

PARTICLE PHYSICS

COLUMBIA SCIENCE HONORS PROGRAM

WEEK 5

EXPERIMENTAL METHODS

Cristóvão Vilela

COURSE POLICIES

- Attendance
 - Up to four excused absences
 - Two with notes from parent/guardian
 - shpattendance@columbia.edu
 - Valid excuses:
 - Illness, family emergency, tests or athletic/academic competitions, mass transit breakdowns
 - Invalid excuses:
 - Sleeping in, missing the train...
 - I will take attendance during class
- No cell phones
- Ask questions!

LECTURE MATERIALS

- <https://twiki.nevis.columbia.edu/twiki/bin/view/Main/ScienceHonorsProgram>
- Questions: cristovao.vilela@stonybrook.edu

LAST WEEK...

QUANTUM MECHANICS

PARTICLES AND WAVES

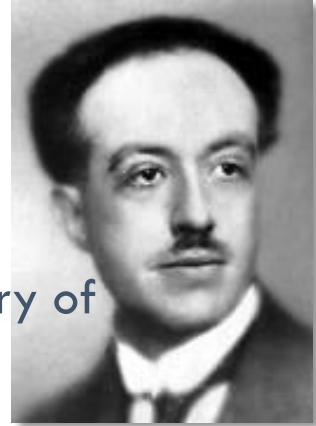
WHAT IS QUANTUM MECHANICS?

- Quantum mechanics is the study of nature at very **small scales** – specifically when the **energies** and **momenta** of the system are of the order of **Planck's constant**:

$$\hbar = \frac{h}{2\pi} = 6.6 \times 10^{-16} \text{ eV s}$$

- On a quantum level, particles exhibit a number of non-classical behaviors:
 1. **Quantization** of energy, momentum, charge, spin, ...
 2. **Particles** exhibit **wave**-like effects: interference, diffraction, ...
 3. Systems can exist in a **superposition** of **states**

THE DE BROGLIE HYPOTHESIS



- de Broglie's suggestion was a bold statement about the symmetry of Nature.
- **Proposal:** the wave aspects of matter are related to its particle aspects in quantitatively *the same way* that the wave and particle aspects of light are related.
- **Hypothesis:** for **matter** and **radiation**, the total energy (E) of a particle is related to the frequency (f) of the wave associated with its motion by:

$$E = hf$$

- If $E=pc$ (recall SR), then the momentum p of the particle is related to the wavelength λ of the associated wave by the equation:

$$p = \frac{h}{\lambda}$$

THE DE BROGLIE HYPOTHESIS

de Broglie relation

$$\lambda = \frac{h}{p} \quad p = \frac{h}{\lambda}$$

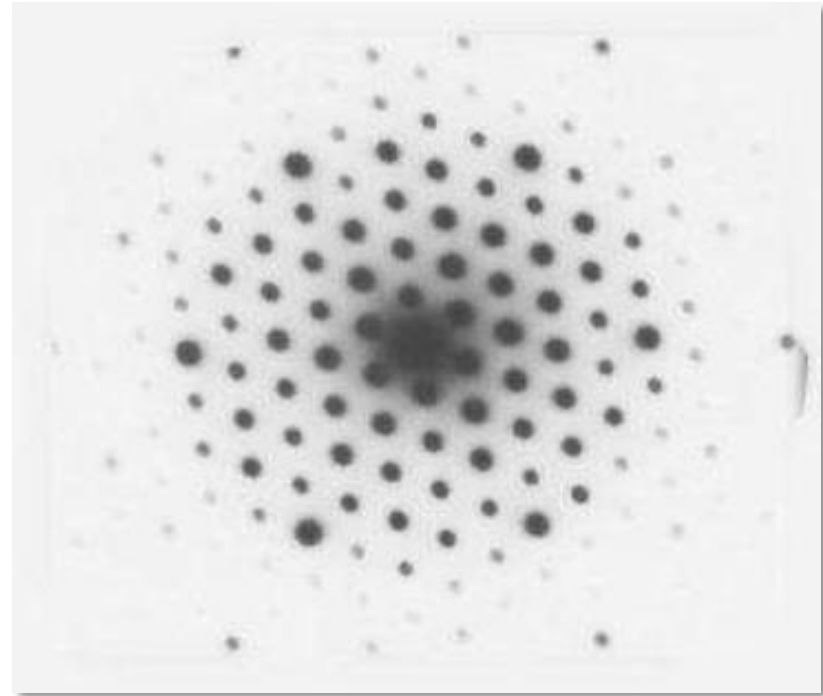
- It holds even for *massive particles*.
- It predicts the de Broglie wavelength of a matter wave associated with a particle of momentum p .

de Broglie hypothesis: particles are also associated with waves, which are extended disturbances in space and *time*.



ELECTRON DIFFRACTION

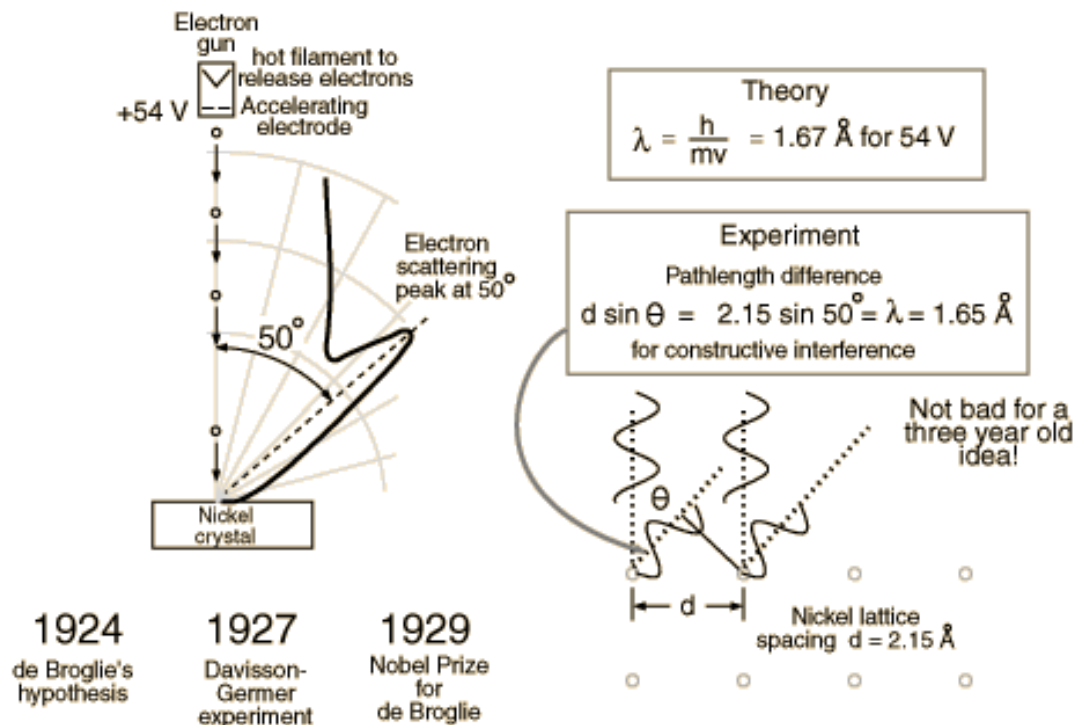
- Scattering **electrons** off crystals also creates a **diffraction** pattern!
- Electron diffraction is only possible if electrons are **waves**.
- Hence, electrons (matter **particles**) can also behave as **waves**.



Diffraction pattern created by scattering electrons off a crystal. (This is a negative image, so the dark spots are actually regions of constructive interference.) Electron diffraction is only possible if electrons are waves.

OBSERVATION OF ELECTRON DIFFRACTION

- Electron diffraction was first observed in a famous 1927 experiment by Davisson and Germer.
- They fired 54 eV electrons at a nickel target and observed diffraction peaks consistent with de Broglie's hypothesis.



UNDERSTANDING MATTER WAVES

- Let's **think** a little more about de Broglie waves.
- In classical physics, energy is transported **either** by **waves** or by **particles**.
 - **Particle**: a definite, localized bundle of energy and momentum, like a bullet that transfers energy from gun to target.
 - **Wave**: a periodic disturbance spread over space and time, like water waves carrying energy on the surface of the ocean.
- In quantum mechanics, the same entity can be described by **both** a **wave** and a **particle** model:
 - Electrons scatter like localized particles, but they can also diffract like extended waves.

QUANTUM WAVES SUMMARIZED

- An elementary particle like a photon can act like a particle (Compton effect, photoelectric effect) or a wave (diffraction), **depending** on the **type** of experiment / observation.
- If it's acting like a **particle**, the photon can be described by its **position** and **momentum** x and p . If it's acting like a **wave**, we must describe the photon with a **wave function** $\psi(x,t)$.
- Two waves can always be **superimposed** to form a third:
 - $\psi = \psi_1 + \psi_2$.
 - This is what gives rise to **interference** effects like diffraction.
- The wave function for a moving particle (a traveling wave) has a simple sinusoidal form.
 - But how do we **interpret** $\psi(x,t)$ physically?

INTERPRETATION OF THE WAVE FUNCTION

- We have seen that a **particle** can be described by a **wave function** $\psi(x,t)$.

- For any wave, we define the wave's intensity I to be:

$$I = |\psi(x,t)|^2 = \int \psi(x,t) \psi(x,t)^* dx$$

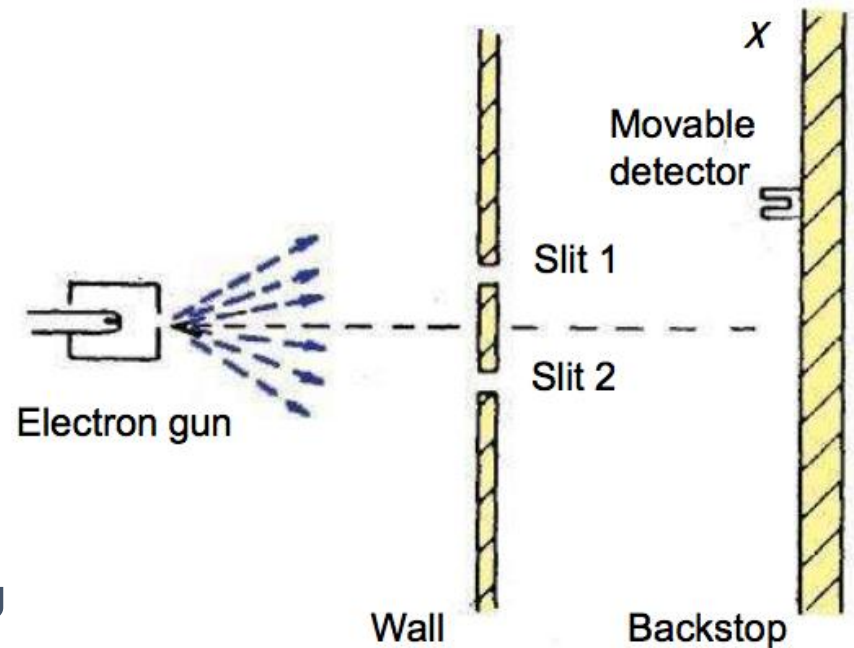
where the asterisk signifies complex conjugation. Note that for a **plane wave** this is the square of A (a **constant**):

$$I = |\psi(x,t)|^2 = |A|^2$$

- Let's use the concept of intensity and a simple thought experiment to get some intuition about the physical meaning of the de Broglie wave function.

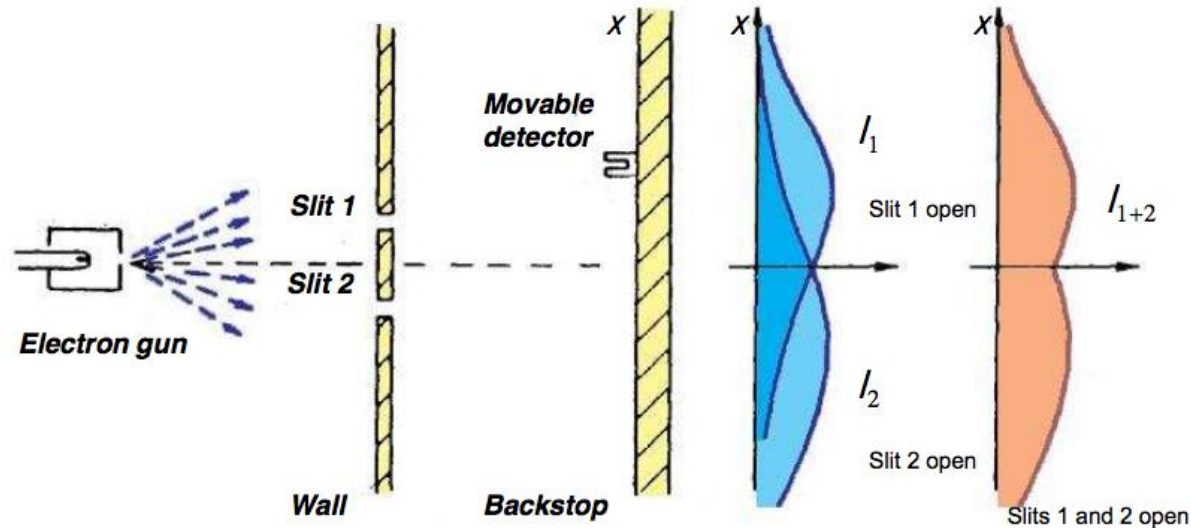
THE DOUBLE SLIT EXPERIMENT

- **Experiment:** a device sprays an electron beam at a wall with **two small holes** in it. The size of the holes is close to the electrons' wavelength λ_{dB} .
- Behind the wall is a screen with an electron **detector**.
- As electrons reach the screen, the detector counts up **how many electrons** strike **each point** on the wall.
- Using the data, we plot the **intensity** $I(x)$: the number of electrons arriving per second at position x .



THE DOUBLE SLIT EXPERIMENT

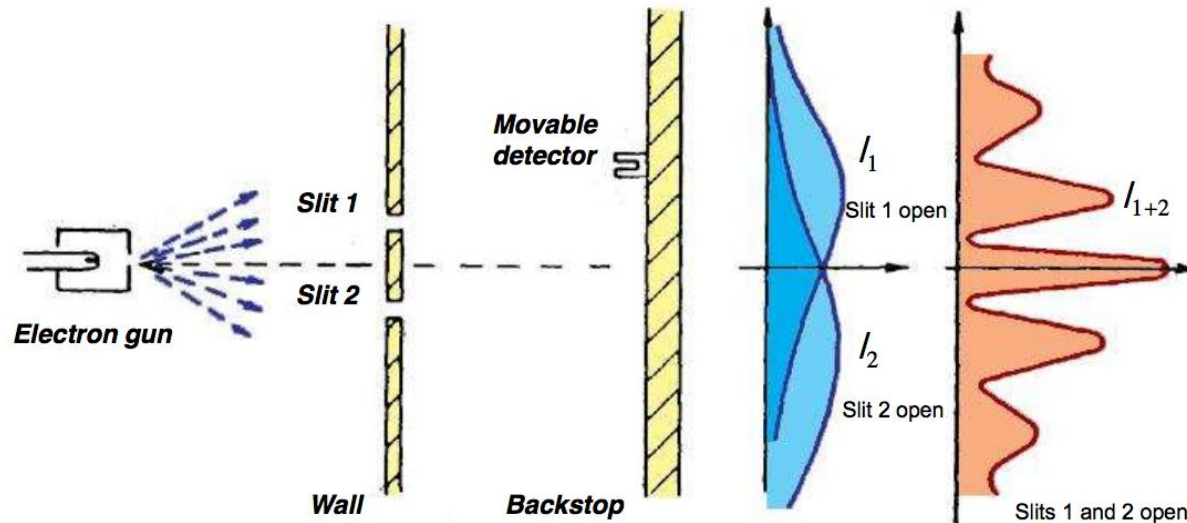
- The **classical** result:



- If electrons were **classical particles**, we would expect the intensity in front of each slit to look like a bell curve, **peaked directly in front** of each slit opening.
- When both slits are open, the **total intensity** I_{1+2} on the screen should just be **the sum of the intensities** I_1 and I_2 when only one or the other slit is open.

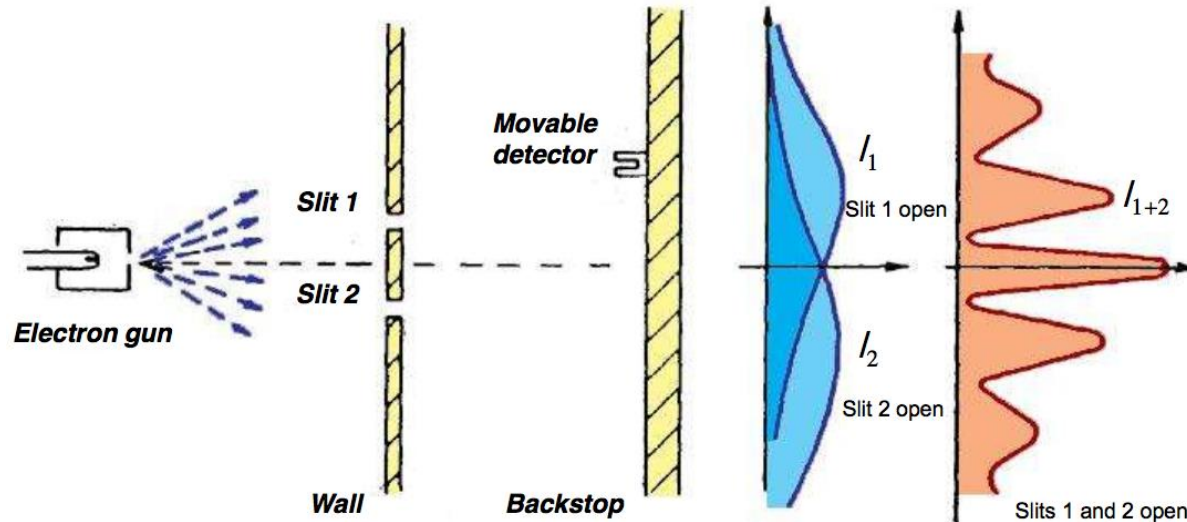
THE DOUBLE SLIT EXPERIMENT

- In reality:



- When we perform the real experiment, a **strange** thing happens.
- When only **one slit** is open, we get the **expected** intensity distributions.
- But when **both slits** are open, a wave-like **diffraction** pattern appears.
- Apparently, the **electrons** are acting like **waves** in this experiment.

WAVE FUNCTION INTERPRETATION

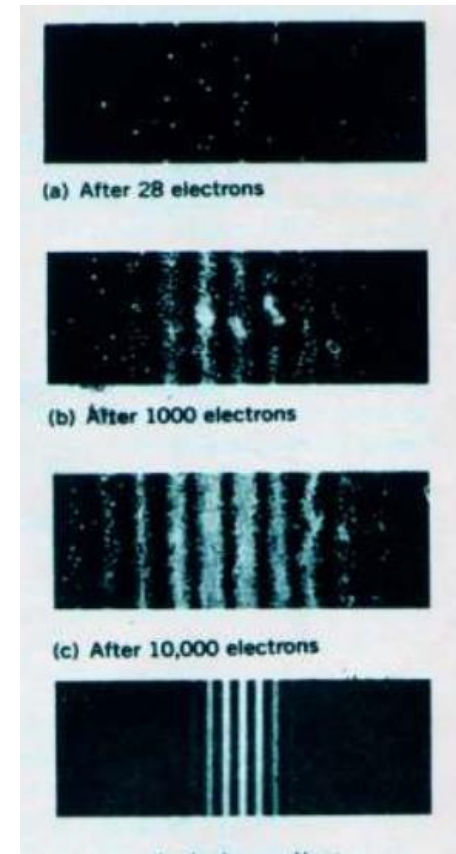


- In terms of waves, the wave function of an electron at the screen when only slit 1 is open is ψ_1 , and when only slit 2 is open it's ψ_2 .
 - Hence, the intensity when only one slit is open is either $I_1 = |\psi_1|^2$ or $I_2 = |\psi_2|^2$.
- With both slits open, the intensity at the screen is $I_{1+2} = |\psi_1 + \psi_2|^2$, not just $I_1 + I_2$!
- When we **add** the wave functions, we get constructive and destructive **interference**; this is what creates the **diffraction** pattern.

WAVE FUNCTION AND PROBABILITY

- If electrons create a diffraction pattern, they must be **waves**. But when they hit the screen, they are detected as **particles**.
 - How do we **interpret** this?
- Max Born: Intensity $I(x) = |\psi(x,t)|^2$ actually refers to **probability** a given electron hits the screen at position x .
- In quantum mechanics, we don't specify the **exact location** of an electron at a given time, but instead state by $I(x) = |\psi(x,t)|^2$ the **probability** of **finding** a particle at a certain location at a given time.

The probabilistic interpretation gives physical meaning to $\psi(x,t)$: it is the “probability amplitude” of finding a particle at x at time t .

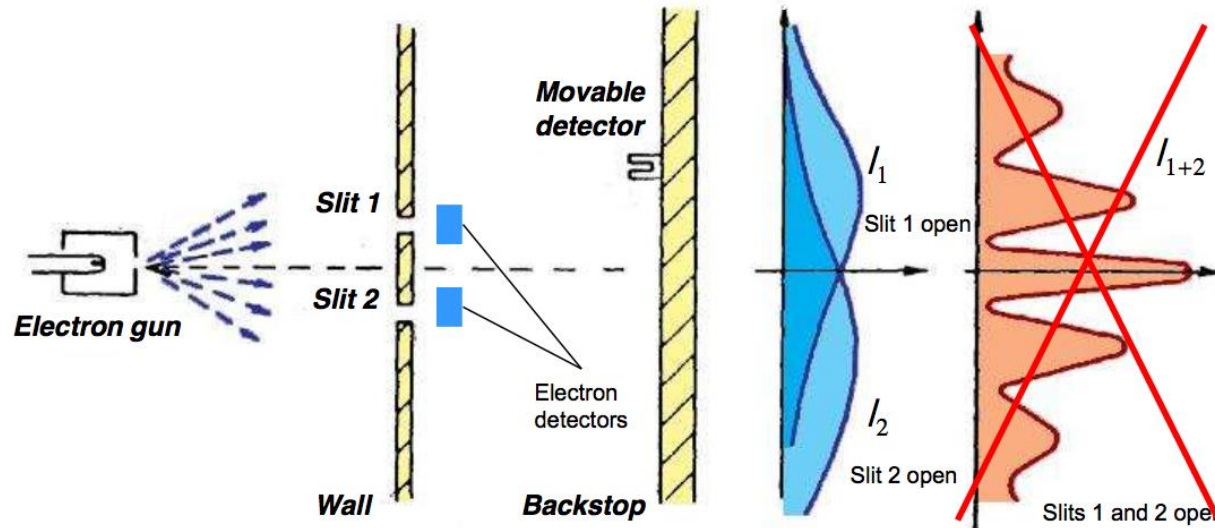


Diffraction pattern from an actual electron double slit experiment. Notice how the interference pattern builds particle by particle.

IS THERE A CONTRADICTION?

- We now **understand** the wave function in terms of the **probability** of a particle being someplace at some time.
 - However, there is another problem to think about.
- Since the electrons **diffract**, they are **waves**; but when they **hit** the screen, they interact like **particles**. And if they are **particles**, then shouldn't they only go through **one slit** at a time?
- If this is the case, how can an electron's wave undergo double slit **interference** when the electron only goes through **one slit**?
 - Seems **impossible**...
- To test what's going on, suppose we slow down the electron gun so that only one electron at a time hits the wall.
- We then insert a device over each slit that tells us if the electron definitely went through one slit or the other.

DESTROYING THE INTERFERENCE PATTERN



- We add electron **detectors** that shine light across each slit.
- When an electron passes through one of the slits, it breaks the beam, allowing us to **see** whether it traveled through slit 1 or slit 2 on its way to the backstop.
- **Result:** if we try to **detect** the electrons at one of the two slits in this way, the interference pattern is **destroyed**! In fact, the pattern now looks like the one expected for classical particles

COMPLEMENTARITY

- Why did the interference pattern **disappear**?
- Apparently, when we used the light beam to localize the electron at one slit, we **destroyed** something in the wave function $\psi(x,t)$, that contributes to interference.
- **Principle of Complementarity (N. Bohr)**: if a measurement proves the wave character of radiation or matter, it is **impossible** to prove the particle character in the same measurement, and vice-versa.
- The link between the wave and particle models is provided by the probability interpretation of $\psi(x,t)$, in which an entity's wave gives the probability of finding its particle at some position.

THE UNCERTAINTY PRINCIPLE

- There seems to be some **fundamental** constraint on quantum mechanics that prevents matter from acting **wave-like** and **particle-like simultaneously**.
- Moreover, it appears that our **measurements** can directly **affect** whether we observe particle or wave-like behavior.
- These effects are encapsulated in the **Uncertainty Principle**.
- **Heisenberg: quantum observations are fundamentally limited in accuracy.**



THE UNCERTAINTY PRINCIPLE

- According to classical physics, we can (at the same instant) measure the position x and momentum p_x of a particle to infinite accuracy if we like. We're only limited by our equipment.
- However, Heisenberg's uncertainty principle states that experiment cannot simultaneously determine the exact values of x and p_x . know
- Quantitatively, the principle states that if we a particle's momentum p_x to an accuracy Δp_x , and its position x to within some Δx , the precision of our measurement is **inherently** limited such that:

$$\Delta p_x \Delta x \geq \frac{\hbar}{2}$$

USING THE UNCERTAINTY PRINCIPLE

- Does the Uncertainty Principle mean that we can't measure position or momentum to arbitrary accuracy?
- No. The restriction is not on the accuracy to which x and p_x can be measured, but rather on the product $\Delta p_x \Delta x$ in a *simultaneous* measurement of both.
- The Uncertainty Principle implies that the more accurately we know one variable, the less we know the other. If we could measure a particle's p_x to infinite precision, so that $\Delta p_x = 0$, then the uncertainty principle states:

$$\Delta x \geq \frac{\hbar/2}{\Delta p_x}$$

$$\Delta p_x \rightarrow 0, \Delta x \rightarrow \infty$$

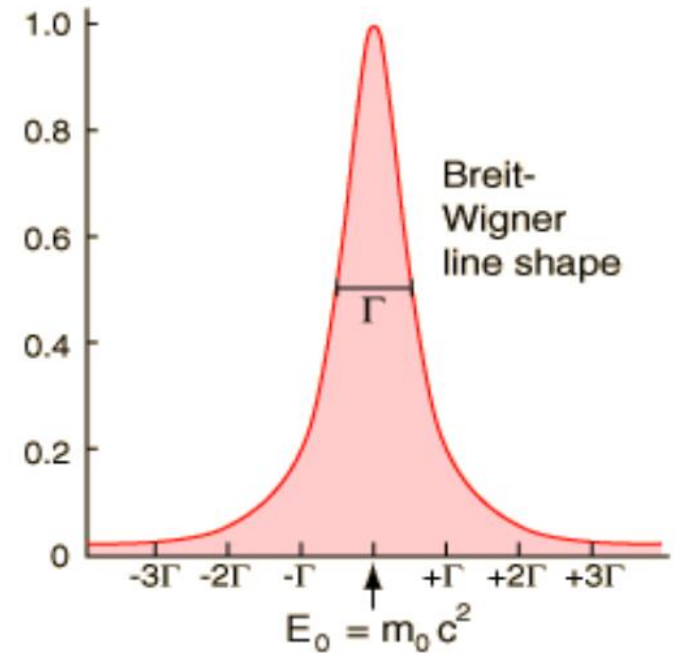
- In other words, after our measurement of the particle's direction (momentum), we lose all information about its position!

THE UNCERTAINTY PRINCIPLE

- The Uncertainty Principle has a second part related to measurements of energy E and the time t needed for the measurements. It states that:

$$\Delta E \Delta t \geq \frac{\hbar}{2}$$

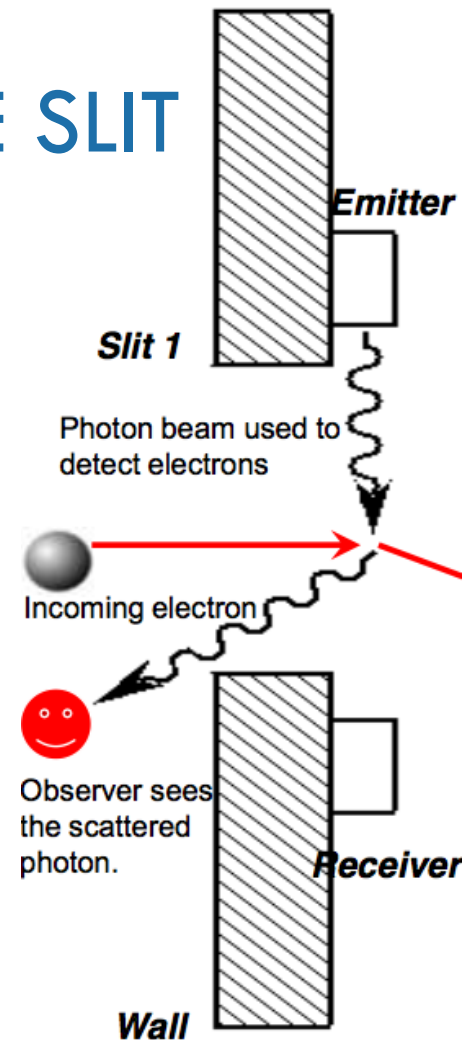
- Example:** estimate the mass of virtual particles confined to the nucleus (see Lecture 2 on estimating Yukawa's meson mass).
- Example:** Δt could be the time during which a photon of energy spread ΔE is emitted from an atom.
- This effect causes spectral lines in excited atoms to have a finite uncertainty $\Delta\lambda$ ("natural width") in their wavelengths.



Atomic spectral lines, the result of transitions that take a finite time, are not thin "delta function" spikes, but actually have a natural width due to the Uncertainty Principle.

UNCERTAINTY AND THE DOUBLE SLIT

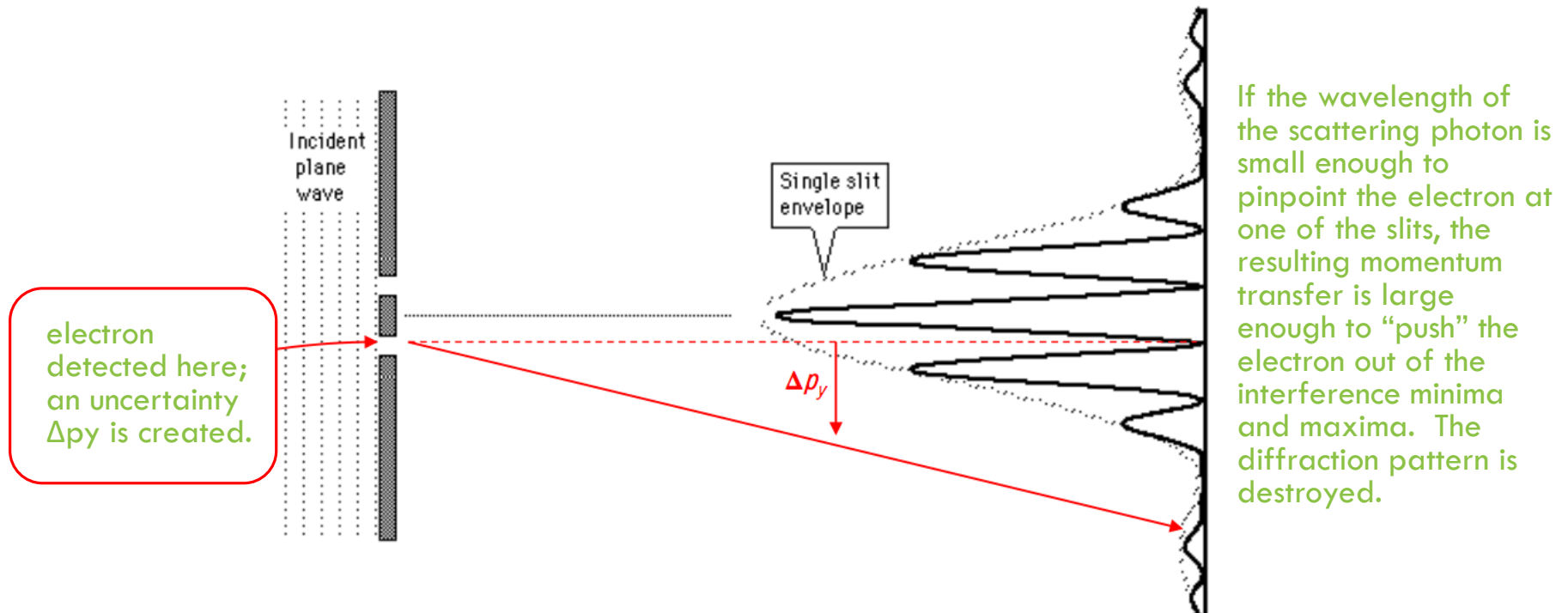
- Now that we know the Uncertainty Principle, we can **understand** why we can't "**beat**" the double slit experiment and simultaneously observe wave and particle behavior.
- Our electron **detector** Compton scatters light off of incoming electrons.
- When an electron uses one of the slits, we **observe** the scattered photon and know that an electron went through that slit.
- Unfortunately, when this happens, the photon **transfers** some of its momentum to the electron, **creating uncertainty in the electron's momentum**.



Detection photon Compton scatters off an incoming electron, transferring its momentum. But there is uncertainty in the momentum transfer.

UNCERTAINTY AND THE DOUBLE SLIT

- If we want to **know** the slit used, the photon's wavelength must be **smaller** than the spacing between the two slits.
- Hence, the photon has to have a **large momentum** (remember, $\lambda = h/p$).
- As a result, a **lot** of momentum gets transferred to the electron - enough to effectively **destroy** the diffraction pattern.



UNCERTAINTY AND THE DOUBLE SLIT

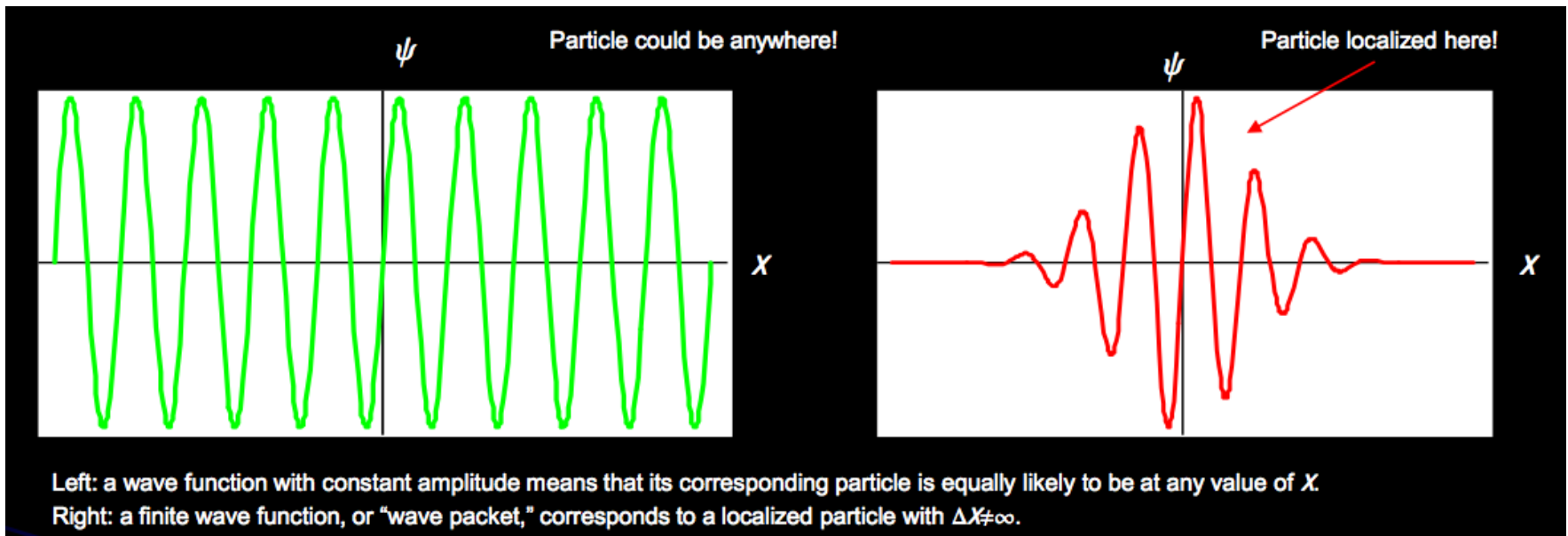
- If we try to pinpoint the electron at one of the slits, its momentum uncertainty gets so big that the interference pattern vanishes.
- Can you think of a way to get around this problem?
- We could use **lower energy photons**; but that dropping of the photon momentum simultaneously increases the photon wavelength...
- It turns out, that just when the photon momentum gets low enough that electron diffraction reappears, **the photon wavelength becomes larger than the separation between the two slits** (see *Feynman Lectures on Physics*, Vol. 3).
- This means we can no longer tell which slit the electron went through!

