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DETECTOR PHYSICS – IN A NUTSHELL

5th Belle II Starterkit Workshop, KEK

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DISCLAIMER

As the title indicates, this is a very very brief introduction into the principle of particle detector physics with no claim of completeness!

It only covers mechanisms relevant to Belle II.

Please look into your favourite textbook for further details on the different topics.

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OUTLINE

- Energy loss in material
- Bethe Bloch formula, delta electrons, fluctuations in energy measurements, bremsstrahlung
- Multiple scattering
- Radiation length
- Cherenkov effect
- Occupancy
- The Belle II detector

ENERGY LOSS IN MATERIAL

- Particles can lose energy in material on several ways
  - Ionisation or excitation of atoms
  - Scattering on or excitation of nuclei
  - Breaking nuclear or structural bonds
  - Bremsstrahlung

  All of the above can be described by one formula (for heavy particles, i.e. all but e^+ / e^-): Bethe-Bloch-Formula
- In addition (also important for Belle II, but not directly energ loss in material)
  - Synchrotron radiation: photons radiated off a charged particle when deflected in magnetic field (mostly applies to beam particles of both beams in final focussing magnets)

BETHE-BLOCH-FORMULA

- Average energy loss per unit distance dx is described by*

$$-\left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle = K\frac{Z}{A}\rho\frac{z^2}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{max}}{I^2} - \beta^2 + \text{corrections}\right]$$

- K = constant, z = charge of traversing particle, Z = atomic number of material, A = mass number of material, I = mean excitation energy, Tmax = maximum kinetic energy transfer by one collision

- Describes dE/dx in range of $0.1 < \beta\gamma < 1000$ for intermediate Z materials very well

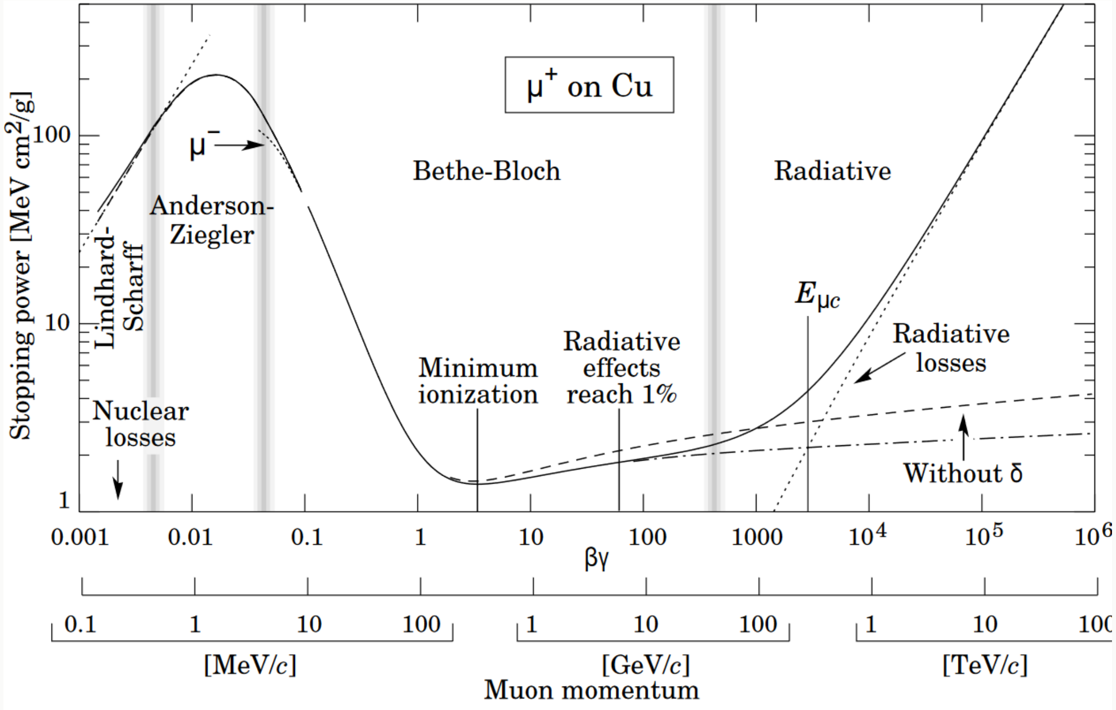
- Equation has minimum at about $\beta\gamma = 2\text{-}3$ → Minimum Ionising Paritcle (MIP)

