Physics 661

Particle Physics Phenomenology

October 7, 2003

Cosmic Rays

- Outline
  - Primary cosmic ray spectrum and abundances
  - Cosmic rays in the atmosphere
  - Cosmic rays at the Earth's surface
  - Cosmic rays underground
  - Air showers
  - Interactions with the CMB
  - Particle acceleration

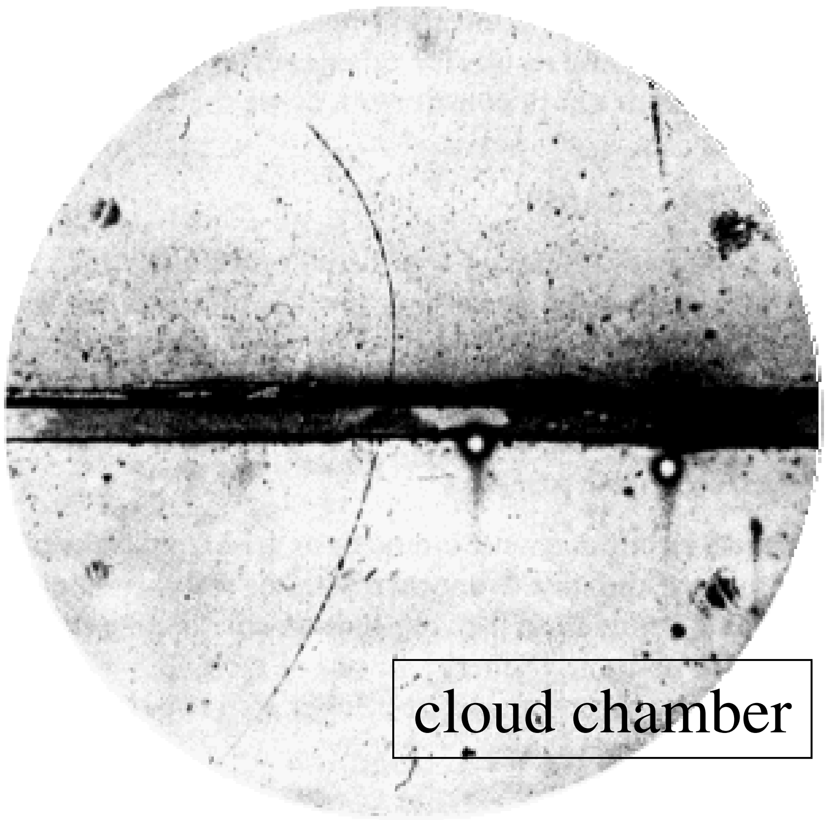
Cosmic Rays

- Ionizing particles falling into the Earth's atmosphere were discovered in 1912 by Victor Hess (balloon flights)
- Mainly atomic nuclei
- ~2% electrons and positrons
- Used to begin the study of particle physics
  - discovery of the positron (1933)
  - discovery of the muon (1937)
  - discovery of the pion (1947)
  - discovery of strange particles (1947) - s quark

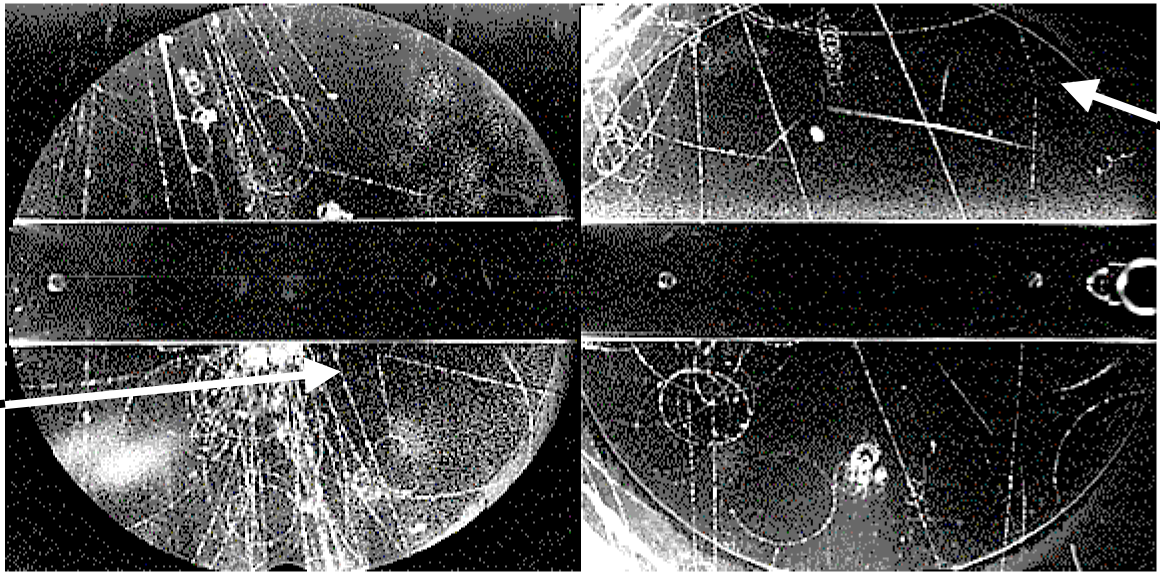
Discovery of antimatter (the positron)

C.D. Anderson, Physical Review 43, 491 (1933)

- Confirmed Dirac's theory of QED and the prediction of antimatter



Discovery of strange particles (the kaons)



Vee reveals decay of neutral kaon

Kink reveals decay of charged kaon

cloud chamber

G.D. Rochester and C.C. Butler, Nature 160, 855 (1947)

Origin of Cosmic Rays

- Solar flares
- Outside the solar system
  - modulated on Earth by solar wind
  - lower energy particles deflected by the geomagnetic field

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- Elements generated by
  - primordial nucleosynthesis
  - nucleosynthesis in stars
  - spallation in the interstellar medium

Cosmic Ray Spectrum

$I_N(E) \approx 1.8\, E^{-\alpha}$ nucleons / cm^2 - s - sr - GeV

$\alpha = 2.7$, from several GeV to beyond 100 TeV,

(galactic origin)

$\alpha = 3.0$,

10^{16} eV < E < 10^{18}eV

(from "knee" to "ankle")

