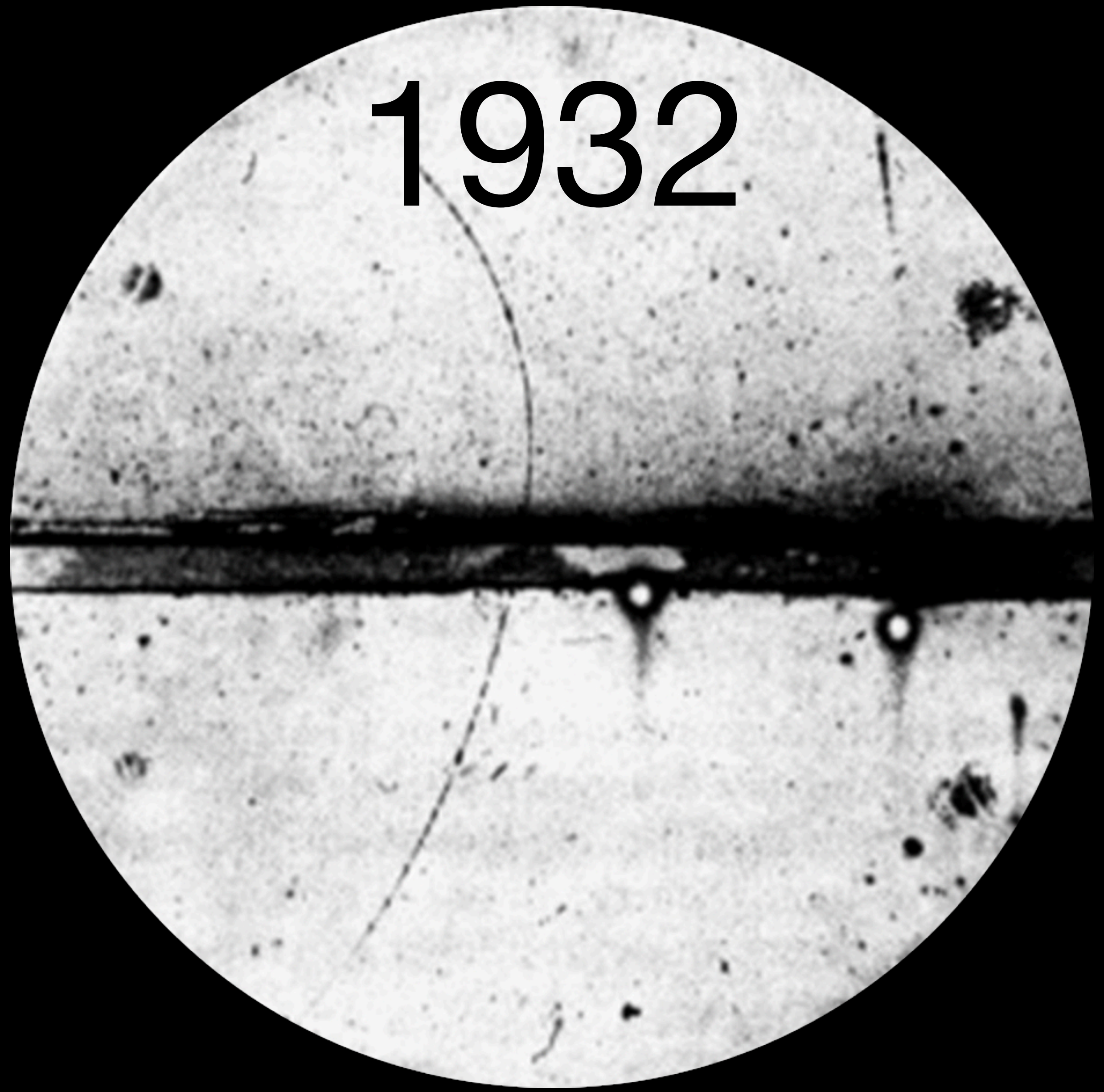
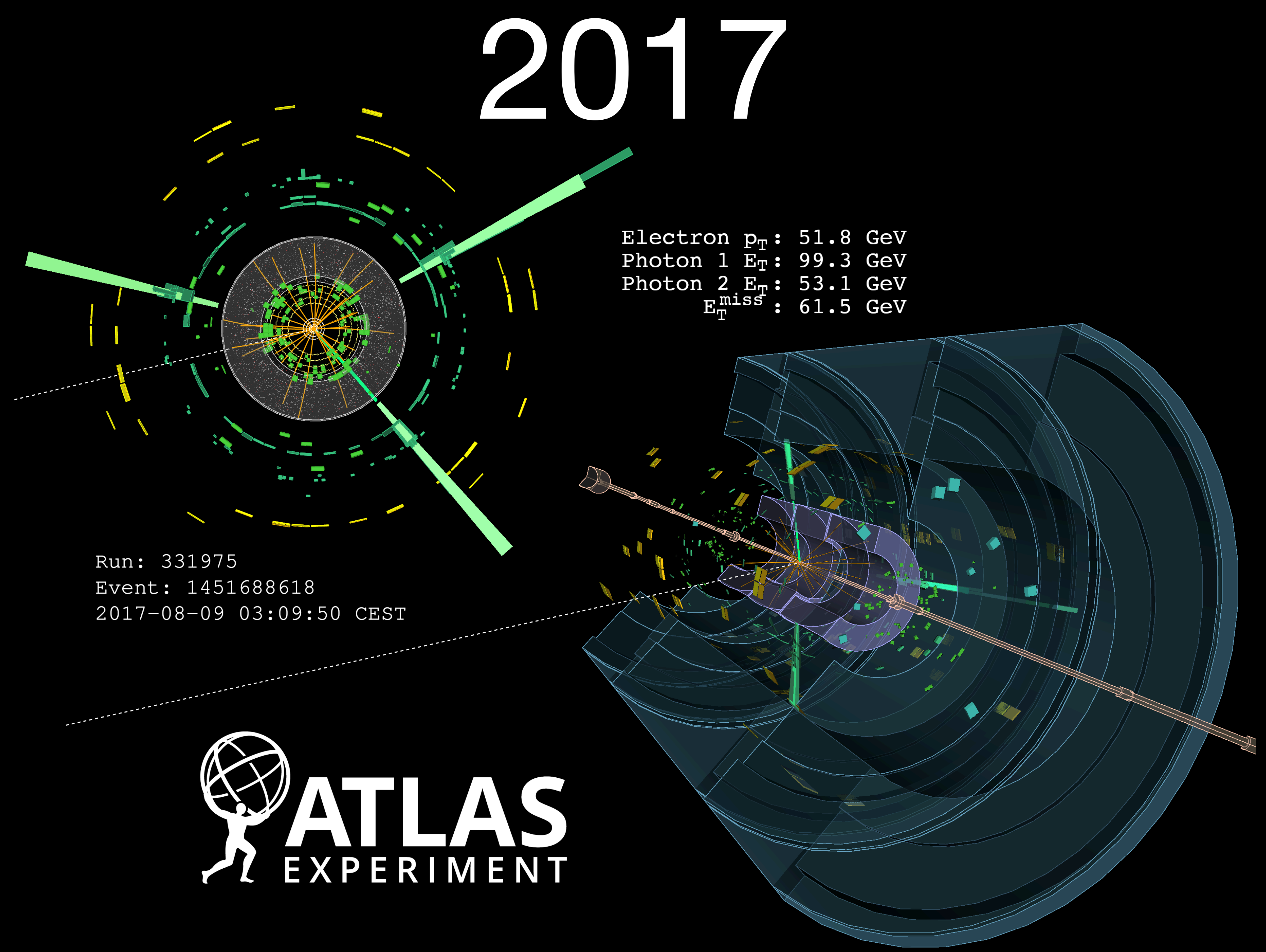
PHYS 7363 - Experimental Particle Detection and Detectors I



