Neutrino Detectors for future facilities

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What do neutrinos look like?

- Neutrino detectors are built to detect the particles produced when neutrinos interact with nuclei
- As such we will need to understand:
    - Some basics of neutrino interactions and event topologies
    - Some basics of the topologies of the particle produced by neutrino interactions

Neutrino facts of life...

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

N_{obs} : number of neutrino events recorded

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

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

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

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

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

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

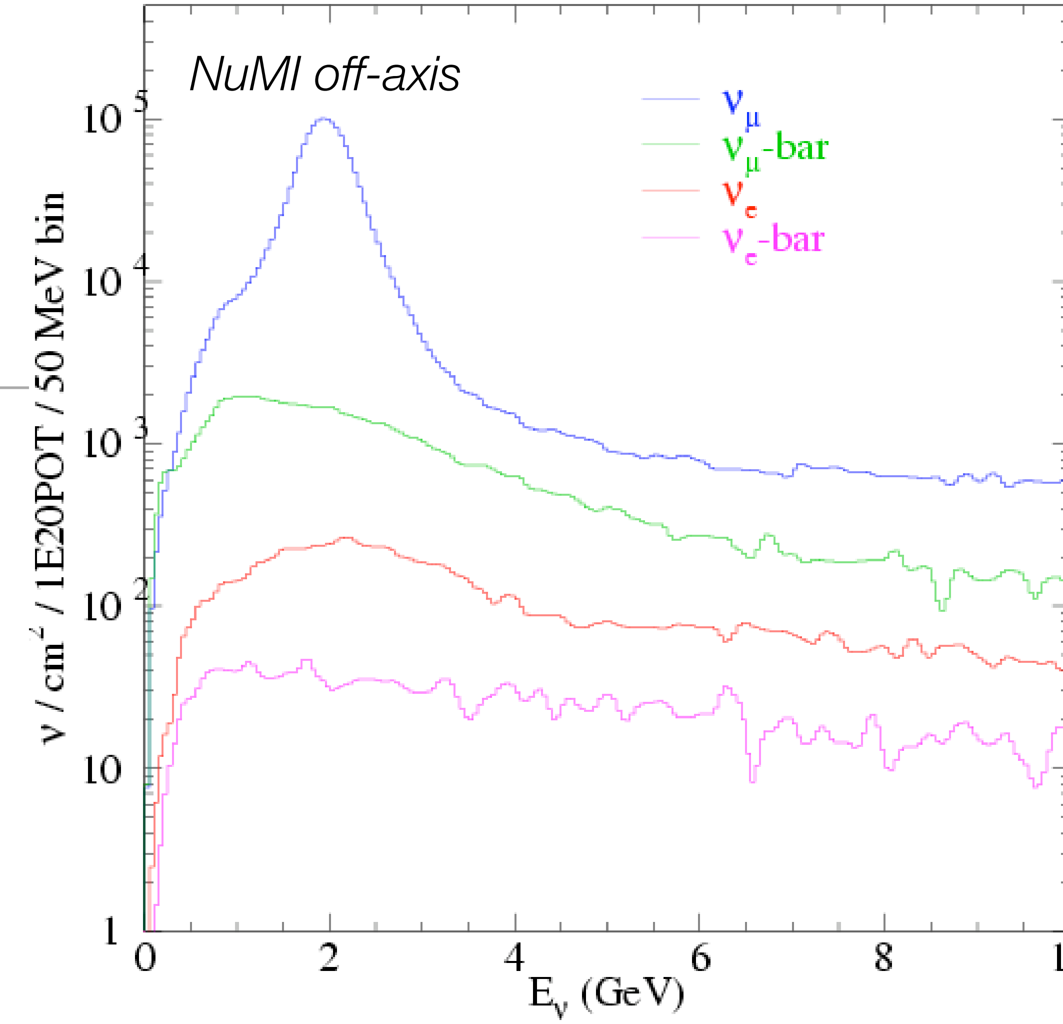
Current and future facilities
"Super-beams"

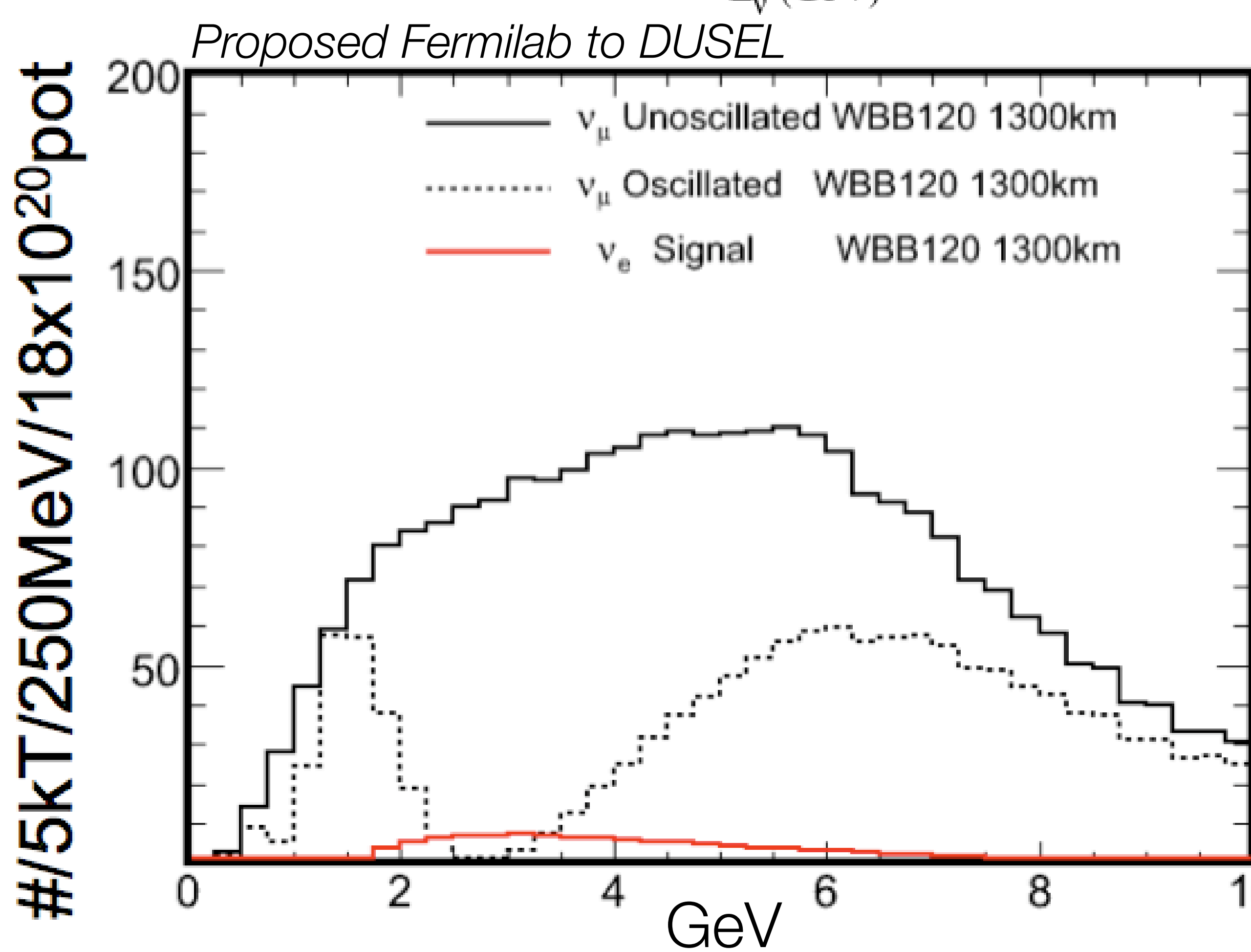
- Super-beams are produced by

$$\begin{aligned} p + A &\rightarrow \pi^{\pm} + K^{\pm}... \\ \pi &\rightarrow \mu + \nu_{\mu} \end{aligned}$$

- Typical energies: 1-10 GeV
- Typical fluxes:
  - 90% ν_μ
  - 9% anti-ν_μ
  - 1% ν_e+anti-ν_e
- In anti-neutrino focus right sign/wrong sign ration worsen due to π^+/π^- ratio and detection cross-section
- Search for: $\nu_\mu \rightarrow \nu_\mu$

$$\begin{aligned} \nu_\mu &\rightarrow \nu_e \\ \nu_\mu &\rightarrow \nu_\tau \end{aligned}$$





Current and future facilities
Beta-beams

- Beta-beams are produced by beta decay of relativistic ions in a storage ring. For example:

$$ {}^{6}_{2}\mathrm{He}^{++} \rightarrow {}^{6}_{3}\mathrm{Li}^{+++}\mathrm{e}^{-}\bar{\nu}_{\mathrm{e}}. $$

$$ {}^{18}_{10}\mathrm{Ne} \rightarrow {}^{18}_{9}\mathrm{F}e^{+}\nu_{\mathrm{e}} $$

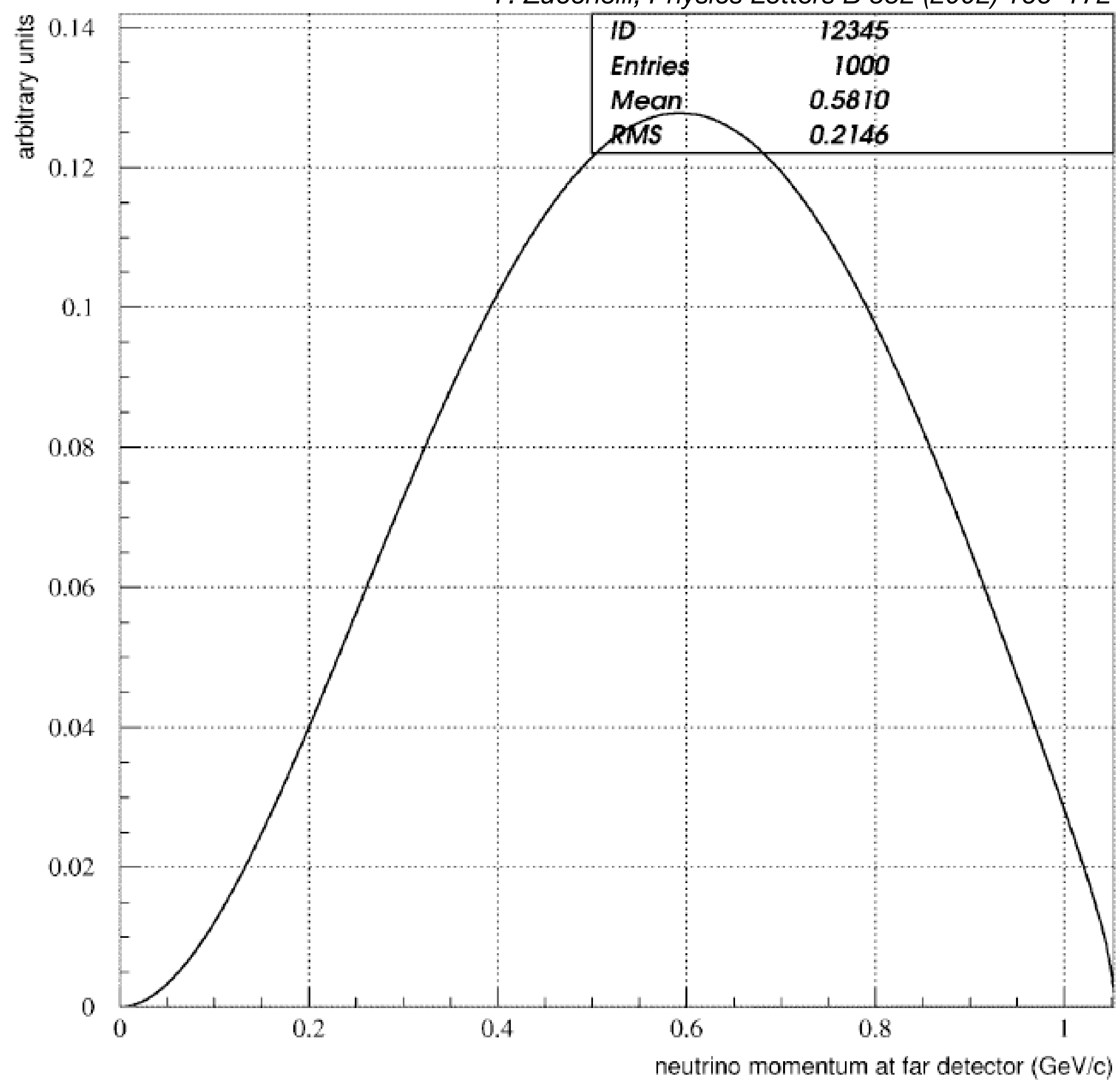
- Typical energies are lower than super-beams (<1 GeV) but higher energies are thought possible (1-5 GeV)

- Pure beam of ν_e or anti-ν_e

- Search for $\nu_e \rightarrow \nu_e$

$$ \nu_e \rightarrow \nu_\mu $$

P. Zucchelli, Physics Letters B 532 (2002) 166–172

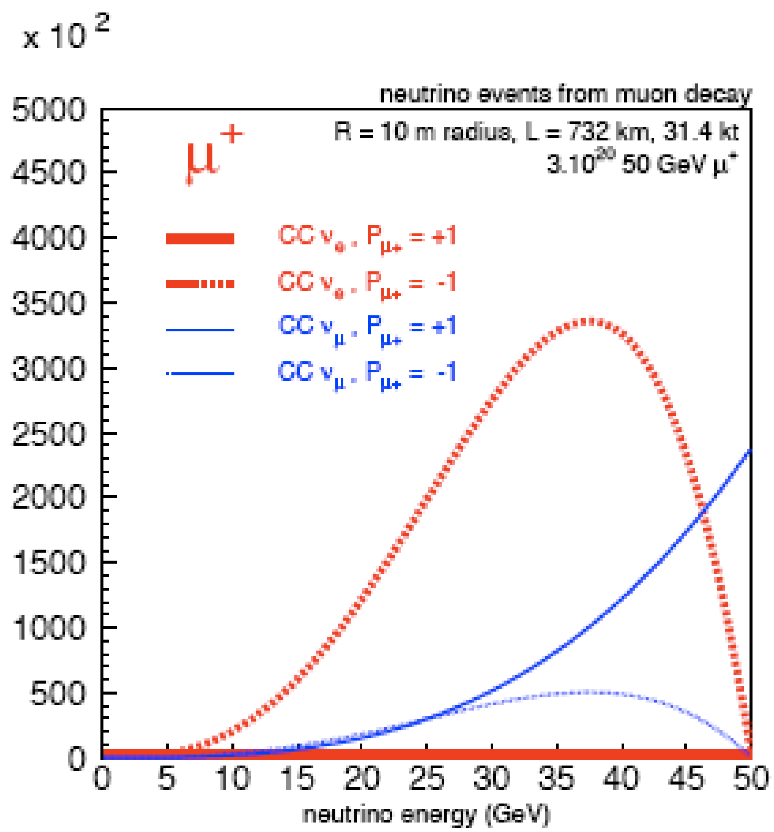


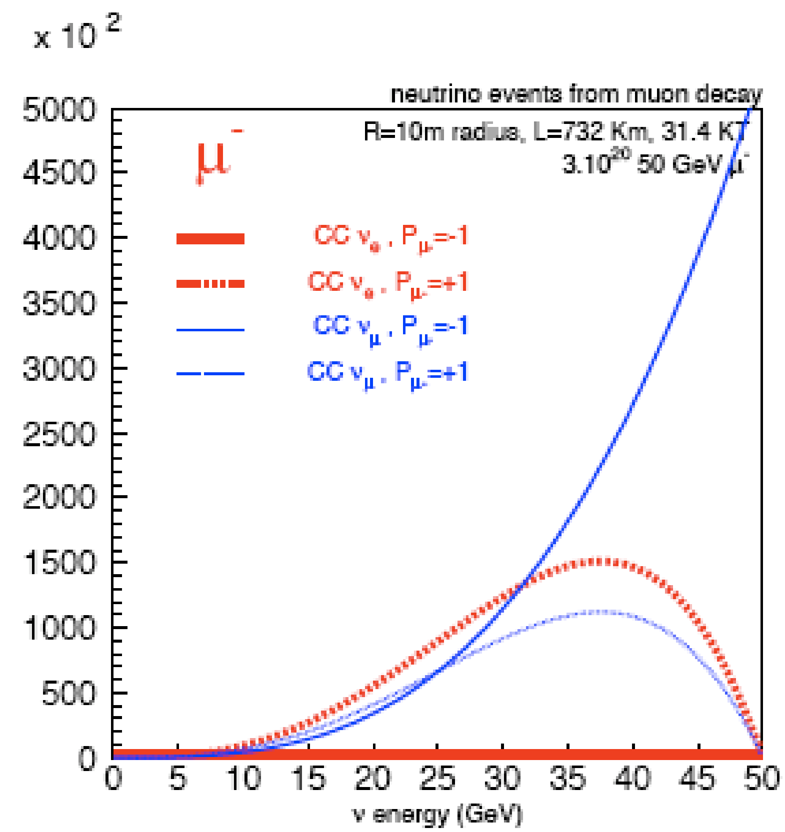
Current and future facilities
Neutrino factories

- Fluxes from neutrino factory are produced by decay of relativistic muons in a storage ring:

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

- Typical energies 10-50 GeV. Low energy (~4 GeV) options also thought possible





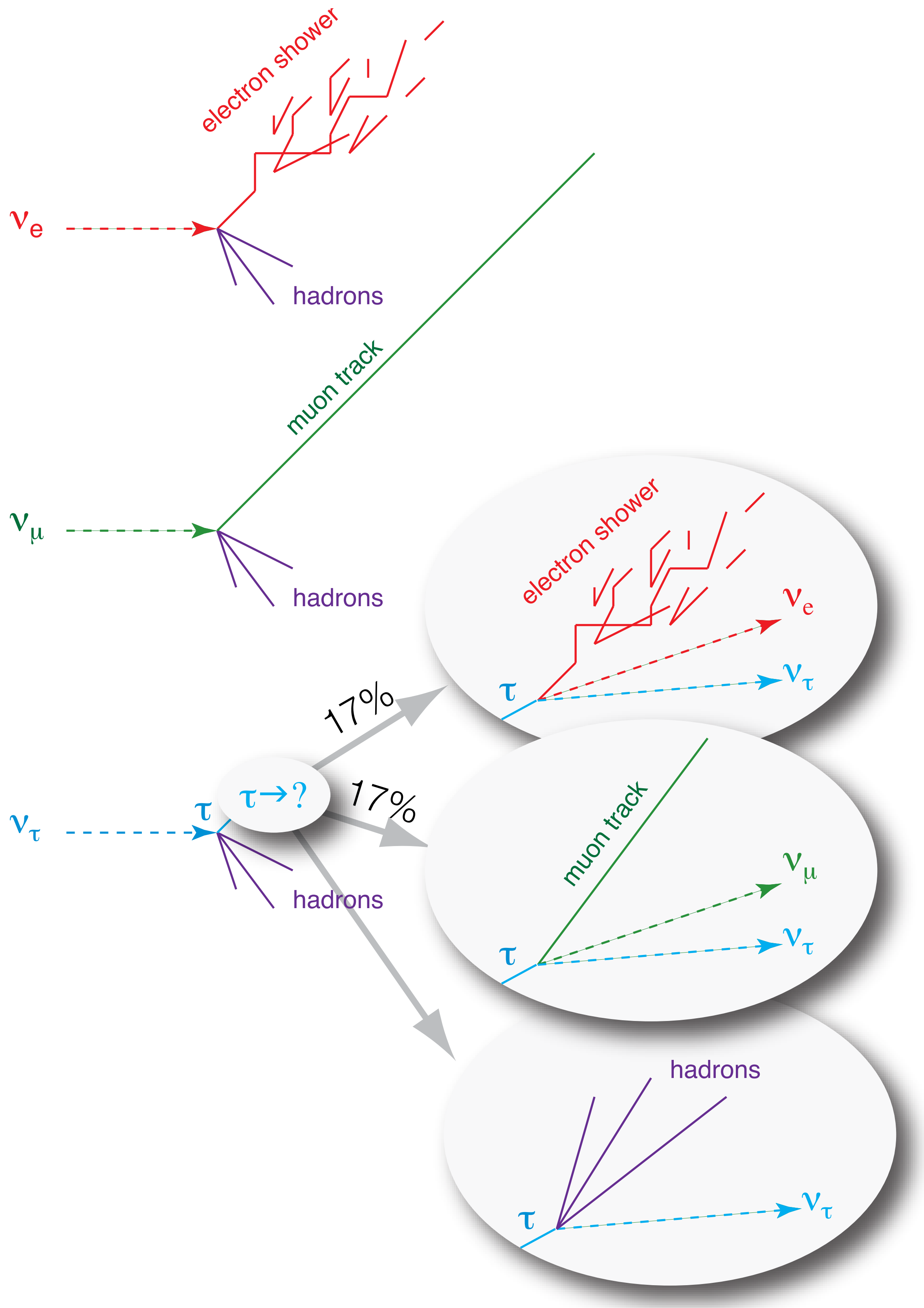
- Mixed beam of ν_e and anti-ν_μ (or anti-ν_e and ν_μ)

- Search for:

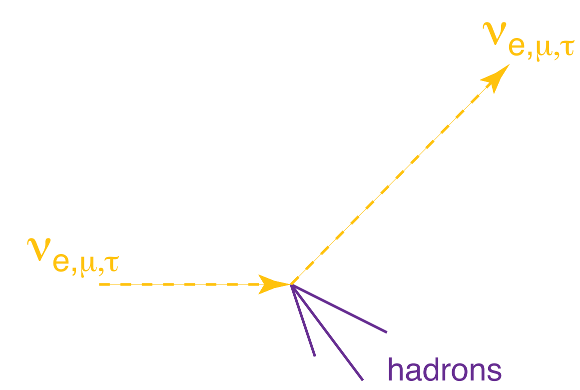
$$\begin{array}{llllll} \nu_e & \rightarrow & \nu_e & \nu_\mu & \rightarrow & \nu_\mu \\ \nu_e & \rightarrow & \nu_\mu & \nu_\mu & \rightarrow & \nu_e \\ \nu_e & \rightarrow & \nu_\tau & \nu_\mu & \rightarrow & \nu_\tau \end{array}$$

