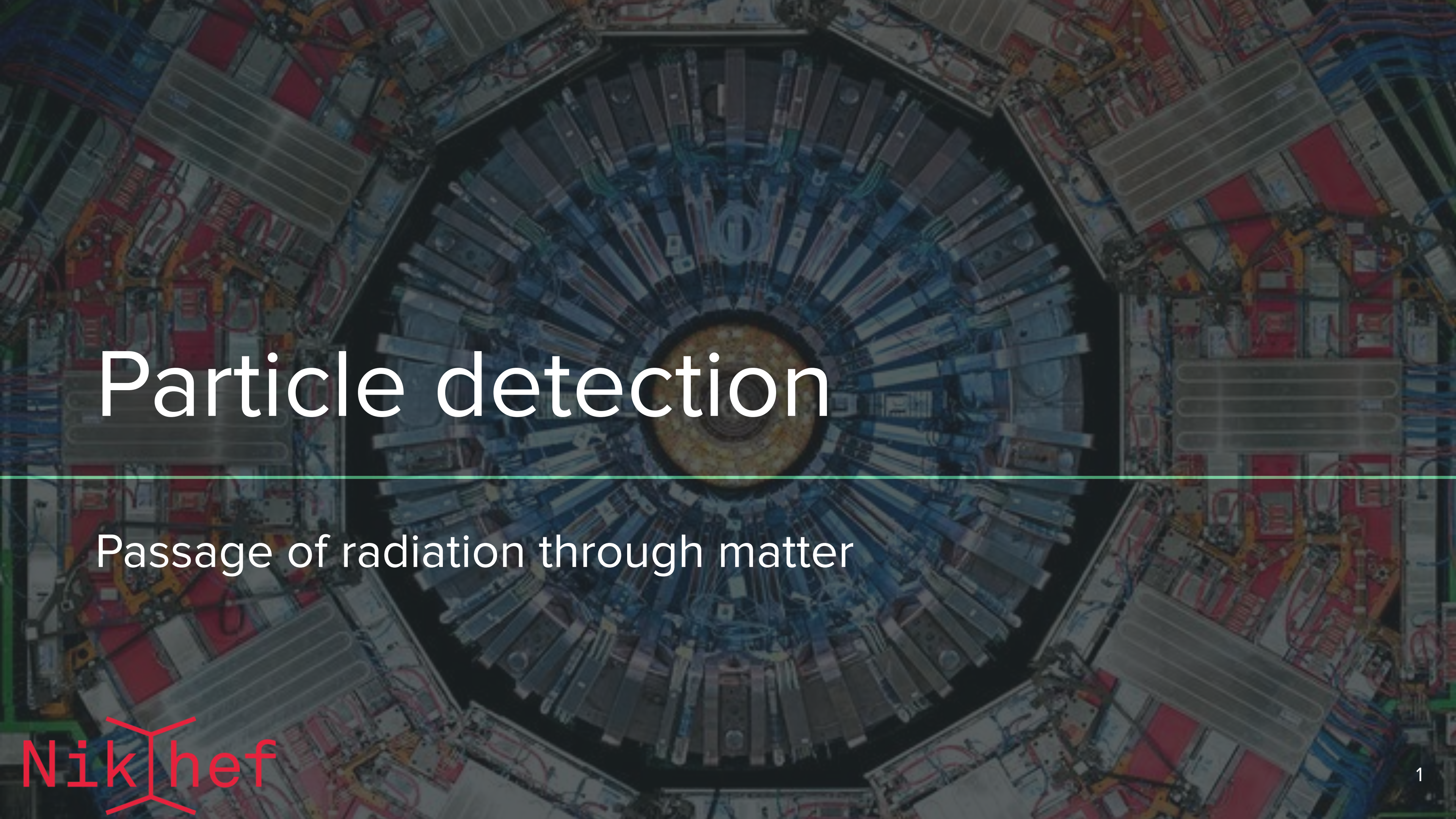


Particle detection

Passage of radiation through matter

KATRIN: neutrino mass measurement

https://www.katrin.kit.edu/img/spectrum_rdax_1200x678.jpg

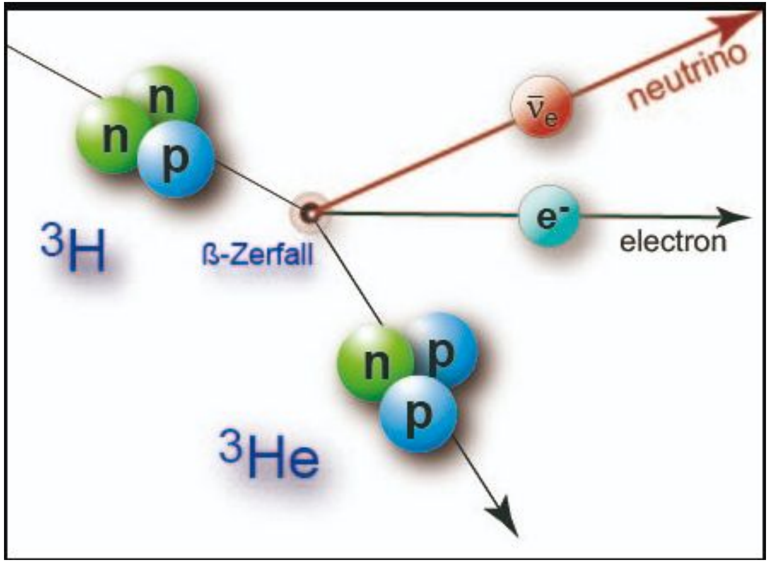
https://upload.wikimedia.org/wikipedia/commons/c/c6/Ortsdurchfahrt-Leopoldshafen.jpg

$m_\nu < 1.1$ eV (90% confidence level): twice as precise as previous measurements!

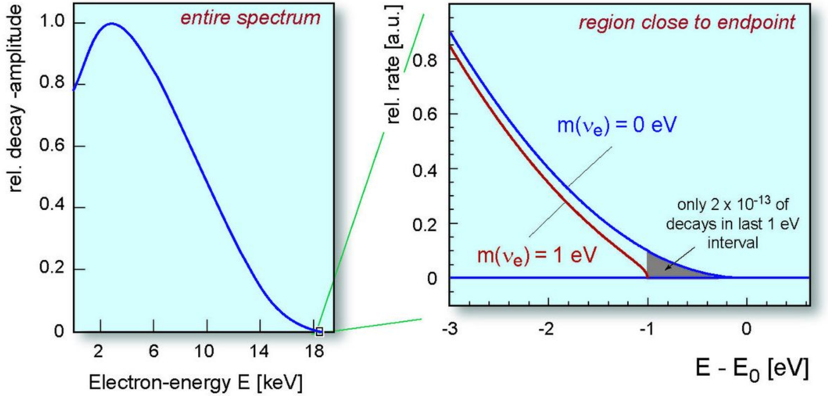
Recently published! https://arxiv.org/abs/1909.06048

KATRIN: neutrino mass measurement

Karlsruhe tritium neutrino experiment



$m_\nu < 1.1$ eV (90% confidence level)



Derive neutrino mass information from electron energy

https://www.katrin.kit.edu/img/spectrum_rdax_1200x678.jpg

https://upload.wikimedia.org/wikipedia/commons/c/c6/Ortsdurchfahrt-Leopoldshafen.jpg

Recently published!

https://arxiv.org/abs/1909.06048

Pre-work: before the lecture

Pre-work due before 2021-02-04

Watch: x-rays and proton beams for curing cancer
Curing Cancer with Proton Beams – with Suzie Sheehy
https://www.youtube.com/watch?v=ZQ7kyocgiho

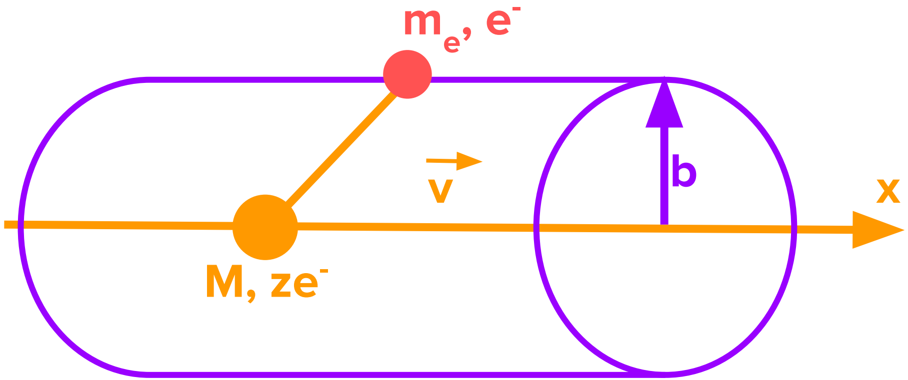
Answer the following questions in the quiz: Why do protons stop and X-rays don't? What are X-rays?

Compute the energy loss classically without quantum effects. Answer the question in the quiz: What is f_{avg} similar to in the Bethe formula?
See following slides for the exercises. This follows p22 WR Leo.

Read from the book Pixel detectors: p29-35 (2.2.2.1 and 2.2.2.2).

Classical energy loss: a collision

This exercise consists of 5 parts.



Gauss's Law:

$$\Phi_E = \oiint_S \mathbf{E} \cdot d\mathbf{A}$$

Bohr computed the energy loss of a heavy charged particle of mass M with charge ze^- in a collision with an electron. Using impulse

$$J = \int F \, dt$$

1. Show that the energy gained by the electron $\Delta E(b) = J^2/(2m_e)$ in this collision with the particle of mass $M \gg m_e$ is equal to

$$\Delta E(b) = 2z^2e^4/(m_e b^2 v^2)$$

You can assume an infinite cylinder centered on the heavy particle trajectory with the radius passing through the position of the electron.

Classical energy loss: validity of formula

At very large b, the time is no longer short, so the impulse calculation is invalid. Similarly at b=0, the formula explodes.

2. Show that the maximum transferable energy assuming maximum relativistic kinetic energy transfer in a head-on collision with momentum conservation gives a minimum b: $b_{min}=ze^2/(\gamma m_e v^2)$ with $\gamma = 1/(1-v^2/c^2)^{-½}$.

3. Show that assuming collision time $t \ll \tau = 1/f_{avg}$ for an average orbital electron frequency f_{avg}, which allows to assume the electron is at rest, gives a maximum b: $b_{max}= \gamma v/f_{avg}$. This is a distance at which the minimum kinetic energy is transferred, $E_{min}= I$ with I the mean ionization potential.

Classical energy loss: stopping power in material

4. Assuming a volume element of $dV = 2\pi b\, db\, dx$ and an electron density N_e, compute the energy lost to all electrons between b and db over a distance dx:
$-dE(b) = \Delta E(b)\, N_e dV$.

5. Write Bohr's classical formula for the energy loss or stopping power $-dE/dx$.

Solutions: will be given next week

Lecture on 2021-02-04 09:00

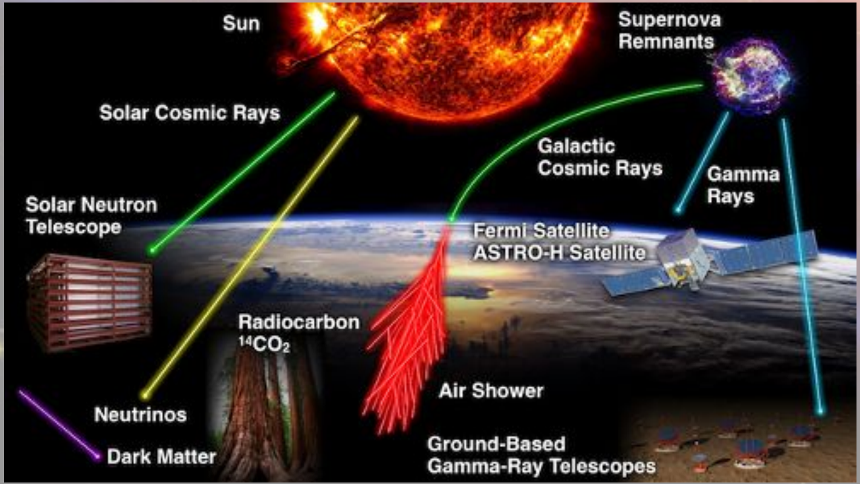
Particles from outer space

10000 times a second you have particles from cosmic rays passing through you

HESS: high energy stereoscopic system, in Namibia, can detect gamma rays

http://www2.cnrs.fr/sites/en/image/hess_new_large_hd.jpg

What are these particles and how do they behave?
What are we and what is the universe made of?

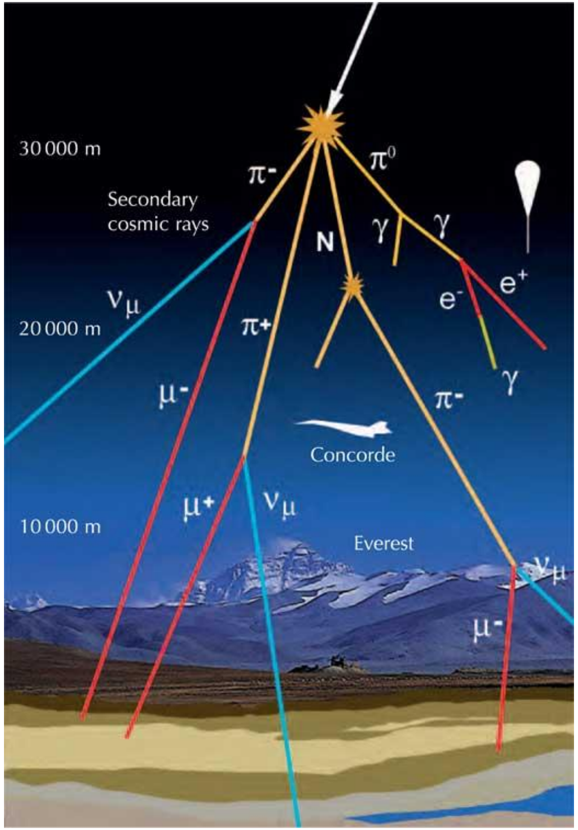


http://www.isee.nagoya-u.ac.jp/en/assets_c/2016/03/study01_1-thumb-500xauto-153.png

What are cosmic rays?
What do we detect?

