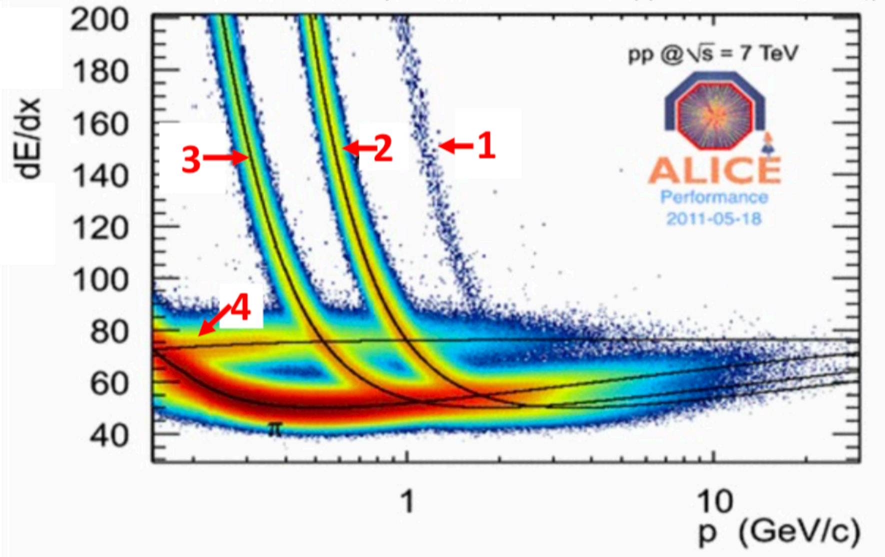
Introduction to Nuclear and Particle Physics

Lesson 5

charged particles in matter

Warmup question 1



This plot shows the mean energy loss of various particles in matter. Each curve can be identified with a certain type of radiation.

Which of the following statements is correct?

A) Curve 2 corresponds to stopping protons.

B) Curve 4 corresponds to stopping muons.

C) All particles in the plot are charged.

D) The less relativistic the particles are, the less they ionize the material.

Warm - up question 2

Electrons with an energy of 100 MeV traverse a thin gold layer.
Which statements are true?

A) The energy loss of the electrons is dominated by Bremsstrahlung.

B) Within the layer, the ionization losses will increase linearly with the depth.

C) Within the layer, the radiative losses will decrease exponentially with the depth.

D) Muons with the same energy would lose similar energies in the layer.

Topics of today

Charged Particles in Matter

ionization

bremsstrahlung

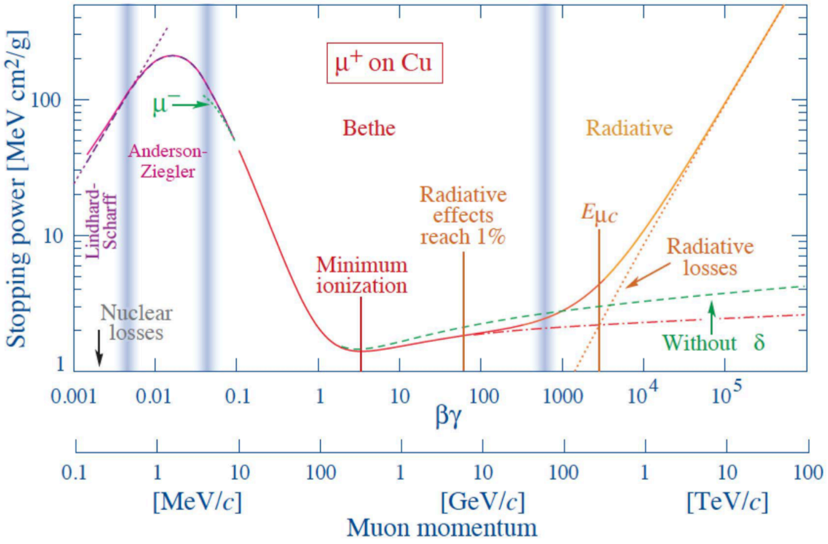
↕

synchrotron radiation

Interaction of charged particles with matter

low-energy **ionization** **radiative**

$\sim \frac{\mathrm{d}E}{\mathrm{d}x}$



$$\frac{\mathrm{d}E}{\mathrm{d}x} = \left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{\text{col}} + \left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{\text{rad}}$$

