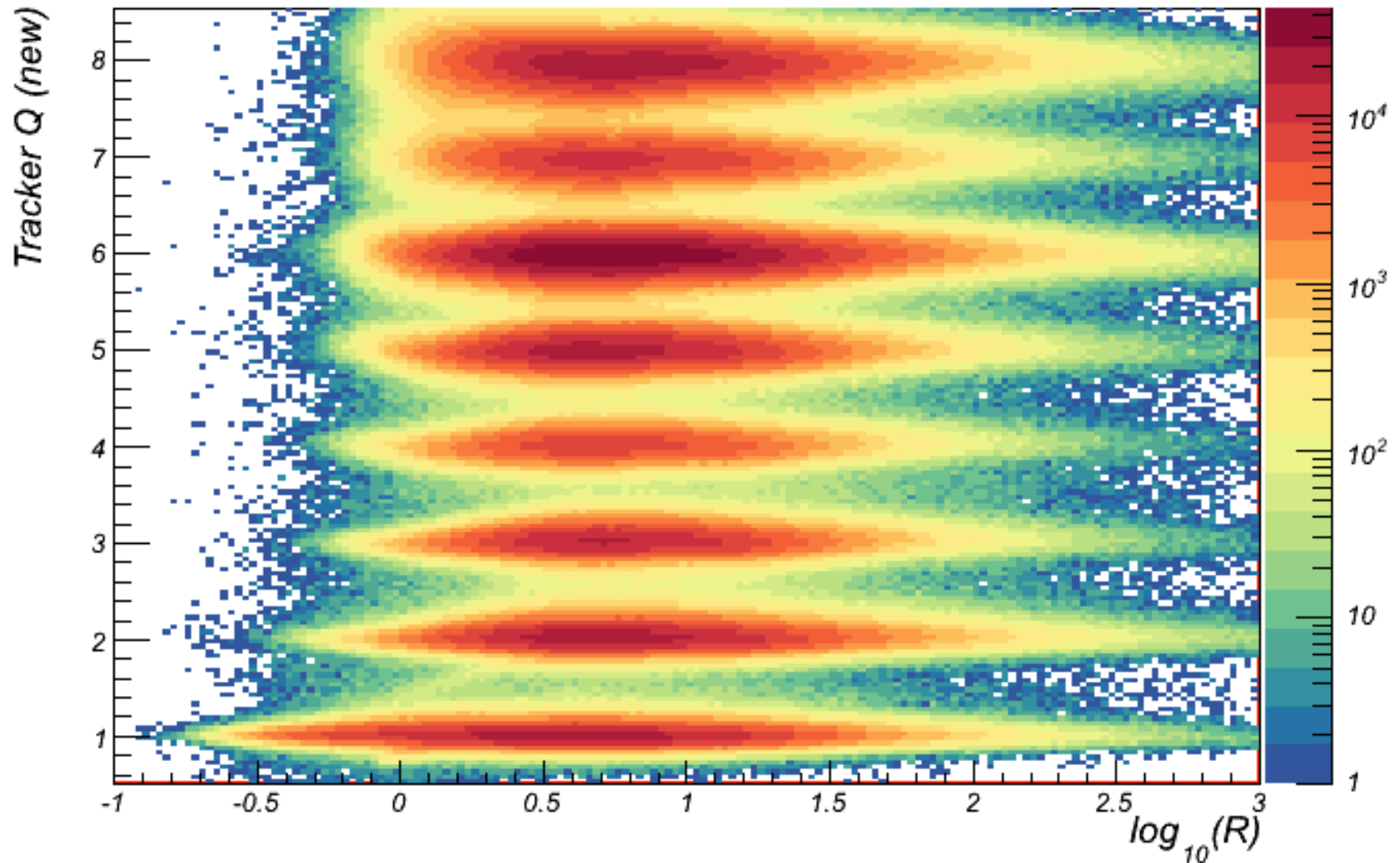
Bethe-Bloch for Protons



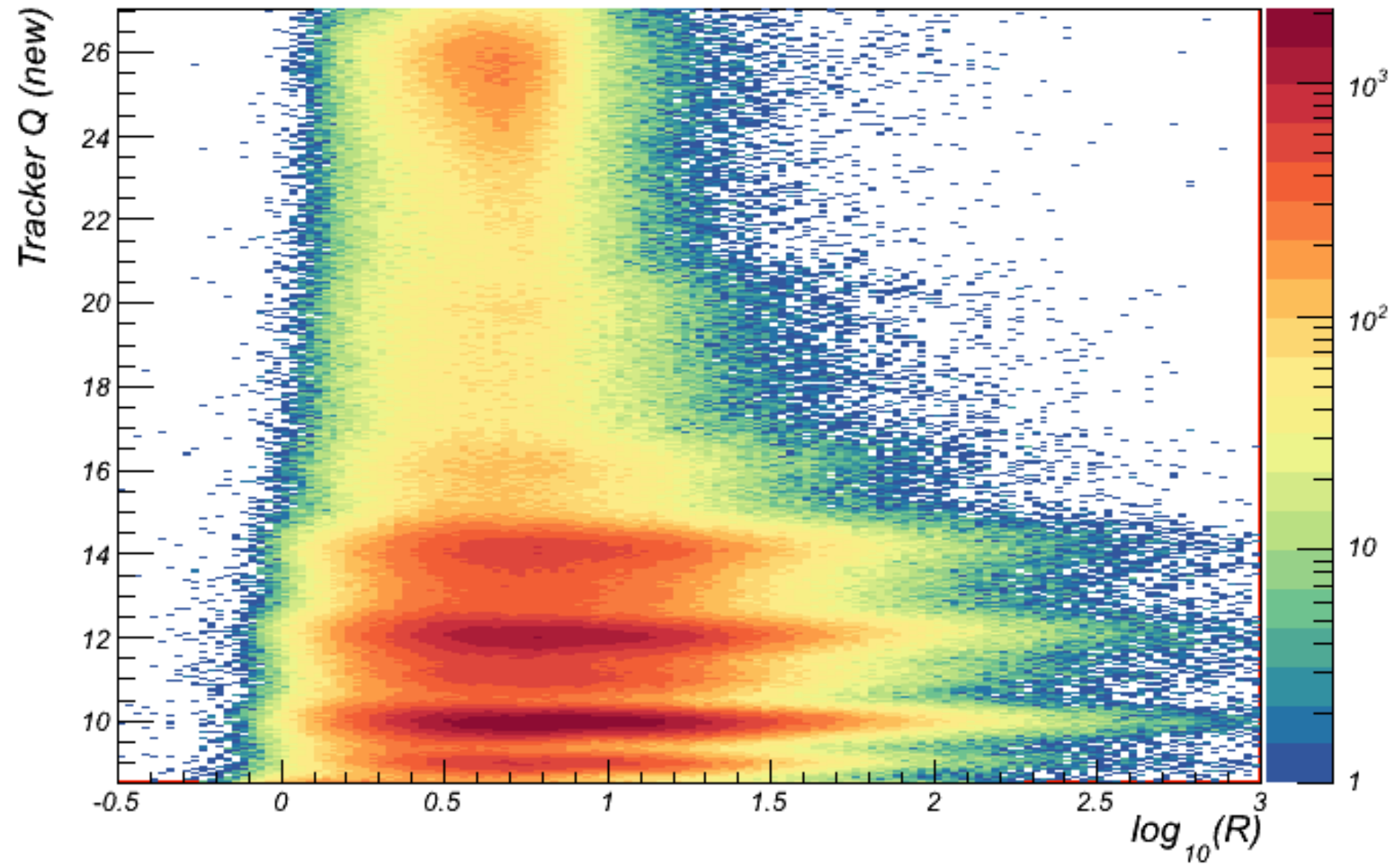
Velocity corrections to the measured dE/dX

To eliminate the velocity dependence of the charge, usually a velocity correction is applied to the measured energy depositions

$$\Delta E_{\text{corr}} = \Delta E_{\text{meas}} * \beta / F(\beta)$$



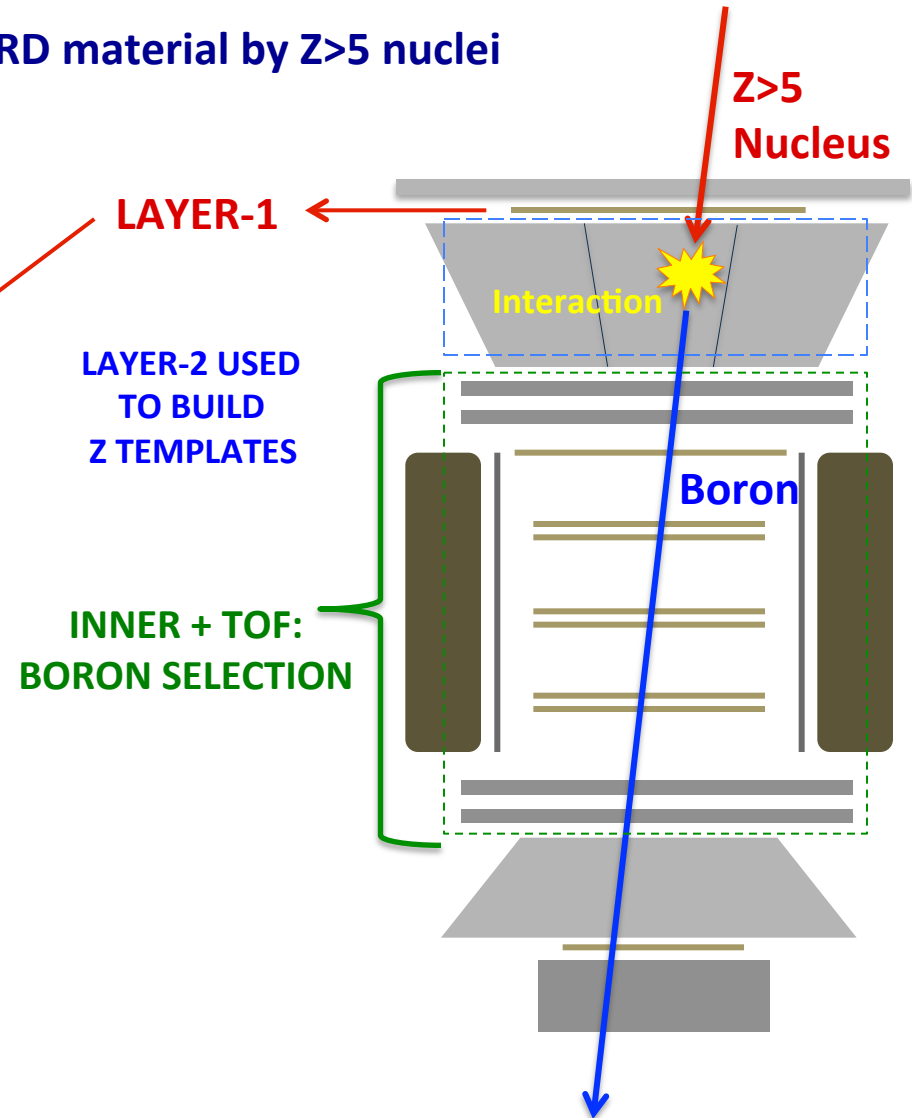
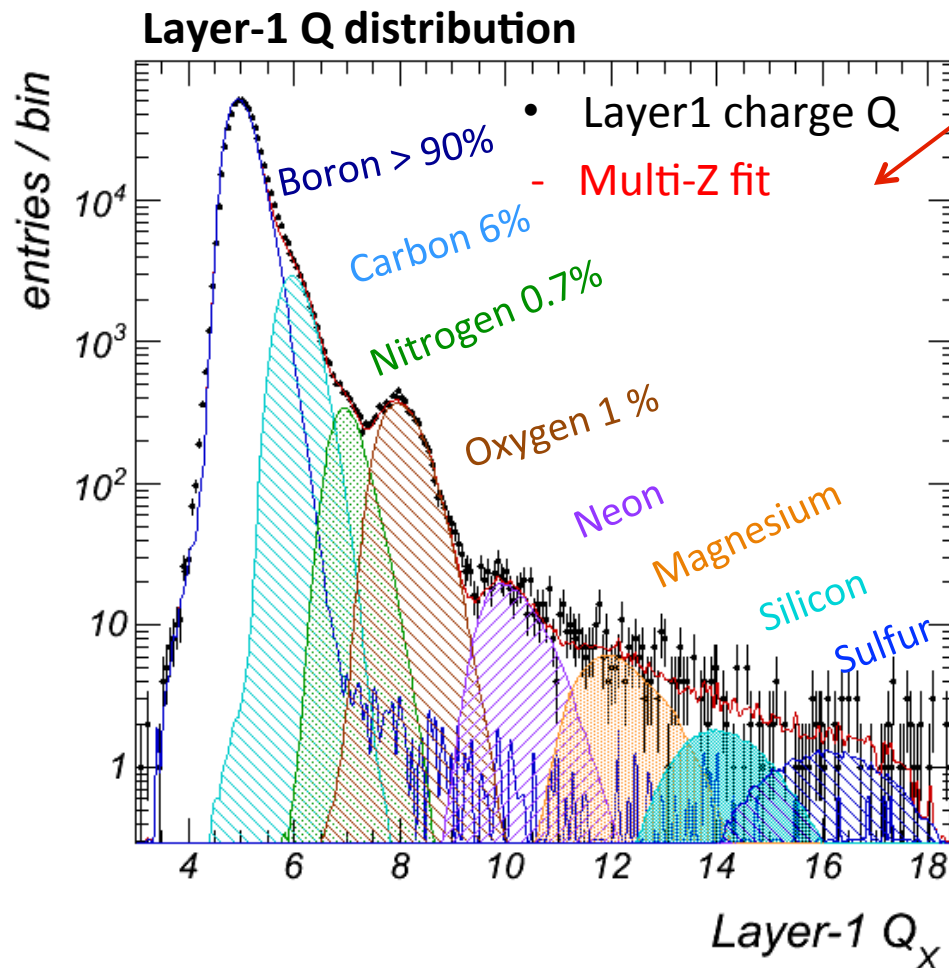
After Rigidity Correction (high-Z)



Fragmentation studies in the detector

Redundancy in Z-measurements allows us to study different fragmentation processes appearing at different levels in the detector.