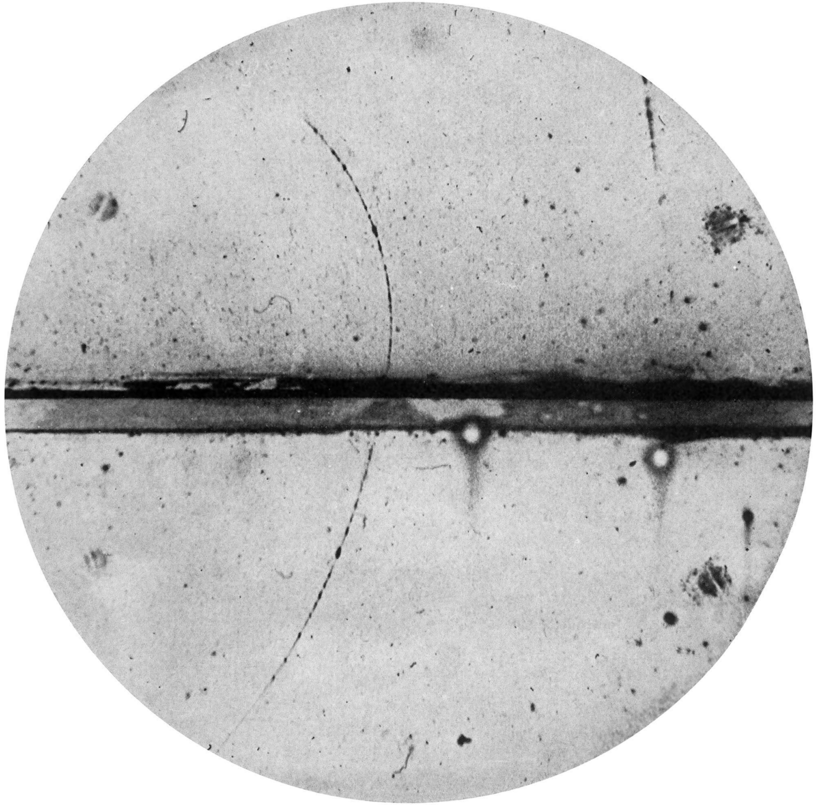
Passage of radiation through matter

Why do the muons reach the earth and the electrons do not?



To detect and identify particles, we need material and we do not want material

What do you see?

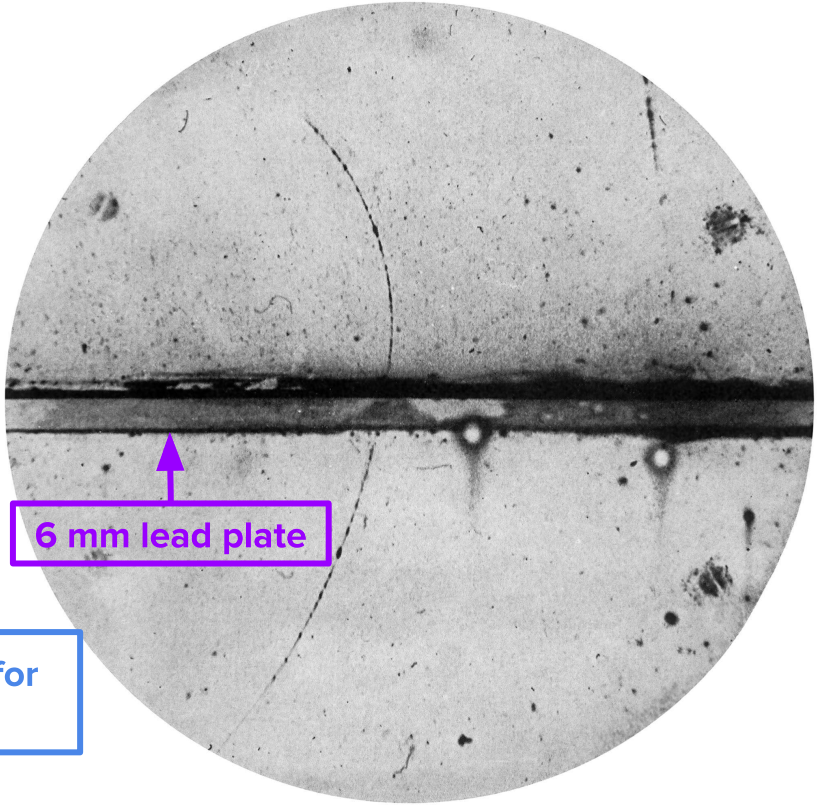


Discovery of antimatter

https://upload.wikimedia.org/wikipedia/commons/6/69/PositronDiscovery.jpg
C.D. Anderson https://journals.aps.org/pr/pdf/10.1103/PhysRev.43.491

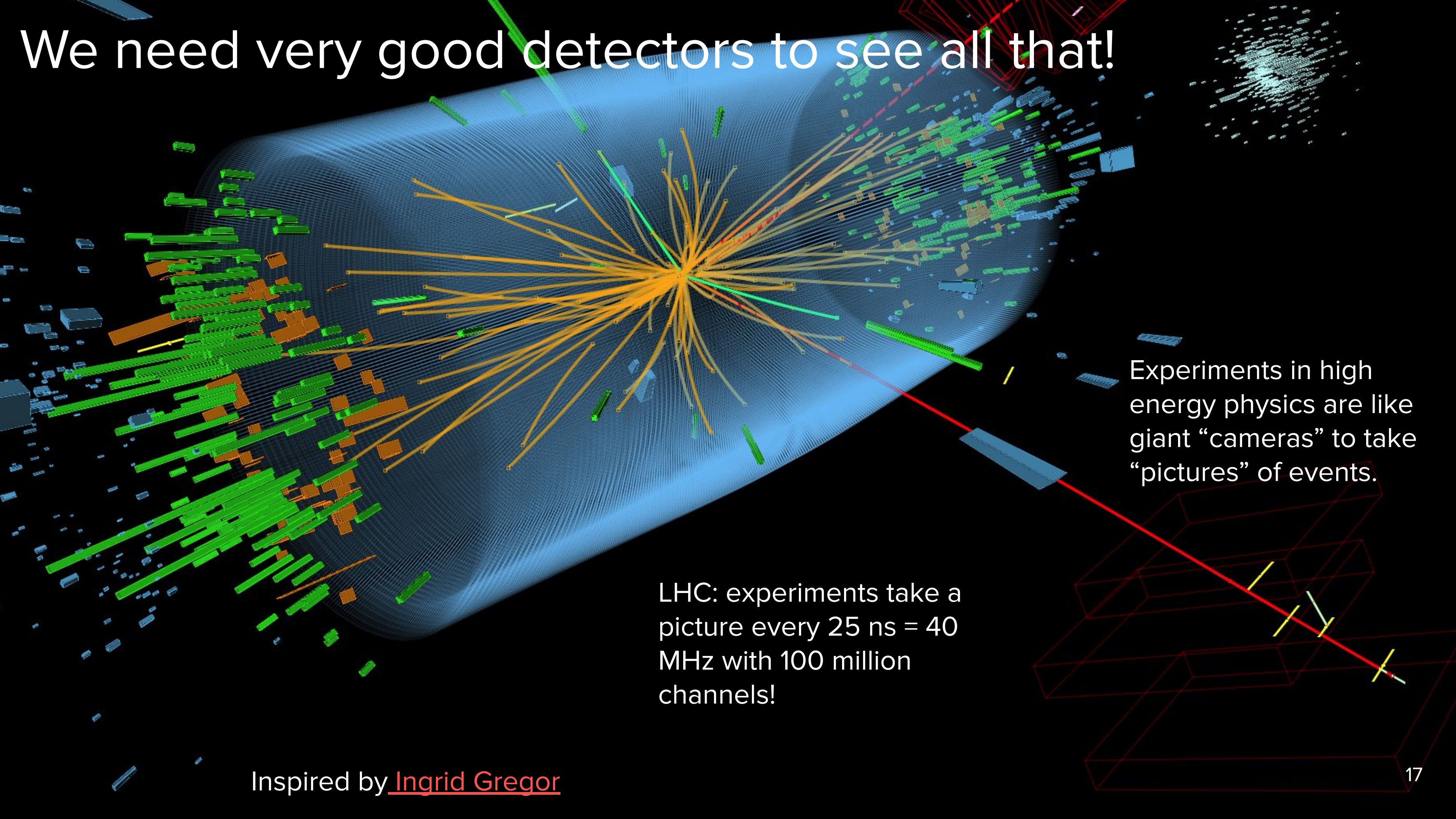
The first positron ever observed!

Wilson cloud chamber: gaseous mixture of supersaturated water or alcohol. Energetic particle ionizes gas and ions form condensation centers visible as a 'cloud'.



15000 Gauss = 1.5T magnetic field Wilson chamber for detecting cosmic rays

We need very good detectors to see all that!

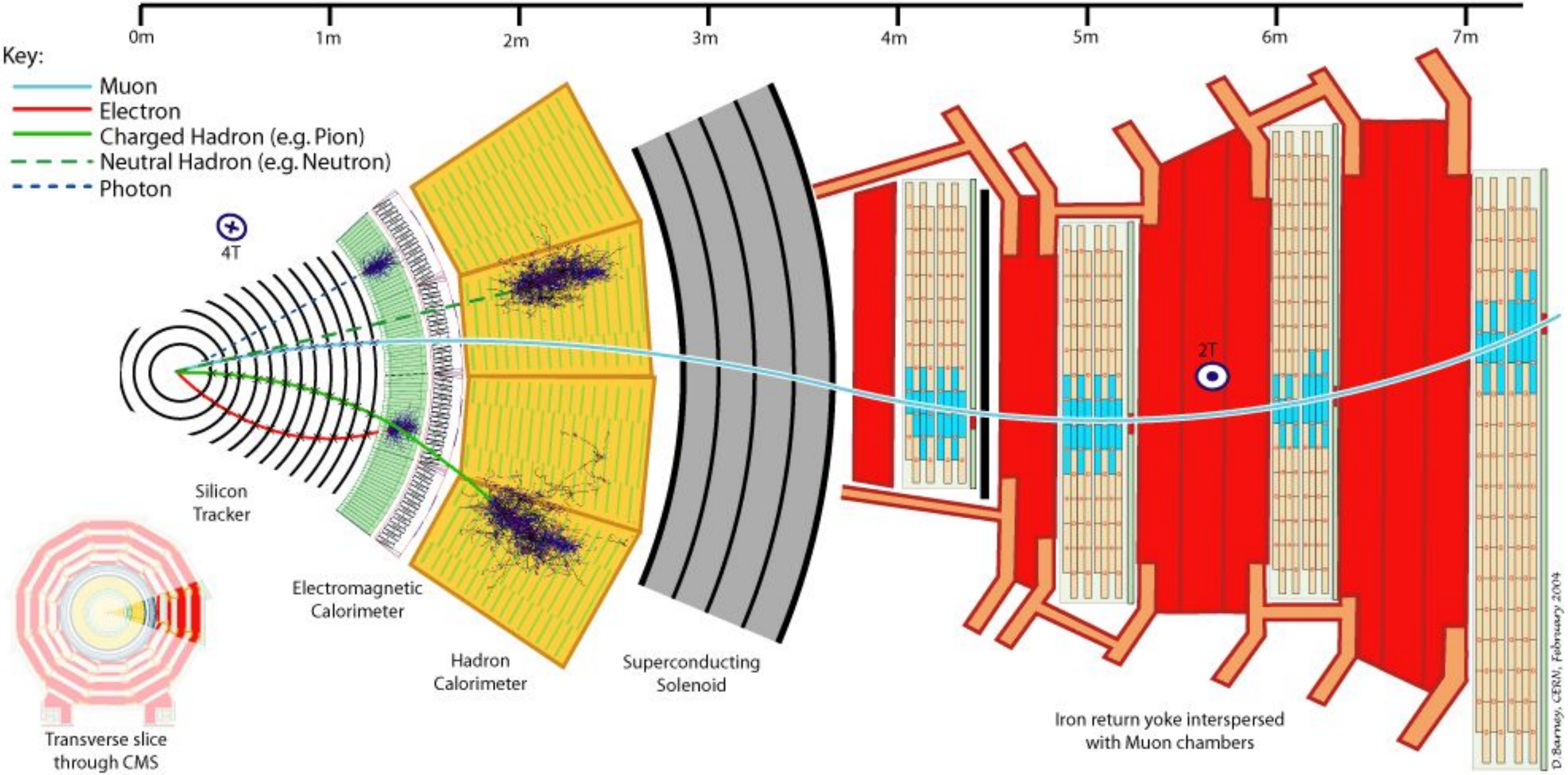


Experiments in high energy physics are like giant “cameras” to take “pictures” of events.

LHC: experiments take a picture every 25 ns = 40 MHz with 100 million channels!

Inspired by Ingrid Gregor

What do you notice in the particle behavior here?



To detect and identify particles, we use their interaction with matter and we do not want too much material

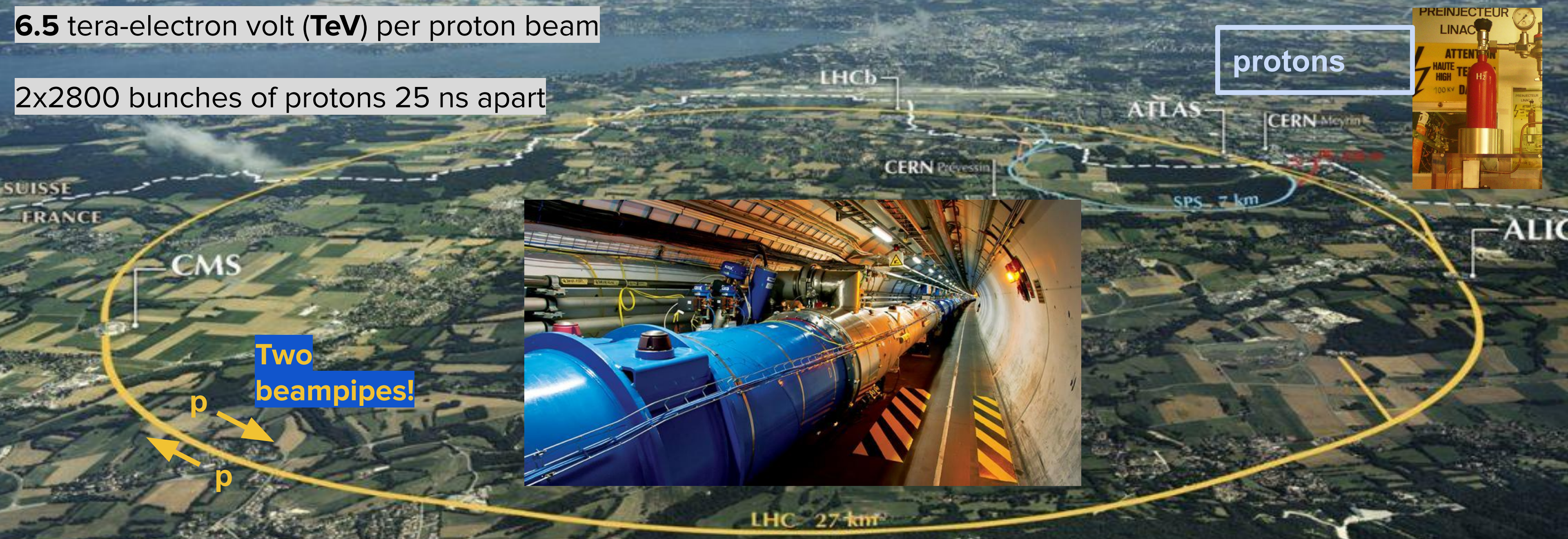
100 meters underground in the CMS cavern

