Radiation-Matter Interaction I

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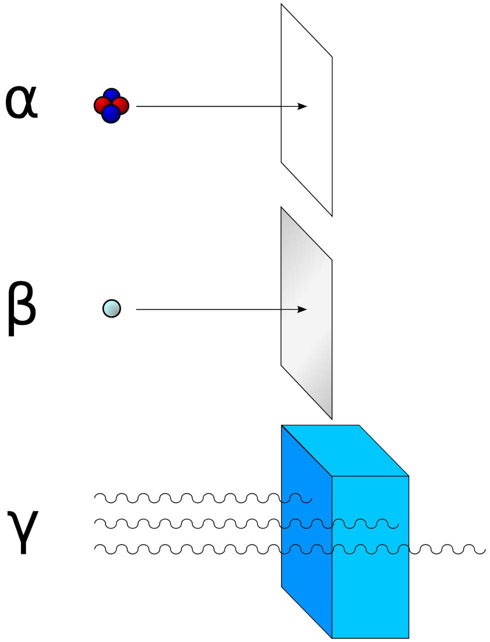
Radiation – matter interaction

__Radiation__:
(remember the wave-particle duality!)

- *EM radiation*
- *high energy particles*
- *microscopic scale*
- *usually relativistic*
- *even single particles*



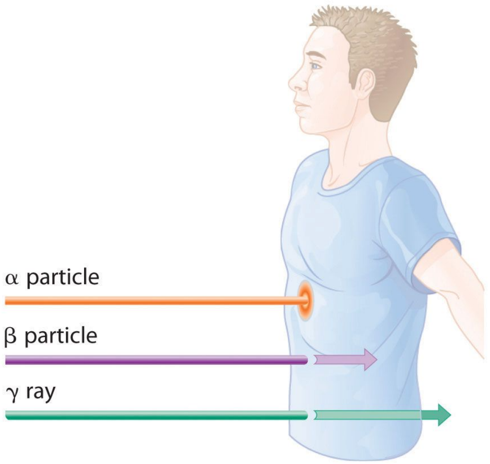
__Matter__:

- *atoms*
- *solid, liquid, gas…*
- *macroscopic scale*
- *non-relativistic*

- Useful to study, e.g.:

➜ effects of radiation to human body

➜ a way to detect high energy particles



Particles – matter interactions for particle detectors

- Processes at the base of **particle-detector** operations
- The **energy lost** by the particles is converted in **electrical signal** to ***measure*** the various observables (positions, energy, momentum…)
- Any observable is measured with a specific detector
- Different particles, different interactions
    - *Heavy charged particles*
    - *Electrons*
    - *Photons*

Interaction and effects diversity

- Interaction (energy loss, effects target) depend on:

Matter composition and structure

Radiation type and energy

Charged particles

Main phenomena

Energy loss

Anelastic collisions with electrons or atomic nuclei

Ionization

Bremsstrahlung

Negligible for heavy charged particles

Deflection

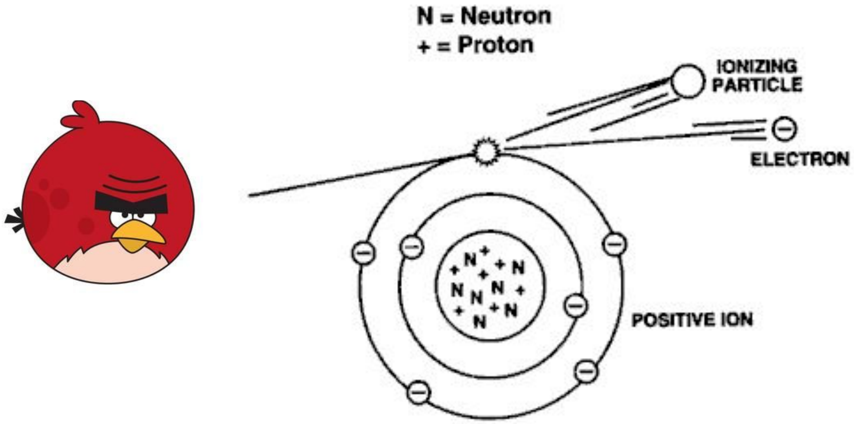
Elastic diffusion from nuclei

Coulombian multiple scattering

Other phenomena

Cherenkov emission, Transition radiation

Heavy charged particles energy loss: Ionization



If the following hypotheses are true

1. Mass M >> m_e
2. Atomic e^- free and in quiet
3. Small transferred momentum

One can evaluate

(-dE/dx) = average rate for the energy loss through ionization of a charged particle

Bohr (classical)

Bethe-Bloch (relativistic)

Bethe-Bloch formula

$$-\frac{dE}{dx} = 2\pi N_A r_e^2 m_e c^2 \rho \frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\frac{2m_e c^2\gamma^2\beta^2 W_{\max}}{I^2} - 2\beta^2 - \delta - 2\frac{C}{Z}\right]$$