WHY THE UNCERTAINTY PRINCIPLE

- Let's **review** what we have said so far about matter waves and quantum mechanics.
- Elementary particles have associated **wave functions** $\psi(x,t)$. The **intensity** of the wave, $I(x) = |\psi(x,t)|^2$, gives the **probability** of finding the particle at position x at time t .
- However, quantum mechanics places a firm **constraint** on the simultaneous measurements we can make of a particle's **position** and **momentum**: $\Delta p_x \Delta x \geq \hbar/2$.
- This last concept, the **Uncertainty Principle**, probably seems very mysterious. However, it turns out that it is just a natural consequence of the wave nature of matter, **for all waves obey an Uncertainty Principle!**

WAVE FUNCTIONS SHOULD BE FINITE

- If a wavefunction is infinite in extent, like $\psi = A \sin 2\pi(x/\lambda - vt)$, the probability interpretation suggests that the particle could be anywhere: $\Delta x = \infty$.
- If we want particles to be **localized to some smaller Δx** , we need one whose amplitude varies with x and t , so that it vanishes for most values of x . But how do we create a function like this?



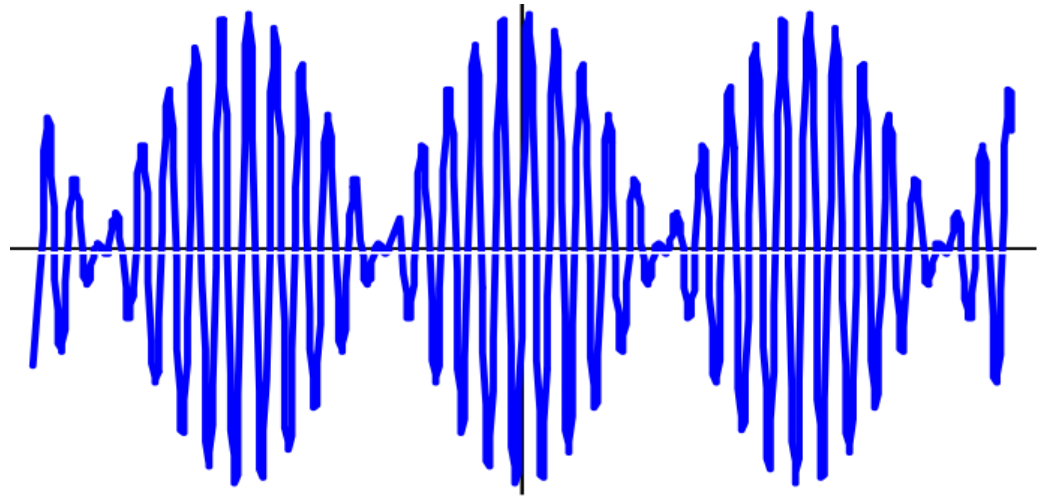
BUILDING WAVE PACKETS

- In order to get localized particles, their corresponding wave functions need to go to zero as $x \rightarrow \pm\infty$. Such a wave function is called a wave packet.
- It turns out to be rather easy to generate wave packets: all we have to do is superimpose, or add up, several sinusoids of different wavelengths or frequencies.
- **Recall the Principle of Superposition:** any wave ψ can be built up by adding two or more other waves.
- If we pick the right combination of sinusoids, they will cancel at every x other than some finite interval (Fourier Theorem).

SUPERPOSITION EXAMPLE: BEATS

- You may already know that **adding** two sine waves of slightly different wavelengths causes the phenomenon of **beats** (see below).
- A typical example: using a **tuning** fork to tune a piano string. If you hear beats when you strike the string and the tuning fork simultaneously, you know that the string is slightly out of tune.

The sum of two sine waves of slightly different wavelengths results in beats. The beat frequency is related to the difference between the wavelengths. This is a demonstration of how adding two sinusoids creates a wave of varying amplitude.



THE CONTINUUM LIMIT

- So, evaluating a sum of sinusoids like:

$$\psi = \sum_k A_k \cos(kx)$$

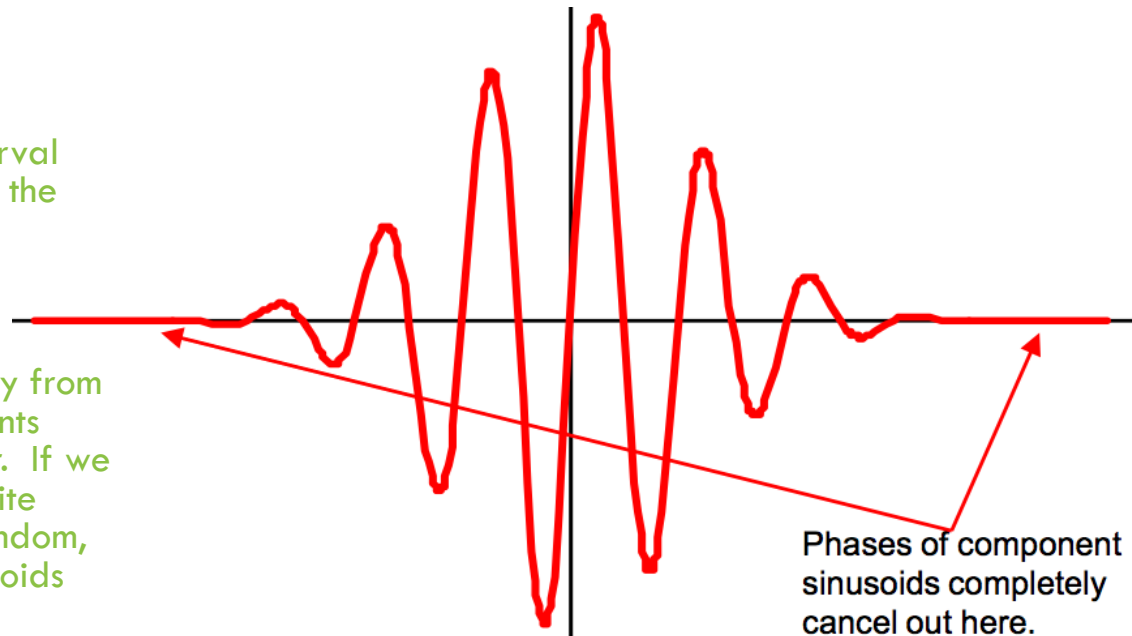
where k is an integer that runs between k_1 and k_2 , we can reproduce any periodic function.

- If we let k run over all values between k_1 and k_2 – that is, we make it a continuous variable – then we can finally reproduce a finite wave packet.

By summing over all values of k in an interval $\Delta k = k_1 - k_2$, we are essentially evaluating the integral

$$\psi = \int_{k_1}^{k_2} dk A(k) \cos(kx)$$

In such a “continuous sum”, the component sinusoids are all in phase near $x=0$. Away from this point, in either direction, the components begin to get out of phase with each other. If we go far enough out, the phases of the infinite number of components become totally random, and cancel out phases of component sinusoids completely.



CONNECTION TO UNCERTAINTY

- So, we can **sum** up sinusoids to get **wave packets**.
 - What does this actually mean?
- **Intuition:** we want a wave function that is non-zero only over some finite interval Δx .
- To build such a function, we start adding sinusoids whose inverse wavelengths, $k=2\pi/\lambda$, take on values in some finite interval Δk .
- **Here's the point:** as we make the interval Δk bigger, the width of the wave packet Δx gets smaller. This sounds like the Uncertainty Principle!

WAVE-RELATED UNCERTAINTIES

- As we sum over sinusoids, making the **range** of k values Δk larger, we decrease the **width** of the resulting function.
- In fact, there is a **fundamental limit** here that looks just like the position-momentum uncertainty relation.
- For any wave, the **minimum width** Δx of a wave packet composed from sinusoids with range Δk is $\Delta x = 1 / (2\Delta k)$, or:

$$\Delta x \Delta k \geq \frac{1}{2}$$

- There is a similar relation between **time** and **frequency**:

$$\Delta t \Delta \omega \geq \frac{1}{2}$$

CONNECTION TO QUANTUM MECHANICS

- If $k=2\pi/\lambda$, and $\lambda=h/p$, then the uncertainty relation for waves in general tells us:

$$\Delta x \Delta k \geq \frac{1}{2} \implies \Delta x \frac{2\pi}{\Delta \lambda} \geq \frac{1}{2} \implies \Delta x \frac{2\pi \Delta p}{h} \geq \frac{1}{2}$$
$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

- We recover the Heisenberg uncertainty relation!
- By a similar argument, we can show that the frequency-time uncertainty relation for waves implies the energy-time uncertainty of quantum mechanics.
- Hence, there is nothing really mysterious about the Uncertainty Principle; if you know anything about waves, you see that it arises rather naturally.

SUMMARY

- Quantum mechanics is the physics of small objects.
 - Its typical energy scale is given by **Planck's constant**.
- In quantum mechanics, variables like position, momentum, energy, etc. tend to take on **discrete values** (often proportional to h).
- **Matter** and **radiation** can have both **particle** and **wave-like** properties, depending on the type of observation.
- But by the **Uncertainty Principle**, objects can never be wavelike or particle-like **simultaneously**.
- Moreover, it is the act of **observation** that determines whether matter behaves like a **wave** or a **particle**.

SCHEDULE

- ~~1. Introduction~~
- ~~2. History of Particle Physics~~
- ~~3. Special Relativity~~
- ~~4. Quantum Mechanics~~
5. Experimental Methods
6. The Standard Model - Overview
7. The Standard Model - Limitations
8. Neutrino Theory
9. Neutrino Experiment
10. LHC and Experiments
11. The Higgs Boson and Beyond
12. Particle Cosmology

EXPERIMENTAL METHODS IN PARTICLE PHYSICS

HOW WE STUDY PARTICLES IN THE LAB

TODAY'S AGENDA

- Review of particle properties
- Passage of particles through matter
 - Ionization
 - Scintillation
 - Cherenkov radiation
- Particle detectors
- Modern detectors

HOW DO WE TELL THEM APART?



Recall

STANDARD MODEL PARTICLE PROPERTIES

<p>QUARKS</p> <p>LEPTONS</p>	<p>mass → $\approx 2.3 \text{ MeV}/c^2$</p> <p>charge → $2/3$</p> <p>spin → $1/2$</p>	<p>u</p> <p>up</p>	<p>c</p> <p>charm</p>	<p>t</p> <p>top</p>	<p>g</p> <p>gluon</p>	<p>H</p> <p>Higgs boson</p>
	<p>d</p> <p>down</p>	<p>s</p> <p>strange</p>	<p>b</p> <p>bottom</p>	<p>γ</p> <p>photon</p>		
	<p>e</p> <p>electron</p>	<p>μ</p> <p>muon</p>	<p>τ</p> <p>tau</p>	<p>Z</p> <p>Z boson</p>		
	<p>ν_e</p> <p>electron neutrino</p>	<p>ν_μ</p> <p>muon neutrino</p>	<p>ν_τ</p> <p>tau neutrino</p>	<p>W</p> <p>W boson</p>		

PARTICLE PROPERTIES

- The **charge**, **mass** and **interactions** that a particle experiences (**weak**, **electromagnetic**, **strong**) are **unique** to that particle type.
- Particle detectors exploit **unique** particle **properties** to detect and **identify** a particle.

HOW DO WE DETECT PARTICLES?

- Principles of a measurement:
 - The particle must **interact** with some detector **material**.
 - An **effect** of the interaction must be **measured**.
 - The detector material may change.
 - The particle may also be affected:
 - Energy loss, scattering, absorption

PARTICLE INTERACTIONS WITH MATTER

Recall

PASSAGE OF PARTICLES THROUGH MATTER

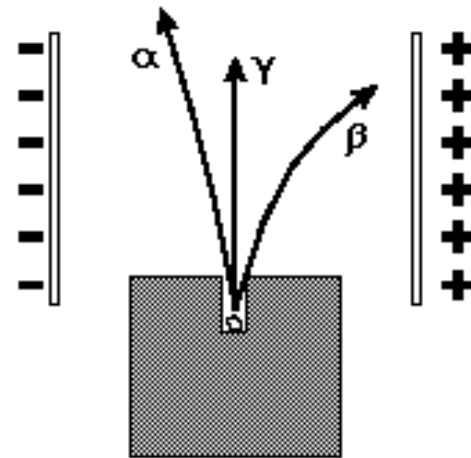
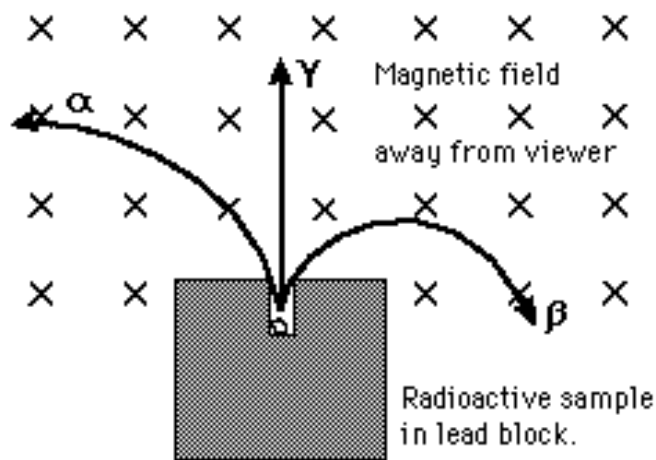
- By the 1890's, new, unstable elements (radioactivity) were being investigated by M. Curie, P. Curie, H. Becquerel, E. Rutherford, et al.
- **Radioactivity:** describes the emission of particles from atomic nuclei as a result of nuclear instability.
- The fact that **atoms** seemed to **spontaneously split** apart also suggests they **are not fundamental** particles.



Recall

PASSAGE OF PARTICLES THROUGH MATTER

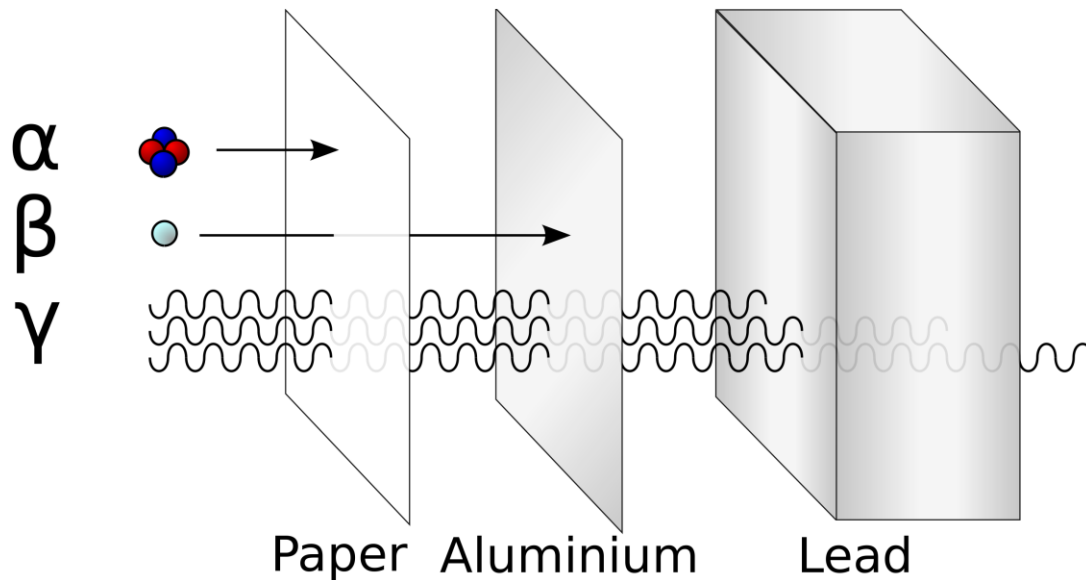
- At the time, it was known that unstable elements tended to emit three types of particles, which were differentiated by their electric charge.



	Electric charge	Mass
Alpha (α)	+2	$4 \times M_p$
Beta (β)	-1	$1/1800 \times M_p$
Gamma (γ)	Neutral	

PASSAGE OF PARTICLES THROUGH MATTER

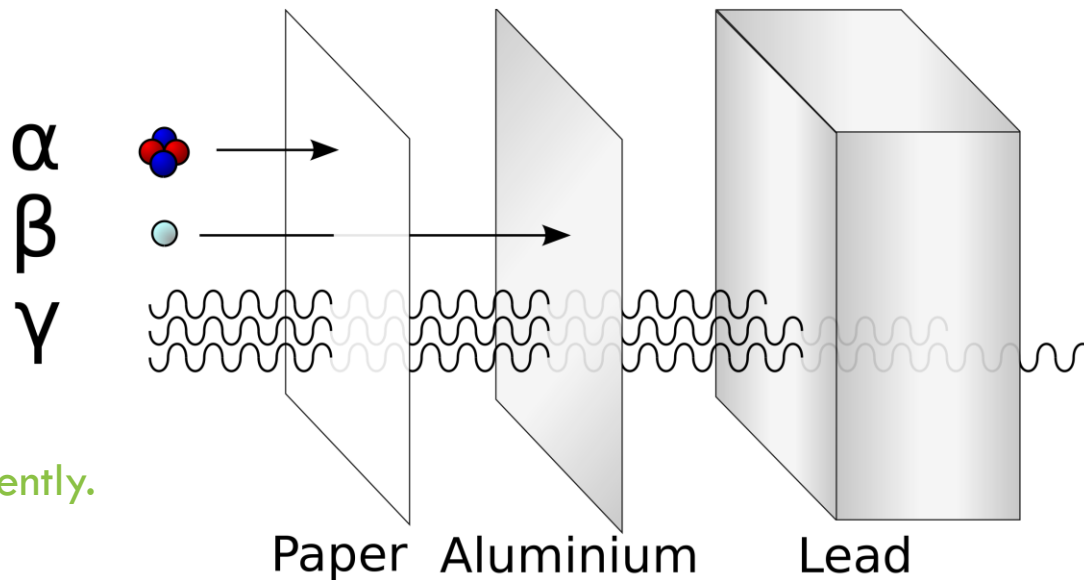
- Alpha, beta, gamma radiation:
 - Classified according to how they bend in a magnetic field.
 - Also differentiated by how easily they can be stopped.



Why do different particles have different penetrating power?

PASSAGE OF PARTICLES THROUGH MATTER

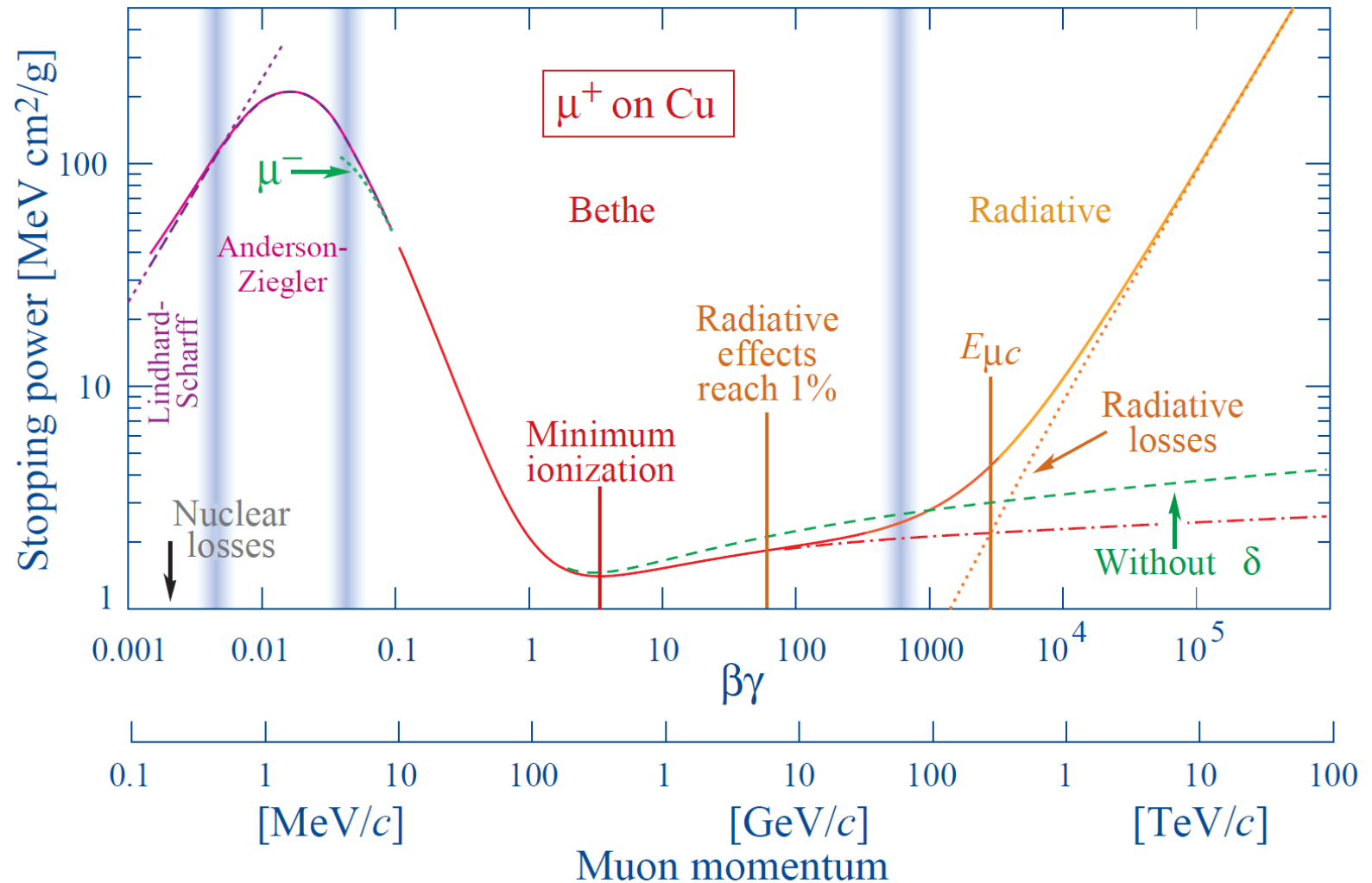
- Alpha, beta, gamma radiation:
 - Classified according to how they bend in a magnetic field.
 - Also differentiated by how easily they can be stopped.



Charged particles interact more frequently. They ionize matter (directly) and lose energy in the process.

Neutral particles interact less often, losing less energy. They ionize matter indirectly.

STOPPING POWER

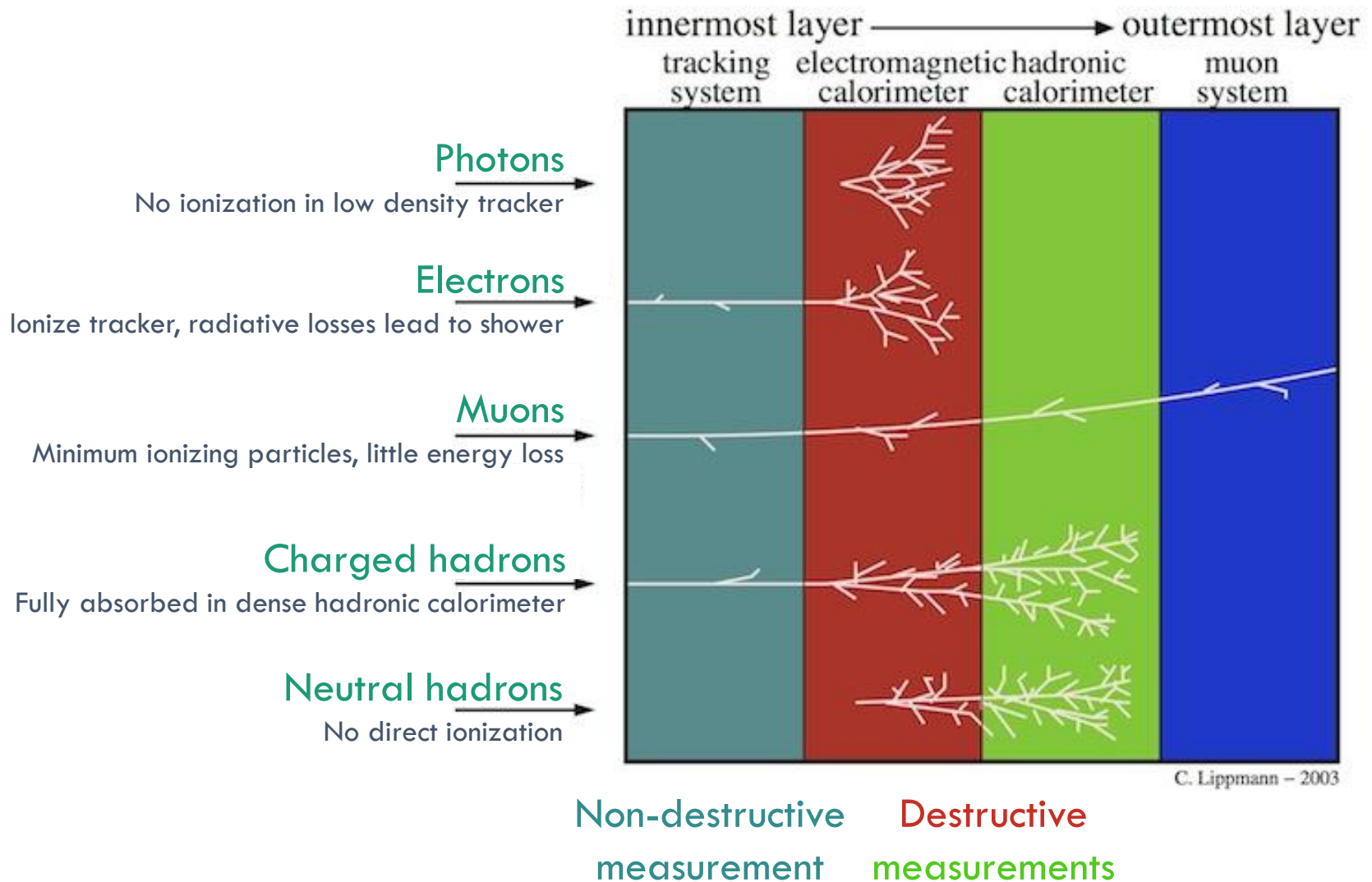


PARTICLE DETECTION

- Different particles undergo different interactions, leading to different detector signatures
- Exploit this to identify particle types

Particles	Type of interaction	Signature
neutrinos	weak (very rarely)	missing energy, interaction products
electrons	electromagnetic	track and electromagnetic shower
muons	electromagnetic	penetrating track
p , K , π	electromagnetic, strong, weak	track and hadron shower
photons	electromagnetic	electromagnetic shower
neutrons, K^0	strong, weak	hadron shower

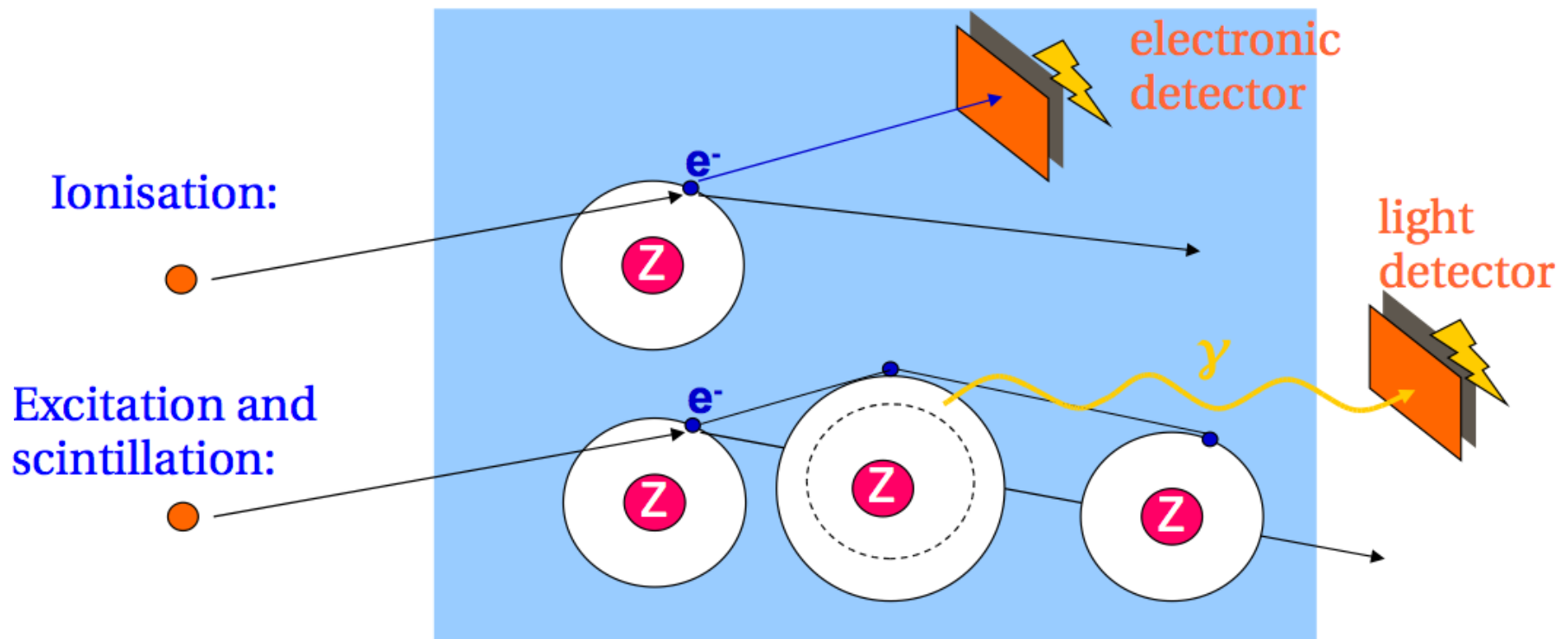
PARTICLE DETECTION



PARTICLE DETECTION

1. MEASUREMENT BY ELECTROMAGNETIC ENERGY LOSS

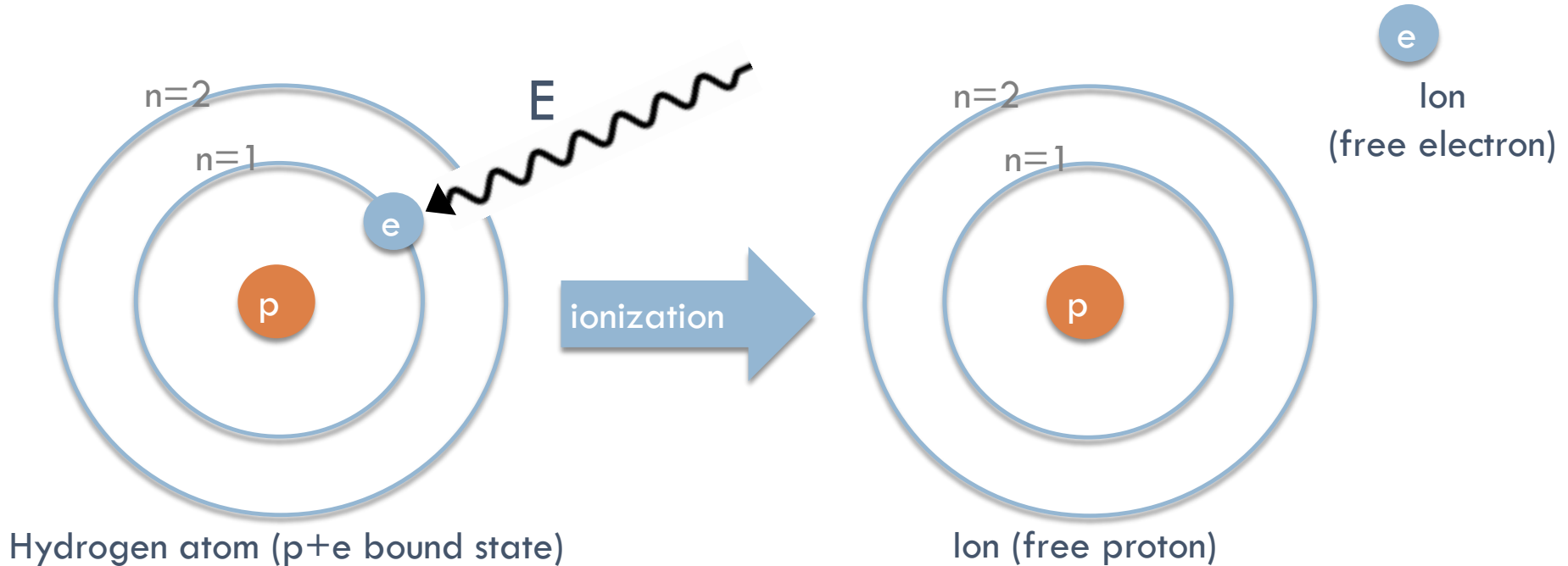
- Applies to all charged particles



Recall

IONIZATION

- **Ion:** positively or negatively charged particle (or part of atom)
- Ions can be produced when enough energy is given to remove one or more electrons from an atom:



IONIZATION

Bethe energy loss formula

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\epsilon_0} \right)^2 \left[\ln \left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)} \right) - \beta^2 \right]$$

$-\frac{dE}{dx}$ Energy loss per distance traveled

$\beta = \frac{v}{c}$ Particle velocity

z Particle charge (in units of electron charge)

n Density of electrons in material

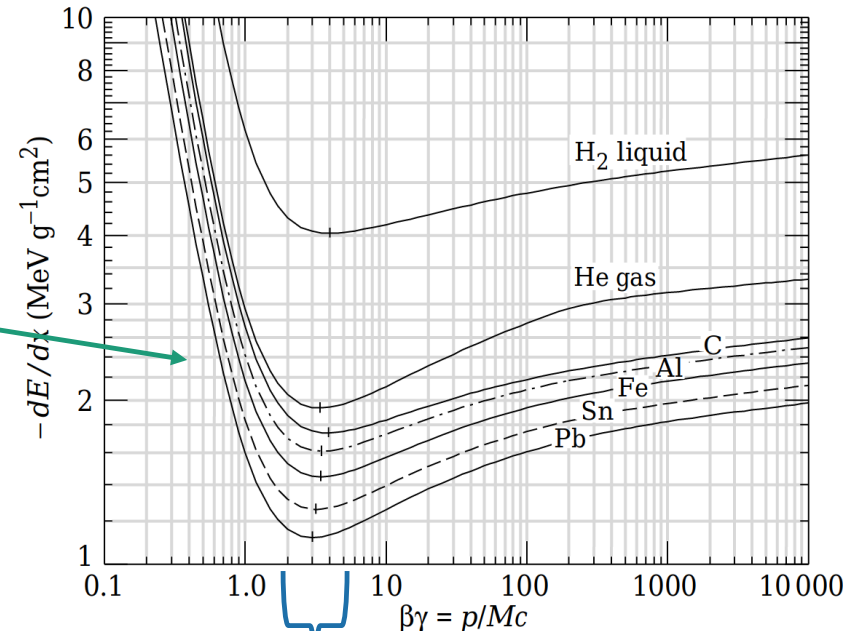
I Mean excitation potential of material

ϵ_0 Vacuum permittivity

e Electron charge

m_e Electron mass

c Speed of light in vacuum



Minimum Ionizing Particles

IONIZATION

Bethe energy loss formula

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\epsilon_0} \right)^2 \left[\ln \left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)} \right) - \beta^2 \right]$$

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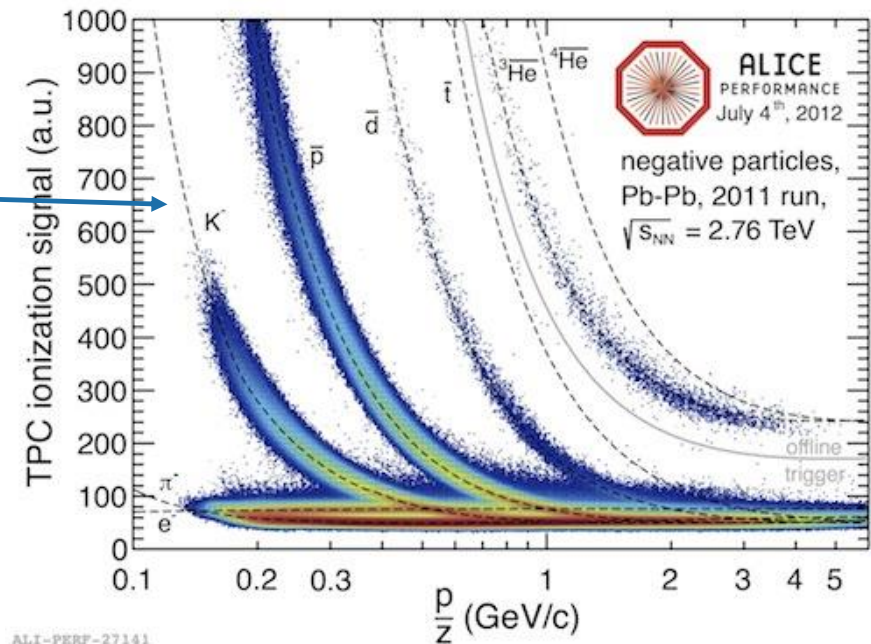
I Mean excitation potential of material

