Detector Basics I

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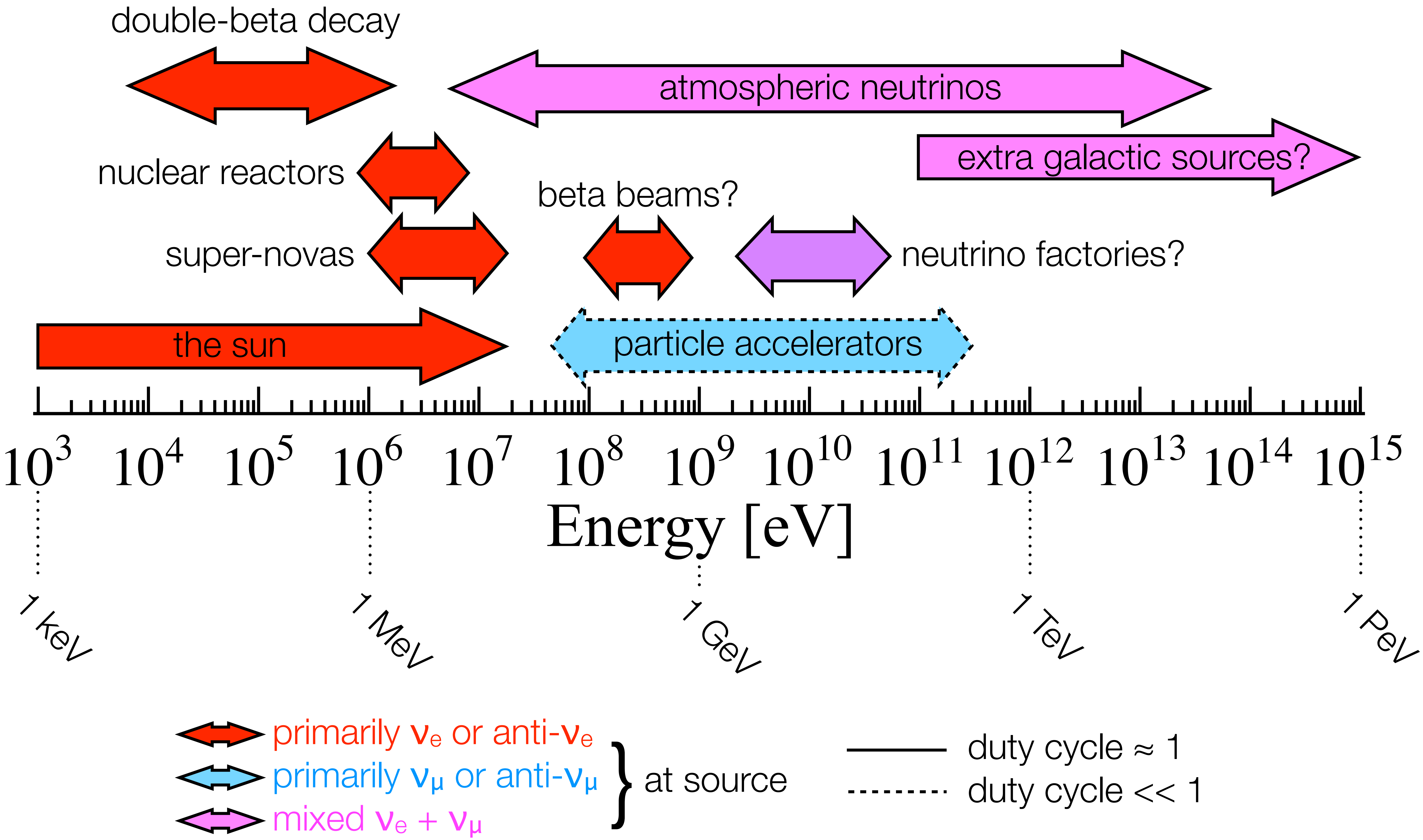
What do neutrinos look like?

- Neutrino detectors are built to detect the particles produced when neutrinos interact with nuclei or the electrons bound to nuclei

- As such in the next few lectures we would like to get some understanding of:
  - The important characteristics of neutrinos and the sources of neutrinos that we want to detect that affect detector design
  - Some basics of neutrino interactions and event topologies
  - Some basics of the topologies of the particles produced by neutrino interactions
  - Applications and specific technologies

Sources for neutrino detectors



Facts of life for the neutrino experimenter...

Numerical example for typical accelerator-based experiment

$$N_{\rm obs} = \left[\int \mathcal{F}(E_\nu)\sigma(E_\nu, ...)\epsilon(E_\nu, ...)dE_\nu d... \right] \frac{M}{A\ m_N} T$$

N_{obs} : number of neutrino events recorded

$\mathcal{F}$: Flux of neutrinos ($\#/\mathrm{cm}^2/\mathrm{s}$)

σ : neutrino cross section per nucleon $\simeq 0.7 \frac{E_\nu}{[\mathrm{GeV}]} \times 10^{-38} \mathrm{cm}^2$

ϵ : detection efficiency

M : total detector mass

A : effective atomic number of detector

m_N : nucleon mass

T : exposure time

typical "super-beam" flux at 1000 km

typical accelerator up time in one year

$$N_{\rm obs} = \left[\frac{1}{\mathrm{cm}^2 \mathrm{s}}\right] \left[0.7 \times 10^{-38} \frac{E_\nu}{\mathrm{GeV}} \mathrm{cm}^2\right] [\epsilon]\, [1\ \mathrm{GeV}] \left[\frac{M}{20 \cdot 1.67 \times 10^{-27}\ \mathrm{kg}}\right] [2 \times 10^7\ \mathrm{s}$$

$$\boxed{N_{\rm obs} = 4 \times 10^{-6} \frac{E_\nu}{[\mathrm{GeV}]} \epsilon \frac{M}{\mathrm{kg}}}$$

need detector masses of 10^6 kg = 1 kton to get in the game

work at high energies if you can

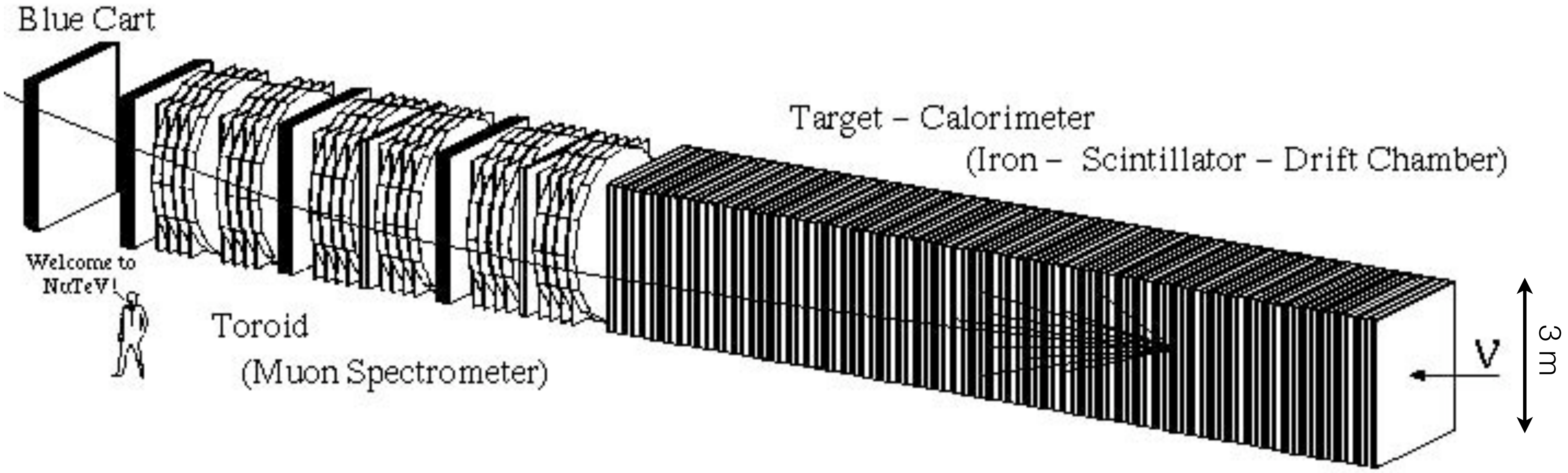
push this as high as you can

Challenge to the experimentalist: maximize efficiency and detector mass while minimizing cost

Detector basics

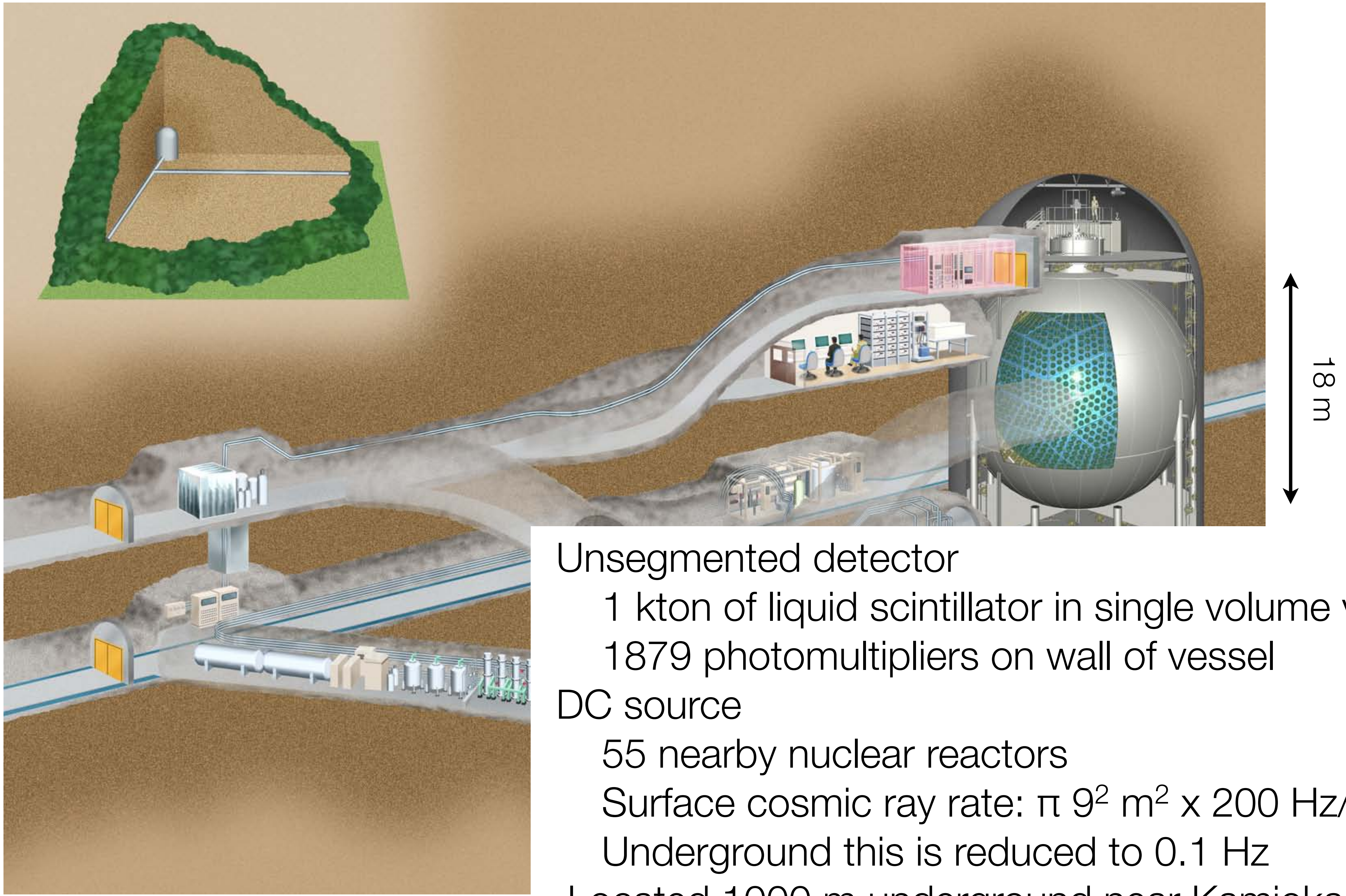
- Due to large size required, neutrino detectors are often rather homogenous
- Two basic geometries
  - *Segmented* - Detector volume is instrumented in small sections. Neutrino target may or may not be the active detector element. Segmentation allows detector to resolve activity from multiple sources.
  - *Unsegmented* - Detector volume is instrumented as a whole. Neutrino target is the active detector element. Multiple sources of activity cannot be resolved.
- Shielding requirements: Neutrino source and geometry determine need for shielding from cosmic-rays incident at rate of ~200 Hz / m^2 on surface
  - Pulsed source: Surface may be OK
  - “DC” source: Go underground
  - Segmented detector: Surface may be OK
  - Unsegmented detector: Probably have to go underground

NuTeV Detector



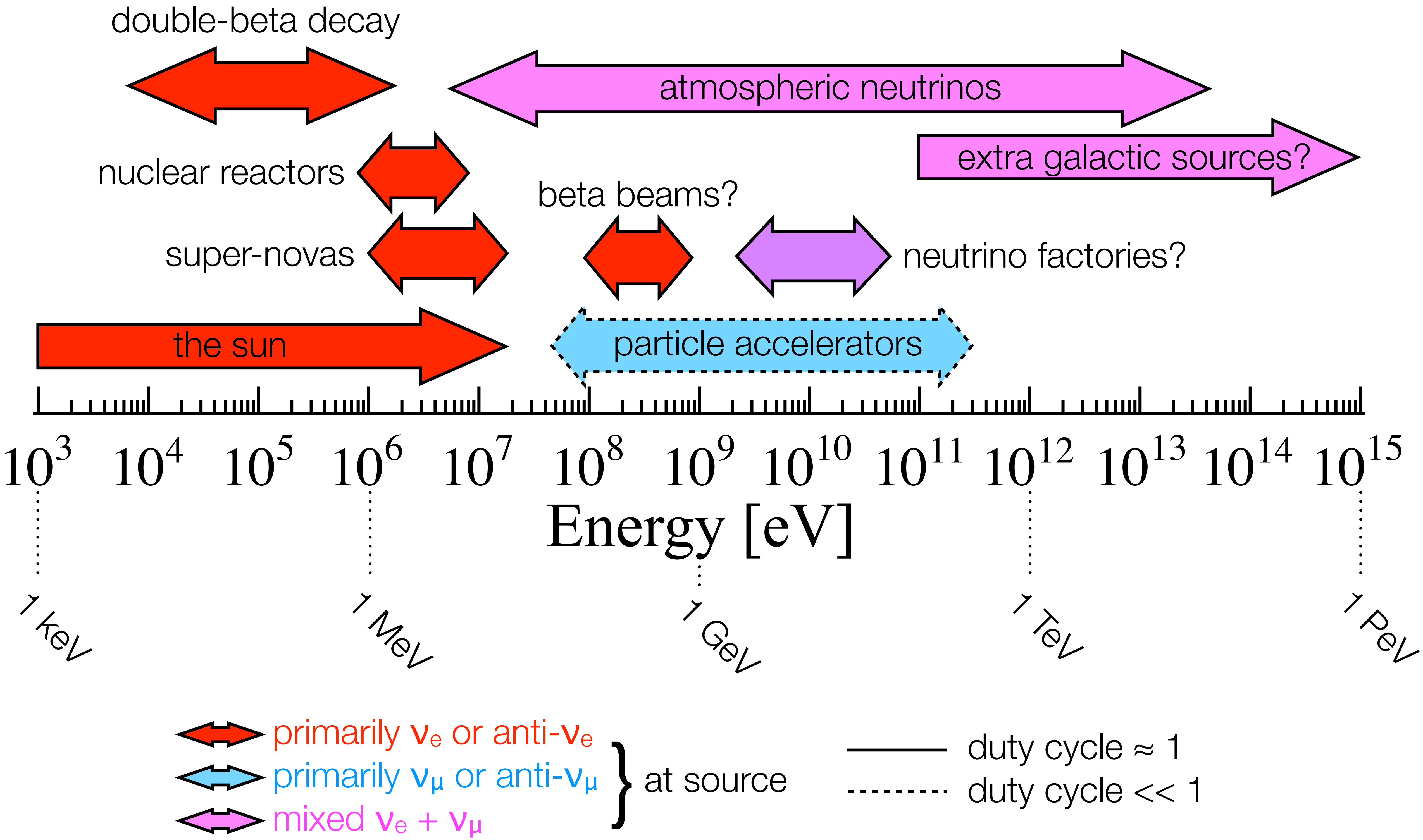
Segmented detector
    Neutrino target: iron planes
    Active detector: drift chamber and scintillator planes
Pulsed source
    FNAL Tevatron: 5 spills/min x 0.002 sec/spill gives duty cycle of 0.00017
    Number of in-spill muons: (3m x 30m x 200Hz/m^2)x(0.002 s) = 40.
Located on surface at FNAL

