

Particle Physics: Experimental Methods

Edward Dunton

Week 5: October 20, 2018
Columbia University Science Honors Program



Course policies

.Classes from 10:00 AM to 12:30 PM (10 min break at ~ 11:10 AM).

.Attendance record counts.

–Up to four absences

–Lateness or leaving early counts as half-absence

–Send email notifications of all absences to shpattendance@columbia.edu.

.Please, no cell phones during class

.Please, ask questions!

.Lecture materials + Research Opportunities + Resources to become a particle physicist

<https://twiki.nevis.columbia.edu/twiki/bin/view/Main/ScienceHonorsProgram>

Schedule

Month	Day	Lecture	Teacher
September	22	Introduction	Yeon-jae
	29	History of Particle Physics	Yeon-jae
October	6	Special Relativity	Edward
	13	Quantum Mechanics	Edward
	20	Experimental Methods	Edward
	27	The Standard Model - Overview	Yeon-jae
November	3	The Standard Model - Limitations	Yeon-jae
	10	Neutrino Theory	Edward
	17	Neutrino Experiment	Edward
	24	No classes, SHP break	
December	1	LHC and Experiments	Yeon-jae
	8	The Higgs Boson and Beyond	Yeon-jae
	15	Particle Cosmology	Edward

Announcements

- The Admissions Office of Columbia College and the School of Engineering will be conducting special information sessions and campus tours for SHP students and their parents:
 - Saturday, October 27, 2018 at 12:45 pm
One house Information session in room 301 Pupin followed by an optional campus tour.
 - Saturday, November 17, 2018 at 12:45 pm
One house Information session in room 301 Pupin followed by an optional campus tour.
- No RSVP necessary – All Welcome.

QUICK REVIEW: 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:

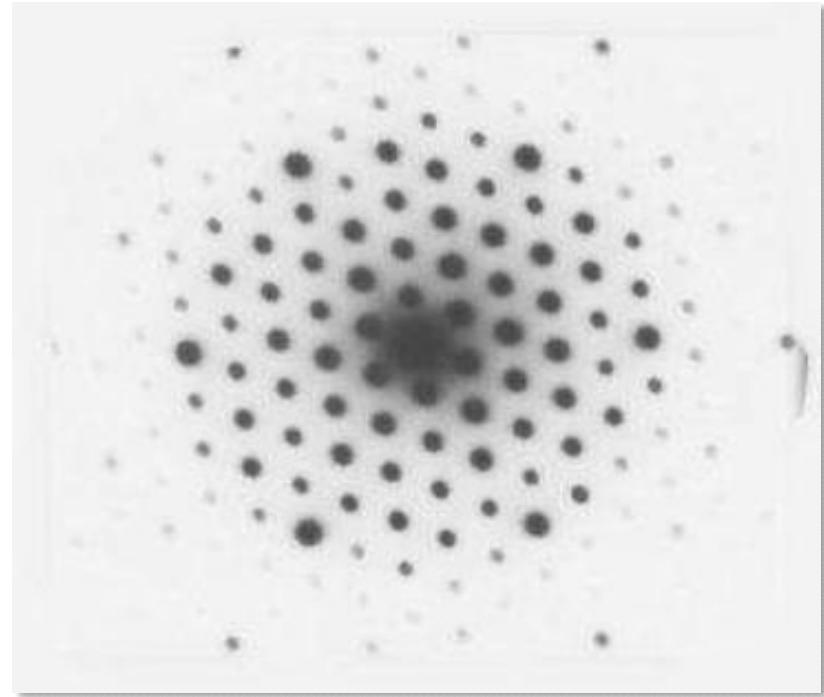
$$E = hf$$

- 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:

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

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.

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 scattering) 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:

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

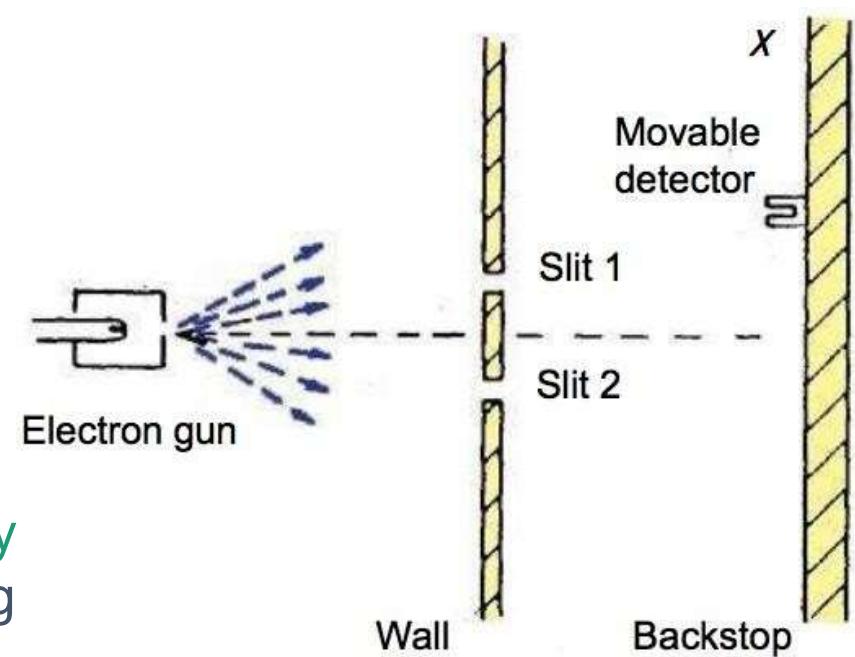
where the asterisk signifies complex conjugation. Note that for a **plane wave** this is a **constant**:

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

- 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.

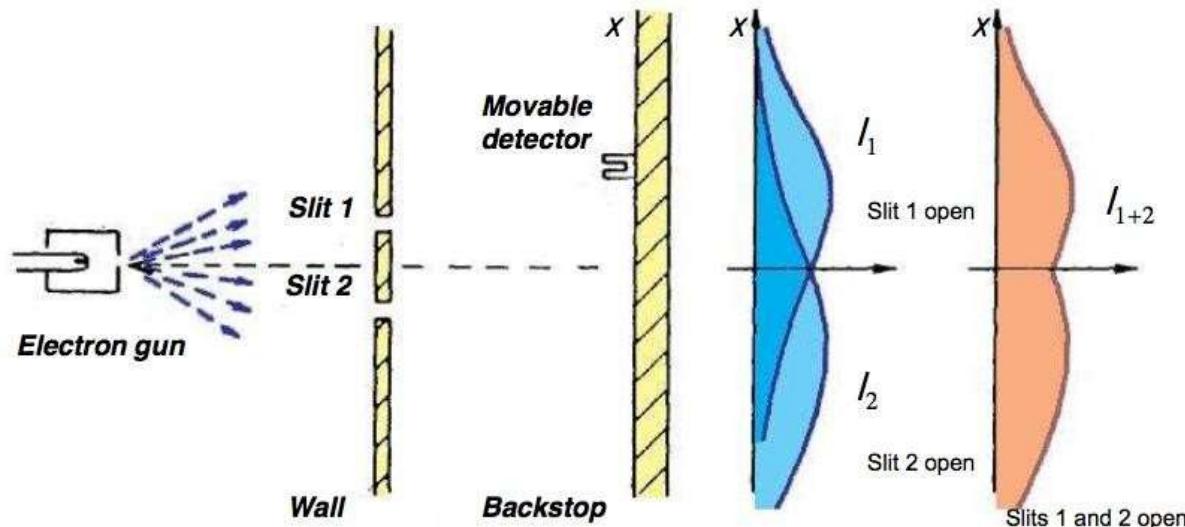
THE DOUBLE SLIT EXPERIMENT

- **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

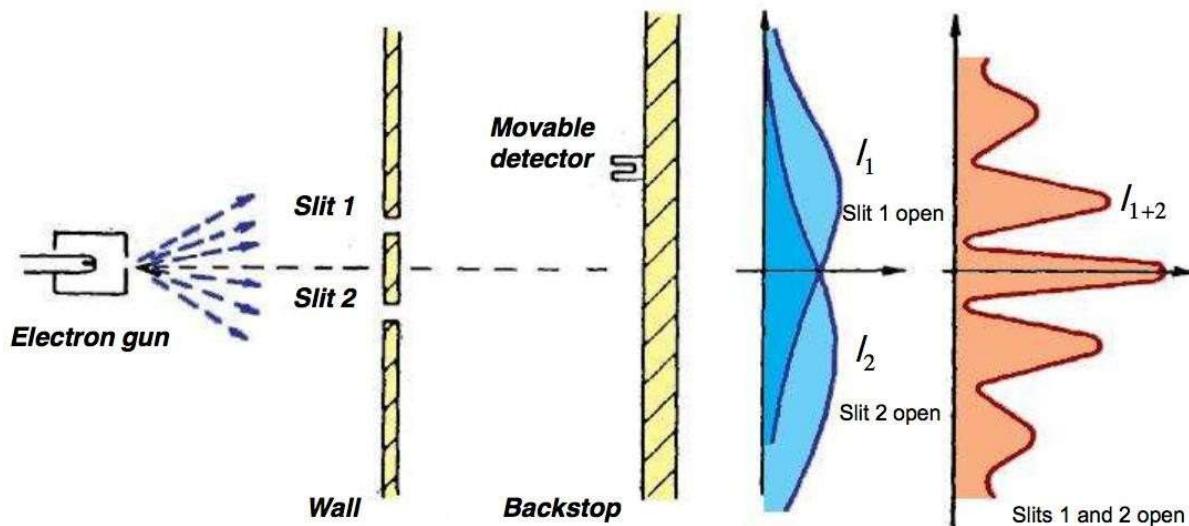
- The **classical** result:



- 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

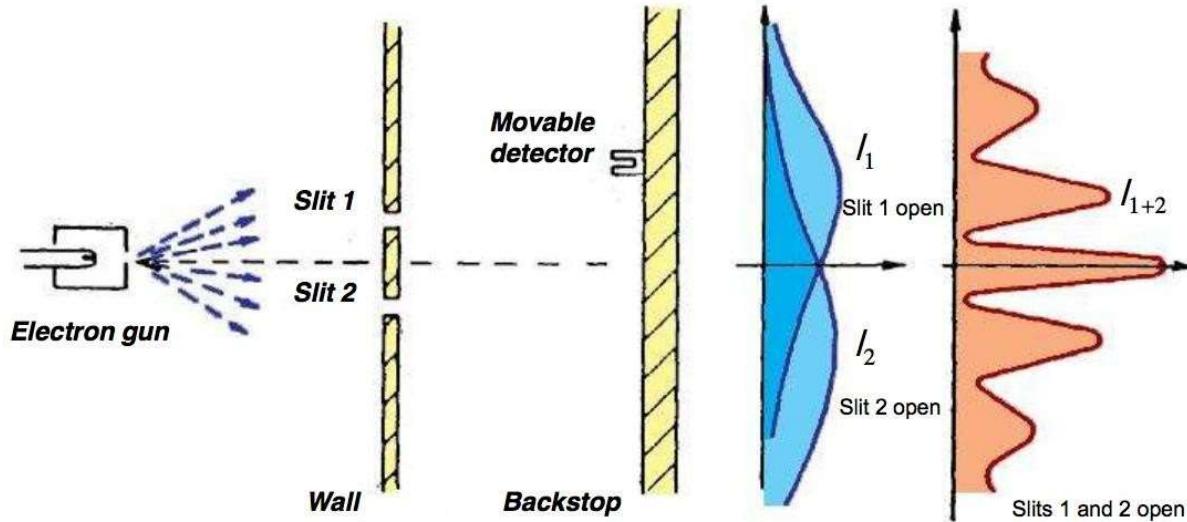
- In reality:



- 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.
- **Electrons act* like waves!**

*When fired through two slits placed a de Broglie wavelength apart.

WAVE FUNCTION INTERPRETATION

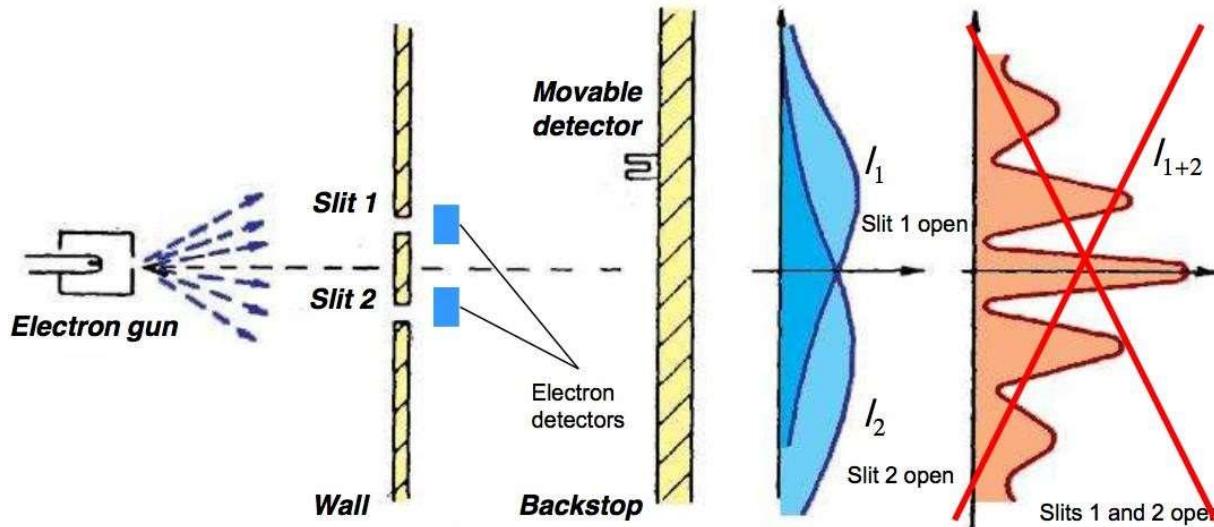


- In terms of **waves**, the wave function of an electron at the screen when only slit 1 is open is ψ_1 , and when only slit 2 is open it's ψ_2 .
 - Hence, the intensity when only one slit is open is **either** $I_1=|\psi_1|^2$ or $I_2=|\psi_2|^2$.
- With both slits open, the intensity at the screen 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.

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 detector.
- **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 $\psi(x,t)$: the wave function gives the probability of finding the 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 an experiment **cannot simultaneously determine** the exact values of x and p_x .
- 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:

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

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

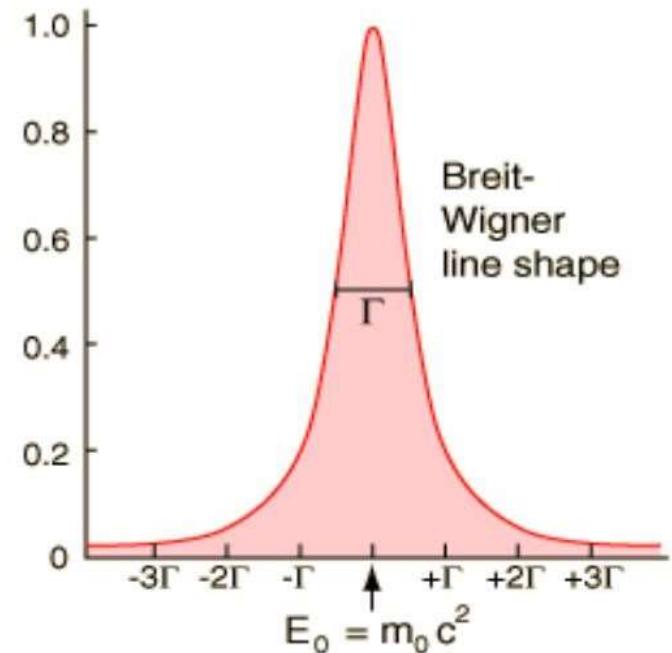
- In other words, after our measurement of the particle's momentum, we lose all information about its position!

THE UNCERTAINTY PRINCIPLE

- The Uncertainty Principle also applies to measurements of **energy** E and the **time** t . It states that:

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

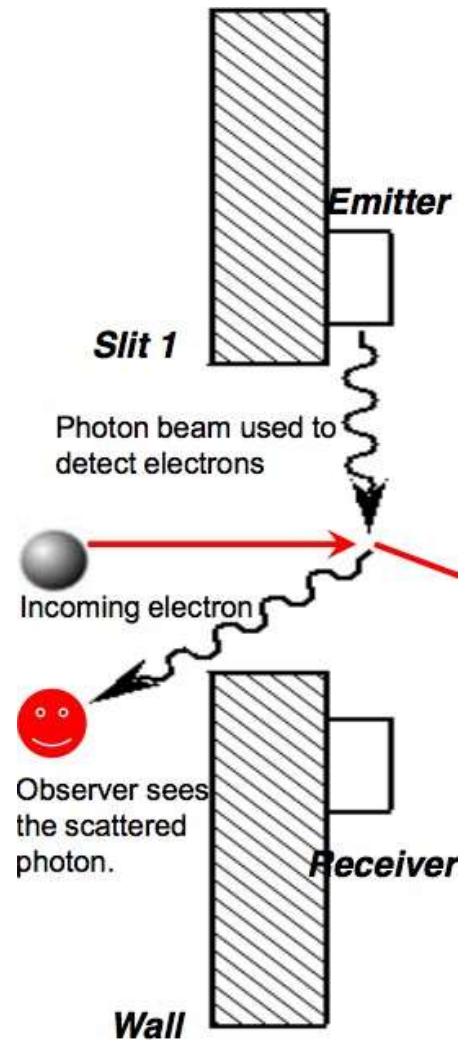
- **Example:** estimate the mass of virtual particles confined to the nucleus (see Lecture 2 on estimating Yukawa's meson mass).
- **Example:** Δt could be the time during which a photon of energy spread ΔE is emitted from an atom.
- **This effect causes spectral lines in excited atoms to have a finite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

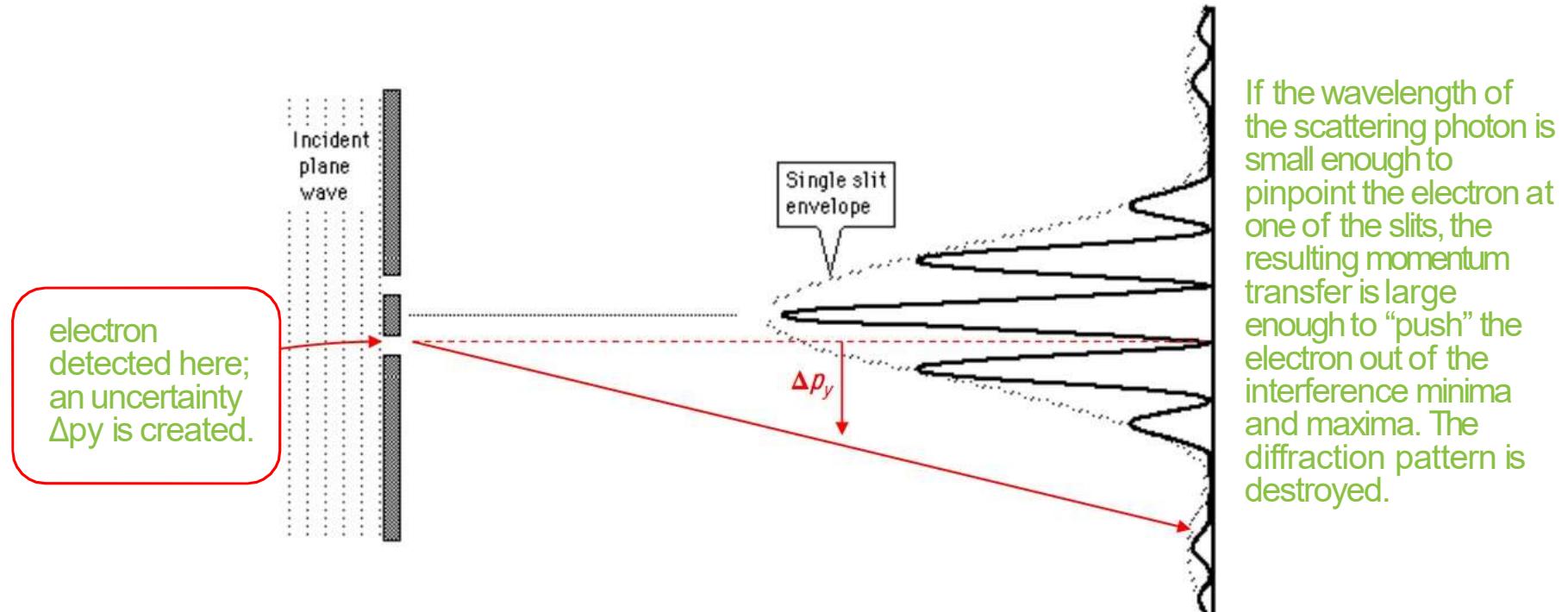
- Now that we know the Uncertainty Principle, we can **understand** why we can't "beat" the double slit experiment and simultaneously observe wave and particle behavior.
- Our electron **detector** Compton scatters light off of incoming electrons.
- When an electron passes through one of the slits, we **observe** the scattered photon and know that an electron went through that slit.
- 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

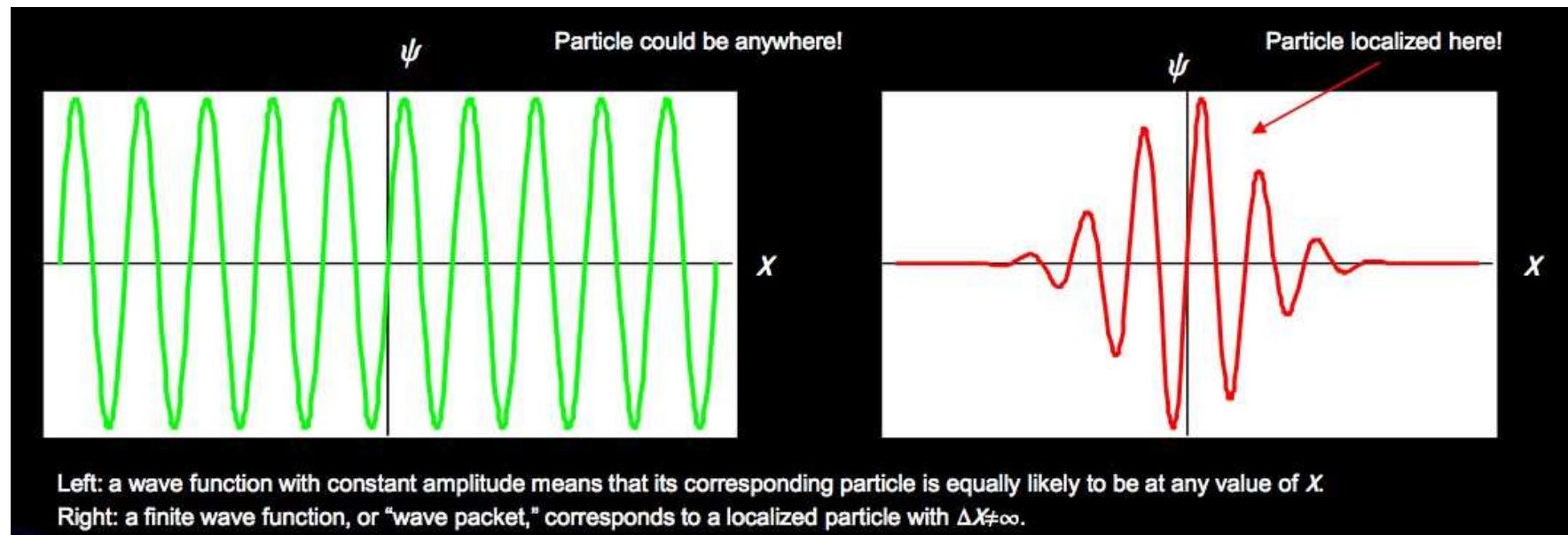
- If we try to pinpoint the electron at one of the slits, its momentum uncertainty gets so big that the interference pattern vanishes.
- Can you think of a way to get around this problem?
- We could use lower energy photons; but that dropping of the photon momentum simultaneously increases the photon 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 .
- 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**, seems very mysterious. However, it turns out that it is just a natural consequence of the **wave** nature of matter: **all waves obey an Uncertainty Principle!**

WAVE FUNCTIONS SHOULD BE FINITE

- If a wave function 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).

THE CONTINUUM LIMIT

- So, evaluating a sum of sinusoids like:

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

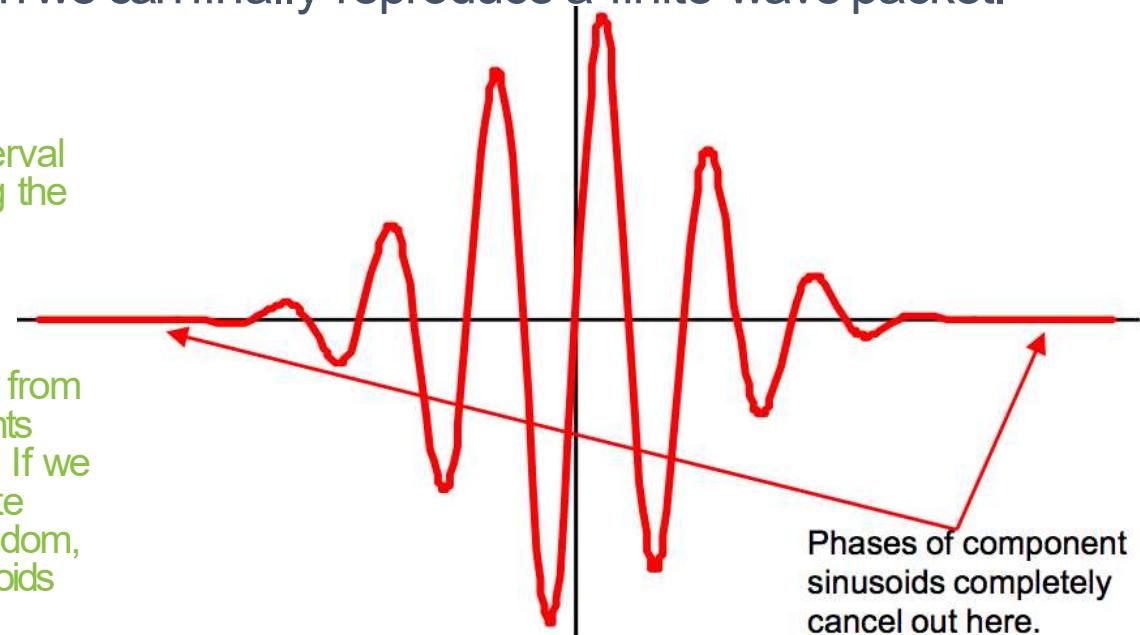
where k is an integer that runs between k_1 and k_2 , we can reproduce any periodic function.

- 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 $\Delta k = k_2 - k_1$, we are essentially evaluating the integral

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

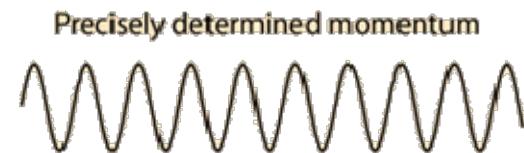
In such a “continuous sum”, the component sinusoids are all in phase near $x=0$. Away from this point, in either direction, the components begin to get out of phase with each other. If we go far enough out, the phases of the infinite number of components become totally random, and cancel out phases of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

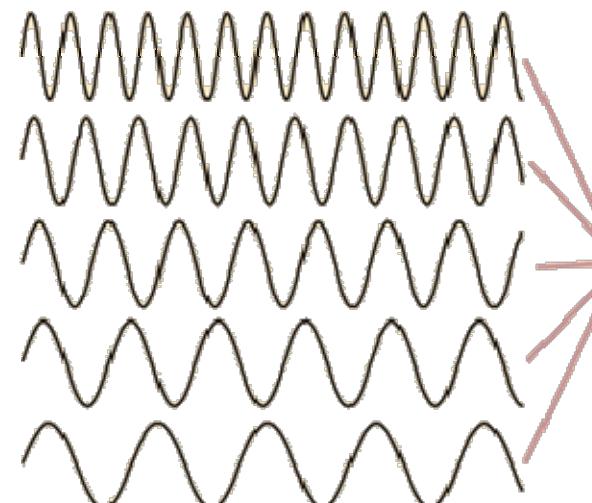
CONNECTION TO UNCERTAINTY



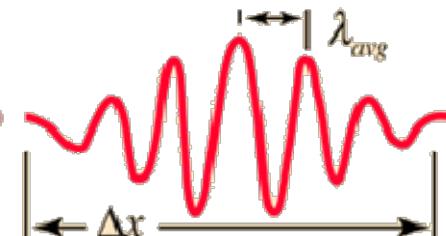
A sine wave of wavelength λ implies that the momentum is precisely known. But the wavefunction and the probability of finding the particle $\Psi^* \Psi$ is spread over all of space!

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

p-precise
x-unknown



Adding several waves of different wavelength together will produce an interference pattern which begins to localize the wave.



But that process spreads the momentum values and makes it more uncertain. This is an inherent and inescapable increase in the uncertainty Δp when Δx is decreased.

$$\Delta x \Delta p > \frac{h}{2}$$

<http://hyperphysics.phy-astr.gsu.edu>

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; it arises rather naturally from properties of (localized) waves.

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 \hbar).
- **Matter** and **radiation** can have both **particle** and **wave-like** properties, depending on the type of observation.
- The **Uncertainty Principle** tells us that there is a fundamental limit to the precision with which we can measure certain **pairs** of **observables**.
- Objects can never be wavelike or particle-like **simultaneously**.

EXPERIMENTAL METHODS IN PARTICLE PHYSICS

HOW WE STUDY PARTICLES IN THE LAB

TODAY'S AGENDA

- What do we want to **know** and what do we **measure**?
- Passage of particles through **matter**:
 - Ionization
 - Scintillation
 - Cherenkov radiation
- Particle detectors
- Modern experiments

Recall

STANDARD MODEL PARTICLE PROPERTIES

QUARKS	LEPTONS	GAUGE BOSONS
<p>u up</p> <p>mass → $\approx 2.3 \text{ MeV}/c^2$</p> <p>charge → 2/3</p> <p>spin → 1/2</p>	<p>d down</p> <p>mass → $\approx 4.8 \text{ MeV}/c^2$</p> <p>charge → -1/3</p> <p>spin → 1/2</p>	<p>c charm</p> <p>mass → $\approx 1.275 \text{ GeV}/c^2$</p> <p>charge → 2/3</p> <p>spin → 1/2</p>
<p>t top</p> <p>mass → $\approx 173.07 \text{ GeV}/c^2$</p> <p>charge → 2/3</p> <p>spin → 1/2</p>	<p>s strange</p> <p>mass → $\approx 95 \text{ MeV}/c^2$</p> <p>charge → -1/3</p> <p>spin → 1/2</p>	<p>b bottom</p> <p>mass → $\approx 4.18 \text{ GeV}/c^2$</p> <p>charge → -1/3</p> <p>spin → 1/2</p>
<p>electron</p> <p>mass → $0.511 \text{ MeV}/c^2$</p> <p>charge → -1</p> <p>spin → 1/2</p>	<p>electron neutrino</p> <p>mass → $< 2.2 \text{ eV}/c^2$</p> <p>charge → 0</p> <p>spin → 1/2</p>	<p>photon</p> <p>mass → 0</p> <p>charge → 0</p> <p>spin → 1</p>
<p>muon</p> <p>mass → $105.7 \text{ MeV}/c^2$</p> <p>charge → -1</p> <p>spin → 1/2</p>	<p>muon neutrino</p> <p>mass → $< 0.17 \text{ MeV}/c^2$</p> <p>charge → 0</p> <p>spin → 1/2</p>	<p>tau</p> <p>mass → $1.777 \text{ GeV}/c^2$</p> <p>charge → -1</p> <p>spin → 1/2</p>
<p>tau neutrino</p> <p>mass → $< 15.5 \text{ MeV}/c^2$</p> <p>charge → 0</p> <p>spin → 1/2</p>	<p>W boson</p> <p>mass → $80.4 \text{ GeV}/c^2$</p> <p>charge → ±1</p> <p>spin → 1</p>	<p>Z boson</p> <p>mass → $91.2 \text{ GeV}/c^2$</p> <p>charge → 0</p> <p>spin → 1</p>

WHAT WE WANT TO KNOW

- Particle **properties**:
 - **Mass**
 - **Spin**
 - **Charge**
- Particle **interactions**:
 - What happens when particles **collide** with each other?
 - What are the interaction **products**?
 - With what **probability** do different types of interactions occur?
 - How long does it take for an **unstable** particle to **decay**?
 - ... and what particles does it decay to?
 - Are there extremely **rare interactions** that we haven't measured yet?
 - Do **new** particles exist that we don't know about yet?
 - Can we **produce** them in high energy **collisions**?

