Particle tracking and Calorimeter in a nutshell

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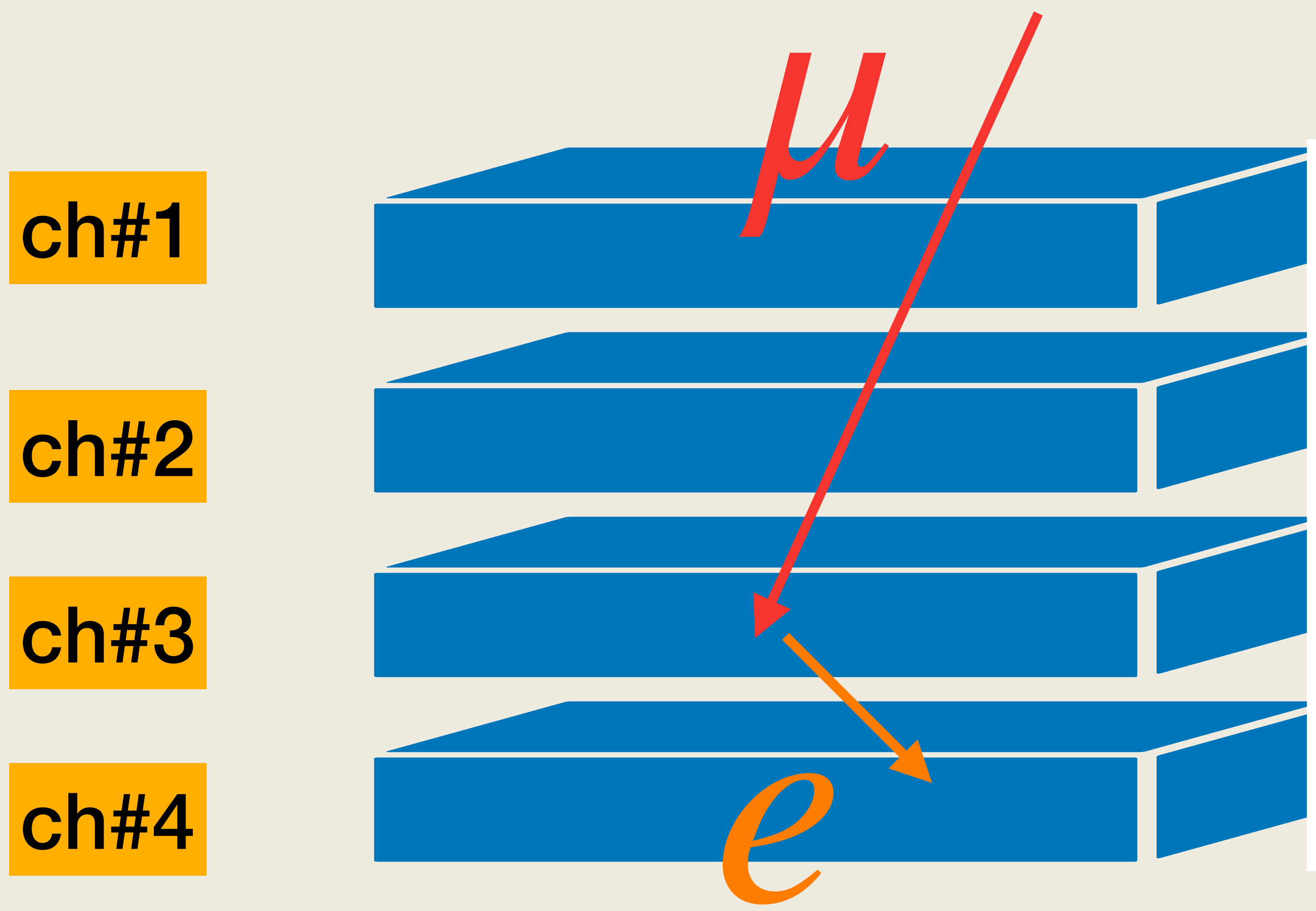
The particle detector is really complicated to be digested in a short lecture.

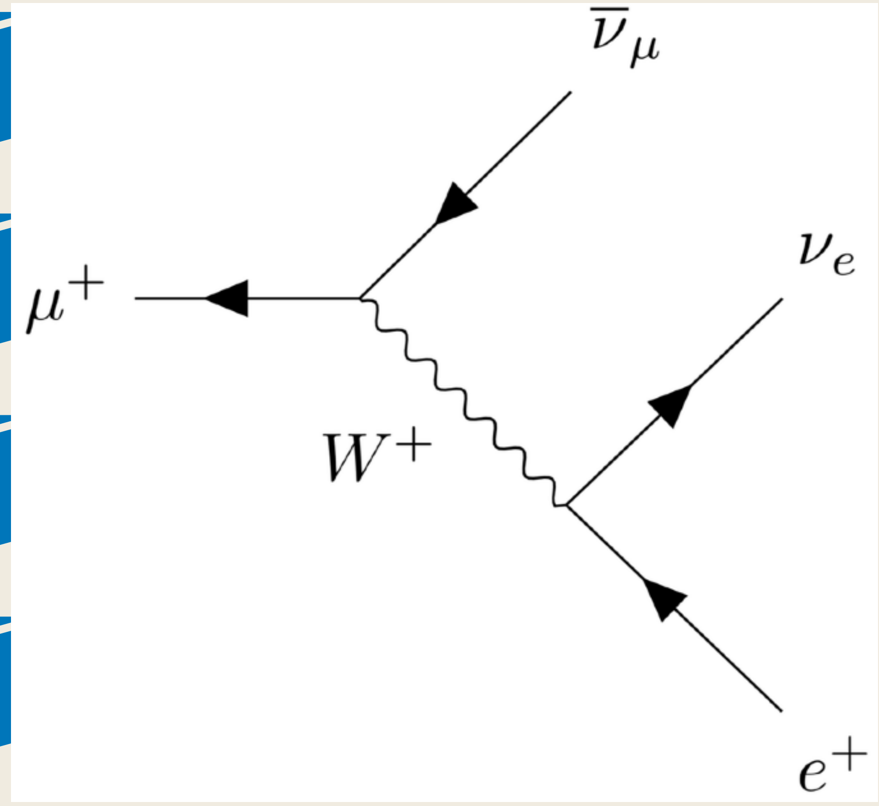
Target: general concepts and relevant technique used during this camp.

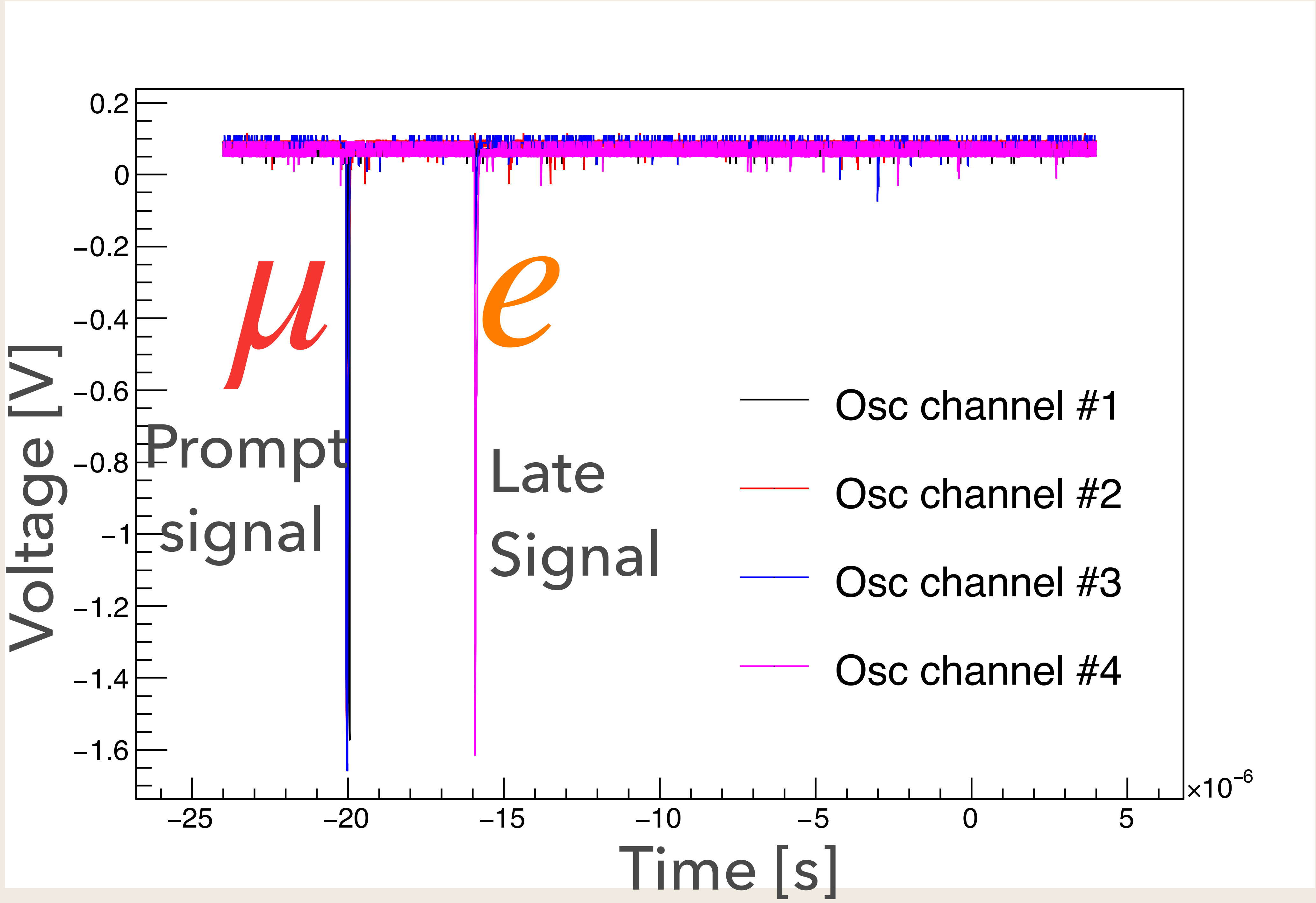
Start w/ questions regarding to muon decay measurement

How can be convinced that we observed is muon-to-electron decay?

- We know this process is possible (*from physics laws*)!
- *We *know** most of radiation/signal observed (*actually trigged w/ specific threshold and coincidence*) are muon induced by cosmic ray
- *We *assume** the late ~us signal is likely induced or related to the prompt signal
- (*Measurement of the timing different btw/ signal gives similar result to what we know well (~2.2us lifetime)*)





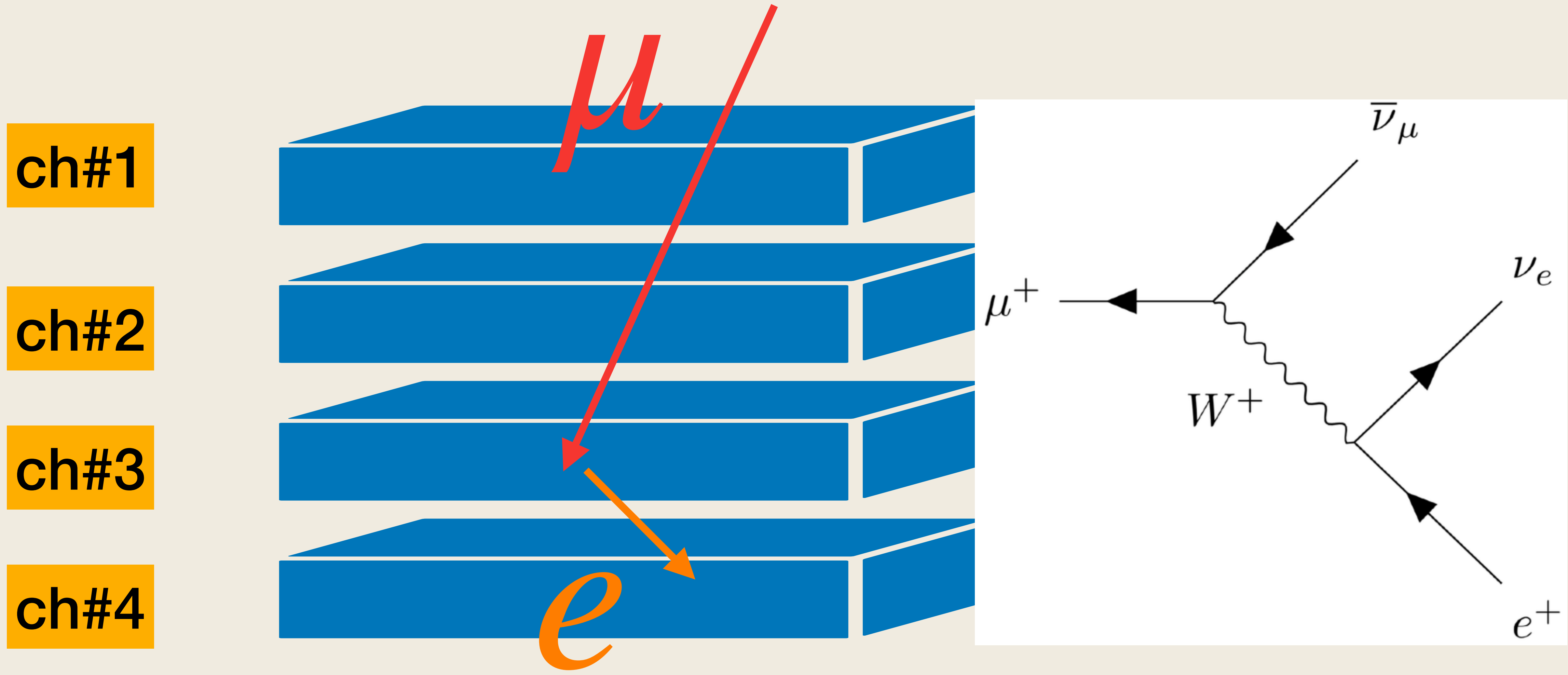


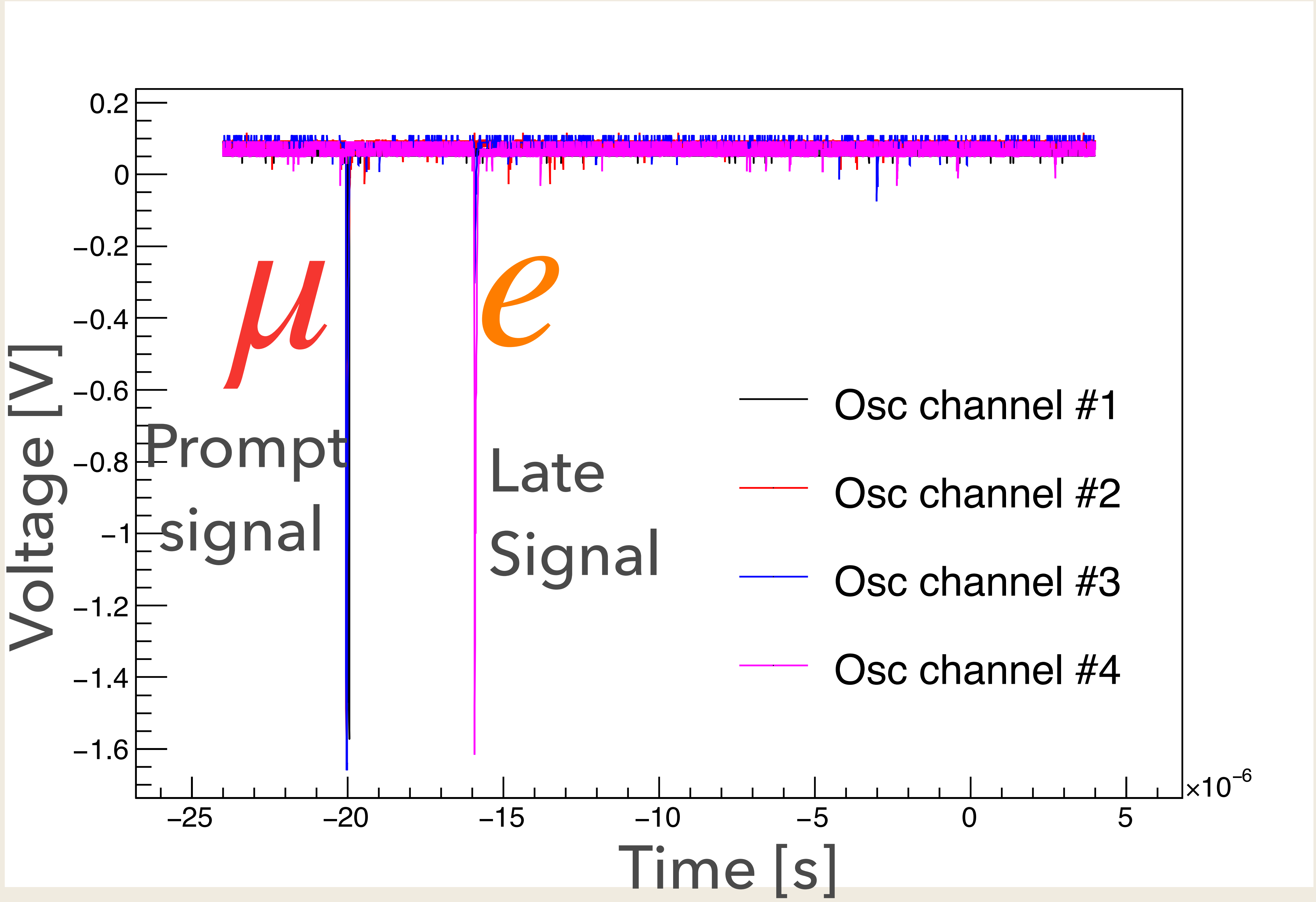
Why measuring cosmic-ray muon decay is useful/interesting?