KamLAND



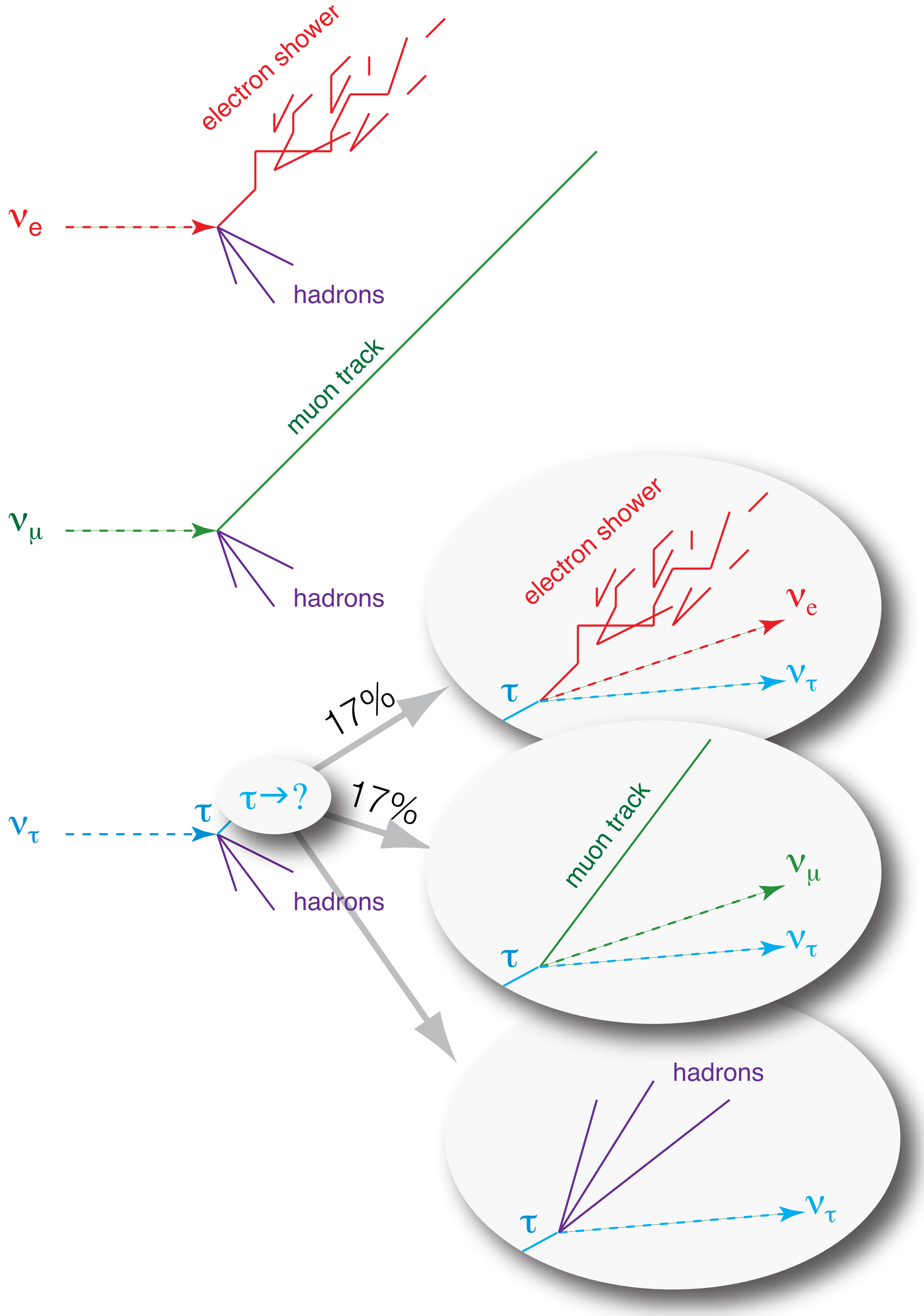
- Unsegmented detector
  - 1 kton of liquid scintillator in single volume viewed by 1879 photomultipliers on wall of vessel
- DC source
  - 55 nearby nuclear reactors
  - Surface cosmic ray rate: $\pi\ 9^2\ \mathrm{m}^2 \times 200\ \mathrm{Hz/m}^2 = 50\ \mathrm{kHz}$
  - Underground this is reduced to 0.1 Hz
- Located 1000 m underground near Kamioka, Japan

Sources for neutrino detectors

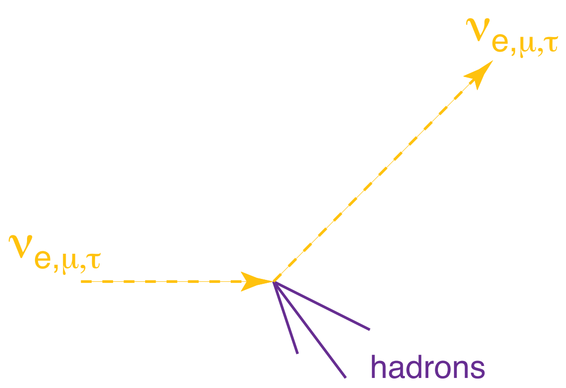


Neutrino detection channels

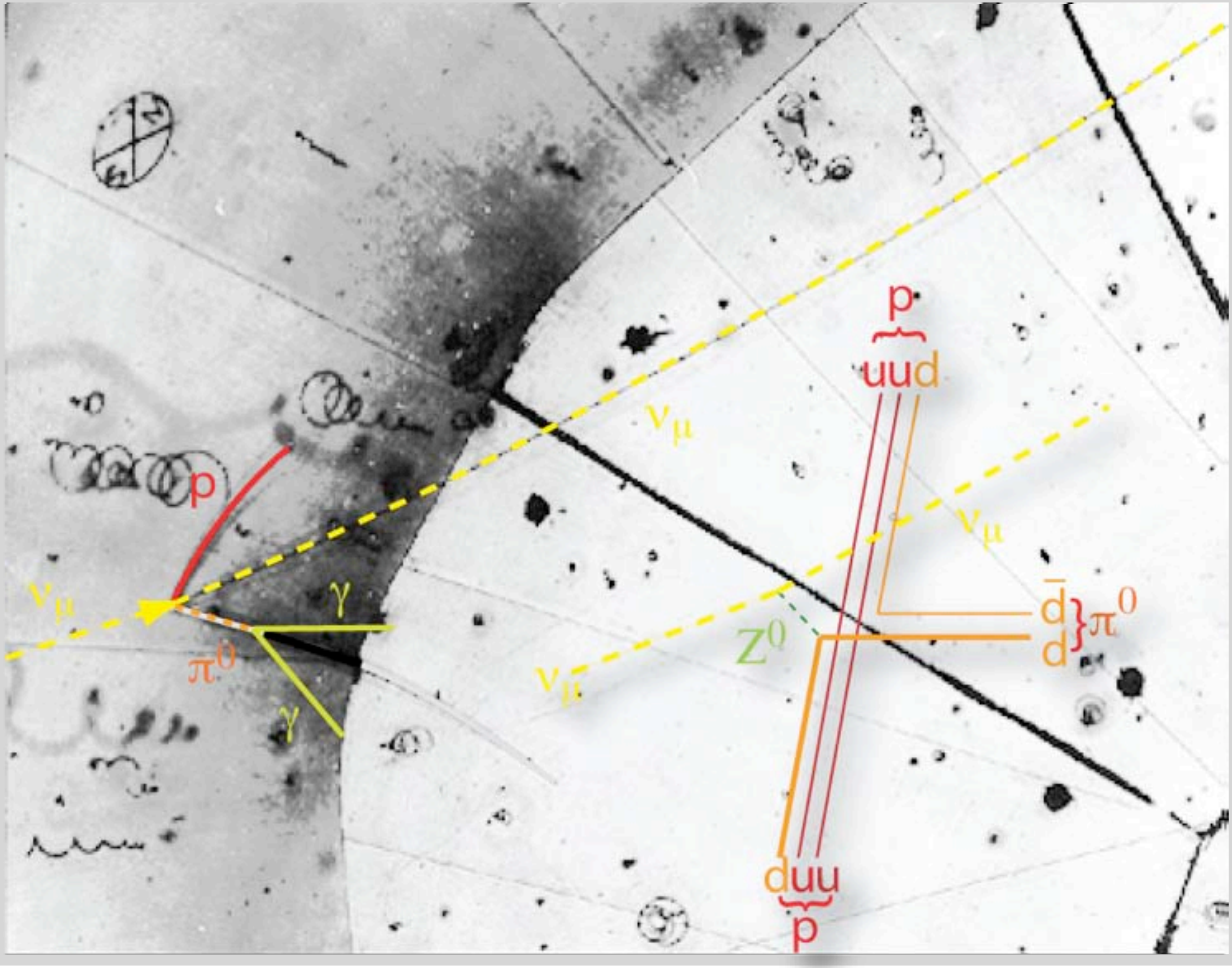
Charged-current



Neutral-current



- In charged-current (CC) events outgoing lepton tags incoming neutrino flavor.
  - *In the case of ν_τ, the presence of a τ must be deduced from the τ decay products*
- In CC events nearly all the neutrino energy is deposited in the detector
- In neutral-current events, only hadrons are present and no information about the incident neutrino flavor is available
- CC rates are affected by oscillations
- NC rates are not affected by oscillations
  - *In only a few analyses are NC events considered to be signal. In most cases NC events are backgrounds to the CC processes*



What’s going on in this event?

12 foot bubble chamber,
Argonne National Lab.
Nov. 13, 1970

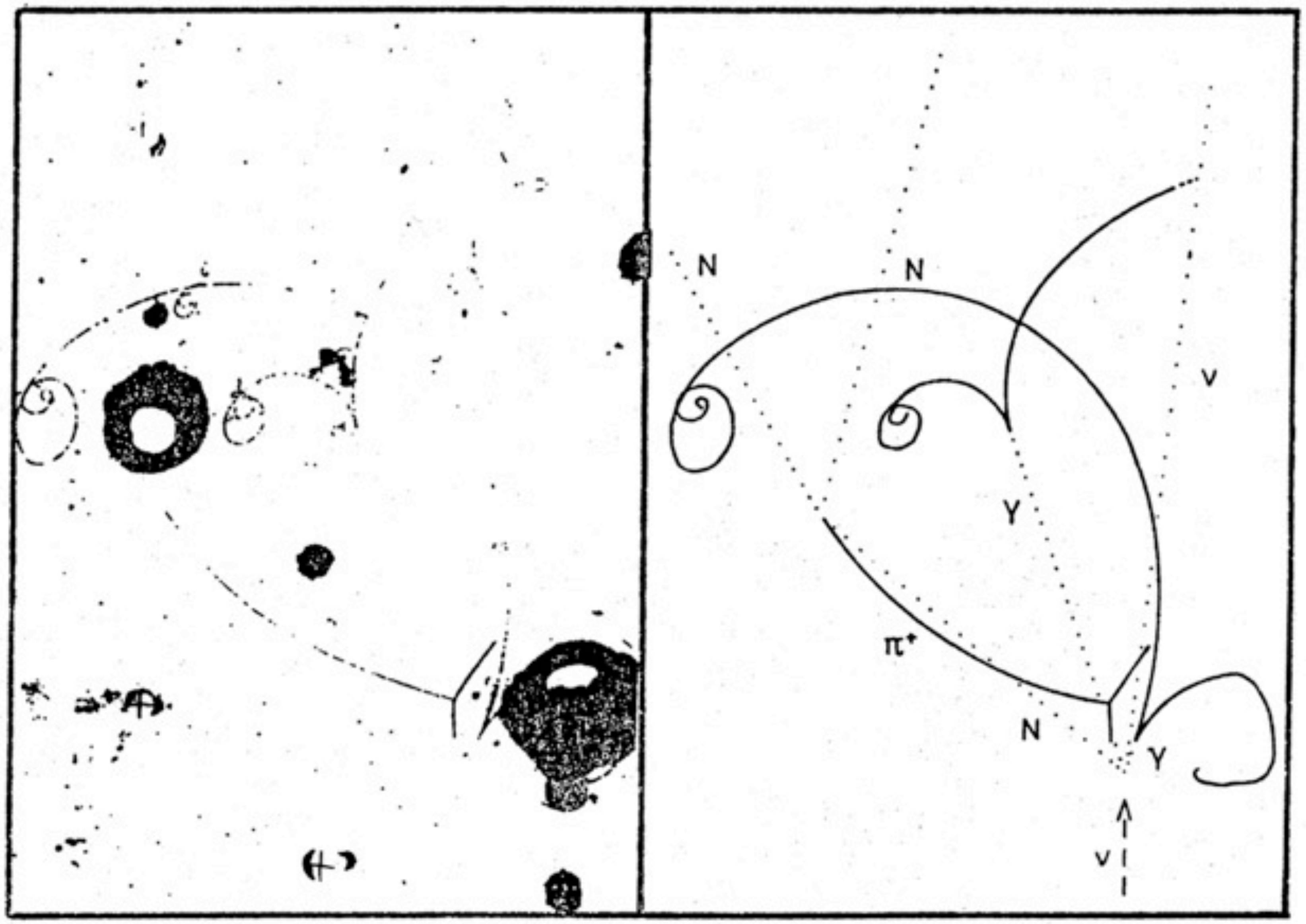
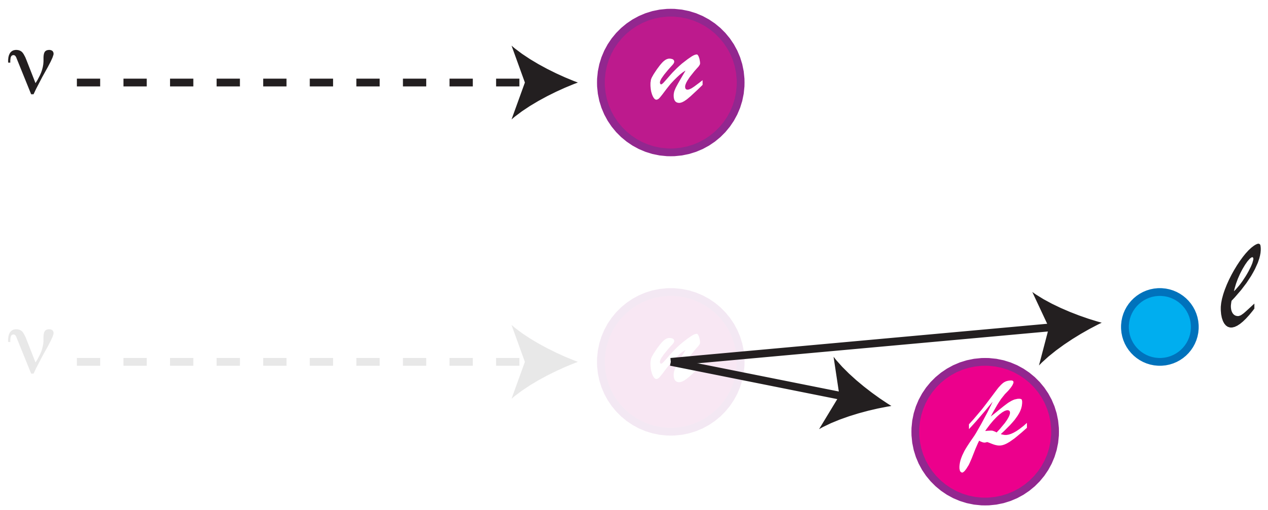


Abb. 15: Ein Kandidat für die Reaktion ($\nu n \rightarrow \nu n \pi^0$). Im Gegensatz zum Normalfall wird das Neutron durch inelastische Reaktion strahlabwärts

Neutral-current event

Gargamelle bubble chamber at CERN

Production thresholds

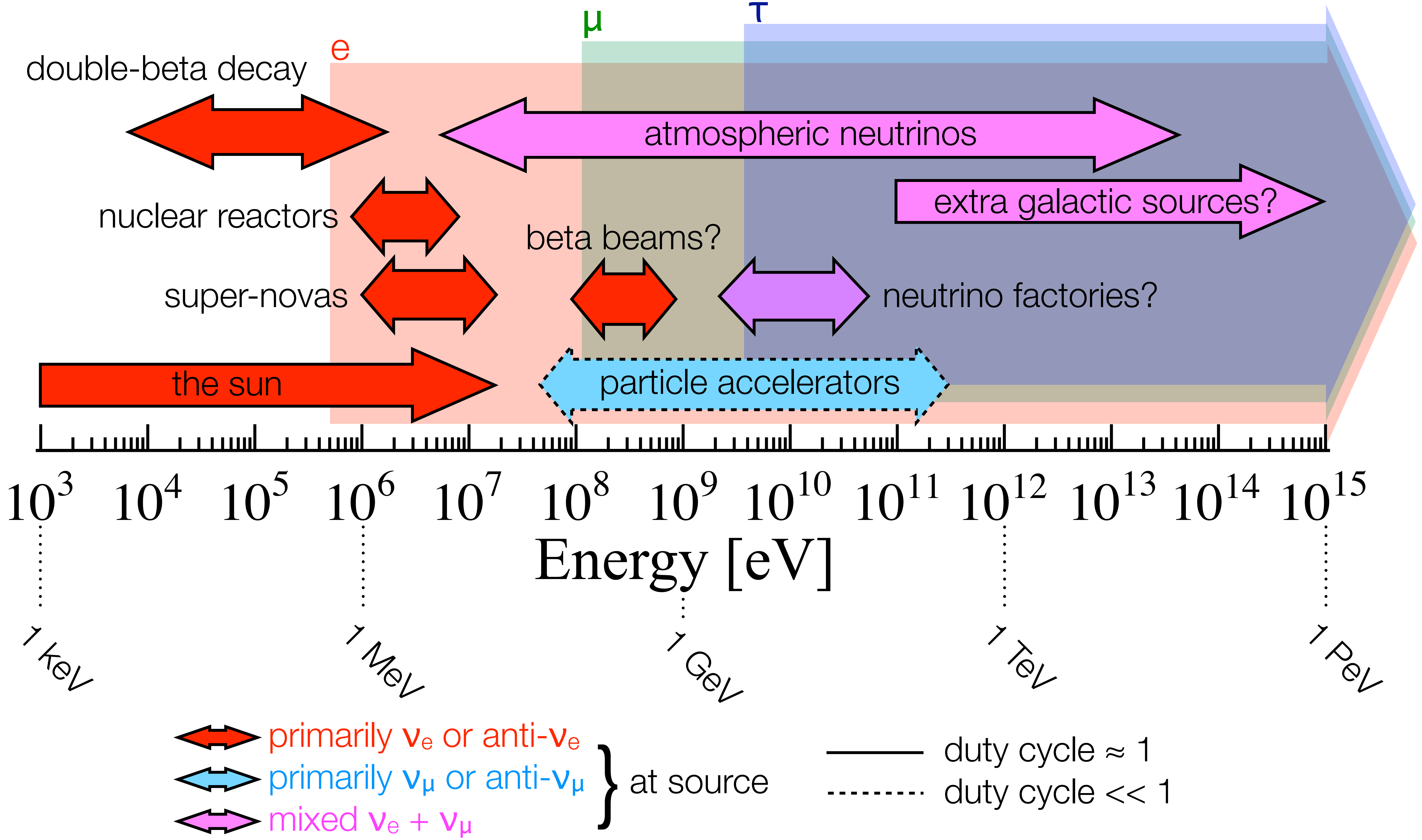


$$l = e \quad m_e = 0.511\ \text{MeV} \quad P_{\text{thresh}} = 0.511\ \text{MeV}$$

$$l = \mu \quad m_\mu = 106\ \text{MeV} \quad P_{\text{thresh}} = 112\ \text{MeV}$$

$$l = \tau \quad m_\tau = 1.78\ \text{GeV} \quad P_{\text{thresh}} = 3.47\ \text{GeV}$$

Sources for neutrino detectors



e

μ

τ

double-beta decay

atmospheric neutrinos

nuclear reactors

extra galactic sources?

beta beams?