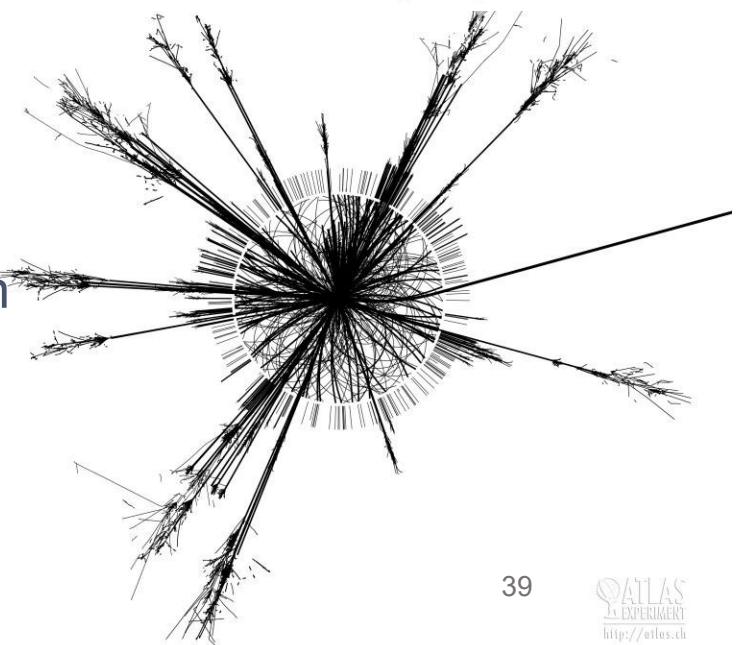
WHAT WE MEASURE

- Particle **trajectories**
 - ... and how they bend in magnetic fields
- Particle **energies**
- **Events:**
 - Collection of particle tracks and energy deposits resulting from an interaction.
 - **Topology:** what particles are produced in the event
 - **Angles** between particles, imbalances in momentum, etc...

WHEN TWO APPLES COLLIDE, THEY CAN BRIEFLY FORM EXOTIC NEW FRUIT. PINEAPPLES WITH APPLE SKIN. POMEGRANATES FULL OF GRAPES. WATERMELON-SIZED PEACHES.

THESE NORMALLY DECAY INTO A SHOWER OF FRUIT SALAD, BUT BY STUDYING THE DEBRIS, WE CAN LEARN WHAT WAS PRODUCED.

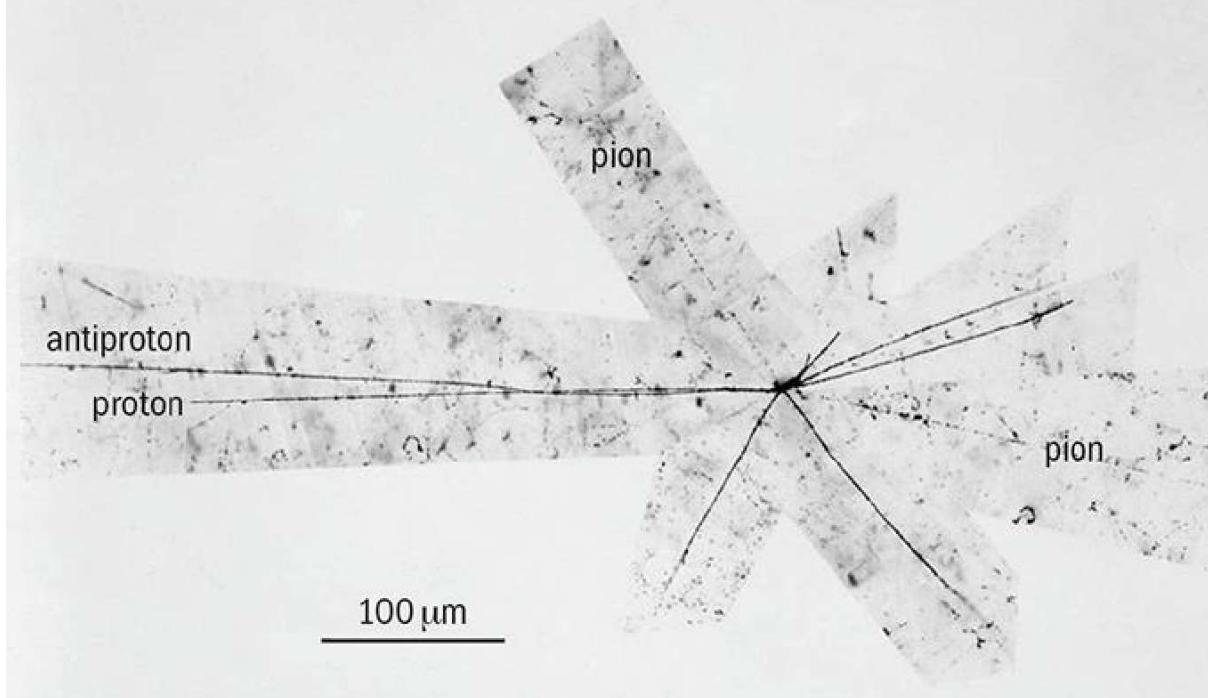
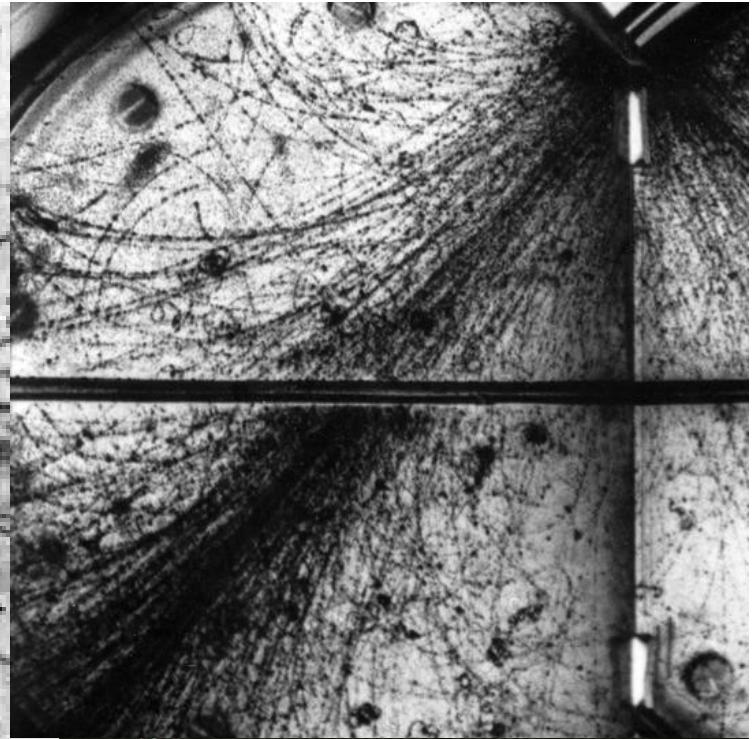
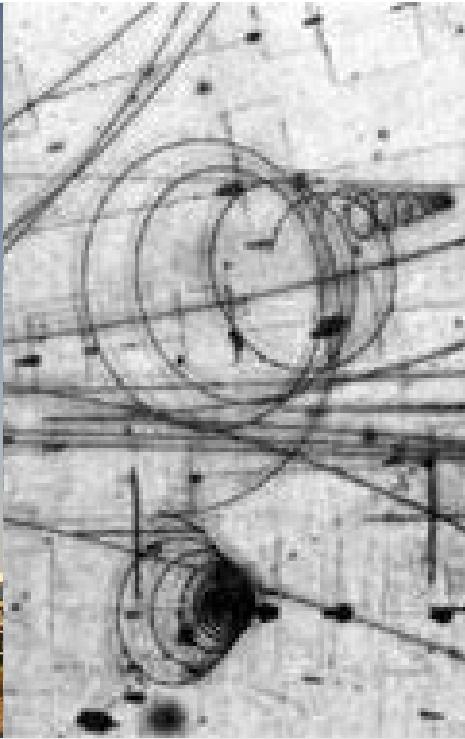
THEN, THE HUNT IS ON FOR A STABLE FORM.



WHAT WE ACTUALLY MEASURE

- Particles interact with **detector materials** and either:
 - **Change** the material's properties in an observable way, or
 - Produce some kind of **disturbance** in the medium.
 - Such as emission of **light** or inducing an **electrical signal** on an electrode.
- “Vintage” techniques:
 - Chemical imprints left on **photographic** plates.
 - “**Clouds**” in supersaturated vapours.
 - Traces of “**bubbles**” in superheated liquids.
 - **Sparks** in a gas with a very high electric field applied to it.





WHAT WE ACTUALLY MEASURE

- Modern techniques:
 - Electrical signals induced by **moving charges** close to electrodes.
 - **Light** that is converted into **electrical signals**.
 - Very small **vibrations** in crystalline structures (heat), converted into **electrical signals**.
 - Mostly used for dark matter searches.
 - **Acoustic** signals picked up by very sensitive microphones and converted into **electrical signals**. (Very rare!)
- Electrical signals are “**digitized**”:
 - Read in by a **computer** system and stored in **digital** format.
 - Some experiments generate very large amounts of **data**.
 - Significant storage and computing challenges!

PARTICLE INTERACTIONS WITH MATTER

Recall

FIRST EXPERIMENTS IN PARTICLE PHYSICS

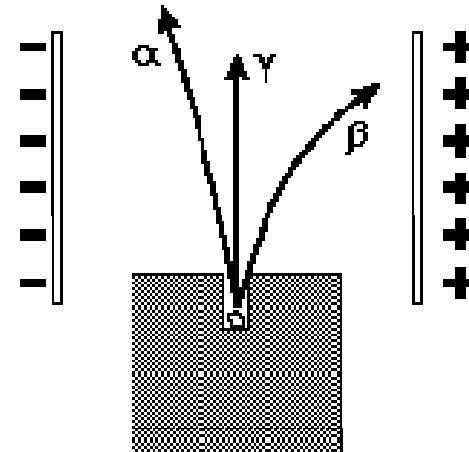
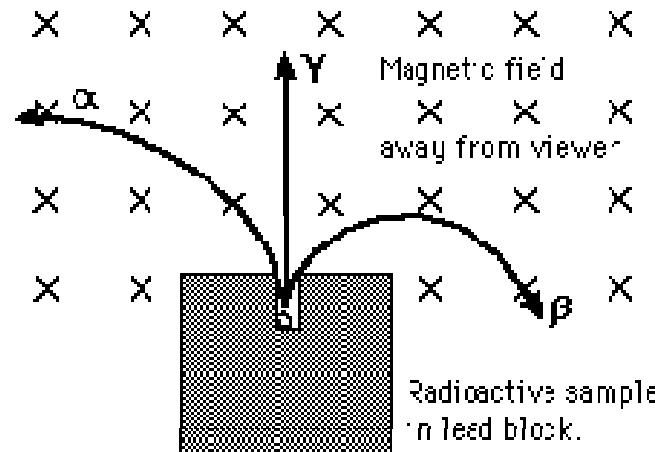
- By the 1890's, new, unstable elements (radioactivity) were being investigated by M. Curie, P. Curie, H. Becquerel, E. Rutherford, et al.
- Radioactivity: describes the emission of particles from atomic nuclei as a result of nuclear instability.
- The fact that atoms seemed to spontaneously split apart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



Recall

FIRST EXPERIMENTS IN PARTICLE PHYSICS

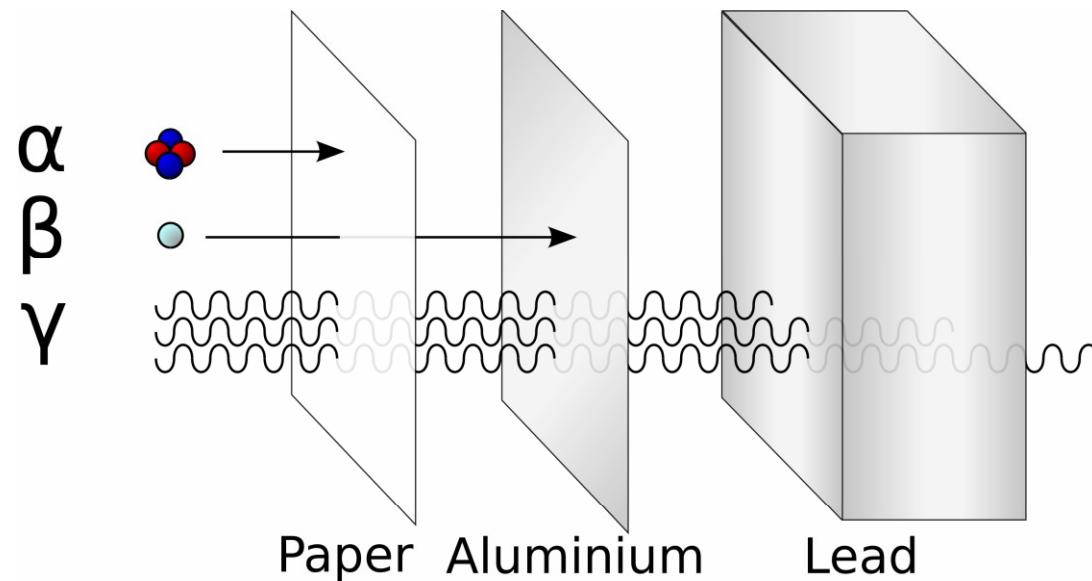
- At the time, it was known that unstable elements tended to emit three types of particles, which were differentiated by their electric charge.



	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.

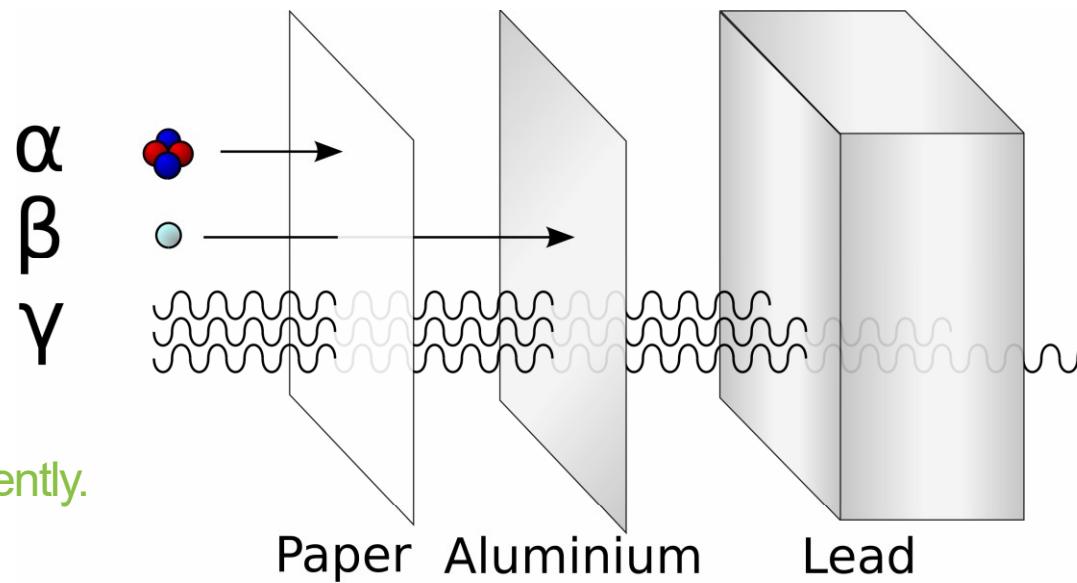


Why do different particles have different penetrating power?

PASSAGE OF PARTICLES THROUGH MATTER

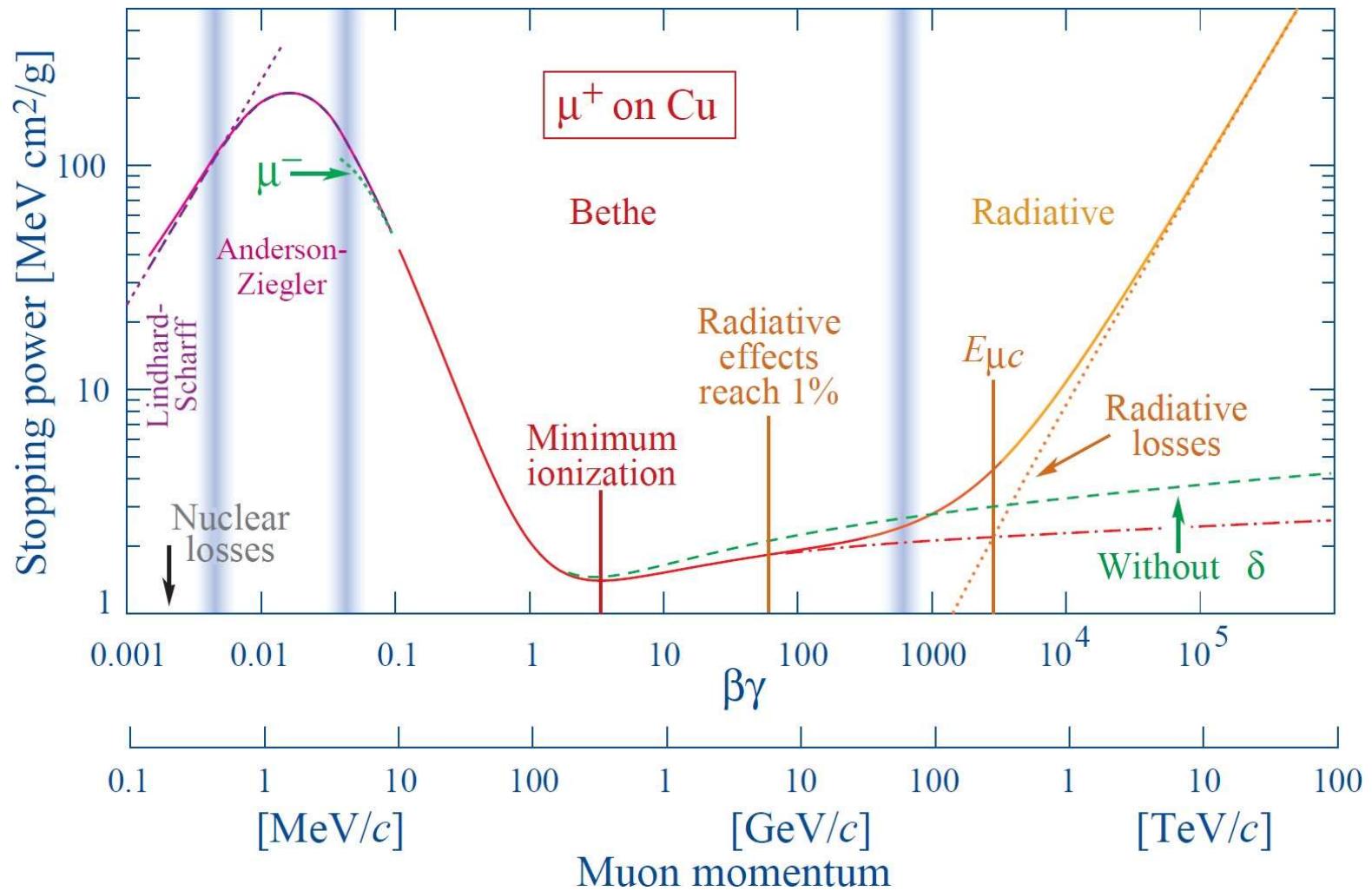
- Alpha, beta, gamma radiation:
 - Classified according to how they bend in a magnetic field.
 - Also differentiated by how easily they can be stopped.

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

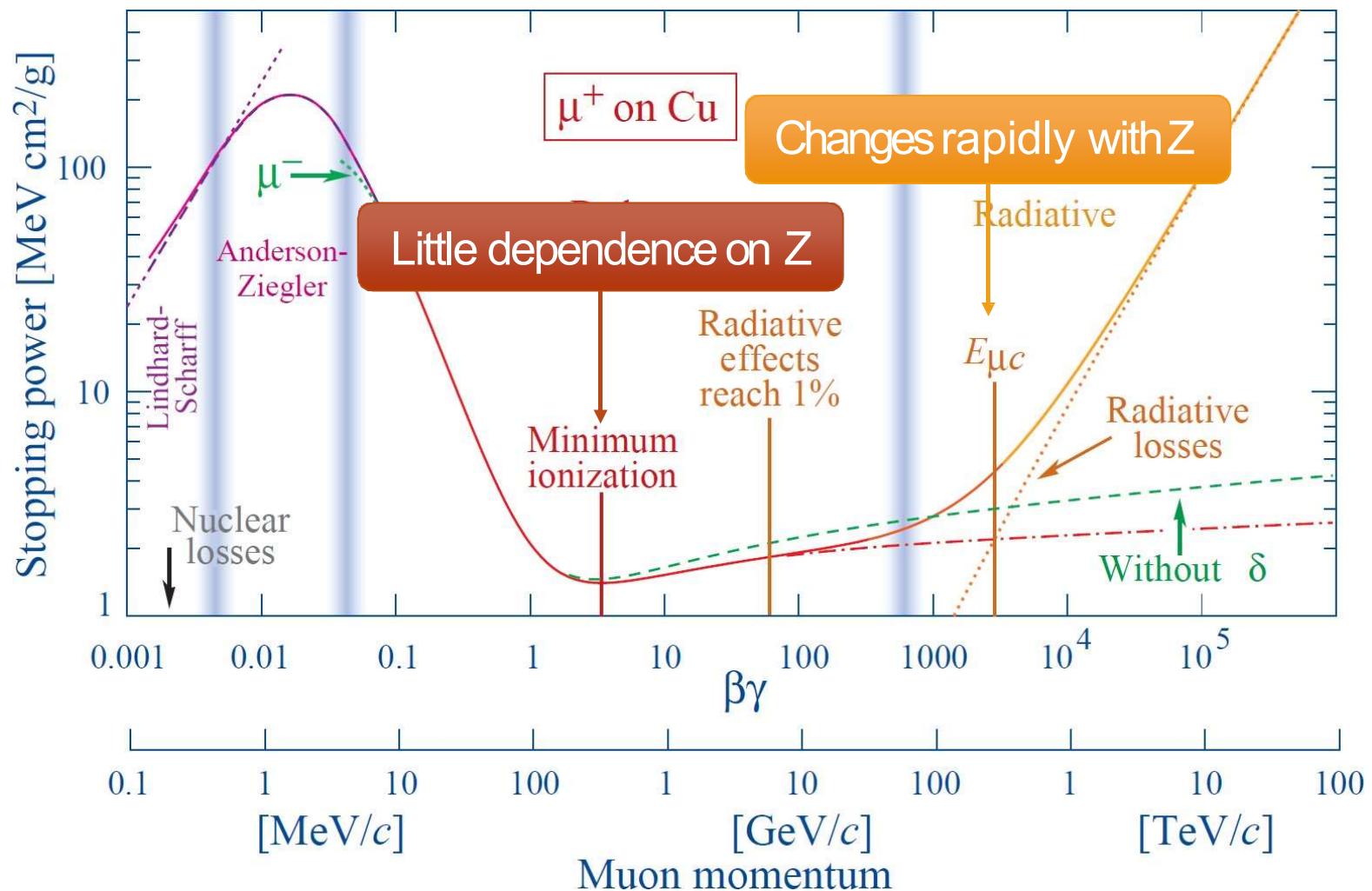


Neutral particles interact less often, losing less energy. They ionize matter indirectly.

STOPPING POWER



STOPPING POWER

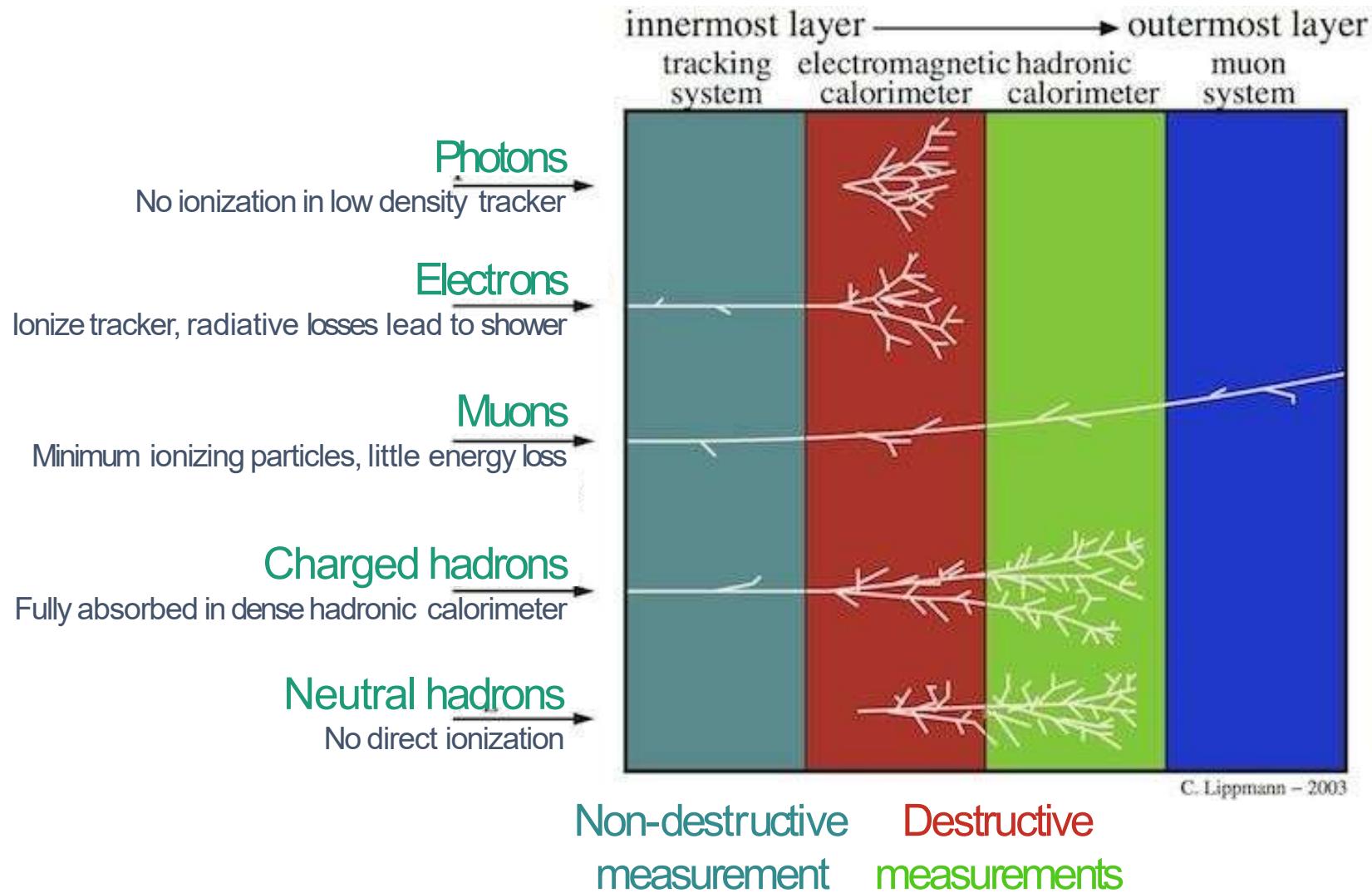


PARTICLE DETECTION

- 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 hadronic shower
photons	electromagnetic	electromagnetic shower
neutrons, K^0	strong, weak	hadron shower