- Will allow us to examine **the "time dilation" in special relativity**
  - **K**nowing 2.2us lifetime, if not taking relativistic effect, muon will travel ~ 600m before stopped
  - But we know most of muons produced in the upper atmospheric, ~ 10km (>>600m). So in classical mechanics, muons shouldn't reach the Earth surface
  - *If include the relativistic effect, range of 4GeV muons before decay is about 13.8 km.*
- Lifetime measurement will allow us to **estimate the Fermi coupling** constant which govern the weak interaction
- Allow to **test the Parity-violation** (*due to polarized nature of cosmic-ray muons and parity violation in the weak interaction*)
- Allow to verify that there are actually **two different kinds of neutrinos** are produced along with electron in muon decay

More arguments to support

- Need to identify the prompt signal as a muon
- Need to identify the late signal as a electron
- It's impossible to identify neutrinos *(since they interact weakly)* but we make sure all detector cover whole space and detect all particles involved
- Need to have *high spatial resolution* of muon and electron trajectories to tell that they seem to closely "meet" at one point
- Measure energy/momentum of muon and electron to be more convinced that muon is from atmospheric (~ 4GeV) and they follow the conservation law (*energy and momentum*)
- (*Parity violation in produced electron, referring to nature of polarized muons, which is decay product of downward pions*)





More arguments to support

- Need to identify the prompt signal as a muon
- Need to identify the late signal as a electron

→ PARTICLE IDENTIFICATION

- It's impossible to identify neutrinos *(since they interact weakly)* but we make sure all detector cover whole space and detect all particles involved

→ DETECTOR DESIGN

- Need to have *high spatial resolution* of muon and electron trajectories to tell that they seem to closely "meet" at one point

→ TRACKING DETECTOR

- Measure energy/momentum of muon and electron to be more convinced that muon is from atmospheric (~ 4GeV) and they follow the conservation law (*energy and momentum*)

→ CALORIMETER

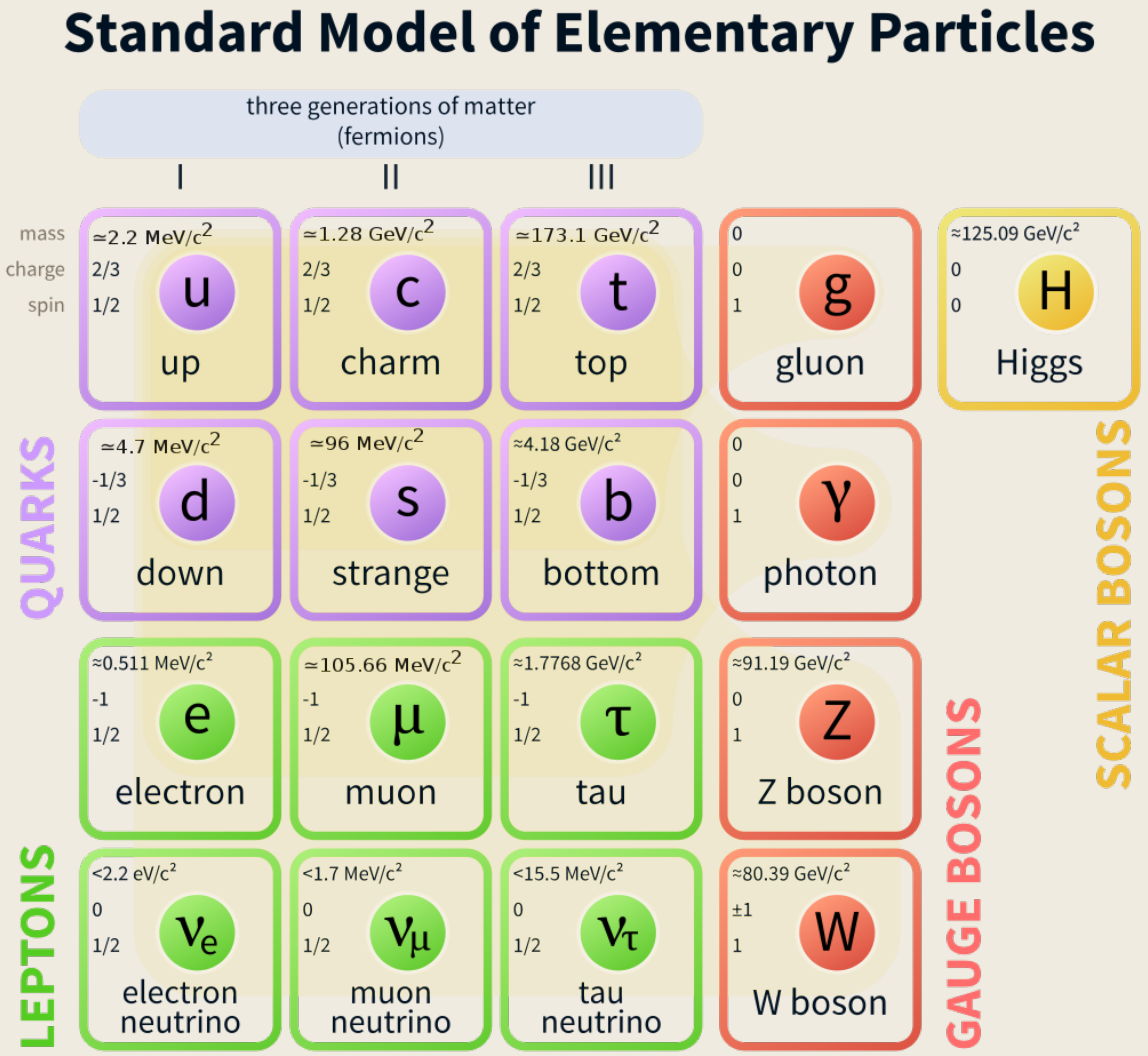
- (*Parity violation in produced electron, referring to nature of polarized muons, which is decay product of downward pions*)

→ PHYSICS LAW AND MOTIVATION

Particle identification

What kind of information used to identify particle?

- Mass
- Charge
- Spin
- "Flavor" (also "color")
  - Eg. *Electron neutrino and electron produced in pair*
- Allowed interaction processes and interaction strength
  - Eg. Leptons (muon, electron, neutrino) do not have strong interaction
- Prompt decay products (*eg. in case of W, Z, Higgs*)



Eg. Muon vs. electron

- They are basically the same except muon is ~ 200 time heavier than electron
  - Find the way to measure some observables which depends on mass. Eg. curvature under strong magnetic field

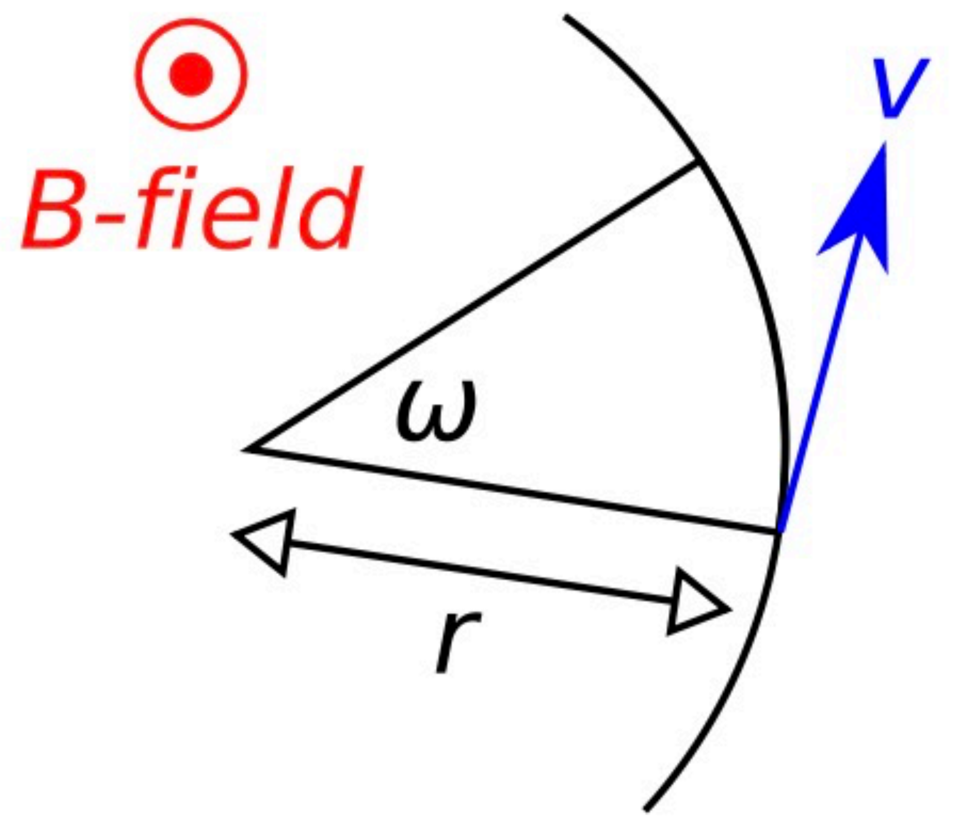


Figure 1: A particle with velocity v entering a magnetic field. In unit time the particle travels a distance v around the circle and turns through an angle ω.

$$F = qvB$$

$$ma = qvB$$

$$m\left(\frac{v^2}{r}\right) = qvB$$

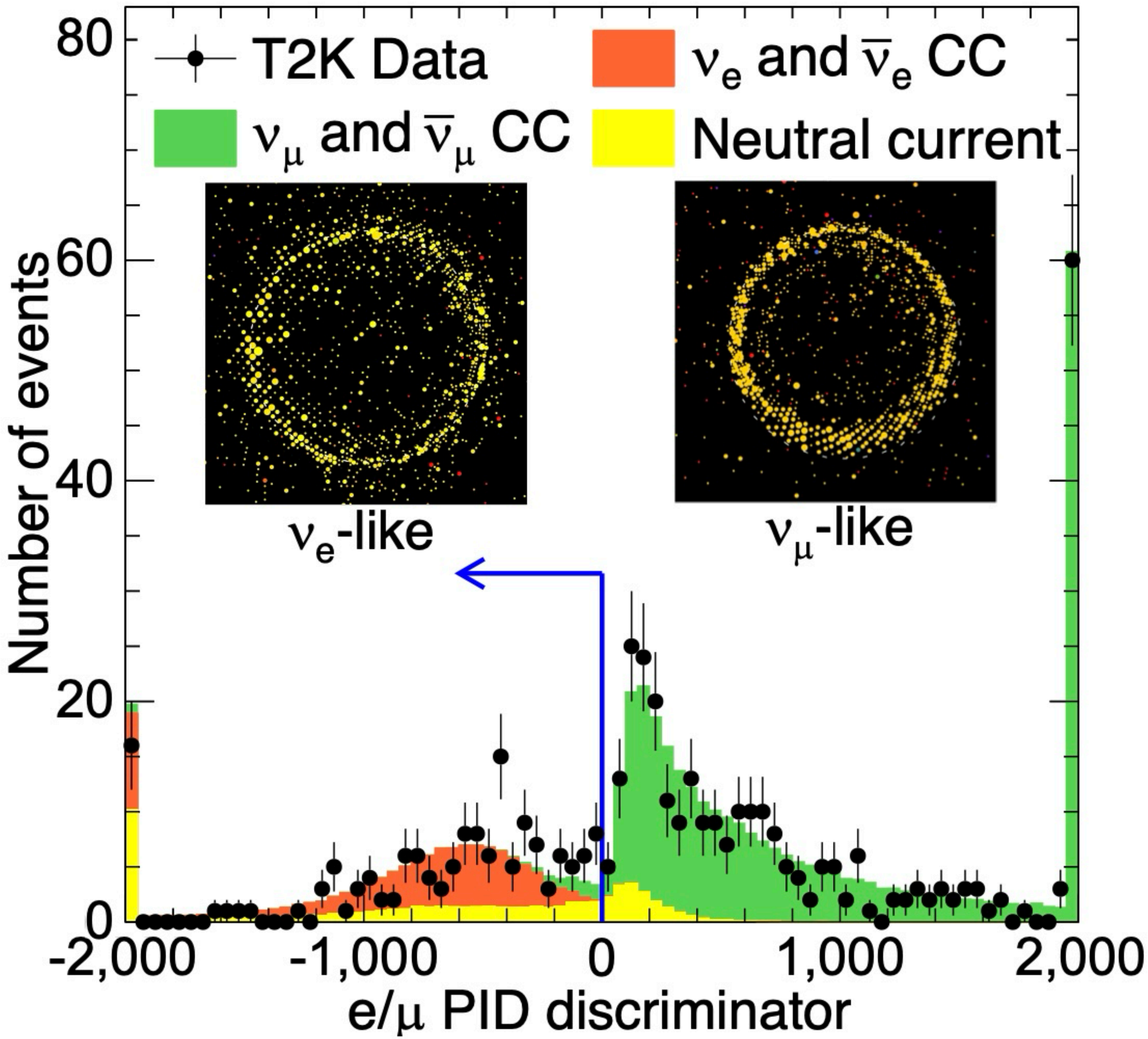
$$\frac{mv}{r} = qB$$

$$r = \frac{mv}{qB} = \frac{p}{qB}$$

$$r \propto p$$

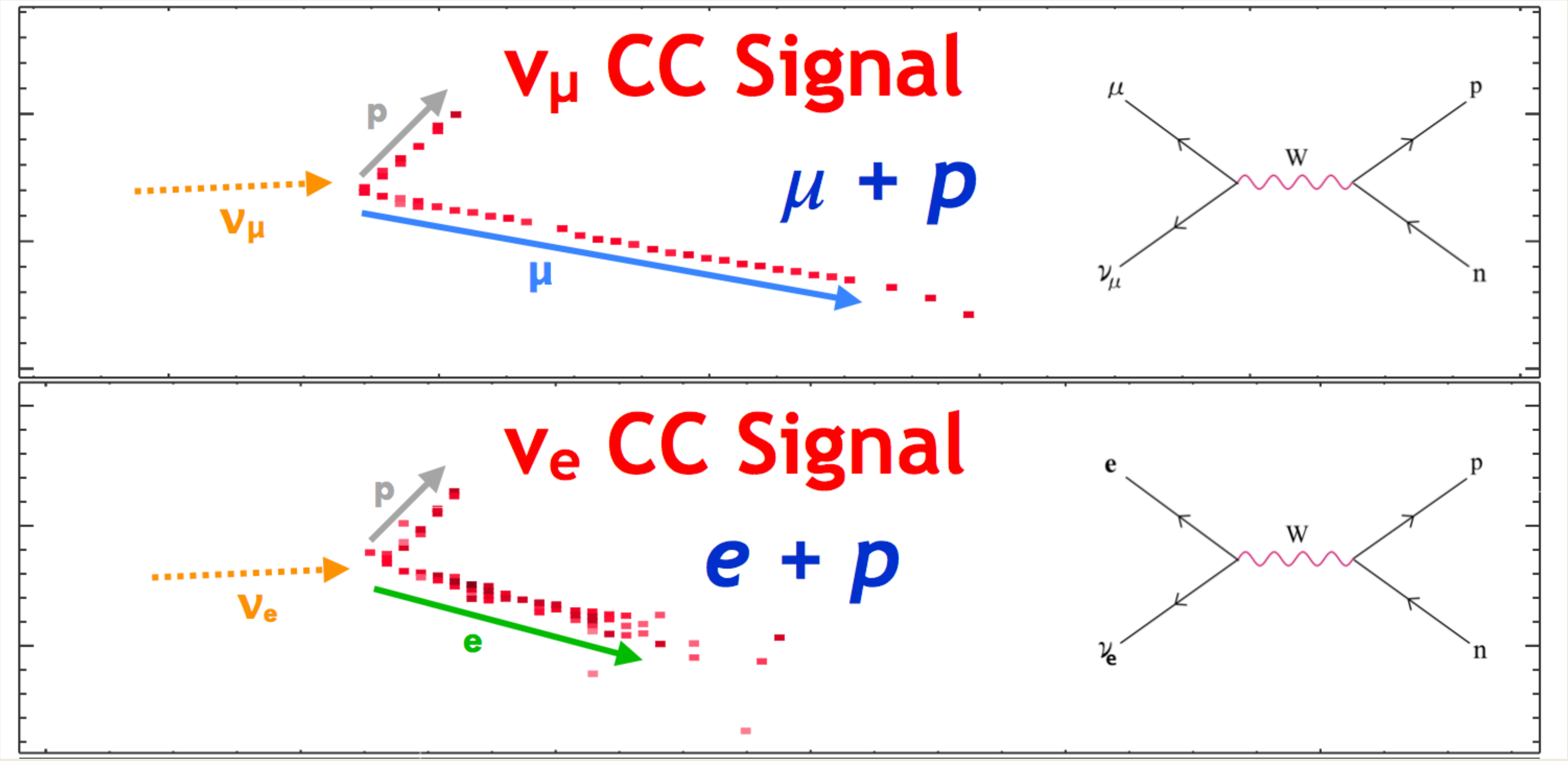
Eg. Muon vs. electron in Cherenkov

- Electron quickly develops electromagnetic shower and give a fuzzy ring pattern than muon
- **The *fuzziness* can be used as particle identity**
- *Also the Cherenkov threshold can be used for particle identity since it depends on particle*



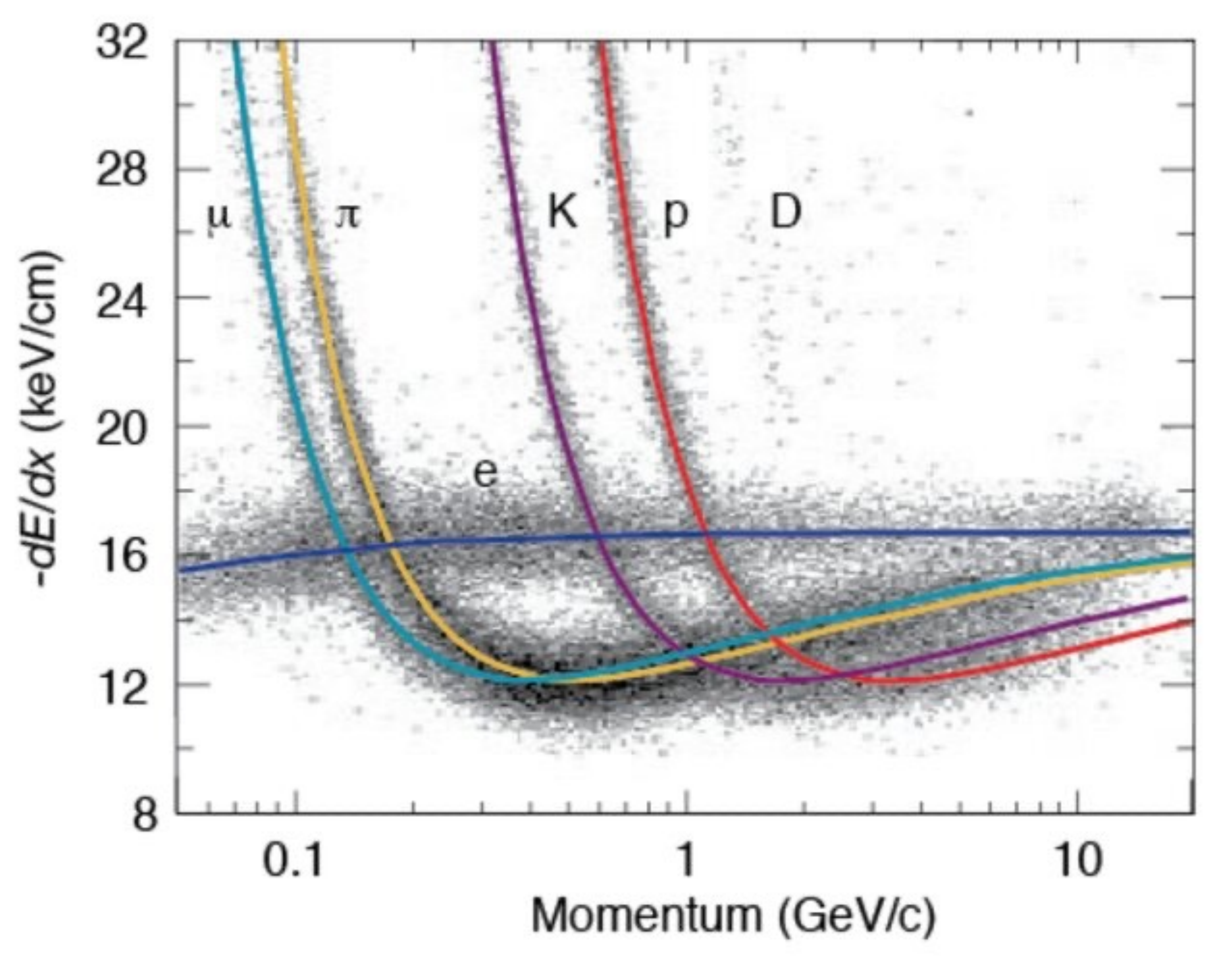
Eg. Muon vs. electron in Scintillator-based detector

NOvA, scintillator technique



More dedicated information/measuring

- **Relevant feature**: muon deposit more energy when slowing down
- If you measure muon decay, one more “convincing” point is that the muon deposit more energy than the non-stopped muon.



