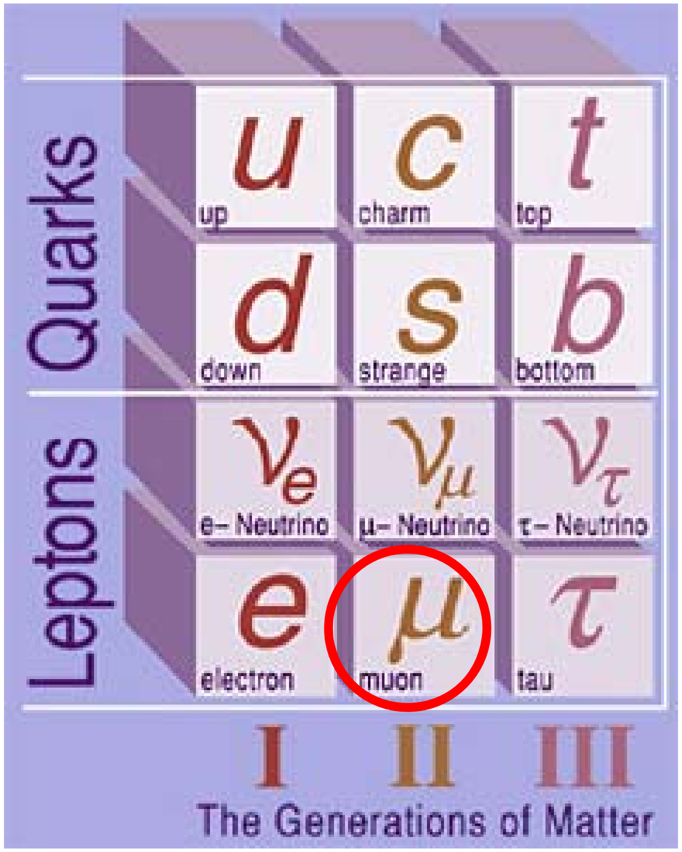
Nature’s building blocks



FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

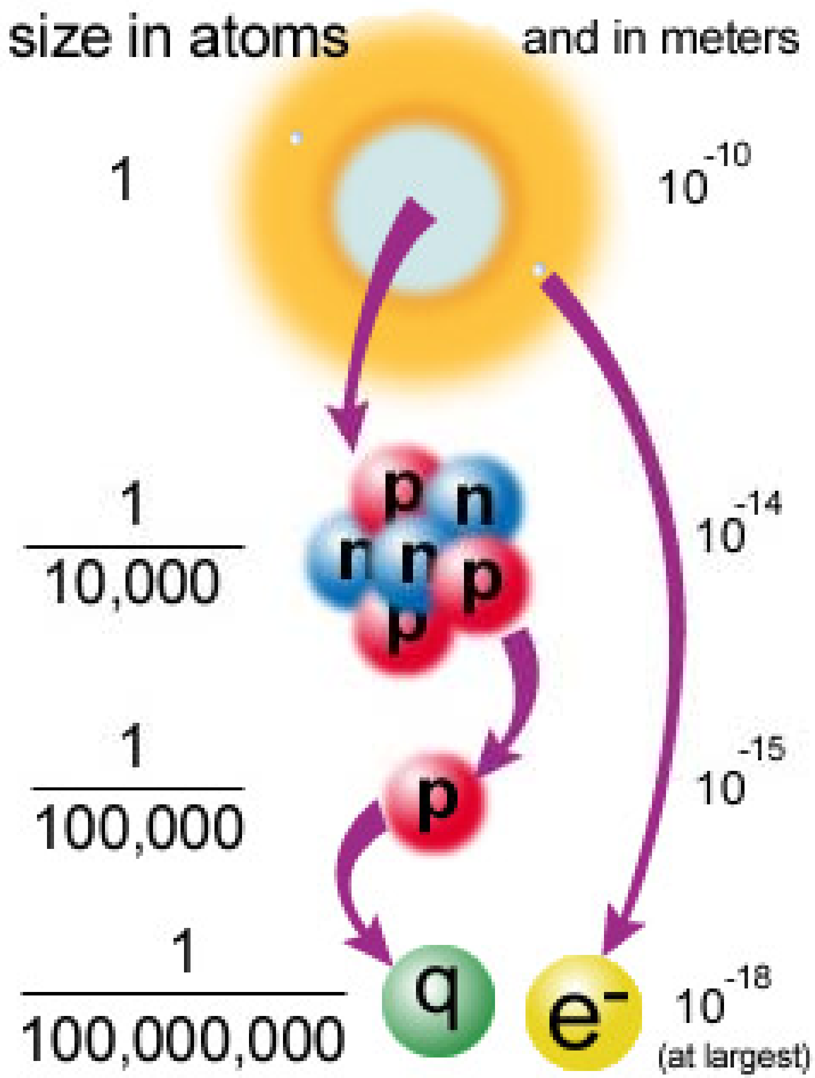
Quarks spin = 1/2

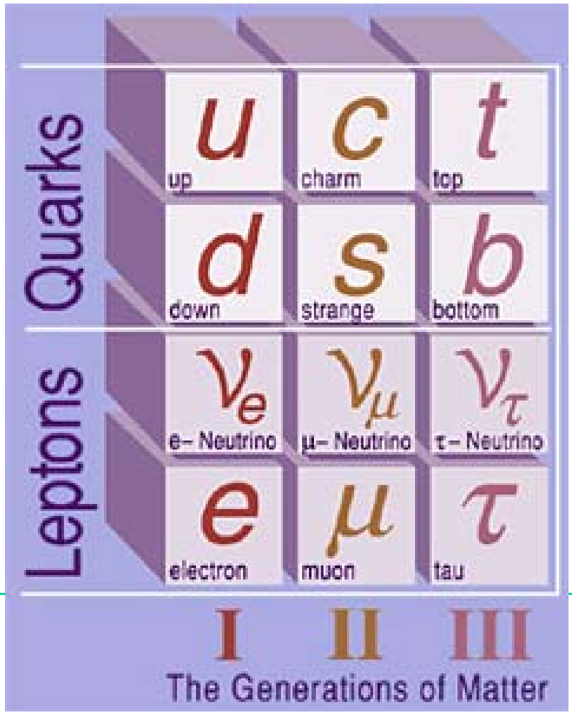
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

building blocks → matter





- Baryons: qqq

Examples:

proton (p) = uud

charge: 1e=(2/3 e) + (2/3 e) + (-1/3 e)

neutron (n) = udd

charge: 0 = (2/3 e) + (-1/3 e) + (-1/3 e)

- Mesons: q anti-q.

Examples:

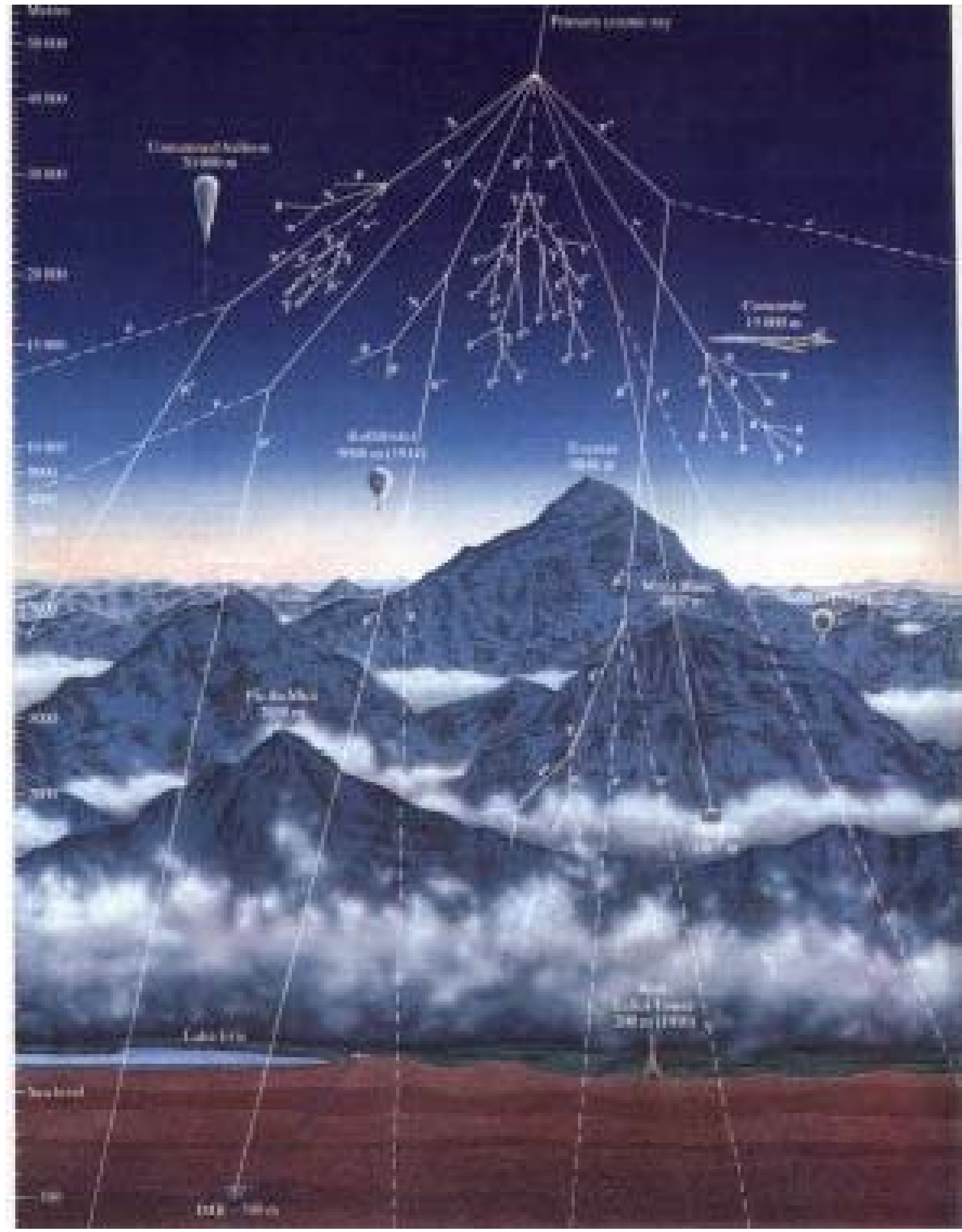
π^+ = u anti-d   charge: 1e=(2/3 e) + (1/3 e)

π^- = d anti-u   charge: -1e=(-1/3 e) + (-2/3 e)

- atoms: p+n+e;   e.g. hydrogen: p + e

Cosmic Rays

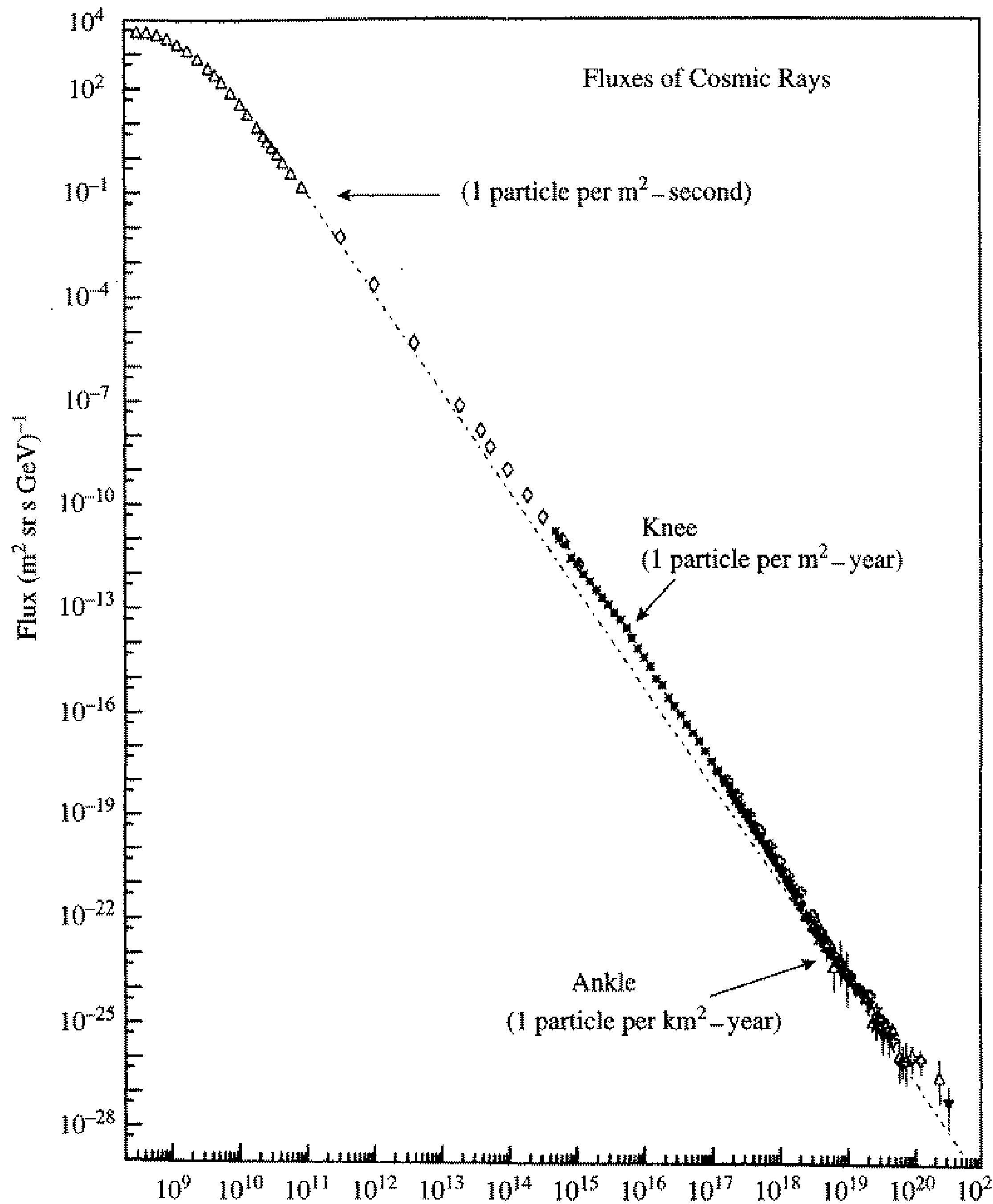
- Outside earth's atmosphere, these are charged particles, 86% protons
- These *primary* cosmic ray particles interact with air high in the atmosphere (~15 km), creating showers of secondary particles
- By time the secondaries reach sea level, muons dominate the flux
- The detectable (vertical) rate at sea level is $\approx 1/cm^2/min$
- Throughout our galaxy, CRs have an energy density of $\approx 1\ eV/cm^3$
    - Starlight: $0.6\ eV/cm^3$
    - CMB: $0.26\ eV/cm^3$
- ~30% of natural radiation (sea level)
- Provide charge and seeds for lightning



from QuarkNet CRD manual

energy and origin of primaries

- Steeply falling, power law energy spectrum
- For E<10^{14} eV, spectrum and flux are consistent with acceleration by shock waves from supernovae ("Fermi acceleration")
- For largest energies, mechanism is unknown (Gamma-ray bursts??)
- For E>10^{19} eV, protons would not be captured by galactic magnetic field (3×10^{-10} T)
  - p_t [GeV] = (0.3q/e)B[T] R[m]
- So higher energy CRs must be extra-galactic (but GZK cutoff)