Neutrino detection channels

Charged-current

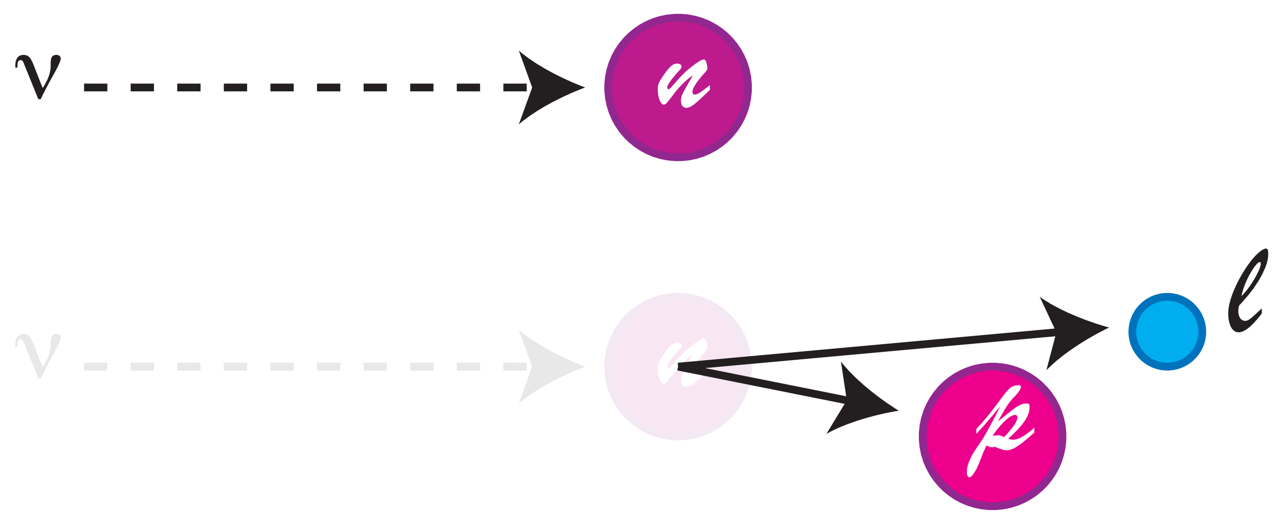


Neutral-current

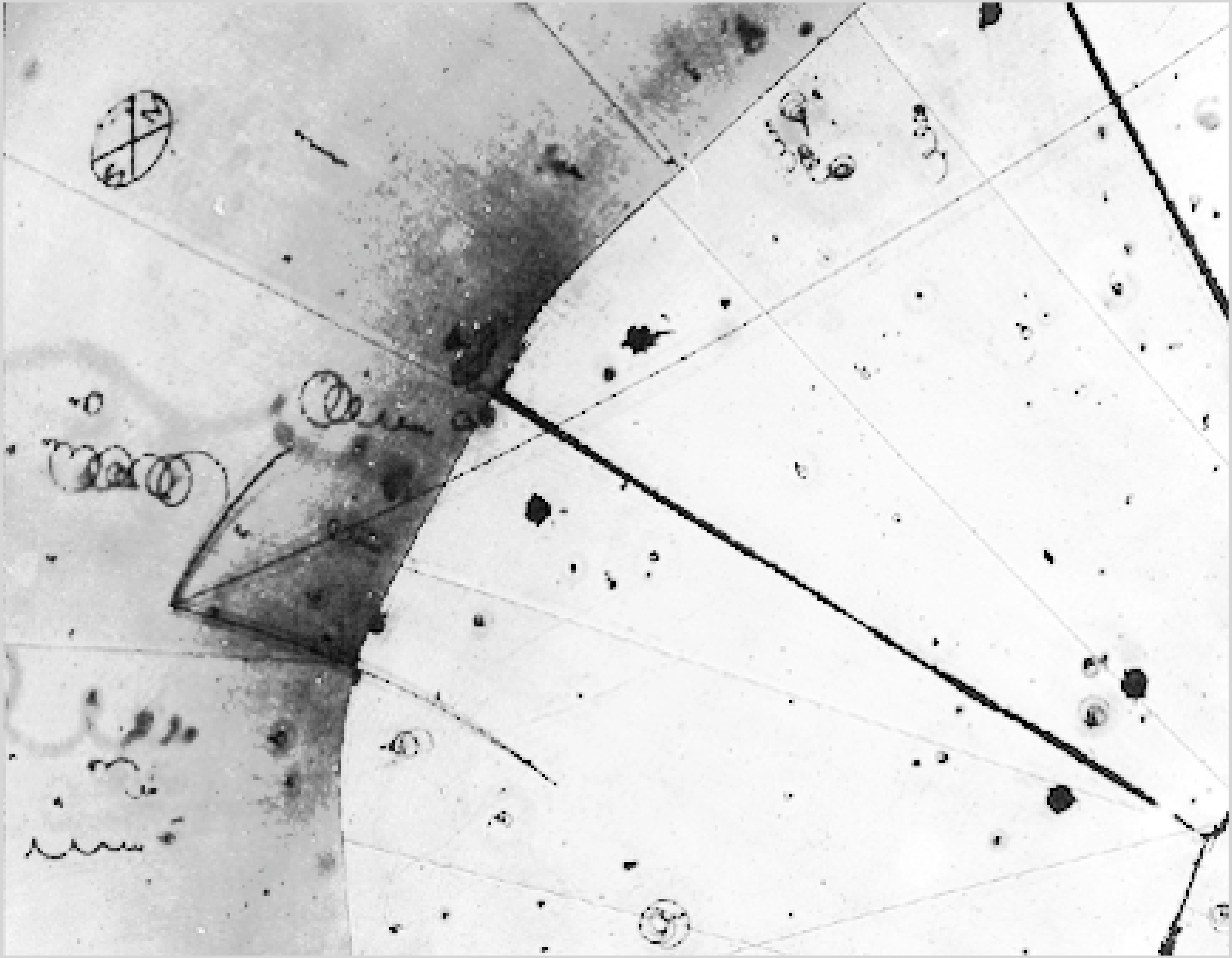


- In charged-current (CC) events outgoing lepton tags incoming neutrino flavor.
  - *In the case of ν_τ, the presence of a τ must be deduced from the τ decay products*
- In CC events nearly all the neutrino energy is deposited in the detector
- In neutral-current events, only hadrons are present and 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*

Production thresholds

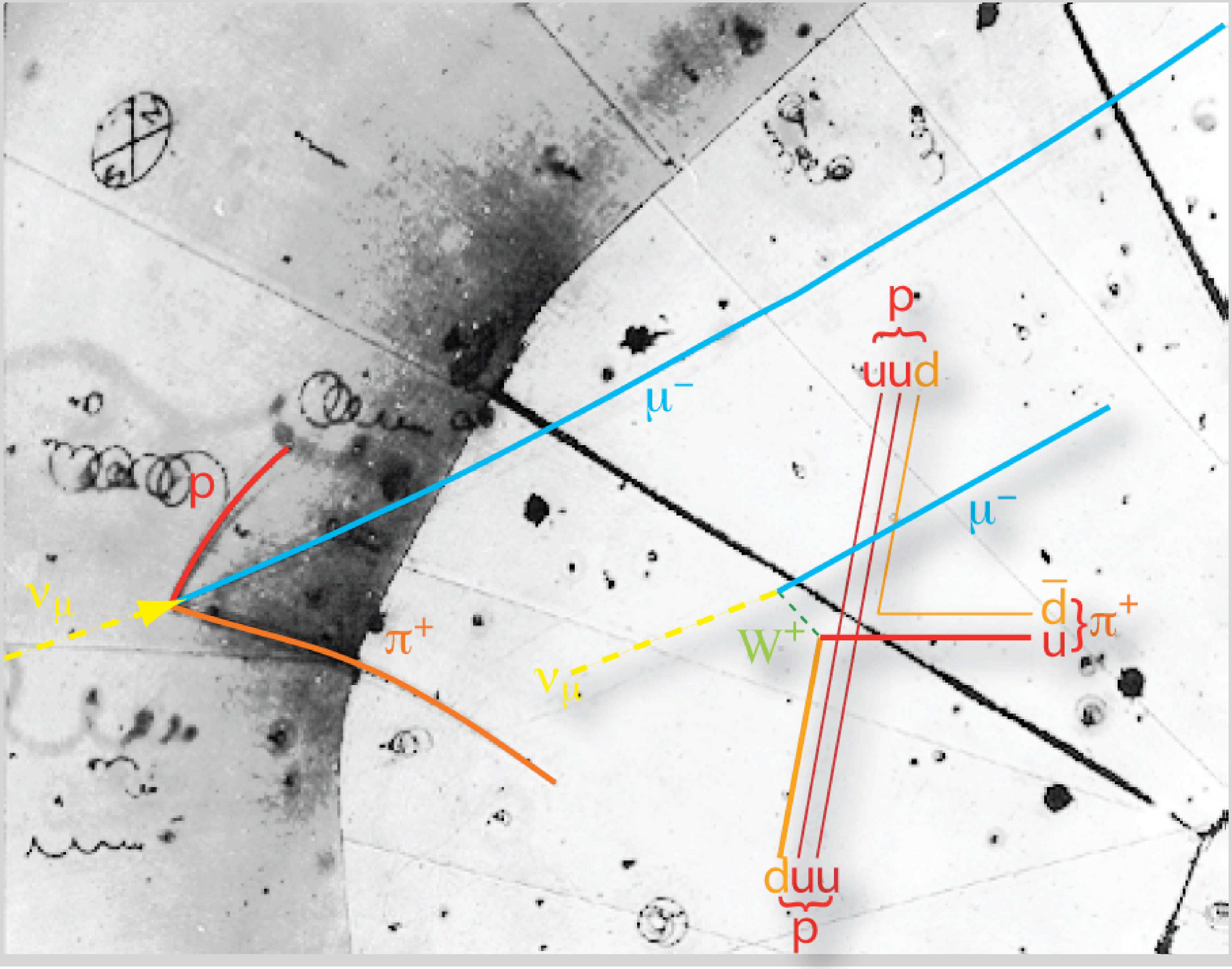


$$\begin{array}{lll} l = e & m_e = 0.511 \text{ MeV} & P_{\text{thresh}} = 0.511 \text{ MeV} \\ l = \mu & m_\mu = 106 \text{ MeV} & P_{\text{thresh}} = 112 \text{ MeV} \\ l = \tau & m_\tau = 1.78 \text{ GeV} & P_{\text{thresh}} = 3.47 \text{ GeV} \end{array}$$



What's going on in this event?

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



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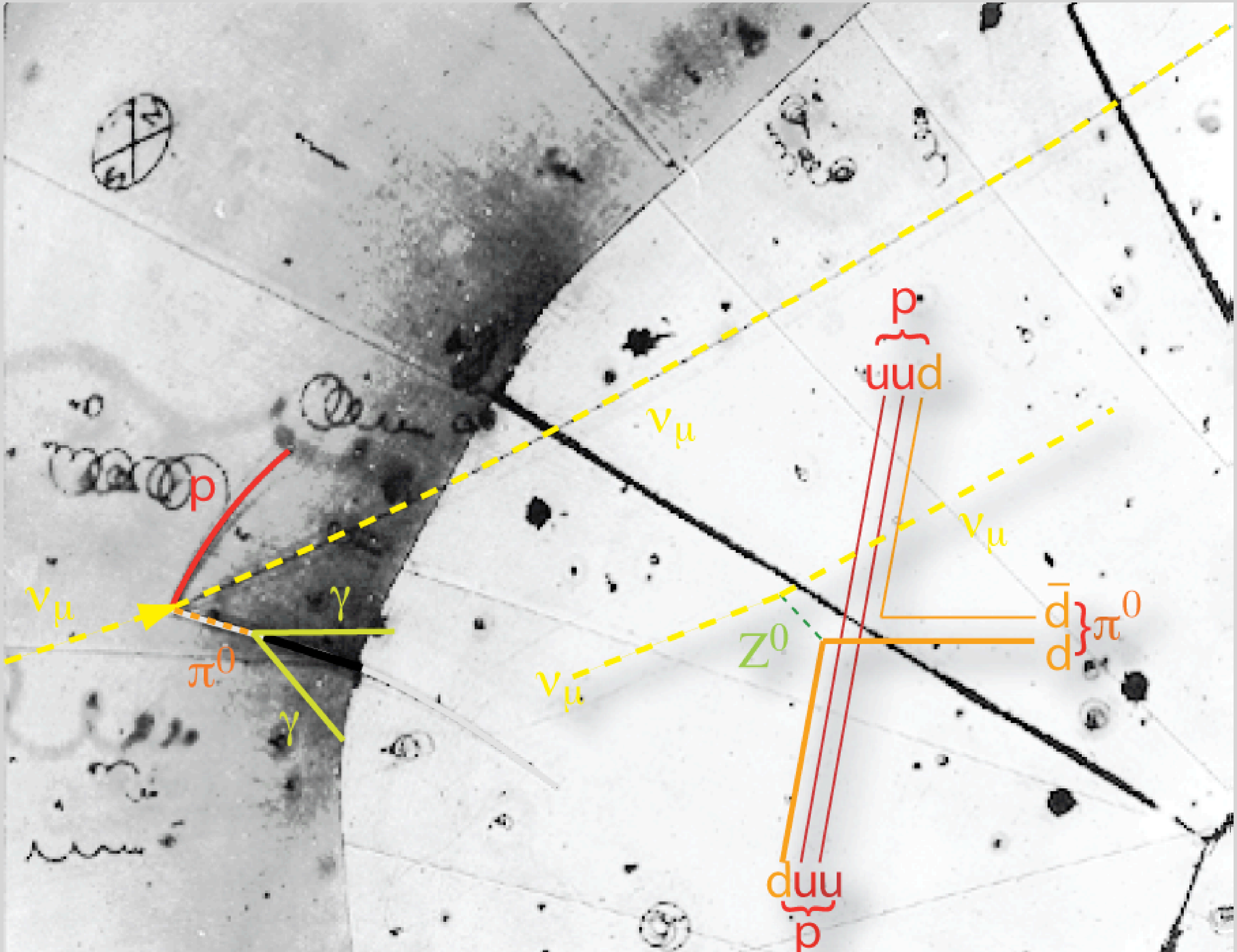

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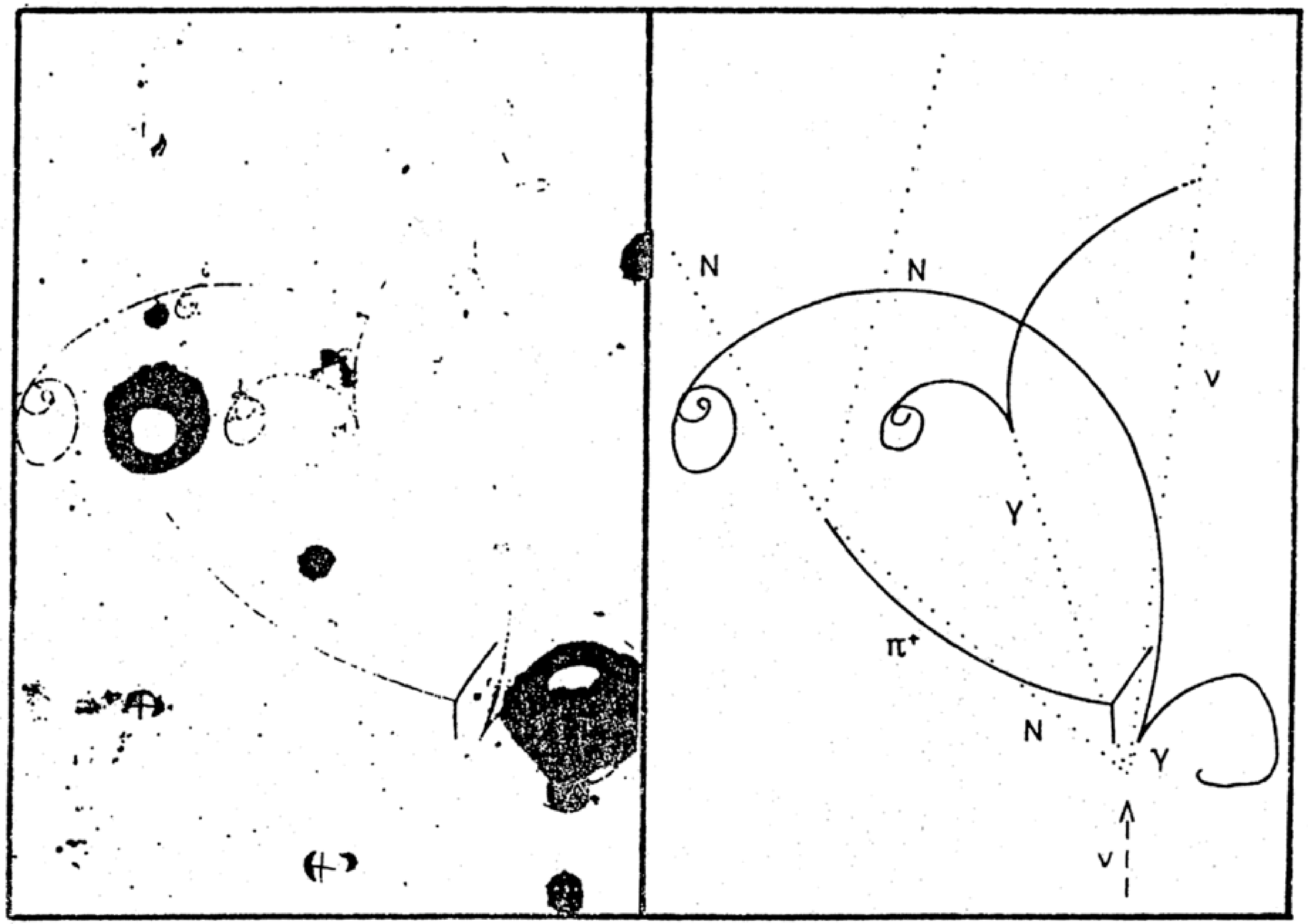


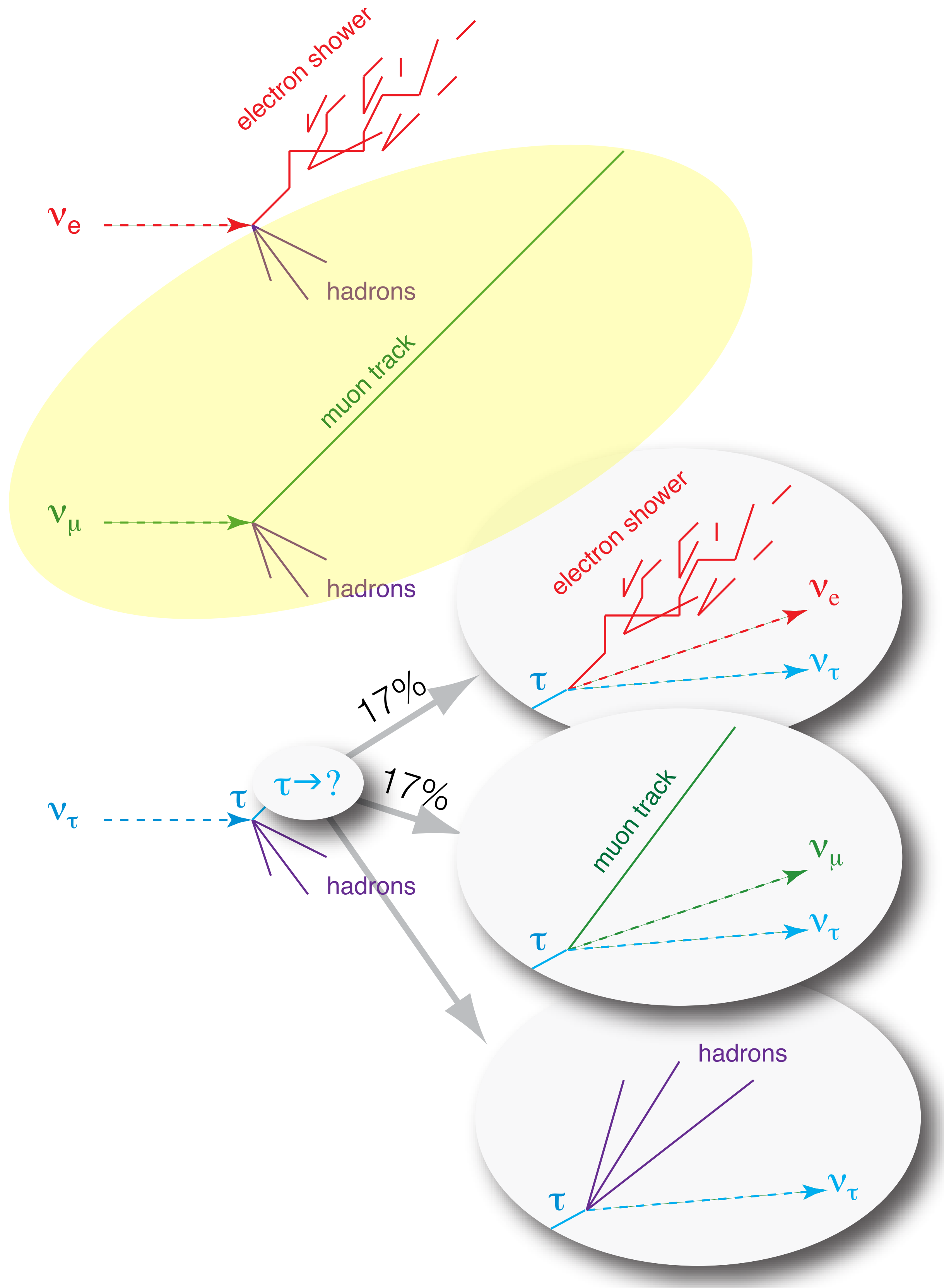
Abb. 15: Ein Kandidat für die Reaktion ($\nu n \to \nu n \pi^0$).
Im Gegensatz zum Normalfall wird das Neutron
durch inelastische Reaktion strahlabwärts