Particle detectors are the workhorses of experimental physics. In this course, we'll dive deep into their physics, exploring the incredible evolution of our experimental techniques over the past nine decades. You'll gain a solid understanding of *particle detection* and *identification*, examine the intricate designs of modern detectors, and learn how machine learning is being harnessed to push the boundaries of detector design. If you're intrigued by how we “see” subatomic particles, this course is for you!



Detect Identify Measure

To discuss prerequisites (and any questions on the content of the course), please contact me: saptaparnab@smu.edu

Schedule

Month	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
August	18	19	20	21	22	23	24
	25 ✅	26	27	28	29 ✅	30	31
September	1	2	3 ✅	4	★ 5 ✅	6	7
	8 1.5 hours	9	Zoom 10	11	12 1.5 hours	13	14
	15	16	17	18	19	20	21
	22	23	24	25	26	27	28
October	29	30	1	2	3	4	5

Key dates

- Weeks 1-4: Particle interaction with matter
  - Interaction of charged and neutral particles
  - Particle showers
- Weeks 5-9: Detector technologies:
  - Tracking detectors (gaseous detectors, semiconductor detectors)
  - Particle detection with photons (scintillators, Cherenkov detectors)
  - Calorimetry (electromagnetic and hadronic calorimeters)
- Weeks 10-12: Large and small scale experiments:
  - Triggering and data acquisition
  - Tracking
  - Full reconstruction (particle flow)
- Week 13-15: Preparation for final project:
  - FCC-ee: https://indico.fnal.gov/event/67484/contributions/314057/attachments/187076/257915/US%20FCC%20Tutorial_FullSim.pdf
  - Muon collider: https://mcd-wiki.web.cern.ch/software/tutorials/fermilab2024/

Resources

- PDG review: Passage of particles through matter
  - https://pdg.lbl.gov/2020/reviews/rpp2020-rev-passage-particles-matter.pdf
- N. Wermes / H. Kolanoski, “Particle Detectors”, Oxford University Press, 2020
- Georg Viehhauser/Tony Weinberg, “Detectors in Particle Physics: A Modern Introduction”, CRC Press, Taylor and Francis Group
- C. Grupen / B. Schwartz, “Particle Detectors”, Cambridge University Press, 2011
- F. Hartmann, “Evolution of Silicon Sensor Technology in Particle Physics”
- A. Strandlie, R. Frühwirth, Pattern Recognition, Tracking and Vertex Reconstruction in Particle Detectors
- LHC experiment design: https://www.nature.com/articles/nature06078