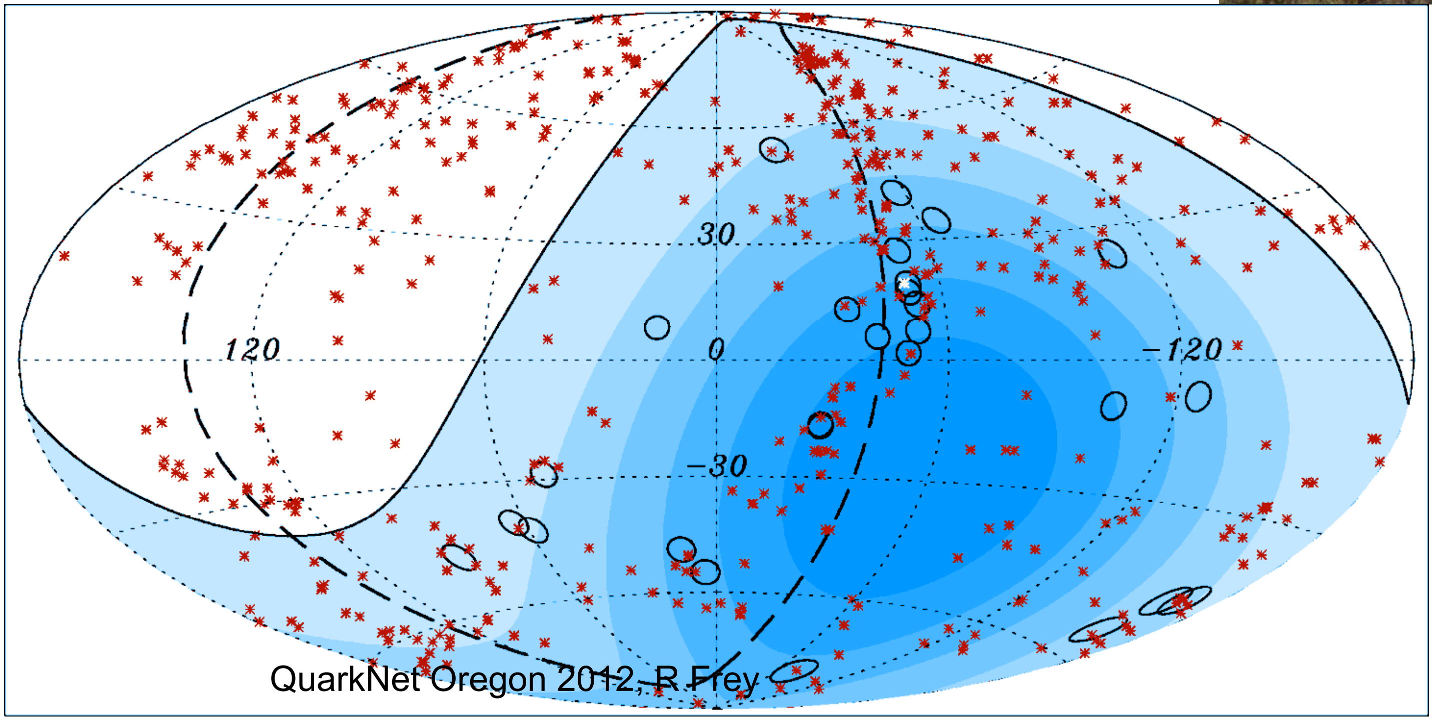


Auger CR observatory
www.auger.org

- Sites in Mexico and Argentina
- Array of detectors: (40x1.5 km)x(40x1.5 km)
- GZK: extragalactic CRs attenuated:

  $p + \gamma\ (\mathrm{CMB}) \rightarrow \Delta^+ \rightarrow p + \pi^\circ,\ \ n + \pi^+$

  - 411 CMB photons/ cm^3 ; $E = k \times 2.7K = 2.4 \times 10^{-4}$ eV
  - No protons $>10^{20}$ eV from further than 5 Mpc
- Summer 2007: No excess above GZK cutoff
- Fall 2007: UHE CRs associated with AGNs

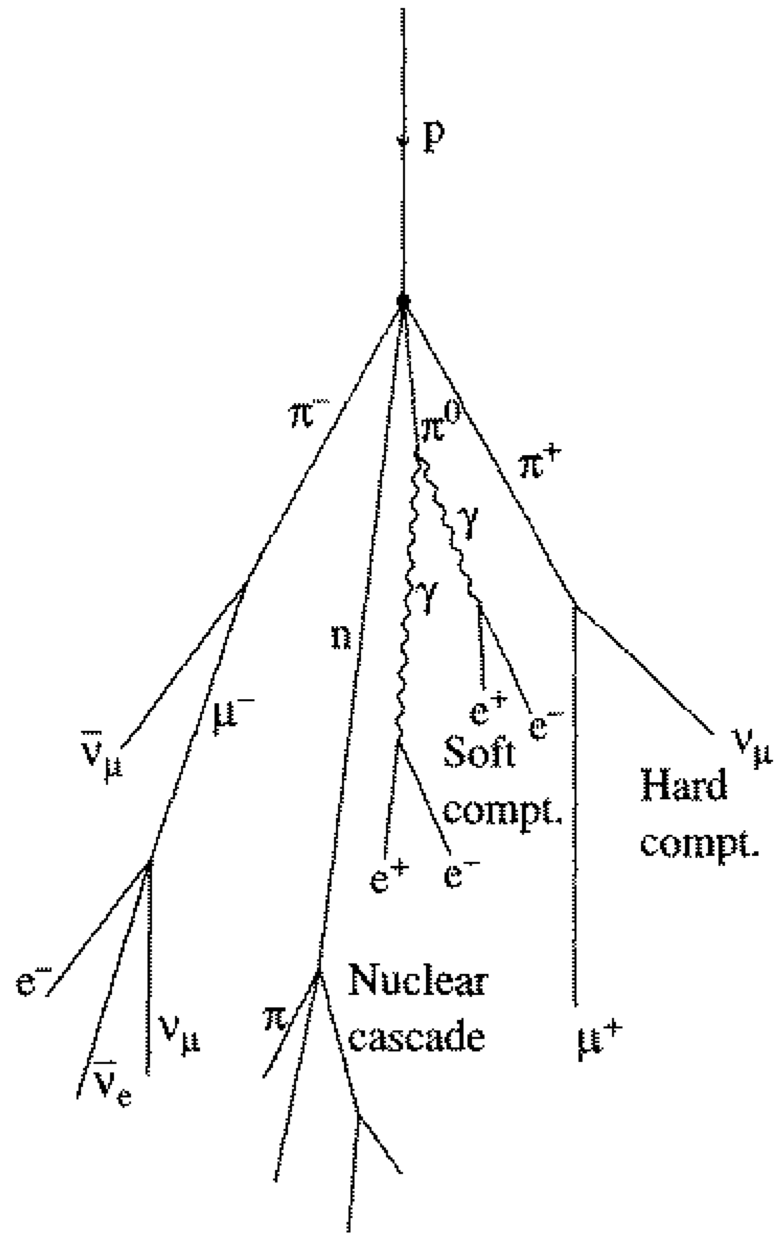


The cosmic ray showers

- Primaries interact in the atmosphere – the maximum production of pions and muons is at $z \approx 15$ km, making showers of (mostly) short-live particles.(e.g. pion ($\pi^{\pm}$) lifetime is 2.6×10^{-8} s)
- Characteristic shower angle:

  $\theta \approx p_t / p_L \approx 0.2$ GeV/E
- The long-lived secondaries are:
  - $e^{\pm}$, photons: mostly absorbed
  - neutrinos (ν): practically invisible
  - muons ($\mu^{\pm}$): τ_{μ}=lifetime is 2.2×10^{-6} s
- Without time dilation, muons would travel $d < c\tau = 660$ m, with a survival fraction