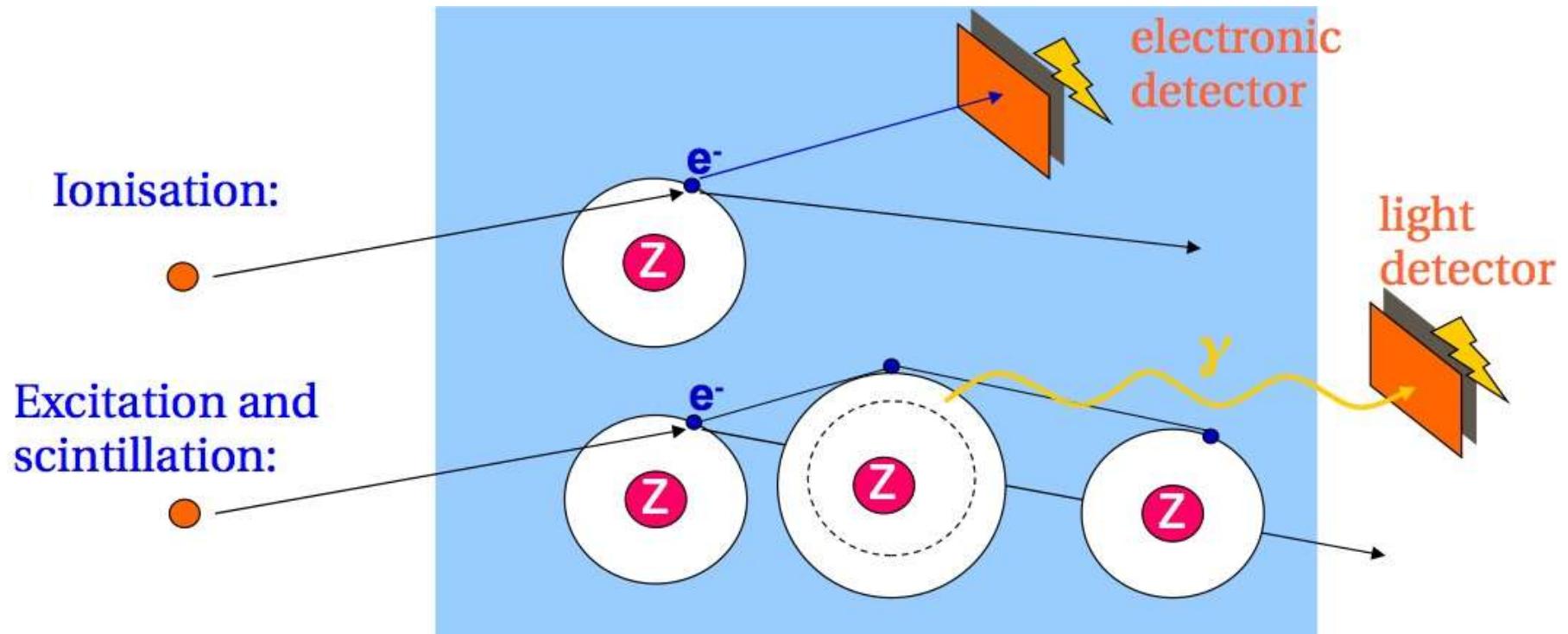
LAYERED DETECTORS



PARTICLE DETECTION

1. MEASUREMENT BY ELECTROMAGNETIC ENERGY LOSS

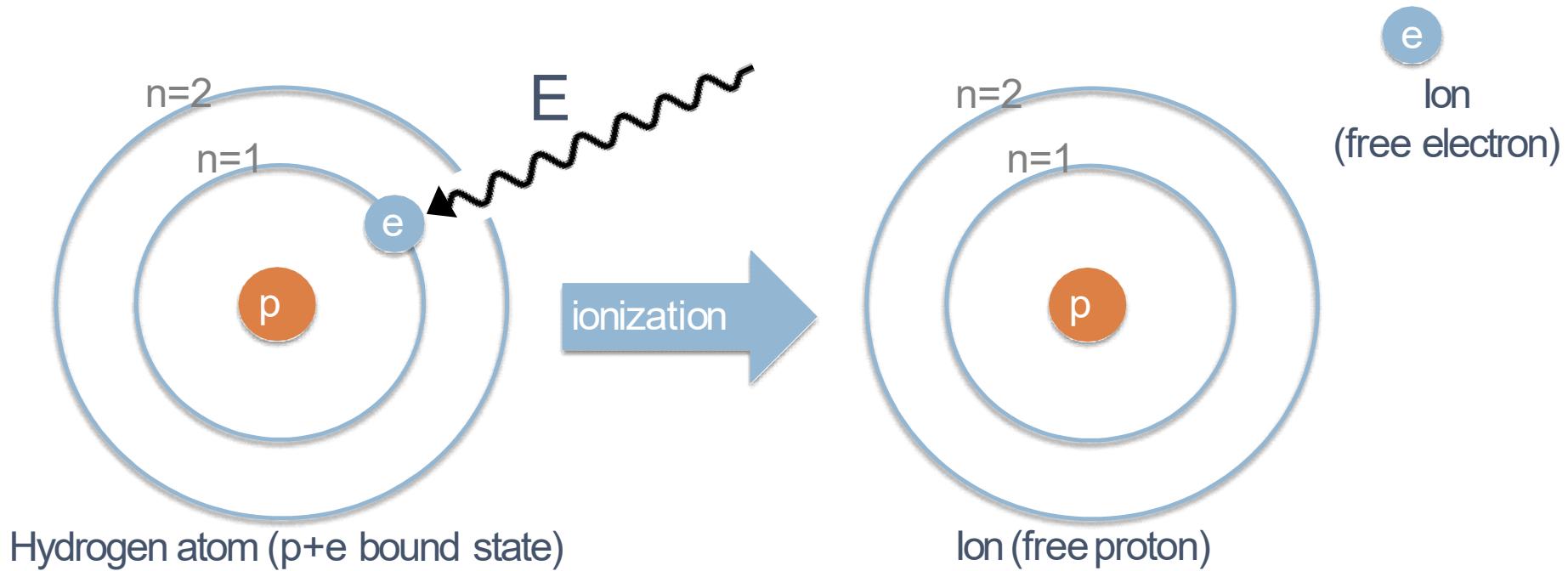
- Applies to all charged particles



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

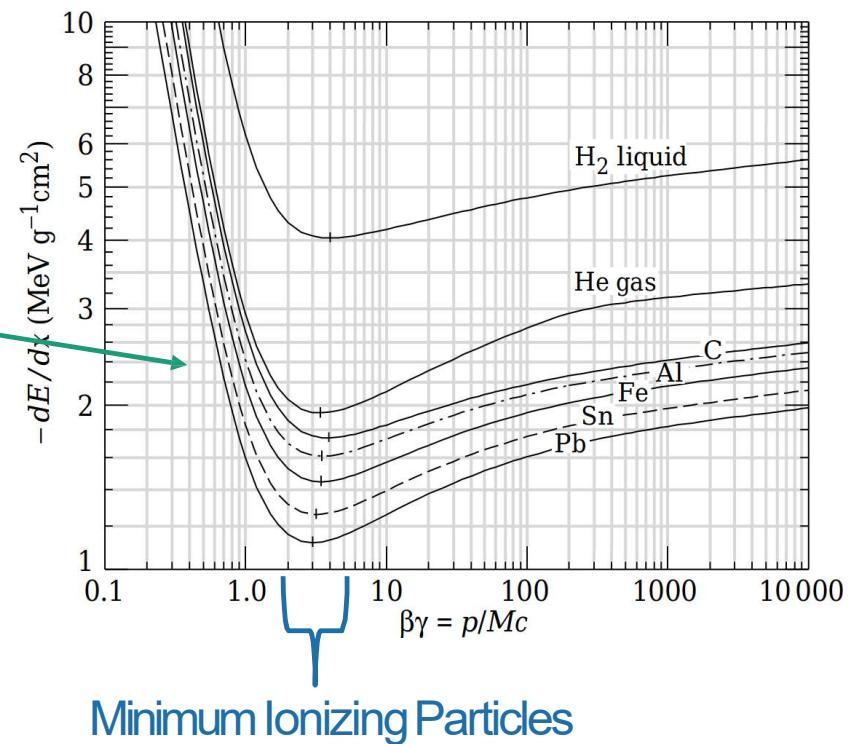
I Mean excitation potential of material

ϵ_0 Vacuum permittivity

e Electron charge

m_e Electron mass

c Speed of light in vacuum

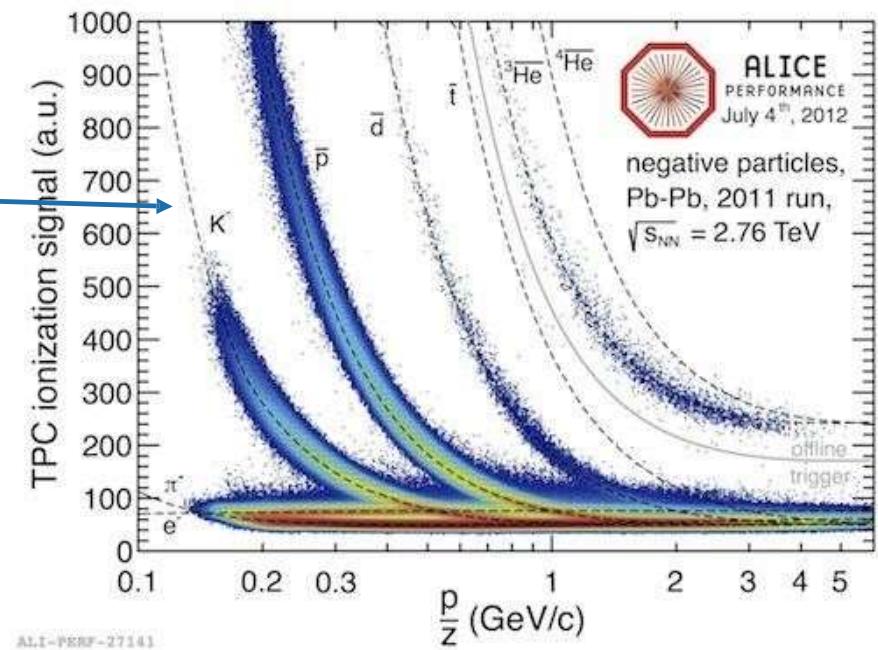


IONIZATION

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- m_e Electron mass
- c Speed of light in vacuum



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

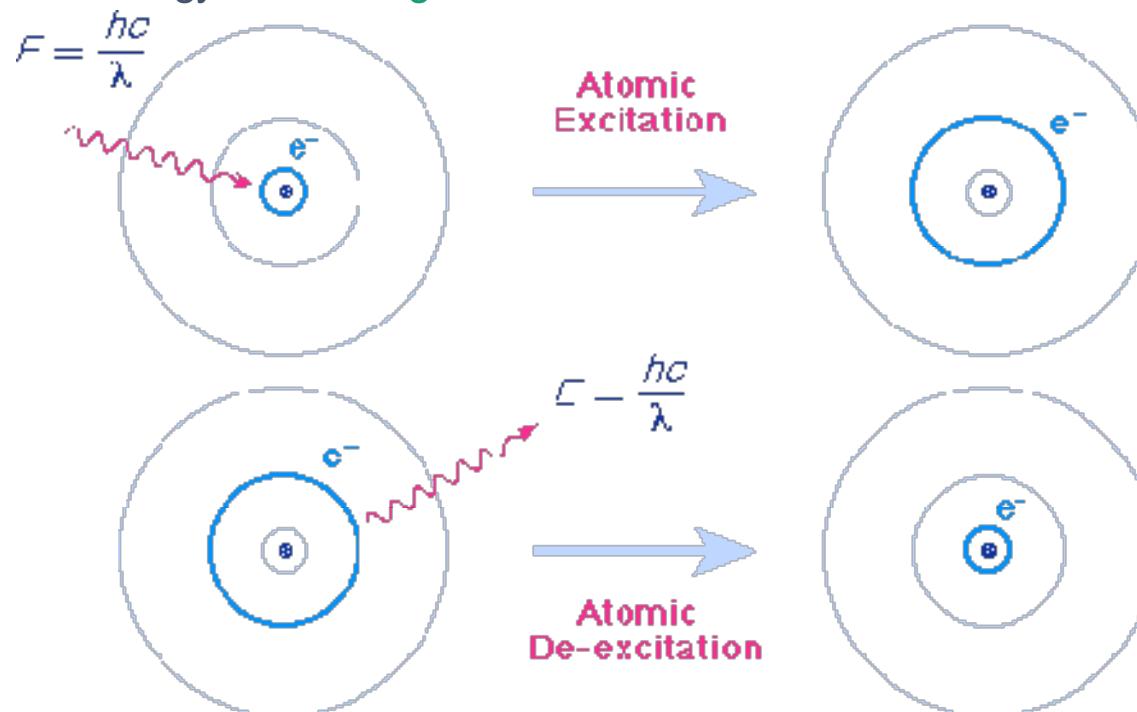
SCINTILLATION

- 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

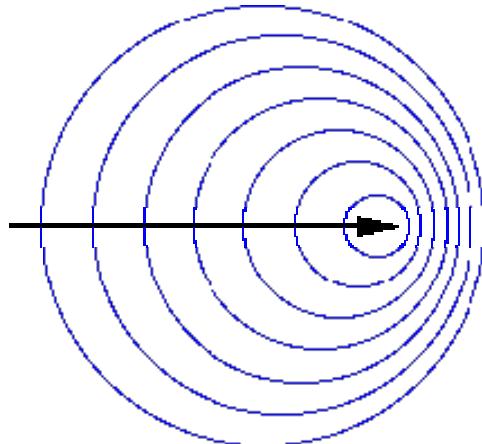
(SAME IDEA AS) ATOMIC EXCITATION

- 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**.

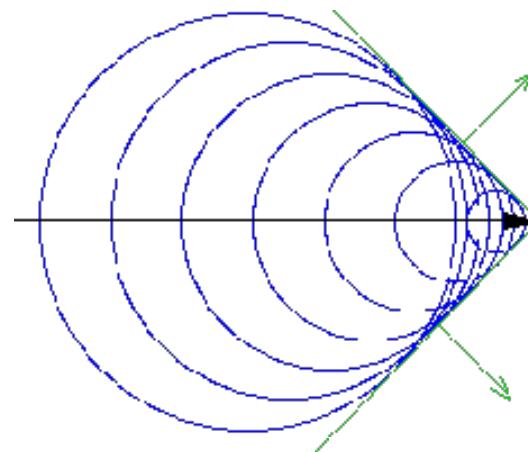


CHERENKOV RADIATION

- 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.



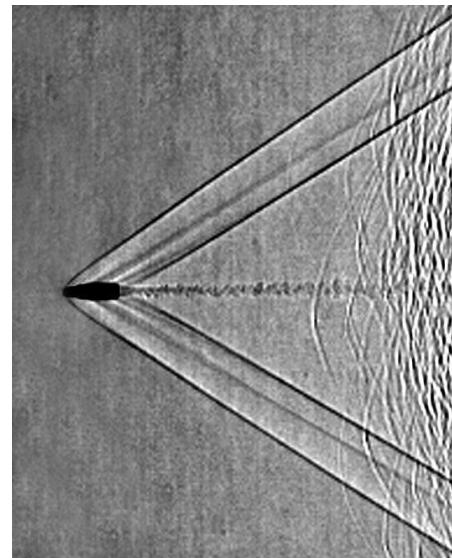
For a particle traveling faster than light, the wave-fronts do overlap, and constructive interference is possible, leading to a significant, observable signal.

CHERENKOV RADIATION

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



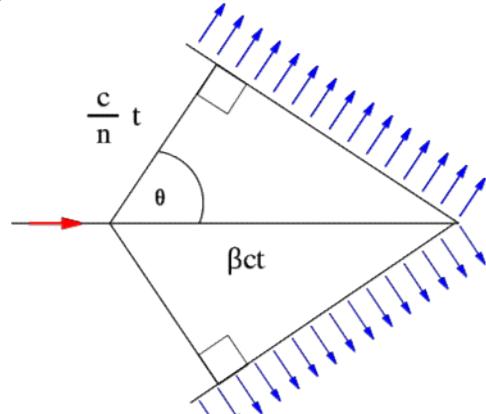
Duck moving slower than the speed at which water waves travel.



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

CHERENKOV RADIATION

- 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 .

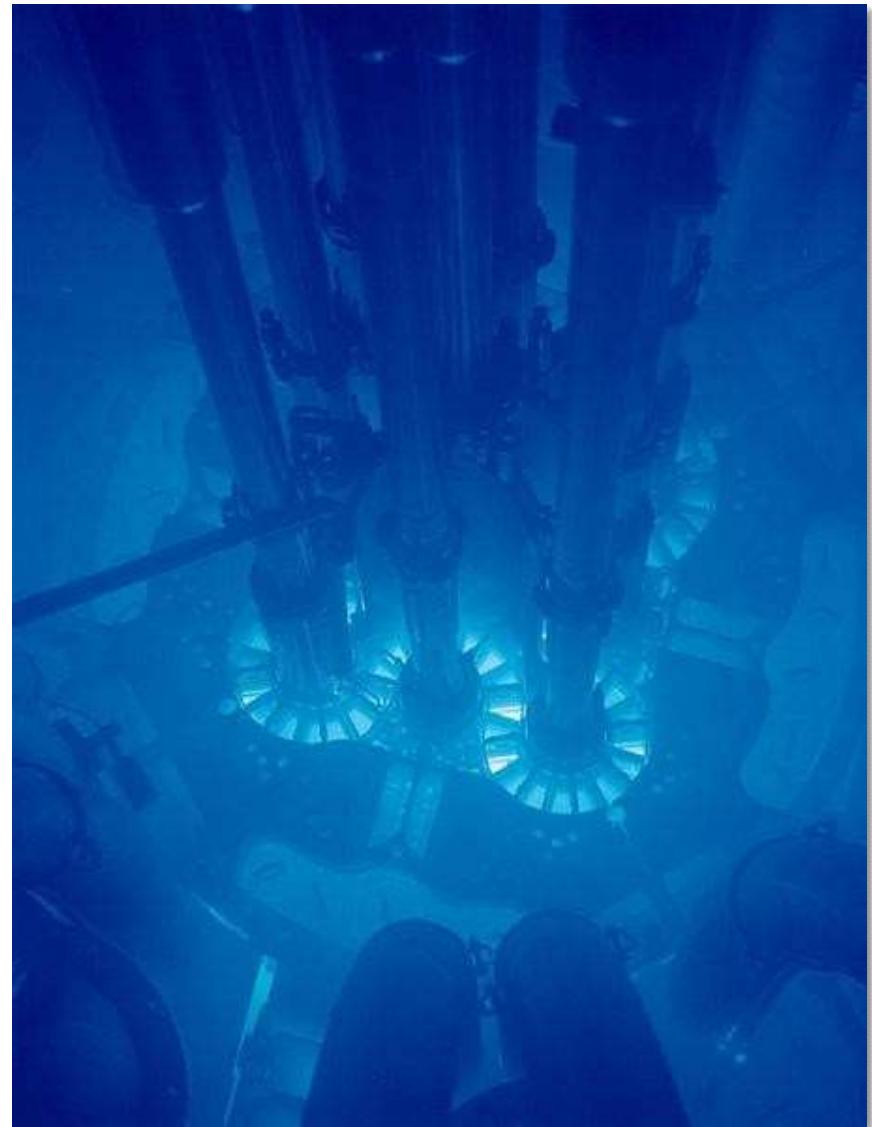


$$\cos\theta_c = \frac{\frac{c}{n} t}{\beta c t} = \frac{1}{\beta n}$$

- 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 .

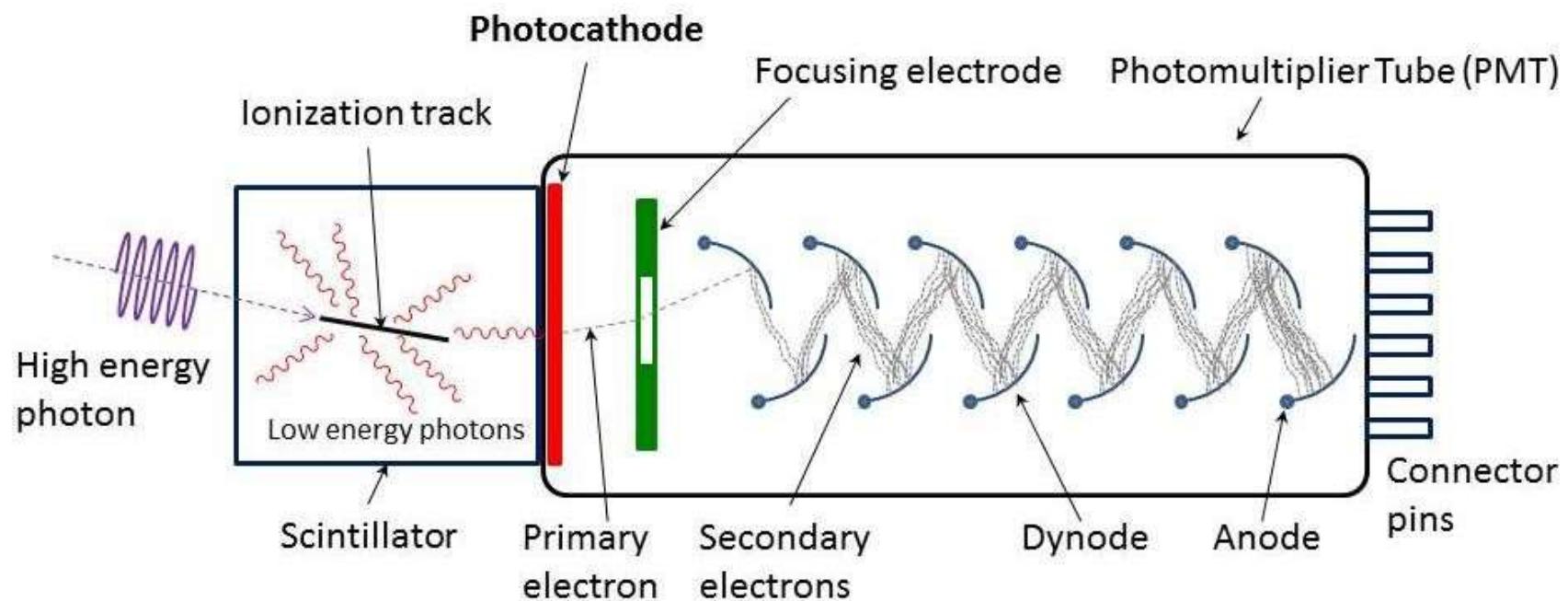
CHERENKOV RADIATION

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



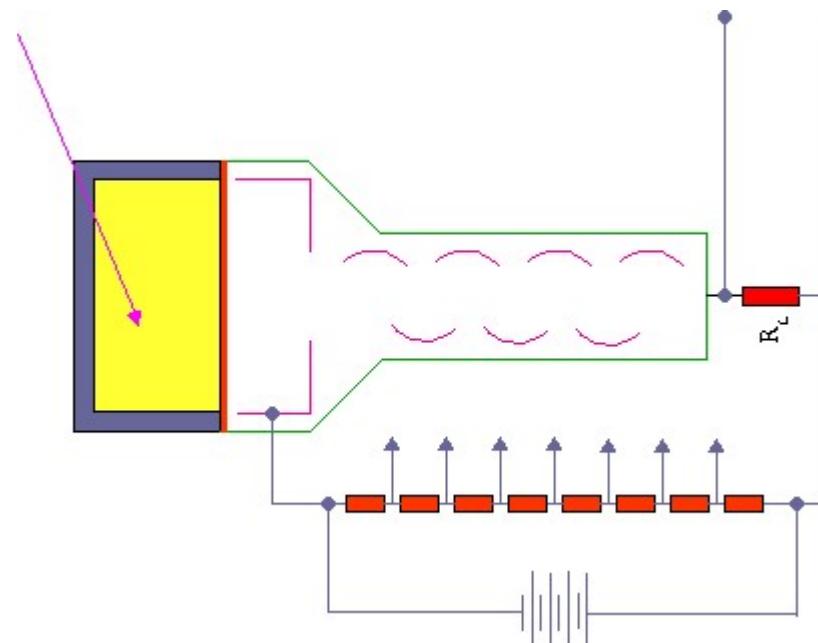
LIGHT DETECTION

- 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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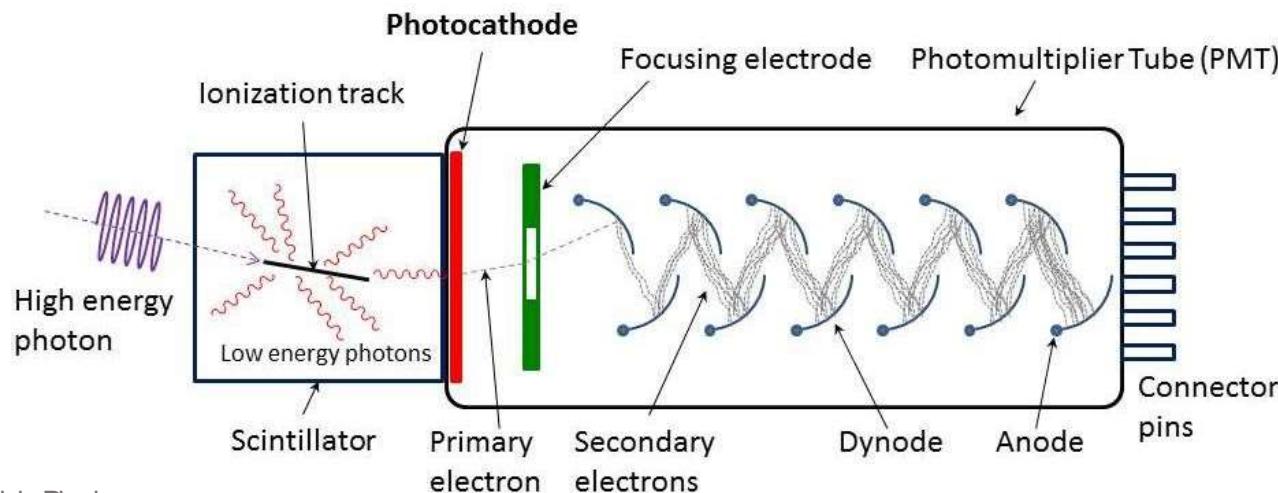
LIGHT DETECTION

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LIGHT DETECTION

- Light falls on a photocathode and a photoelectron is emitted (photoelectric effect).
 - Quantum Efficiency depends on cathode and wavelength (QE~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 nanoseconds transit time!
- Gain can be much lower in magnetic fields, depending on orientation.



PHOTON INTERACTIONS IN MATTER

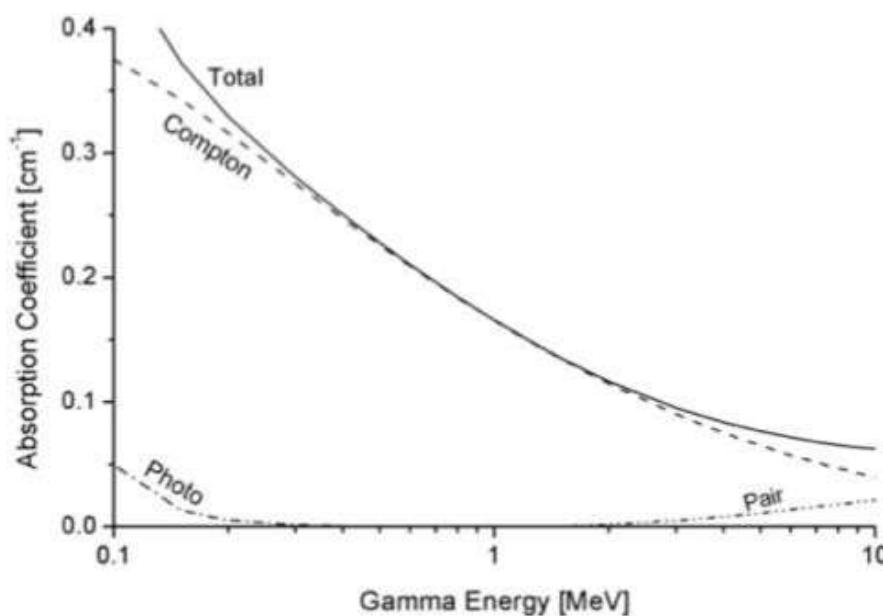
- Photoelectric effect ✓
- Compton scattering ✓
- Pair production (today)

- How does each process contribute to the total energy loss?

PHOTON INTERACTIONS IN MATTER

- Absorption coefficient of Al

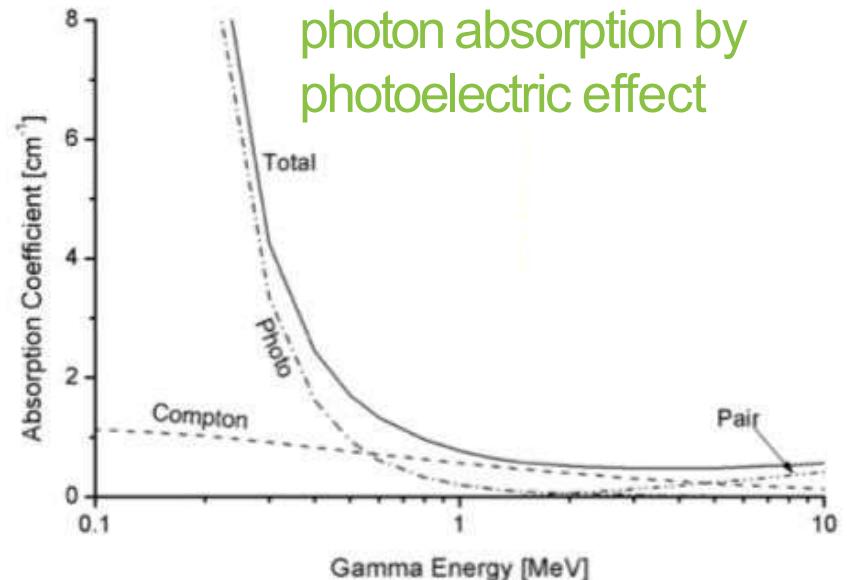
$$Z= 13$$



- Absorption coefficient of Pb

$$Z= 82$$

Higher Z materials favour photon absorption by photoelectric effect

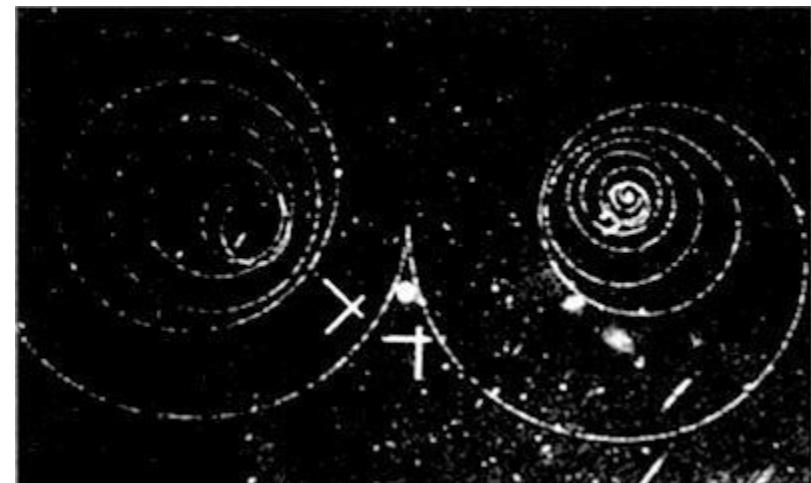
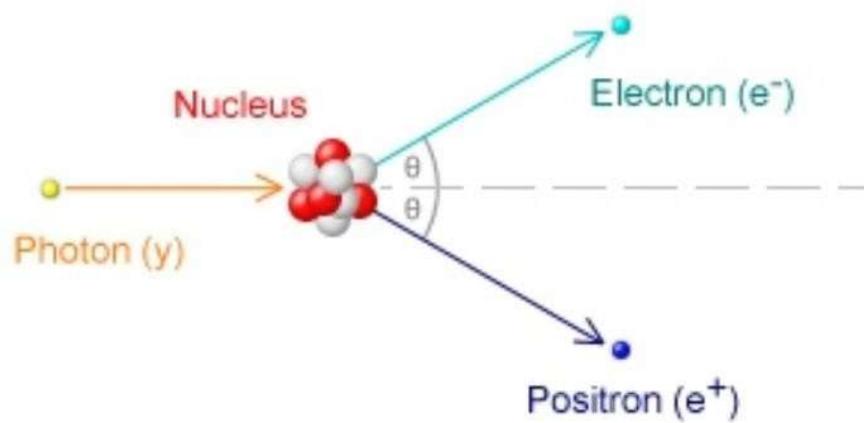


Probability of interaction depends on number of protons (Z)

PHOTON INTERACTIONS IN MATTER

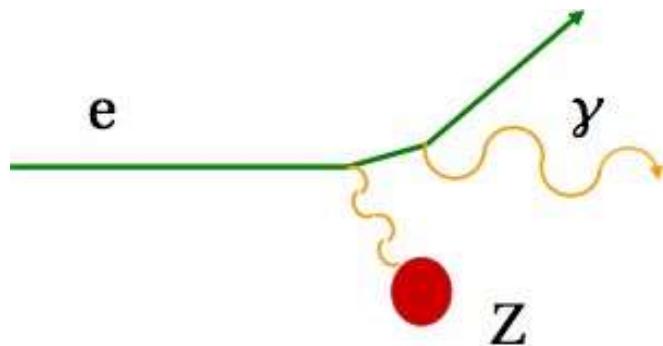
PAIR PRODUCTION

- 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.

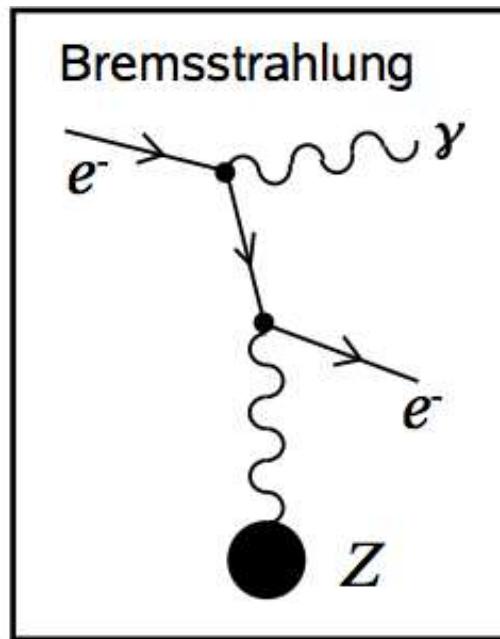
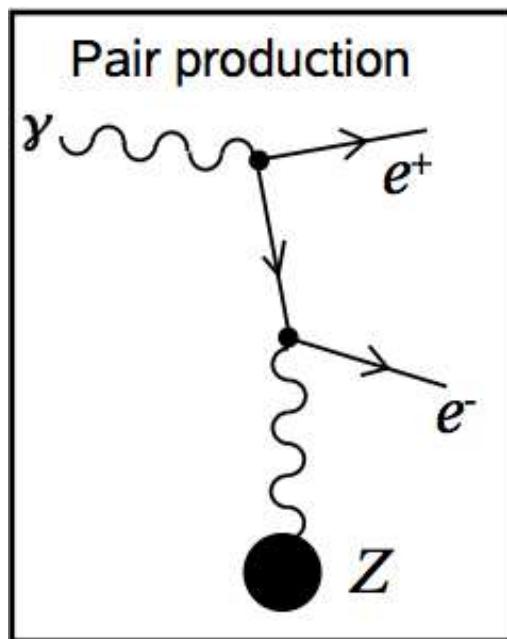
$$\text{Pb: } X_0 = 0.56 \text{ cm}$$

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

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

PAIR PRODUCTION AND BREMSSSTRAHLUNG

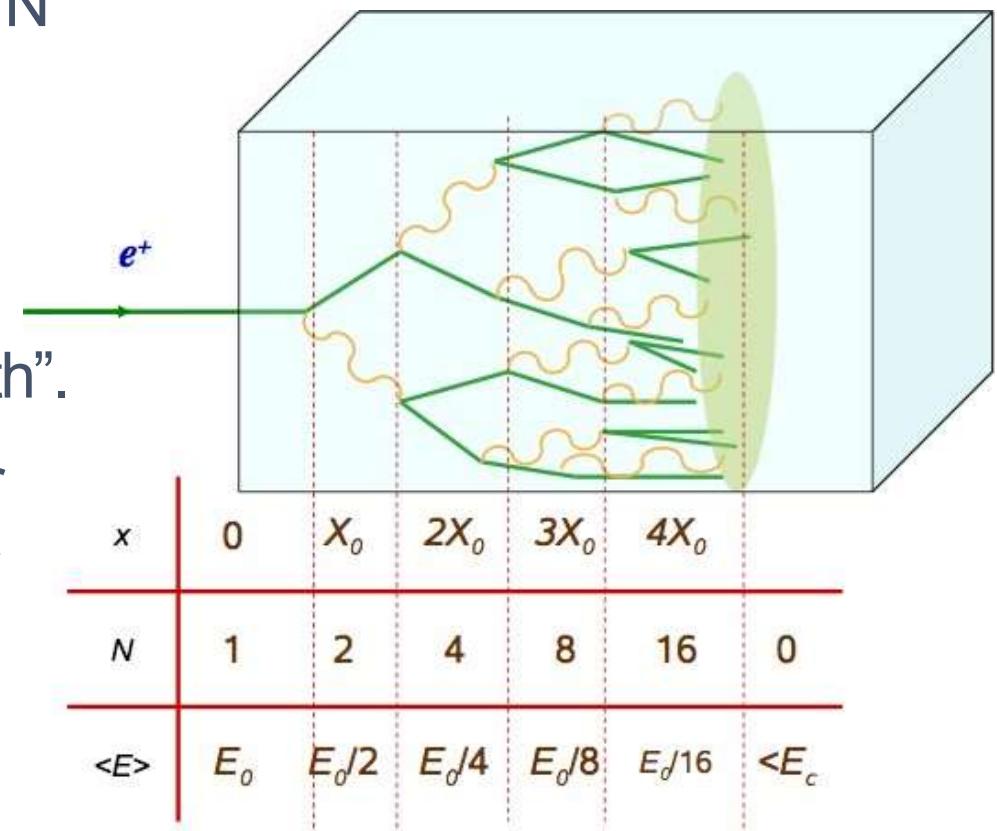
- Pair production and Bremsstrahlung radiation are complementary processes: both lead to **electromagnetic showers**.



