Queen Mary
University of London
Science and Engineering

Radiation Detectors (SPA 6309)

Lecture 2

Last revised 22January 2020

What is this lecture about?

- The principles of detection of ionising radiation
  - Interaction of charged and neutral particles with matter
  - Gaseous sensors
  - Semiconductor sensors
  - Scintillators
- Sensor systems used in particle and nuclear physics
  - Calorimeters
  - Tracking detectors
  - Neutrino detectors

Definition

Cross-section

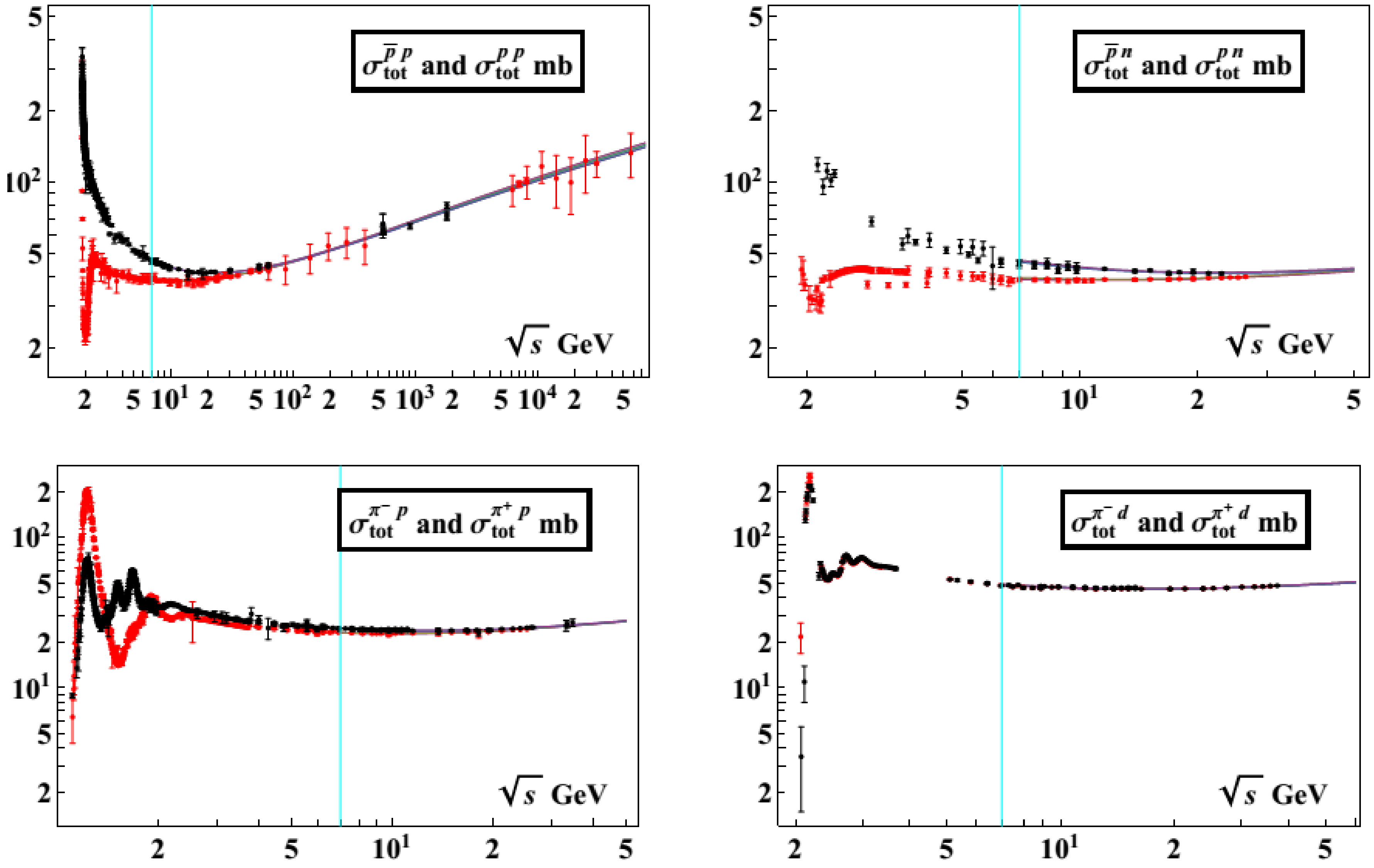
- Measures the probability of an interaction
- Assume that on average N_s particles are scattered per unit time from a beam (of flux F) into an element of solid angle $d\Omega$