Average energy loss by a charged particle per length dx

Bethe-bloch formula

$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e^2 c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2}\left(\ln \frac{2 m_e c^2 \gamma^2 \beta^2}{I} - \beta^2 - \frac{\delta}{2} \right)$$

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

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

$N_A = 6.022 \cdot 10^{23} \text{mol}^{-1}$ = Avogadro number

$r_e = \frac{1}{4\pi\varepsilon_0} \frac{e^2}{m_e c^2}$ = classical electron radius

ε_0 – permittivity of free space

m_e^2 = electron mass

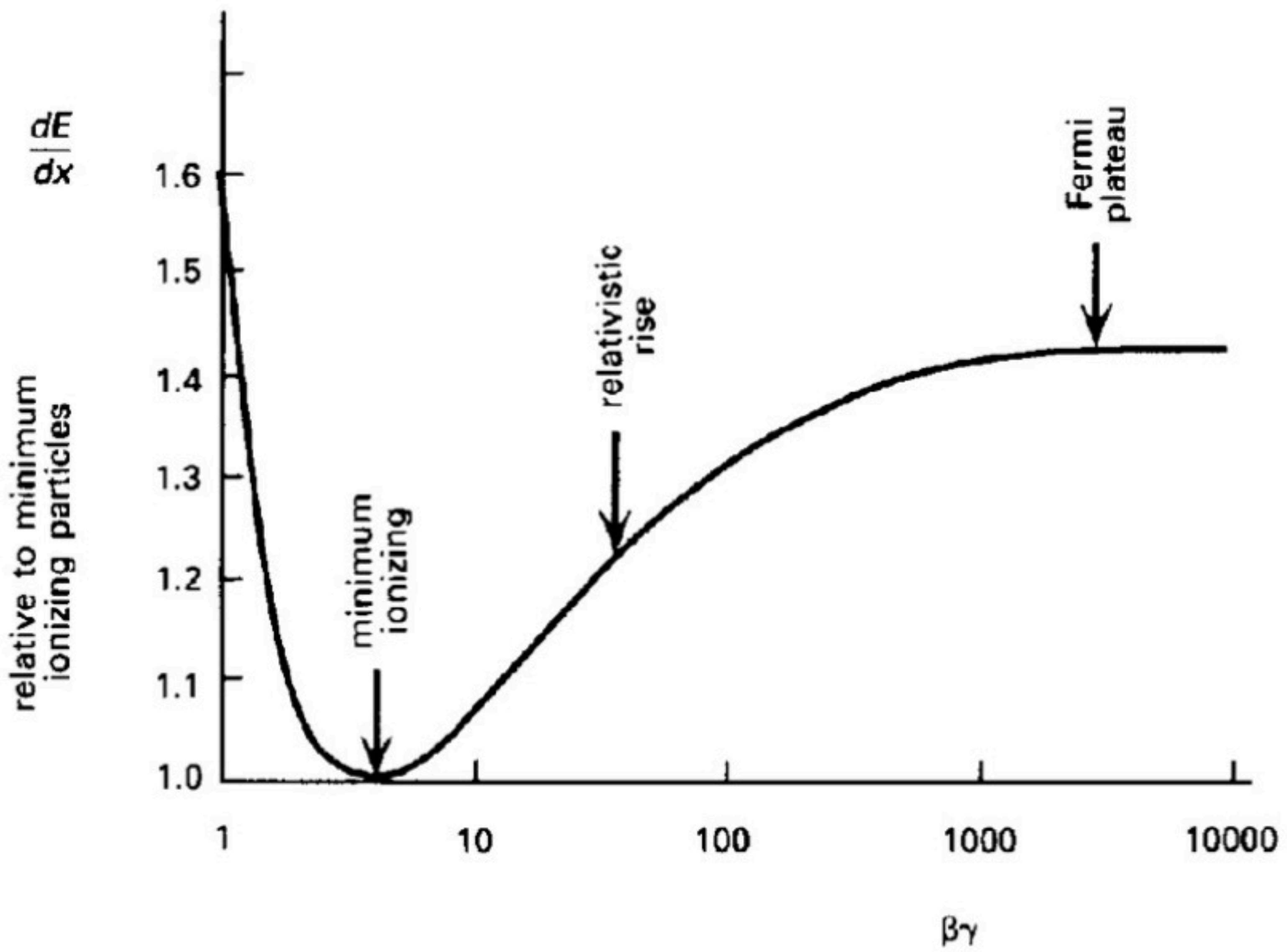
c = speed of light

z = charge of the incident particle

$\frac{Z}{A}$ = atomic number and weight of target

I = effective ionization potential

δ = density correction



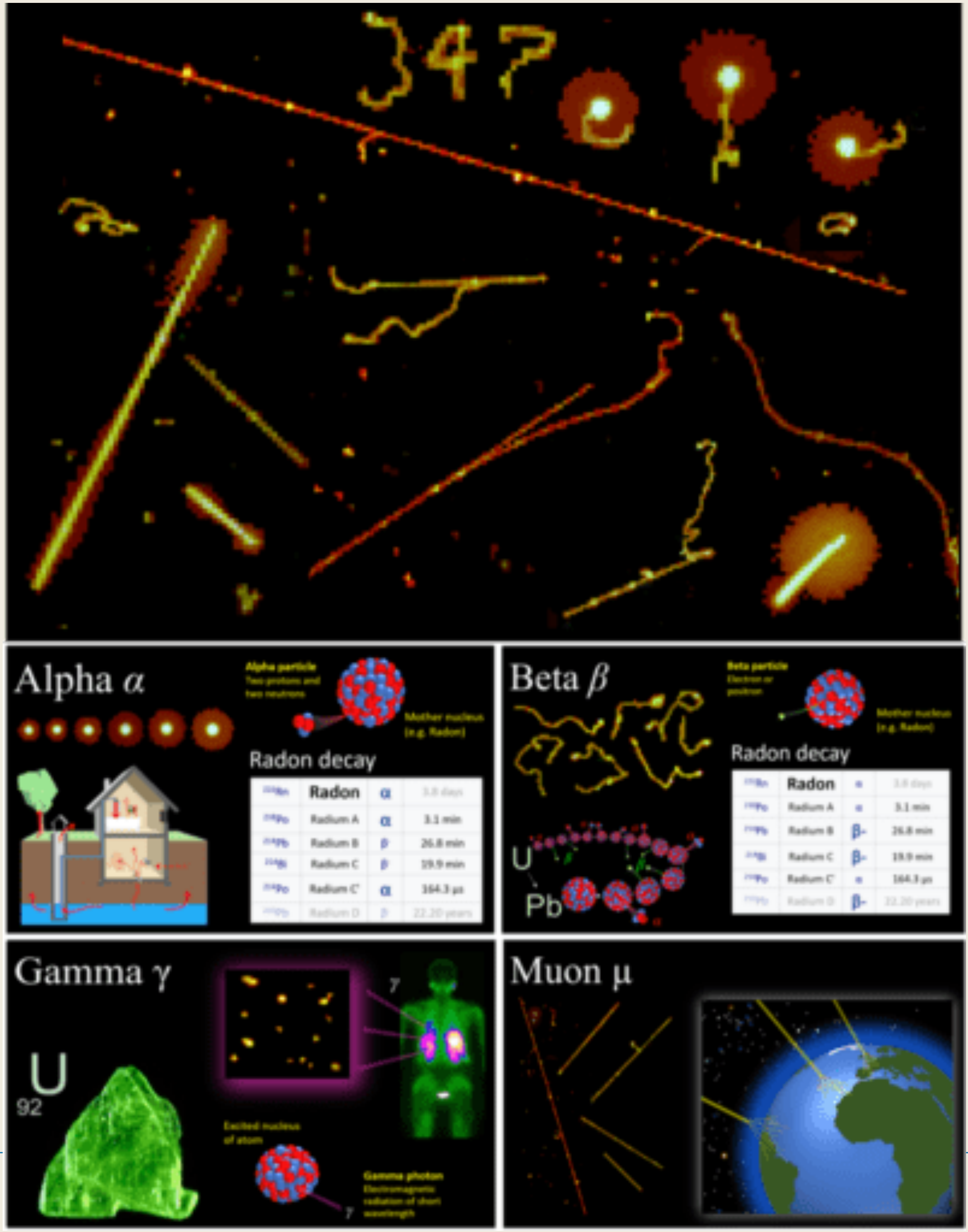
Tracking detector

Tracking detector

To reveals the path, or "track", of a (charged) particle by providing

- Spatial information
- Temporal information
- *While tracking, the detector also provide (partly) information of particle energy via measuring of the energy loss*
- *Sometimes, tracking detector can be designed to measure some particle properties, eg. charge, and/or momentum.*

Eg. State-of-art of radiation tracking to the classroom



A transferred technology by CERN, being use by NASA

(Sometimes in the future, we hope to have this!)

https://advacam.com/application/education/

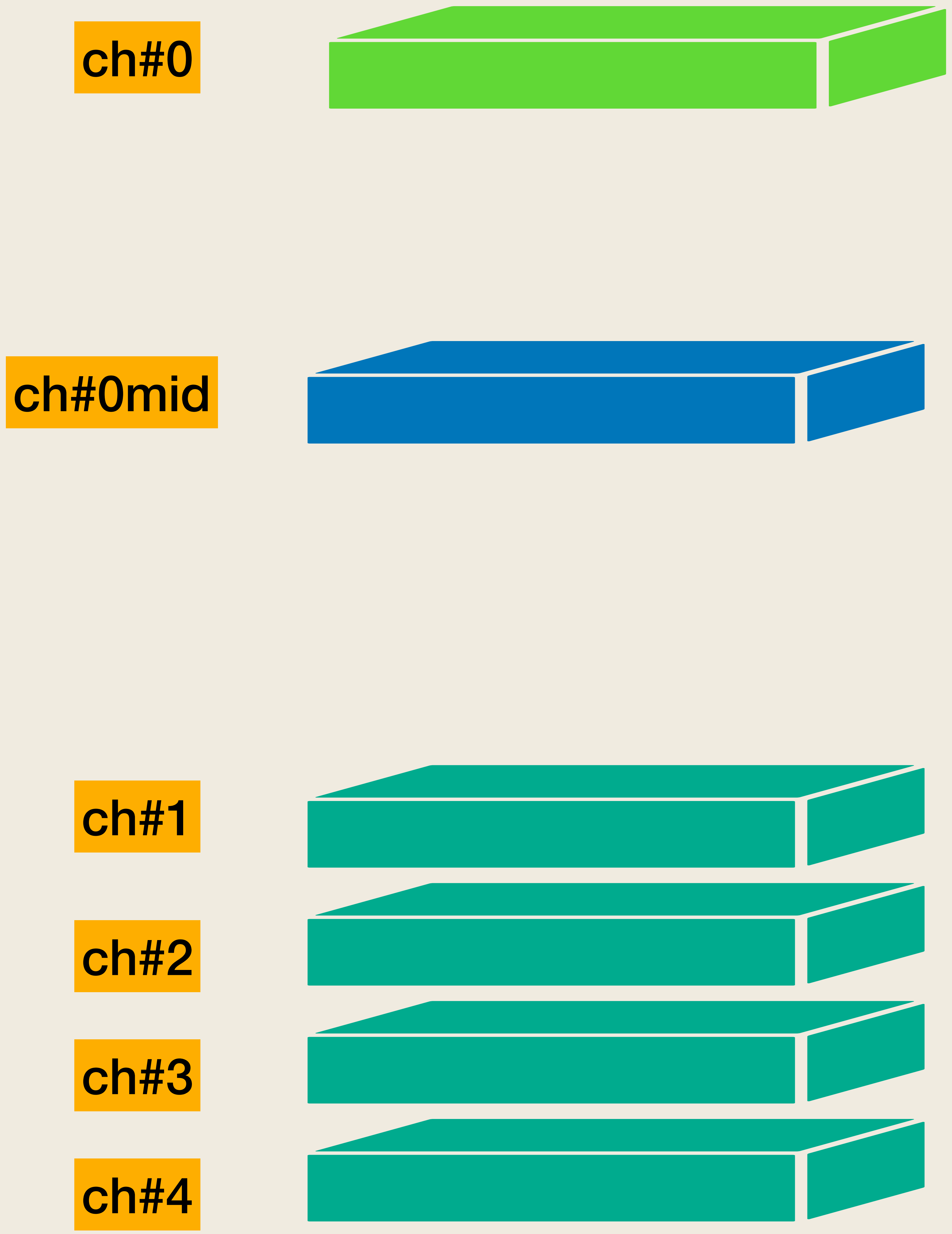
Principle for tracking

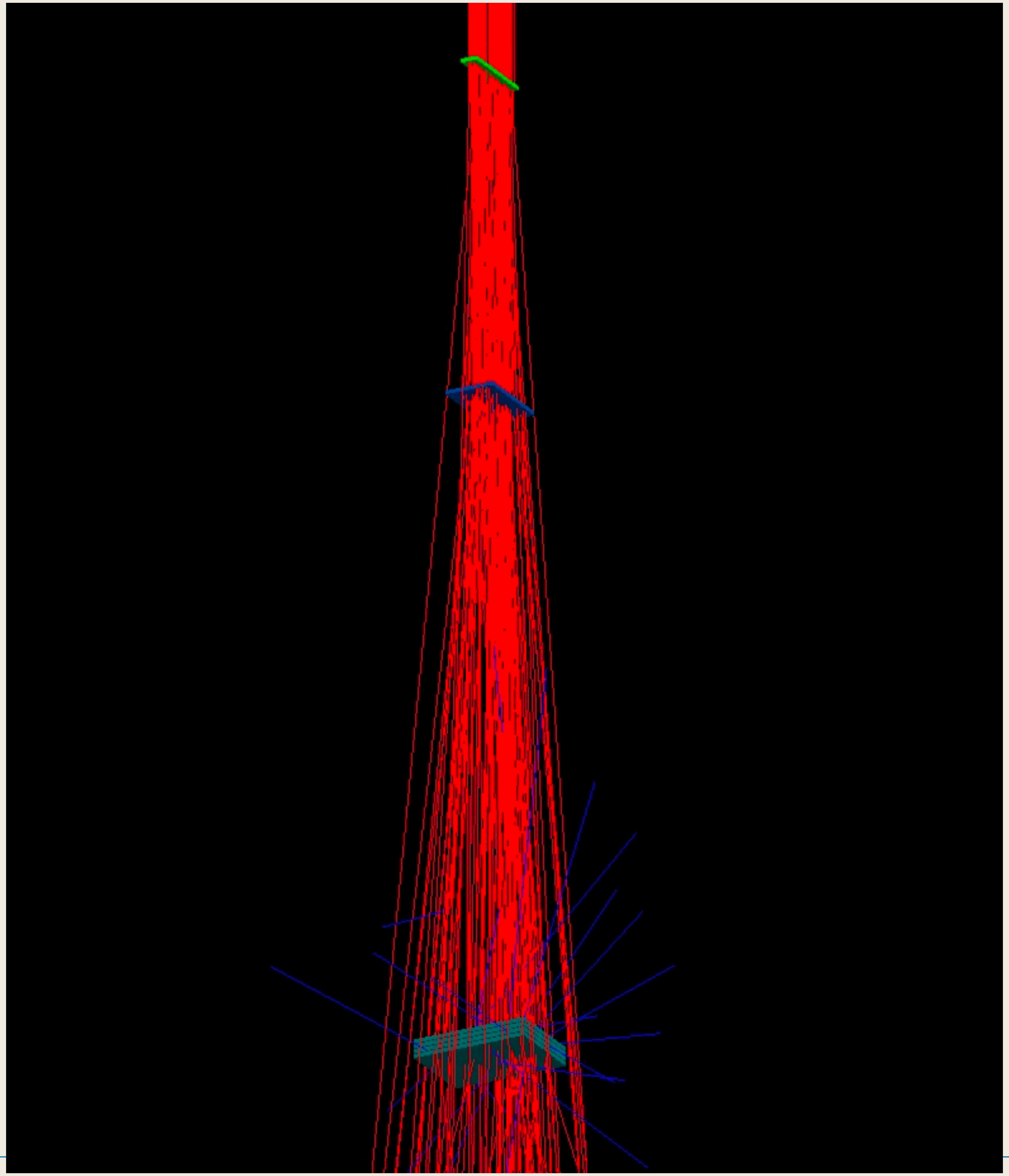
Charged particle passing through matter

- Create **electron-ion pairs** in the gas
- **Electron-hole pairs** in semiconductor
- **Scintillation light** from excited molecules (liquid/plastic scintillators)
- **Cherenkov light** in the transparent materials
- …

Understand these fundamental processes is critical for designing a tracking system.