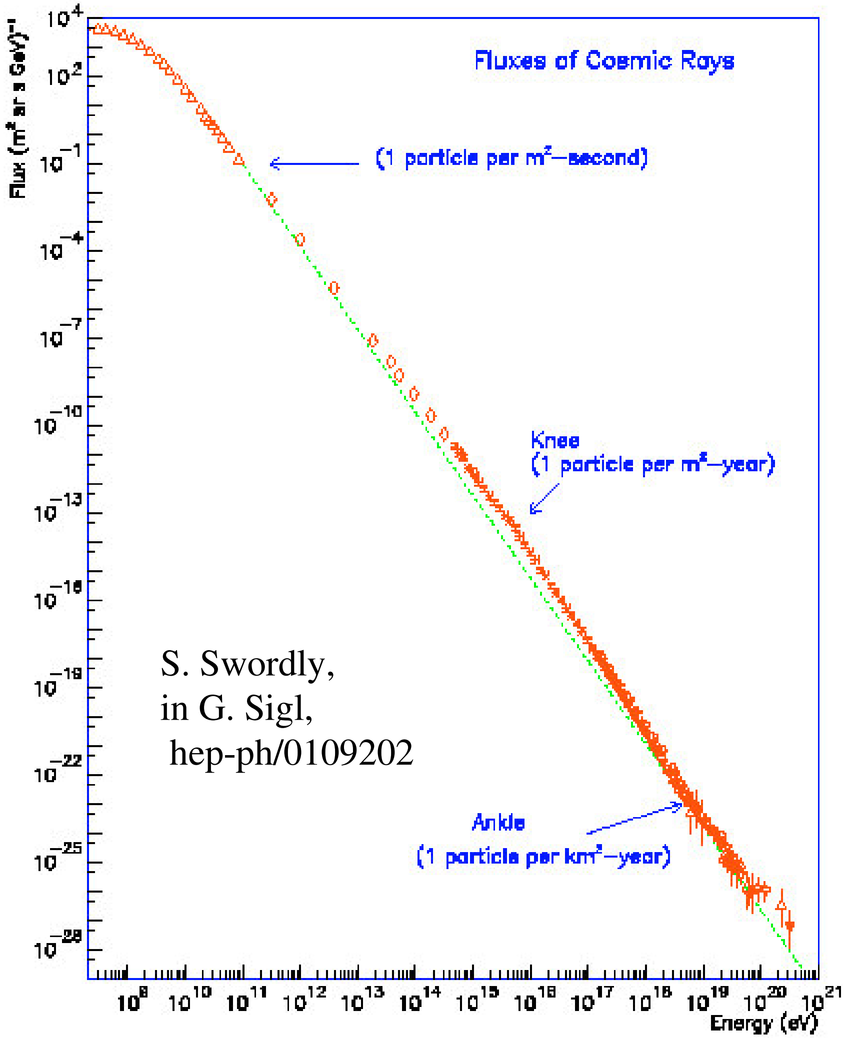
(galactic origin)

$\alpha = 2.8$,

10^{18} eV < E (above "ankle")

(extragalactic origin)