$$\frac{d\sigma}{d\Omega}(E,\Omega)=\frac{dN_S}{F d\Omega}$$

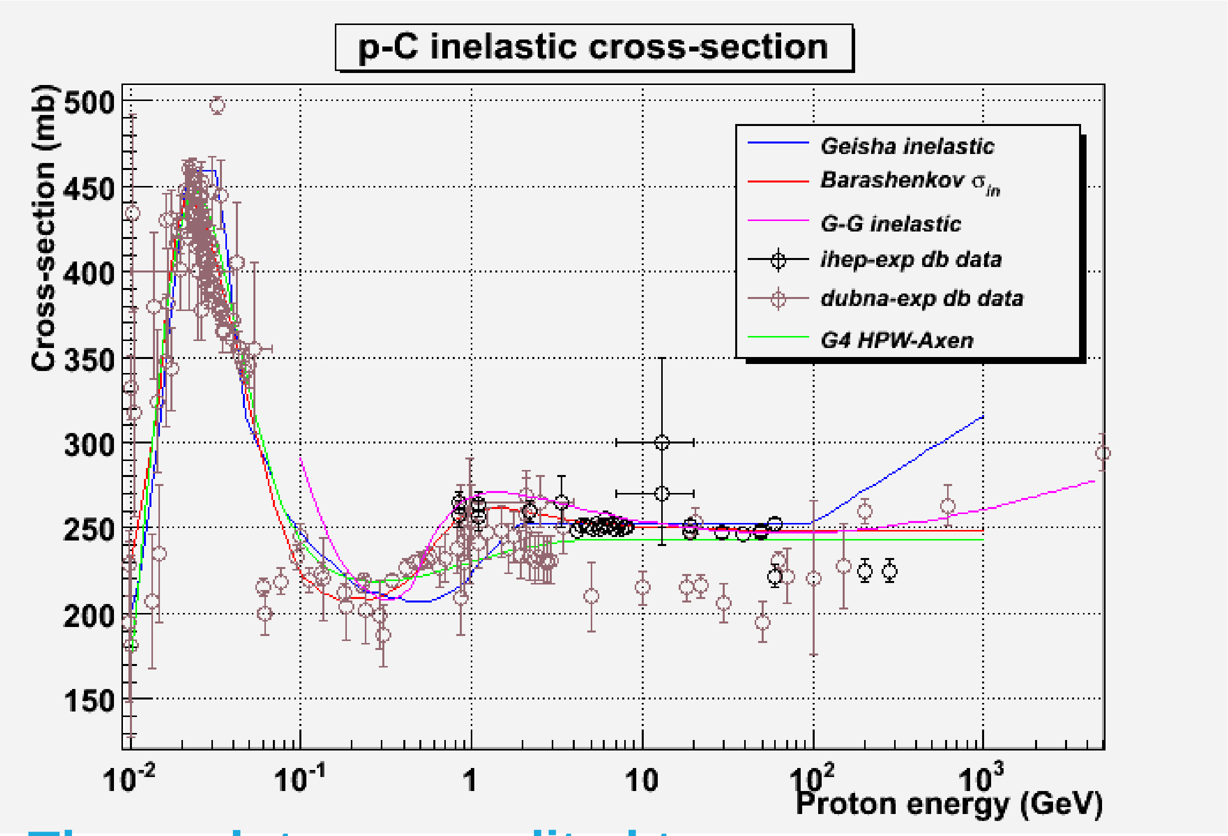
For a thin target of area A (less than the beam area), the total number scattered into all angles is