ϵ_0 Vacuum permittivity

e Electron charge

m_e Electron mass

c Speed of light in vacuum



$$p = \frac{1}{\sqrt{1-\beta^2}} m$$

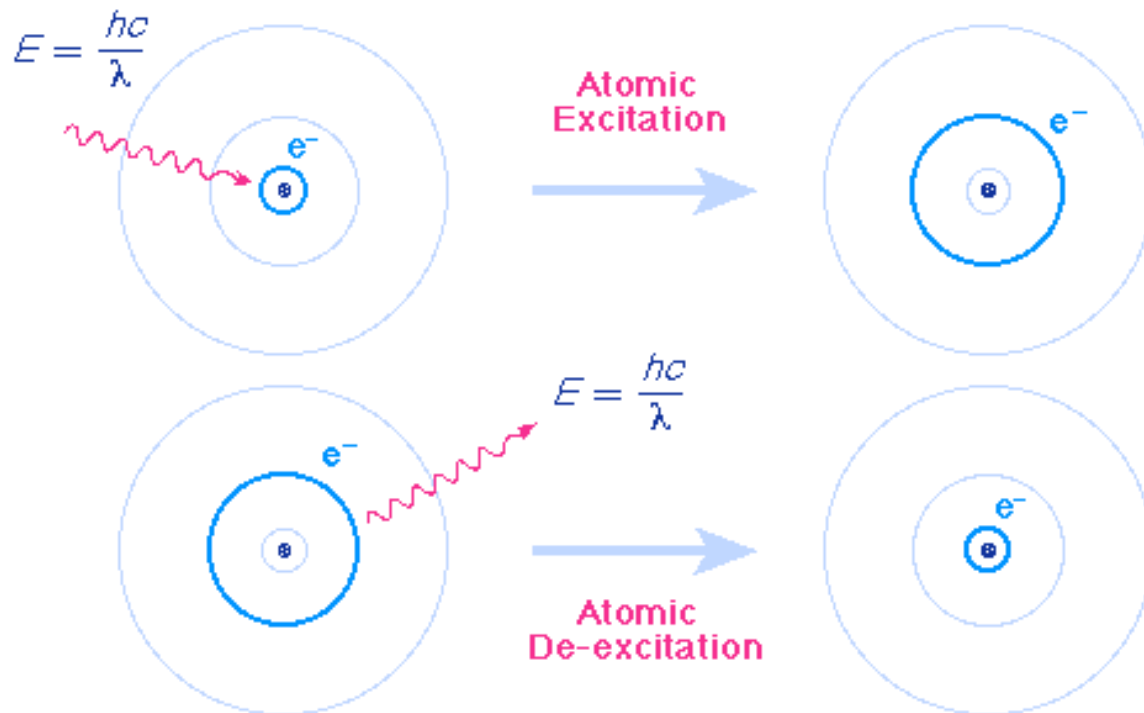
SCINTILLATION

- Scintillation is the **emission of light** of a characteristic wavelength spectrum, following the **absorption of radiation**.
 - The emitted radiation is usually less energetic than that absorbed.
- Scintillation **occurs** in:
 - Some types of **organic molecules** with complicated electronic structures
 - p-Terphenyl: $C_{18}H_{14}$
 - “PPO”: $C_{15}H_{11}NO$
 - **Inorganic** crystals and gases / liquids
 - NaI, CaF_2
 - He, Ar, Xe

Recall

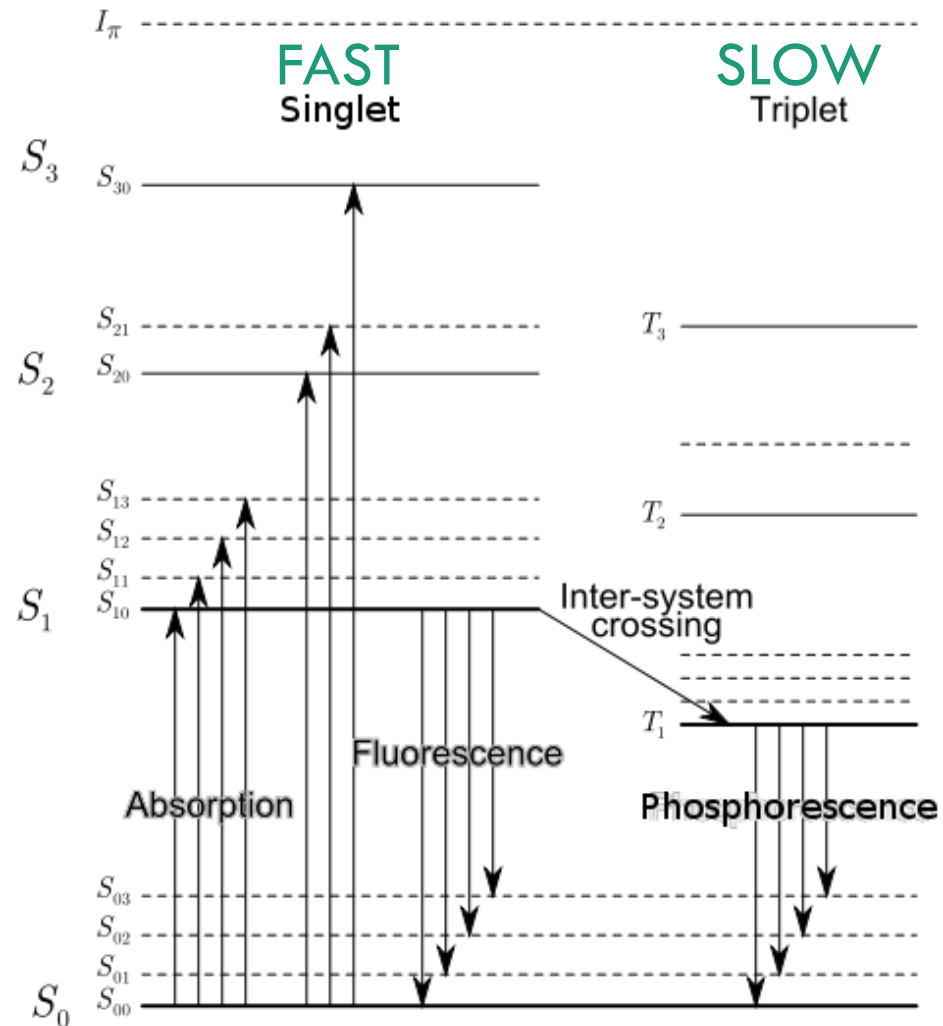
(SAME IDEA AS) ATOMIC EXCITATION

- An atom is excited when it has the potential to spontaneously produce energy.
 - This happens when one or more of the electrons occupy a higher-energy state.
 - When the electron returns to a lower energy state, the energy difference is given off in the form of radiation.
- The lowest energy state is the **ground state**.



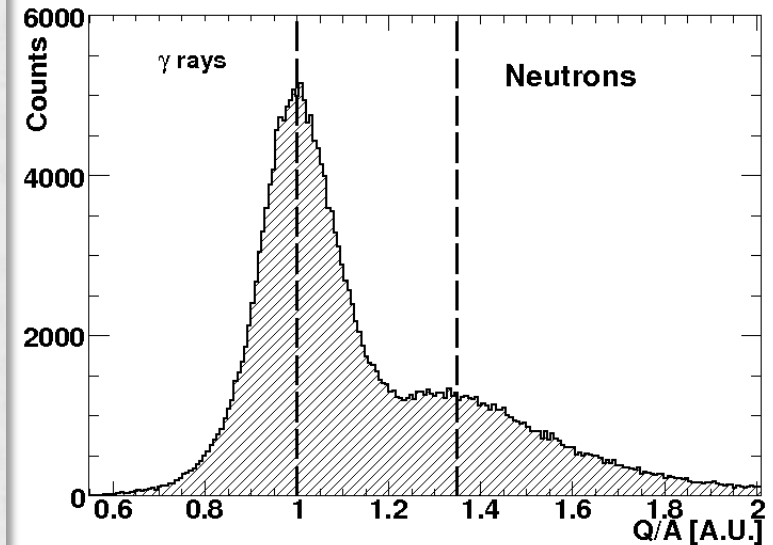
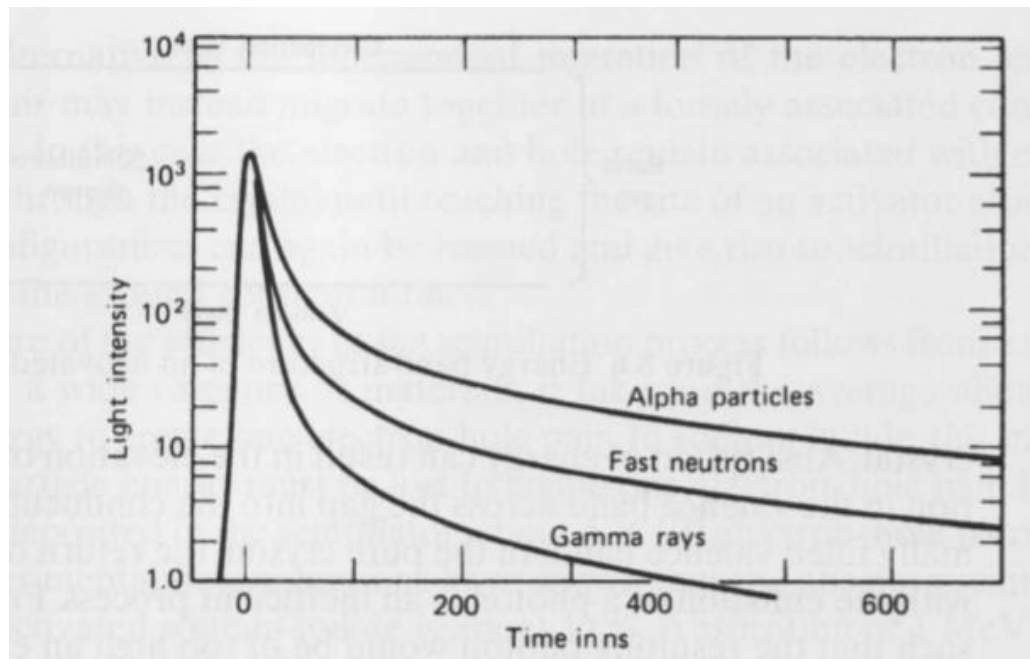
SCINTILLATION

- Depending on the particle dE/dx , the **fast** and **slow** states are occupied **differently**
- The **relative intensities** in the light output of these states **depend** on the ionizing **particle type**
- This property of scintillators allows for **pulse shape discrimination**: it is possible to identify which particle was detected by looking at the scintillation light **times**



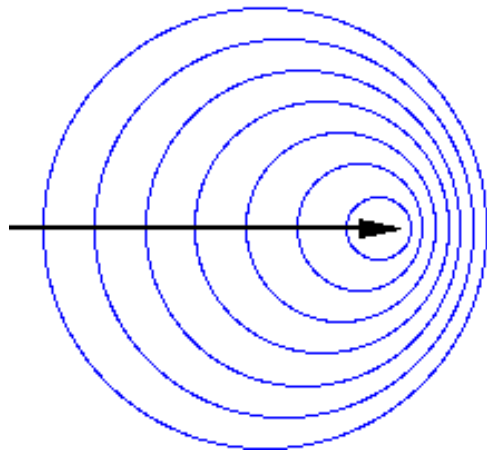
SCINTILLATION

- Pulse shapes can be used to discriminate among different particle types:

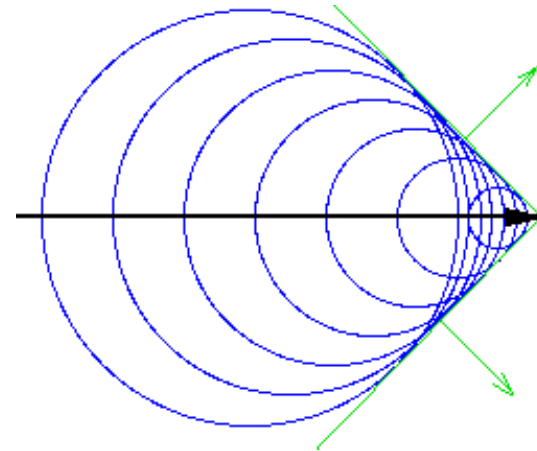


CHERENKOV RADIATION

- Cherenkov effect: a charged particle moving **faster than the speed of light** in a medium ($v > c/n$) emits Cherenkov radiation.



As a particle passes through matter, the surrounding atoms polarize and depolarize, and a weak electromagnetic wave spreads out from the position of the particle. For a particle traveling more slowly than light, wave-fronts originating at different times can never meet, and no interference is possible.



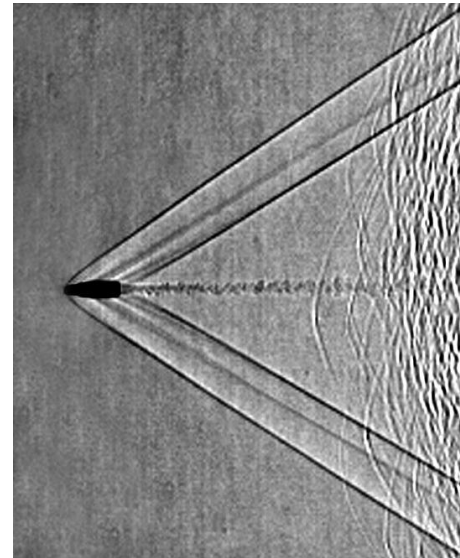
For a particle traveling faster than light, the wave-fronts do overlap, and constructive interference is possible, leading to a significant, observable signal.

CHERENKOV RADIATION

- Cherenkov effect: a charged particle moving **faster than the speed of light** in a medium ($v > c/n$) emits Cherenkov radiation.



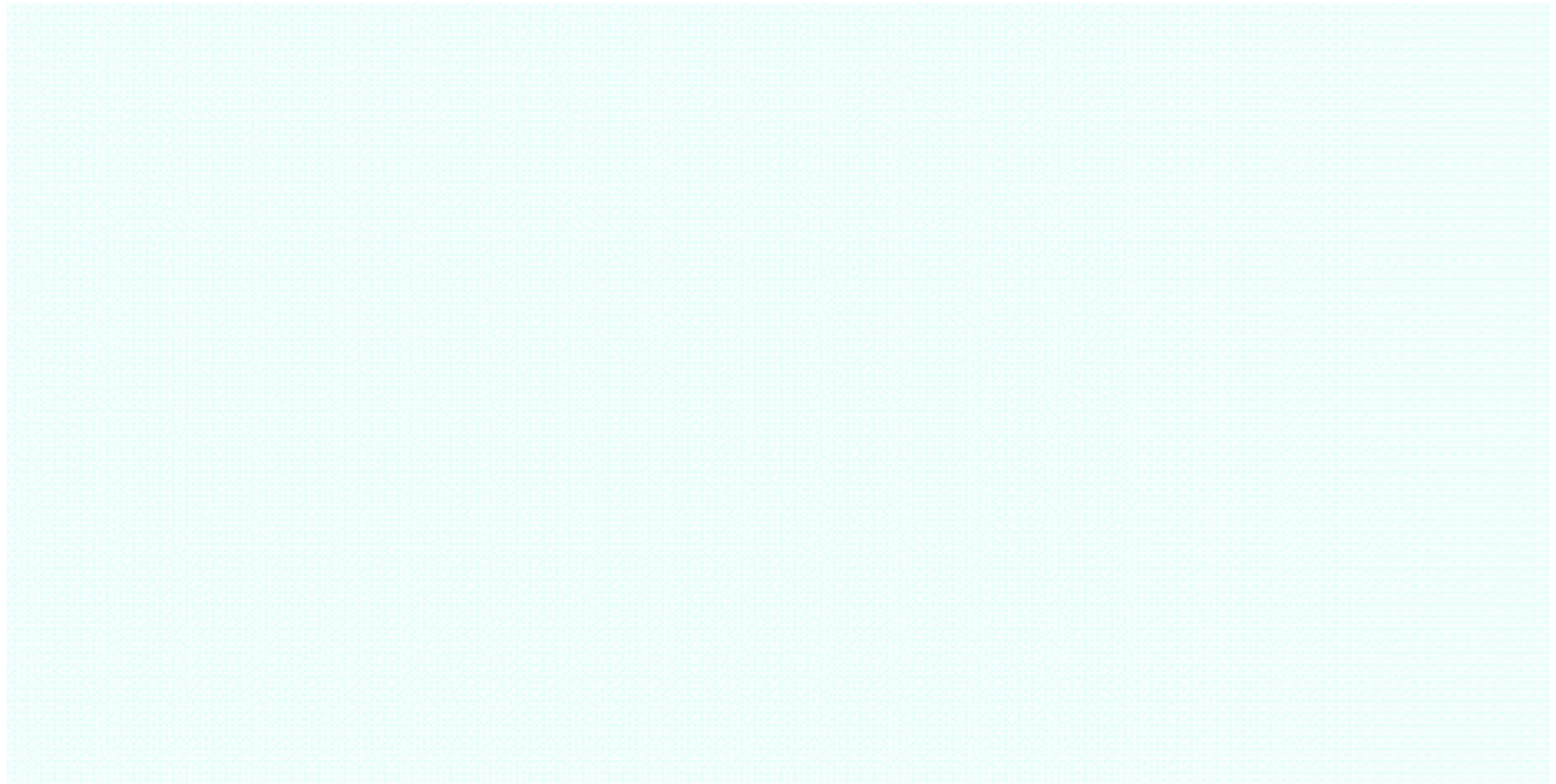
Duck moving slower than the speed at which water waves travel.



Bullet moving faster than the speed at which air waves travel – the speed of sound.

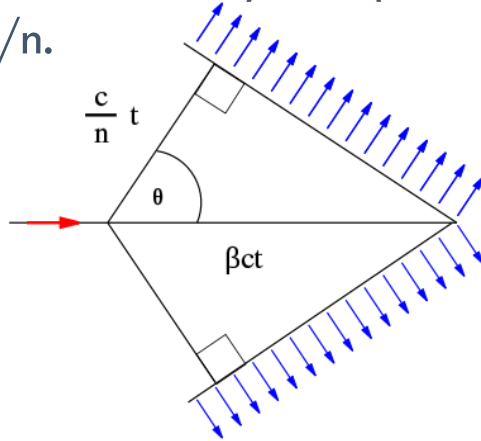
CHERENKOV RADIATION

- Cherenkov effect: a charged particle moving **faster than the speed of light** in a medium ($v > c/n$) emits Cherenkov radiation.



CHERENKOV RADIATION

- A particle can not, of course, travel faster than the speed of light in vacuum.
- In a medium of refractive index n , the speed of light is c/n , and there is no reason why the speed of the particle, βc , cannot be greater than c/n .

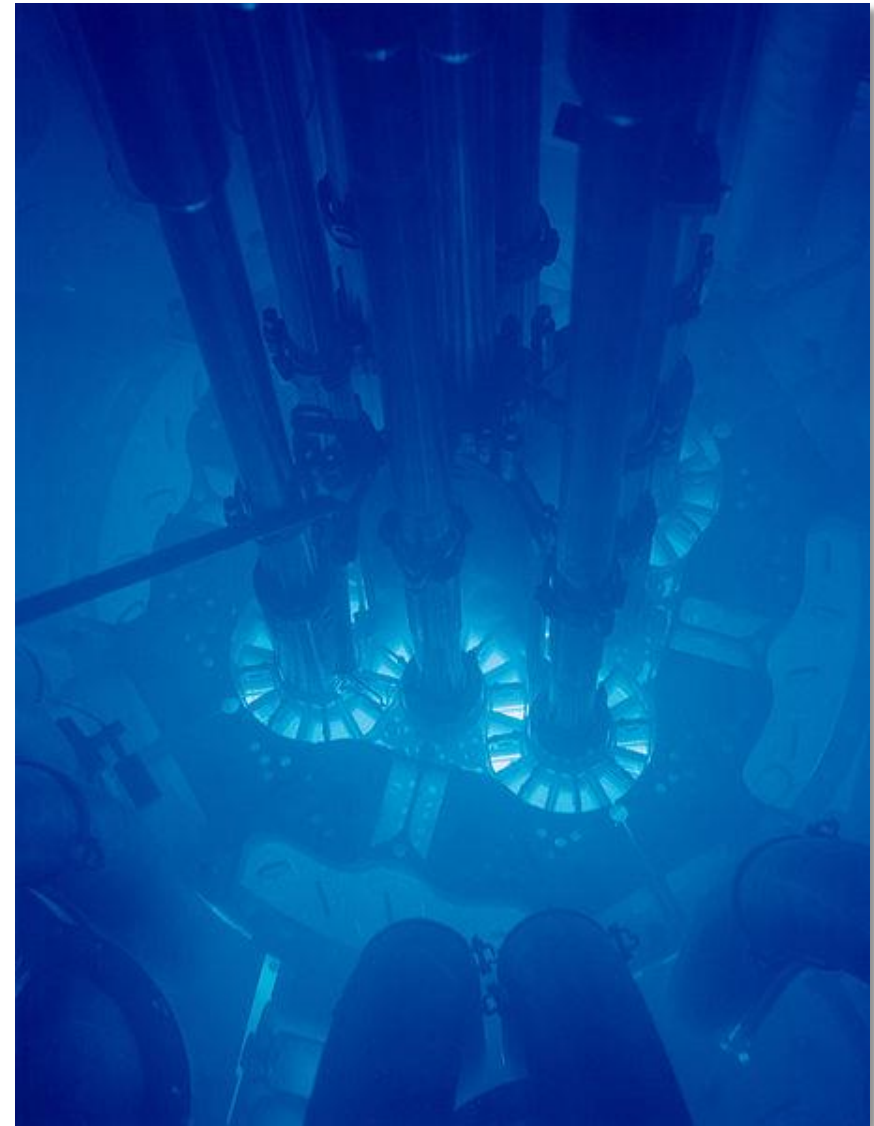


$$\cos\theta_c = \frac{\frac{c}{n}t}{\beta ct} = \frac{1}{\beta n}$$

- A highly relativistic particle passing through a medium is observed to emit visible light known as Cherenkov radiation if $\beta > 1/n$. As can be seen from the above diagram, a cone of light radiates out from each point on the particle's track.
- The Cherenkov cone angle is related to the particle's β .

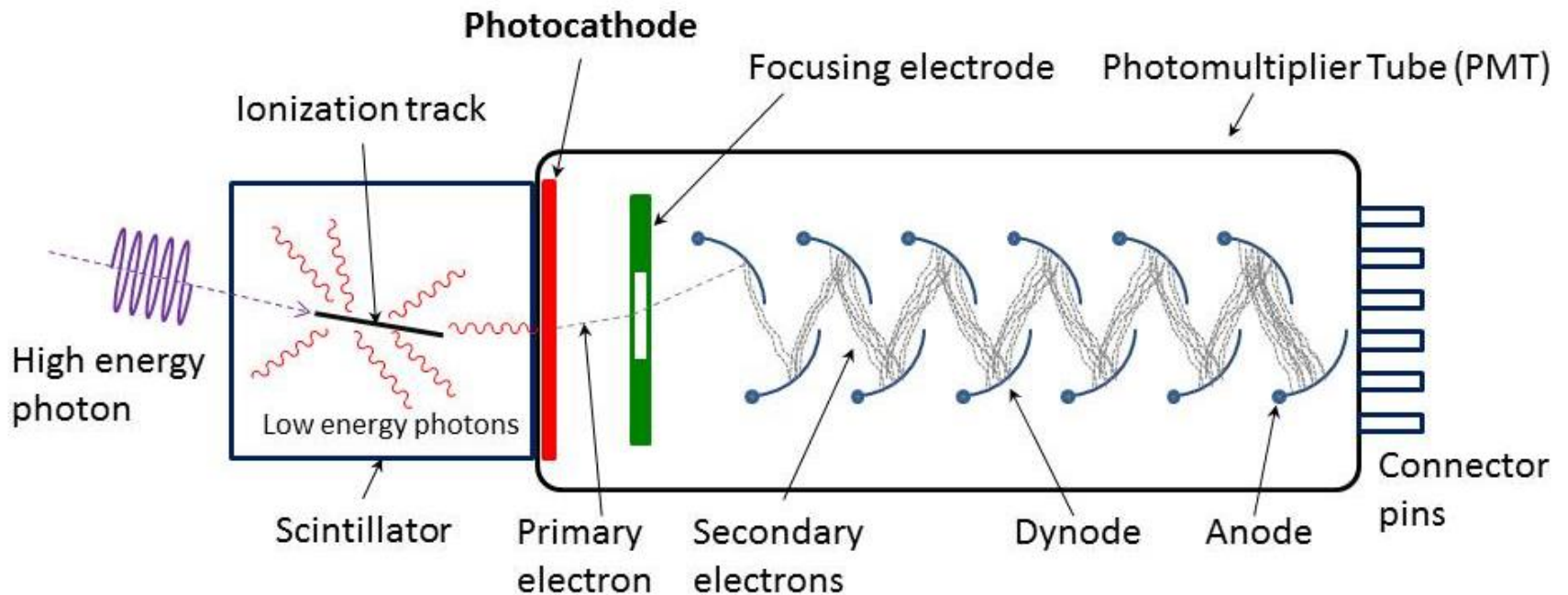
CHERENKOV RADIATION

- The characteristic blue glow of nuclear reactors is due to Cherenkov radiation.



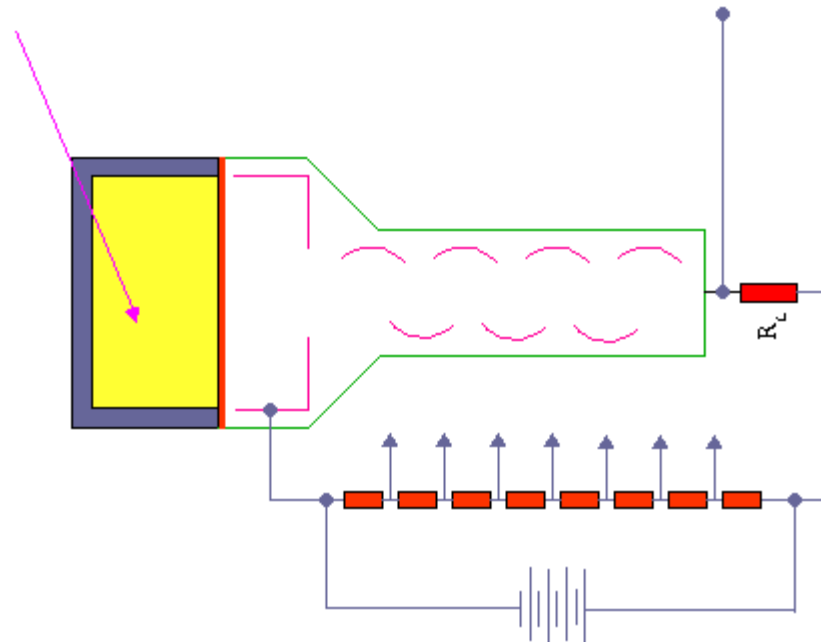
LIGHT DETECTION

- A **photomultiplier tube** (PMT) is a commonly used instrument for detecting visible photons.
- Basic of operation: photoelectric effect
 - Single photons converted to electrons and multiplied to a measurable electronic signal.



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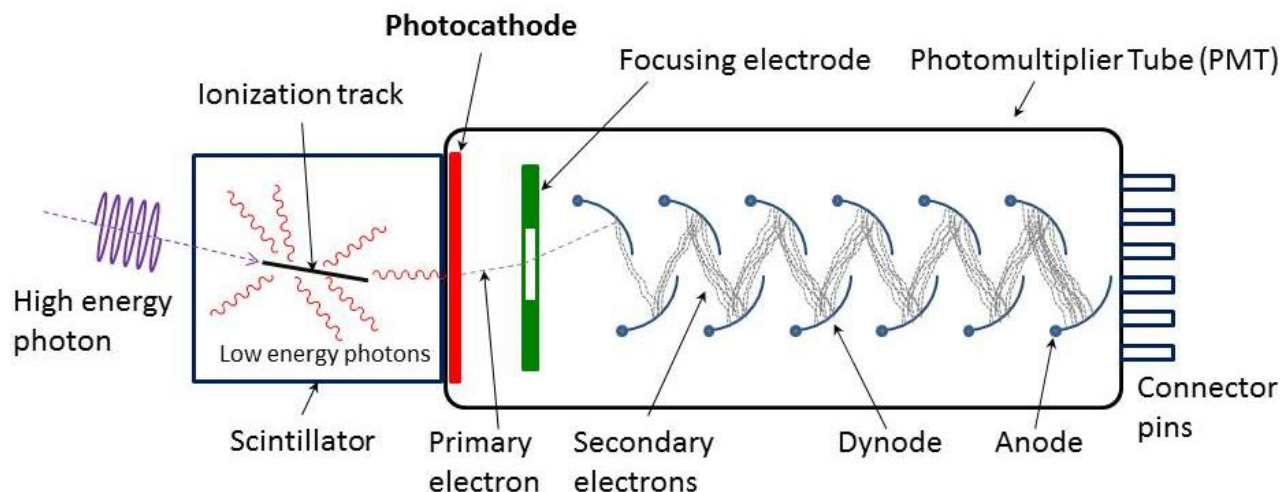
LIGHT DETECTION

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- Basic of operation: photoelectric effect
 - Single photons converted to electrons and multiplied to a measurable electronic signal.



LIGHT DETECTION

- Light falls on a photocathode and a photoelectron is emitted (photoelectric effect).
 - Quantum Efficiency depends on cathode and wavelength ($QE \sim 25\%$).
- Photoelectron focused and accelerated towards the first dynode by electric field.
- Photoelectron strikes dynode and several electrons are emitted (on average $n \sim 5$).
- Several dynodes (~ 10) give high gain (10^7).
- High speed: few ns transit time!
- Gain can be much lower in magnetic fields, depending on orientation.



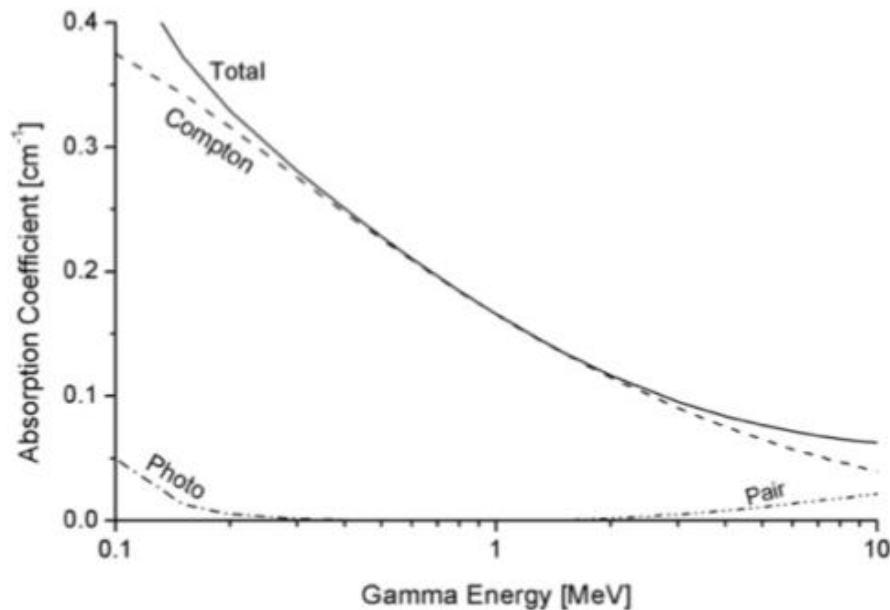
PHOTON INTERACTIONS IN MATTER

- Photoelectric effect ✓
 - Compton scattering ✓
 - Pair production (today)
-
- How does each process contribute to the total energy loss?

PHOTON INTERACTIONS IN MATTER

- Absorption coefficient of Al

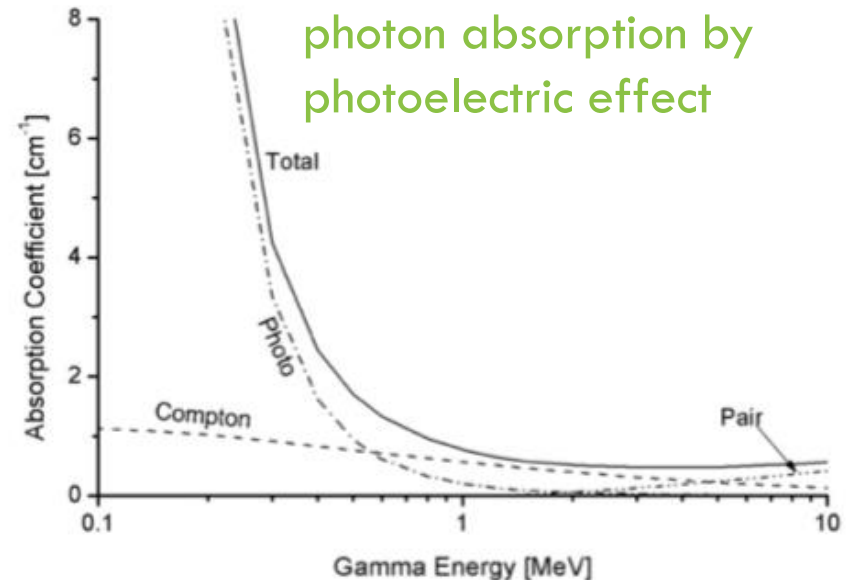
$Z = 13$



- Absorption coefficient of Pb

$Z = 82$

Higher Z materials favour photon absorption by photoelectric effect

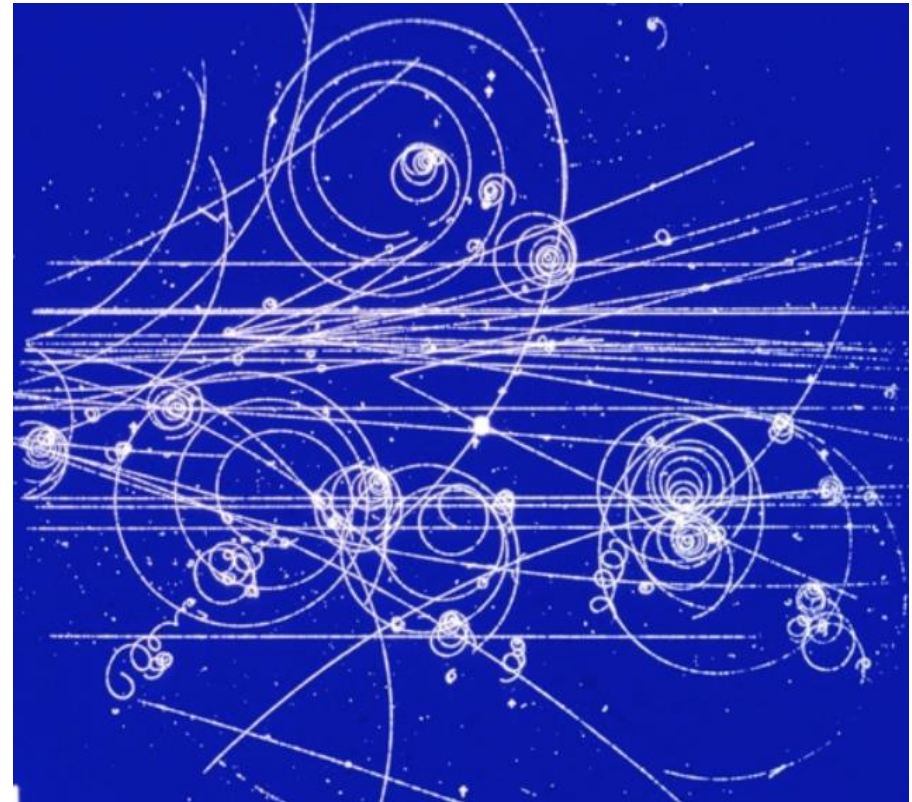
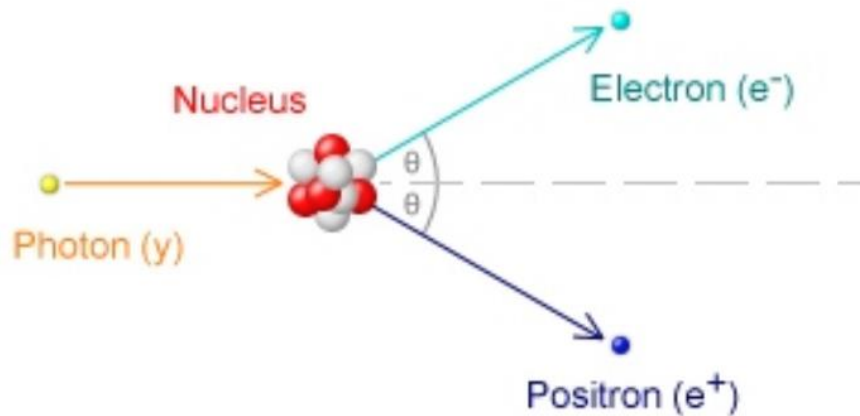


Probability of interaction depends on number of protons (Z)

PHOTON INTERACTIONS IN MATTER

PAIR PRODUCTION

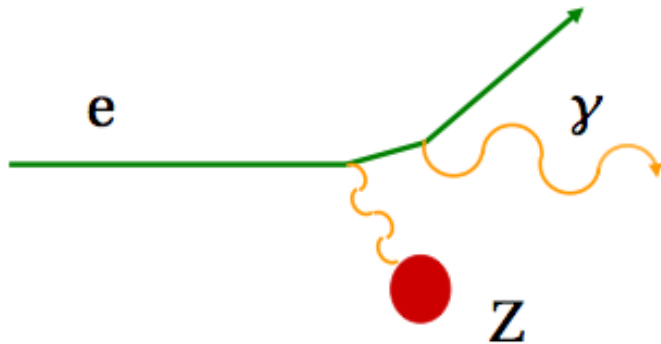
- Dominant process at high energy, above 4 MeV for lead (material dependent).