- Attention: Unit of dE/dx is MeV/cm (*linear* stopping power), but often it's given with unit MeV cm^2 / g (*mass* stopping power). In this case the density goes to the lhs

*see PDG

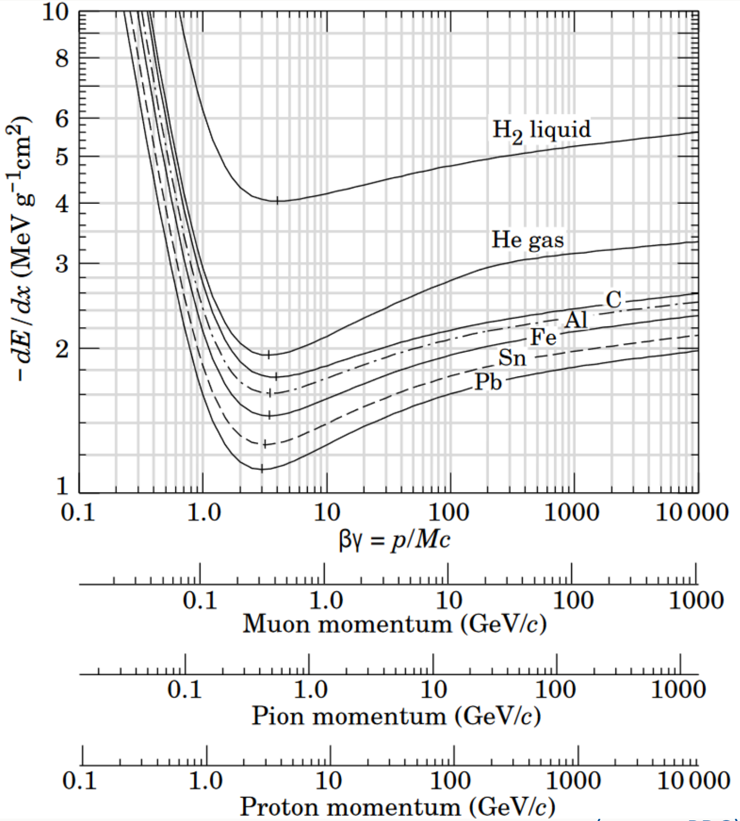
BETHE-BLOCH-FORMULA

Muon in copper (notice: vertical axis in MeV cm² / g, not MeV / cm) (from PDG)