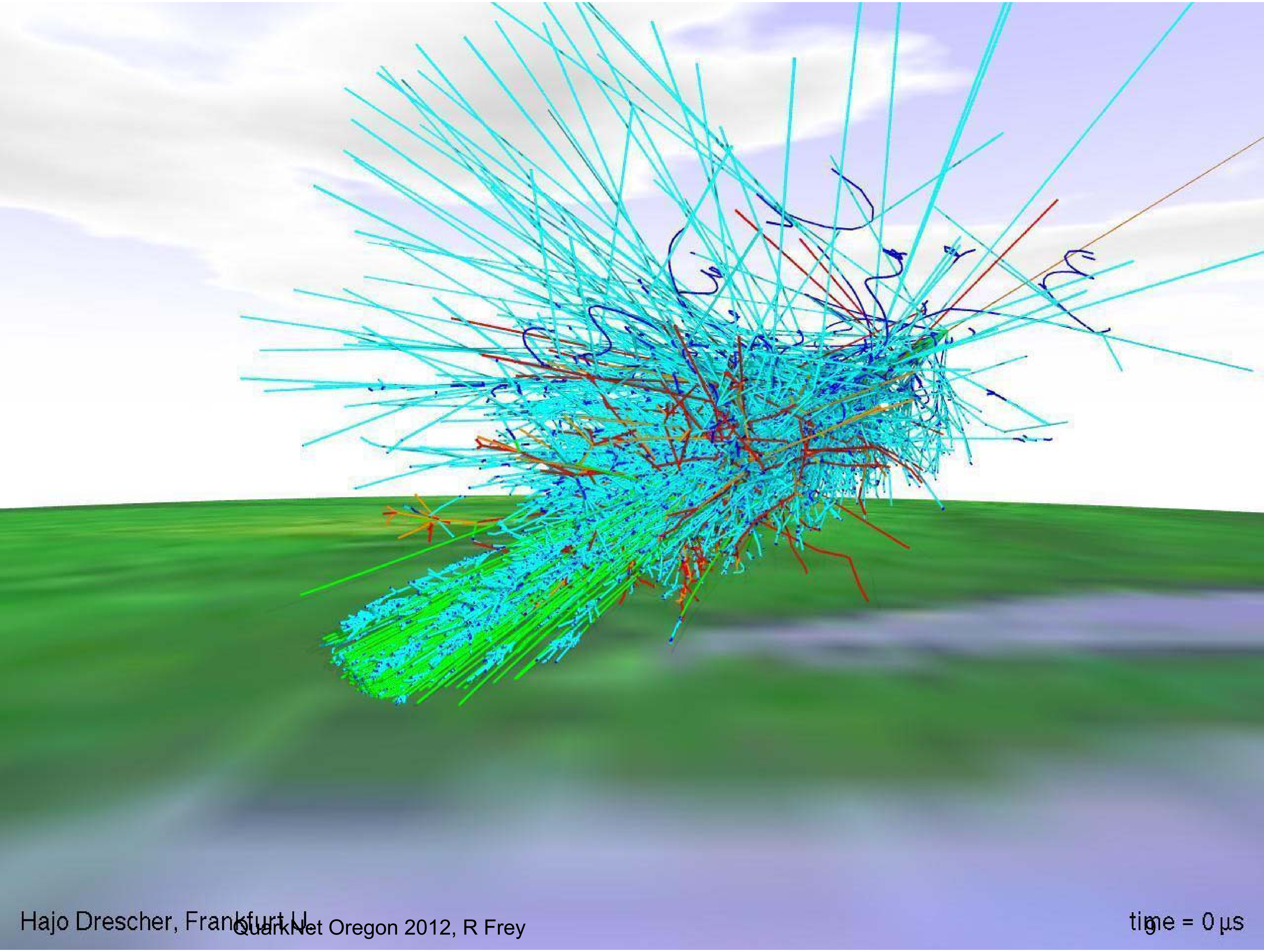
  $e^{-0.66/15} \approx 10^{-10}$
- Instead, for a 10 GeV muon, $\gamma \approx 10/0.1 = 100$, then mean distance is 66 km. (OK)



cosmic rays at earth's surface

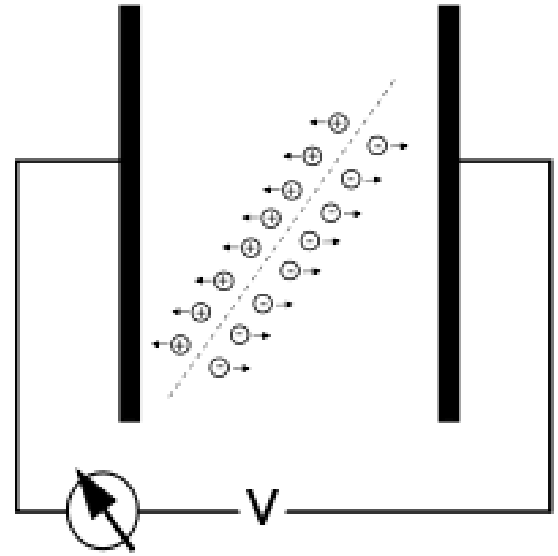
- Predominantly muons
- Detectable (vertical) flux is $\approx 1/\ cm^2/\ min$
- Mean energy $\approx$ 4 GeV
- Originate at altitude of 15 km, on average
- The very low energy muons ($\approx$1-3 GeV) mostly decay
  - 15 km decay length corresponds to a 2.4 GeV muon
- The higher energy muons lose about 2 GeV (on average) due to ionization in the atmosphere
  - and about 4 MeV / cm in concrete


Hajo Drescher, Frankfurt U.
time = -300 µs

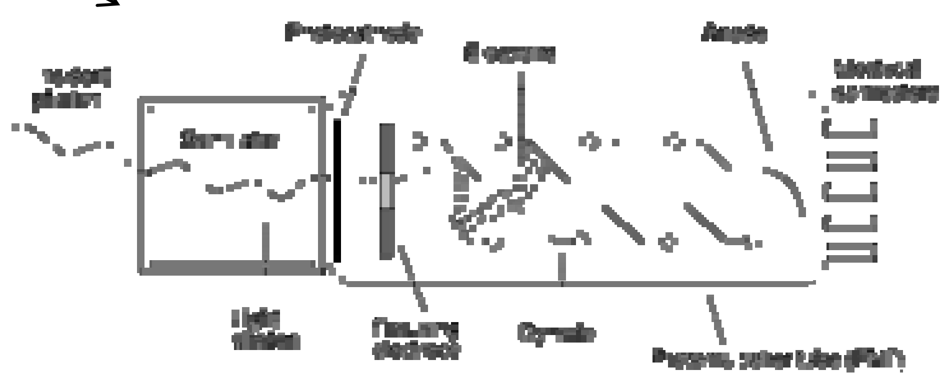

Hajo Drescher, Frankfurt U.
time = 0 µs

Basic principle of particle detectors

- High-energy charged particles (e.g. cosmic rays, nuclear decays, LHC collisions x-rays, gamma rays, etc) ionize the medium they pass through.
- The ionization is detected directly or by separation amplification) of the charge pairs.
- Uncharged particles (e.g. x/gamma-rays) similar
- That's it (almost).