Pair production in a bubble chamber

ELECTRON INTERACTIONS IN MATTER

BREMMSTRAHLUNG



- Bremsstrahlung: $e Z \rightarrow Z e \gamma$
electromagnetic radiation produced by the deceleration of an **electron**, when deflected by an **atomic nucleus**.

$$-\frac{dE}{dx} = \frac{E}{X_0}$$

$$X_0 [cm] = \frac{716}{\rho [g/cm^3]} \frac{A}{Z} \frac{1}{(Z+1) \ln(287/\sqrt{Z})}$$

X_0 is the mean distance over which a high-energy electron loses all but $1/e$ of its energy.

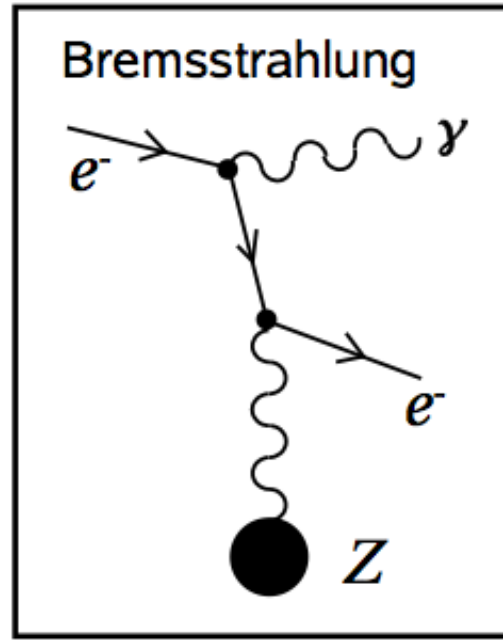
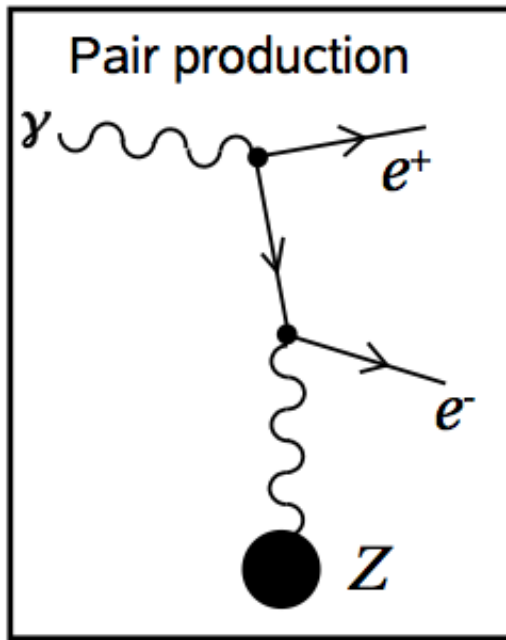
$$\text{Pb: } X_0 = 0.56 \text{ cm}$$

$$\text{Si: } X_0 = 8.9 \text{ cm}$$

$$\Leftrightarrow E = E_0 e^{-x/X_0}$$

PAIR PRODUCTION AND BREMMSTRAHLUNG

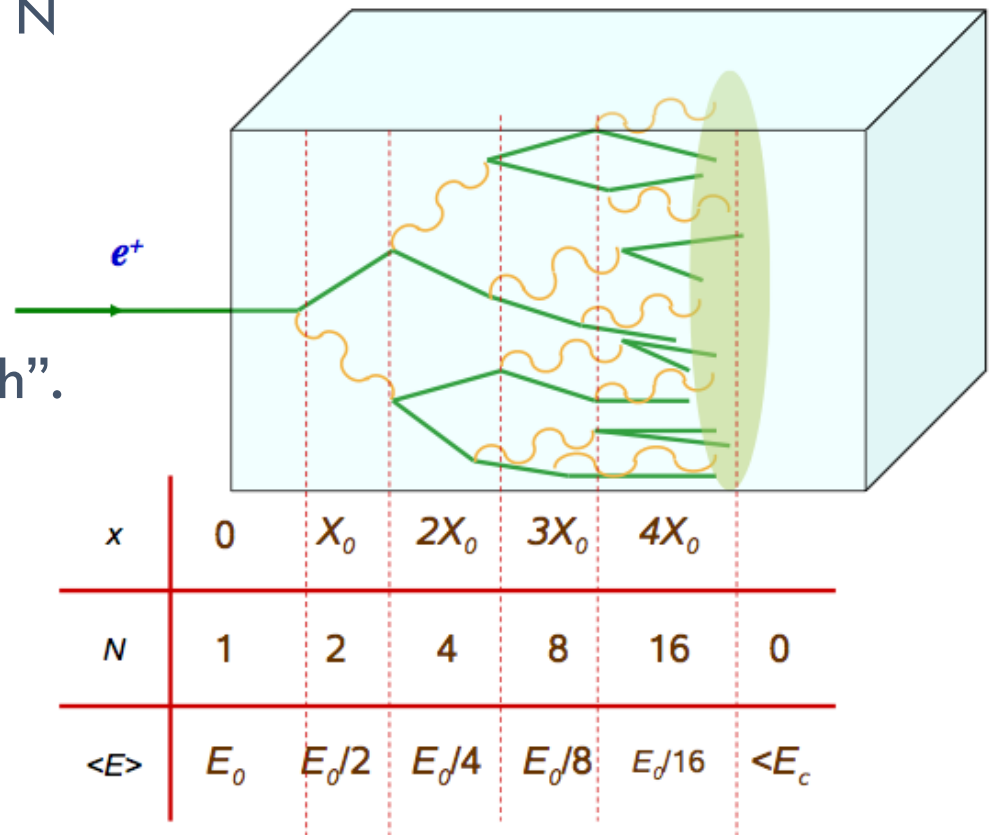
- Pair production and Bremsstrahlung radiation are complementary processes: both lead to **electromagnetic showers**.



- Very similar Feynman diagrams
- Just two arms swapped
- At high energy: $\sigma_\gamma = \frac{7}{9}\sigma_e$

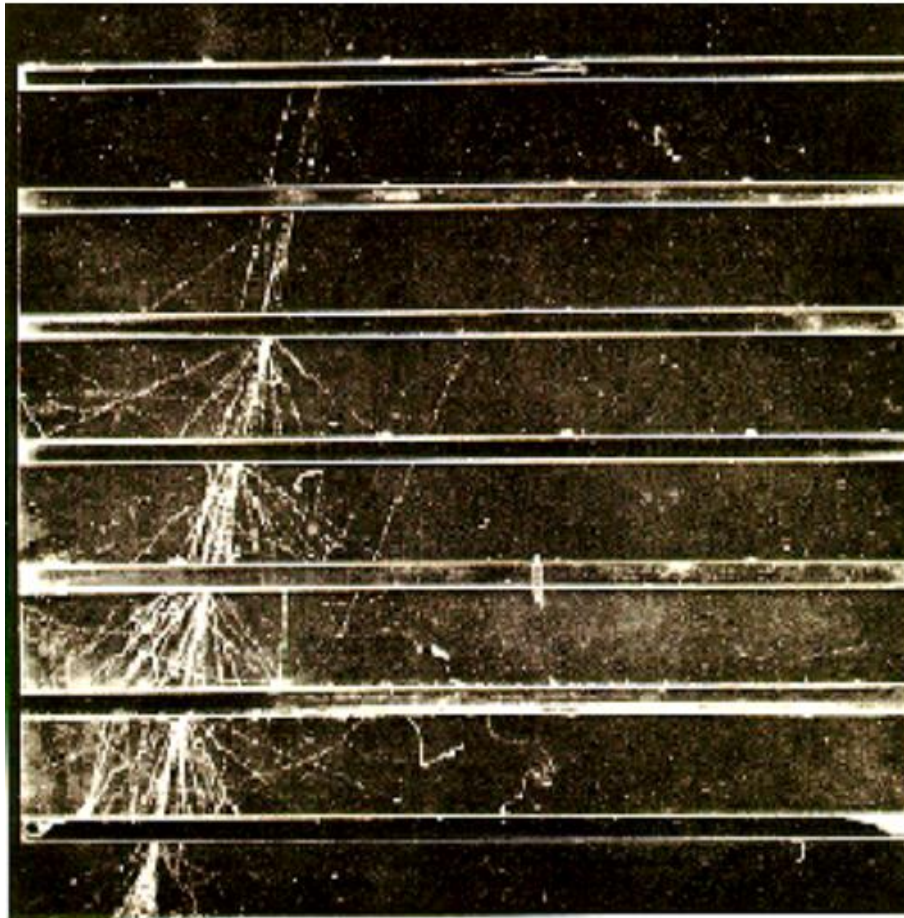
ELECTROMAGNETIC SHOWERS

- The number of particles increases as a 2^N , where N is the number of X_0 over which the shower has developed.
- X_0 is the “radiation length”.
- The length of the shower depends on the primary electron energy.



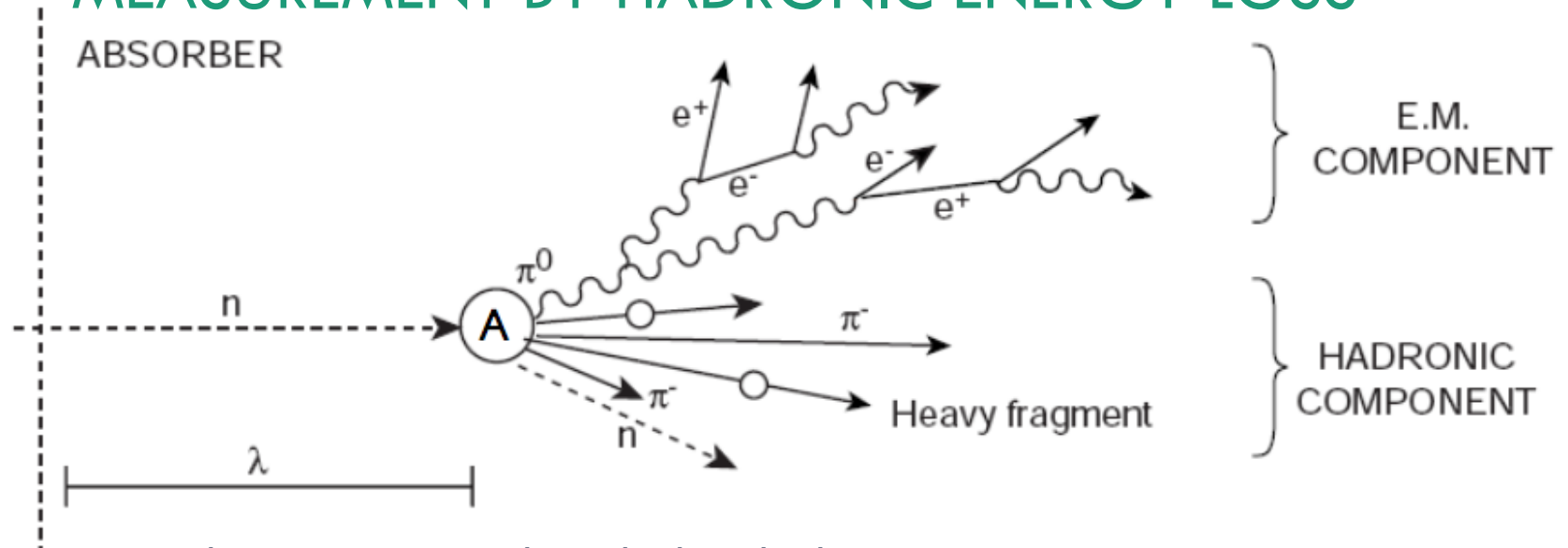
ELECTROMAGNETIC SHOWERS

- Cloud chamber image of a shower between lead plates.



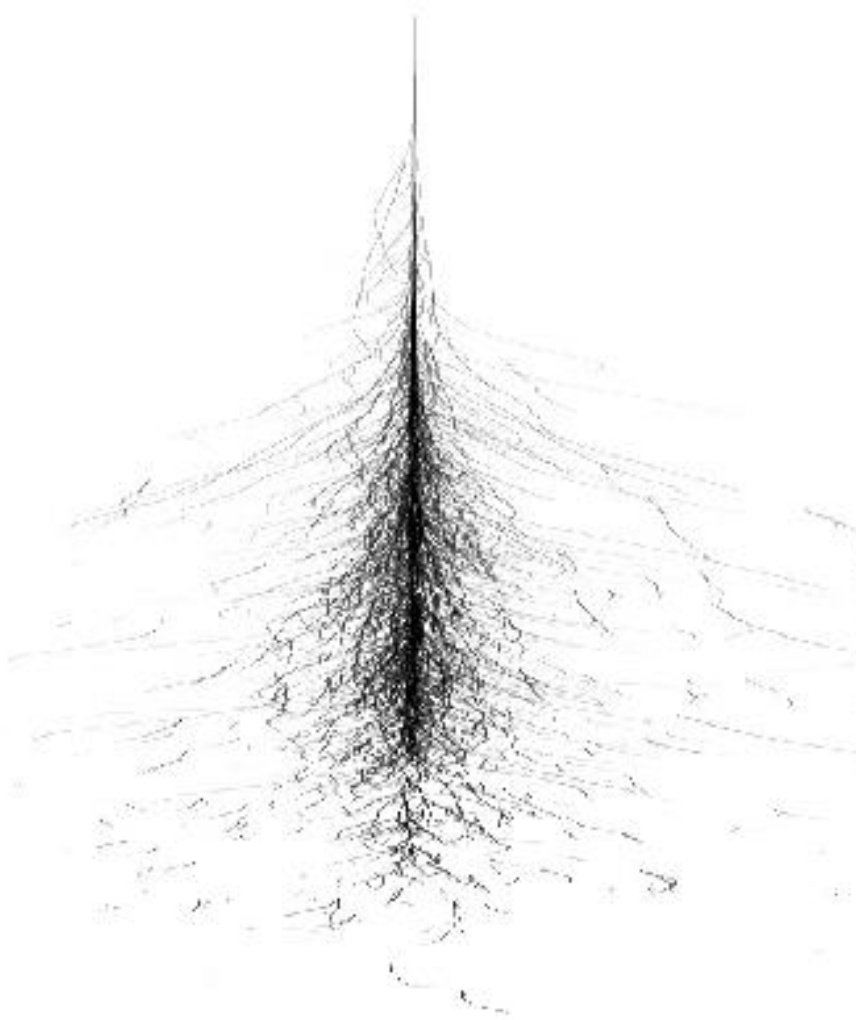
PARTICLE DETECTION

MEASUREMENT BY HADRONIC ENERGY LOSS

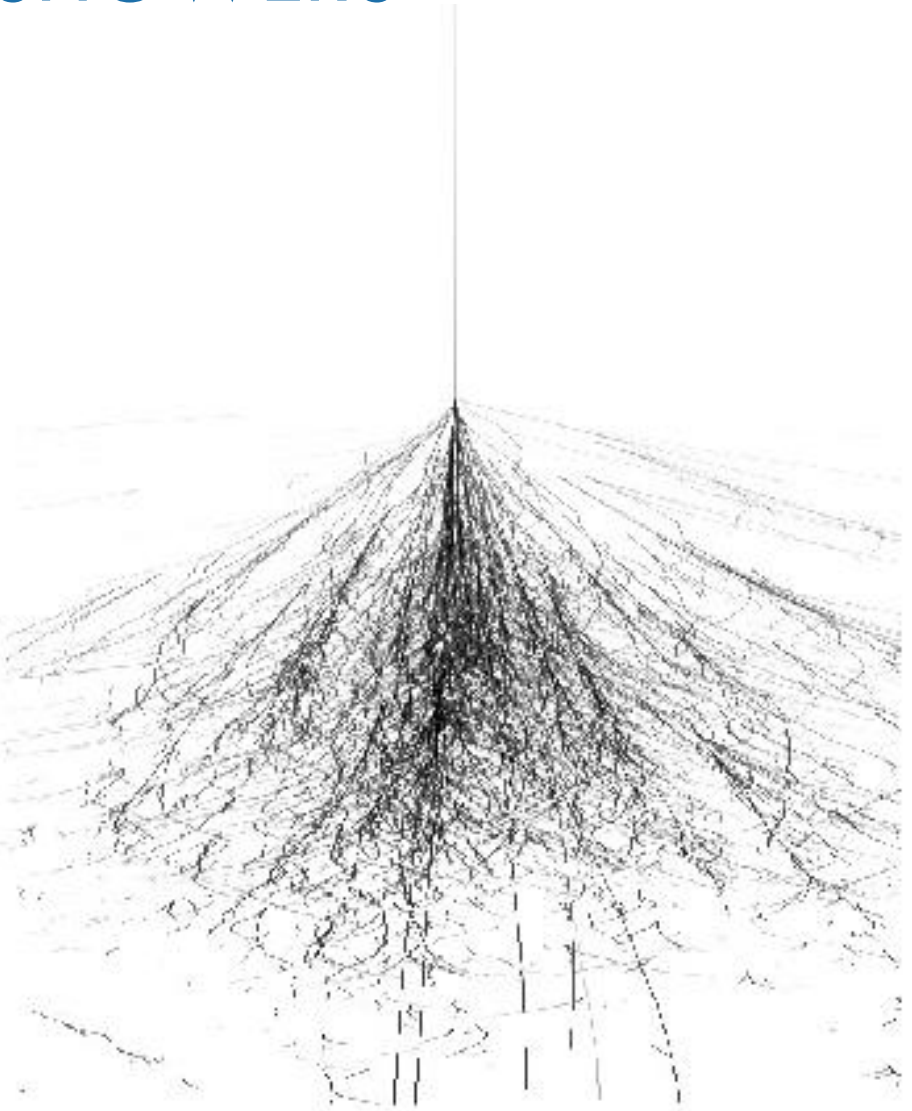


- Hadronic interactions have high multiplicity:
 - Shower is to 95% contained in $\sim 7\lambda$ at 50 GeV (1.2 m of iron).
- Hadronic interactions produce π^0 :
 - $\pi^0 \rightarrow \gamma\gamma$, leading to local EM showers.
- Some energy loss in nuclear breakup and neutrons (“invisible energy”)
- Stronger fluctuations in a hadronic shower:
 - Worse energy resolution.

HADRONIC VS EM SHOWERS

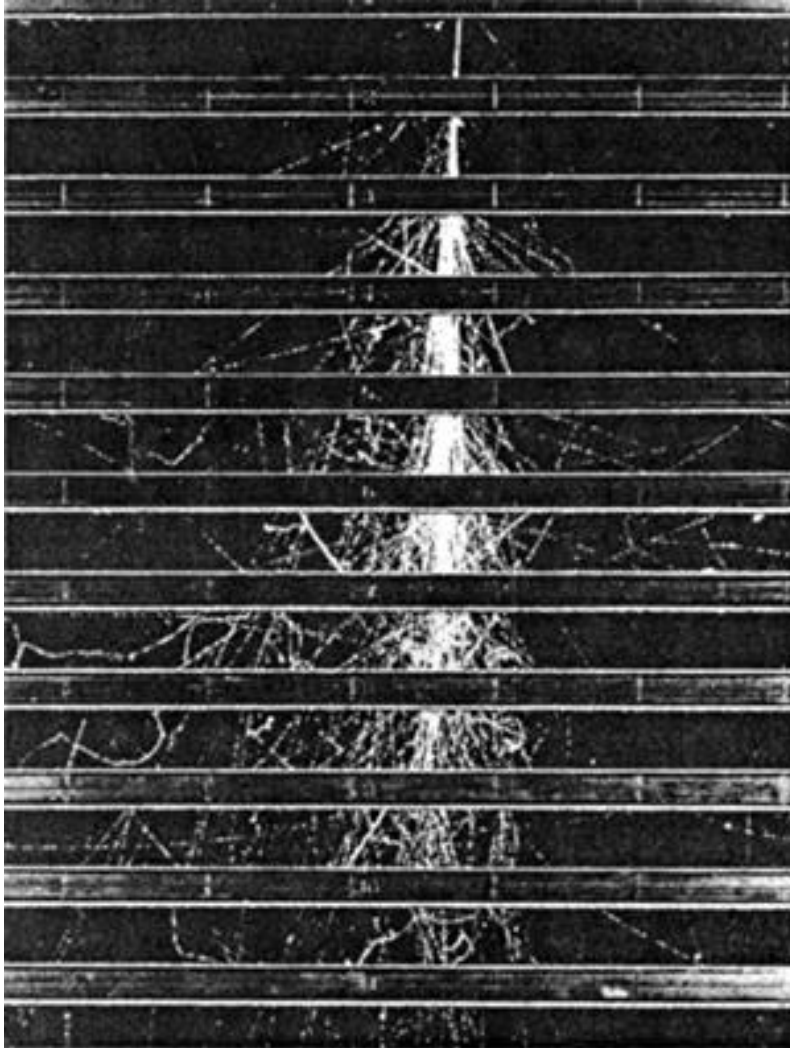


Gamma shower



Hadronic shower

HADRONIC VS EM SHOWERS



ASIDE

A NOTE ABOUT CROSS-SECTIONS

- A measure of interaction probability in particle physics.
- “Effective area of collision”
- Used to calculate predicted interaction rates:

$$N = \Phi \times \sigma$$

The diagram illustrates the equation $N = \Phi \times \sigma$ with three arrows pointing to the variables and their units:

- A green arrow points from the text **Interaction rate** (events/second) to the variable N .
- A blue arrow points from the text **Flux of incoming particles** (particles/cm²/second) to the variable Φ .
- An orange arrow points from the text **Cross-section** (cm²) to the variable σ .

ASIDE

A NOTE ABOUT CROSS-SECTIONS

- A measure of interaction probability in particle physics.
- “Effective area of collision”
- Used to calculate predicted interaction rates:

$$N(E) = \Phi(E) \times \sigma(E)$$

Interaction rate
events/second

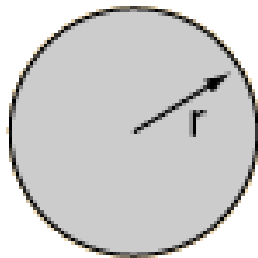
Flux of incoming particles
particles/cm²/second

Cross-section
cm²

ASIDE

A NOTE ABOUT CROSS-SECTIONS

- Example:



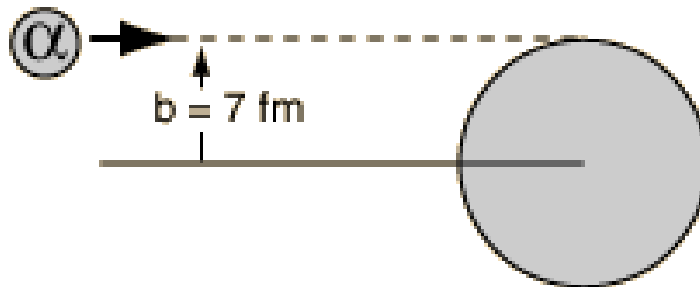
Gold nucleus
 $Z=79$, $A=197$

$$r = 7 \text{ fermi} = 7 \times 10^{-15} \text{ m}$$

$$A = \pi r^2 = 154 \text{ fermi}^2 = 1.54 \times 10^{-28} \text{ m}^2$$

$$A = 1.54 \text{ barns}$$

$$1 \text{ barn} = 10^{-28} \text{ m}^2 = 100 \text{ fm}^2$$



A 6 MeV alpha particle approaching a gold nucleus with an impact parameter equal to the gold nuclear radius of 7 fm would be scattered through an angle of almost 140° . We would say that the cross section for scattering at or greater than 140° is 1.54 barns.

ASIDE

A NOTE ABOUT CROSS-SECTIONS

- Example:
- Rutherford worked out the scattering cross-section for alpha particles of kinetic energy KE scattering off a single nucleus with atomic number Z . The cross-section for scattering at a greater angle than some chosen angle is:

$$\sigma = \pi Z^2 \left(\frac{ke^2}{KE} \right)^2 \left(\frac{1 + \cos \theta}{1 - \cos \theta} \right)$$

Depends on chosen angle (geometric nature of cross-section).

Increases with Z^2 , the number of protons in a nucleus.

Depends on k , the Coulomb force constant (strength of electromagnetic interaction).

Decreases with the kinetic energy squared (KE^2) of the incoming particle.

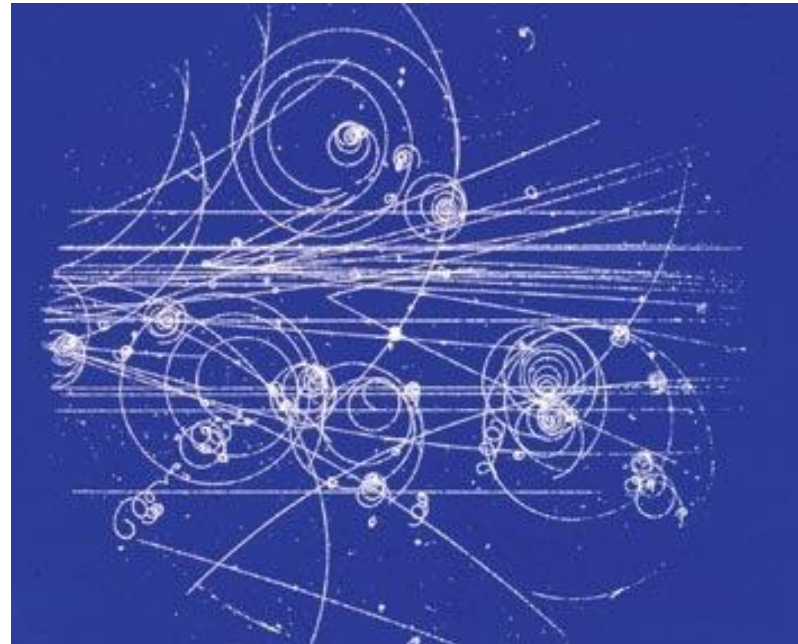
DETECTING PARTICLES

DETECTING PARTICLES

*When charged particles pass through matter, they ionize atoms in their path, liberating charges, and causing the emission of detectable light (scintillators) or the formation of tracks of droplets (cloud/bubble chambers). **This is how we “see” them.***

- Experimental physicists use many kinds of particle detectors, including:

- Geiger counters
- Cloud chambers *
- Bubble chambers *
- Spark chambers *
- Photographic emulsions *
- Wire chambers
- Cherenkov detectors
- Scintillators
- Photomultiplier tubes
- Calorimeters



→ Note: most are sensitive to electrically charged particles only!

PARTICLE DETECTORS

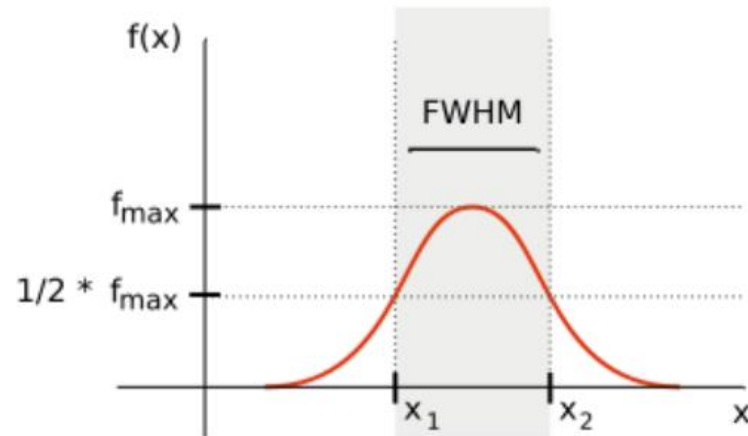
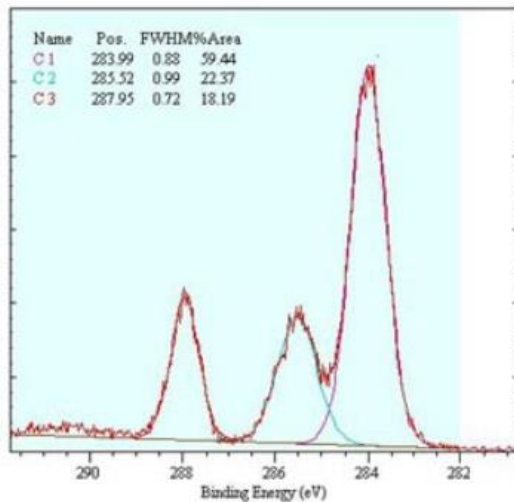
- Detectors usually specialize in:
 - Tracking: measuring **positions** / **trajectories** / **momenta** of charged particles, e.g.:
 - Silicon detectors
 - Drift chambers
 - Calorimetry: measuring **energies** of particles:
 - Electromagnetic calorimeters
 - Hadronic calorimeters
- But they can also be a combination.

PARTICLE DETECTORS

- Design Criteria:
 - Coverage and hermeticity:
 - Captures all particles produced in an interaction.
 - No holes, no cracks, no dead regions.
 - Resolution:
 - Resolve all particles (high granularity, each “granule”/channel read out individually).
 - Measure energies and directions with high precision.
 - Constraints:
 - Cost and available technology.

ENERGY RESOLUTION

- The ability to differentiate amounts of energy deposition.

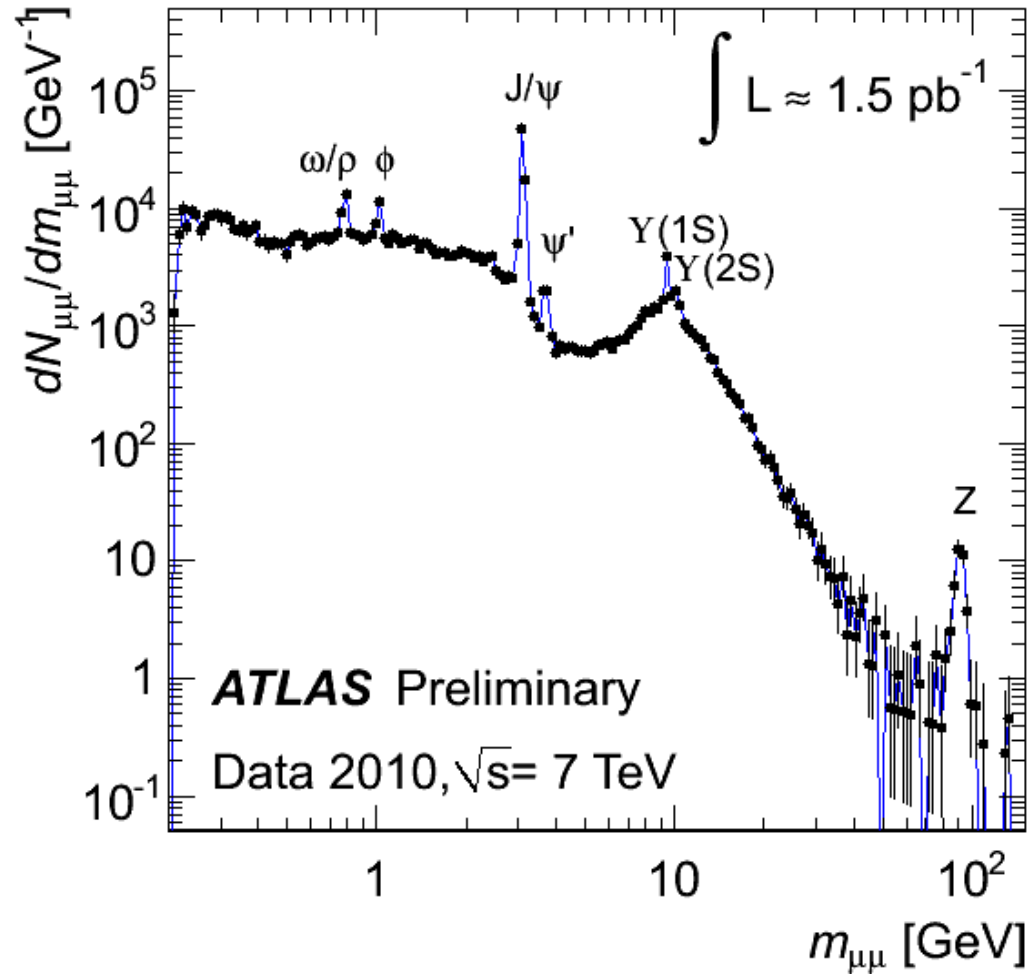


- Quantitatively described by the **full width at half maximum**:

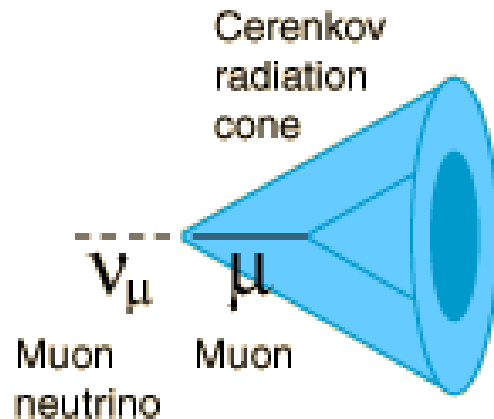
$$\text{FWHM} = 2\sqrt{2\ln 2}\sigma \approx 2.35\sigma$$

- It determines when two peaks can be separated.

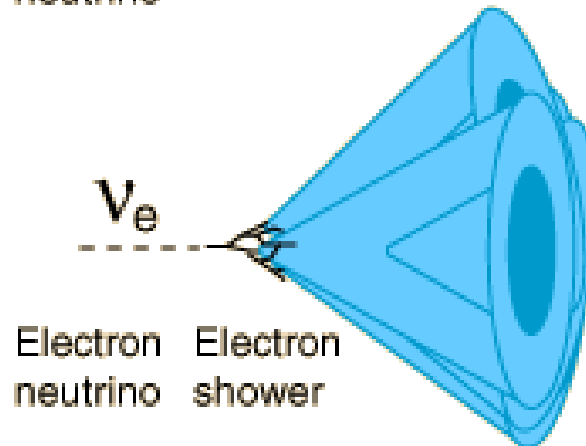
ENERGY RESOLUTION



CHERENKOV DETECTORS

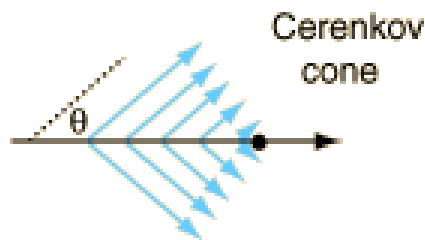


The Cerenkov radiation from a muon produced by a muon neutrino event yields a well defined circular ring in the photomultiplier detector bank.



The Cerenkov radiation from the electron shower produced by an electron neutrino event produces multiple cones and therefore a diffuse ring in the detector array.