Large Hadron Collider

Hadron: composite particle made of quarks held together by the strong force

6.5 tera-electron volt (**TeV**) per proton beam

2x2800 bunches of protons 25 ns apart



Two beampipes!

https://www.youtube.com/watch?v=NhXMXiXOWAA

https://cdn.zmescience.com/wp-content/uploads/2015/05/cern-lhc-aerial.jpg

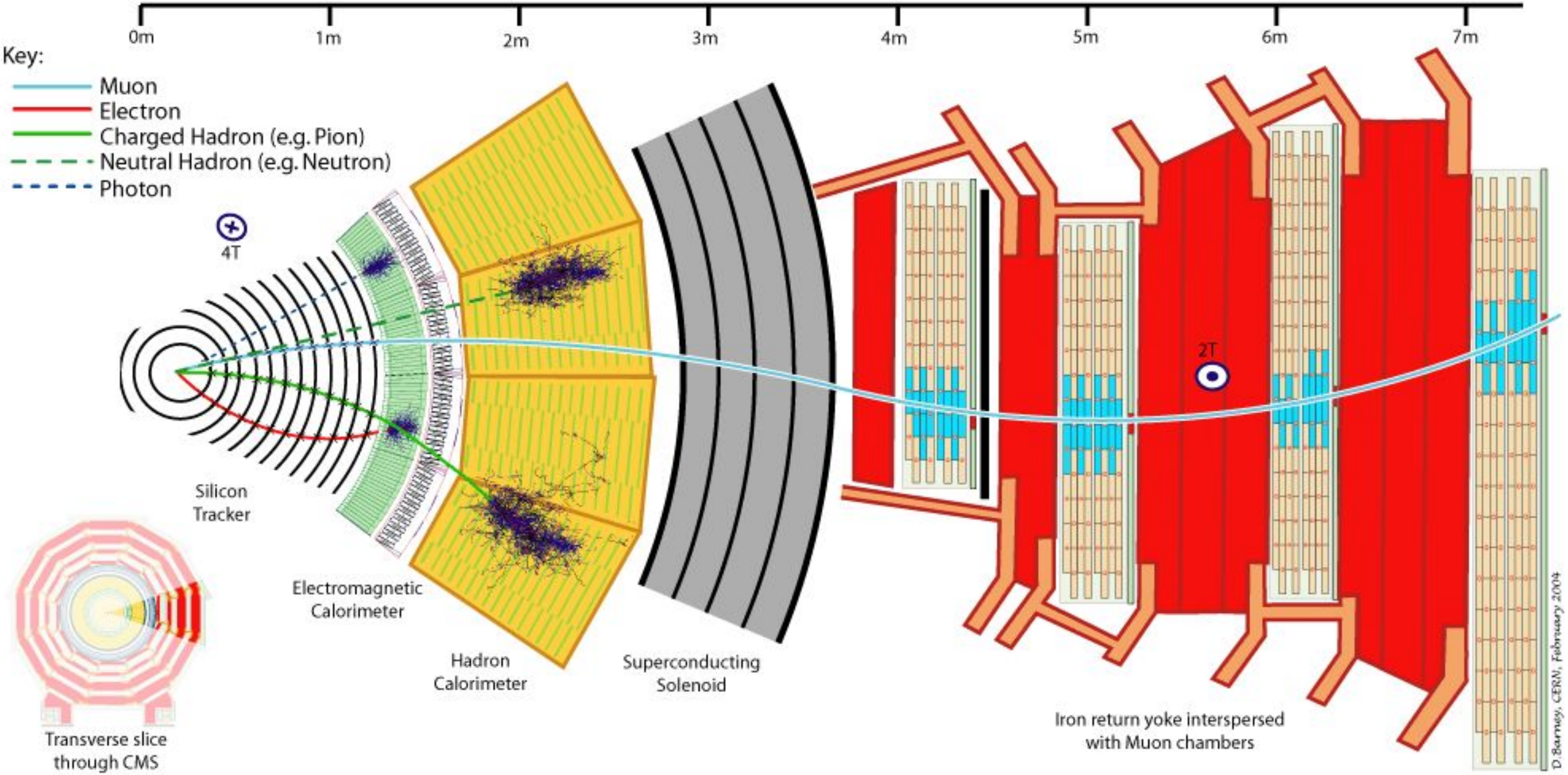
Http://sites.uci.edu/energyobserver/files/2012/11/lhc-aerial.jpg

https://home.cern/sites/home.web.cern.ch/files/image/inline-images/old/lhc_long_1.jpg

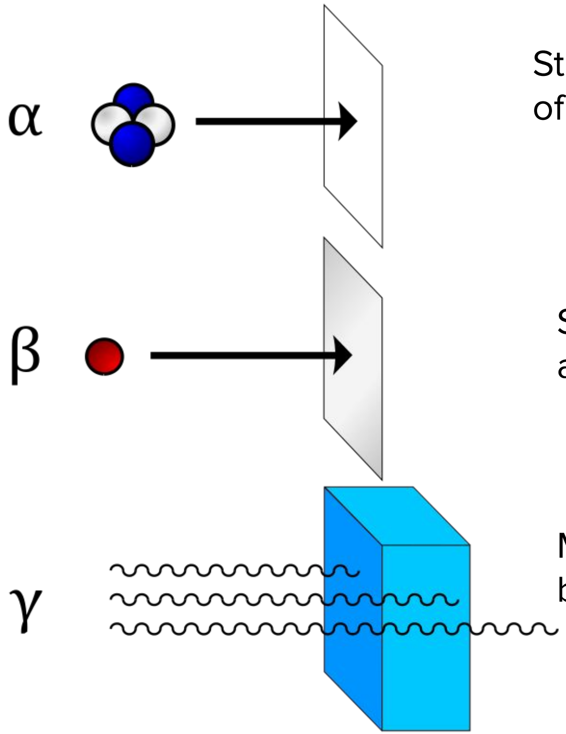
https://upload.wikimedia.org/wikipedia/commons/6/62/CERN_LHC_Proton_Source.JPG

https://www.sciencemag.org/sites/default/files/styles/inline__699w__no_aspect/public/ca_0914NID_CMS_Detector_online.jpg?itok=EzPQHkIv

Different detector types for different measurements



Passage of radiation through matter



Helium-4 nucleus

Stopped by a sheet of paper

electrons

Stopped by aluminum plate

photons

Many are stopped by a block of lead

What do we detect?

How can we detect these particles?

Directly detect:

Decay products

jets

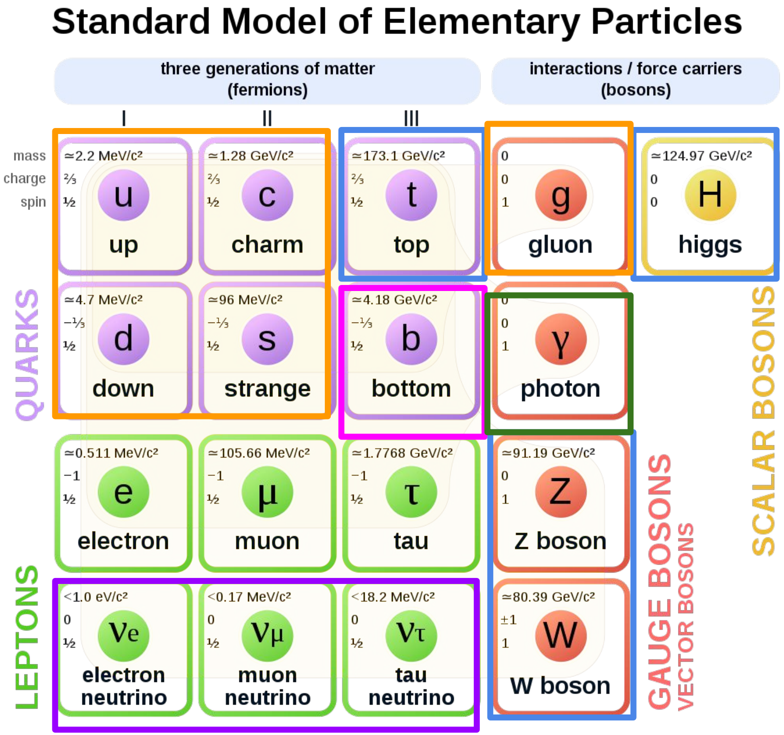
Indirectly detect:

Missing energy

Secondary vertex + jets

Neutral particles

Should be able to detect and identify:
$e^{\pm}, \mu^{\pm}, \gamma, \pi^{\pm}, K^{\pm}, p^{\pm}, K^0, n$
using mass, charge, interaction



From https://upload.wikimedia.org/wikipedia/commons/0/00/Standard_Model_of_Elementary_Particles.svg

What do we measure and how?

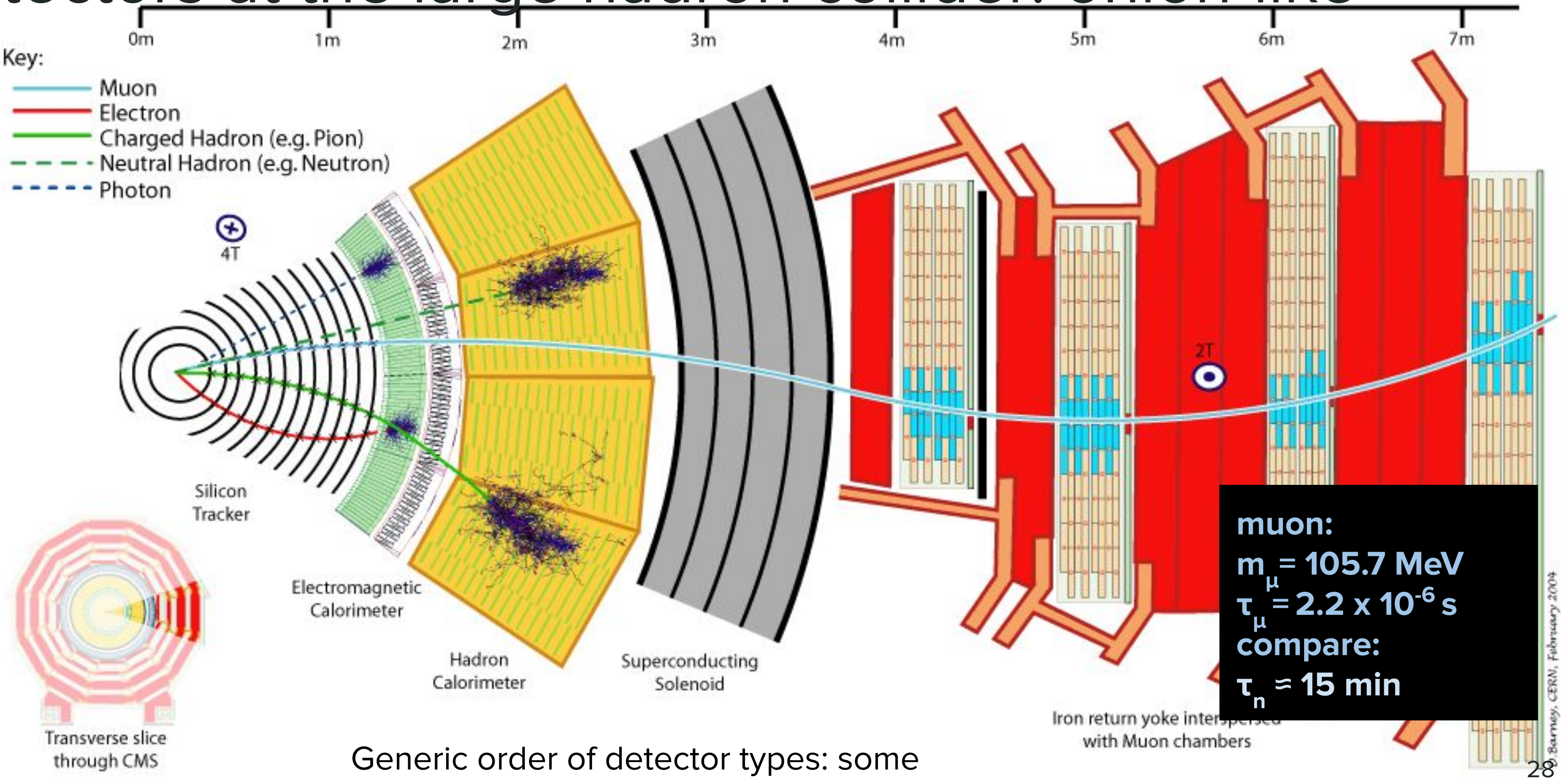
Observable	**Measurable quantity**
Momentum (p)	Bending radius in magnetic field
Speed (v)	Time of flight, Cherenkov radiation
Charge (Q)	Bending in magnetic field
Lifetime (τ)	Distance traveled before decay
Energy (E)	Absorption in calorimeters
Mass (m)	Indirectly from momentum
Spin	Angular distributions

- $d = c\tau\gamma$
- $\gamma = 1/\sqrt{(1-\beta^2)}$
- $\beta = v/c$
- $E^2 = m^2c^4 + p^2c^2$
- $p = \gamma mv = mv/\sqrt{(1-v^2/c^2)}$

For some examples of measuring spin see https://arxiv.org/pdf/1202.6660.pdf and http://moriond.in2p3.fr/QCD/2013/proceedings/Muehlleitner.pdf