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

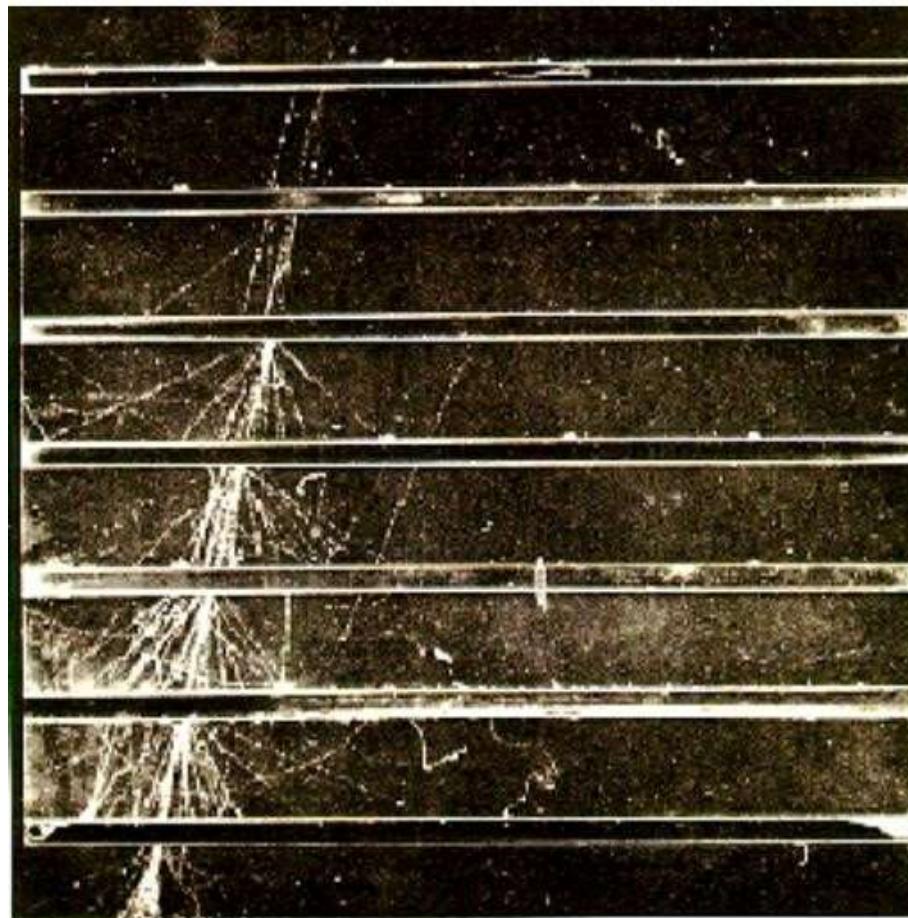
ELECTROMAGNETIC SHOWERS

- 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.

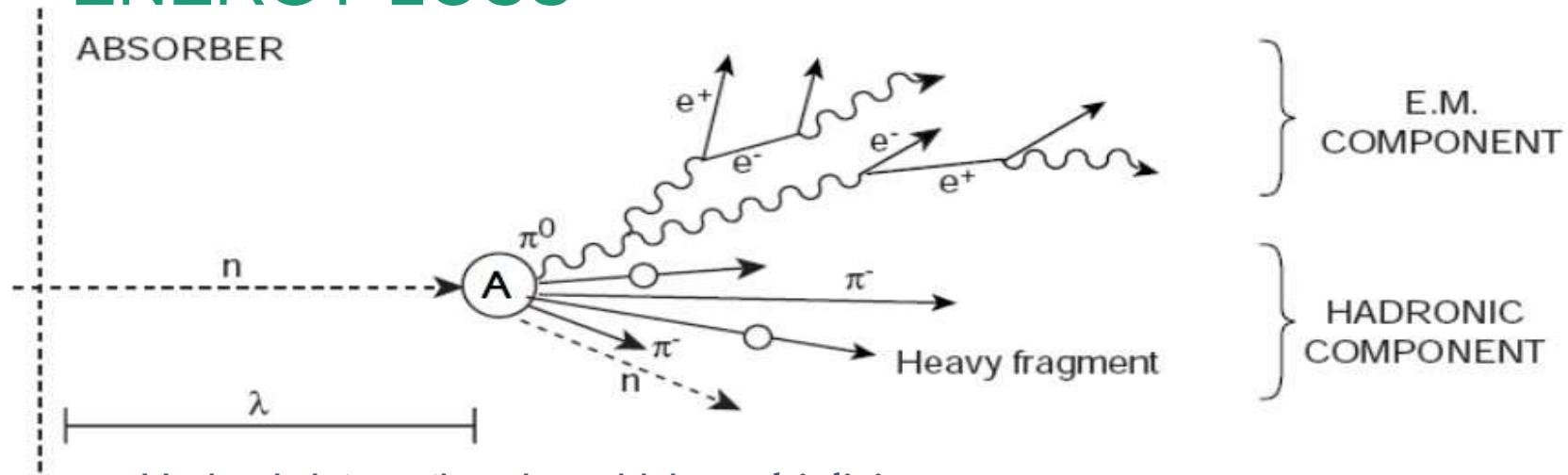


ELECTROMAGNETIC SHOWERS

- Cloud chamber image of a shower between lead plates.

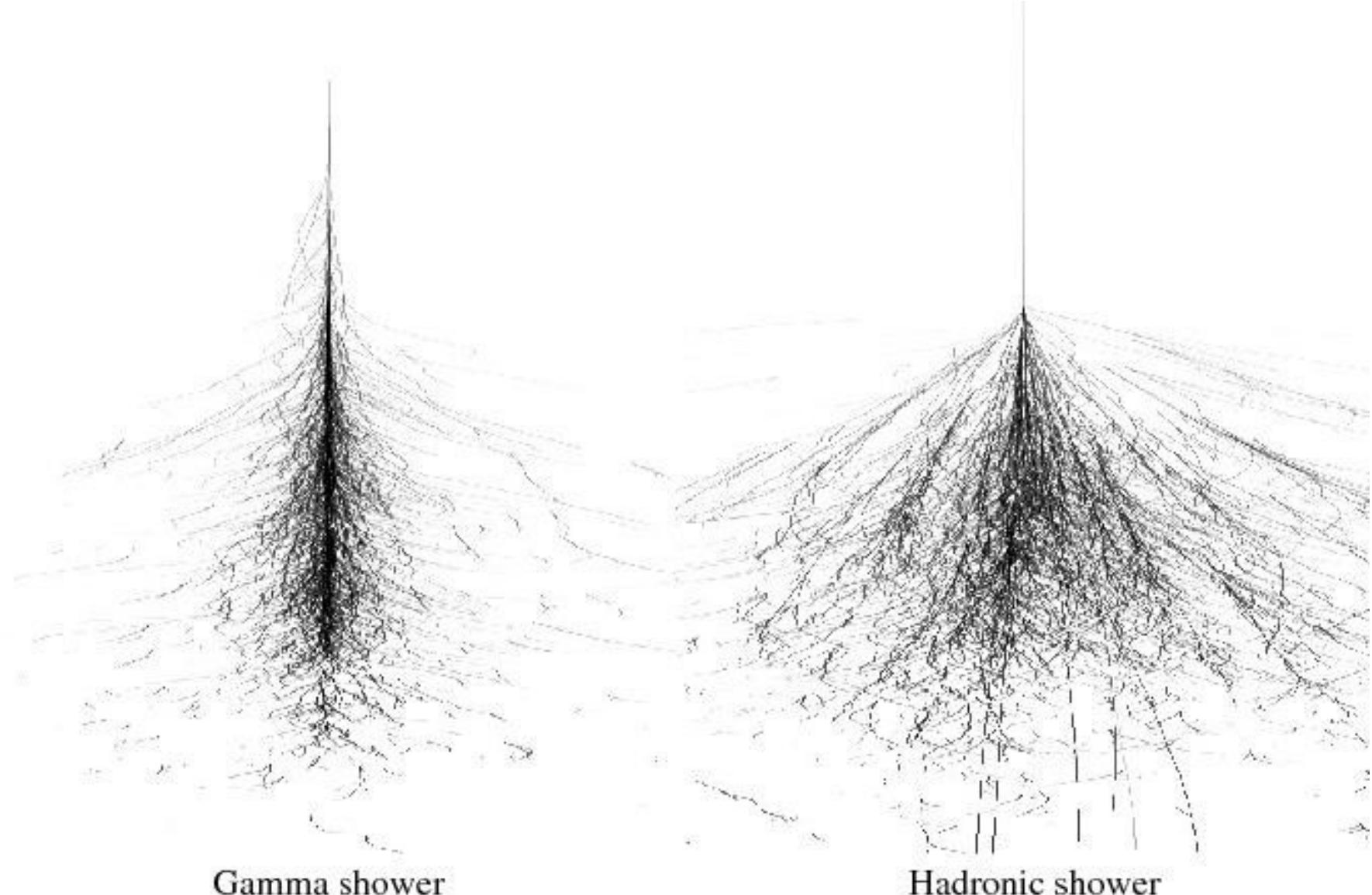


PARTICLE DETECTION MEASUREMENT BY HADRONIC ENERGY LOSS

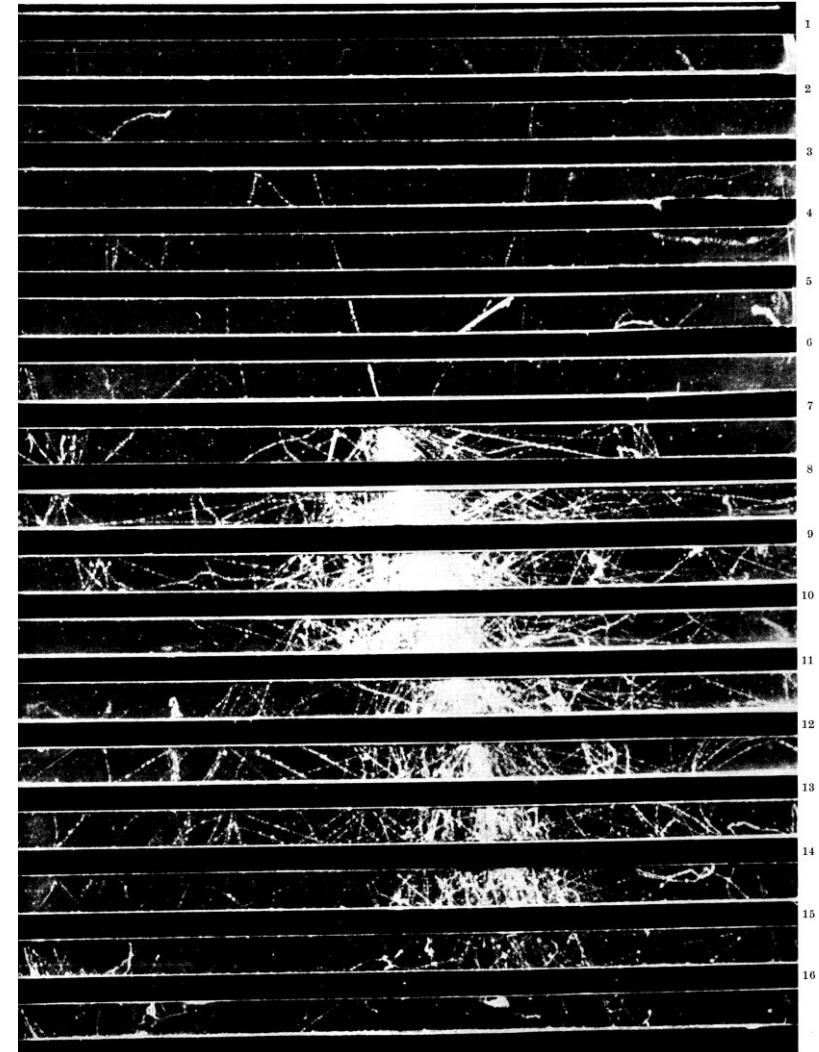
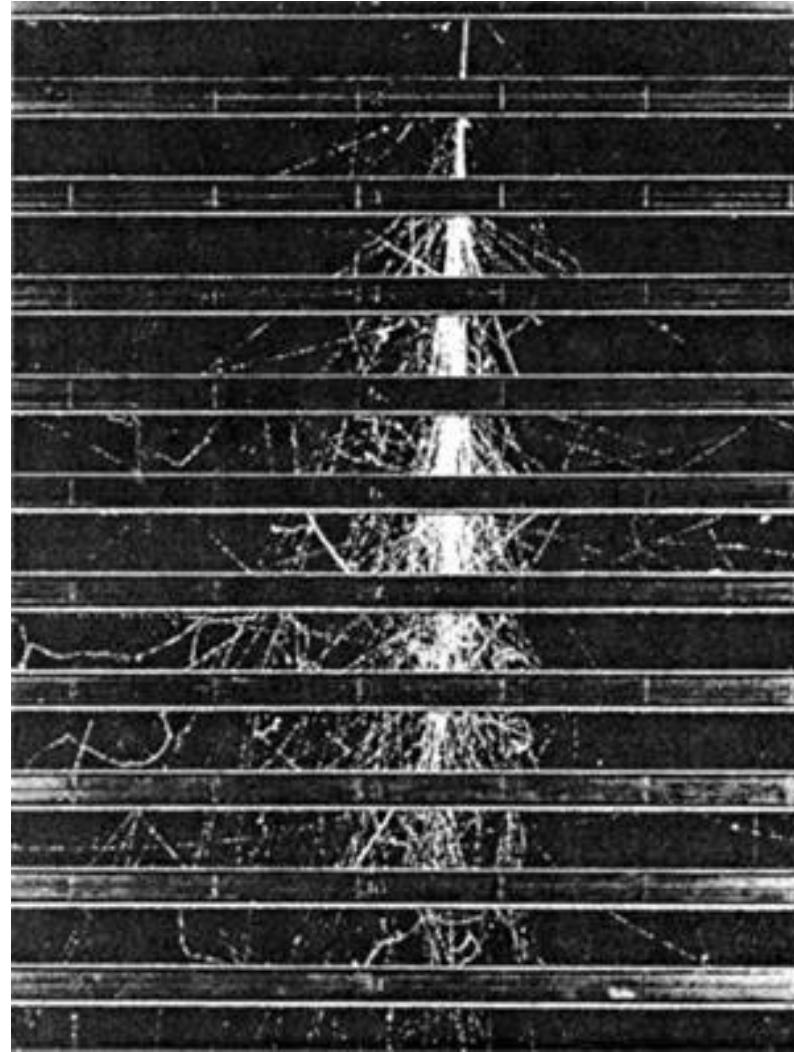


- Hadronic interactions have high **multiplicity**:
 - Shower is to 95% contained in $\sim 7\lambda$ at 50 GeV (1.2 m of iron).
- Hadronic interactions produce π^0 :
 - $\pi^0 \rightarrow \gamma\gamma$, leading to **local EM showers**.
- Some energy loss in nuclear breakup and neutrons ("in**visible**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

HADRONIC VS EM SHOWERS



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:

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

Interaction rate
events/second

Flux of incoming particles
particles/cm²/second

Cross-section
cm²

ASIDE

A NOTE ABOUT CROSS-SECTIONS

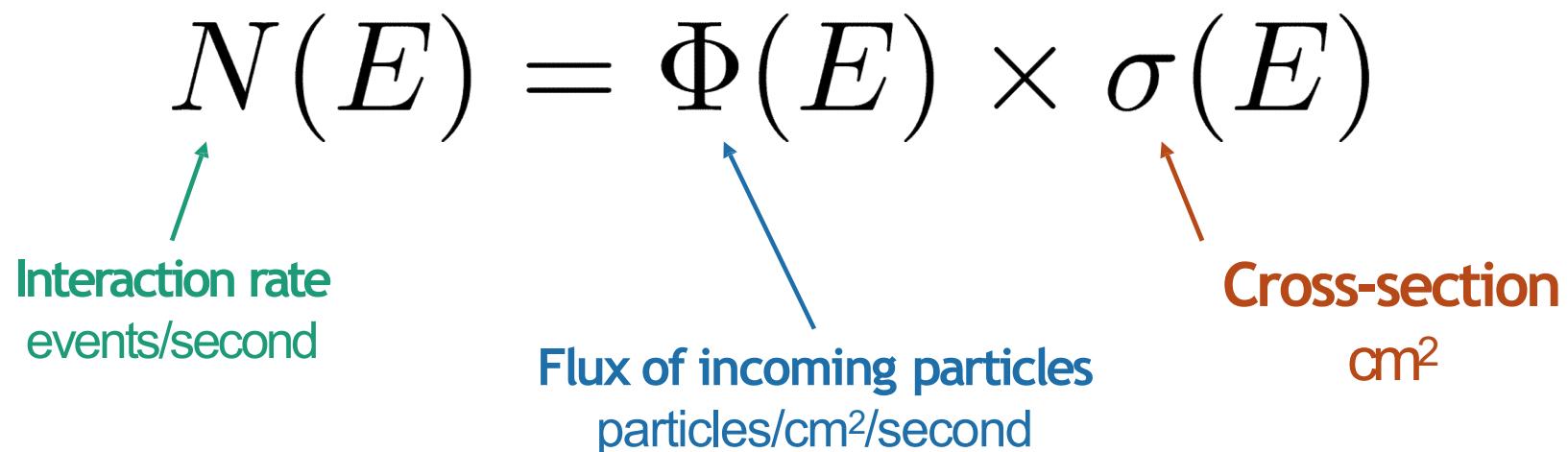
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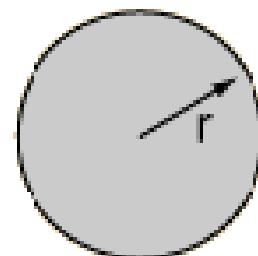
Cross-section
cm²



ASIDE

A NOTE ABOUT CROSS-SECTIONS

- Example:



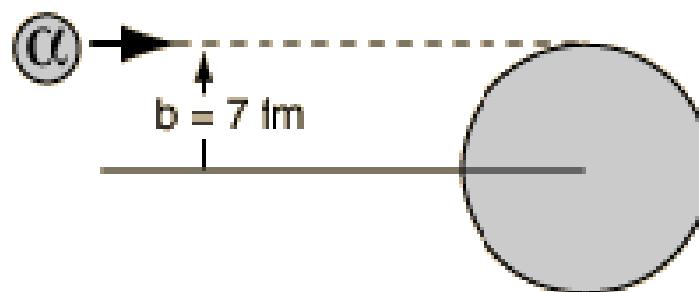
Gold nucleus
 $Z=79, A=197$

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

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

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

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



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

PARTICLE DETECTORS

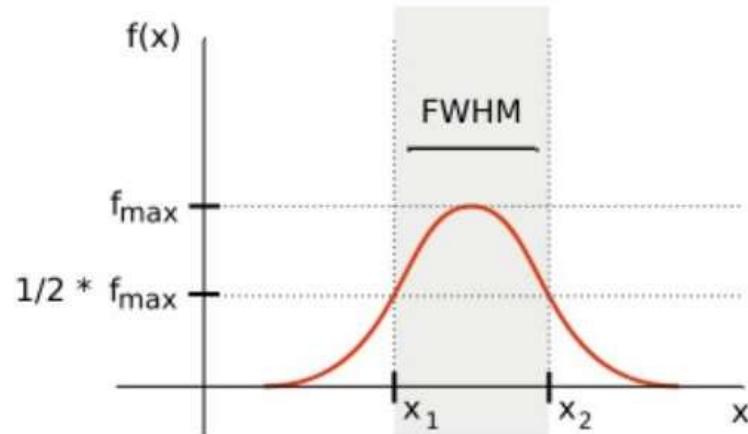
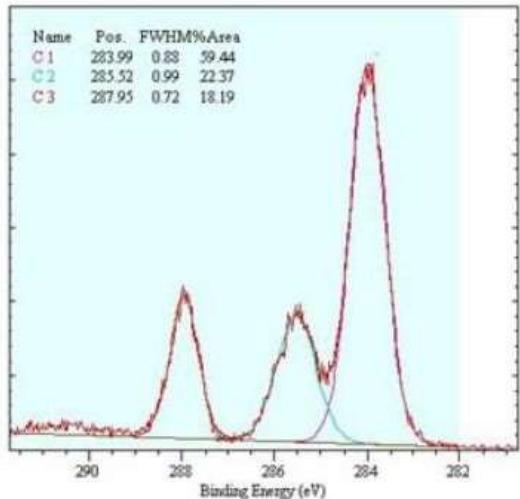
- Detectors usually specialize in:
 - Tracking: measuring **positions** / **trajectories** / **momenta** of charged particles, e.g.:
 - Silicon detectors
 - Drift chambers
 - Calorimetry: measuring **energies** of particles:
 - Electromagnetic calorimeters
 - Hadronic calorimeters
- But they can also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

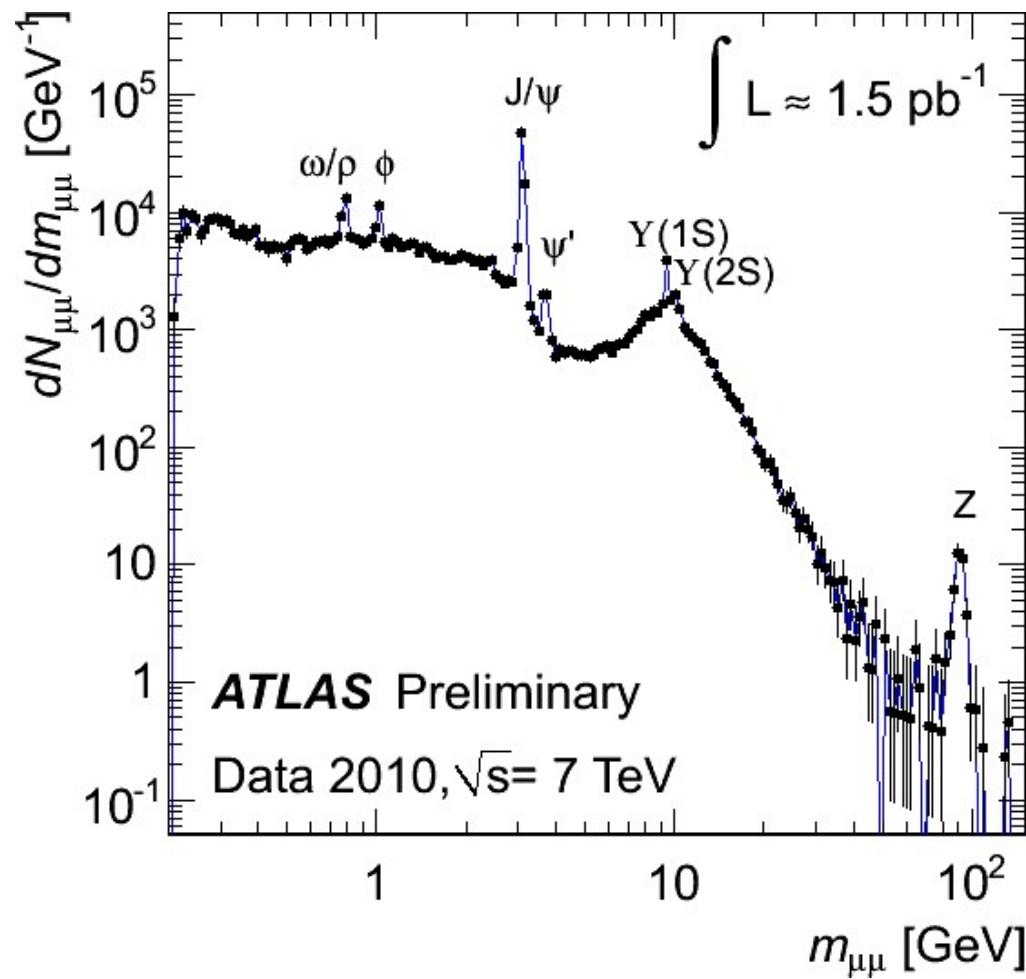


- Quantitatively described by the **full width at half maximum**:

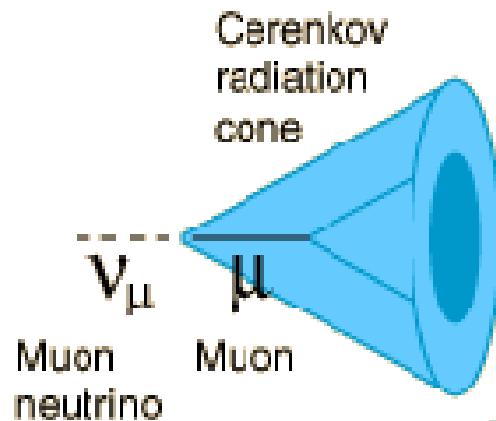
$$\text{FWHM} = 2\sqrt{2\ln 2}\sigma \approx 2.35\sigma$$

- It determines when two peaks can be separated.

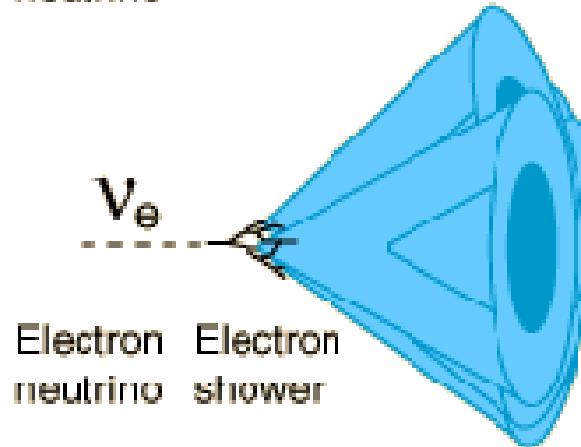
ENERGY RESOLUTION



CHERENKOV DETECTORS



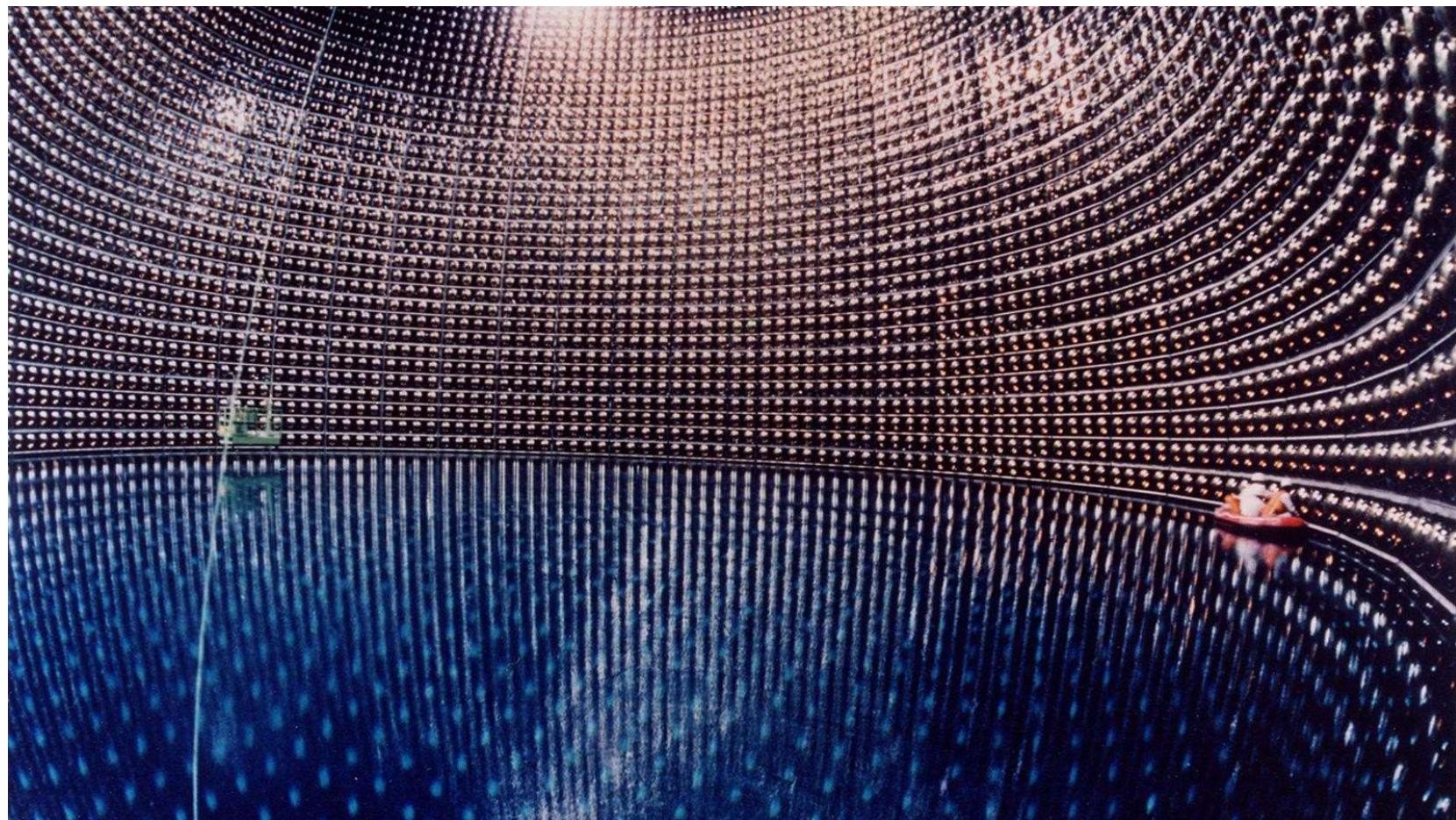
The Cerenkov radiation from a muon produced by a muon neutrino event yields a well defined circular ring in the photomultiplier detector bank.



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.