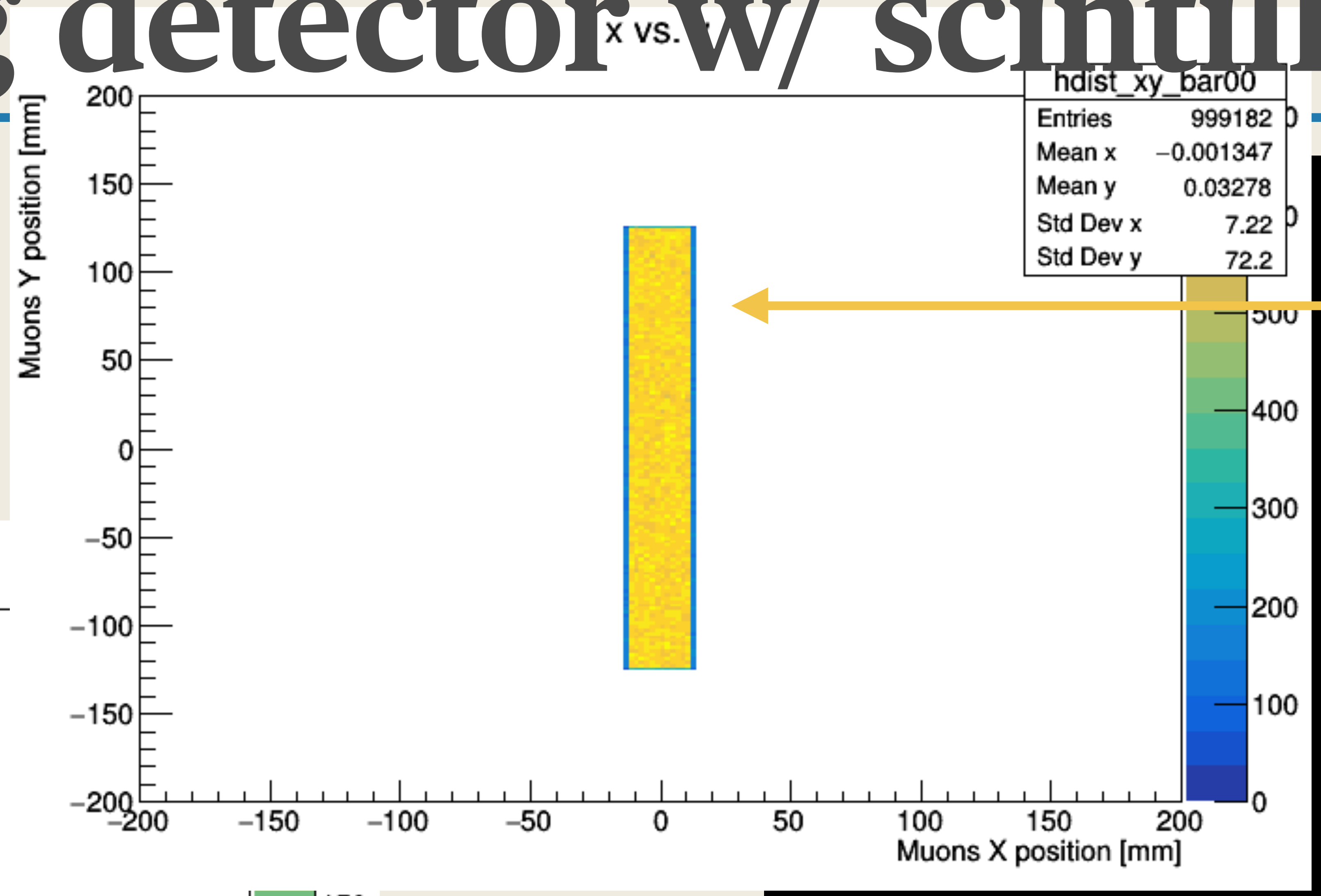
Simple tracking detector w/ scintillator (Simulation)

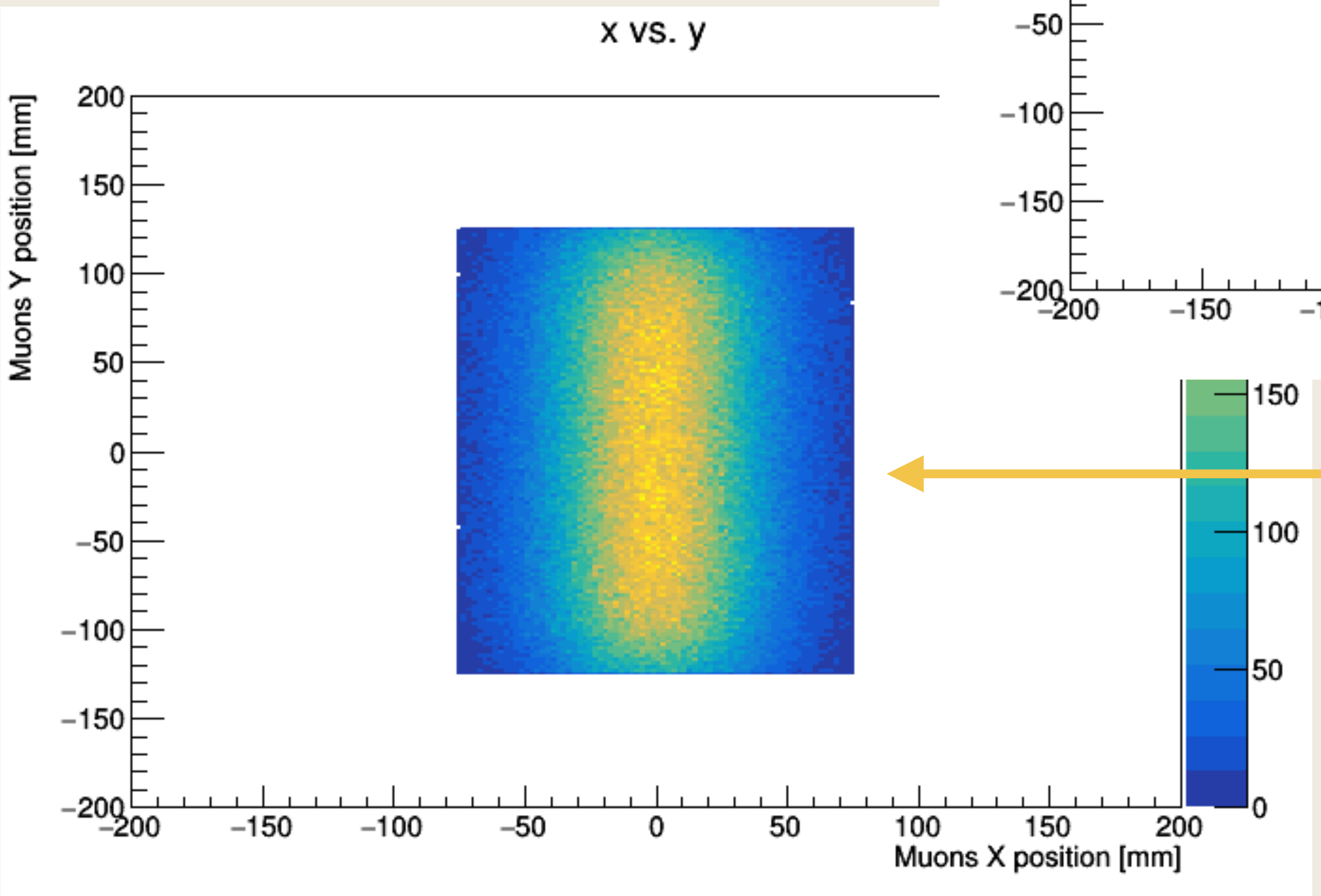


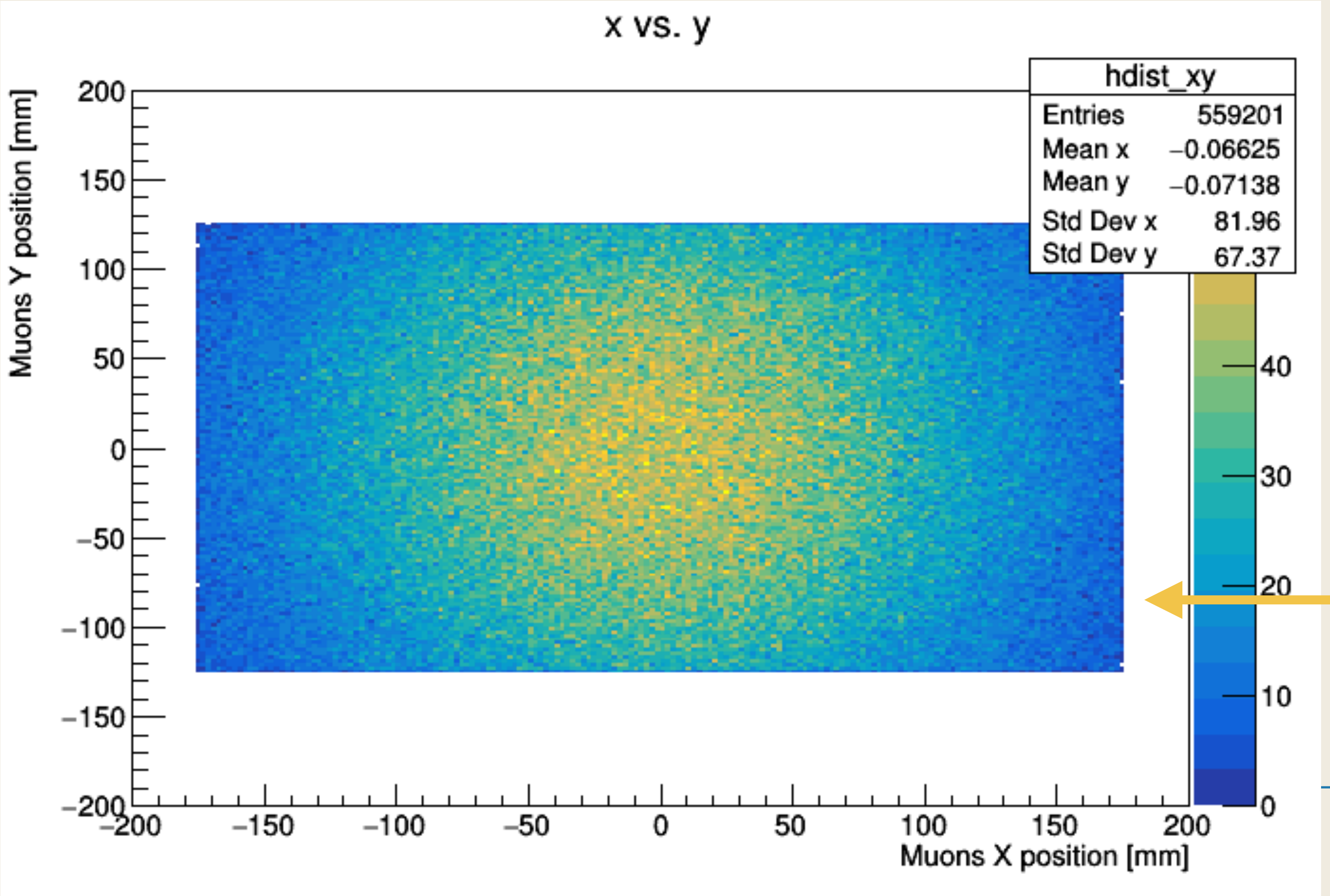


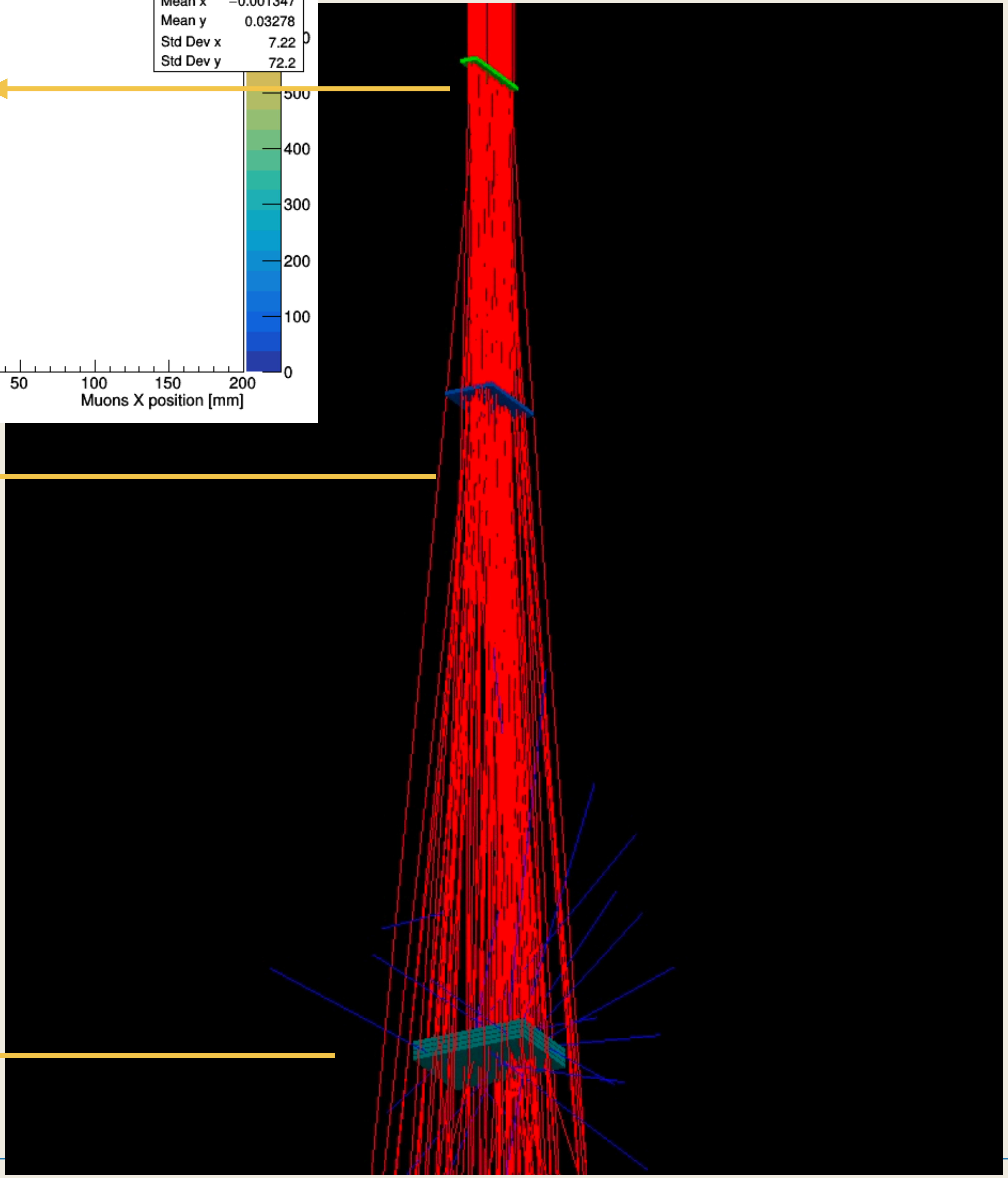
Simple tracking detector w/ scintillator (Simulation)