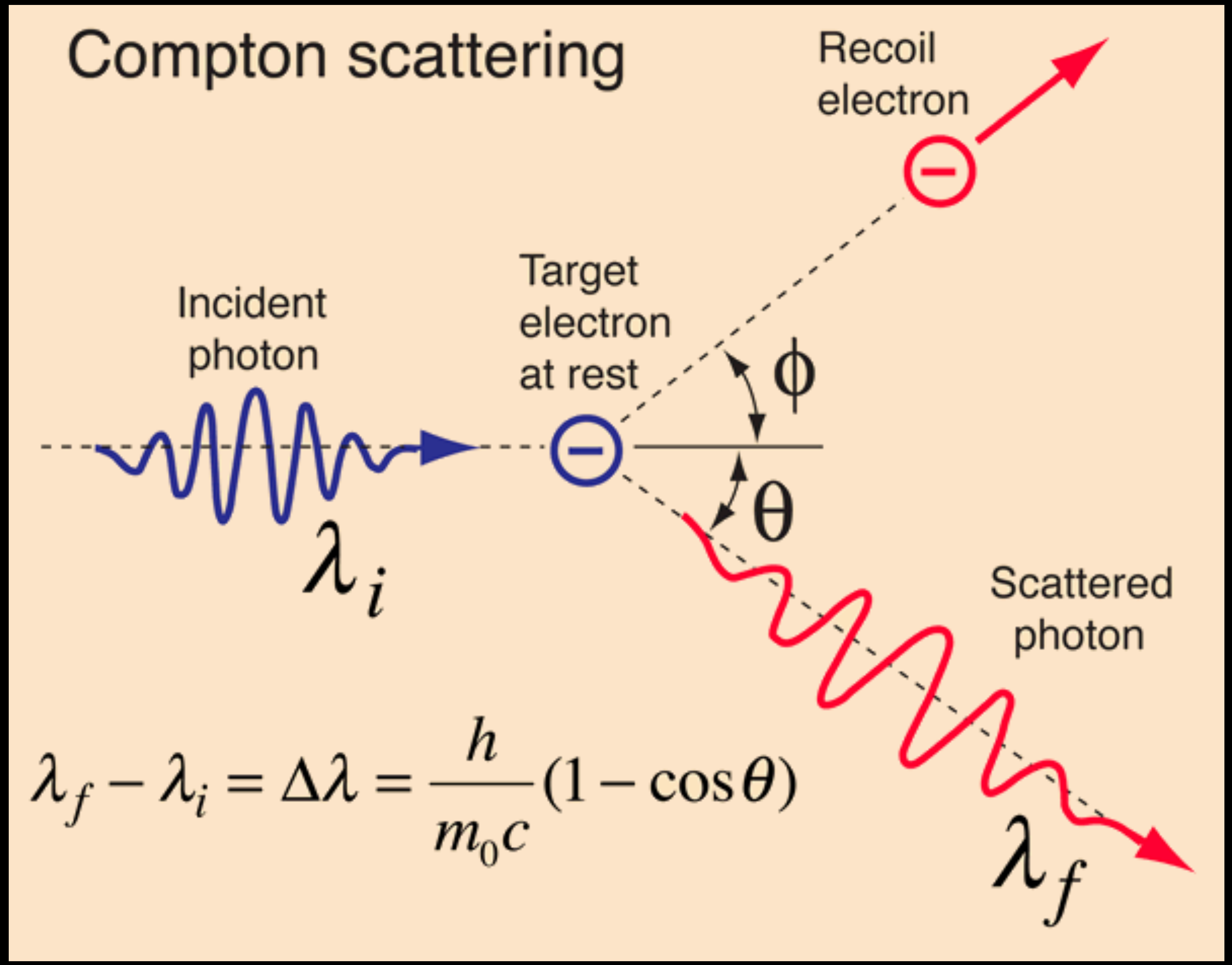
Particle interaction with matter

Particle detection through interaction

- What did we learn last time?