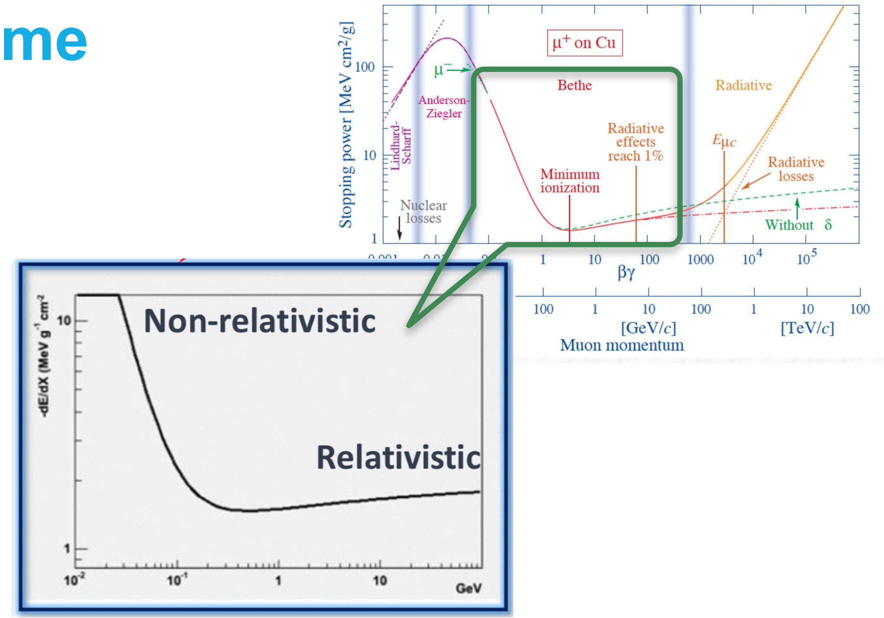
Bethe-Bloch

only depends on v (not m, p)

approx. $\sim \frac{Z^2 E}{m^2}$

important for e⁻ and ultra-relativistic particles

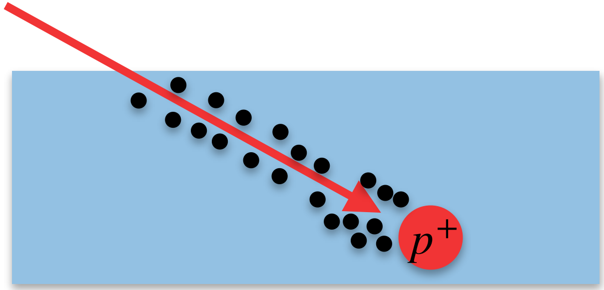
Ionization: Bethe-Bloch regime



Bethe-Bloch formula:

Describes energy loss of charged particles (ions) due to ionization of atoms.

dE/dx increases when the particle leaves relativistic regime



dE/dx depends only on v!

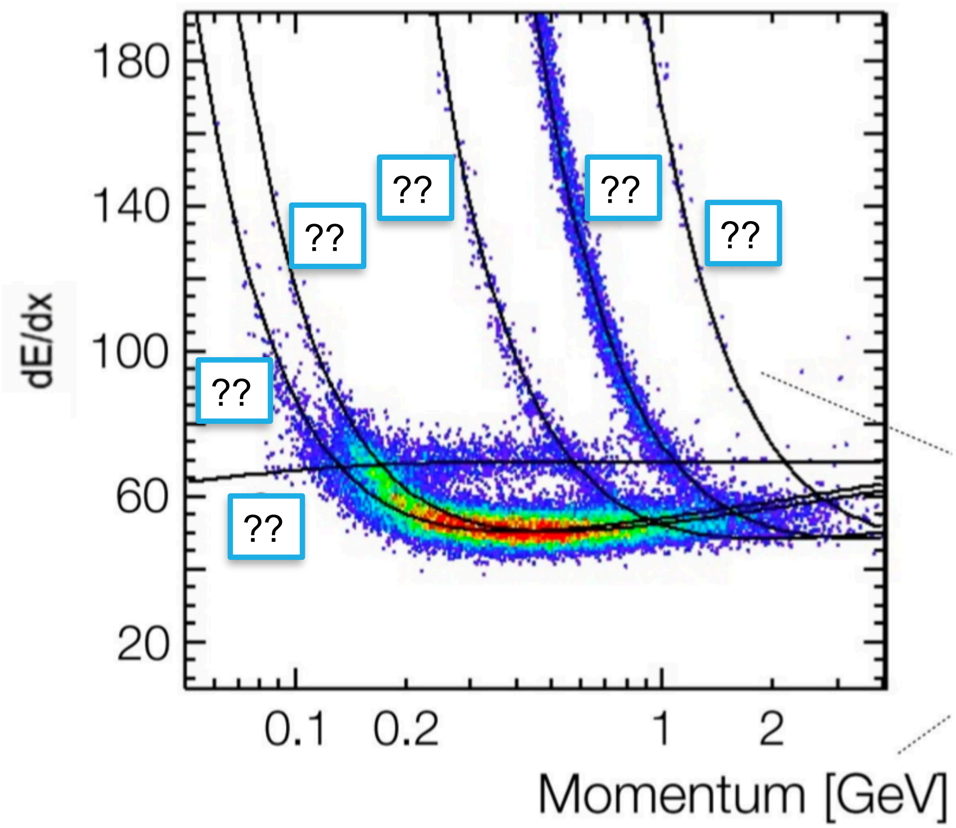
Special case electrons:

- More chaotic (small mass)
- Additional bremsstrahlung

Bethe Bloch puzzle

Which particle belongs to which energy loss function?