EG. SPATIAL INFORMATION



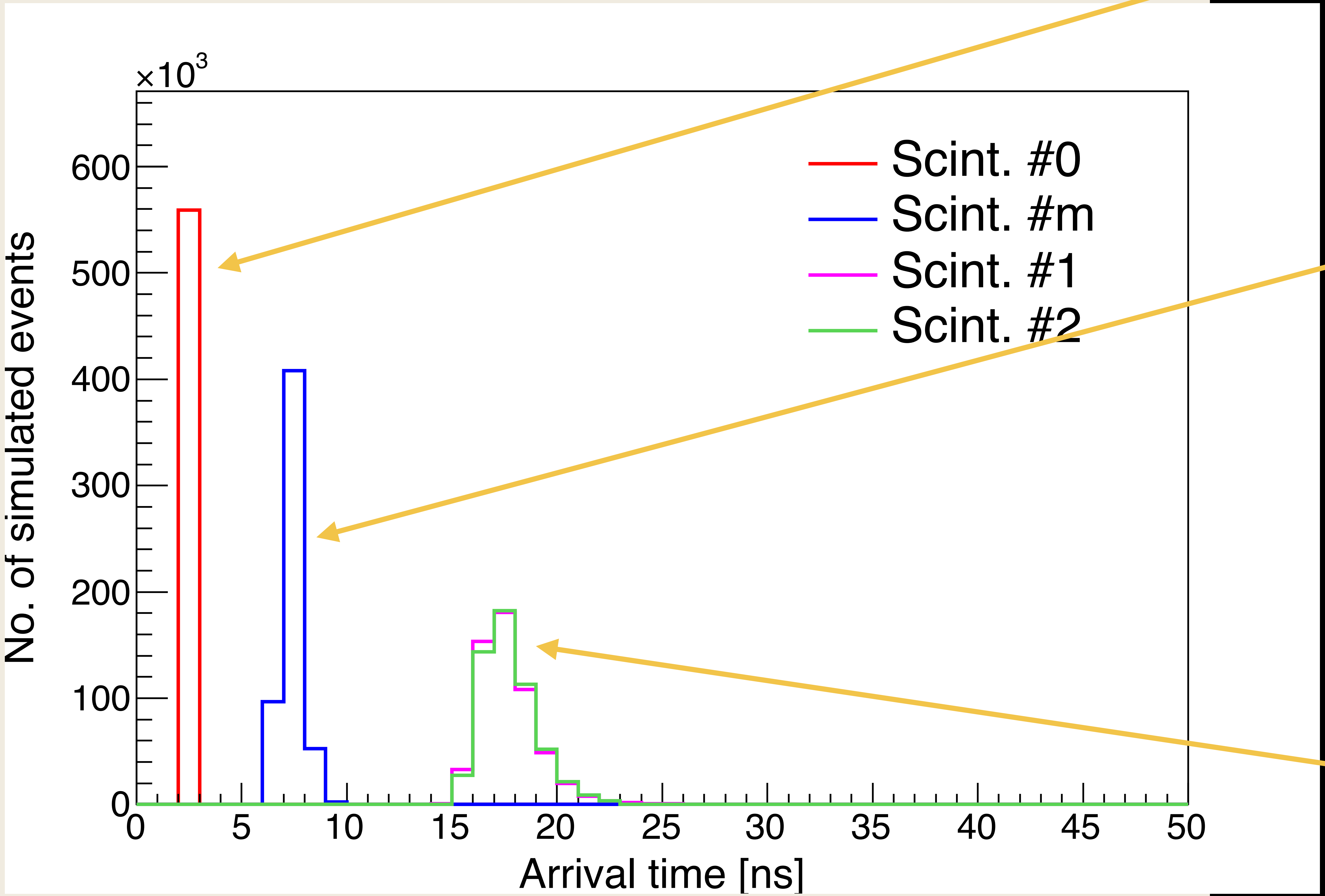


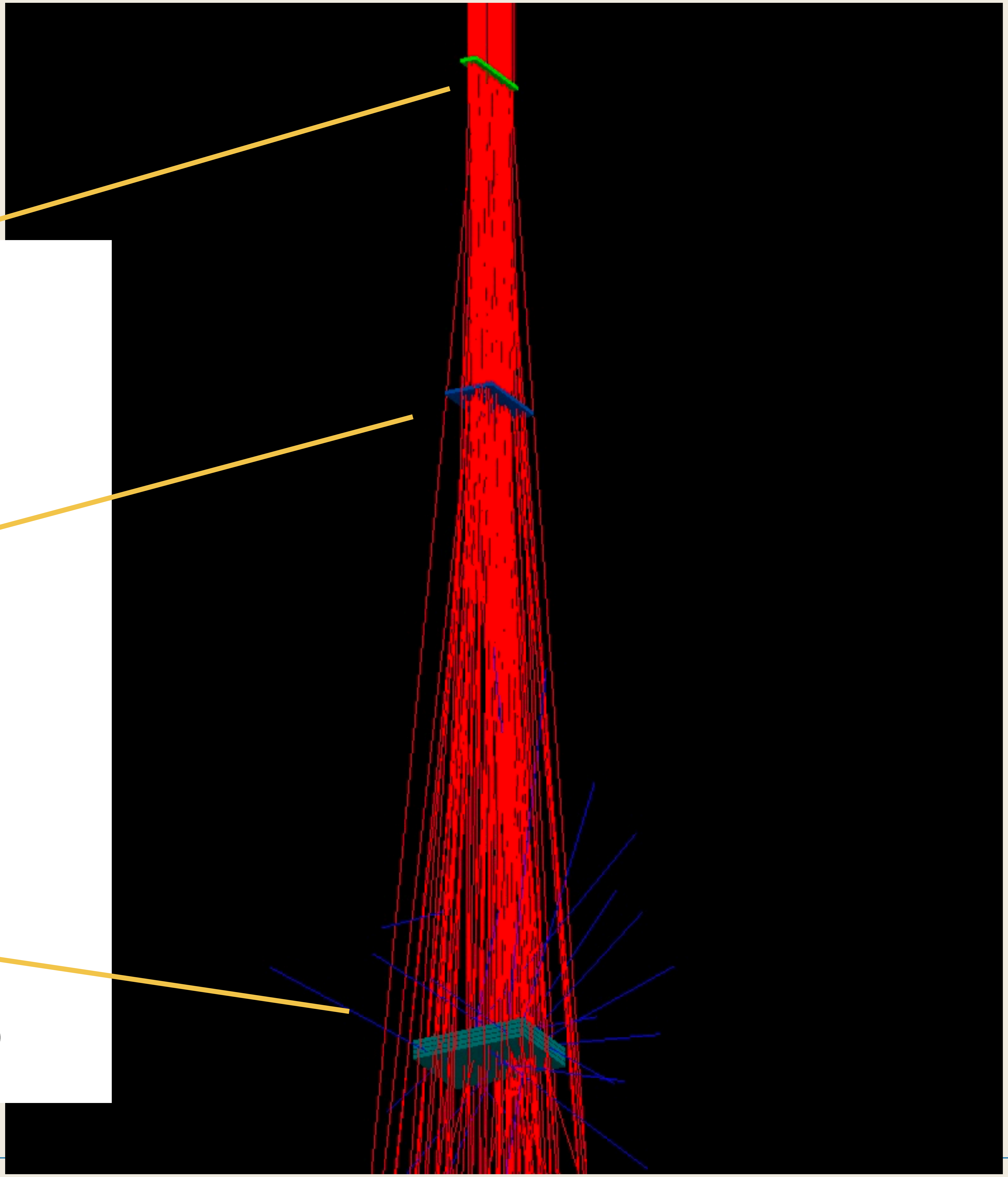




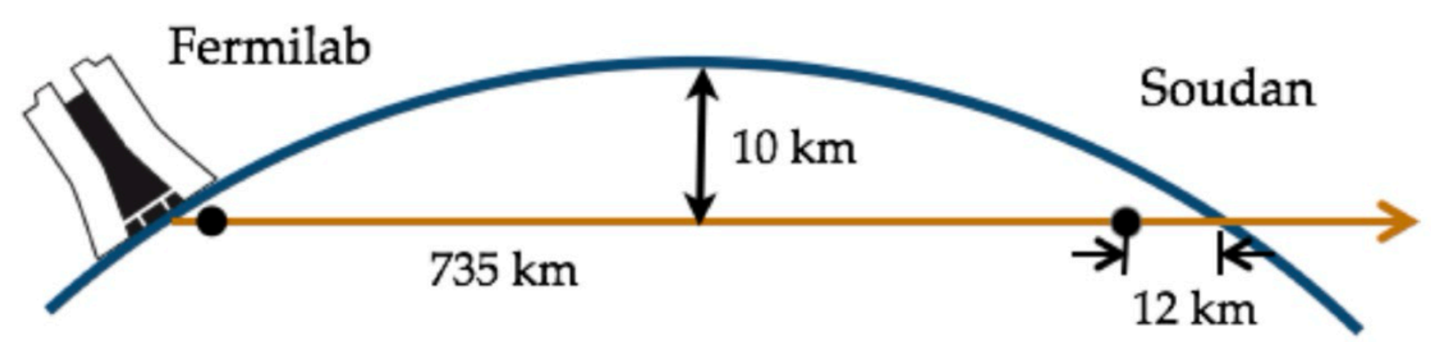
Simple tracking detector w/ scintillator (Simulation)

EG. TEMPORAL INFORMATION

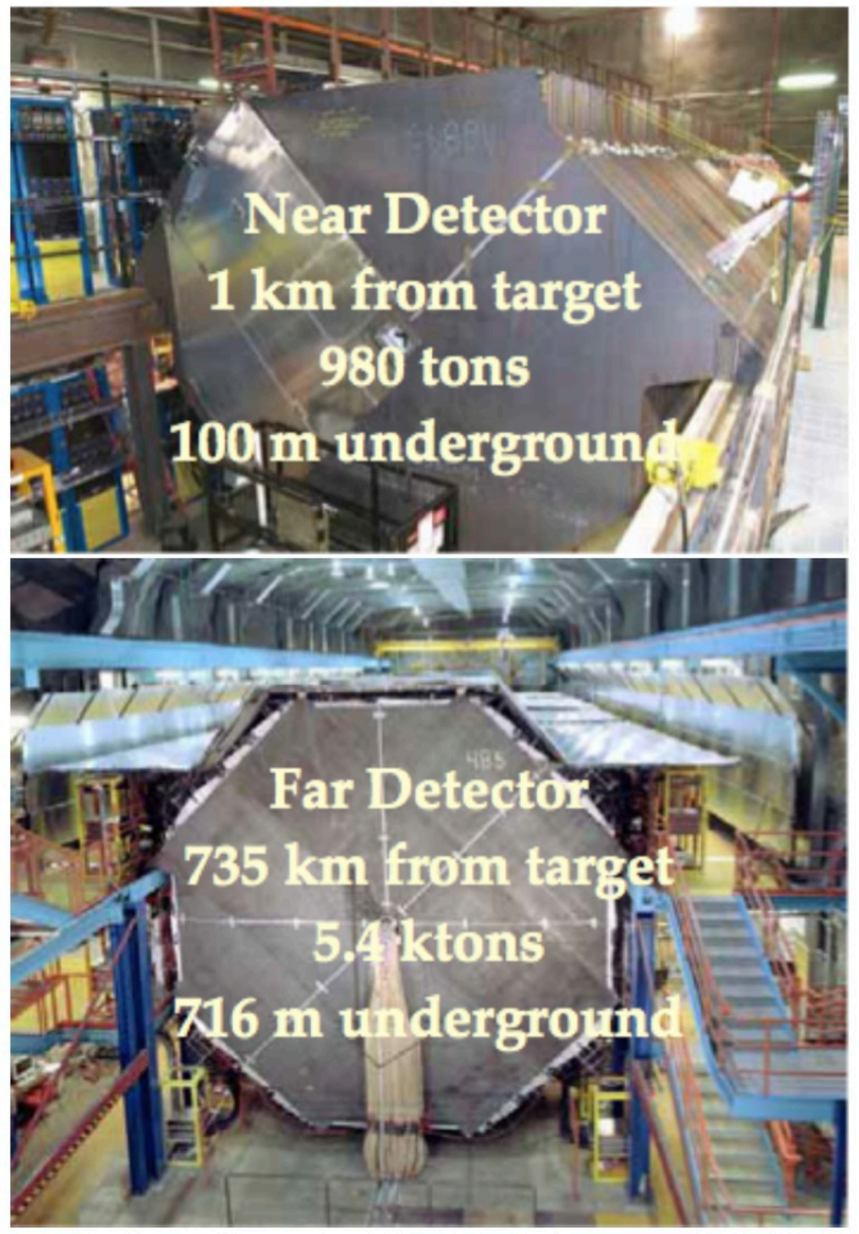


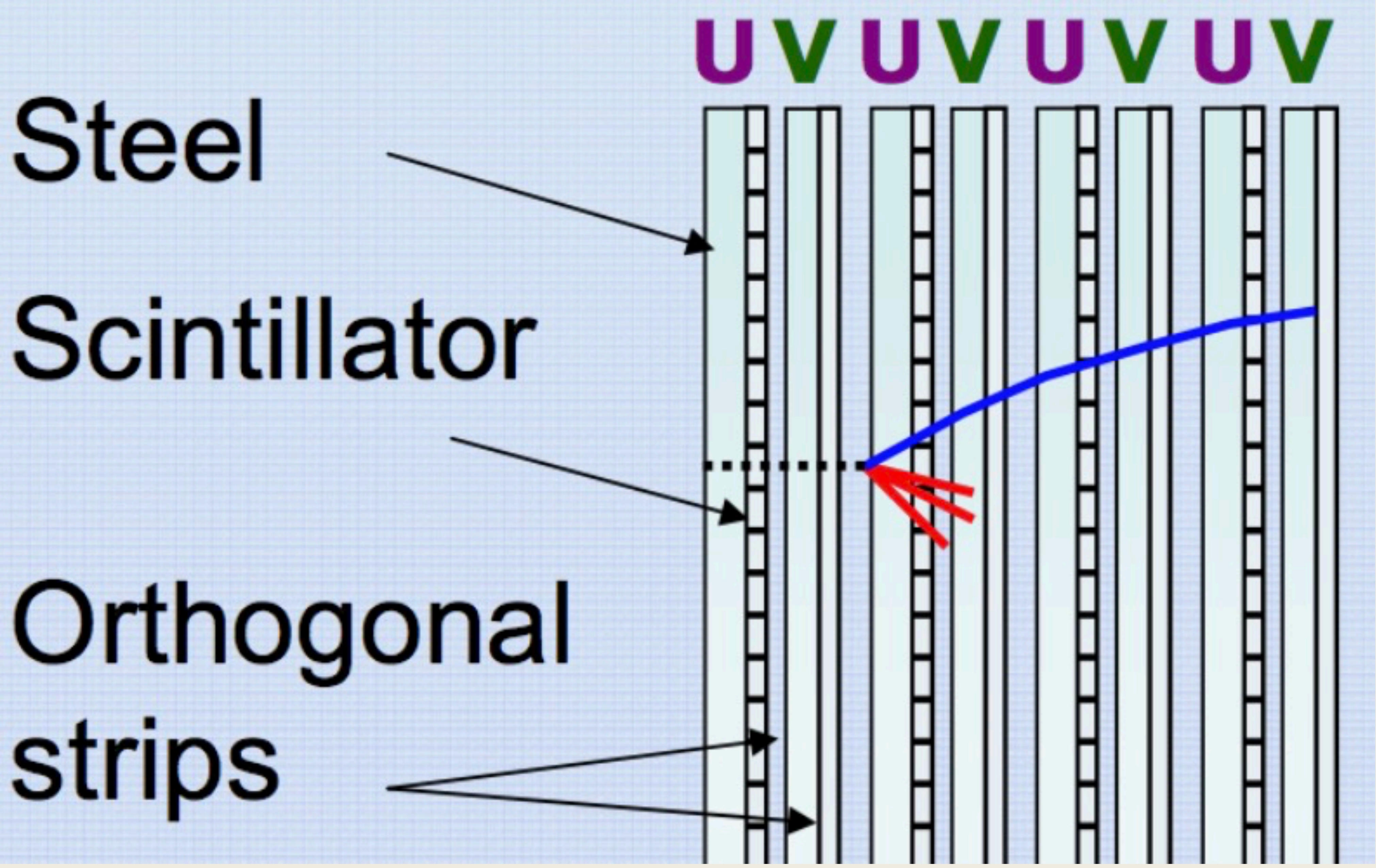


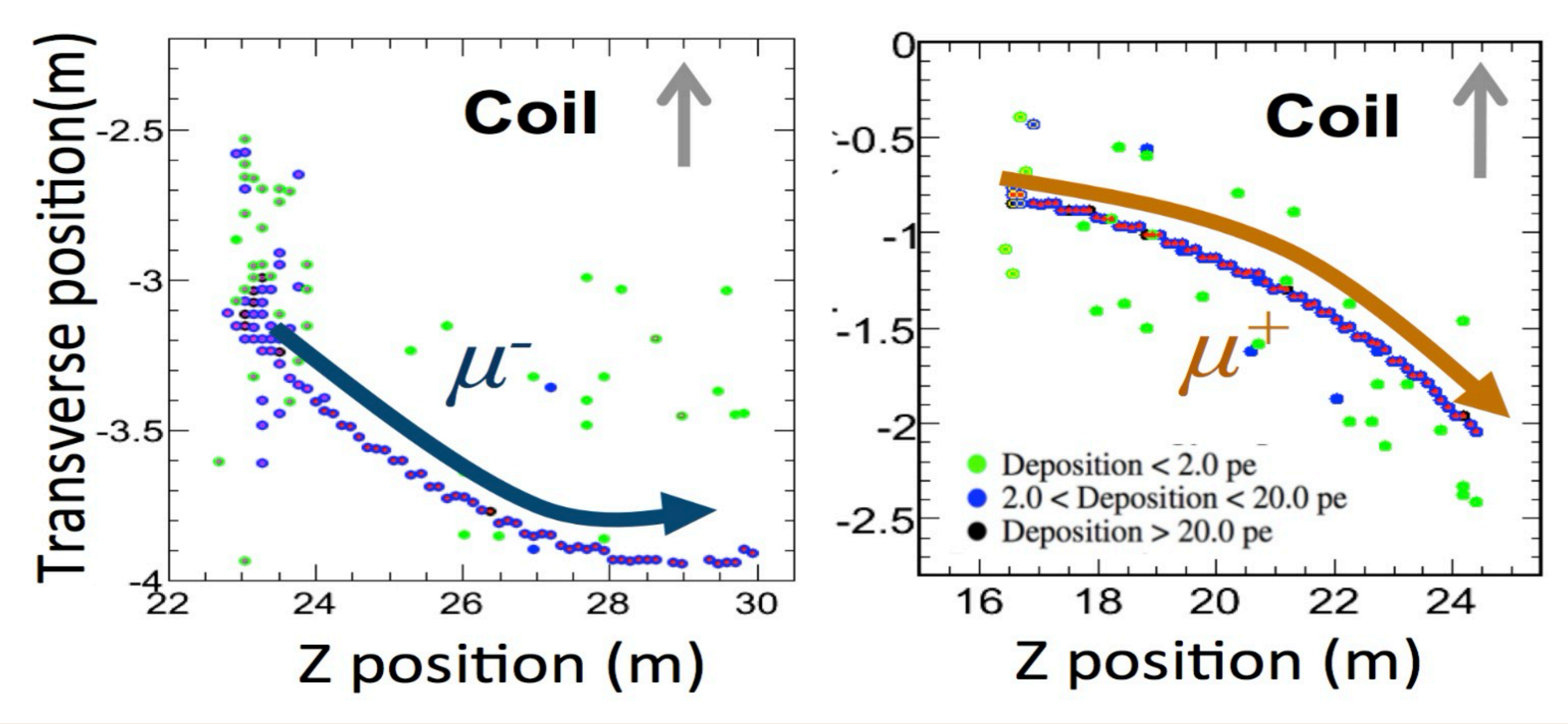
Eg: Tracking with MINOS experiment



- ✧ NuMI high intensity neutrino beam
- ✧ Near Detector at Fermilab, IL
- ✧ Far Detector at Soudan, MN
- ✧ Two-detector design to mitigate systematic uncertainties