Valid for $\beta > 0.1$

I = average ionization potential

Z, A, ρ = characteristics of the material

z, β, γ = characteristics of the incident particles

W_{max} = max energy transferred in one collision

r_e = classical radius of the electron

m_e = electron mass

$N_{\mathbf{a}}$ = Avogadro number

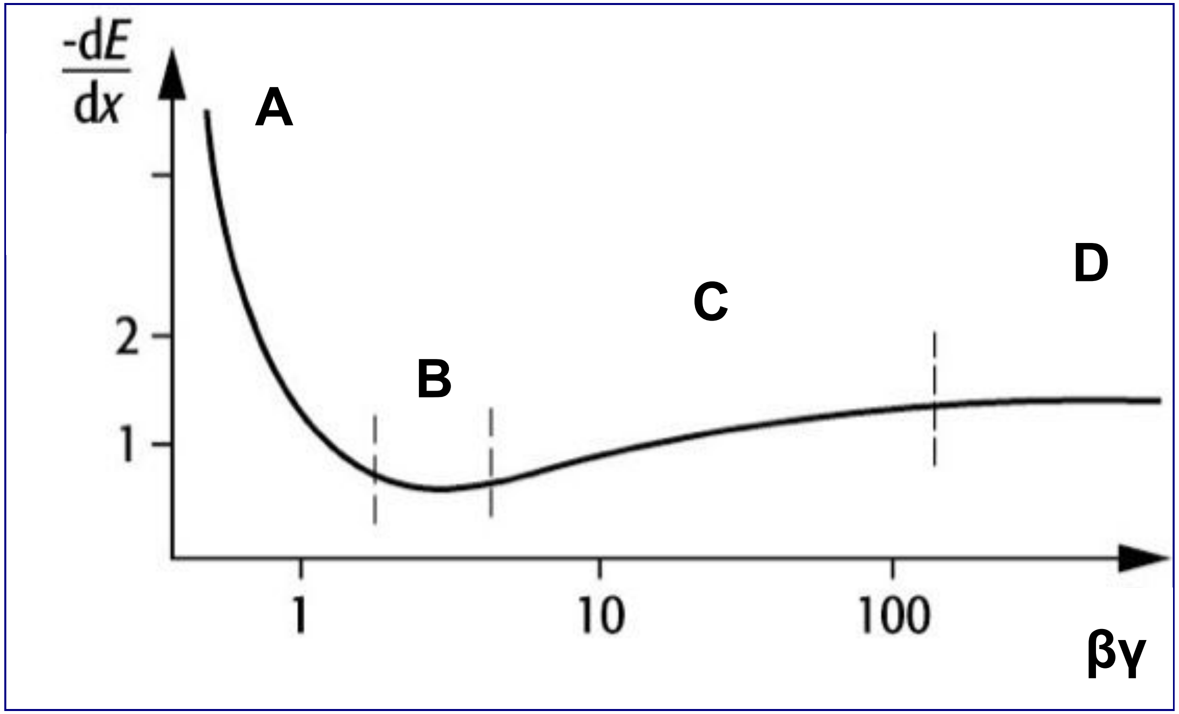
C = shell correction

δ = density effect

Bethe-Bloch formula - comments

$$-\frac{dE}{dx} = 2\pi N_A r_e^2 m_e c^2 \rho \frac{Z}{A}\frac{z^2}{\boxed{\beta^2}}\left[\ln\frac{2m_e c^2 \boxed{\gamma^2\beta^2} W_{\max}}{I^2} - \boxed{2\beta^2} - \delta - 2\frac{C}{Z}\right]$$

- **Zone A:** fast decrease proportional to 1/β²
- **Point B:** minimum of the energy loss
- **Zone C:** slow relativistic increase proportional to ln**γ**



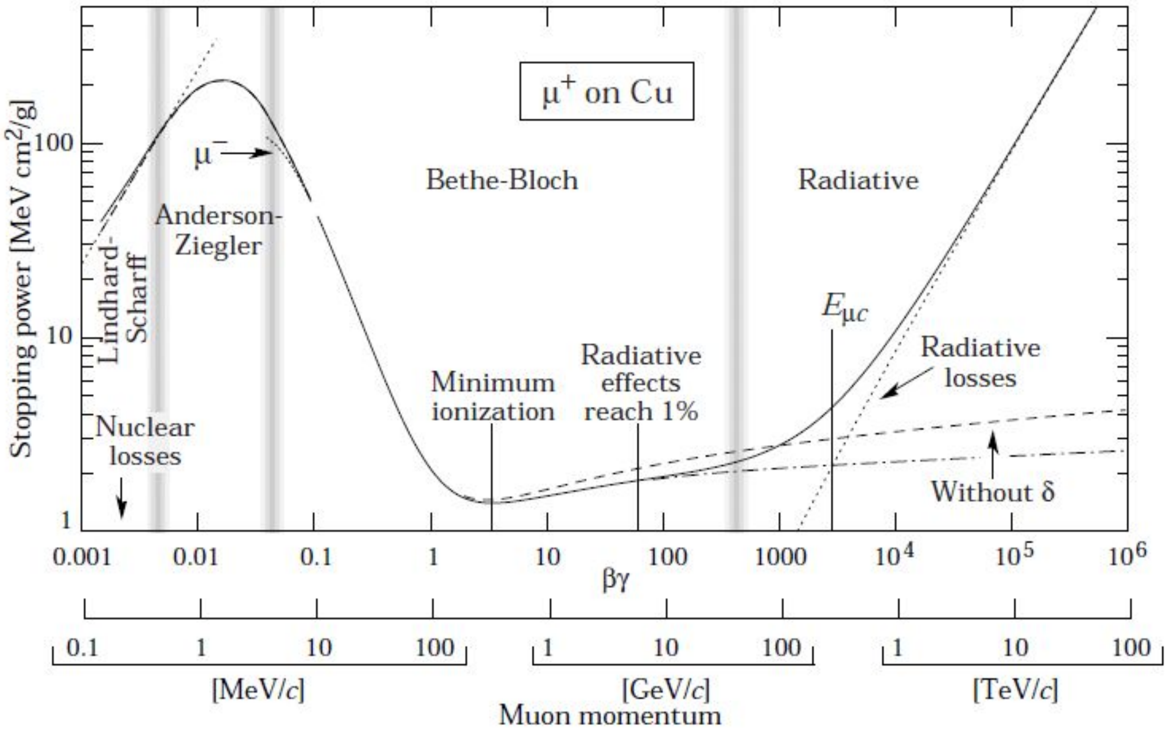
- **Zone D:** constant energy loss per unit length, ionization limited by *density effects*

