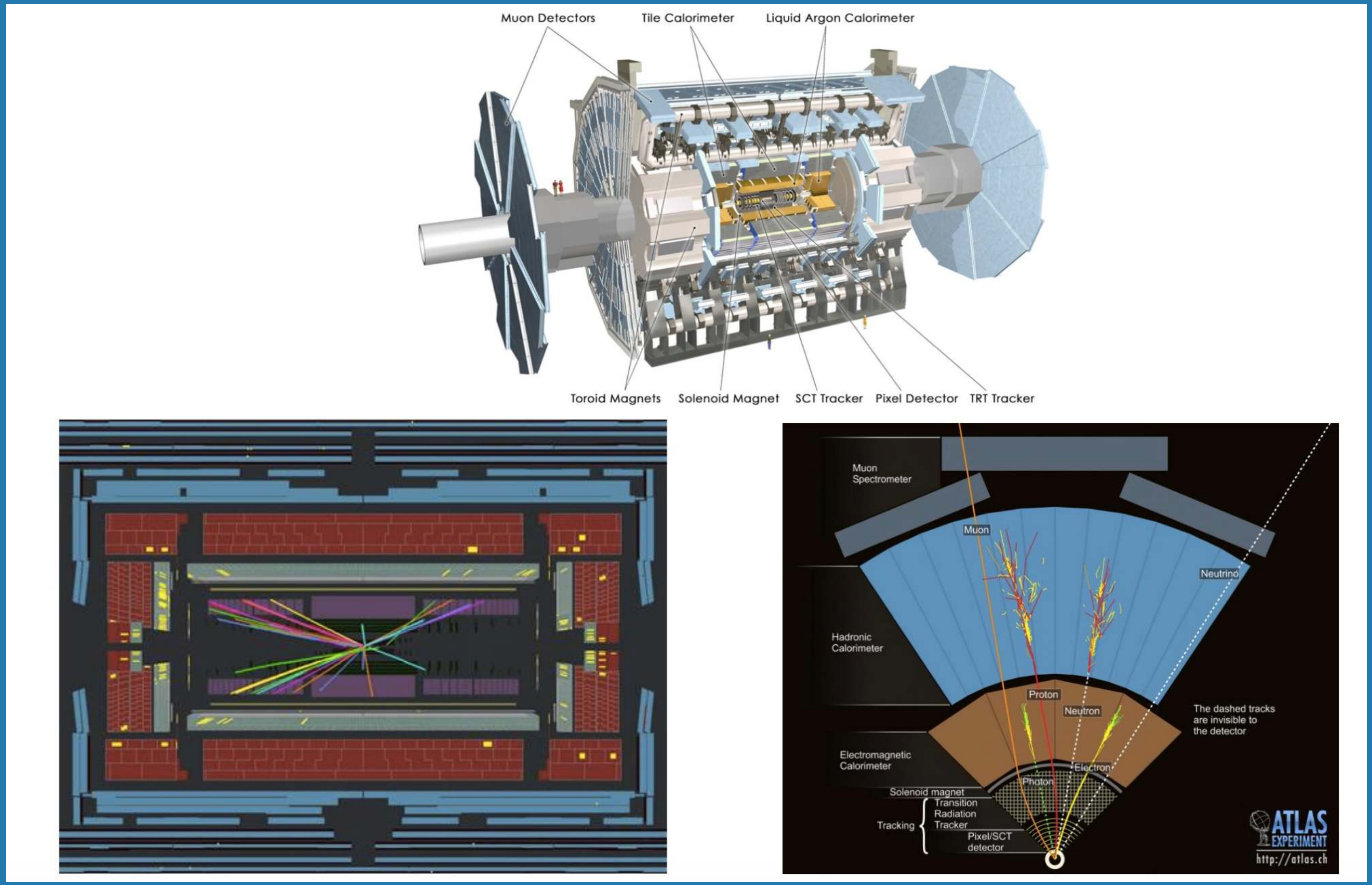
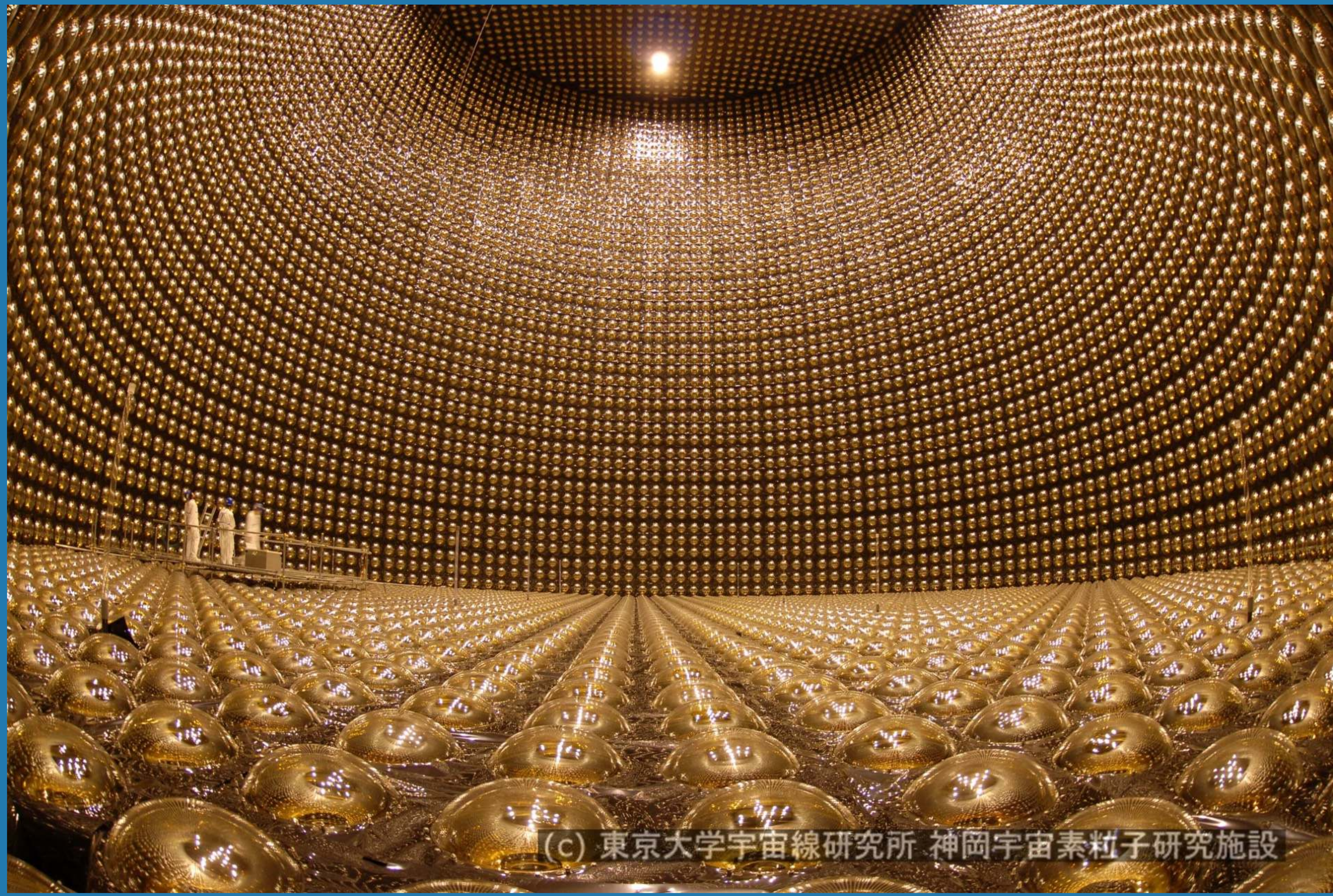
Particle tracking and Calorimeter in a nutshell

Son Cao, IFIRSE, ICISE

Most of particle detectors are big and compliciated





ATLAST

Super-Kamiokande

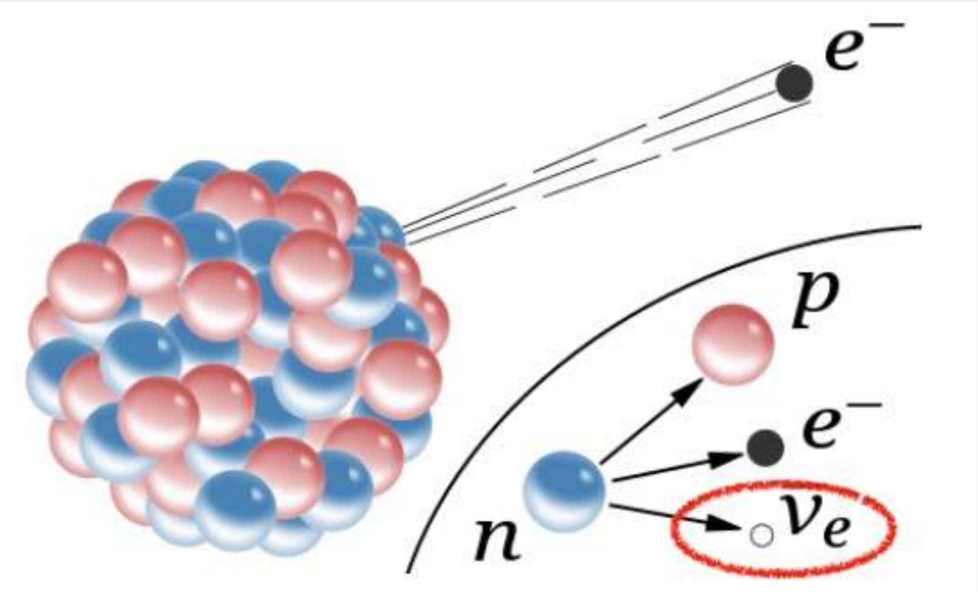
“The real voyage of discovery consists, not in seeking new landscapes, but in having new eyes”

~Marcel Proust~

General concept of particle detectors

Particle interaction

- **We can't see the interaction itself but the end products of the interaction**



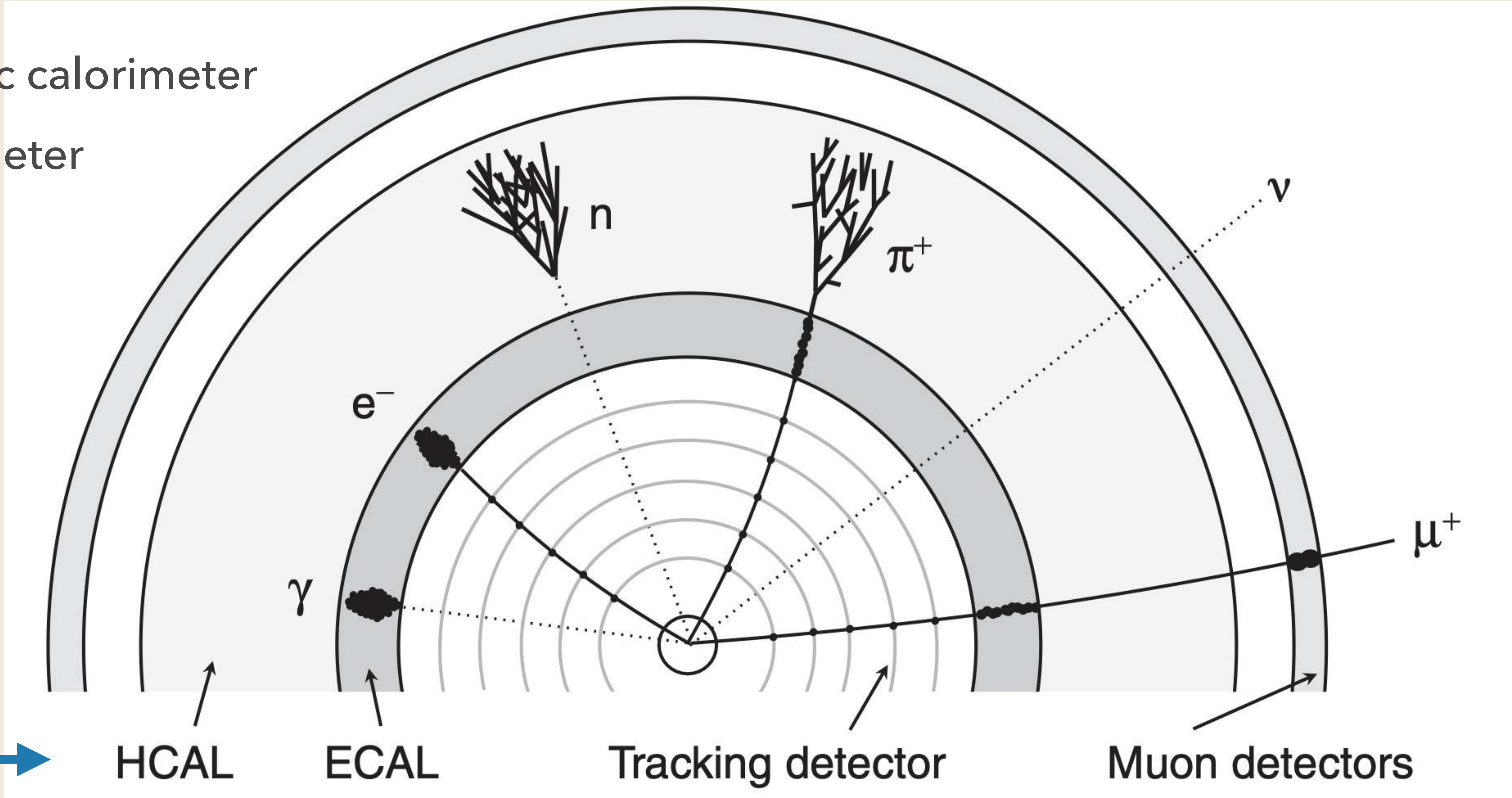
  - Eg. Story of Pauli's proposal of "invisible" end product in beta decay
  - *End products* are used to make sense of the underlying interaction
  - *End products* are detected via their interaction with matter
  - Only relatively "stable" end-products $\gamma, e^\pm, \mu^\pm, p, n, \pi^\pm, \alpha$ (or He^{2+}) can leave **visible track** in the detector.
    - Produced ν is stable but interact weakly, so mostly passing detector without any interaction → referred with so-called missing energy
    - Produced π_0 decay quickly into 2 photon (γ), which provides a quite distinct feature in detector

	Particle type	Rest mass [MeV/c]	Mean life τ [s]	Main decay mode
Photons	(γ)	0	Stable	–
Leptons	Electron (e^-), positron (e^+)	0.511	Stable	–
	Muon (μ^+, μ^-)	105.66	2.2×10^{-6}	$\mu^- \rightarrow e^-\bar{\nu}_e\nu_\mu$ $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$
Hadrons	Proton (p)	938.27	Stable	–
	Neutron (n)	939.57	880	$n \rightarrow pe^-\bar{\nu}_e$
	Charged pion (π^+, π^-)	139.57	2.6×10^{-8}	$\pi^- \rightarrow \mu^-\bar{\nu}_\mu$ $\pi^+ \rightarrow \mu^+\nu_\mu$
	Neutral pion (π^0)	134.98	8.5×10^{-17}	$\pi^0 \rightarrow \gamma\gamma$

EXAMPLE OF PARTICLE SIGNATURES IN THE DETECTOR

ECAL: Electromagnetic calorimeter

HCAL: Hadron calorimeter



Ignore these technical terms

You can consider them as "sense organ" of the detector

Can you try to match: eyes, ear, nose, tongue, skin

EXAMPLE OF PARTICLE SIGNATURES IN THE DETECTOR

ECAL: Electromagnetic calorimeter

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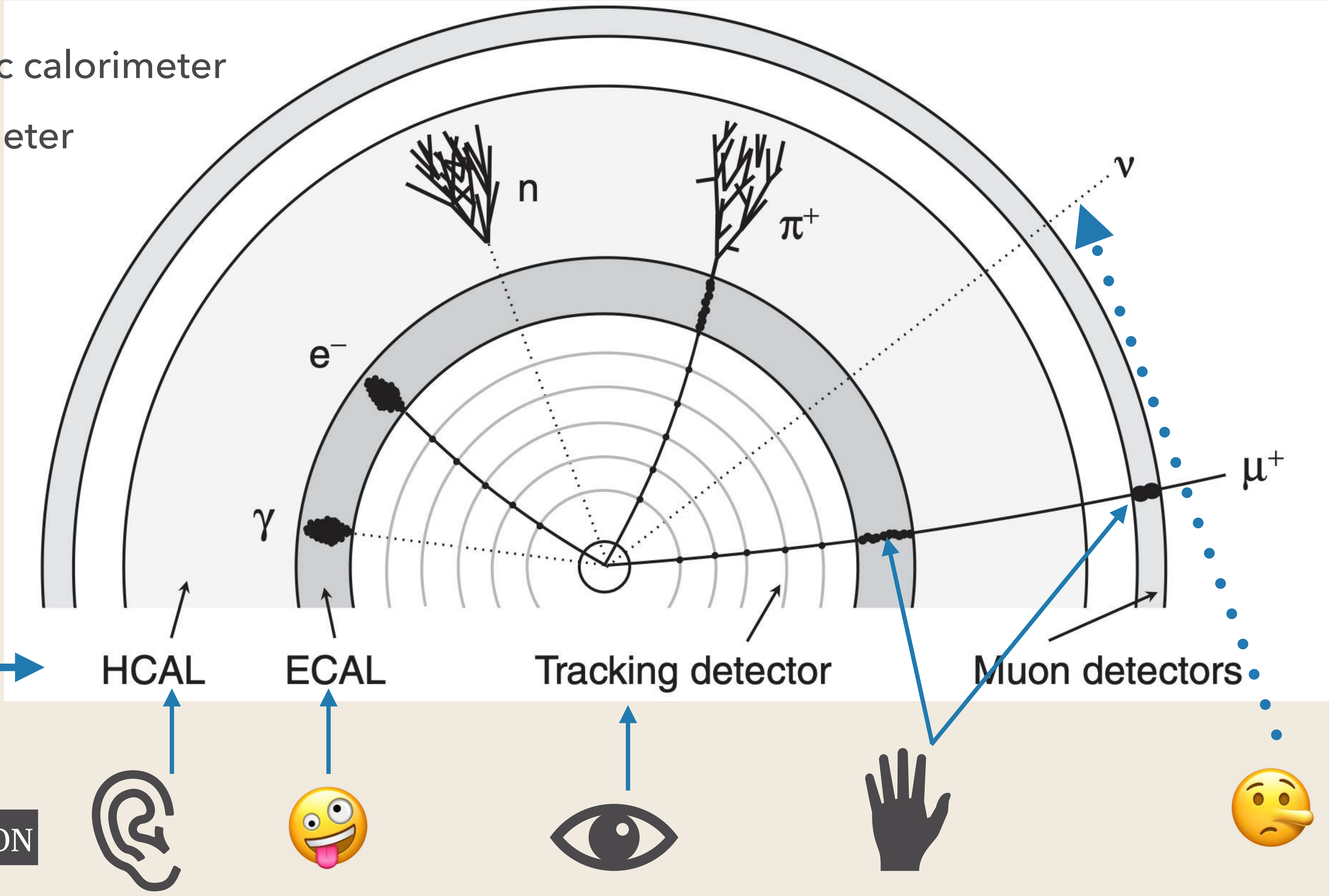


Ignore these technical terms

SOME SUGGESTION

Conceptual particle detector

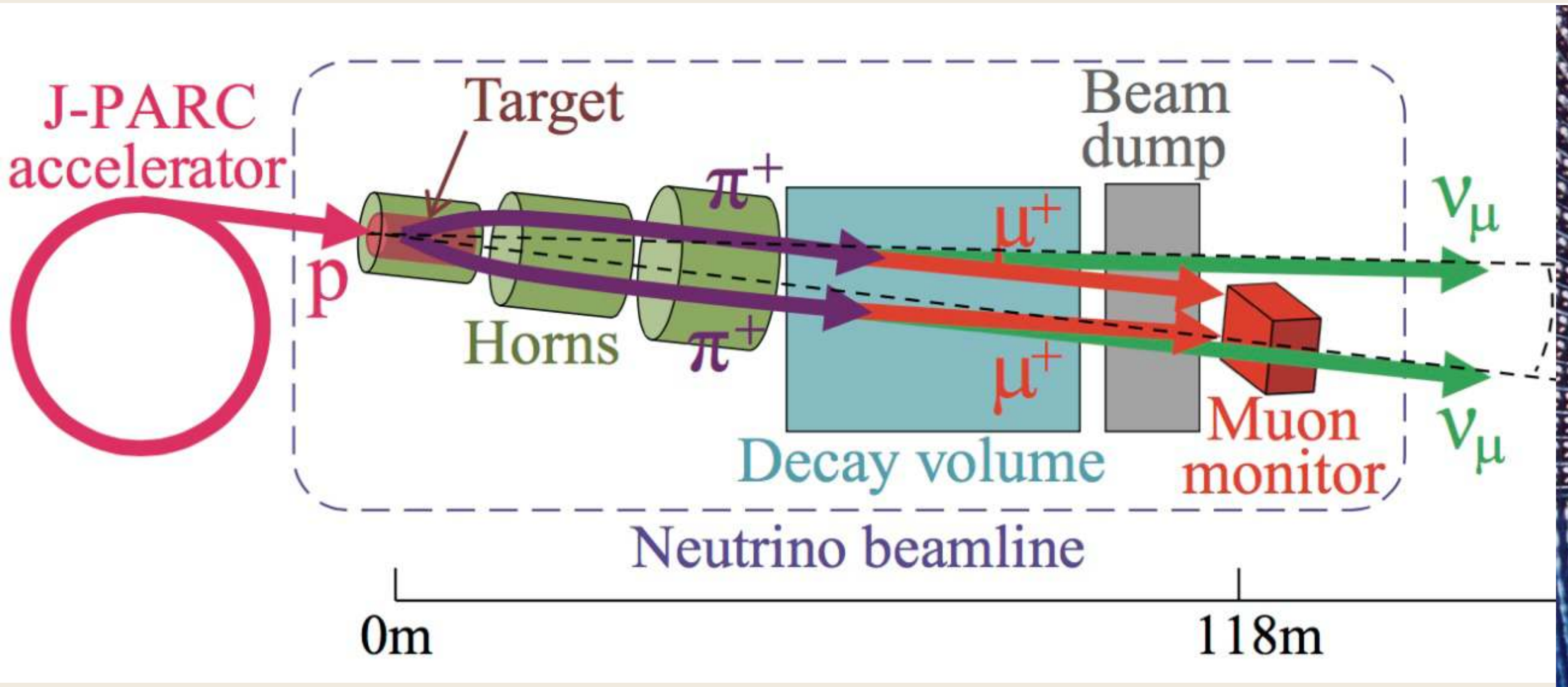
<u>Ideally</u> (*here particles = end products of the interaction*)

- Excellent identification of all produced particles
- Excellent tracking (*spatial and temporal*) of all particles
- Precise measurement of energy/momentum of all particles

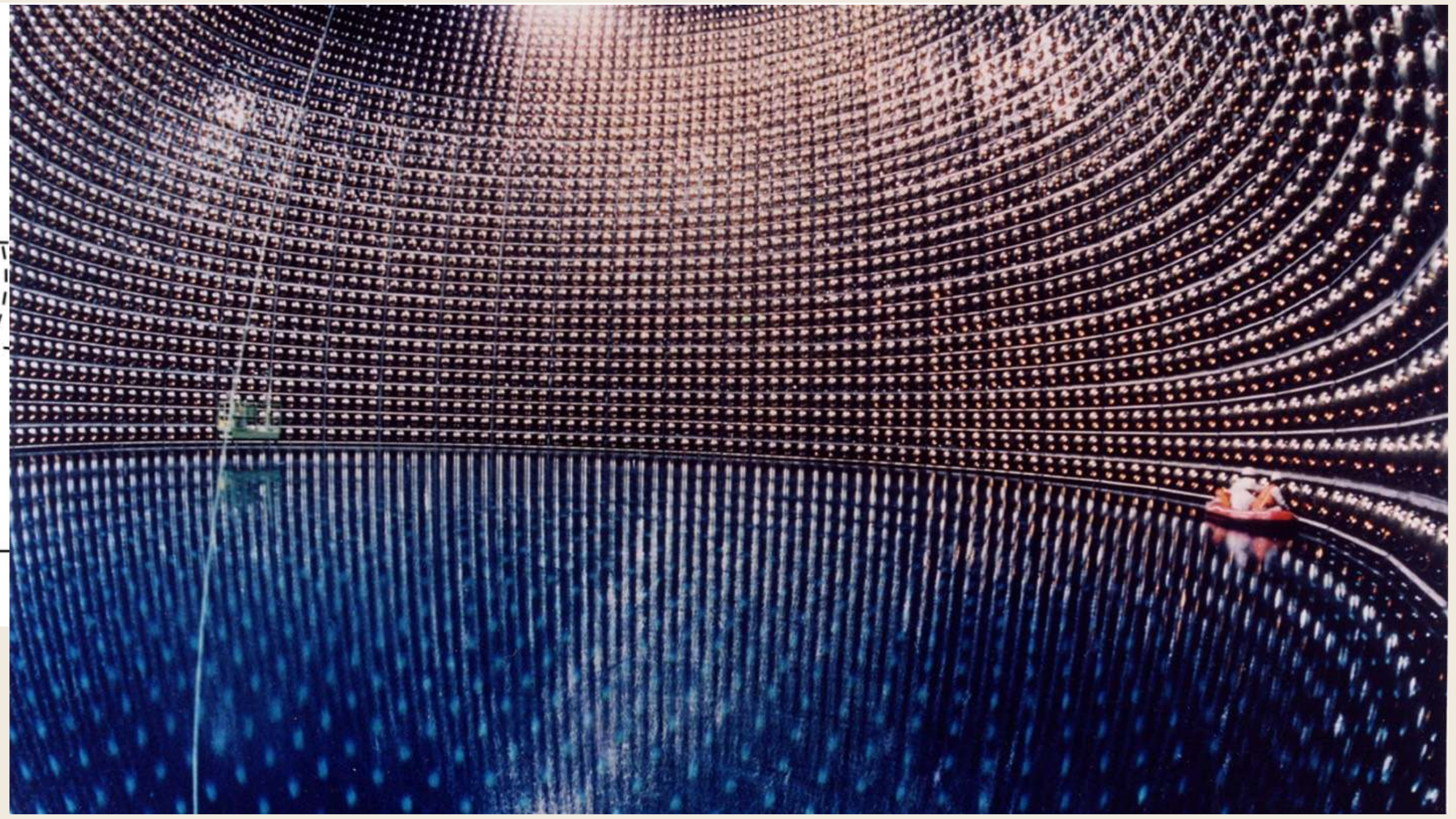
- Additional features
  - Record **High rate events**: collider, near detector of neutrino experiments
  - **Radiation tolerance**: eg collider; MUMON detector of T2K ; caused eg. displacement of the lattice atom/ defection
  - **Continuous operation** for ~ 10 years with little/no intervention
  - **Compromise**: existing technology, money, space, time…

Bodies of particle experiment

- The essential:
  - (1)**Particle sources**: can be man-made or natural source
    - (2)*Active* **volume for particle interactions**
      - (3)Apparatus to **"capture/visualize" the interaction process**
        - (4)System for **signal processing and analysis**