K p
μ
d π
e

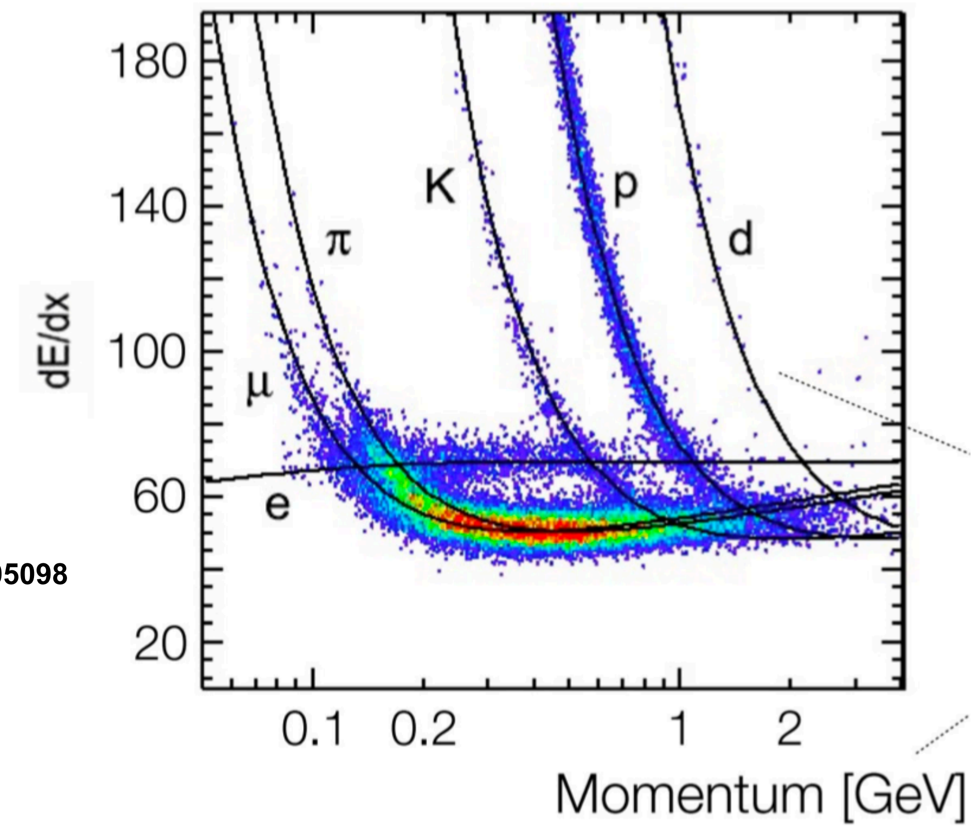


Bethe Bloch puzzle

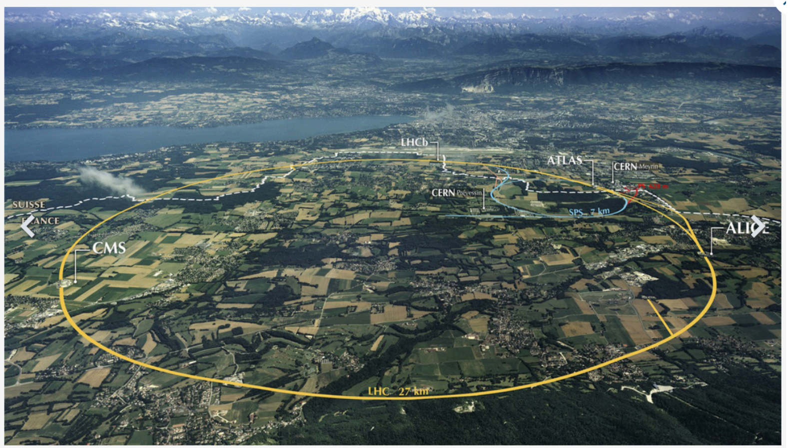
Which particle belongs to which energy loss function?

More information on how this can be measured:

www.sciencedirect.com/science/article/pii/S0168900212005098



Question: LHC with electrons?