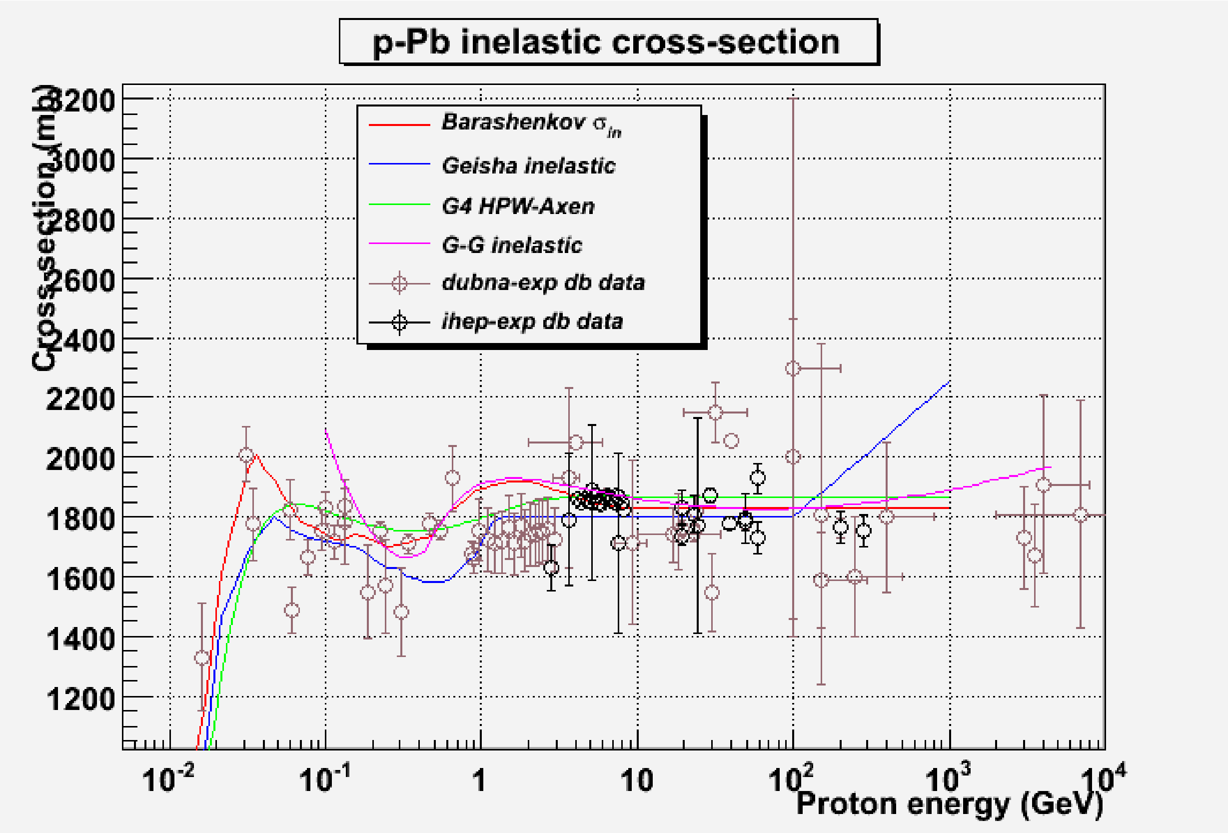
$$N_{tot} = FAN\delta x\sigma$$

p, n and pion


$\sigma_{tot}^{\bar{p}p}$ and σ_{tot}^{pp} mb
$\sqrt{s}$ GeV
$\sigma_{tot}^{\bar{p}n}$ and σ_{tot}^{pn} mb
$\sqrt{s}$ GeV
$\sigma_{tot}^{\pi^- p}$ and $\sigma_{tot}^{\pi^+ p}$ mb
$\sqrt{s}$ GeV
$\sigma_{tot}^{\pi^- d}$ and $\sigma_{tot}^{\pi^+ d}$ mb
$\sqrt{s}$ GeV

Nuclear





These plots are credited to:
http://geant4.web.cern.ch/geant4/results/validation_plots/cross_sections/hadronic/inelastic/test1/inelastic.shtml

Energy Loss

Heavy Charged Particles

- Protons, alphas, pions, muons …
  - Loss of energy
  - Change of trajectory
- Main processes
  - Inelastic atomic collisions ($\sigma \cong 10^{-16}$ cm^{-2})
  - Elastic scattering from nuclei
- Other processes
  - Cherenkov, nuclear, bremsstrahlung

dE/dx

Stopping Power (or *dE/dx*)

Classical calculation of Bohr (insight) then more complete QM treatment of Bethe, Bloch et al.

Bohr's assumptions:

- A particle of charge *ze* interacts with a free electron at rest
- No deviation of particle trajectory (e.g. really is massive)
- Impulse assumption (short time period)

$$I = \int F dt = e\int E_{perp} \frac{dt}{dx} dx = e\int E_{perp} \frac{dx}{v}$$

Simple model (insight)

Eq. 1 $$\Delta p = \int_{-\infty}^{\infty} e\overline{E}(t)\,dt = \frac{2Z_1 e^2}{bv}$$

where $\overline{E}$ is the transverse electrical field. The energy transferred is then:

Eq. 2 $$\Delta E = \frac{(\Delta p)^2}{2m} = \frac{2{Z_1}^2 e^4}{mv^2}\left(\frac{1}{b^2}\right)$$

From Zegler JF, *J.Appl.Phys* **85** (1999) 1249

Bethe Bloch formula

To calculate the total energy loss integrate over some range of impact parameters that *do not* violate the initial assumptions. One can get a reasonably useful formula (and one that is more or less relativistically correct by this procedure) however it doesn't work well for particles lighter than the alpha.