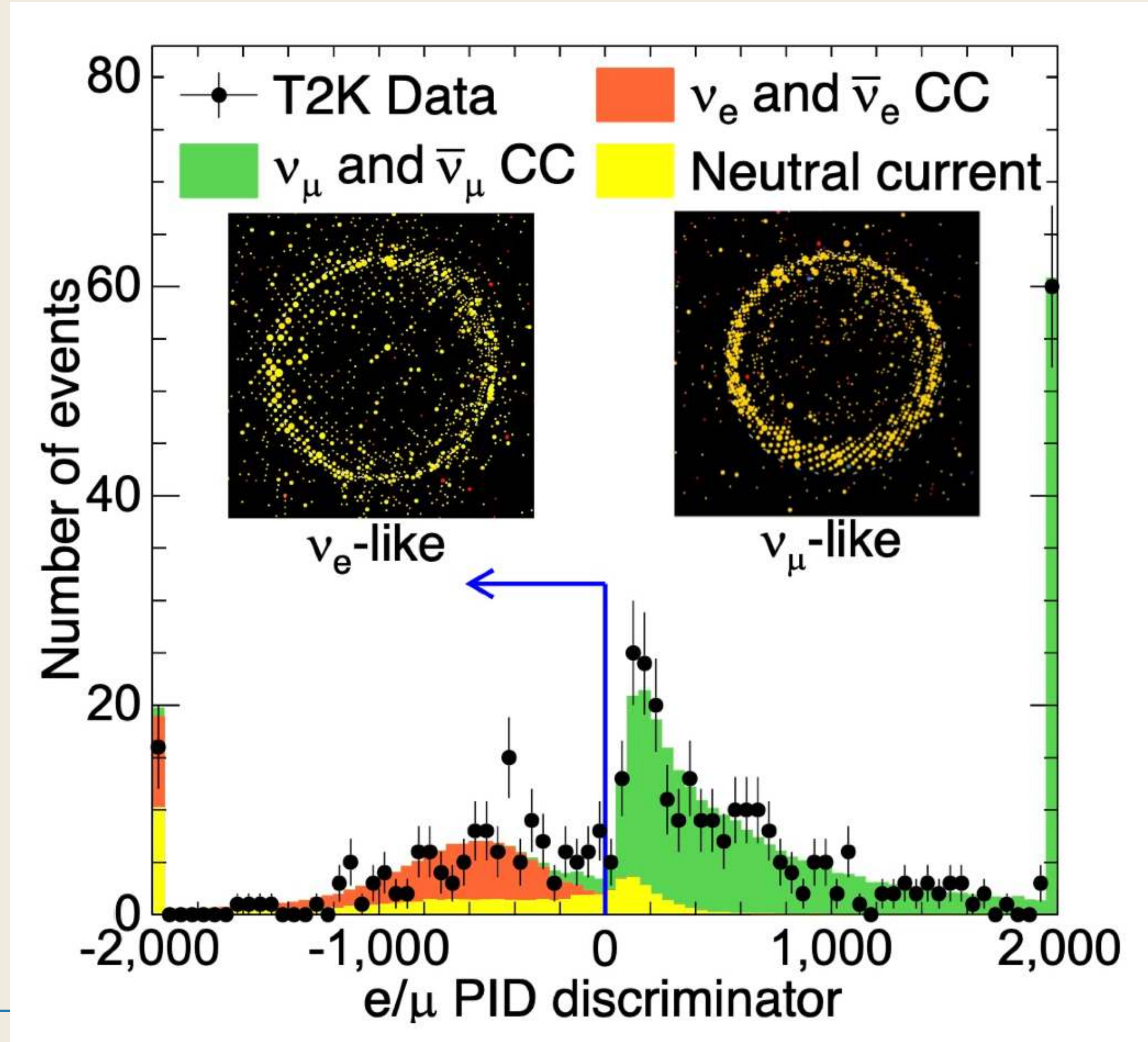
(1) J-PARC neutrino beam



(2) pure water/ Gd-loaded

(3) Photosensor

(4)



Bodies of particle experiment

- The essential:
  - (1)**Particle sources**: can be man-made or natural source
    - (2)*Active* **volume for particle interactions**
      - (3)Apparatus to **“capture/visualize” the interaction process**
        - (4)System for **signal processing and analysis**
- **Supporting setup**
  - Passive and active “Isolation”/shielding
    - Underground, high Z materials
    - Veto / outer detector
  - Additional detectors: to understand particle source, particle interaction, detector performance. Eg. Near detector complex in neutrino experiments
  - Additional facility to test/calibrate the detector’s performance
  - …

Working principle of particle detectors

Any effect of particle inducing observable distinction when interacting with matter can be used as working principle of particle detector

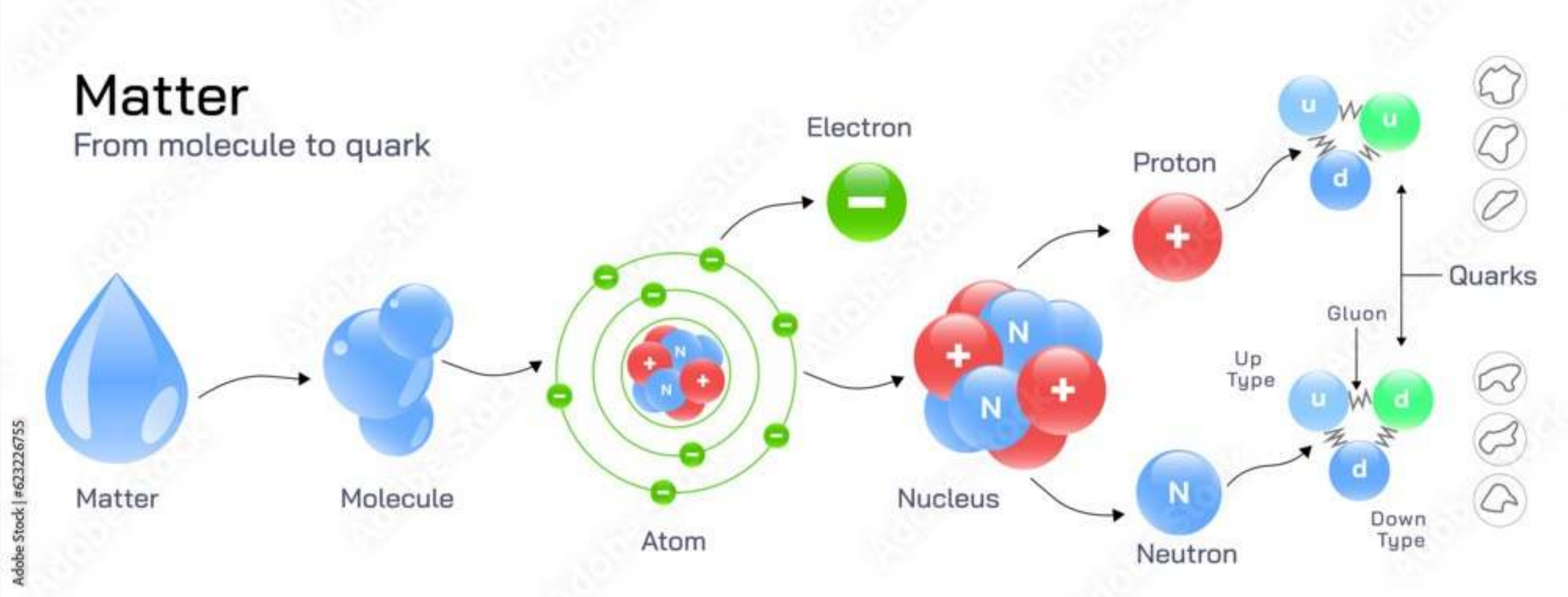
					strong	electromagnetic	weak
Quarks	down-type	d	s	b	✓	✓	✓
	up-type	u	c	t			
Leptons	charged	e^-	μ^-	τ^-		✓	✓
	neutrinos	ν_e	ν_μ	ν_τ			✓

These gives the overall framework to compute, but it likes "black-box", not giving you features/observables to quantitatively measure.

Take-away message: fundamental properties of particle (radiation) and its interaction in the matter is essential not only for building particle detectors but for radiation-based technology

Working principle of particle detectors

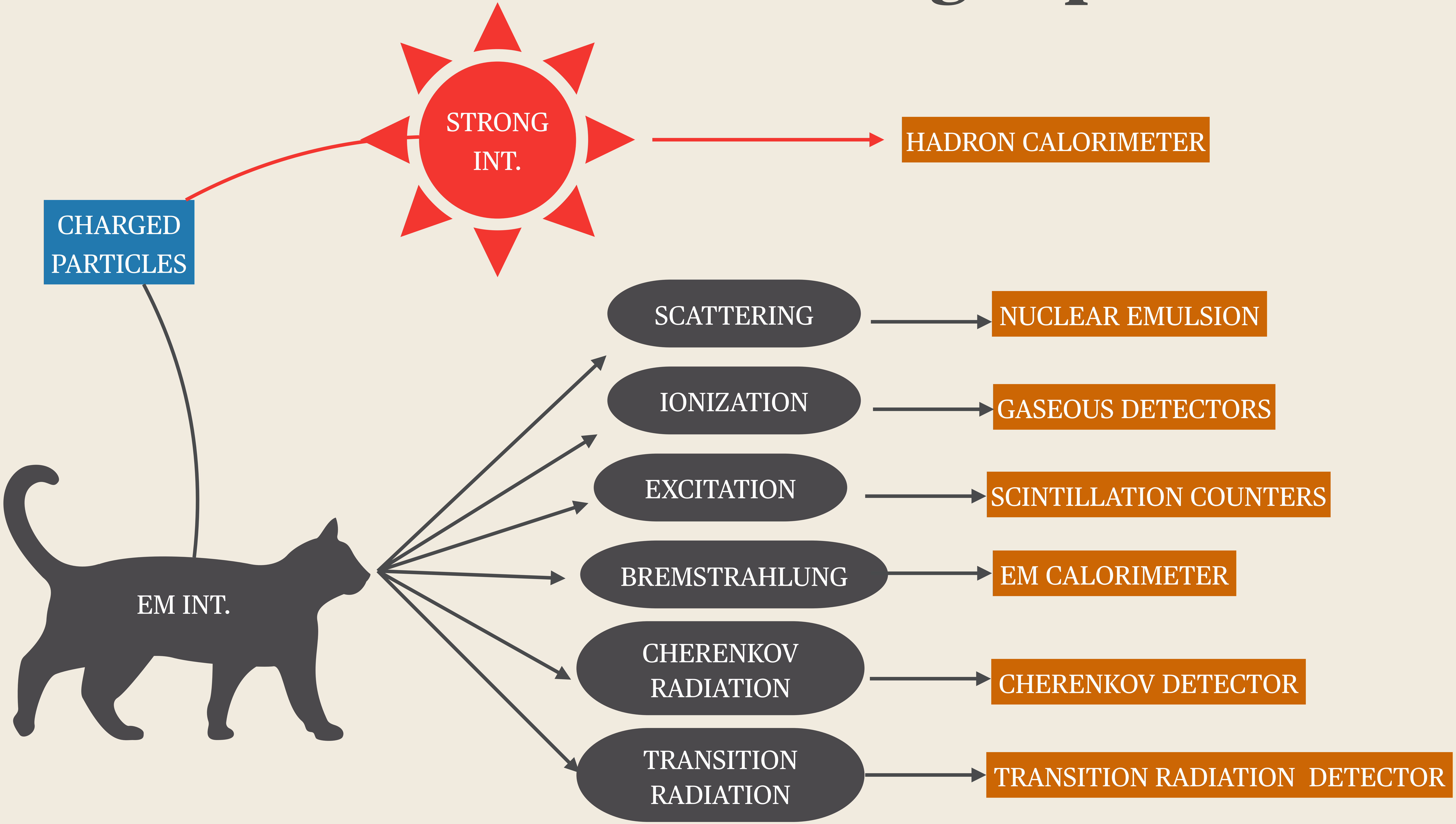
Any effect of particle inducing observable distinction when interacting with matter can be used as working principle of particle detector



Fundamental effects:

- **Coherent scattering** (*keep targeting atom intact*), release some recoiled energy
- **Ionize atom** by liberating electron
- **Excite the atom/molecule** and produce new particle(s)
- **Emit photon(s)**: Cherenkov radiation, transition radiation, scintillation, fluorescence
- **Break down nucleus** via inelastic nuclear scattering results in number of particles

Detection of charged particles



Important point to keep in mind

- We don’t see particle interaction directly, but its end products
- End products are detected via their interaction with active volume in the particle detector
- Any observable effect of particle when interacting with matter can be used as working principle of particle detector

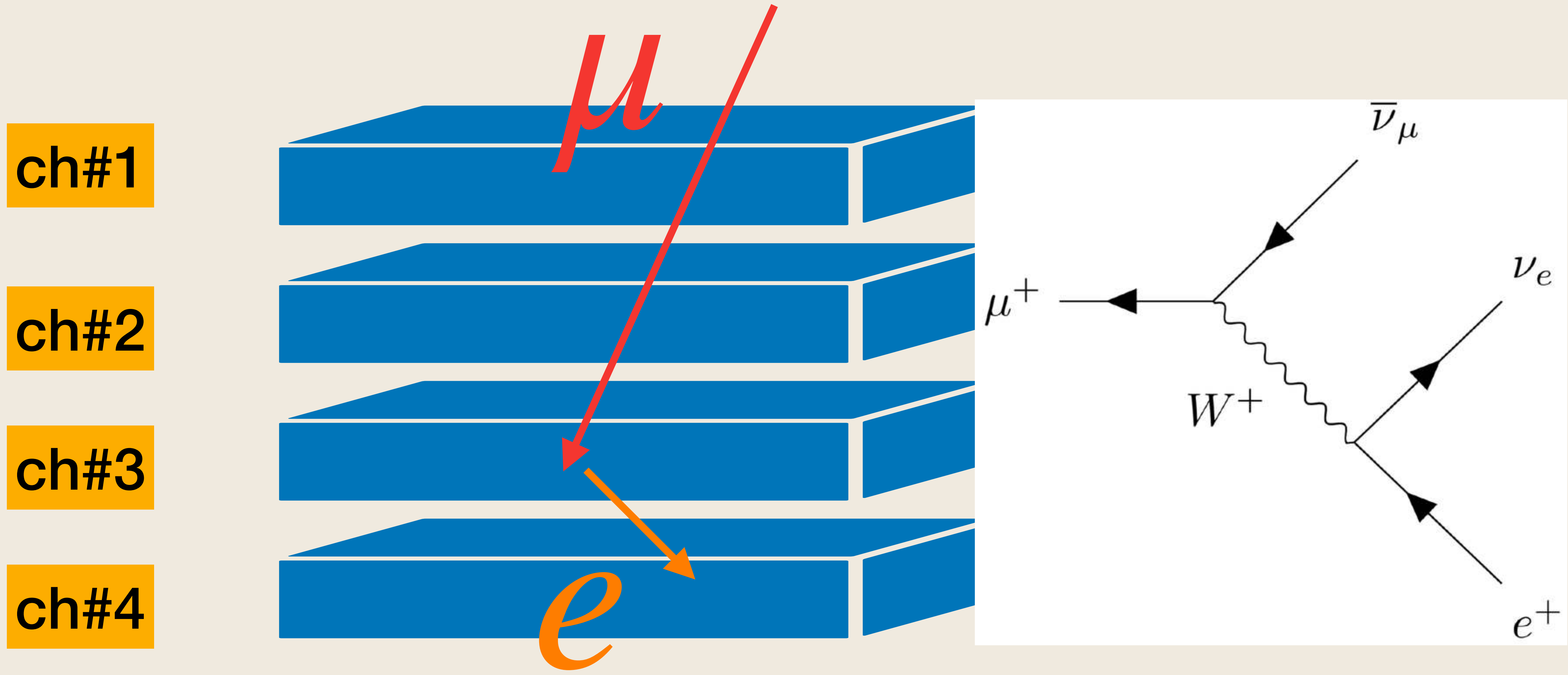
The particle detector is really complicated to be digested in a short lecture.

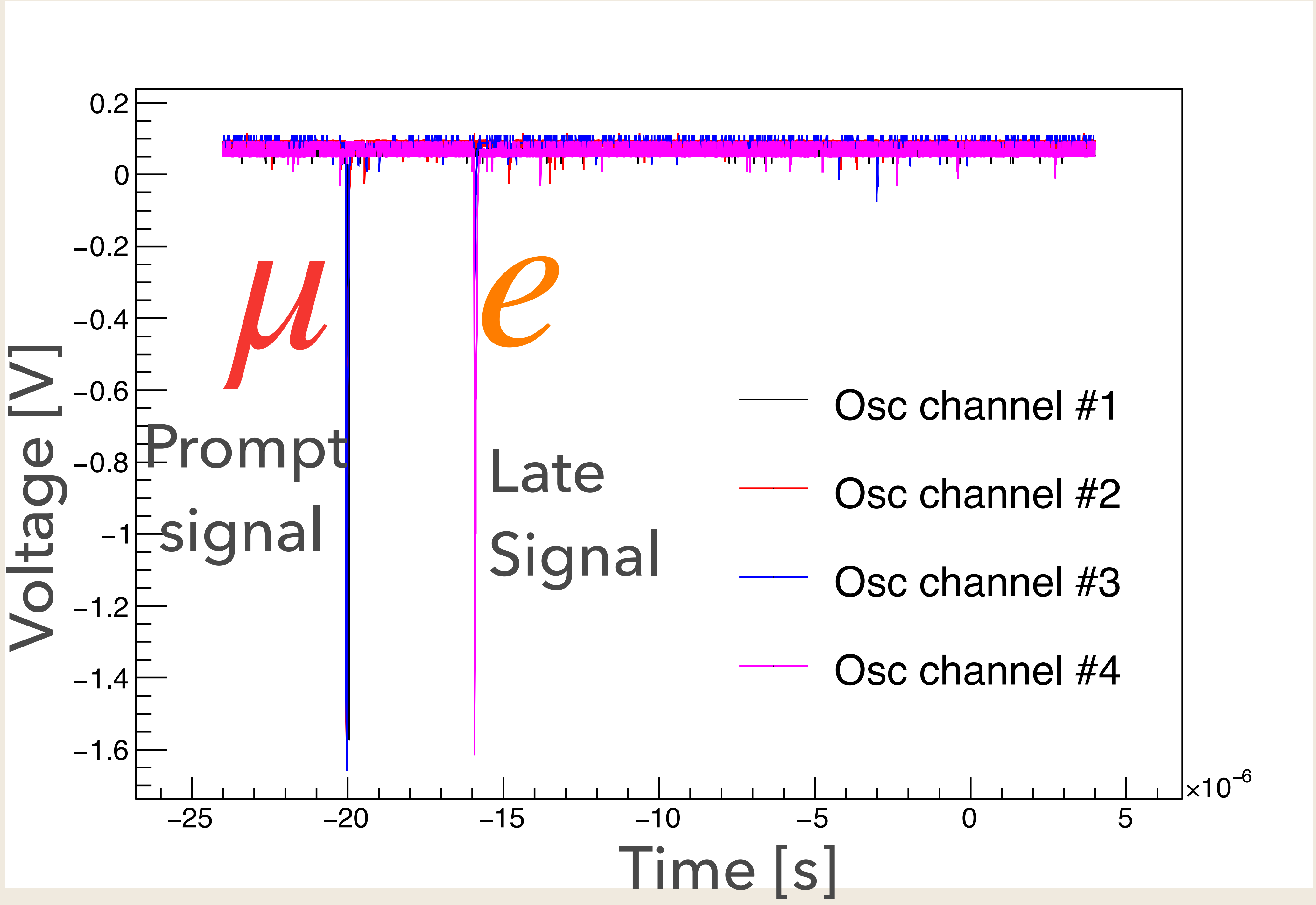
Target: **general concepts and relevant technique used during this camp.**

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)*)



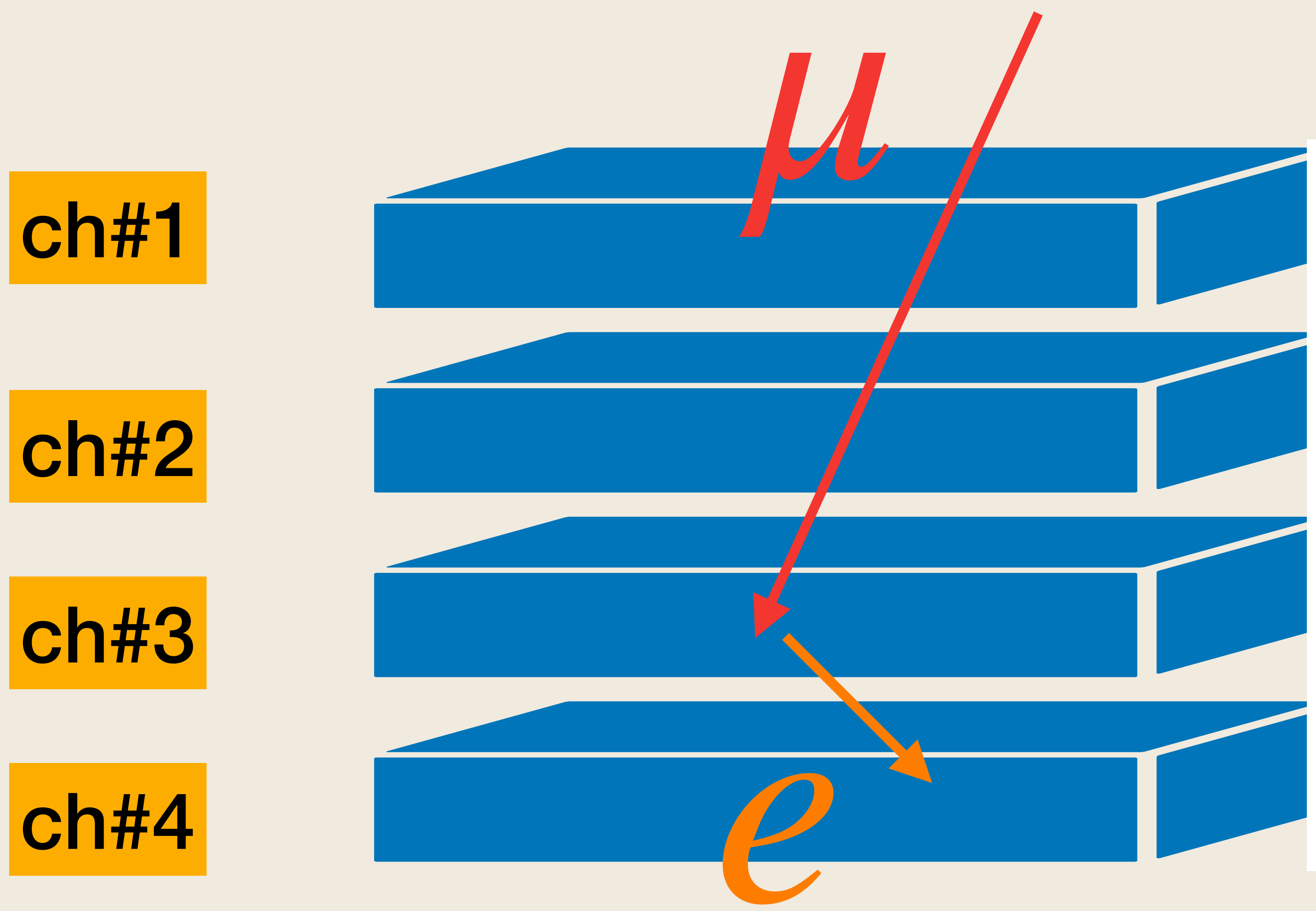


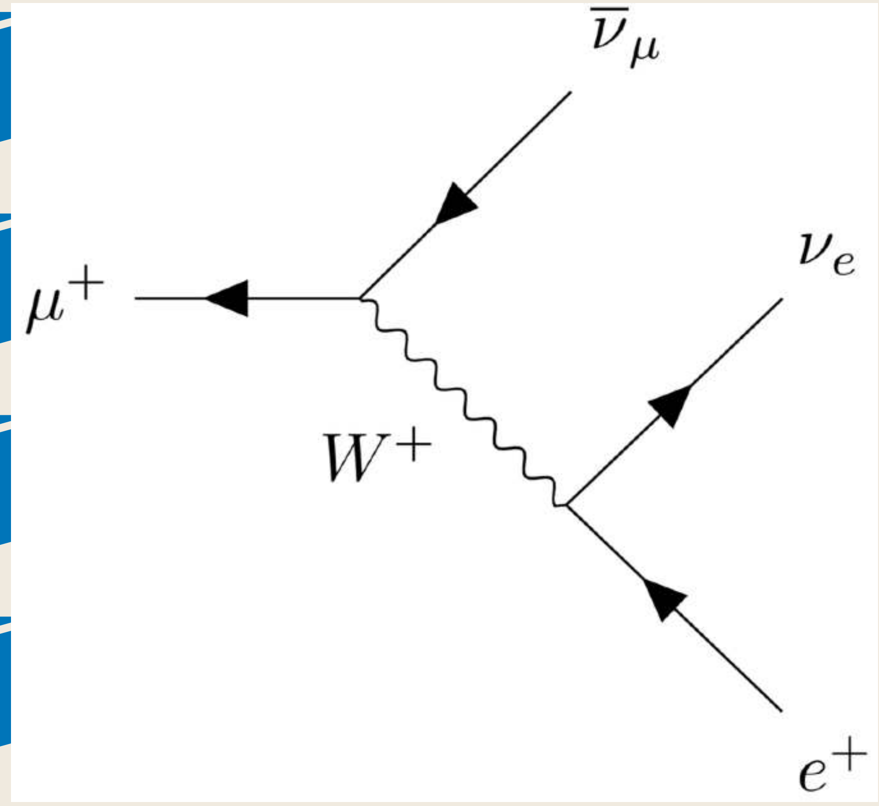
Why measuring cosmic-ray muon decay is useful/interesting?