super-novas

neutrino factories?

the sun

particle accelerators

10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15}

Energy [eV]

1 keV

1 MeV

1 GeV

1 TeV

1 PeV

primarily ν_e or anti-ν_e

primarily ν_μ or anti-ν_μ

mixed $\nu_e + \nu_\mu$

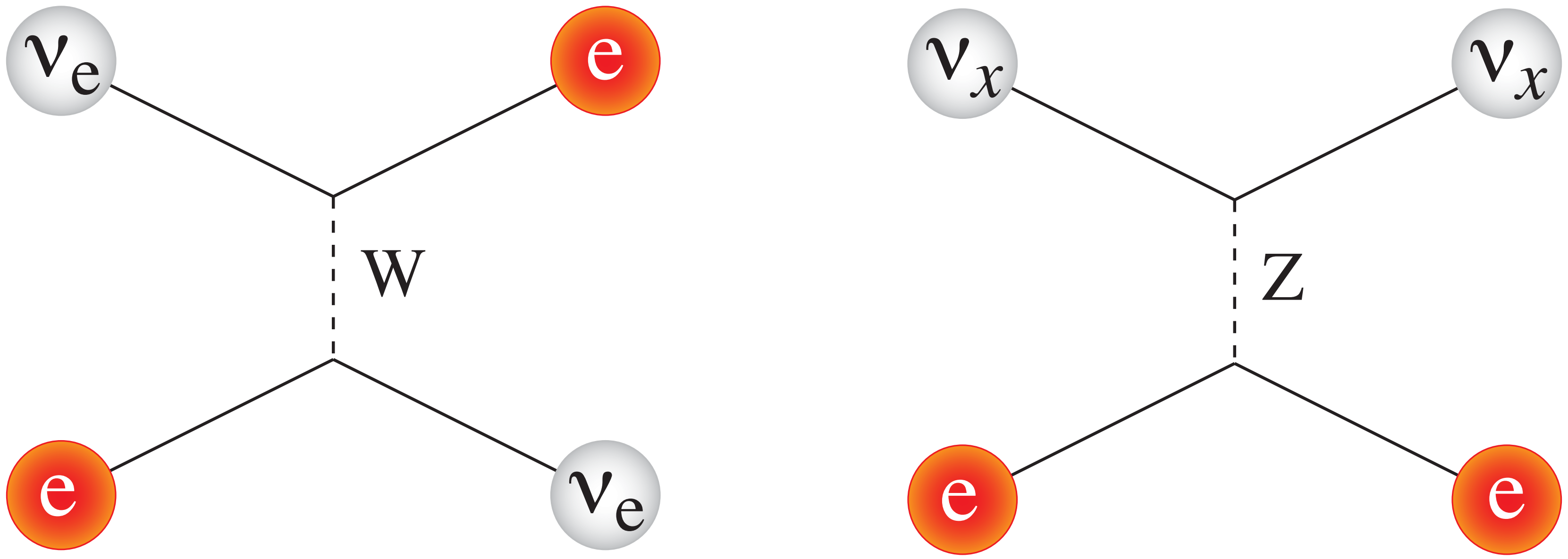
} at source

duty cycle ≈ 1

duty cycle << 1

Low energy detection channels

Cross-sections for bound nucleons turn off below ~200 MeV. At low energies either use a target containing free nucleons (eg. D_2O), or, more commonly, rely on neutrino-electron elastic scattering:

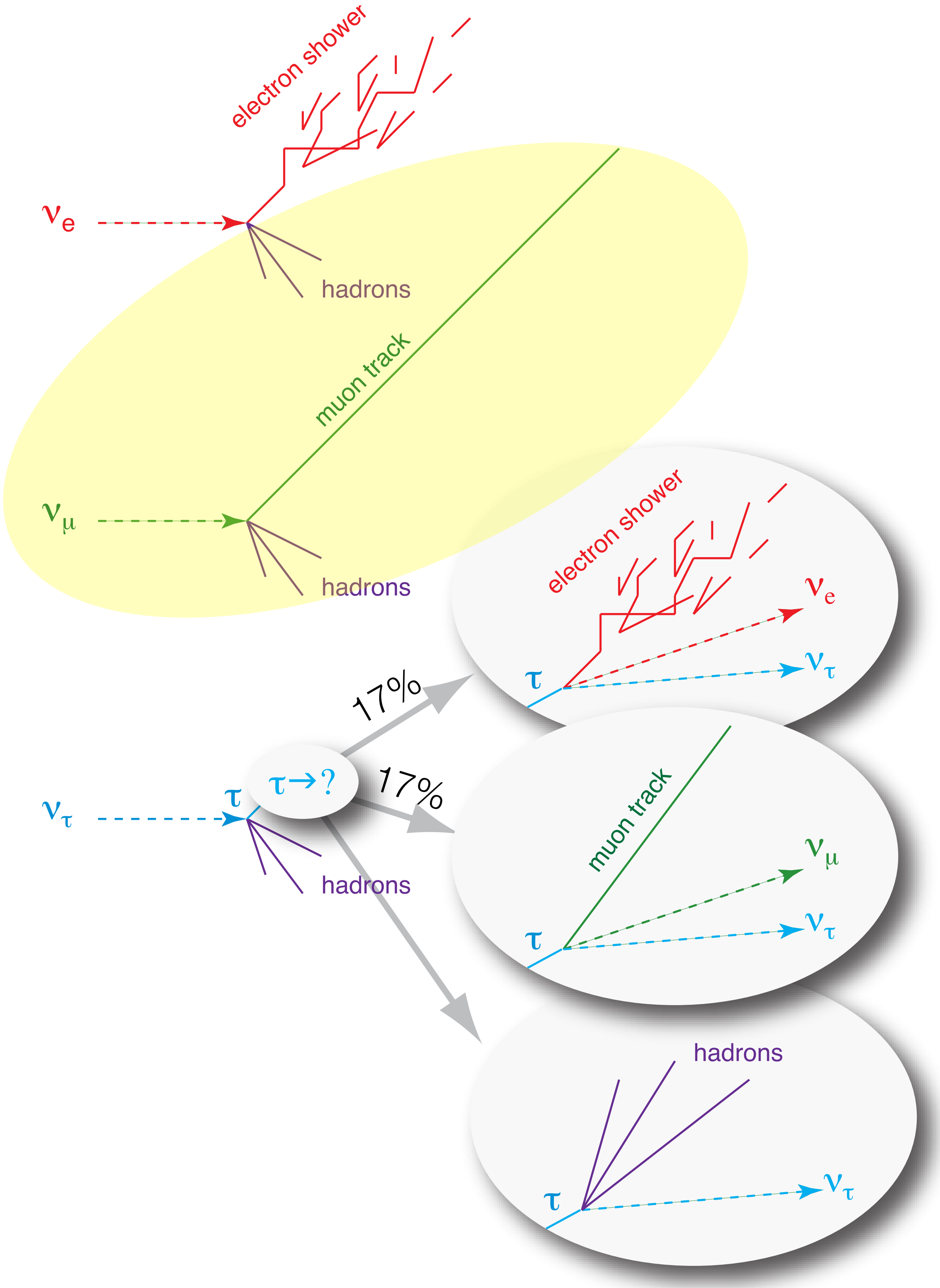


Elastic scattering

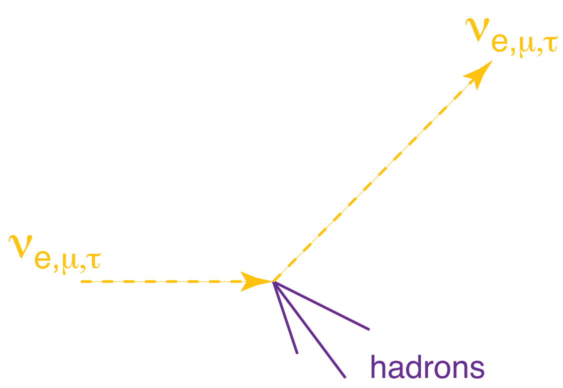
- σ_{CC}/σ_{NC} ~= 1/6
- Electron sent primarily in forward direction
- Energy of electron ~uniformly distributed between 0 and E_ν

Neutrino detection channels

Charged-current



Neutral-current



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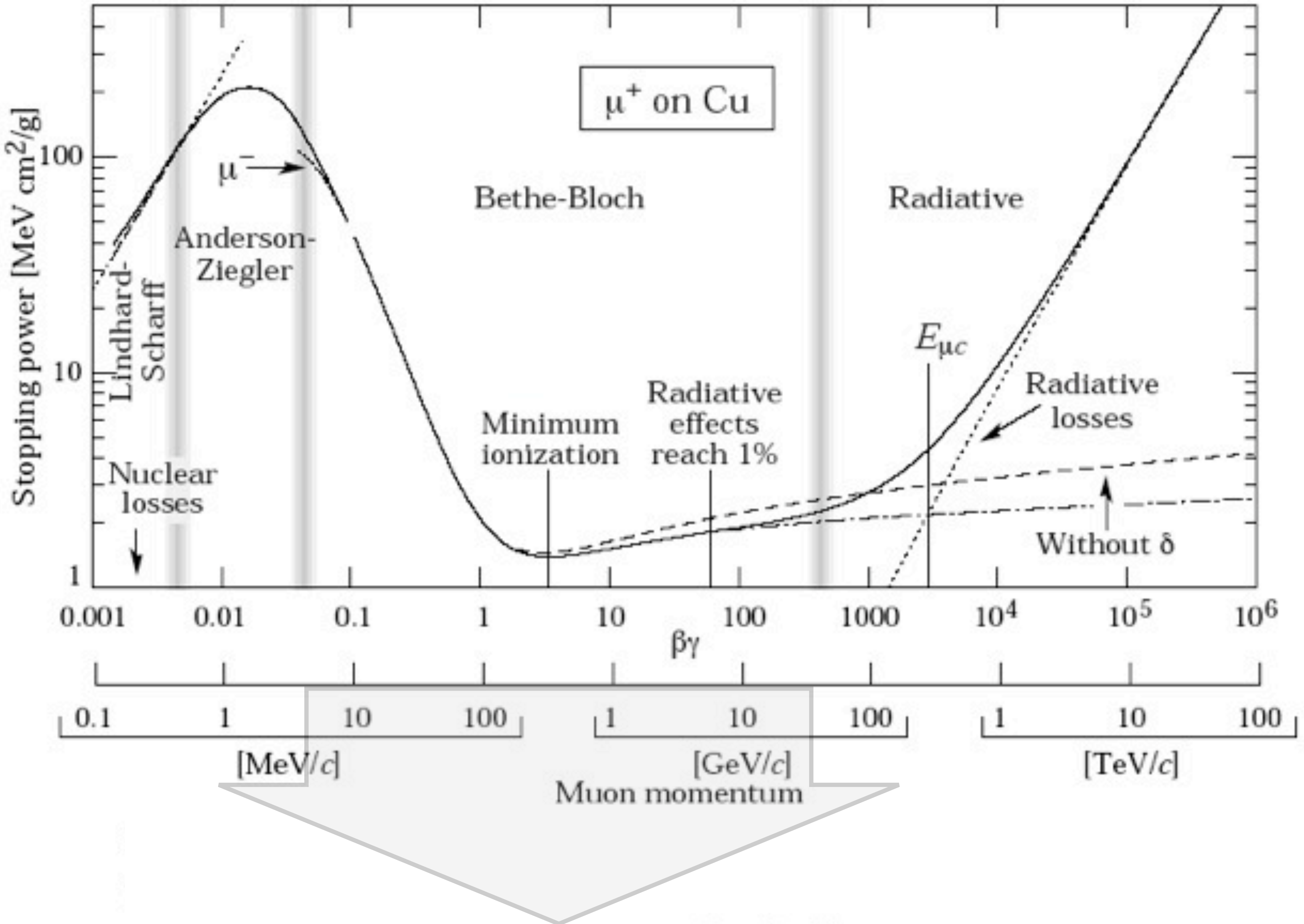
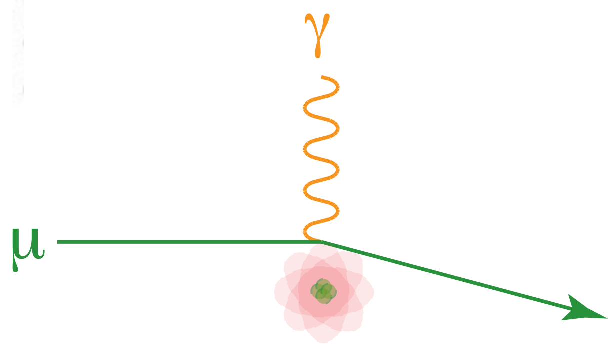
Muons

- Muons with momenta in the 0.1-100 GeV lose their energy almost entirely through ionization
- Occasionally muons will produce large showers via
  - Delta-rays aka “knock on” electrons
  - Radiative loses (bremsstrahlung) when E is above $E_{\mu c}$~100 GeV
- Ionization loses are given by the Bethe-Bloch equation at right
- Typical value: 2 MeV cm^2/g

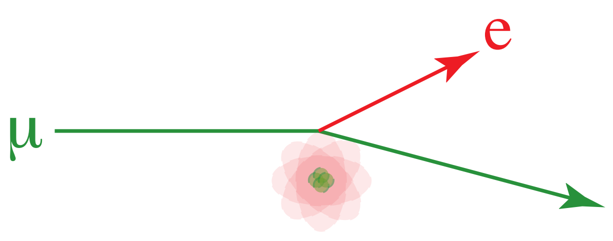
W.-M. Yao et al., Journal of Physics G 33, 1 (2006)
available on the PDG WWW pages (URL: http://pdg.lbl.gov/)



$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$



bremsstrahlung



delta ray or “knock on”

Range

As seen in the plot at the right, the range of a particle with momentum in the GeV range has roughly a power law dependence:

$$\frac{R}{M}\left[\frac{\mathrm{g}}{\mathrm{cm}^2\ \mathrm{GeV}}\right] = C\left(\frac{p}{M}\right)^n$$

Above βγ=5:

$$n = 1, C = \frac{A}{Z}(210 + 38\log Z)$$

Below βγ=1:

$$n = 3, C = \frac{A}{Z}(39 + 13\log Z)$$

(my parameterizations of the plot at right)

In between βγ=1 and 5 choosing the smaller of the two calculations overestimates the range by as much as 30%

W.-M. Yao et al., Journal of Physics G 33, 1 (2006)
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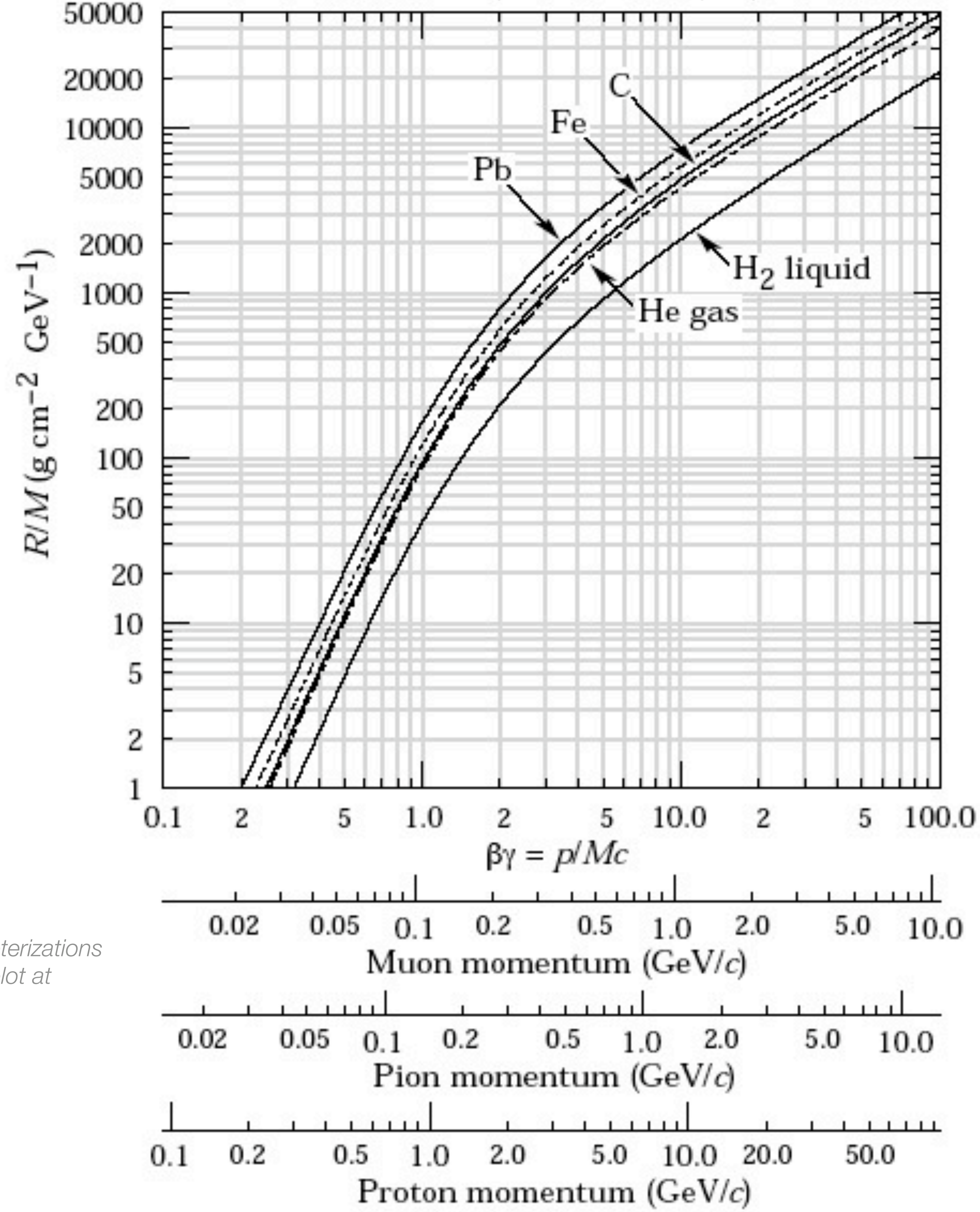
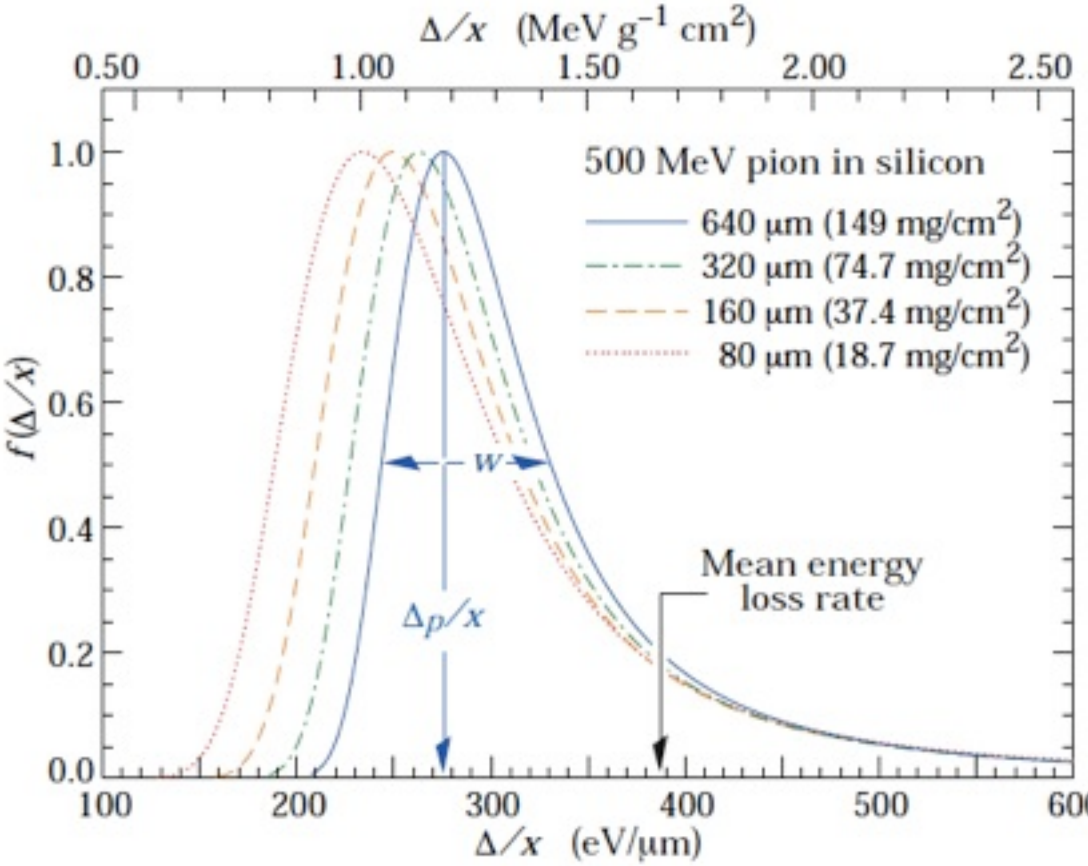