Neutral-current event

Gargamelle bubble chamber at CERN

Neutrino detection channels

Charged-current



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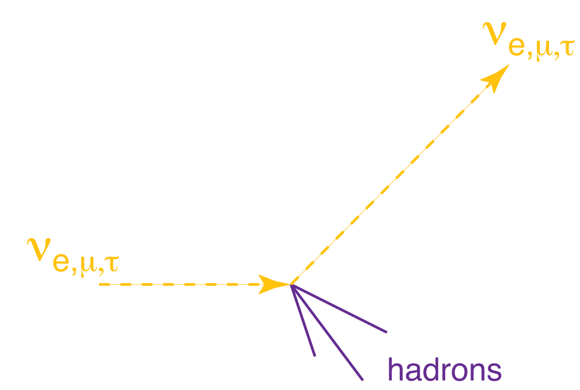

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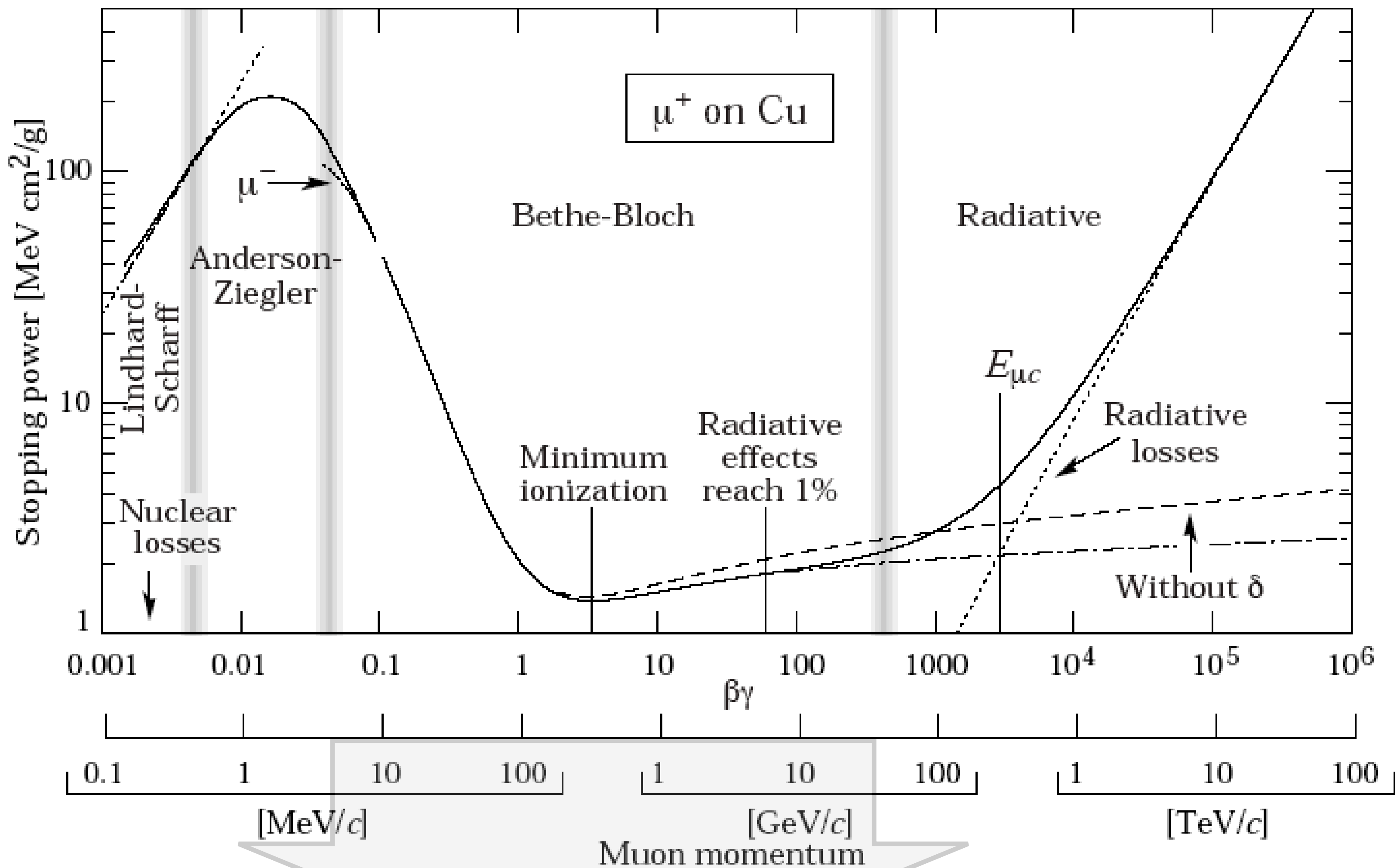
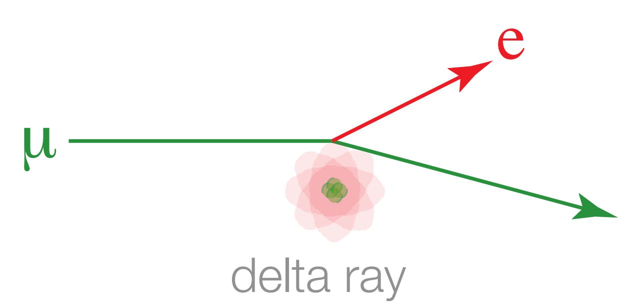
Muons

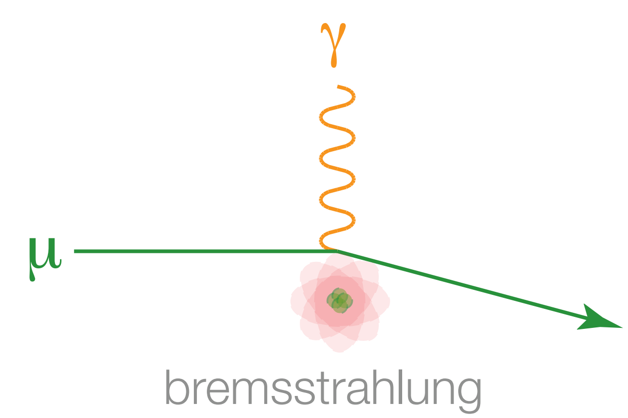
- Muons in the energy regions of interest for current and future neutrino facilities (0.1-100 GeV) lose their energy almost entirely through ionization:
    - Radiative loses (delta rays and bremsstrahlung) are important only above $E_{\mu c}$~100 GeV
    - Nuclear loses are important only below 1 MeV
- 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/)



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





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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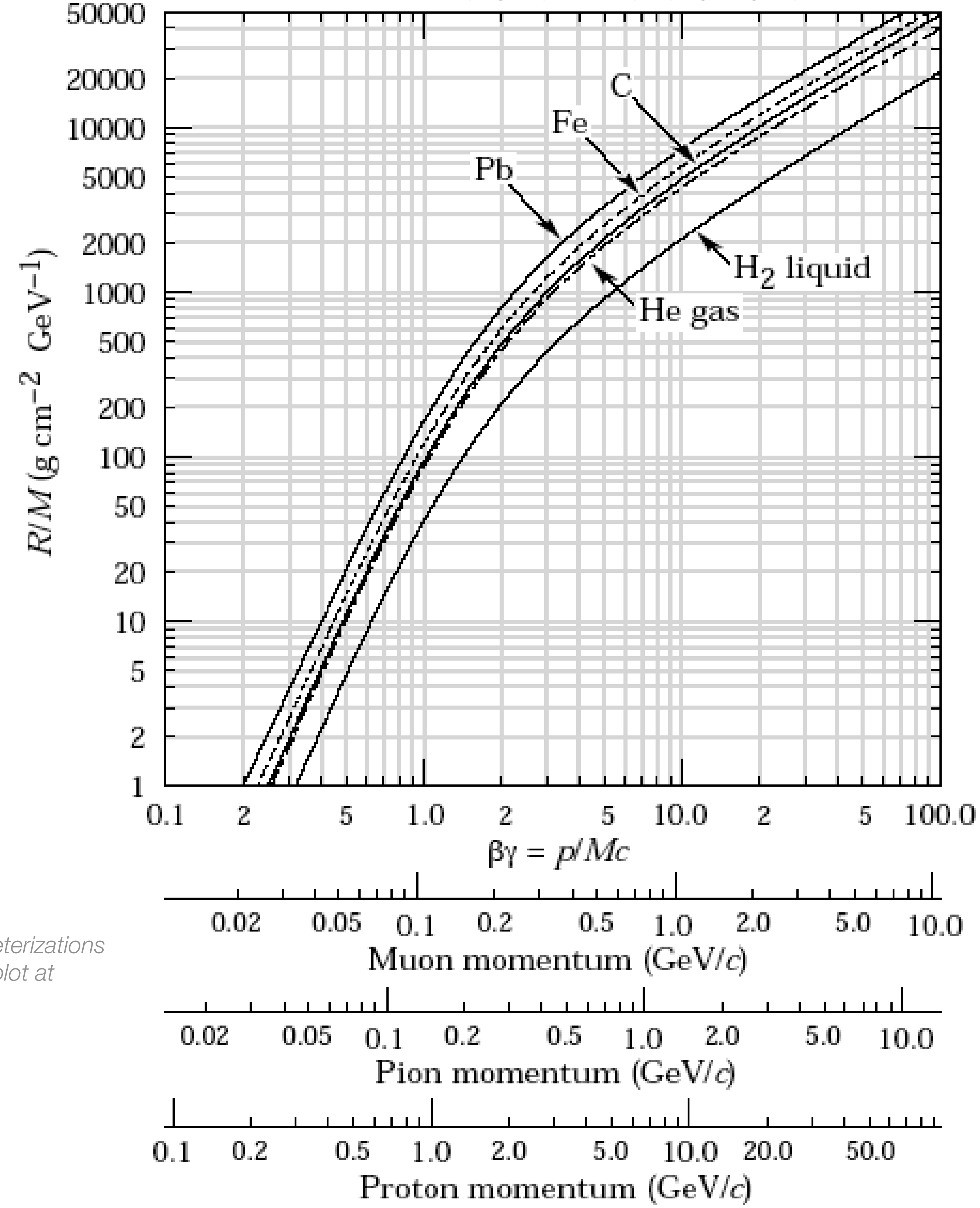

Figure 27.4: Range of heavy charged particles in liquid (bubble chamber) hydrogen, helium gas, carbon, iron, and lead. For example: For a K^+ whose momentum is 700 MeV/c, $\beta\gamma = 1.42$. For lead we read $R/M \approx 396$, and so the range is 195 g cm^{-2}.

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

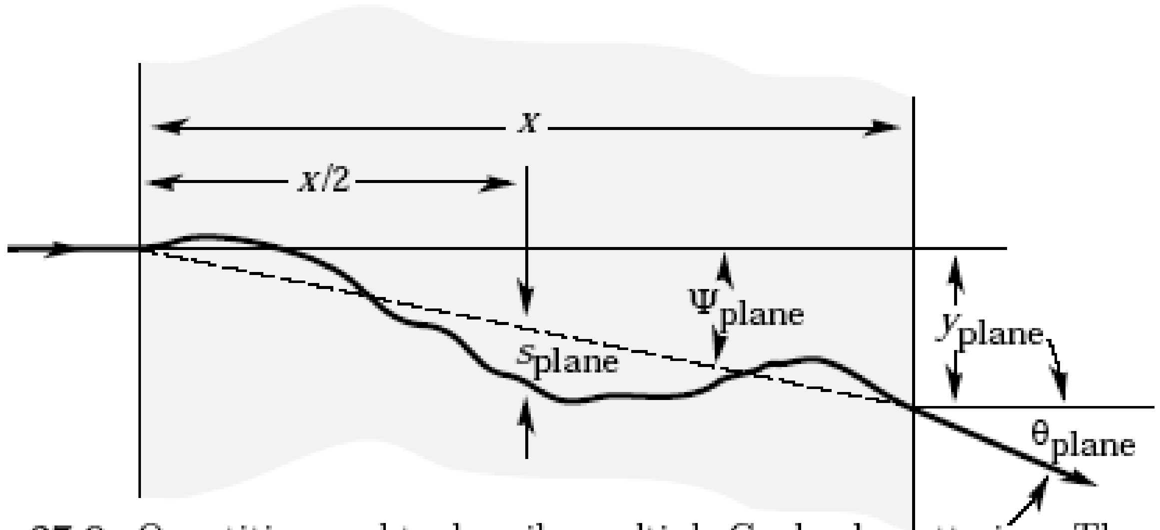

Figure 27.9: Quantities used to describe multiple Coulomb scattering. The particle is incident in the plane of the figure.

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

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

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

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

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

Multiple scattering

		$p = 1$ 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

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

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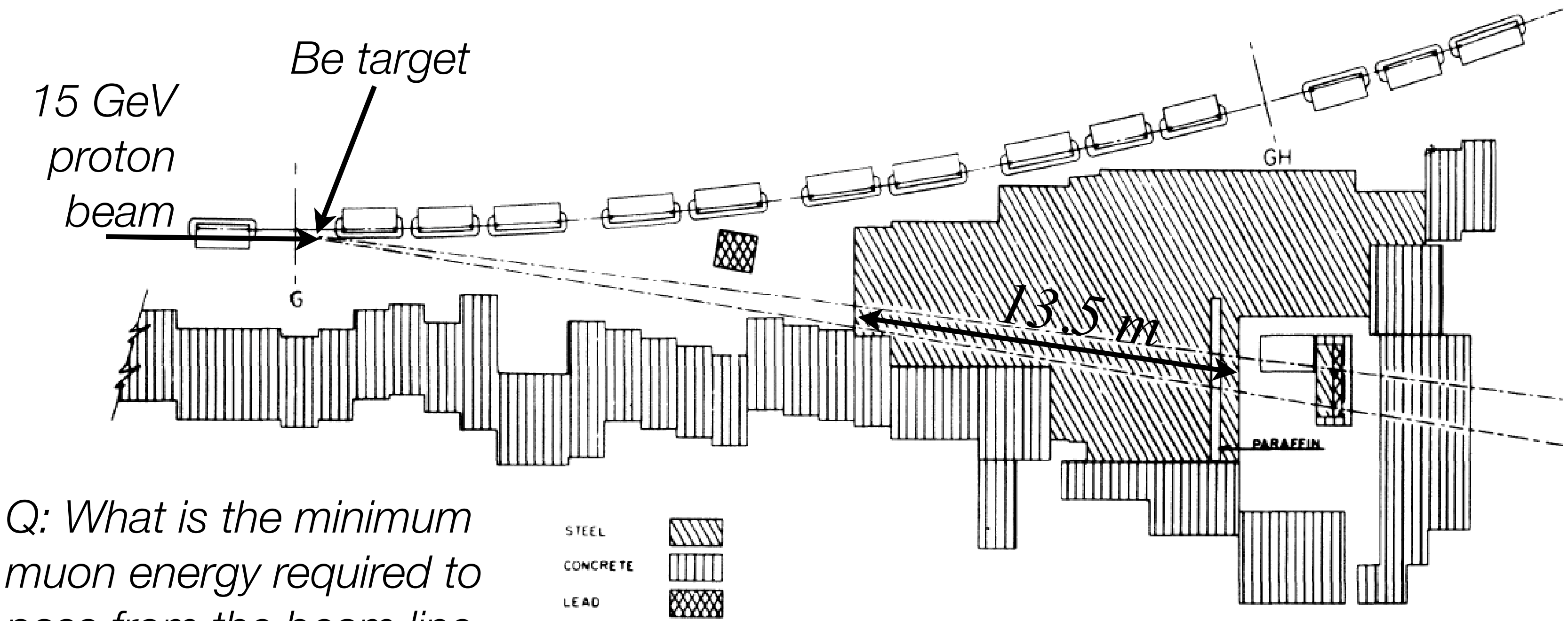
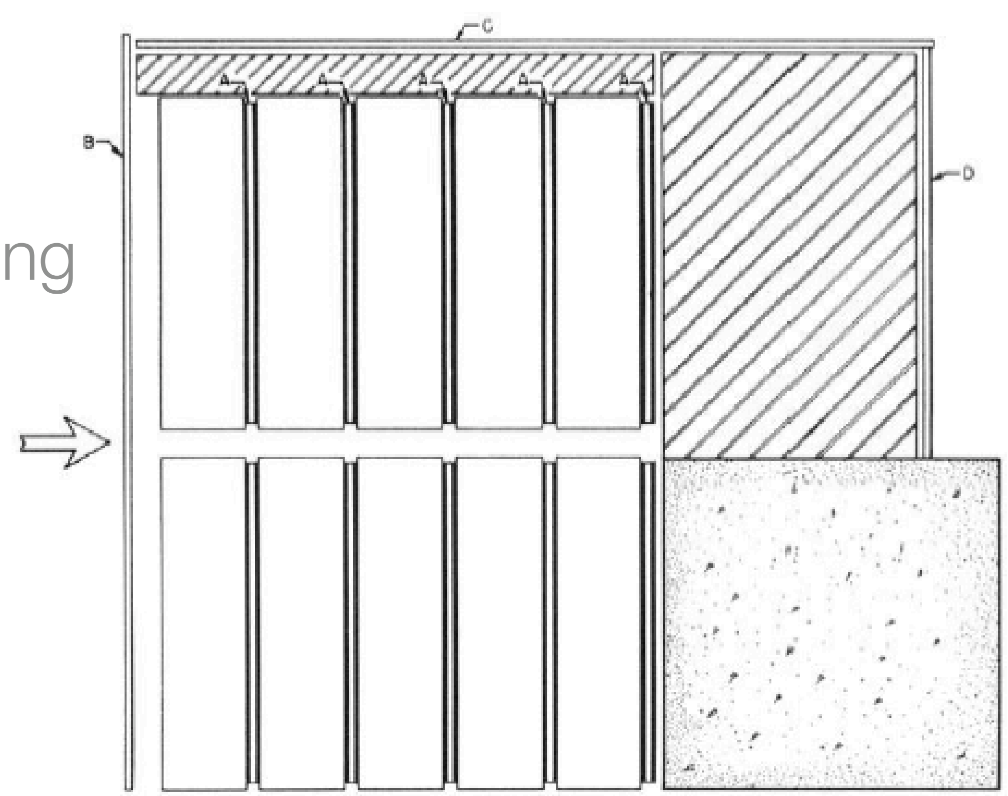


FIG. 1. Plan view of AGS neutrino experiment.

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

B,C,D vetos against entering tracks



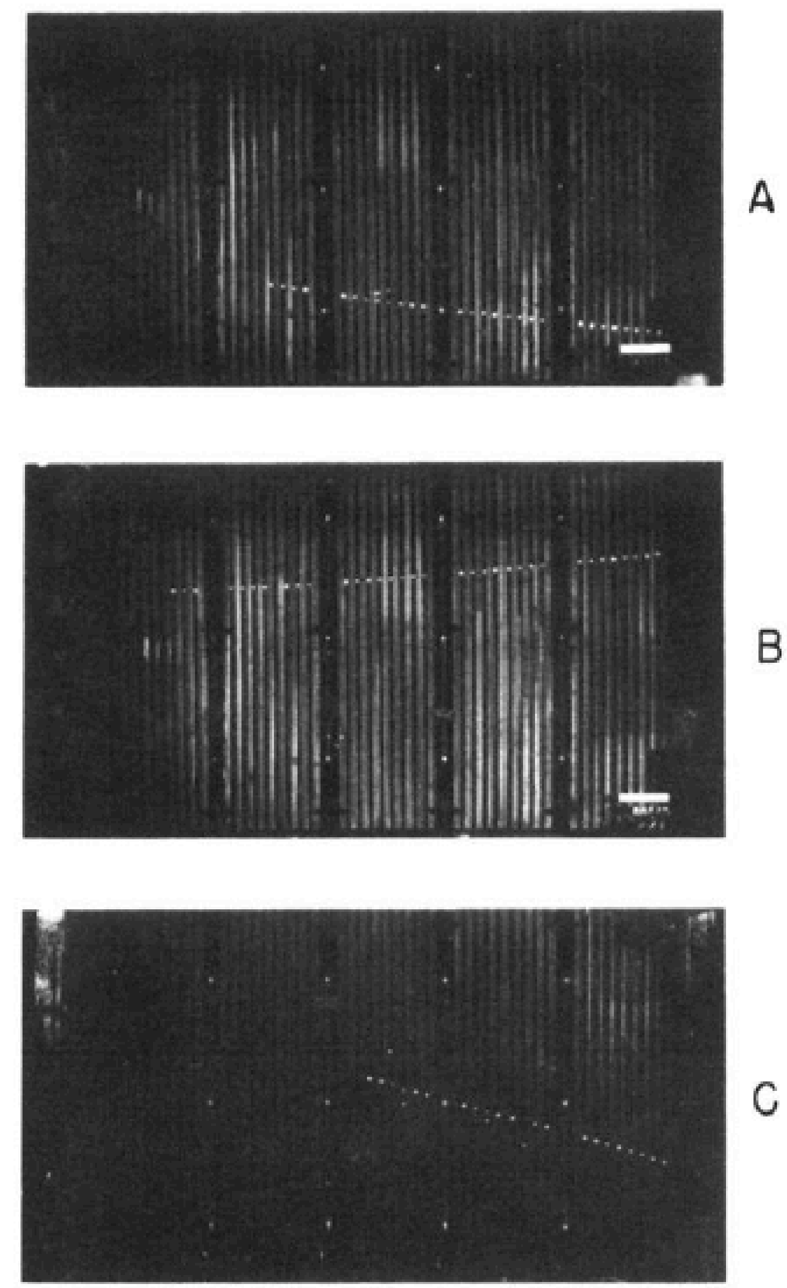


FIG. 5. Single muon events. (A) $p_\mu > 540$ MeV and δ ray indicating direction of motion (neutrino beam incident from left); (B) $p_\mu > 700$ MeV/c; (C) $p_\mu > 440$ with δ ray.