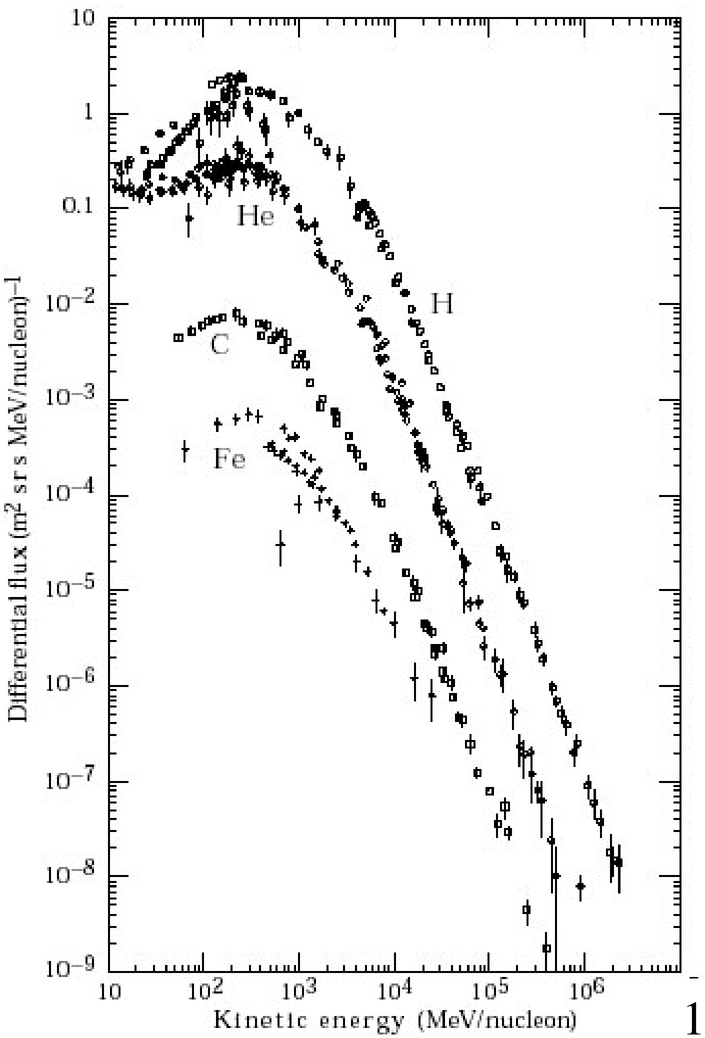
100 TeV = 10^{14} eV



Cosmic Ray Spectrum

Heavy nuclei

- similar spectra
- however, slightly "flatter" spectra



10^{13} eV

Cosmic Ray Composition

~79% of nucleons are protons

~14% of nucleons are within helium nuclei

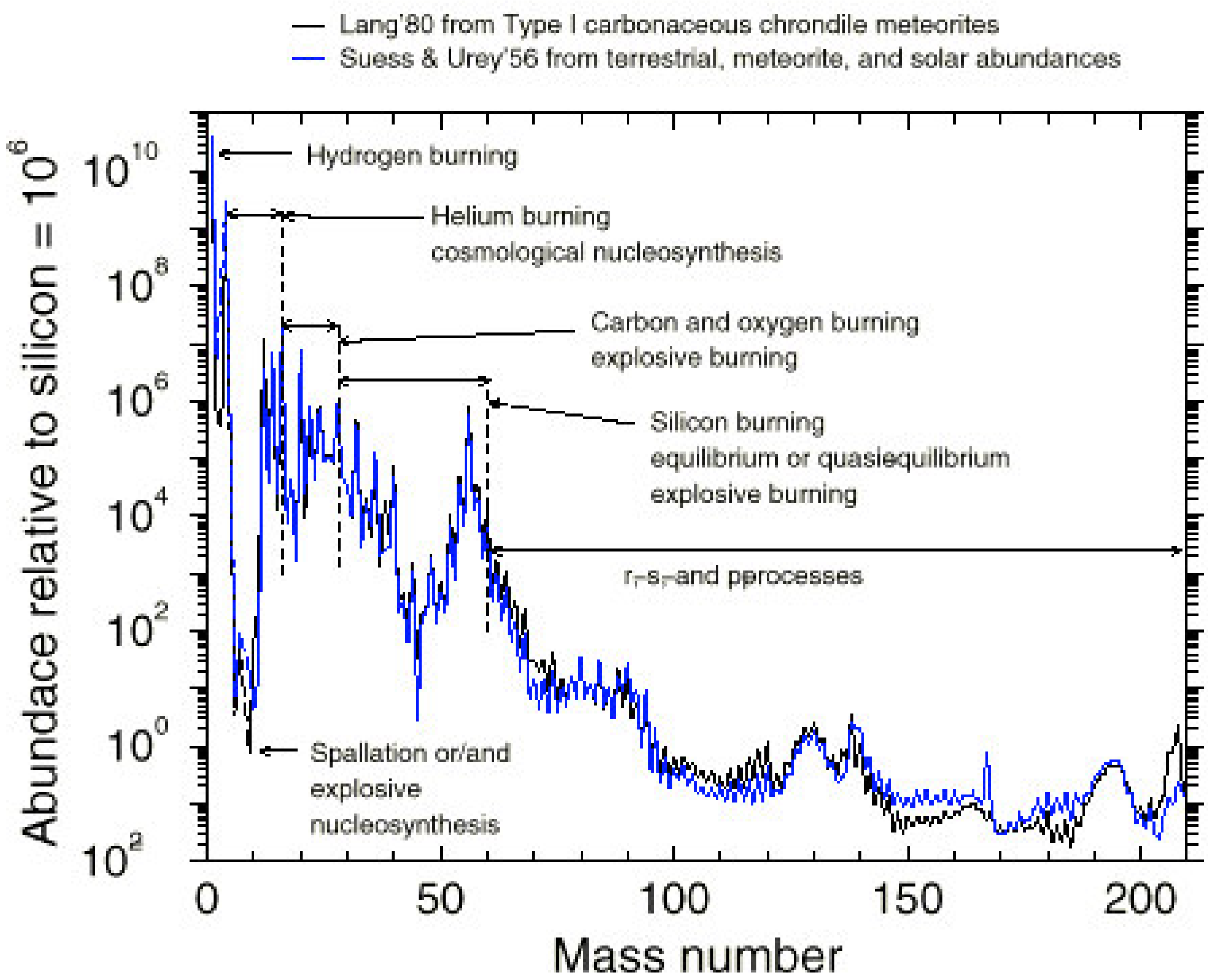
Z	element	abundance
1	H	485
2	He	26
3-5	Li-B	0.40
6-8	C-O	2.20
9-10	F-Ne	0.30
11-12	Na-Mg	0.22

Z	element	abundance
13-14	Al-Si	0.19
15-16	P-S	0.03
17-18	Al-Ar	0.01
19-20	K-Ca	0.02
21-25	Sc-Mn	0.05
26-28	Fe-Ni	0.12

Above 10 GeV, 10^{-4} antiprotons/proton

No evidence for primary component of antiprotons

Cosmic Ray Composition



S. Mashnik, astro-ph/0008382

Cosmic Ray Composition

- Relative abundances of protons and helium nuclei are smaller than in Solar System
  - primordial composition of CR sources?
  - or acceleration mechanism? (hi q -> more acc.)
- Two groups of elements are more abundant in CRs than in SS (Li,Be,B) and (Sc,Ti,V,Cr,Mn)
  - overabundance of Li, Be, B due to spallation of C and O
  - Sc,Ti,V,Cr,Mn due to spallation of iron

Cosmic Ray Composition (CR vs. SS)