Bethe-Bloch formula - comments

$(\rho/A)\ N_a =$
N (numerical atomic density)

-$(dE/dX) \sim ZN$

A ***dense*** *material and with* ***high atomic number*** *gains more energy from the incident particle*



The energy released does not depends on the mass of the incident particle

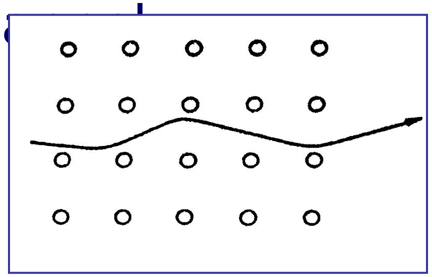
- A **fast** particle releases ***less energy***
- A particle with higher **charge**, releases ***more energy***

Bethe-Bloch formula - comments

- **Density effects** *(important at high energies):* atom polarization screens the electrical field for the electrons which are far away, so that the collisions with these electrons contribute less to the total energy loss

- **Shell corrections** *(important at low energies):* when particle velocity ~ orbital electron velocity ⇒ stationary-electron assumption not valid anymore

- **Channeling** in materials with a symmetric atomic structure:
  the energy loss is smaller if the particles move through a cha



This happens when the angle is smaller than a critical value

Bethe-Bloch formula - comments

Relativistic limit:
$v = 0.96\ c$

Ionization minimum:
$dE / dx \sim 2$ MeV cm^2/g

First part of the curve

- Small β and $\gamma \sim 1$
- Non-relativistic particle
  $E \sim mc^2 + mv^2 / 2$, $p = mv$
- The term $1/\beta^2$ is dominant
- dE/dx as a function of energy and momentum

particle discrimination

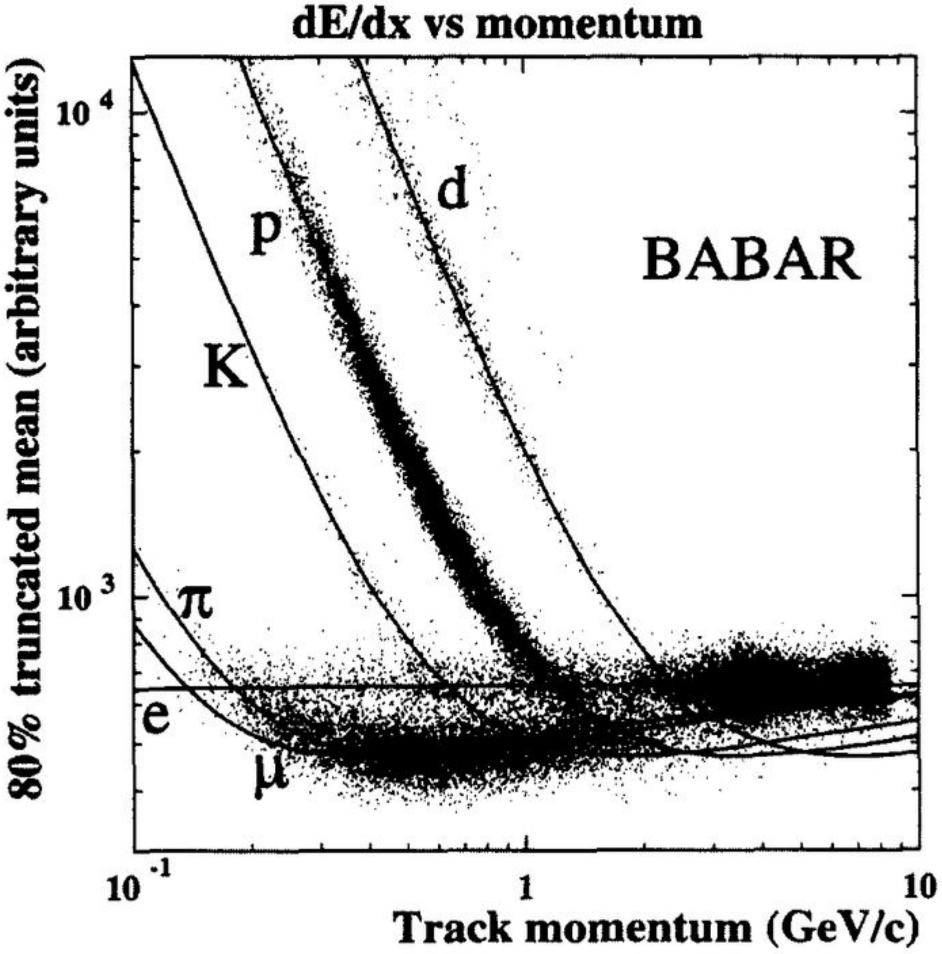
Second part of the curve

- Large $\beta \sim 1$ and γ
- Relativistic particle:
  $E \sim pc$ $E = m\gamma c^2 >> mc^2$
- The term $\ln(\gamma^2\beta^2)$ is dominant
- Logarithmic growth as a function of energy