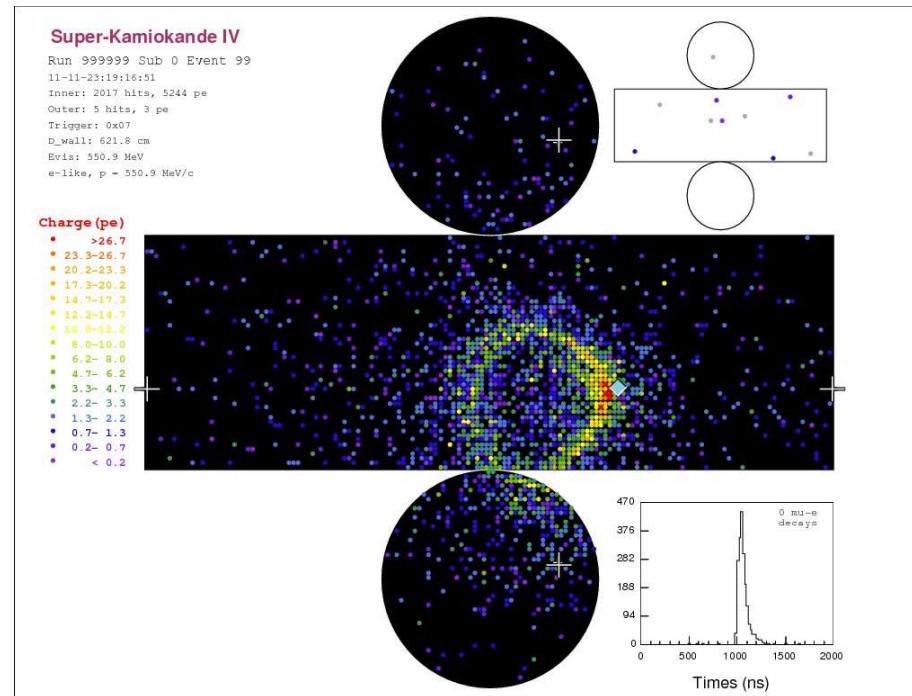
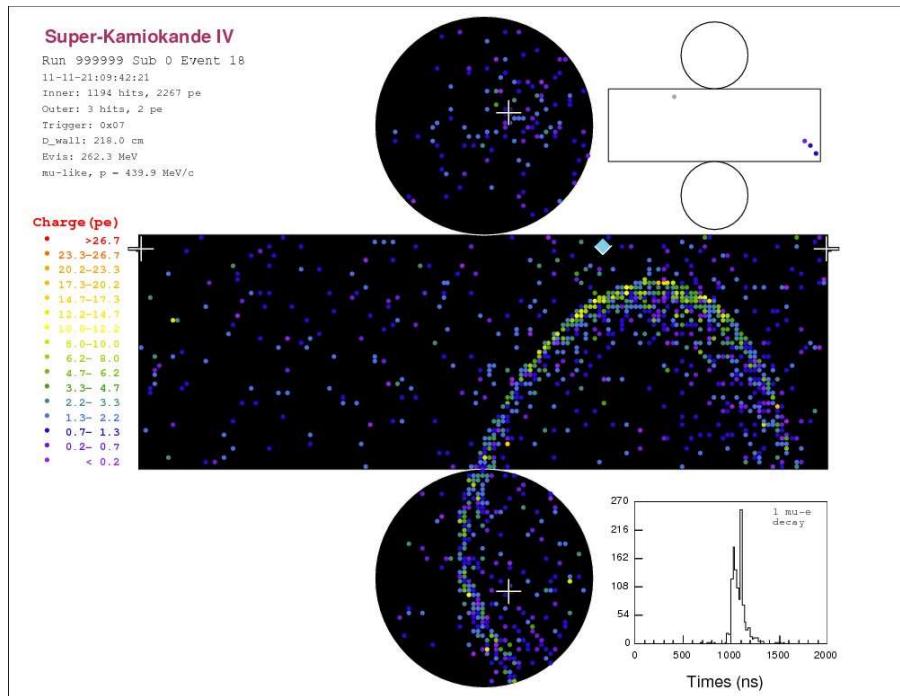
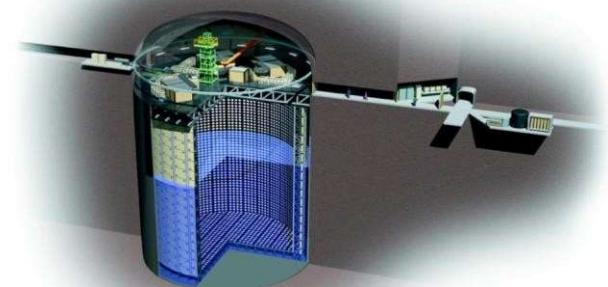
CHERENKOV DETECTORS

- Super-Kamiokande in Japan.
 - The world's largest neutrino detector!

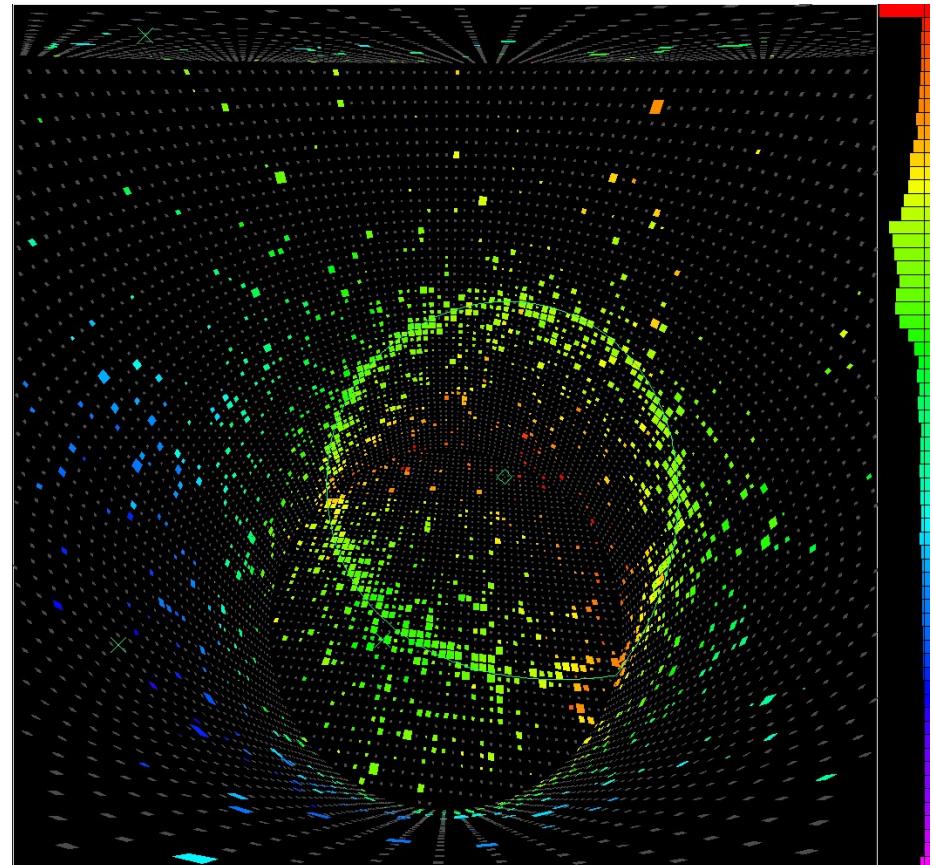
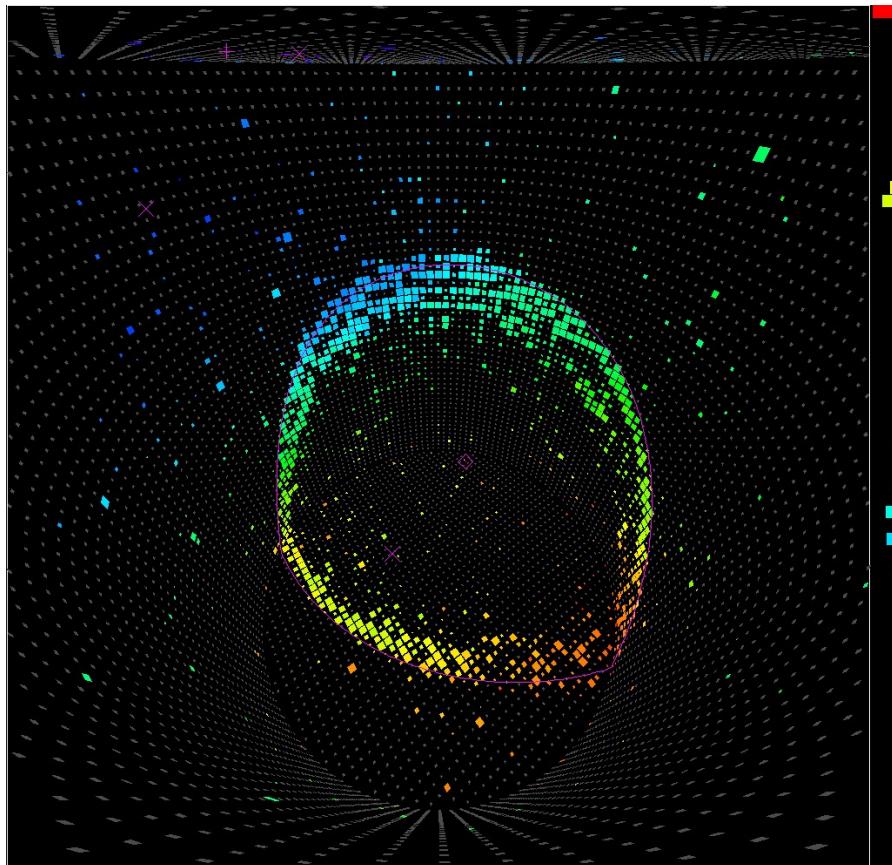


NEUTRINO DETECTION AT SUPER-K

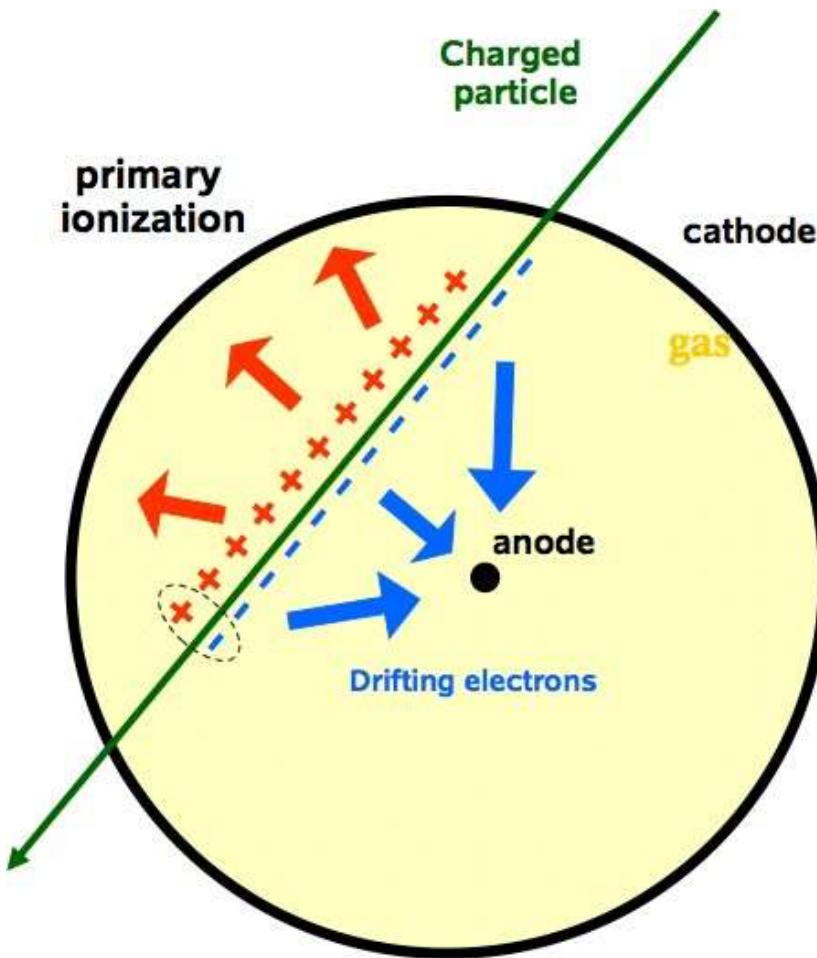
- Electrons and muons resulting from neutrino interactions in the water



NEUTRINO DETECTION AT SUPER-K



IONIZATION DETECTOR

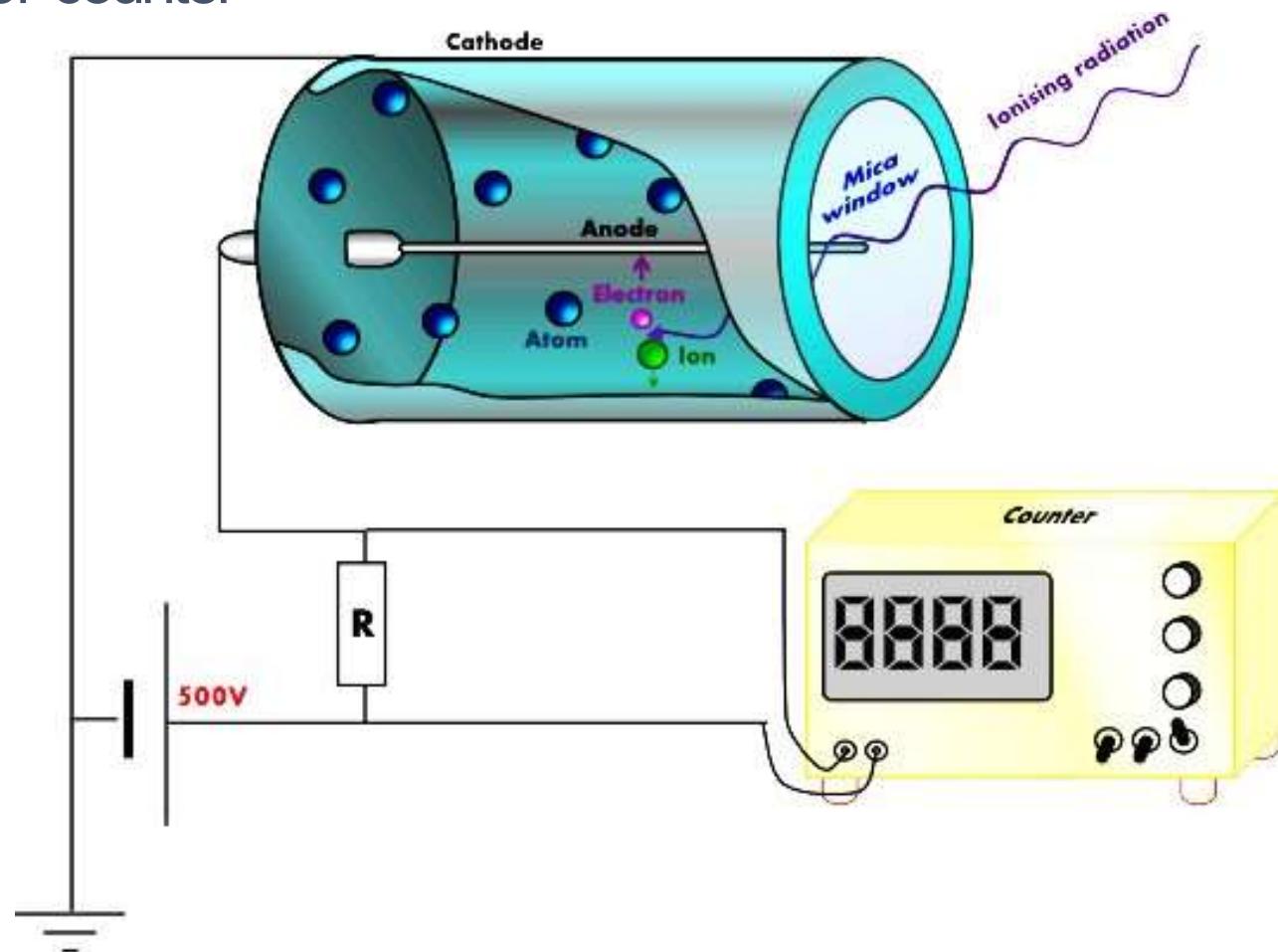


- Drifting electrons should not be trapped:
 - ▶ Use noble gas, e.g. Ar.
- Want large primary ionization yield:
 - ▶ Ar gives 25 ions/cm at normal T, p for a minimum ionizing particle.
- The primary electrons may ionize further atoms:
 - ▶ $\times 3$ or $\times 4$ increase.
- Xe and/or higher pressure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

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

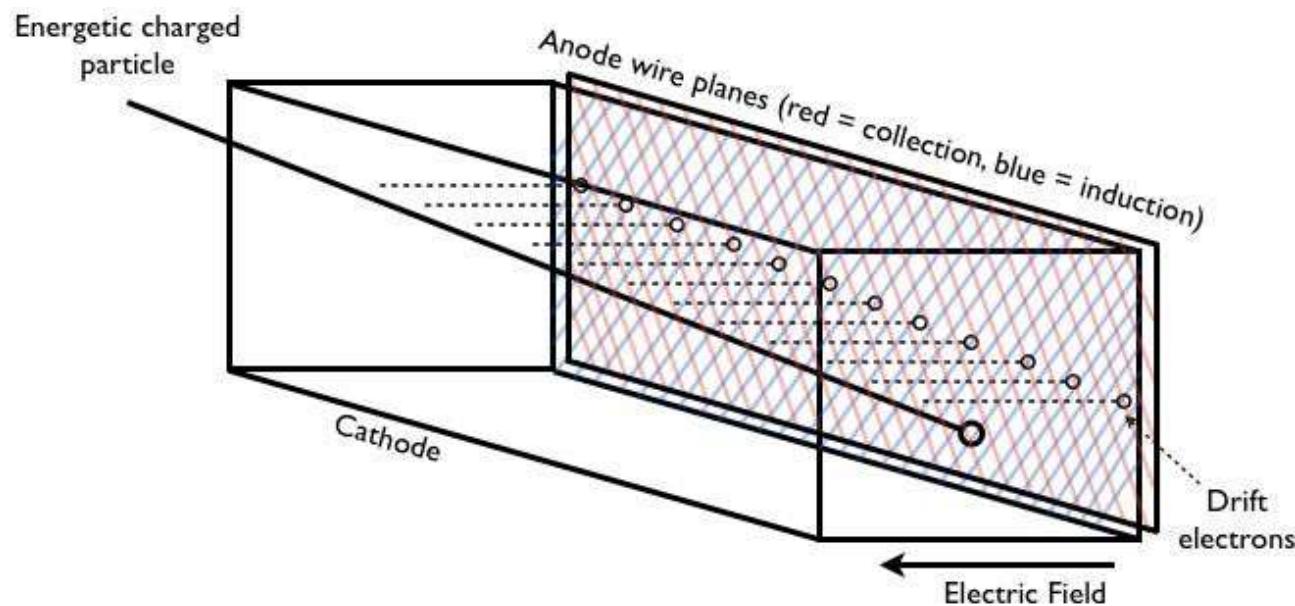
IONIZATION DETECTOR

- Geiger counter



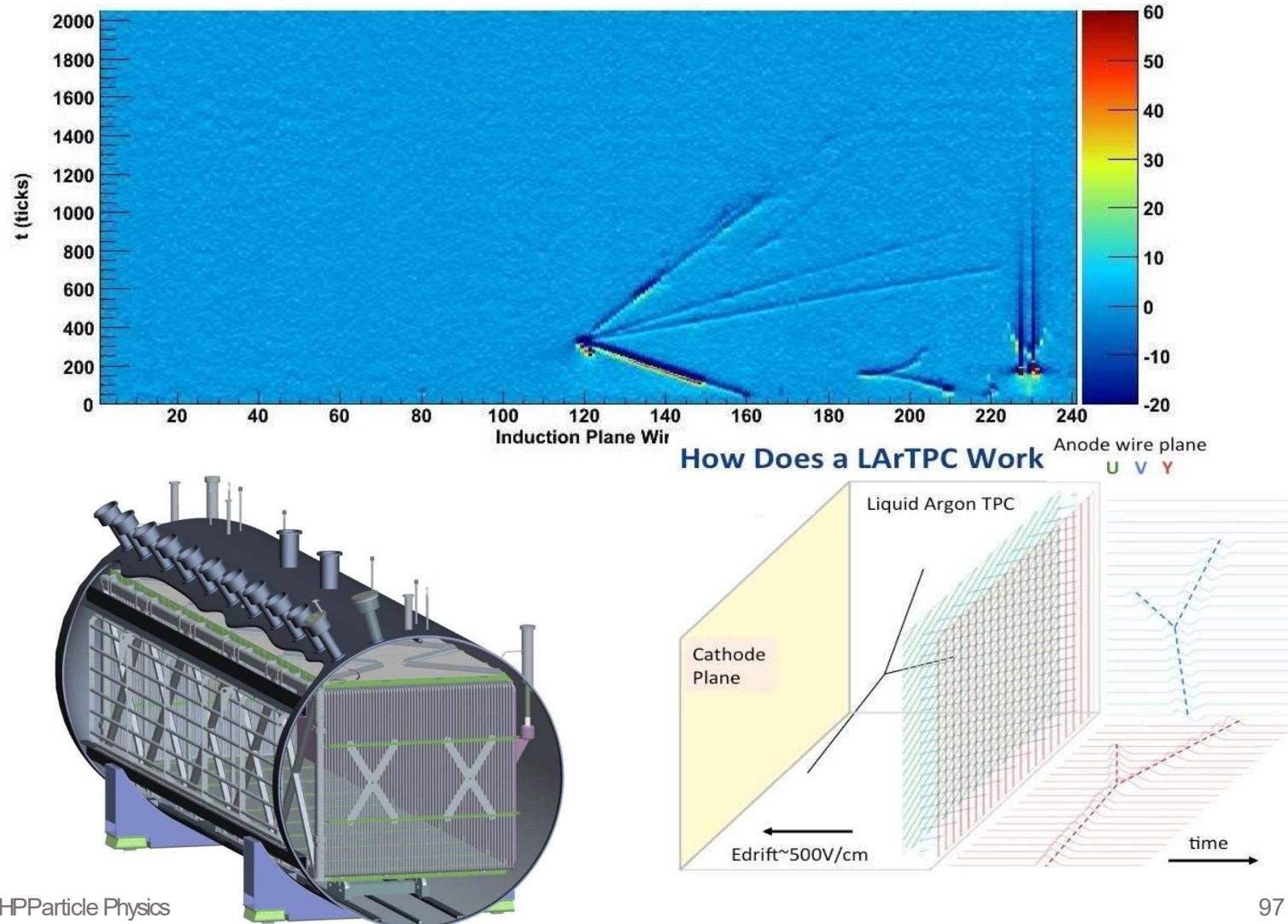
TIME PROJECTION CHAMBER

- 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



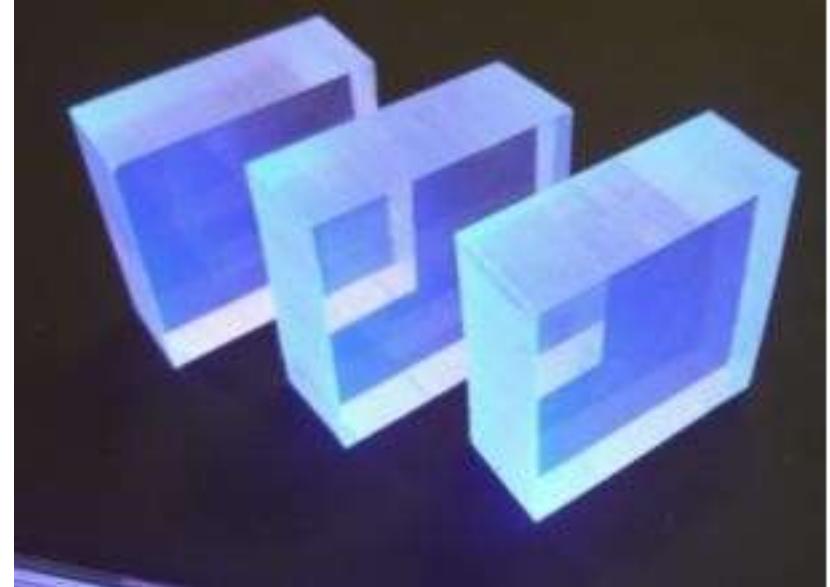
TIME PROJECTION CHAMBER

- MicroBooNE liquid argon TPC at Fermilab



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.



MODERN EXPERIMENTS

PARTICLE SOURCES

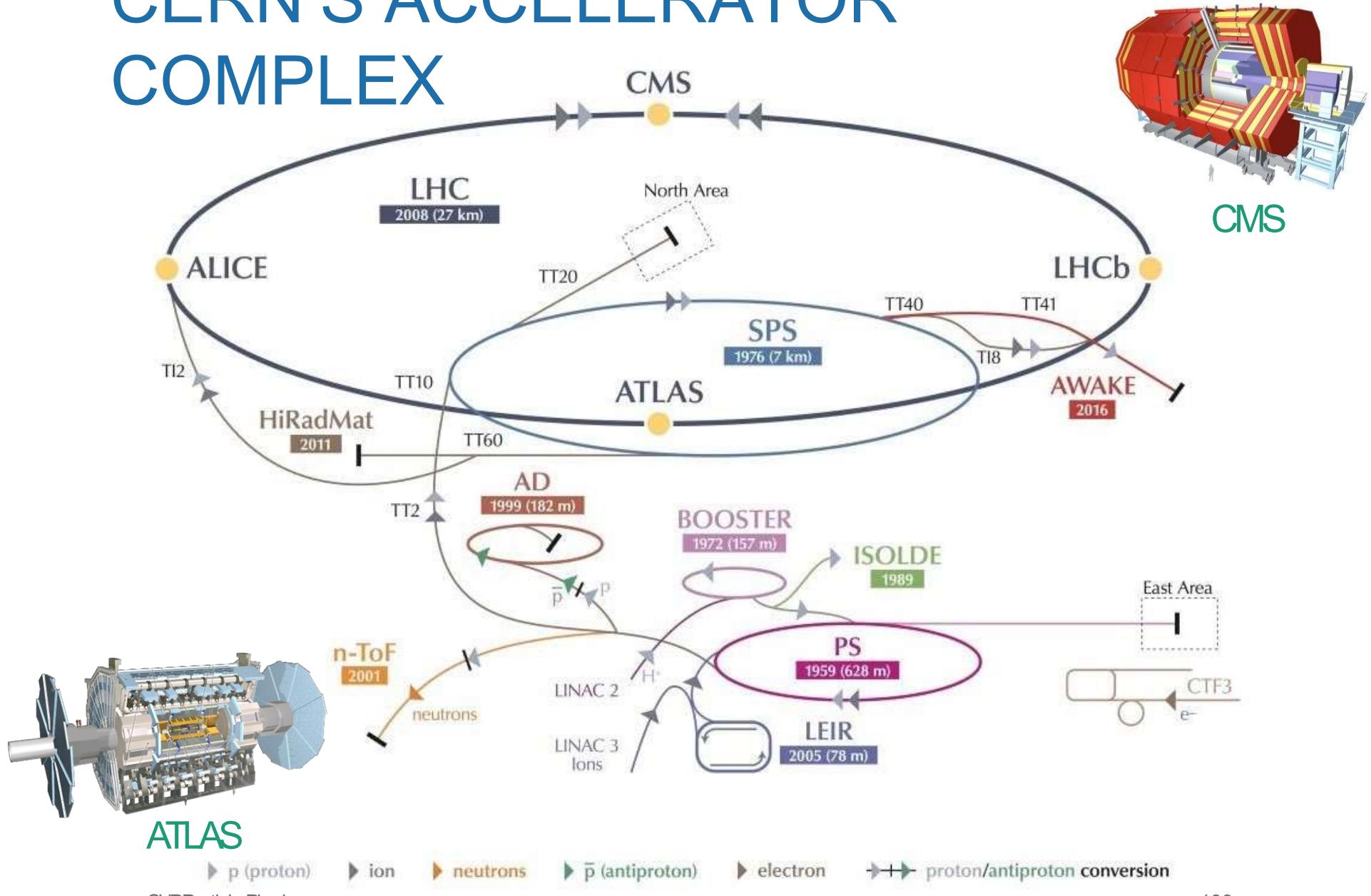
- Particle physics experiments use different **sources** of particles
- Artificial **beams** produced in accelerators
 - **Colliders** – beams are made to collide against each other.
 - Highest **energy** interactions from artificial sources
 - Beams are aimed at **fixed targets** / detectors
 - Lower 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

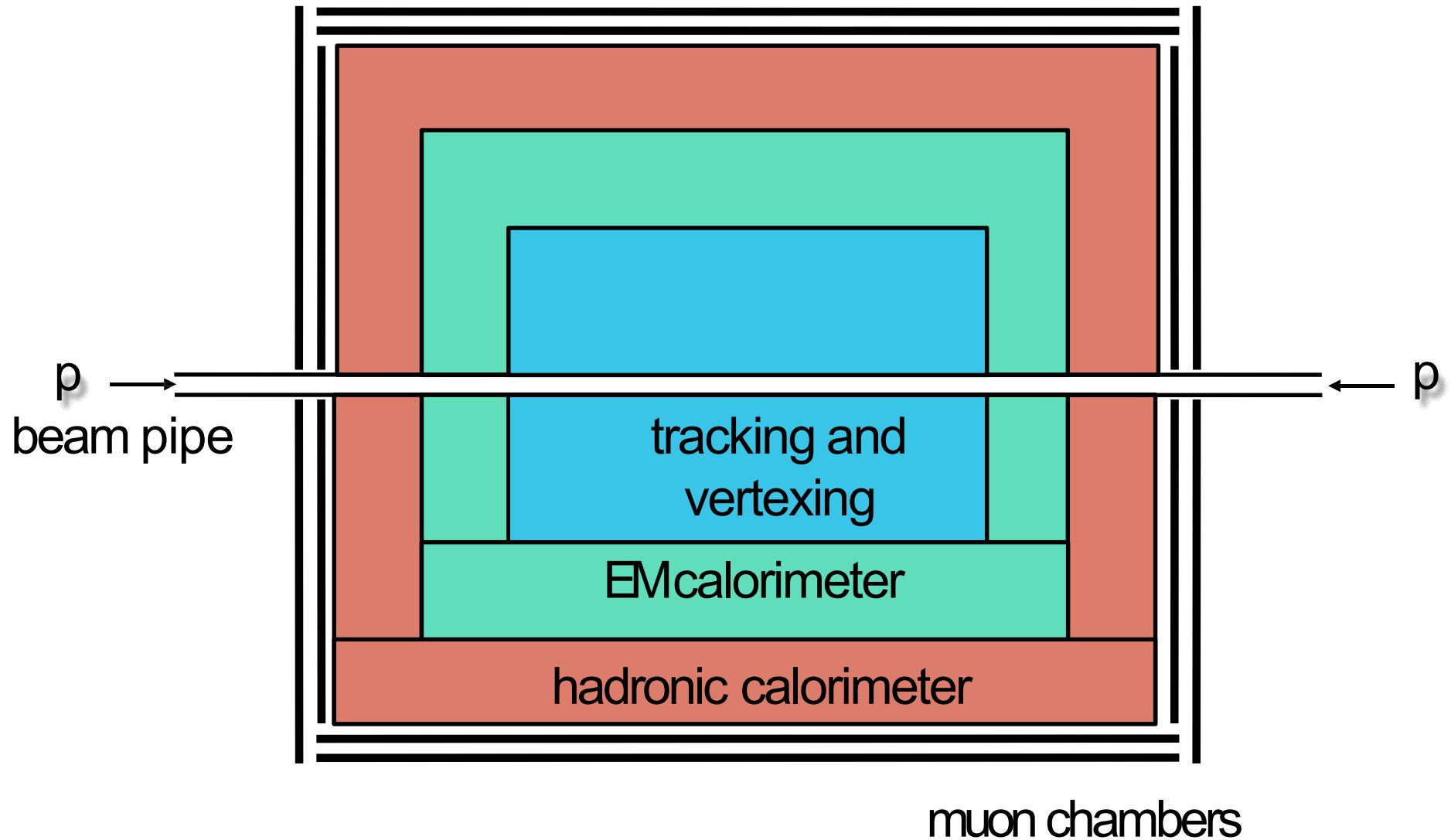
SLAC, California	SLC	1989-1998	$e^- e^+$	50 GeV e^- and 50 GeV e^+
	PEP II	1997-2008	$e^- e^+$	9.0 GeV e^- and 3.1 GeV e^+
Fermilab, nr Chicago	Tevatron	1987-2009	$p \bar{p}$	980 GeV p and 980 GeV \bar{p}
CERN, Geneva	LEP	1989-2000	$e^- e^+$	E_{CM}: 89 to 206 GeV
	LHC	2008-...	$p p$	E_{CM}: 14 TeV
DESY, Hamburg	HERA	1990-2007	$e^- p$	920 GeV p and 30 GeV e^-
KEK, near Toyko	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