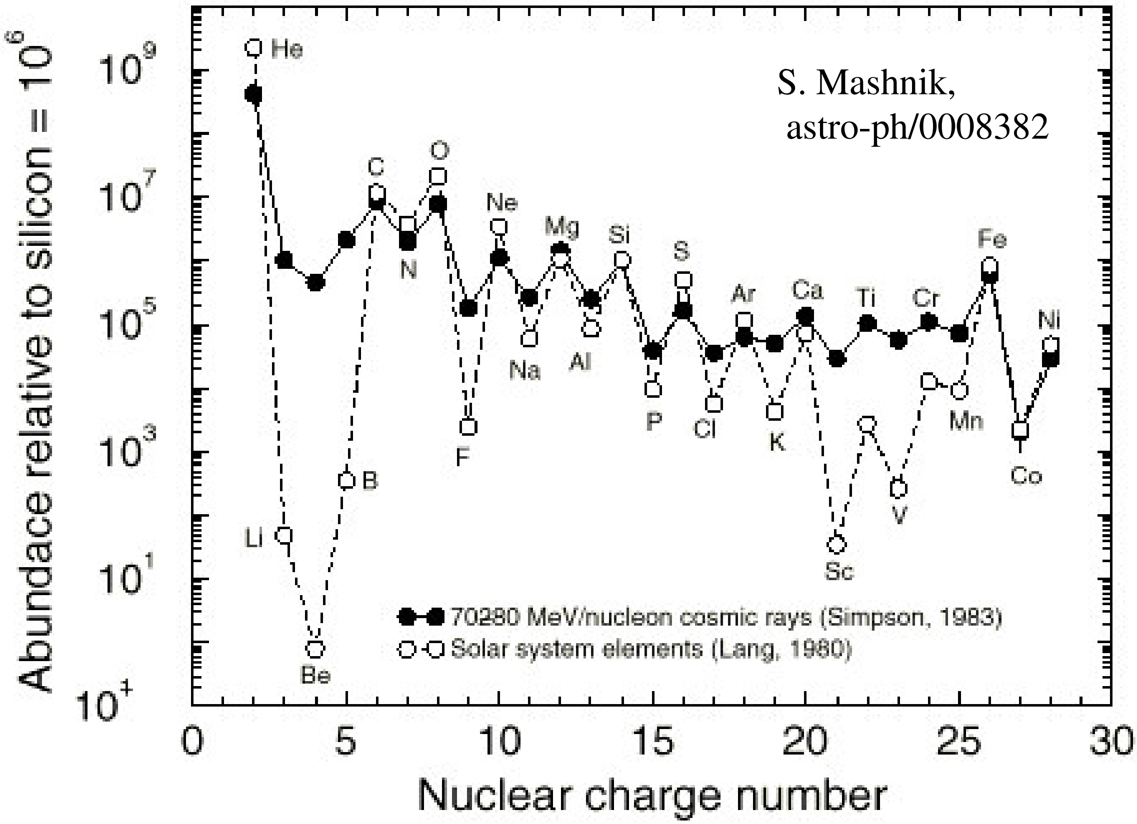
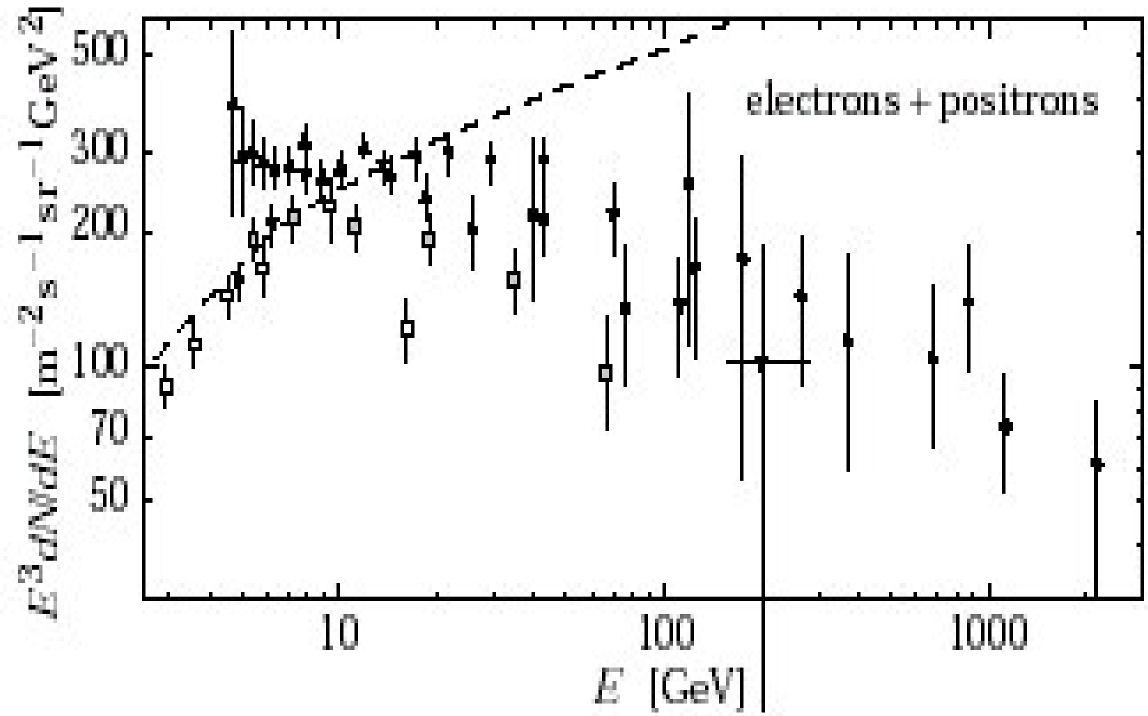


Fig. 2.— The relative elemental abundances of 70-280 Mev/nucleon cosmic rays (closed circles, taken from Tab. 2 by Simpson, 1983) compared to the solar system abundances (open circles, taken from Tab. 38 by Lang, 1980) normalized to Si = 10^6.

Similarities

- peaks for C,N,O,Fe
- Even/odd mass number effect (nuclear stability)