equal for all the particles

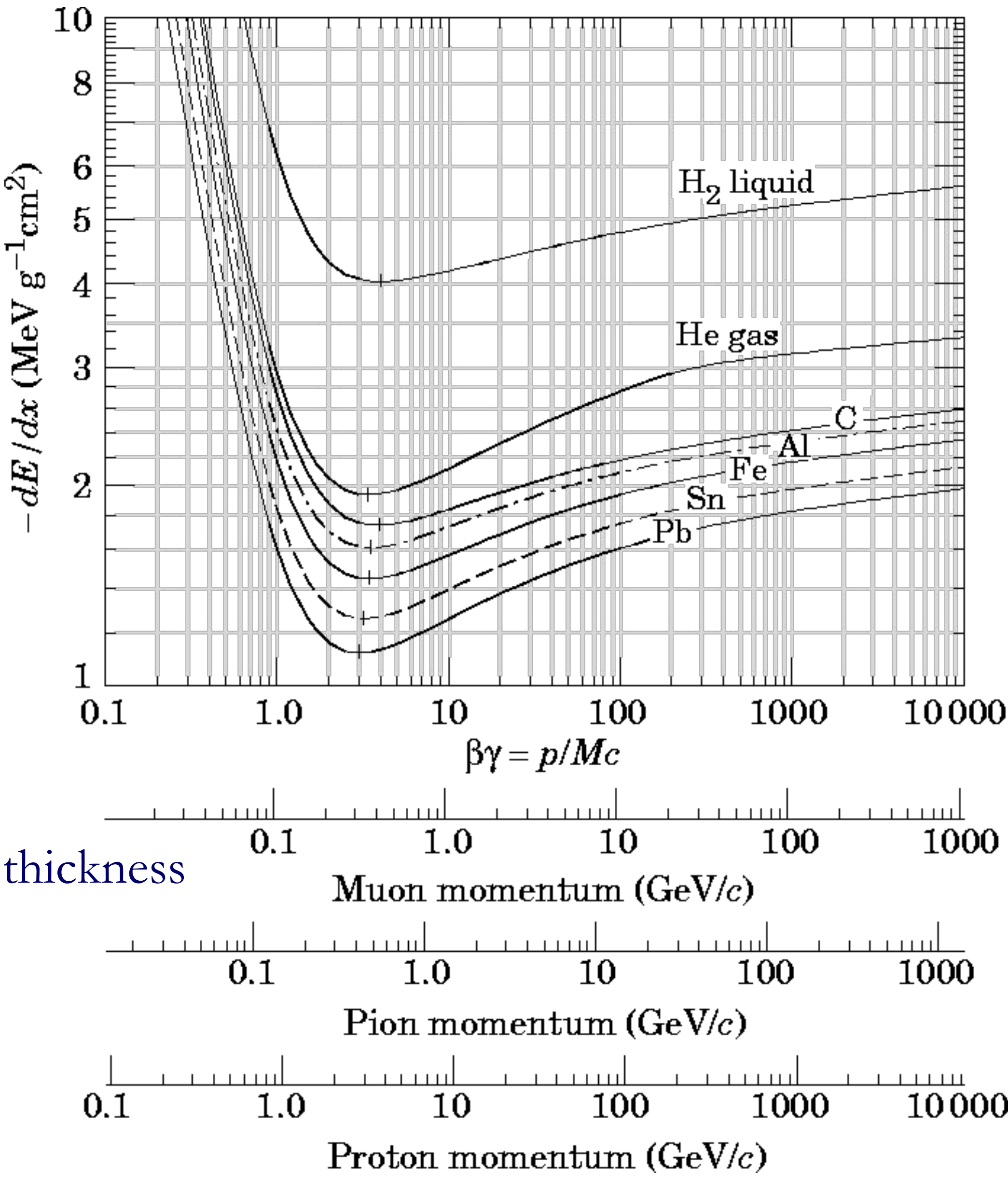
Minimum Ionization

- The energy which corresponds to the ionization minimum depends from the mass of the incident particle.
- Heavier particles reach the minimum at higher energies
- The relativistic raise is the same for all the particles.



Dependency on the material

- Energy loss increases as Z/A increases
- Particles with the same velocity have about the same energy loss in different materials
- Linear absorbing power: (dE/dx)*(1/ρ) normalize materials with different mass density

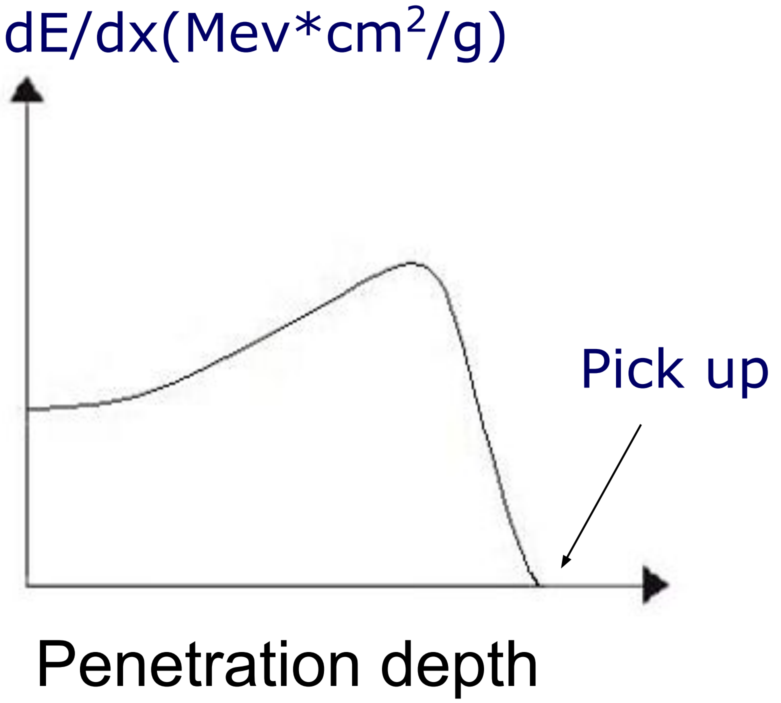


ϱ=mass density, l=thickness, ϱ*l= mass thickness

Different materials with the same ***mass thickness*** have the same effect in the same radiation