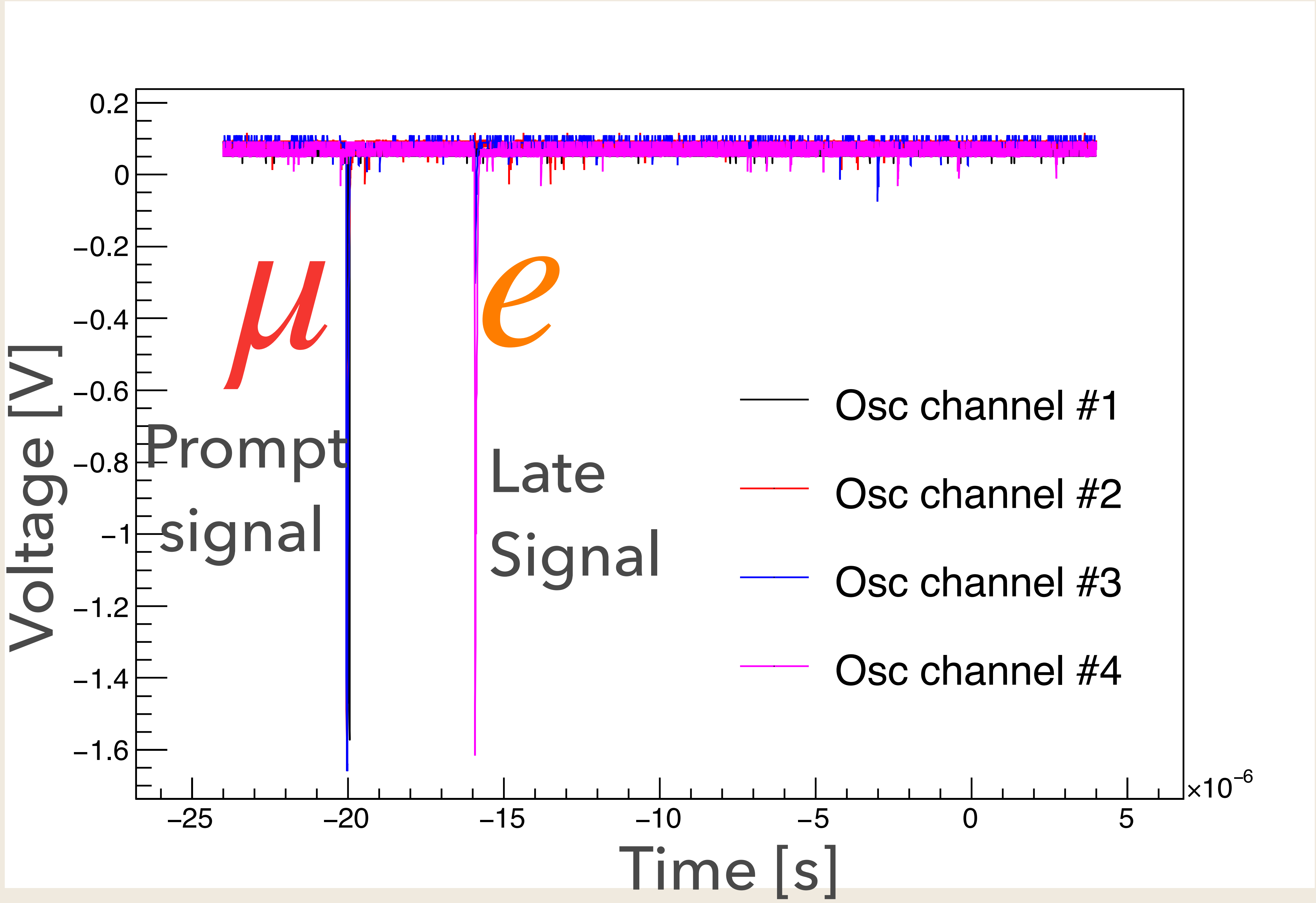
- Will allow us to examine **the "time dilation" in special relativity**
  - Knowing 2.2us lifetime, if not taking relativistic effect, muon will travel ~ 600m before stopped
  - But we know most of cosmic-ray muons produced in the upper atmospheric, ~ 10km (>>600m). So in classical mechanics, muons 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 detector cover whole space and detect all particles involved
- Need to have *high spatial resolution* of muon and electron trajectories to tell that they likely originate from the same interaction vertex
- 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
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PARTICLE IDENTIFICATION

- It's impossible to identify neutrinos *(since they interact weakly)* but we make sure 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 likely originate from the same interaction vertex

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

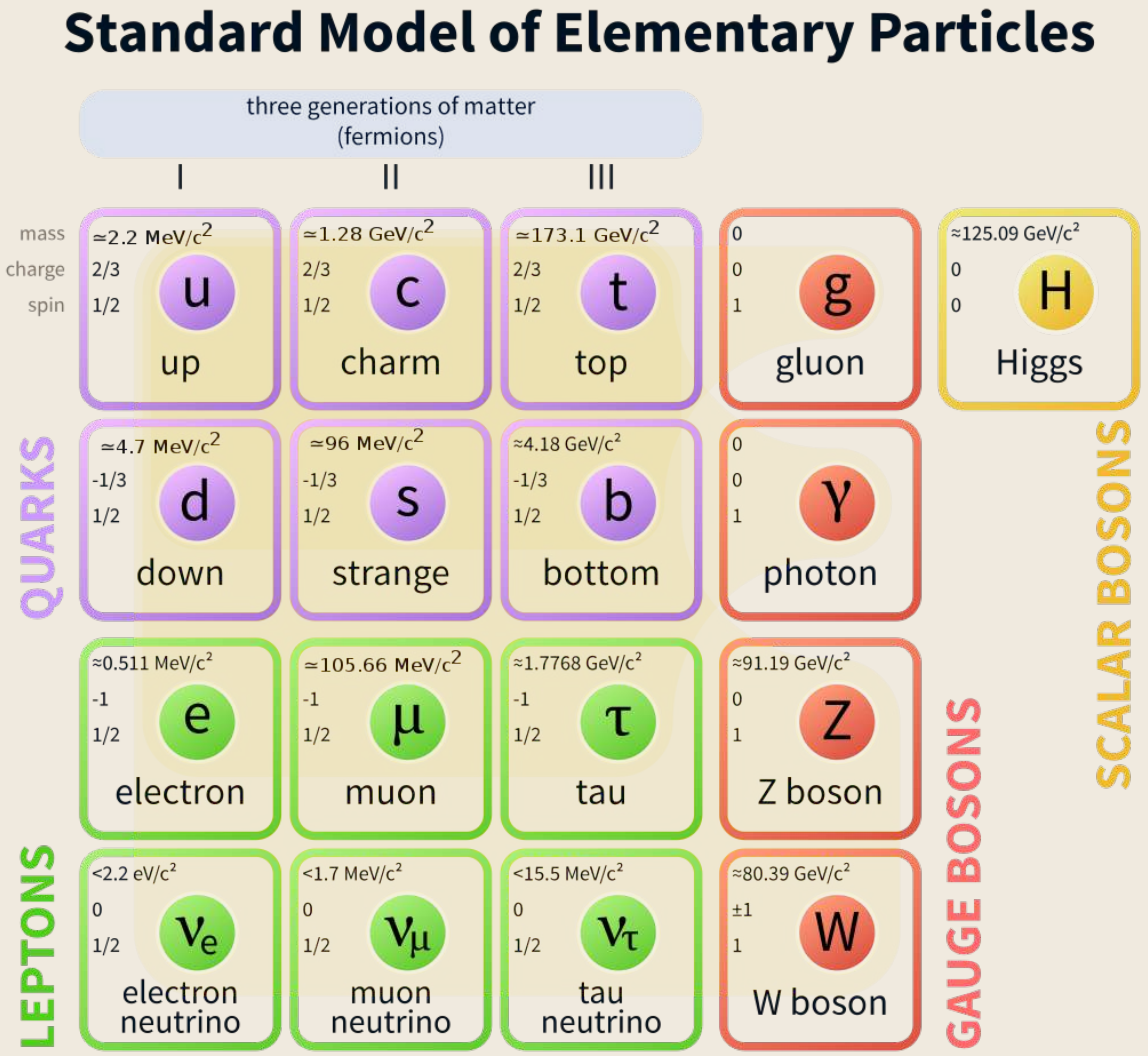
- (*Parity violation in produced electron, referring to nature of polarized muons, which is decay product of downward pions*)

PHYSICS LAW AND MOTIVATION

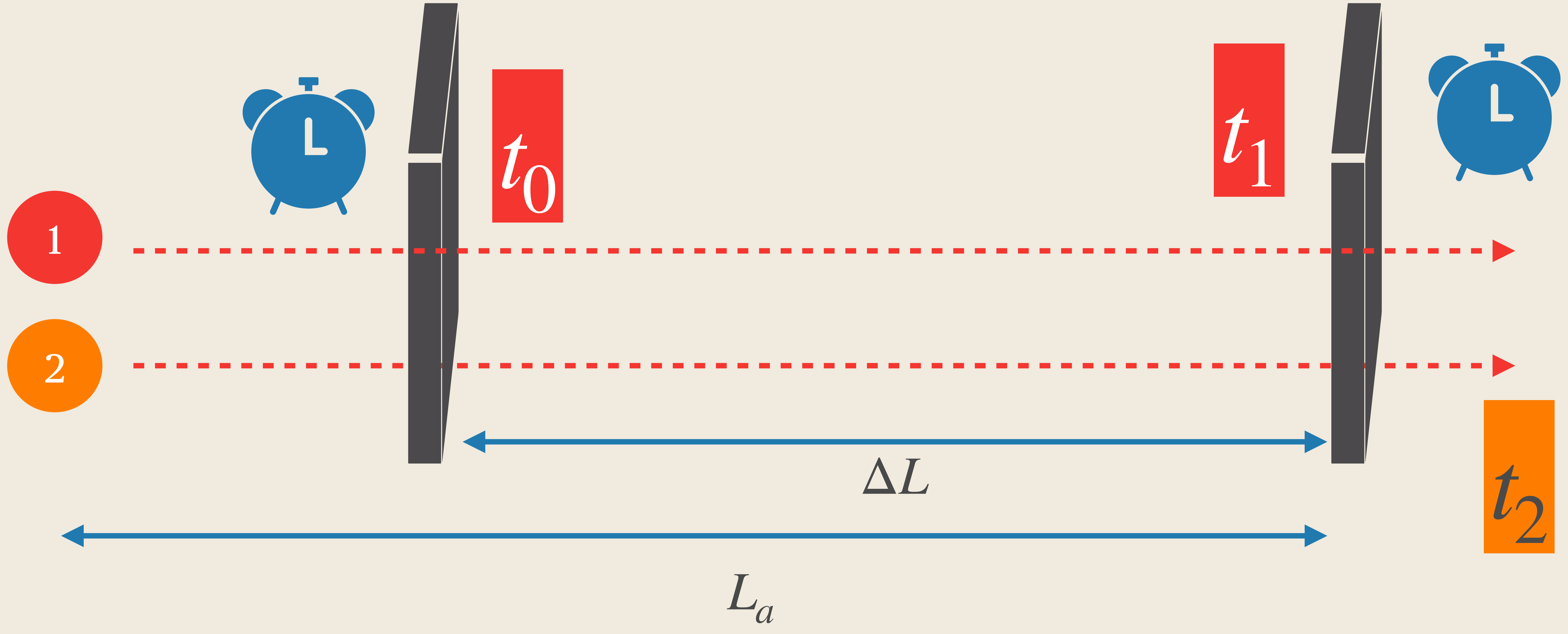
Particle identification

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*)



PID w/ Time-of-flight (TOF)



- Absolute TOF: $t_1 - t_0 = \dfrac{\Delta L}{\beta c} = \dfrac{\Delta L}{c}\sqrt{1 + \dfrac{m^2c^2}{p^2}}$

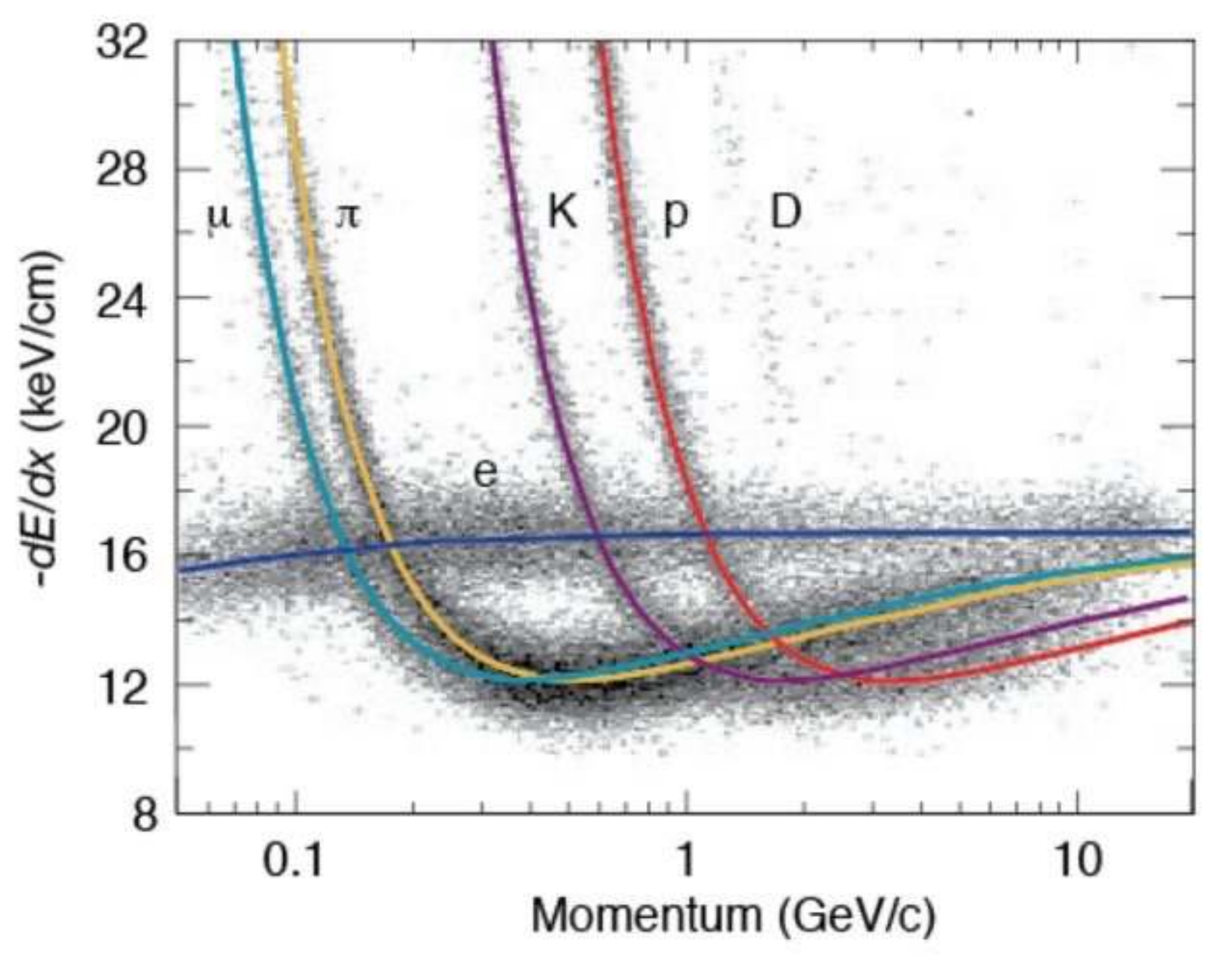
m CAN BE MEASURED IF ONE KNOWS $\Delta t_1, \Delta L, p$

- Relative TOF: $t_2 - t_1 = \dfrac{\Delta L}{\beta c} = \dfrac{L_a}{c}\left(\sqrt{1 + \dfrac{m^2c^2}{p^2}} - \sqrt{1 + \dfrac{m^2c^2}{p^2}}\right) \approx \dfrac{L_a c(m_1^2 - m_2^2)}{2p^2}$

USEFUL CONVERSION: AT SPEED OF LIGHT, PARTICLE PASS 1 METER IN 3.3 NANOSECOND

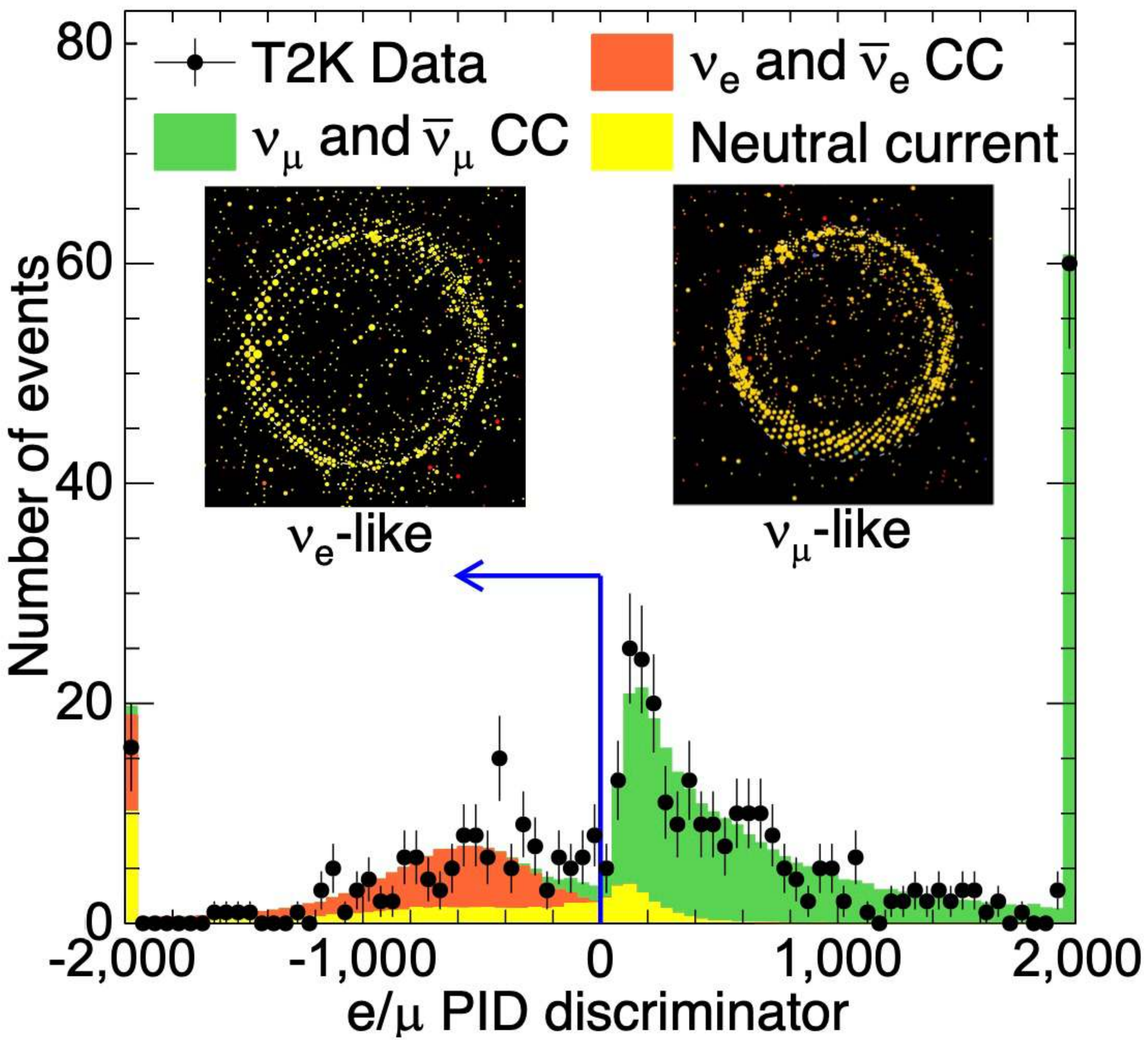
Particle identification using dE/dx

- If one can measure dE/dx simultaneously with momentum, particle can be classified
- Behavior of electron is different due to Bremsstrahlung process