The proper solution is due to Bethe et al, and the energy transfer is parameterised in terms of momentum transfer rather than impact parameter. There is a detailed review of all the many corrections and refinements to the original formula of Bethe & Bloch available at:
http://www.srim.org/SRIM/SRIMPICS/THEORYCOMPONENTS.htm

srim.org/SRIM/History/HISTORY.htm

What does it mean?

“Bethe-Bloch” Formula

$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2}\left[\ln\left(\frac{2m_e\gamma^2 v^2 W_{\max}}{I^2}\right) - 2\beta^2 - \text{corrections}\right]$$

where the correction terms are :

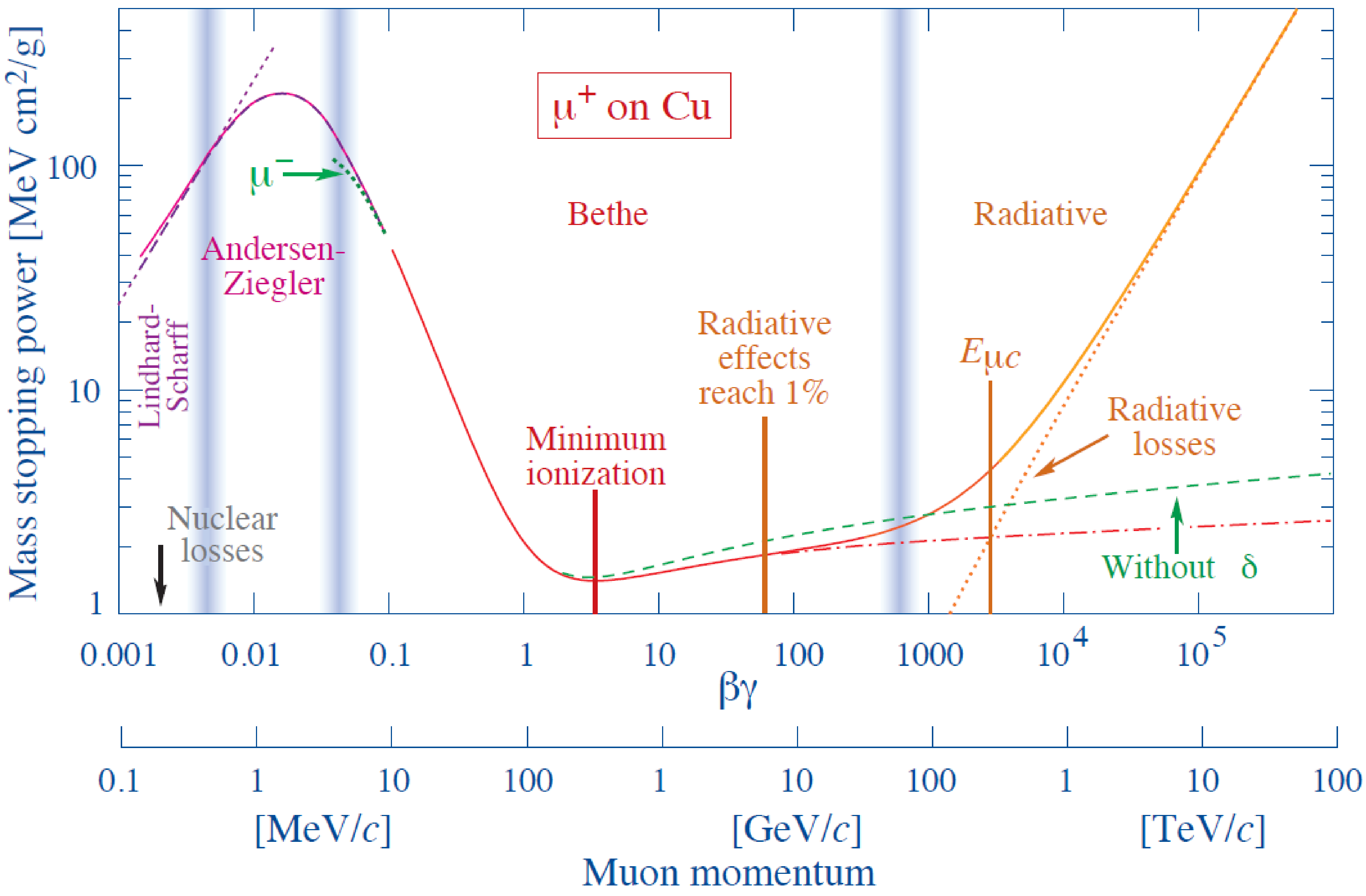
δ the density effect correction and

$2\frac{C}{Z}$ due the shell correction C

Maximum energy transfer in a single collision ($W_{\max}$)

