Interaction of particles with matter

- Energy loss
  - Bethe-Bloch formula
  - fluctuations
  - energy loss by radiation – radiation length
  - energy loss by strong interactions – interaction length

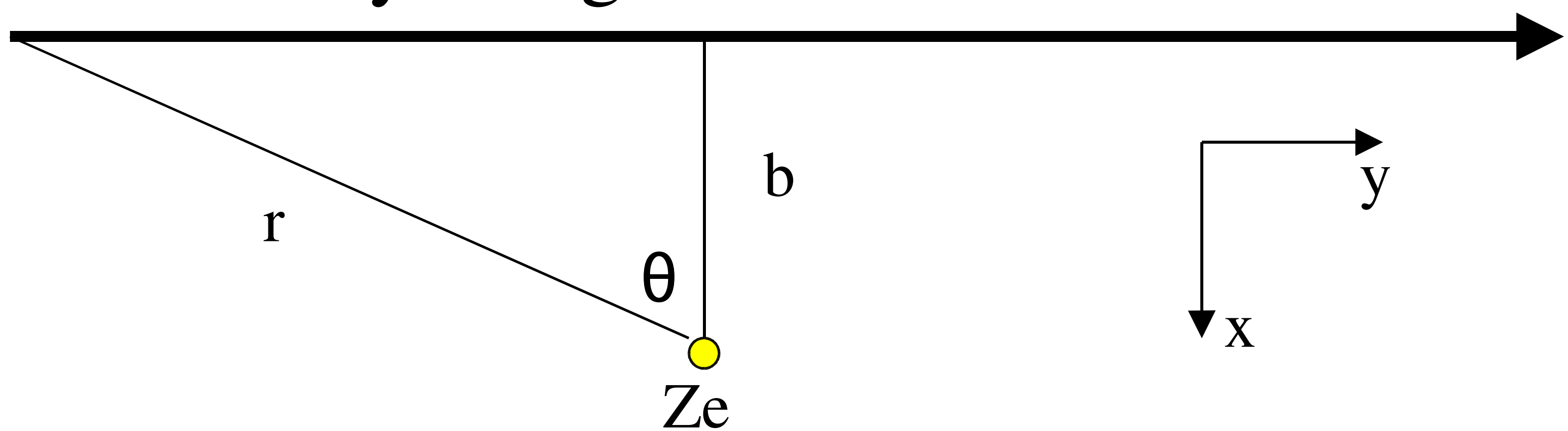
- Detectors for particles
  - Geiger-Mueller and proportional chambers
  - MWPC's and TPC's
  - Si detectors
  - calorimeters
  - Cerenkov and transition radiation detectors

Bethe-Bloch formula

- Describes how heavy charged particles ($m>>m_e$) loose energy when travelling through material
- Exact theoretical treatment difficult because of necessity to treat
  - Atomic excitations
  - Screening
  - Bulk material effects such as index of refraction and density of the material

Momentum transfer to target

- Consider particle of charge ze, passing a stationary charge Ze



- Compute momentum and energy transferred to target

non-relativistic approximation

- Force on projectile

$$F_x = \frac{Zze^2}{r^2}\cos\theta = \frac{Zze^2}{b^2}\cos^3\theta$$

- transfer of momentum to target

$$\Delta p = \int_{-\infty}^{\infty} dt\, F_x = \frac{2\,Zze^2}{\beta\, b}$$

- transfer of energy

$$\Delta E = \frac{\Delta p^2}{2\,M} = \frac{(2\,Zze^2)^2}{2\,M\,\beta^2 b^2}$$

example

- Consider α-particle traversing a sheet of material
  - Mass of nucleus: $M=A*m_p$
  - Mass of electron: $M=m_e$
- energy transfer in general

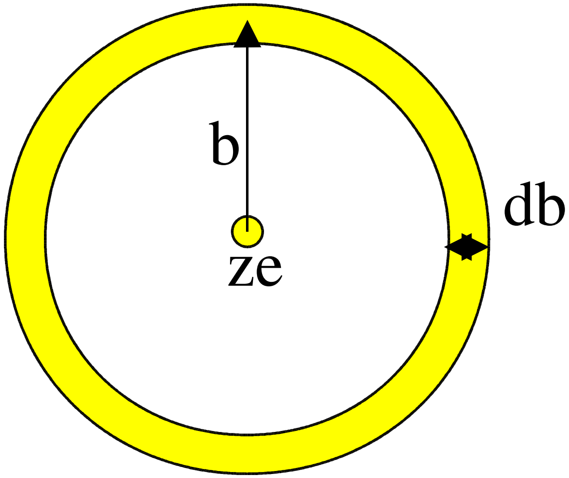
$$\Delta E = \frac{\Delta p^2}{2M} = \frac{(2Zze^2)^2}{2M\beta^2 b^2} \propto \frac{Z^2}{M}$$