Bragg Curve

- When particle slows down it loses more energy
- Most of the energy is deposited
  at the end: this is important for medical application
- The curve goes to zero for the electrons **pick up** (particle becomes neural)



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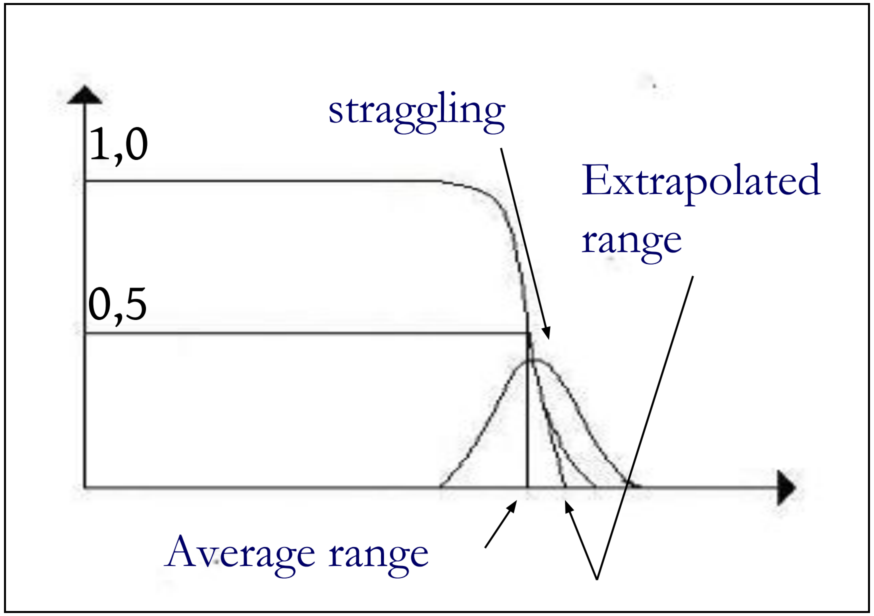
Penetration Depth (Range)

Range: distance crossed by the particle in the material

Heavy charged particles

Outgoing/ingoing particles as a function of the material thickness



- Beam degraded in energy
- Many collisions
- No large deflections: range defined

↓ ma

Particle-matter interaction: statistical process

↓

Range straggling

★ *NB: In general the range does not coincide exactly with the thickness of the material needed to stop the particle, due to the presence of the scattering*

Statistical fluctuations

Bethe-Bloch: <dE/dx> =
average value of the energy loss in a material via ionization

Statistical fluctuations on:

1. Number of collisions
2. Energy transfer in each collision

Thin absorbers

Large energy transfer are possible in one single collision

Landau distribution

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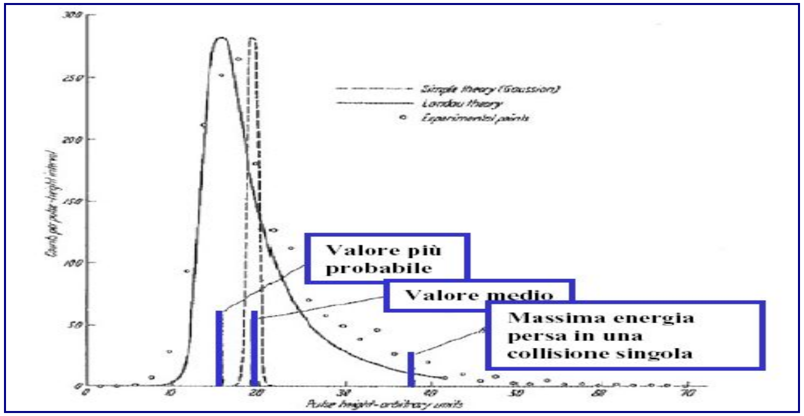
Large tails at high energy

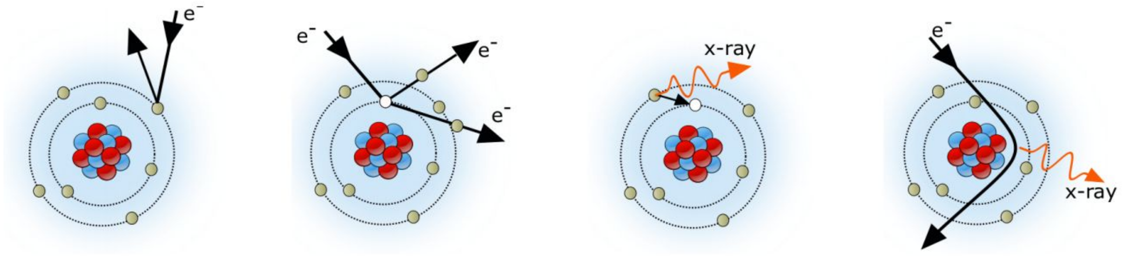
Thick absorbers

Large number of collisions

Gauss distribution



Electron – matter interaction



- Coulomb interactions with:
    - *Nuclei* (elastic collisions, deflession)
    - *Atomic electrons* (anelastic collisions, energy losses)

- Energy transfers in a single collision larger than in the case of heavy charged particles:

    ⇒ electrons less penetrating than heavy charged particles since they lose energy in a smaller number of collisions

    ⇒ trajectories perturbed → can just extrapolate the range

Ionization via electrons

Modifications to the Bethe-Bloch formula:

Small m_e

↓

Large deviations possible

Scattering between identical particles

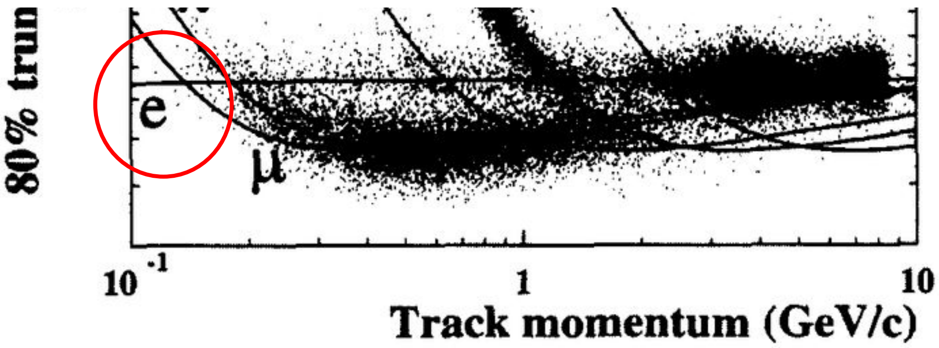
↓

Quantum-mechanics rules

$$\frac{dE}{dx}(ion) = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A}\frac{1}{\beta^2}\left[\ln\frac{\tau^2(\tau+2)}{2(I\cdot m_e c^2)^2} + F(\tau - \delta - 2\frac{C}{Z})\right]$$

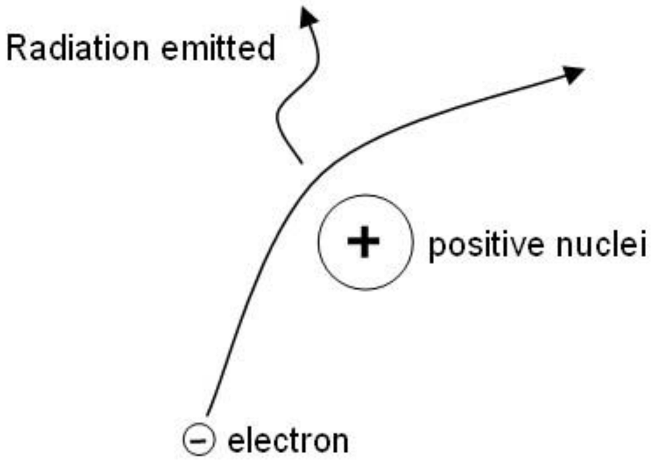
τ = kinetic energy of the particle in $m_e c^2$ units

Flat behaviour



Bremsstrahlung

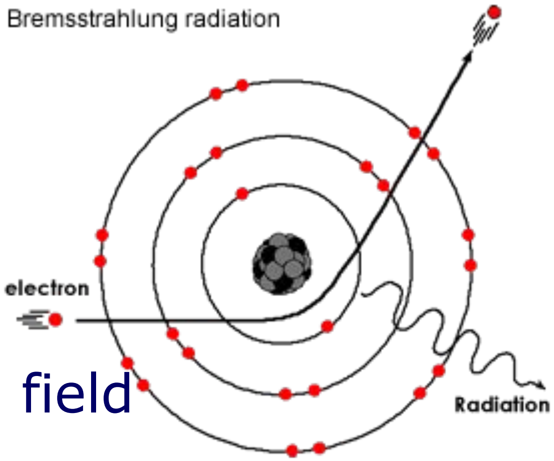
$e^-N \rightarrow e^-N\gamma$



- Radiation emission for diffusion electrical field of the nucleus (*bremsstrahlung* = braking)
- The energy is not transferred to material but to the emitted photon(s)

Below few hundreds of GeV only electrons undergo this loss of energy $\sigma \sim 1/m^2$

Negligible effect for heavy particles



- It depends on the strength of the electrical field «seen» by the incoming electron

Electron energy loss

$$(dE/dx)tot = (dE/dx)rad + (dE/dx)coll$$

- IONIZATION → *up to few MeV*
- BREMSSTRAHLUNG → *from tenths of MeV*

✦ There is a *critical energy* above which Bremsstrahlung dominates

The critical energy strongly depends from the absorbing material $Ec \cong \frac{600MeV}{Z}$

For each material, one defines a critical energy E_c at which the energy loss by radiation is equal to the energy loss due to collisions.