Need 1) a magnetic field and 2) interaction with material

Detectors at the large hadron collider: onion-like



http://inspirehep.net/record/826852/files/EPS_CMS_Slice.png

muon:

m_μ = 105.7 MeV

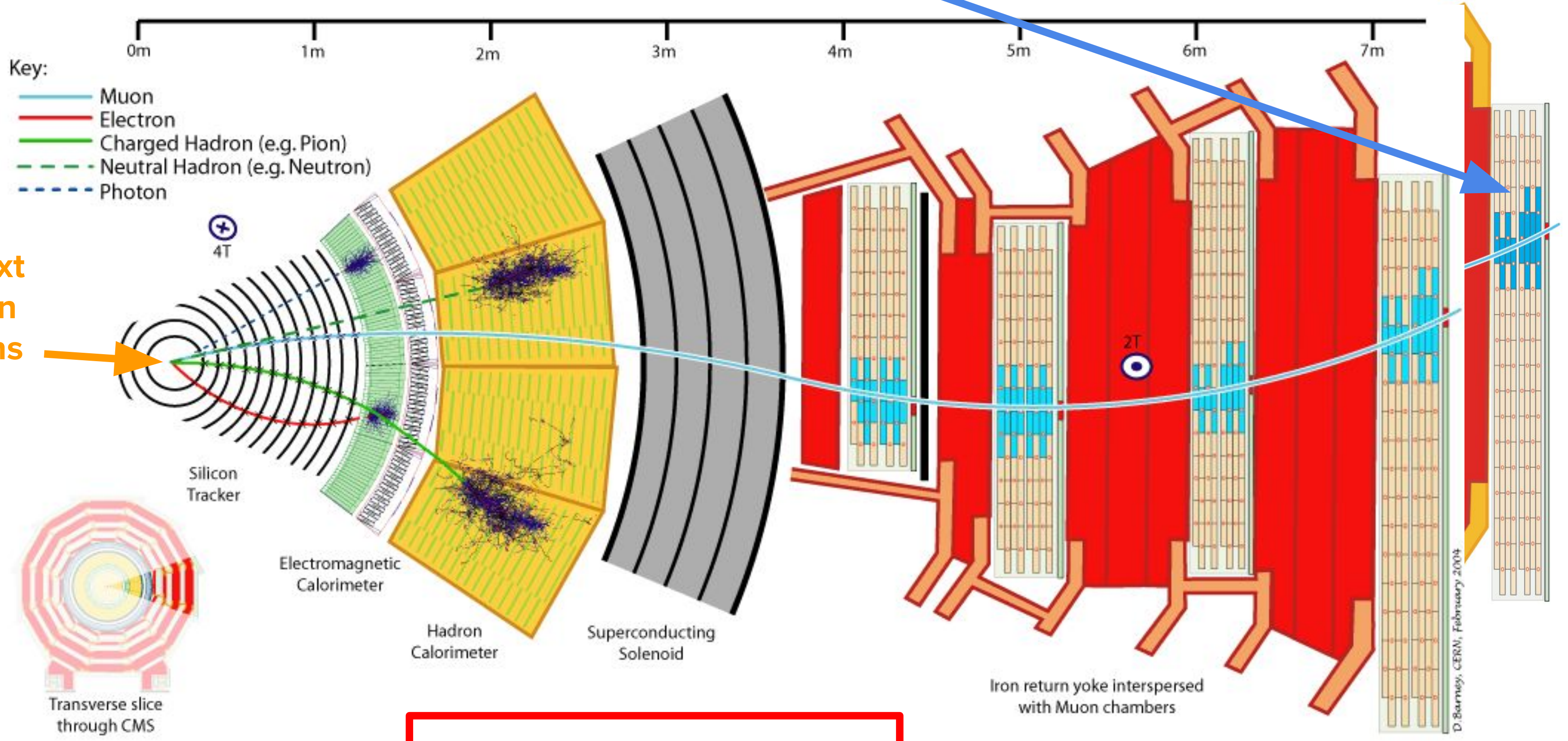
τ_μ = 2.2 x 10^{-6} s

compare:

τ_n ≈ 15 min

Generic order of detector types: some measurements destructive!

Note when the muon arrives here

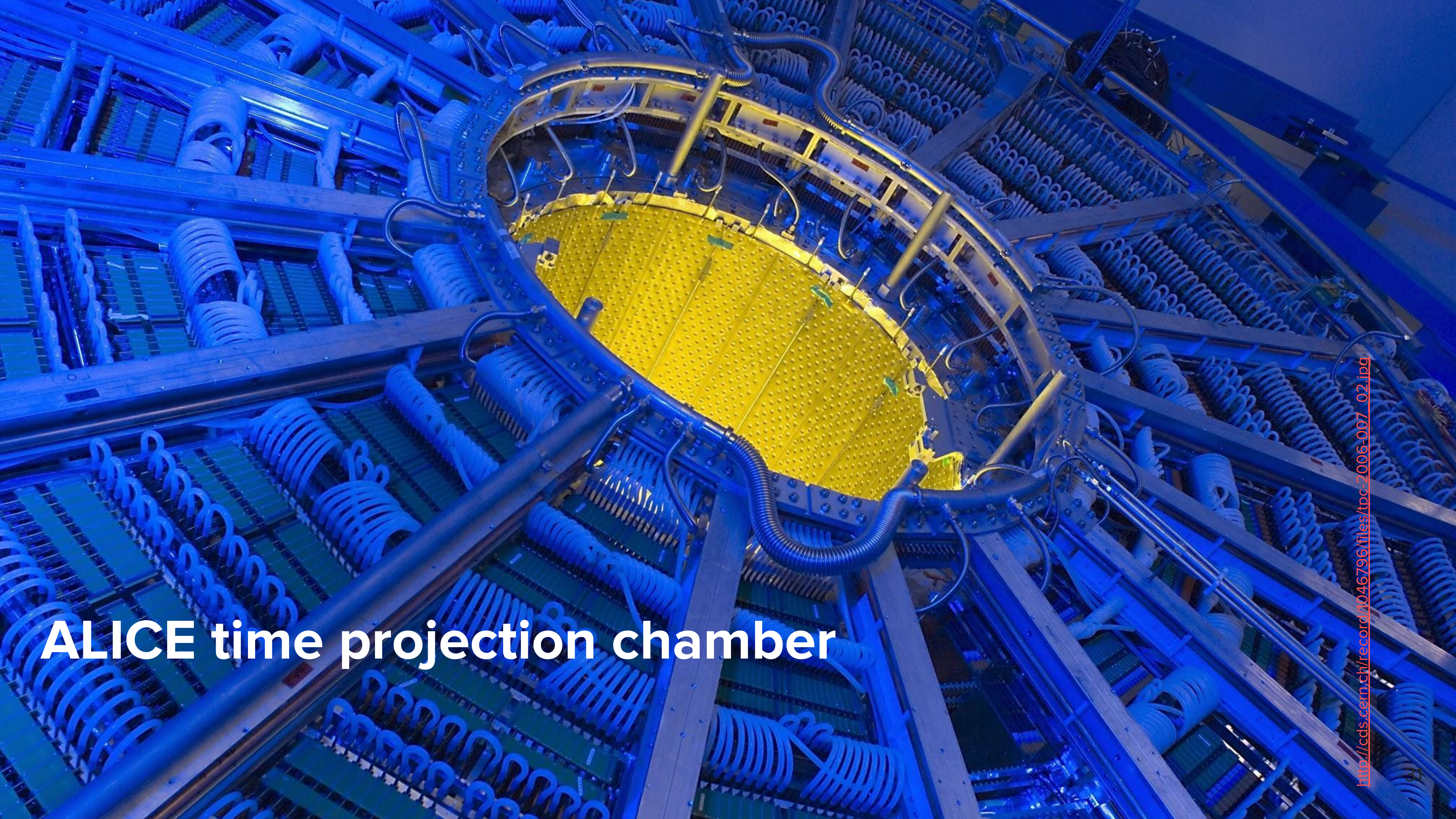


The next collision happens here:

25 ns • c ≅7.5m

http://inspirehep.net/record/826852/files/EPS_CMS_Slice.png

Ionization of a gas

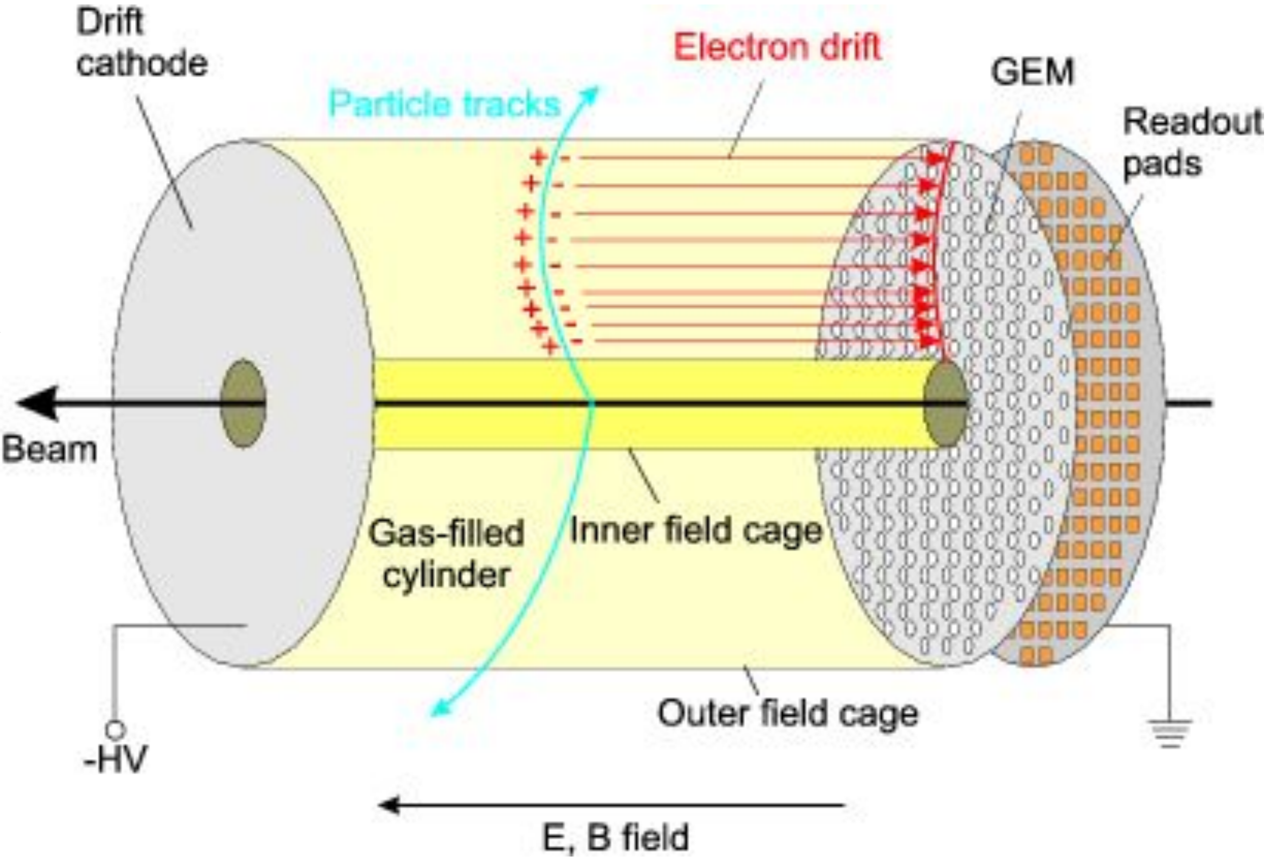


ALICE time projection chamber

http://cds.cern.ch/record/1046796/files/tpc-2006-007_02.jpg

TPC

1. Ionization of gas in **chamber** with electric field causes electron drift
2. Signal gets amplified, in this case by gas electron multipliers ➜ electron avalanche
3. Readout pads can detect signal that can be **projected** onto trajectory
4. z (along beam) information from **timing**



http://aliceinfo.cern.ch/Public/Objects/Chapter2/DetectorComponents/tpc_operation.gif

Energy loss in matter

Bohr vs Bethe formula for energy loss

Parts from Erika Garutti

Bethe:

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0} \right)^2 \cdot \left[\ln\left(\frac{2 m_e c^2 \beta^2}{I \cdot (1-\beta^2)} \right) - \beta^2 \right]$$

$I = \hbar f_{avg}$

Electron density n (N_e):

$$n = \frac{N_A \cdot Z \cdot \rho}{A \cdot M_u}$$

Bohr (from your pre-work):

$$-\frac{dE}{dx} = \frac{4\pi z^2 e^4}{m_e v^2} N_e \ln \frac{\gamma^2 m_e v^3}{z e^2 f_{avg}}$$

ρ is the density of the material, Z its atomic number, A its relative atomic mass, N_A the Avogadro number and M_u the Molar mass constant.

Bohr vs Bethe formula for energy loss

Bethe:

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\boxed{\beta^2}} \cdot \left(\frac{e^2}{4\pi\varepsilon_0} \right)^2 \cdot \left[\ln\left(\frac{2 m_e c^2 \beta^2}{I \cdot (1-\beta^2)} \right) - \beta^2 \right]$$

Dominates for lower non-relativistic energies: dE/dx decreases until a minimum is reached at around v=0.96c.

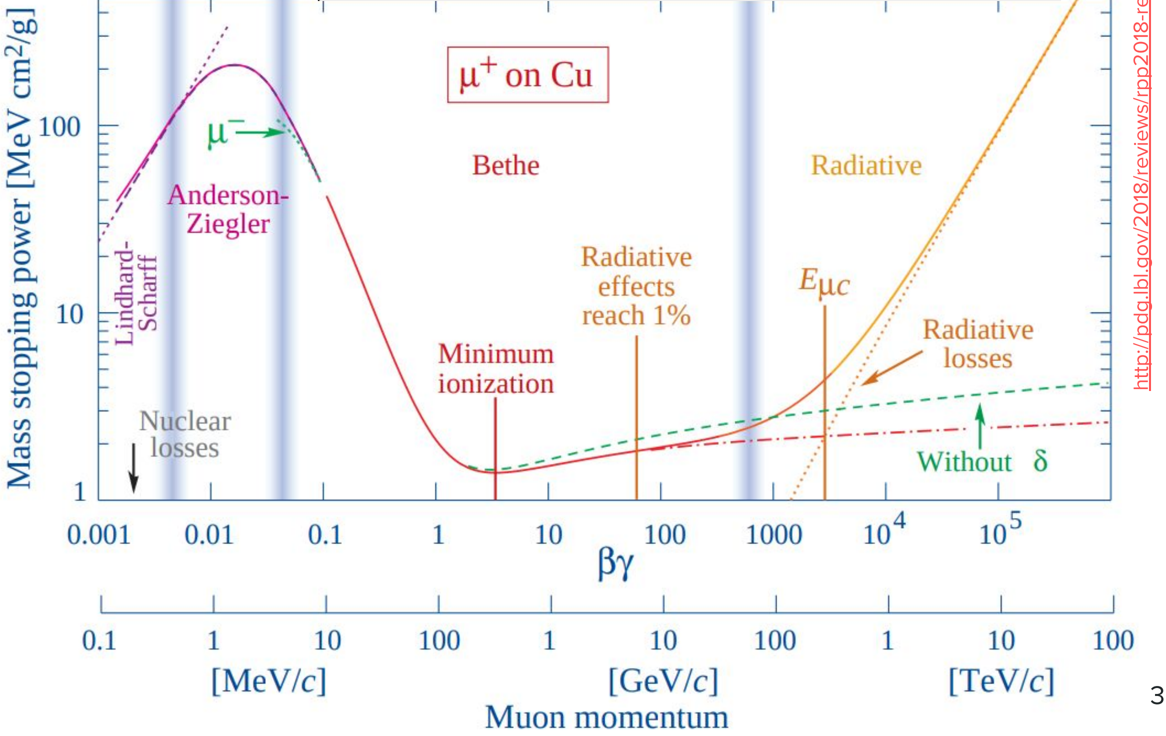
At much larger energies: dE/dx rises again due to log term -- save a **density correction:** outer electrons are shielded by inner electrons polarized by electric field of incoming particle

Ionization loss

- Can measure ionization loss dE/dx
- K is a coefficient: K = .307 MeV mol^{-1}cm^{-2}
- I is the mean excitation energy