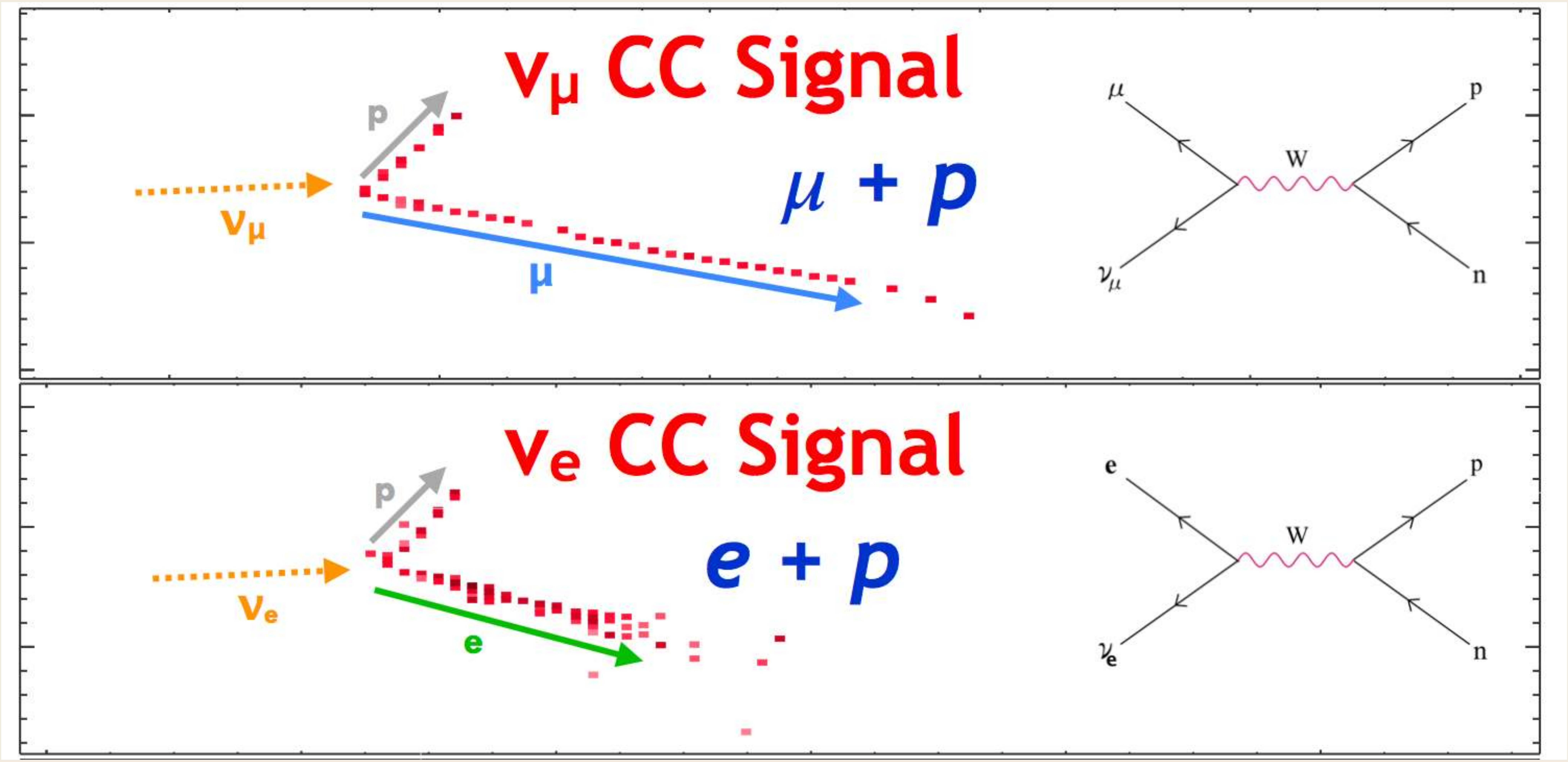
Electromagnetic shower development

- 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*



Ranging and Electromagnetic shower development

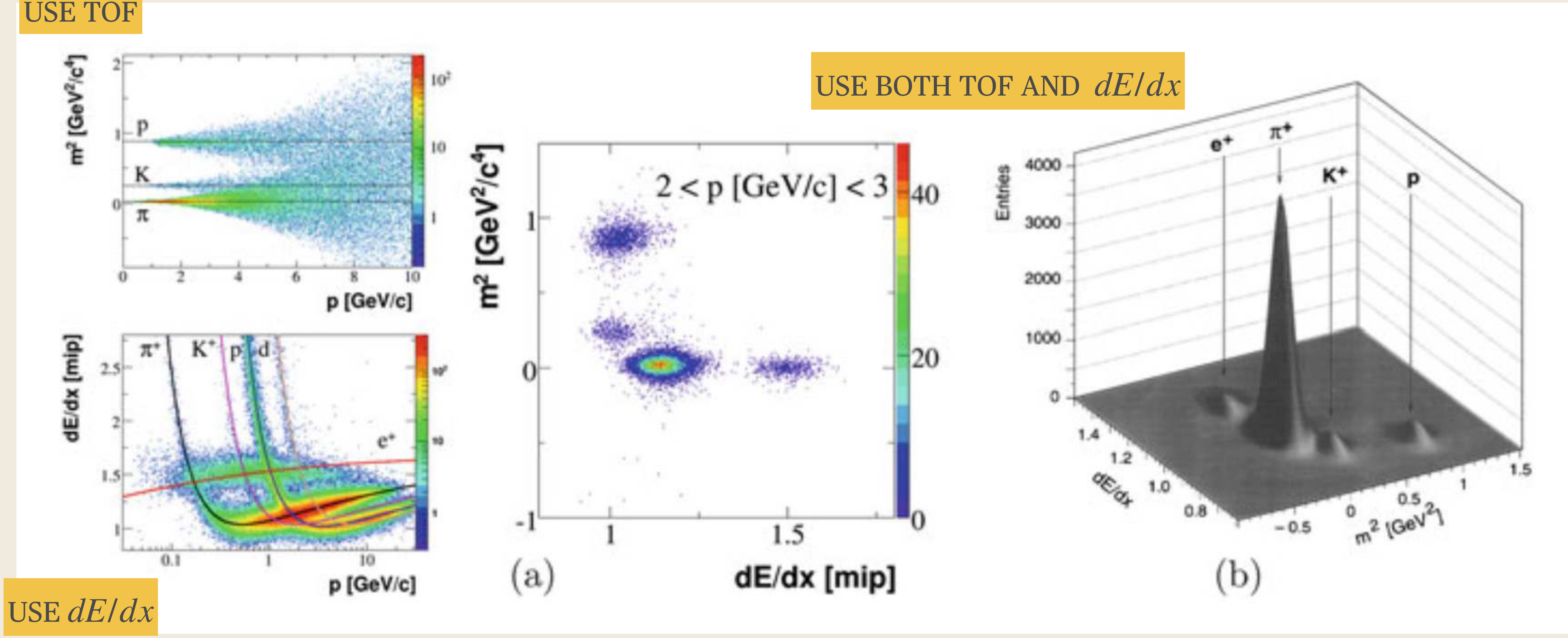
NOvA, scintillator technique



NA49 experiment: Use TOF and dE/dx

USE TOF

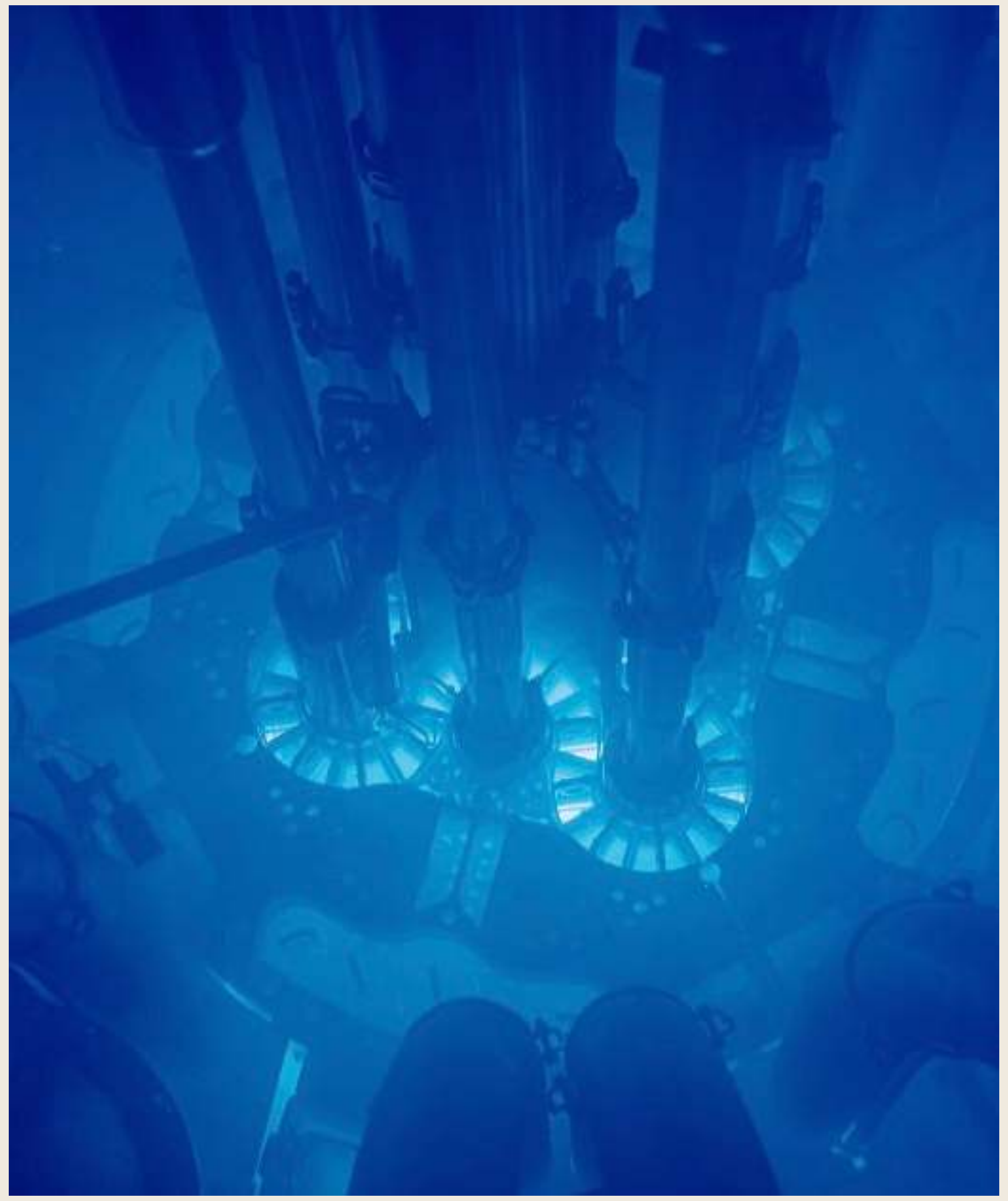
USE BOTH TOF AND dE/dx



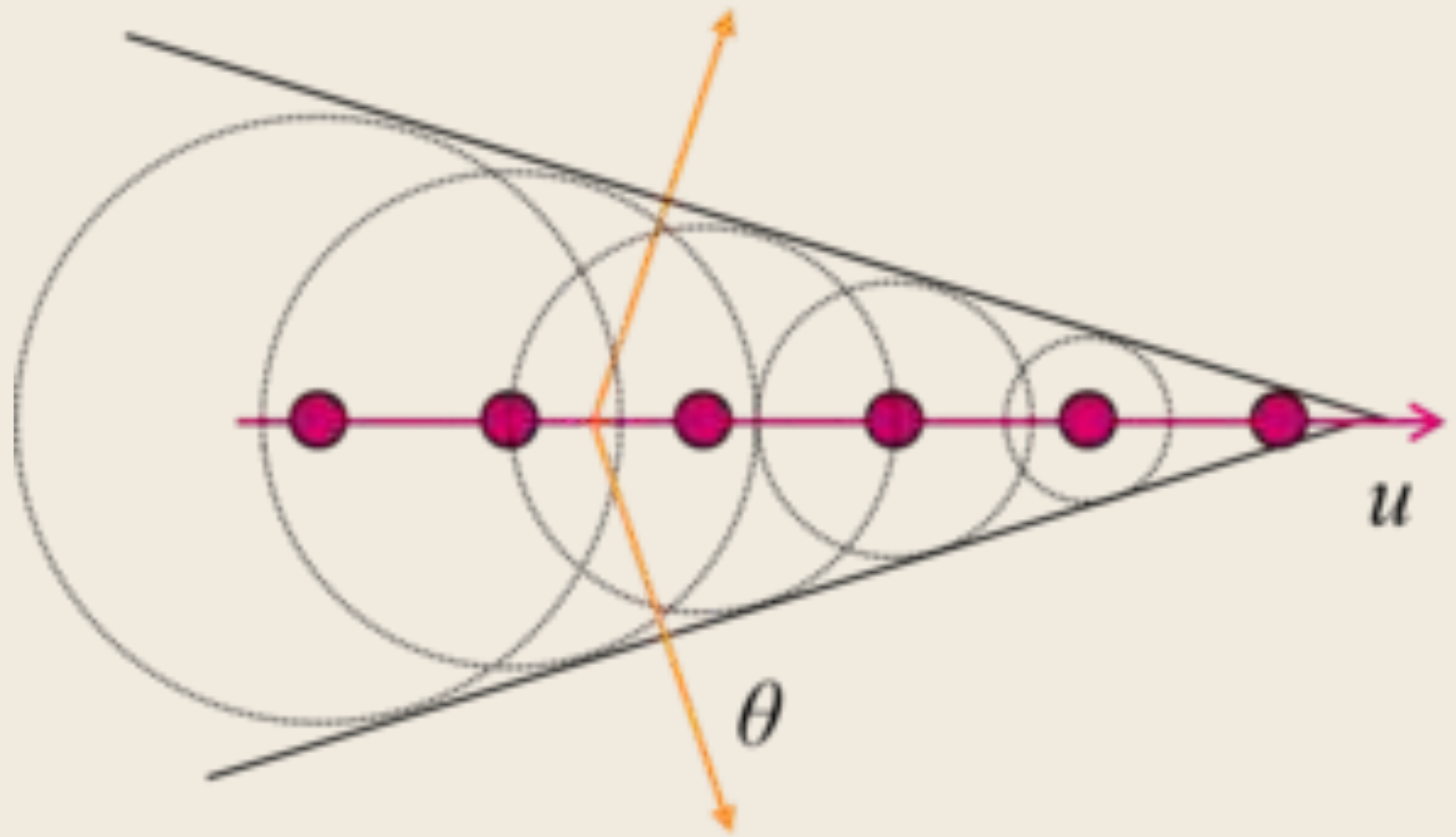
USE dE/dx

Cherenkov radiation for PID

- Discovered by Pavel A. Cherenkov in 1937
- It happens when a charged particle passing through a polarizable medium with speed higher than the speed of light in that medium.
  - $v = \beta c > c/n \rightarrow \beta n > 1$ where n is refractive index
- Mechanism: molecules are polarized in the direction of the charged particle moving
  - Excited molecules emit the light when back to the normal state
  - When particle moves faster than c/n, these emitted light added up constructively (interference) to emit the light at specific angle θ_C

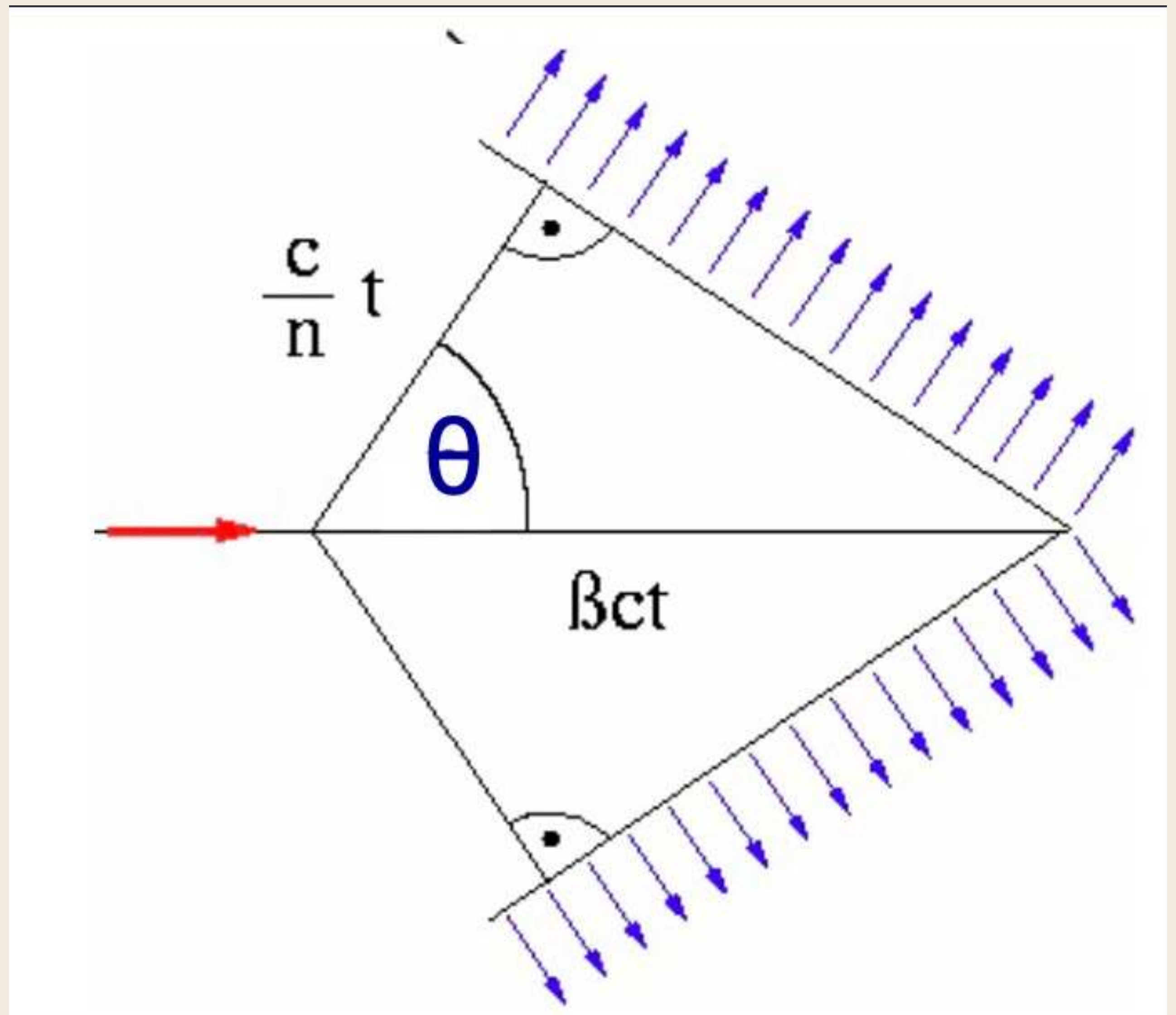


"Blue" water near reactor core



Cherenkov radiation for PID

- Threshold in Cherenkov radiation: $p_{th.} = \dfrac{mc/n}{\sqrt{1 - n^{-2}}}$
  - In the air, threshold for pions is 5GeV/c but for Kaon is 20 GeV/c
  - In water, threshold for electron is 0.77 MeV, for muon is 160 MeV, for tau is 2.7 GeV

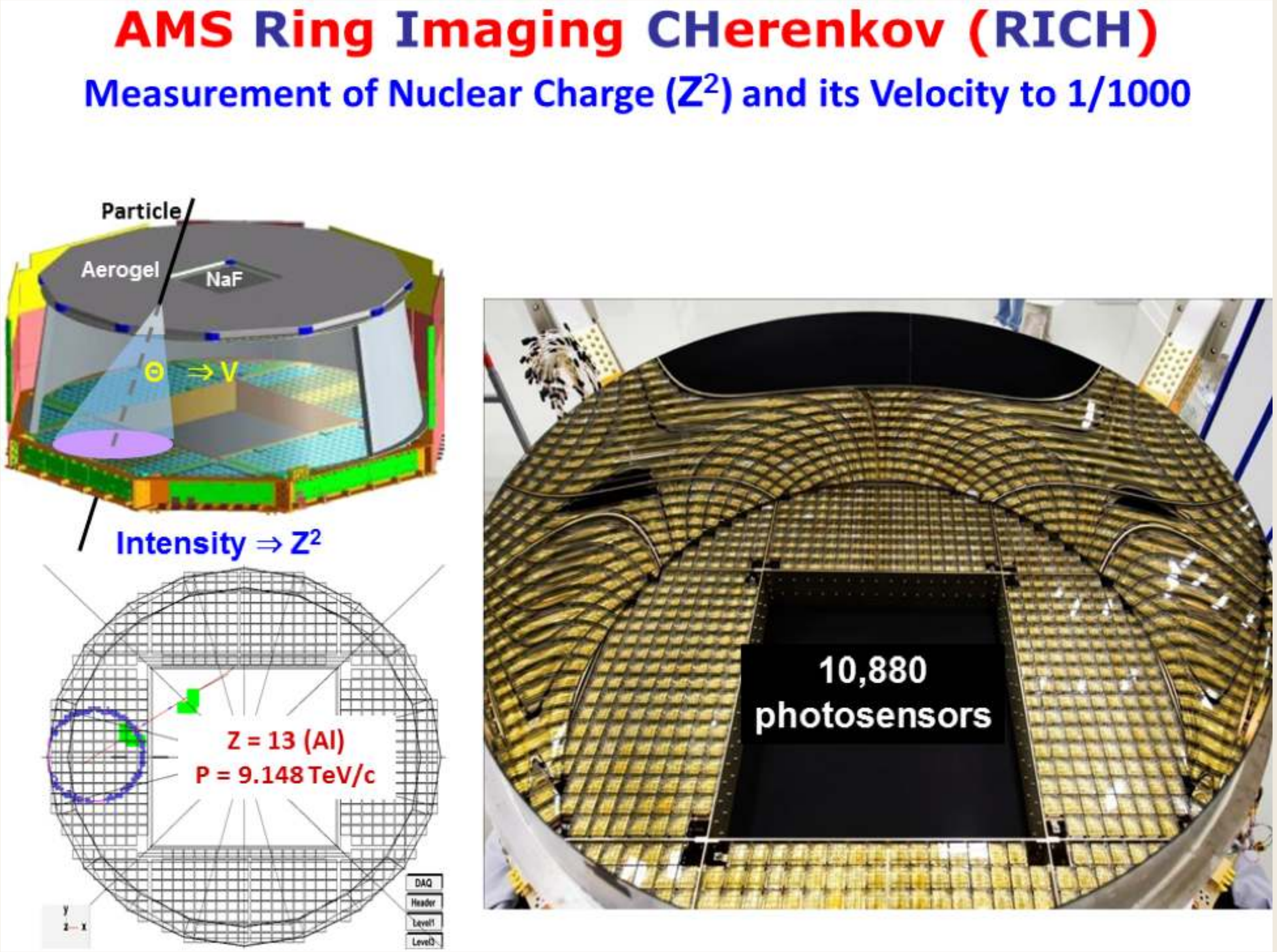


- Cherenkov angle $\cos\theta_C = \dfrac{1}{\beta n}$, **depend on** β
- Number of photons from Cherenkov radiation at a given wavelength $\dfrac{\partial^2 N}{\partial x \partial \lambda} = 2\pi\alpha(1 - 1/\beta^2 n^2)1/\lambda^2$
  - More photon at lower wavelength, so Cherenkov mostly at blue and UV range
  - **Also depend on** β

Cherenkov radiation for PID

Material	n-1	β_c	θ_c	photons/cm
solid natrium	3.22	0.24	76.3	462
Lead sulfite	2.91	0.26	75.2	457
Diamond	1.42	0.41	65.6	406
Zinc sulfite	1.37	0.42	65	402
silver chloride	1.07	0.48	61.1	376
Flint glass	0.92	0.52	58.6	357
Lead crystal	0.67	0.6	53.2	314
Plexiglass	0.48	0.66	47.5	261
Water	0.33	0.75	41.2	213
Aerogel	0.075	0.93	21.5	66
Pentan	1.70E-03	0.9983	6.7	7
Air	2.90E-03	0.9997	1.38	0.3
He	3.30E-05	0.999971	0.46	0.03

Cherenkov radiation for PID: RICH exp.



https://ams02.space/detector/ring-imaging-cherenkov-detector-rich

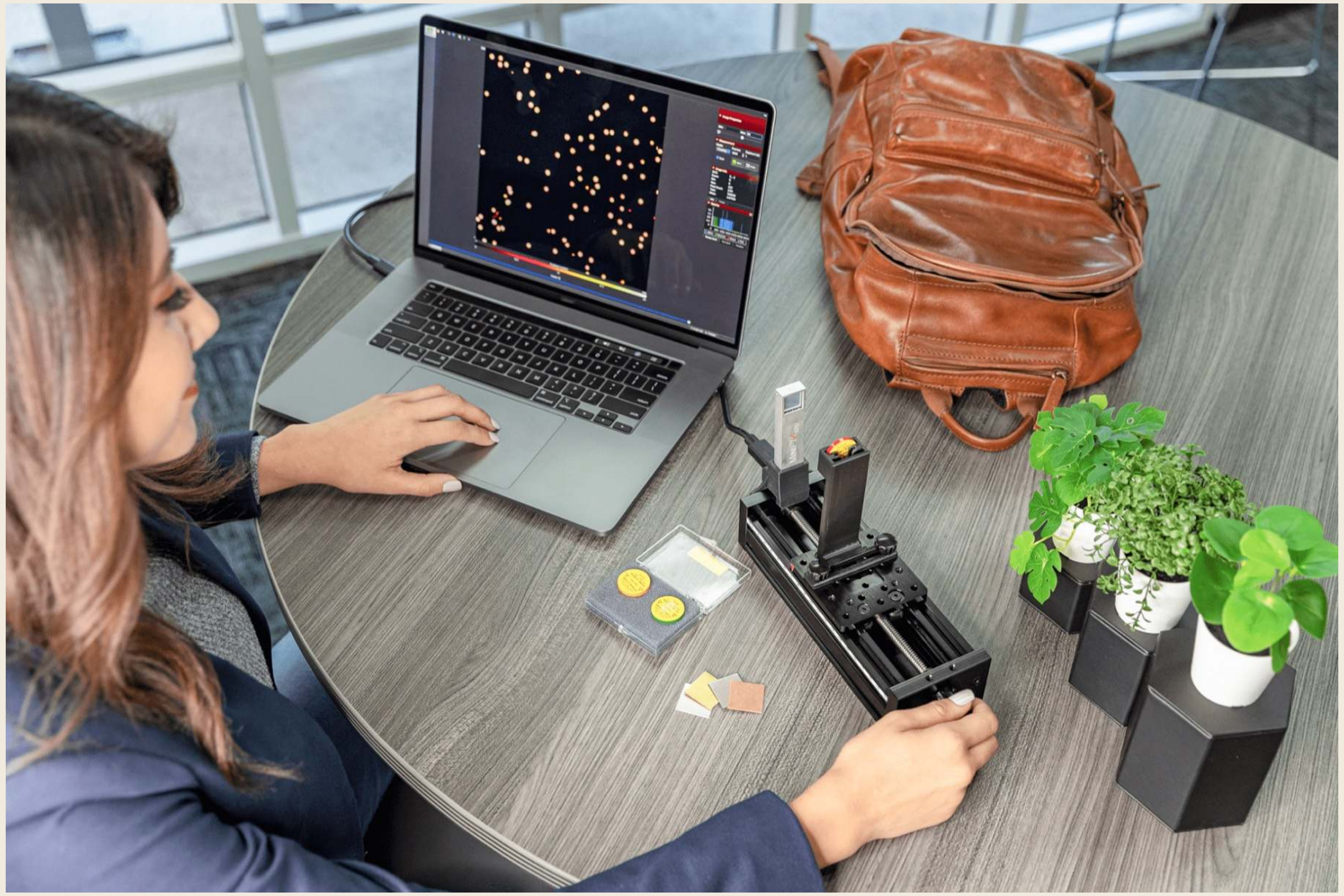
Tracking detector

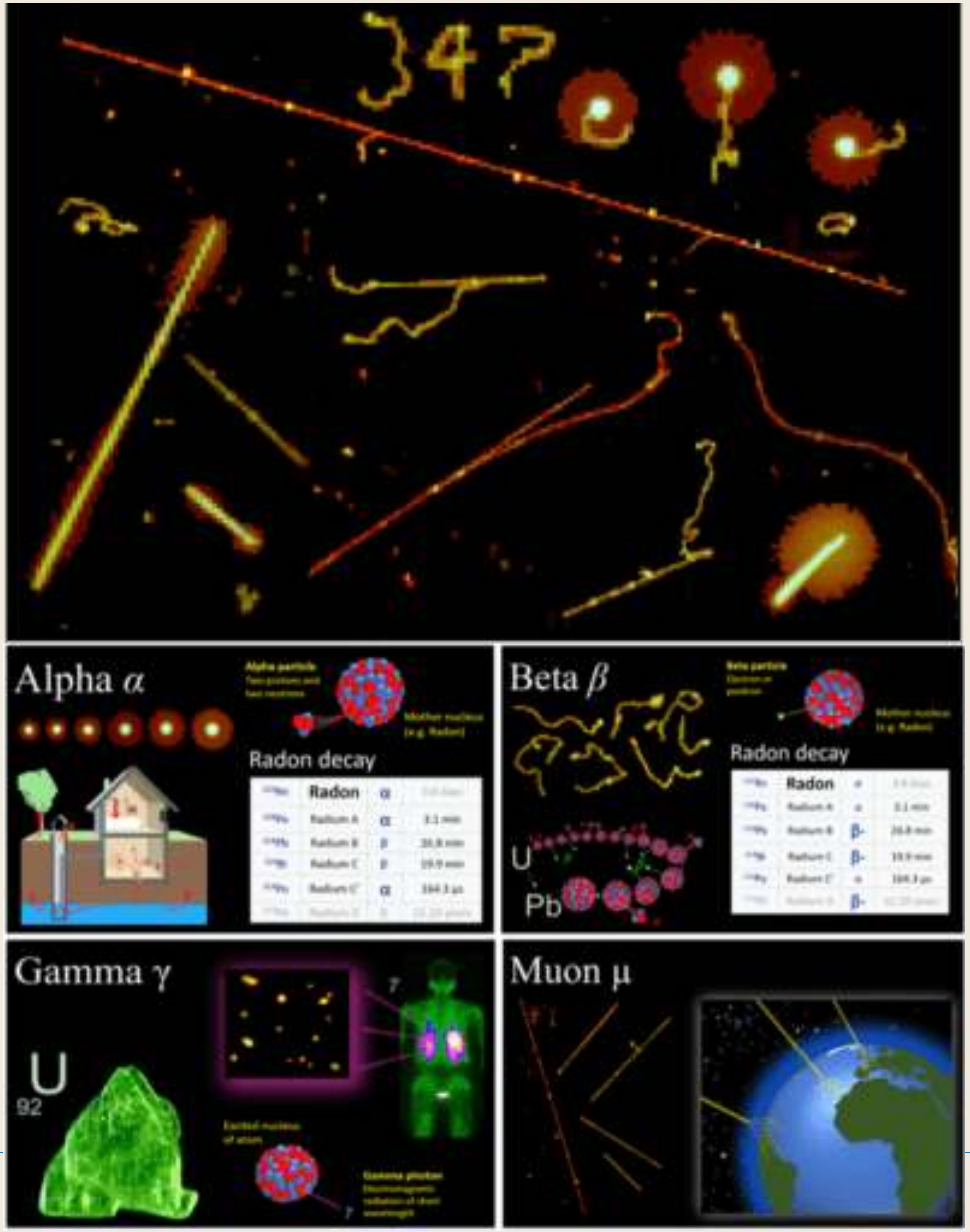
Tracking detector

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

More at Timepix section.

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

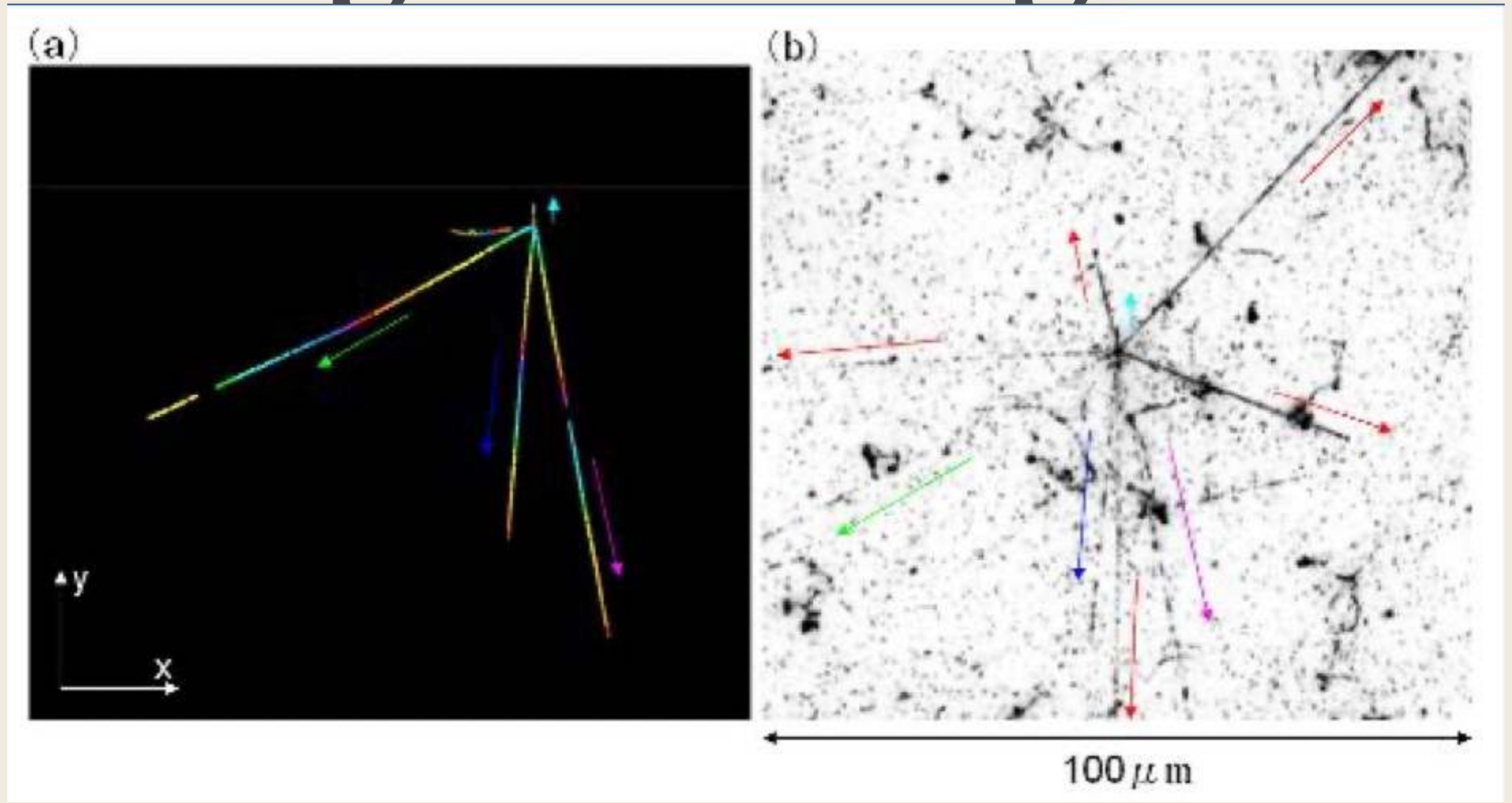
Principle for tracking

Charged particle passing through matter

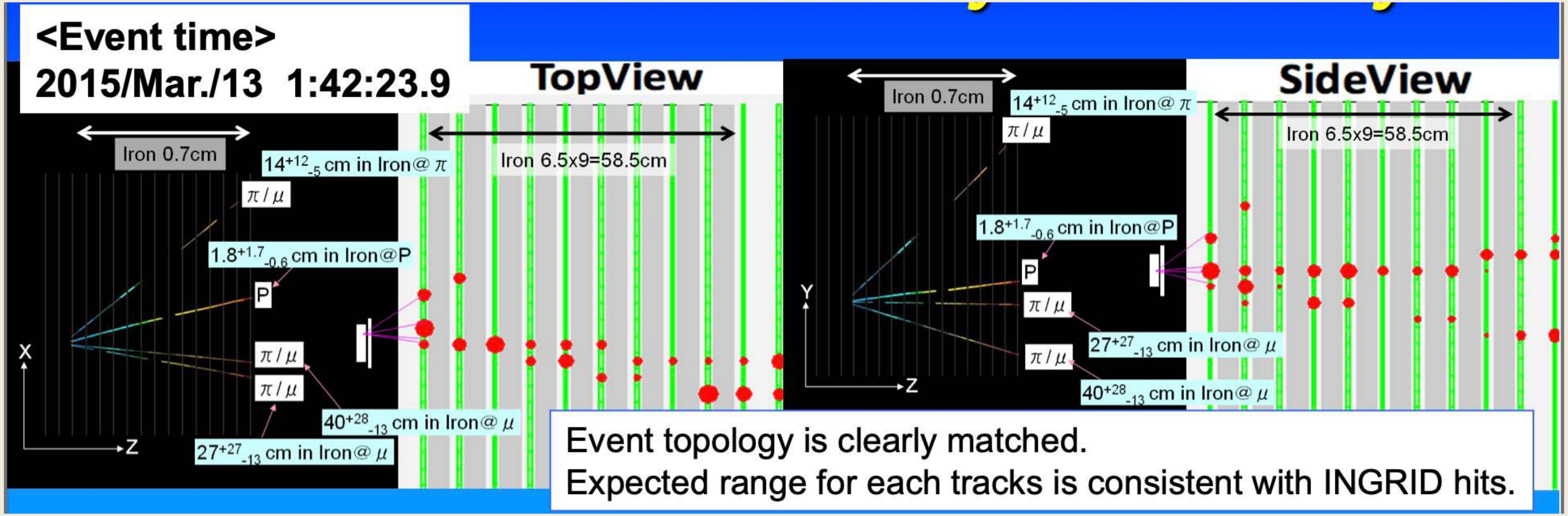
- Create **electron-ion pairs** in the gas
- **Electron-hole pairs** in semiconductor
- **Scintillation light** from excited molecules (liquid/plastic scintillators)
- **Cherenkov light** in the transparent materials
- …