$$(dE/dx)rad = (dE/dx)coll$$

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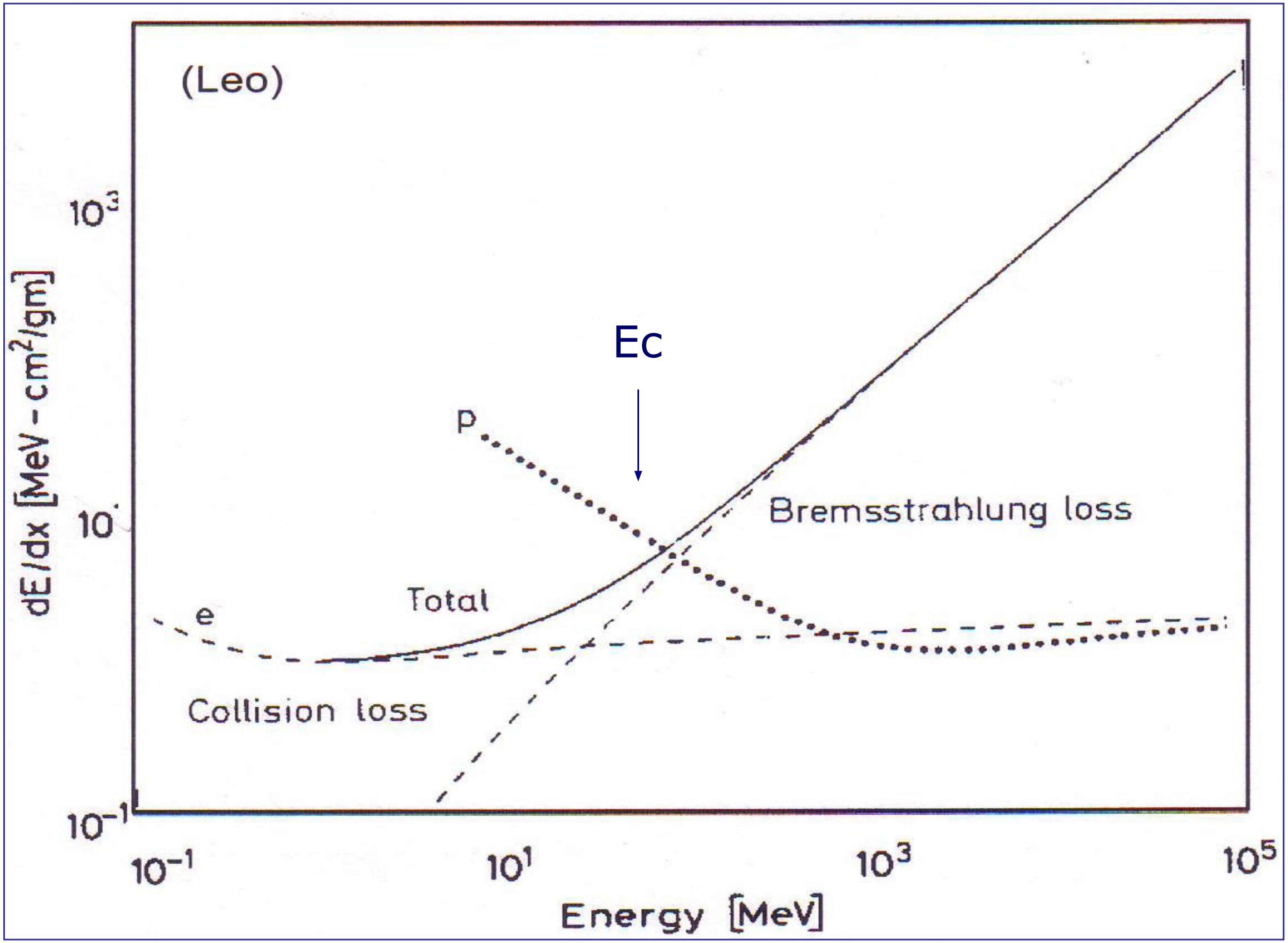
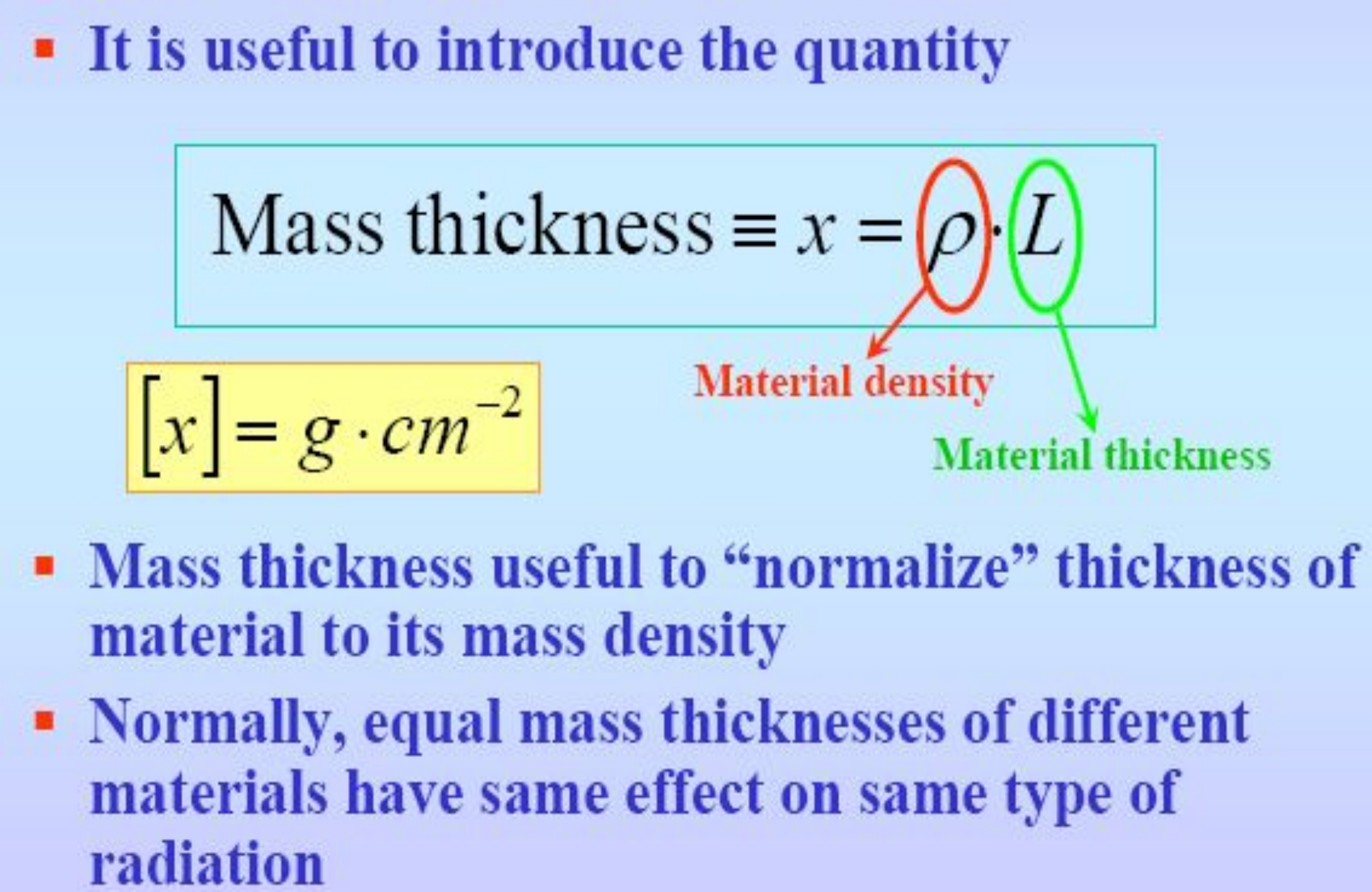
Energy loss electron vs. proton