[CERN]

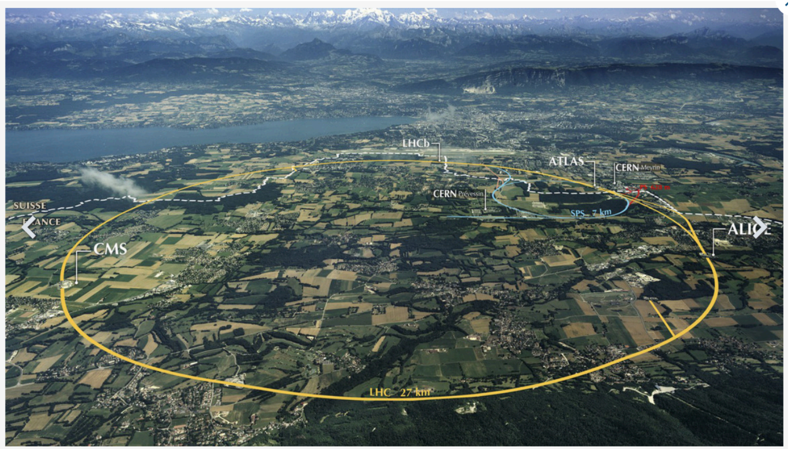
At the LHC, protons are collided with a maximal center-of-mass energy of 13 TeV. Why is it not possible to collide e+ / e- at the same energy using the LHC ring?

A) At the same energy, the bending radius in the magnetic fields is completely different for electrons than for protons

B) At comparable energies, circling electrons lose much more energy than protons. Therefore electrons need stronger acceleration in a circular collider.

C) A part of the energy in the center of mass comes from the proton mass. Since electrons are much lighter, they would need a much higher momentum to reach comparable energies.

Question: LHC with electrons?



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Radius is similar!

$$R = \frac{p_\perp}{eB}$$

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C) A part of the energy in the center of mass comes from the proton mass. Since electrons are much lighter, they would need a much higher momentum to reach comparable energies.

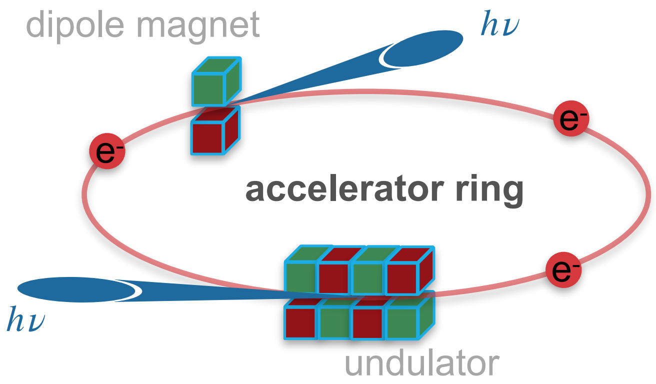
Ultra-relativistic protons!

$$E = \sqrt{m^2 + |p|^2} \approx |p|$$

Synchrotron radiation

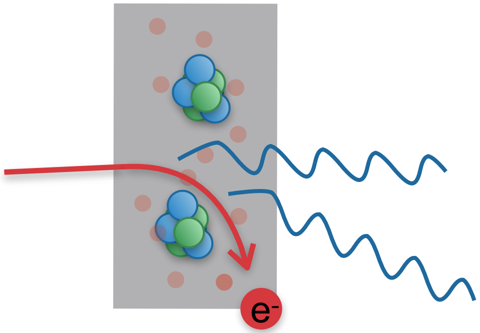
Charged particles radiate when accelerated!

Synchrotron radiation at accelerators

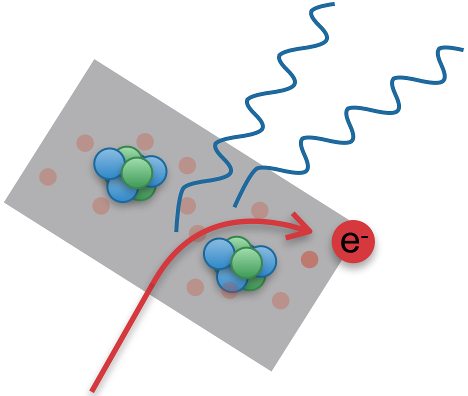


charged particles in matter:

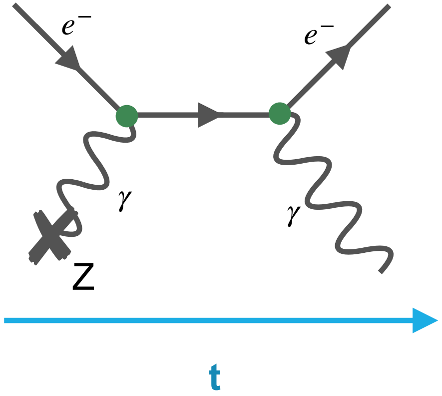
Bremsstrahlung $\left(\frac{dE}{dx}\right)_{rad}$