- energy transfer to an electron

$$E_e(b) = \Delta E = \frac{2z^2e^4}{m_e\beta^2 b^2}$$

summing up of impact parameters

- Energy transfer is determined by impact parameter b
- Integration over all impact parameters



$$\frac{dn}{db} = 2\pi b \times \left(number\, of\, electrons\, per\, unit\, area \right)$$

$$= 2\pi b \times Z \frac{N_A}{A} \rho \Delta x$$

Average over impact parameters

- average energy loss

$$\overline{\Delta E} = \int_{b_{min}}^{b_{max}} db \frac{dn}{db} E_e(b) = 2C \frac{m_e}{\beta^2} \frac{Zz^2}{A} \rho \Delta x \left[\ln b \right]_{b_{min}}^{b_{max}}$$

$$= C \frac{m_e}{\beta^2} \frac{Zz^2}{A} \rho \Delta x \left[\ln E \right]_{E_{min}}^{E_{max}}$$

with $C = 2\pi N_A \left(\frac{e^2}{m_e} \right)^2$

- logarithmic divergence
- limits for E_{min} from electron binding and E_{max} from kinematics

estimates:

- approximations for integration limits
  - From relativistic kinematics

$$E_{max} = \frac{2\gamma^2\beta^2 m_e}{1+2\gamma\frac{m_e}{M}+\left(\frac{m_e}{M}\right)^2} \approx 2\gamma^2\beta^2 m_e$$

  - Inelastic collision

$$E_{\min} = I_0 \equiv \text{ average ionisation energy}$$

- result:

$$\frac{\overline{\Delta E}}{\Delta x} \approx 2C\frac{m_e}{\beta^2}\frac{Zz^2}{A}\rho\ln\left(\frac{2\gamma^2\beta^2 m_e}{I_0}\right)$$

relativistically correct formula

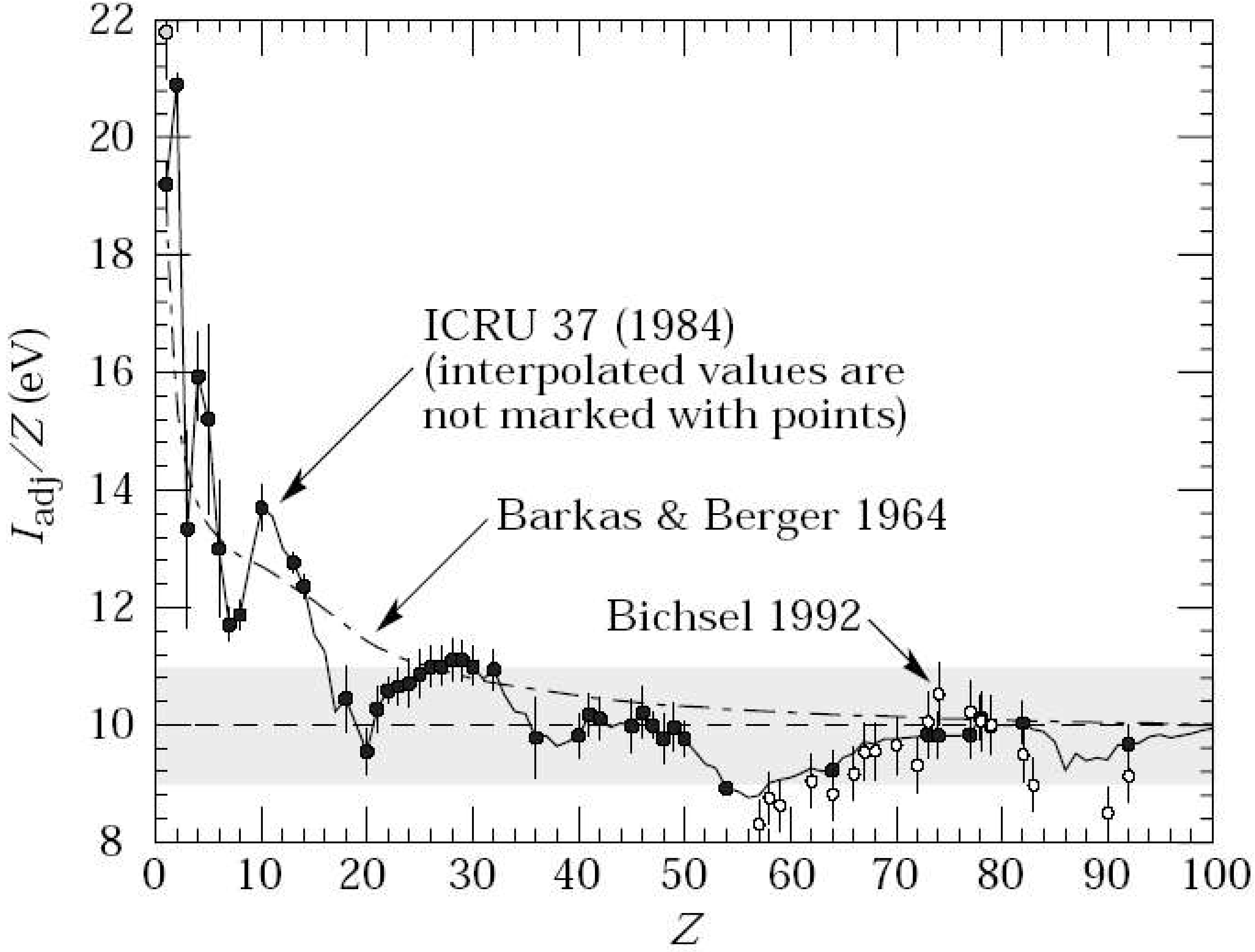
- valid also at high energies, including:
  - Fermi density plateau
  - screening of tightly bound electrons
- result:

$$\frac{\overline{\Delta E}}{\Delta x} \approx 2C \frac{m_e}{\beta^2} \frac{Zz^2}{A} \rho \left[\frac{1}{2} \ln\left(\frac{2\gamma^2 \beta^2 m_e E_{max}}{I_0^2} \right) - \beta^2 - \frac{\varepsilon}{2} - \frac{\delta(\beta)}{2} \right]$$

with

- ε screening correction of inner electrons
- δ density correction, because of polarisation in medium

Average Ionisation Energy



Fermi density effect

- depends on polarizability of material
- parameters:

$$\delta = \begin{cases} 2(\ln 10)x - \overline{C} & \text{if } x \geq x_1; \\ 2(\ln 10)x - \overline{C} + a(x_1 - x)^k & \text{if } x_0 \leq x < x_1; \\ 0 & \text{if } x < x_0 \text{ (nonconductors)}; \\ \delta_0 10^{2(x-x_0)} & \text{if } x < x_0 \text{ (conductors)} \end{cases}$$

- with
  - $x = \log_{10}(p/M)$
  - C, δ_0, x_0 material dependent constants

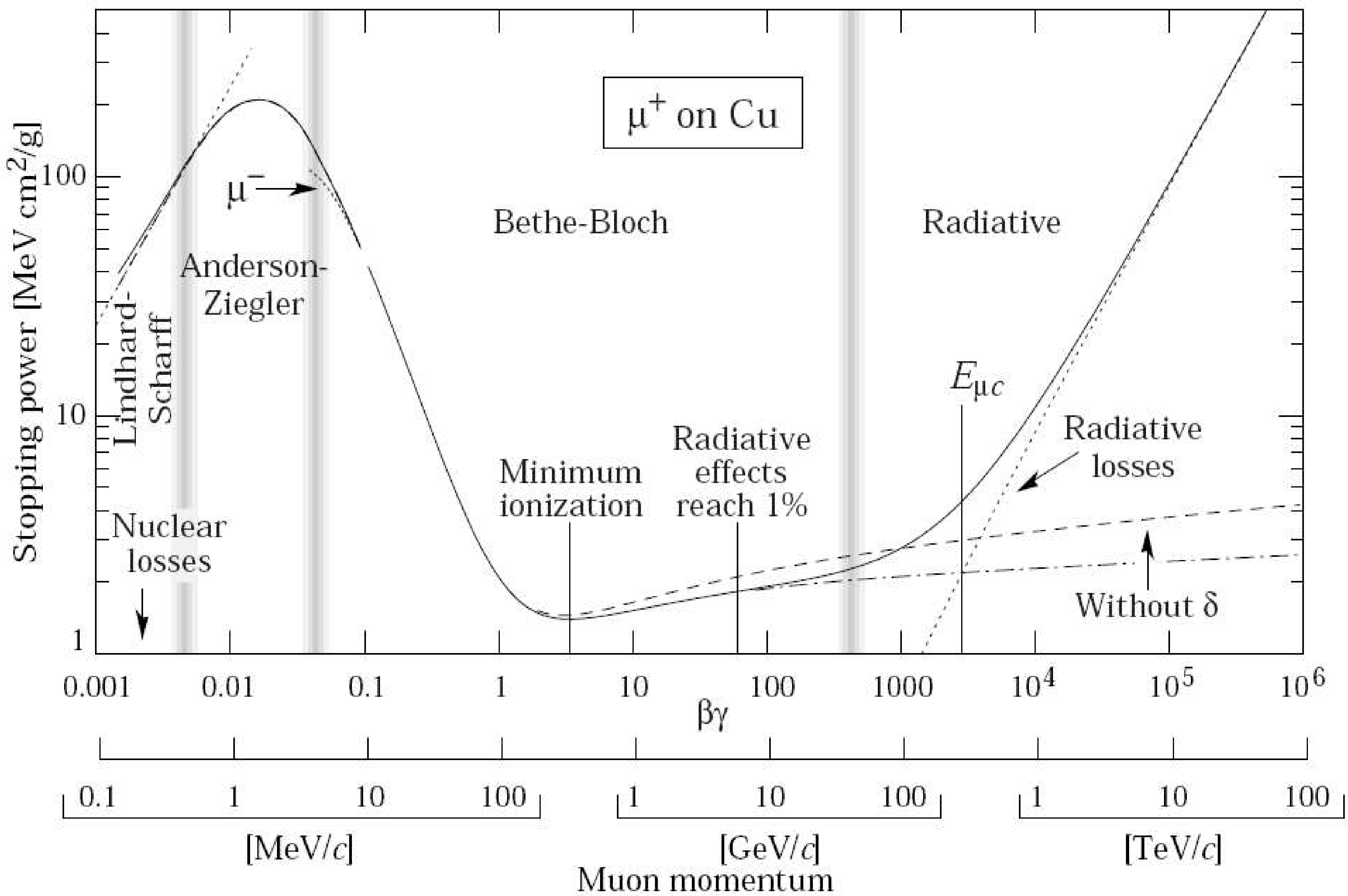
The key people

Hans Bethe

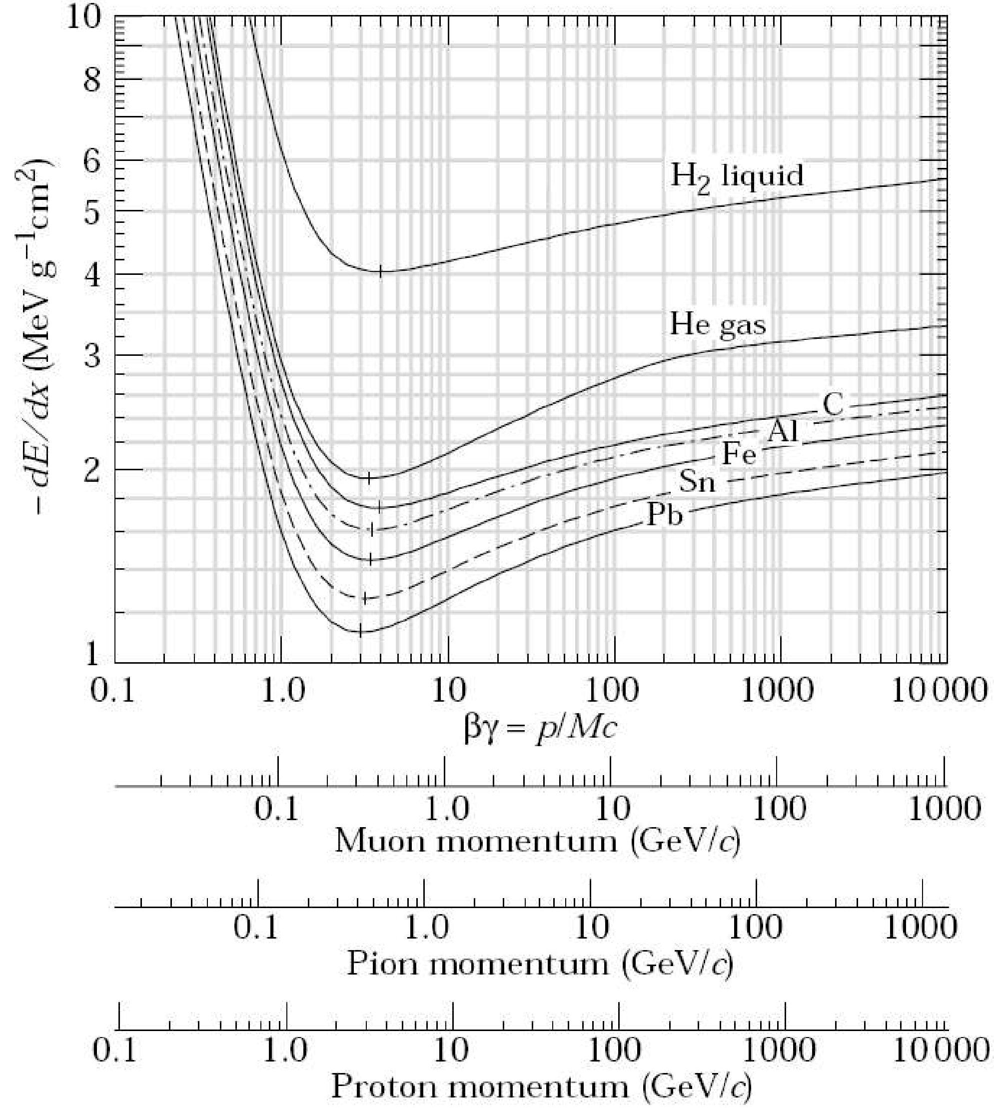
Felix Bloch

Enrico Fermi

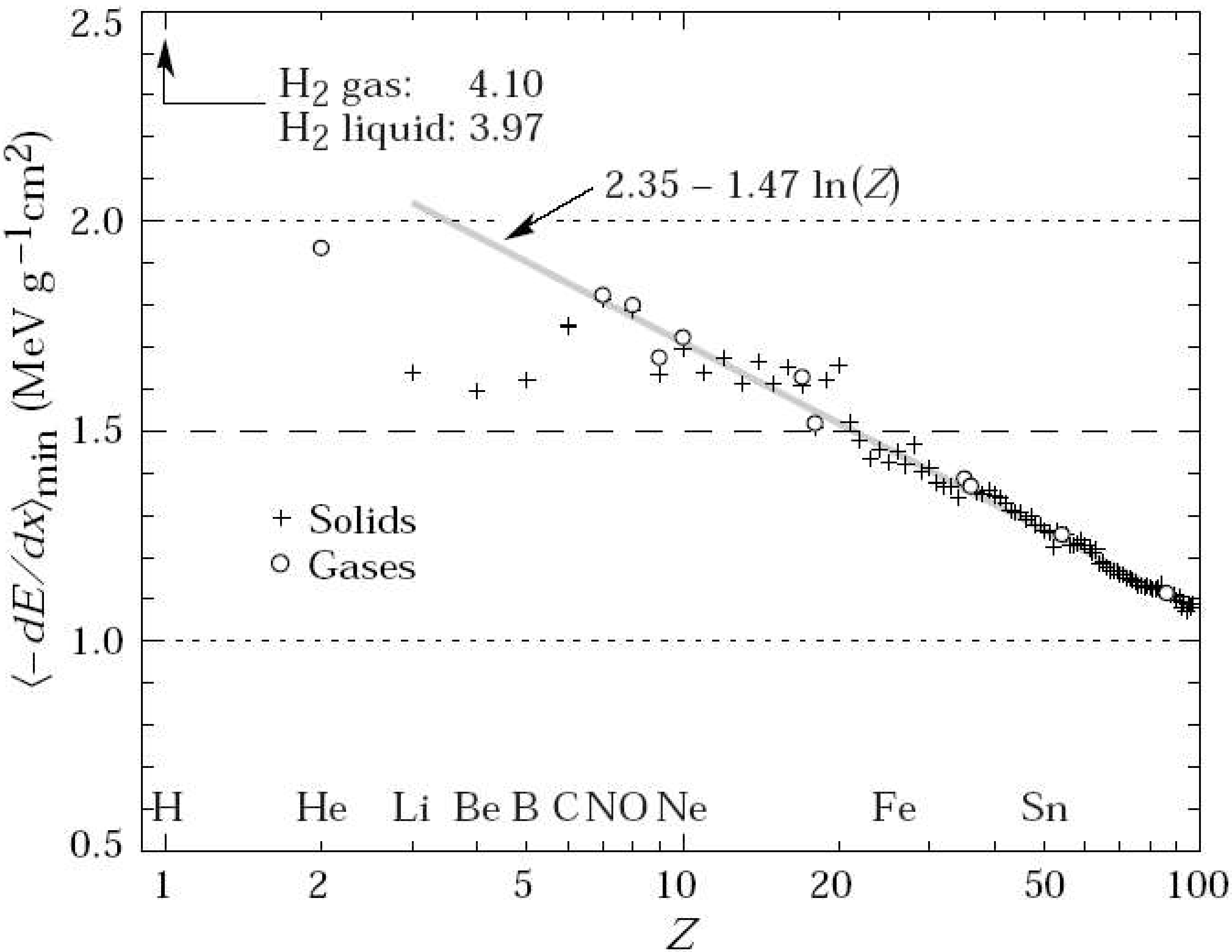