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

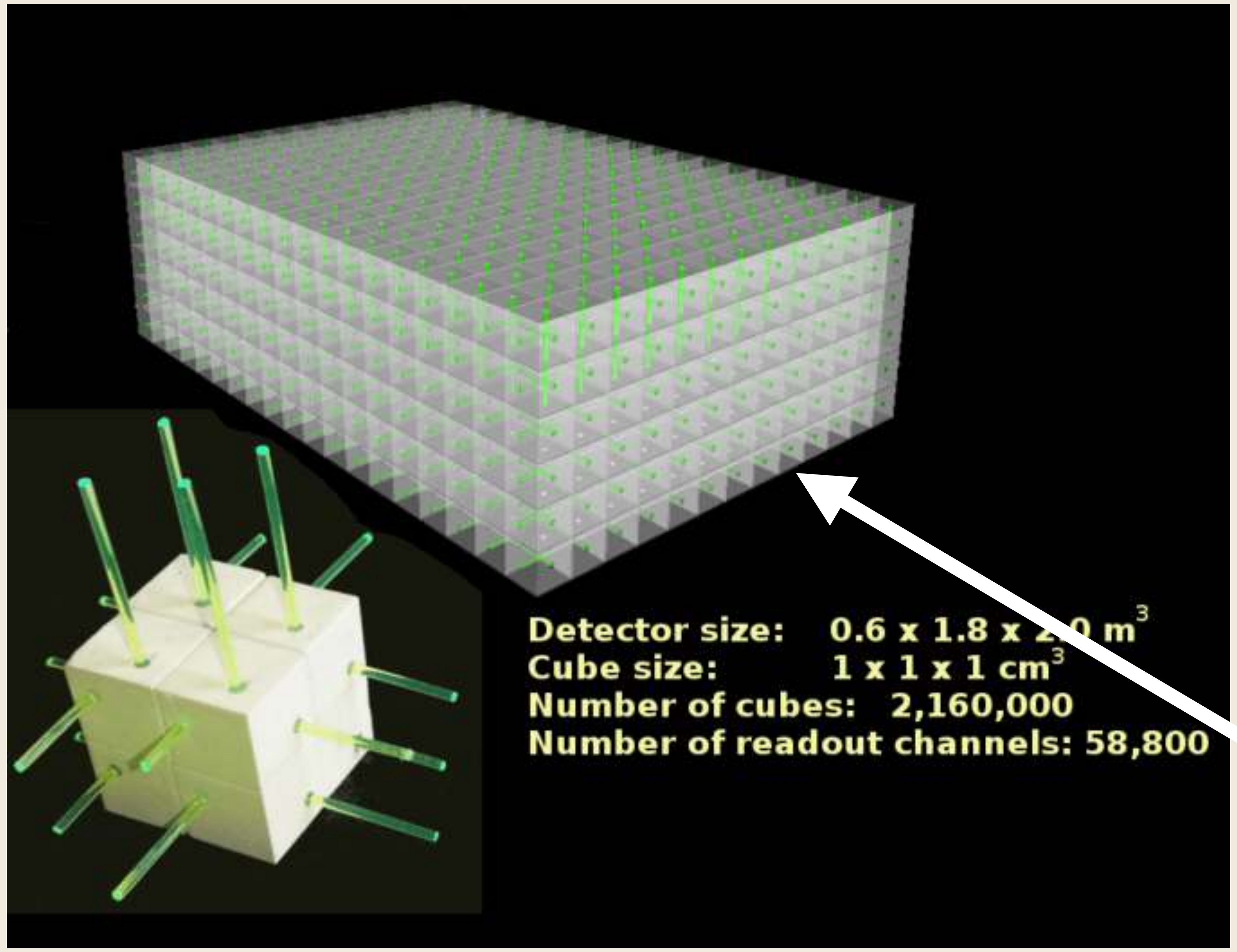
Eg: Tracking with NINJA (Emulsion technique)



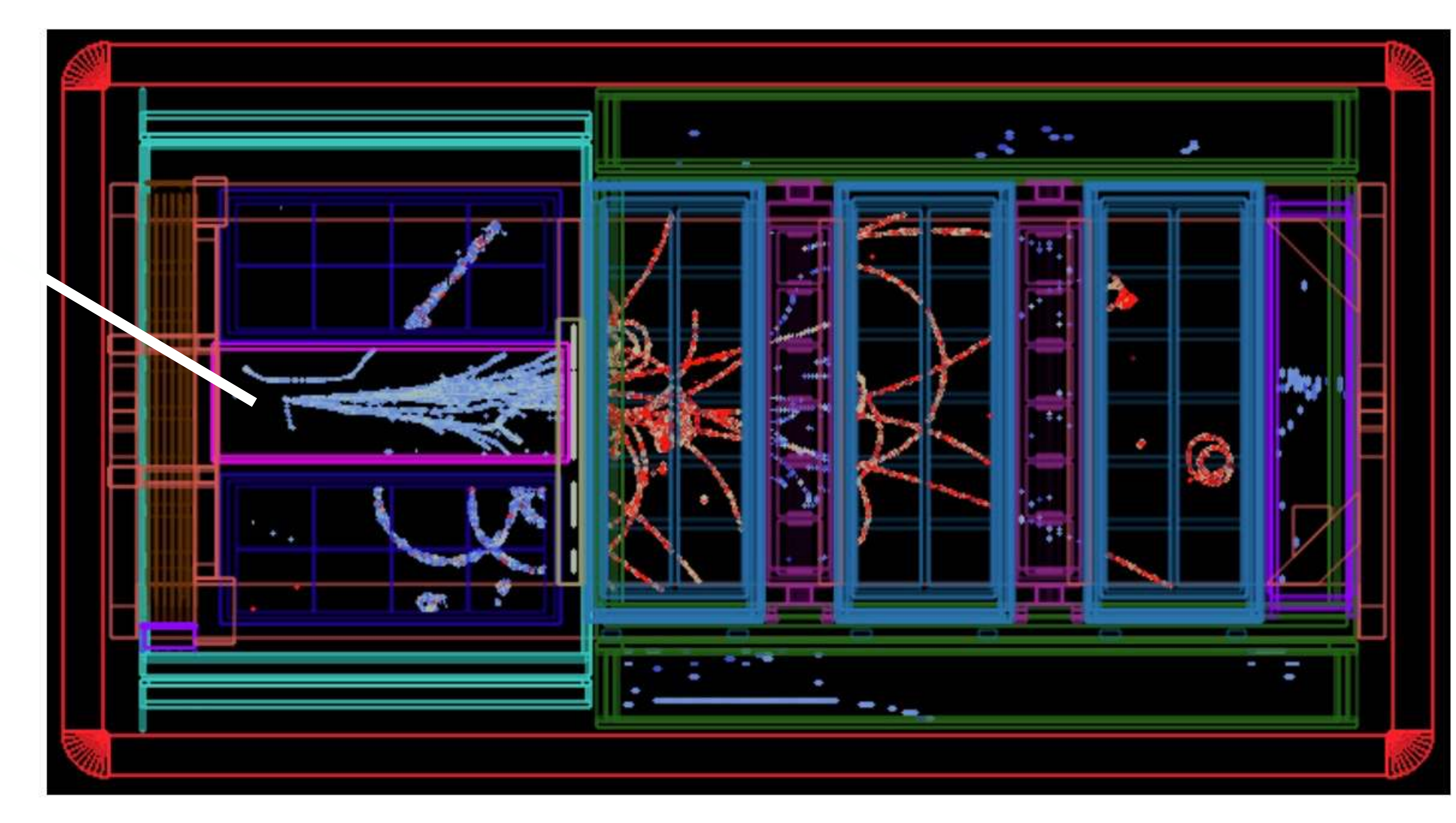
In hybrid w/ other detector



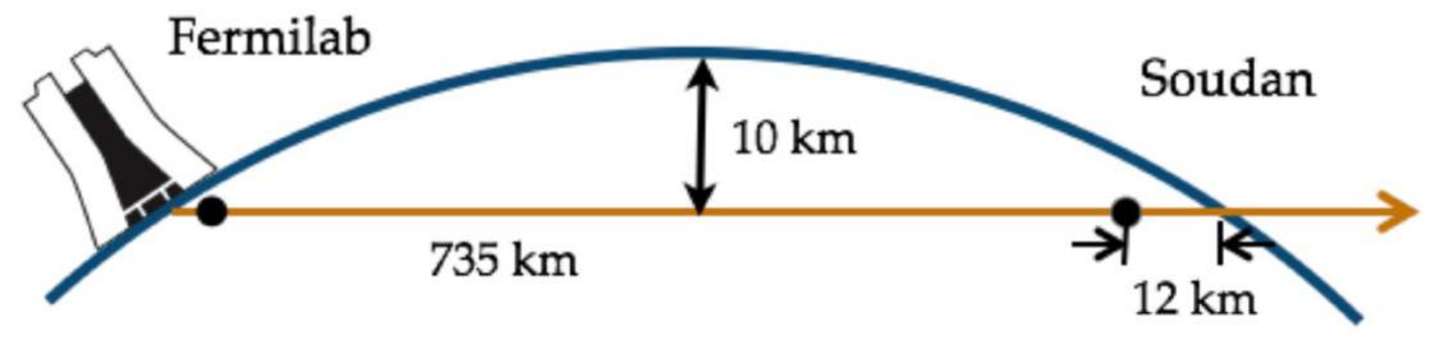
Eg: Tracking with Super-FGD



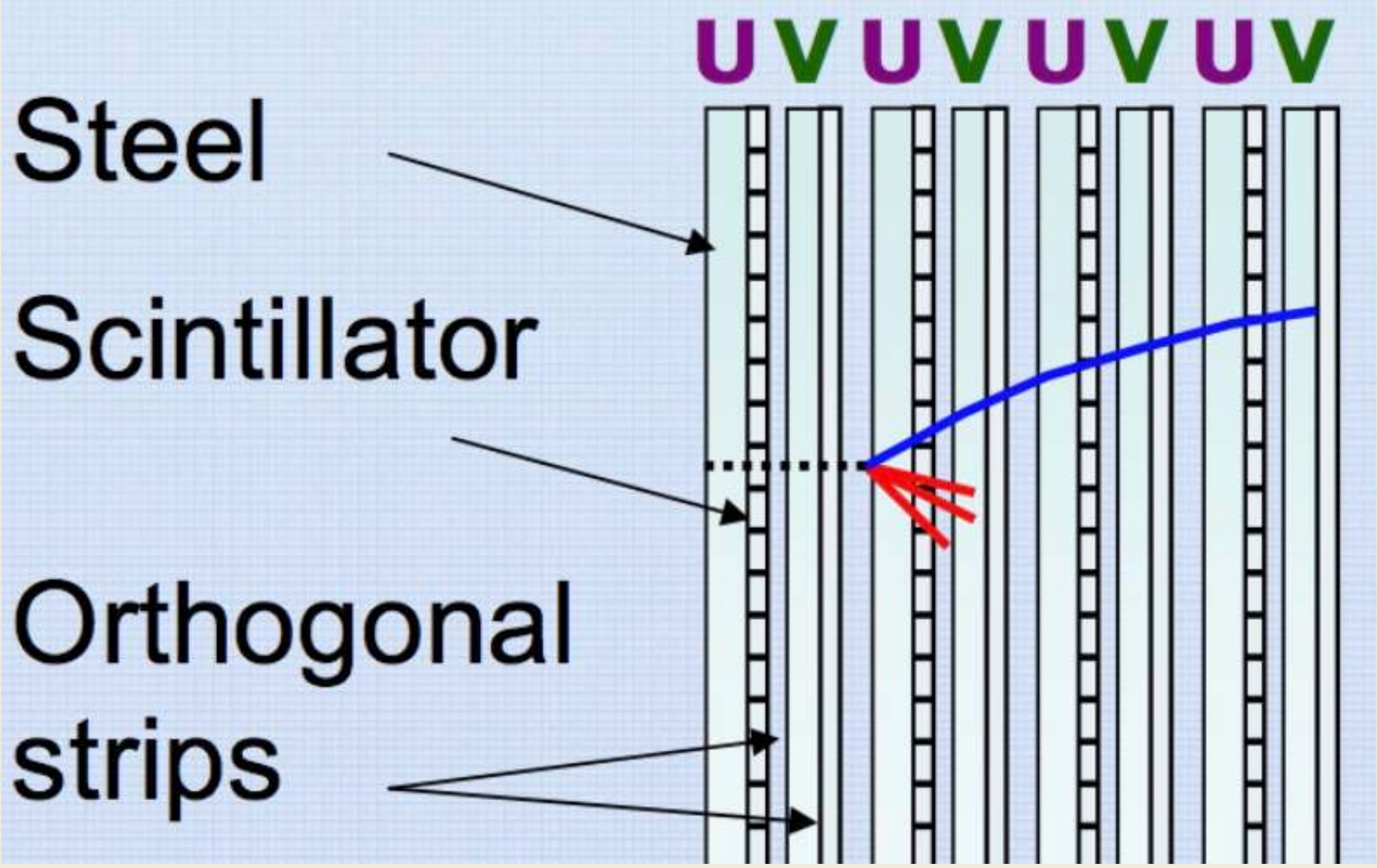
SCINTILLATION CUBES

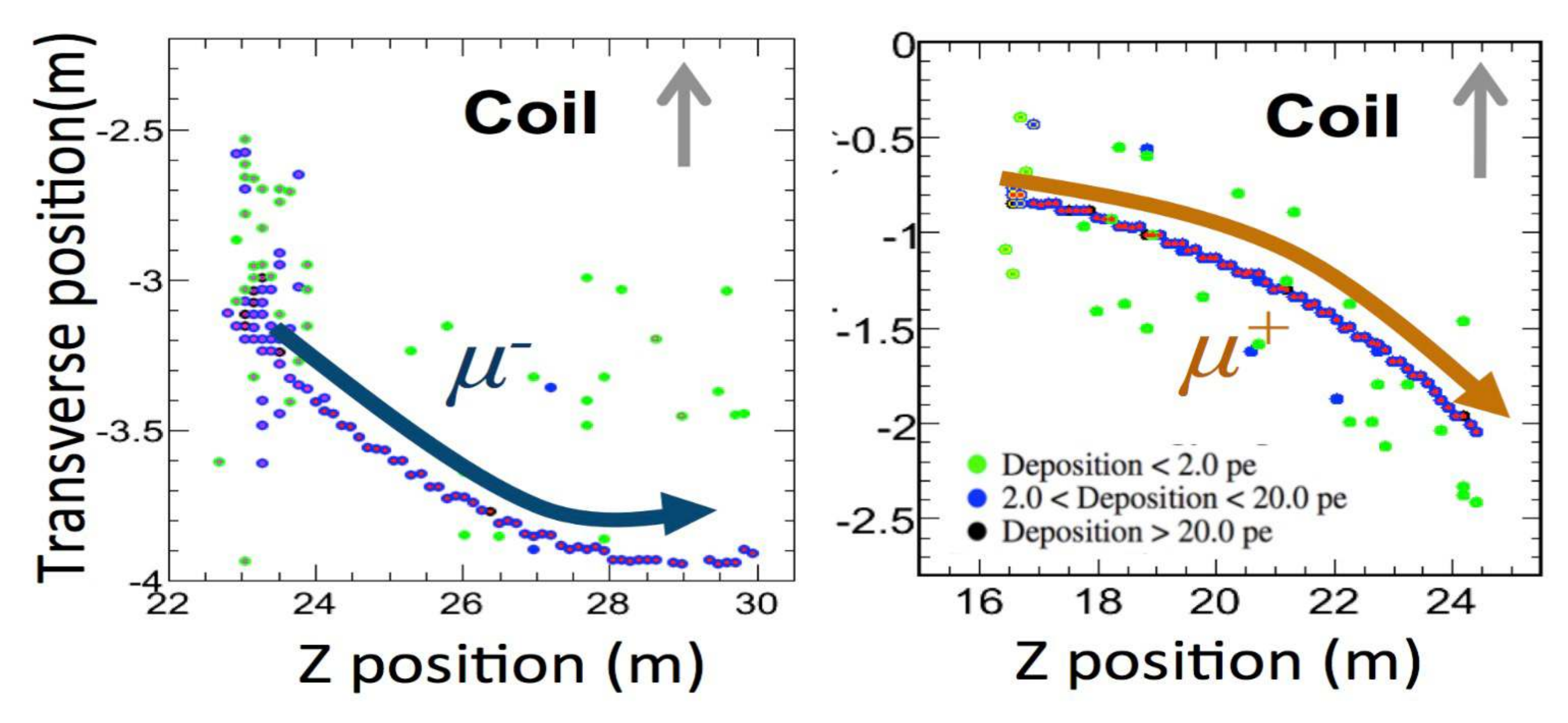


Eg: Tracking with charge identification



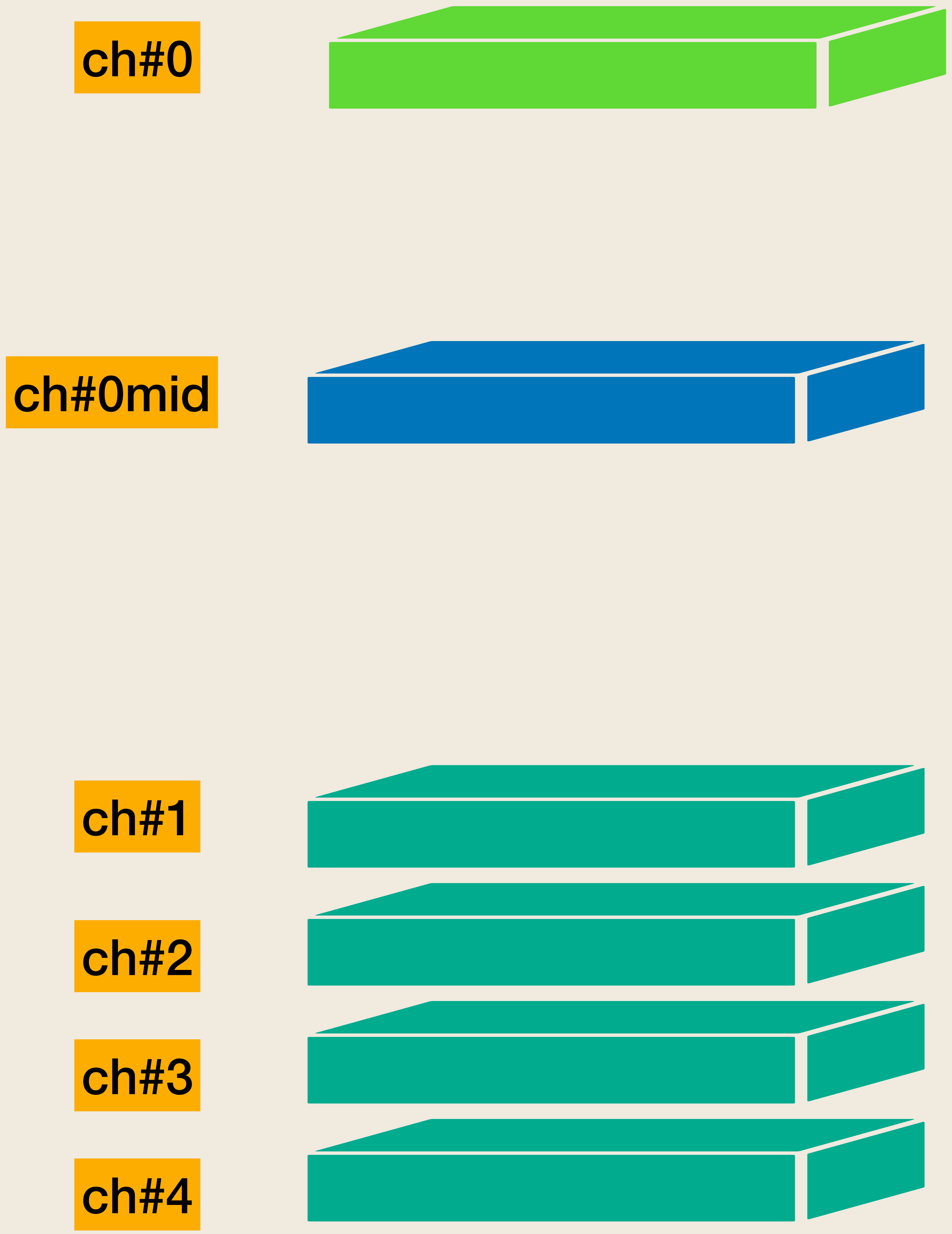
- ✧ NuMI high intensity neutrino beam
- ✧ Near Detector at Fermilab, IL
- ✧ Far Detector at Soudan, MN
- ✧ Two-detector design to mitigate systematic uncertainties

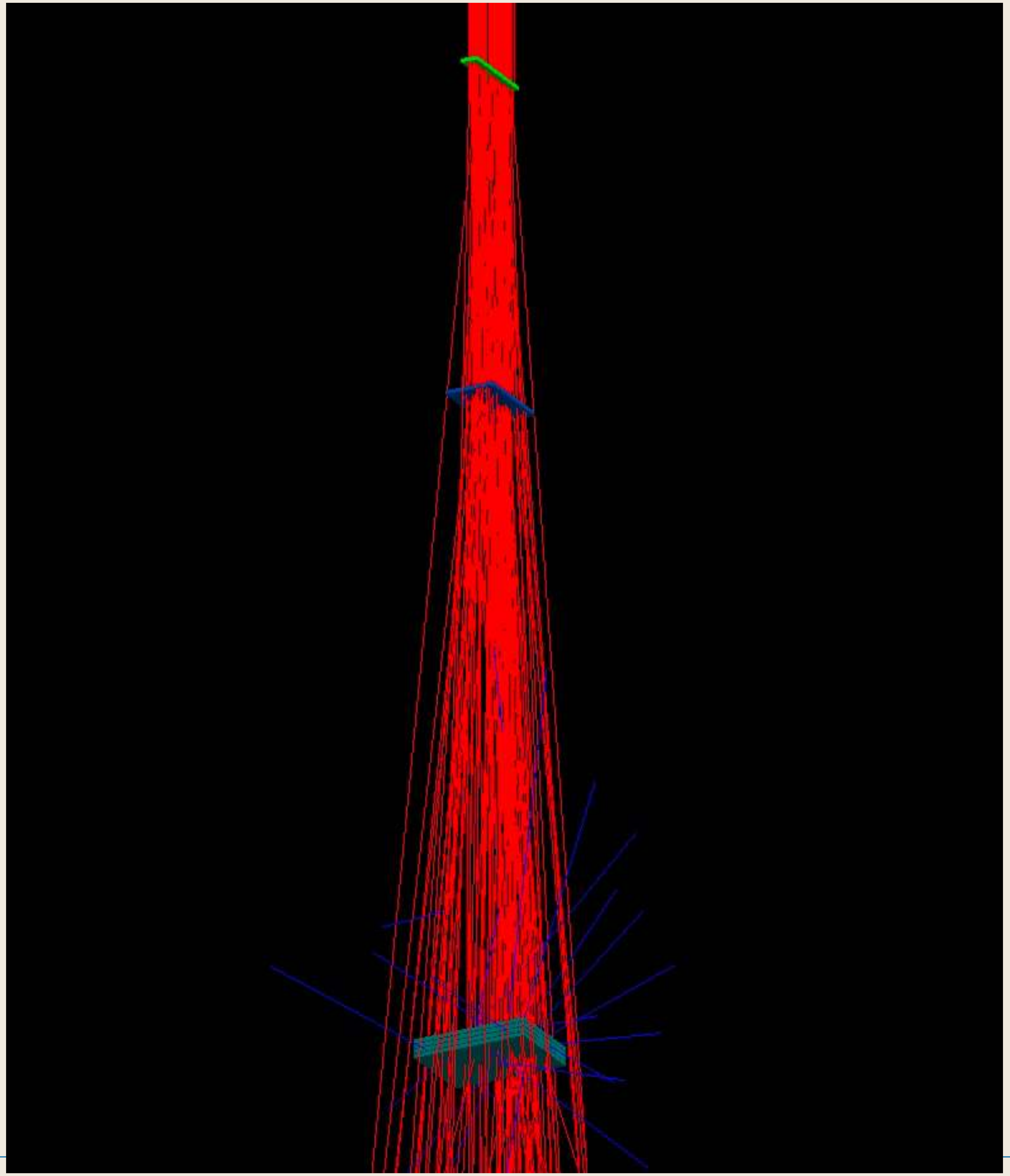




Tracking cosmic ray muons with simple scintillator setup

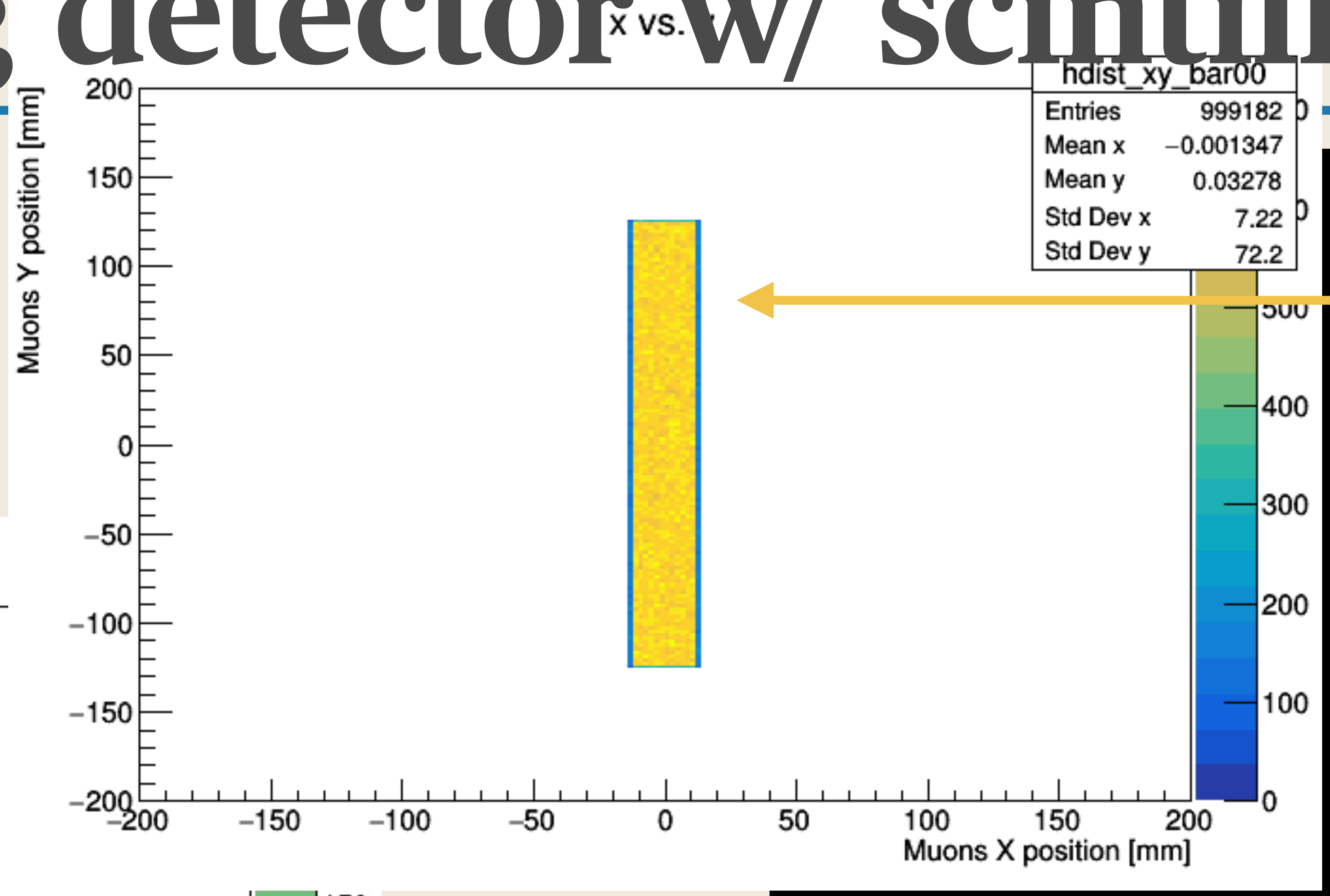
Simple tracking detector w/ scintillator (Simulation)