Backup

Mass thickness



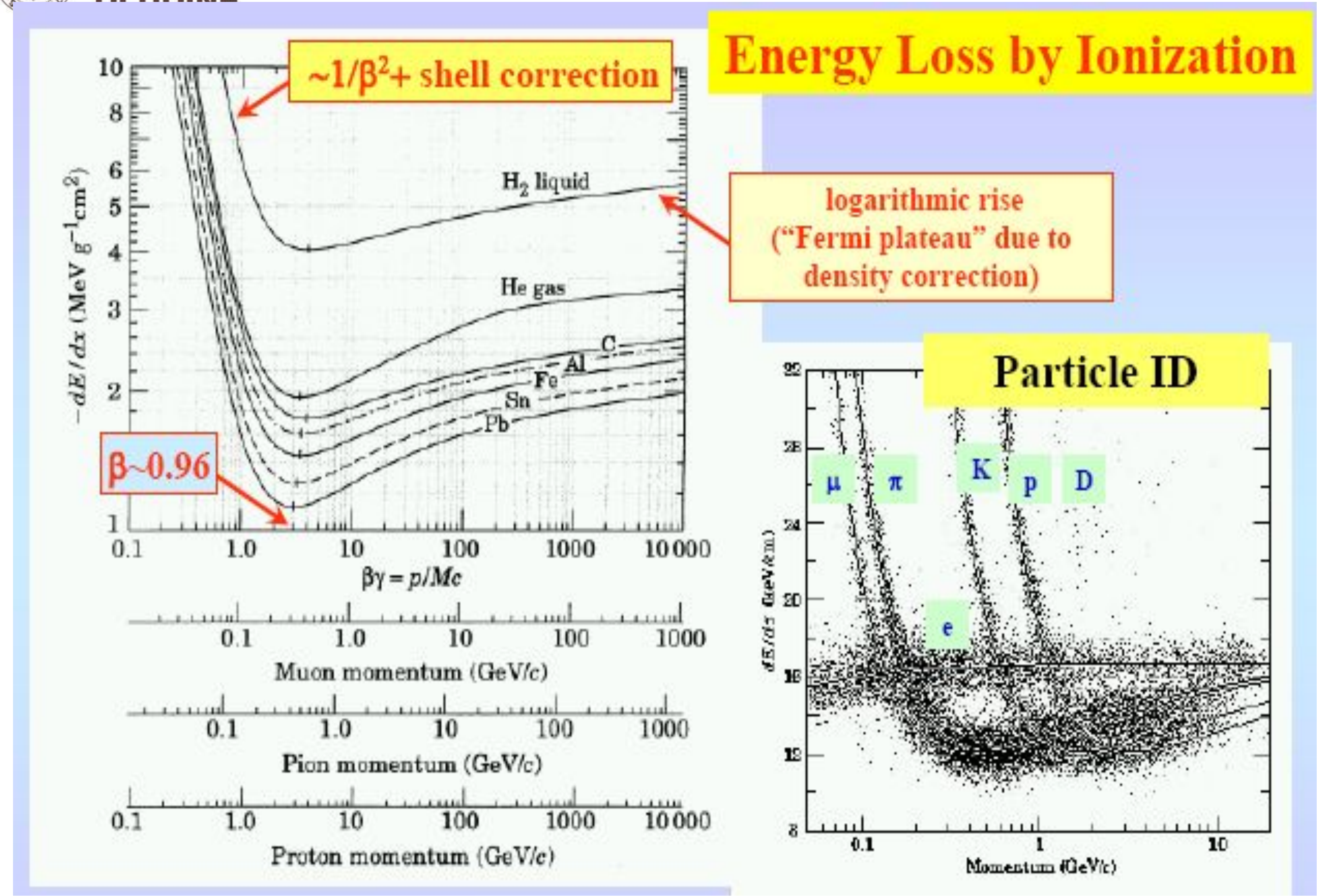
- It is useful to introduce the quantity

$$\text{Mass thickness} \equiv x = \underbrace{\rho}_{\text{Material density}} \cdot \underbrace{L}_{\text{Material thickness}}$$

$$[x] = g \cdot cm^{-2}$$

- Mass thickness useful to “normalize” thickness of material to its mass density
- Normally, equal mass thicknesses of different materials have same effect on same type of radiation

Bethe-Bloch



Energy Loss by Ionization

$\sim 1/\beta^2$+ shell correction

logarithmic rise
("Fermi plateau" due to
density correction)

$\beta \sim 0.96$

Particle ID