CHERENKOV DETECTOR



$$\cos \theta = \frac{c}{vn}$$

v = particle velocity
 n = index of refraction of the medium

For water with $n=1.33$, the limiting angle for high speed particles is given by:

$$\theta = \cos^{-1} \frac{1}{1.33} = 41.2^\circ$$

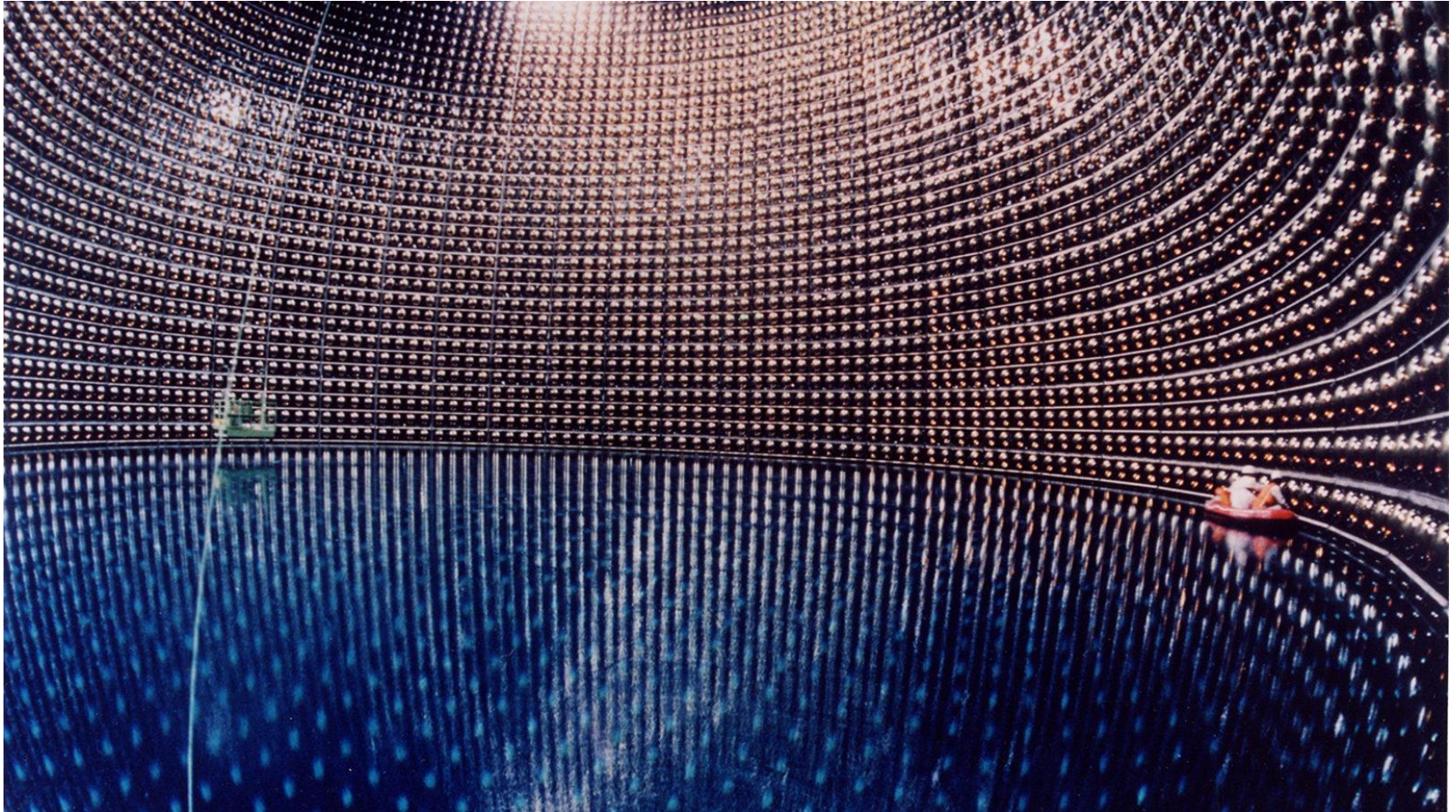
The threshold particle speed for Cerenkov radiation is $v = c/n$, which for an electron in water gives a threshold particle kinetic energy of 0.26 MeV.

$$\beta = 0.752, E_{\text{electron}} = \gamma m_e c^2 = \frac{1}{\sqrt{1 - \beta^2}} m_e c^2 = (1.52)(0.511 \text{ MeV}) = .775 \text{ MeV}$$

$$\text{Kinetic energy} = 0.775 \text{ MeV} - 0.511 \text{ MeV} = 0.26 \text{ MeV}$$

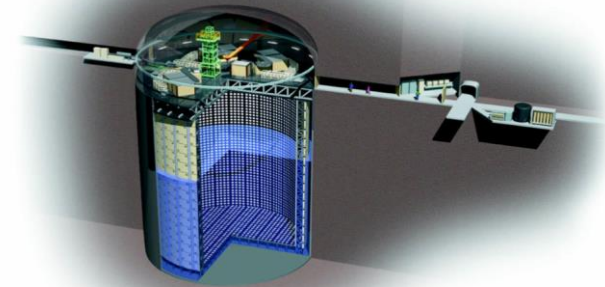
CHERENKOV DETECTORS

- Super-Kamiokande in Japan



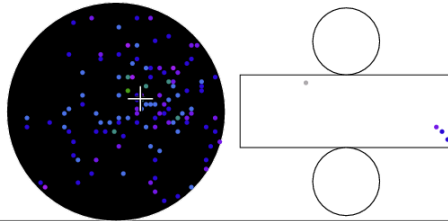
NEUTRINO DETECTION AT SUPER-K

- Electrons and muons resulting from neutrino interactions in the water



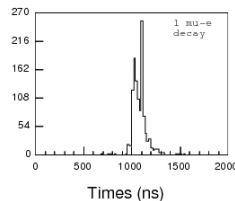
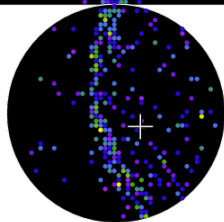
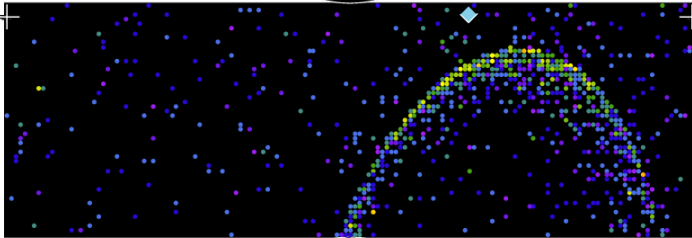
Super-Kamiokande IV

Run 999999 Sub 0 Event 18
11-11-21:09:42:21
Inner: 1194 hits, 2267 pe
Outer: 3 hits, 2 pe
Trigger: 0x07
D_wall: 218.0 cm
Evis: 262.3 MeV
mu-like, $p = 439.9$ MeV/c



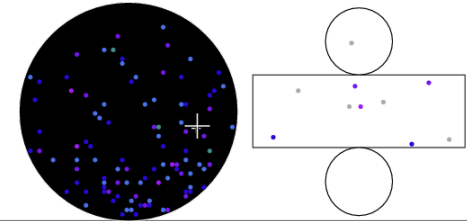
Charge (pe)

- >26.7
- 23.3-26.7
- 20.2-23.3
- 17.3-20.2
- 14.7-17.3
- 12.2-14.7
- 10.0-12.2
- 8.0-10.0
- 6.2- 8.0
- 4.7- 6.2
- 3.3- 4.7
- 2.2- 3.3
- 1.3- 2.2
- 0.7- 1.3
- 0.2- 0.7
- < 0.2



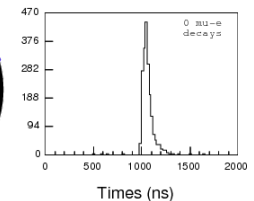
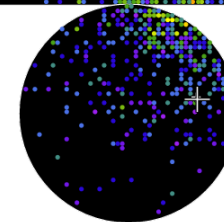
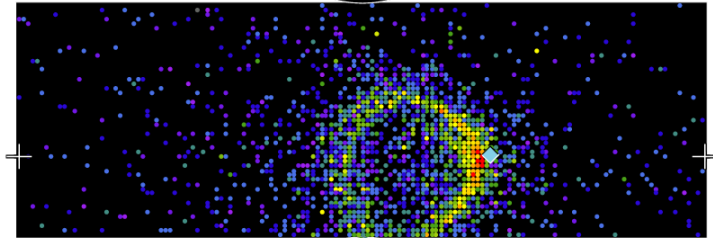
Super-Kamiokande IV

Run 999999 Sub 0 Event 99
11-11-23:19:16:51
Inner: 2017 hits, 5244 pe
Outer: 5 hits, 3 pe
Trigger: 0x07
D_wall: 621.8 cm
Evis: 550.9 MeV
e-like, $p = 550.9$ MeV/c

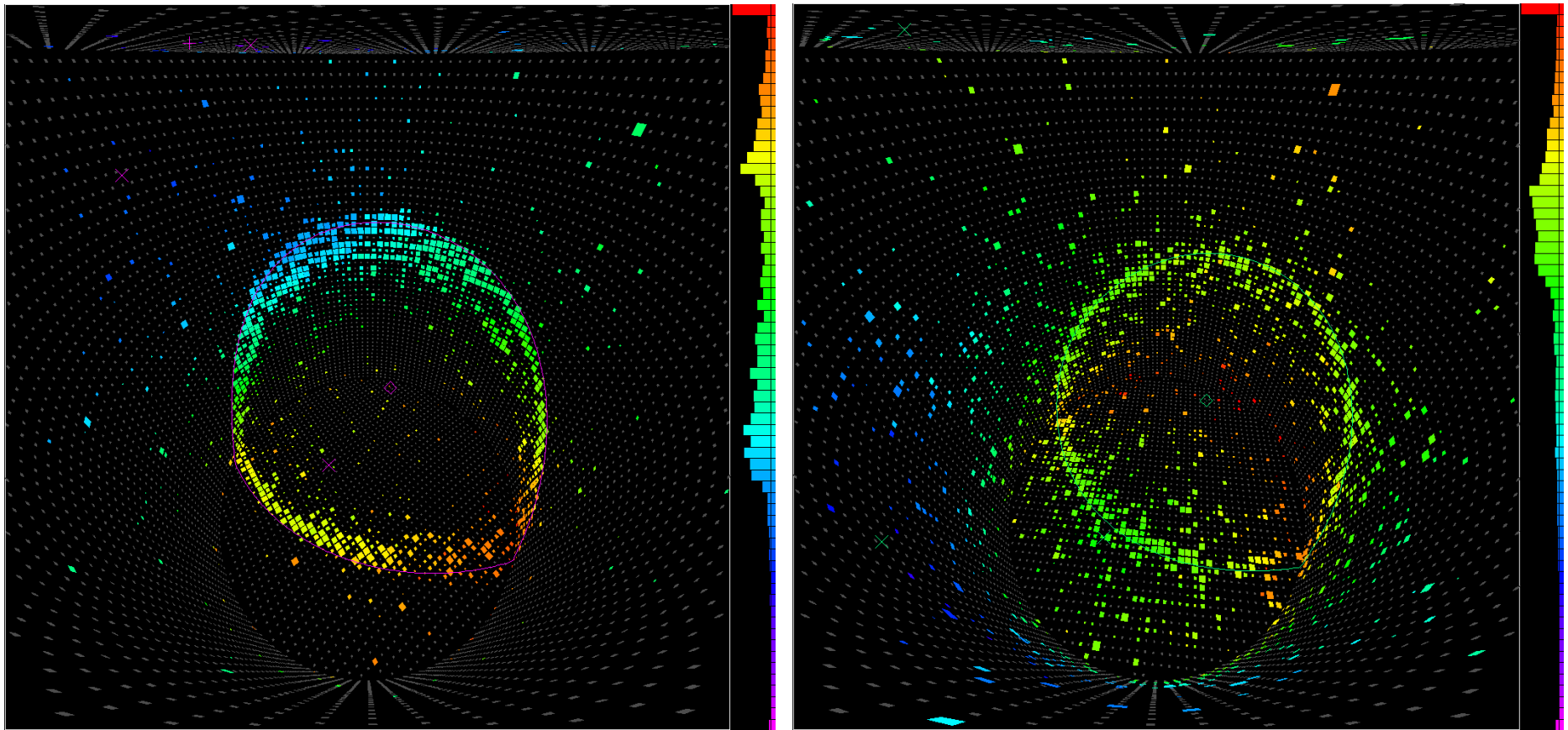


Charge (pe)

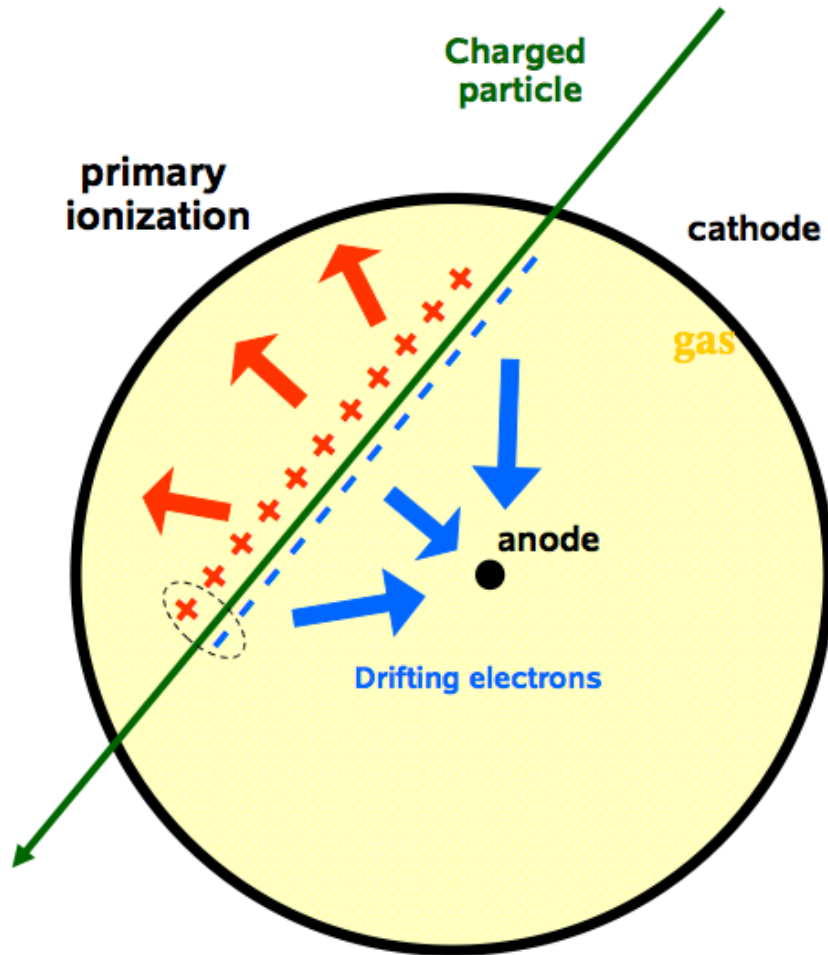
- >26.7
- 23.3-26.7
- 20.2-23.3
- 17.3-20.2
- 14.7-17.3
- 12.2-14.7
- 10.0-12.2
- 8.0-10.0
- 6.2- 8.0
- 4.7- 6.2
- 3.3- 4.7
- 2.2- 3.3
- 1.3- 2.2
- 0.7- 1.3
- 0.2- 0.7
- < 0.2



NEUTRINO DETECTION AT SUPER-K



IONIZATION DETECTOR

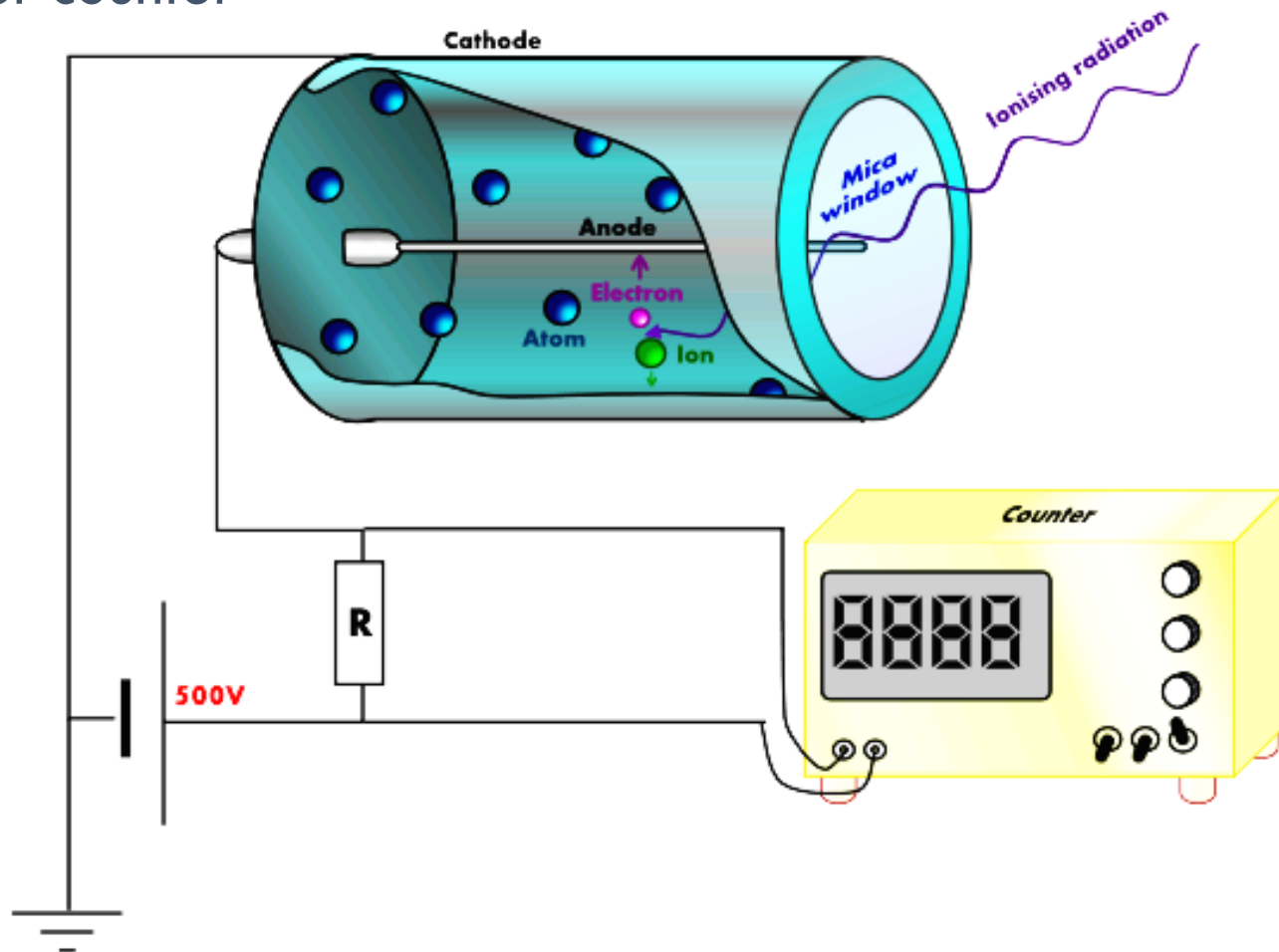


- Drifting electrons should not be trapped:
 - ▶ Use noble gas, e.g. Ar.
- Want large primary ionization yield:
 - ▶ Ar gives 25 ions/cm at normal T, p for a minimum ionizing particle.
- The primary electrons may ionize further atoms:
 - ▶ $\times 3$ or $\times 4$ increase.
- Xe and/or higher pressure are even better (and more expensive).

Induced electrical signal on anode can be measured to estimate number of drift electrons: E lost to ionization.

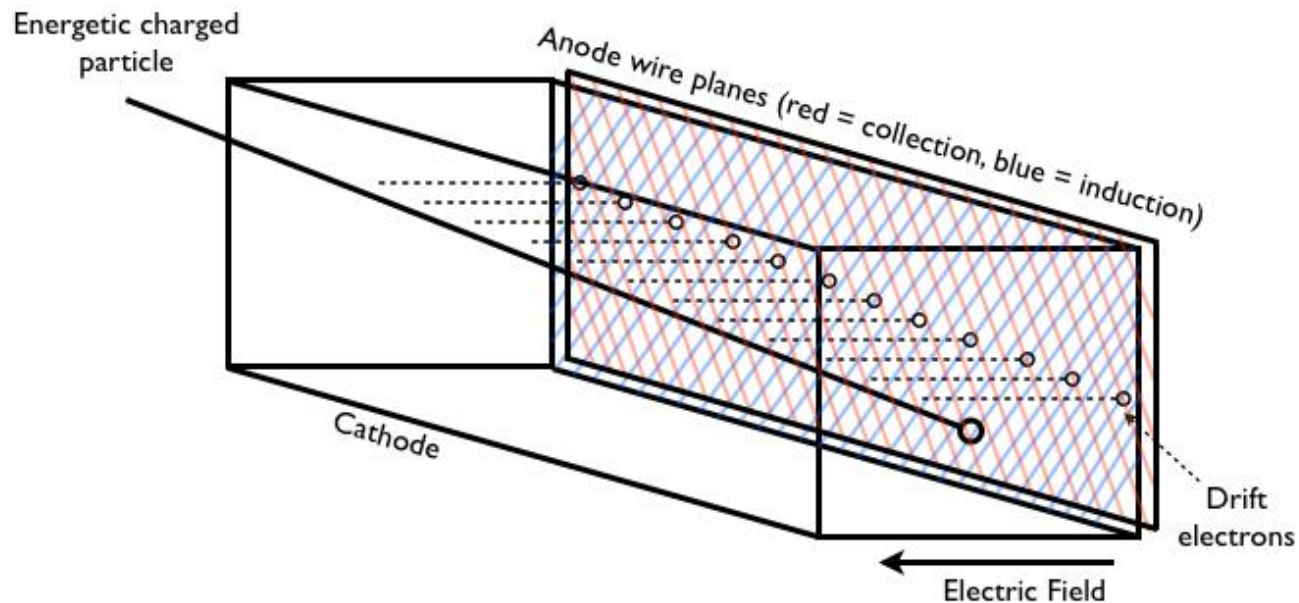
IONIZATION DETECTOR

- Geiger counter



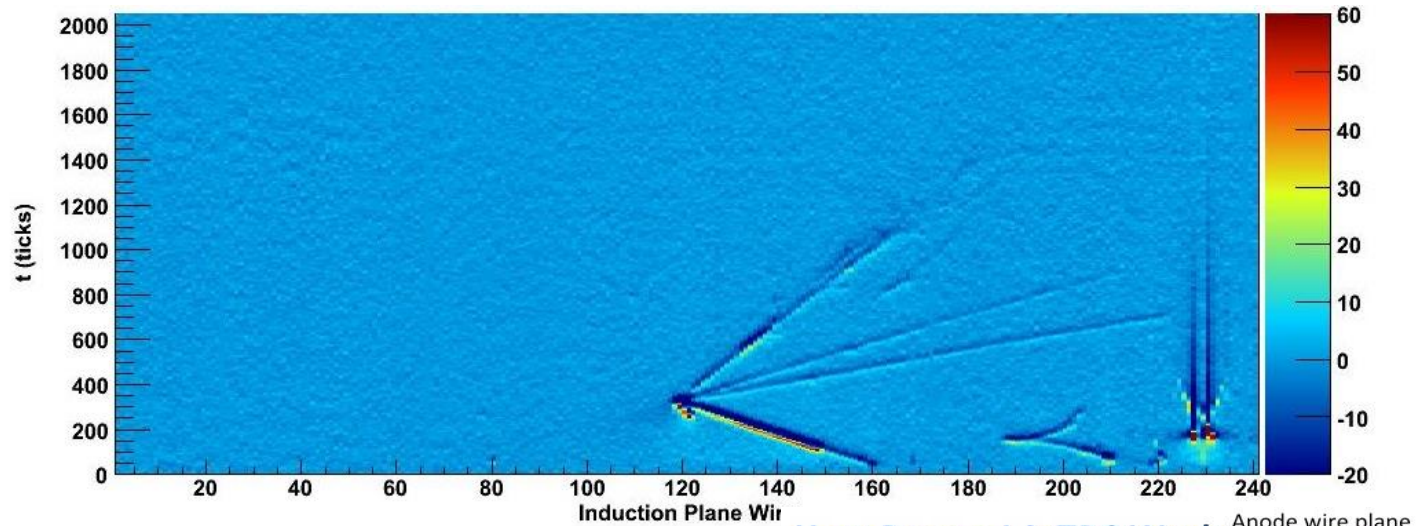
TIME PROJECTION CHAMBER

- Exploits ionization energy losses of charged particles.
- Electrons are drifted onto a fine grained plane of wires, and the particle trajectories can be mapped out, along with their ionization energy loss, dE/dx

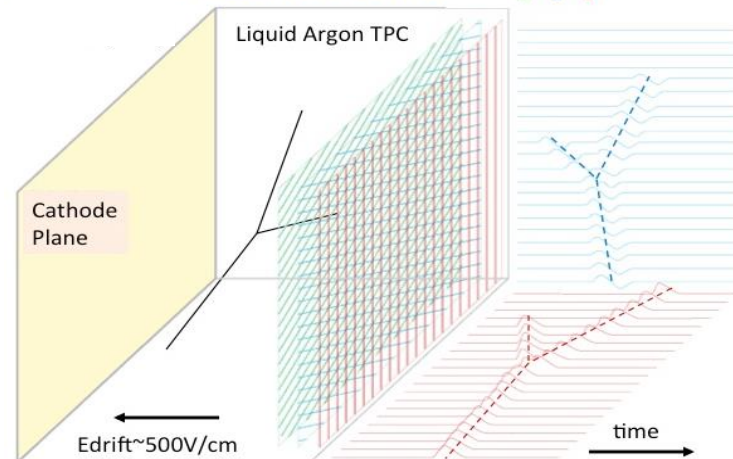
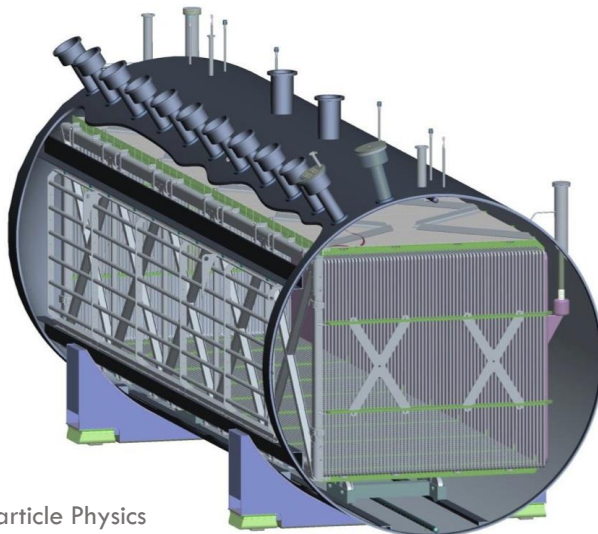


TIME PROJECTION CHAMBER

- MicroBooNE liquid argon TPC at Fermilab

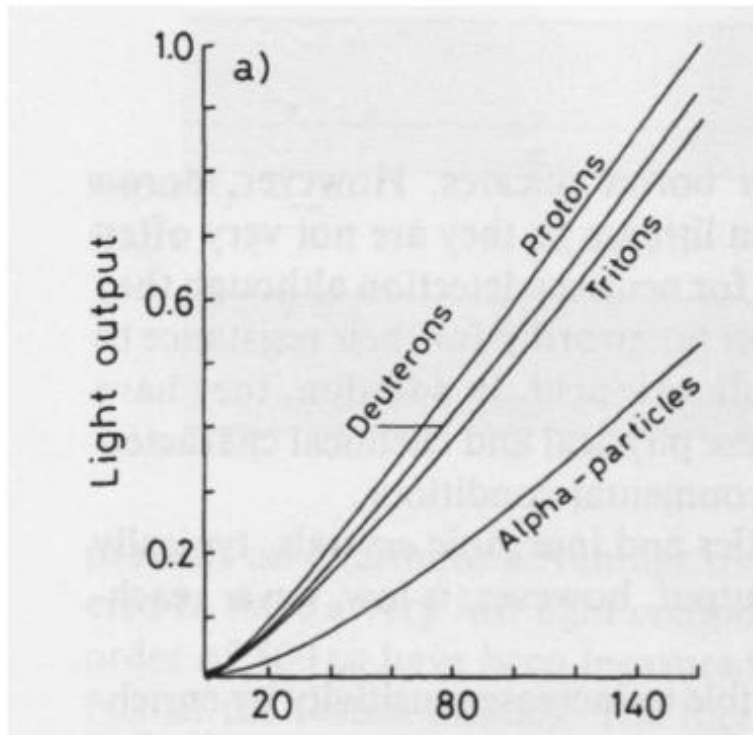


How Does a LArTPC Work

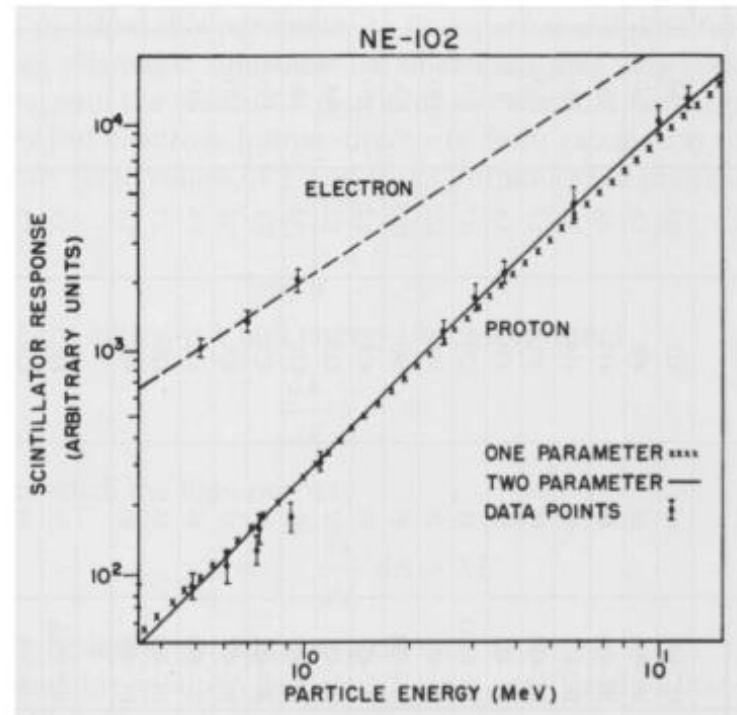


SCINTILLATION DETECTORS

- Light output and type of particles / radiation.



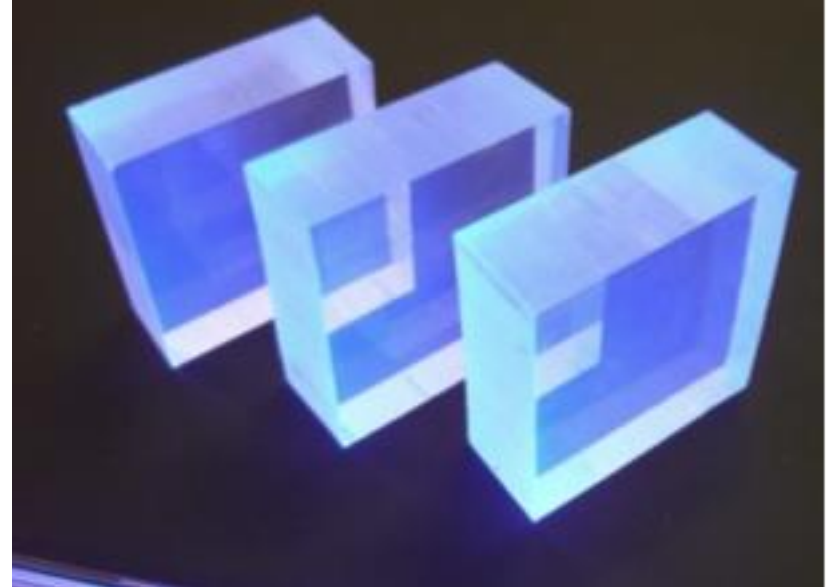
particle energy [MeV]



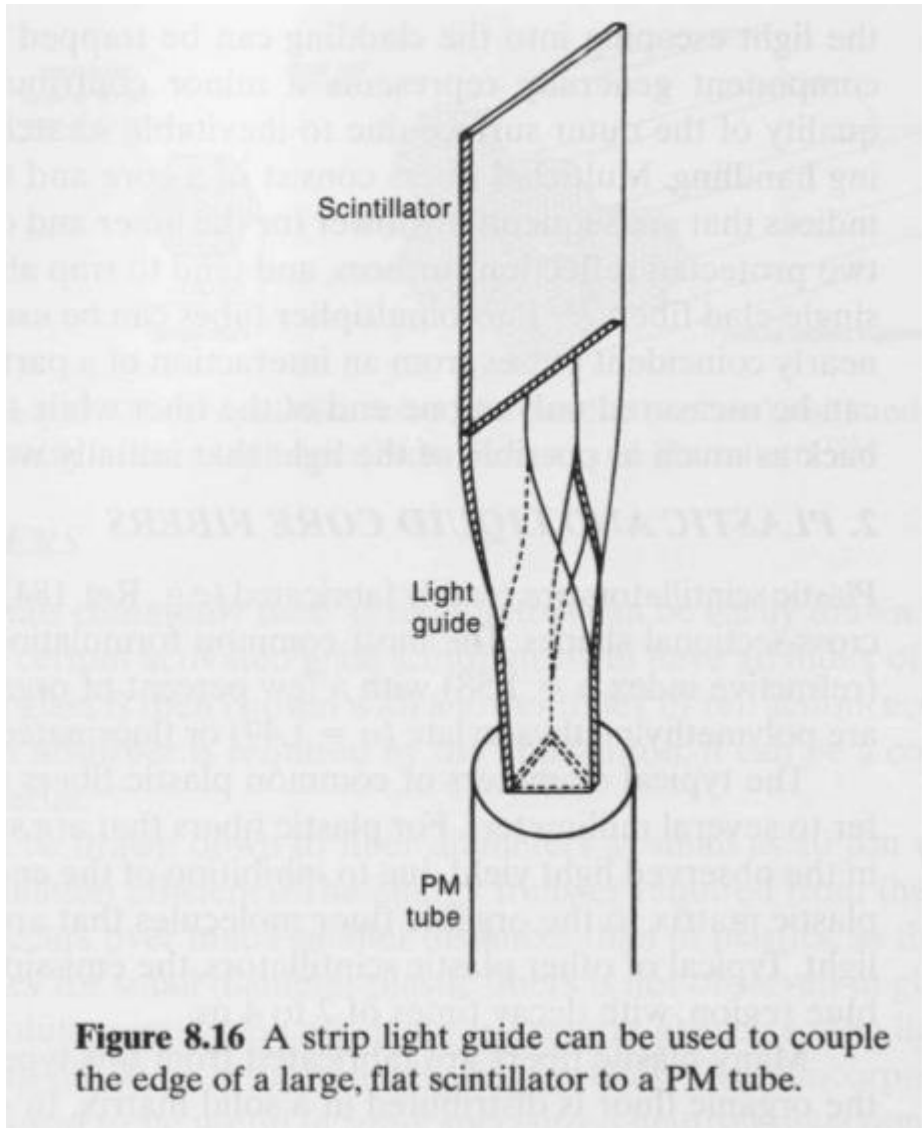
NE-102 = common plastic scintillator

SCINTILLATION DETECTORS

- Emitted light depends on detector material.
 - Usually in the visible to UV range.
- Sometimes requires the use of wavelength-shifting materials to shift UV light to visible, so it can be efficiently measured by commonly used photomultiplier tubes.