Mean excitation potential (I)

Details



μ+ on Cu
Mass stopping power [MeV cm2/g]
100
10
1
Lindhard-Scharff
Andersen-Ziegler
μ−
Bethe
Radiative
Radiative effects reach 1%
Eμc
Radiative losses
Minimum ionization
Nuclear losses
Without δ
0.001
0.01
0.1
1
10
100
1000
10^4
10^5
βγ
0.1
1
10
100
1
10
100
1
10
100
[MeV/c]
[GeV/c]
[TeV/c]
Muon momentum

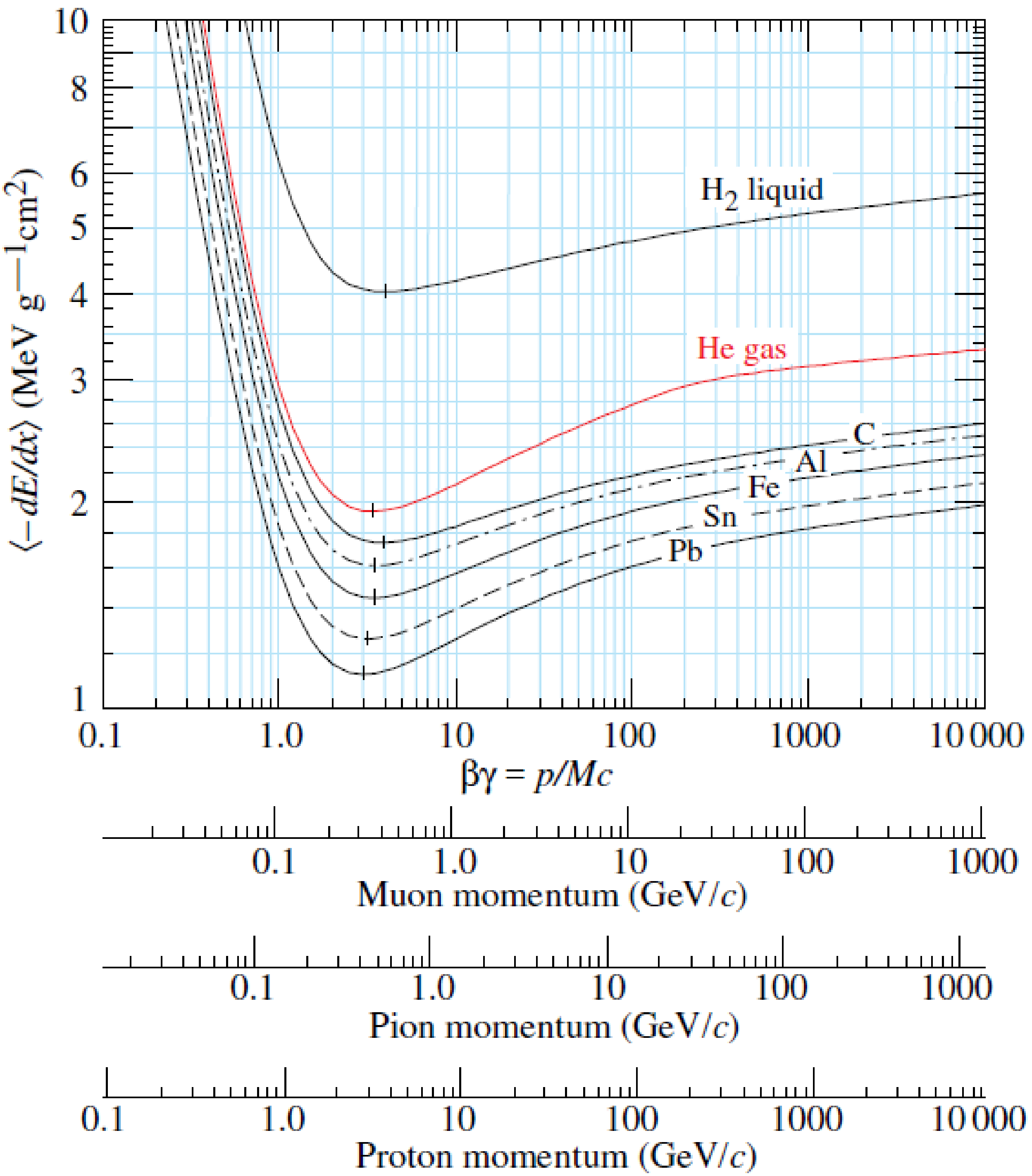
Very important approximation

Re-writing the formula in terms of "mass thickness" (ρt) we find that :