Electrons and positrons

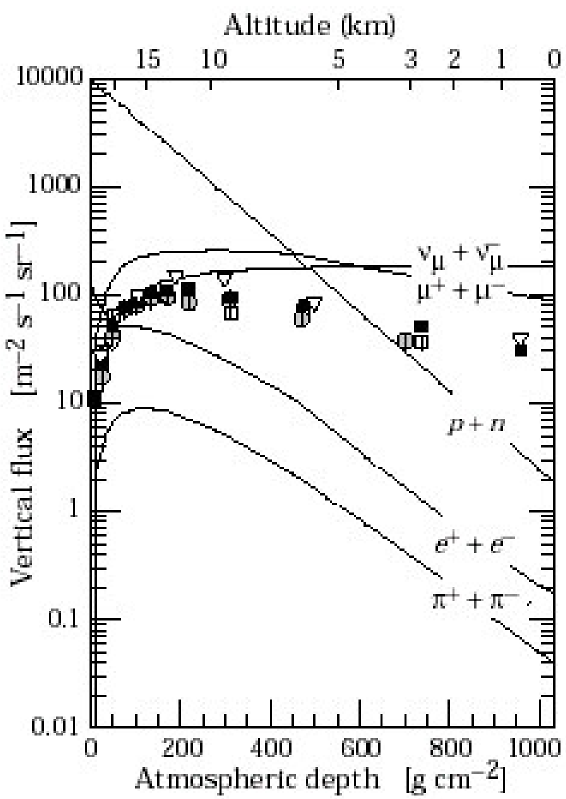


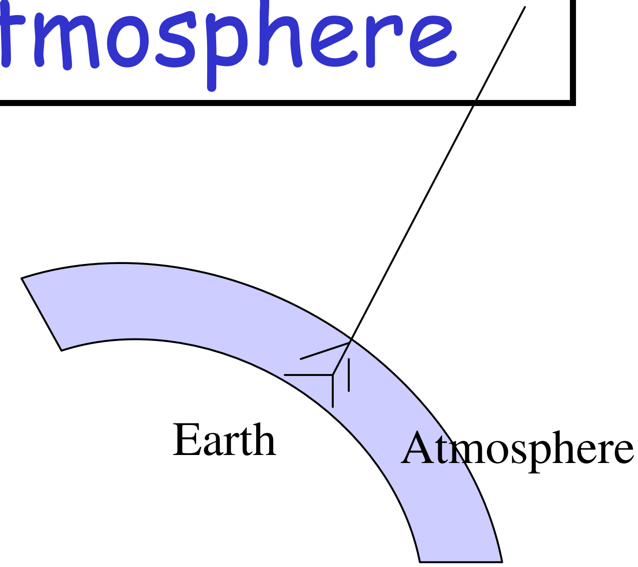
dashed line is proton spectrum x 0.01

Positron fraction (measured below 50 GeV) few percent

Cosmic Rays in the Atmosphere

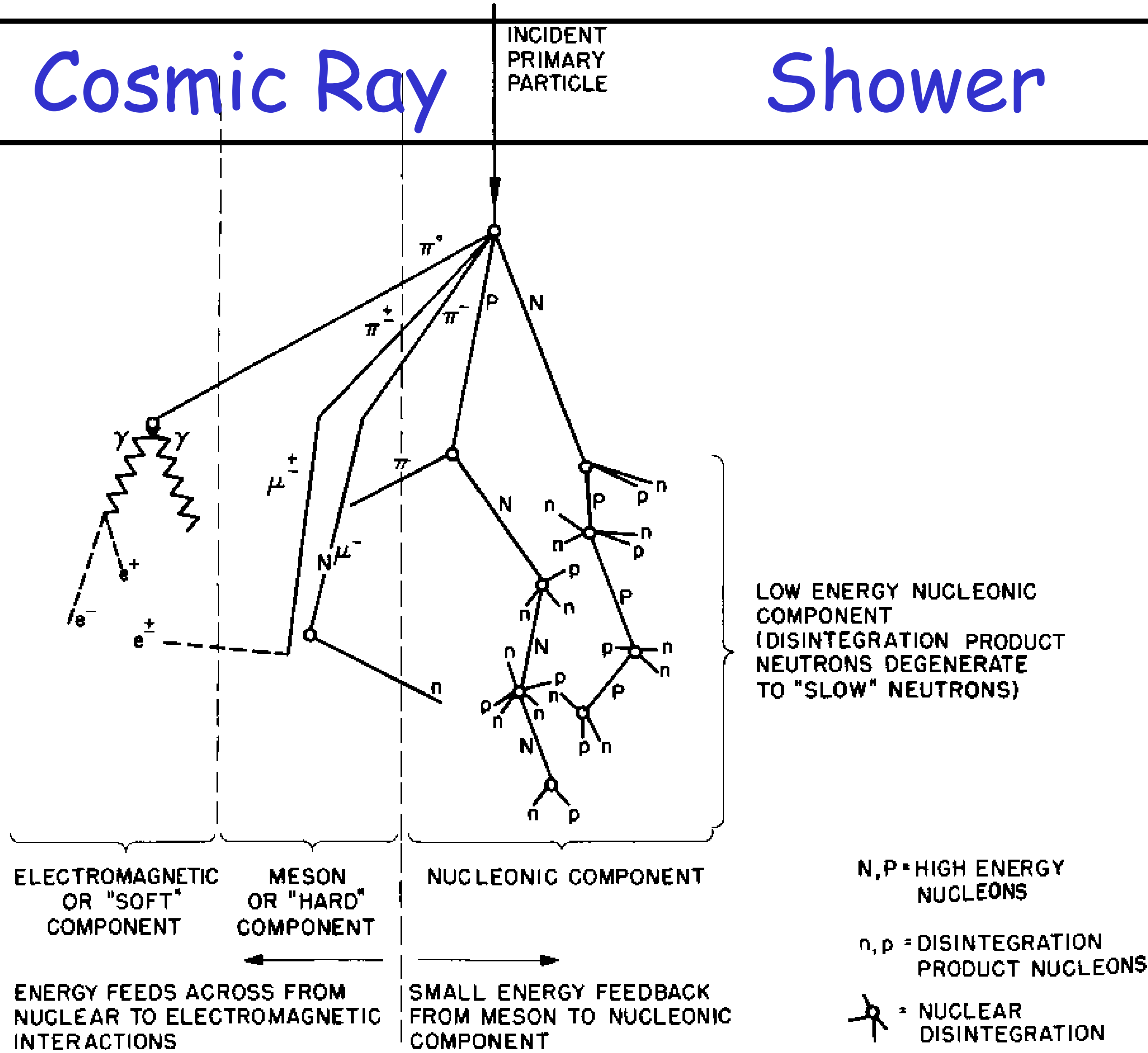
- The primary cosmic rays interact in the atmosphere, producing secondary particles





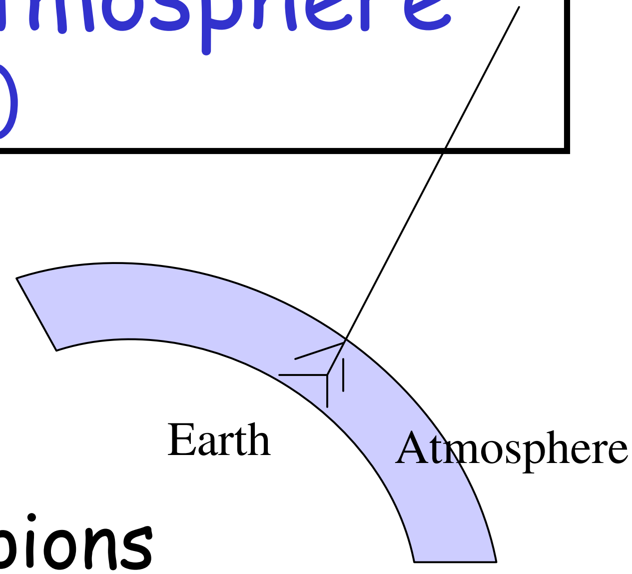
Lines are calculations for E > 1 GeV from the nucleon flux; data points are measurements of negative muons with E_μ > 1 GeV