BETHE-BLOCH-FORMULA

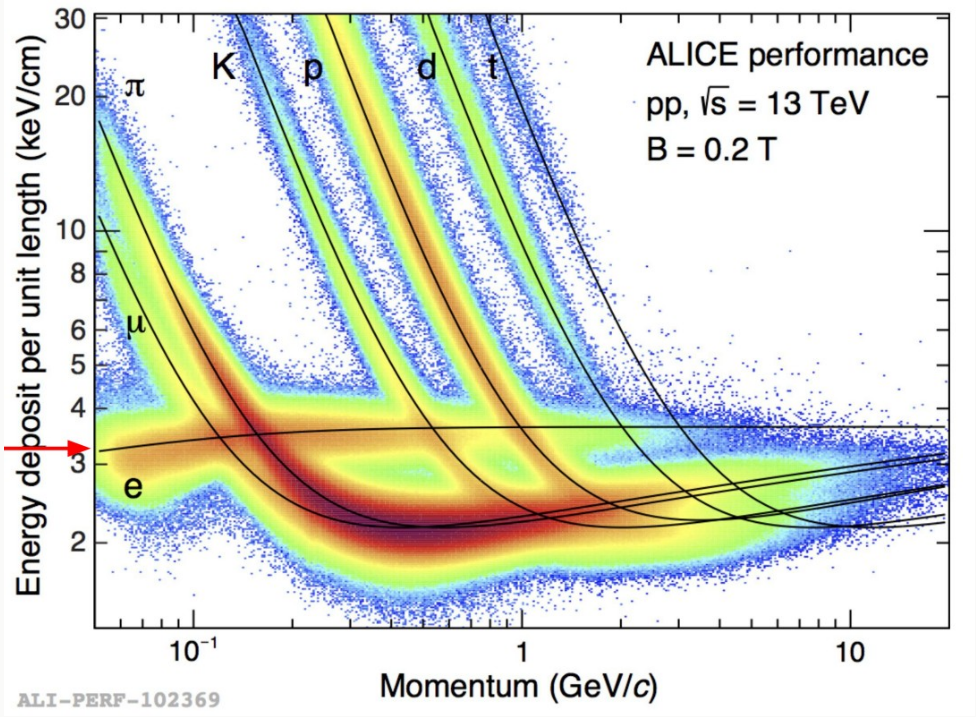
- Factoring out the density brings the minima close together in vertical direction
- Typical values:
  - Minimum at βγ of 2-3 (= MIPs)
  - Minimum of 1.5 – 2 MeV cm² / g
- Here e.g. Pb and He are close together for a MIP, which is not the case for dE/dx in MeV/cm
- As you can see from the bottom part: you can distinguish particles this way (when they are in the MIP region). This is also used in Belle II (see CDC talk)



(source: PDG)

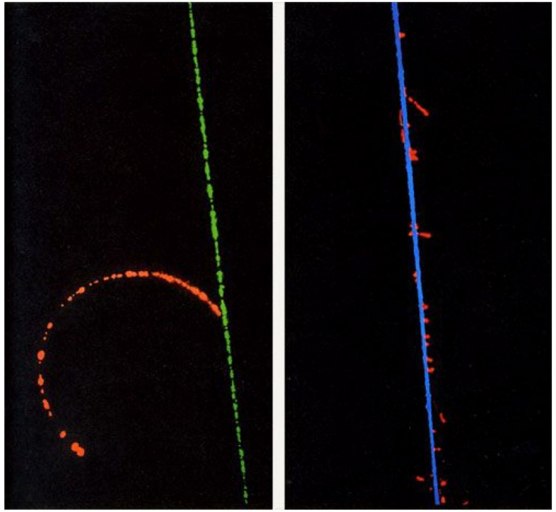
BETHE-BLOCH-FORMULA

- Identifying particles because of their energy loss in material (ALICE TPC)

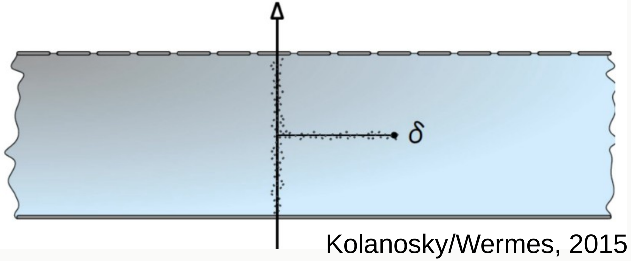


DELTA ELECTRONS

- High energetic electrons that are directly hit by a traversing particle, transferring a lot of energy (O(several MeV)) to that electron
- Nearly always ~perpendicular to particle trajectory (lower energy), nearly no particles with small angles compared to particle trajectory (but with higher energy)
- Produce secondary ionization + random variability in dE/dx
- In gas detectors: curl in magnetic field
- In silicon detectors: distribute signal over more strips / pixels than compared to a usual hit, creating a larger cluster