Figure 27.4: Range of heavy charged particles in liquid (bubble chamber) hydrogen, helium gas, carbon, iron, and lead. For example: For a K^+ whose momentum is 700 MeV/c, $\beta\gamma = 1.42$. For lead we read $R/M \approx 396$, and so the range is 195 g cm^{-2}.

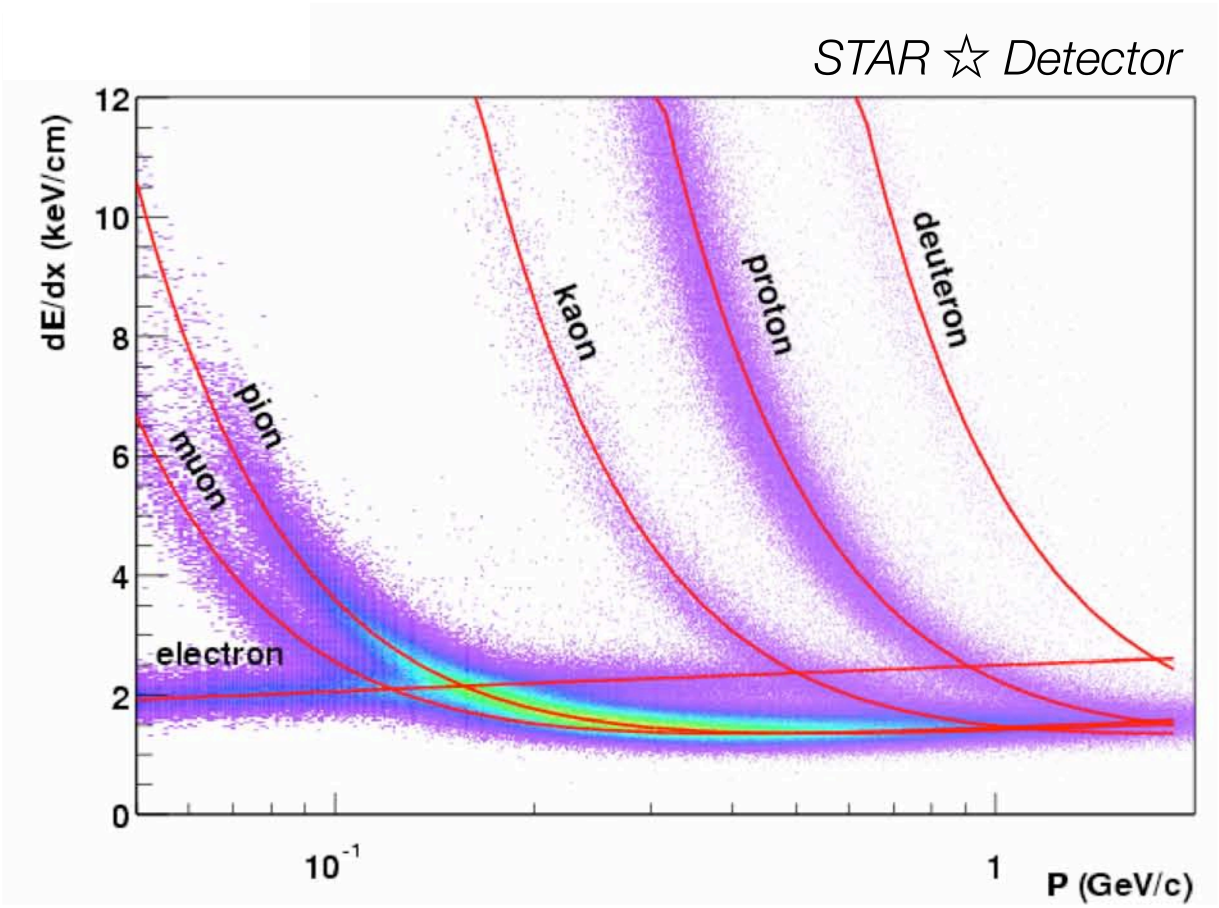
Variations in range: “Straggling”

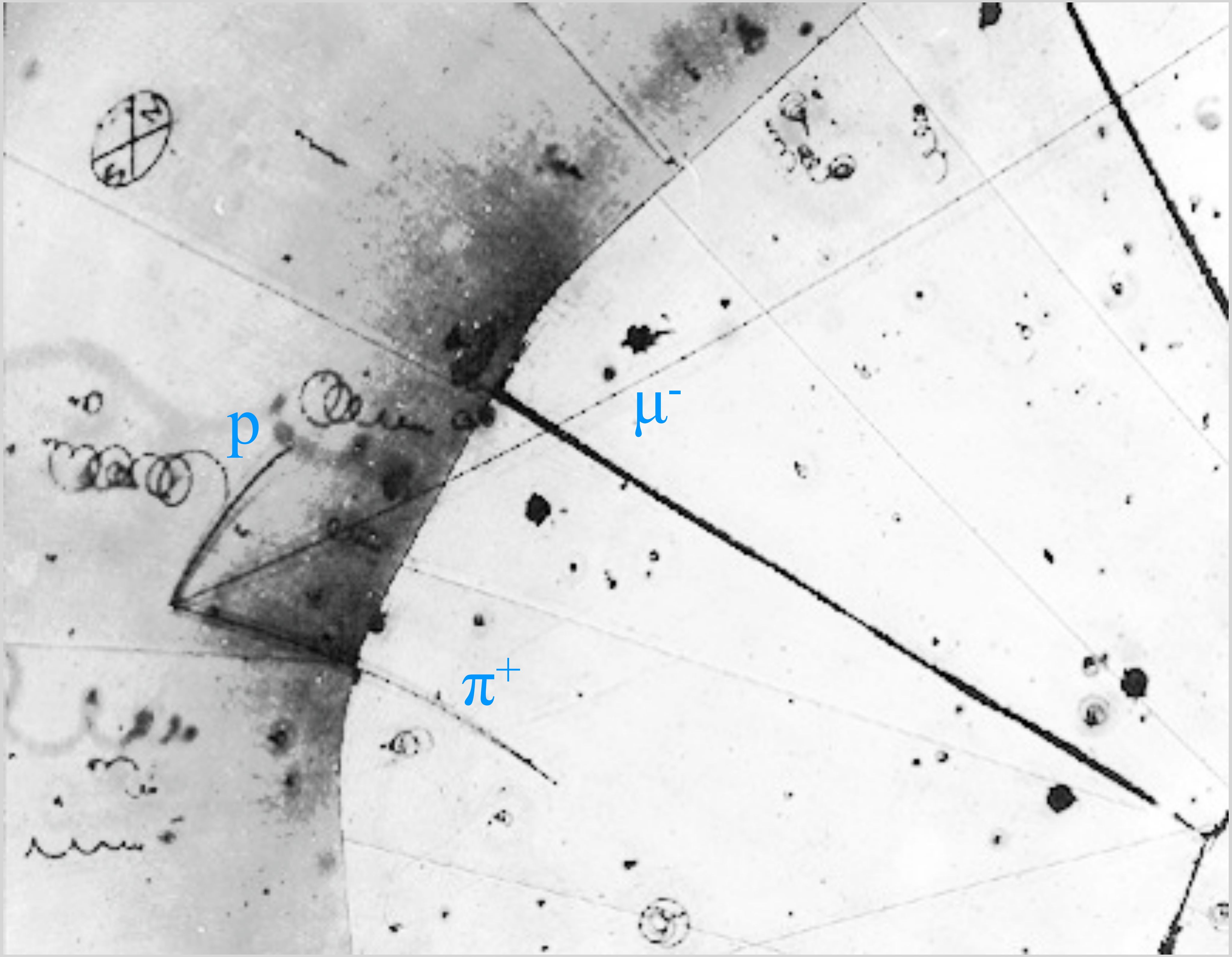
- The previous formulas for dE/dx and range are for averages.
- Fluctuations in dE/dx are roughly given by a Landau distribution. To mitigate against large fluctuations it is common to compute a truncated mean for dE/dx when using dE/dx for particle ID to estimate the most probable value of this distribution.
- Fluctuations in dE/dx cause fluctuations in range. At high energies, the size of the variations is approximately: $$\frac{\sigma_R}{R} \simeq \frac{1}{2}\sqrt{m/M}$$ where m is the electron mass and M is the particle mass. For muons and pions this is roughly 3%. For protons, 1%. This sets a limit for muon energy measurement using range



W.-M. Yao et al., Journal of Physics G 33, 1 (2006)

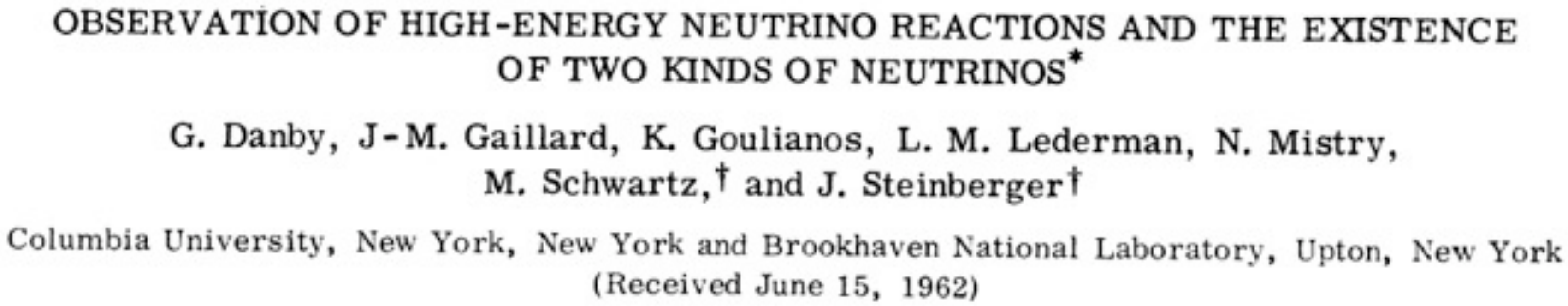
Figure 27.7: Straggling functions in silicon for 500 MeV pions, normalized to unity at the most probable value δ_p/x. The width w is the full width at half maximum. See full-color version on color pages at end of book.





Compare the proton, muon, and pion tracks

12 foot bubble chamber,
Argonne National Lab.
Nov. 13, 1970

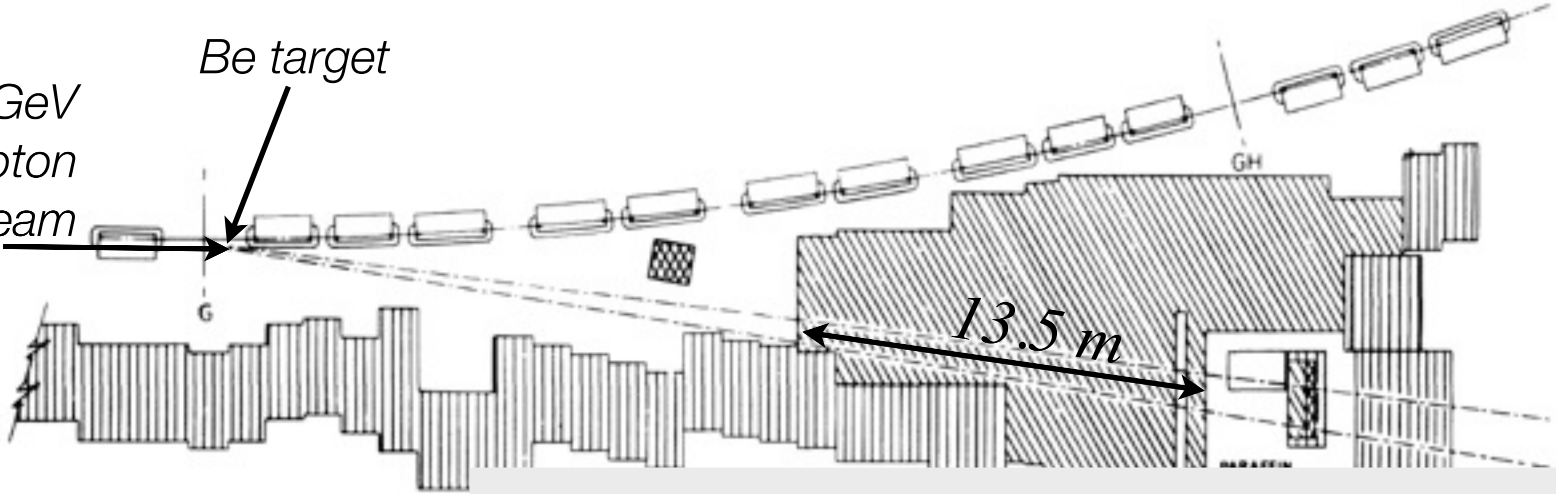


OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz,† and J. Steinberger†

Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York

(Received June 15, 1962)



15 GeV proton beam

Be target

13.5 m

Q: What is the minimum muon energy required to pass from the beam line to the detector?

Simple guess:

$(2\ \text{MeVcm}^2/\text{g} * 7.87\ \text{g/cm}^3 * 1350\ \text{cm}) = 21\ \text{GeV}$

$R/M = (7.87\ \text{g/cm}^3)*(1350\ \text{cm} / 0.106\ \text{GeV}) = 100{,}000\ \text{g/cm}^2/\text{GeV}$ which is off the plot on the previous page. So all we can say from the plot is that $p>10$ GeV.