Bremsstrahlung



- Process of energy loss for charged particles in matter
- Charge accelerated in nuclear field ⇒ radiation of x-rays



Dependencies (approximately)

$$\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{rad} \sim \frac{Z^2 E}{m^2}$$

⇒ **important for electrons and ultra-relativistic particles**

exponential energy decrease if radiation dominated

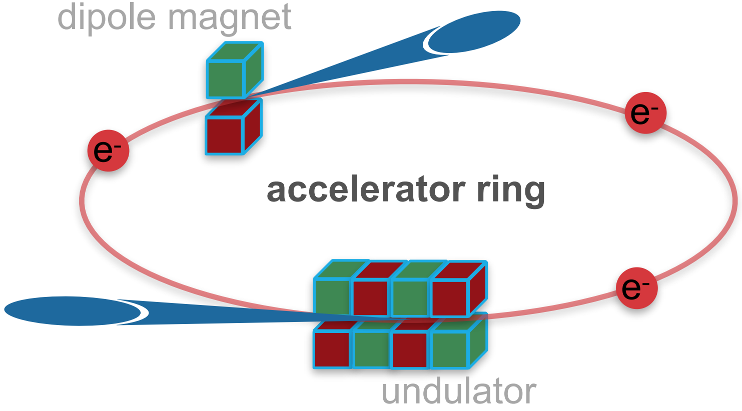
$$E(x) = E(0)\ e^{-\frac{x}{X_0}}$$

"radiation length" X_0

Synchrotron radiation and accelerators

radiated power on circular motion: $P_{rad} \sim \frac{E^4}{m^4 \; R^2}$ (exercise)

centripetal acceleration!



	LEP e^+/e^-	vs	LHC p^+
beam energy	100 GeV		6.5 TeV
loss / turn	3 GeV		7 keV

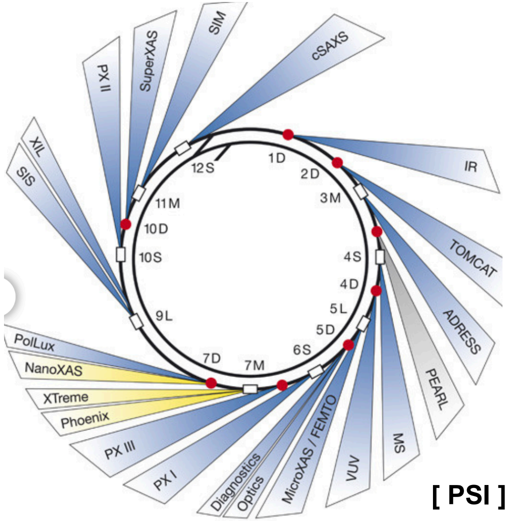
Application: **best x-rays ever!**

synchrotron light sources

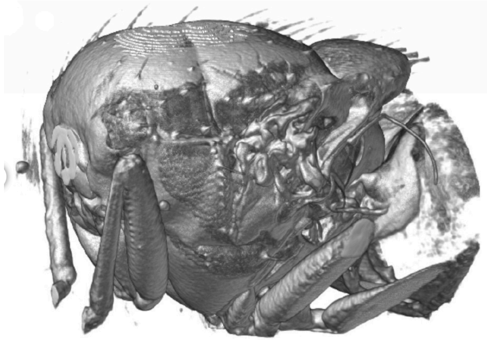
at PSI: SLS and SwissFEL

Swiss Light Source at PSI

[PSI]



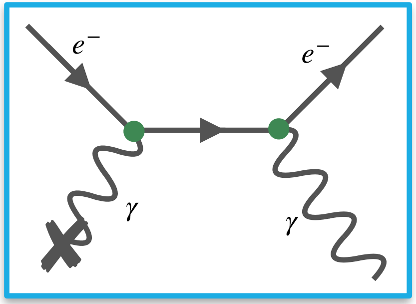
[PSI]



left: x-ray of a fly (alive, in motion)

more: https://www.psi.ch/en/media/our-research/x-rays-film-inside-live-flying-insects-in-3d

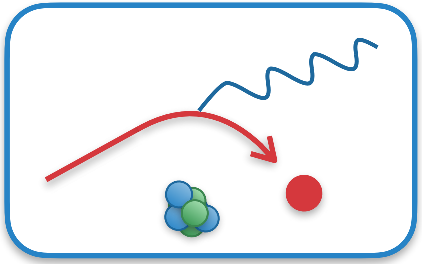
Bremsstrahlung vs synchrotron radiation



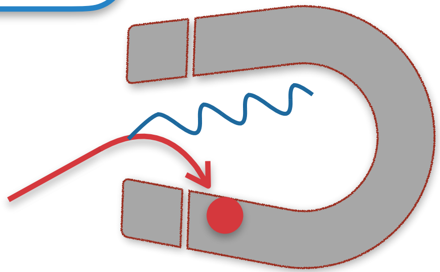
Without external acceleration (by exchange of virtual photon) it is not possible for electrons to irradiate a photon.