The Particle Explosion, Close, Marten, Sutton



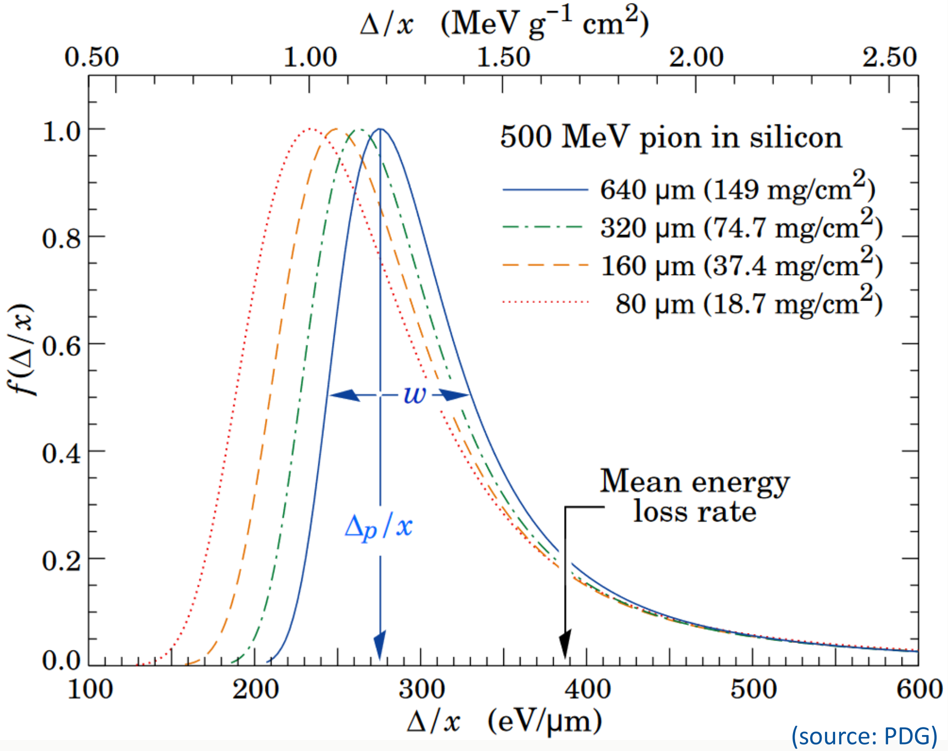
Kolanosky/Wermes, 2015

FLUCTUATIONS IN ENERGY MEASUREMENTS

- Energy loss is a statistical process
- Including the delta electrons, the distribution becomes skewed with a long tail for higher energy losses over the distance in traversed material:

  Landau distribution

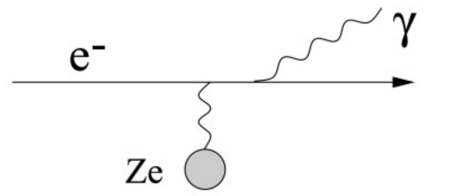
- Mean energy loss different from most probable energy loss (maximum)
- Can be seen in Belle II in PXD, SVD, CDC, since in these the particles are not fully stopped (within short distance)

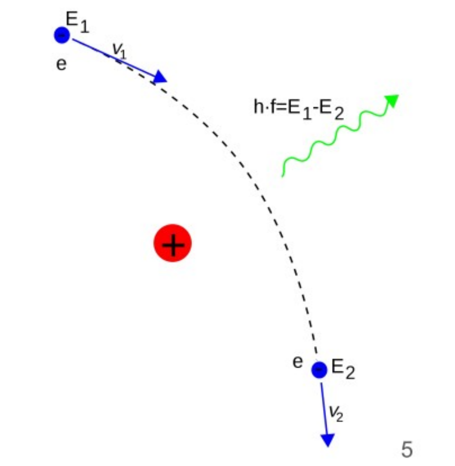


(source: PDG)

BREMSSTRAHLUNG

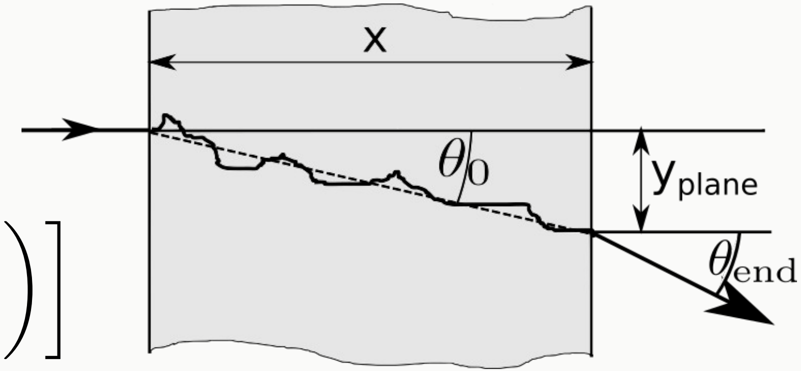
- Energy loss of charged particle by scattering in the E-field of the nucleus
- Energy loss -dE leads to photon emission due to conservation of energy
- Energy loss rate proportional to Z^2E/m^2
  - Mostly relevant for electrons (positrons) because of their low mass
  - Mostly dominant at high energies