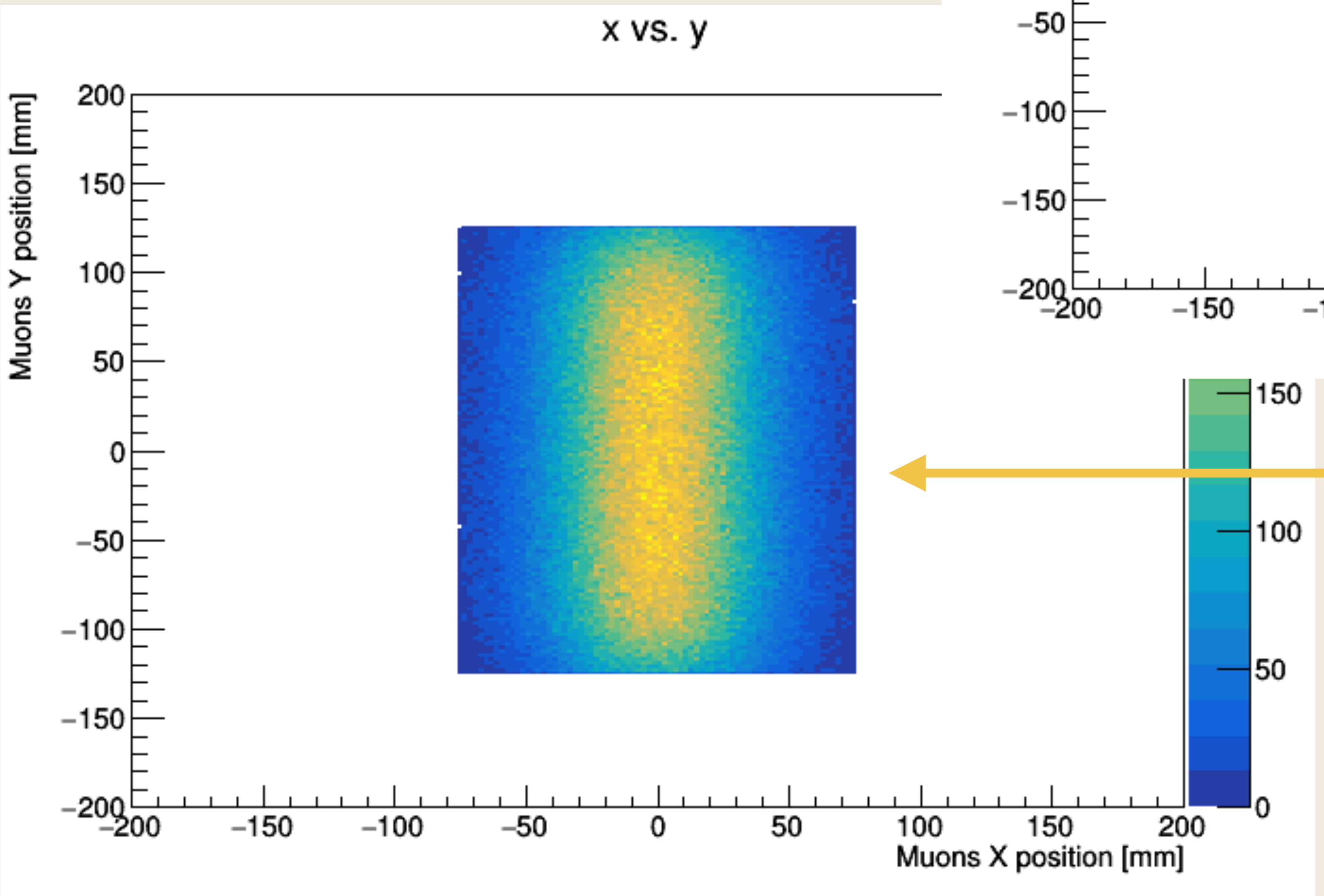


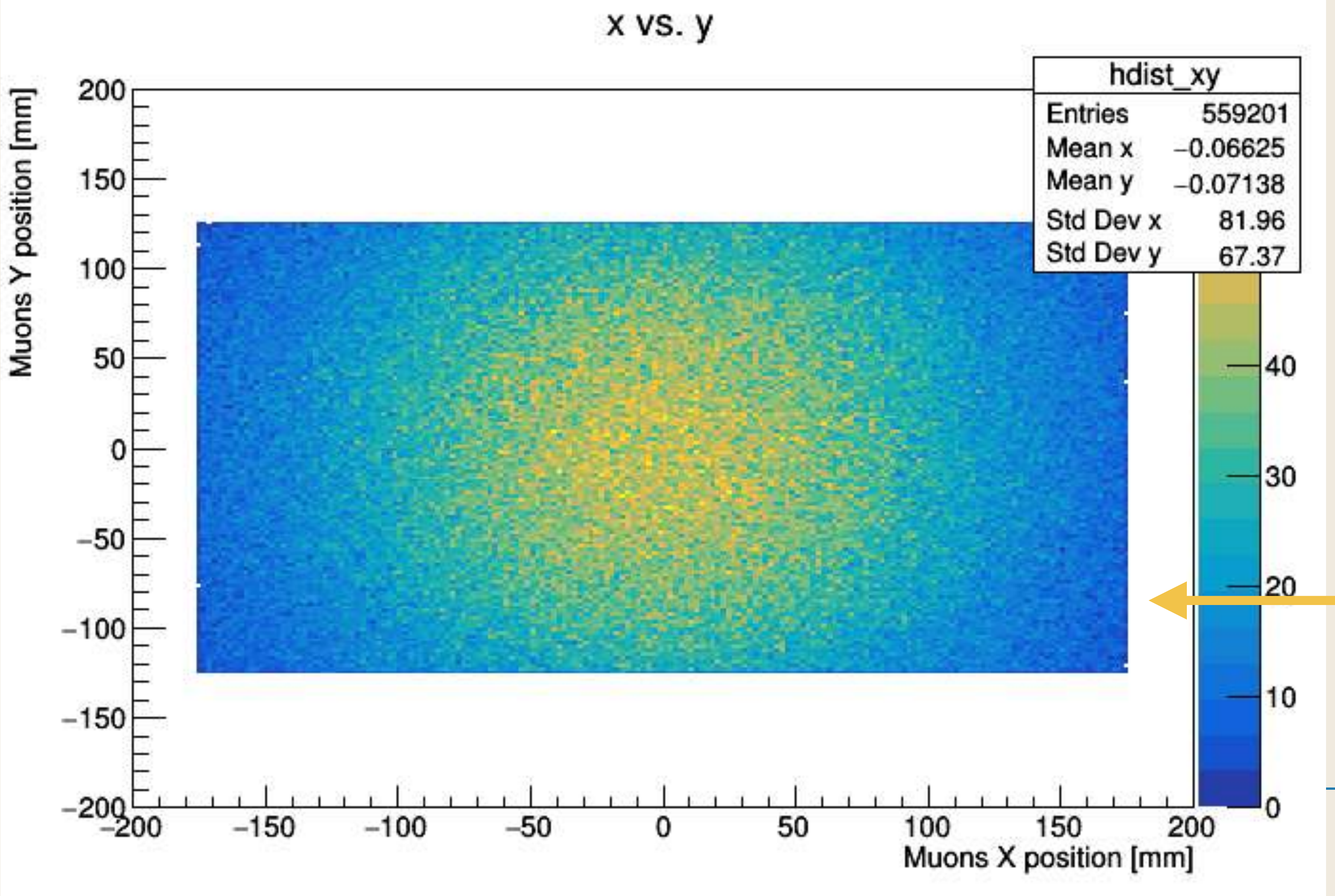


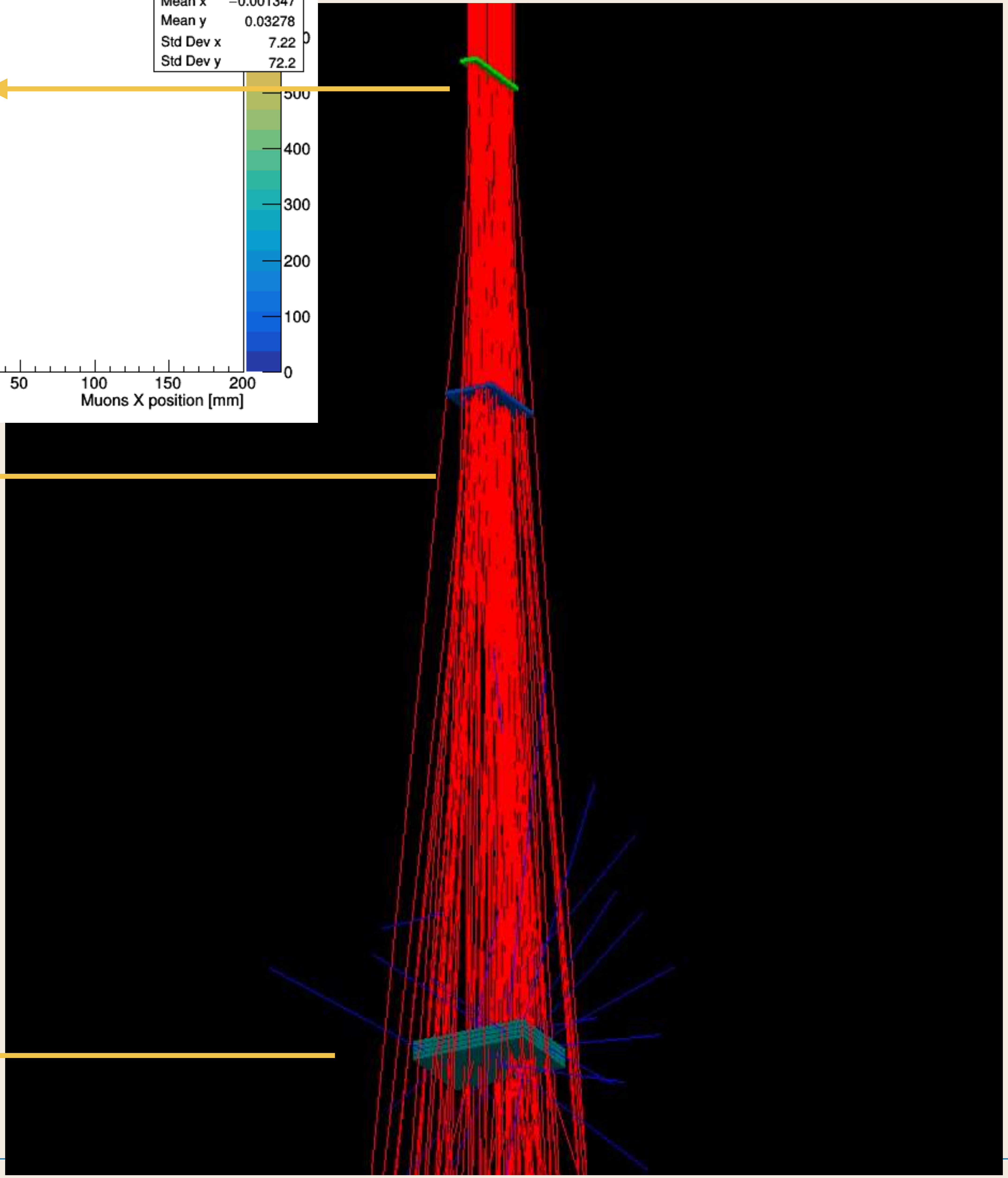
Simple tracking detector w/ scintillator (Simulation)

EG. SPATIAL INFORMATION



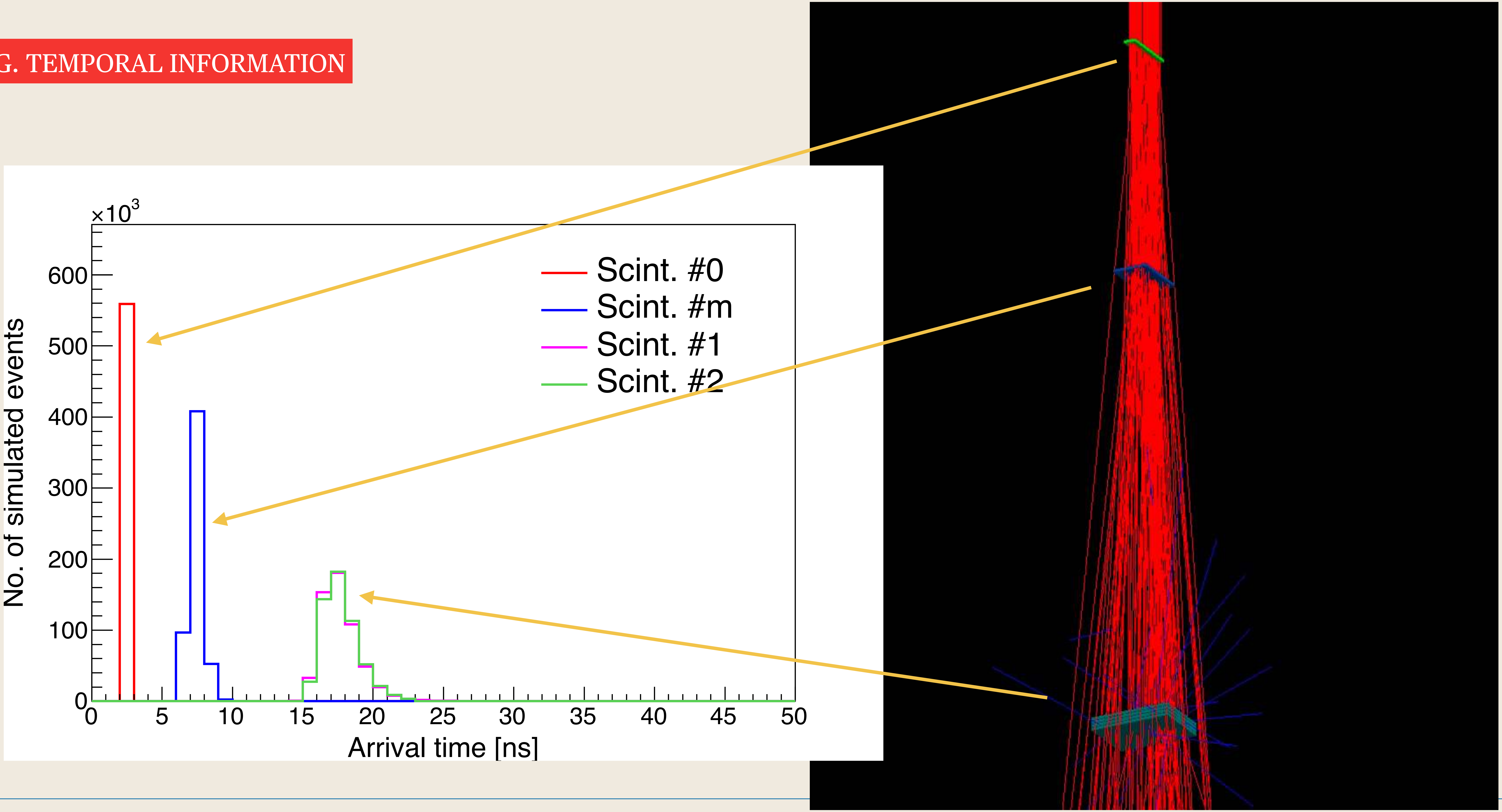






Simple tracking detector w/ scintillator (Simulation)

EG. TEMPORAL INFORMATION

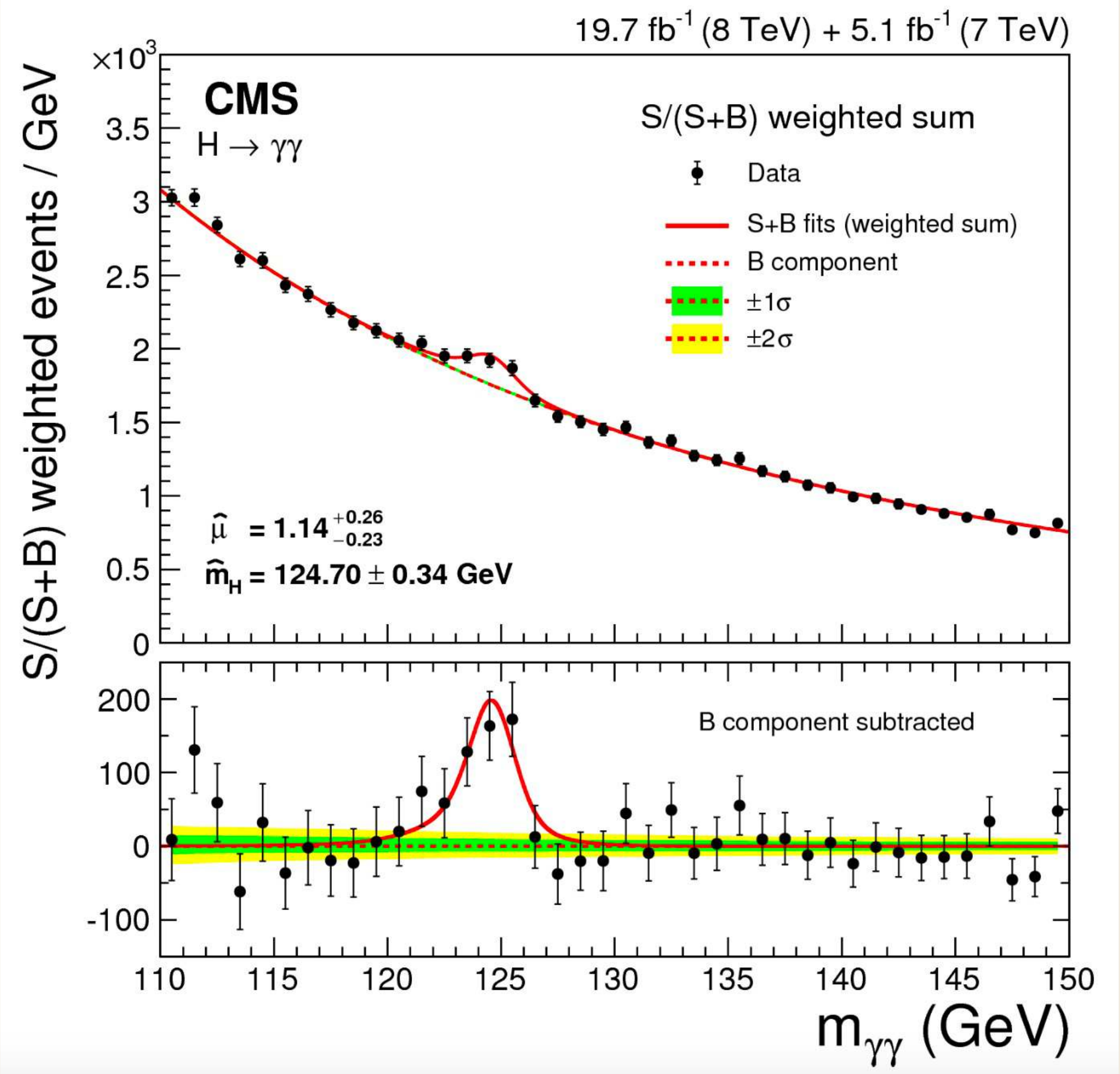


Calorimeter

Importance of energy measurement

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

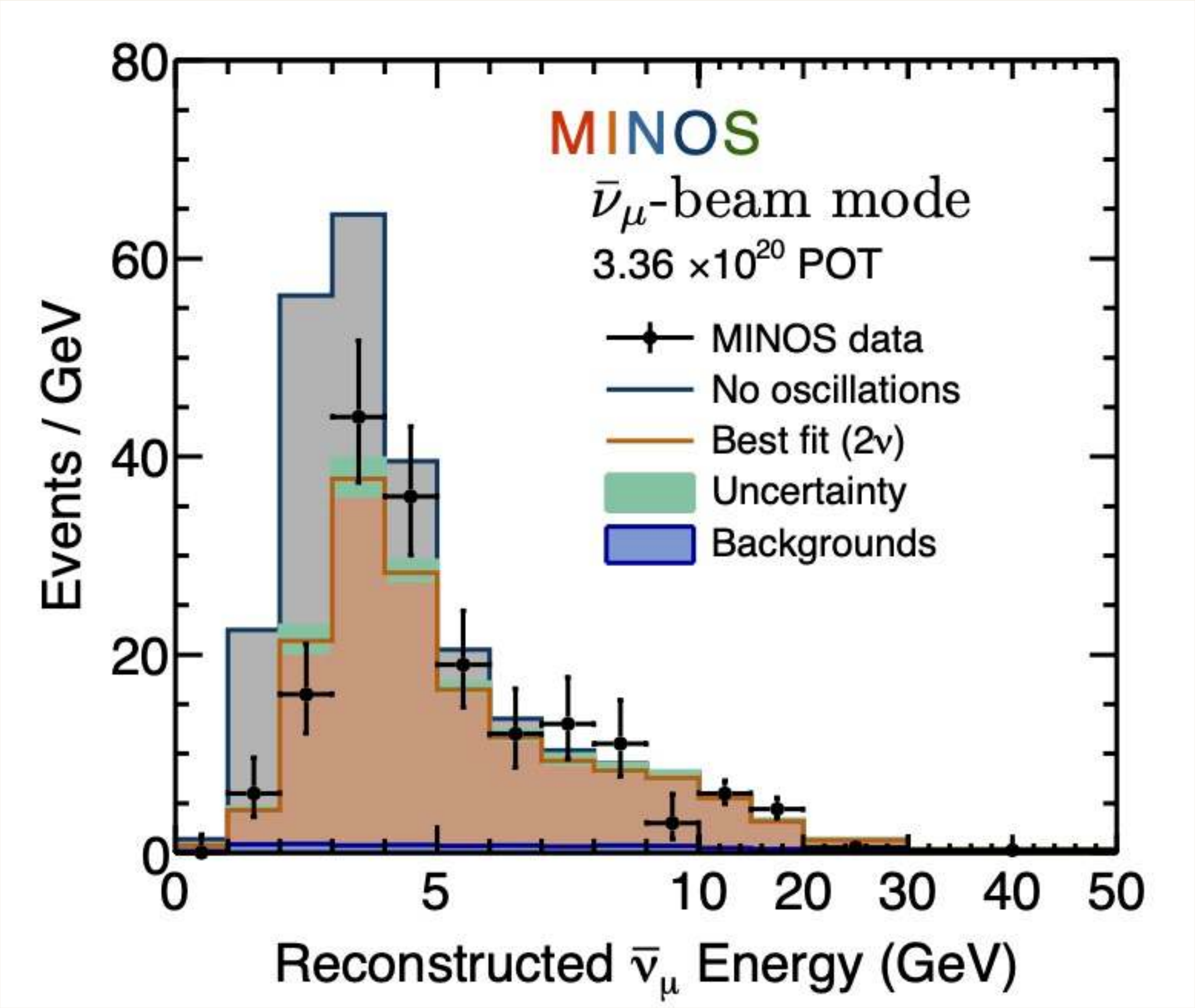
- You can't measure directly but reconstruct from the signal induced of energy loss of particle
- Energy loss is proportional to the particle energy
- For some physics (*eg. Higgs discovery, neutrino oscillation…*), measuring the energy precisely is vital