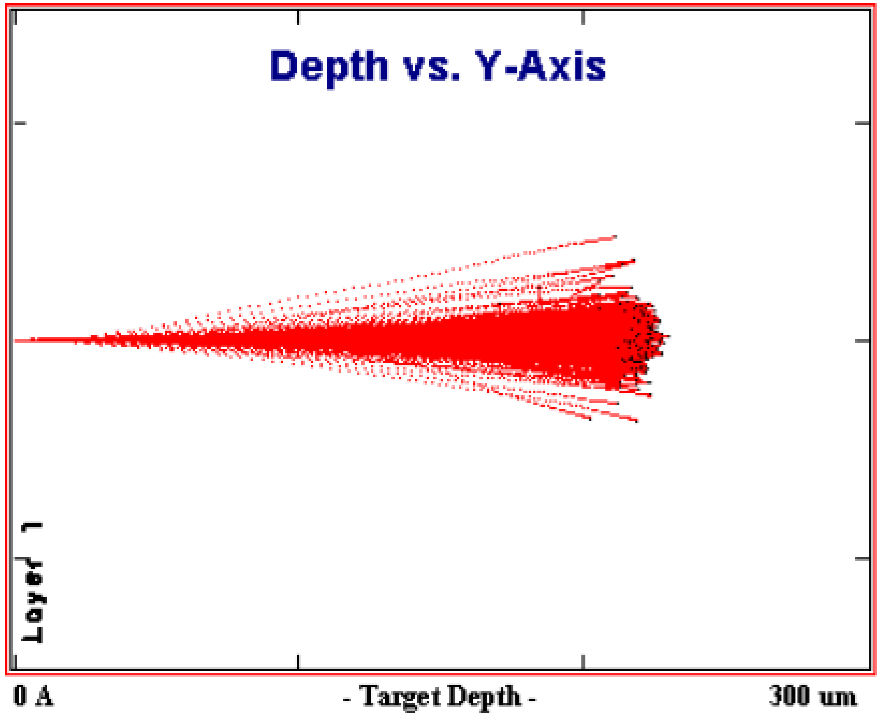
$$-\frac{dE}{\rho dx} = z^2 \frac{Z}{A} f(\beta, I)$$

Z/*A* doesn't vary much, and the dependence on *I* comes in only logarithmically therefore the density normalised energy loss is almost independent of the material.

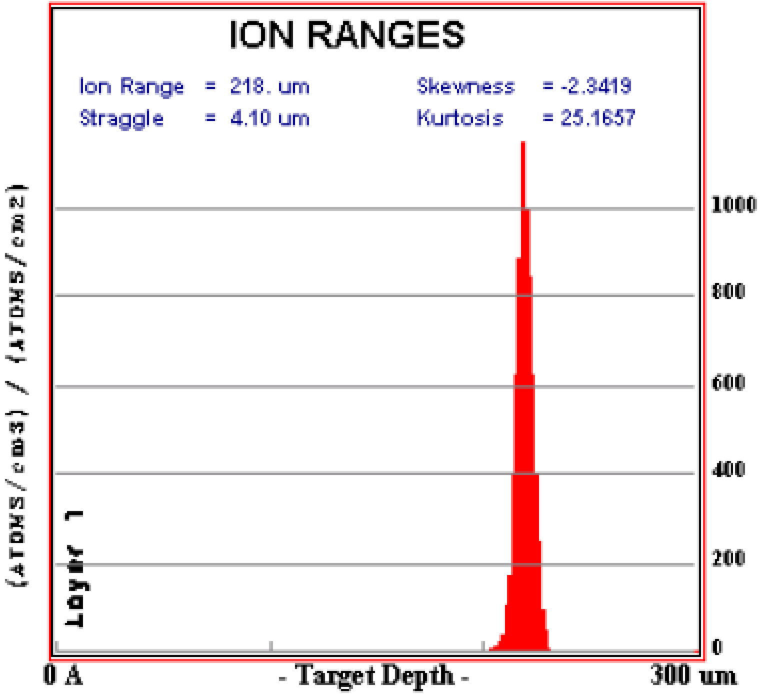
How good is it?