MULTIPLE SCATTERING

- Elastic scattering of a particle when interacting with the field of the atomic nucleus – Coulomb scattering
- Particle is deflected, but doesn‘t lose energy
- Can happen multiple times while traversing a single detector
- Causes displacement between entry and exit point
- Causes angular deflection



$$\theta_{\text{end}} = \frac{13.6\,\text{MeV}}{\beta c p} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln\left(\frac{x}{X_0}\right)\right]$$

- This is one reason why we want to have thin detectors (small x) in tracking!

RADIATION LENGTH

- Radiation length X_0 is the distance in a material where energy of a high energy electron has dropped to 1/e of its original energy

  $E(x) = E_0 \exp(-x/X_0)$

- Concept can also be applied to charged particles traversing material
- Material dependent: in general smaller for solid materials and larger for gaseous materials
  - Energy loss (per unit length) in solid state materials like Si is lager compared to gases
  - Proportionality (important for composite materials): $\frac{1}{X_0} \propto \rho \frac{Z^2}{A}$
- Define material budget: amount of material a particle has traversed in terms of X_0

RADIATION LENGTH

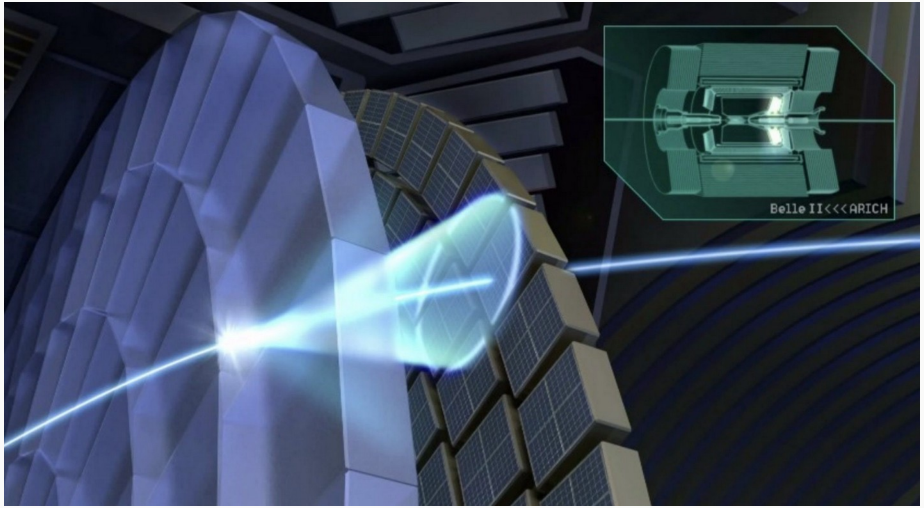
- For tracking detectors we usually want to have low material budget
  - Thin and light detectors (if small X_0) like silicon detectors in Belle II, or larger detectors with larger X_0 like CDC
- Same for PID detectors: as little energy loss as possible (but enough to have the particle produce a useful signal)
- Different for calorimeter: here you want to stop the particle and make it lose all its energy
  - Thick(er) detector with many units of X_0