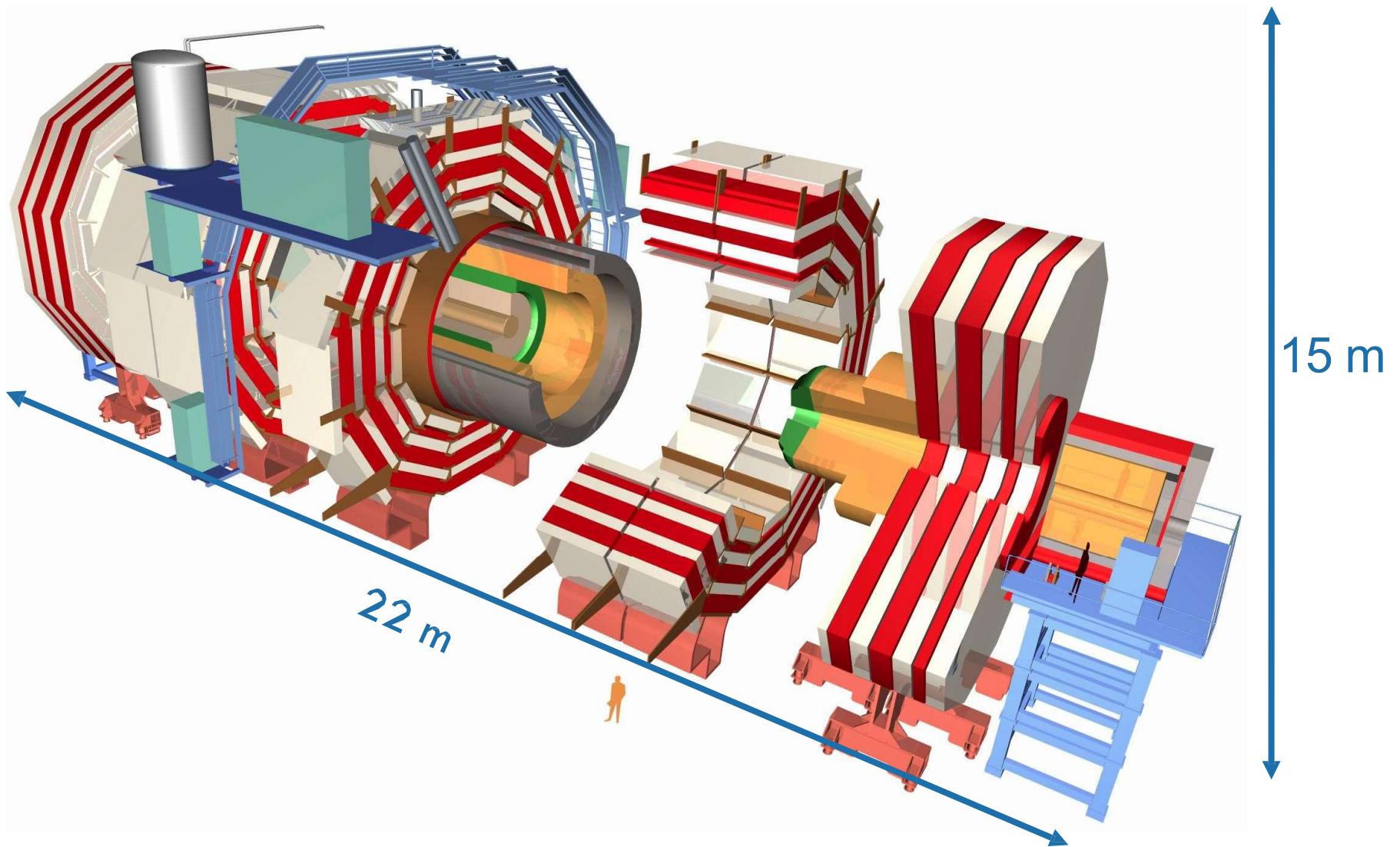
CERN'S ACCELERATOR COMPLEX



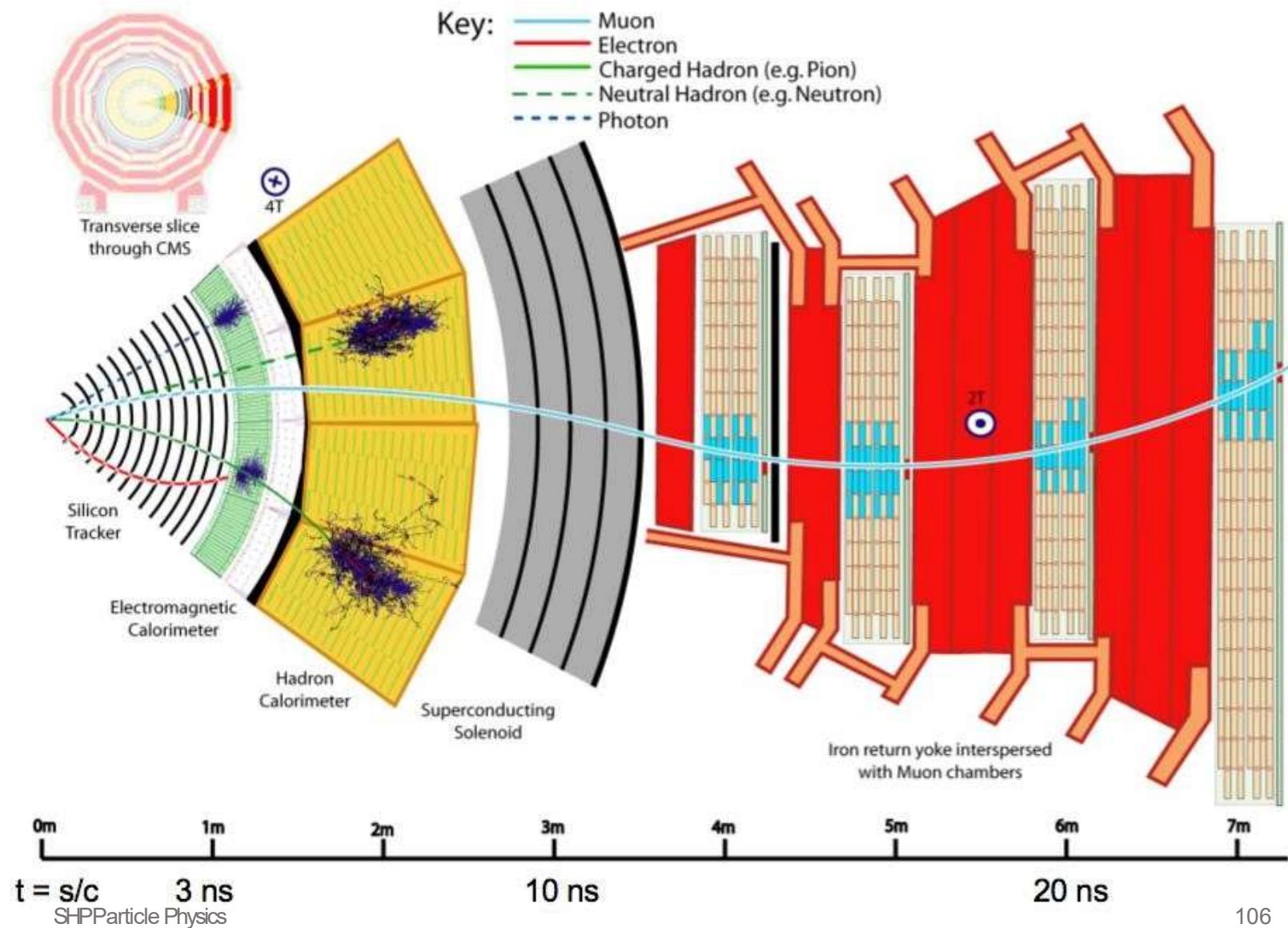
A GENERAL PURPOSE DETECTOR



THE CMS DETECTOR

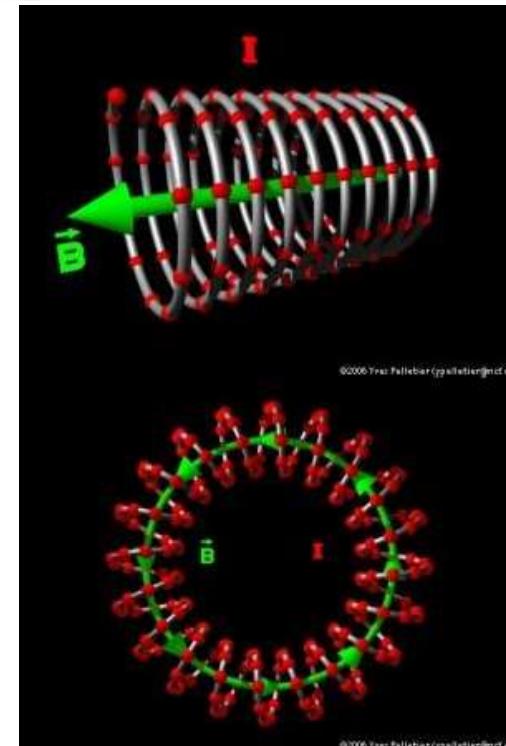
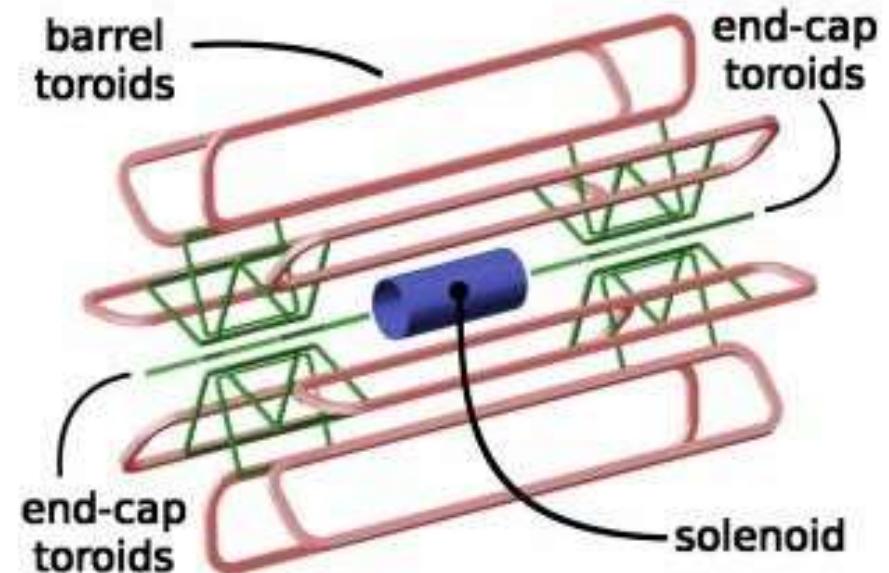


A SLICE OF CMS



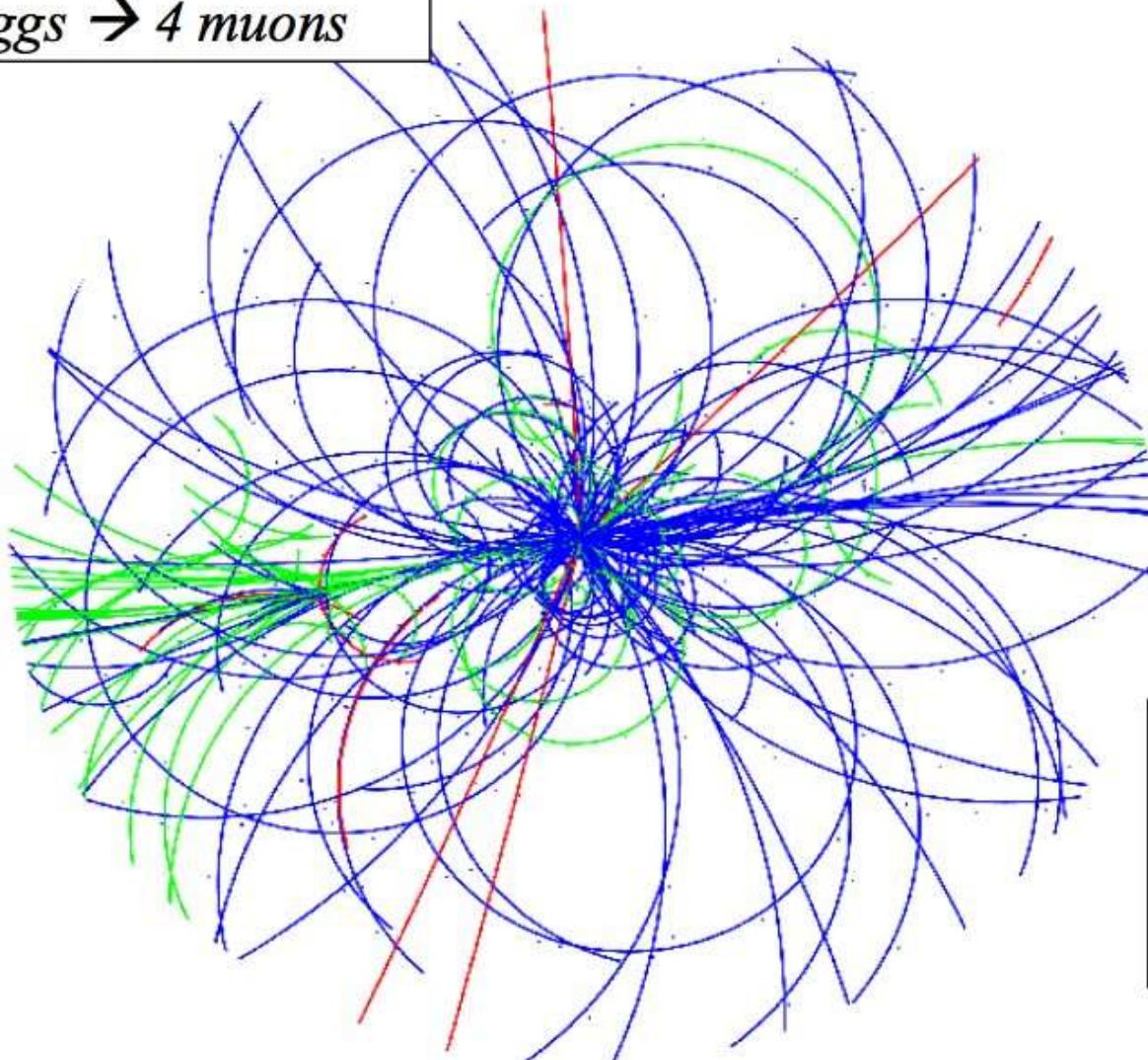
MAGNET SYSTEMS

- 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 $\sim 50 \text{ }\mu\text{T}$.



EVENT SIGNATURES

Higgs $\rightarrow 4$ muons

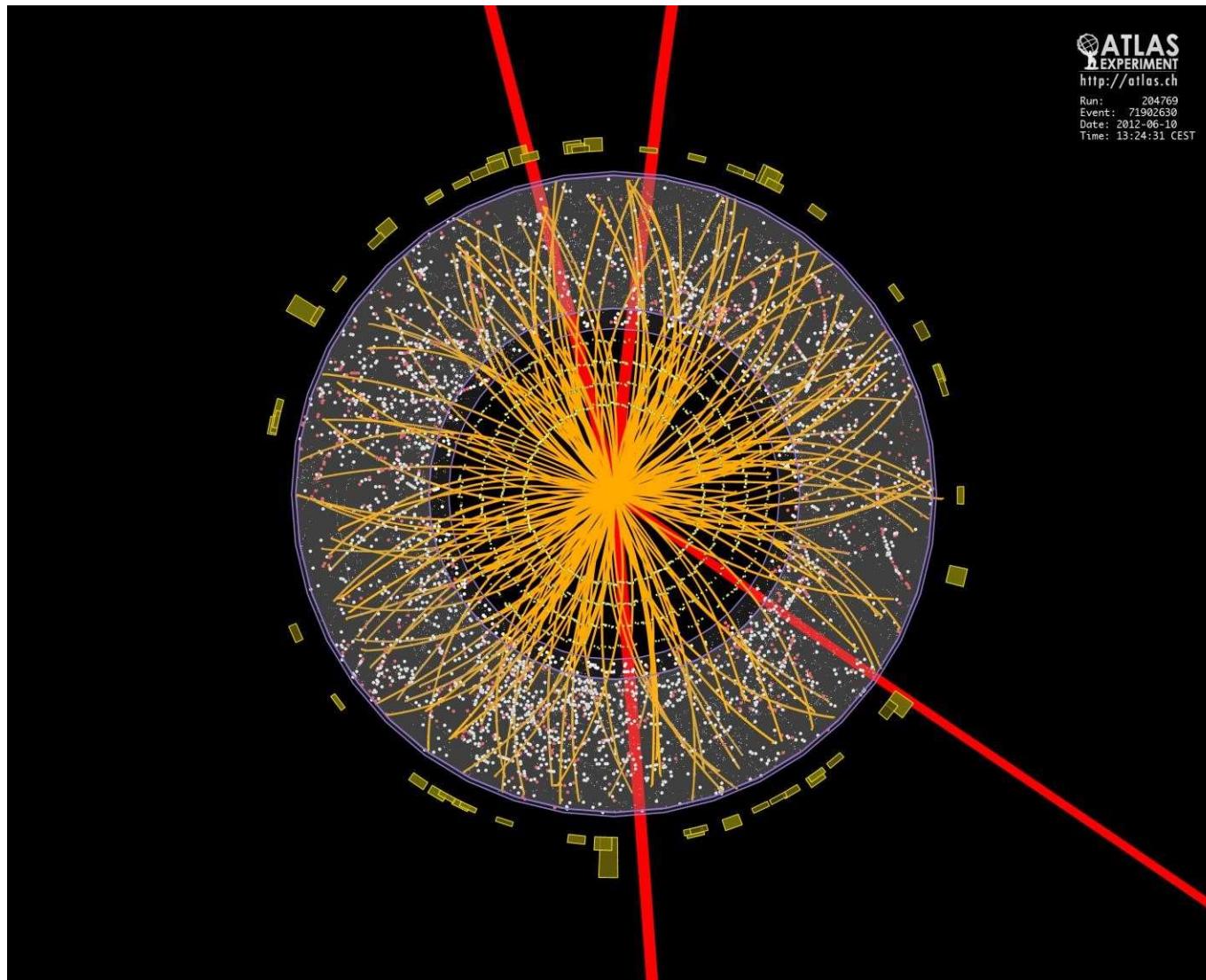


Charged particles bend in the magnetic field

The lower the particle momentum the more they bend.

Straight tracks from high momentum particles are the most interesting!

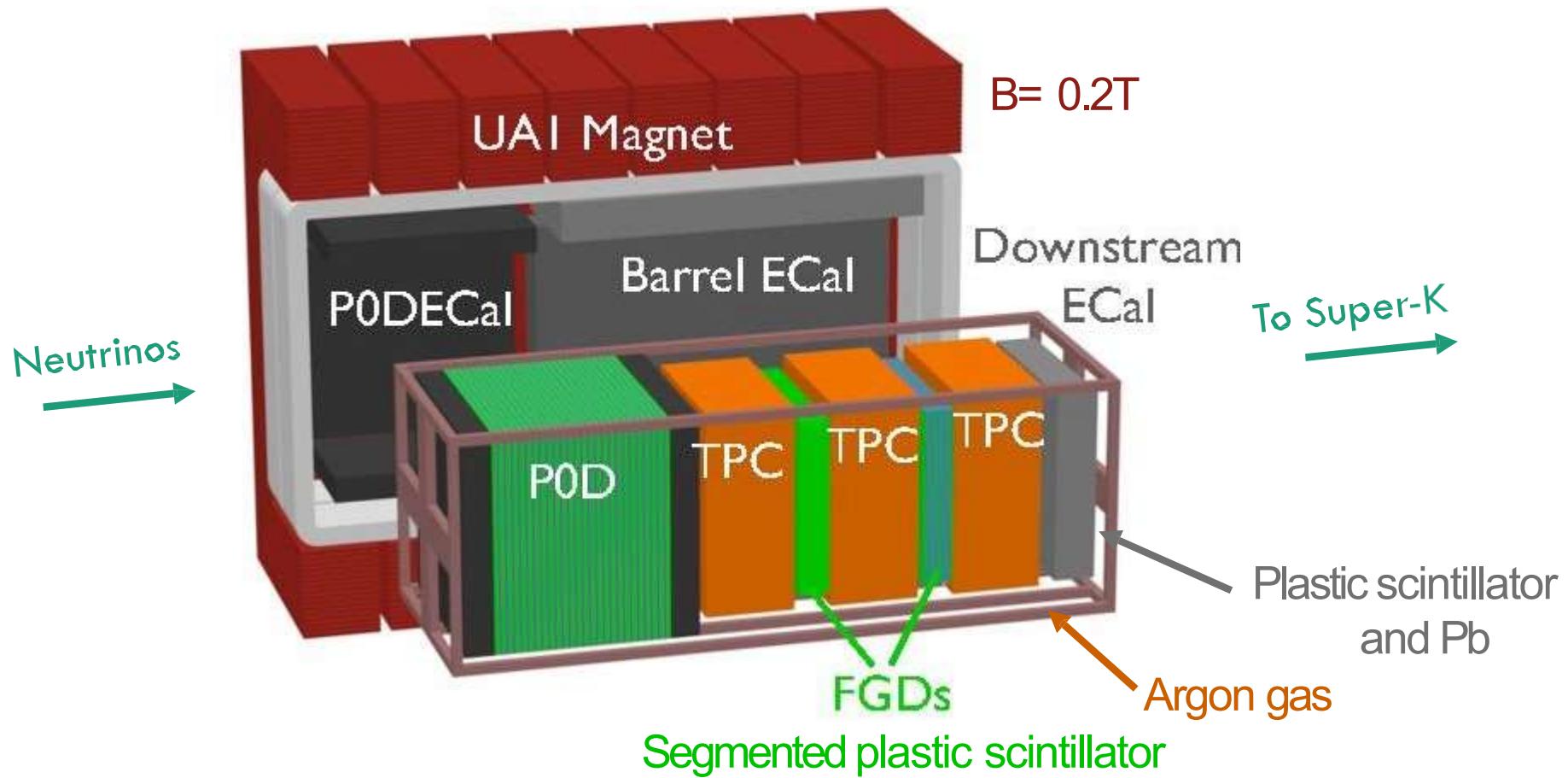
A REAL EVENT



T2K: ND280

A GENERAL PURPOSE NEUTRINO DETECTOR

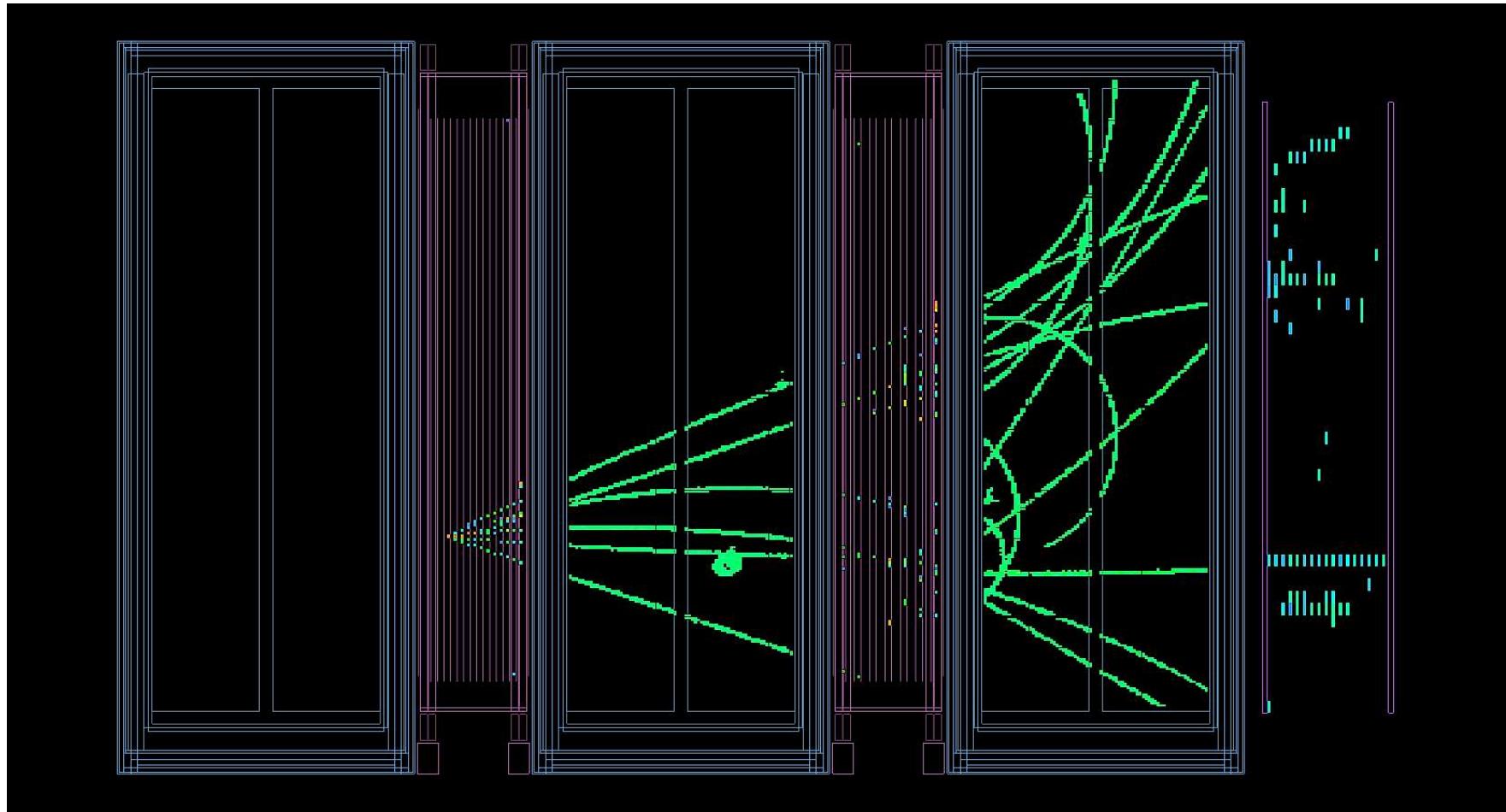
- Beam of neutrinos produced at the J-PARC proton accelerator in Japan



THE ND280 DETECTOR WITH MAGNET OPEN FOR MAINTENANCE



A NEUTRINO INTERACTION IN ND280

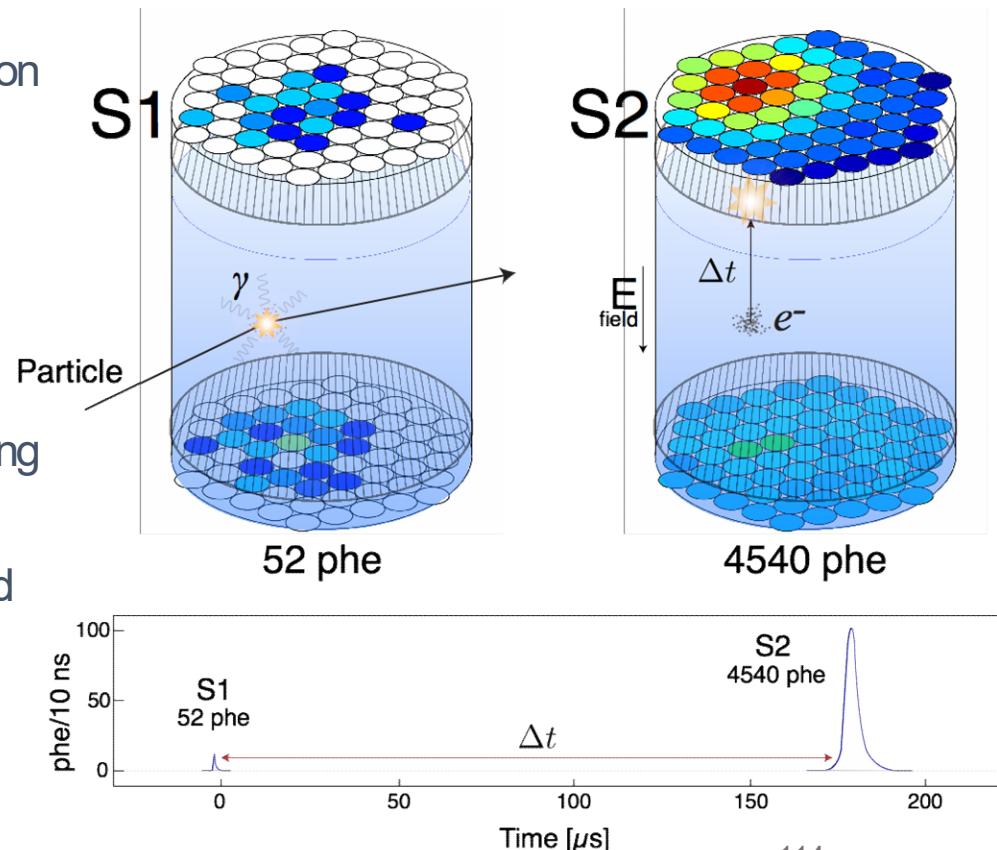


WHAT ABOUT DARK MATTER?

- Does not interact through weak, electromagnetic, or strong force.
- But it **might interact**, very very weakly.
- We need very “quiet” (cryogenic, deep underground) detectors to see dark matter interactions.
 - Scattering off of nuclei → transfer of kinetic energy.

THE LUX DARK MATTER EXPERIMENT

- The Large Underground Xenon (LUX) and XENON-1t experiments look for evidence of weakly interacting massive particle (WIMP) dark matter interactions.
- A few hundred to a ton of liquid xenon as the TPC medium.
- Aim to directly detect galactic dark matter in underground laboratories about 1 mile deep
- The detectors are 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



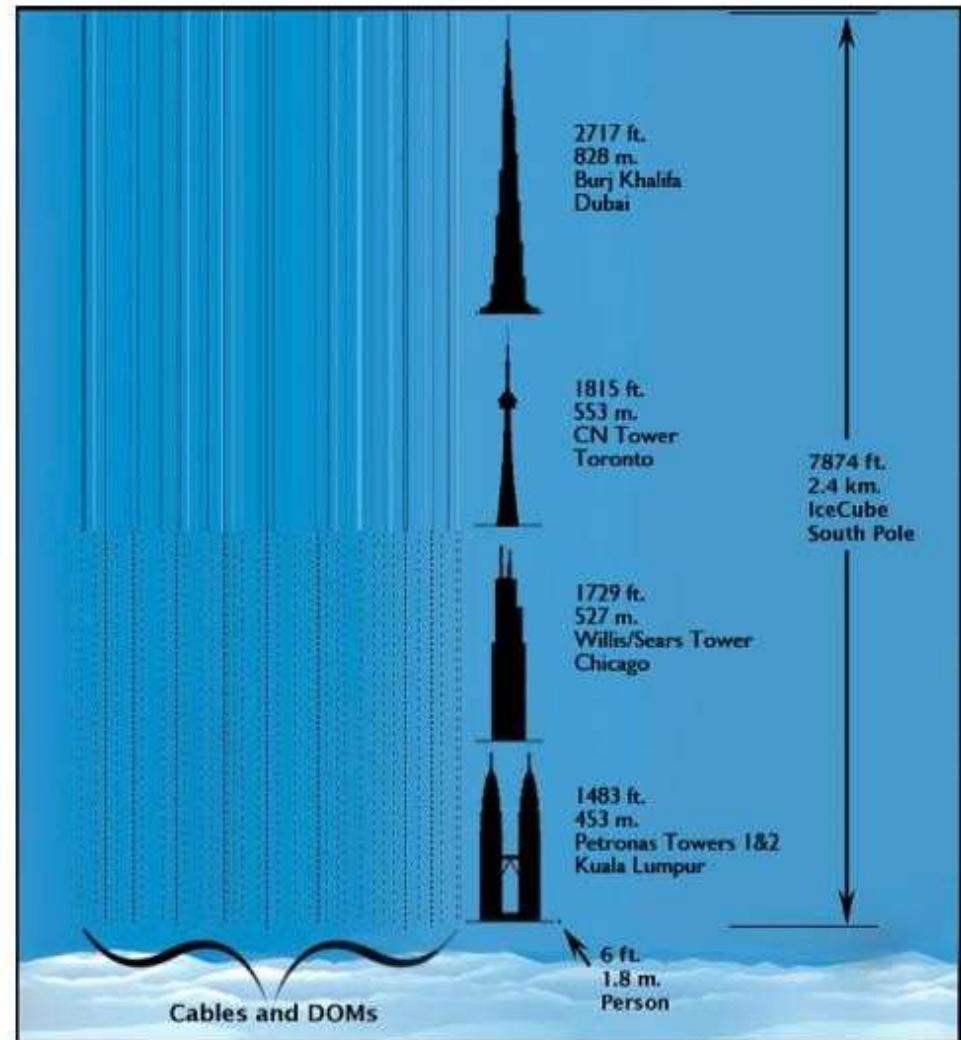
PARTICLE DETECTORS AT THE SOUTH POLE



Why do we go to such remote places for science?

ICE FISHING FOR SPACE NEUTRINOS!