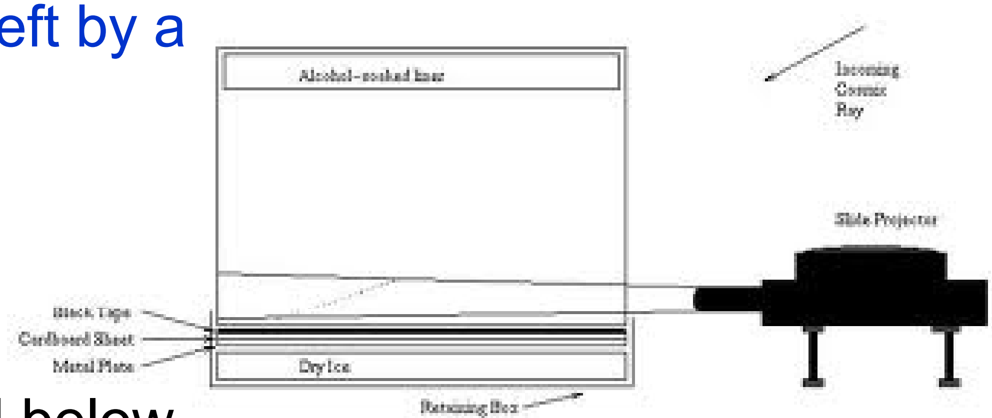


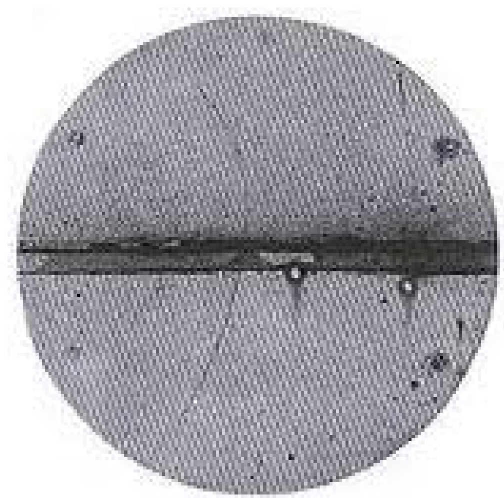
- Examples:
  - Geiger and other gaseous counters
  - Scintillator (e.g. quarknet CRDs)
  - Smoke detectors
  - Semiconductor detectors
  - Bubble chambers
  - Spark chambers
  - Cloud chambers



Cloud chambers

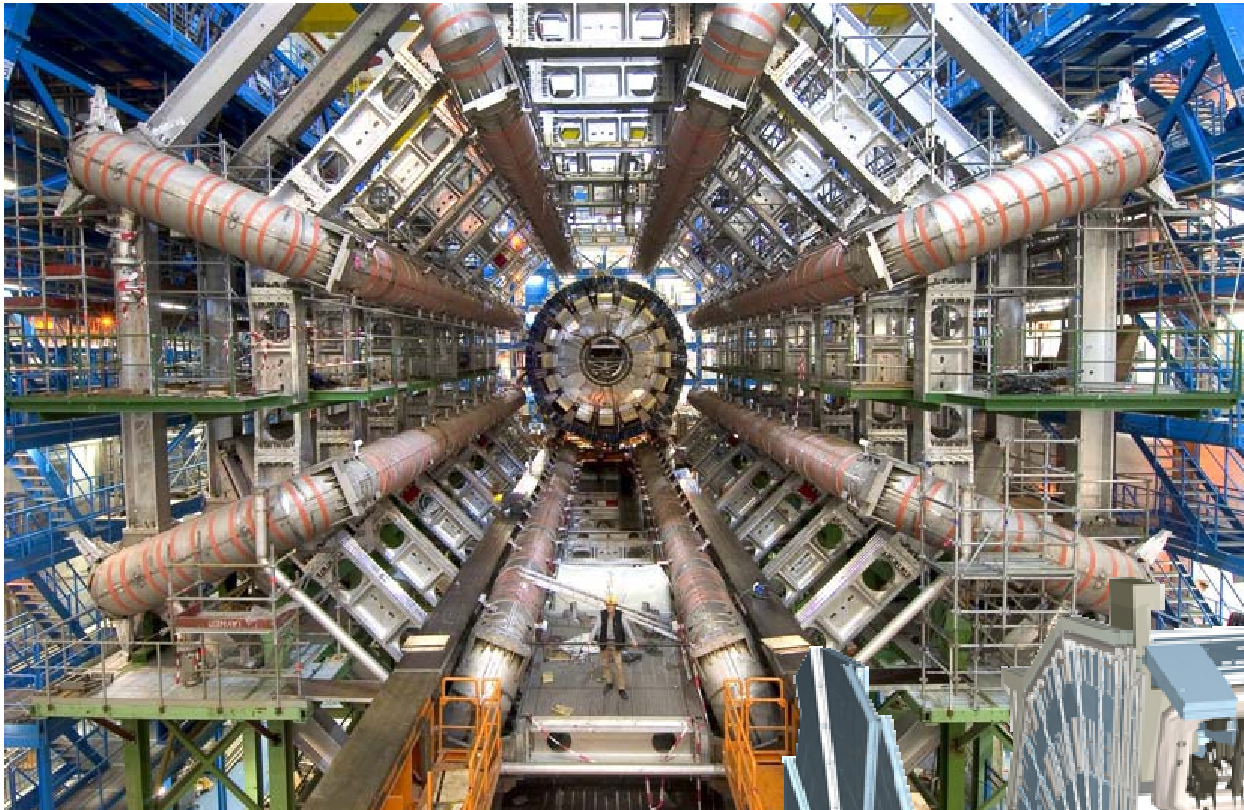
- A supersaturated vapor will preferentially condense along the ionization trail left by a passing particle.
- Basic ingredients are:
  - A fluid with high vapor pressure (alcohol)
  - A cold plate at temperature well below boiling point
  - Very still conditions
  - A strong light and black background
  - An electric field is sometimes applied

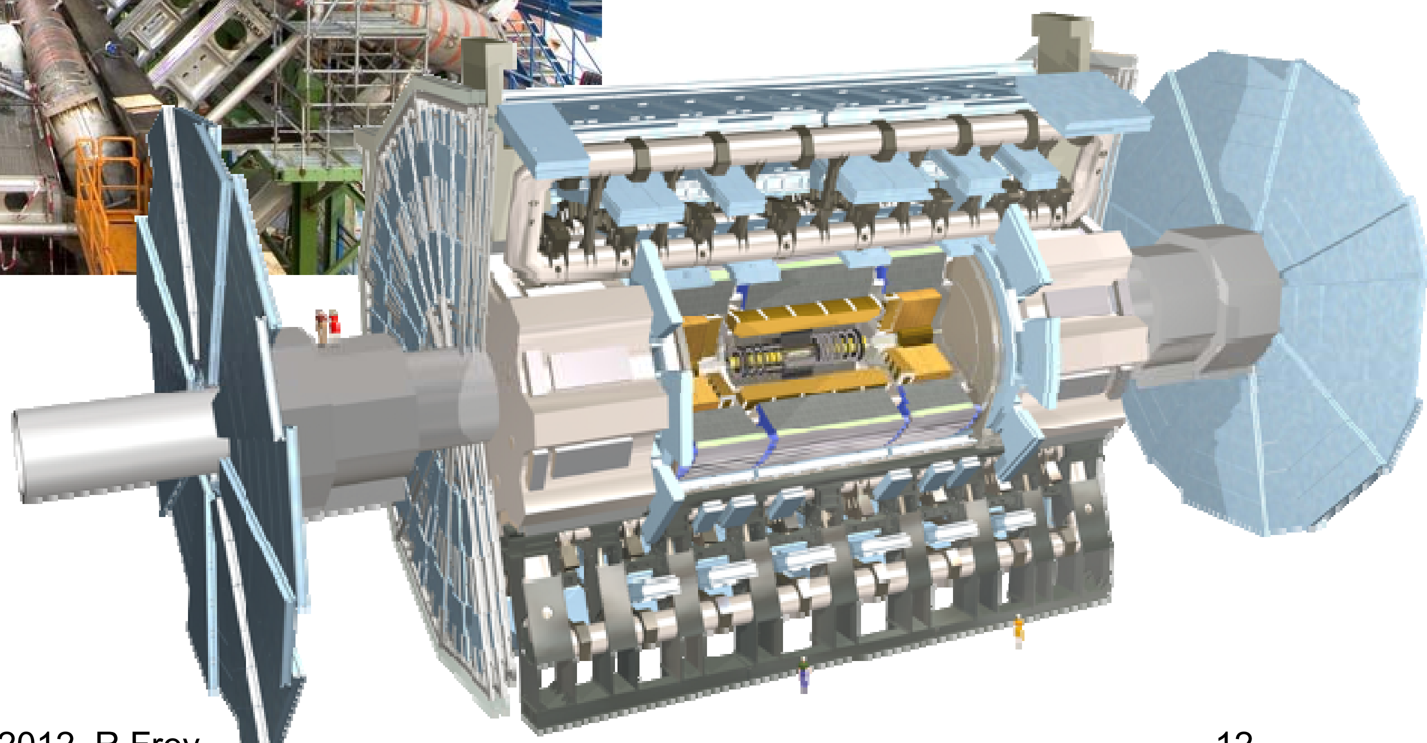




- Invented by Wilson (1911)
- Used to discover positron (1932) by Anderson
- Replaced by other techniques for HEP

Modern particle detectors





What particles are actually detected?