Cosmic Ray Shower



Schematic Diagram of Cosmic Ray Shower

Cosmic Rays in the Atmosphere
(approx. model)



- Vertical intensity of nucleons:
- $I_N(E,X) \approx I_N(E,0)e^{-X/\Lambda}$

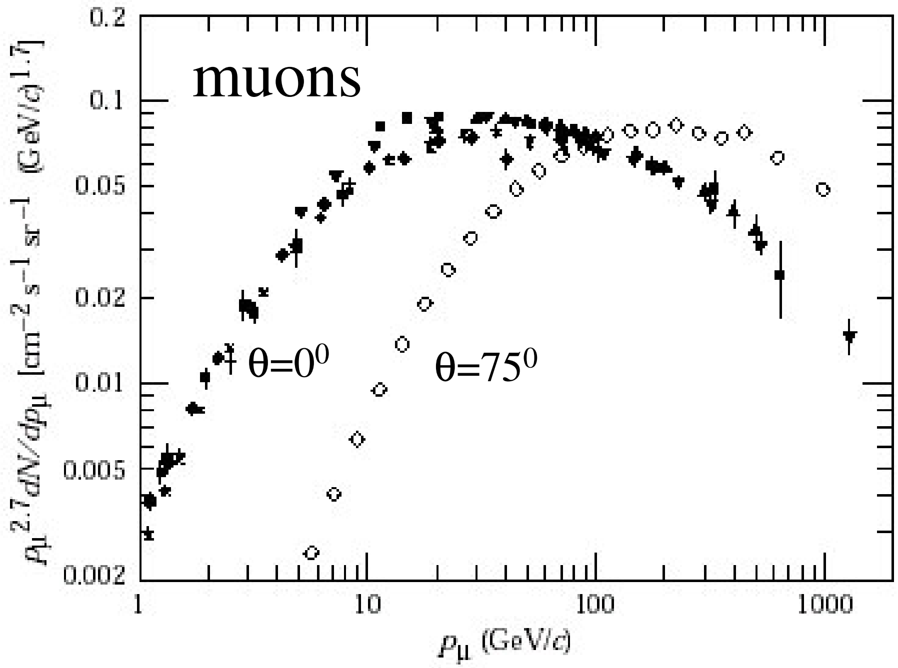
- Vertical intensity of charged pions ($E_\pi << \varepsilon_\pi = 115$ GeV)
- $I_N(E_\pi,X) \approx Z_{N\pi}\, I_N(E_\pi,0)e^{-X/\Lambda}\, X\, E_\pi/(\lambda_N\, \varepsilon_\pi)$

  - max at $X = \Lambda \approx 120$ g/cm^2 (15 km)
  - $Z_{N\pi}$ is spec-wtd moment of incl. charged pion from int. of nucleons in atmos. (≈ 0.079, pions decay)

Cosmic Rays at the Earth's Surface

- At the surface of the Earth, all particles have been produced by interactions of the primary cosmic rays
- Muons are the most numerous charged particles at sea level
- Typically produced

  15 km up, lose 2 GeV
- Mean energy 4 GeV
- $\approx$ 1 cm^{-2} min^{-1} (hor. det.)



Cosmic Rays at the Earth's Surface

- Electromagnetic component
  - electrons, positrons, and photons
  - from decays of neutral and charge mesons, and muon decays
  - $\approx 30\ m^{-2}\ s^{-1}\ sr^{-1}$ (E > 10 MeV)
  - $\approx 6\ m^{-2}\ s^{-1}\ sr^{-1}$ (E > 100 MeV)
  - $\approx 0.2\ m^{-2}\ s^{-1}\ sr^{-1}$ (E > 1000 MeV)

- Protons
  - $I_N(E,X) \approx I_N(E,0)e^{-X/\Lambda}$, $\Lambda = 123$ g cm^{-2}
  - $\approx 0.9\ m^{-2}\ s^{-1}\ sr^{-1}$ (E > 1 GeV/c)