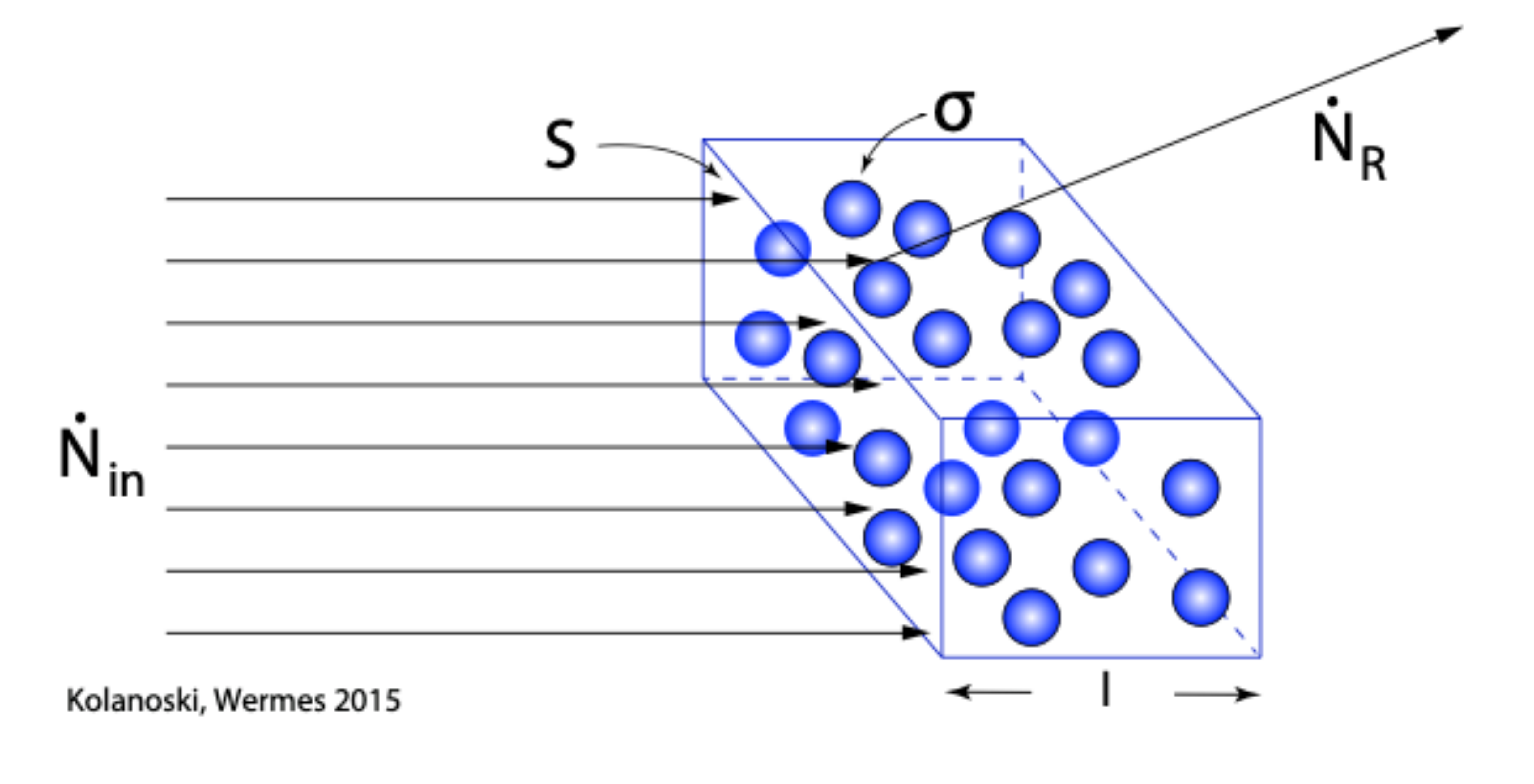
Particle detection through interaction

- Particles can be detected by their interaction with matter. Detectors typically use the following processes:
  - Ionization and excitation of atoms in media by charged particles (electron-ion pairs)
  - bremsstrahlung: photon radiation emitted by charged particles in the fields of atomic nuclei
  - photon scattering (Compton scattering) and photon absorption (registers the presence of light by absorbing photons and converting that absorbed energy into an electrical signal, such as a current or voltage, proportional to the number of photons)
  - Cherenkov (charged particle traveling faster than speed of light in a medium) and transition radiation
  - nuclear reactions: hadrons (p, n, π, α) with nuclear matter
  - weak interactions constituting the only possibility to detect neutrinos



Particle detection through interaction: cross sections

- The cross section is a measure of the probability of a particle reaction
- Depends on the kind and strength of the interactions between particles
- Represented by an effective area
- The cross section σ represents the effective area of the target particle as seen by an incoming beam
- Assume beam has no spatial extent
- How did we express the cross section?



$\dot{N}_{\text{in}}$: incoming particle rate

$\dot{N}_R$: incoming reaction rate

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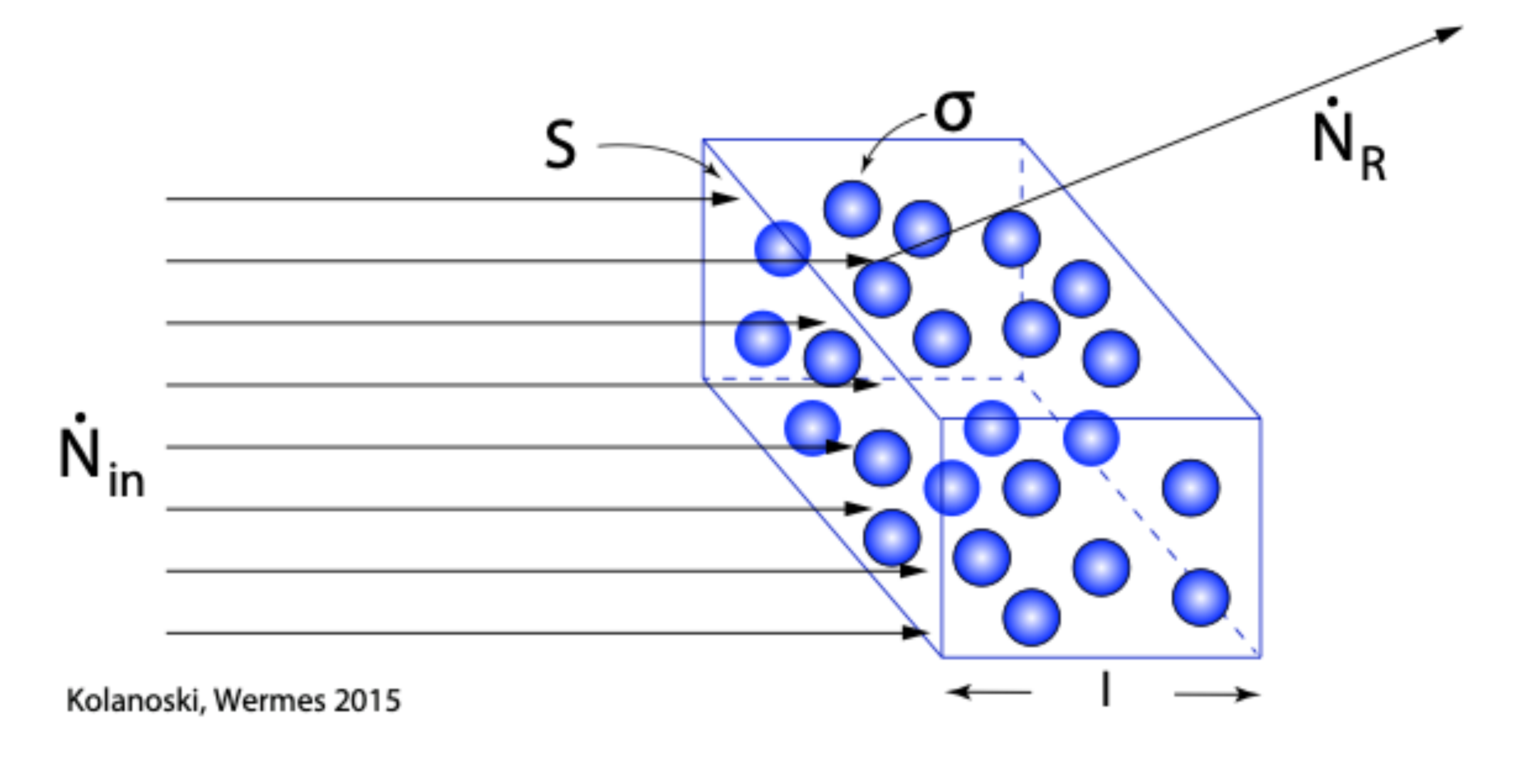
- Assume beam has no spatial extent
  - The cross section (σ) can be expressed as:
  - $\sigma = \frac{\dot{N}_R}{\dot{N}_{\text{in}}} \frac{1}{nl}$
- Reaction rate is proportional to the cross section, proportionality constant is L
- $\dot{N}_R = \sigma L, L = \dot{N}_{\text{in}}\, nl$