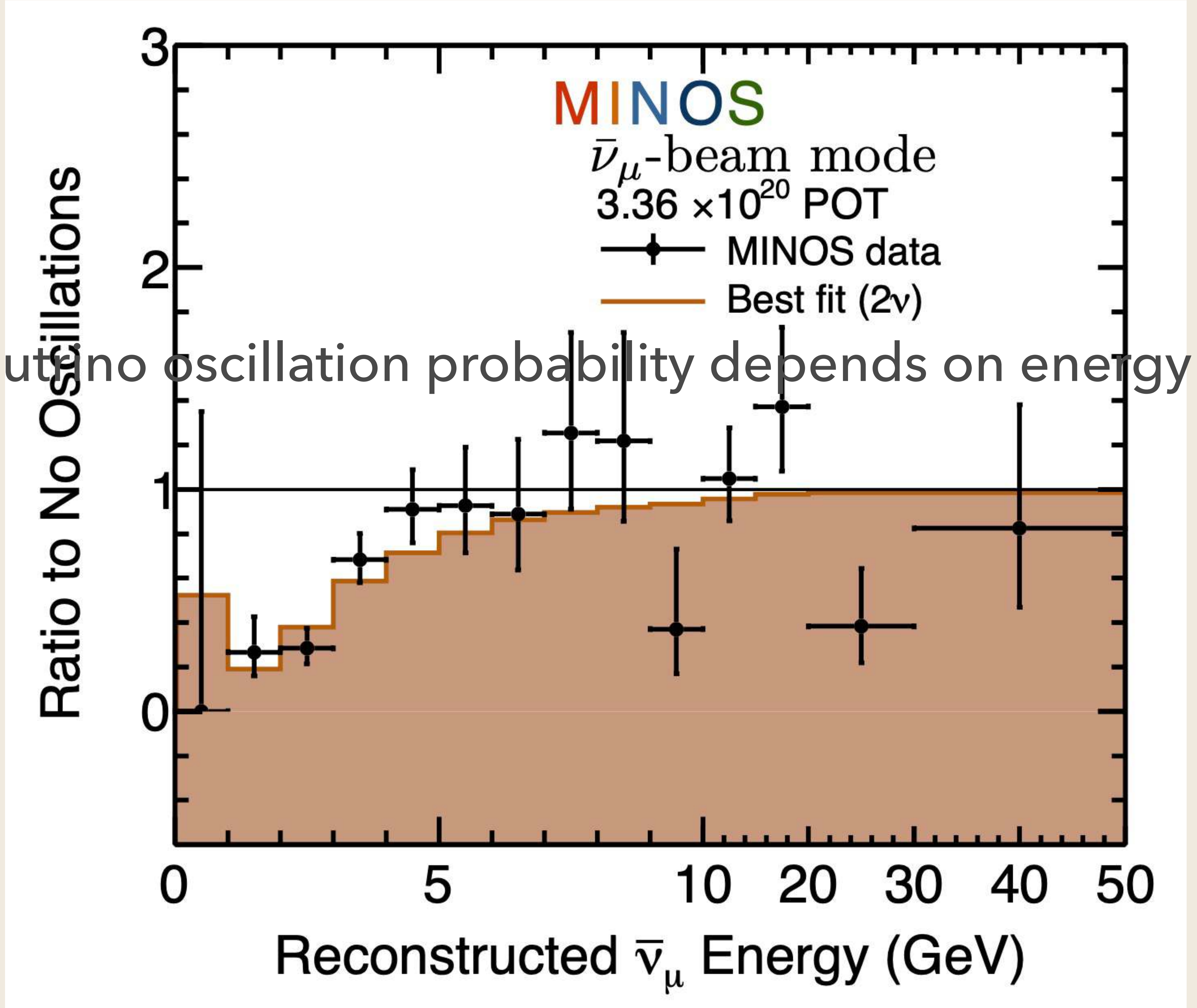


Higgs particle discovery thanks to
the precise measurement of photon energy

Calorimeter for neutrino oscillation measurement

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



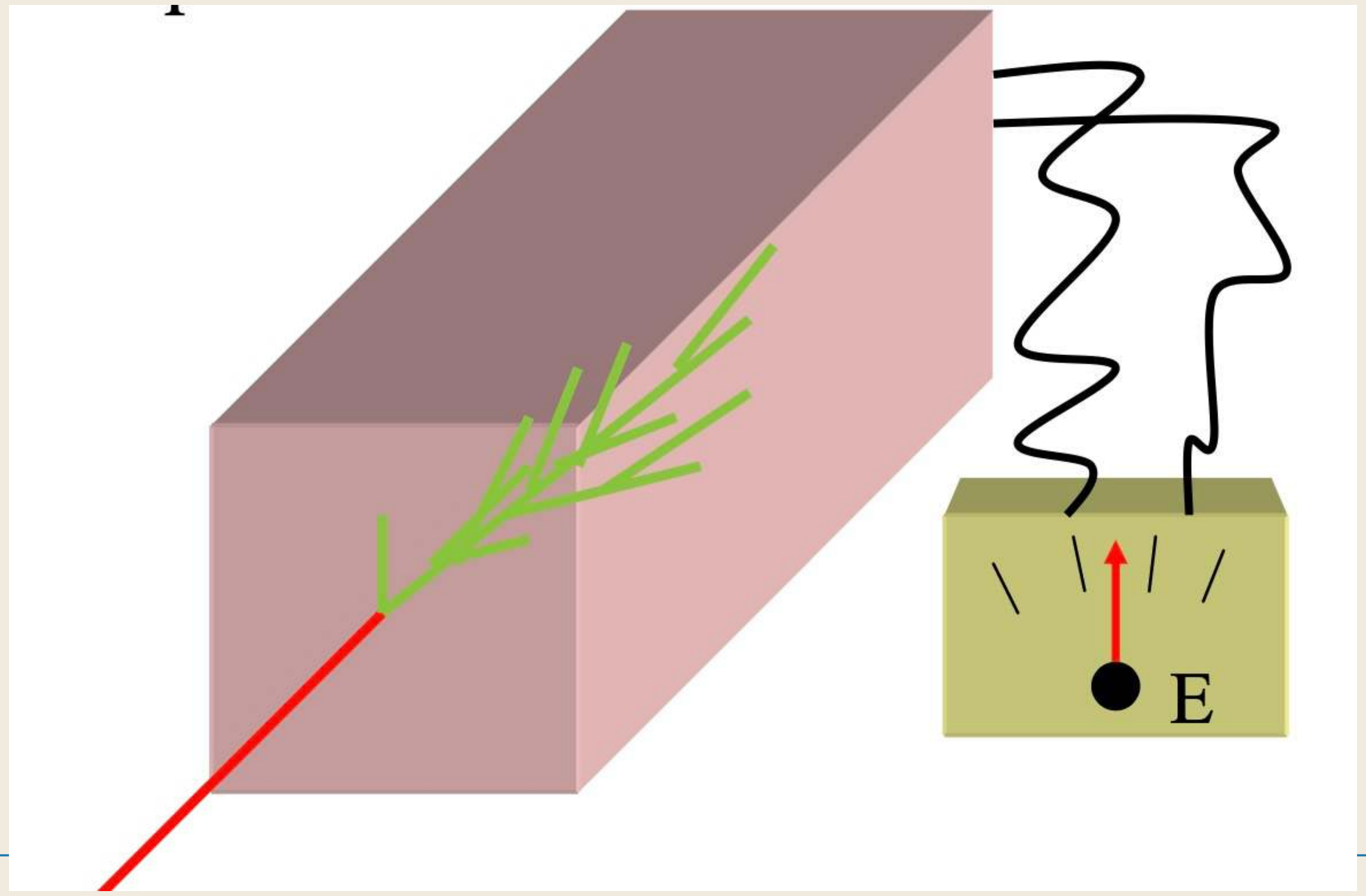


Neutrino oscillation probability depends on energy

Calorimeter: design consideration

Principle: detect particles through total absorption in matter volume of the detector

- **Large enough** and/or **high-density material** to **absorb all of the energy** of to-be-measured particles (*include both charged and neutral particle*)
- R**ecord signal (charge or light collection) to refer to the energy lost**
- Sufficiently **granular** to tell not just how much but where energy was deposited
- **Other practical consideration**: small enough to fit in detector, not too expensive, radiation hardness; fast read-out depending on event rate…



Energy resolution of calorimeter

- Spectrometer performance is characterized by "energy resolution" , typically as σ_E/E
  - Ideally $E \sim N$; $\sigma_E \sim \sqrt{N}$. So $\dfrac{\sigma_E}{E} \sim \dfrac{1}{\sqrt{E}}$
  - In reality $\dfrac{\sigma_E}{E} \sim \dfrac{a}{\sqrt{E}} \oplus b \oplus \dfrac{c}{E}$

STOCHASTIC TERM

CONSTANT TERM

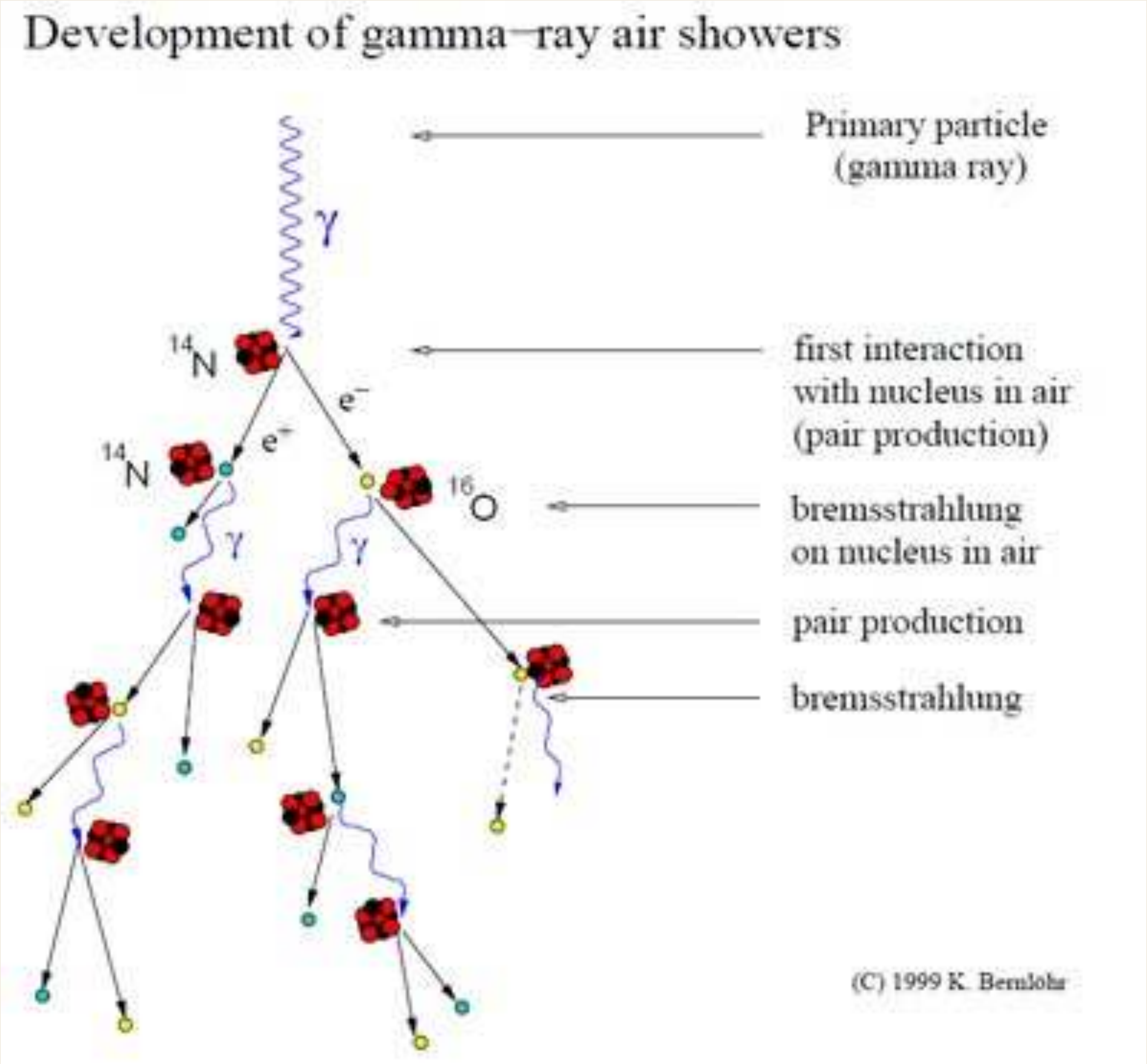
NOISE TERM

- Essential task: calibrate conversion btw. what observed (eg. Scintillation light) to energy

Electromagnetic shower development

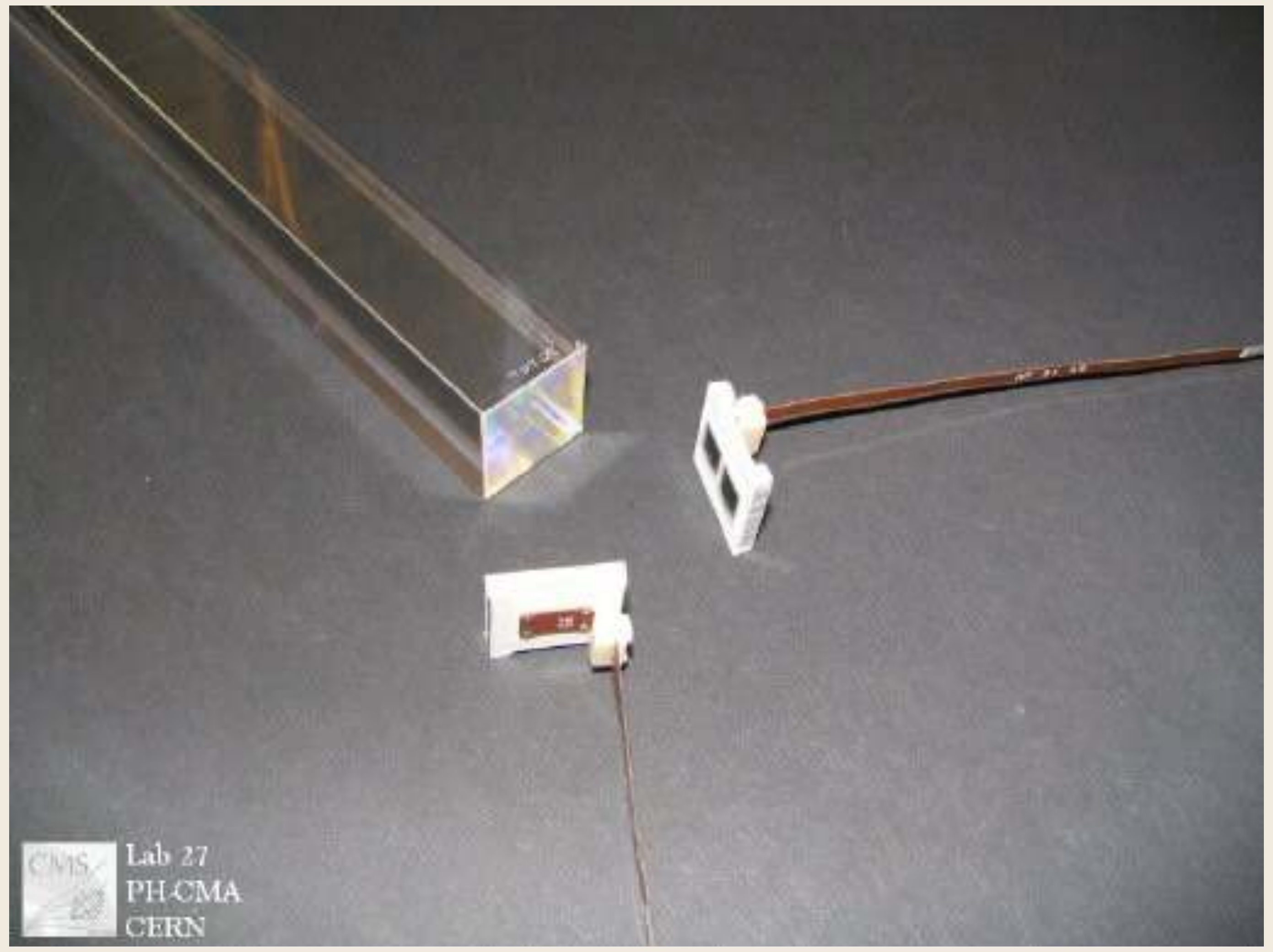
- Electromagnetic shower: High-energy photons produce pair of electrons and positrons
- Electrons and positrons radiate photons via Breamsstrahlung when travel through matter, interacting with fields of atoms
- One electron fall below critical energy, more energy loss via ionisation than bremsstrahlung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

$$\frac{\sigma_E}{E} \sim \frac{3\% - 10\%}{\sqrt{E/\mathrm{GeV}}}.$$



Broadly two types: homogeneous and sampling

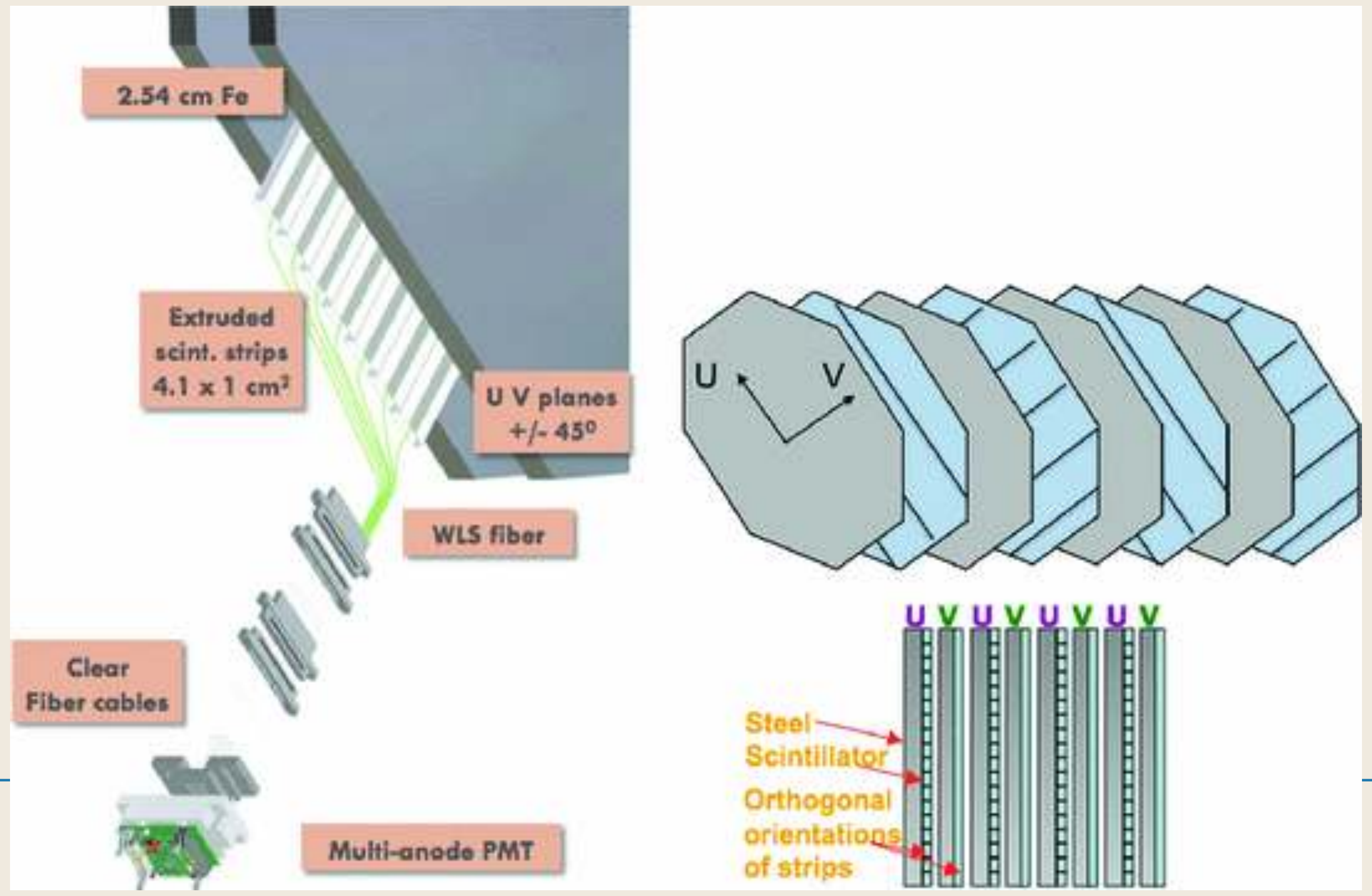
- **Homogeneous** type: all active volume, typically with high density transparent materials
  - Pros: excellent energy resolution
  - Cons: expensive; some limit in spatial resolution
- **Sampling**: consists of both passive (high Z materials like iron, tungsten) and active (scintillator) absorbers
  - Pros: cost-effective
  - Cons: not good energy resolution like the homogeneous type



CMS ECAL: USE 80,000 $PbWO_4$ CRYSTAL

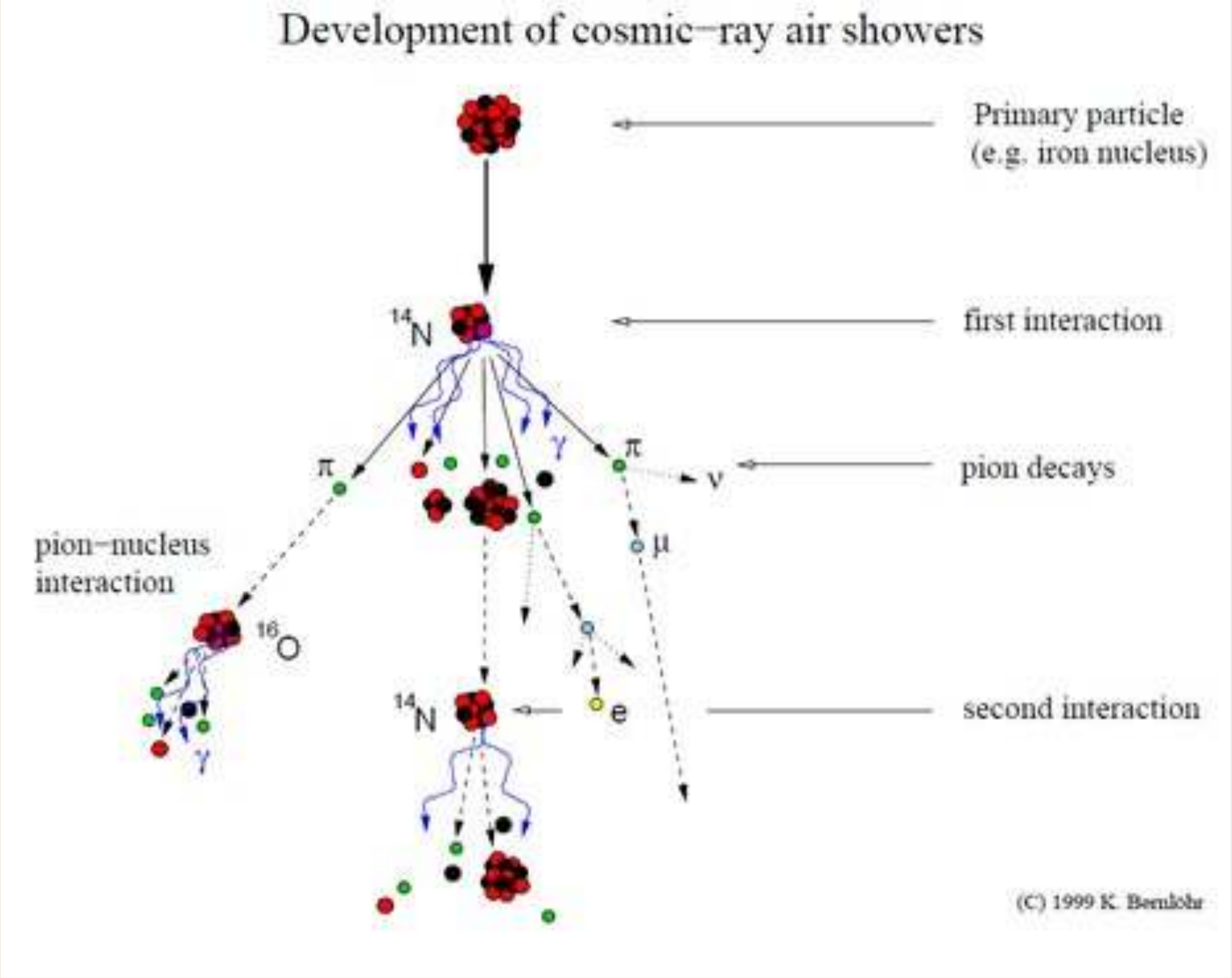
Can achieve $$\frac{\sigma_E}{E} \sim \frac{2.7\,\%}{\sqrt{E}} \oplus 0.55\% \oplus \frac{0.2}{E}$$

MINOS (+): STEEL-SCINTILLATOR SANDWICH



Hadronic shower development

- Driven by inelastic nuclear scattering
- Interaction length $\lambda_{int.} = 35\ [g/cm^2]\ A^{1/3}$, only depend on detector material
  - Eg. In iron, $\rho \approx 7.8\ g/cm^3$, A=28, interaction is about X_0= 13cm
  - Calorimeter thickness is about 9 X_0
- Complicated shower with pion, neutron, photon (from neutral pion), neutrino
- Some energy loss can't be observed, eg. Neutrino, nuclear binding energy …
- Typically, hadronic shower energy resolution is worse than EM shower



$$\frac{\sigma_E}{E} \gtrsim \frac{50\%}{\sqrt{E/\mathrm{GeV}}},$$

Hadron calorimeter thickness

Medium	**Density ρ [g/cm^3]**	**Interaction length λ_{INT} [cm]**
Copper (Cu)	**9.0**	**15.1**
Lead (Pb) (ATLAS)	**11.4**	**17.1**
Uranium (U) (ZEUS)	**19.0**	**10.5**
Iron (Fe)	**7.9**	**16.8**
Plastic scintillator	**~1.0**	**~80**
Concrete	**~2.5**	**~40**

For “full” containment calorimeter thickness needed is about 9 λ_{INT}:

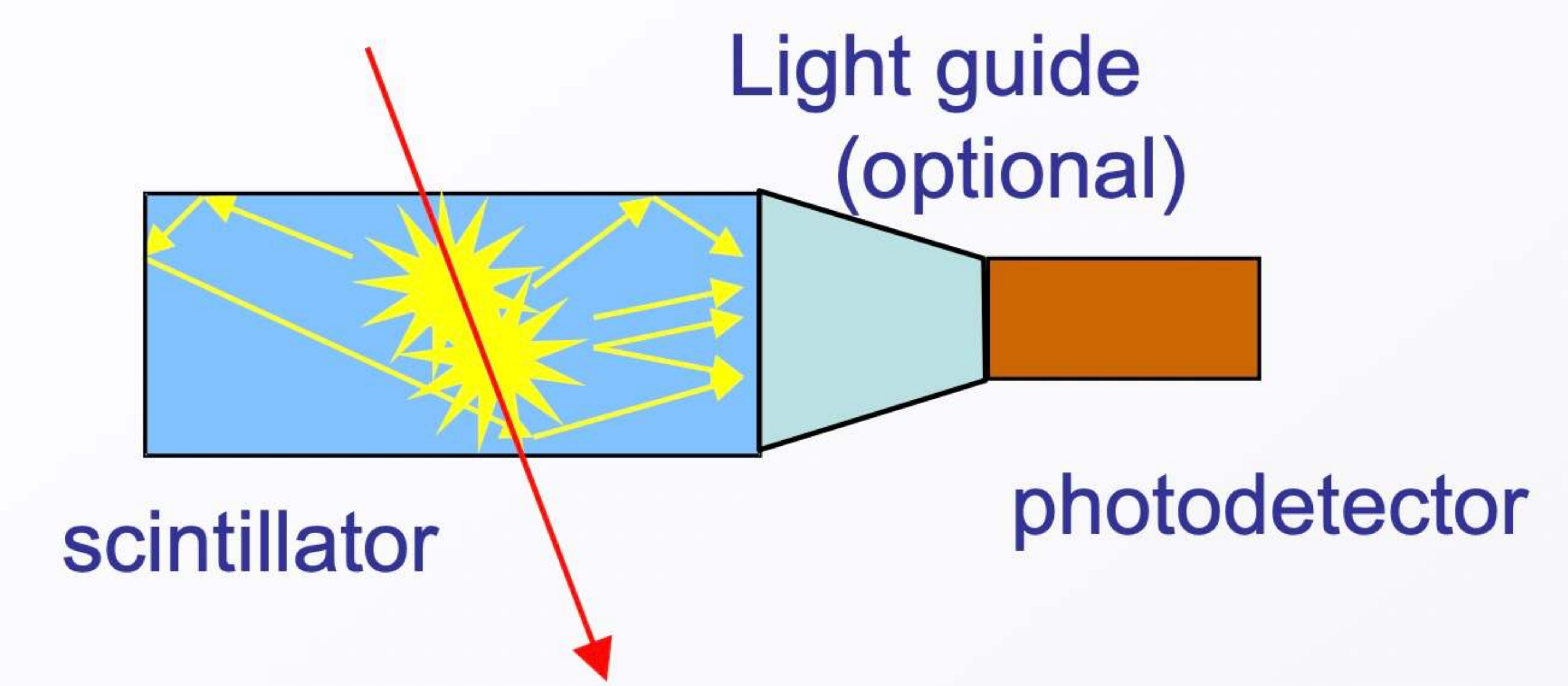
- **136 cm of copper**
- **154 cm of lead**
- **95 cm of uranium**
- **150 cm of iron**
- **~7 m of plastic-scintillator!!**
- **~3.6 cm of concrete**

Hadron calorimeters need to be deep!