FERMIONS
matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
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c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

BOSONS
force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$
Baryons are fermionic hadrons.
There are about 120 types of baryons.

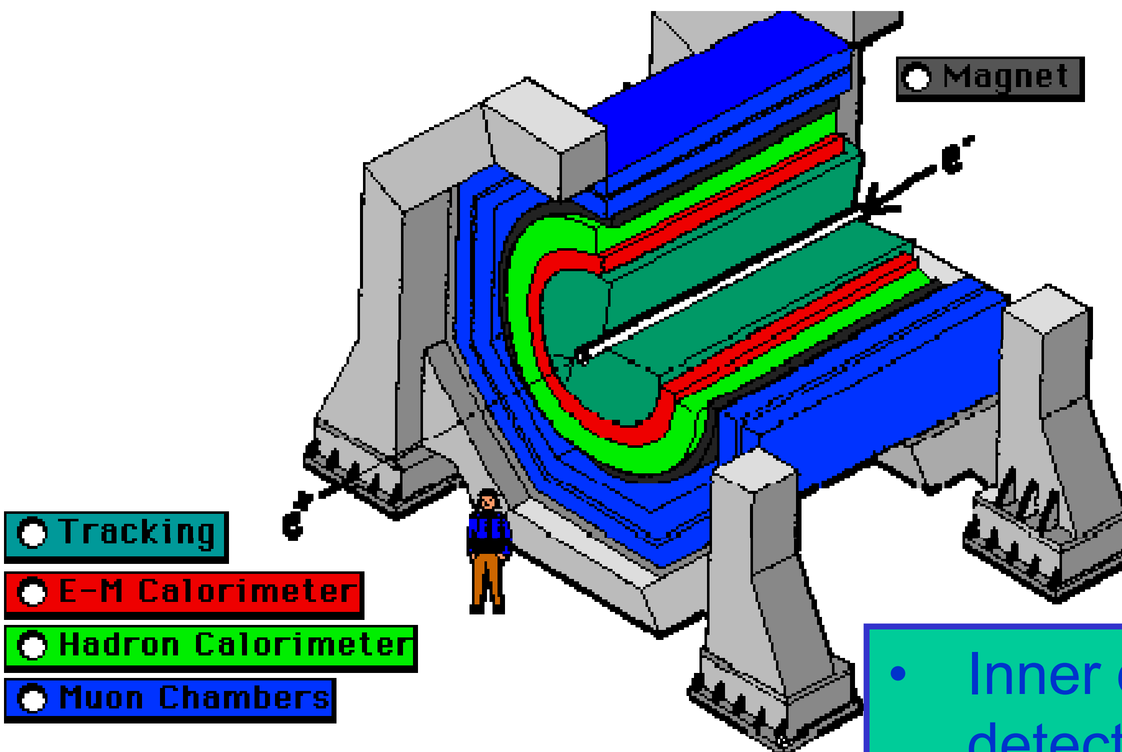
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	−1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	−1	1.672	3/2

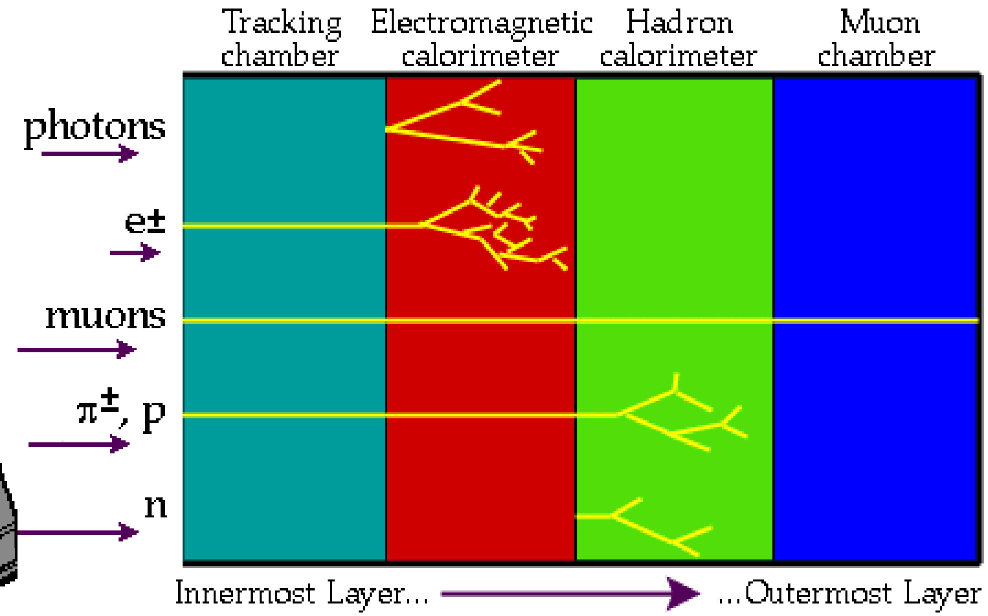
(mostly)

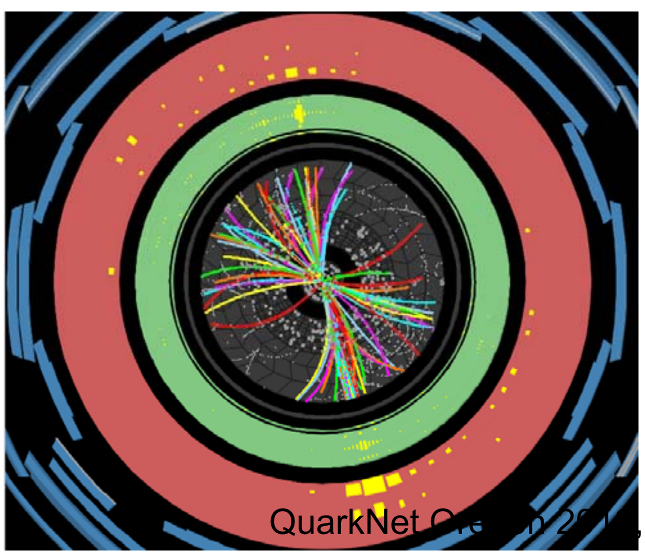
Mesons $q\bar{q}$
Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	−1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Detectors revealed