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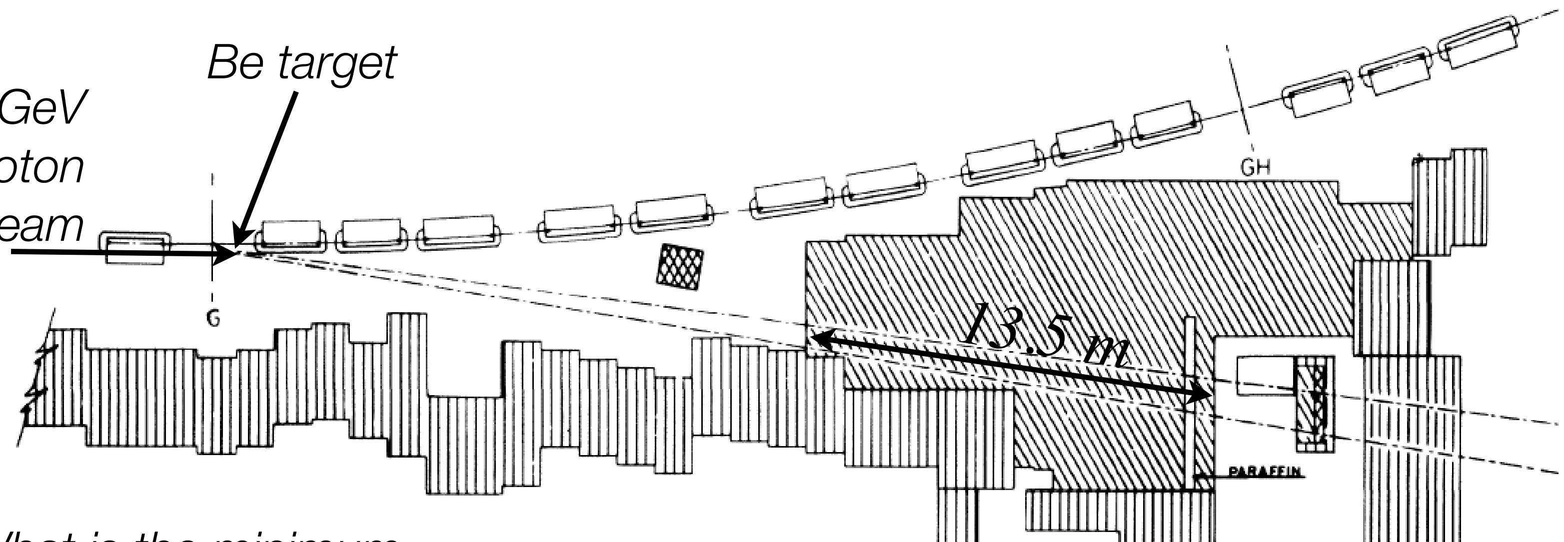

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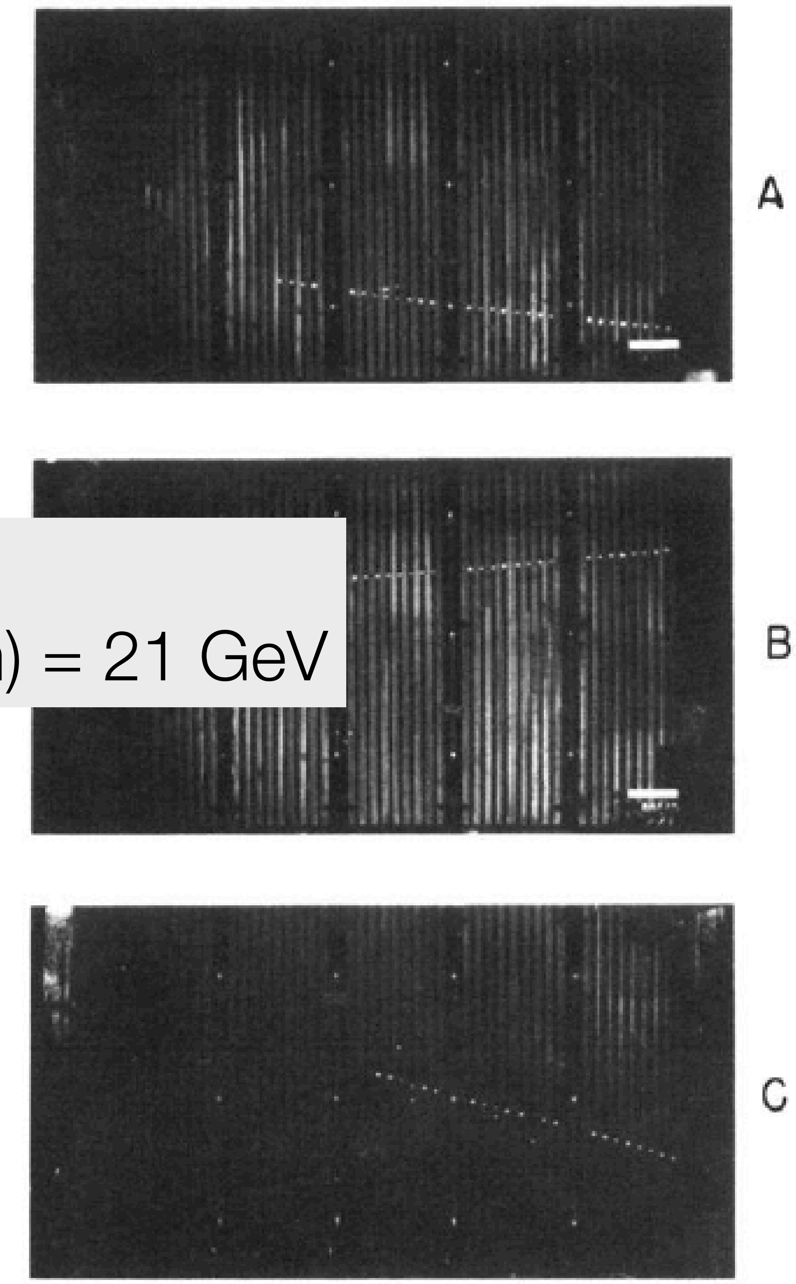

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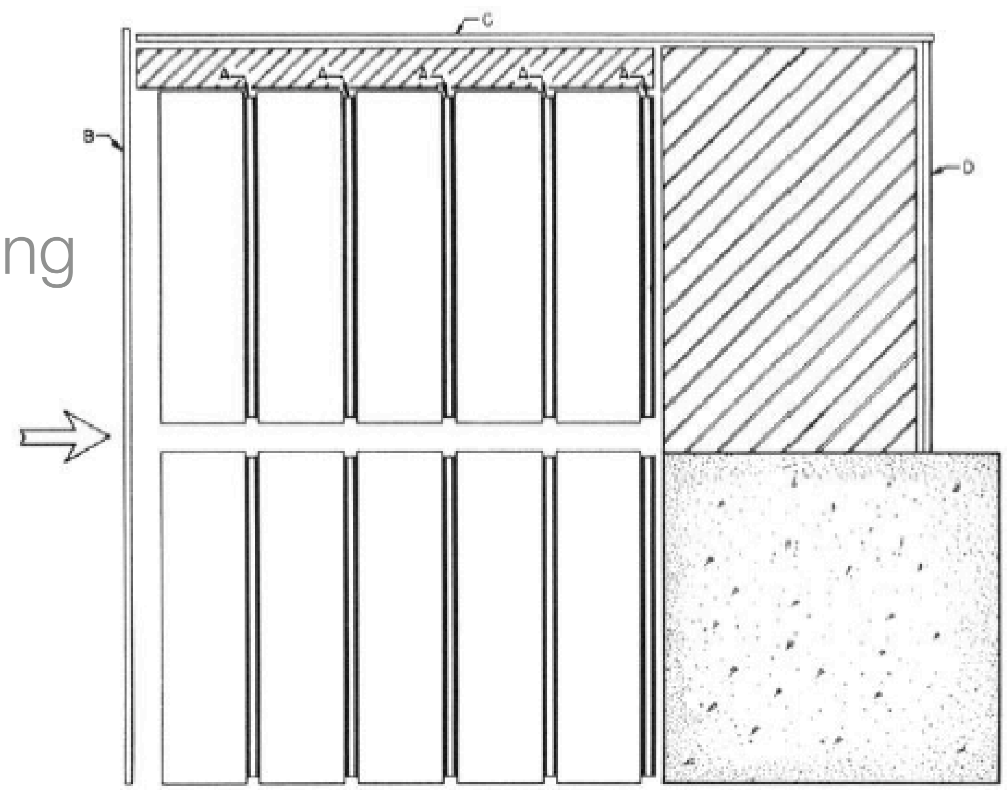

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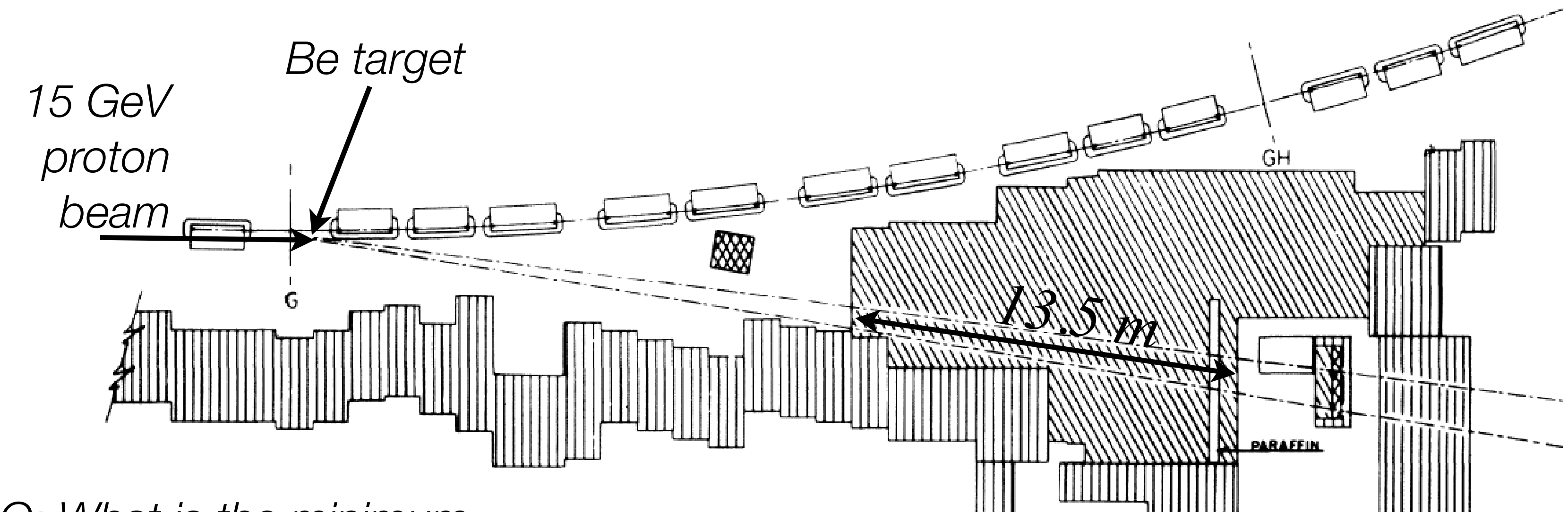

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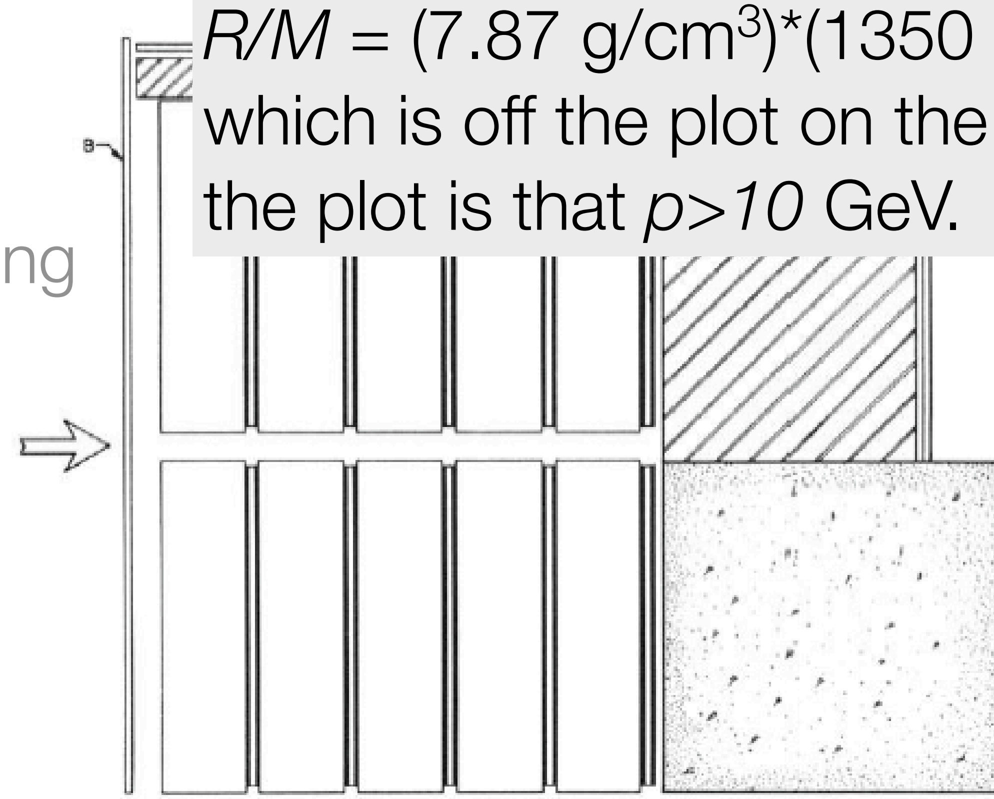

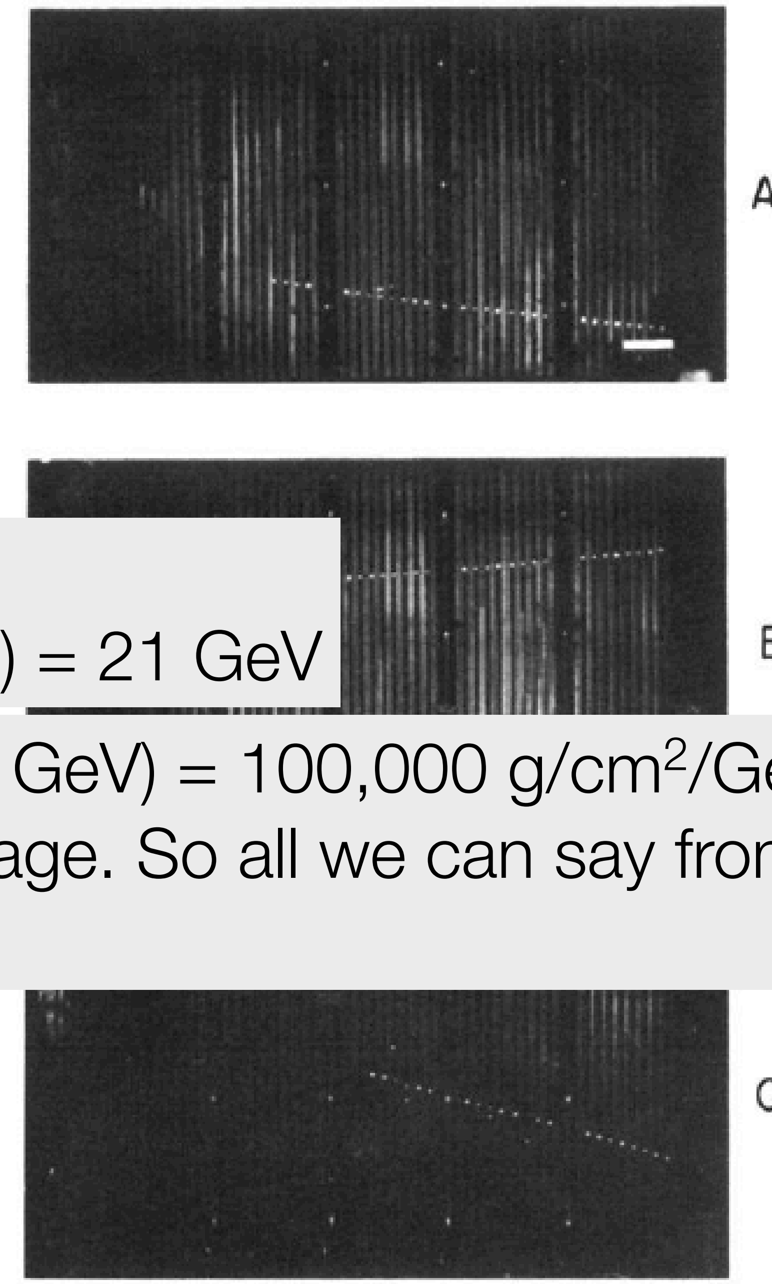

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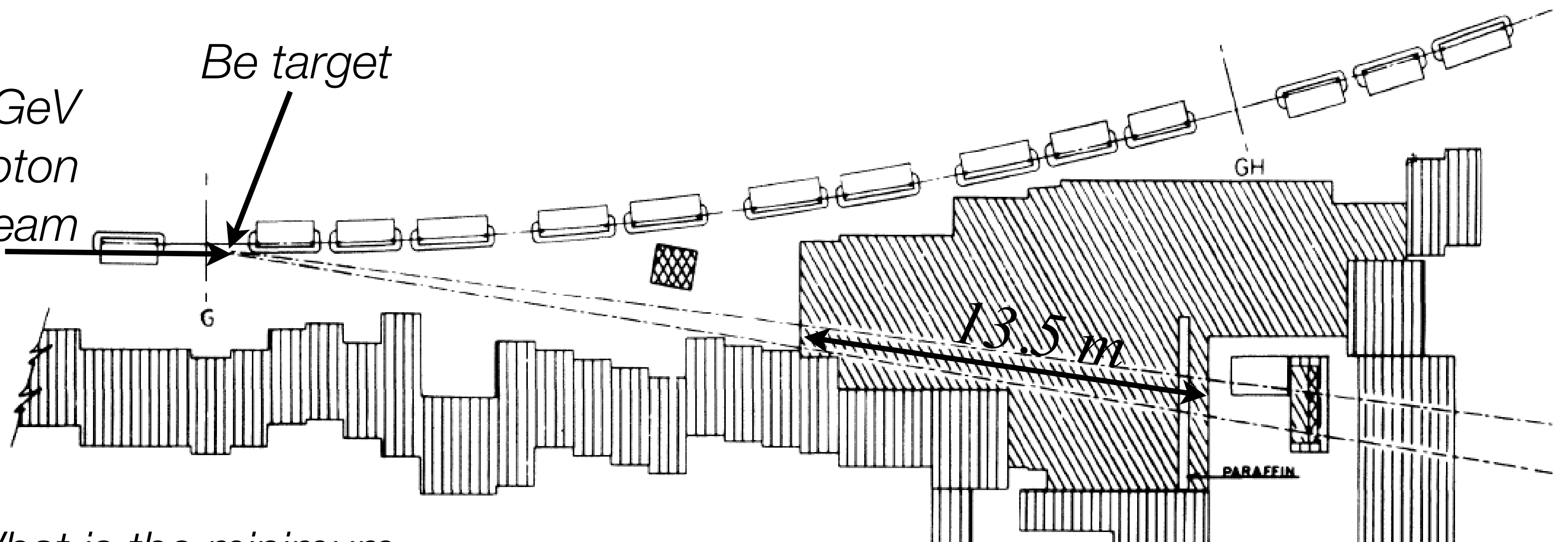