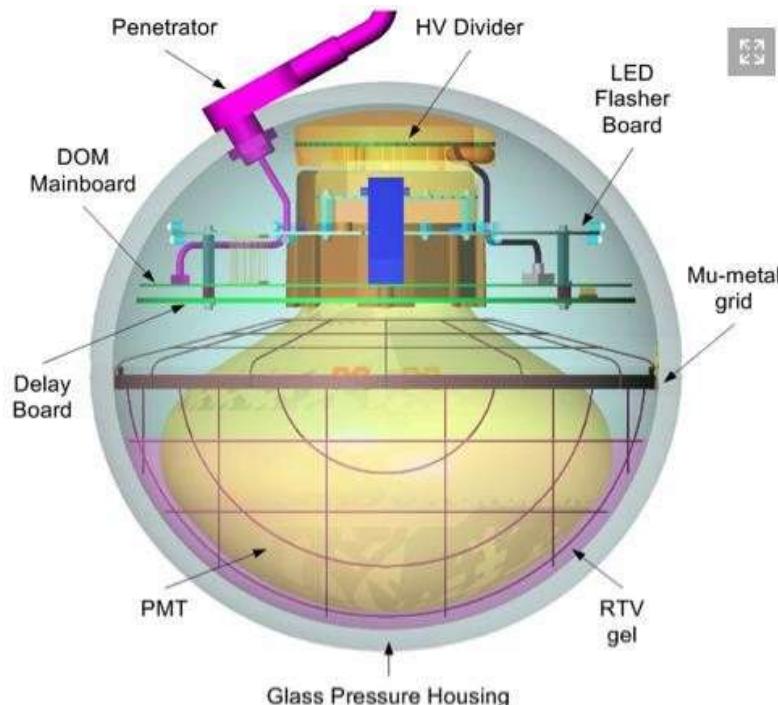
- IceCube detector at the South Pole
 - A neutrino detector: a neutrino telescope.
- Looks for extra-terrestrial sources of neutrinos.
 - Like taking an “X-ray” picture of the Universe.
- Use the Antarctic ice as a **Cherenkov detector!**



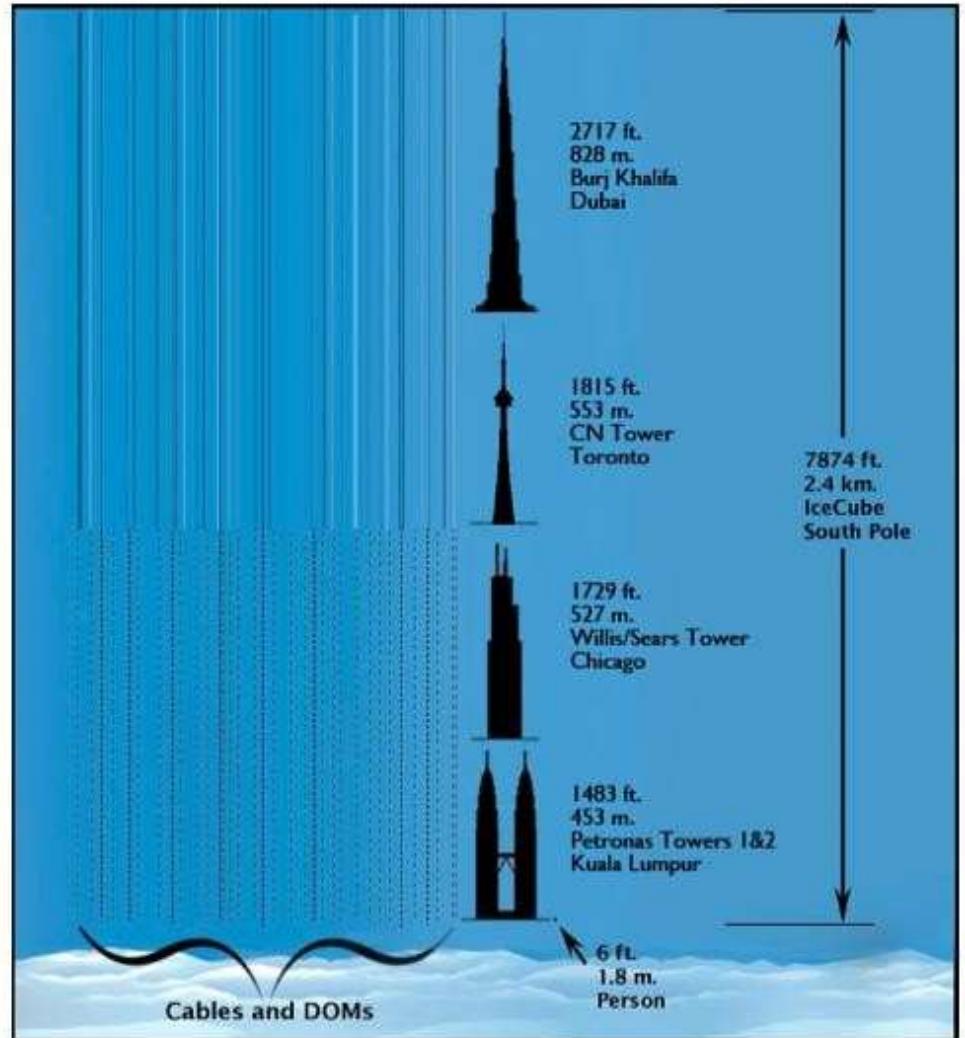
IceCube in Scale: The dashed lines above represent the portion of the cables that have DOMs attached

ICE FISHING FOR SPACE NEUTRINOS!

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

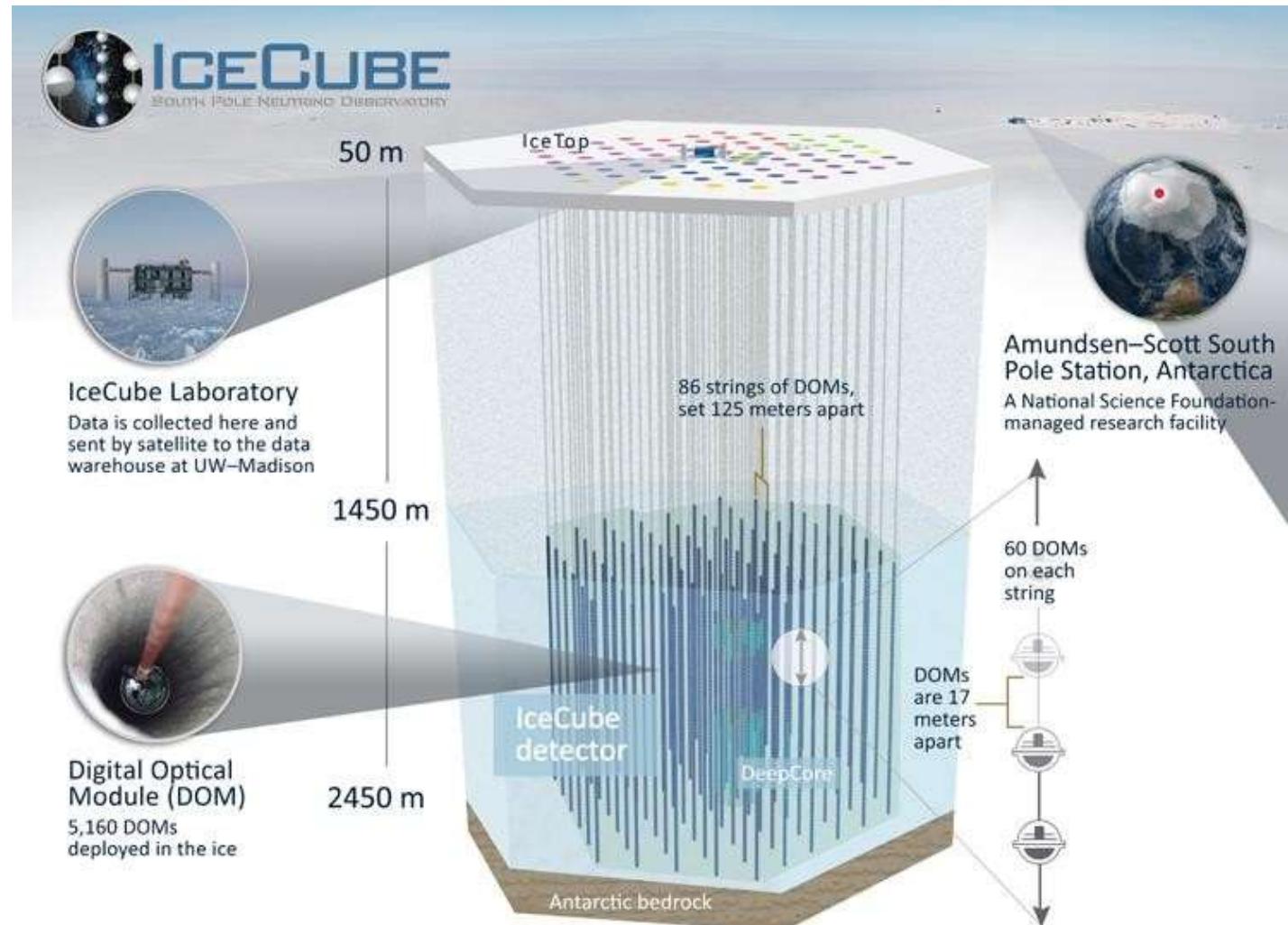


SHPParticle Physics



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

THE ICECUBE DETECTOR

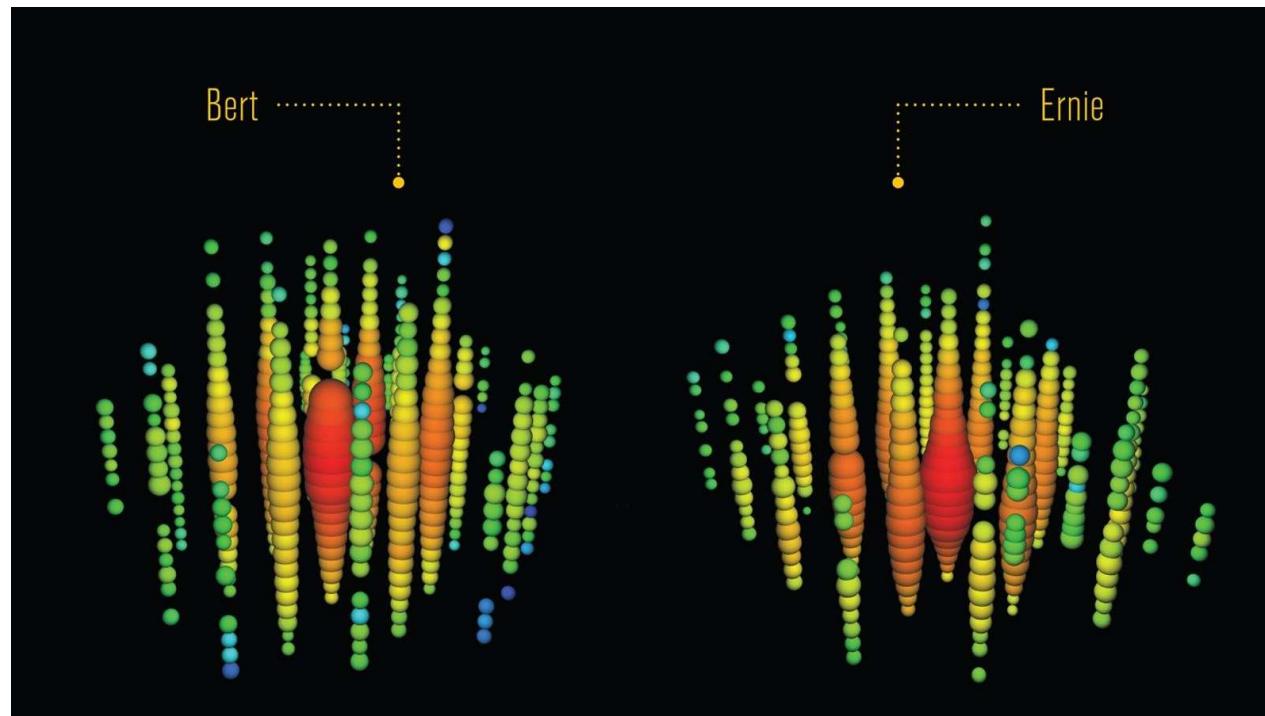


ICECUBE PHYSICS

- 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

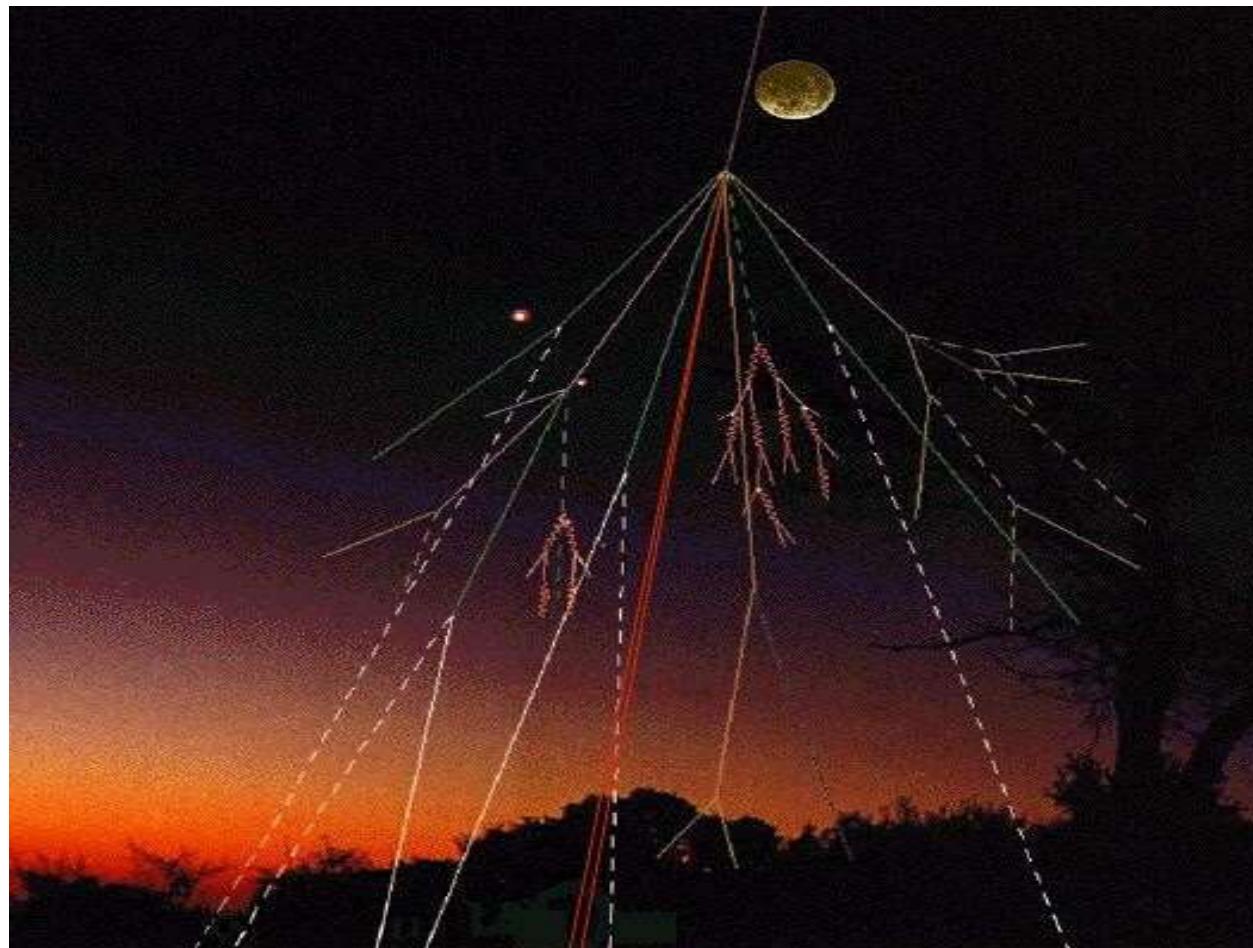
BERT, ERNIE AND MANY OTHERS

- 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.

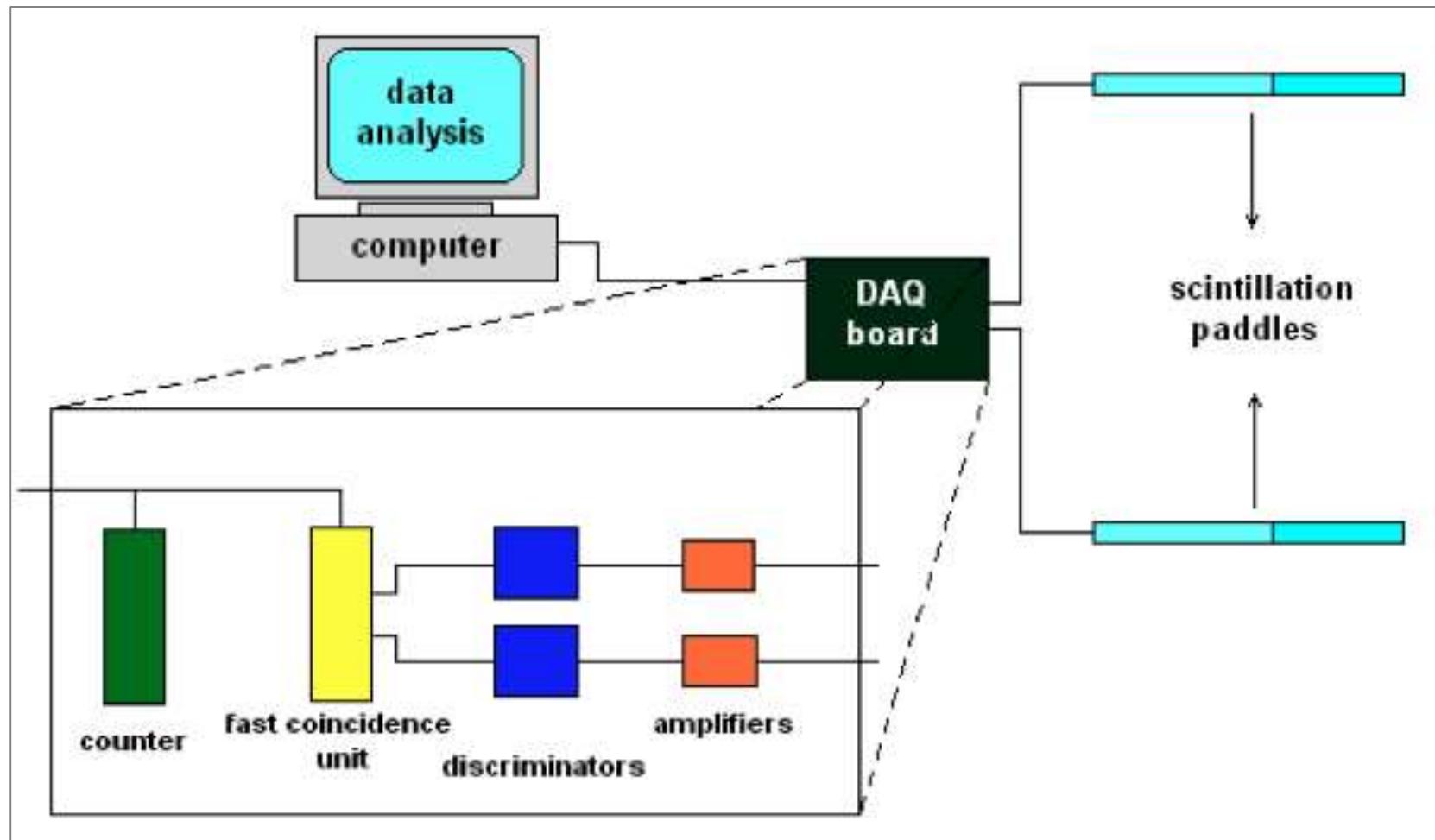


APPLICATION OF SCINTILLATION DETECTORS

- Cosmic ray muon detection

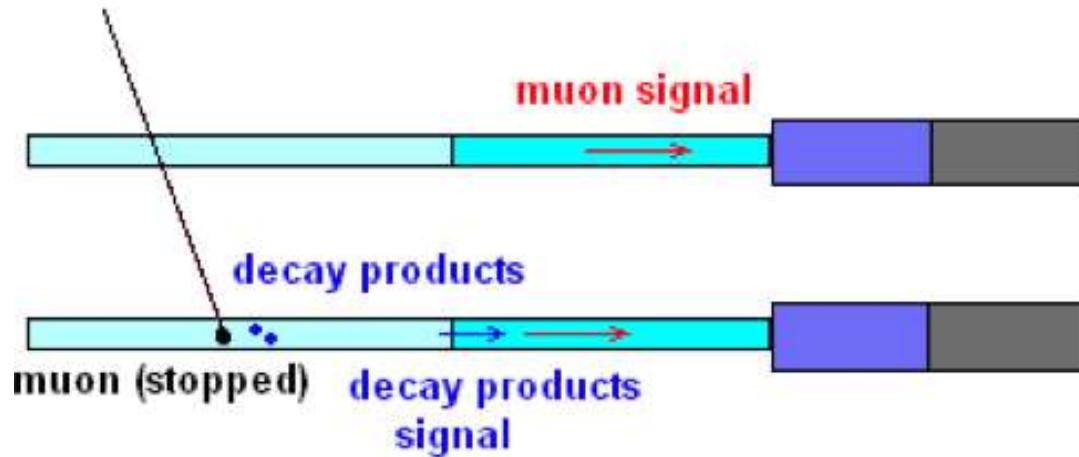


COSMIC RAY MUON DETECTION



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:

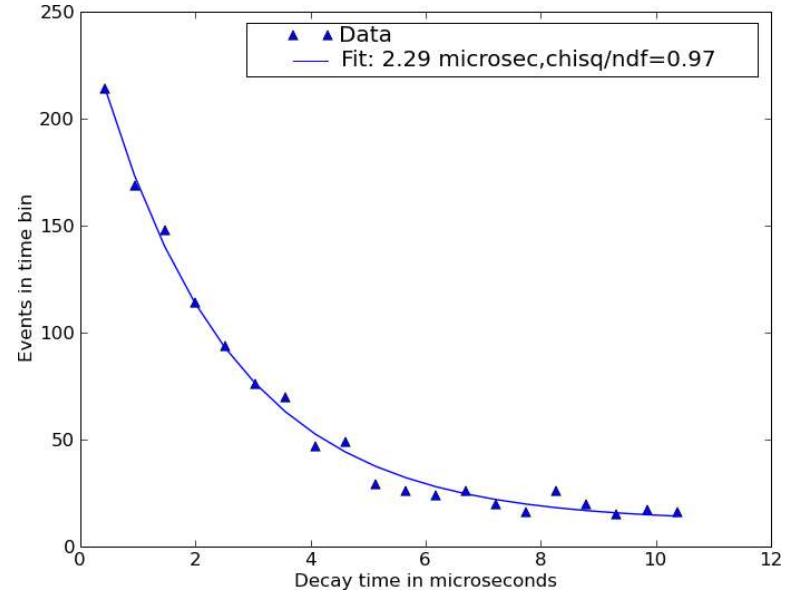
$$N(t) = N_0 e^{-t/T}$$

where T = muon lifetime

COSMIC RAY MUON DETECTION

- Measurement of the muon lifetime

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

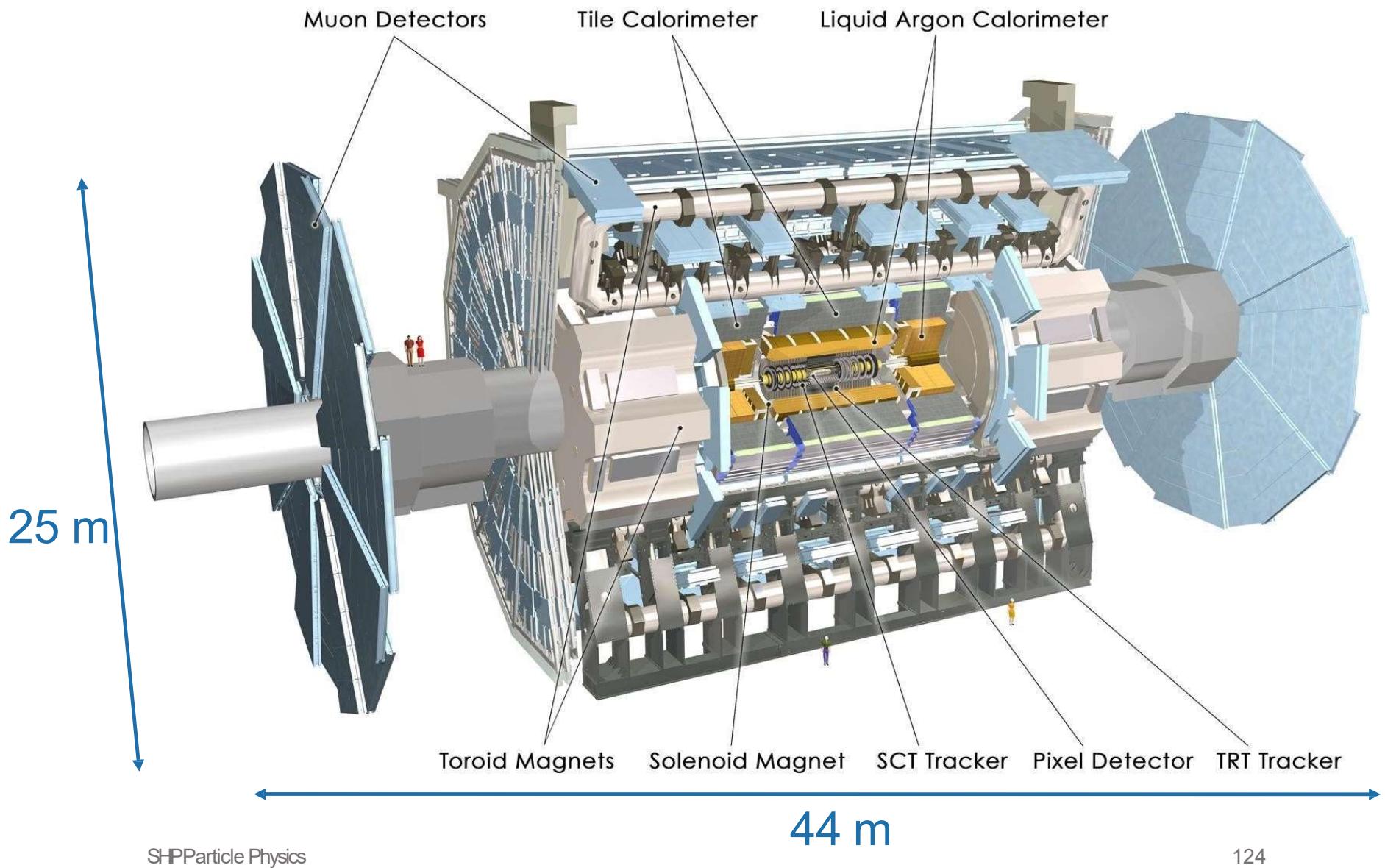


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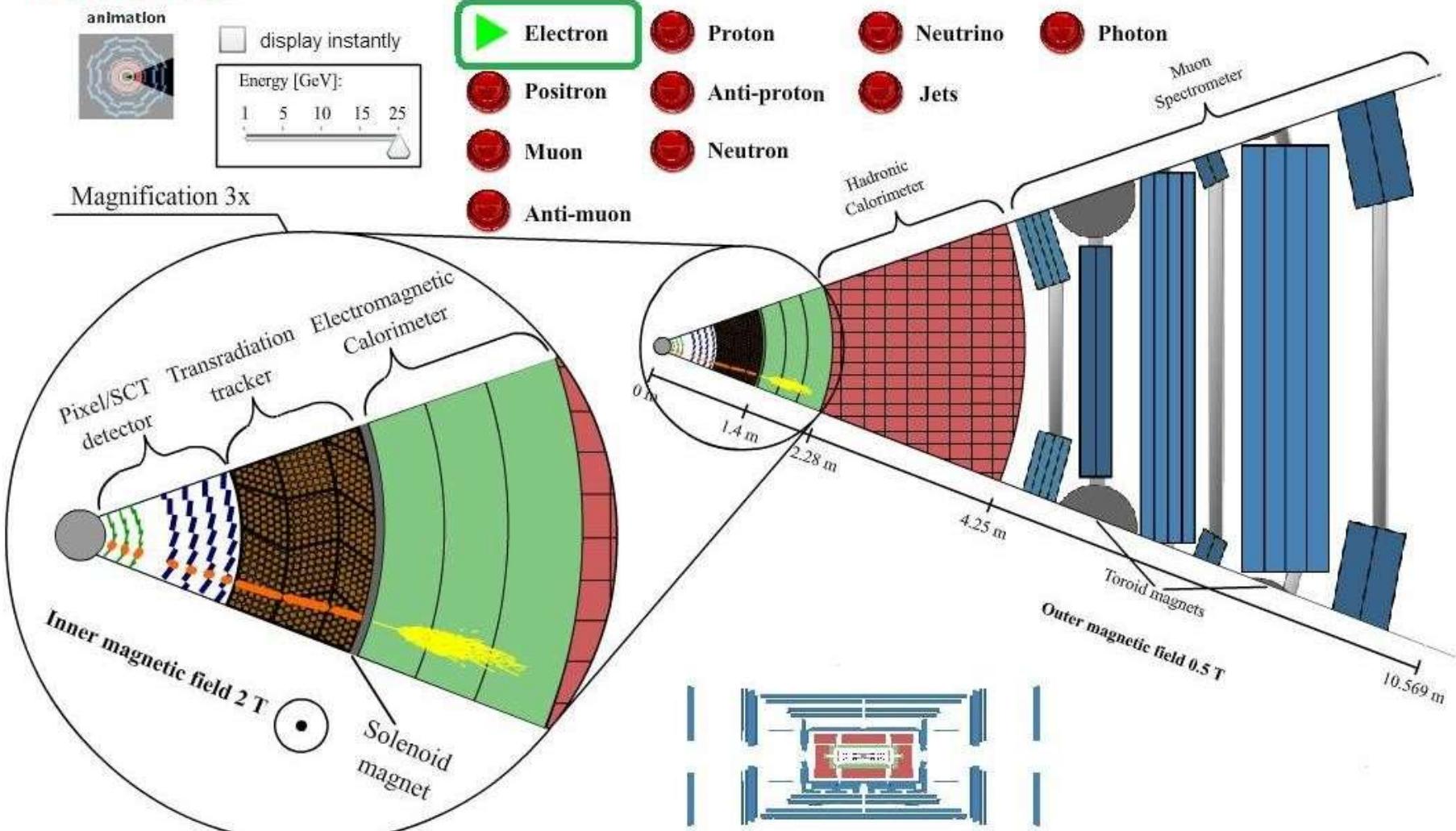
where T = muon lifetime

THE ATLAS DETECTOR



THE ATLAS DETECTOR

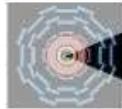
ATLAS



THE ATLAS DETECTOR

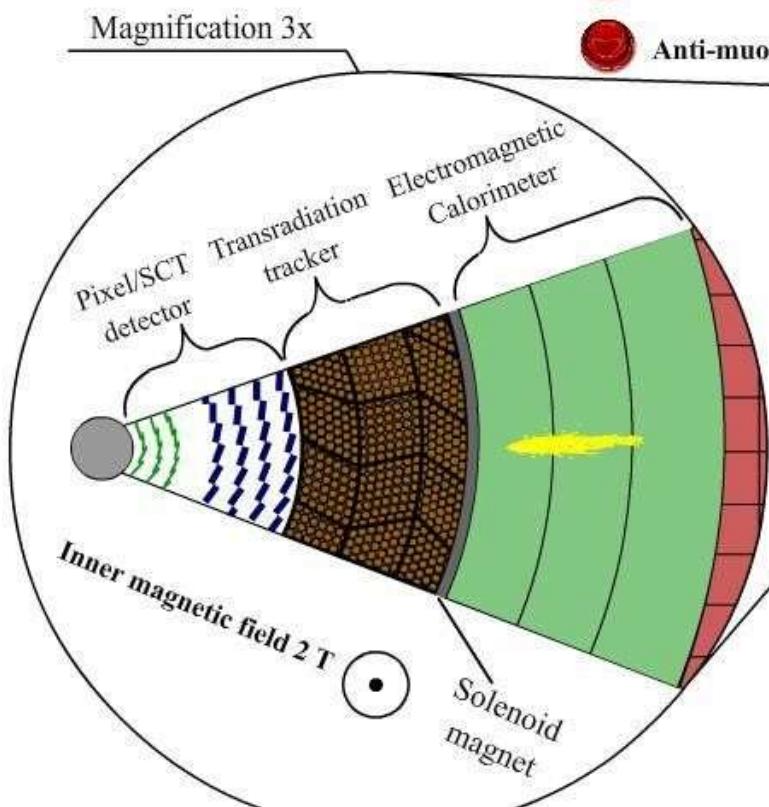
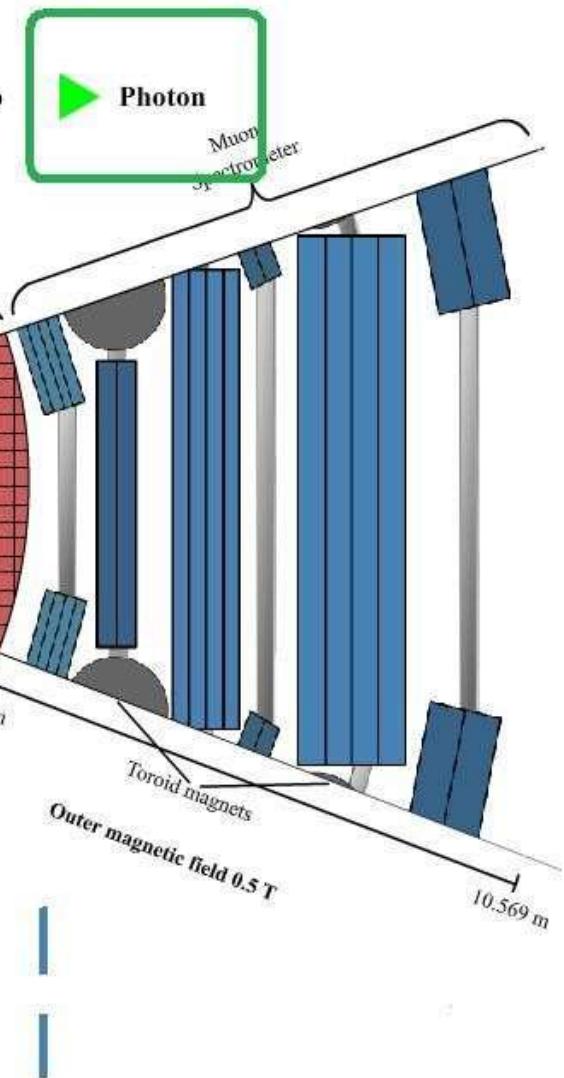
ATLAS

animation



display instantly

- Electron
- Proton
- Neutrino
- Positron
- Anti-proton
- Jets
- Muon
- Neutron
- Anti-muon