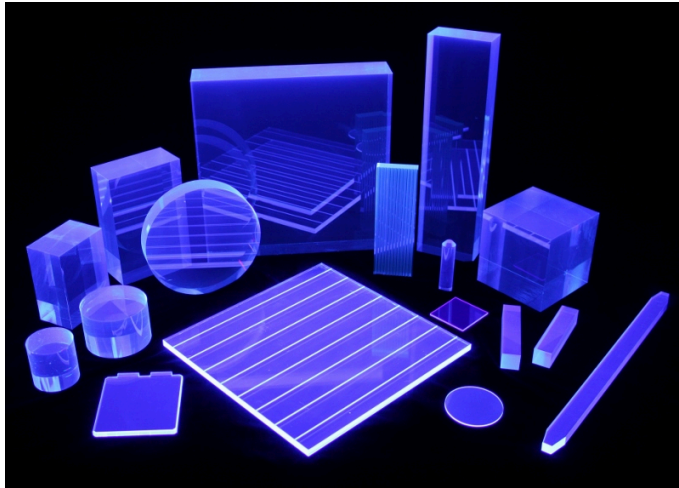
Example: secondary production of Boron in TRD material by $Z > 5$ nuclei



dE/dX measurements

Scintillators

Conversion of ionization energy in photons detected with photodetectors

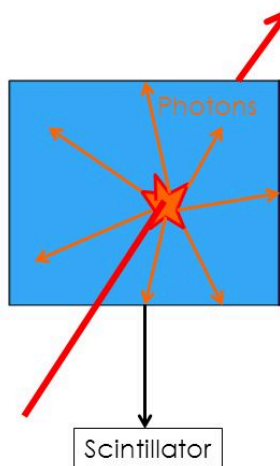


Organic/plastic scintillators:

- low Z, density = 1 g/cm³
- fast (ns)
- low light yield
- used for timing applications

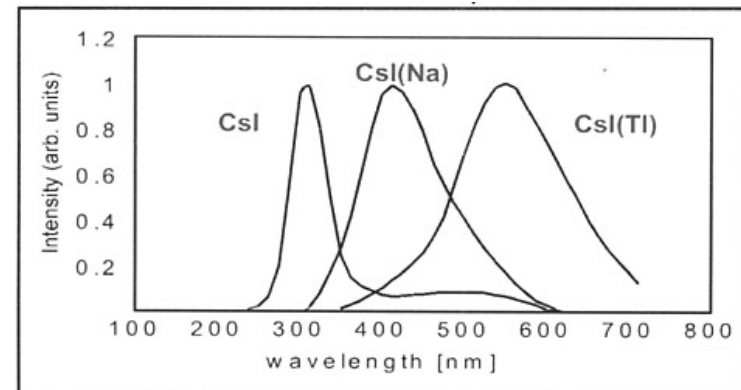
Inorganic/crystal scintillators:

- high Z, dense
- slow
- high light yield
- used for calorimetric applications



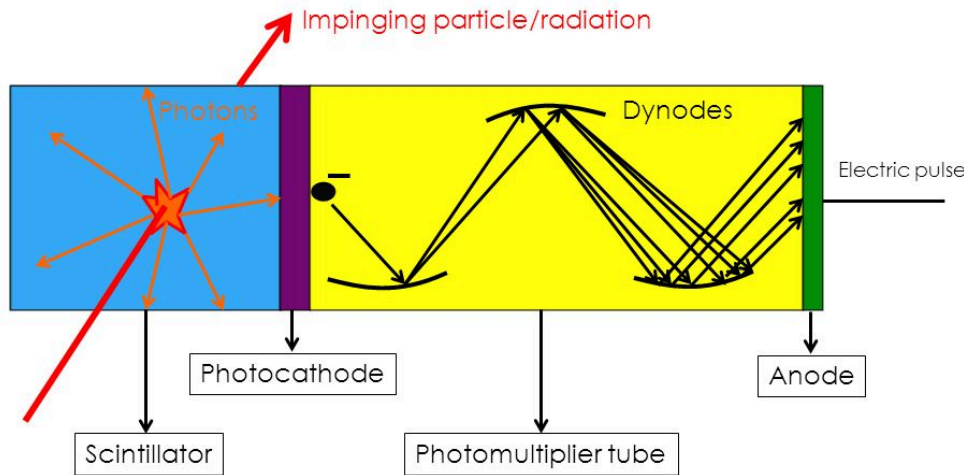
A fraction of energy deposited in the scintillator creates photons in the visible range (details depend on the material)

Typical energy to create one photon
= 100 eV/ γ



dE/dX measurements

Scintillators



Photomultipliers (PMT) convert photons in measureable electric pulses

$$I_{PMT} \propto N_{\gamma} \propto \Delta E$$

Photocathode: photons generate a free photoelectron via photoelectric effect

Dynodes: d.d.p. (kV) between dynodes accelerates electrons. Electrons hitting dynodes may generate a number (approx 3-5) of free electrons to be accelerated

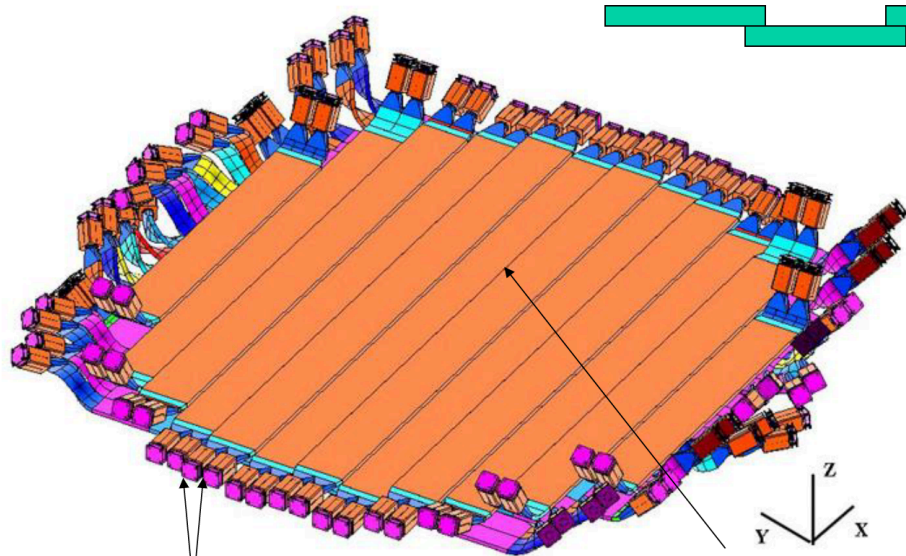
Anode: at the end of many diodes (approx. 10), electrons are collected

For each photoelectron, approx. 10^7 electrons are collected at the anode (gain of the PMT)

Photo-detection efficiency < 30% for PMTs

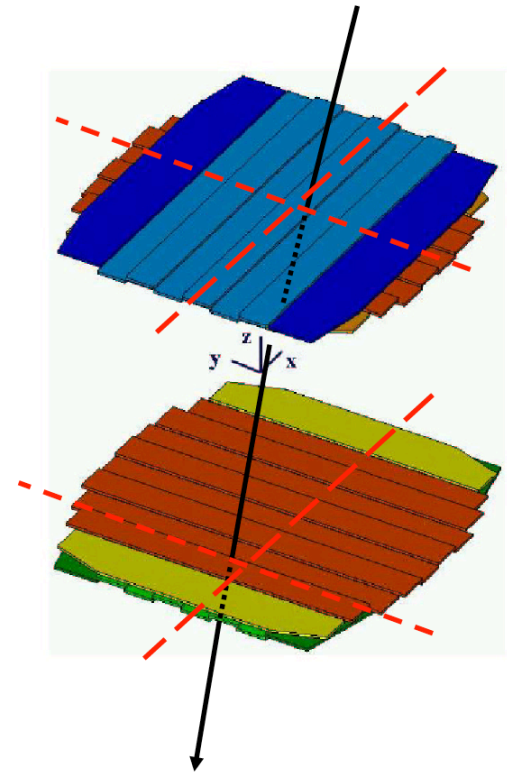
dE/dX measurements

Scintillators



Dual Photomultipliers for Redundancy
and time resolution

Scintillator Paddles

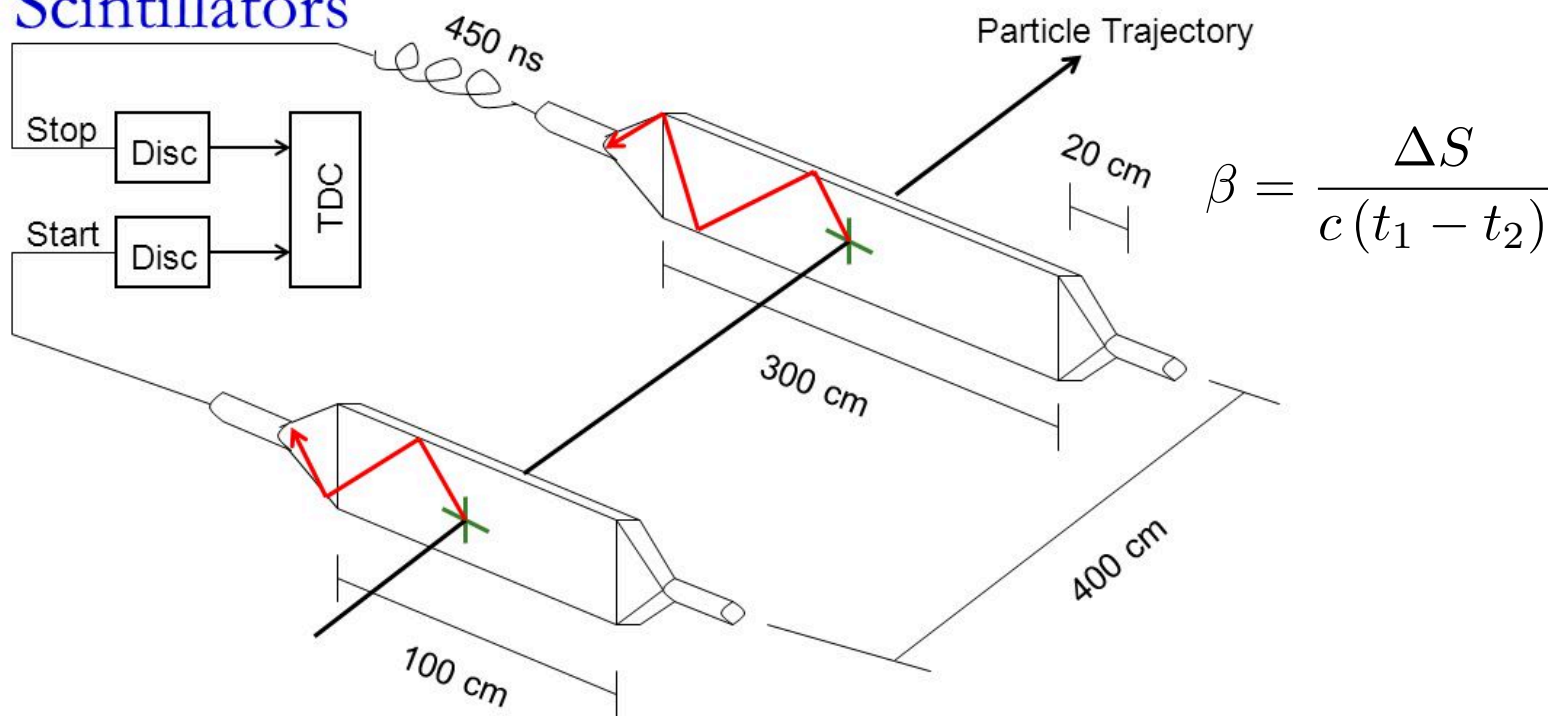


Plastic scintillators are used in space detectors as planes to “**trigger**” (i.e. start) the data acquisition of the whole detector

Time coincidence between different planes used as fast trigger signal

Time of flight

Measure the Flight Time between two Scintillators

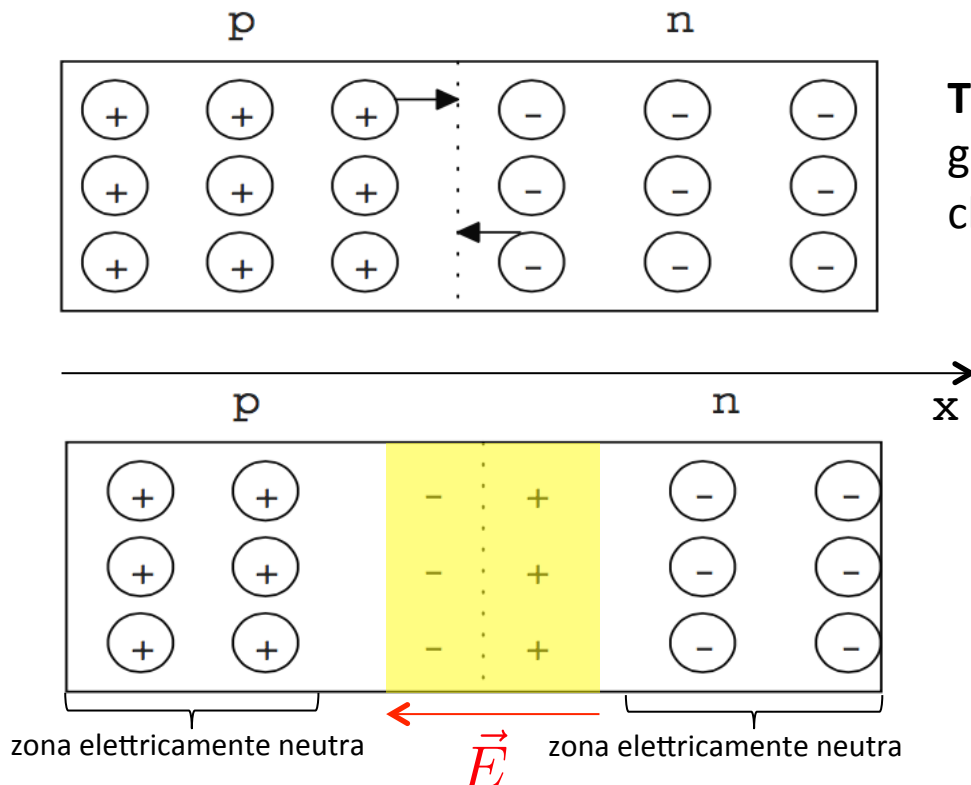


- Path of relativistic particles: 30 cm/ns
- Typical spans are order of 1m $\rightarrow$ time resolution of ns are needed to measure the particle velocity up to c
- Fast Scintillators coupled to fast photodetectors (PMT, SiPM) are commonly used

dE/dX measurements

Solid state detectors

p-n junction



TRANSIENT:

gradient of concentration --> **diffusion** of charge carriers

EQUILIBRIUM:

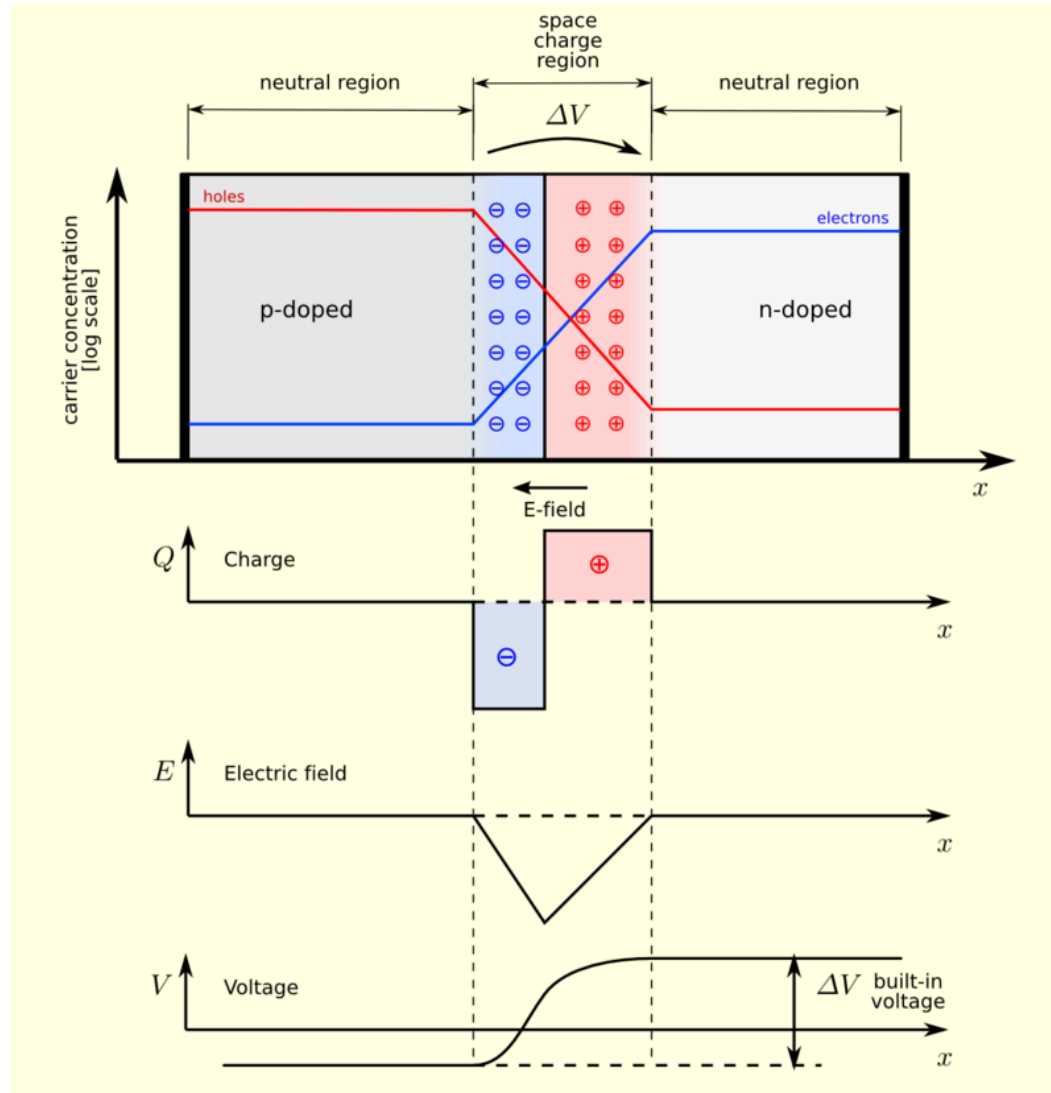
creation of space charge zone

depleted zone: no charge carrier, net electric charge $\neq 0$

P and N zone: charge equilibrium, net electric charge $= 0$

dE/dX measurements

Solid state detectors



dE/dX measurements

Solid state detectors

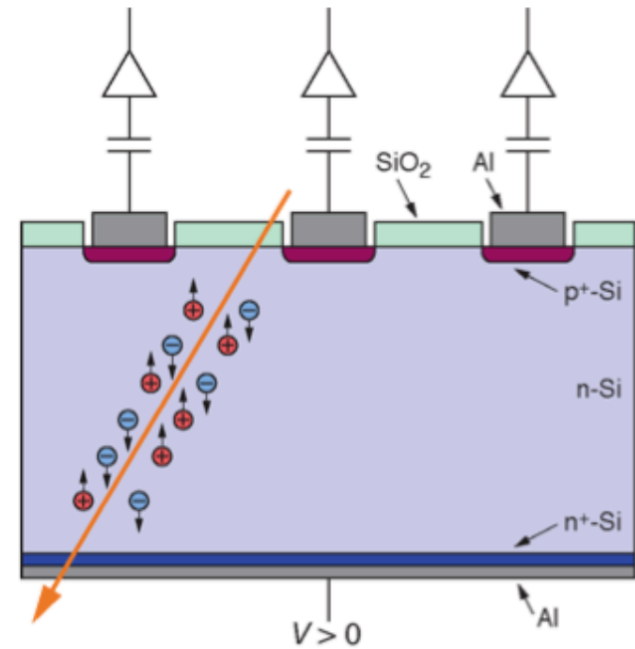
The depletion zone is maximized by application of a reverse bias voltage

Through going charged particles create e^-h^+ pairs in the depletion zone (about 30.000 pairs in standard detector thickness). These charges drift to the electrodes. The drift (current) creates the signal which is amplified by an amplifier connected to each strip. From the signals on the individual strips the position of the through going particle is deduced.

The charge is collected in one (or few more strips) -> this provides information on the particle crossing position

Strip readout pitch approx $100\mu\text{m}$ (or less) -> can achieve **position resolution down to $10\mu\text{m}$ or better** using center of gravity of energy deposit.

The amount of charge, proportional to the ionization and to Z^2 , is used to infer the charge of the particle



dE/dX measurements

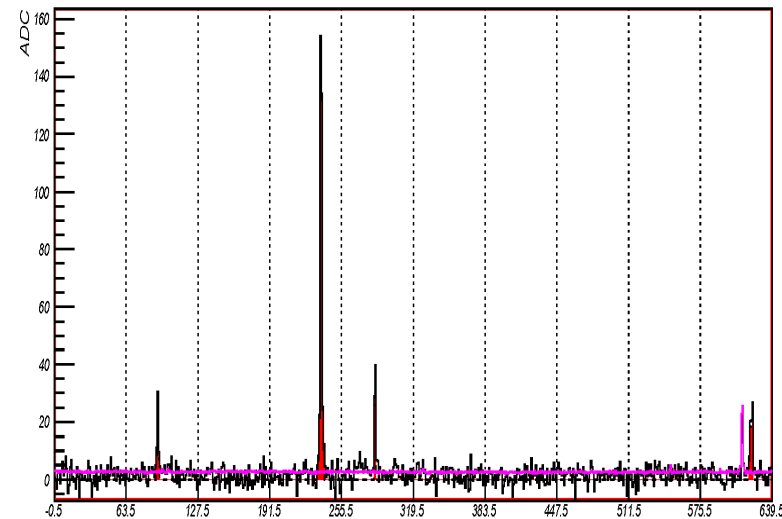
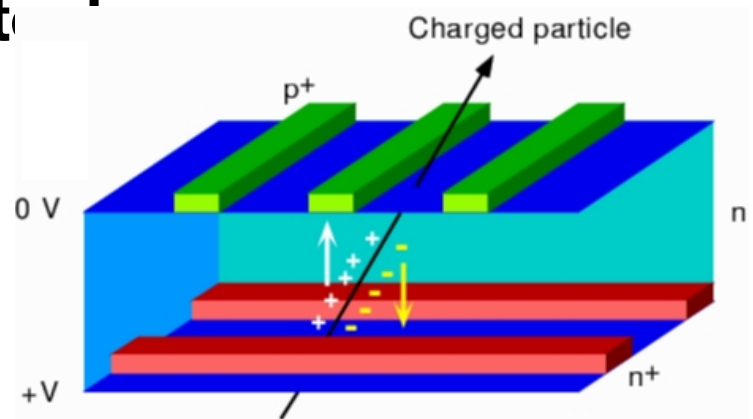
Solid state detector

A charged particle crosses a thin layer of n-doped silicon (typically 300 μm) and interacting with the material frees in average 100 e/h pairs per μm , for a total of $30 \cdot 10^3$ pairs in 300 μm

In the silicon surface, thin p+ strips are implanted (c.a. 10 μm every c.a. 100 μm). The p+/n system is kept in reverse polarization. Less than 100V are needed to completely deplete the silicon bulk.

The e/h pairs are collected on the opposite sides of the silicon.

In some cases, n+ strips are added running in the opposite direction on the opposite side of p+ strips (**double sided silicon**). This allows the measurement of both coordinates.



Coordinata
(in “canali”, da convertire in posizione)

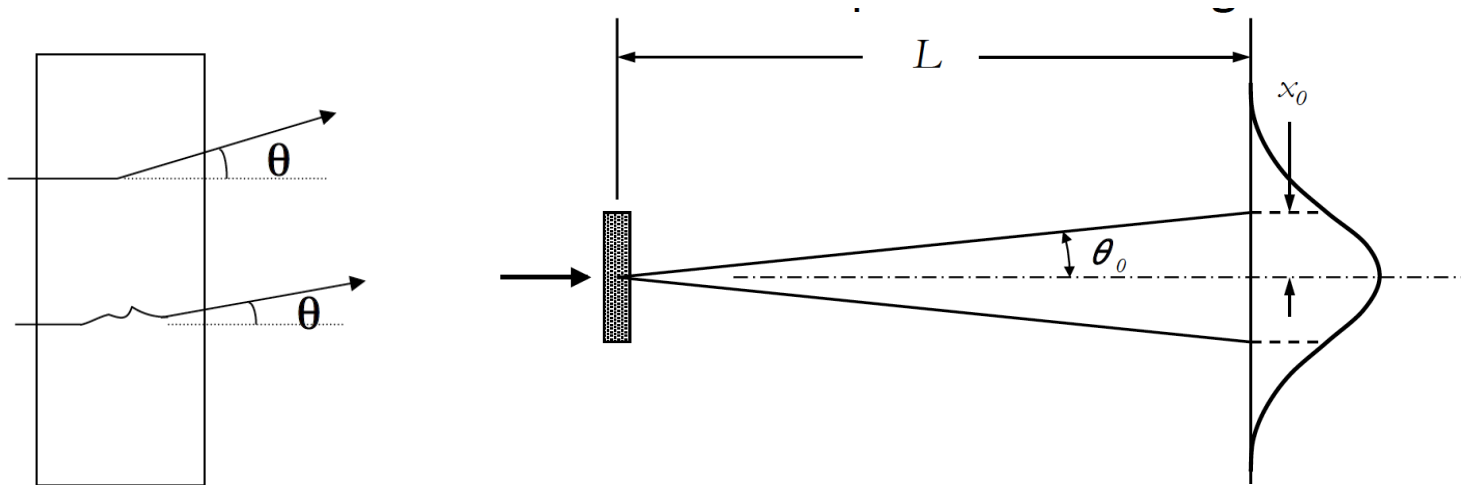
Collisioni fra particelle cariche: Multiple Scattering

- Quindi quando una particella attraversa un mezzo continuo siamo interessati a conoscere:
 - quanta E deposita $\rightarrow$ Bethe-Bloch
 - che deviazione subisce
- Tratteremo i due processi in maniera indipendente (anche se perdite di energia e deviazione NON sono in realta' indipendenti)

Multiple Scattering

- Looking at dE/dx from ionization, ignore nuclei.
 - Energy transfer small compared to scattering from (lighter) electrons.
- However, scattering from nuclei does change the **direction** of the particles momentum, if not its **magnitude**.
 - Deflection of particle's path limits the accuracy with which the curvature in a magnetic field can be determined, and hence the momentum measured.