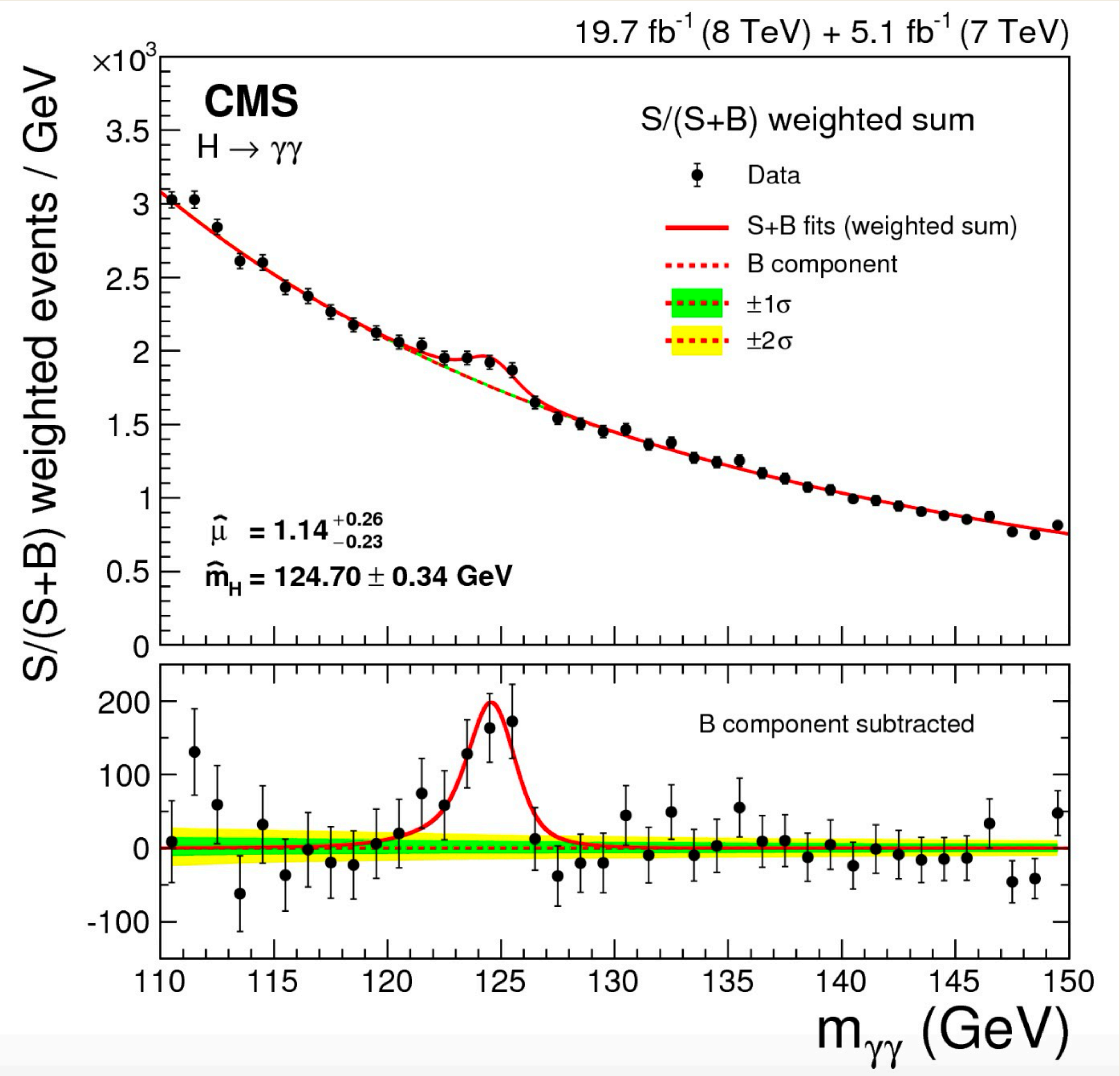


Calorimeter

Calorimeter

To determine the energy of particle with some level of precision using the "energy loss phenomena"

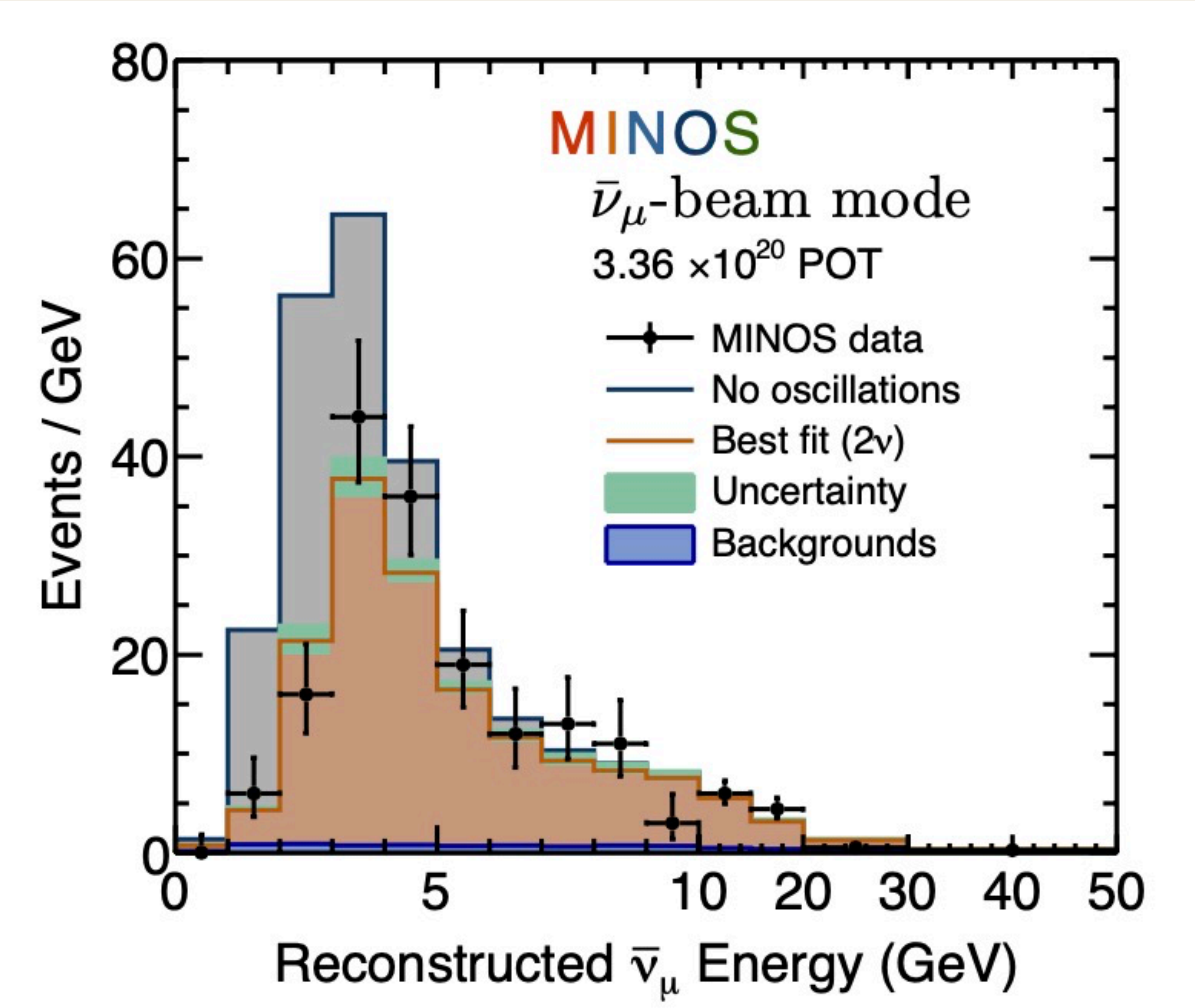
- You can't measure directly but reconstruct from the signal induced of energy loss of particle
- Energy loss is proportional to the particle energy
- For some physics (*eg. Higgs discovery, neutrino oscillation…*), measuring the energy precisely is vital

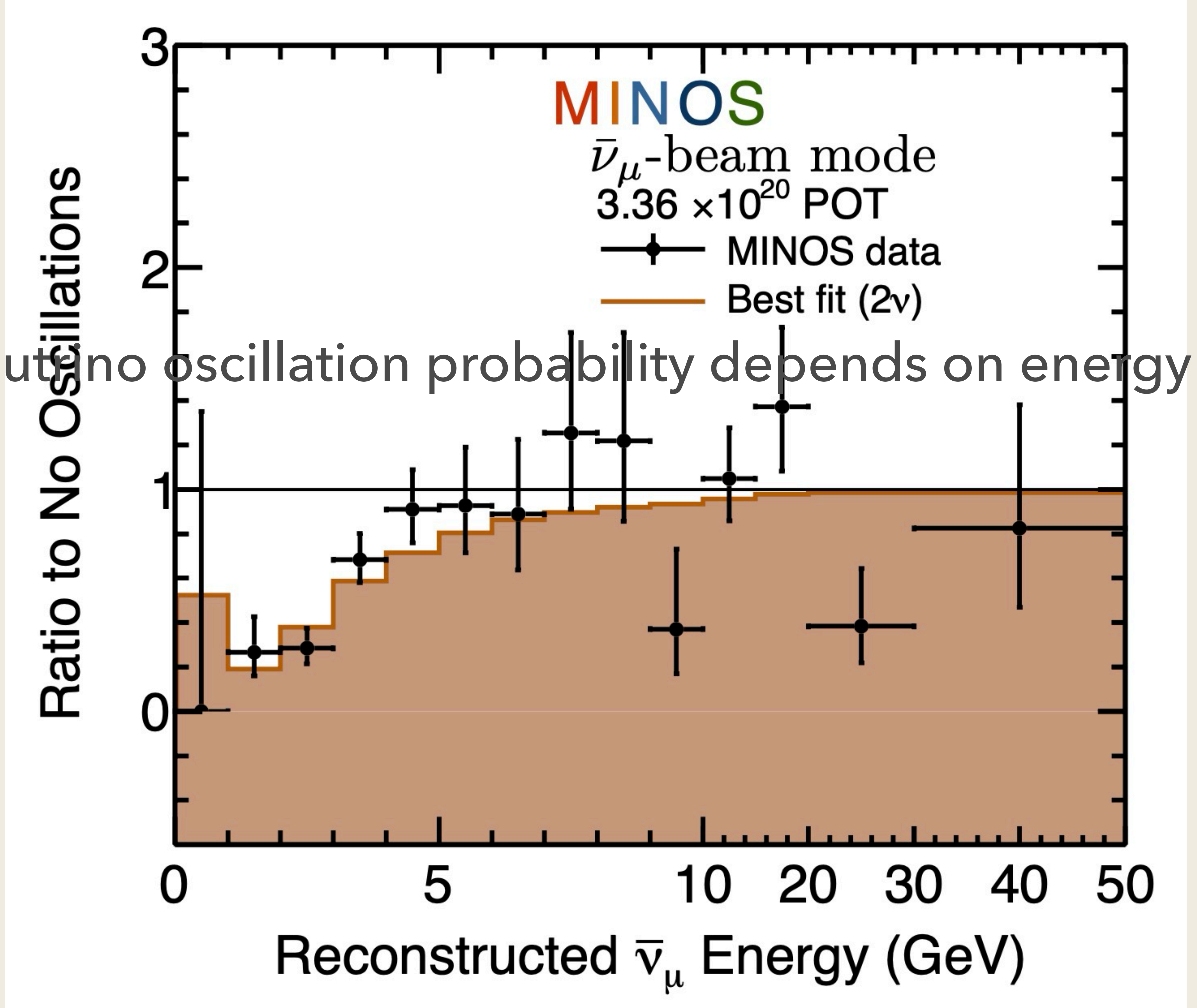


Higgs particle discovery thanks to
the precise measurement of photon energy

Calorimeter for neutrino oscillation measurement

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{31}^2 L}{4E_\nu}$$





Neutrino oscillation probability depends on energy

Calorimeter: design consideration

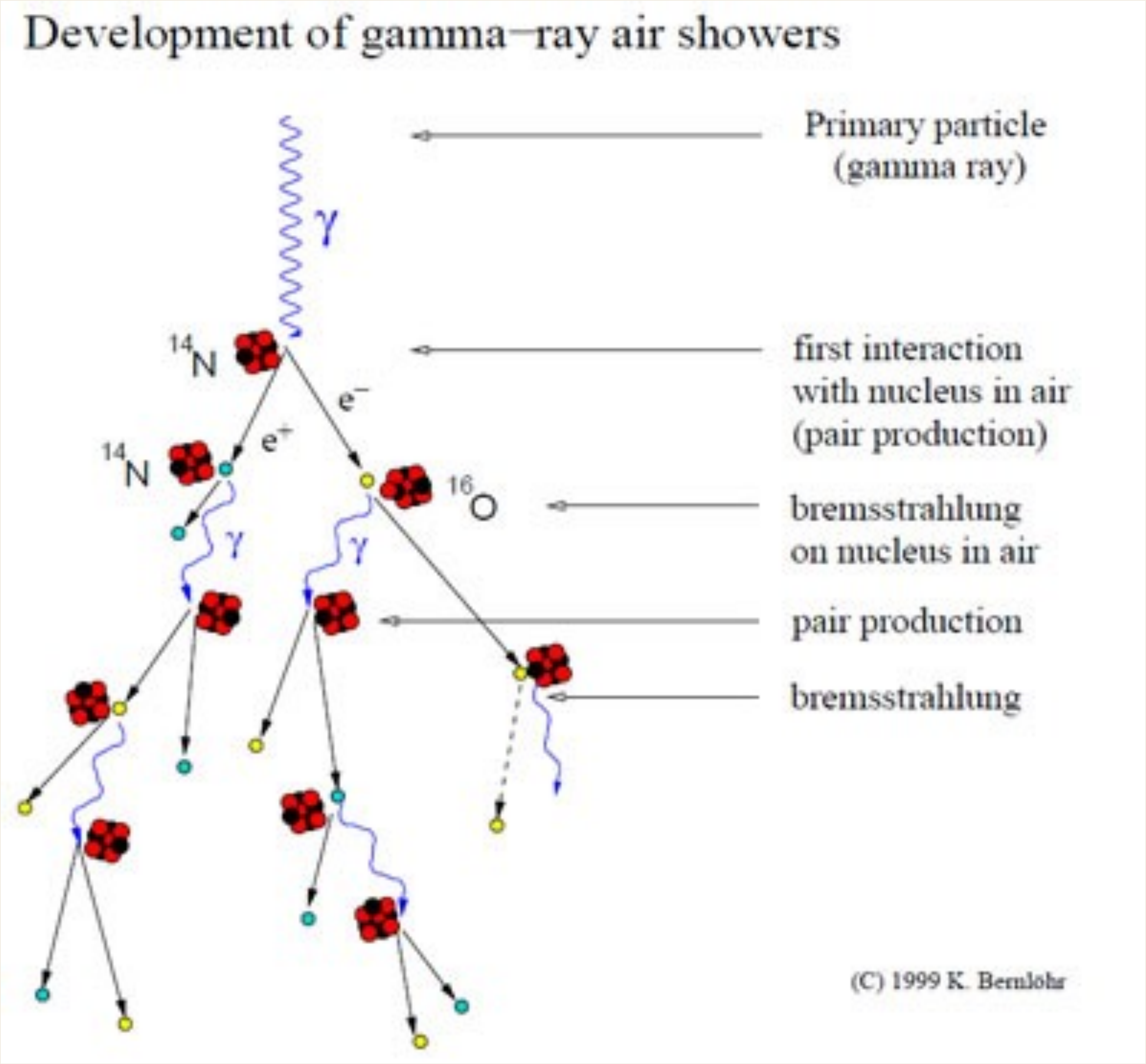
- **Large enough** to **contain all of the energy** of to-be-measured particle
- Must r**ecord signal to refer to the energy lost**
- Sufficiently **granular** to tell not just how much energy was deposited but where
- **Other practical consideration**: small enough to fit in detector, not too expensive, radiation hardness; fast read-out depending on event rate…

Calorimeter basics

- Calorimeters: to determine the energy of particle using the “energy loss phenomena“
- Loss: electromagnetic or hadronic showers
- Common modern use:
  - Scintillator detector
  - Cherenkov detector
  - …

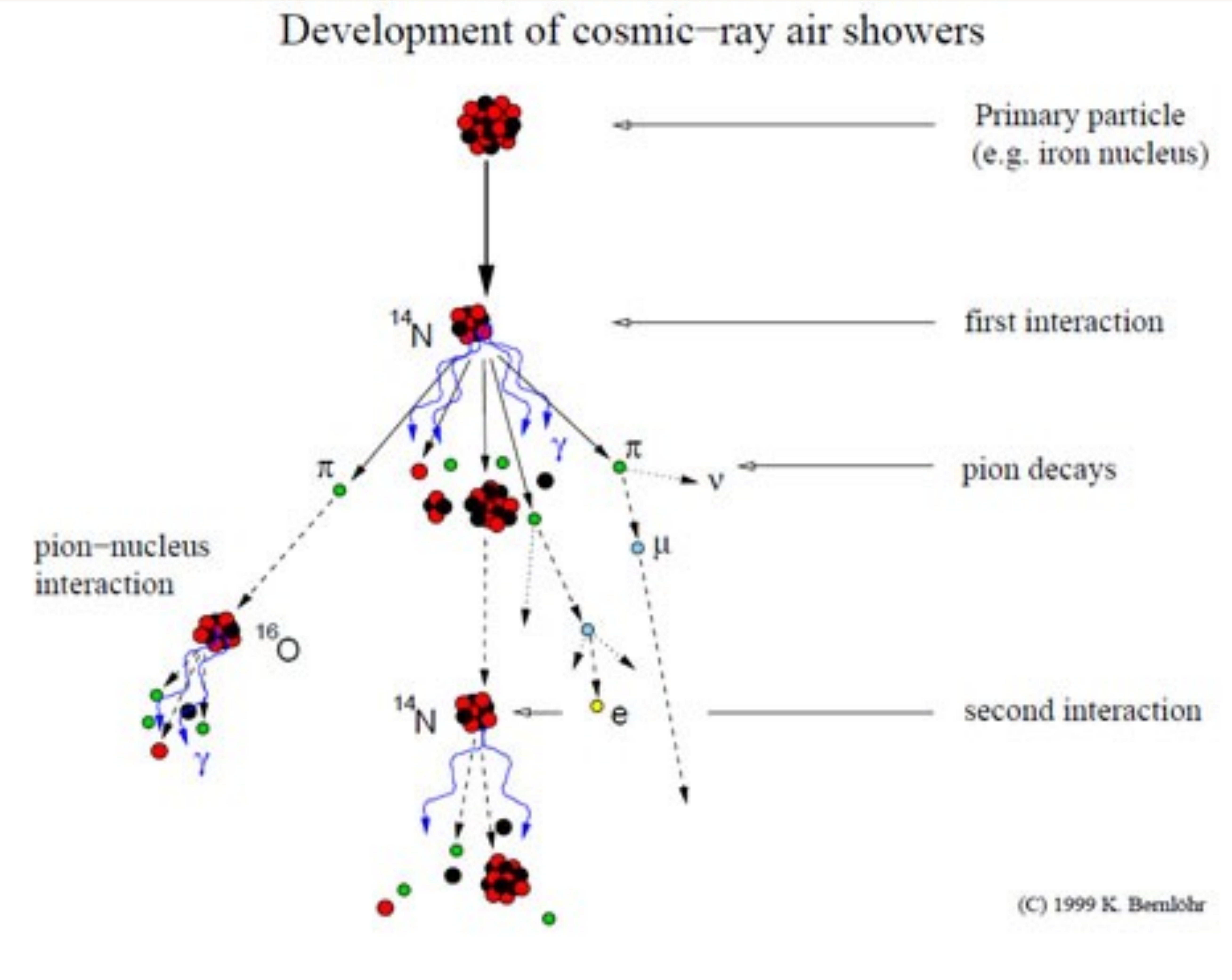
Electromagnetic shower development

- Electromagnetic shower: High-energy photons produce pair of electrons and positrons
- Electrons and positrons radiate photons via Breamsstrahlung when travel through matter, interacting with fields of atoms
- One electron fall below critical energy, more energy loss via ionisation than bremsstrahlung and the shower stops growing