Particle Range

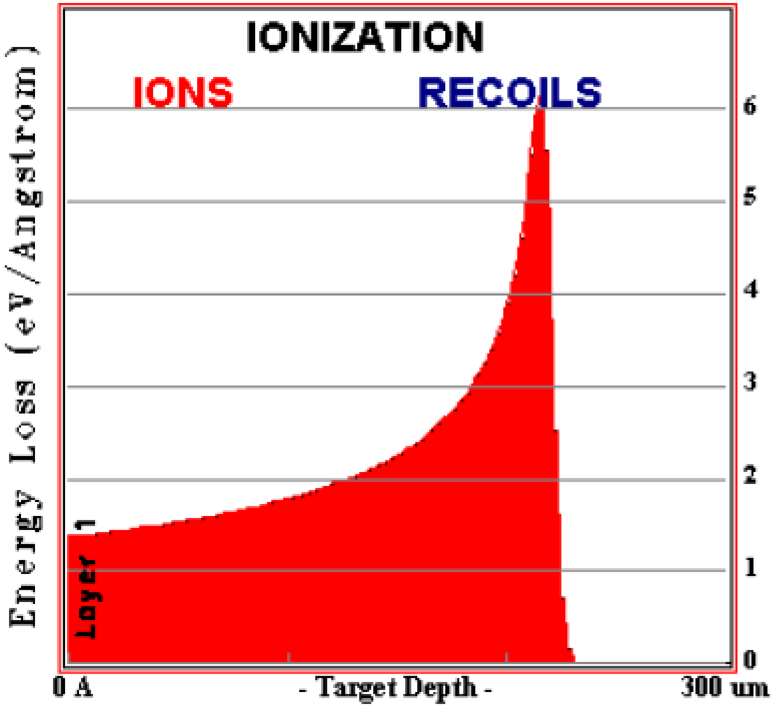


5 MeV proton into solid silicon

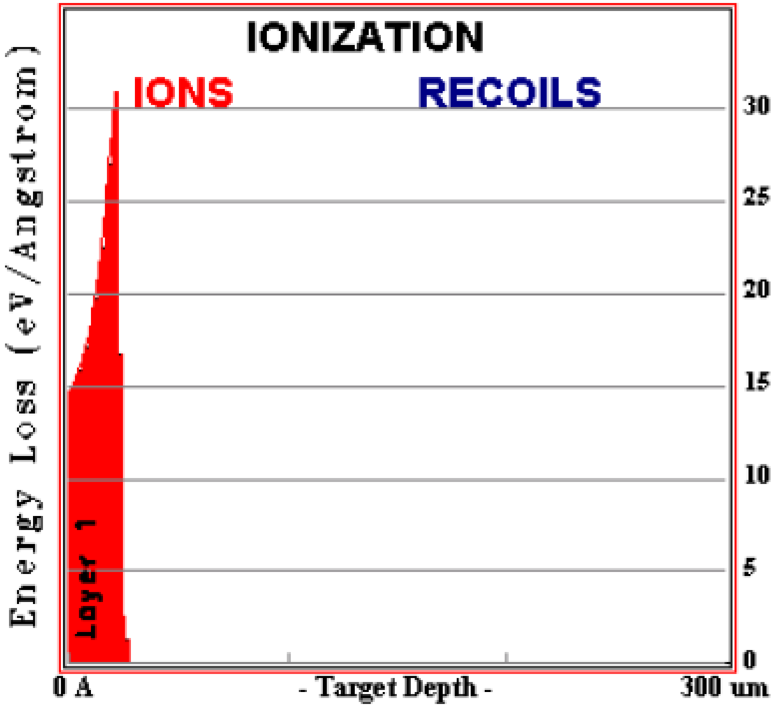


Monte Carlo simulation using SRIM code

Bragg "peak"