Multiple scattering



Many small angle deviations can result in a net angle when traversing a material slab

In average $\langle \theta \rangle = 0$, but the distribution has a width

$$\theta_0 = \theta_{plane}^{RMS} \approx \frac{13.6 MeV}{p\beta c} z \sqrt{\frac{L}{X_0}} \quad \text{i.e.} \quad \theta_0 \propto \frac{1}{p} \sqrt{\frac{L}{X_0}}$$

Charge of incident particle

Radiation length of absorbing material

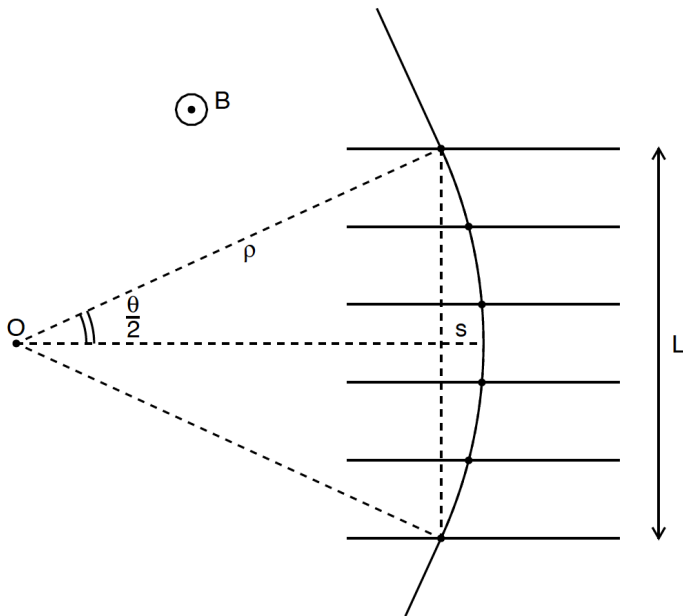
This results in a limit of resolution for tracking applications.

The less material, the better the tracking resolution.

Spectrometers

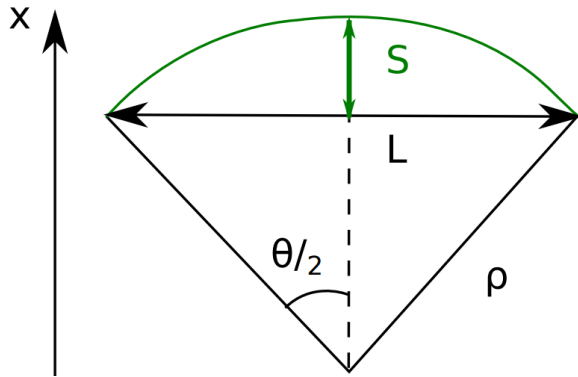
Magnetic Spectrometers

Simple 2D sagitta model



- Charged particle bent in magnetic field
- The sagitta is measured by sampling the particle trajectory through different planes
- Master formula of charged particle in MF
 $R(\text{GeV}) = q B \rho = 0.3 B(\text{T}) \rho(\text{m})$
- Rigidity $R = p/Ze$ defines the particle trajectory in a magnetic field

Spectrometers



$$\theta \approx L/\rho = qBL/p$$

Sagitta

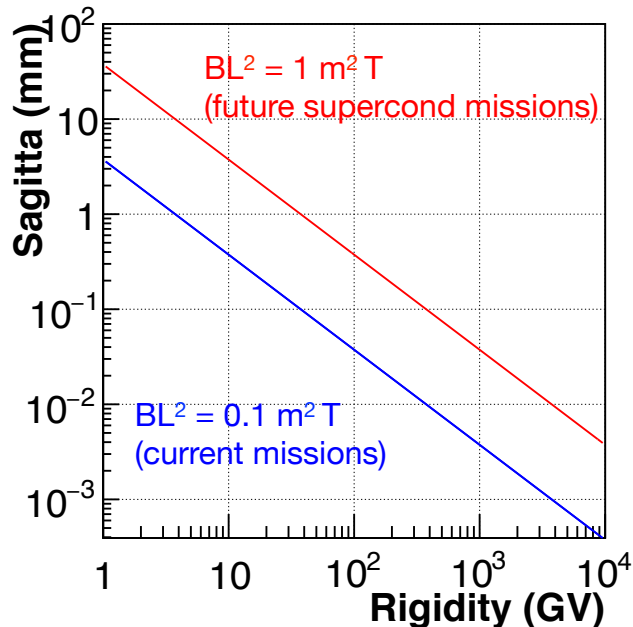
$$S = \rho - \rho \cos \frac{\theta}{2} = \rho \left(1 - \cos \frac{\theta}{2} \right)$$

$$= 2\rho \sin^2 \frac{\theta}{4}$$

for small θ

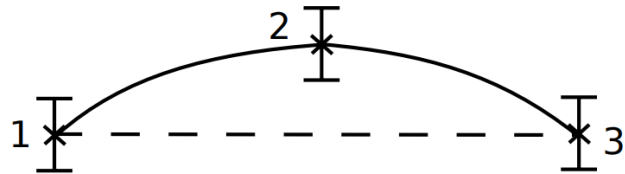
$$S \simeq \frac{\rho \theta^2}{8}$$

$$s(m) = \frac{0.3 B L^2}{8 p}$$



BL^2 “Bending power”: characteristic parameter of spectrometer performance

Spectrometers



Sagitta defined by the measurement of at least 3 points. The error on the sagitta is determined by the accuracy of the coordinate measurement

$$s = \frac{x_1 + x_3}{2} - x_2 \quad \sigma^2(s) = \frac{\sigma^2(x)}{4} + \frac{\sigma^2(x)}{4} + \sigma^2(x) \quad \sigma(s) = \sqrt{\frac{3}{2}} \sigma(x)$$

$$\frac{\sigma(p)}{p} = \frac{\sigma(R)}{R} = \frac{\sigma(s)}{s} = \sqrt{\frac{3}{2}} \frac{8 \sigma(x)}{0.3 B L^2} \cdot p$$

$$\frac{\sigma(p)}{p} \propto p, \sigma(x), \frac{1}{B L^2}$$

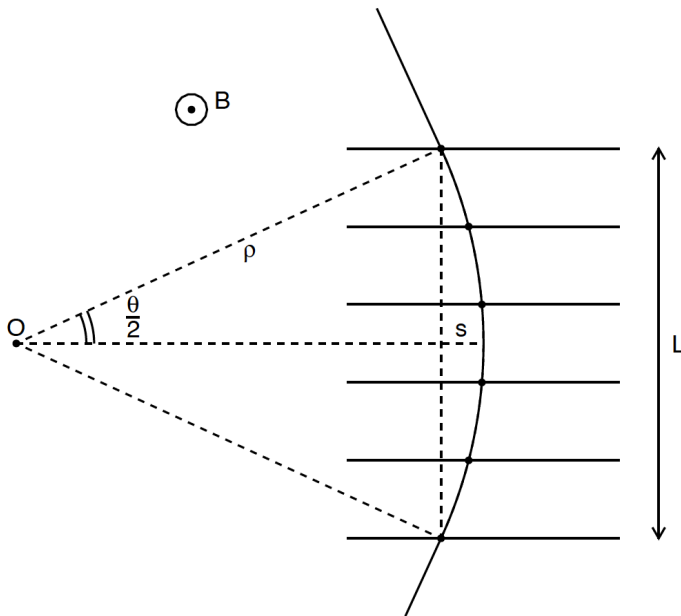
Spectrometer resolution worsens at high rigidities and can be improved by better coordinate measurement accuracy and better bending power

- $L \sim$ [Spectrometer dimensions](#), limited by the space constraints
- B , limited by [magnet size and technology](#) (superconducting magnet in space?)
- $\sigma(x) \sim$ [position resolution](#) $\rightarrow$ experimental effort to achieve resolutions below $10\mu\text{m}$

Spectrometers

Magnetic Spectrometers

Simple 2D sagitta model



- Charged particle bent in magnetic field
- The sagitta is measured by sampling the particle trajectory through different planes
- The particle rigidity is inferred via

$$R(GV/c) = \frac{0.3 B(T) L(m)^2}{8 s(m)}$$

- Rigidity resolution scale linearly as

$$\frac{\sigma_R}{R} = \frac{\sigma_s}{s} \propto R$$

- Maximum Detectable Rigidity MDR

$$\frac{\sigma_R}{R} = 1 \Rightarrow R^{(MDR)} \propto \frac{L^2 B}{\sigma_s}$$

- $L \sim$ **Spectrometer dimensions**, limited by the space constraints
- B , limited by **magnet size and technology** (superconducting magnet in space?)
- $\sigma_s \sim$ **position resolution** $\rightarrow$ experimental effort to achieve resolutions below $10\mu\text{m}$

Scattering multiplo

Notiamo: lo scattering multiplo è un fattore limitante per le misure.

- **Misure d' impulso** precisione della misura limitata dallo scattering multiplo.
- **Sciami elettromagnetici** dimensioni trasverse dello sciame dovute allo scattering multiplo.

Effect of Multiple Scattering on Resolution

■ Approximate relation (PDG):

$$\theta_0 = \theta_{plane}^{RMS} \approx \frac{13.6 MeV}{p\beta c} z \sqrt{\frac{L}{X_0}} \quad \text{i.e.} \quad \theta_0 \propto \frac{1}{p} \sqrt{\frac{L}{X_0}}$$

Charge of incident particle Radiation length of absorbing material

■ Apparent sagitta due to multiple scattering (from PDG):

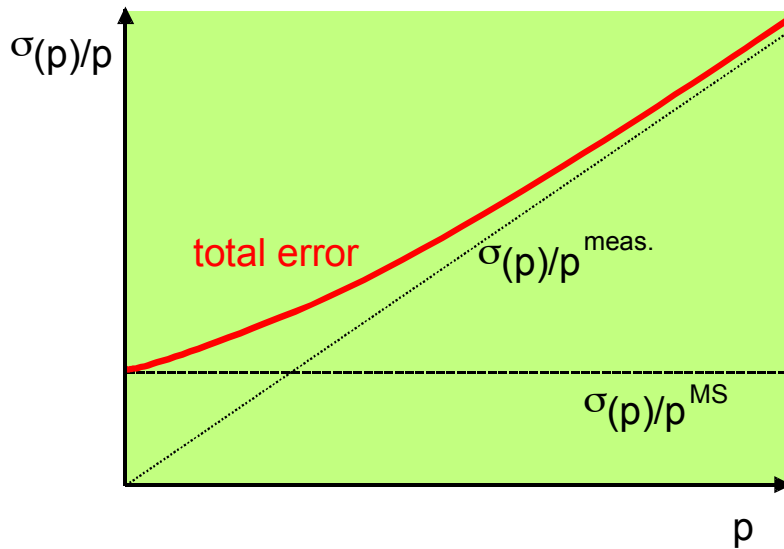
$$s_{plane} = \frac{L\theta_0}{4\sqrt{3}}$$

■ Contribution to momentum resolution from multiple scattering:

$$\left. \frac{\sigma_p}{p} \right|_{MS} = \frac{s_{plane}}{s} \approx \frac{0.05}{B\sqrt{LX_0}} \quad \text{using } s \approx \frac{0.3BL^2}{8p_T} \quad \text{i.e.} \quad \left. \frac{\sigma_p}{p} \right|_{MS} \propto \frac{1}{B\sqrt{LX_0}}$$

Independent of p!

Effect of Multiple Scattering on Resolution



■ Example:

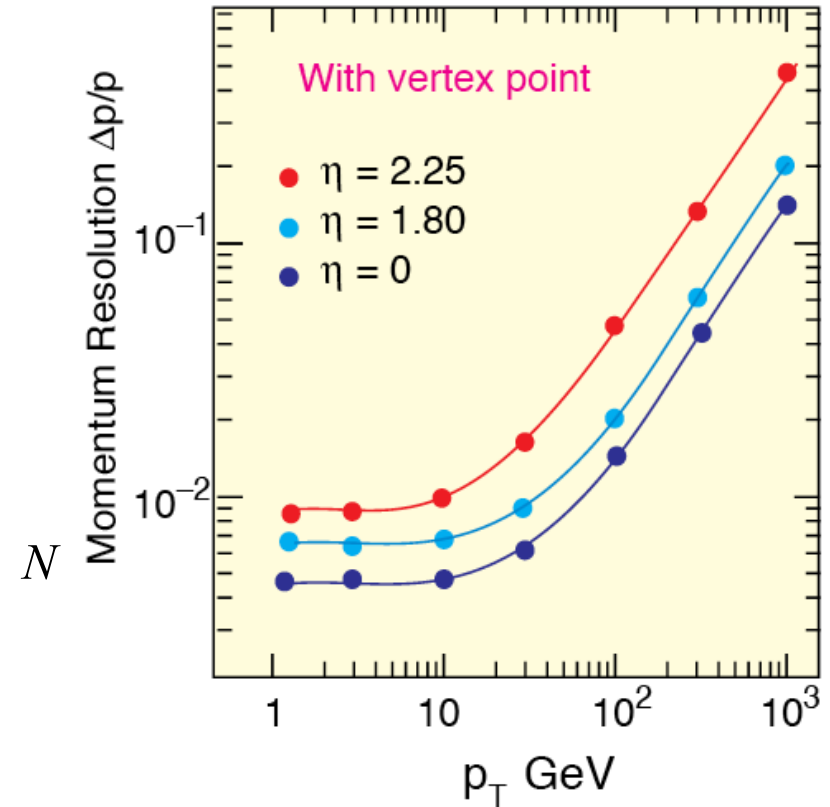
- $p_T = 1 \text{ GeV}/c$, $L = 1\text{m}$, $B = 1 \text{ T}$,
 $= 10$, $\sigma_x = 200\mu\text{m}$:

$$\left. \frac{\sigma_p}{p} \right|_{\text{meas}} \approx 0.5\%$$

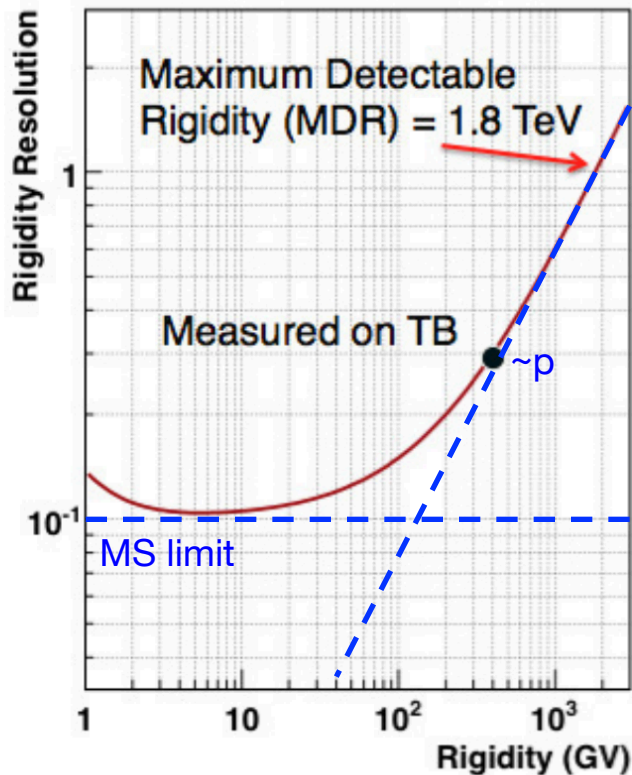
- For detector filled with Ar, $X_0 = 110\text{m}$:

$$\left. \frac{\sigma_p}{p} \right|_{\text{MS}} \approx 0.5\%$$

Estimated Momentum Resolution vs p_T in CMS

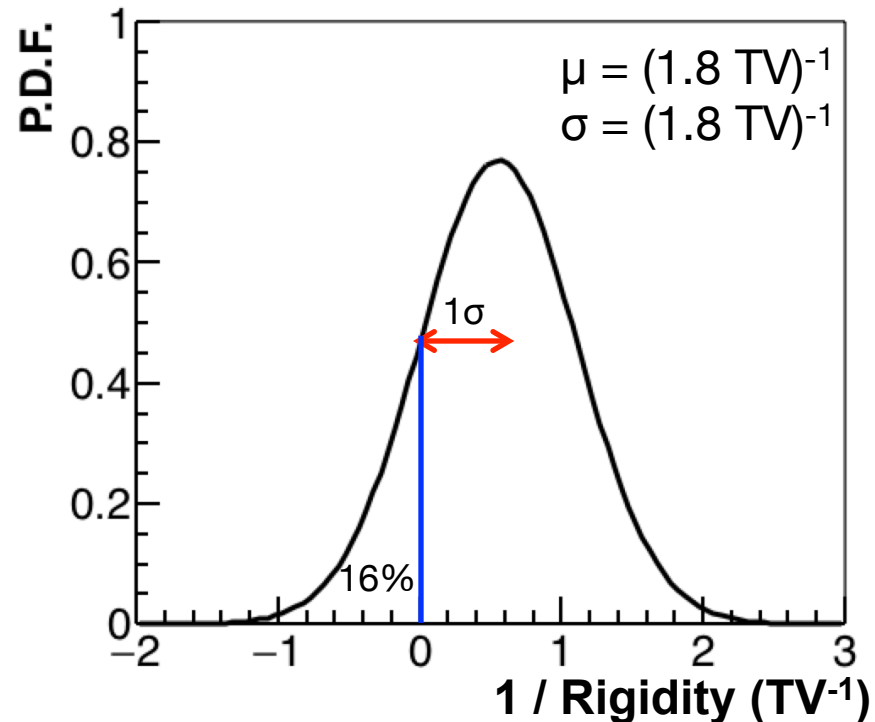


Spectrometers



Performance parameter:
Maximum Detectable Rigidity (MDR):

$$\frac{\sigma_R}{R} = 1 \Rightarrow R(\text{MDR}) \propto \frac{L^2 B}{\sigma_s}$$

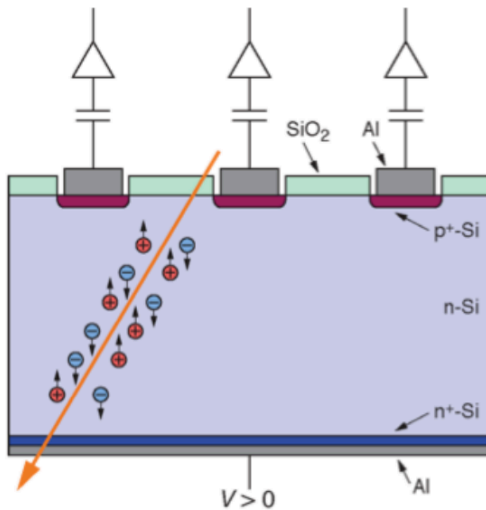


At high energies $\frac{\sigma(p)}{p} \propto p$

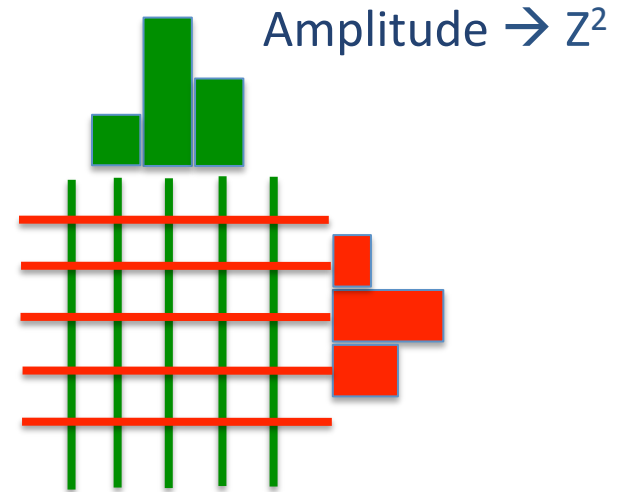
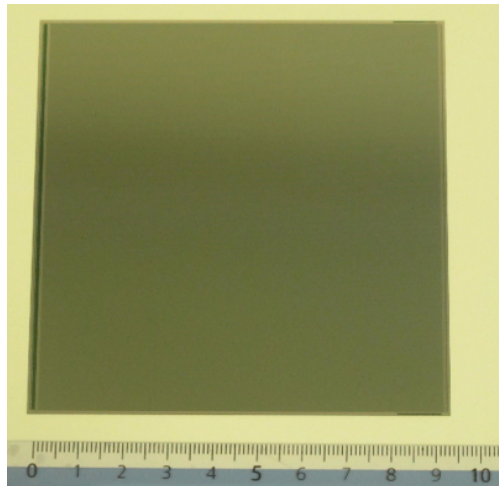
At low energies $\frac{\sigma(p)}{p} \approx \text{const}$
(Multiple scattering)

“Spillover”: events that are reconstructed with opposite sign of charge

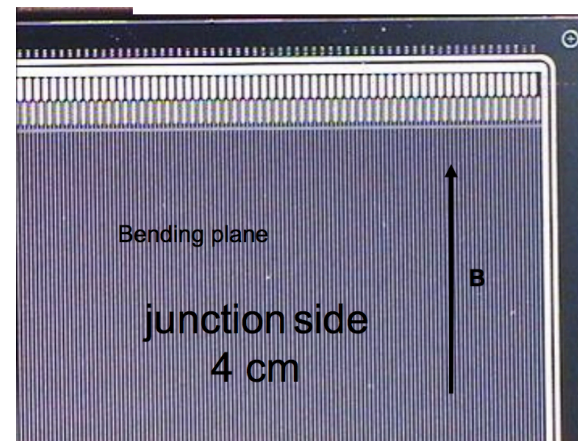
Silicon Microstrip Detectors



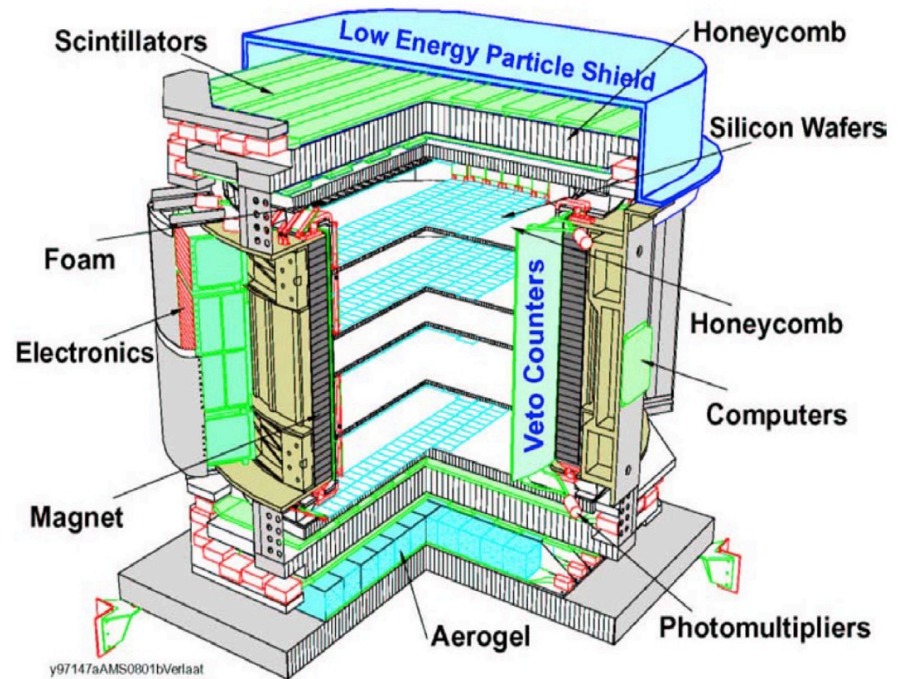
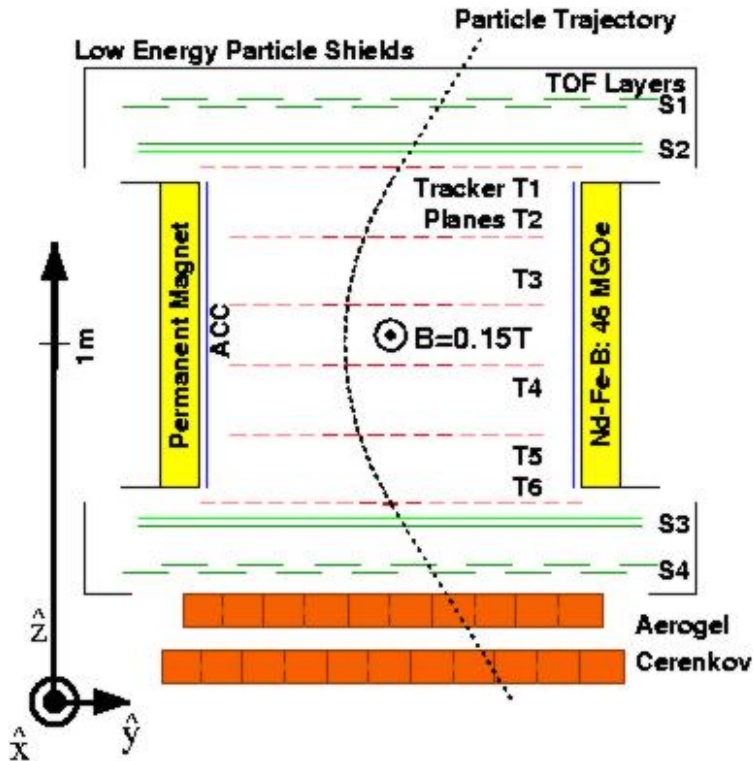
Single sensor $\approx 10 \times 10 \text{ cm}^2$... or less



Position from the center of gravity of the signal released on adjacent strips (50-200 μm)



AMS-01: First magnetic spectrometer with a silicon tracker in space



Time Of Flight : measure time $\rightarrow$ velocity, arrival direction, $dE/dX \rightarrow Z$

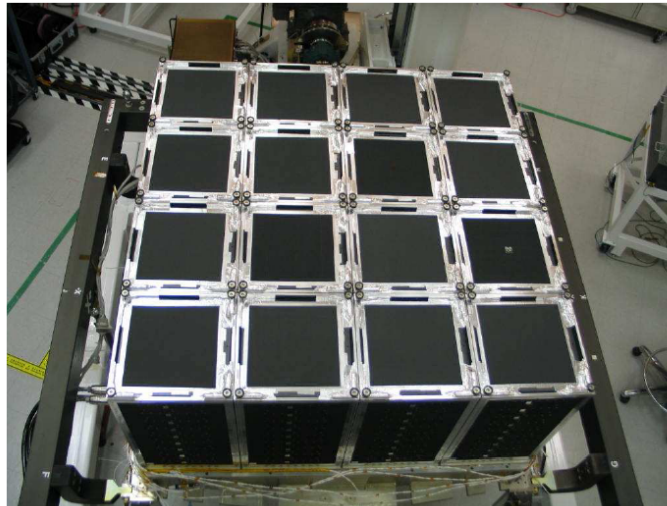
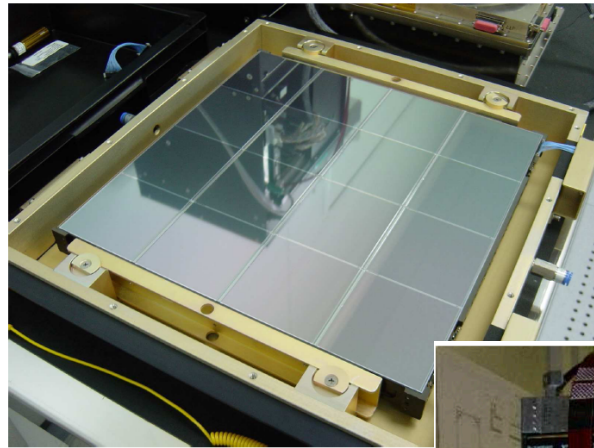
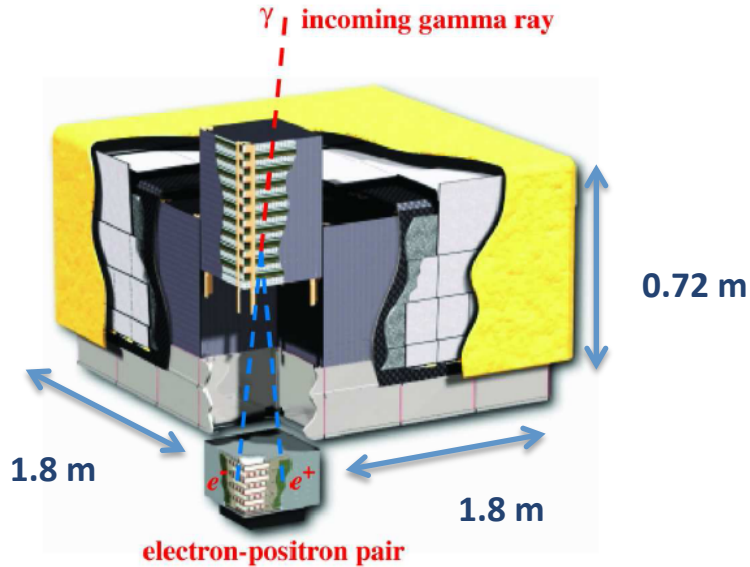
Magnet: 2.2 Ton of Nd-Fe-B blocks providing a 15kGauss field inside, < 2 Gauss outside