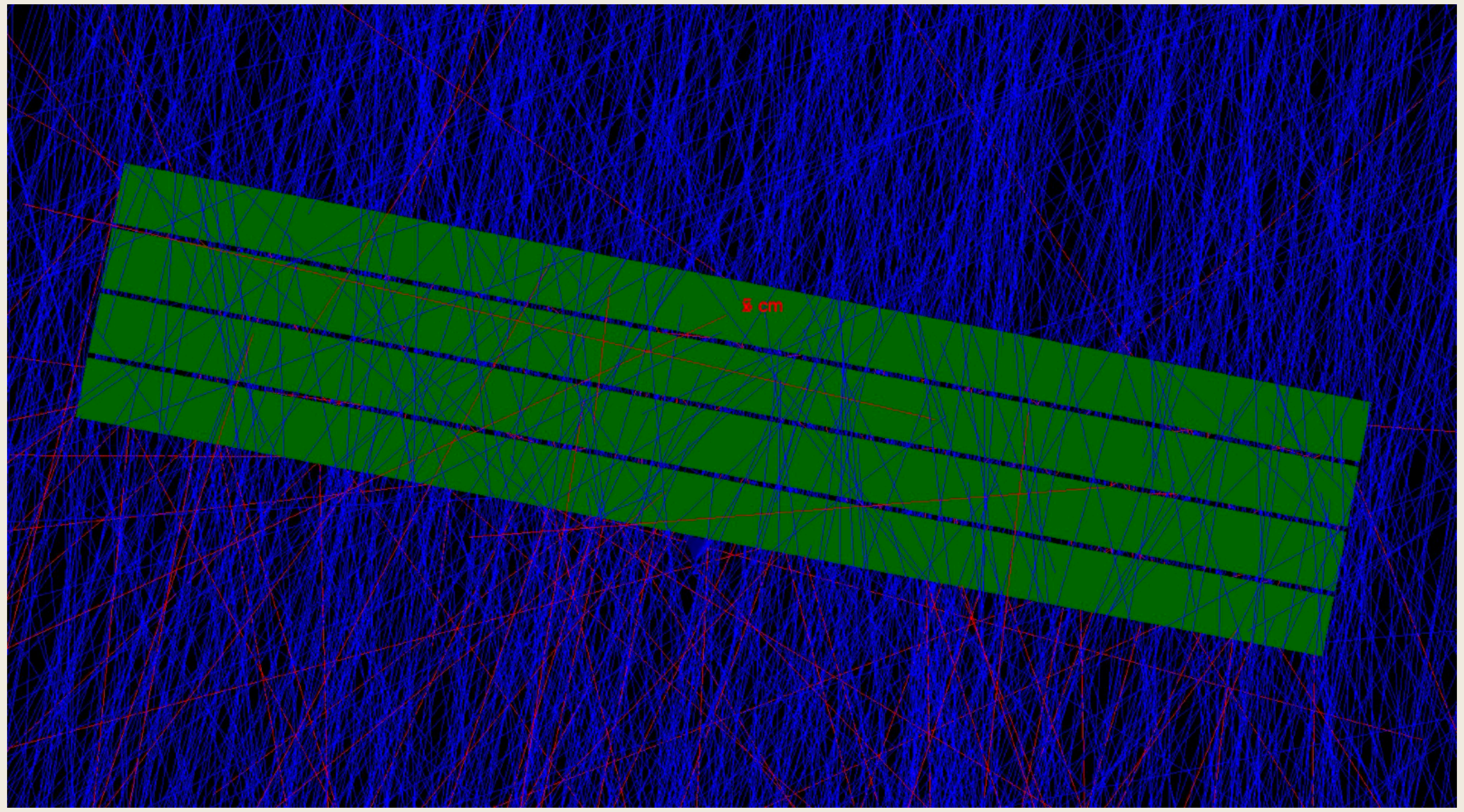


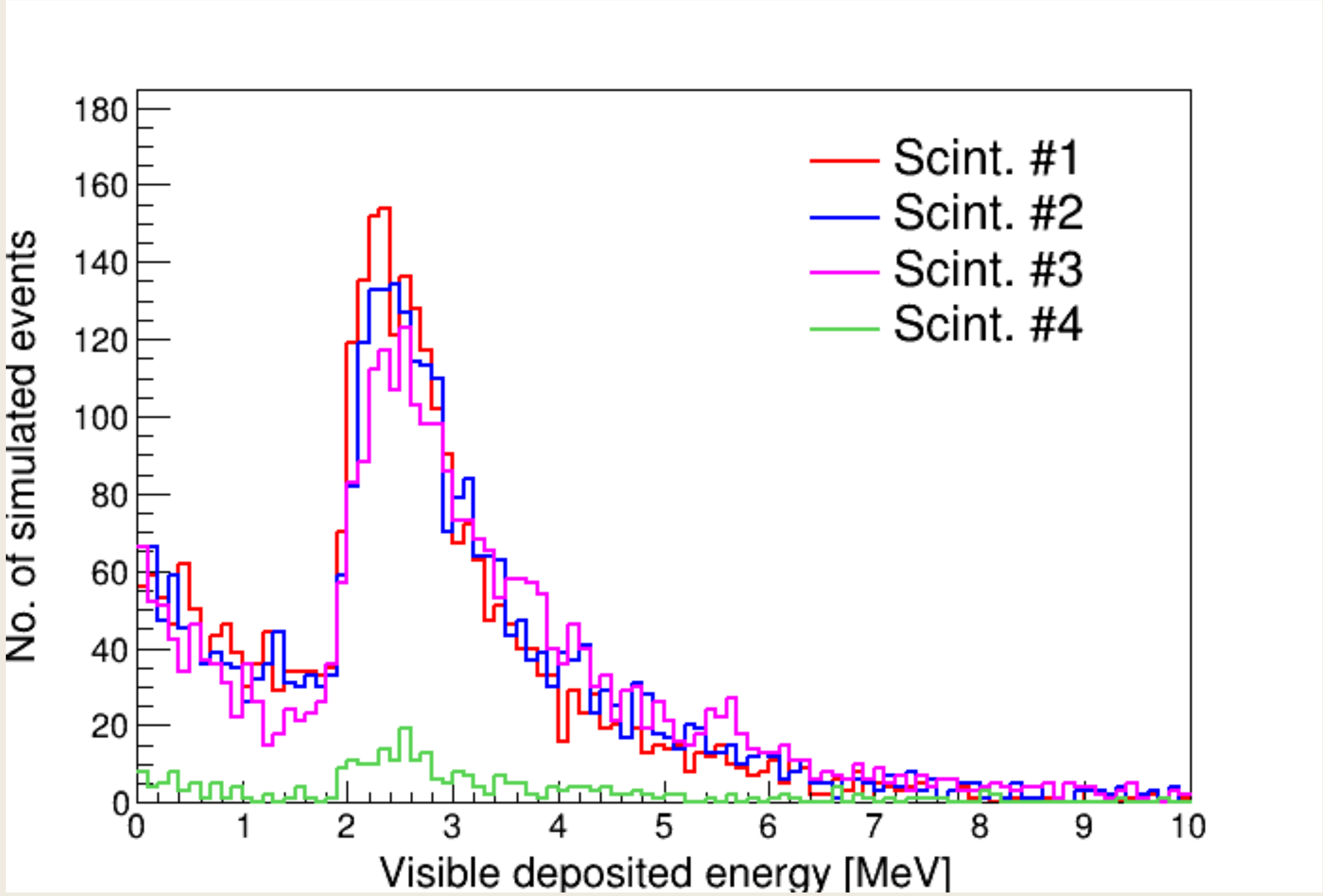
Hadronic shower development

- More complicated shower
- Main products are charged and neutral pion
- Neutral pion decays into pair of gammas, which initiates the EM sub-shower



Example of energy deposit by muon on plastic scintillator

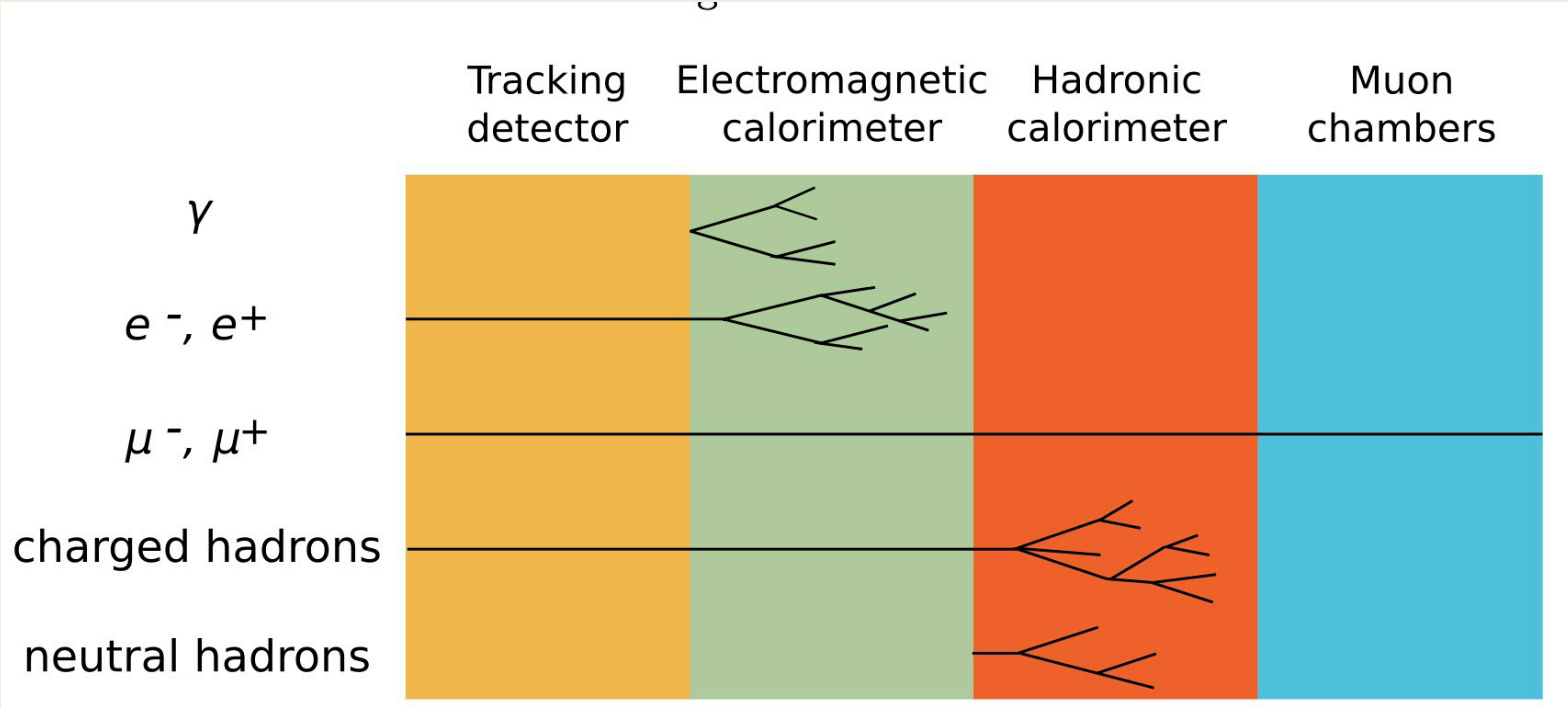




- We do not measure this amount of energy deposit directly
- We in fact count No. of photoelectron trigged by the produced scintillation light (captured, re-emitted, and transported by WLS) with photodetector
- **Understanding the physics of energy deposit process and the response of photodetector, scintillator, WLS allows us to make a conversion from what we observed to energy deposit.**