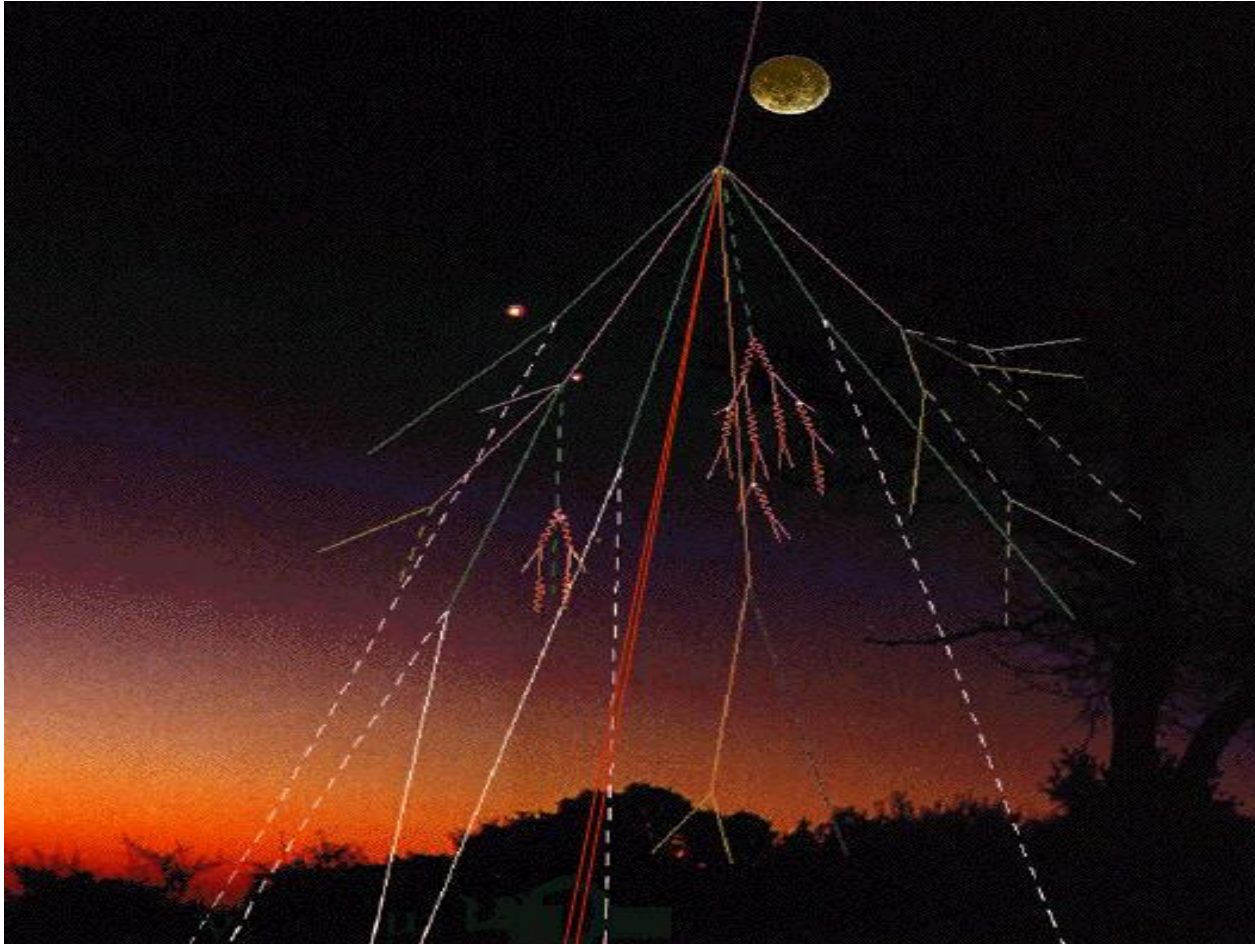


SCINTILLATION DETECTORS

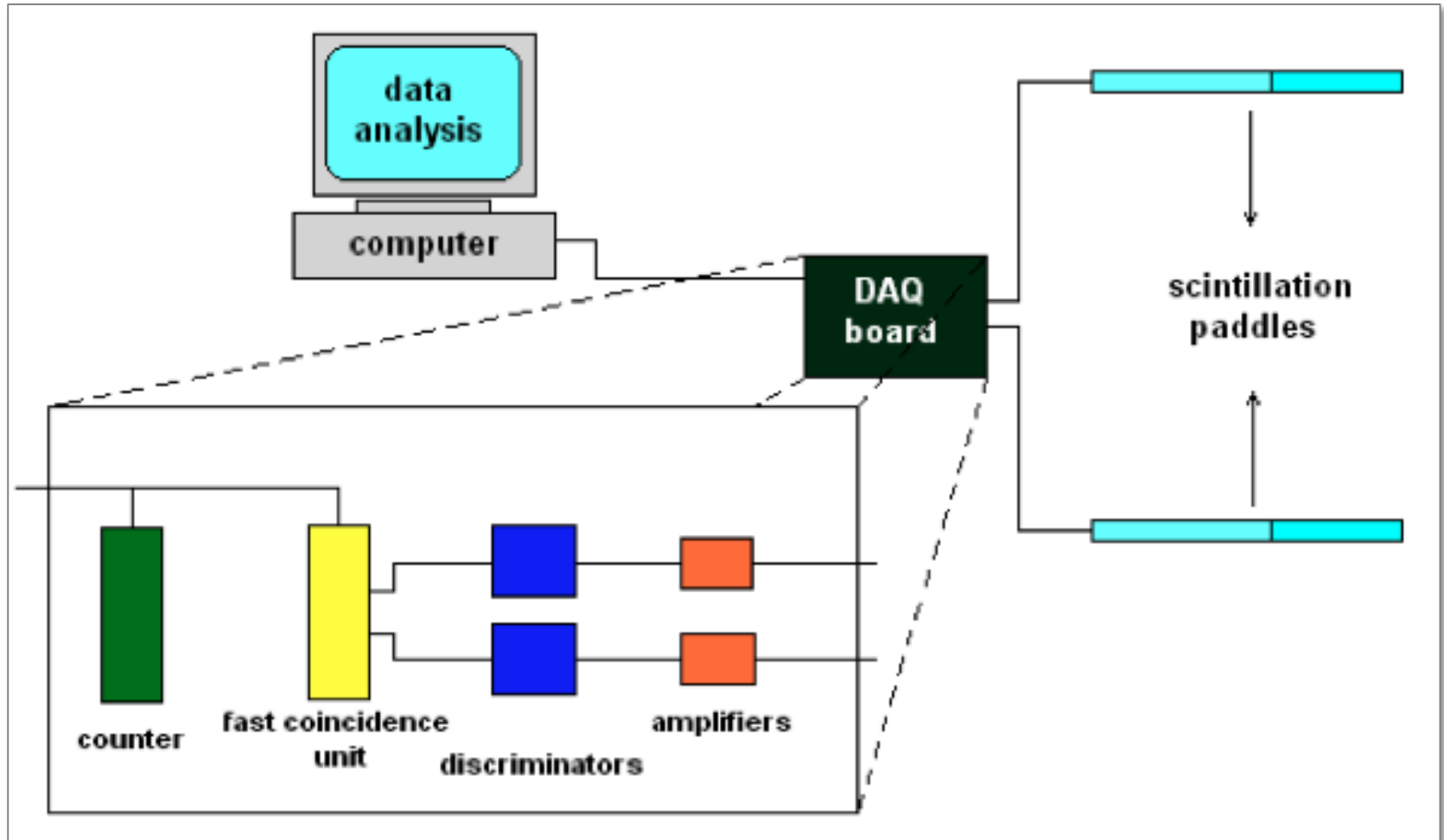


APPLICATION OF SCINTILLATION DETECTORS

- Cosmic ray muon detection

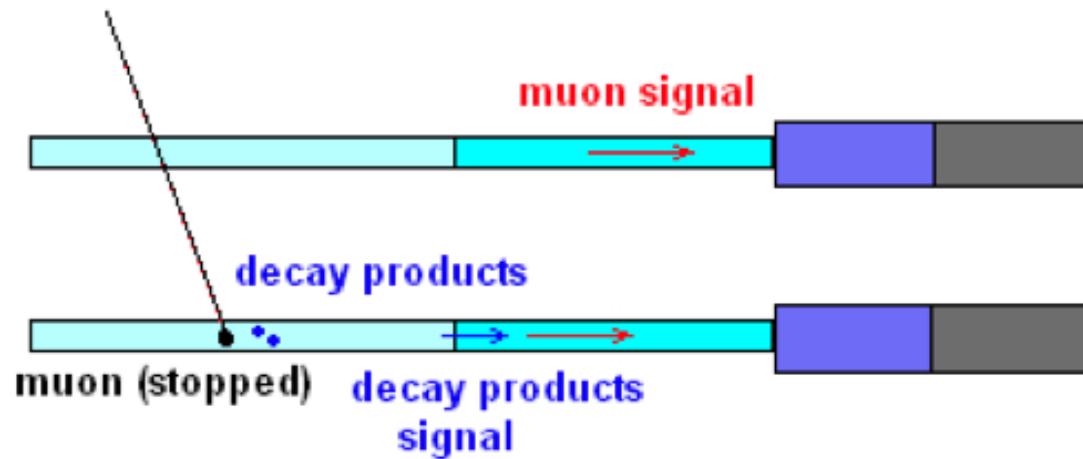


COSMIC RAY MUON DETECTION



COSMIC RAY MUON DETECTION

- Measurement of the muon lifetime



1. Measure t_{decay} (difference between muon signal and decay signal in the second scintillator paddle) of a sample N_0 of low energy muons.
2. Fit the data to an exponential curve of the form:

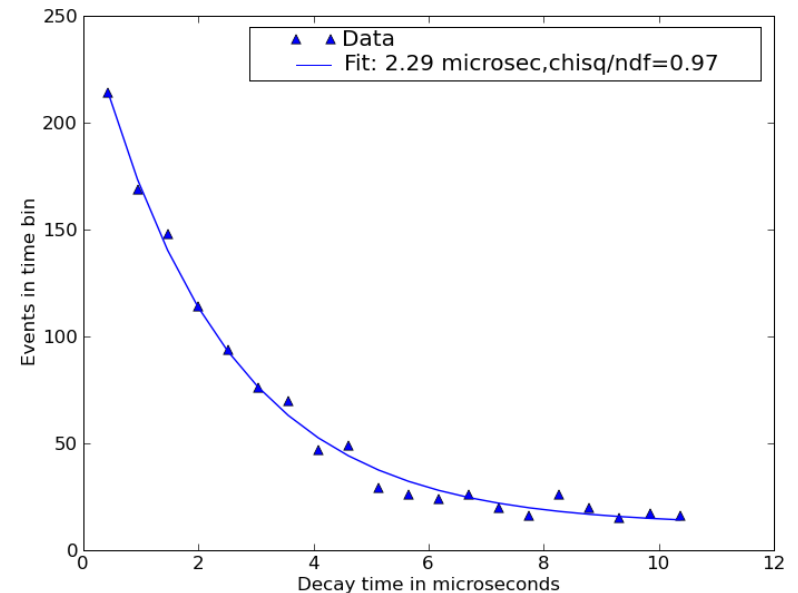
$$N(t) = N_0 e^{-t/T}$$

where T = muon lifetime

COSMIC RAY MUON DETECTION

- Measurement of the muon lifetime

Lifetime T:
 $T = 2.29\mu\text{s}$
 $T_{\text{th}} = 2.1970\mu\text{s}$



1. Measure t_{decay} (difference between muon signal and decay signal in the second scintillator paddle) of a sample N_0 of low energy muons.
2. Fit the data to an exponential curve of the form:

$$N(t) = N_0 e^{-t/T}$$

where T = muon lifetime

MODERN EXPERIMENTS

PARTICLE SOURCES

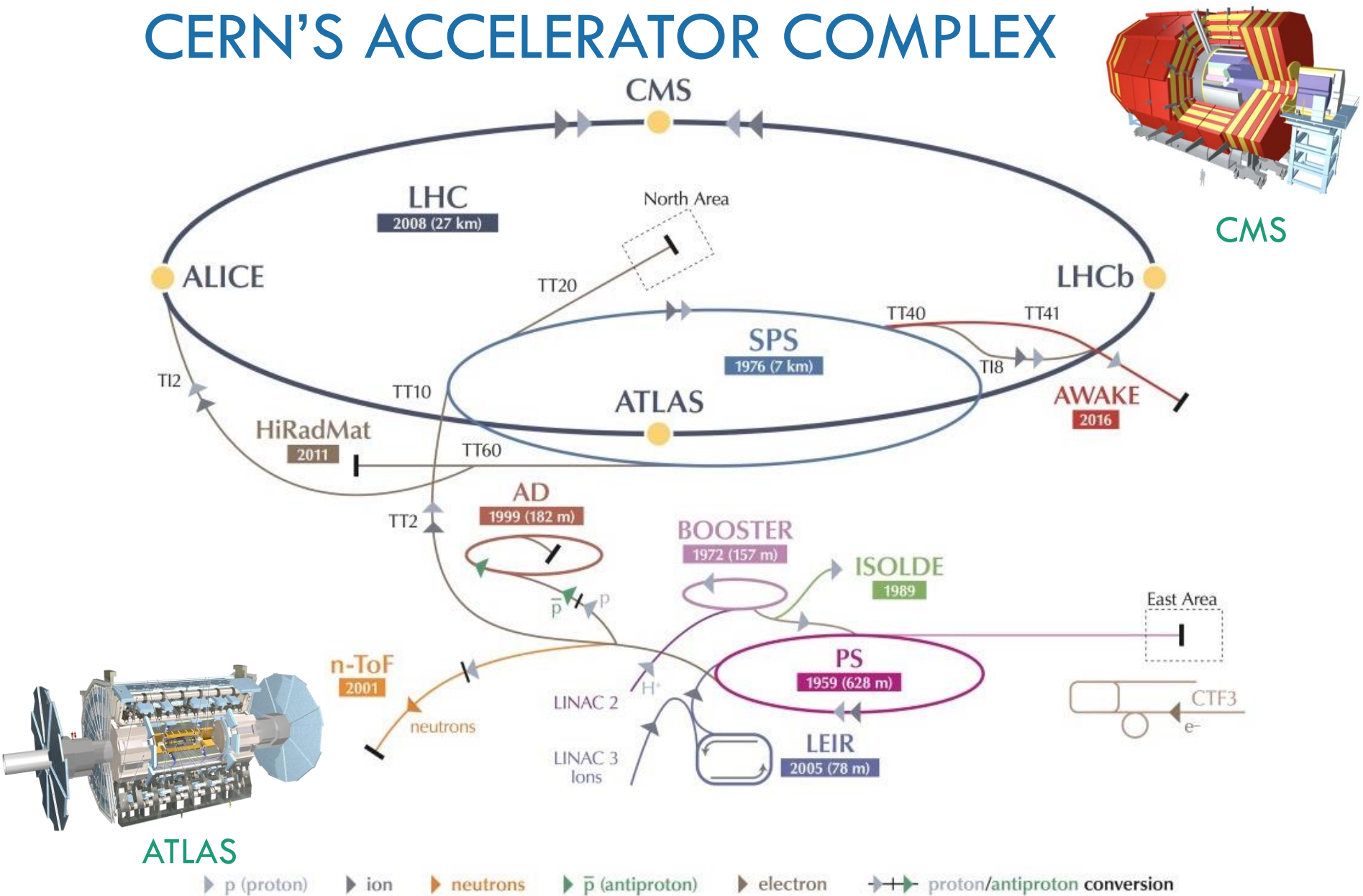
- Particle physics experiments use different **sources** of particles
- Artificial **beams** produced in accelerators
 - **Colliders** – beams are made to collide against each other.
 - **Highest energy** interactions from artificial sources
 - Beams are aimed at **fixed targets** / detectors
 - Lower energy, but typically more **intense**
- **Natural** sources
 - Particles resulting from **cosmic** ray interaction in the atmosphere
 - **Radioactive** sources
 - **Astrophysical** sources
 - **Dark matter** ?

PARTICLE COLLIDERS AROUND THE WORLD

SLAC, California	SLC	1989-1998	$e^- e^+$	50 GeV e^- and 50 GeV e^+
	PEP II	1997-2008	$e^- e^+$	9.0 GeV e^- and 3.1 GeV e^+
Fermilab, nr Chicago	Tevatron	1987-2009	$p \bar{p}$	980 GeV p and 980 GeV \bar{p}
CERN, Geneva	LEP	1989-2000	$e^- e^+$	E_{CM}: 89 to 206 GeV
	LHC	2008-...	$p p$	E_{CM}: 14 TeV
DESY, Hamburg	HERA	1990-2007	$e^- p$	920 GeV p and 30 GeV e^-
KEK, near Tokyo	KEKB	1999-...	$e^- e^+$	8.0 GeV e^- and 3.5 GeV e^+
Brookhaven National Lab, Long Island	RHIC	2000-...	AuAu, CuCu	200 GeV/nucleon



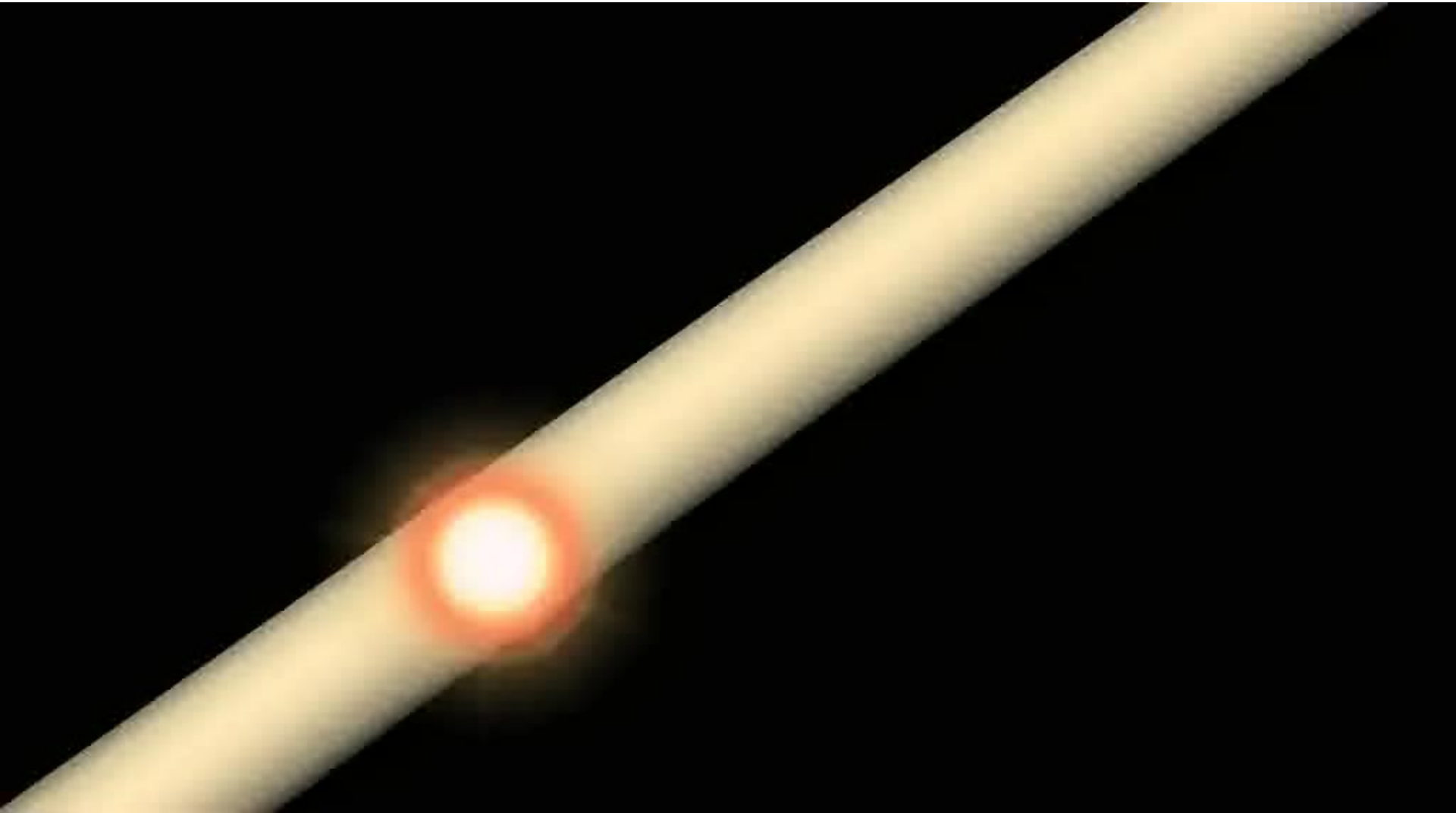
CERN'S ACCELERATOR COMPLEX



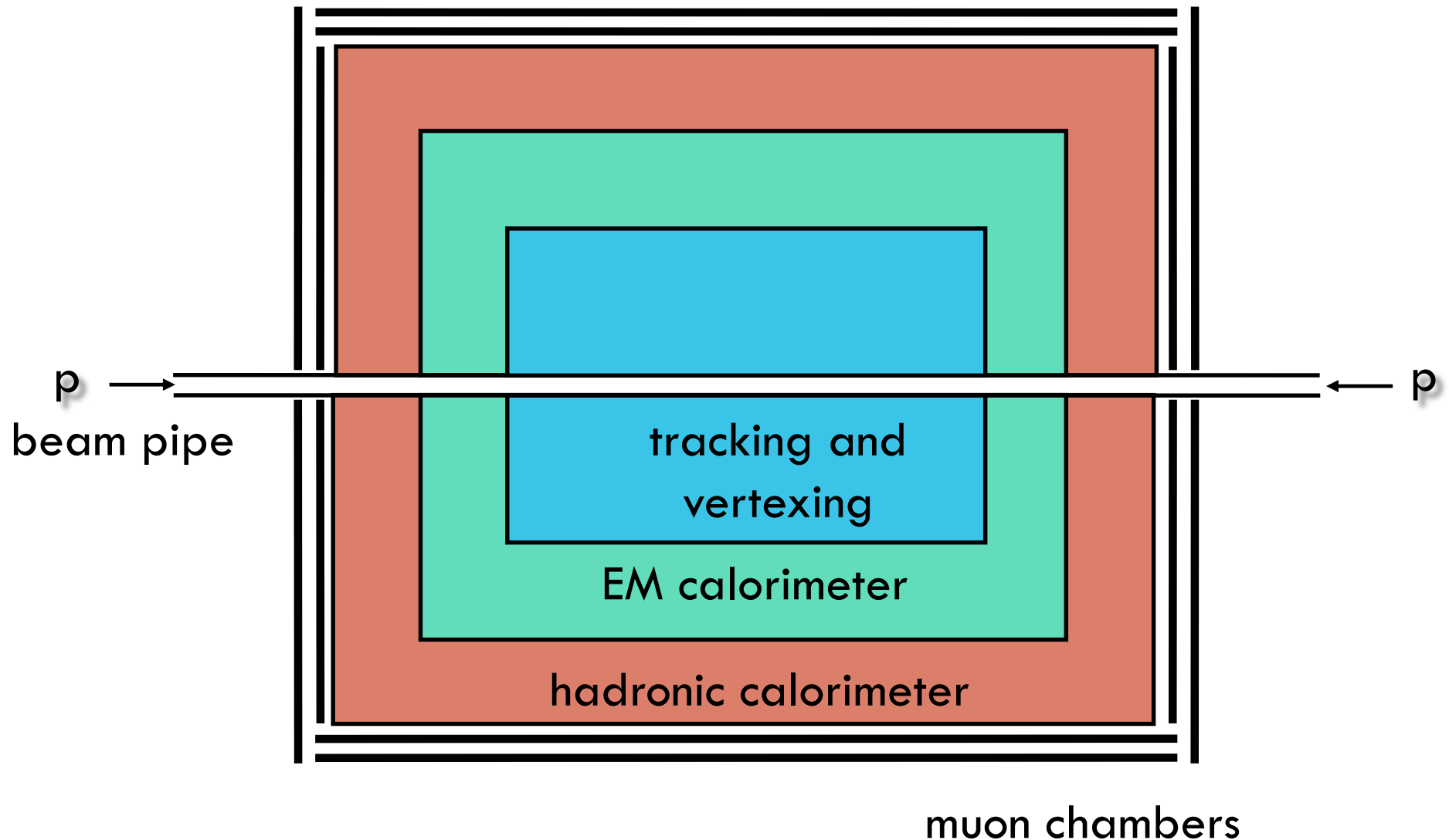
ATLAS

CMS

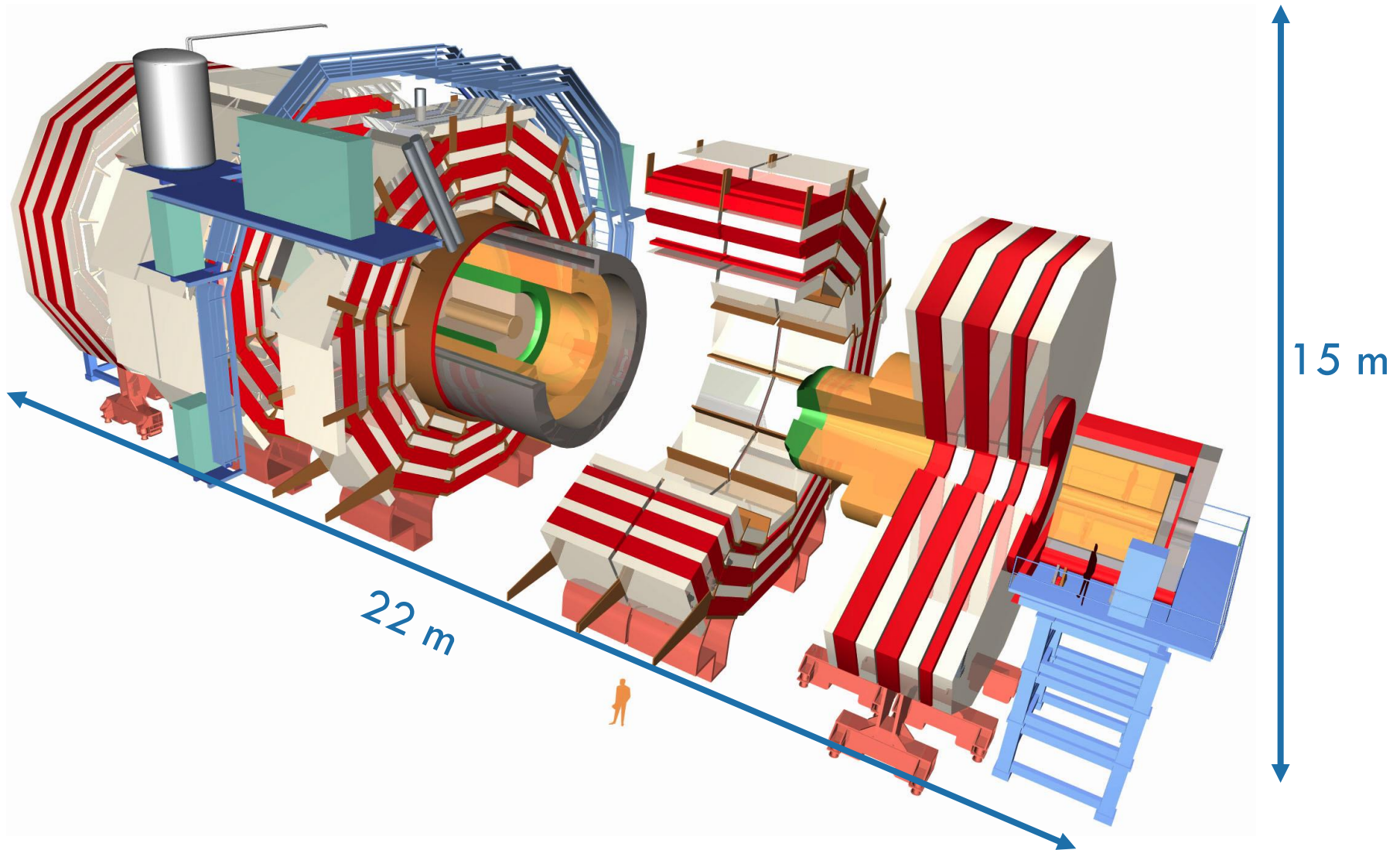
PROTON-PROTON COLLISIONS



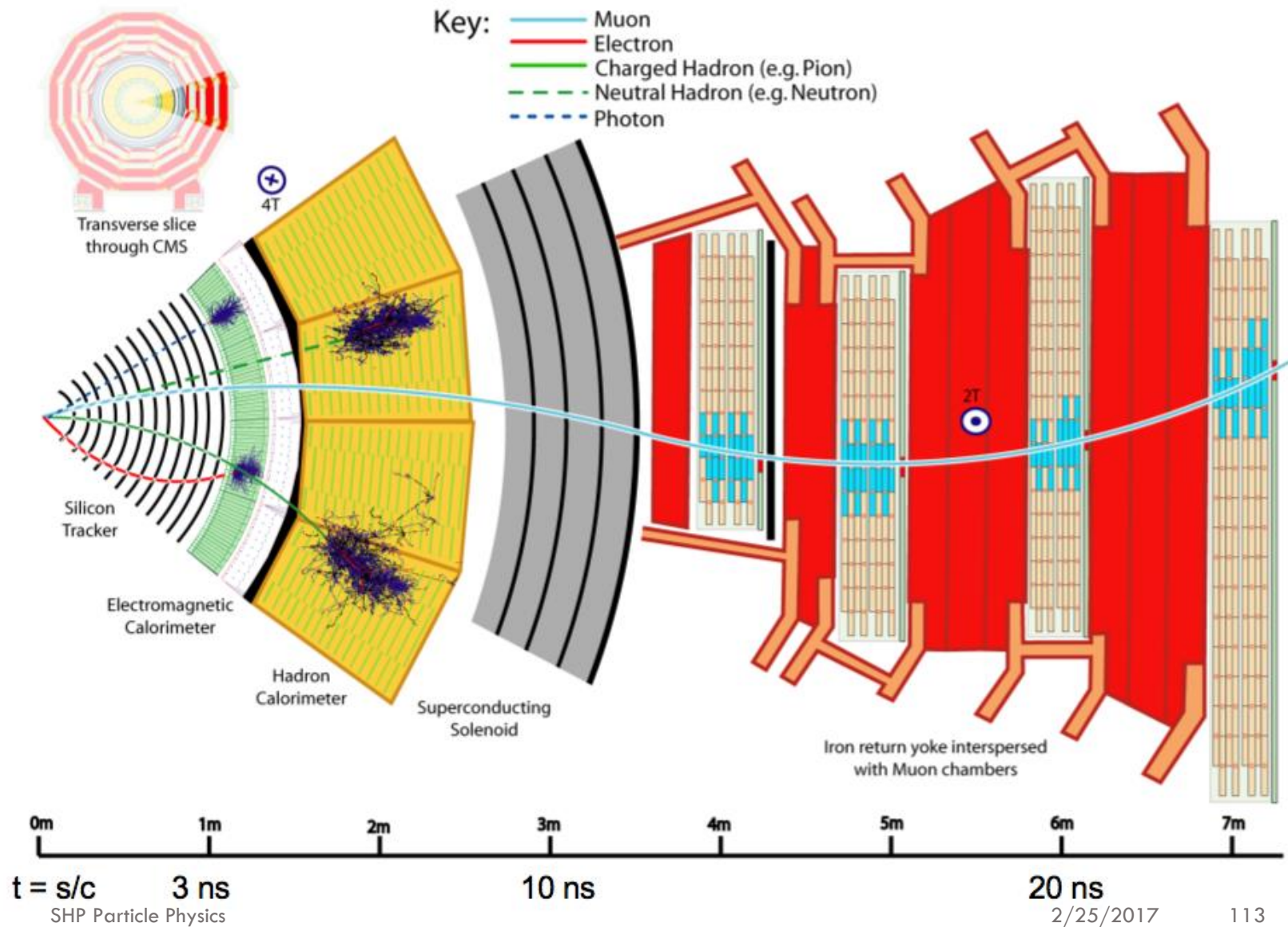
A GENERAL PURPOSE DETECTOR



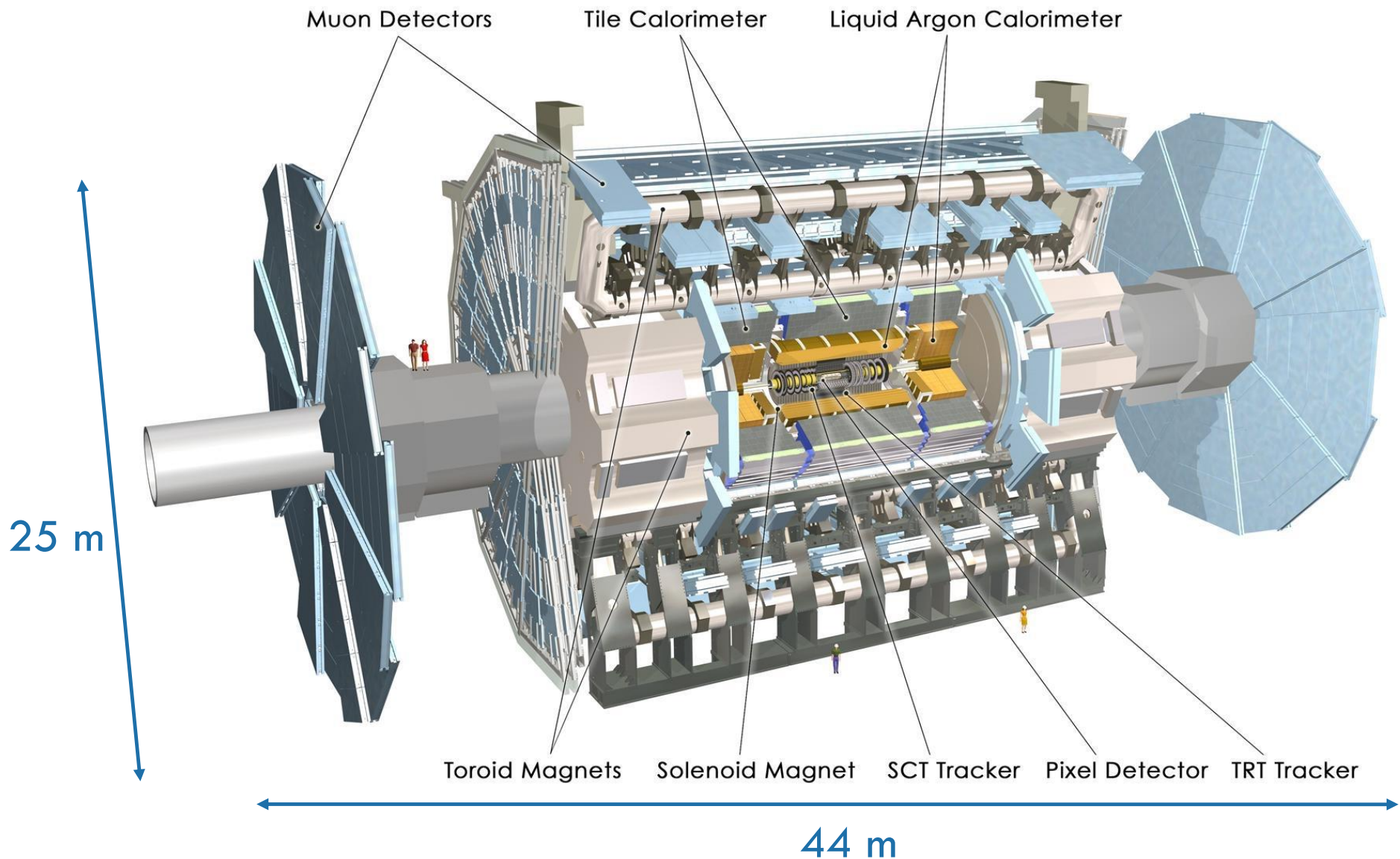
THE CMS DETECTOR



A SLICE OF CMS



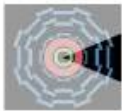
THE ATLAS DETECTOR



THE ATLAS DETECTOR

ATLAS

animation



☐ display instantly

Energy [GeV]:

1 5 10 15 25



Electron



Proton



Neutrino



Photon



Positron



Anti-proton



Jets



Muon

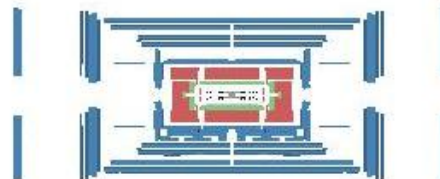
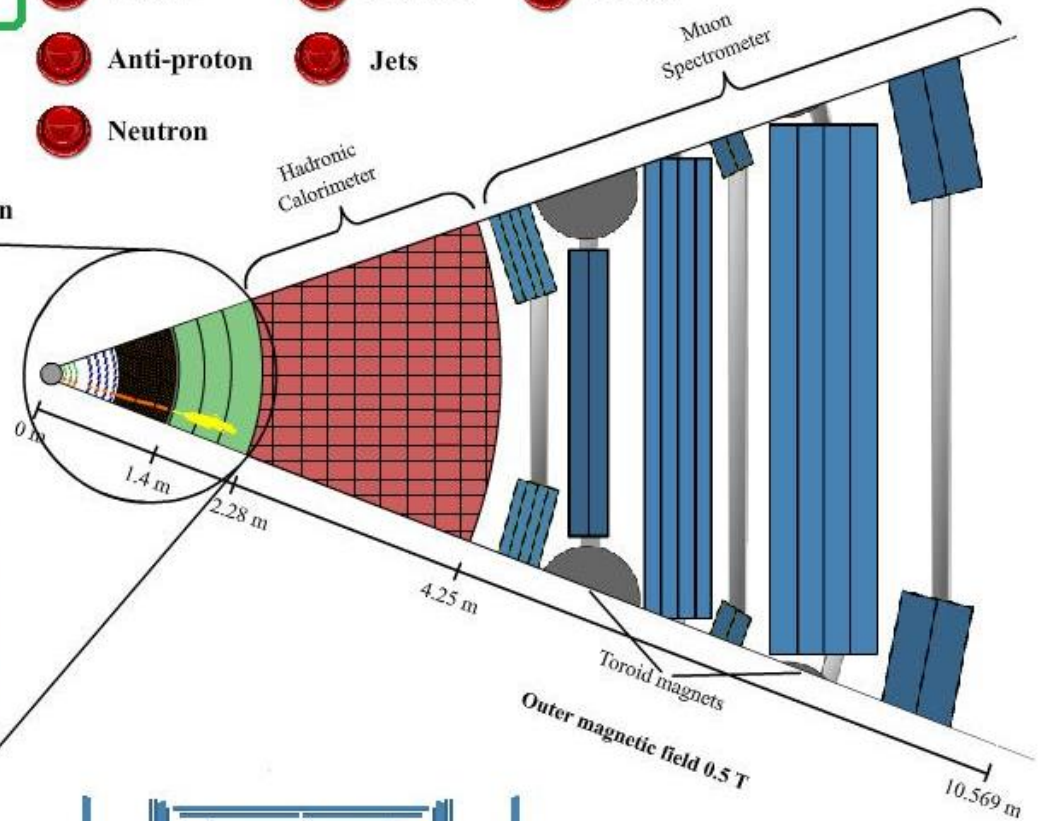
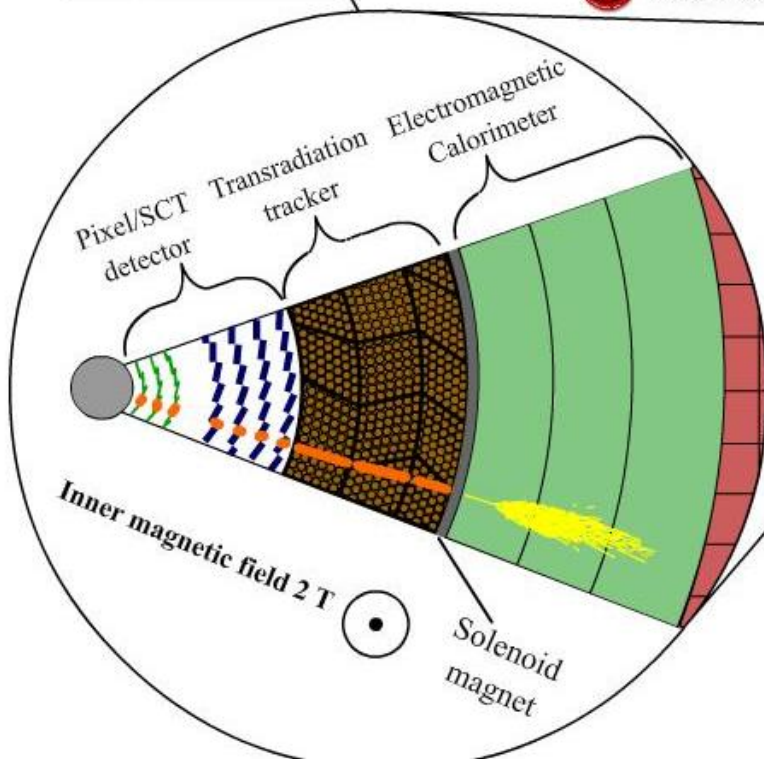


Neutron



Anti-muon

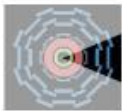
Magnification 3x



THE ATLAS DETECTOR

ATLAS

animation



☐ display instantly



Electron



Proton



Neutrino



Photon



Positron



Anti-proton



Jets



Muon

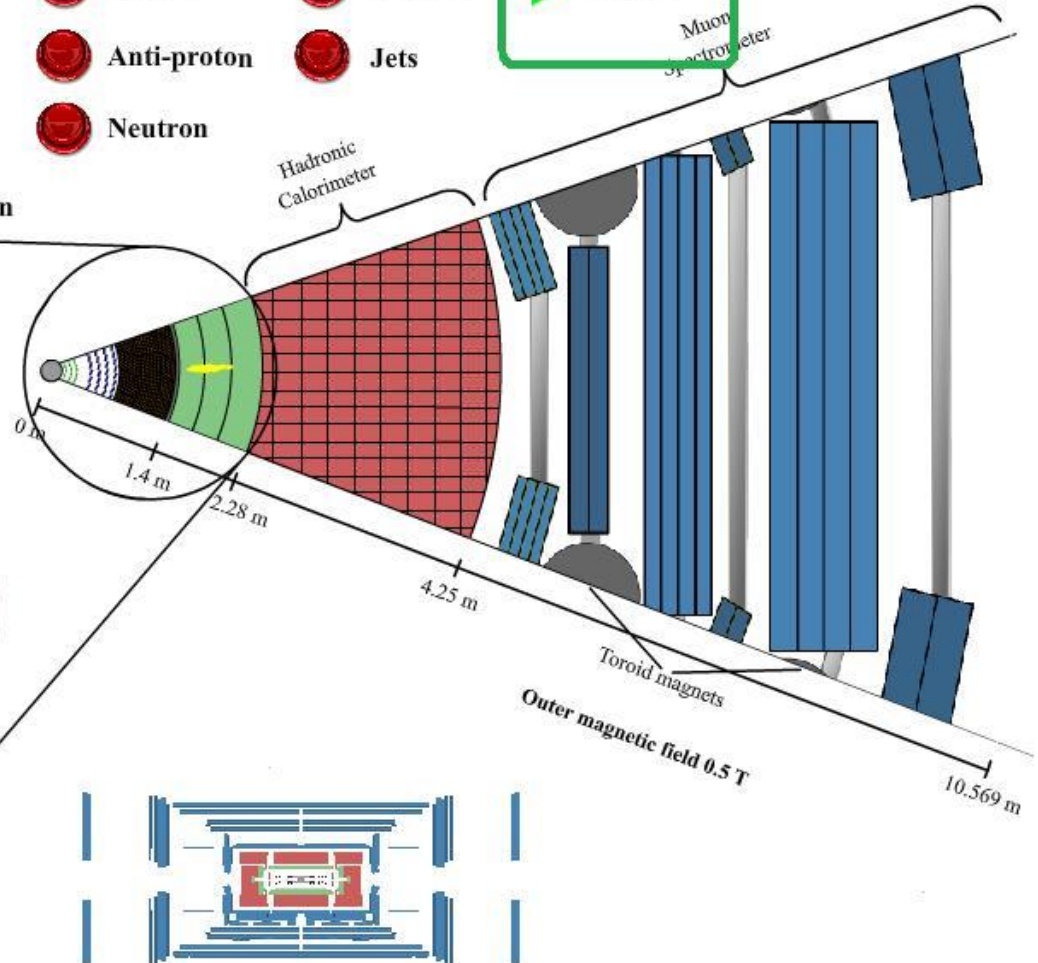
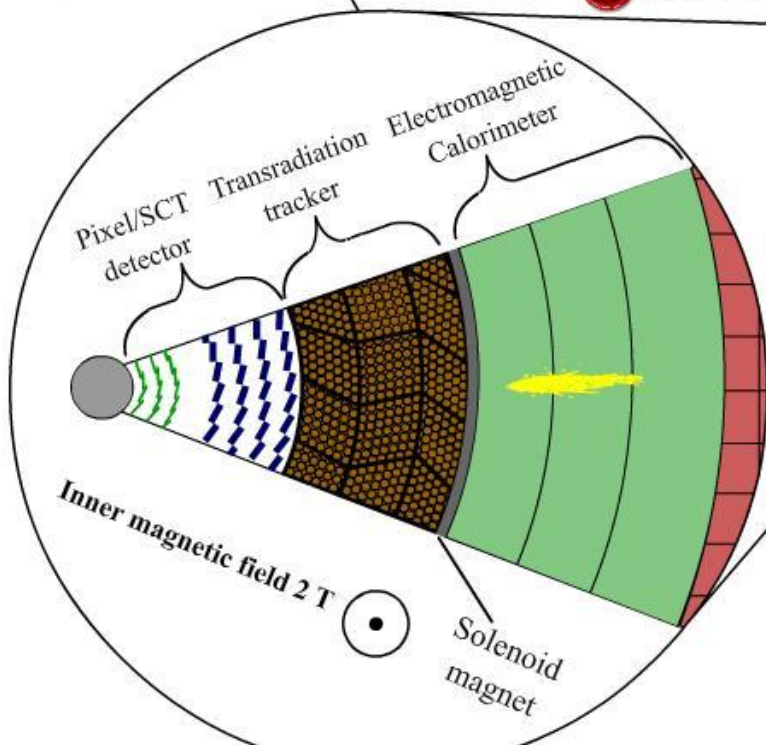


Neutron



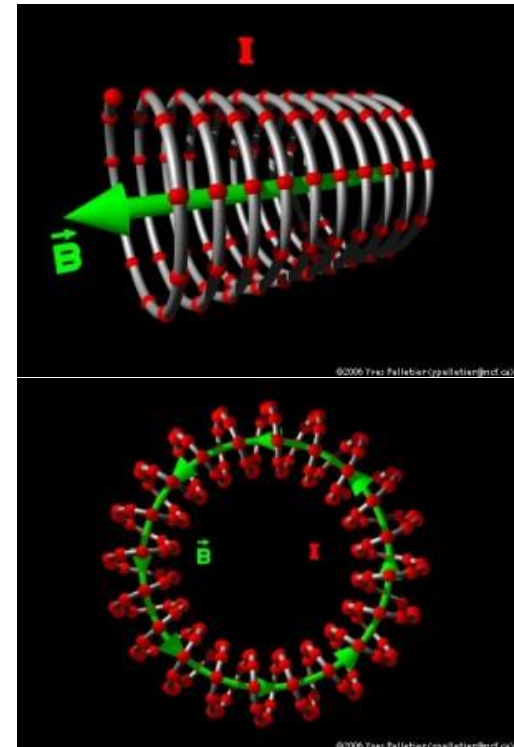
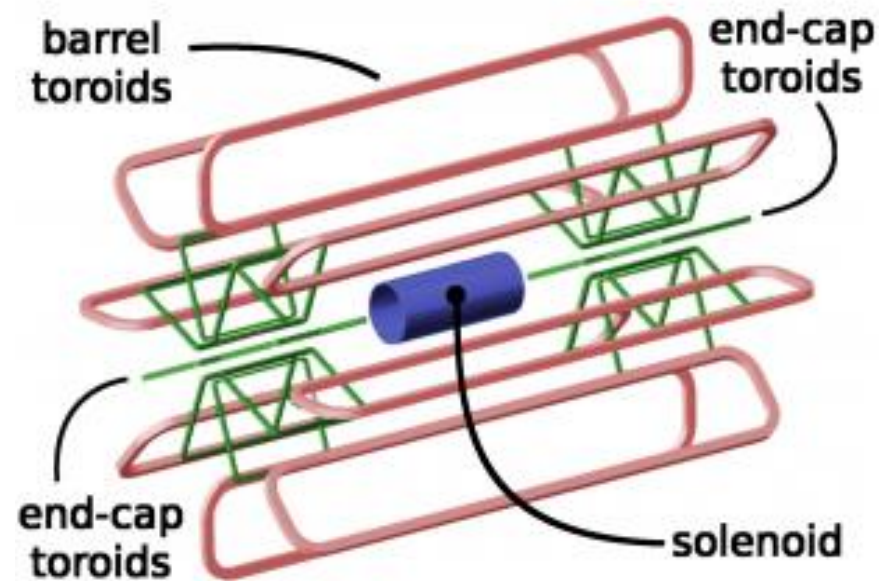
Anti-muon

Magnification 3x



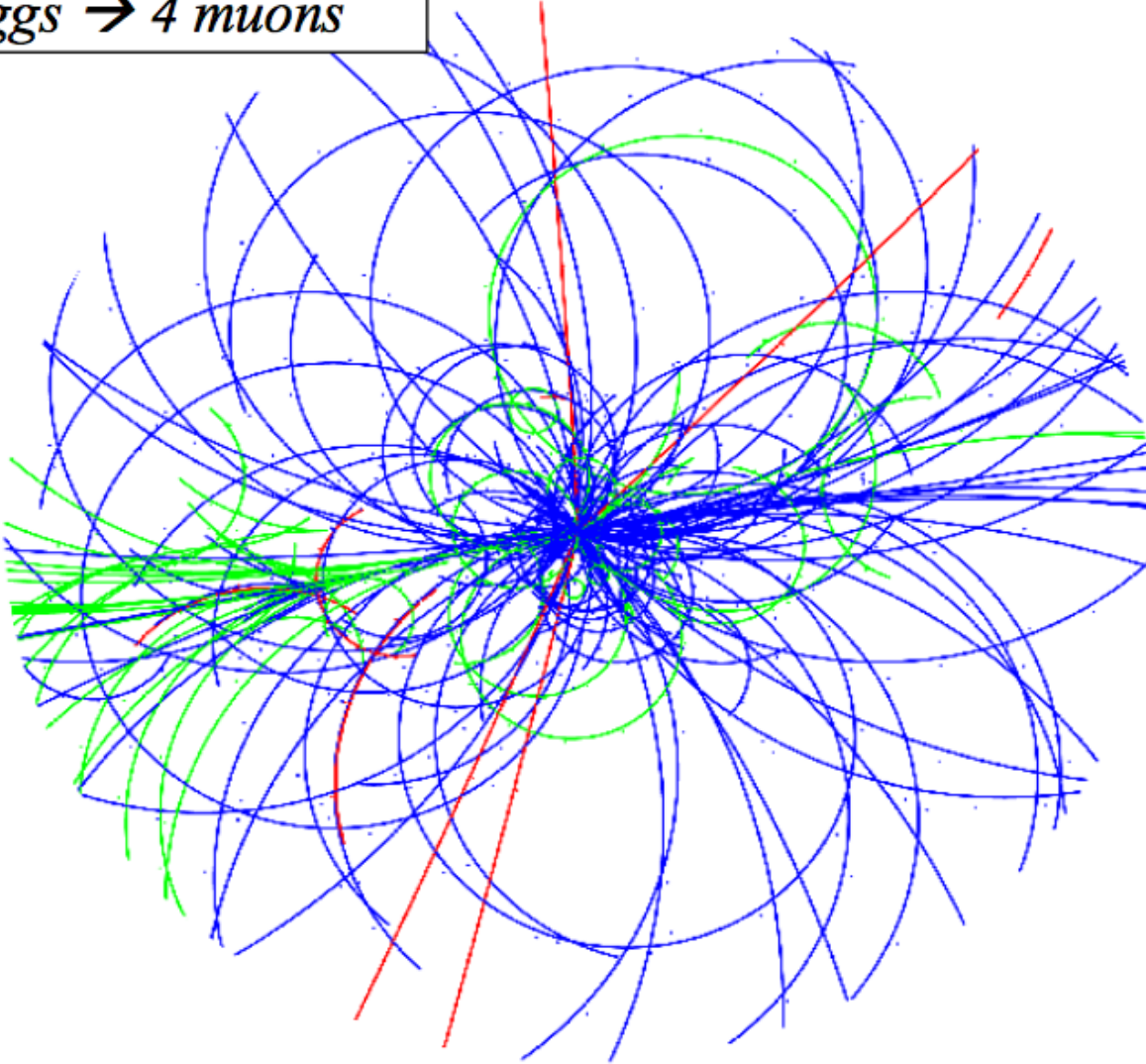
MAGNET SYSTEMS

- Solenoid and toroidal magnets.
- Solenoid coils in CMS and ATLAS:
 - Field direction along beam axis.
 - Homogenous field inside the coil.
 - e.g. CMS superconducting magnet
 - $I = 20 \text{ kA}$, $B = 4 \text{ T}$
 - Temperature 4K .
- For comparison, Earth's magnetic field at surface is $\sim 50 \mu\text{T}$.



EVENT SIGNATURES

Higgs \rightarrow 4 muons

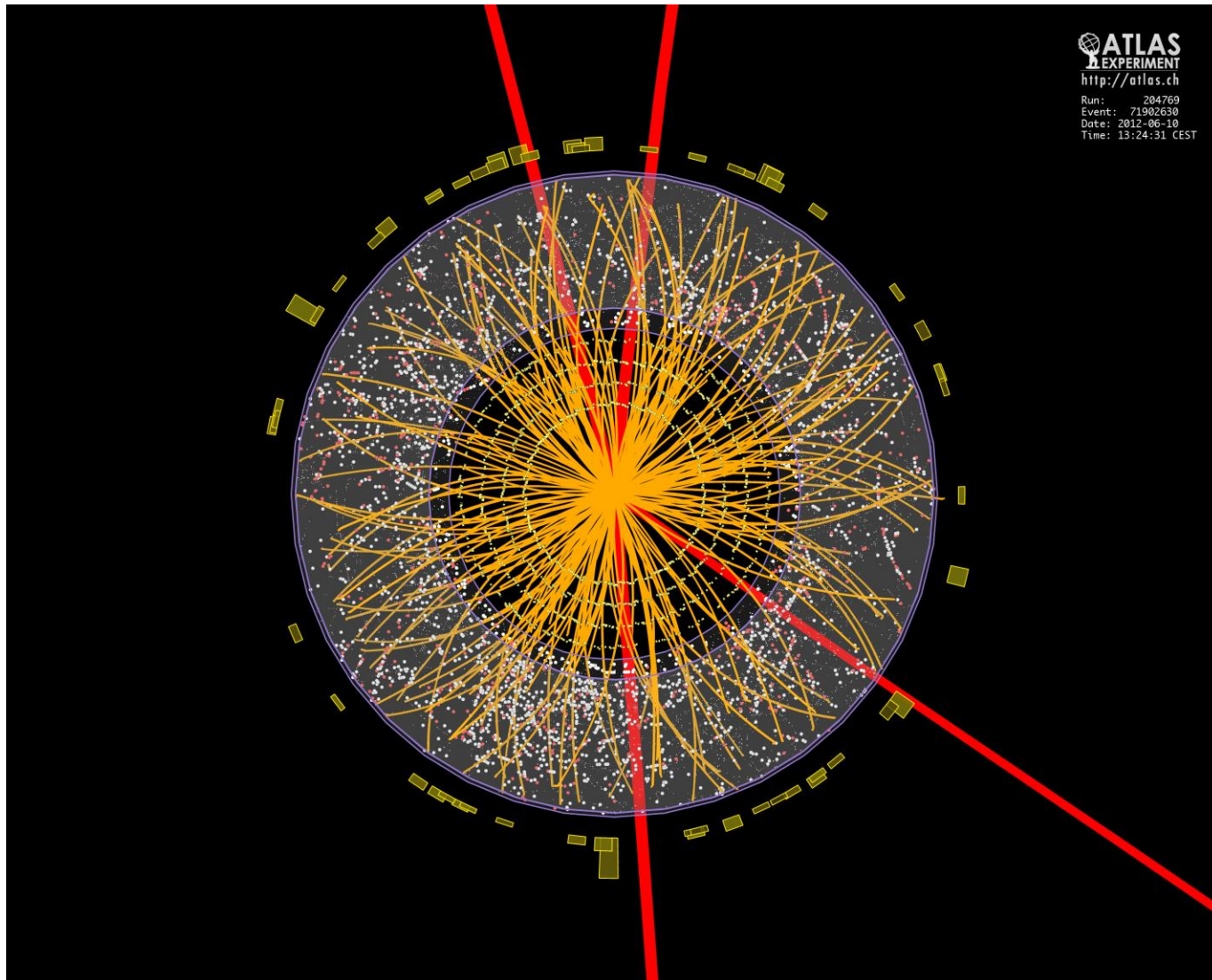


*Charged particles
bend in the
magnetic field*

*The lower the
particle
momentum the
more they bend.*

*Straight tracks from
high momentum
particles are the most
interesting!*

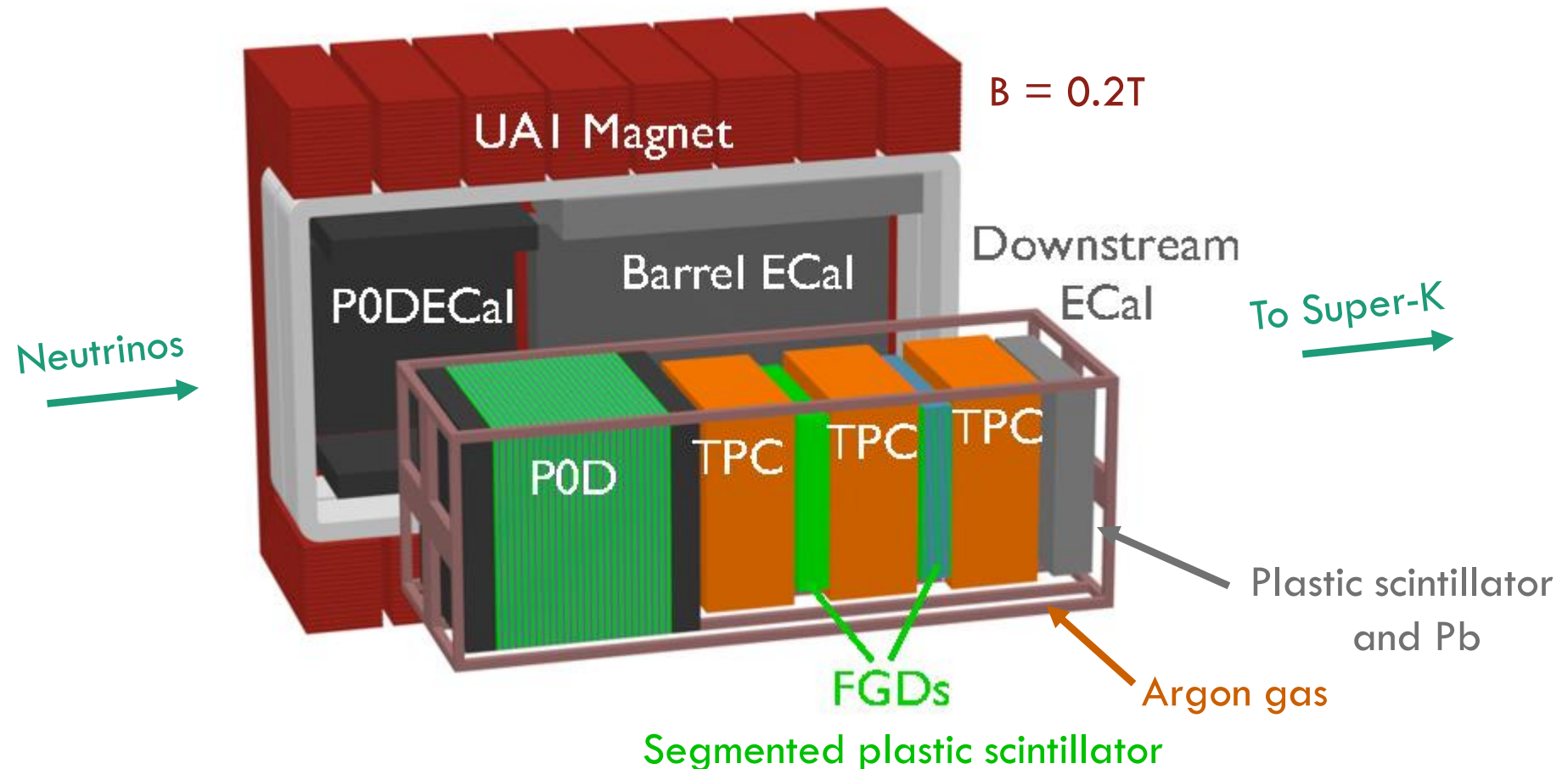
A REAL EVENT



T2K: ND280

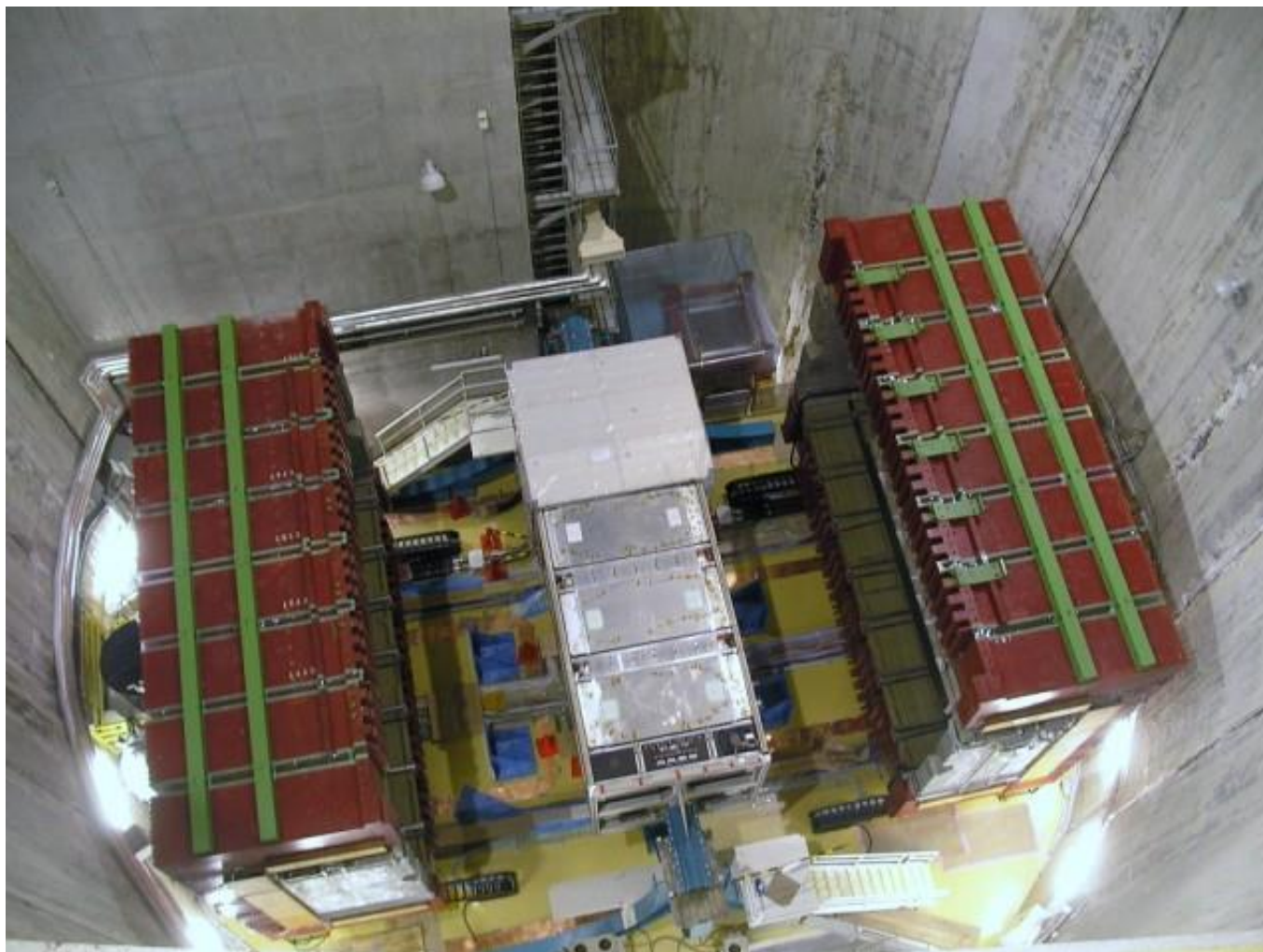
A GENERAL PURPOSE NEUTRINO DETECTOR

- Beam of neutrinos produced at the J-PARC proton accelerator in Japan

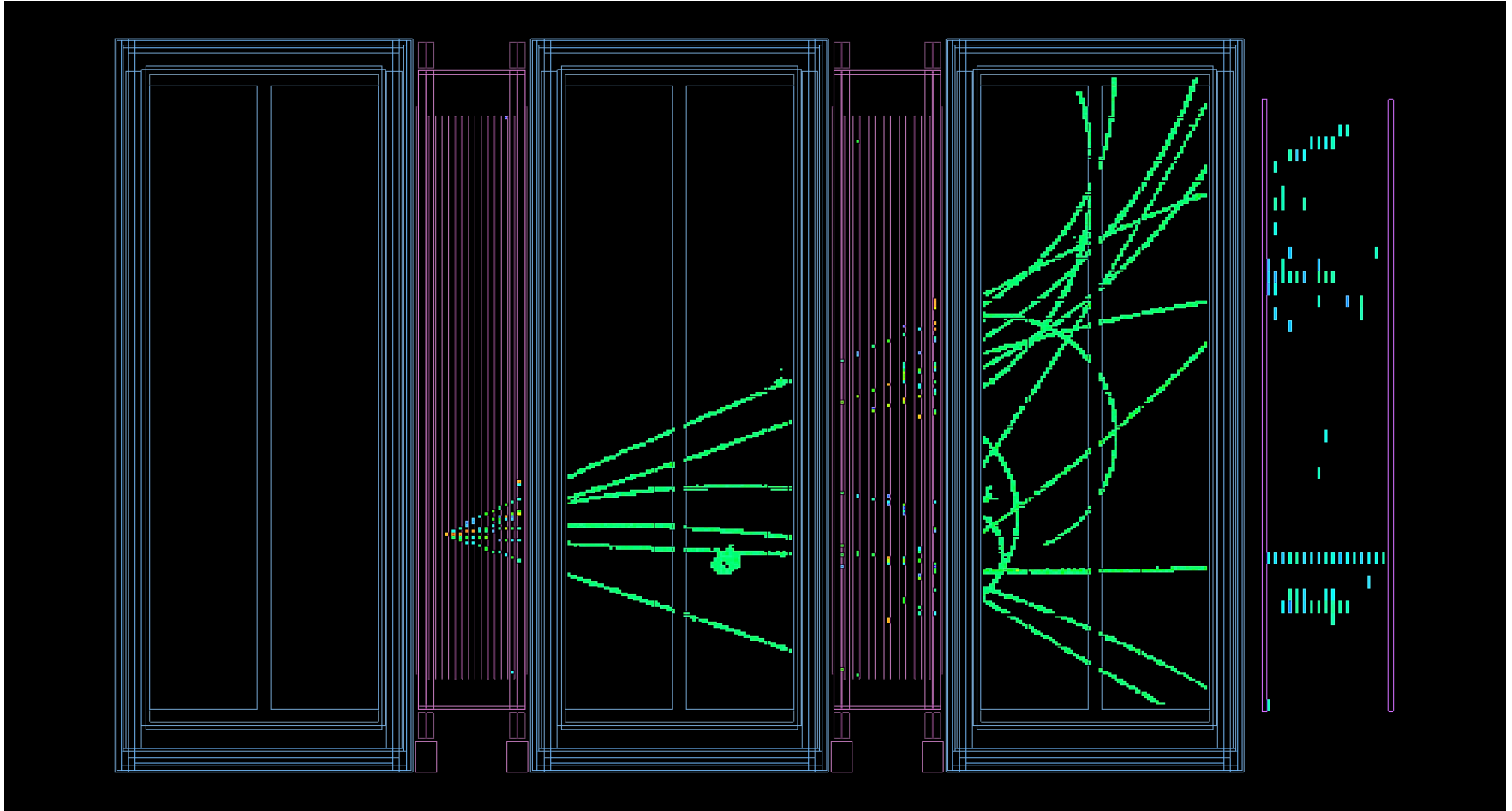


THE ND280 DETECTOR

WITH MAGNET OPEN FOR MAINTENANCE

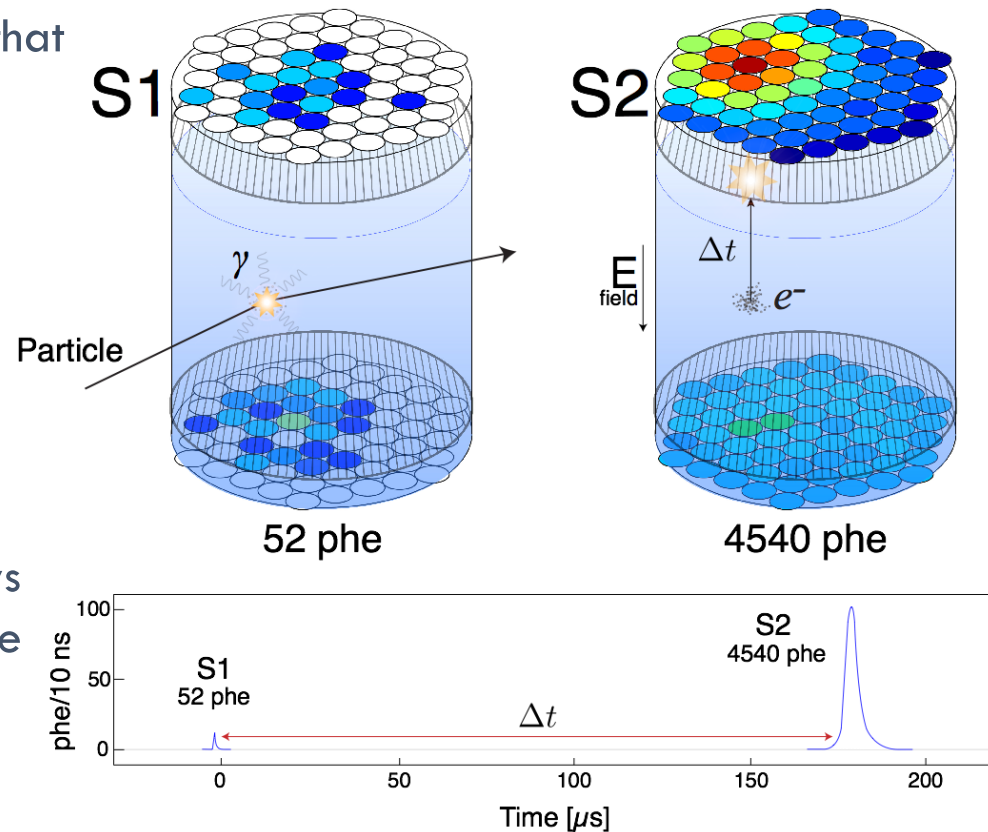


A NEUTRINO INTERACTION IN ND280



THE LUX DARK MATTER EXPERIMENT

- The Large Underground Xenon experiment (LUX) physics experiment looks for evidence of weakly interacting massive particle (WIMP) dark matter interactions.
- It is a 370 kg liquid xenon TPC that aims to directly detect galactic dark matter in an underground laboratory 1 mile deep
- The detector is shielded from background particles by a surrounding water tank and the earth above.
- This shielding reduces cosmic rays and radiation interacting with the xenon.



PARTICLE DETECTORS AT THE SOUTH POLE



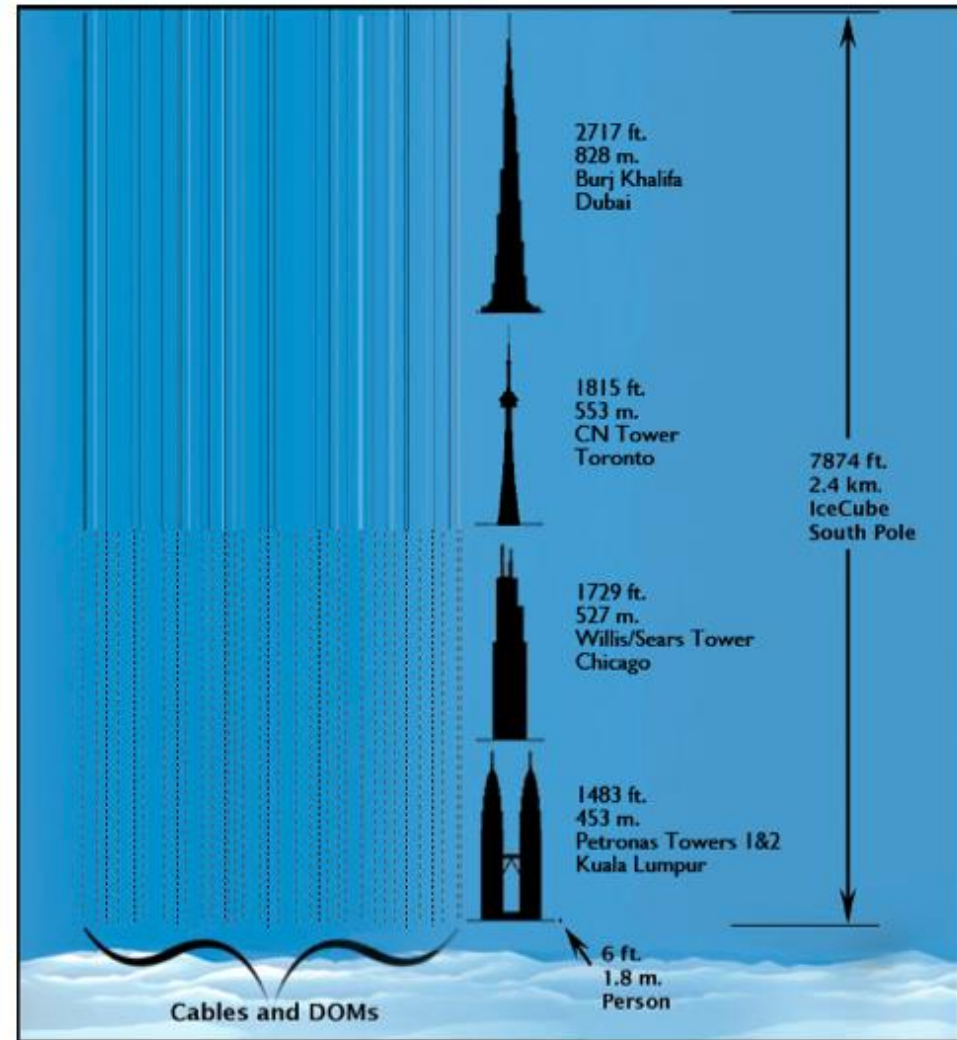
PARTICLE DETECTORS AT THE SOUTH POLE

Why do we go to such remote places for science?