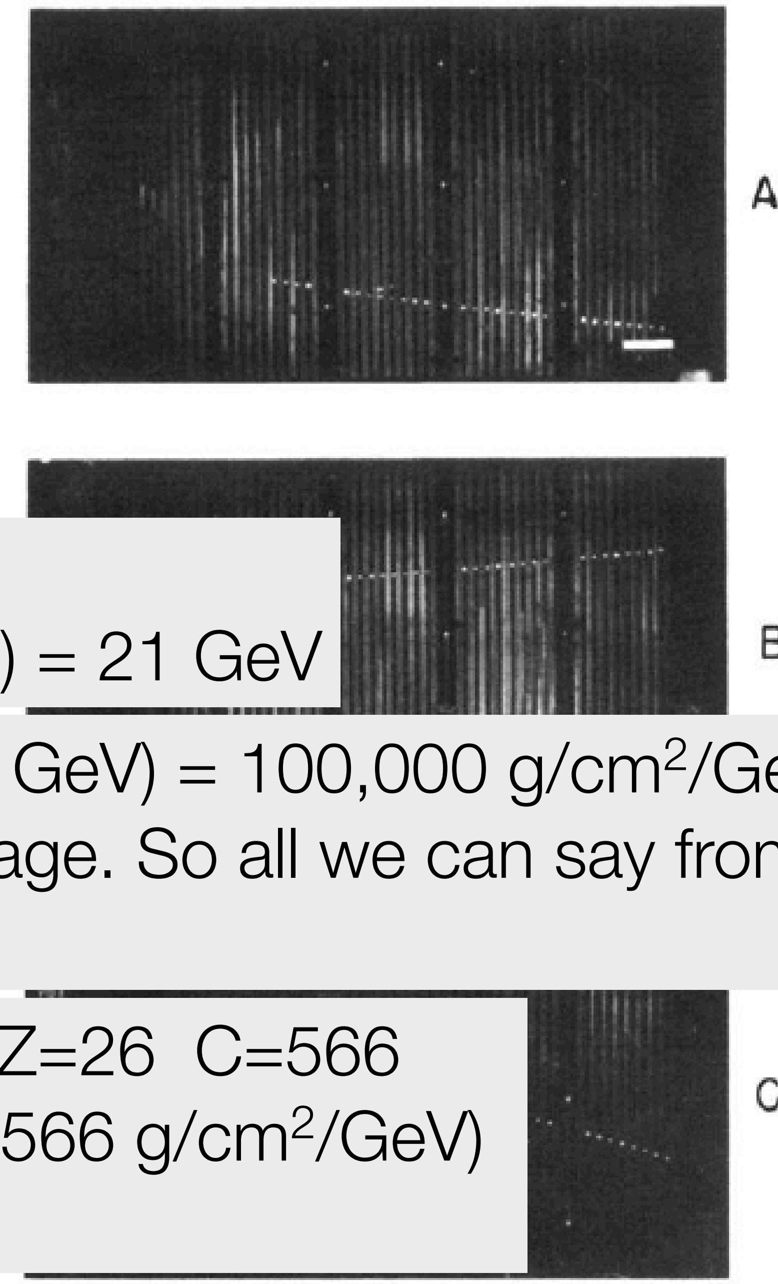

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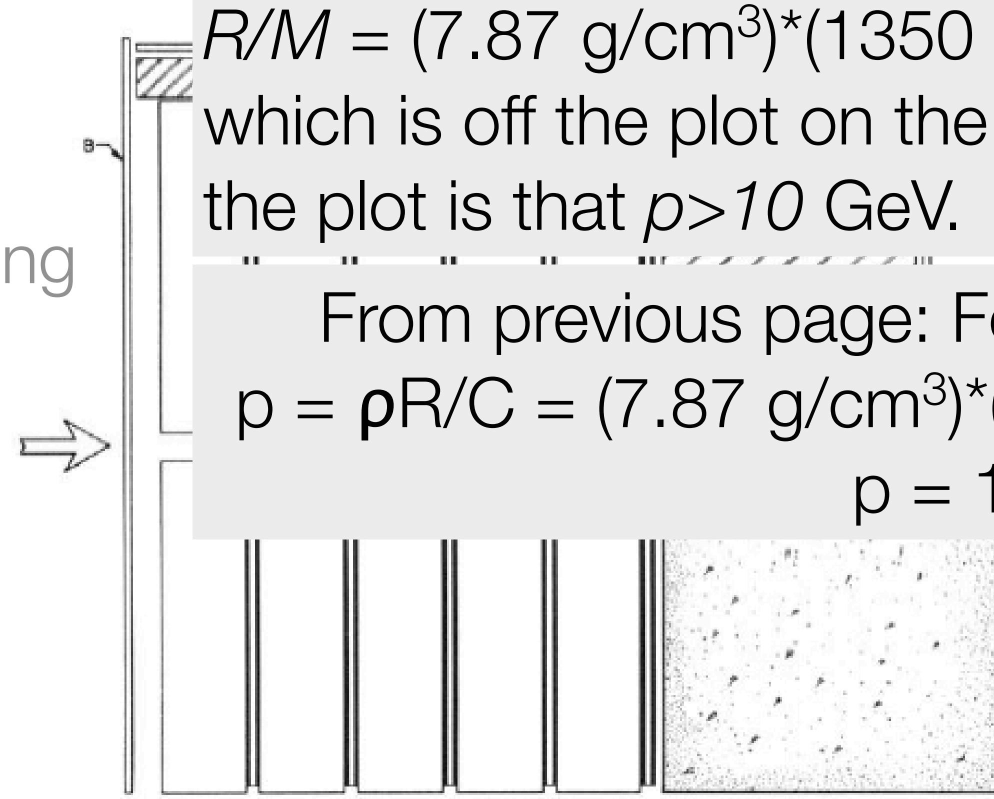
From previous page: For A=55.8, Z=26 C=566
p = ρR/C = (7.87 g/cm^3)*(1350 cm)/(566 g/cm^2/GeV)
p = 19 GeV

B,C,D vetos against entering tracks



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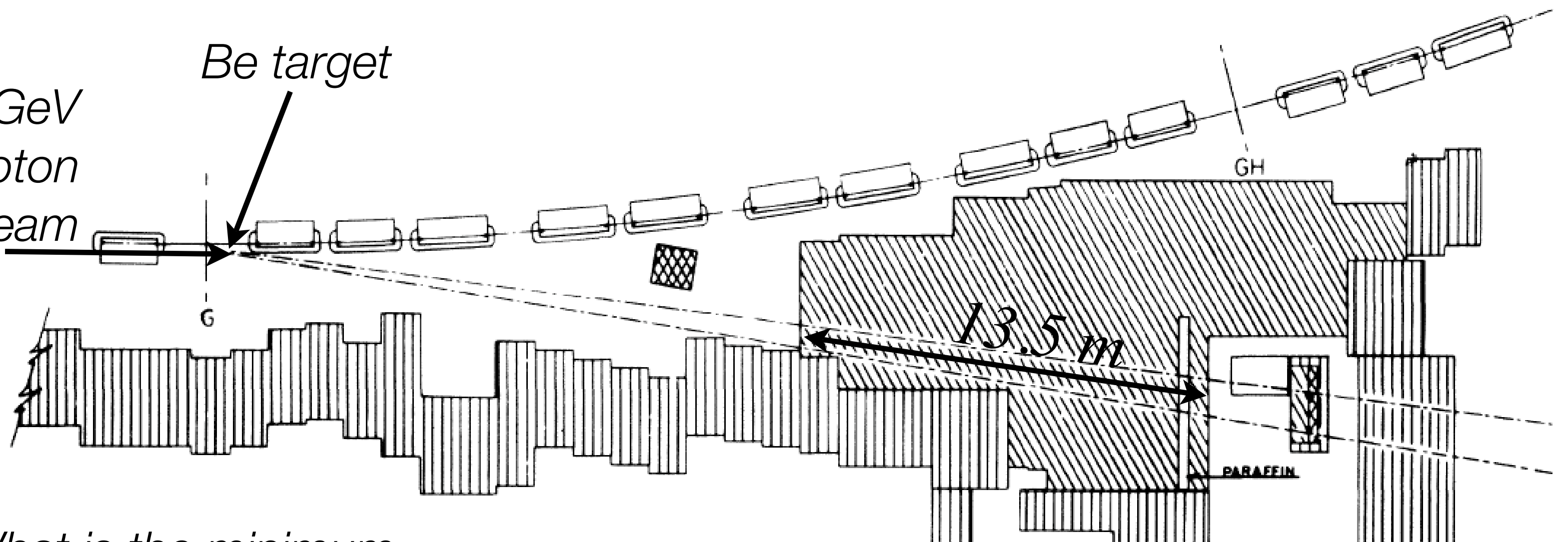

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Paper says 17.5 GeV

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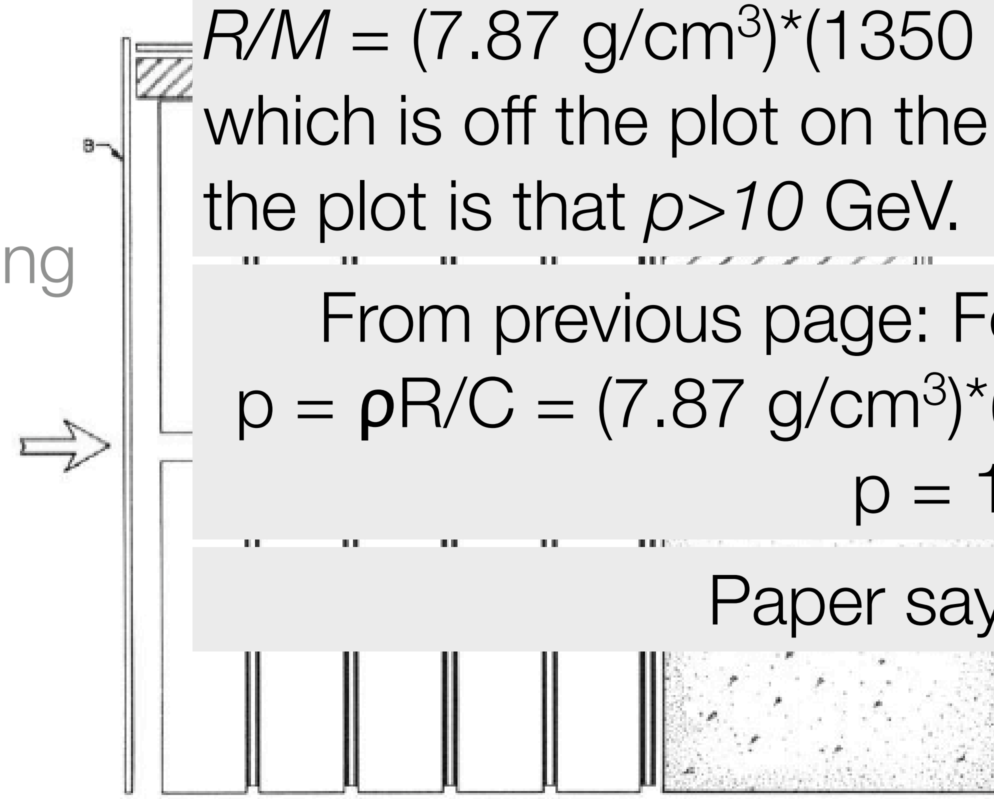

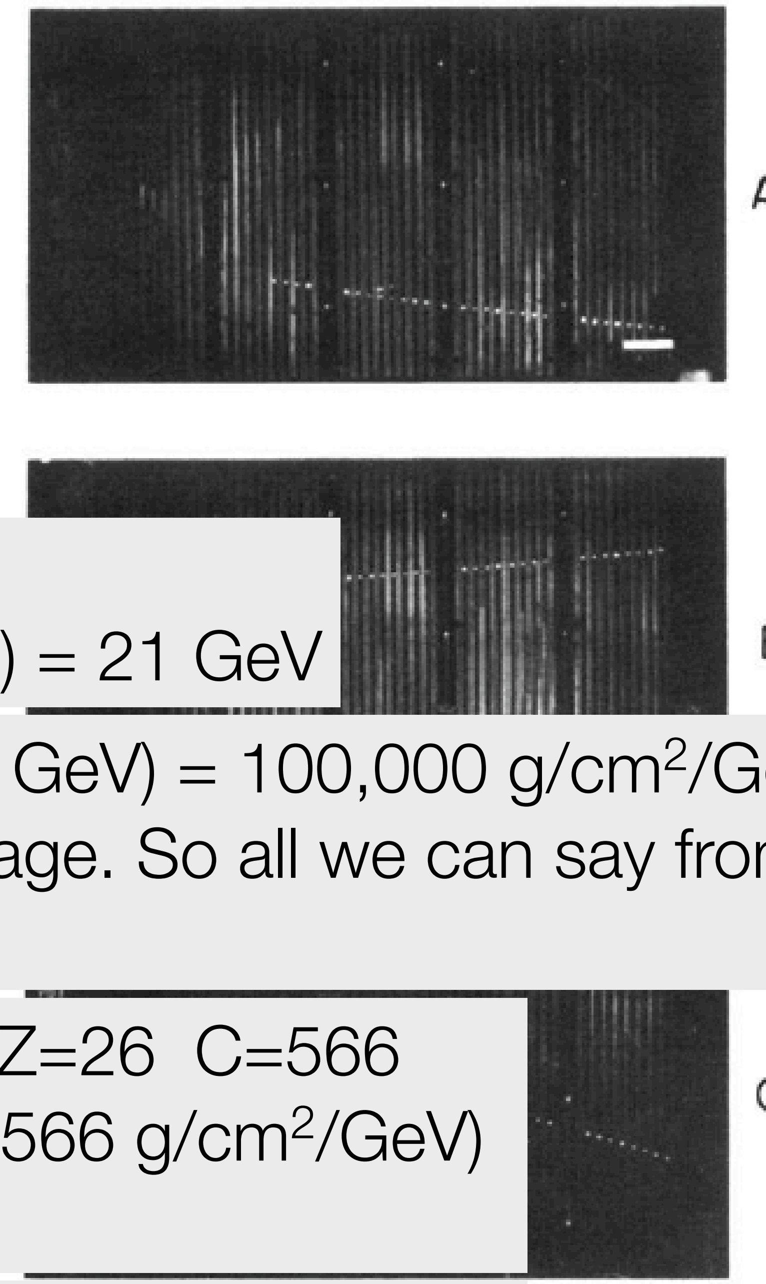

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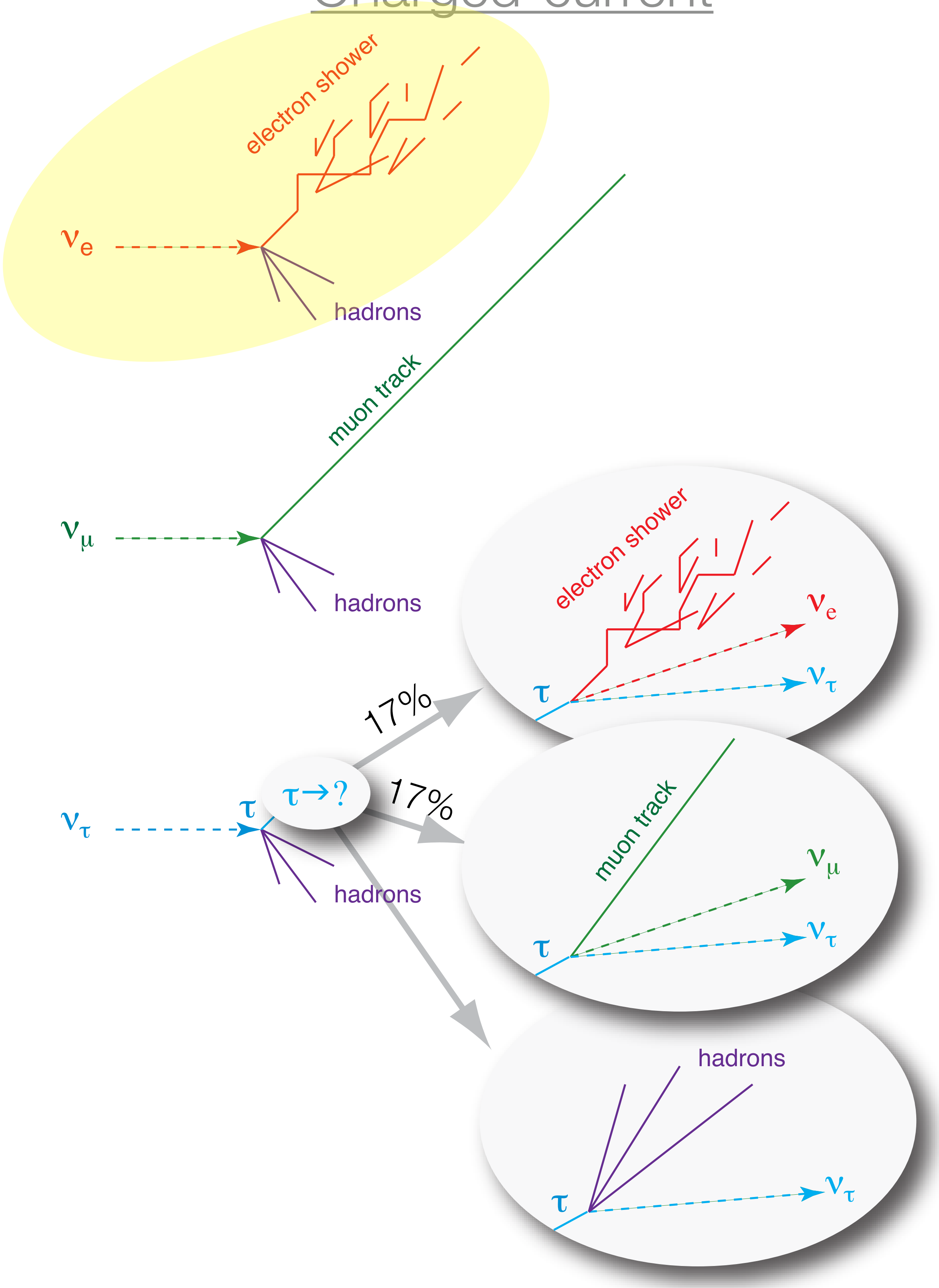
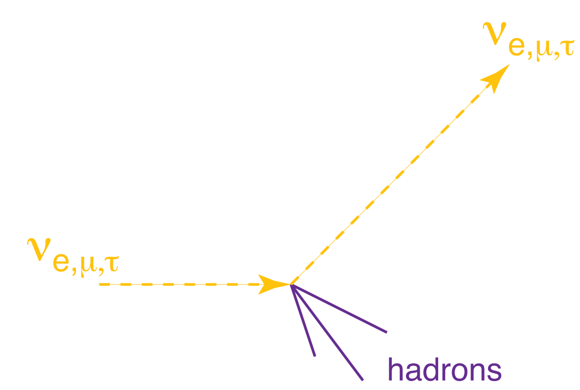
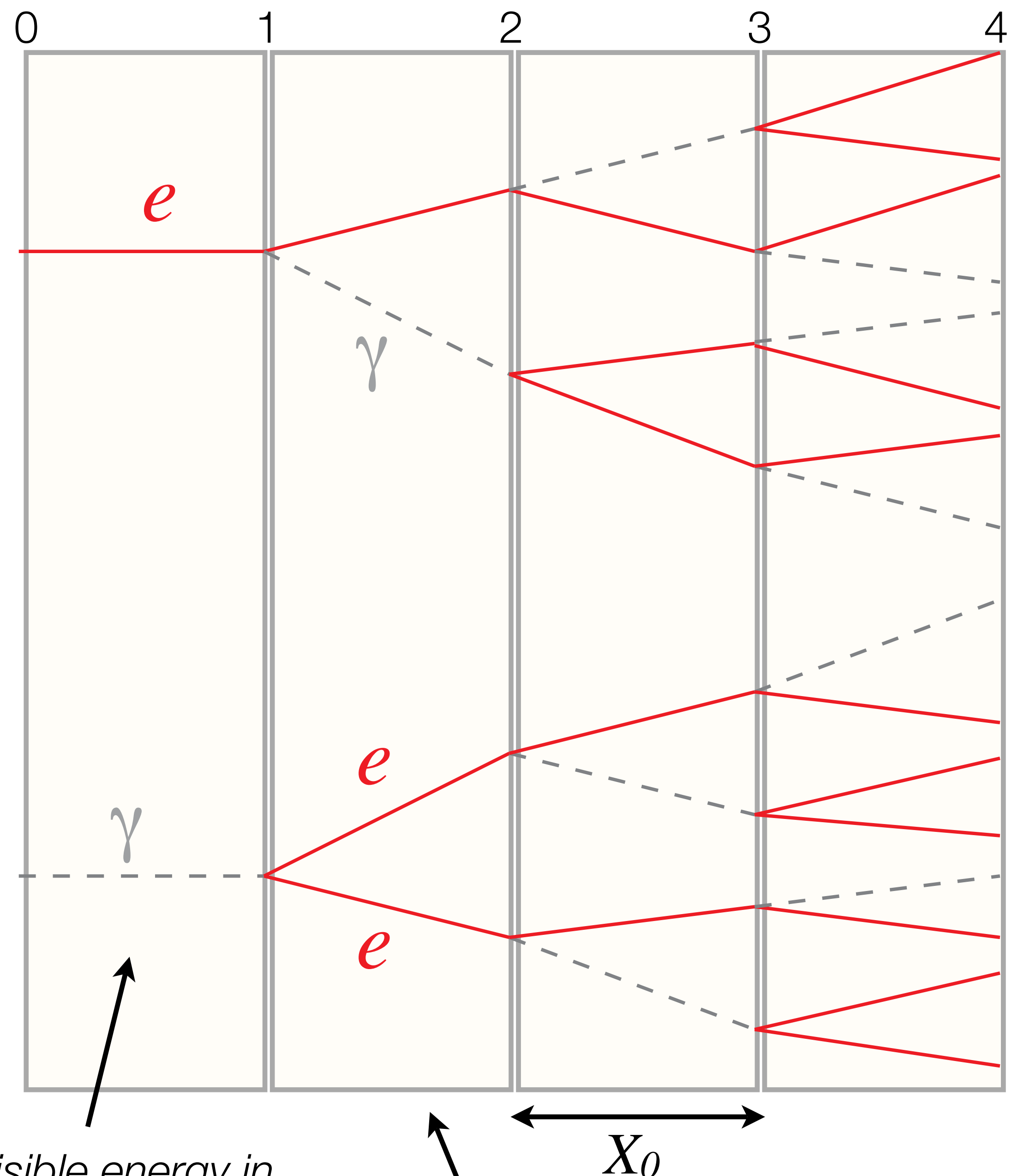


Neutral-current



- 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*

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/)