Depends on charge, atom number, ionization energy, density

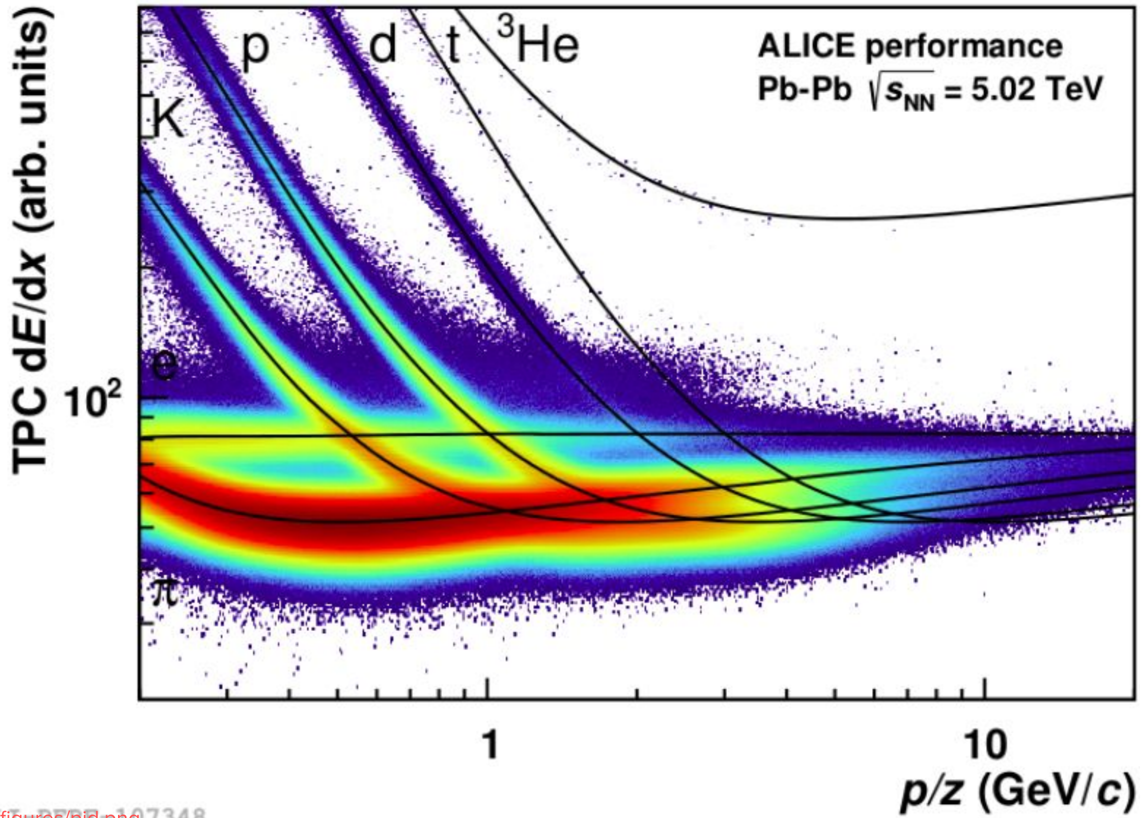
$$-\left\langle \frac{dE}{dx} \right\rangle \approx K q^2 \frac{1}{\beta^2} \frac{Z}{A} \left[\ln\left(\frac{2 m_e c^2}{I} \beta^2 \gamma^2 \right) - \beta^2 \right]$$



http://pdg.lbl.gov/2018/reviews/rpp2018-rev-passage-particles-matter.pdf

Identification of particles with the ALICE TPC

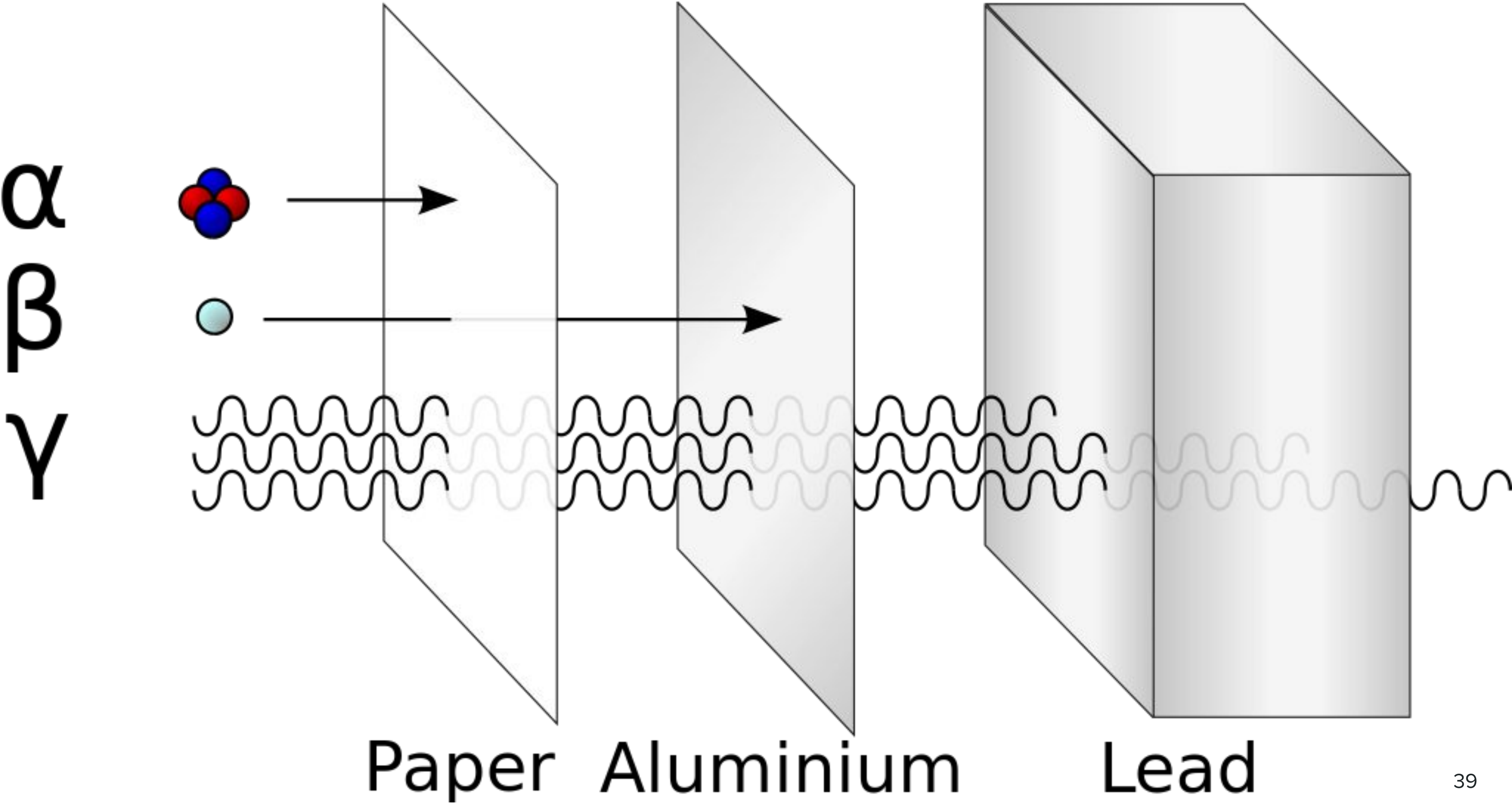
- Every point is one measurement!
- Can identify particles for low momenta
- For higher momenta, all particles behave like a minimum ionizing particle (MIP)



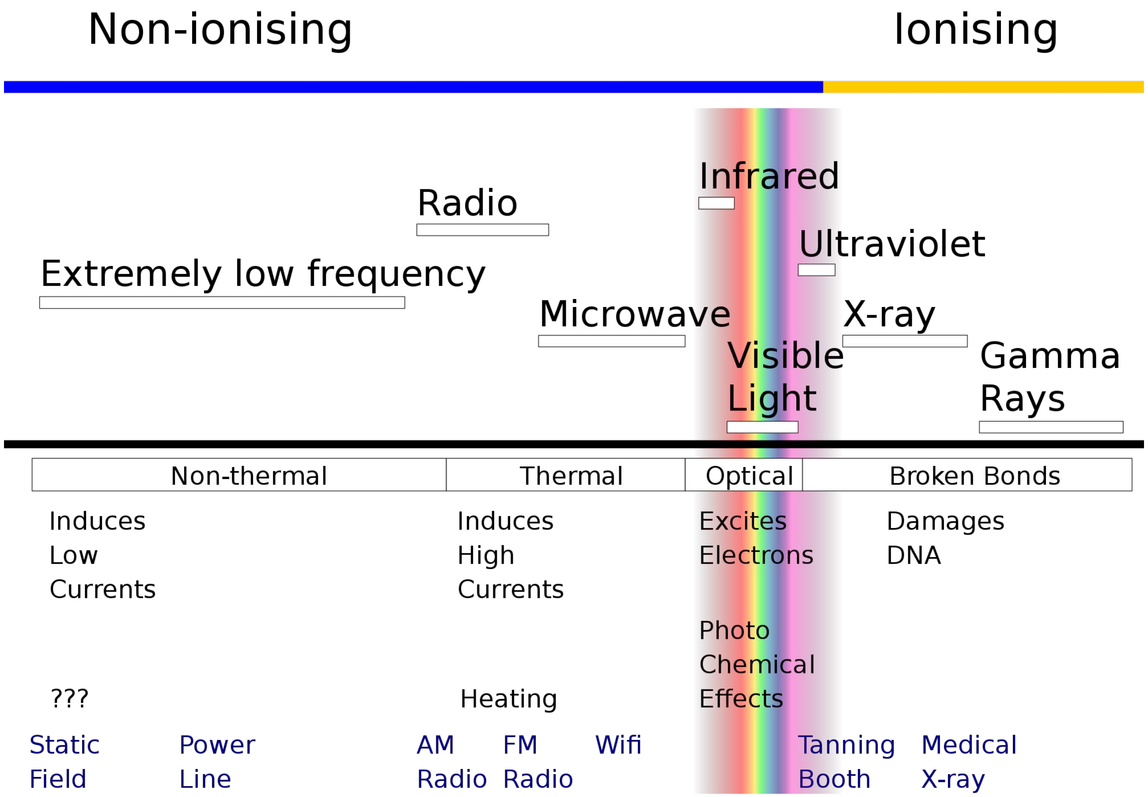
https://scx1.b-cdn.net/csz/news/800/2015/55d25b5d82741.png

https://alice-doc.github.io/alice-analysis-tutorial/analysis/figures/pid.png

We use the interaction of particles with material to detect, measure and identify them


α
β
γ
Paper
Aluminium
Lead

Ionizing vs non-ionizing radiation



Radiation: energy in the form of waves or particles

Ionizing radiation: radiation that, when passing through matter, strips electrons off atoms or molecules. **This can be damaging to living tissue.**

Types of ionizing radiation

Naturally:

- Cosmic rays
- Beta decay
- Positrons
- Electrons
- Protons
- Alpha particles (helium nuclei)

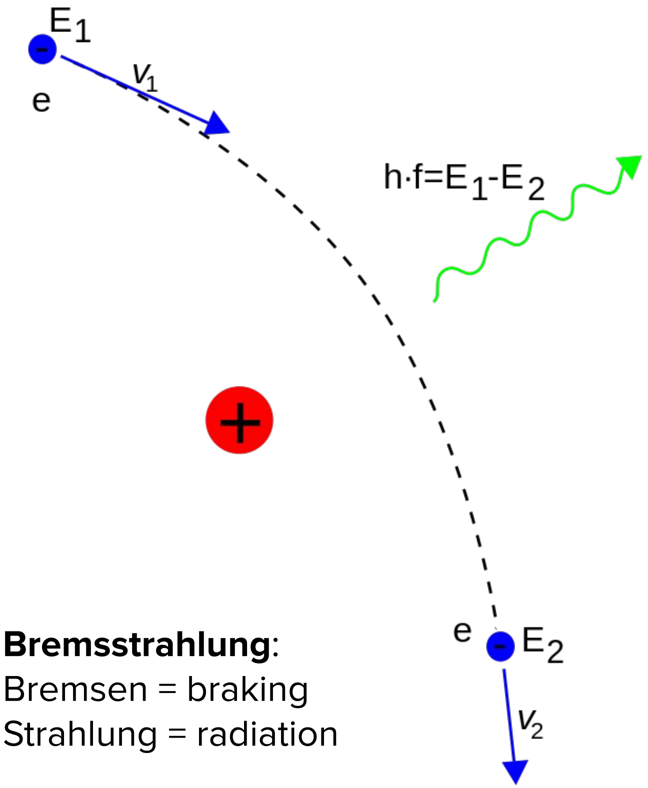
Artificially:

- X-rays
- Particle accelerators

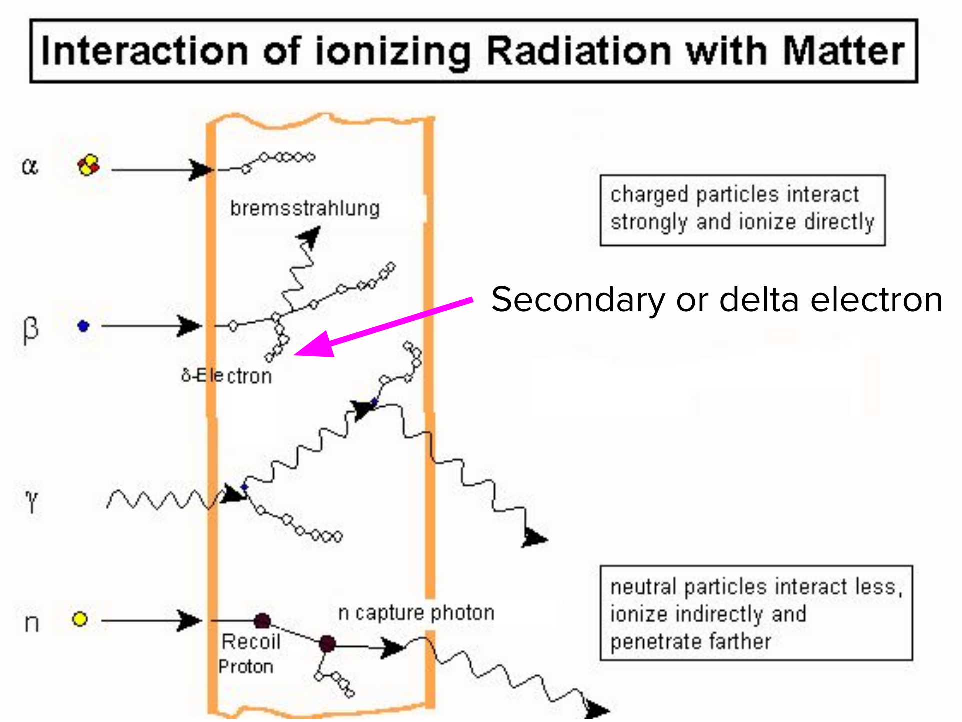
Direct from charged particles:

- Heavy charged particles: elastic scattering
- Electrons: Brehmsstrahlung (= braking radiation)
- Electrons: secondary or delta-electrons
- Positrons: electron-positron annihilation
- …

Stopping particles



Bremsstrahlung:
Bremsen = braking
Strahlung = radiation

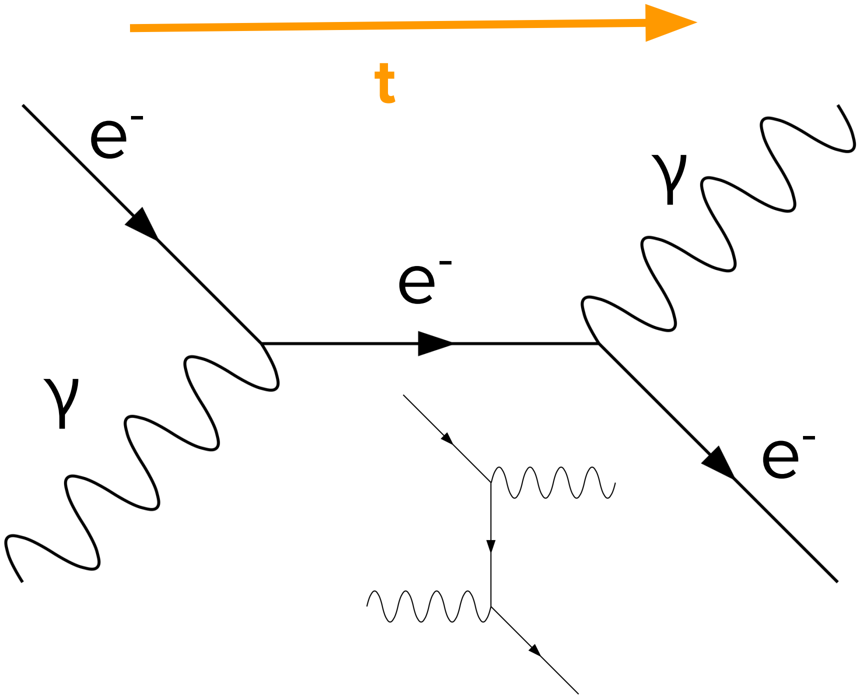


charged particles interact strongly and ionize directly

neutral particles interact less, ionize indirectly and penetrate farther

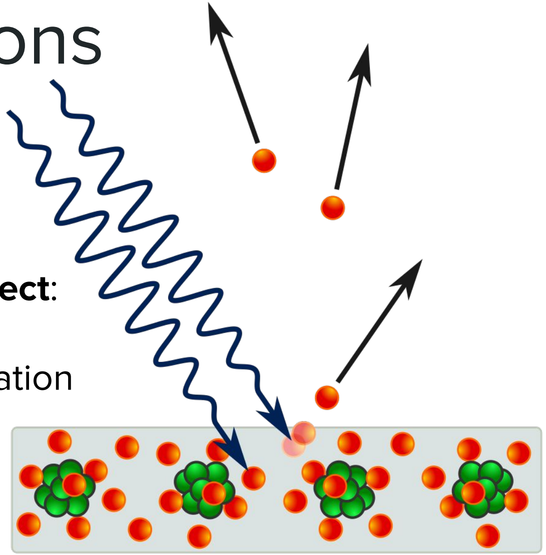
Secondary or delta electron

Indirect ionizing radiation from photons

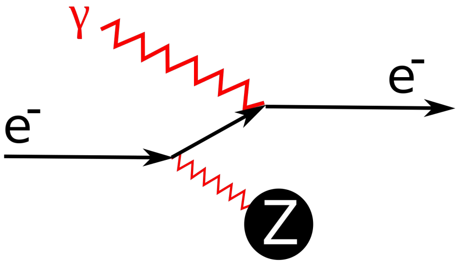


Compton scattering of a photon and electron. To first order only.

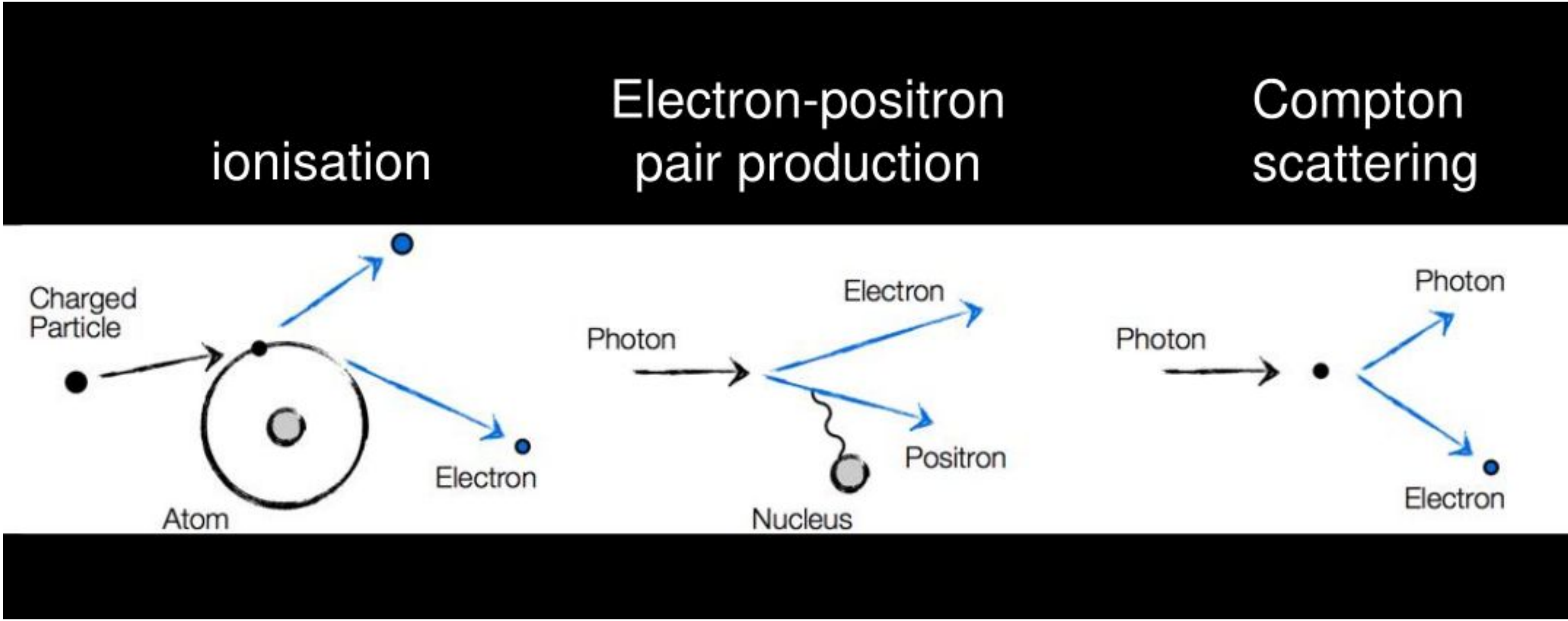
Photoelectric effect: absorption of a photon and ionization of an atom.



Or: an electron interacting with a photon and thereby changing its energy level in the atom Z

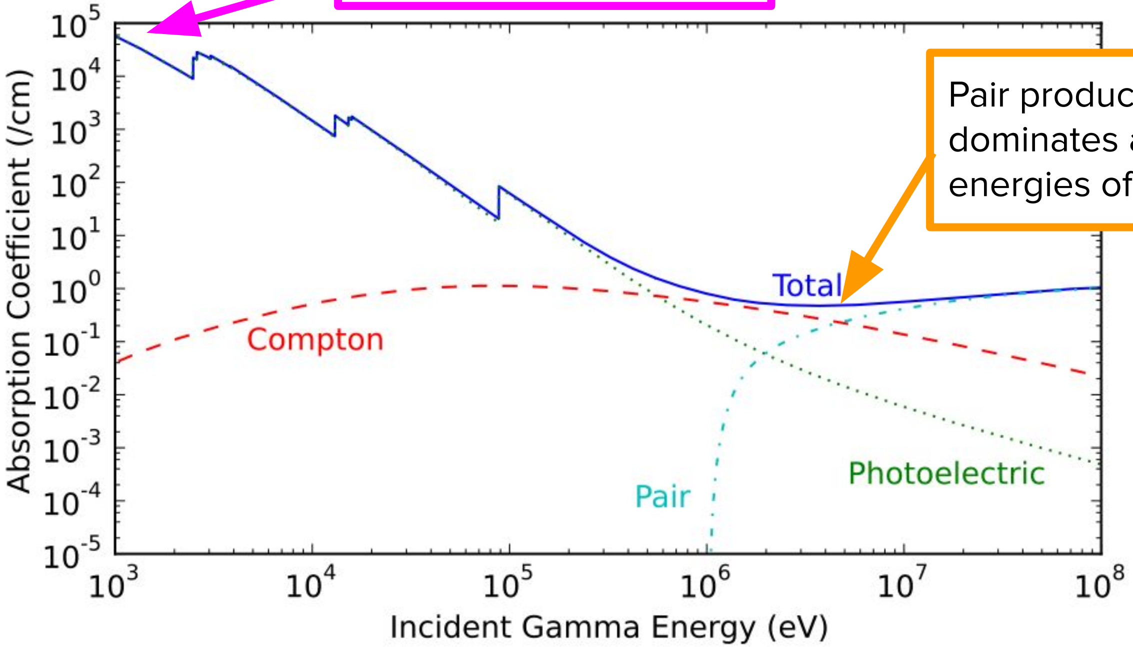


Interaction with matter



Different photon interactions in lead

See also the particle data group review on the passage of radiation through matter

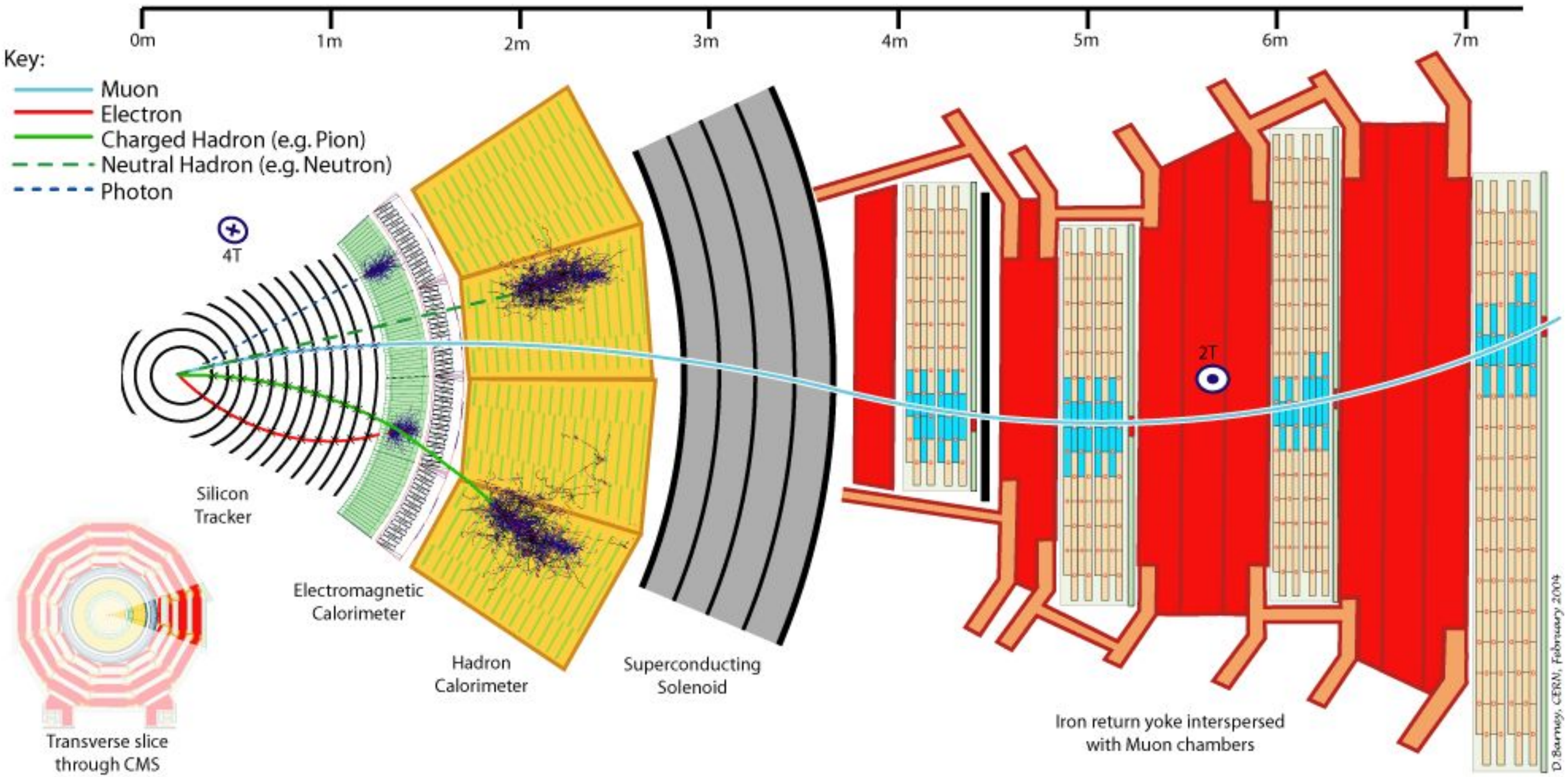


Photoelectric effect dominates

Pair production dominates above energies of 5 MeV

Intended energy loss: using matter to detect particles

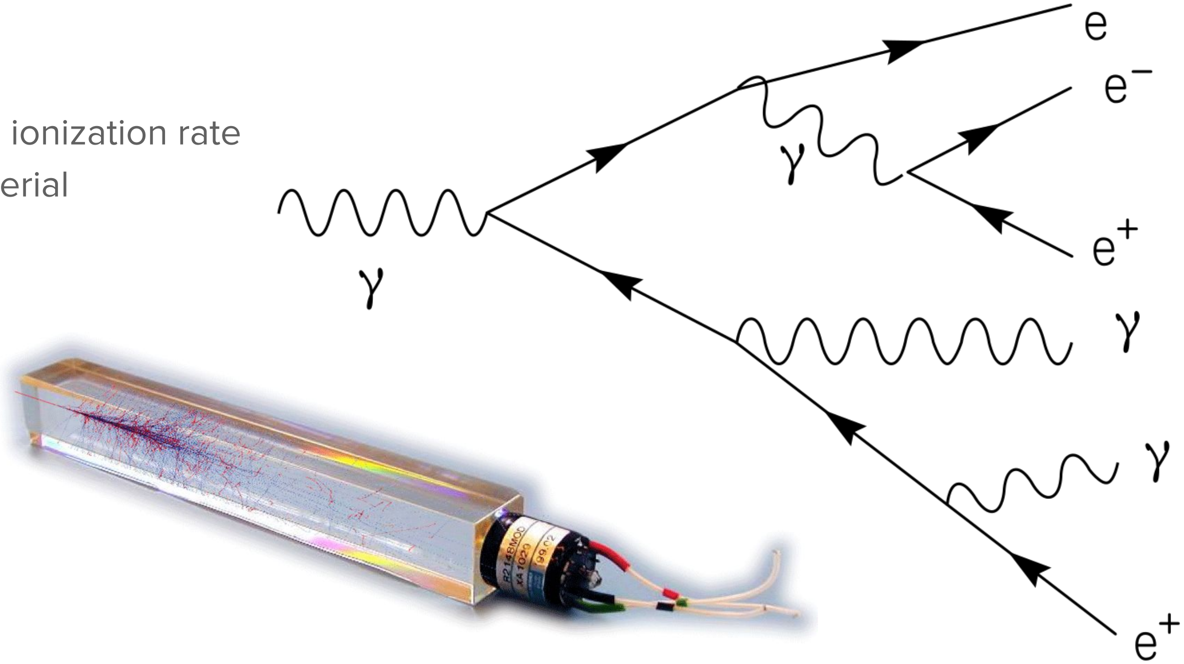
Where are the “destructive measurements”?