Where does this external momentum come from…

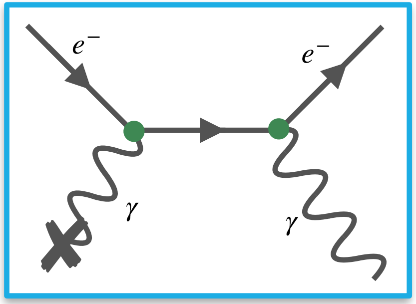
A) … in the case of bremsstrahlung of electrons in matter?



B) … in the case of electrons turning in a magnetic bending field?



Bremsstrahlung vs synchrotron radiation



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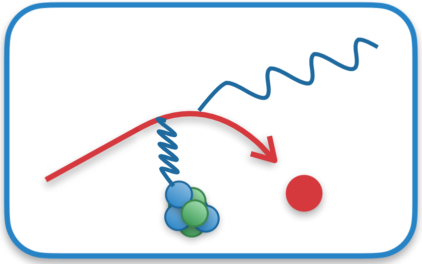
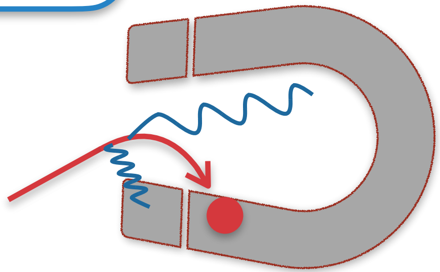


-> exchange of momentum with nucleus

B) … in the case of electrons turning in a magnetic bending field?



-> coupling of virtual photon to (electro-) magnetic field

(magnet experiences tiny momentum transfer)

Group activity: summarize interaction of particles in matter together

Charged particles

Bethe bloch formula

IONISATION
- dominant for non-relativistic particles
-velocity dependence non-relativistic part
-causes Bragg peak
due to low energy particles
-transition to relativistiv part around particle mass
- cancer treatment

RADIATION
- strong in electrons
- Bremsstrahlung
- exponential(stochastic)
- relativistic regime

Heavy charged (protons): little radiative losses
rutherford/mott cross section

Photons

- photo effect(low energy)
-compton scattering
virtual and real photons
pair creation(high energy)
exponential decay (intensity loss)
Compton Effect
-strong at low energies
(no bragg peak)

Overview: Energy loss of e/m particles in matter

Photons

$$I(x) = I_0 \cdot e^{-\mu x}$$

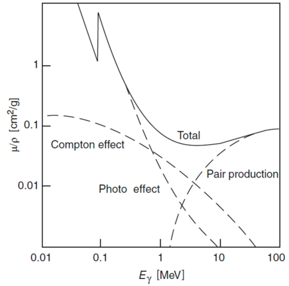
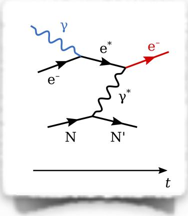
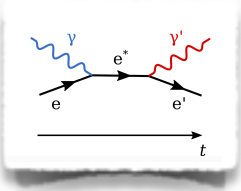


Photo effect



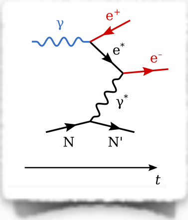
$$\mu_{PE} \sim \frac{Z^n}{E_\gamma^{3.5}}$$

Compton effect



$$\mu_{PE} \sim \frac{Z}{E}$$

Pair production



$$\mu_{PC} \sim Z^2 E_\gamma$$

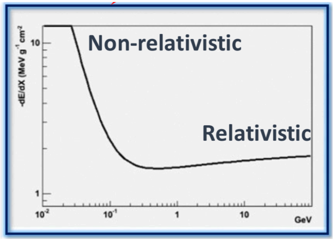
Additionally: elastic photon scattering

Charged particles

$$\frac{dE}{dx} = \left(\frac{dE}{dx}\right)_{\text{col}} + \left(\frac{dE}{dx}\right)_{\text{rad}}$$

ionization losses

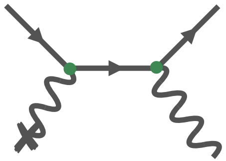
Bethe-Bloch



all particles similar
only depends on v

radiative losses

$$\left(\frac{dE}{dx}\right)_{rad} \sim \frac{Z^2 E}{m^2}$$



- important for e^+/e^-
- heavier particles: only ultra-relativistic

The group Monte Carlo

Processes photons:

Photo effect *Compton effect* *Pair creation*

Processes electrons:

Bremsstrahlung *Ionization*

Electron with 100 MeV falls into lead block.