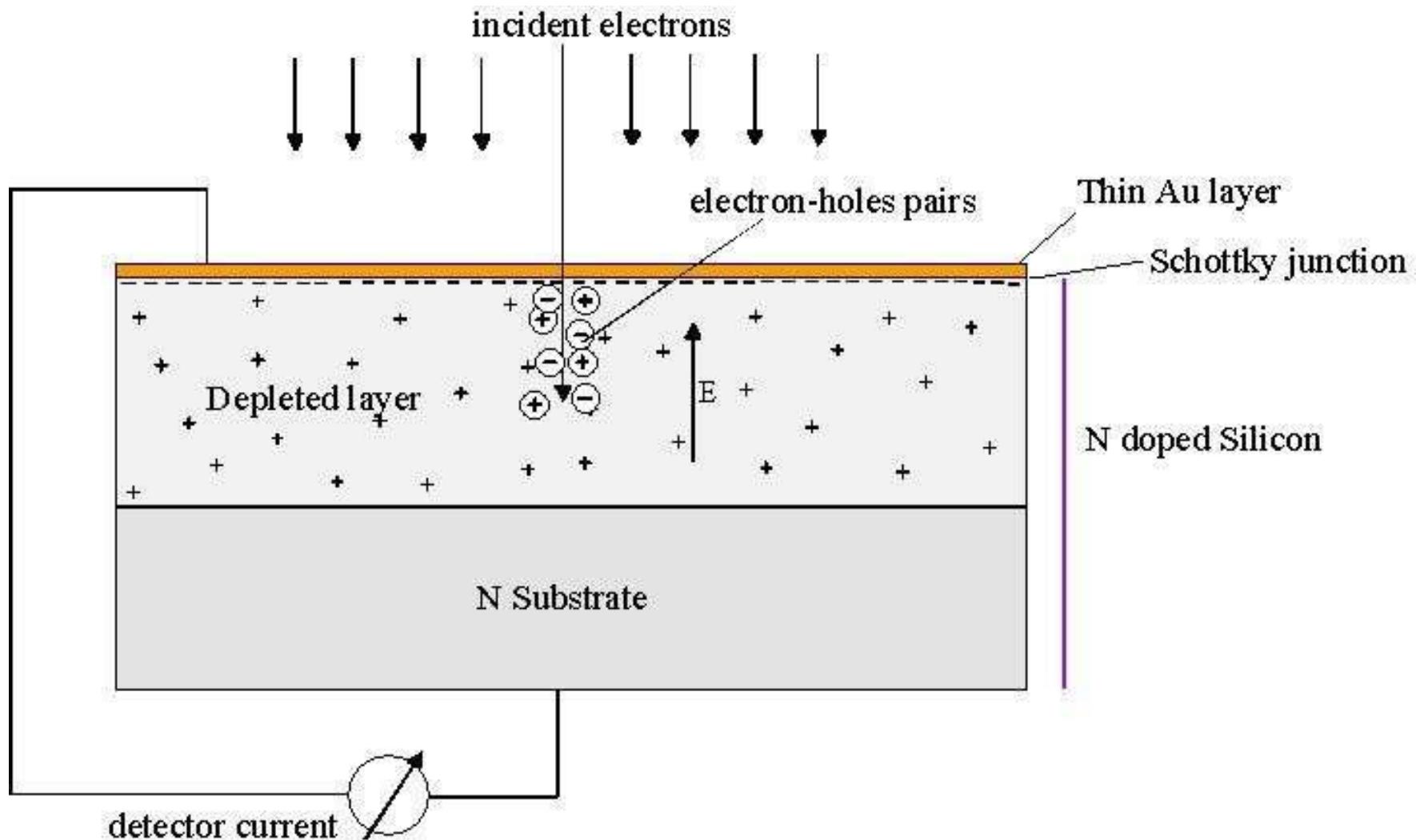


THAT'S ALL FOR THIS WEEK

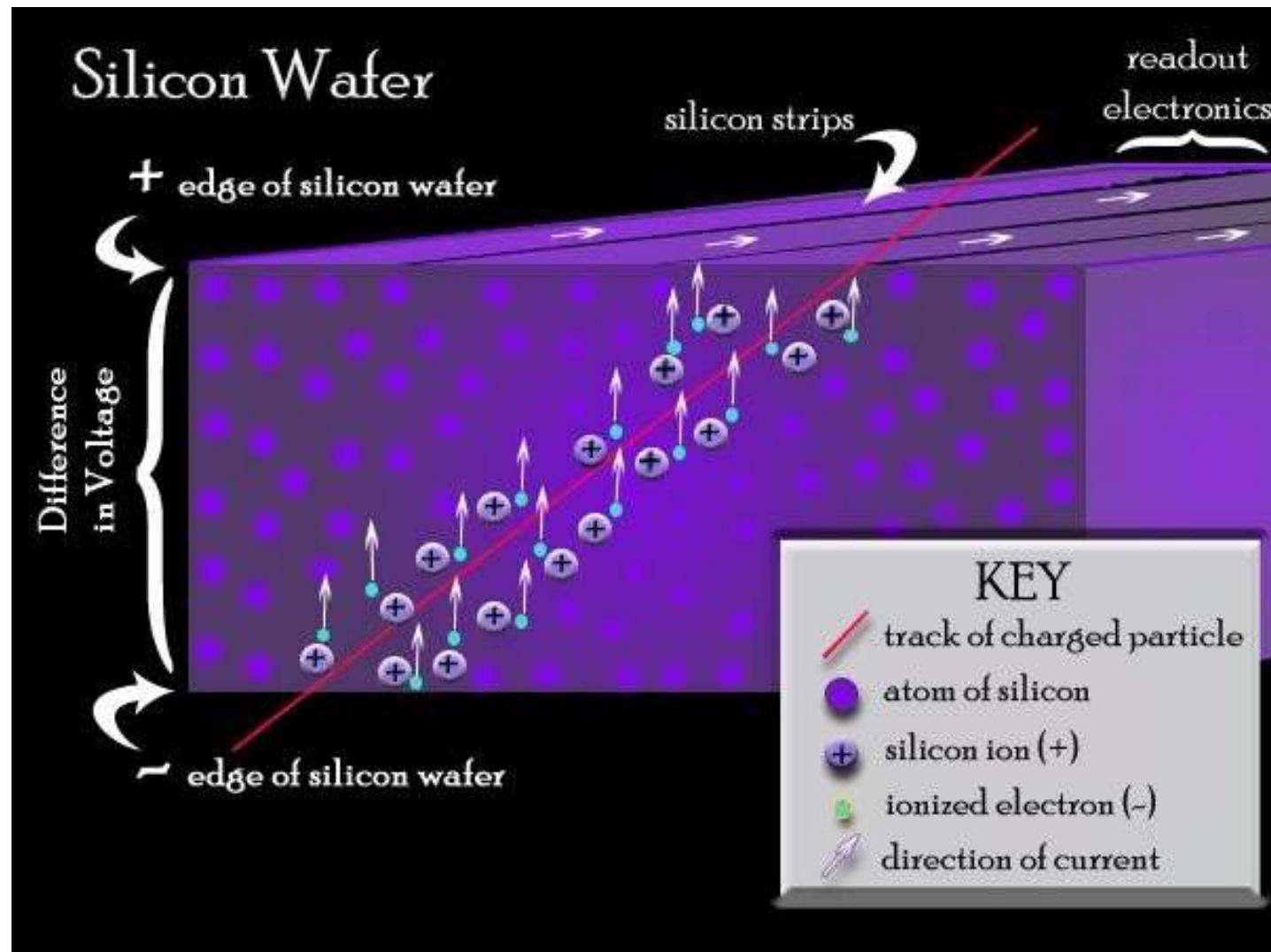
- Next week:
 - An overview of the Standard Model

BONUS

SOLID-STATE DETECTORS

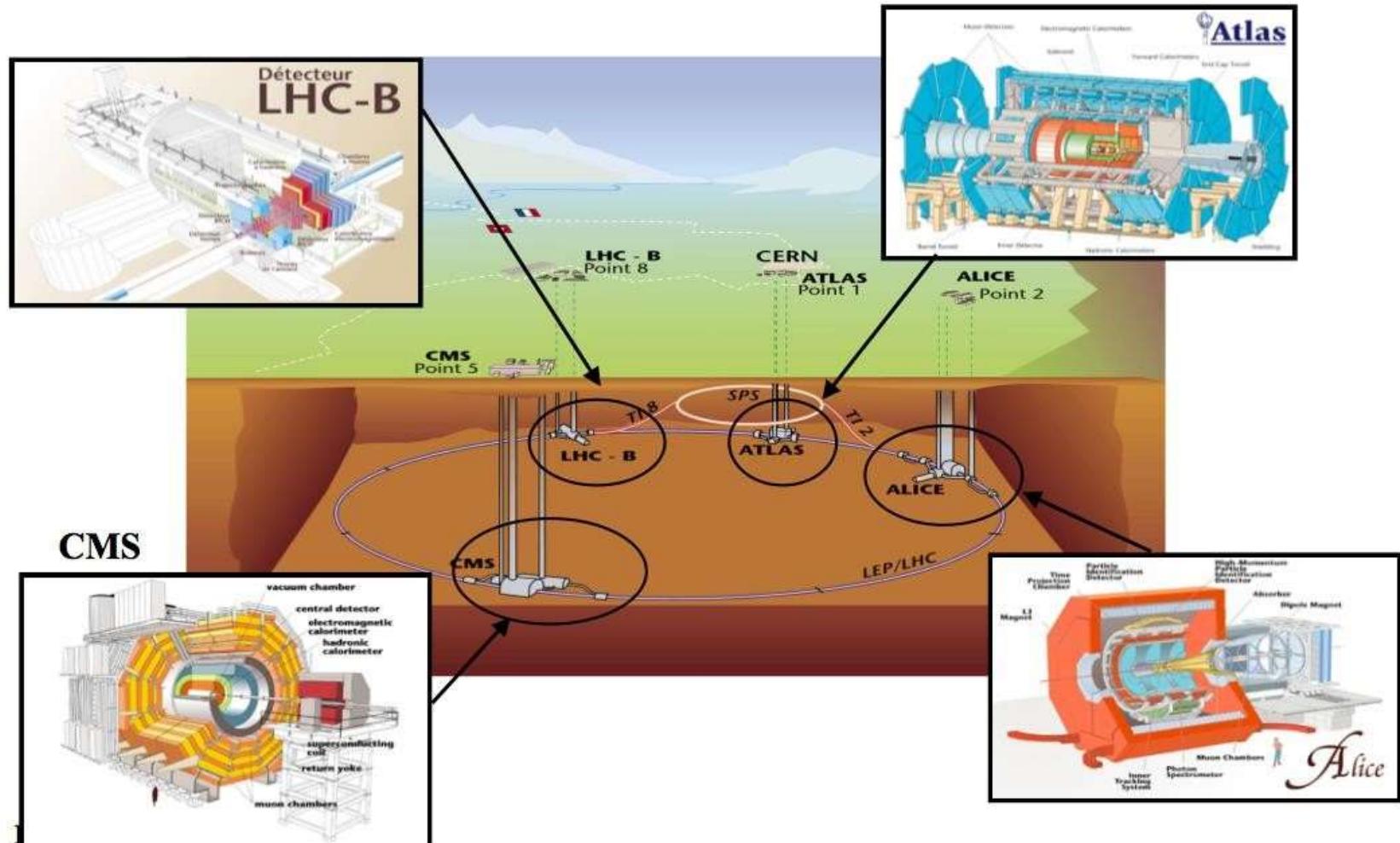


SOLID-STATE DETECTORS



COLLIDER EXPERIMENTS

LHC Experiments underground



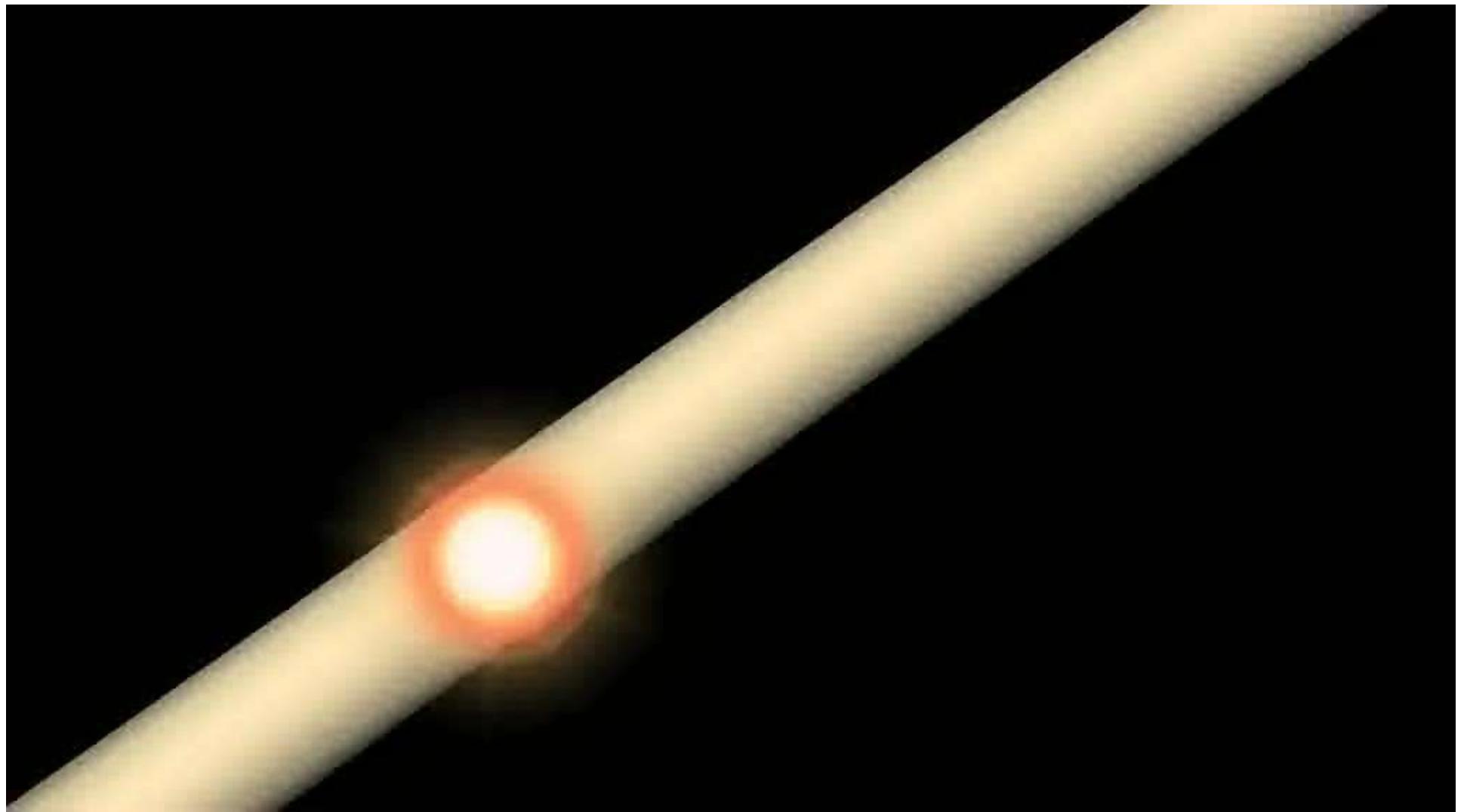
WHY BUILD THE LARGE HADRON COLLIDER?

- 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 → high E_{cm} → 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.

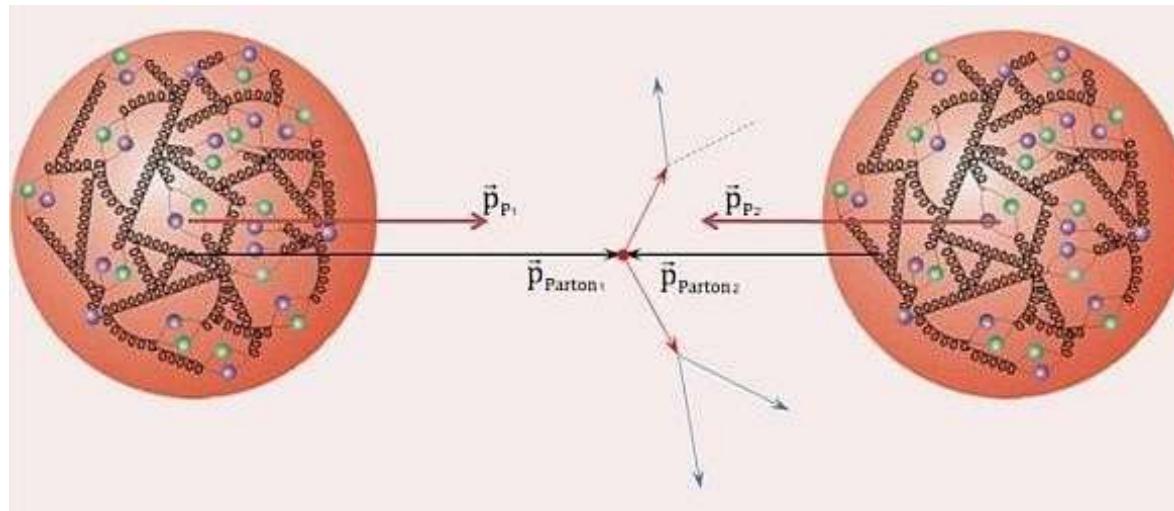
PROTON-PROTON COLLISIONS



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

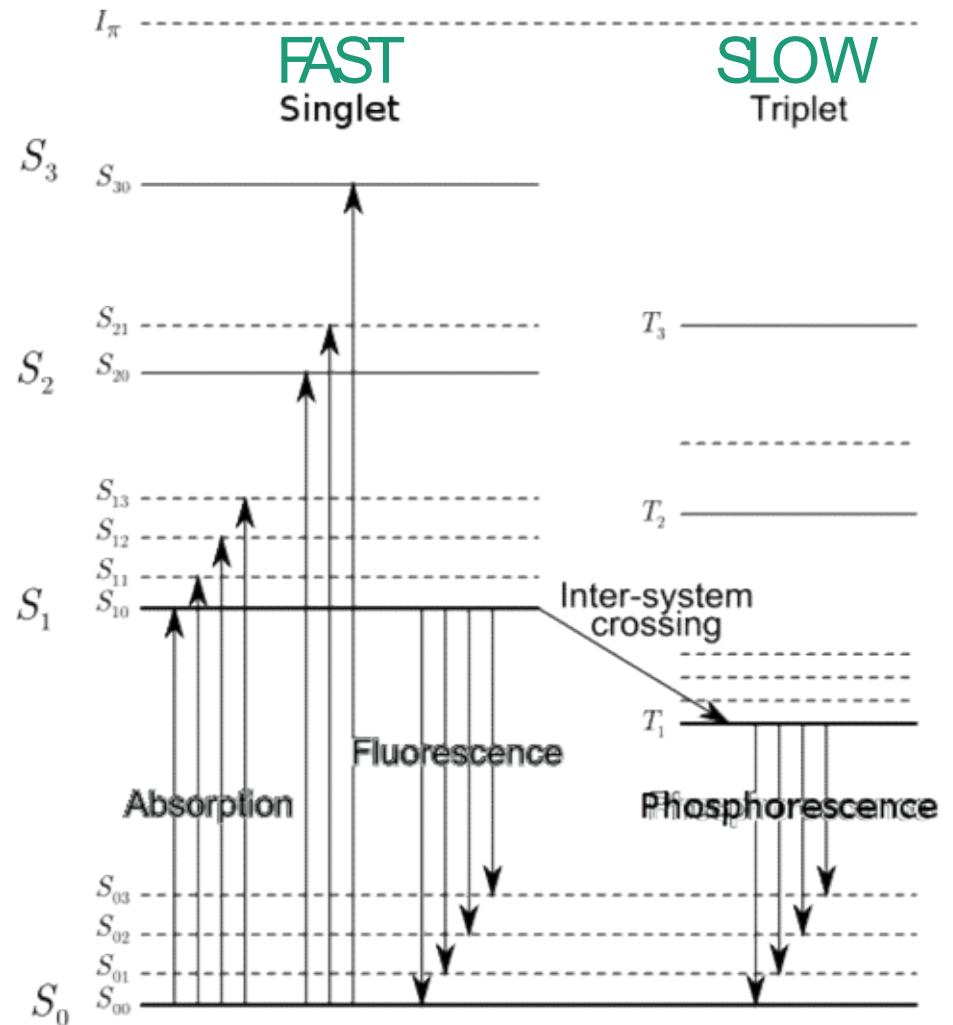
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH



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

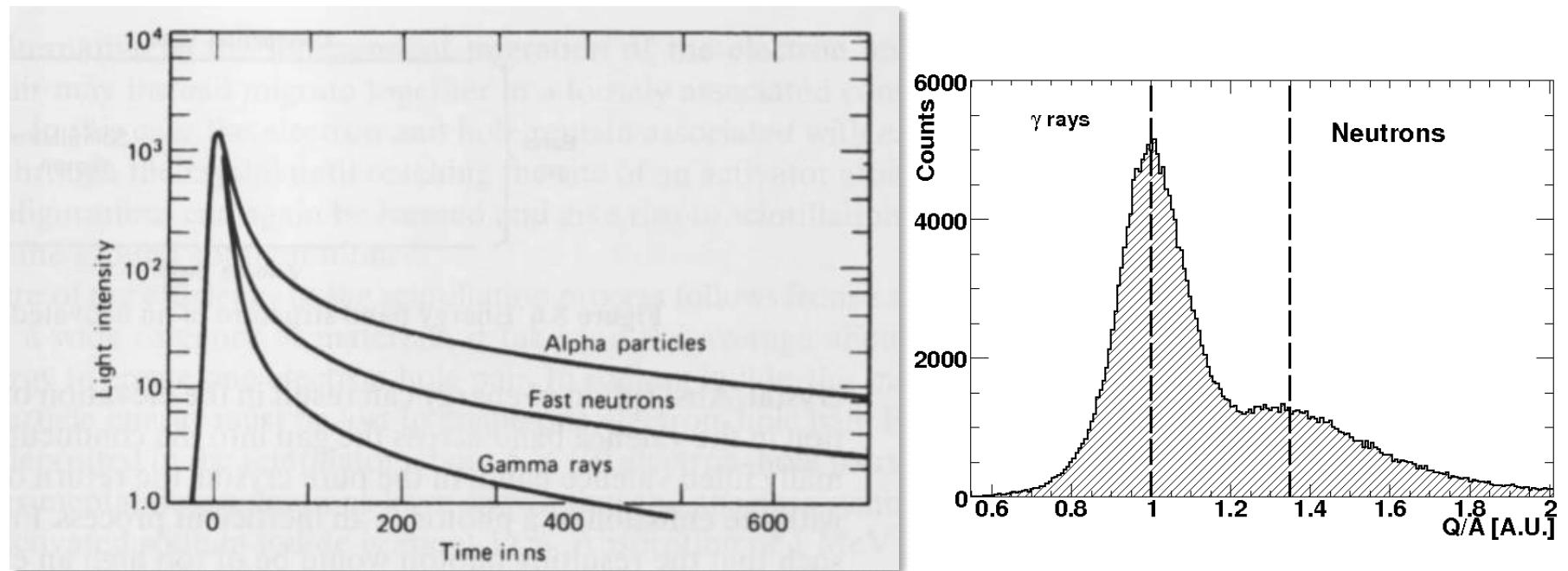
SCINTILLATION

- 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:



ASIDE A NOTE ABOUT CROSS-SECTIONS

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

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

Interaction rate
events/second

Flux of incoming particles
particles/cm²/second

Cross-section
cm²

ASIDE

A NOTE ABOUT CROSS-SECTIONS

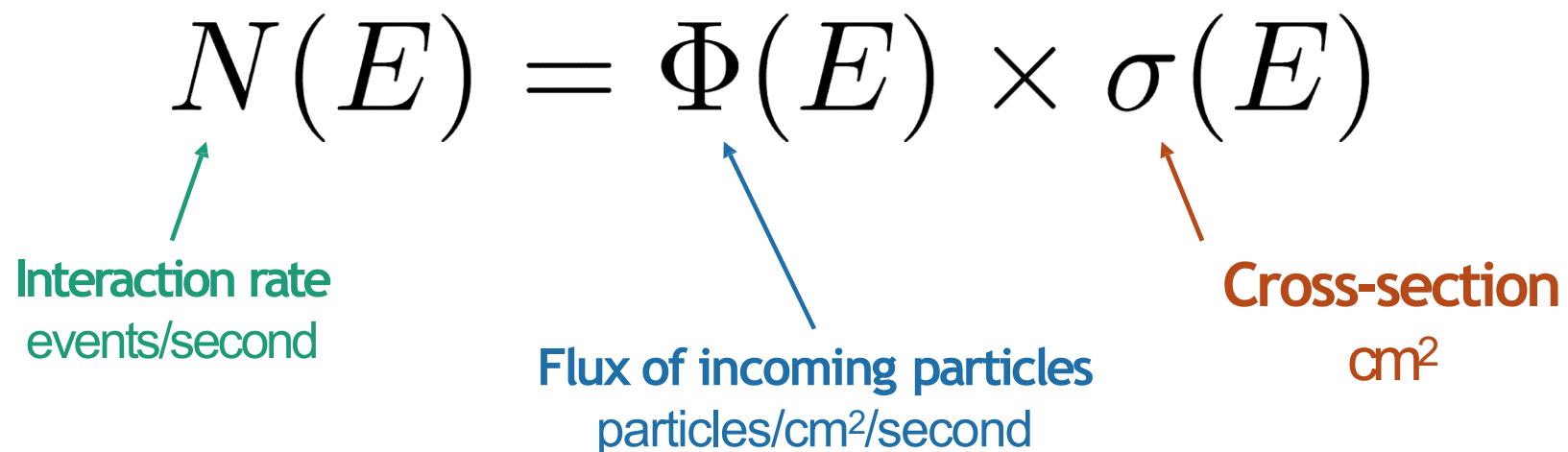
- A measure of interaction probability in particle physics.
- “Effective area of collision”
- Used to calculate predicted interaction rates:

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

Interaction rate
events/second

Flux of incoming particles
particles/cm²/second

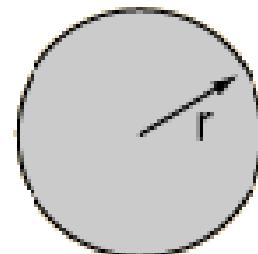
Cross-section
cm²



ASIDE

A NOTE ABOUT CROSS-SECTIONS

- Example:



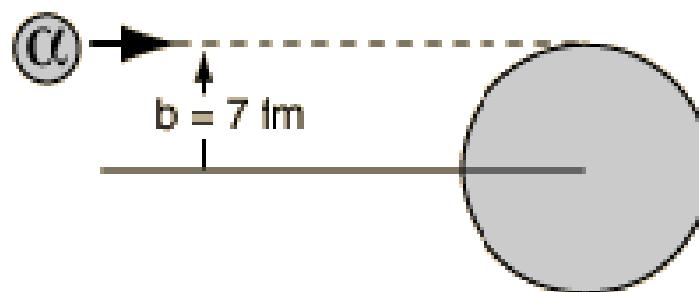
Gold nucleus
 $Z=79, A=197$

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

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

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

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



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 $KE_{\text{scattering}}$ 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).

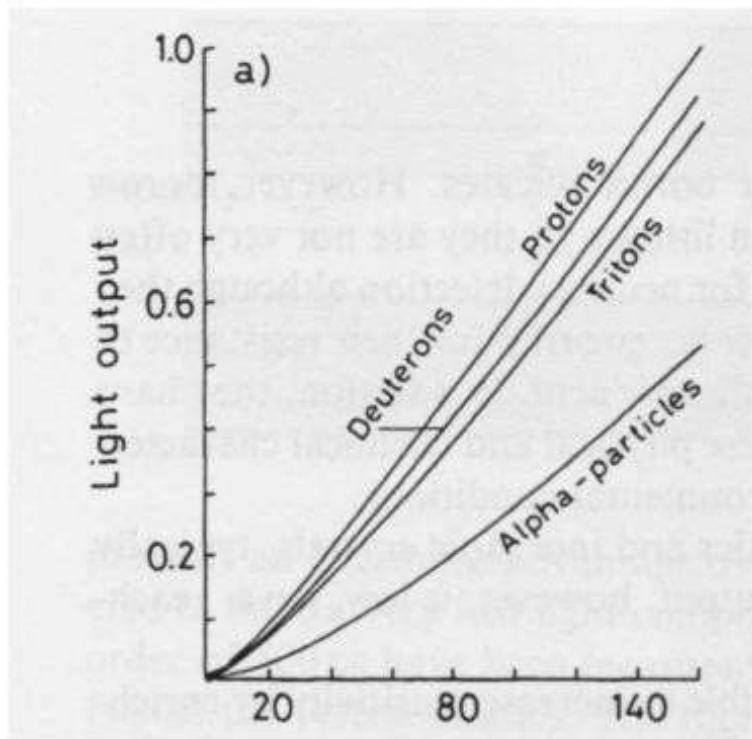
Increases with Z^2 , the number of protons in a nucleus.

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

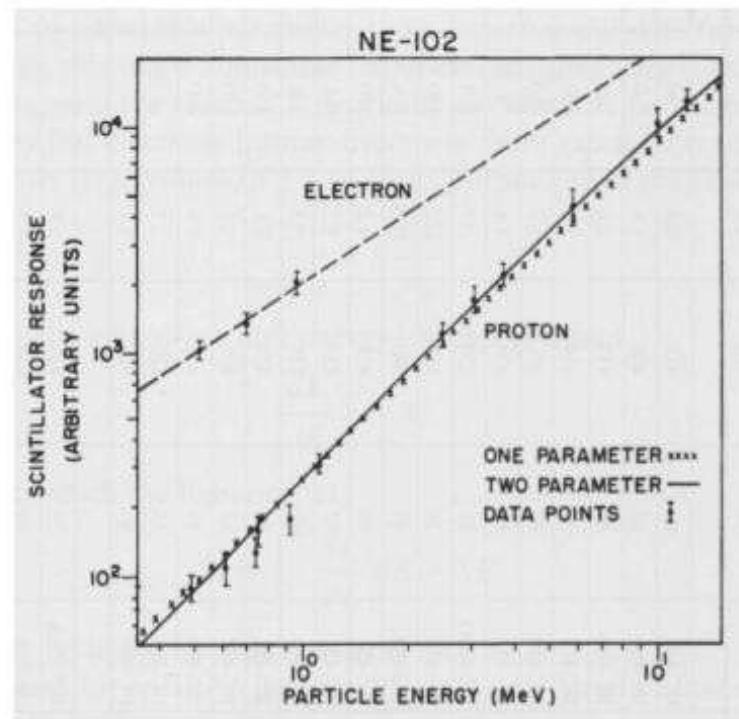
Decreases with the kinetic energy squared (KE^2) of the incoming particle.

SCINTILLATION DETECTORS

- Light output and type of particles / radiation.



particle energy [MeV]



NE-102 = common plastic scintillator