ICE FISHING FOR SPACE NEUTRINOS!

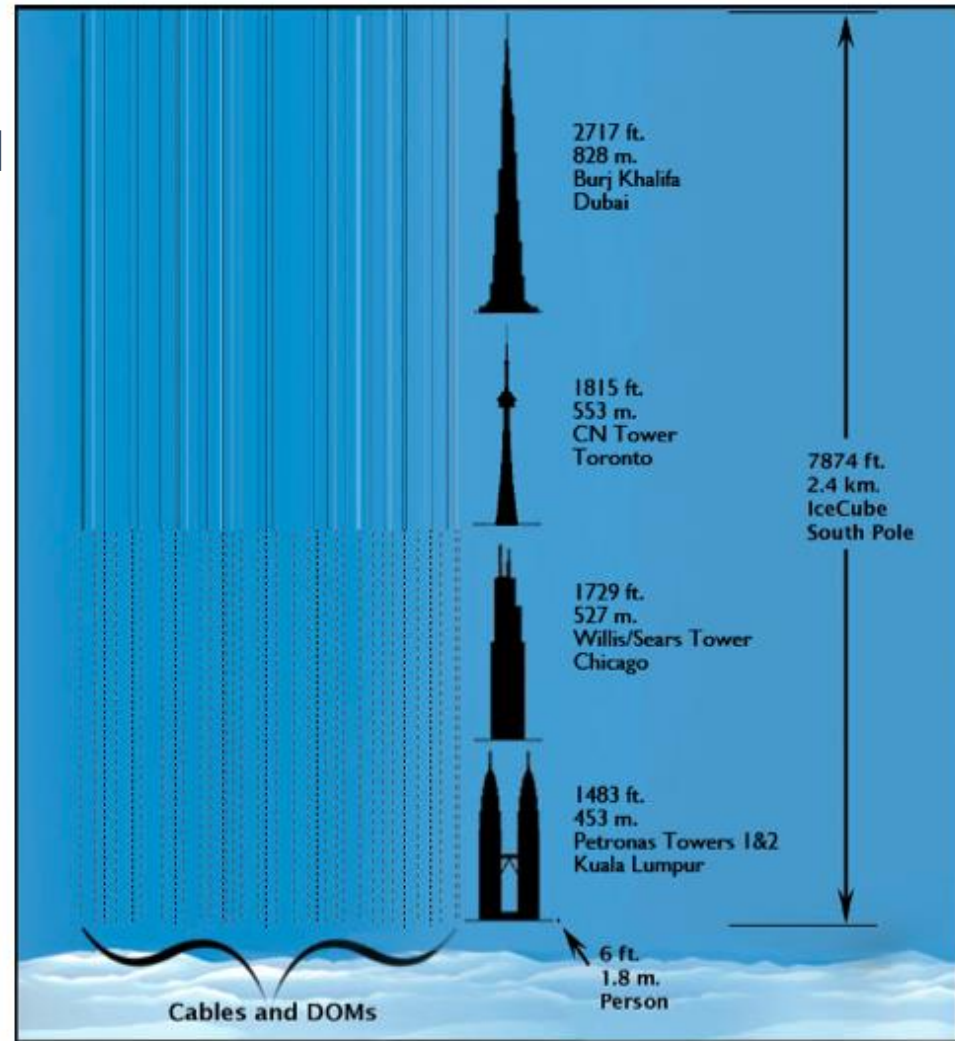
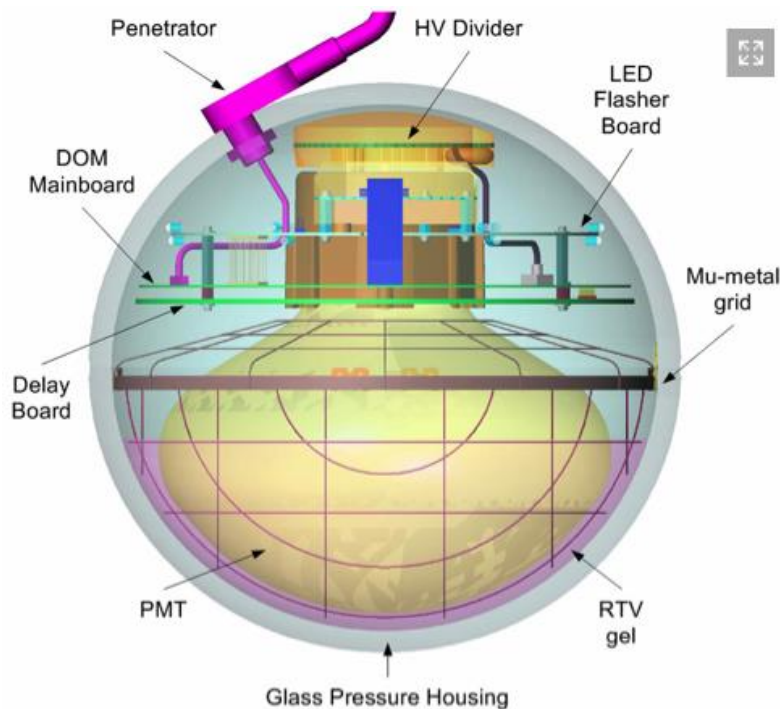
- IceCube detector at the South Pole
 - A neutrino detector: a neutrino telescope.
- Looks for extra-terrestrial sources of neutrinos.
 - Like taking an “X-ray” picture of the Universe.



IceCube in Scale: The dashed lines above represent the portion of the cables that have DOMs attached

ICE FISHING FOR SPACE NEUTRINOS!

- Made up of strings of thousands of basketball-sized photon detectors
 - Digital Optical Modules



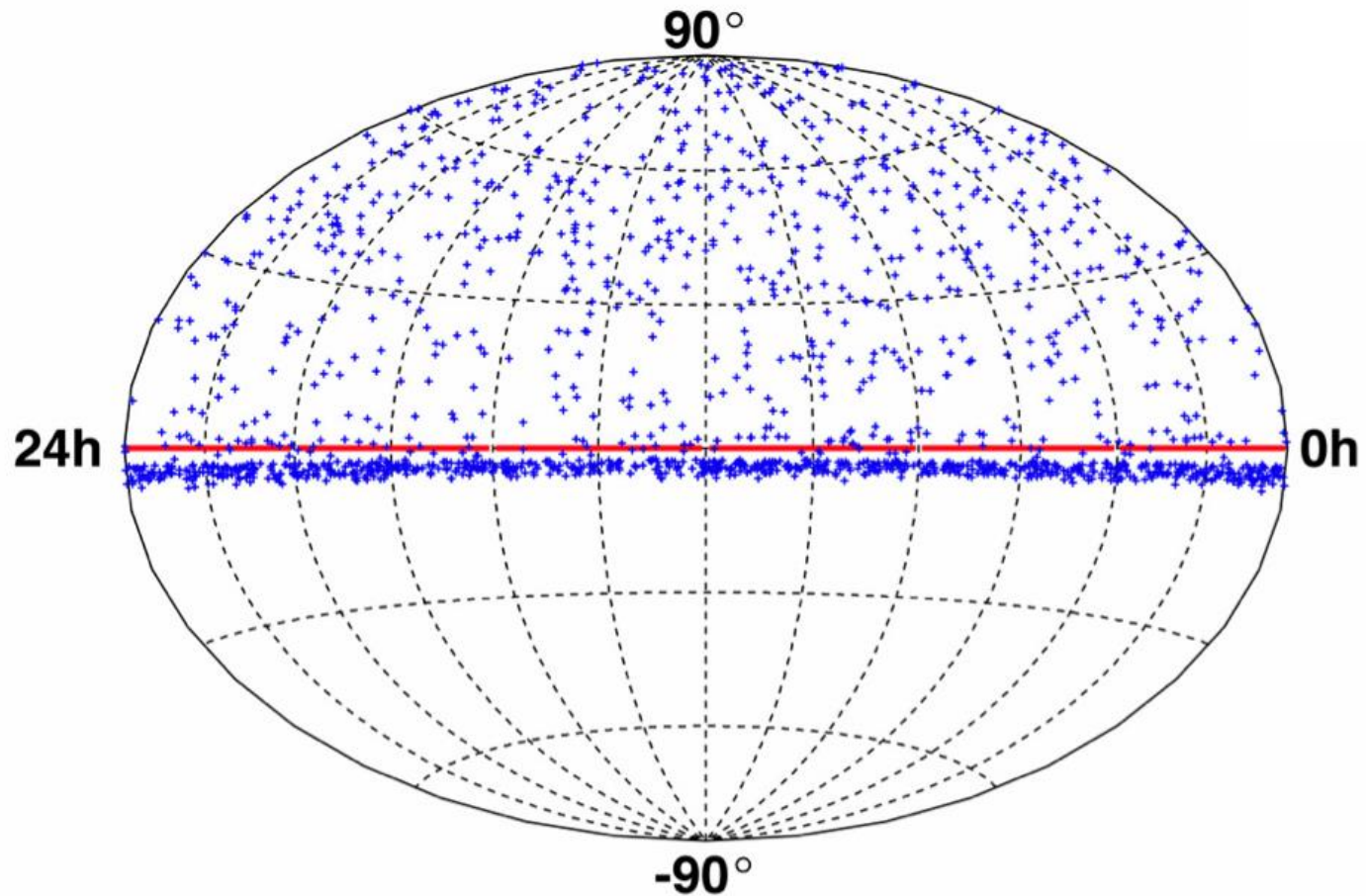
IceCube in Scale: The dashed lines above represent the portion of the cables that have DOMs attached

ICECUBE DETECTION PRINCIPLE

- How does IceCube detect neutrinos?
 - A **neutrino** interacts with an atomic nucleus, and produces a **charged lepton** (electron, muon or tau)
 - The lepton radiates **Cherenkov** photons that are detected by the **DOMs**.
 - The **direction** and **intensity** of the light is used to identify neutrino sources in the Universe.

ICECUBE DETECTION PRINCIPLE

- South pole: maps out neutrinos from the northern sky

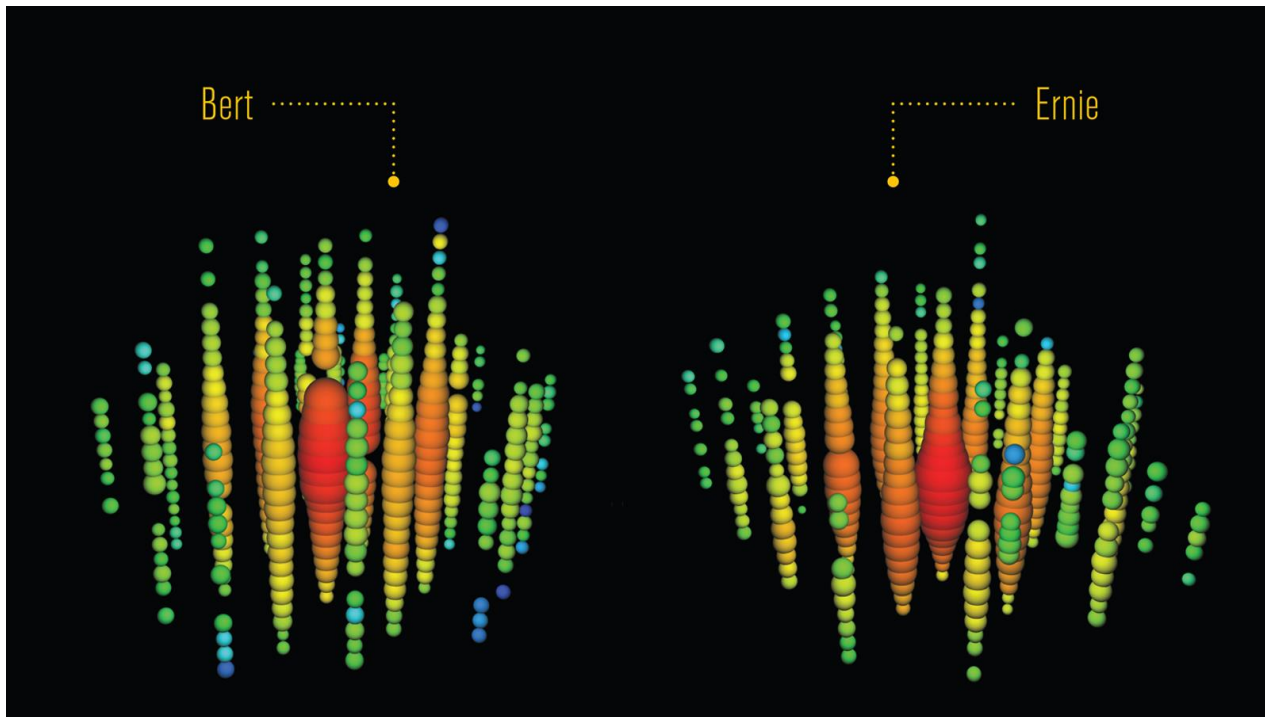


ICECUBE PHYSICS

- Used to study extra-galactic, extremely high-energy sources.
 - Neutrinos, being nearly massless and without charge, are **ideal messengers**. They carry **directional information**.
 - Charged particles are bent by magnetic fields, neutrons decay before reaching the earth and high-energy photons are absorbed.
- E.g. gamma ray bursts: hadronic or electromagnetic origin?
- Can only be done in the South Pole!
- Vast, extremely clean ice; it's there for free!
 - Recall, detector constraints: cost and detector technology

BERT, ERNIE AND MANY OTHERS

- In 2013, IceCube announced that it had detected 28 neutrinos likely originating from outside the Solar System.
 - These are ultra-high energy (PeV) neutrino events.

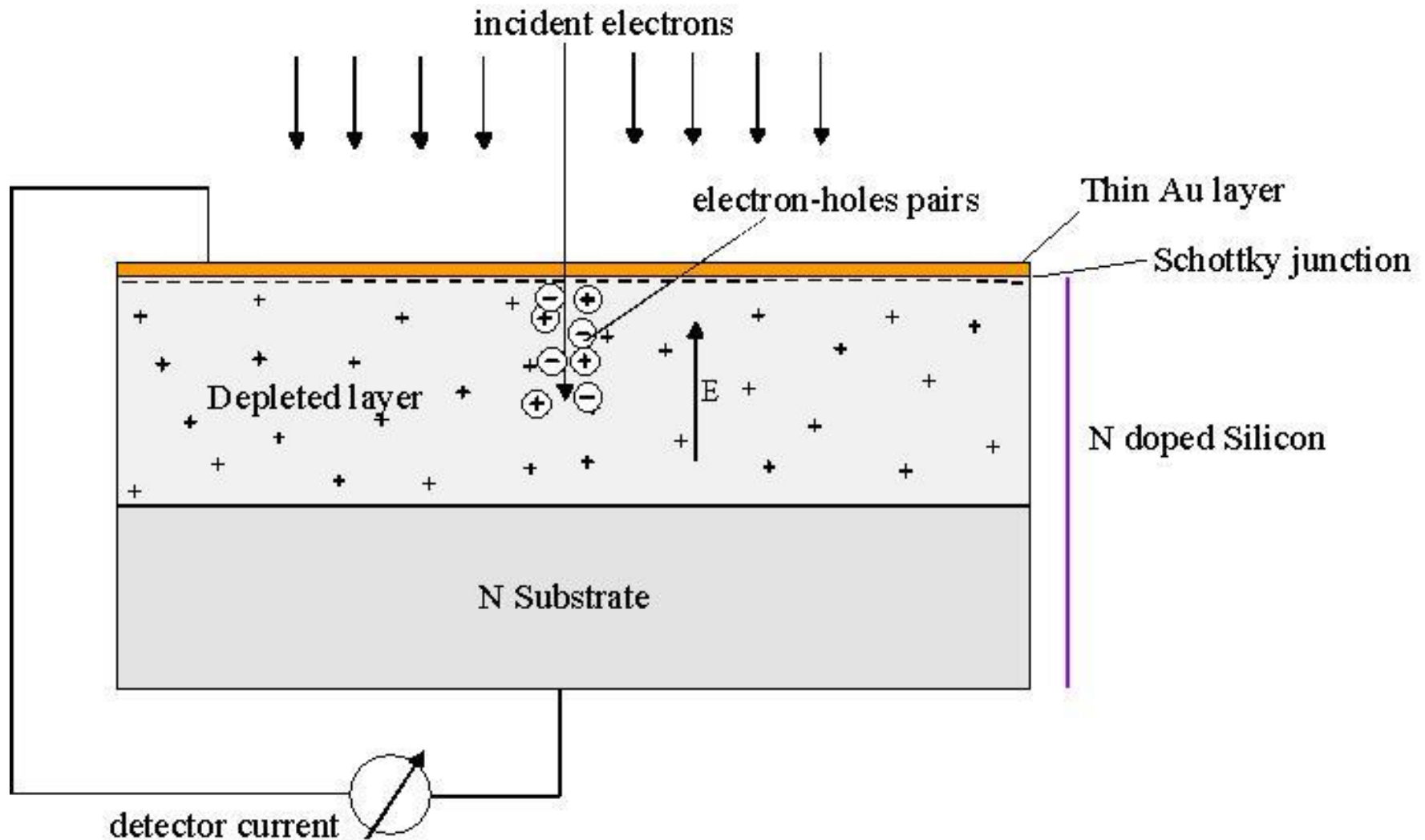


THAT'S ALL FOR THIS WEEK

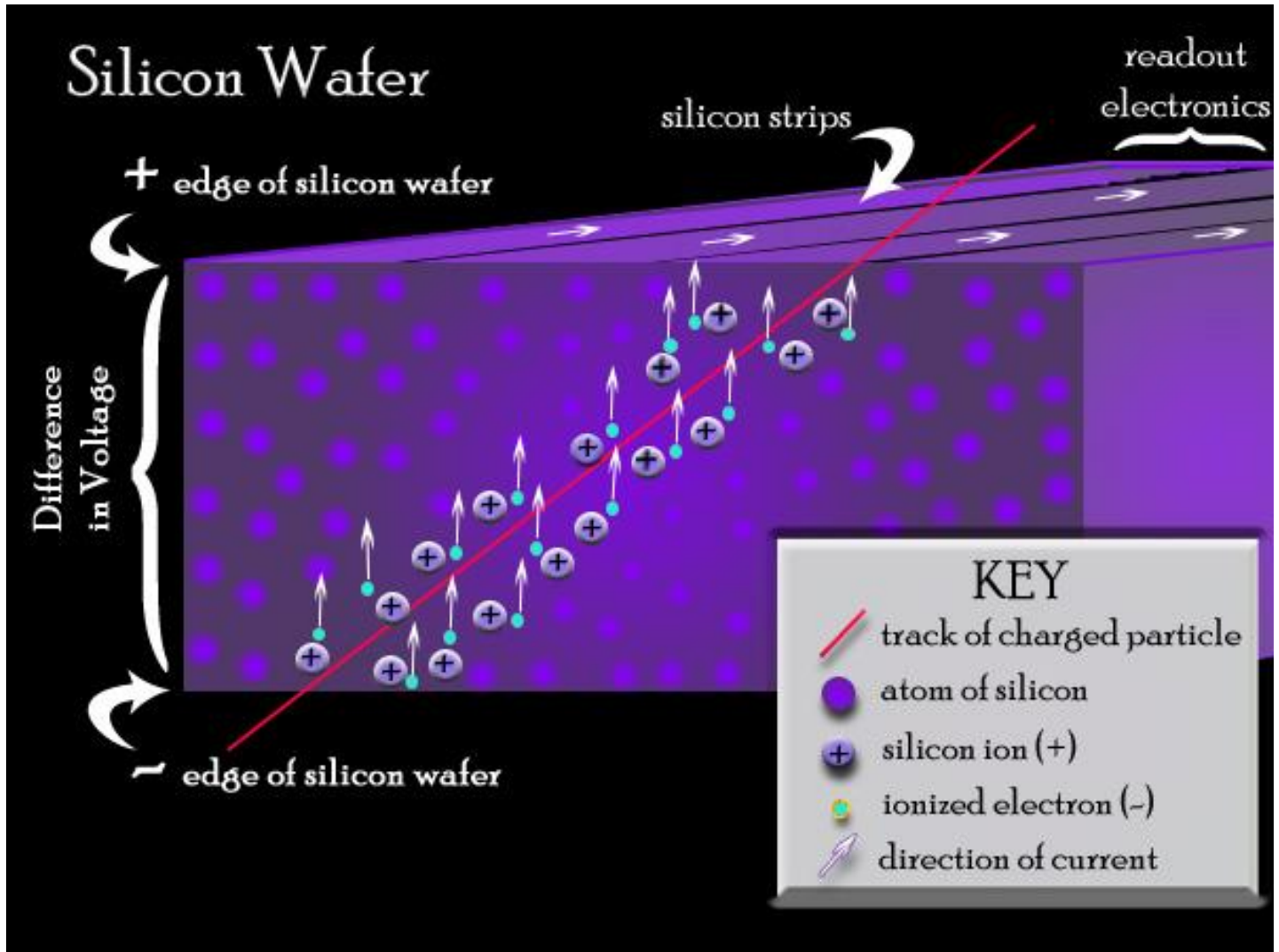
- Next week:
 - An overview of the Standard Model

BONUS

SOLID-STATE DETECTORS



SOLID-STATE DETECTORS



PERTURBATION THEORY

- Use a power series in a parameter ε (such that $\varepsilon \ll 1$) - known as perturbation series - as an approximation to the full solution.
- For example:

$$A = A_0 + \epsilon A_1 + \epsilon^2 A_2 + \dots$$

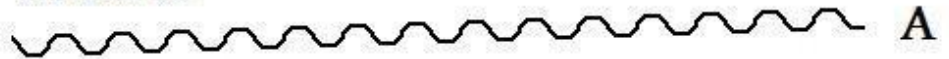
- In this example, A_0 is the “leading order” solution, while A_1, A_2, \dots represent higher order terms.
- **Note:** if ε is small, the higher-order terms in the series become successively smaller.
- Approximation:

$$A \approx A_0 + \epsilon A_1$$

PERTURBATION THEORY IN QFT

- Perturbation theory allows for well-defined predictions in quantum field theories (as long as they obey certain requirements).
- Quantum Electrodynamics (QED) is one of those theories.
- Feynman diagrams correspond to the terms in the perturbation series!

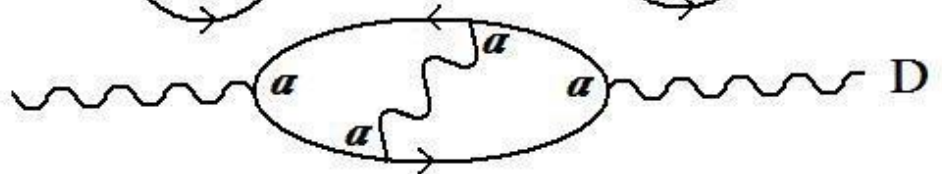
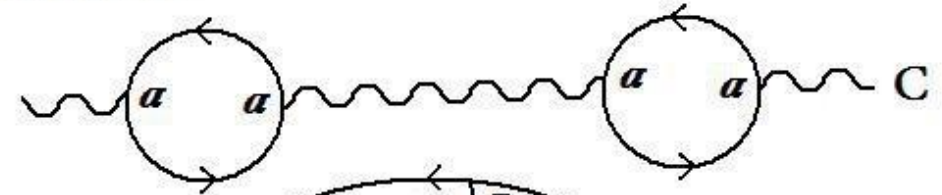
order 0:



order 2:



order 4:

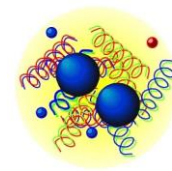


$$P = A + B\alpha^2 + (C + D)\alpha^4 + \dots$$

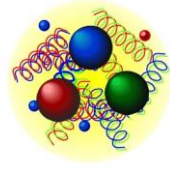
Diagrams define a series in α

QUANTUM CHROMODYNAMICS (QCD)

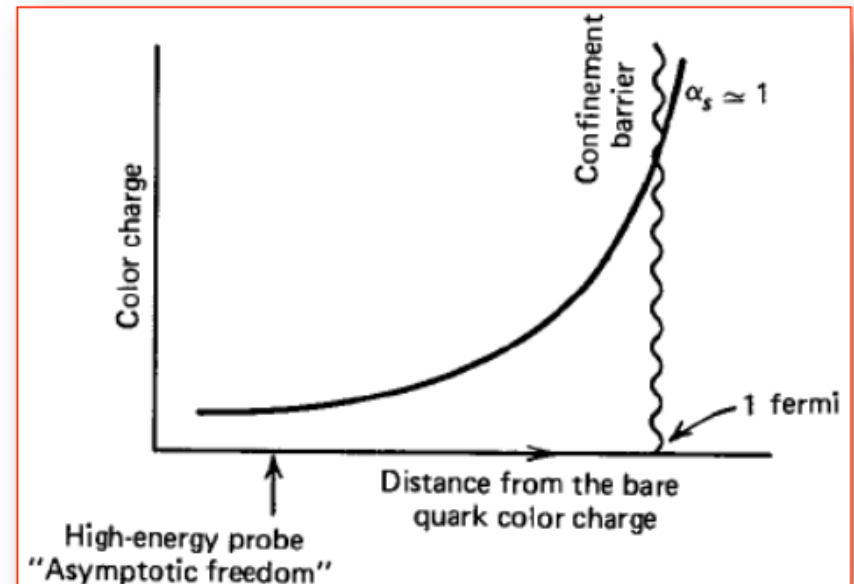
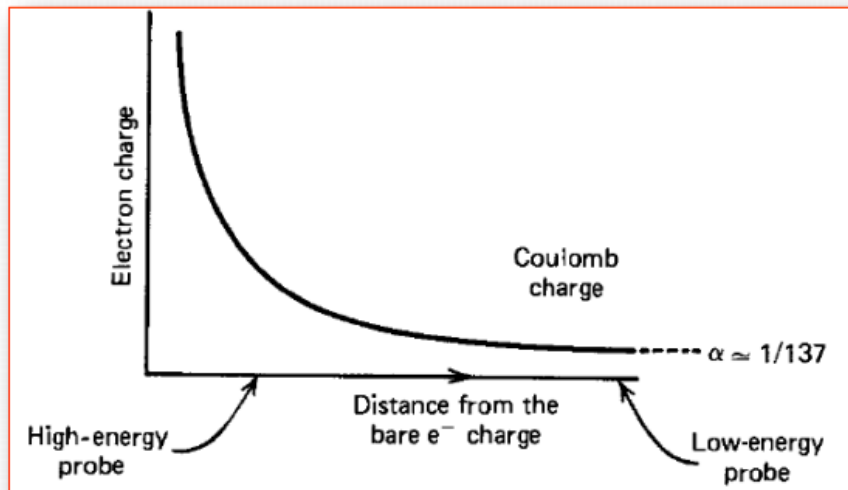
- Theory of strong interactions. Recall: gluons are the force carriers.
- Confinement: why we don't see free quarks.
- Asymptotic freedom: at very high energies, the interaction scale is smaller than at low energies, and we're in the perturbative regime.



meson

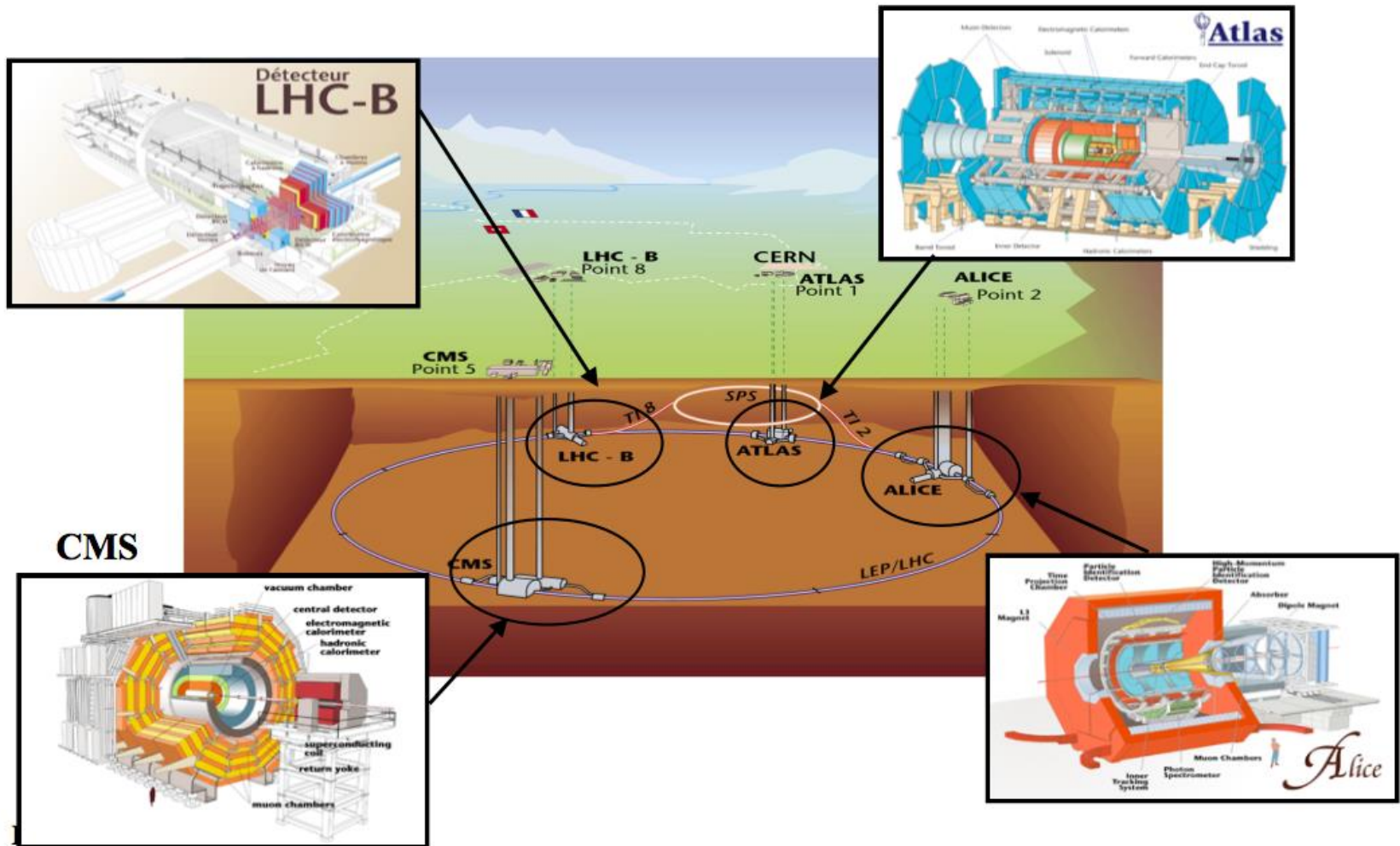


baryon



COLLIDER EXPERIMENTS

LHC Experiments underground



WHY BUILD THE LARGE HADRON COLLIDER?

- Large accelerator complex:
 - Long-lived charged particles can be accelerated to high momenta using electromagnetic fields.
 - The LHC accelerates protons and heavy ions; older generation accelerators collided e.g protons - anti-protons, and electrons - positrons, ...

- Why accelerate particles?

- High beam energies \rightarrow high E_{CM} \rightarrow more energy to create new particles!
- Higher energies probe physics at shorter distances. De Broglie wavelength:

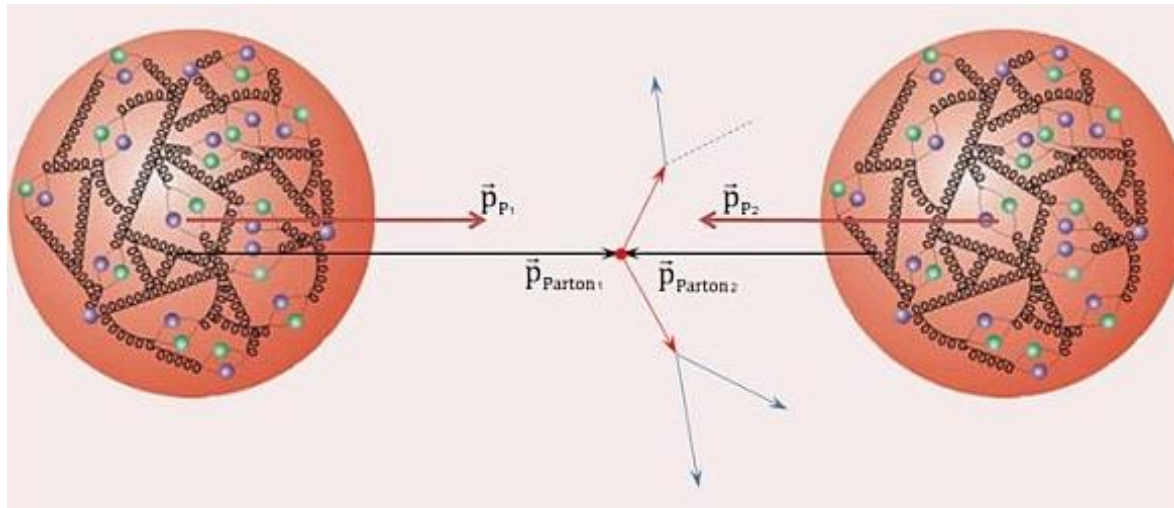
$$\frac{\lambda}{2\pi} = \frac{\hbar c}{pc} \approx \frac{197 \text{ MeV fm}}{p [\text{MeV}/c]}$$

- e.g. 20 GeV/c probes a distance of 0.01 fm.
- An accelerator complex uses a variety of particle acceleration techniques to reach the final energy.

PROTON-PROTON COLLISIONS

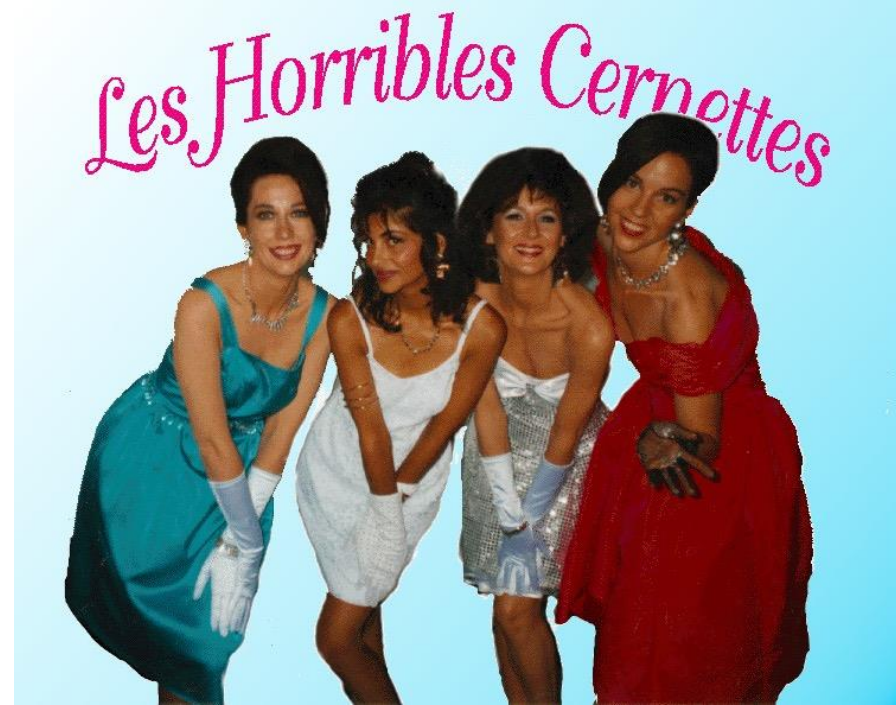
- Quantum Chromodynamics theory is expressed in terms of quarks and gluons (partons)
 - We are colliding composite objects.
- At the LHC energies, quarks and gluons collide and the actual collision energy is a fraction of the total:

$$\sqrt{\hat{s}} \ll \sqrt{s} = E_{\text{cm}} = 2E_p$$



CERN

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH



- Founded in 1954. Currently operates a network of six accelerators.
- A few of the scientific and computing achievements:
 - Neutral currents in Gargamelle bubble chamber
 - W/Z bosons in UA1 and UA2 experiments
 - The World Wide Web!