Cosmic Rays Underground

- Muons lose energy by ionization and radiative processes

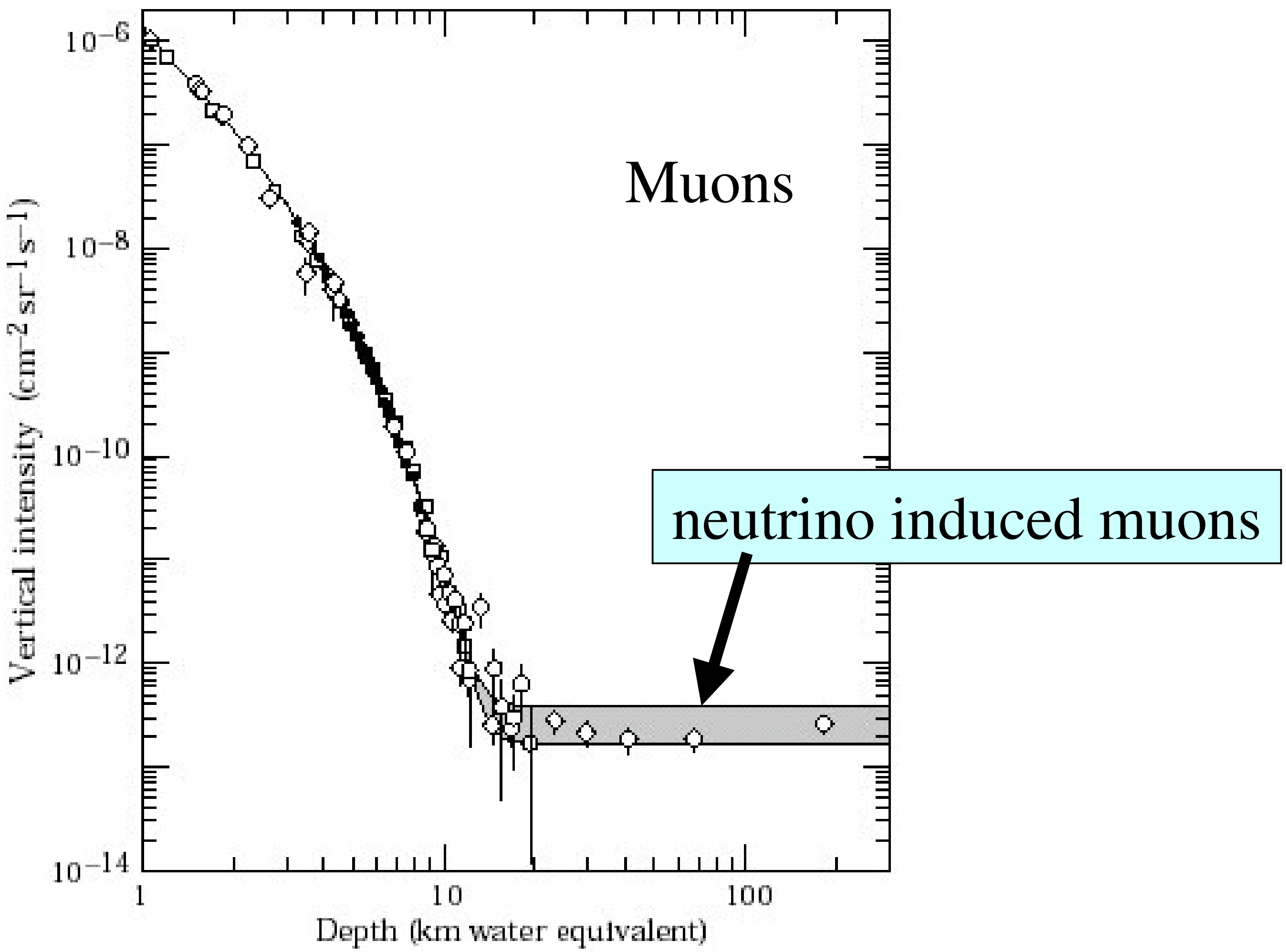
$$-dE_\mu/dx = a + b\,E_\mu$$

Table 20.2: Average muon range R and energy loss parameters calculated for standard rock[30]. Range is given in km-water-equivalent, or 10^5 g cm^{-2}.

E_μ GeV	R km.w.e.	a MeV g^{-1} cm^2	$b_{\rm brems}$	$b_{\rm pair}$ 10^{-6} g^{-1} cm^2	$b_{\rm nucl}$	$\sum b_i$
10	0.05	2.17	0.70	0.70	0.50	1.90
100	0.41	2.44	1.10	1.53	0.41	3.04
1000	2.45	2.68	1.44	2.07	0.41	3.92
10000	6.09	2.93	1.62	2.27	0.46	4.35

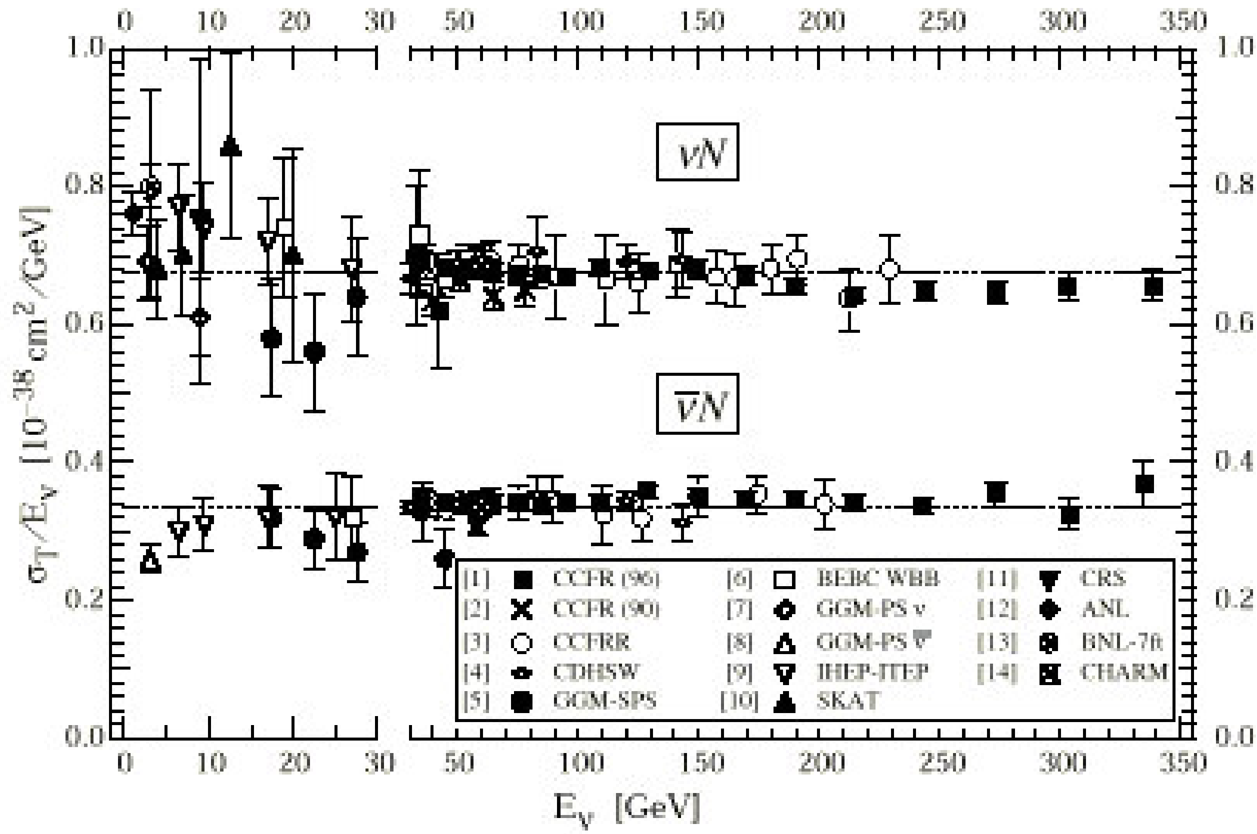
Standard rock is $\rho = 2.65$ g cm^{-3}