5 MeV proton into solid silicon



5 MeV alpha into solid silicon

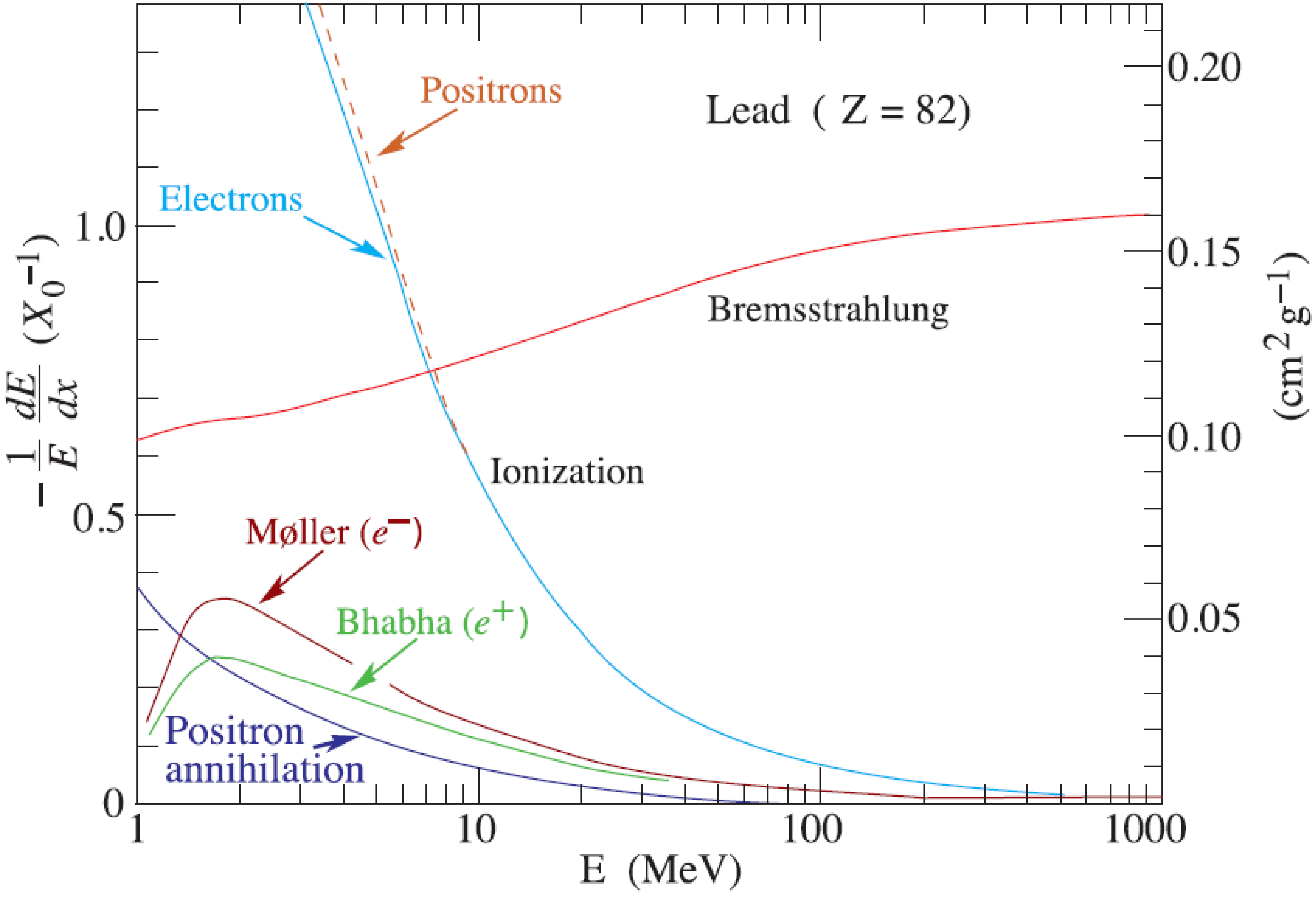
Electron energy loss: processes

For “low” energies (depends on critical energy see later slides) most energy lost is by IONISATION.

At “high” energy most energy (essentially all about 1 GeV) is by bremmstrahlung, the emission of a gamma ray.

At very low energies (less than ~ 10 MeV in Pb) then there are small contributions from scattering.

Electron energy loss plot



Critical Energy (important to help understand electromagnetic calorimeters)

- The *critical energy* is the energy at which radiative and ionisation/collisional losses are equal
- It depends strongly on the absorbing material
- For Pb it is 9.5 MeV, for Al it is 51 MeV and for polystyrene it is 109 MeV
- Approximately you can use (for solids):

$$E_c \cong \frac{610\ \text{MeV}}{Z + 1.24}$$

Radiation Length – a critical design parameter for calorimeters

A really useful practical resource for you is available here:

http://pdg.lbl.gov/2019/AtomicNuclearProperties/index.html

- The *radiation length* (X_0) is defined as the distance over which the electron energy is reduced by a factor of $1/e$ due to radiation losses only.
- Radiation loss is more or less independent of material when thickness is expressed in X_0
- Extremely useful concept for design of calorimeters