Which processes might happen?
Together, let us invent a realistic event step by step.

(One student at a time picks a process and energies of the new particles)

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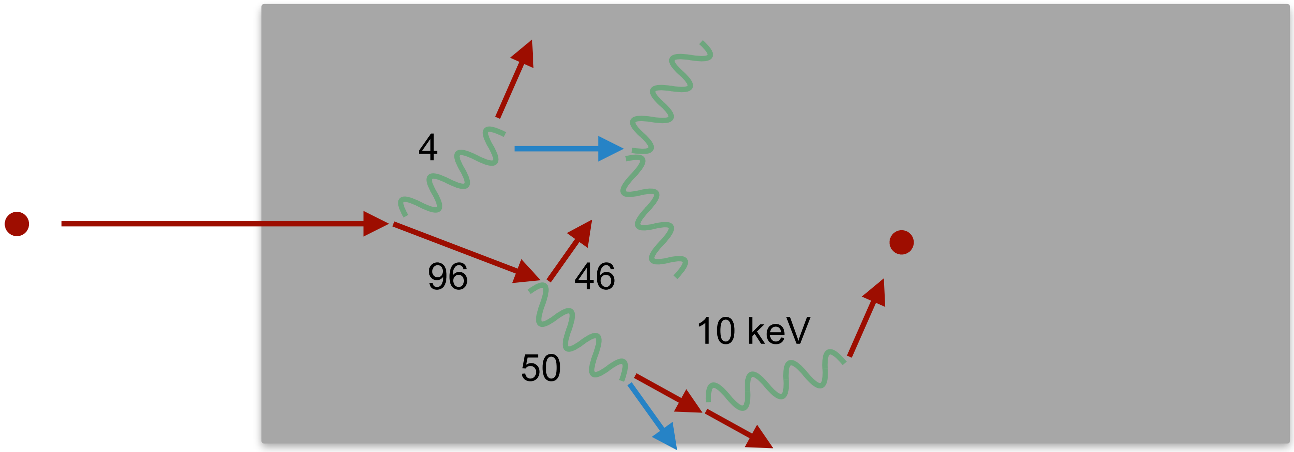
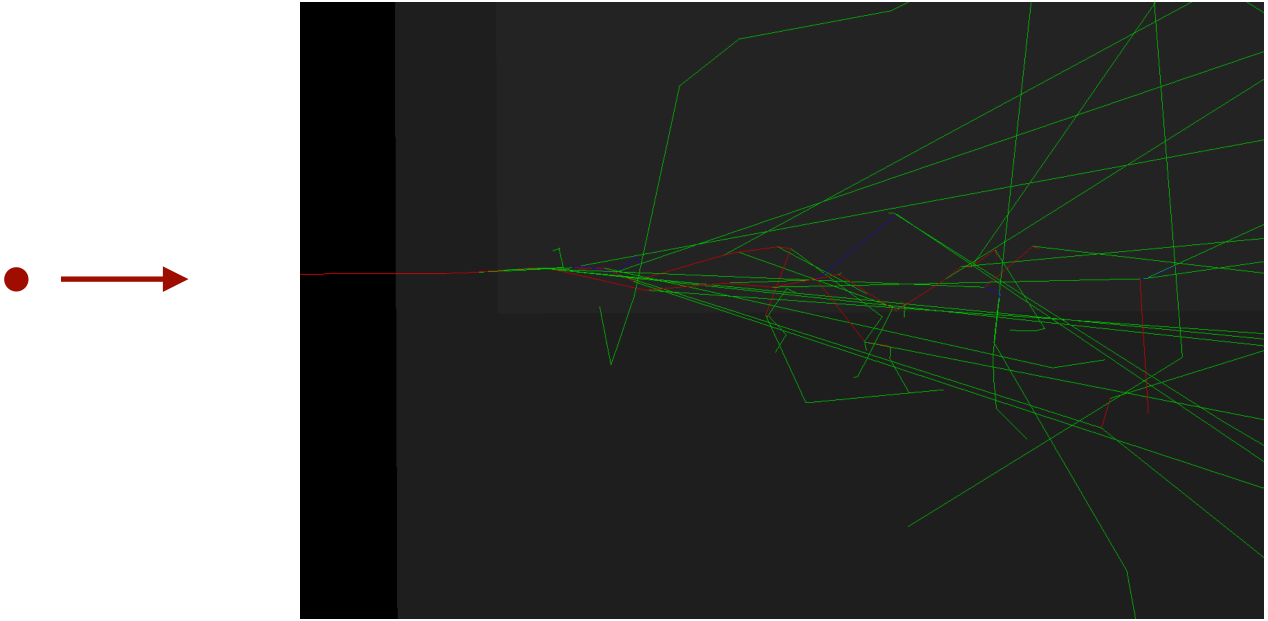
Example for result of the activity:



Example for Monte Carlo event

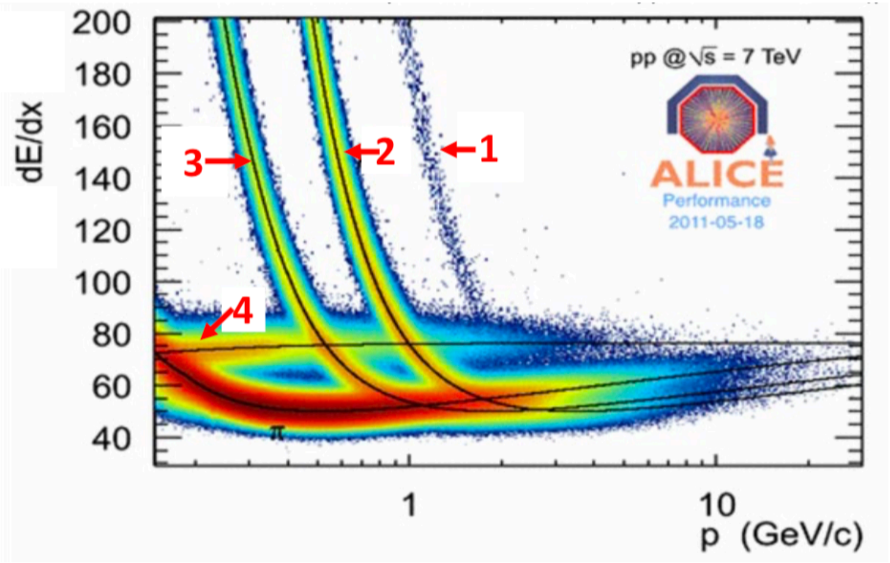


green: gamma

red: electron

blue: positron

Warmup question 1



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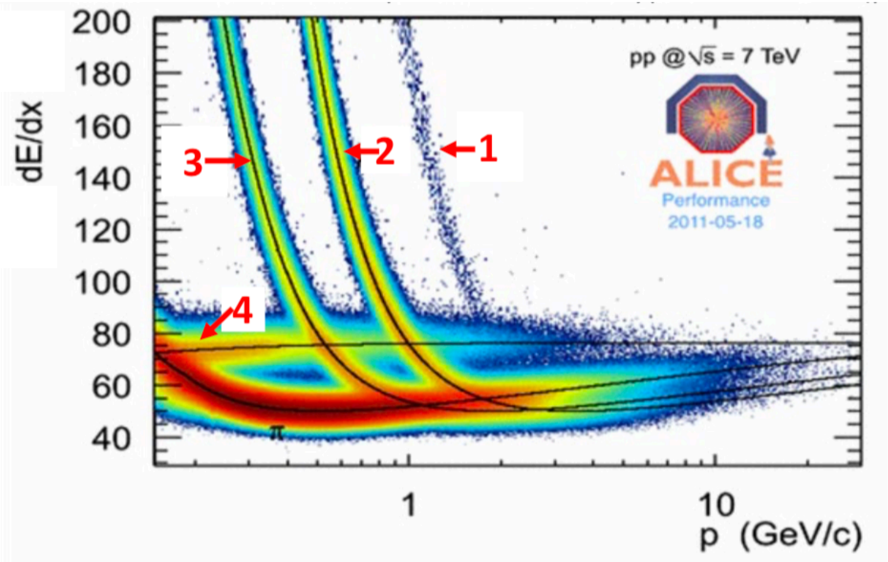

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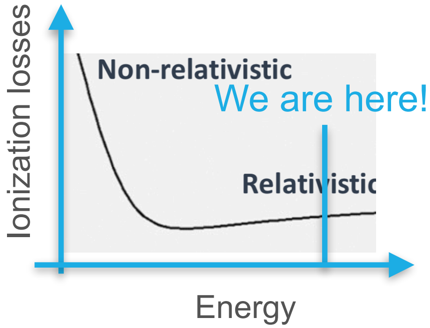

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$$E_{rad}(x) = E_{rad}(0)\ e^{-\frac{x}{X_0}}$$

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