$\dot{N}_{\text{in}}$: incoming particle rate

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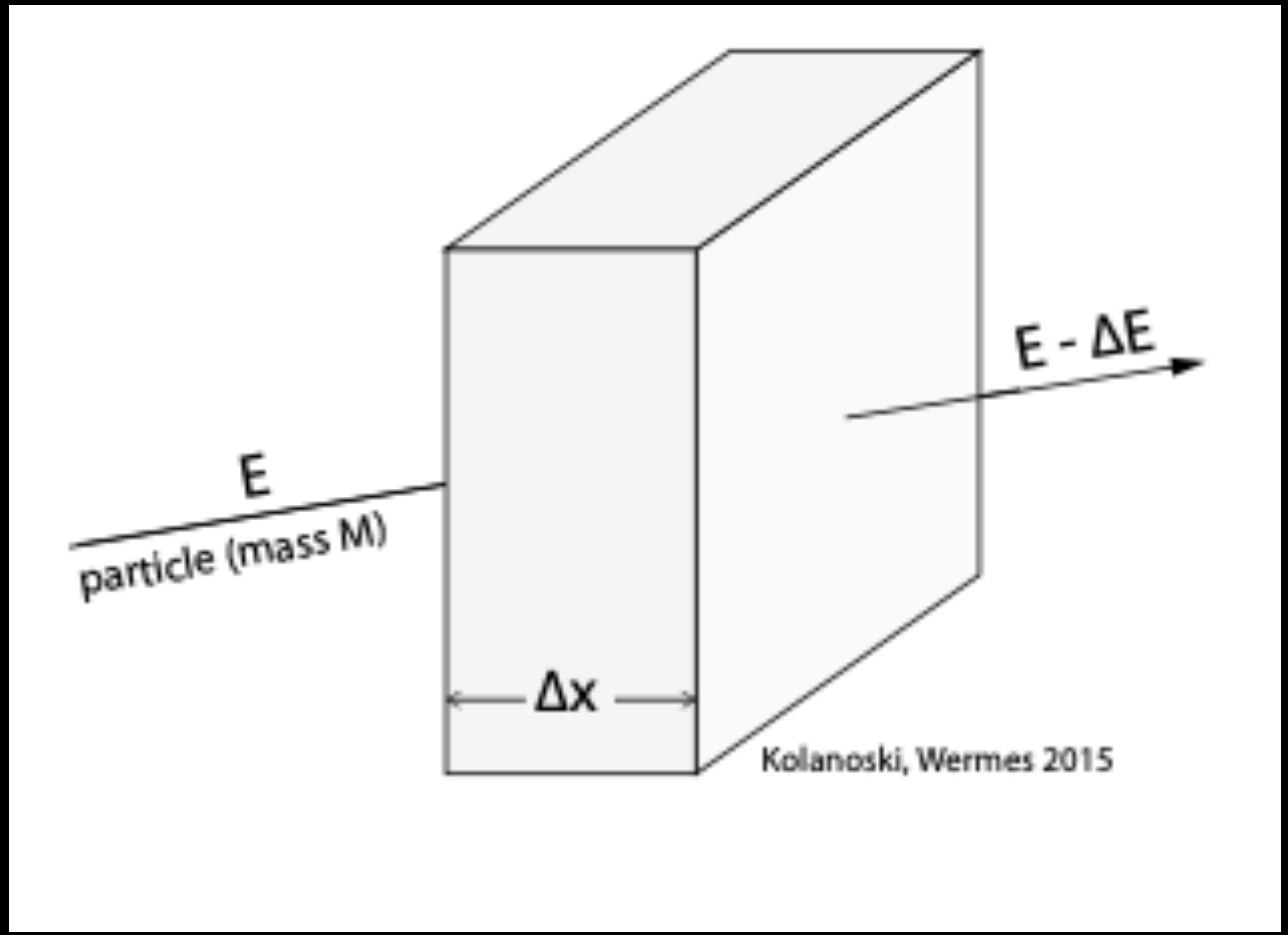
Energy loss of charged particles by ionization

- When penetrating a medium, charged particles lose energy by ionization and excitation of the medium's atoms
- The energy loss per path length is described by the Bethe-Bloch formula
- Energy loss of a particle passing through matter arises from a sequence of individual stochastic processes
- The average energy loss per path length depends on the properties of the medium a, mass of the particle M and the velocity of the particle, β
  - $$-\left\langle \frac{dE}{dx} \right\rangle = n \int_{T_{min}}^{T_{max}} T \frac{d\sigma_a}{dT}(M, \beta, T)\ dT$$
  - Here n is the target number density and $d\sigma_a/dT$ (differential cross section for a loss of kinematic energy T in the collision)
  - The integral from T_{min} to T_{max} comprises the region of all possible energy transfers

Energy loss of charged particles by ionization

- Restricting ourselves to heavy charged particles
  - Representative of all charged particles except electrons and positrons
- Subdivide energy losses ($T \geq T_1$) with large losses T of the particle's kinetic energy
  - Low energy region ($T < T_1$), where binding energies of the electrons cannot be neglected (quantum mechanical treatment)
  - $$-\left\langle \frac{dE}{dx} \right\rangle = n_e \int_{T_1}^{T_{max}} T \frac{d\sigma}{dT} dT - \left\langle \frac{dE}{dx} \right\rangle_{T<T_1}$$



T_1 dividing these regions is typically between 0.01 MeV to 0.1 MeV

Energy loss of charged particles by ionization

- Scattering takes place on shell electrons, relevant target density:
  - $n_e = Z\frac{\rho N_A}{A}$, Z = number of electrons per atom
- High energy region:
  - Velocity of the incoming particle is large compared to electron orbit velocity
  - Energy transferred to an electron is large compared to its binding energy
  - Think of electrons as "quasi-free"
  - Consider projectile with mass M ($M \gg m_e$), charge ze and 4-momentum vectors: P and P' before and after the interaction