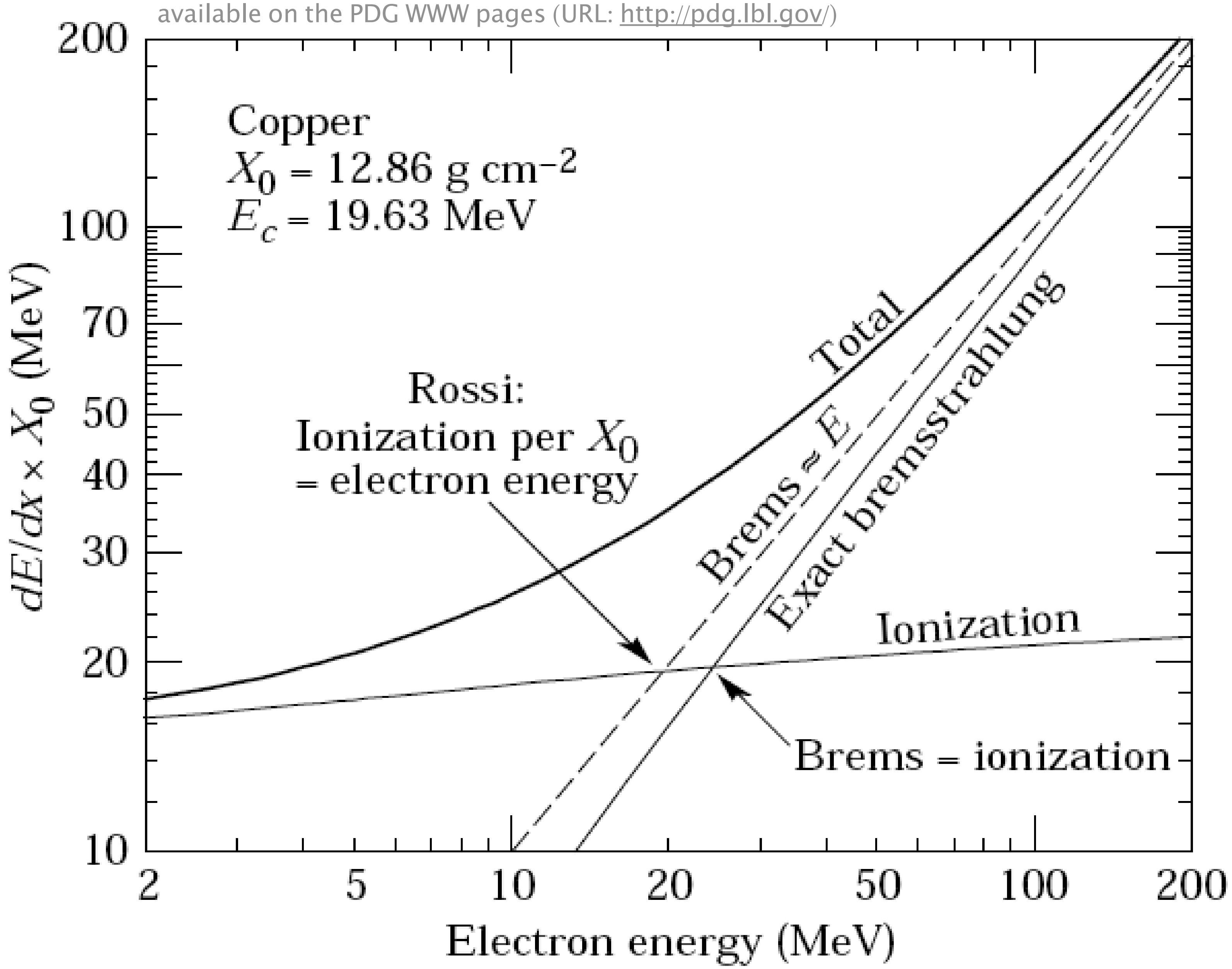


Figure 27.12: Two definitions of the critical energy E_c.

$$\left(\frac{dE}{dx}\right)_{\text{rad}} = \left(\frac{dE}{dx}\right)_{\text{col}}$$ *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

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

- Approximate formula for X_0:

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

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

$$R_M = X_0 \frac{21.2\ \mathrm{MeV}}{E_C}$$

- 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:

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

$$
\begin{aligned}
p_i &: \text{fraction by weight of element } i \\
A_i &: \text{atomic mass of element } i \\
Z_i &: \text{atomic number of element } i
\end{aligned}
$$

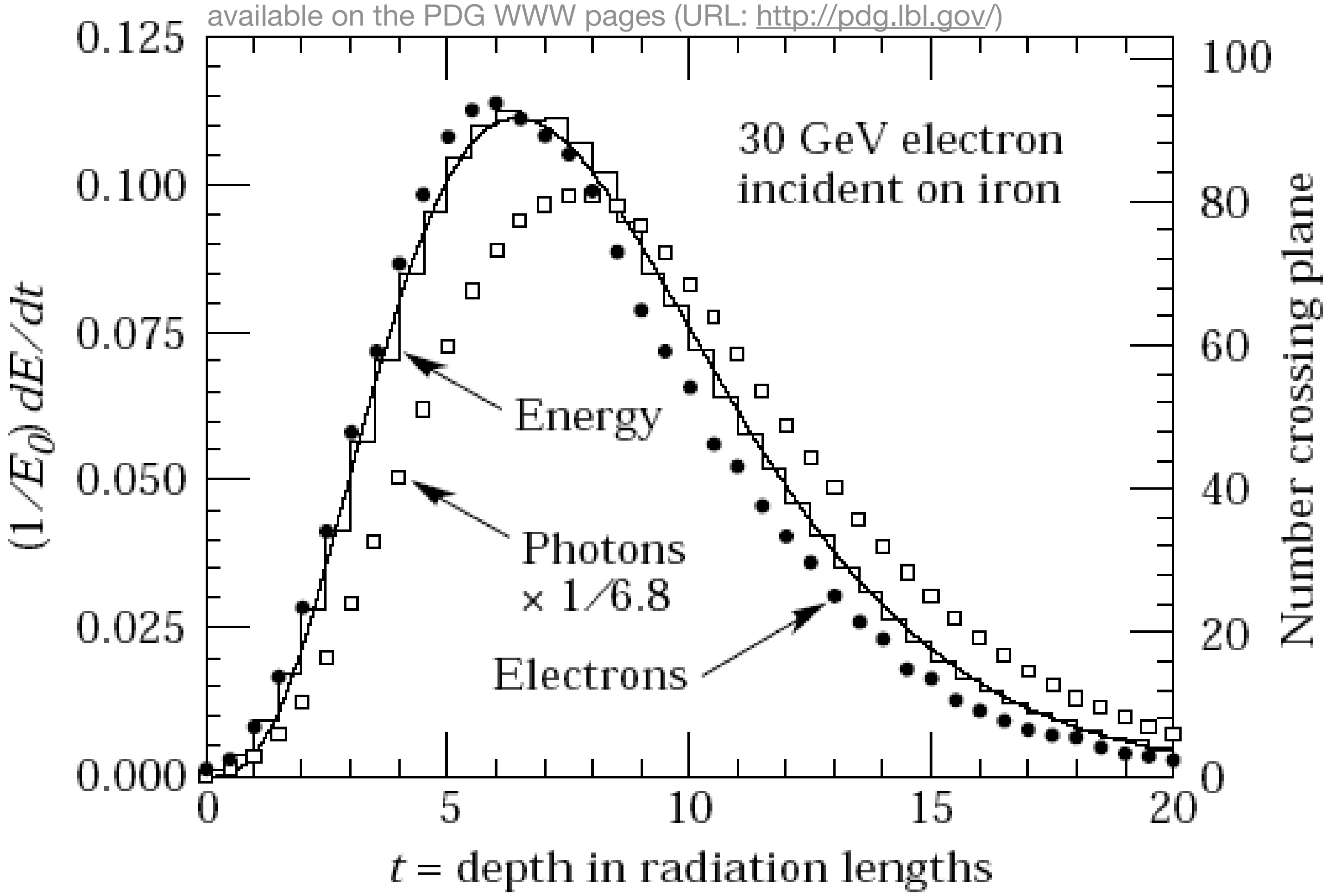
Electrons: Radiation length and Moliere radius

	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:

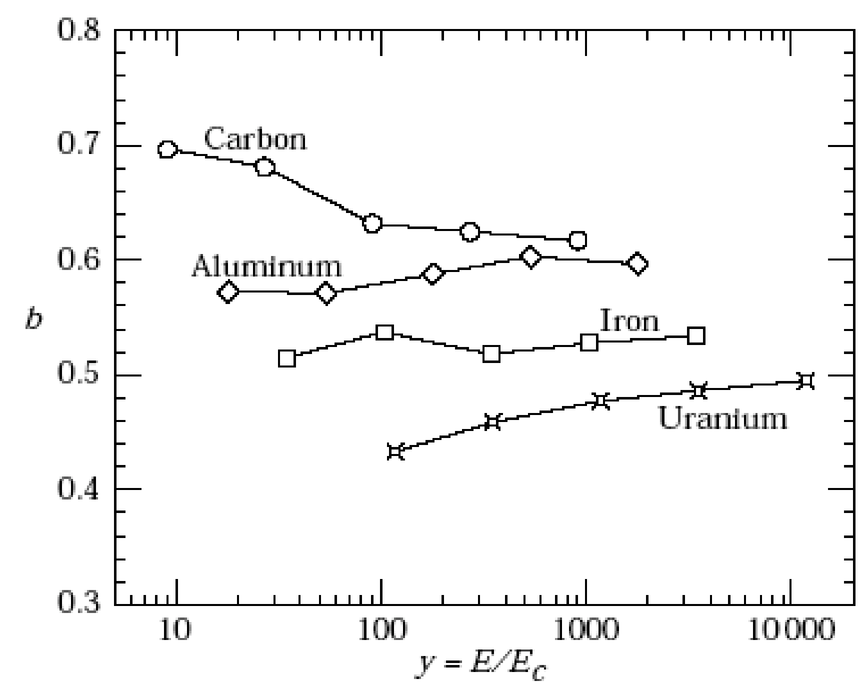


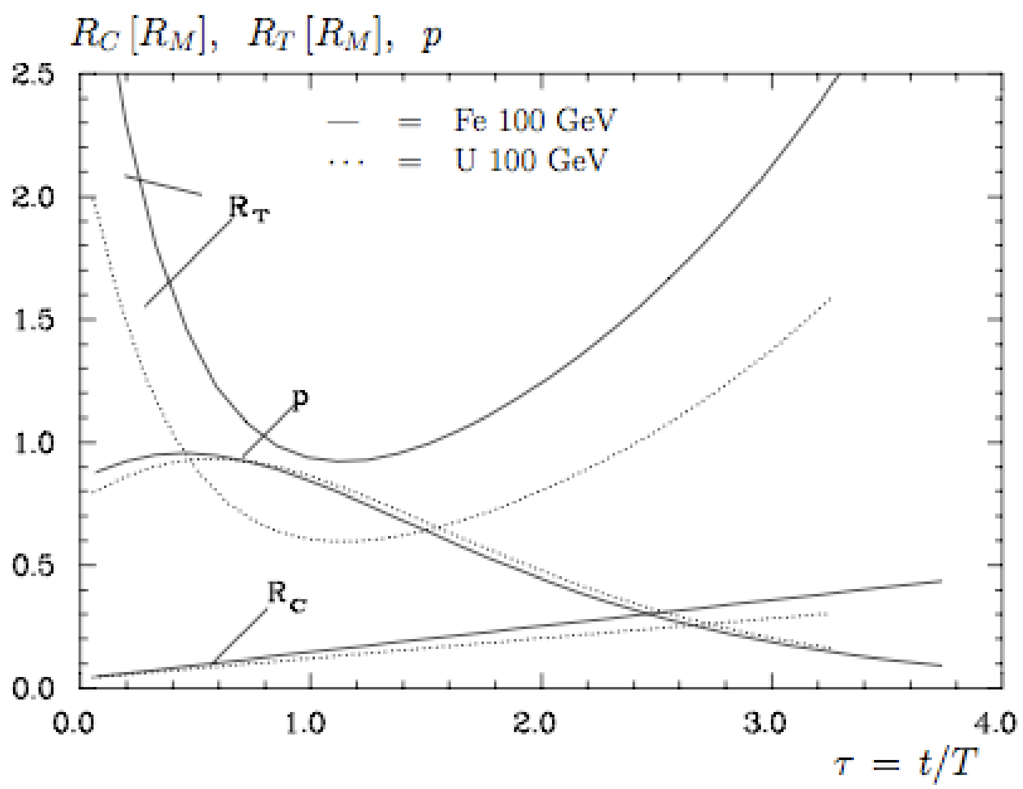
Figure 27.19: Fitted values of the scale factor b for energy deposition profiles obtained with EGS4 for a variety of elements for incident electrons with $1 \leq E_0 \leq 100$ GeV. Values obtained for incident photons are essentially the same.

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 $2R_M$ of the shower axis.
- The transverse distribution is not Gaussian:

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

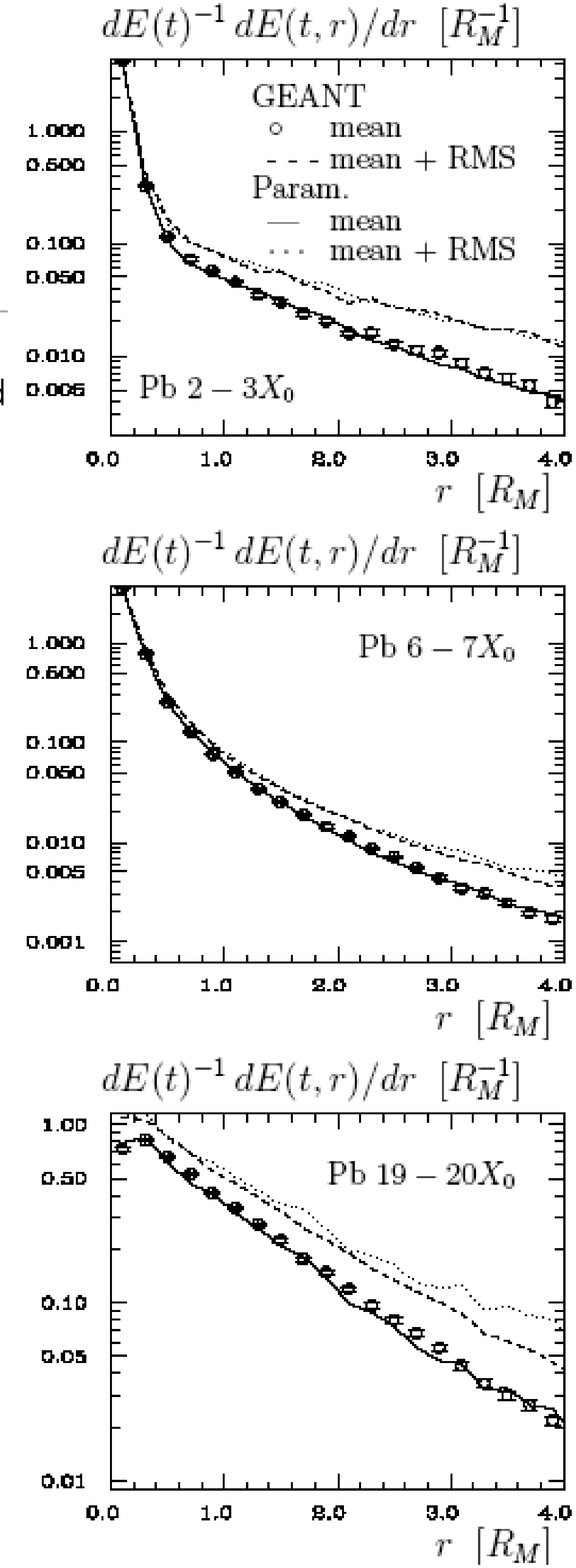
$$f(r) = p \frac{2rR_C^2}{(r^2 + R_C^2)^2} + (1-p) \frac{2rR_T^2}{(r^2 + R_T^2)^2}$$



Grindhammer and Peters hep-ex/0001020

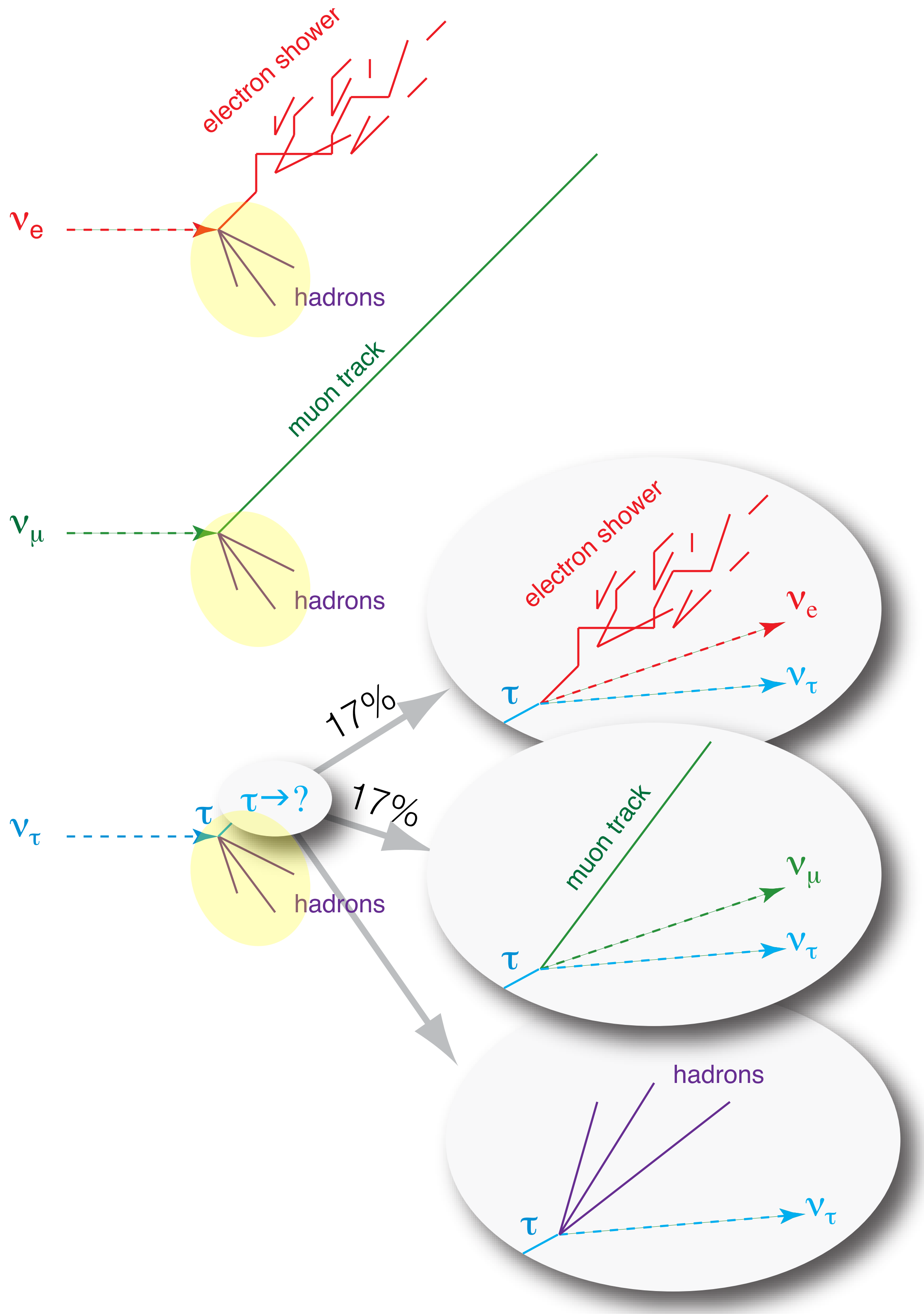
core dominated

tail dominated

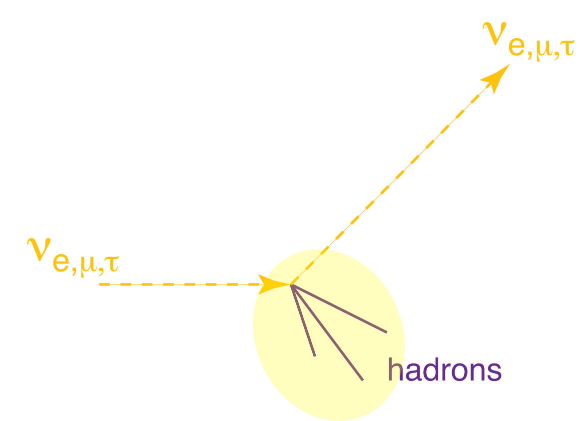


Neutrino detection channels

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
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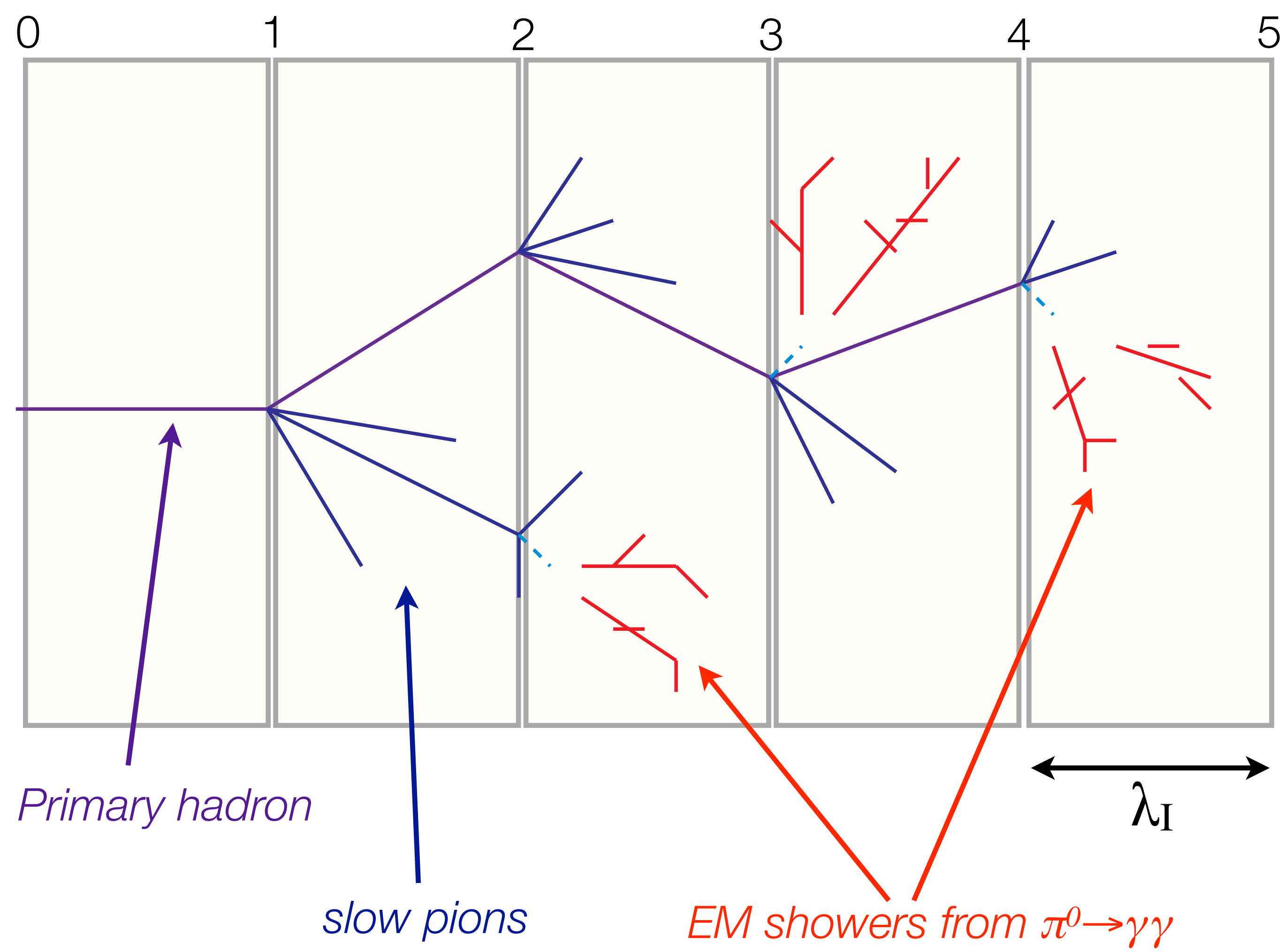
- CC rates are affected by oscillations
- NC rates are not affected by oscillations
  - *In only a few analyses are NC events considered to be signal. In most cases NC events are backgrounds to the CC processes*

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 pi0 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

Comparison of EM and hadron shower

- Electromagnetic processes tend to be forward peaked
- Hadronic processes typically produce particles with P_T~= 300 MeV/c

➡EM showers tend to be relatively 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.