Tracker: 2m² of silicon sensors arranged in 6 planes

Aerogel Cerenkov threshold counter: discrimination of e/p based on Cherenkov emission

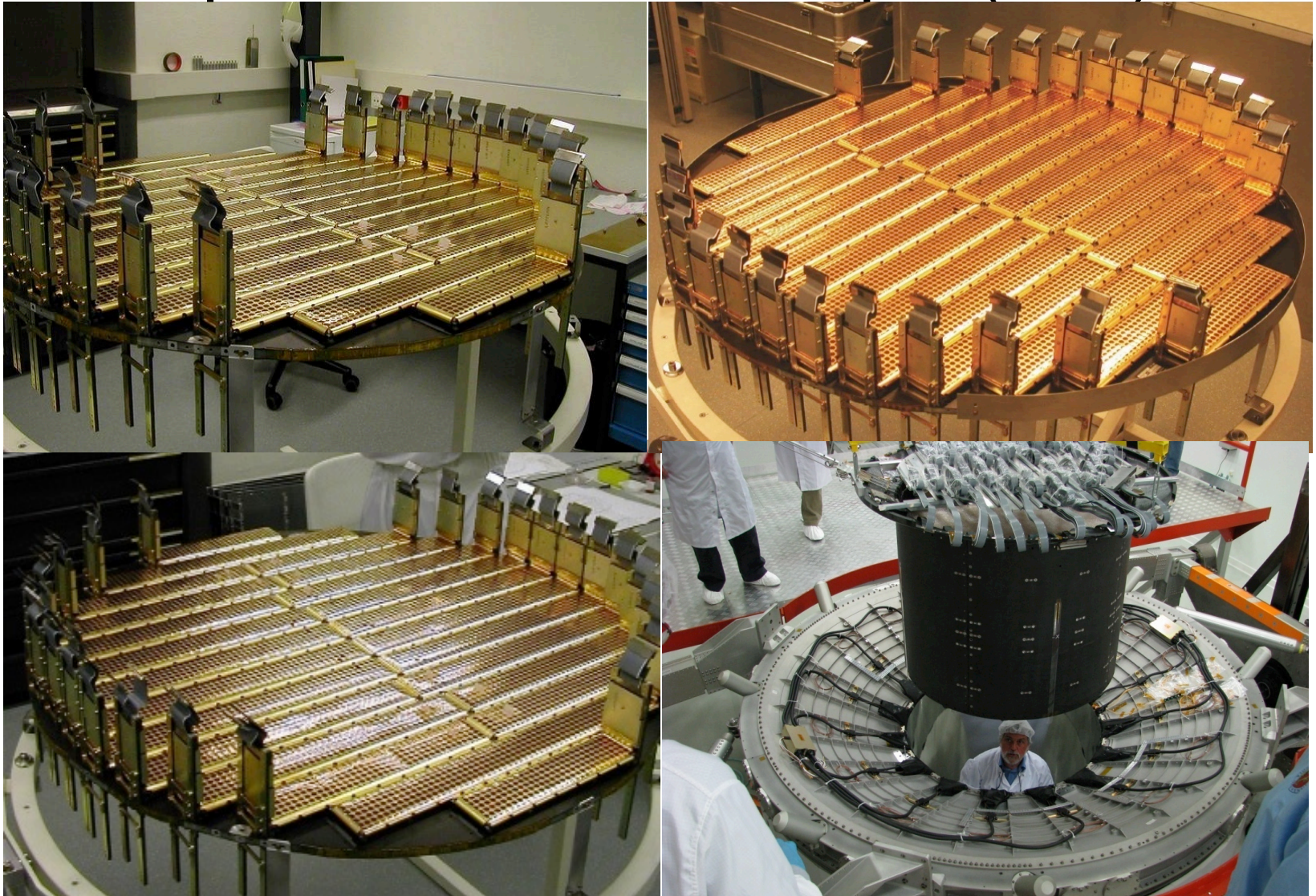
Fermi (2008)

73m² of silicon sensors in space



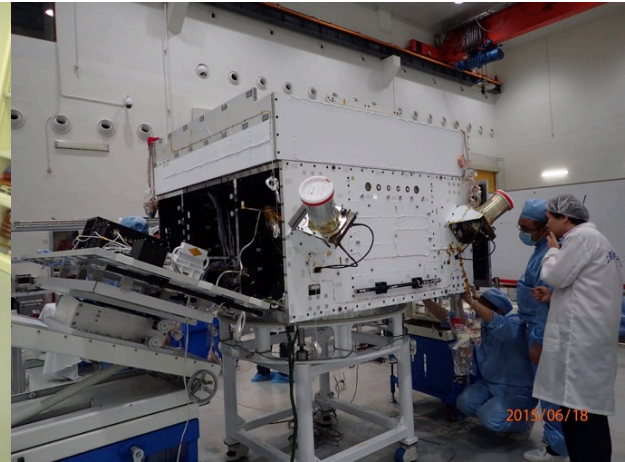
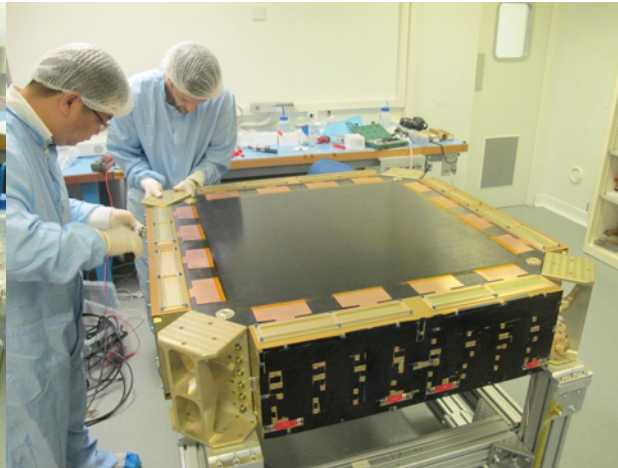
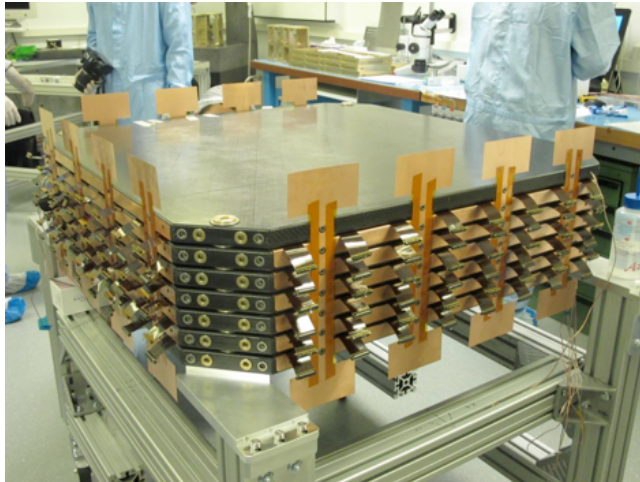
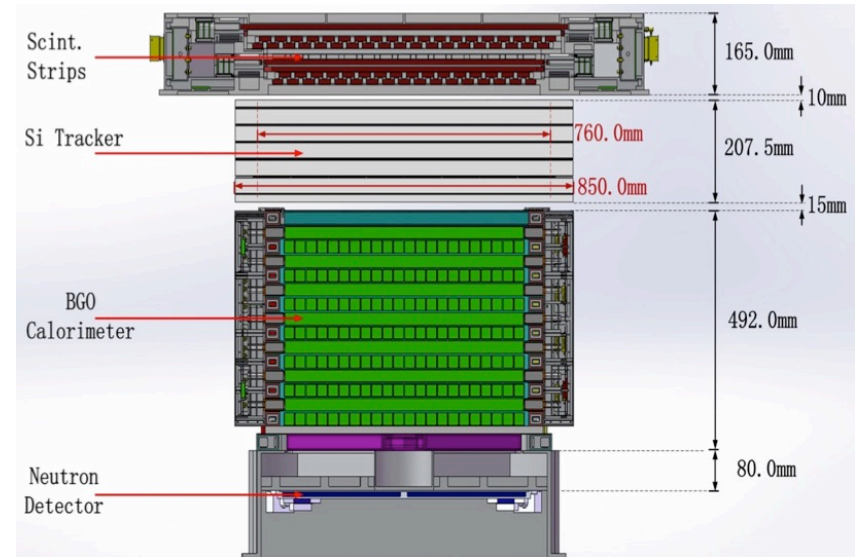
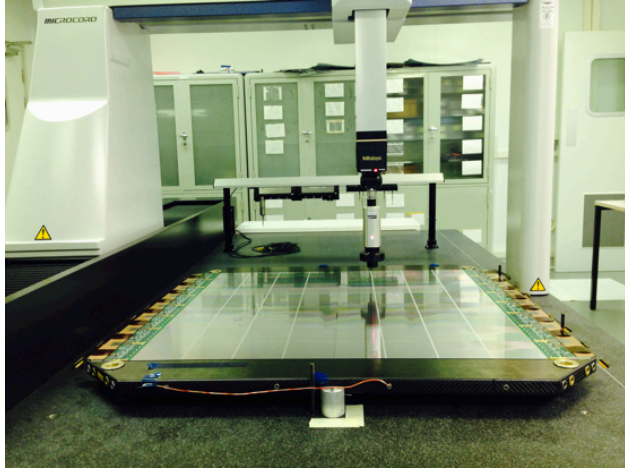
AMS-02 (2011)

9 planes of silicon sensors in space (6.4 m²)



DAMPE (2015)

6 planes of silicon sensors in space (7.7 m²)



Calorimetry

- **Calorimeters: instruments in which particles are partially or completely absorbed to measure their energy**
- Electromagnetic calorimeters (homogeneous, sampling)
- Hadronic calorimeters (sampling)
- Destructive detectors, sited at the “end” of the detector.
- Many techniques and technology, depending on the particle to be measured. We focus only on the simpler electromagnetic calorimeters for high energy particles

Electron radiative energy losses

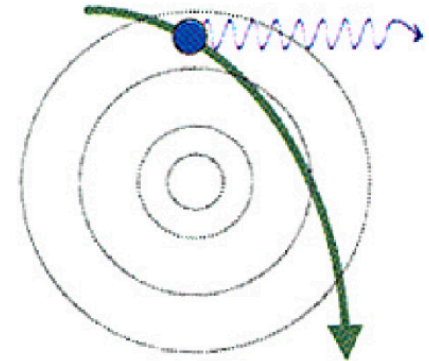
- Electrons differ from other charged particles due to their lighter mass.
- A charged particle accelerated in an electromagnetic field release energy.
- Classical description: $\frac{dE}{dt} = \left(\frac{2}{3} \frac{e^2}{c^3} \right) a^2$

Relativistic electrons accelerated in the electric field of a nucleus radiate energy via the **Bremsstrahlung** effect.

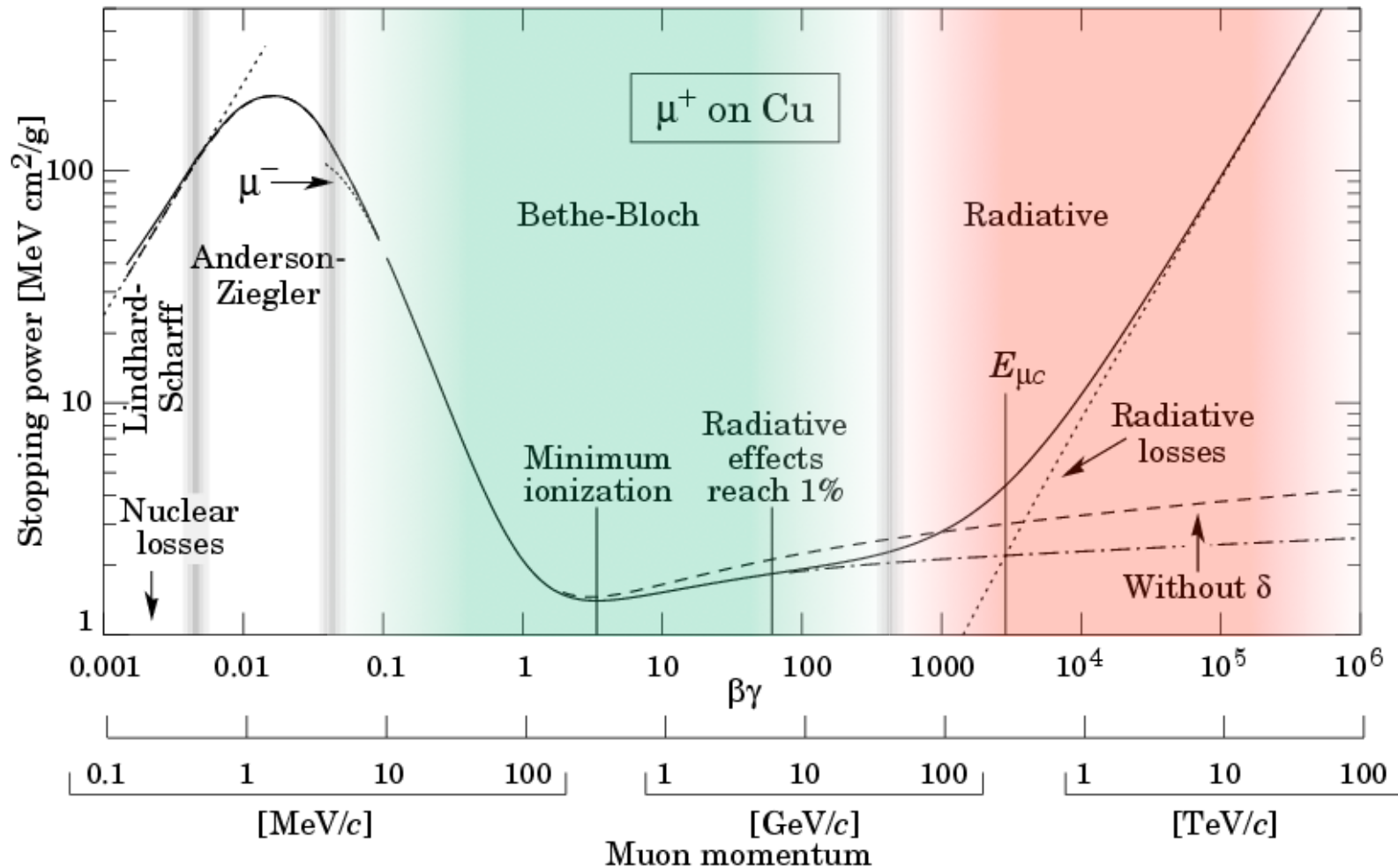
In a continuous medium, the losses are continuous and the electron energy degrades as $E(x) = E_0 e^{(-x/X_0)}$