Energy loss of charged particles by ionization

- Consider projectile with mass M ($M \gg m_e$), charge ze and 4-momentum vectors: P and P' before and after the interaction
- The 4-momentum vectors: p_e and p_e' before and after the interaction
- With the 4-momentum transfer:
  - $Q^2 = -(P - P')^2 = -(p - p_e')^2$
  - Lorentz-invariant form of Rutherford scattering:
    - $$\frac{d\sigma}{dQ^2} = \frac{4\pi z^2 \alpha^2 \hbar^2 c^2}{\beta^2} \frac{1}{Q^2}$$
    - Here βc is the velocity of the particles relative to each other
    - In the system in which the on-shell electron is at rest, it has an energy $E_e = m_e c^2$ before the collision

Energy loss of charged particles by ionization

- In the system in which the on-shell electron is at rest, it has an energy $E_e = m_e c^2$ before the collision
- After the collision, the energy is:
  - $E'_e = T + m_e c^2$
  - Squared 4-momentum transfer is:
    - $Q^2 = -(p_e - p'_e)^2 = 2m_e c^2 T$
  - Differential cross section (differential in the incoming particle's energy loss T):
    - $\dfrac{d\sigma}{dT} = \dfrac{2\pi z^2 \alpha^2 \hbar^2}{\beta^2 m_e} \dfrac{1}{T^2}$

Energy loss of charged particles by ionization

- Differential cross section (differential in the incoming particle's energy loss T):
  - $$\frac{d\sigma}{dT} = \frac{2\pi z^2\alpha^2\hbar^2}{\beta^2 m_e}\frac{1}{T^2}$$
  - Take spin flip of electron into account (Mott cross section):
    - $$\frac{d\sigma}{dT} = \frac{2\pi z^2\alpha^2\hbar^2}{\beta^2 m_e}\frac{1}{T^2}\left(1 - \beta^2\frac{T}{T_{\text{max}}}\right)$$
- Putting all the components together to solve the original formulation of energy loss:
  - $$-\left\langle \frac{dE}{dx} \right\rangle = n\int_{T_{min}}^{T_{max}} T\frac{d\sigma_a}{dT}(M,\beta,T)\ dT$$

Energy loss of charged particles by ionization

- Putting all the components together to solve the original formulation of energy loss:
  - $-\left\langle \frac{dE}{dx} \right\rangle = n \int_{T_{min}}^{T_{max}} T \frac{d\sigma_a}{dT}(M, \beta, T)\ dT$
  - $-\left\langle \frac{dE}{dx} \right\rangle_{T>T_1} = n_e \int_{T_1}^{T_{max}} T \frac{2\pi z^2 \alpha^2 \hbar^2}{\beta^2 m_e T^2} \left(1 - \beta^2 \frac{T}{T_{\text{max}}}\right)\ dT$
  - $-\left\langle \frac{dE}{dx} \right\rangle_{T>T_1} = n_e \frac{2\pi z^2 \alpha^2 \hbar^2}{\beta^2 m_e} \left(\ln \frac{T_{\text{max}}}{T_1} - \beta^2\right)$
  - $\beta^2 \left(1 - \frac{T_1}{T_{\text{max}}}\right)$ approximated by β^2, assuming $T_1 \ll T_{\text{max}}$

Maximum energy transfer

- Maximum energy transfer can be computed from the kinematics of an elastic collision of the particle with the shell electron
  - Assume $\overrightarrow{P}$, $\overrightarrow{P}'$, $\overrightarrow{p}'_e$ are all parallel
  - Incoming particle energy, momentum expressed in terms of Lorentz factors β, γ:
    - $E = \gamma M c^2$, $|\overrightarrow{P}| = \beta\gamma M c$
    - The kinetic energy of the outgoing electron:
      - $T = E'_e - m_e c^2$
    - Neglecting binding energy, maximum kinematic energy:
      - $T_{\text{max}} = \dfrac{2 m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}$ (book forward references section 3.2.2)

Minimum energy transfer

- Classically energy transferred can become arbitrarily small
- Quantum mechanically, however, it must be considered that below the ionization threshold only discrete energy transfers are allowed in a single collision
- The quantum mechanical treatment of atomic excitations and corrections caused by screening effects of atomic shells is the most difficult problem in the computation of energy loss in matter
- Bohr explained a passing electrons's energy loss by the generation of “vibrations” of the atom electrons of the absorbing material

Minimum energy transfer

- First rigorous treatment was given by Bethe
  - $$-\left\langle \frac{dE}{dx} \right\rangle_{T<T_1} = n_e \frac{2\pi z^2 \alpha^2 \hbar^2}{\beta^2 m_e} \left[\ln \frac{2 m_e c^2 \beta^2 T_1}{I^2} - \ln \frac{1}{\gamma^2} - \beta^2 \right]$$
  - Corresponds to an integral over an energy region between an effective minimal energy transfer $T_{\text{min}} = I^2/2m_e c^2 \beta^2$
  - I = mean excitation energy
  - Logarithm of I = Weighted sum of logarithms of excitation energies
  - Taken from a fit to experimental data

Bethe-Bloch formula

$$-\left\langle \frac{dE}{dX} \right\rangle = K \frac{Z}{A} \rho \frac{z^2}{\beta^2} \left[\frac{1}{2} \ln \left(\frac{2 m_e c^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} \right) - \beta^2 - \frac{\delta(\beta\gamma)}{2} - \frac{C(\beta\gamma, I)}{Z} \right]$$