Cosmic Rays Underground



Neutrinos Underground

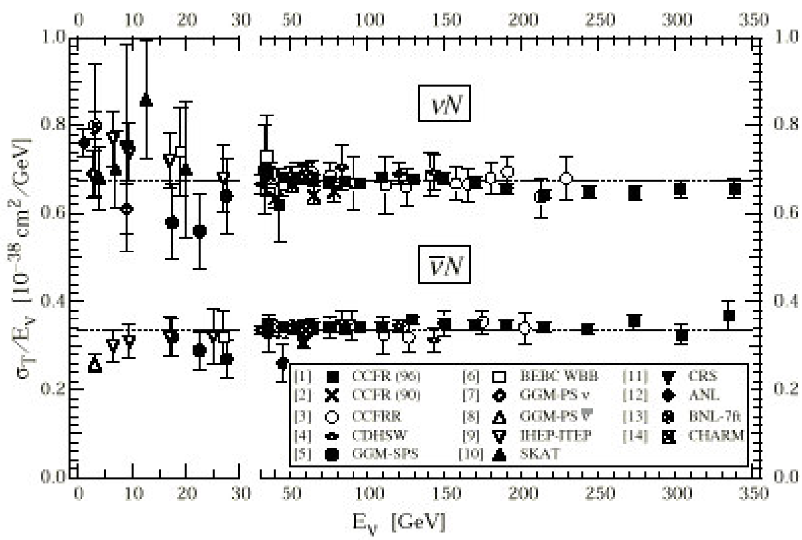
- Neutrino cross sections are so small that they generally penetrate the Earth without interacting



Neutrinos Underground

- $\sigma \approx 0.5 \times 10^{-38}\ \mathrm{cm}^2\ E_\nu/\mathrm{GeV}$

- $\lambda = 1/(\sigma N)$
  $\approx 10^{14}\ \mathrm{cm}\ /(E_\nu/\mathrm{GeV})$
  $\approx 4\mathrm{x}10^{4}\ D_{earth}\ /(E_\nu/\mathrm{GeV}$



- Neutrino components underground
  - Solar neutrinos
    - E ~ MeV
  - Cosmic ray induced in Earth's atmosphere
    - E $\geq$ GeV
  - Other sources

Problem Set Background

- The weakest force is gravity
- The coupling becomes large only at a very large energy scale, known as the Planck scale
- Planck scale is given by equation

$$(\hbar c/G_N)^{1/2} = 1.2 \times 10^{19} \text{ GeV}$$

- Quantum gravitational effects become important only at this scale

Helpful Example

- At what energy would a proton incident on a proton at rest be able to produce an antiproton
- The required reaction is $p\, p \rightarrow p\, p\, p\, \bar{p}$
- This reaction would require an energy in the center-of-mass of $4\, m_p$

$$\text{So, } E_{CM}^2 = (E_p + m_p)^2 - (p_p - 0)^2 > (4m_p)^2$$

$$= E_p^2 + 2\, E_p m_p + m_p^2 - p_p^2$$

$$= 2\, E_p m_p + 2\, m_p^2 > (4m_p)^2$$

$$E_p m_p > 7\, m_p^2$$

$$\boxed{E_p > 7\, m_p}$$

Background on Curvature in B Field

- Curvature of a relativistic charged particle in a magnetic field

- Lorentz force: $\vec{F} = q\,\vec{v}/c \times \vec{B}$

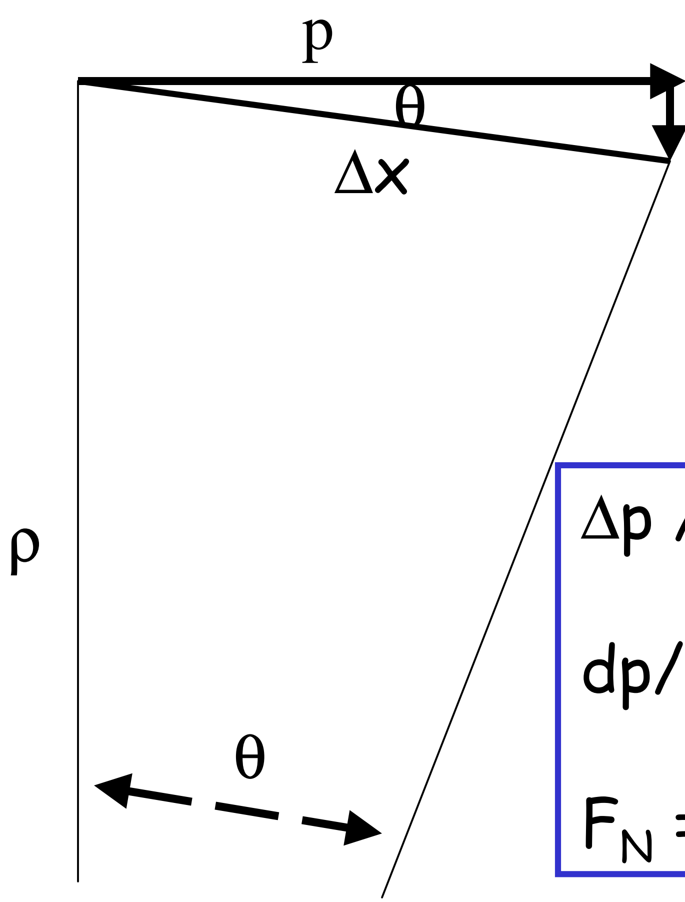
- Motion: $d\vec{p}/dt = \vec{F}$

- Radius of curvature (ρ): $F_n = pv / \rho$

  so $q\,(v/c)\,B = pv / \rho$ or $\rho = cp/qB$

  $p\,(\mathrm{GeV}/c) = 0.3\,B(\mathrm{Tesla})\,\rho(\mathrm{meters})\,q$

Background on Curvature in B Field



$\Delta p = dp/dt\ \Delta x/v$

$\Delta p / p = \Delta x / \rho$

$dp/dt\ (\Delta x/v) / p = \Delta x / \rho$

$F_N = vp / \rho$