From previous page: For A=55.8, Z=26 C=566

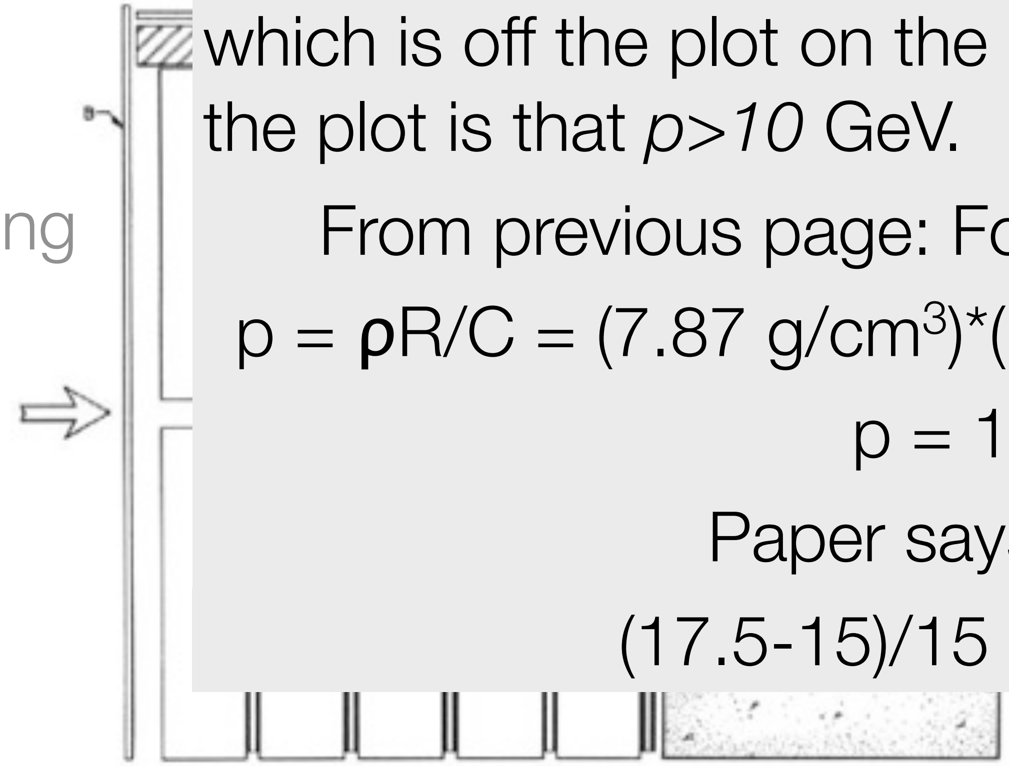
$p = \rho R/C = (7.87\ \text{g/cm}^3)*(1350\ \text{cm})/(566\ \text{g/cm}^2/\text{GeV})$

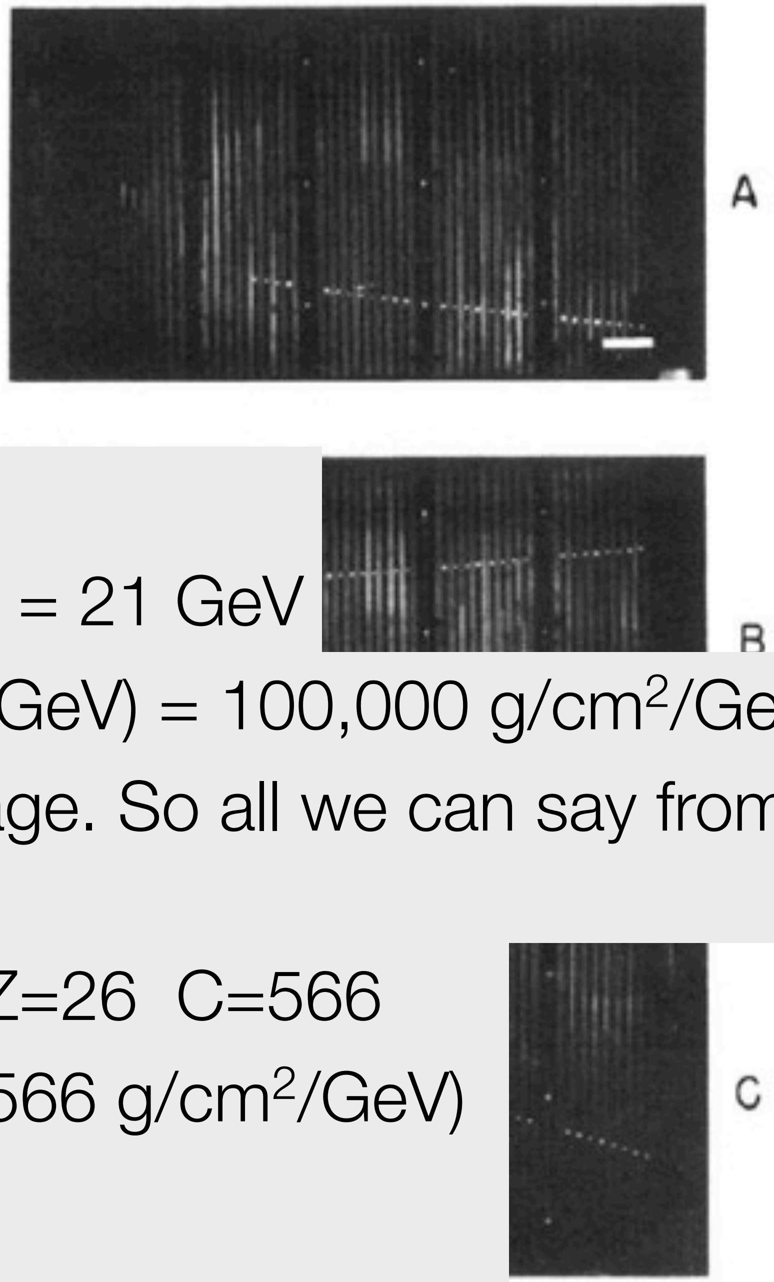
$p = 19$ GeV

Paper says 17.5 GeV

(17.5-15)/15 = 17% >> 3%

B,C,D vetos against entering tracks





) p_μ >540 MeV and
n (neutrino beam in-
/c; (C) p_μ >440 with
δ ray.

W.-M. Yao et al., Journal of Physics G 33, 1 (2006)
available on the PDG WWW pages (URL: http://pdg.lbl.gov/)

Multiple scattering

- As charged particles pass through matter they experience Rutherford scattering off of nuclei.
- Typically there are a large number of scatters which all go more-or-less in the forward direction. Given the large number of scatters it is common to work in a Gaussian approximation
- Affects path length through material and can make measurements of curvature difficult

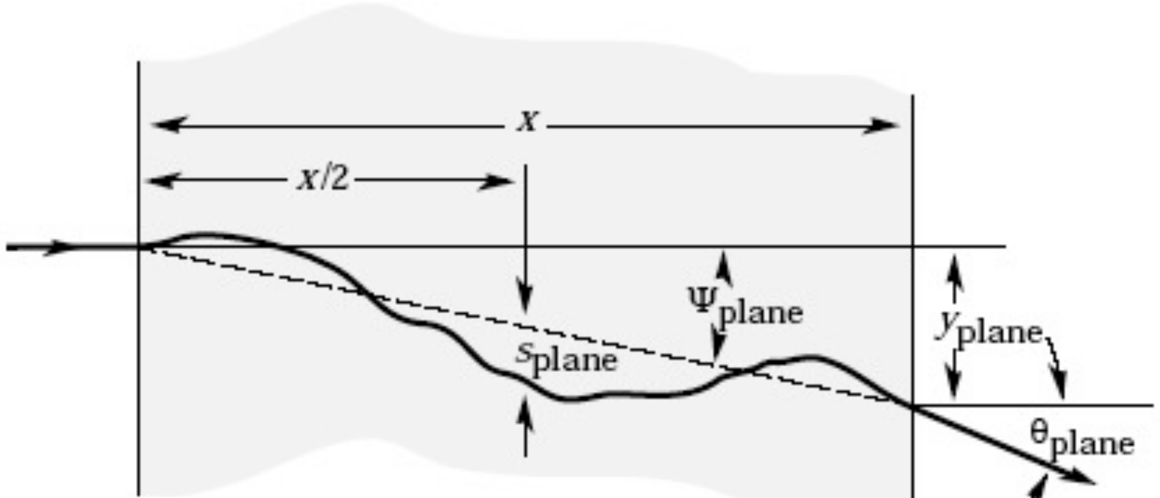


Figure 27.9: Quantities used to describe multiple Coulomb scattering. The particle is incident in the plane of the figure.

$$\theta_0 = \frac{13.6 \text{ MeV}}{\beta c p} \, z \, \sqrt{x/X_0}\Big[1 + 0.038 \ln(x/X_0)\Big]$$

$$\theta_0 = \theta^{\text{rms}}_{\text{plane}} = \frac{1}{\sqrt{2}} \theta^{\text{rms}}_{\text{space}}$$

$$\psi^{\text{rms}}_{\text{plane}} = \frac{1}{\sqrt{3}} \theta^{\text{rms}}_{\text{plane}} = \frac{1}{\sqrt{3}} \theta_0 \ ,$$

$$y^{\text{rms}}_{\text{plane}} = \frac{1}{\sqrt{3}} x \, \theta^{\text{rms}}_{\text{plane}} = \frac{1}{\sqrt{3}} x \, \theta_0 \ ,$$

$$s^{\text{rms}}_{\text{plane}} = \frac{1}{4\sqrt{3}} x \, \theta^{\text{rms}}_{\text{plane}} = \frac{1}{4\sqrt{3}} x \, \theta_0 \ .$$

Multiple scattering

few mrad at 1 GeV, 1 cm
↓

scales like 1/p

		$p = 1$ GeV/c			$p = 10$ GeV/c		
	X_0 [cm]	x=1 cm	10 cm	100 cm	x=1 cm	10 cm	100 cm
Air	30420	0.05	0.17	0.61	0.004	0.017	0.061
LqH_2	866	0.35	1.2	4.3	0.034	0.12	0.42
Scint.	42.5	1.8	6.3	21.7	0.18	0.62	2.15
H_2O	36.1	1.97	6.84	23.6	0.20	0.68	2.35
C	18.8	2.80	9.7	33.5	0.28	0.97	3.34
LqAr	14.0	3.29	11.4	39.3	0.33	1.13	3.91
Fe	1.76	10.1	34.7	118.9	1.00	3.46	11.82

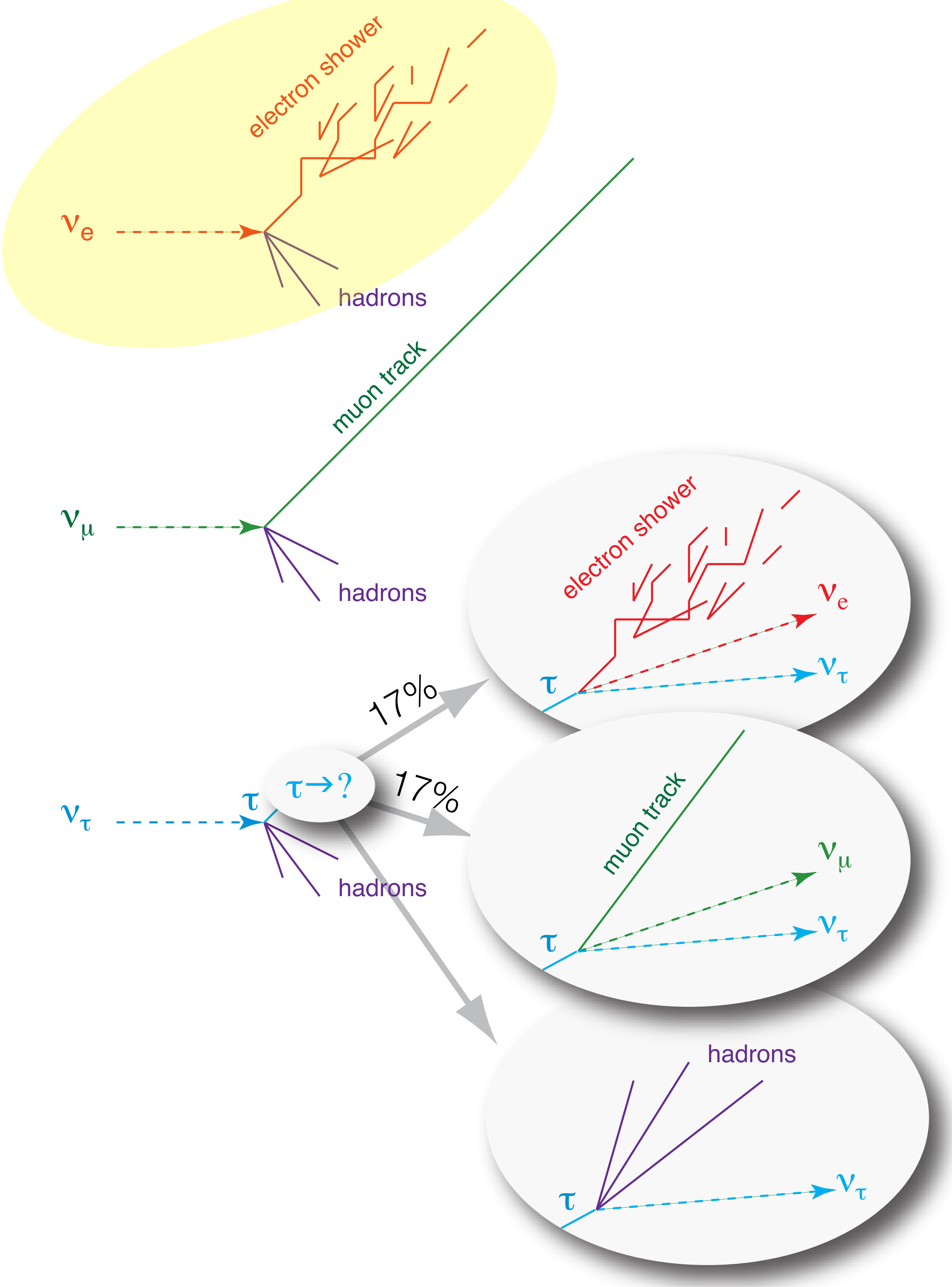
Multiple scattering of angles in mrad of 1 and 10 GeV muons for various materials of thicknesses of 1, 10, and 100 cm

↘×3↗ ↘×3↗

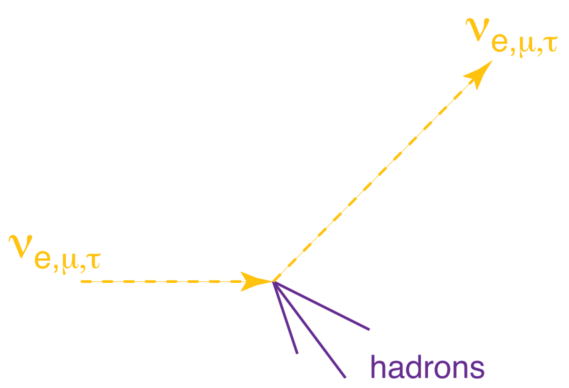
Factor 3 for each factor of 10 in thickness

Neutrino detection channels

Charged-current



Neutral-current



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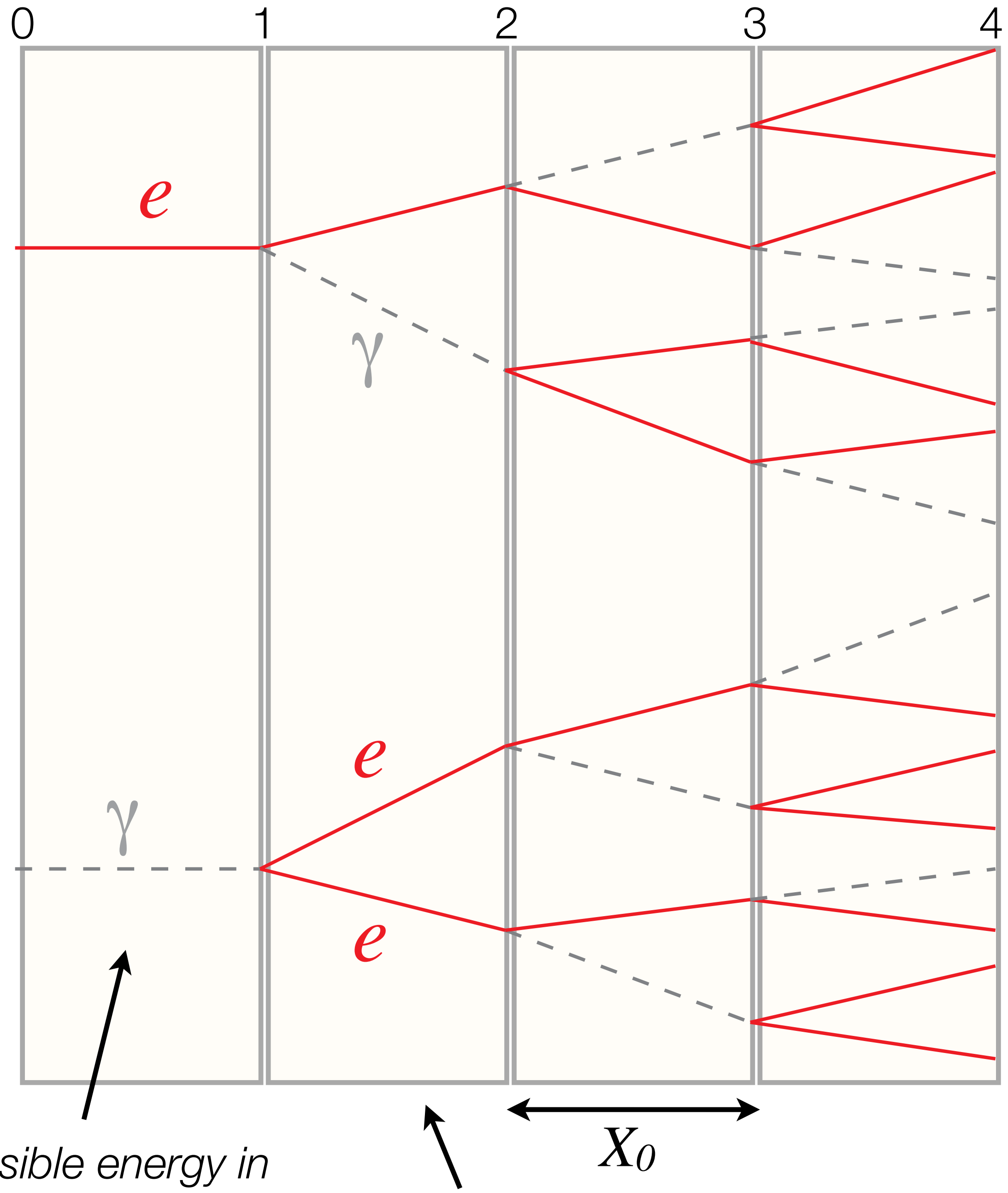
Electromagnetic showers



No visible energy in photon shower inside first conversion distance

Visible start of photon shower has twice as much energy as the visible start of the electron shower

Simple model of shower development:

- e^+/e^-'s with $E>E_c$ travel one X_0 then brem a γ with energy $E/2$. E_c is a "critical energy" at which energy losses due to brems and ionization are equal. Typically $E_c \cong 20$ MeV.
- γs with $E>E_c$ travel ~one X_0 then pair produce e^+/e^- each with energy $E/2$
- When $E<E_c$ electrons lose their energy through collisions and don't radiate

This model is simple and useful. However, it does have limitations:

I) You may be temped to assume that the number of particles at some particular depth obeys Poisson statistics. However, fluctuations in the particle numbers at any given layer are correlated with what happens in previous layers.