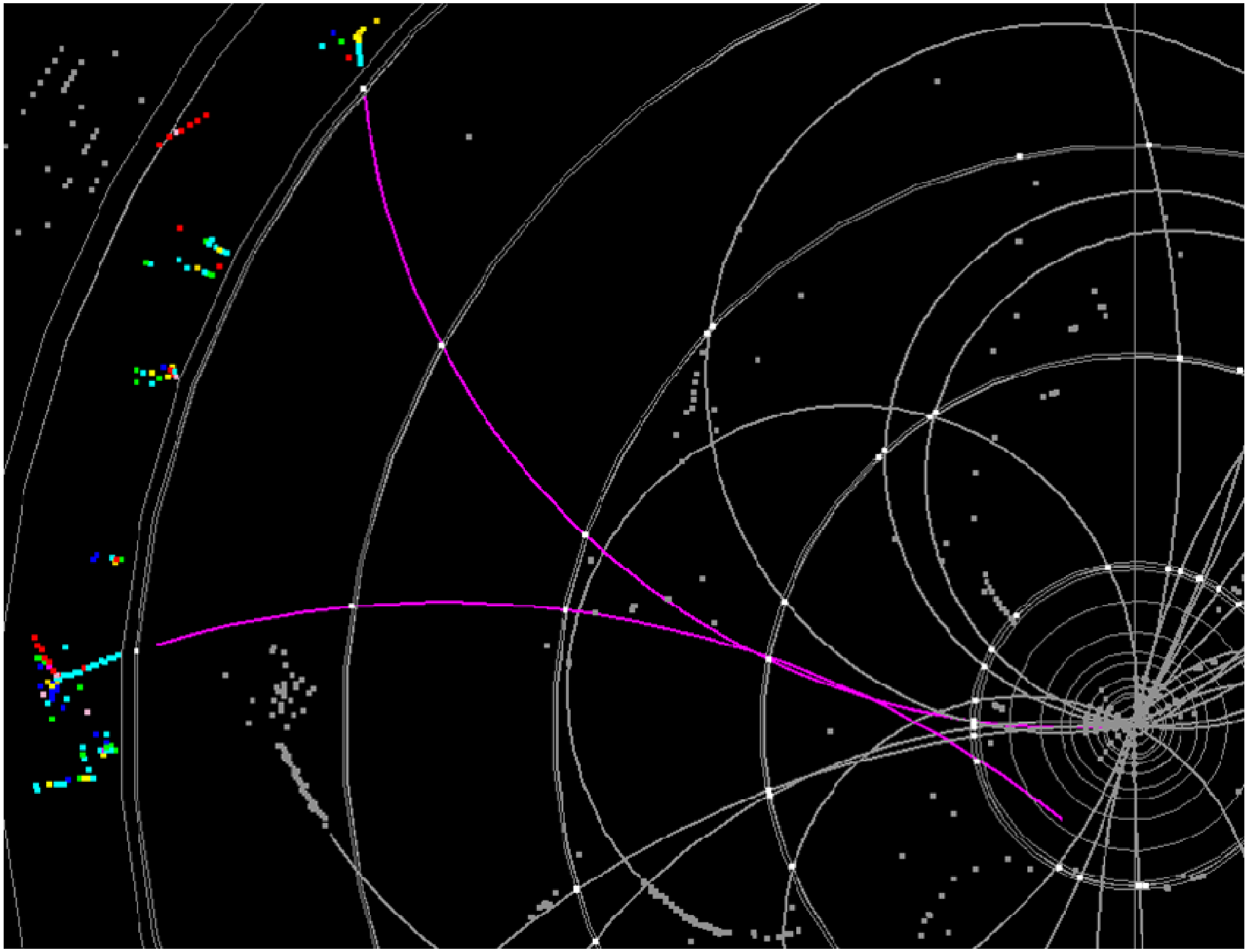


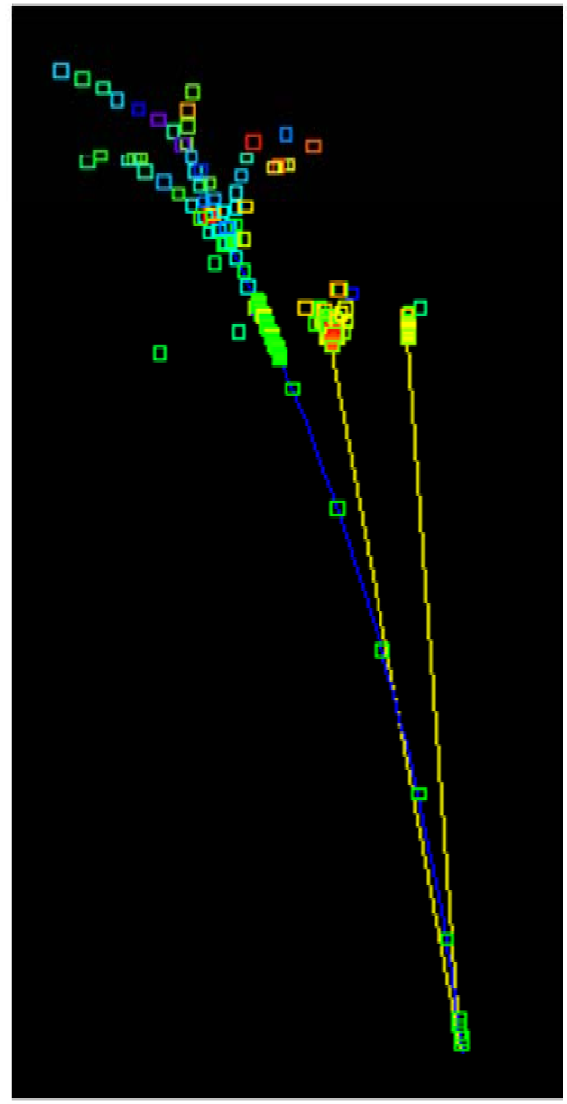




- Inner detectors: Low density ionization detectors to measure trajectory of charged particles (gas, thin silicon) in a uniform magnetic field (p=qvB). [trackers]
- Outer detectors absorb and measure particle energies. [calorimeters]
- Muons (and neutrinos) survive.
- **Energy & Momentum conservation to reconstruct the processes**

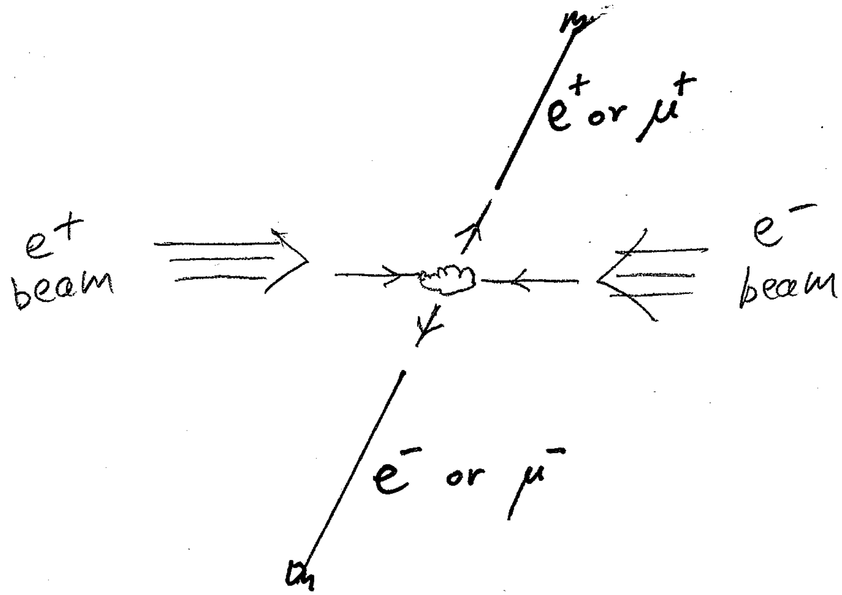
pix (silicon detectors)