Particle detectors

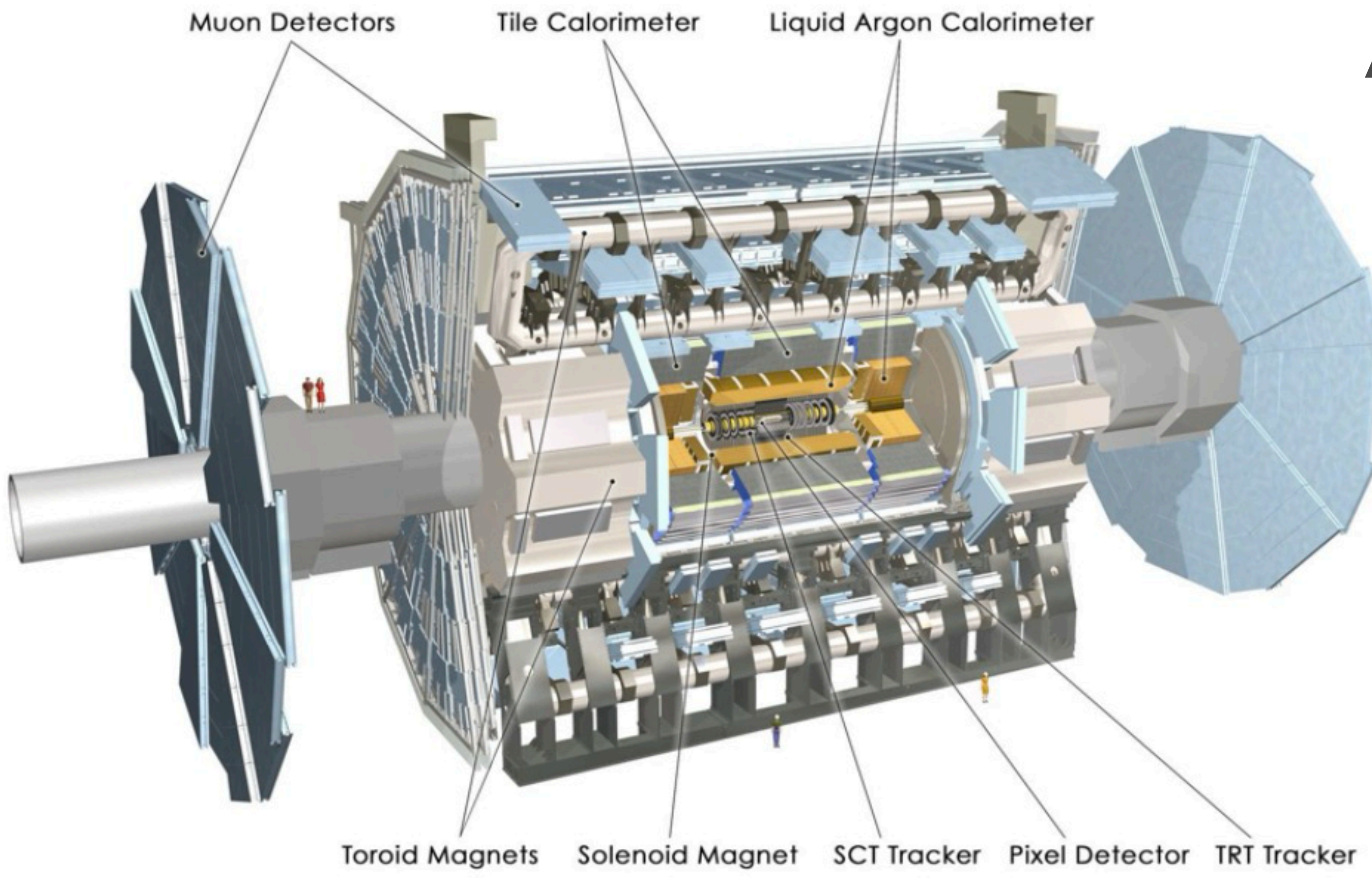
State-of-art of particle detection

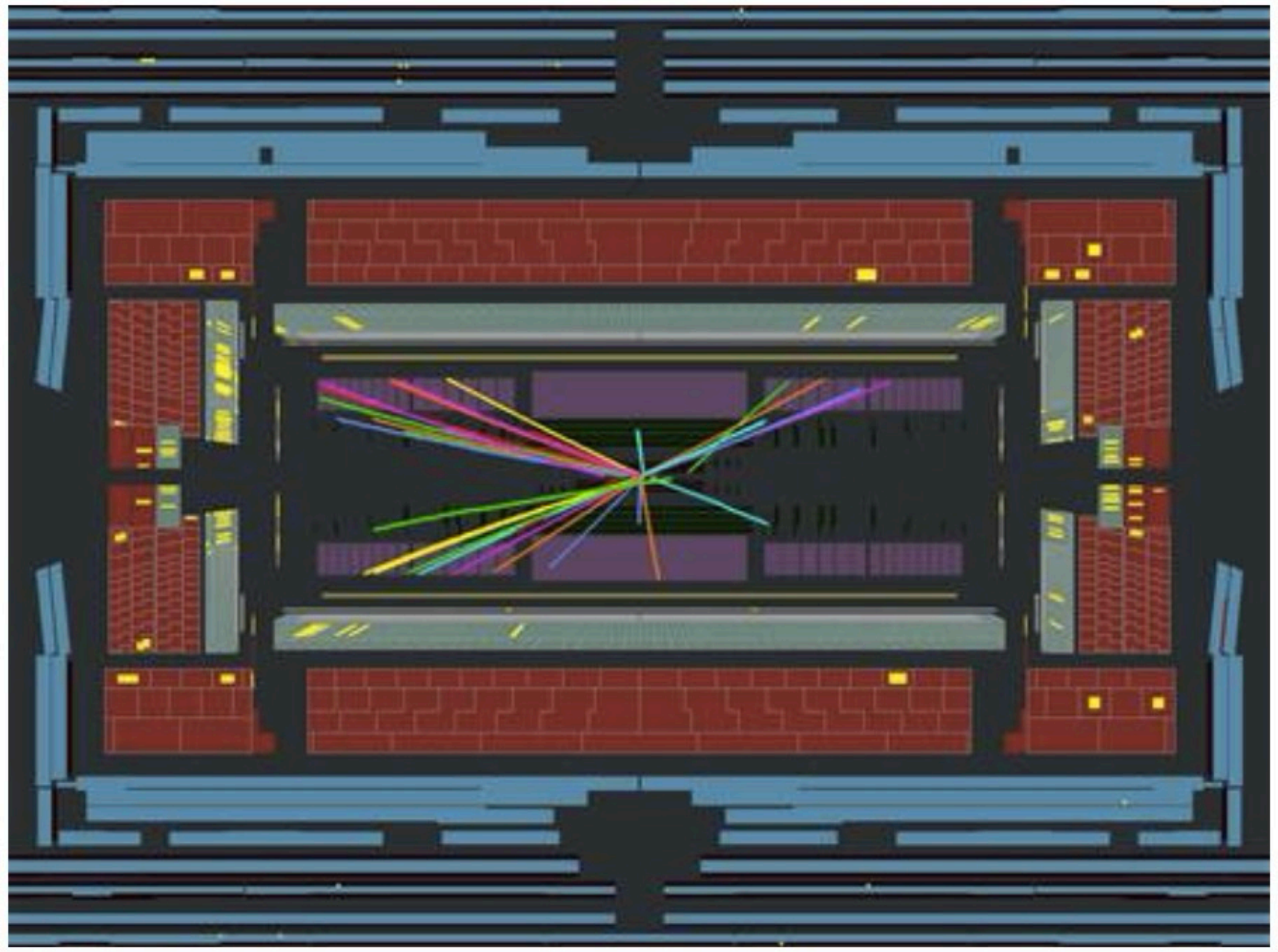


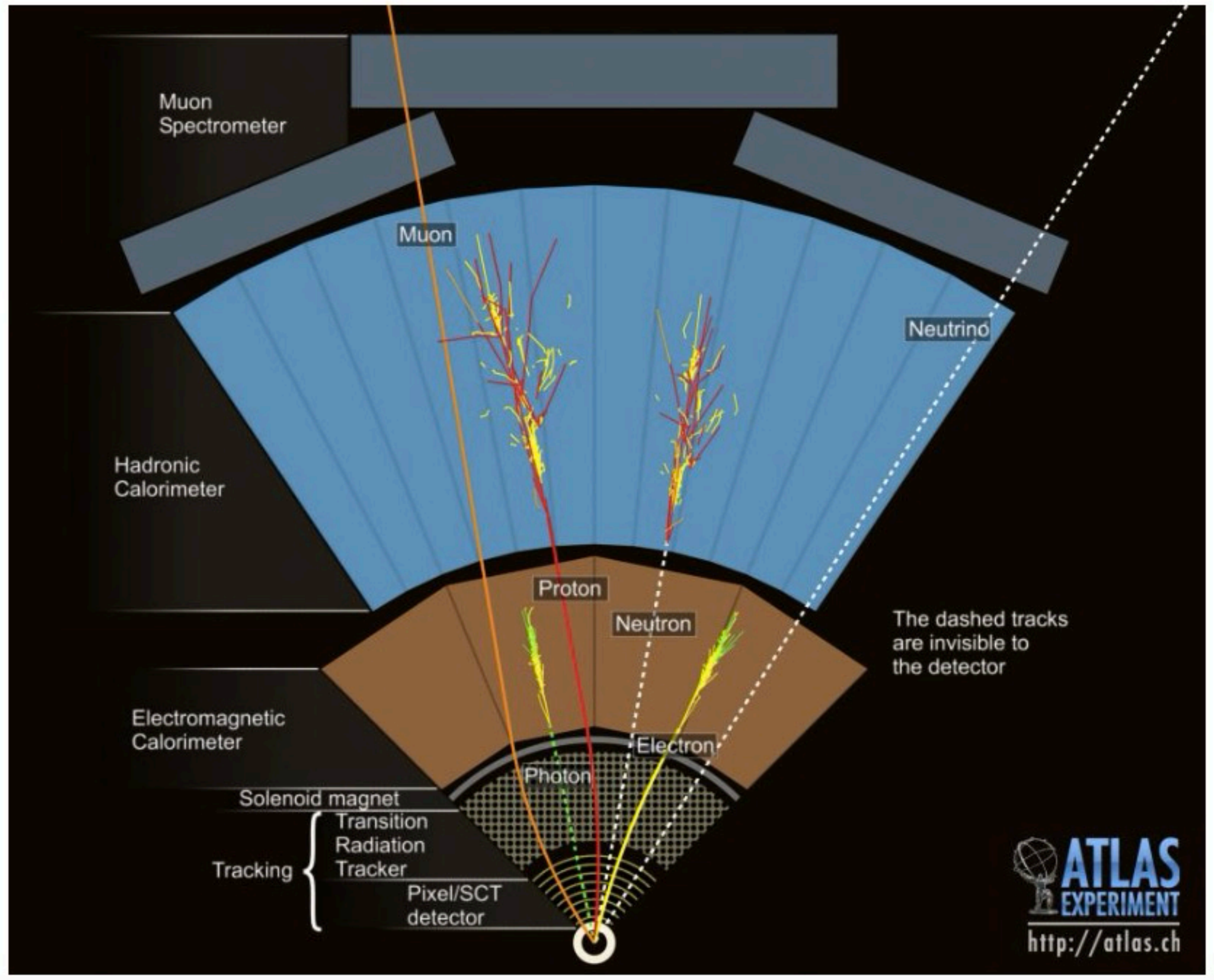
To put all sub-detector together for maximizing the physics potential output with other (*cost, space, radiation, power…*) consideration.

State-of-art of particle detection

ATLAST experiment

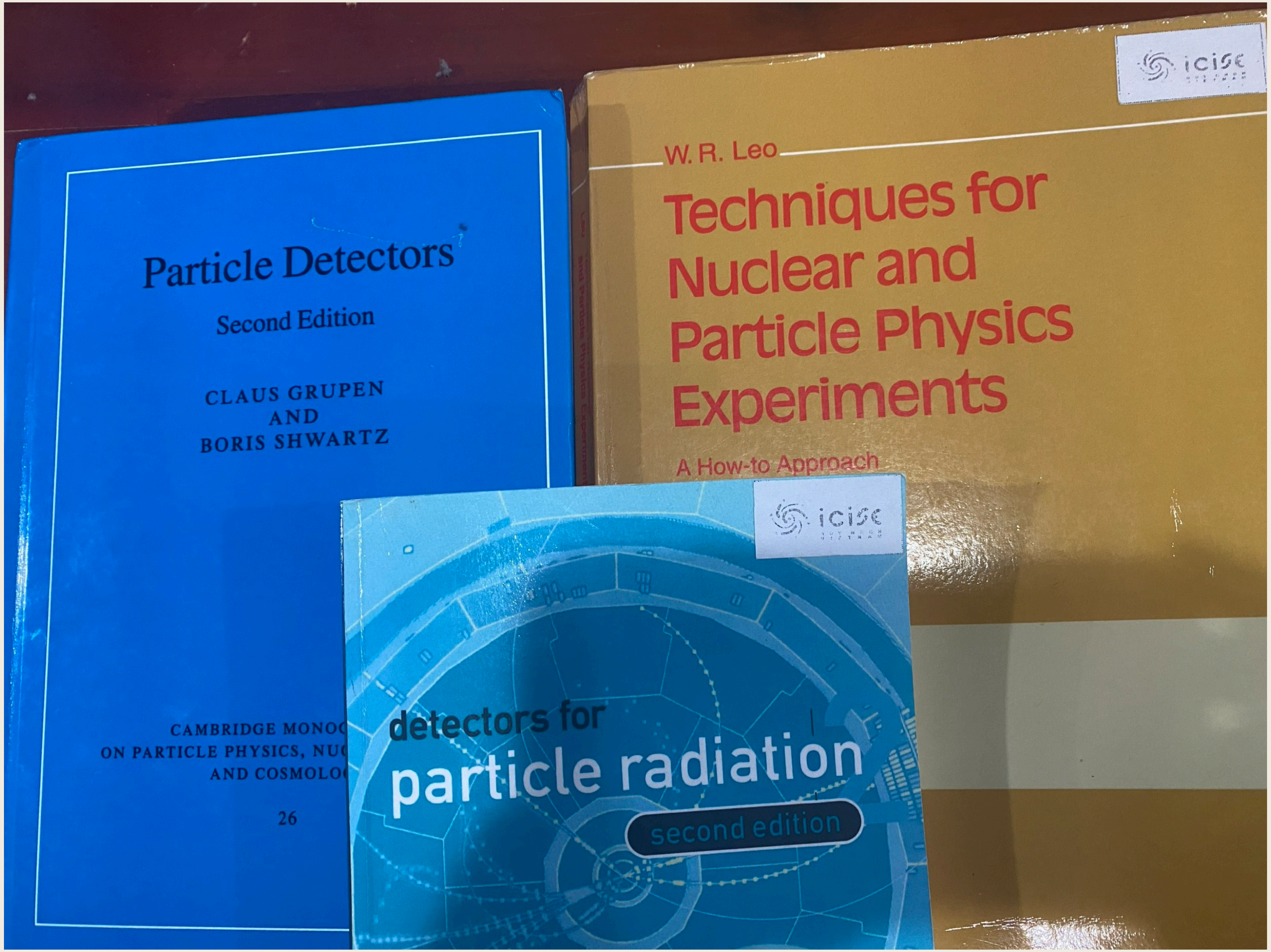






Details in the textbooks

Available in our bookshelf



Backup

Cherenkov Threshold

- Threshold in Cherenkov detector $p_{th.} = \dfrac{mc/n}{\sqrt{1 - n^{-2}}}$
  - In the air, threshold for pions is 5GeV/c but for Kaon is 20 GeV/c

Parity violation in muon decay

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad \text{and} \quad \pi^- \rightarrow \mu^- + \bar{\nu}_\mu.$$

Spin =0

Left-handed

right-handed

Left-handed

right-handed

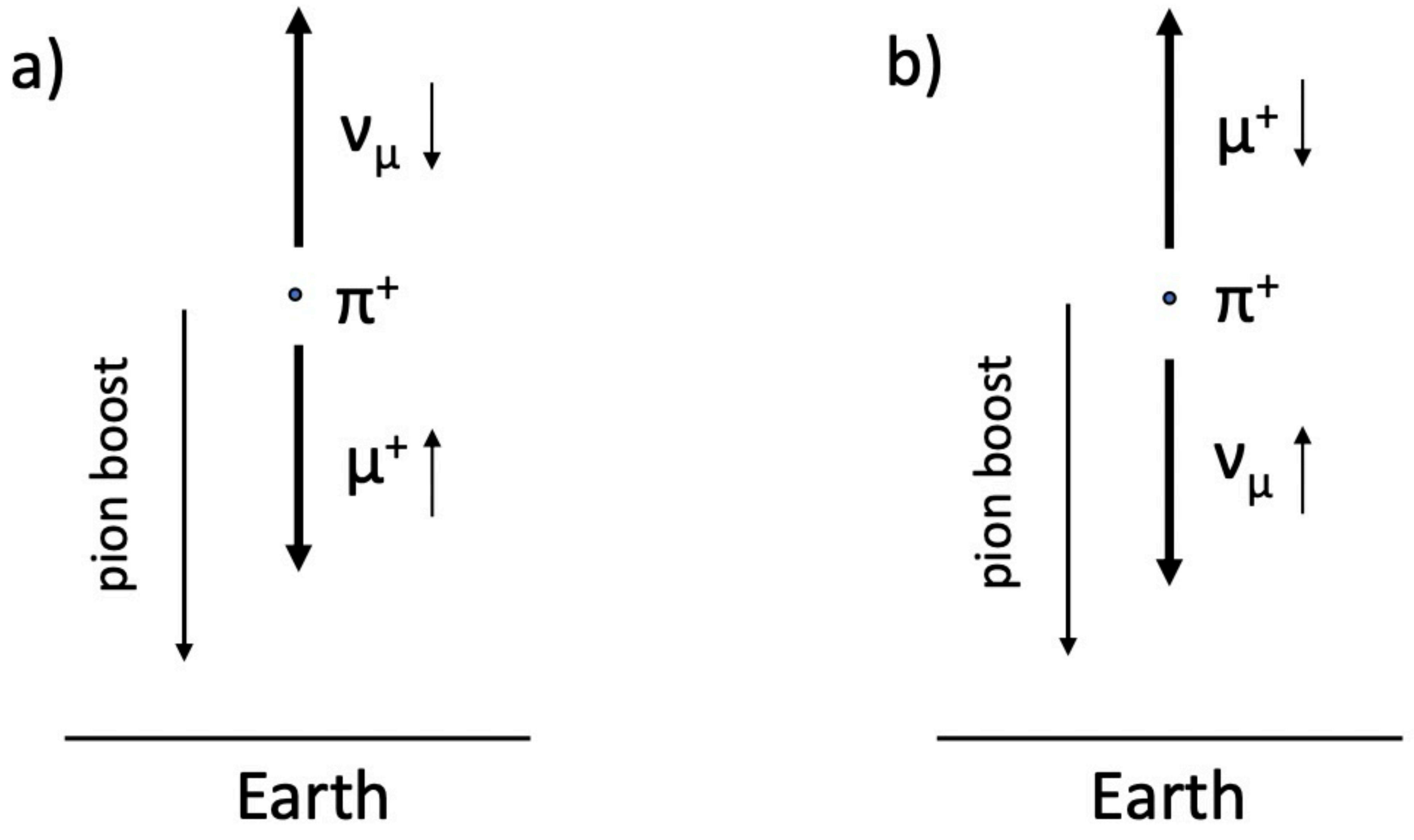


FIG. 1. a) A positive muon emitted in the pion boost direction in the rest frame of decaying pion. b) A positive muon emitted in the opposite direction of the pion boost in the rest frame of a decaying pion.

Down-ward positive muon
Have upward spin

Down-ward negative muon
Have downward spin

Parity violation in muon decay

Electron energy is from 0, to 55MeV (half of muon mass), peak around 50meV

$$\pi^+ \to \mu^+ + \nu_\mu \quad \text{and} \quad \pi^- \to \mu^- + \bar{\nu}_\mu.$$

Spin =0

Left-handed

right-handed

Left-handed

right-handed

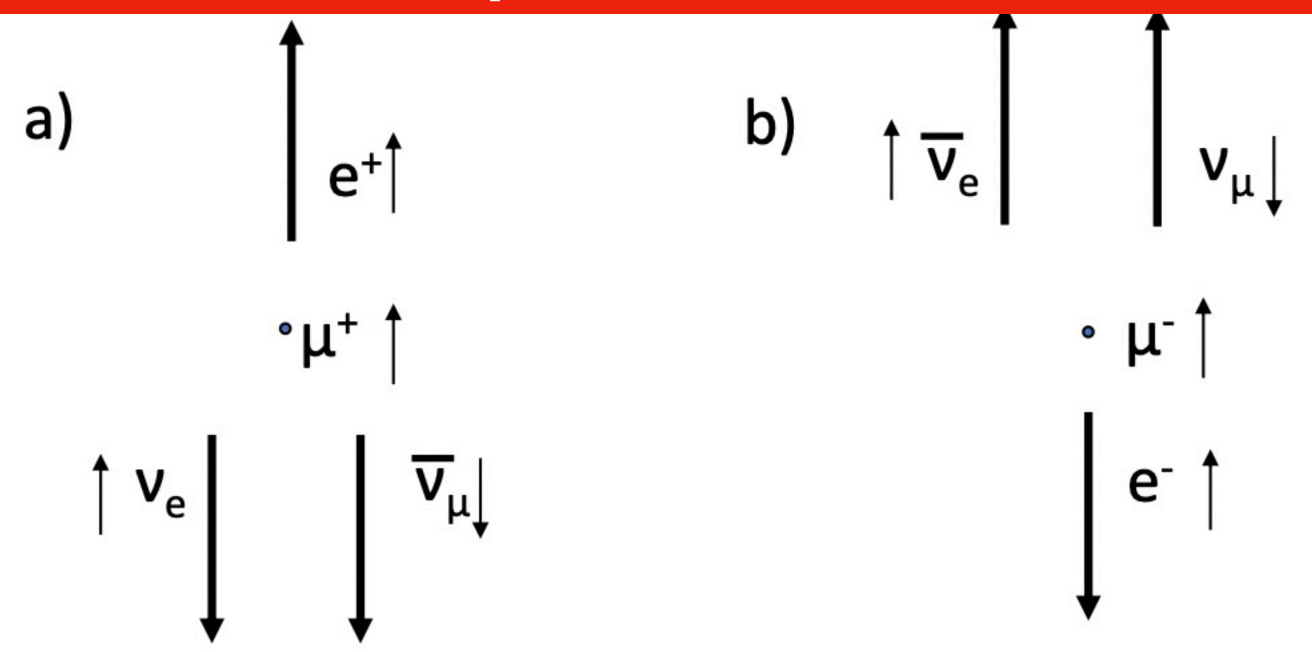


FIG. 2. Decay at the rest of a positive (a) and a negative (b) muon with the emission of the most energetic positron and electron, respectively.

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \quad \text{and} \quad \mu^- \to e^- + \bar{\nu}_e + \nu_\mu.$$

Down-ward positive muon
Have upward spin

Down-ward negative muon
Have downward spin

In extreme case, positron (electron) get most energy
When two (anti-)neutrino produces in the same direction
Net neutrino spin is zero -> positron (electron) will prefer to have same spin direction as their parent . Sin positron (left) is right (left) handed
Both positron and electron will prefer to emit upward