CHERENKOV RADIATION

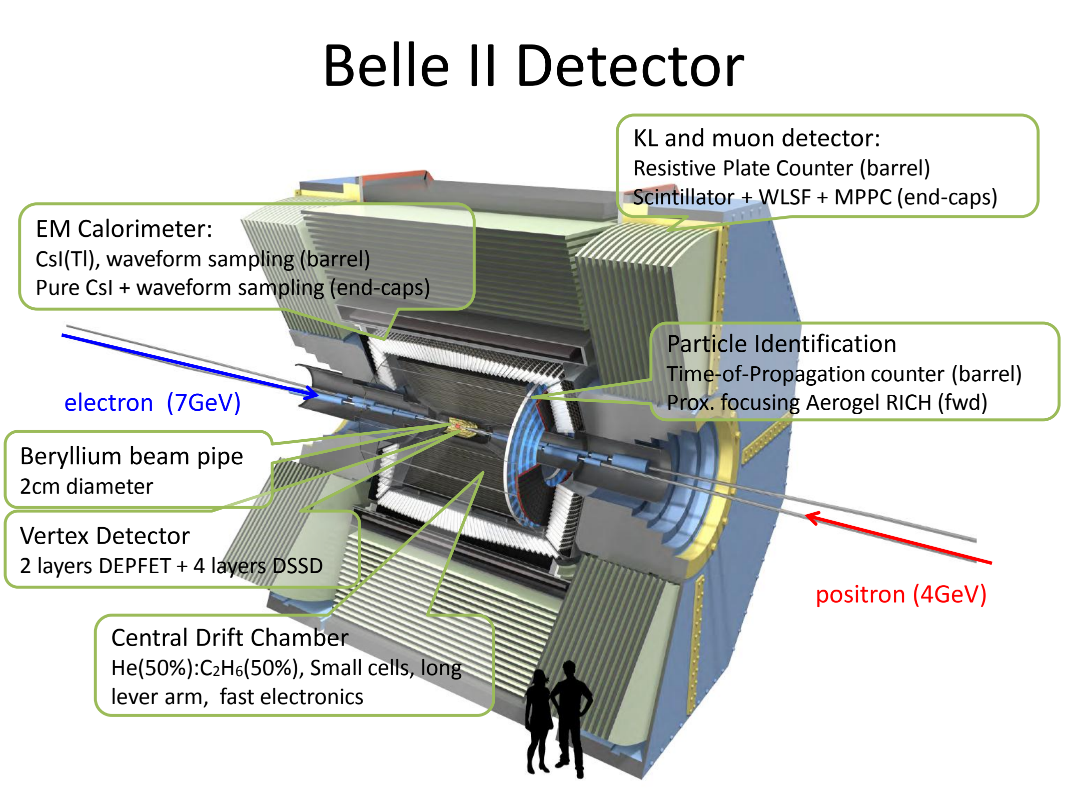
- Radiation emitted from a particle in a medium where the particle‘s speed is faster than the speed of light in that material
- I don‘t want to cover more details here
- Radiation is emitted with a characteristic angle (n is refractive index of material):

$$\cos\theta = \frac{1}{n\beta}$$

- Measure the angle → measure the speed
- If you in addition measure the momentum, you get the particle mass unambiguously
- Used in ARICH and TOP



THE BELLE II DETECTOR



OCCUPANCY

- In the following talks you will hear about occupancy
- Occupancy is the fraction of active readout channels in a (sub) detector compared to the total number of readout channels, usally with respect to the readout time or the integration time
- Example: Consider a pixel detector with 150k pixels, that is read out within 100 ns. If in this time 3000 pixels are hit (= have a signal above threshold), than the occupancy is 2%.
- If the readout time instead is 200 ns, but the particle rate is constant, 6000 pixel are hit during the readout cycle, thus the occupancy is 4%
- Usually a detector only works reliably up to a specific occupancy, or e.g. tracking only yields useful results (= tracks) up to a specific occupancy

CLOSING REMARKS

- I hope this very brief introduction is enough for you to be able to follow the next lectures if you never before had a lecture in particle physics. Further information on how the different concepts are used in the different detectors will be given in the following lectures and in the lectures on PID tomorrow
- Usually a lecture on particle detectors and the physics behind them can easily fill one or two semesters
- We have experts for most of the Belle II subdetectors in the room. In case of questions, just ask them
- Further information on how the different concepts are used in the different detectors will be given in the following lectures and in the lectures
- In case of more questions: now is the time! :-)

THANK YOU FOR YOUR ATTENTION!