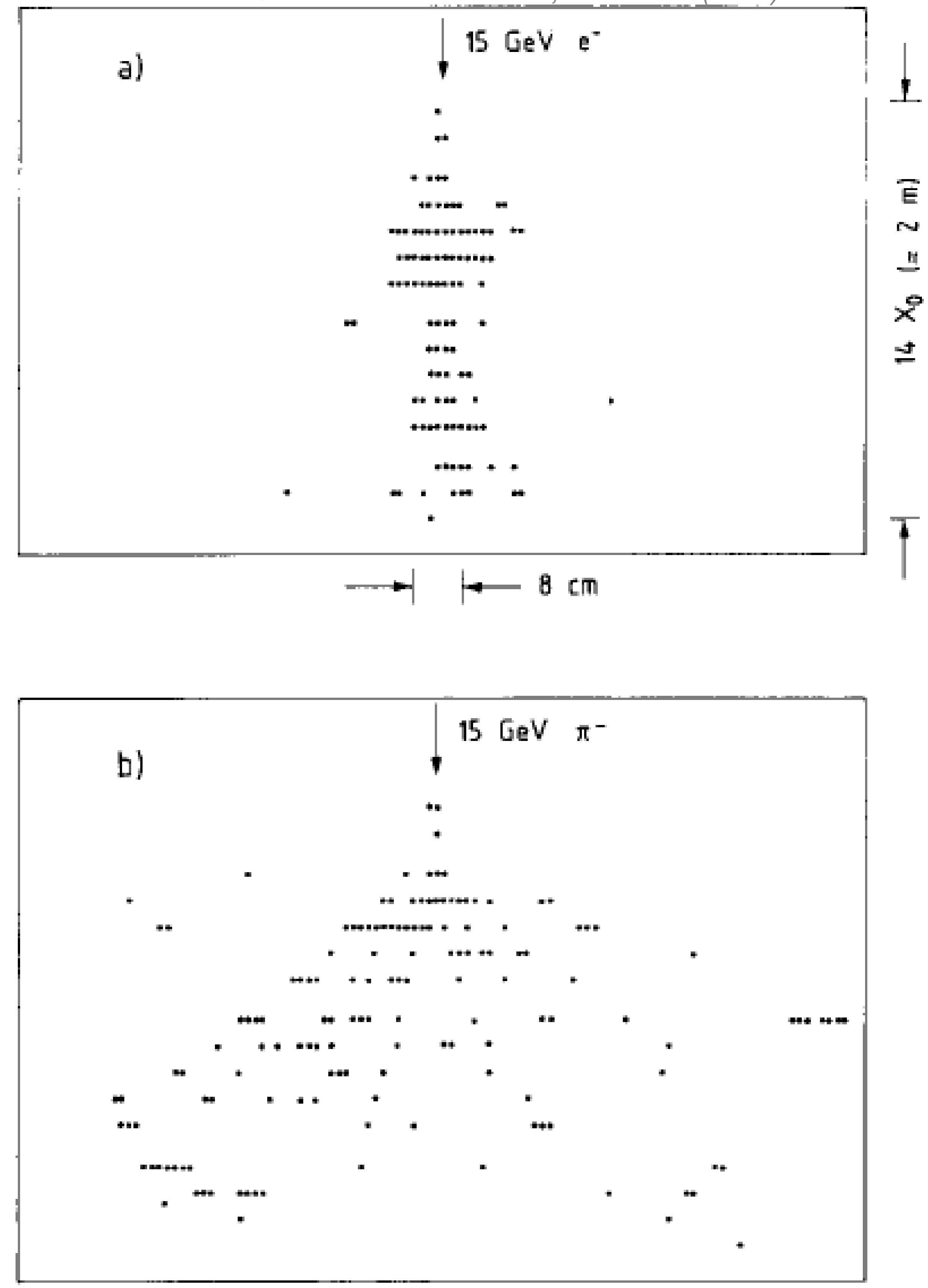
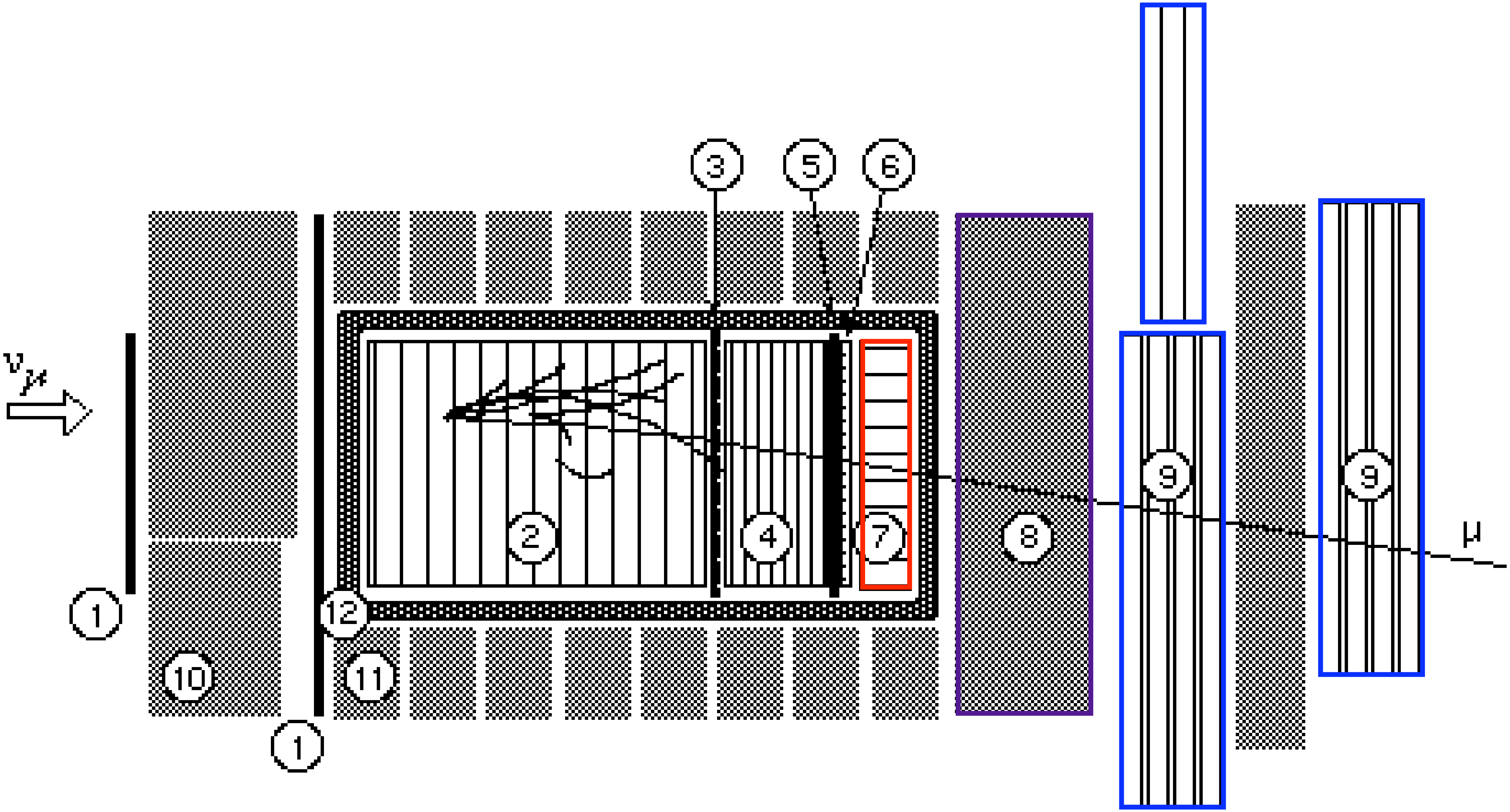


Fig. 13. Pattern of tube hits for two typical events: (a) electron-induced, (b) pion-induced.

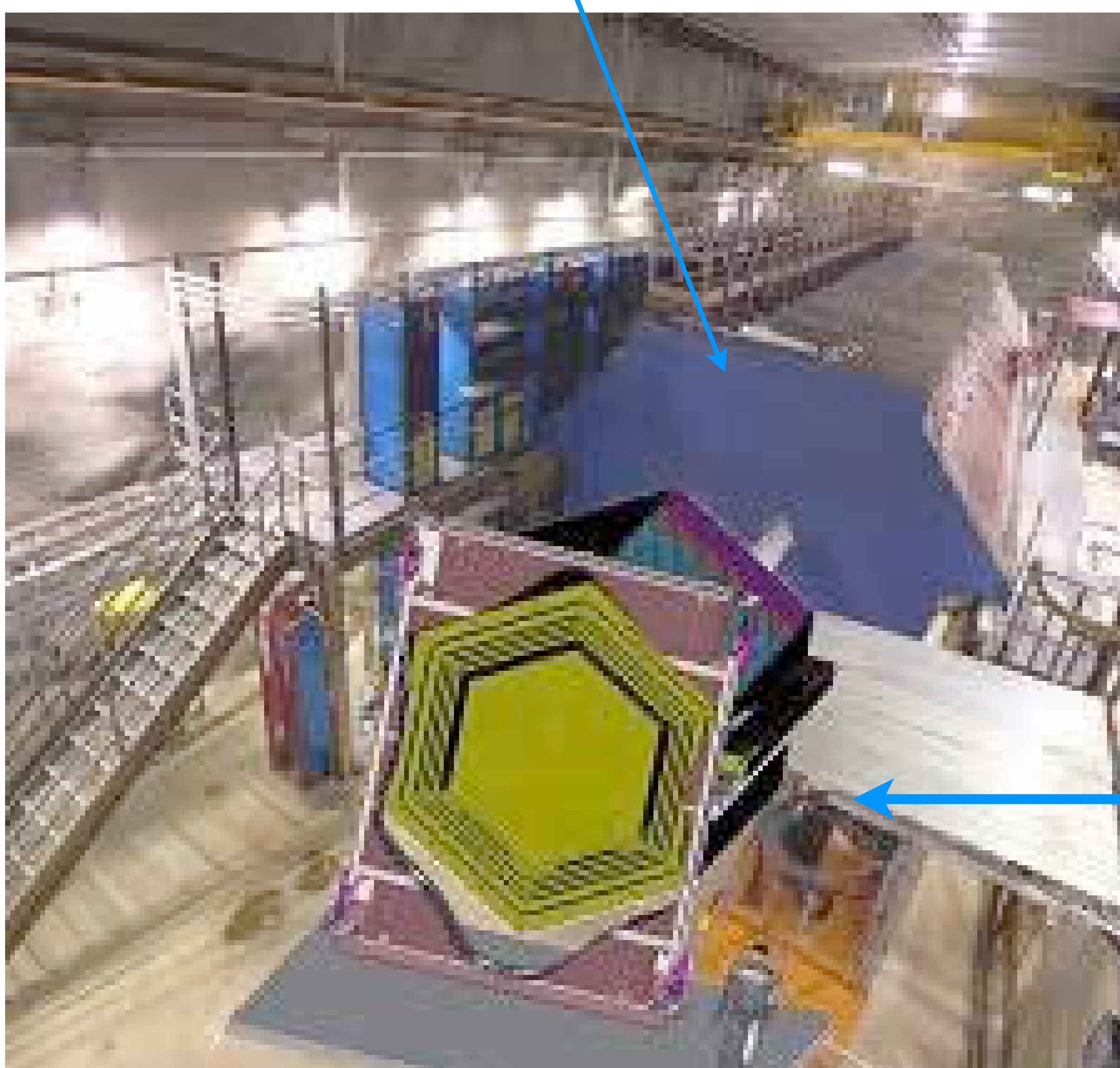
ν_μ CC event in the NOMAD detector

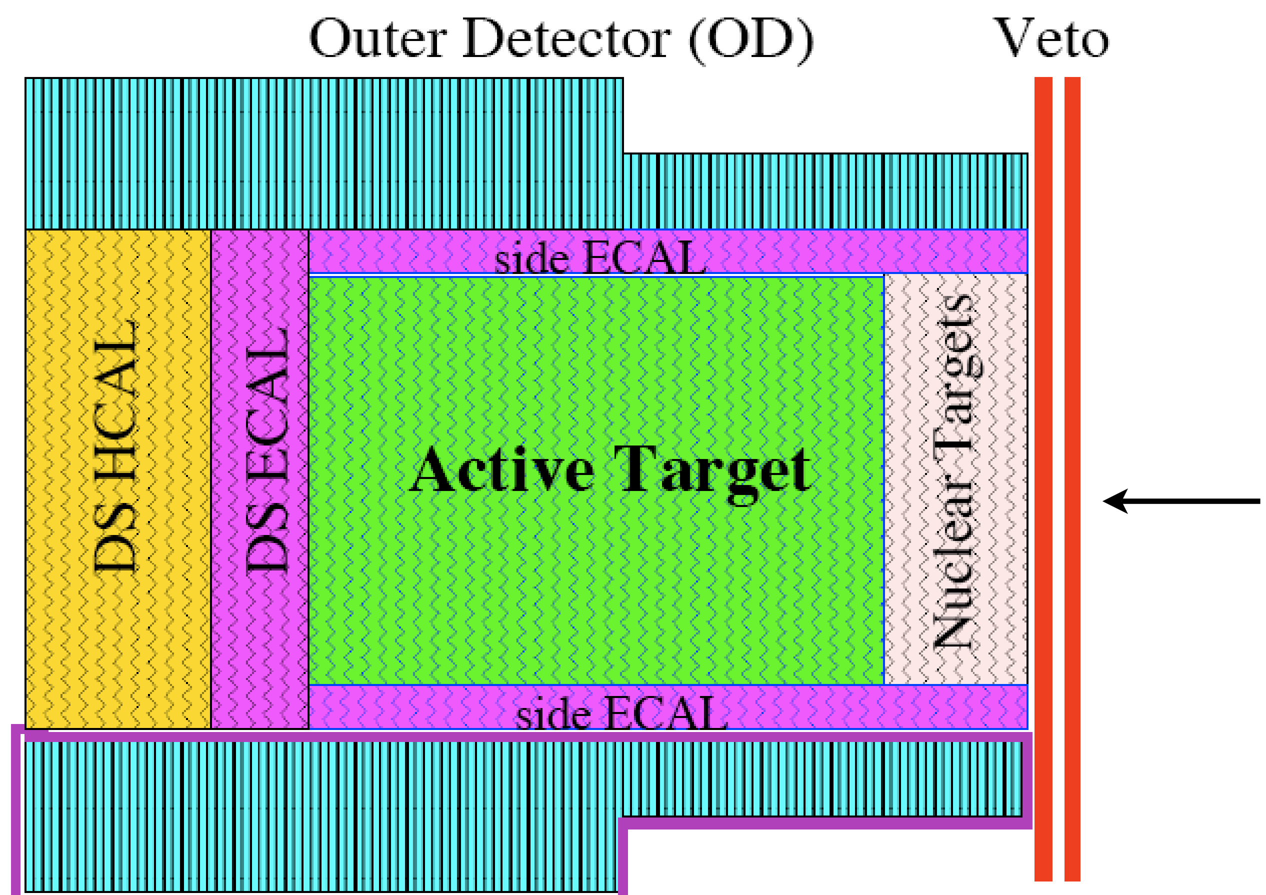


(1) Veto wall
(2) Drift chambers
(3) Trigger plane
(4) Transition radiation tracker
(5) Trigger plane
(6) Preshower region
(7) Electromagnetic calorimeter
(8) Hadron calorimeter
(9) Muon tracking
(10) Forward calorimeter
(11) Magnet return yoke
(12) Magnet