II) Fluctuations occur such that a certain point in the shower there may only be only γs creating gaps in the shower, an effect which this model fails to capture

Electrons: Critical energy

W.-M. Yao et al., Journal of Physics G 33, 1 (2006)
available on the PDG WWW pages (URL: http://pdg.lbl.gov/)

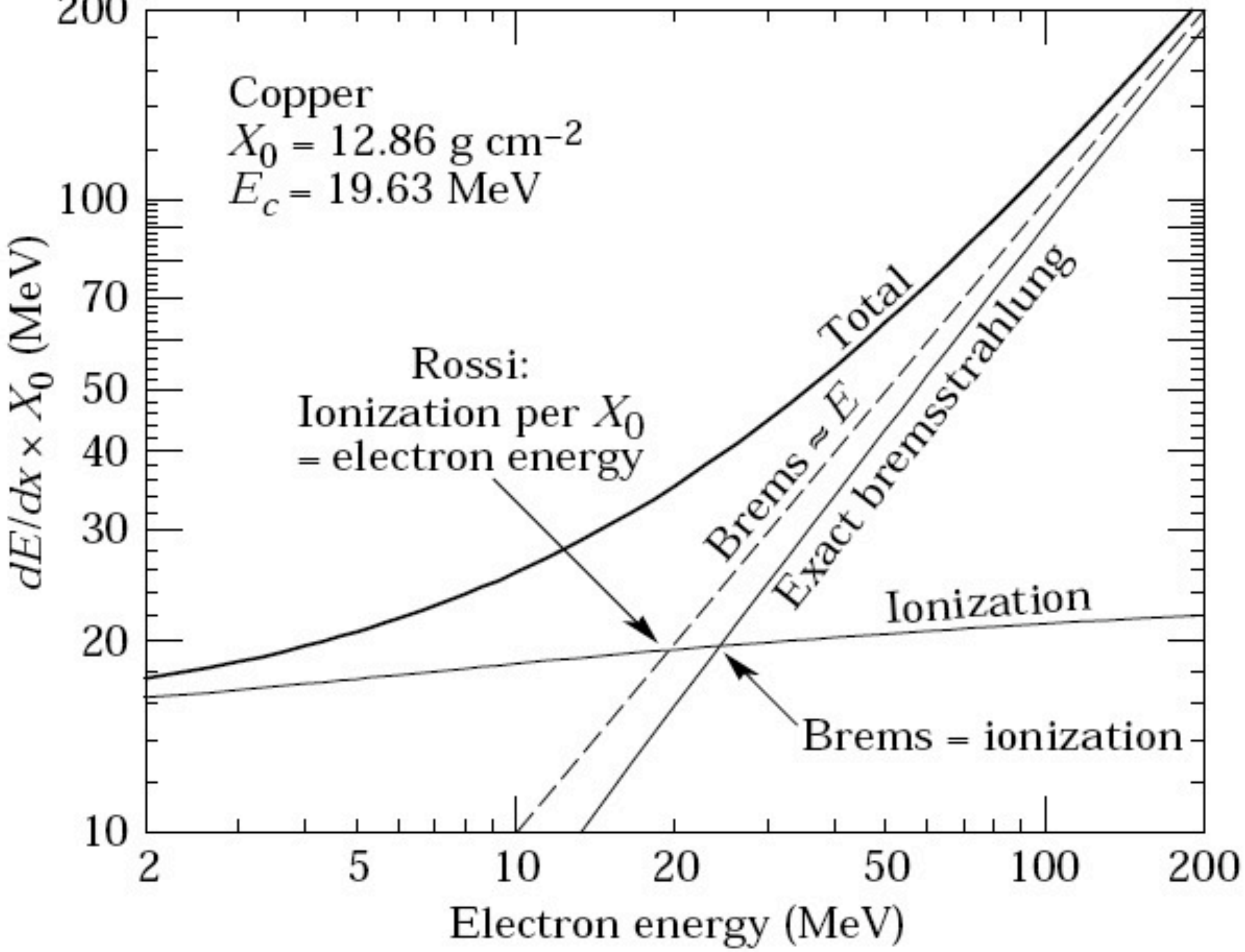


Figure 27.12: Two definitions of the critical energy E_c.

$\left(\frac{dE}{dx}\right)_{\text{rad}} = \left(\frac{dE}{dx}\right)_{\text{col}}$ *seems to be in more common usage*

- Due to their relatively small mass, energy losses due to bremsstrahlung ("brems") are more important for electrons than for muons.
- Above a critical energy, E_c, electrons lose energy mostly to brems. Ionization losses are only important below the critical energy.
- Approximately:

$$E_C = \frac{800 \text{ MeV}}{Z + 1.2}$$

Electrons: Radiation length and Moliere radius

- The radiation length, X_0, of a material is defined as the distance over which an electron loses $1/e$ of its energy via radiation. X_0 is measured in cm or in g/cm^2
- Roughly speaking, an electron emits one photon through bremsstrahlung for every $1\ X_0$ traversed
- X_0 also controls the distance over which photons pair produce

$$\lambda_{\text{pair}} = \frac{9}{7} X_0$$

- Approximate formula for X_0:

$$X_0 = \frac{716.4A}{Z(Z+1)\ln(287/\sqrt{Z})} \left[\frac{\text{g}}{\text{cm}^2}\right]$$

- Development in the transverse direction scales with the Moliere radius:

$$R_{\text{M}} = \frac{21.2\ \text{MeV}}{E_C} X_0 = 0.0265(Z+1.2)X_0$$

- If the shower longitudinal shower profile is measured in units of X_0 transverse profile is measured in units of R_M then (roughly speaking) all showers look the same independent of material and energy

Effective Z and A

- For mixtures, one can compute an effective Z and A based on the fraction by weight of each of the component elements:

$$\begin{aligned} A_{\text{eff}} &= p_i A_i \\ Z_{\text{eff}} &= p_i Z_i \end{aligned}$$

p_i : fraction by weight of element i

A_i : atomic mass of element i

Z_i : atomic number of element i

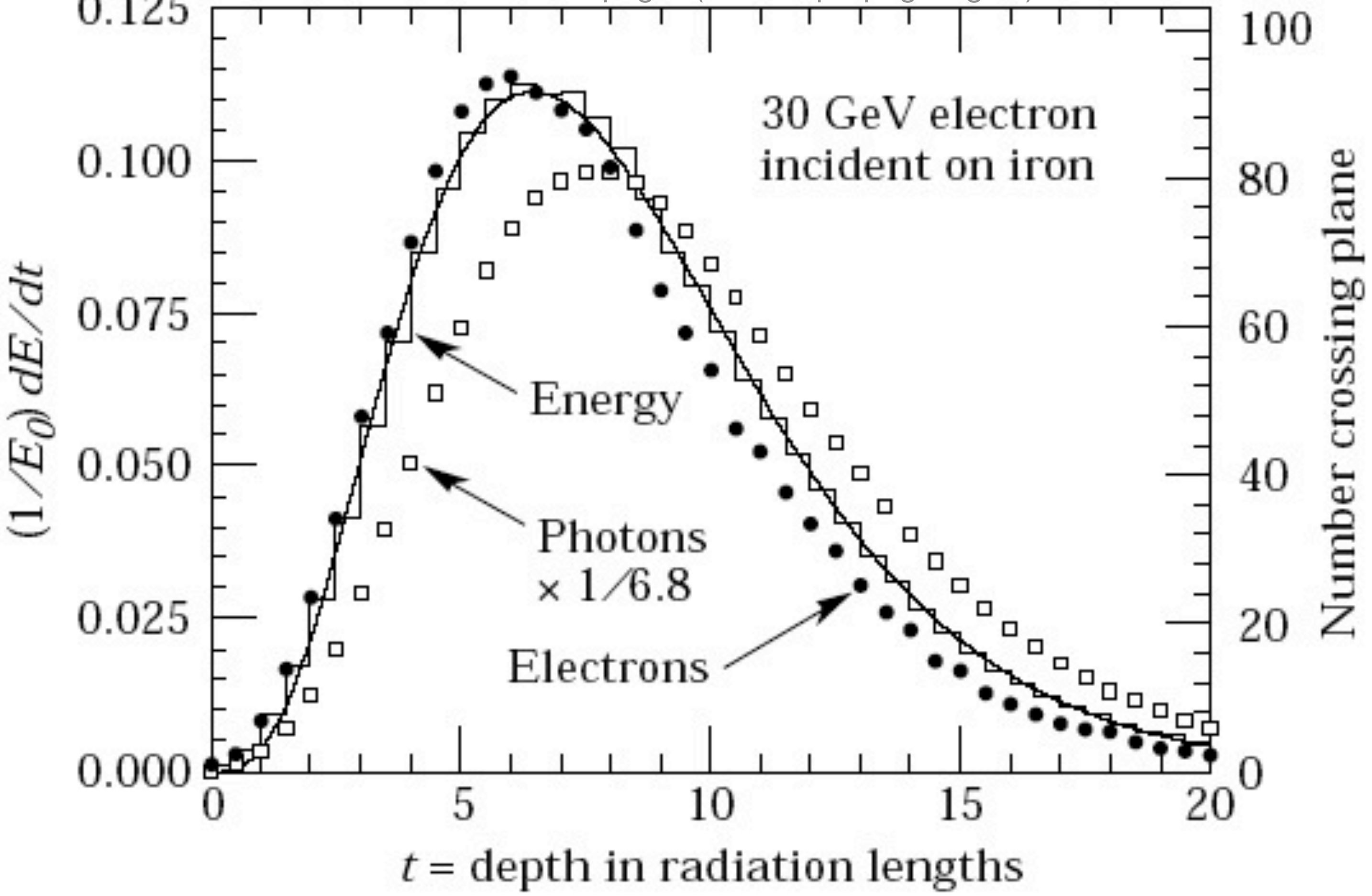
Electrons: Radiation length and Moliere radius

	Radiation length		Moliere radius	
	g/cm^2	cm	g/cm^2	cm
liquid H_2	61.28	866	3.57	50.49
liquid Ar	19.55	14.0	9.95	7.12
C	42.70	18.8	8.15	3.59
Fe	13.84	1.76	10.71	1.36
Air	36.66	30420	7.62	6322
H_2O	37.08	36.1	8.31	8.32
SiO_2	27.05	12.3	8.61	3.91
Polystyrene scintillator	43.72	42.4	8.50	8.25
Liquid scintillator	51.07	43.9	8.93	7.68

A sample of radiation lengths and Moliere radii for materials common in neutrino detectors

Topology of electromagnetic showers: Longitudinal development

W.-M. Yao et al., Journal of Physics G 33, 1 (2006)
available on the PDG WWW pages (URL: http://pdg.lbl.gov/)



longitudinal depth ⟶

$$\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

$$\frac{X_0}{b} \equiv \text{"the shower length"}$$

Shower maximum occurs at

$$t_{max} = \frac{a-1}{b} = \ln \frac{E_0}{E_C} + C_i$$

where $C_{i=e} = -0.5$ for electron showers and $C_{i=\gamma} = +0.5$ for gamma showers.

The parameter b has been tabulated for several materials:

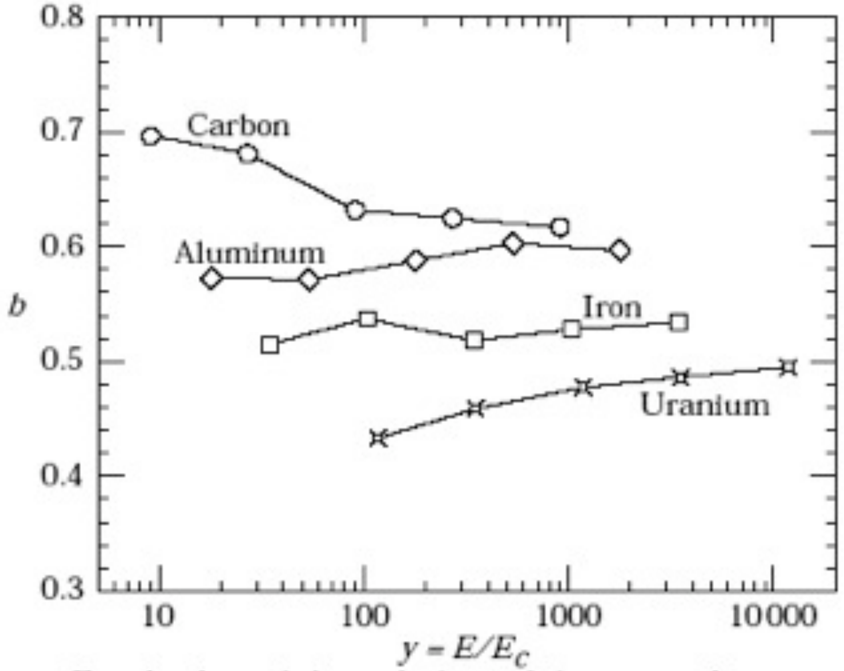


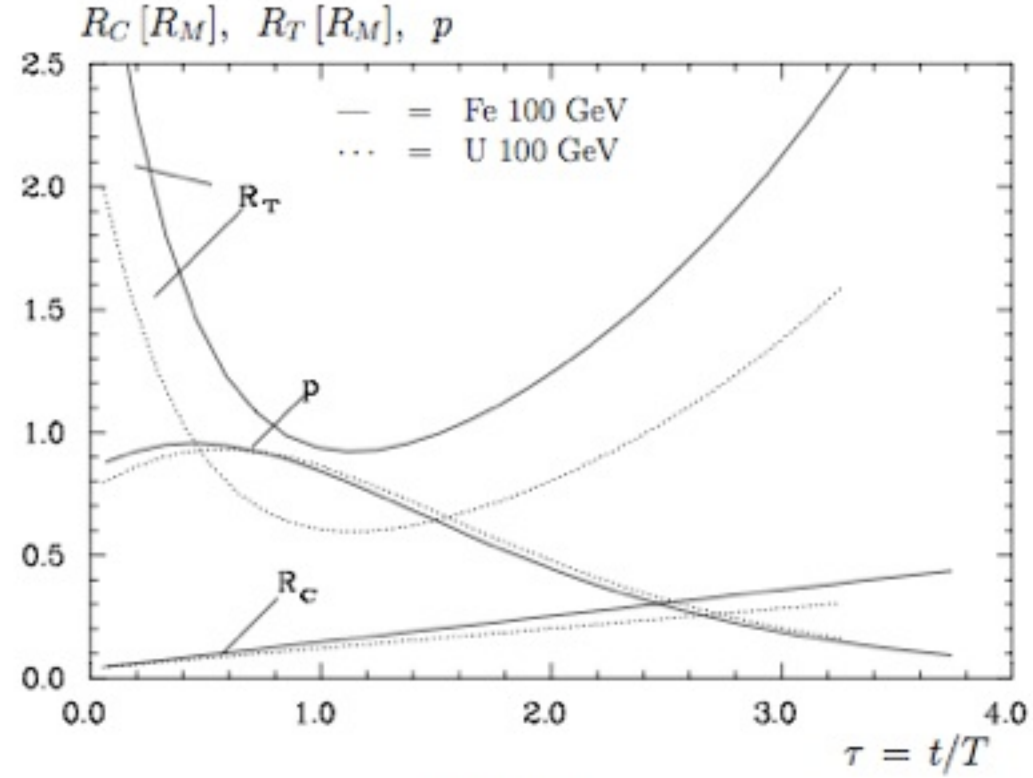
Figure 27.19: Fitted values of the scale factor b for energy deposition profiles obtained with EGS4 for a variety of elements for incident electrons with $1 \leq E_0 \leq 100$ GeV. Values obtained for incident photons are essentially the same.

Topology of electromagnetic showers Transverse development

- In the transverse direction, shower profiles scale with the Moliere radius R_M. Roughly 90% of the energy is located within $1R_M$ of the shower axis, 95% within 2 R_M.
- The transverse distribution is not Gaussian:

$$f(r) \equiv \frac{1}{dE(t)} \frac{dE(t,r)}{dr}$$

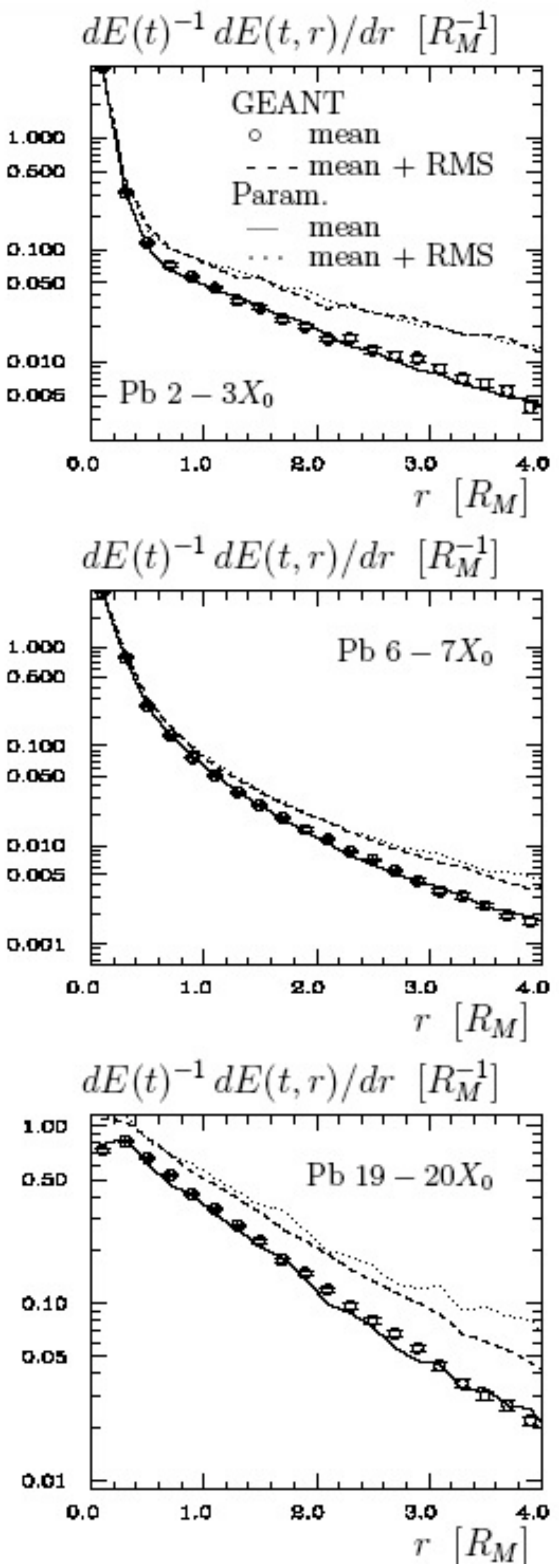
$$f(r) = p\frac{2rR_C^2}{(r^2+R_C^2)^2} + (1-p)\frac{2rR_T^2}{(r^2+R_T^2)^2}$$



Grindhammer and Peters hep-ex/0001020

core dominated

tail dominated



EM Shower checkup

	Radiation length		Moliere radius	
	g/cm^2	cm	g/cm^2	cm
liquid H_2	61.28	866	3.57	50.49
liquid Ar	19.55	14.0	9.95	7.12
C	42.70	18.8	8.15	3.59
Fe	13.84	1.76	10.71	1.36
Air	36.66	30420	7.62	6322
H_2O	37.08	36.1	8.31	8.32
SiO_2	27.05	12.3	8.61	3.91
Polystyrene scintillator	43.72	42.4	8.50	8.25
Liquid scintillator	51.07	43.9	8.93	7.68

Q: How wide are electron showers in the NOvA detector? (Liquid scintillator with 4 cm transverse sampling)

A: R_M ~= 7.7 cm, $4R_M$ diameter cylinder contains 95% of shower energy, $4R_M$/4 cm/cell ~= 8 cells

Q: A LqAr detector has a 1 meter cubic target volume. How large should the detector be to contain 15 GeV electron showers?