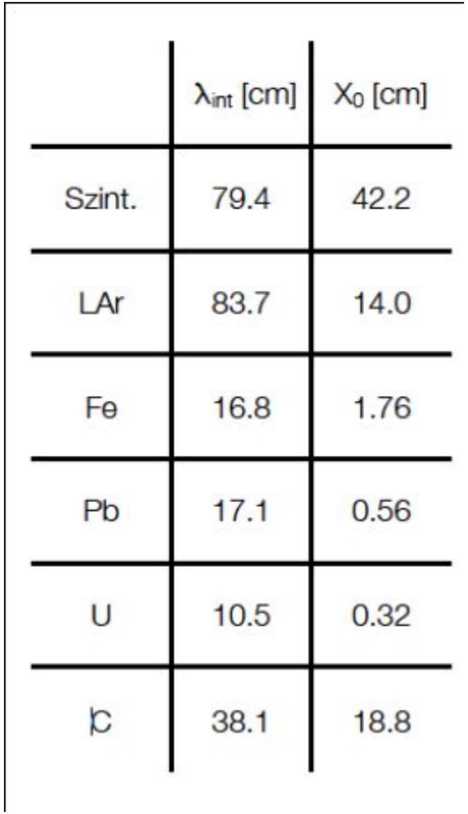
Electromagnetic calorimeter

- Electromagnetic shower by interaction with material
- Depth of shower in a material is determined by
  - Energy
  - Critical energy where Brehmsstrahlung rate = ionization rate
  - Radiation length of material

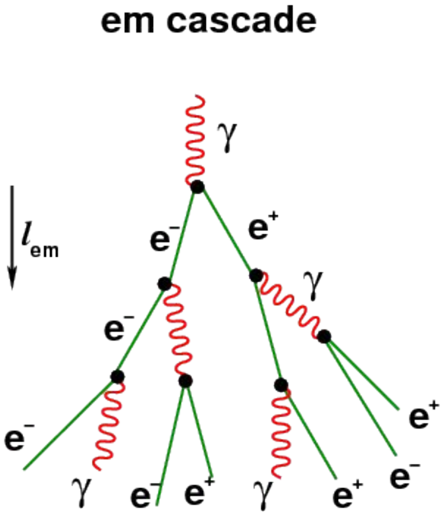
$$X = X_0 \frac{\ln(E_0/E_c)}{\ln 2}$$

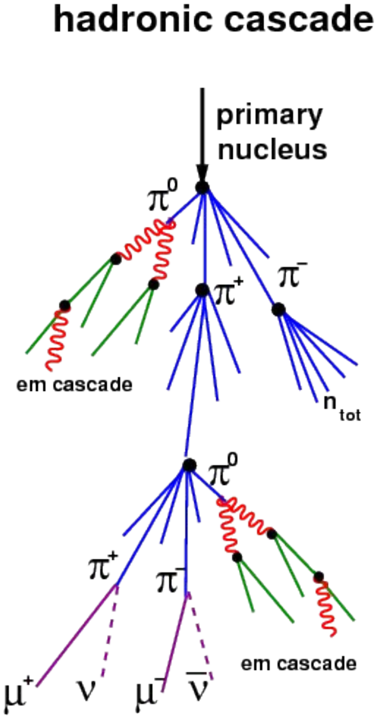


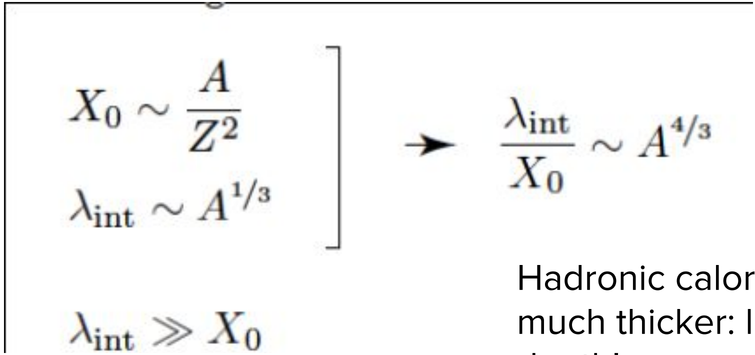
Hadronic calorimeter



	λ_{int} [cm]	X_0 [cm]
Szint.	79.4	42.2
LAr	83.7	14.0
Fe	16.8	1.76
Pb	17.1	0.56
U	10.5	0.32
C	38.1	18.8







$$\left.\begin{array}{l} X_0 \sim \dfrac{A}{Z^2} \\ \lambda_{\text{int}} \sim A^{1/3} \end{array}\right] \rightarrow \frac{\lambda_{\text{int}}}{X_0} \sim A^{4/3}$$

$$\lambda_{\text{int}} \gg X_0$$

Hadronic calorimeters are much thicker: larger shower depth!

Energy loss: practical examples

Protons vs X-rays

You have seen: x-rays and proton beams for curing cancer

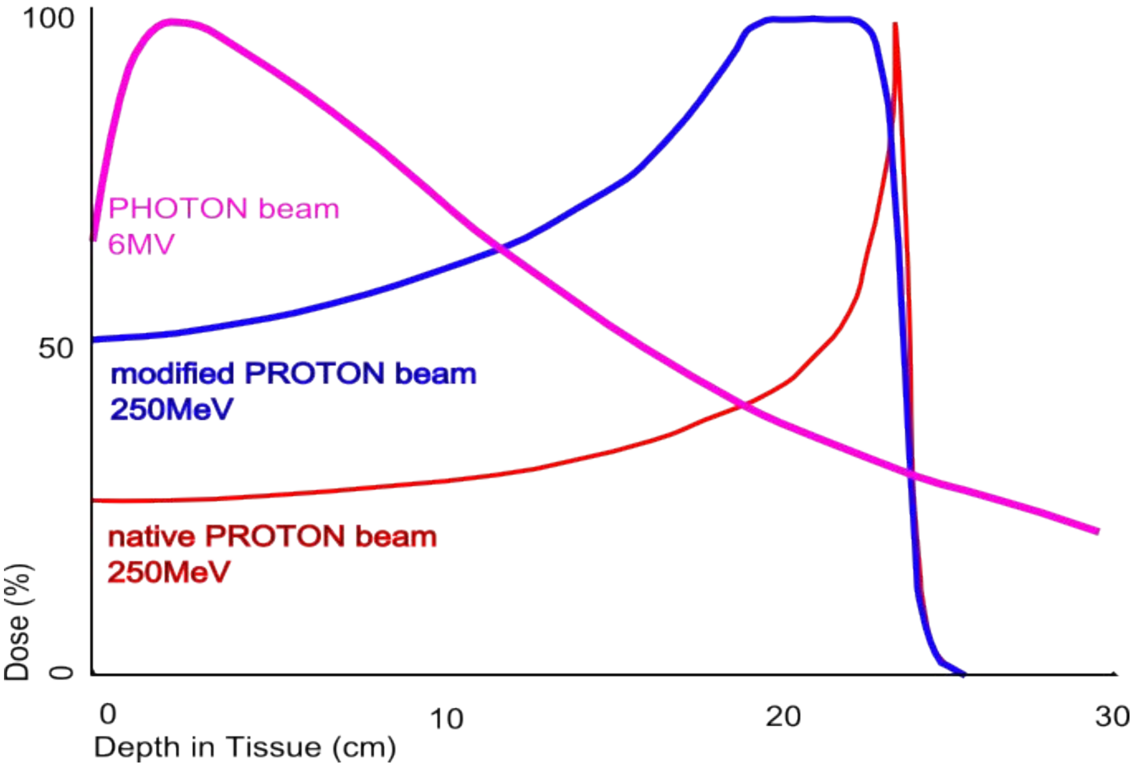
Curing Cancer with Proton Beams – with Suzie Sheehy

https://www.youtube.com/watch?v=ZQ7kyocgiho

Why do protons stop and X-rays don't? What are X-rays?

Bragg peak

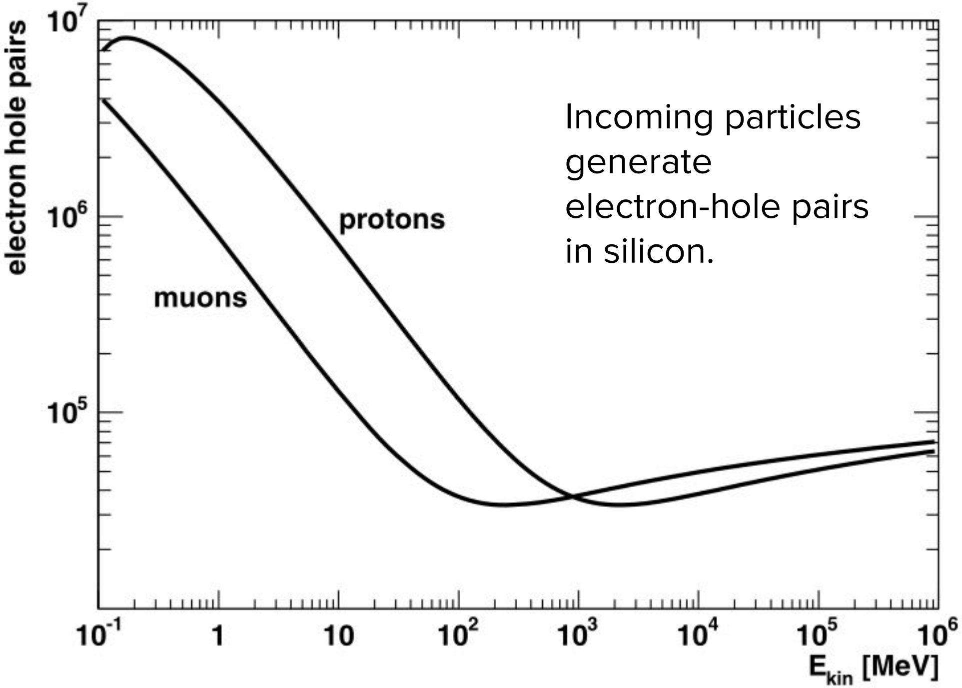
As the particle loses more energy on its path, the higher the probability of interaction with the material.



Minimum ionizing particle

Typically, 23000 e^- are collected in a 300 µm silicon detector from a minimum ionizing particle.

A 388 MeV muon is a minimum ionizing particle -- using v = 0.96 c for where particles become minimum ionizing.



Incoming particles generate electron-hole pairs in silicon.

Fig. 2.2. Number of electron–hole pairs generated in a 300-µm-thick silicon layer

Unintended energy loss: we don’t want matter when detecting particles!

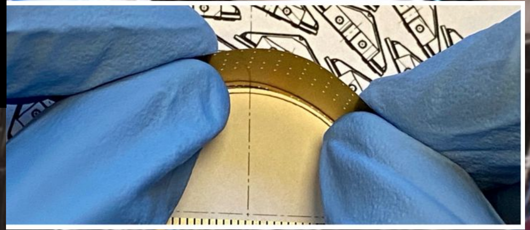
Multiple scattering

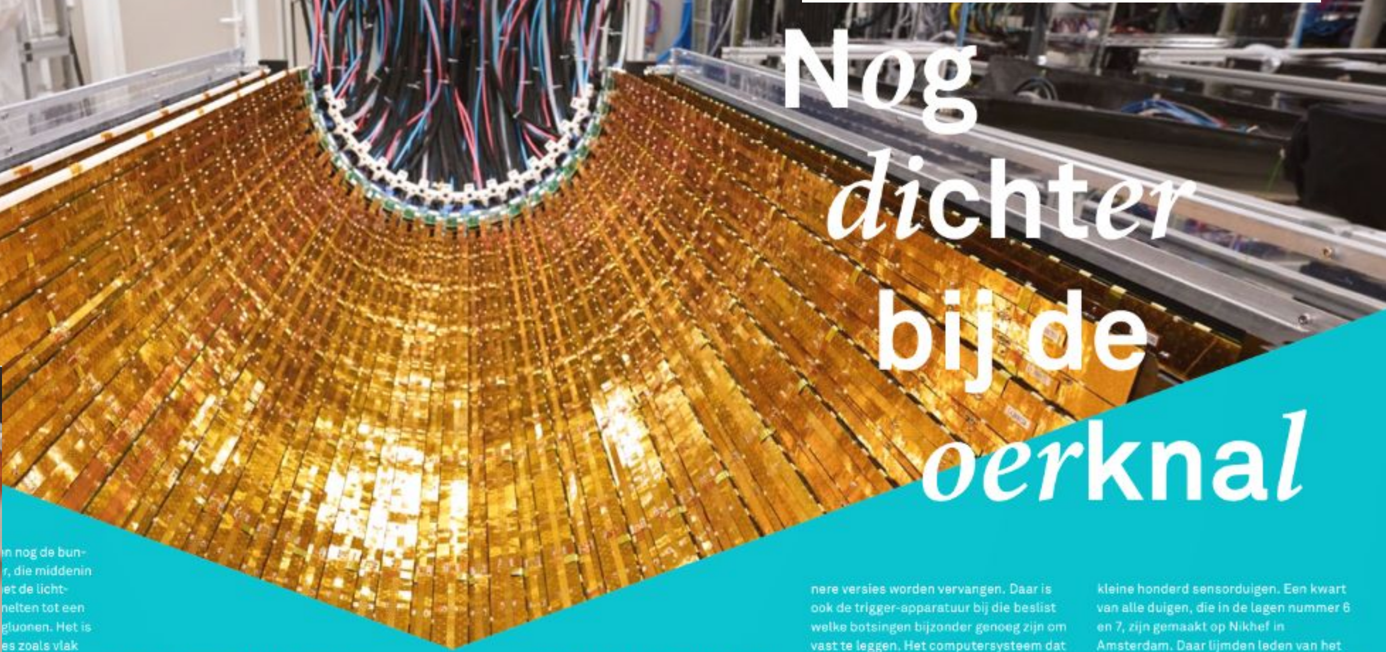
- Material is used for detection but also deflects charged particles
- Mainly through Coulomb force, also strong interaction for hadrons
- X_0 or radiation length indicates
- The radiation length X_0 of silicon is 9.36 cm ← → 21.82 g/cm^2

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

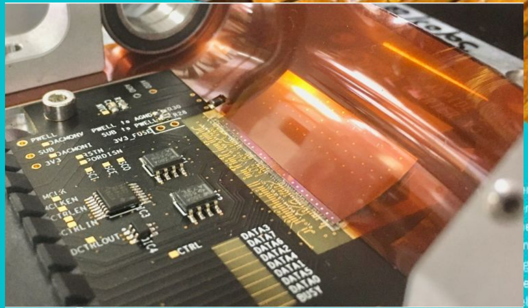
A pixel detector built for LHC has a thickness of about 2% of a radiation length per layer, changing the trajectory of a 1 GeV particle by an angle rms of ≈ 0.1 ° .