$K = 4\pi N_A r_e^2 m_e c^2 = 0.307$ MeV cm^2/mol, using the classical electron radius

z, β: charge and velocity of the projectile

Z, A are the atomic number and mass

I is the mean excitation energy

T_{max} is the maximum possible energy transfer to a shell electron

δ is the density correction, important at high energies

C/Z is a shell correction

Mean energy loss of charge particles by ionization

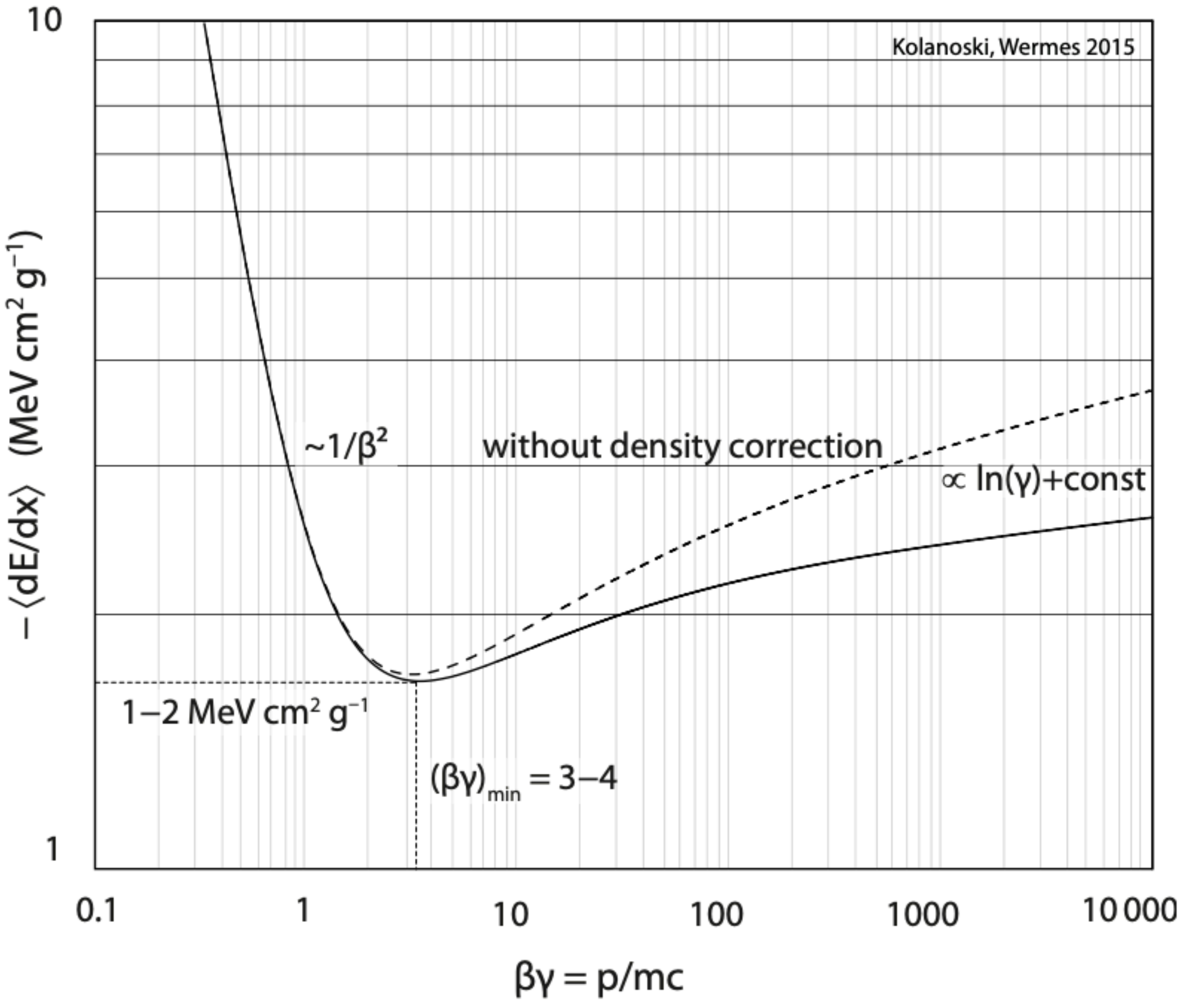


Fig. 3.5 Mean energy loss of charged particles by ionisation as a function of $\beta\gamma = p/mc$, here given for charged pions in silicon. The range indicated for the minimum of the energy loss is valid for most media. At high energies the density effect is evident as the deviation from the log γ trend due to the polarisation of the medium by the charged particle and hence screening further extension of the transverse electric field.

The Bethe–Bloch formula describes how particles are stopped in matter

Understanding the distribution

- The mean energy loss $-\left\langle \frac{dE}{dX} \right\rangle$ as a function of the energy of the in- coming particle for a typical example (π in silicon).
- At low energies the $1/\beta^2$ term dominates
- At high energies the $\ln\gamma$ term is dominant
- In between both regions there is a broad minimum around $\beta\gamma \approx 3 - 3.5$ ($\beta \approx 0.95$) depending on Z.
- Particles in this kinematic range are thus called *minimum-ionising particles* (*mips*).
- Since the increase in $\frac{dE}{dX}$ for energies corresponding to $\beta\gamma > 3.5$ is only moderate compared to the steep rise $\propto 1/\beta^2$ towards energies lower than the minimum, it is common practice to use the term *mip* for all charged particles with energies larger than those at the minimum

Understanding the distribution

- Low energy regime:
  - The $1/\beta^2$ dependence can be explained by the fact that the momentum transfer increases with the effective interaction time Δt which is longer for slower particles
- High energy regime:
  - Asymptotic increase of the maximum energy transfer T_{max} with γ: purely kinematic effect
  - For subtlety of large impact parameter and increasing transverse extension of the electric field with γ refer to the book!