A: To contain showers, we need roughly 20 X_0 in depth and 5 R_M on the sides.

*L = 1 m + (20*0.14 m) = 3.8 m*

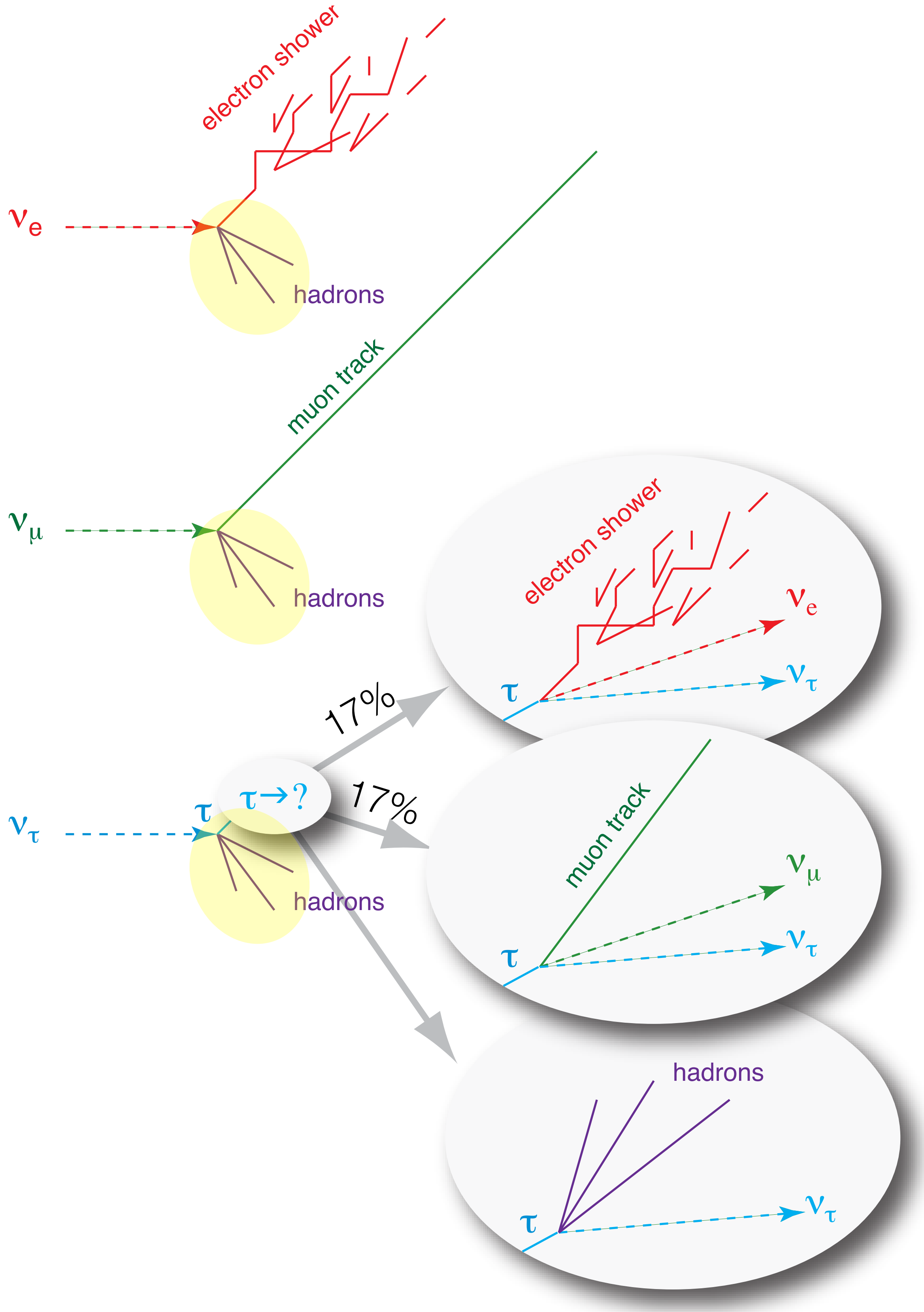
*W = 1 m + 2 * (5 * 0.07 m) = 1.7 m*

Q: The SciBar detector used by the SciBooNE experiment is made of solid scintillator and is 1.7 m deep. What is the probability that one photon from a π^0 decay escapes the detector undetected?

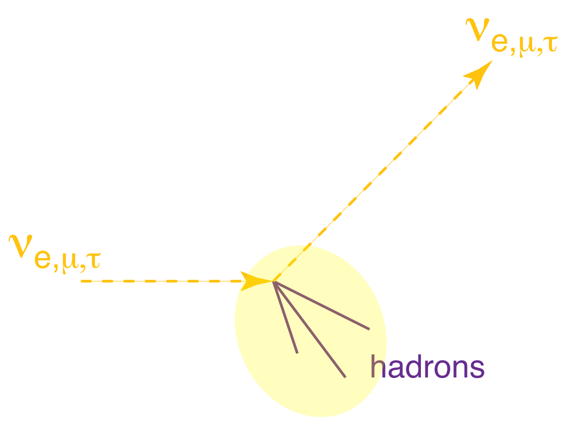
$$1 - P_C = 1 - \int_0^d \frac{1}{\lambda_C} e^{-x/\lambda_C} dx = e^{-d/\lambda_C} \left\{ \begin{array}{rcl} \lambda_C & = & \frac{11}{9} 42.4 \text{ cm} = 51.8 \text{ cm} \\ d & = & 170 \text{ cm} \end{array} \right\} = e^{-170/51.8} = 4\%$$

Neutrino detection channels

Charged-current



Neutral-current



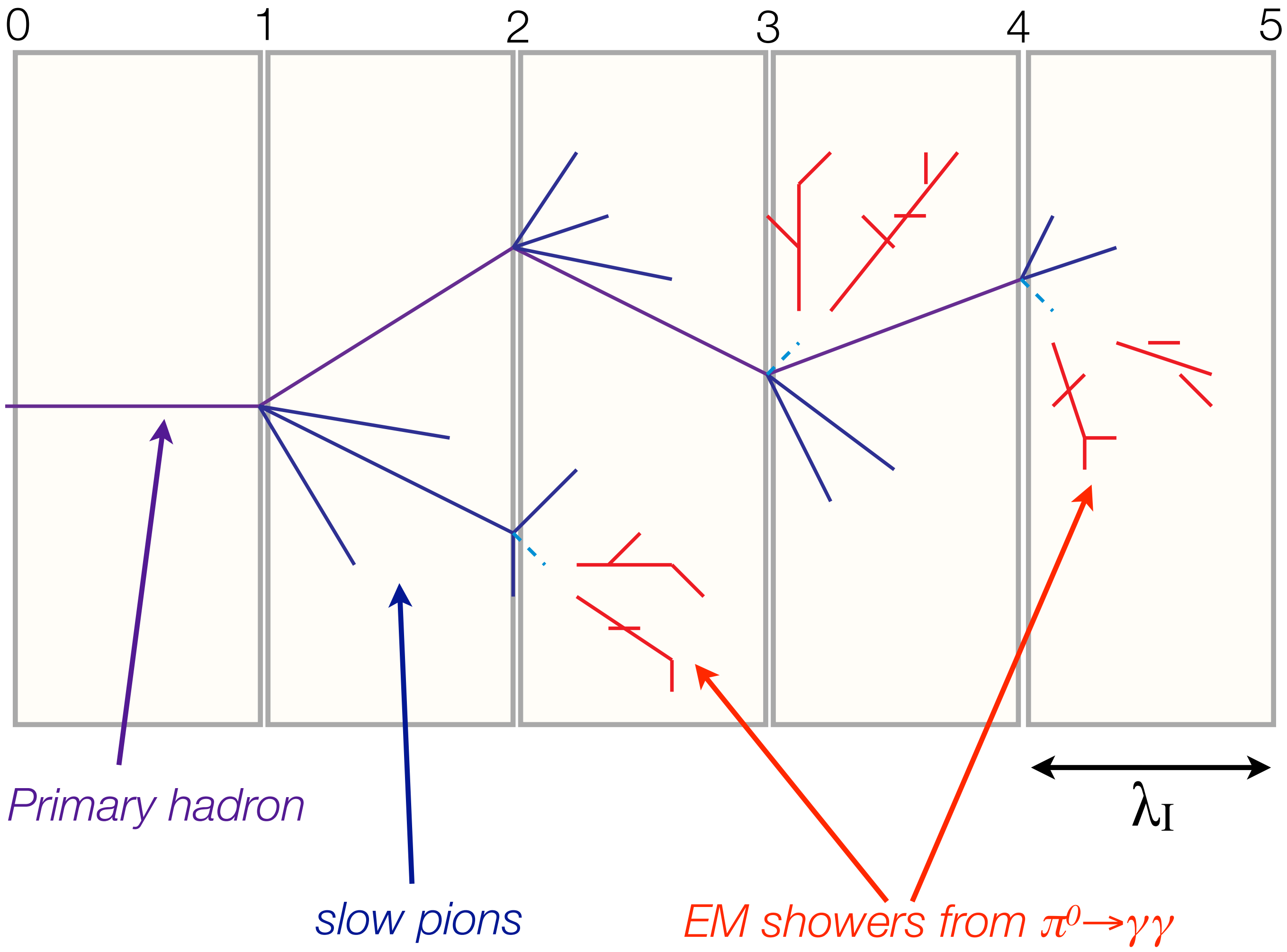
- In charged-current (CC) events outgoing lepton tags incoming neutrino flavor.
  - *In the case of ν_τ, the presence of a τ must be deduced from the τ decay products*
- In CC events nearly all the neutrino energy is deposited in the detector
- In neutral-current events, only hadrons are present and no information about the incident neutrino flavor is available
- CC rates are affected by oscillations
- NC rates are not affected by oscillations
  - *In only a few analyses are NC events considered to be signal. In most cases NC events are backgrounds to the CC processes*

Hadron showers

Hadrons will interact strongly in a material after traversing one “interaction length” ≡ λ_I

Hadrons can produce tracks or showers depending on the relative importance of energy loss due to collisions and energy loss due to strong interactions. When:

- range due to ionization < λ_I ➜ track
- range due to ionization > λ_I ➜ shower



Simple hadron shower model:

I) Hadron travels one interaction length and interacts strongly
II) ~1/2 of the energy is carried by a single secondary hadron
III) Remaining energy carried off by several slow pions
IV) Process continues until secondary hadrons lose all their energy through collisions

Depending on rate of π^0 production, hadron showers will have EM showers embedded in them

...Adding interaction length to our table

	Radiation length		Moliere radius		Interaction length	
	g/cm^2	cm	g/cm^2	cm	g/cm^2	cm
liquid H_2	61.28	866	3.57	50.49	50.8	717.5
liquid Ar	19.55	14.0	9.95	7.12	117.2	84.0
C	42.70	18.8	8.15	3.59	86.3	38.1
Fe	13.84	1.76	10.71	1.36	131.9	16.8
Air	36.66	30420	7.62	6322	90.0	69600
H_2O	37.08	36.1	8.31	8.32	83.6	83.6
SiO_2	27.05	12.3	8.61	3.91	97.4	44.3
Polystyrene scintillator	43.72	42.4	8.50	8.25	81.9	79.4
Liquid scintillator	51.07	43.9	8.93	7.68	81.9	95.2

Radiation length is often shorter than interaction length and EM showers are less subject to straggling: EM calorimeters come first, then hadron calorimeters

Comparison of EM and hadron shower

- Angle of photon emission for bremsstrahlung is $\approx m_e/E$
- Hadronic processes typically produce particles with $P_T \sim= 300$ MeV/c
- For 1 GeV:
    - $\theta_{EM} \approx 0.5$ mrad
    - $\theta_{Had} \approx 300$ mrad

➡*EM showers are compact in the transverse direction compared to hadron showers which tend to be more diffuse in the transverse direction*

- Example at right shows 15 GeV e and π in glass (Z~=11).

CHARM-II collaboration, NIM A277 (1989) 83-91.

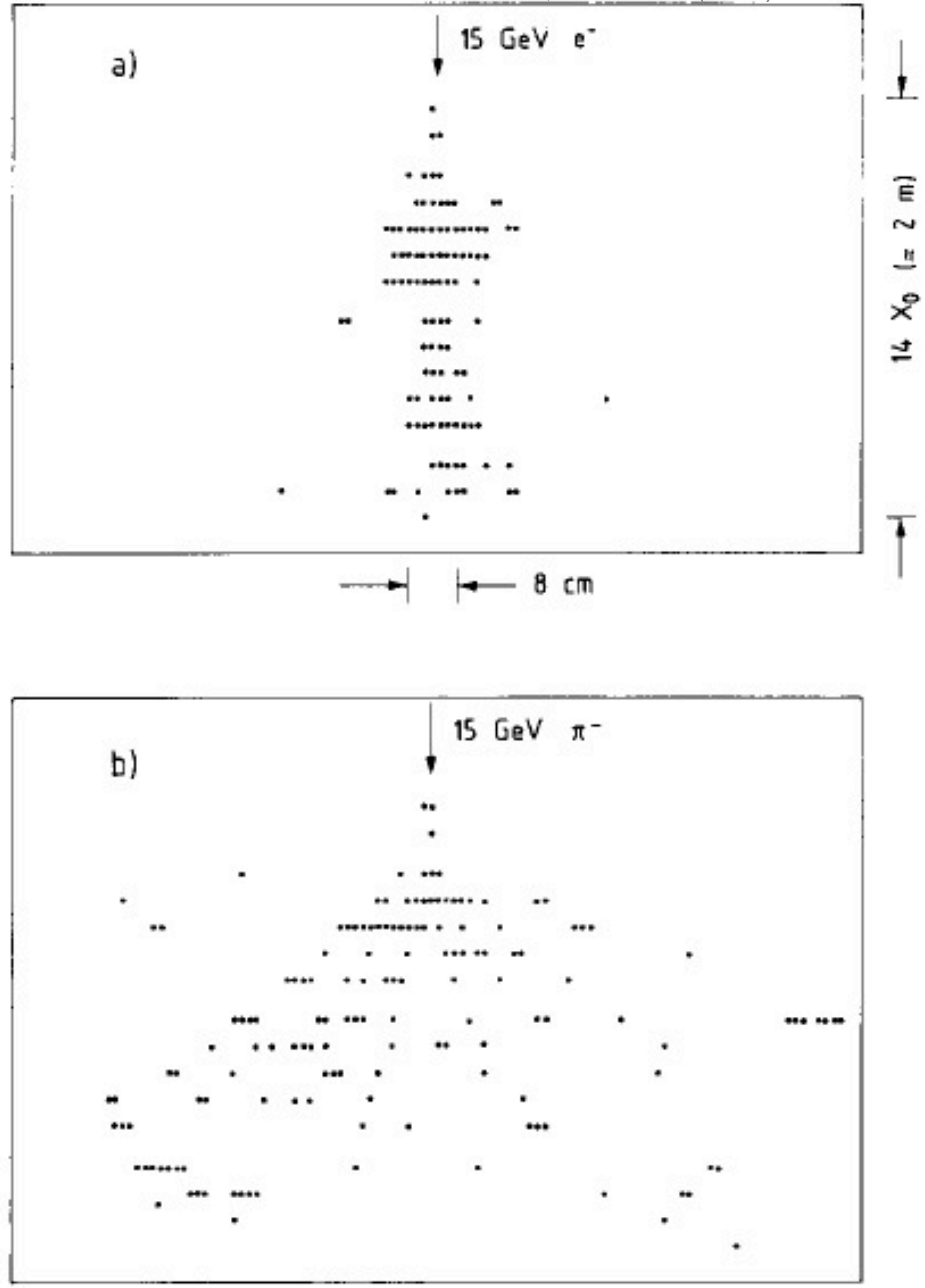
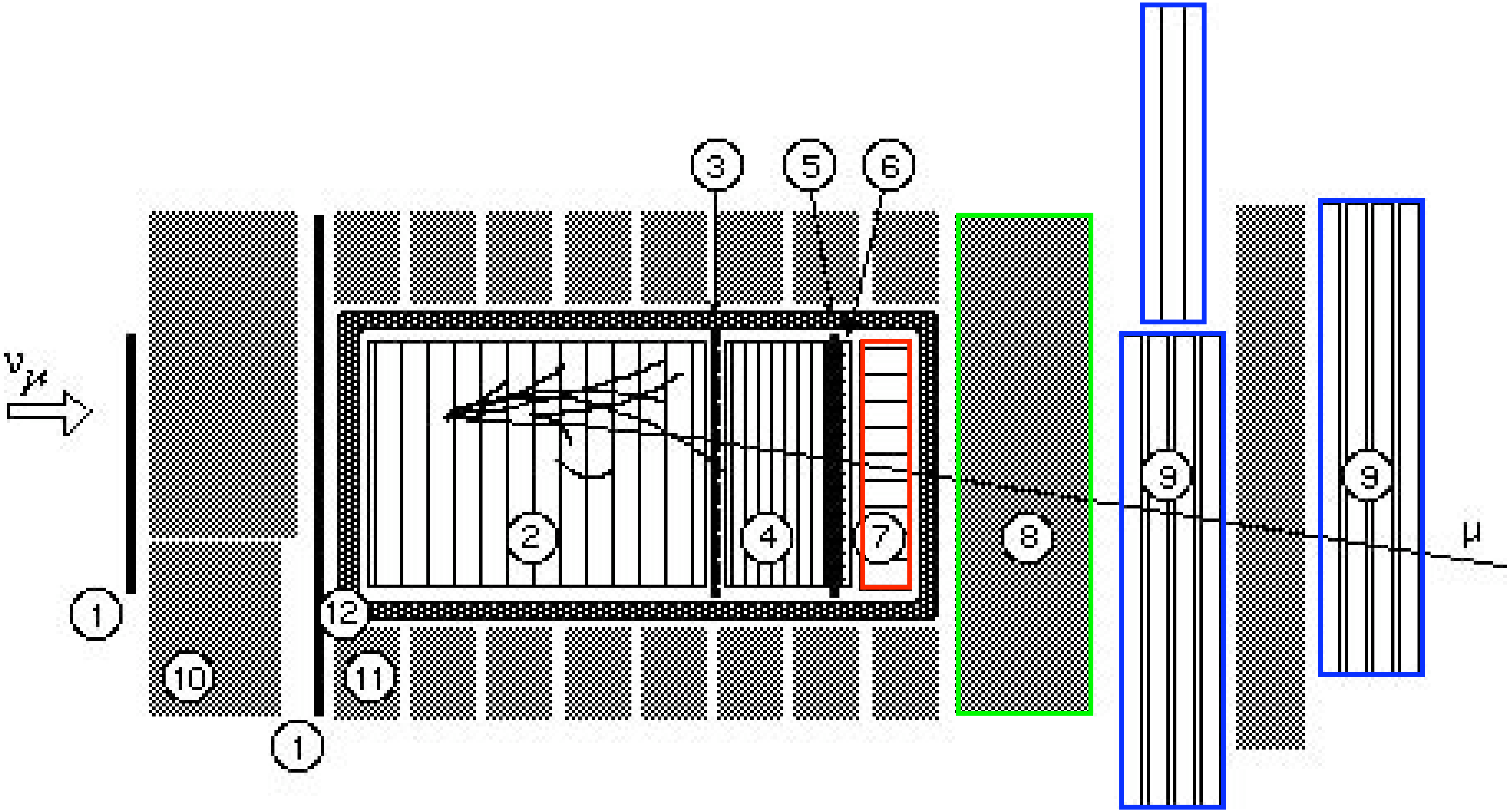


Fig. 13. Pattern of tube hits for two typical events: (a) electron-induced, (b) pion-induced.