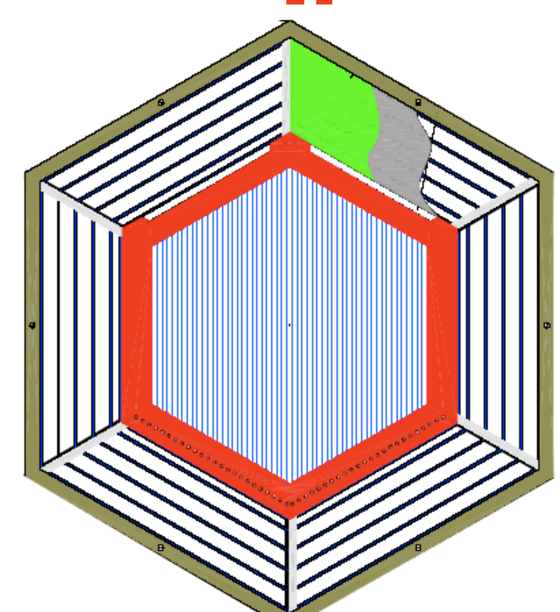
The MINERvA Detector

MINOS steel/
scintillator detector
used as muon
ranger



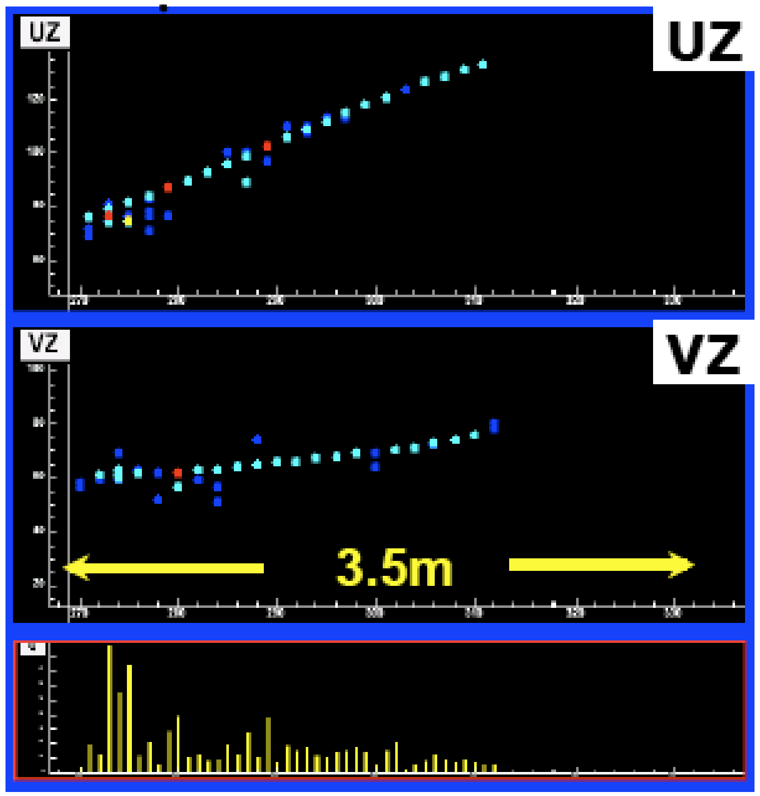


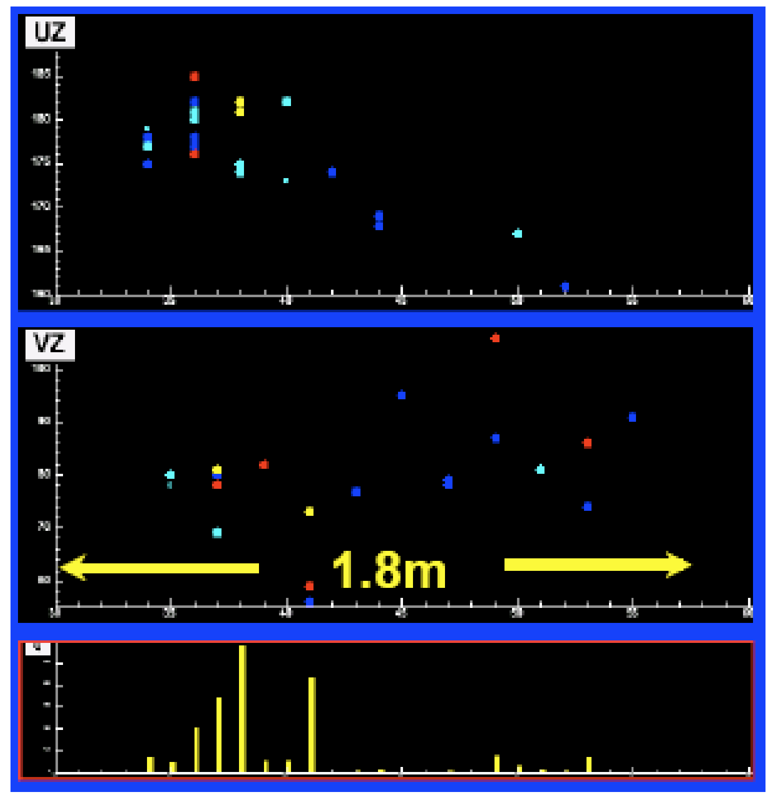
Plan view

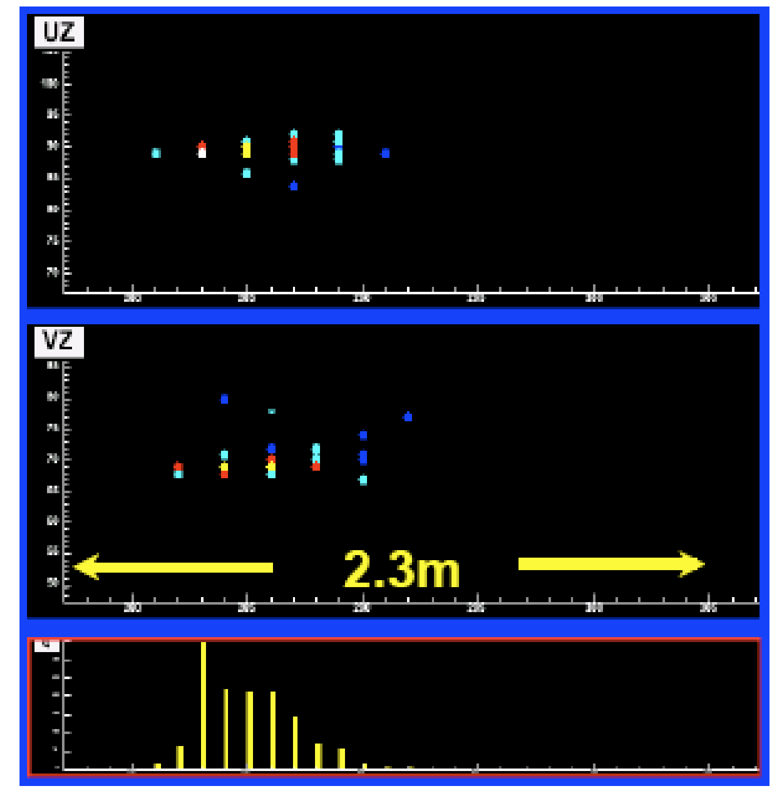


Front view

Can you classify these events from the MINOS experiment?

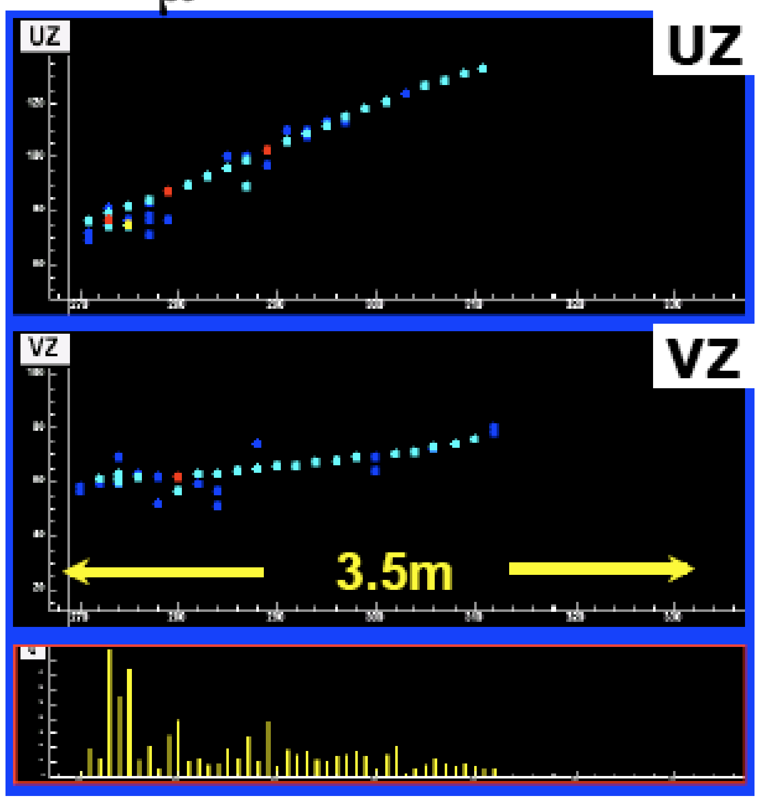


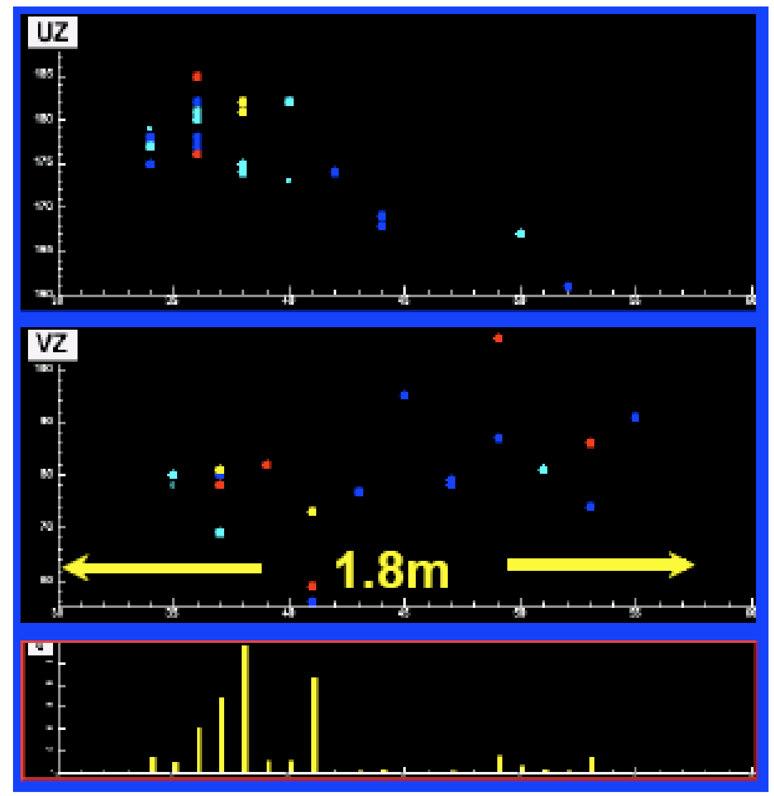


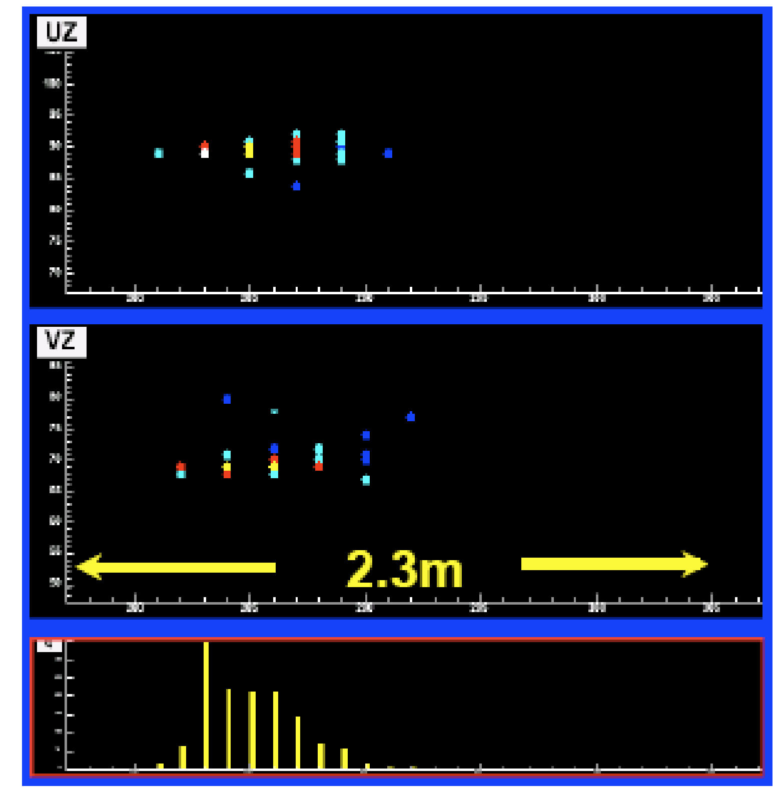


Can you classify these events from the MINOS experiment?

ν_μ CC Event



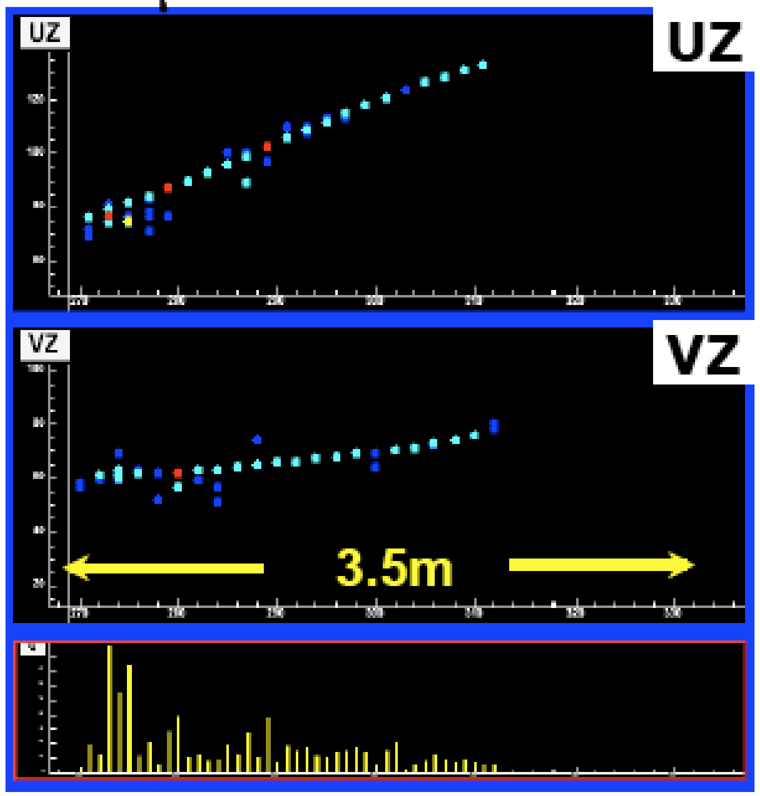




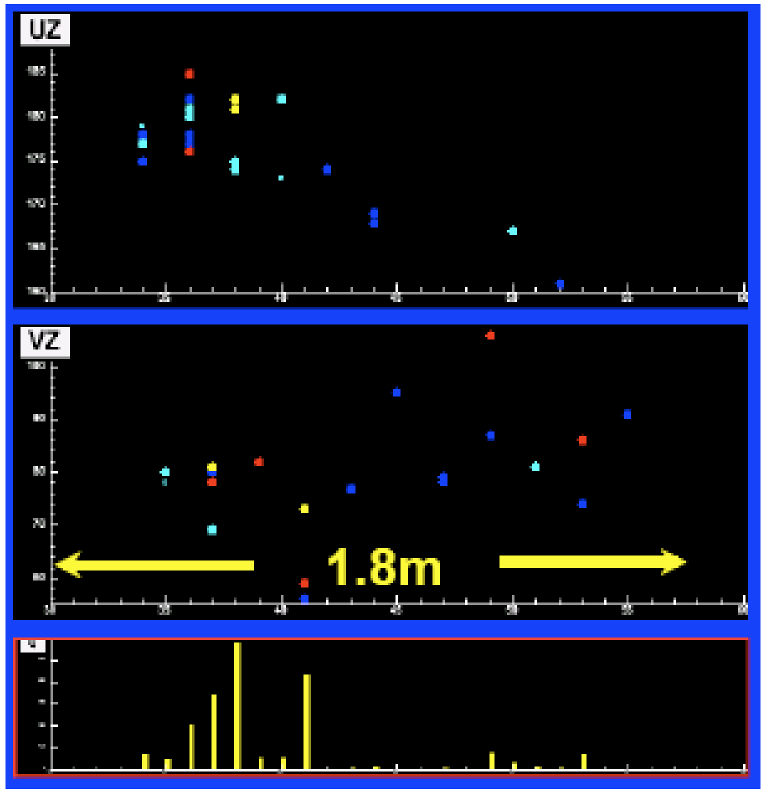
- long μ track+ hadronic activity at vertex

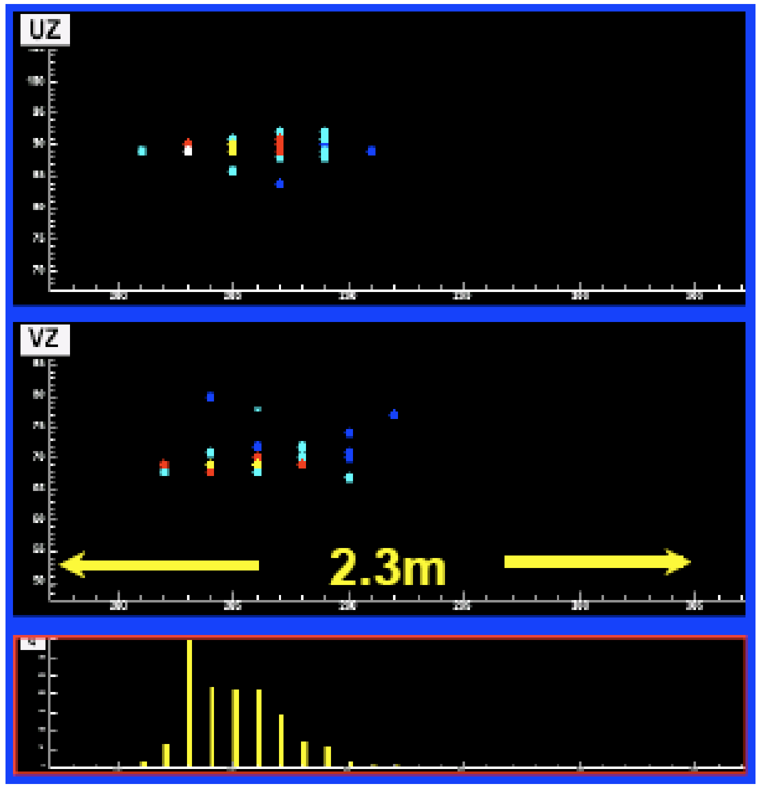
Can you classify these events from the MINOS experiment?

ν_μ CC Event



NC Event



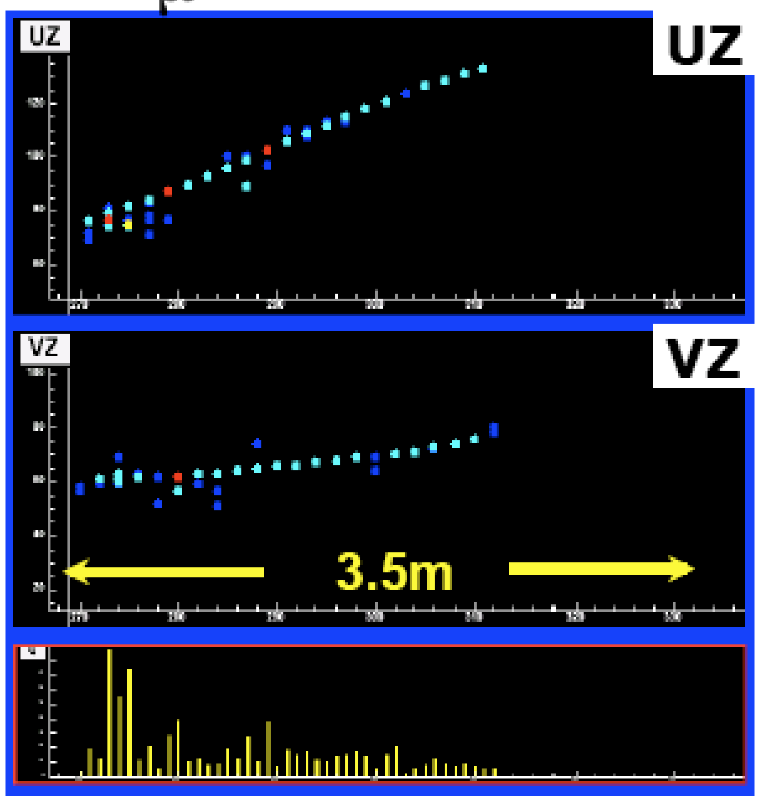


- long μ track+ hadronic activity at vertex

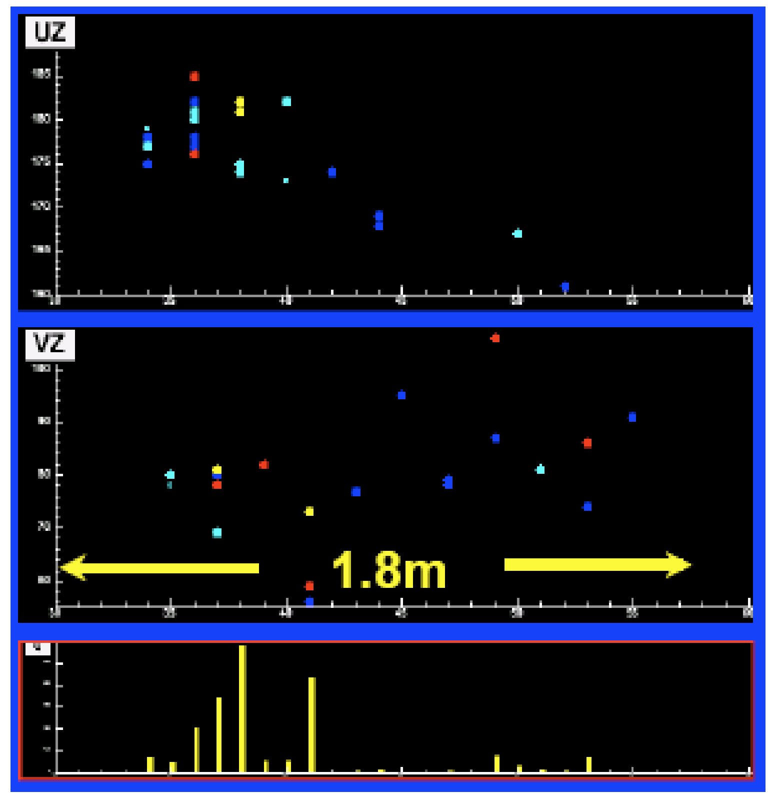
- short event, often diffuse

Can you classify these events from the MINOS experiment?

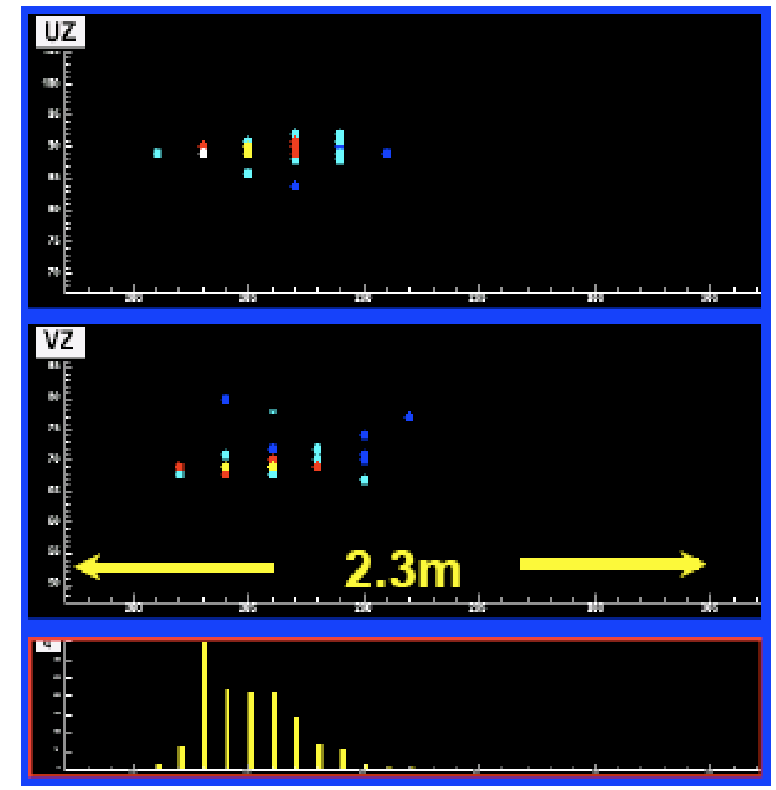
ν_μ CC Event



NC Event



ν_e CC Event



- long μ track+ hadronic activity at vertex

- short event, often diffuse

- short, with typical EM shower profile

Tutorials

- 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 posted at:
  http://enrico1.physics.indiana.edu/messier/nufact08