Scaling laws and particle identification

- Average energy loss (ionization part of the energy loss):
- $\frac{dE}{dx} \approx z^2 Z f_\beta(\beta) = z^2 Z f_p(p/M) = z^2 Z f_T(T/M)$
- $p/Mc = \beta\gamma,\ T/Mc^2 = \gamma - 1$
- Independent of the exact medium (independent of the identity and mass)

Scaling laws and particle identification

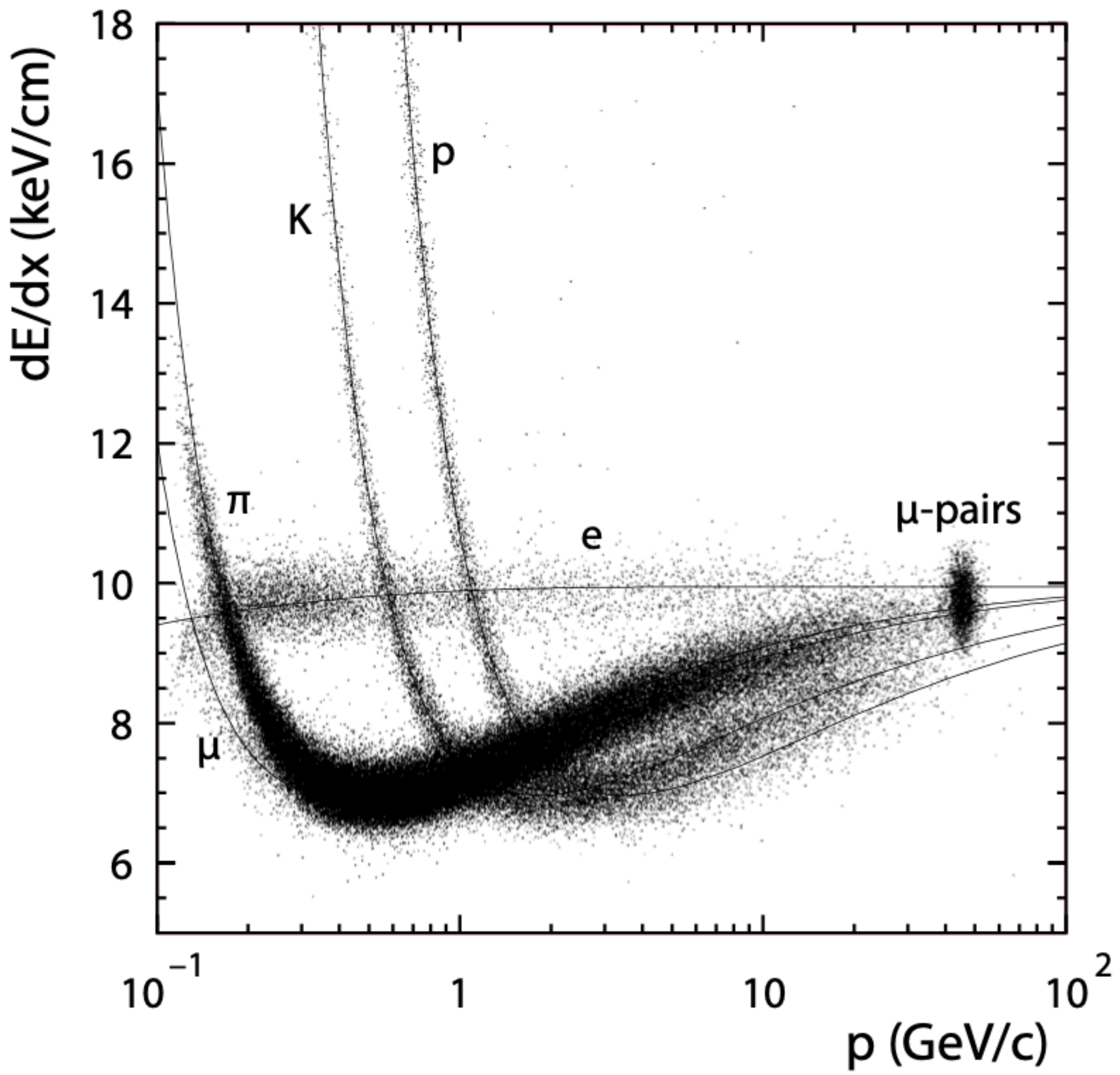


Fig. 3.7 Average ionisation energy loss of charged particle tracks measured as a function of their momentum on 159 anode wires (and averaged) in a drift chamber filled mainly with argon. For the averaging the 'truncated mean' method is employed by discarding the 30% highest values of a track (see section 14.2.2 and fig. 14.9). Every dot represents a measurement for one particle track, observed in decays of the Z^0 boson ($m_Z = 91\,\text{GeV}/c^2$) (LEP, OPAL detector [509], with kind permission by Elsevier).

https://cds.cern.ch/record/224558/files/cer-000137343.pdf
https://www.sciencedirect.com/science/article/pii/016890029290501T

A simple derivation

- Delta or δ electrons or high energy knock-on electrons are emitted with collisions of the projectile particle with shell electrons are close to central, causing high energy transfers
- Elastic collisions with quasi-free electrons: define (incoming and outgoing collision partners) P, P', p_e, p'_e
- Momentum conservation:
  - $P + p_e = P' + p'_e$
  - $EE'_e - E'm_ec^2 = |\overrightarrow{P}c||\overrightarrow{P}_ec|\cos\theta$ (How did I get here?)
  - $\cos\theta = \dfrac{T(\gamma + m_e/M)}{\gamma\beta\sqrt{T^2 + 2Tm_ec^2}}$
  - $T(\theta) = \dfrac{2m_ec^2\beta^2\gamma^2\cos^2\theta}{\gamma(1-\beta^2)\cos^2\theta + 2\gamma m_e/M + m_e^2/M^2}$
  - When do I get T_{min} and T_{max}?

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  - When do I get T_{min} and T_{max}?
  - T_{max} when $\theta = 0°$
  - T_{min} when $\theta = 90°$