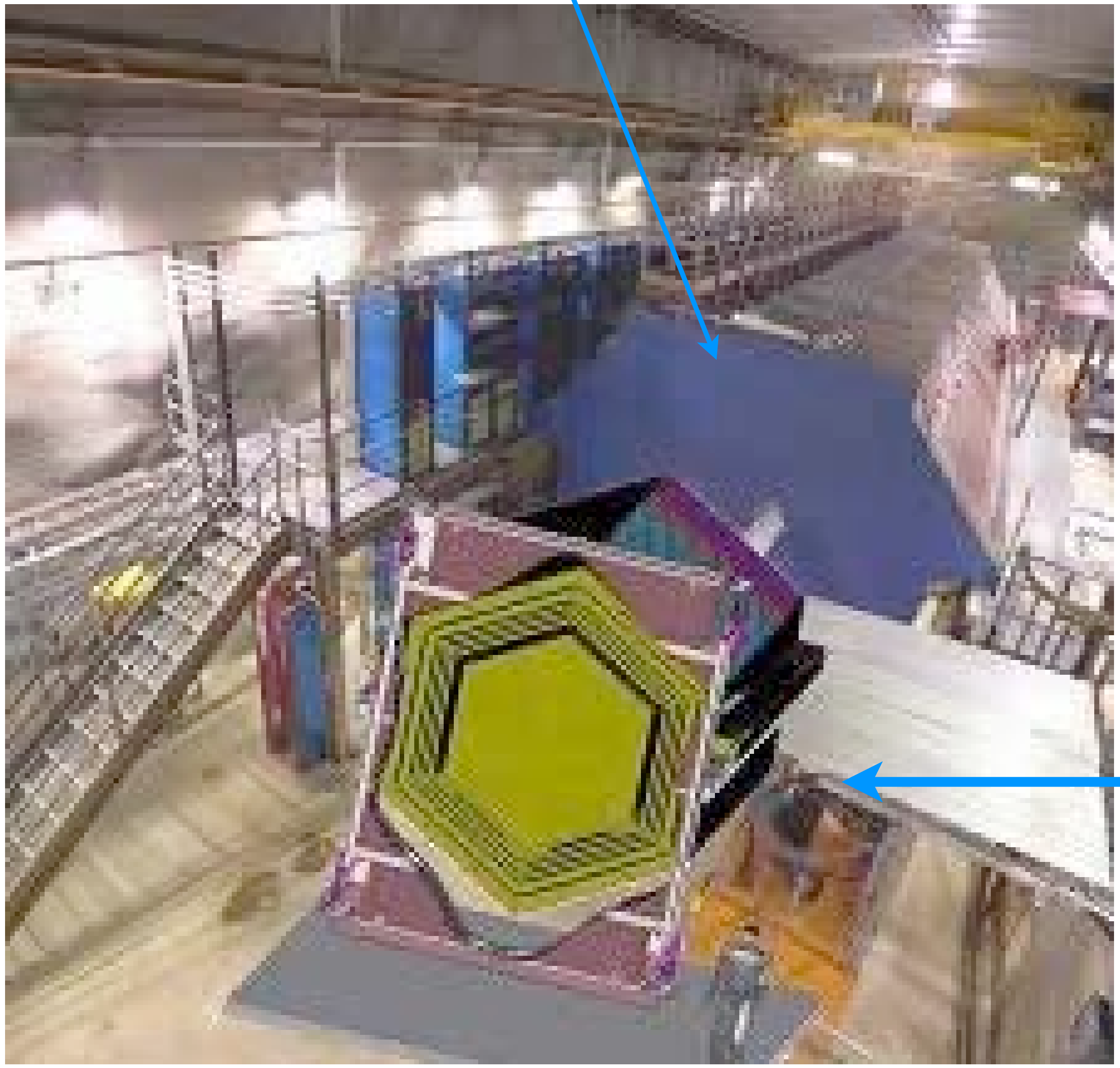
ν_μ CC event in the NOMAD detector

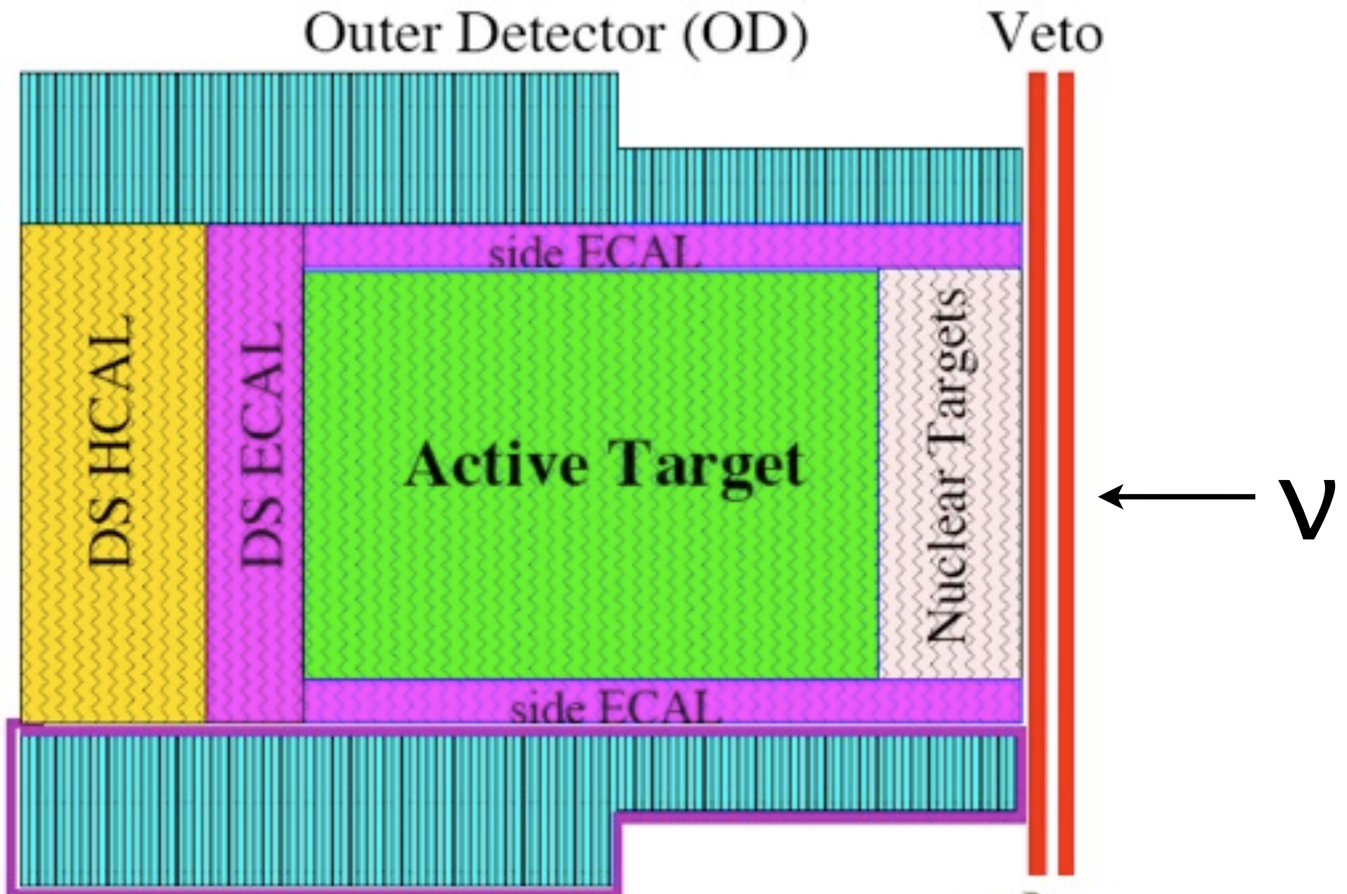


(1) Veto wall
(2) Drift chambers
(3) Trigger plane
(4) Transition radiation tracker
(5) Trigger plane
(6) Preshower region
(7) Electromagnetic calorimeter
(8) Hadron calorimeter
(9) Muon tracking
(10) Forward calorimeter
(11) Magnet return yoke
(12) Magnet

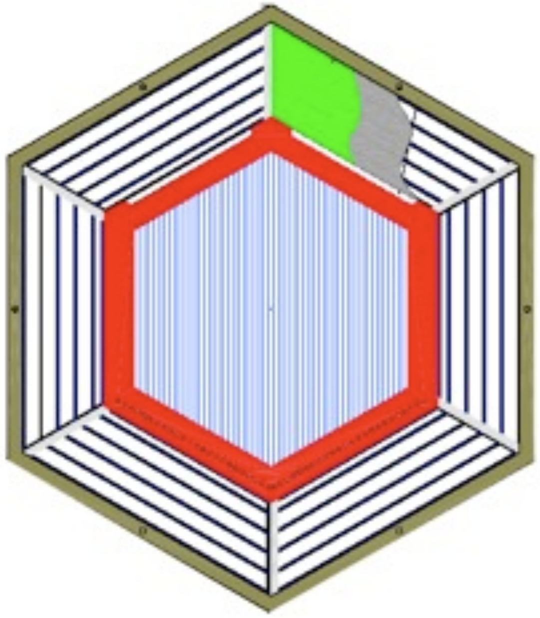
The MINERvA Detector

MINOS steel/ scintillator detector used as muon ranger



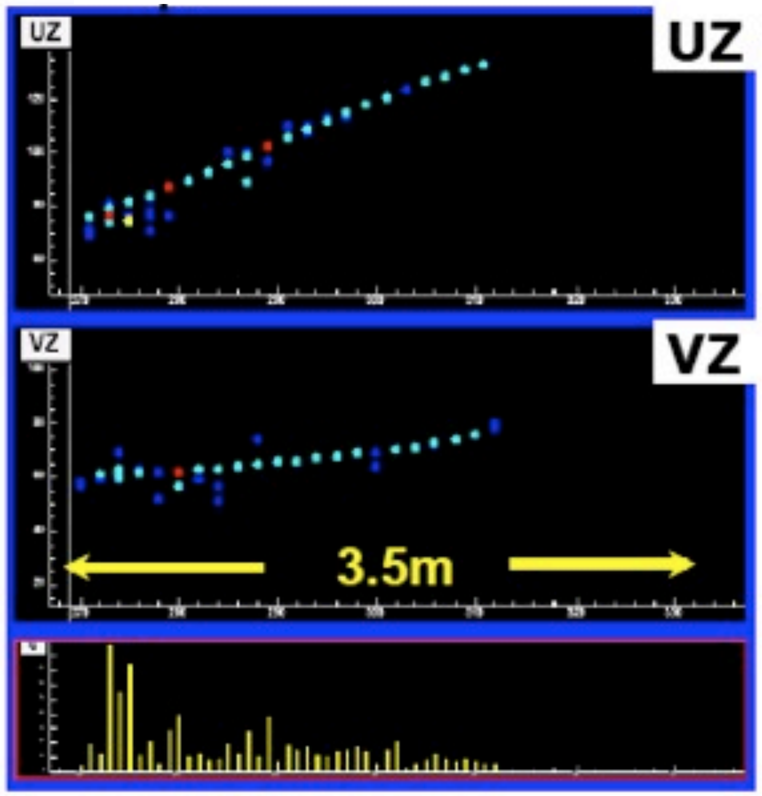


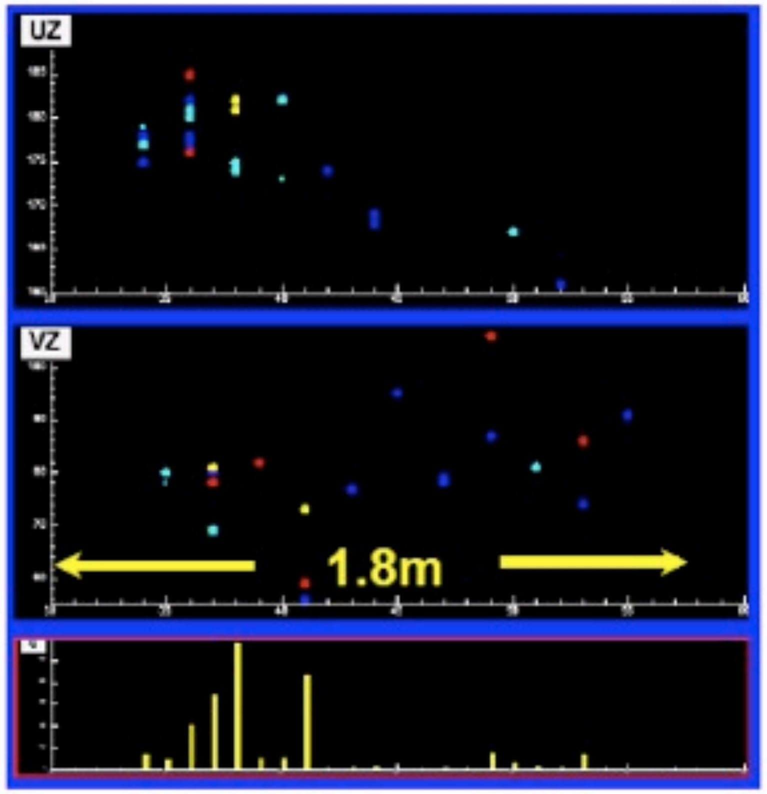
Plan view

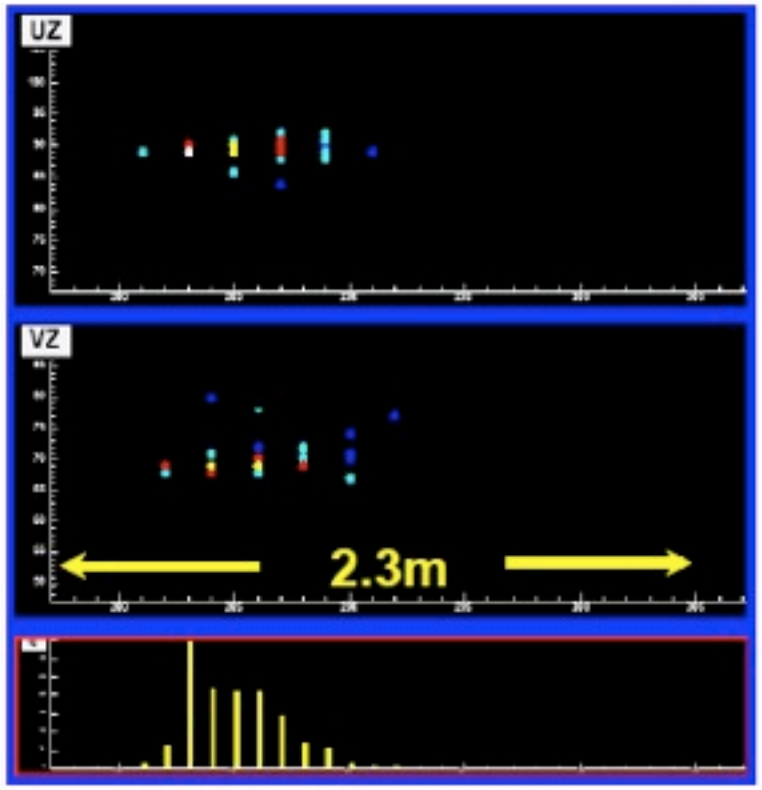


Front view

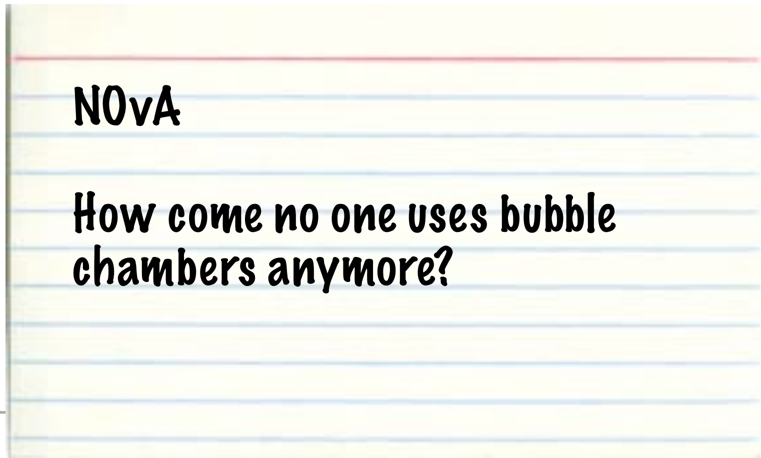
Can you classify these events from the MINOS experiment?







Tutorials



NOvA

How come no one uses bubble chambers anymore?

- On your note cards, please indicate what experiment you’re working on and one question you wanted to ask today, but didn’t get a chance

- For the tutorials, we will be working with neutrino interactions as calculated by the NEUGEN3 program. The interactions are stored as root trees, so you will need access to a computer with root installed.

- Instructions for tutorial posted at: http://enrico1.physics.indiana.edu/messier/nss09