X_0 (radiation length) = typical length scale of radiative energy losses

$$X_0 = \frac{716.4 \cdot A}{Z_2^2 \ln \frac{287}{Z_2^{1/2}}} \quad (g / cm^2)$$



Energy losses



Critical energy: $\frac{dE}{dx}|_{ion} = \frac{dE}{dx}|_{brem}$ $E_C \approx 700/(Z + 1) \text{ MeV}$
 $E_C \propto \frac{1}{m^2} \Rightarrow E_C(\mu) \approx 4 \cdot 10^4 E_C(e)$

Interactions of photons

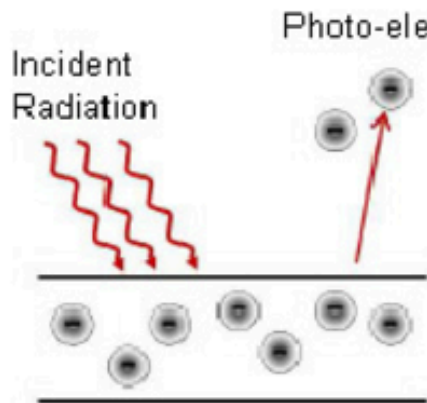
- For low energies ($500 \text{ keV} \geq E_\gamma \geq \text{ionisation energy}$) the photoelectric effect dominates,

$$\gamma + \text{atom} \rightarrow \text{atom}^+ + e^-$$
- In the range of medium energies ($E_\gamma \approx 1 \text{ MeV}$) the Compton effect, which is the scattering of photons off quasi-free atomic electrons,

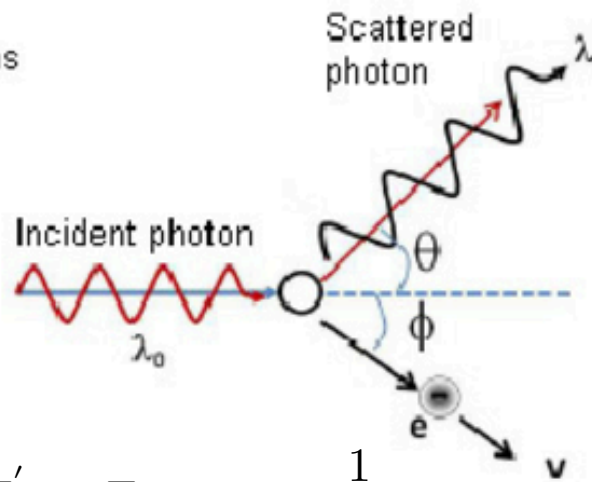
$$\gamma + e^- \rightarrow \gamma + e^-$$

 has the largest cross section,
- and at higher energies ($E_\gamma \gg 1 \text{ MeV}$, typically 50 MeV) the cross section for pair production dominates,

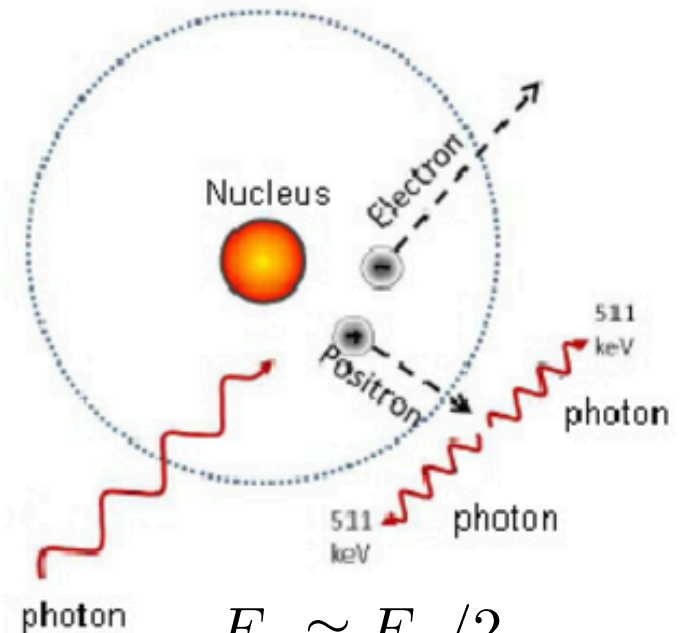
$$\gamma + \text{nucleus} \rightarrow e^+ + e^- + \text{nucleus}$$



$$E_e = E_\gamma - W_e$$

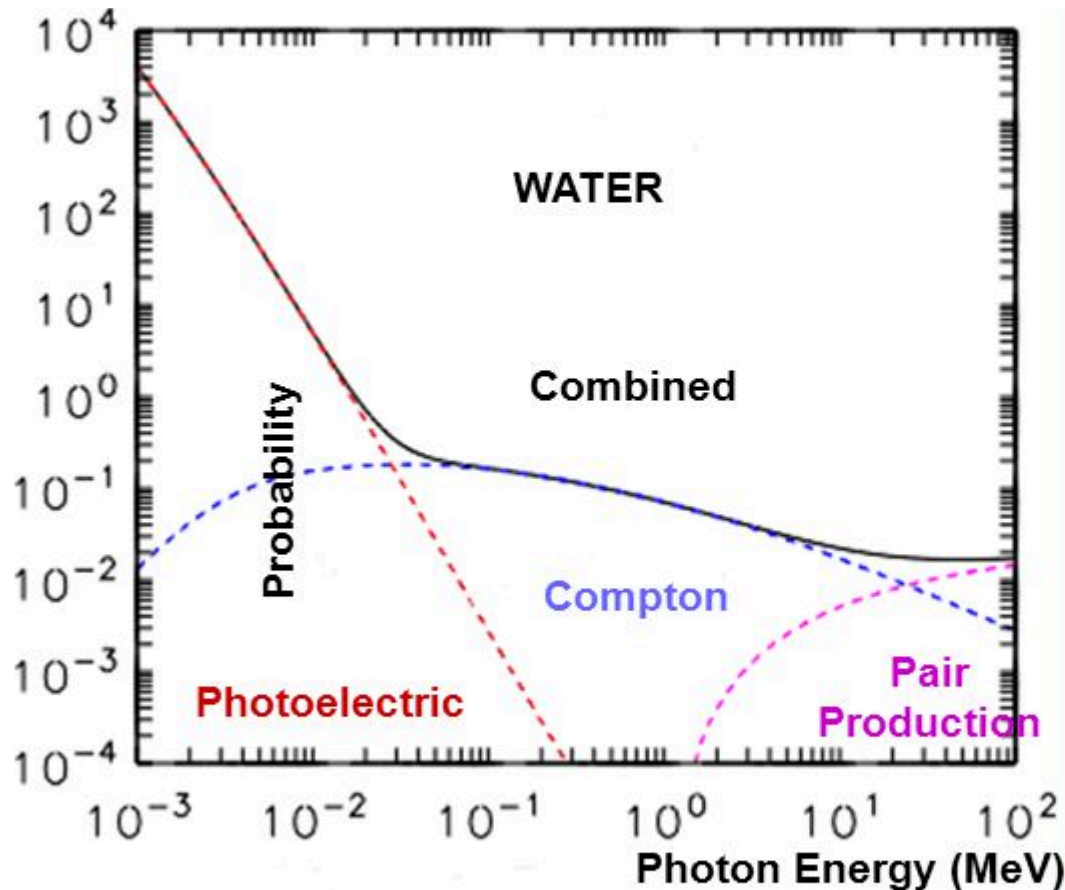


$$E'_\gamma = E_\gamma \frac{1}{1 + \frac{E_\gamma}{m_e}(1 - \cos(\theta))}$$



$$E_e \approx E_\gamma / 2$$

Interactions of photons



The profile strongly depends on the material, but in general above the pair production energy threshold ($E_{th} = 2m_e$) pair production rapidly becomes the dominating energy loss mechanisms for photons

Calorimetry

- ❖ A causa del bremsstrahlung, un fascio di e^+ di energia iniziale E_0 , dopo un tratto x di materiale ha un'energia:

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

- ❖ In un mezzo omogeneo di lunghezza di radiazione X_0 , a causa della produzione di coppie, l'intensità di un fascio monocromatico di γ , diminuisce dopo un tratto x di materiale:

$$I = I_0 e^{-(7/9)x/X_0}$$

NB: nel primo caso il numero di e^- e' costante, cambia l'energia delle particelle, non il loro numero. Nel secondo, l'energia dei fotoni rimane la stessa ma scompaiono particelle

Electromagnetic showers

The physics of e-m. shower is well known (hadronic showers are more complicated)
Simplest parametrization by Rossi describes the main shower properties.
More accurate descriptions involve Monte Carlo simulations.

Lo sciame è creato da e^+ , e^- che emettono γ per BREMS e γ che creano coppie e^+ , e^-

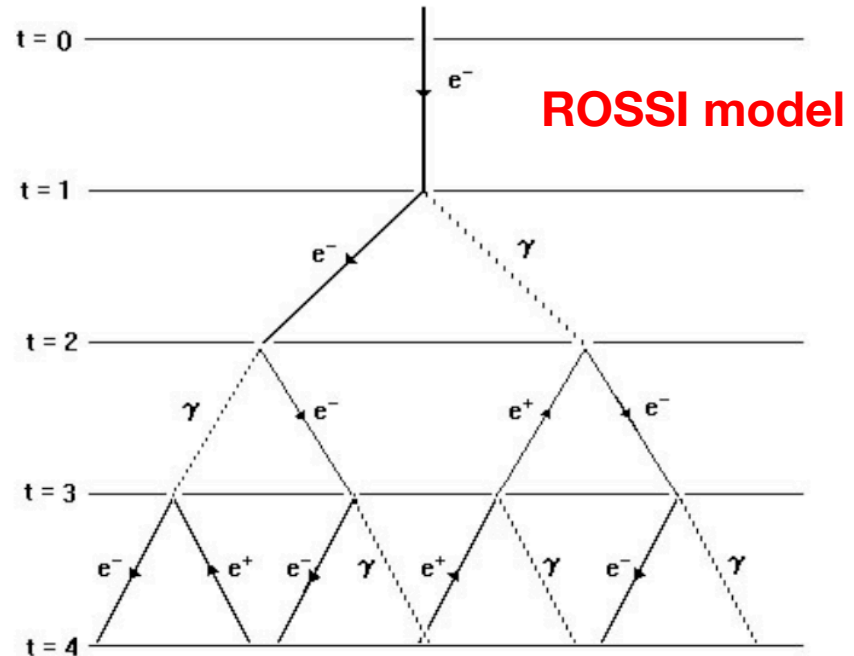
- Questi processi avvengono a distanza di $1 X_0$

- In ogni processo $E = E_i / 2$

Alla distanza X abbiamo n processi avvenuti con:

- $n = X/X_0$
- $E_s = E_0/2^n$
- $N_s = 2^n$

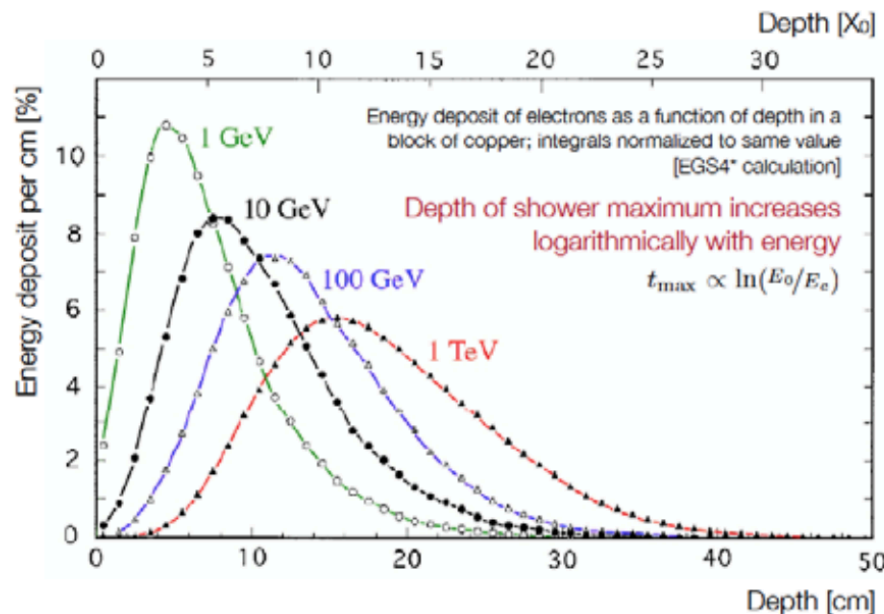
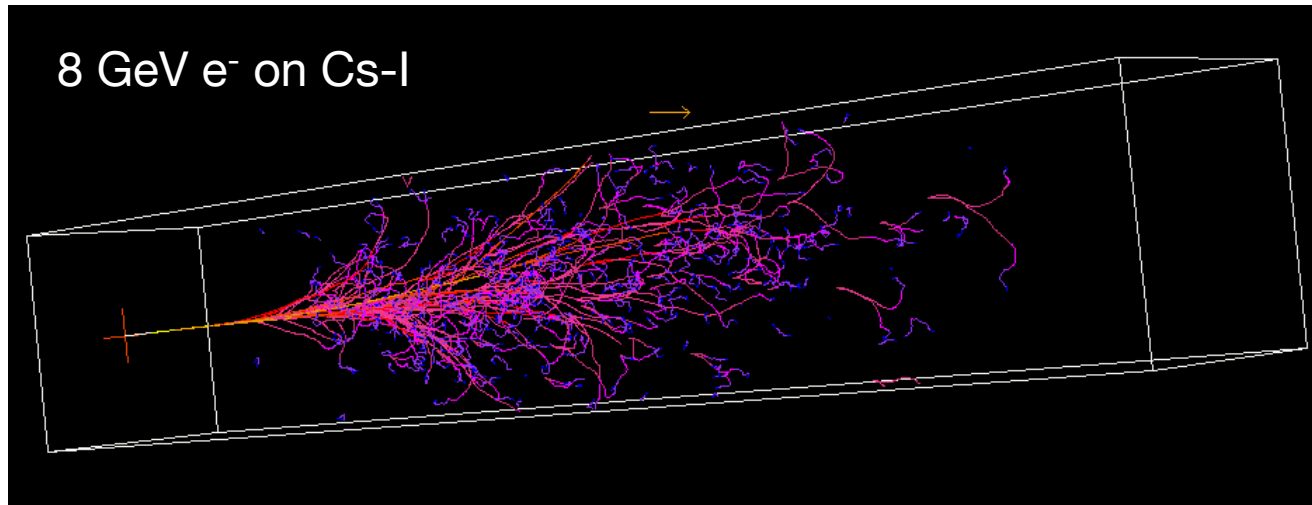
La valanga si ferma ad $E_s = E_c$



Il massimo dello sciame si ottiene ad $L_{\max} = \ln(E_0/E_c) / \ln 2$

Lo sciame procede poi con processi dissipativi tipo ionizzazione, effetto Compton o fotoelettrico. Si forma così la coda dello sciame

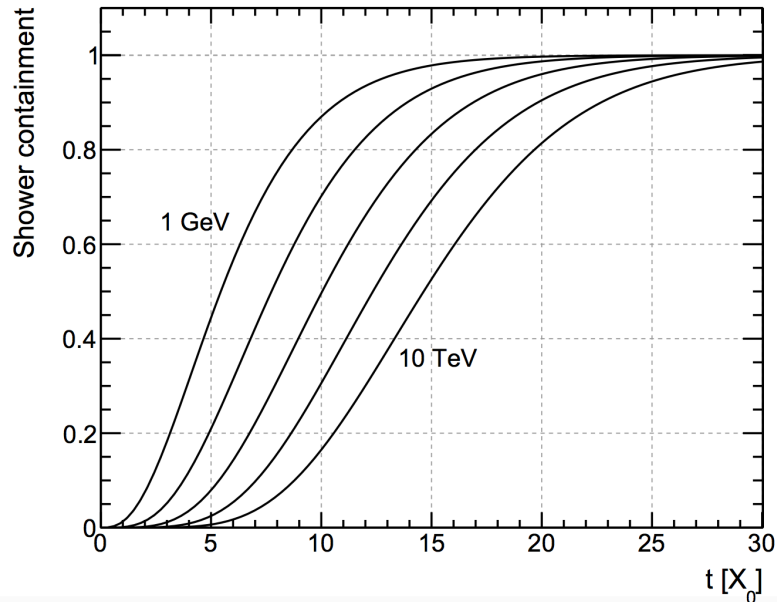
Electromagnetic showers



- Shower depth described by the material interaction length X_0
- **Increases logarithmically**
- At least $10 X_0$ to absorb low energy showers
- Lateral width independent on energy. 95% of energy deposit contained in cylinder with **Molière radius**

$$R_M = 21 \text{ MeV} \cdot X_0 / E_C$$

Electromagnetic showers



Material	X_0 [g cm ⁻²]	ρ [g cm ⁻³]	X_0 [cm]
Pb	6.37	11.350	0.561
BGO	7.97	7.130	1.12
CsI	8.39	4.510	1.86
W	6.76	19.3	0.350
C (graphite)	42.70	2.210	19.3
Si	21.82	2.329	9.37
Air	36.62	1.2×10^{-3}	30,500

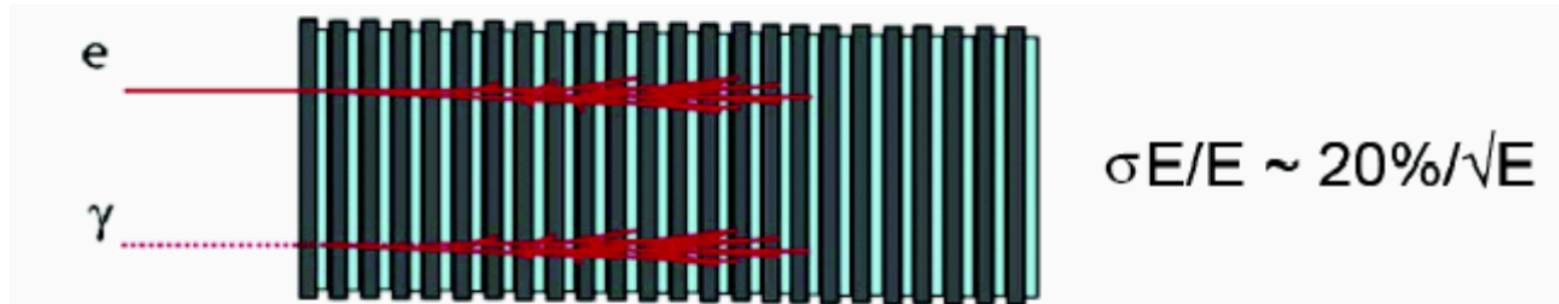
Space calorimeters must be compact and thick (in terms of X_0)

Two solutions:

- Homogeneous calorimeters (BGO, PWO,)
- Sampling calorimeters: passive material + active materials. Energy is sampled only in the active layers (silicon, gas, fibers, ...)

Electromagnetic showers

Calorimetro a 'sandwich' scintillatore/piombo



Calorimetro a cristalli omogenei



la misura di energia è un processo **distruittivo**:
dopo la misura calorimetrica la particella iniziale non esiste più

Electromagnetic showers

Energy resolution of a calorimeter can be parametrised as

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c \quad \oplus \text{ means quadratic sum}$$

- **a** the **stochastic term** accounts for any kind of Poisson-like fluctuations
 - natural merit of homogeneous calorimeters
 - several contributions add to the “intrinsic one”
- **b** the **noise term** responsible for degradation of low energy resolution
 - mainly the energy equivalent of the electronic noise
 - contribution from pileup: the fluctuation of energy entering the measurement area from sources other than the primary particle
- **c** the **constant term** dominates at high energy
 - its relevance is strictly connected to the small value of **a**
 - it is mostly dominated by the stability of calibration
 - contributions from energy leakage, non uniformity of signal generation and/or collection, loss of energy in dead materials,...

Calorimetry

I calorimetri si suddividono ulteriormente in:

- Calorimetri omogenei:

- Rivelatore = assorbitore
- Buona risoluzione in energia ($\sim 1-2\%$)
- Risoluzione spaziale limitata nella direzione longitudinale
- Usati solo per calorimetria e.m.
- alto costo e danneggiabili dalle radiazioni

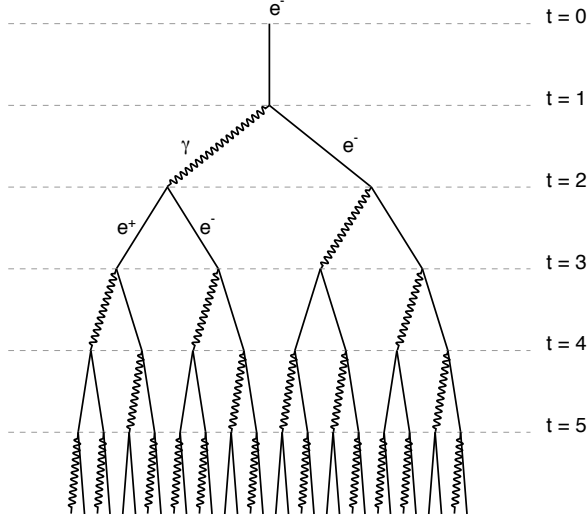
- Calorimetri a campionamento:

- Rivelatore ed assorbitore separati → solo parte dell'energia viene misurata
- Risoluzione in energia limitata
- Buona risoluzione spaziale nella direzione longitudinale
- Usati sia per calorimetria adronica che e.m.

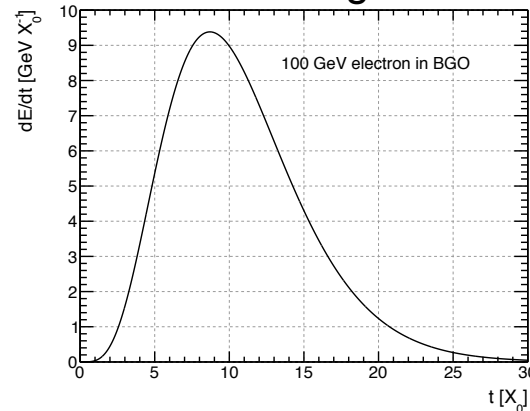
Calorimetry

Calorimeters

Simple electromagnetic shower profile



- Calorimeters measures the energy releases of the particle
 - Homogeneous / Sampling
 - Electromagnetic / Hadronic



$$\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

- The energy resolution improves as the energy increases

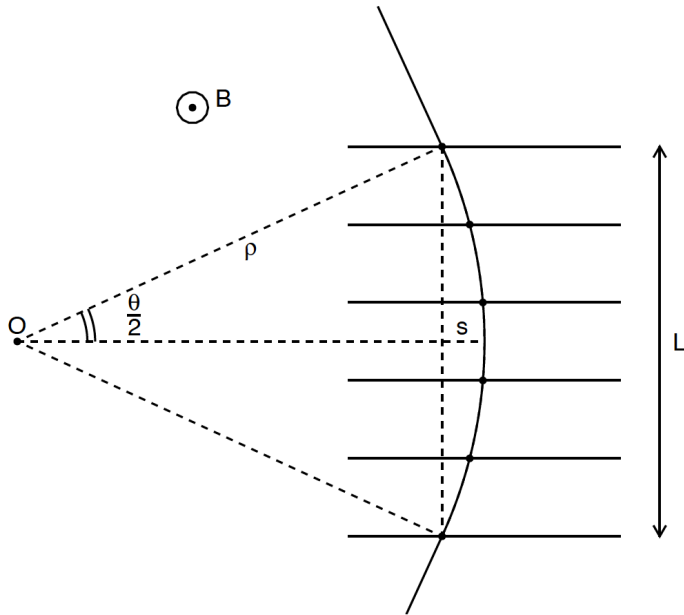
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

↑ Statistical fluctuations ↑ Inhomogenities, calibration, energy leaks, ...
↑ Electronics

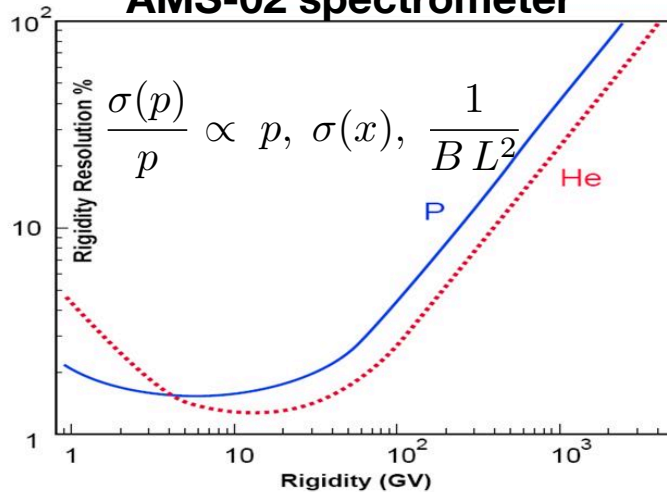
- BUT: energy resolution is not everything. Typically the dominant systematic is the knowledge of the energy scale!!
 - Resolution $\rightarrow$ Symmetric smearing of measured energy
 - Energy scale $\rightarrow$ Systematic shift of measured energy

Energy measurements

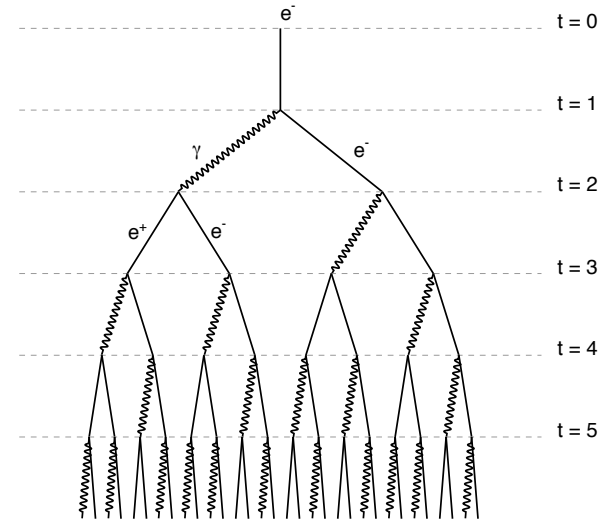
Magnetic Spectrometers



AMS-02 spectrometer



Calorimeters



AMS-02 electromagnetic calorimeter