energy loss of muons in matter



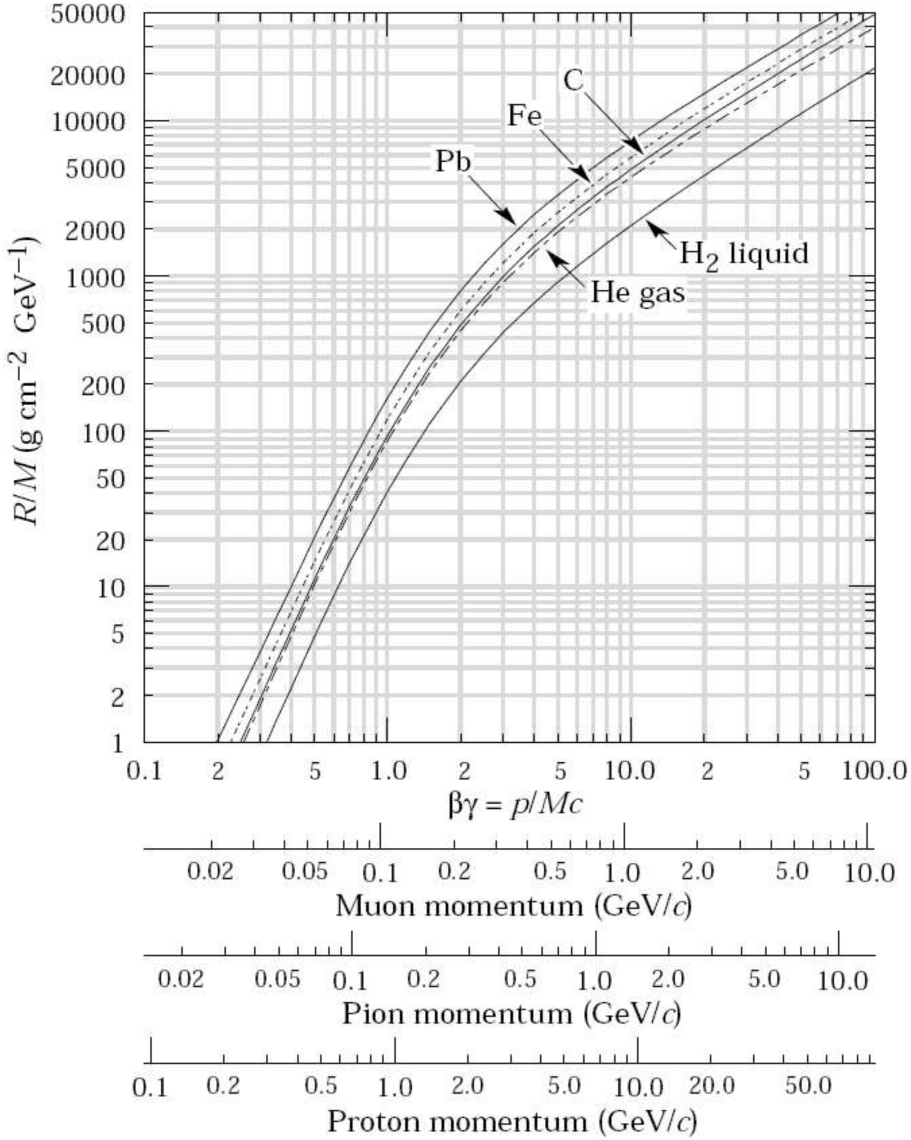
energy loss of protons, pions and muons



Dependence of min. ion. value on material



Range for protons, pions, and muons



Electrons and Positrons

- Electrons are different ➔ not only ionization
  - Bremsstrahlung
  - Pair production