ALICE inner tracking system: towards 0.1% X_0





Nog *dichter* bij de *oerknal*



Het goud is overigens geen goud, maar polyimide-folie met ragdunne koperen voedingskabels voor de sensoren. Dun genoeg om vrijkomende

n nog de bun-
r, die middenin
et de licht-
nelten tot een
gluonen. Het is
es zoals vlak
lal zelf moet
zijn ontstaan. ITS moet de deeltjes betrappen die uit die ziedende oersoep ontsnappen en de fysici vertellen wat er daarbinnen precies gaande is.

geven, is de verwachting. De nieuwe inner tracker doet dat van nog dichterbij dan de eerdere versie. Daardoor kunnen de kernbotsingen preciezer worden bekeken.

dezelfde plak silicium zitten. Dat scheelt kabels en elektronica in de detector.

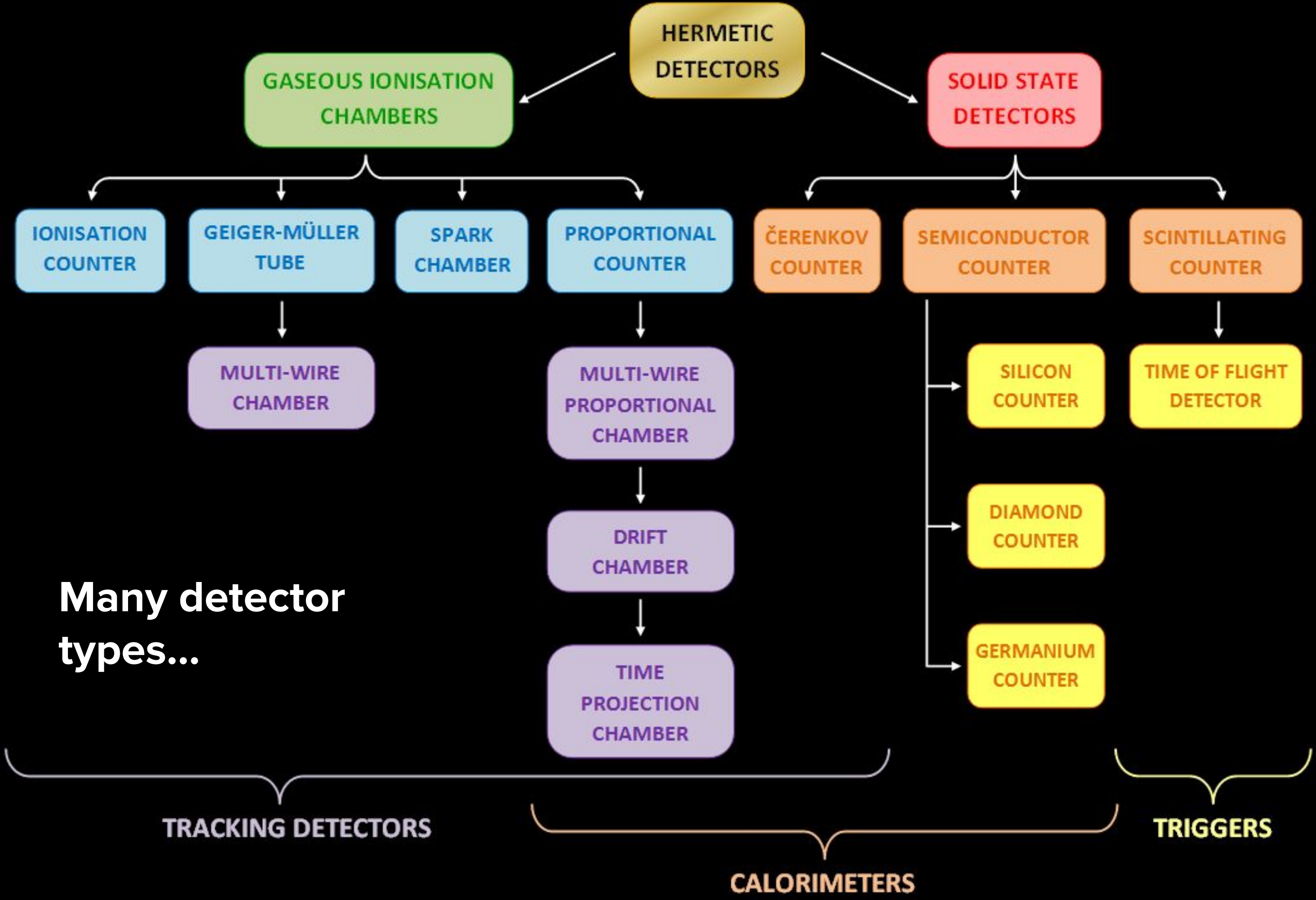
In de komende meetperiode kan ITS gemakkelijk honderd keer zoveel meetgegevens verzamelen als alles wat ALICE in

nere versies worden vervangen. Daar is ook de trigger-apparatuur bij die beslist welke botsingen bijzonder genoeg zijn om vast te leggen. Het computersysteem dat data verzamelt en toegankelijk maakt, wordt eveneens vernieuwd.

De upgrade-periode is een hectische tijd. Het binnenste van de grote ondergrondse detector is vorig jaar meteen

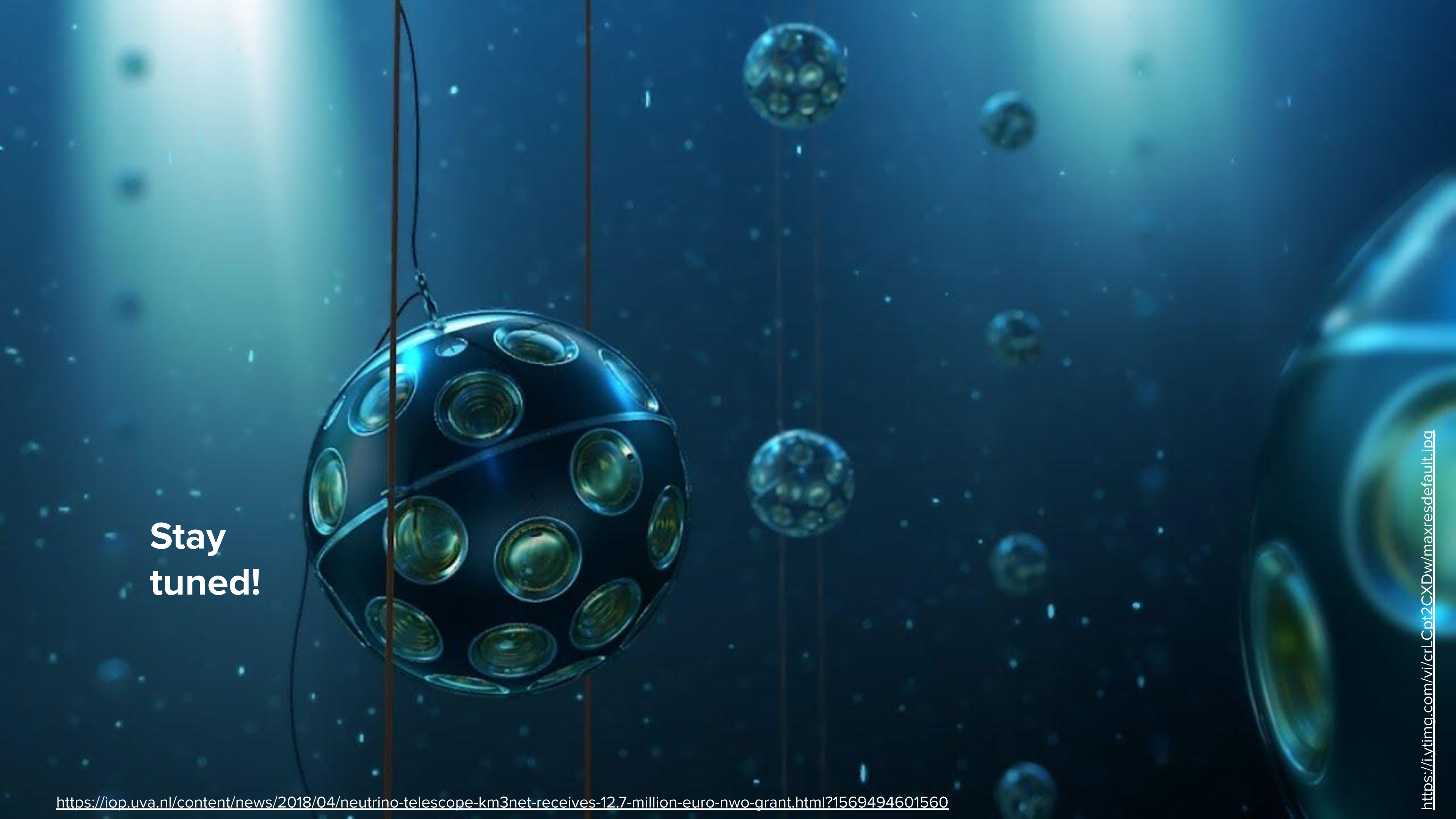
kleine honderd sensorduigen. Een kwart van alle duigen, die in de lagen nummer 6 en 7, zijn gemaakt op Nikhef in Amsterdam. Daar lijmden leden van het ALICE-team met eindeloos geduld de koeling en de sensoren stuk voor stuk handmatig op de ijle koolstofvezel dragers. Deze sensorduigen zijn vorig najaar al in trillingsvrije kratten van Amsterdam

Passage of radiation through matter can be used to measure as well as to stop particles



Many detector types...

https://upload.wikimedia.org/wikipedia/commons/c/c0/Detectors_summary_3.png



Stay tuned!

https://iop.uva.nl/content/news/2018/04/neutrino-telescope-km3net-receives-12.7-million-euro-nwo-grant.html?1569494601560

https://i.ytimg.com/vi/crLCpt2CXDw/maxresdefault.jpg

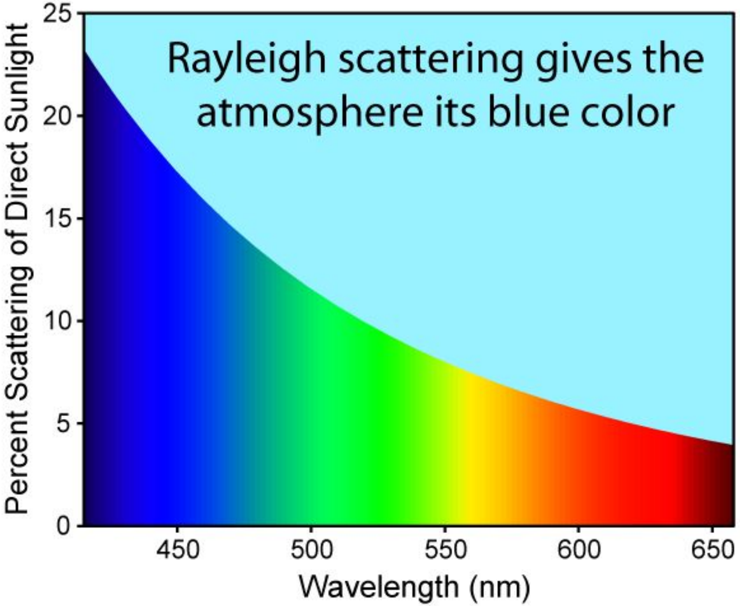
Additional material

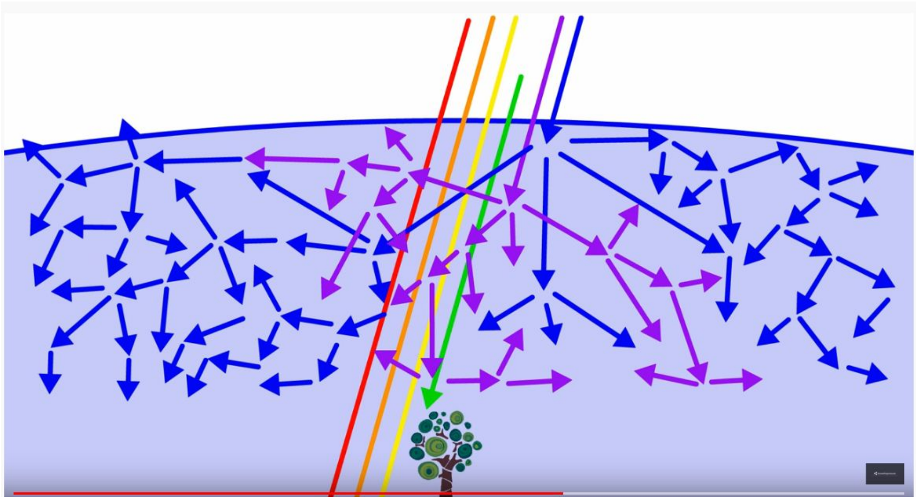
Other sources used

- Slides from Erik Butz (see also here), Simon Spannagel, Freya Blekman, Peter Schleper, Erika Garutti, Ingrid-Maria Gregor
- Book on Pixel detectors by Rossi, Fischer, Rohe, Wermes
- Book on Semiconductor Detector Systems by Helmuth Spieler, see also online notes
- Particle data group review: passage of radiation through matter
- Book on particle radiation by Konrad Kleinknecht
- Book on Techniques in experimental particle physics by WR Leo

See also links behind pictures in the slides for more sources.

Remark about photons: blue sky





Rayleigh scattering cross section:

$$\sigma_s = \frac{2\pi^5}{3}\frac{d^6}{\lambda^4}\left(\frac{n^2-1}{n^2+2}\right)^2$$

$$\frac{\sigma_{blau}}{\sigma_{rot}} = \frac{1/\lambda_{blau}^4}{1/\lambda_{rot}^4} = \left(\frac{650\,nm}{450\,nm}\right)^4 \approx 4.4$$