Calorimeter techniques

- Common modern techniques used:
  - Gaseous/liquid Argon ionization
  - Scintillator detector
  - Cherenkov detector
  - …

Scintillation detector



- One of the most common techniques in PN physics
- To detect energy deposited by ionizing particles or photons
- Broadly categorized into: organic scintillator and inorganic scintillator
- Main detection characteristics: linearity to energy; fast response (fast rising time)

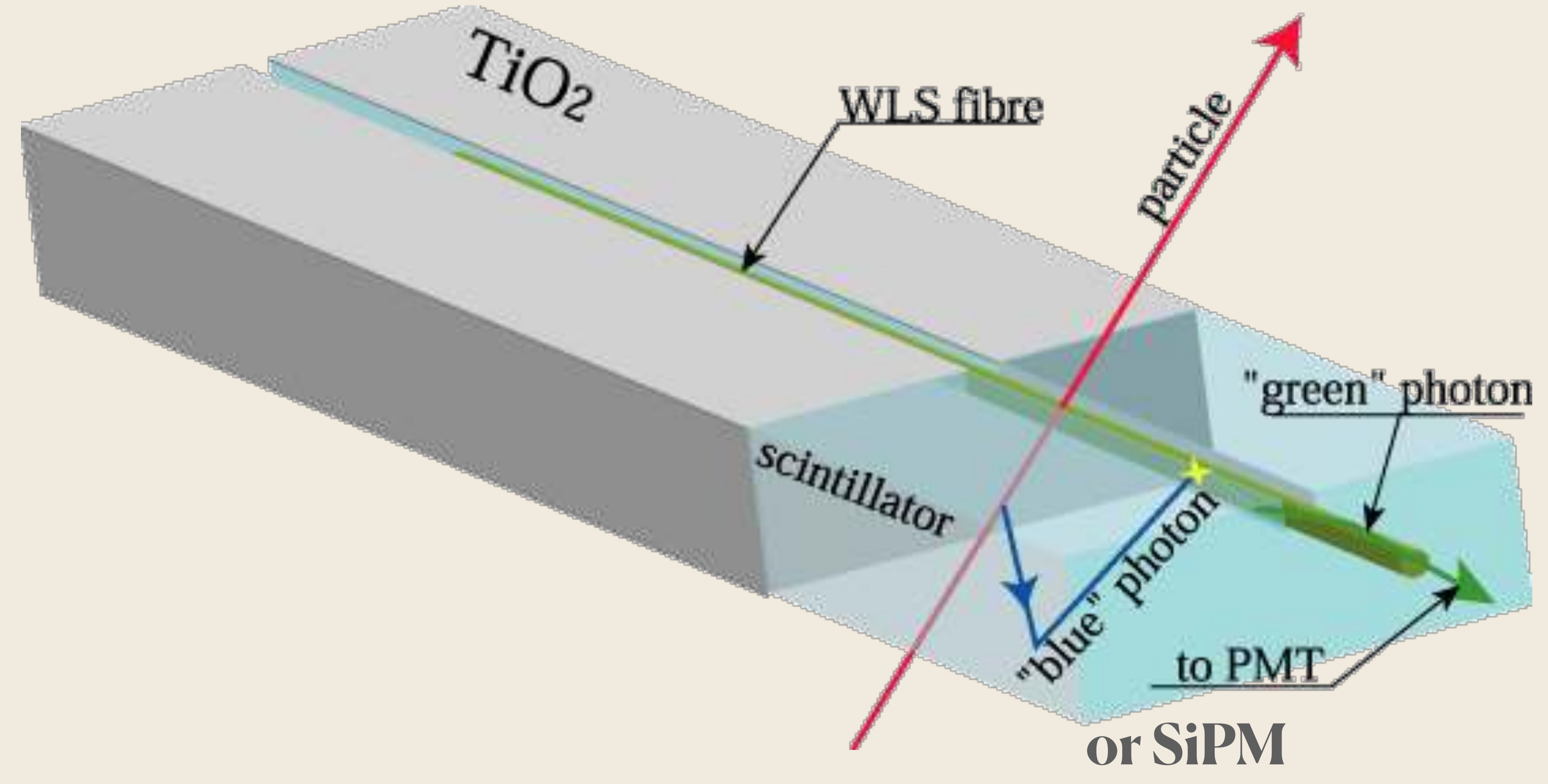
- Inorganic Scintillators
  - Advantages
    - high light yield [typical; $\varepsilon_{sc} \approx 0.13$]
    - high density [e.g. $PBWO_4$: 8.3 g/cm^3]
    - good energy resolution (→Calorimeters)
  - Disadvantages complicated crystal growth
  - large temperature dependence

Light yield $\varepsilon_{sc} \equiv$ fraction of energy loss going into photons

EXPENSIVE

- Organic Scintillators
  - Advantages
    - very fast ➔pulse shape discrimination possible
    - easily shaped
    - small temperature dependence
  - Disadvantages
    - lower light yield [typical; $\varepsilon_{sc} \approx 0.03$]
    - low density [e.g. 1 g/cm^3]
    - radiation damage

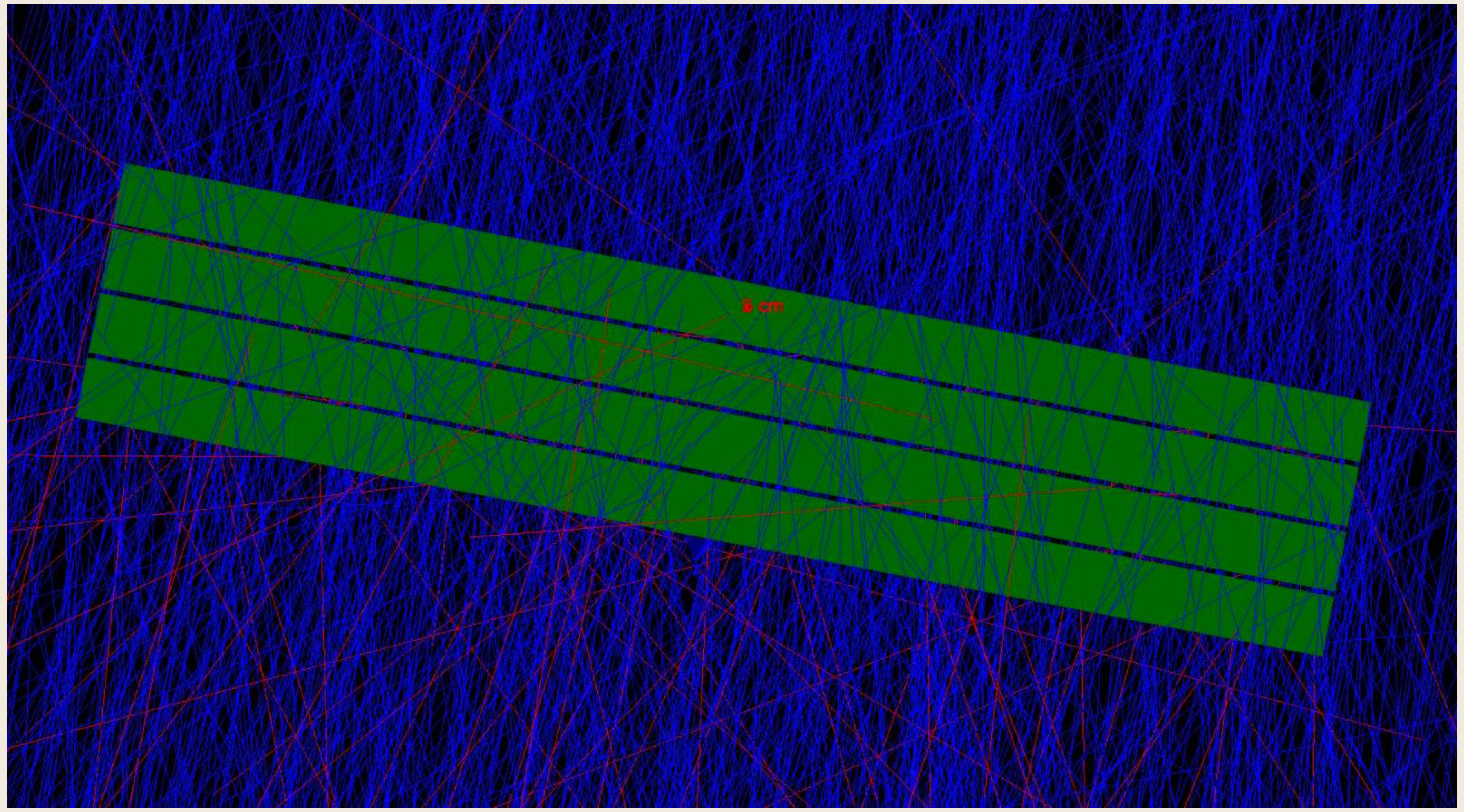
CHEAP

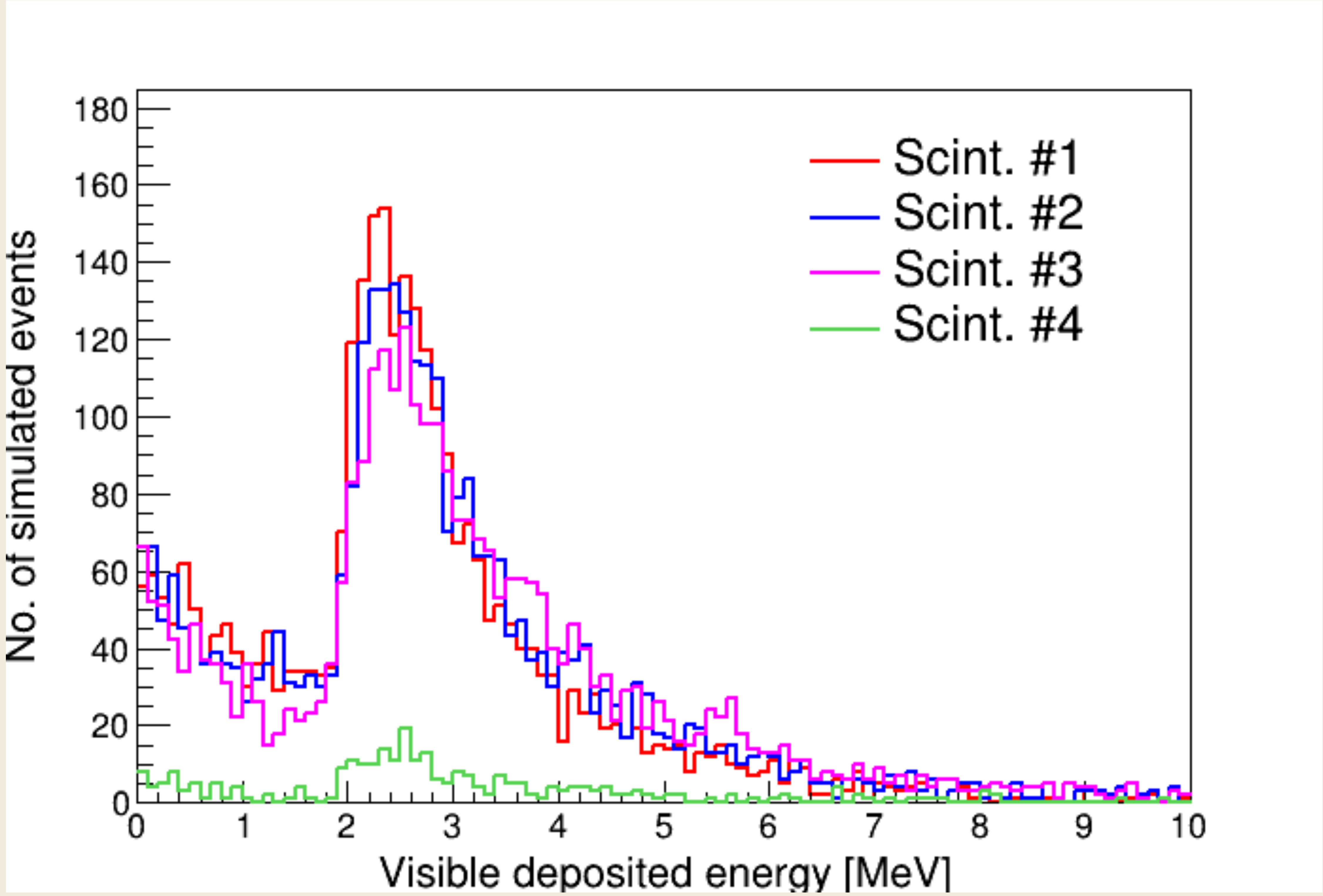


Sometimes need to use with WLS

And normally read out with fast photo-sensor

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.**

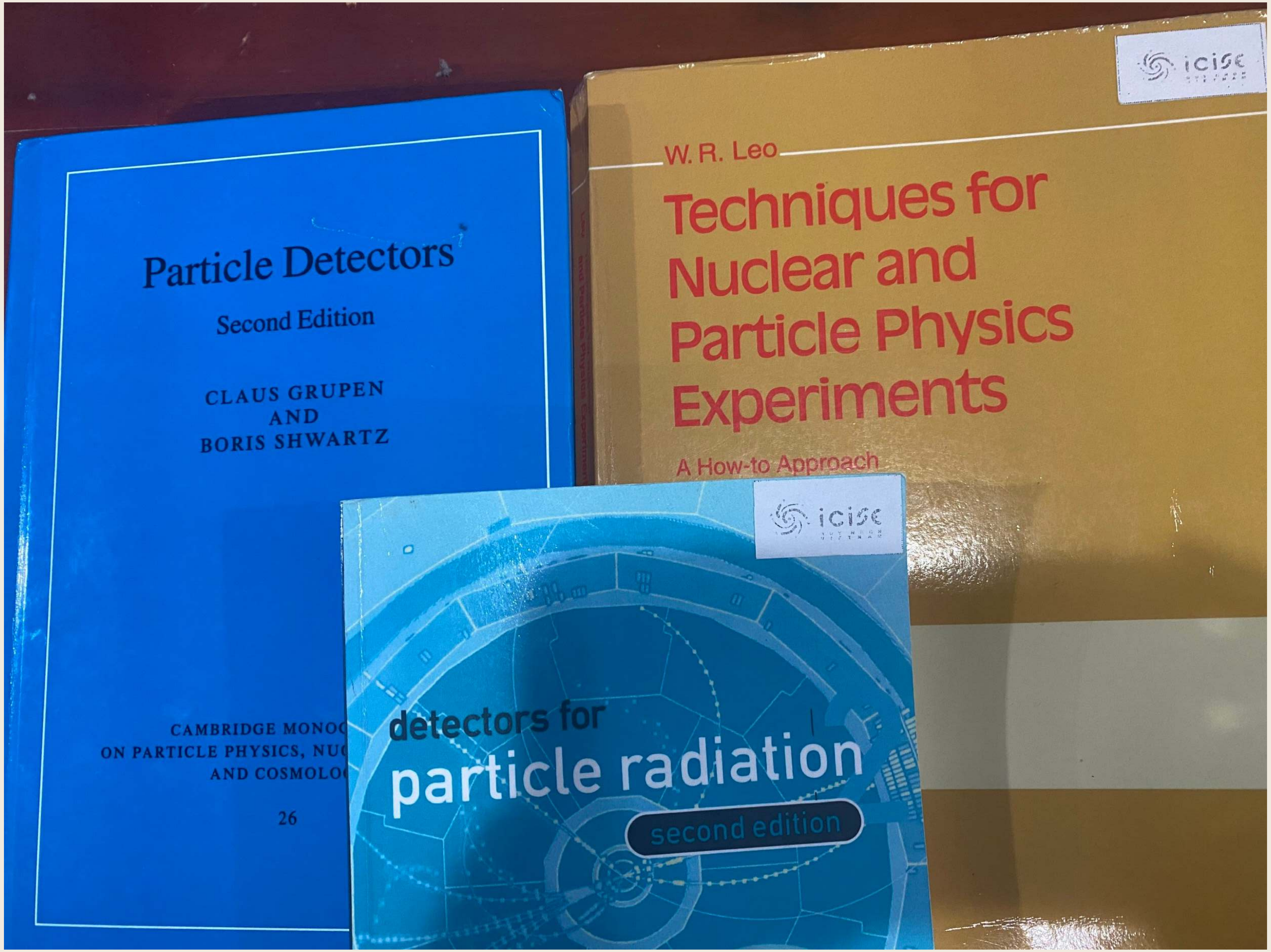
Recent developments

Recent developments (*personal interest*)

- **Dual readout**: read both Cherenkov light and Scintillation light; eg. Water-based liquid scintillator
- **High granularity**, eg. SuperFGD with ~2 millions of 1cm x1cm x1cm cube for improving spatial resolution and energy resolution
- Improve the particle identification, noise suppression with **Time-of-flight** techniques based on fast photodetector, eg. TOF, T2K Near Detector
- **Machine learning/ AI** for event filtering, particle identification, anomaly event catching, energy regression…
- …

Details in the textbooks

Available in our bookshelf



Backup

Cherenkov Threshold

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

Parity violation in muon decay

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

Spin =0

Left-handed

right-handed

Left-handed

right-handed

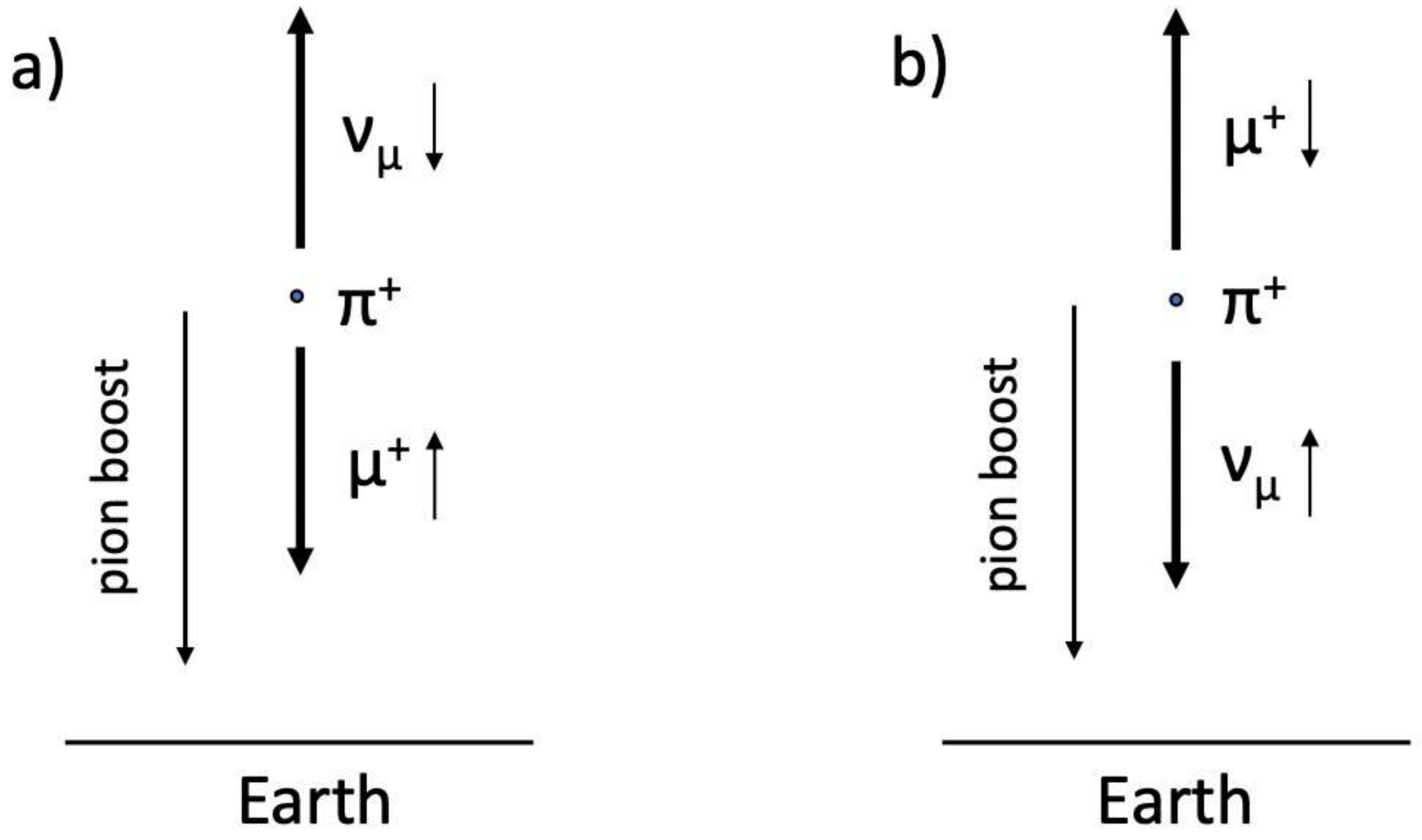


FIG. 1. a) A positive muon emitted in the pion boost direction in the rest frame of decaying pion. b) A positive muon emitted in the opposite direction of the pion boost in the rest frame of a decaying pion.

Down-ward positive muon
Have upward spin

Down-ward negative muon
Have downward spin

Parity violation in muon decay

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

Spin =0

Left-handed

right-handed

Left-handed

right-handed

Down-ward positive muon
Have upward spin

Down-ward negative muon
Have downward spin

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

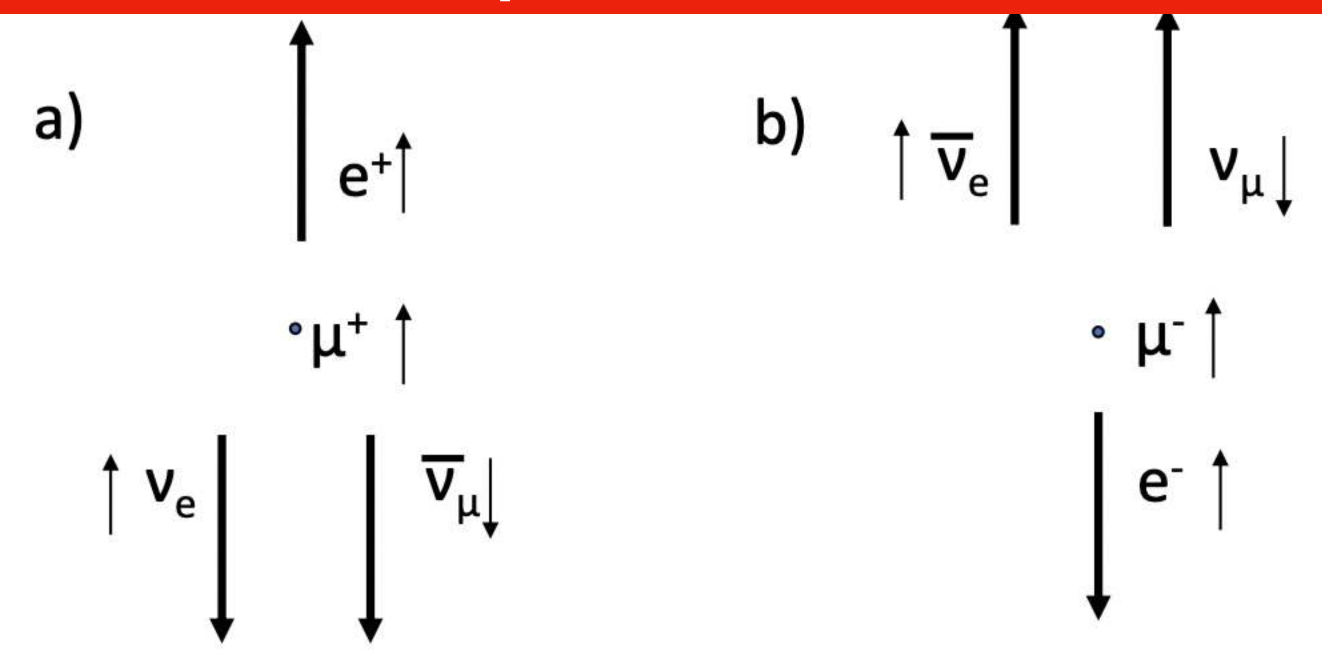


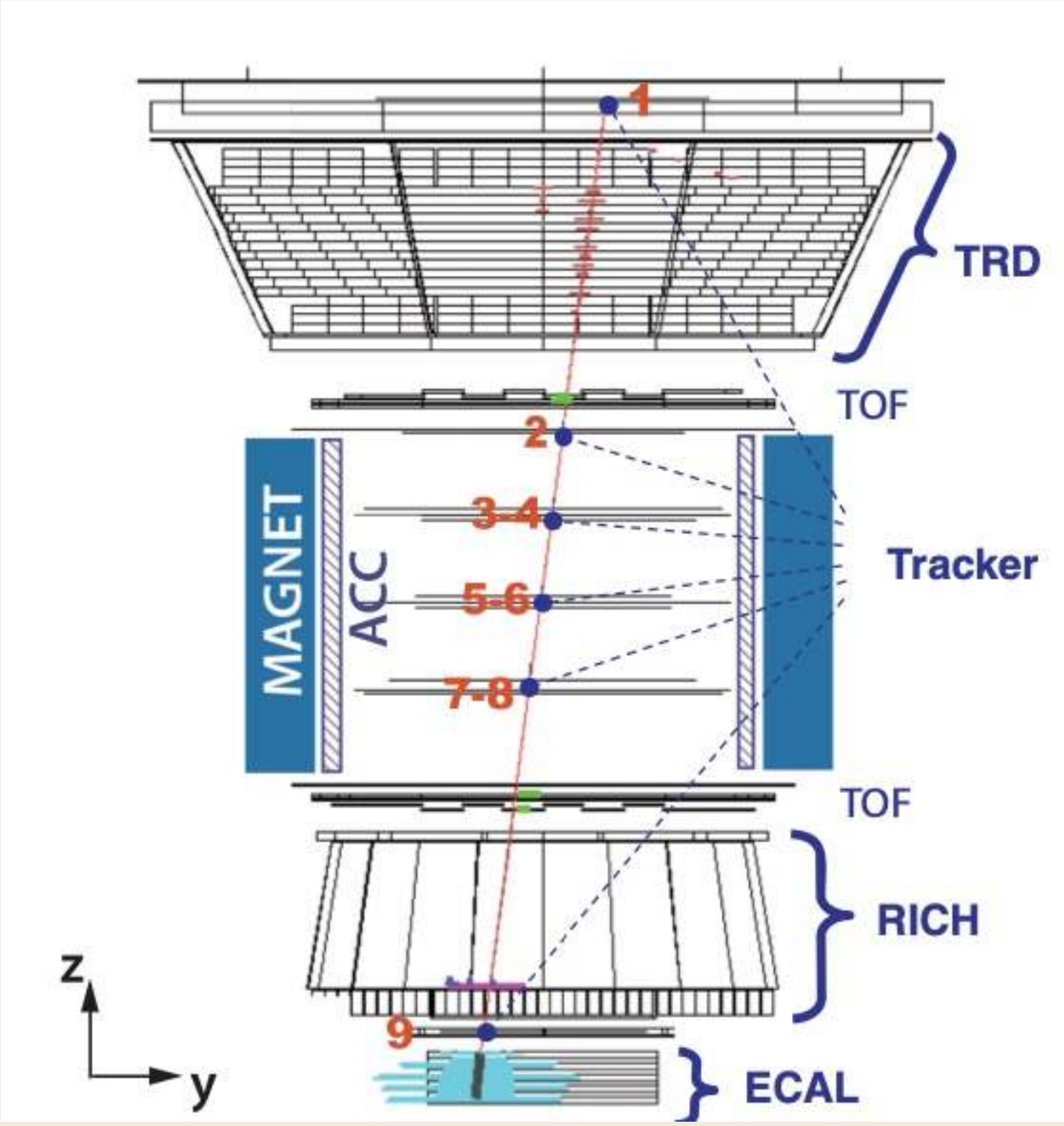
FIG. 2. Decay at the rest of a positive (a) and a negative (b) muon with the emission of the most energetic positron and electron, respectively.

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

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

AMS02 / ISS

- Since 2011 May 19th / Alpha Magnetic Spectrometer



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