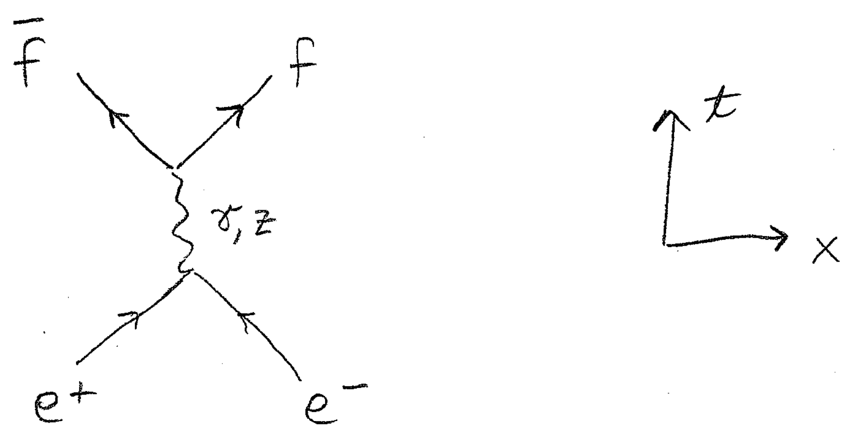


$$e^+e^- \to f\bar{f}\,, \quad f = \begin{cases} e,\ \mu,\ \tau,\ \nu \\ u, d, s, c, b, t \end{cases}$$

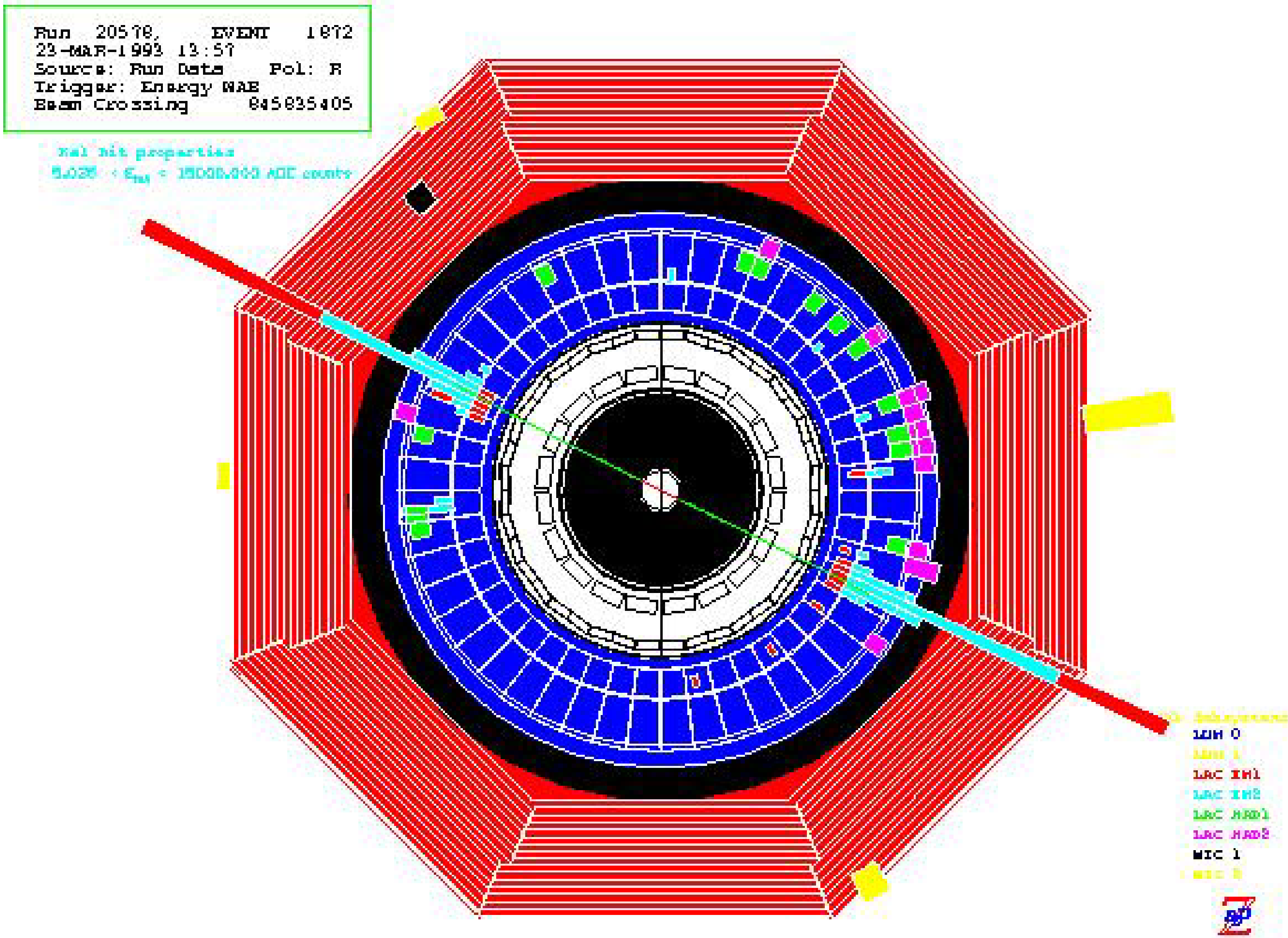
detector :



Fundamental :
(Feynman diagram)

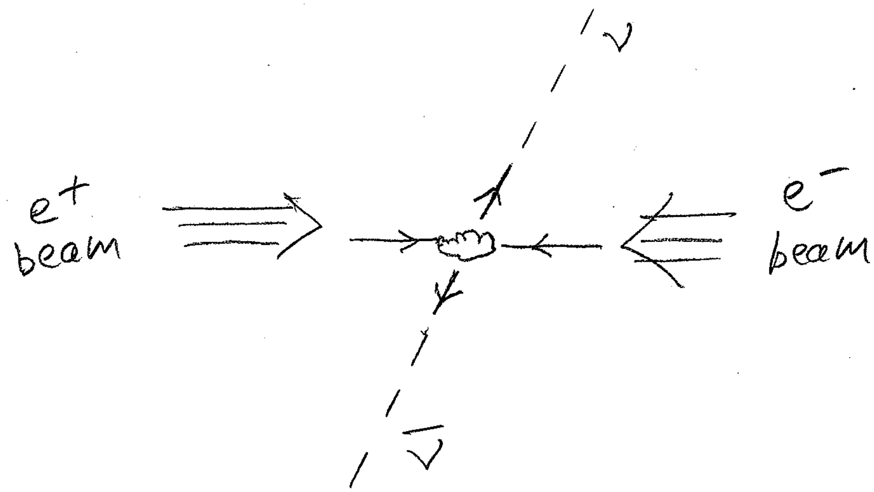


e.g. e+e- → e+e- at E=91 GeV



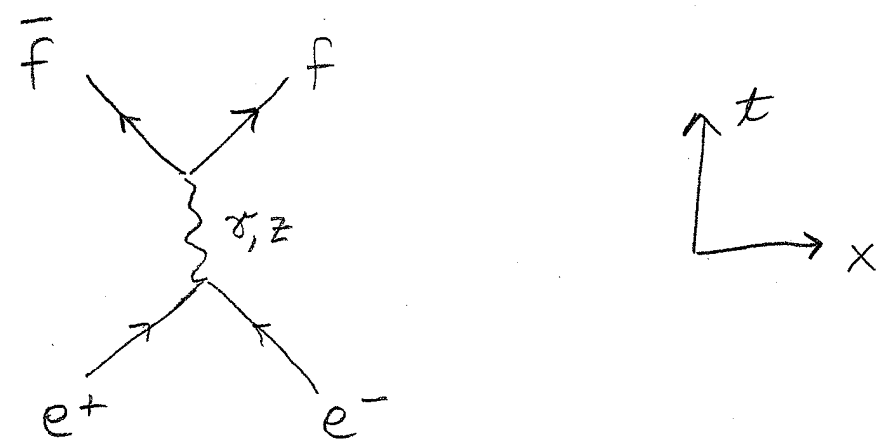
$$e^+e^- \to f\bar{f}\,, \quad f = \begin{cases} e, \mu, \tau, \nu \\ u, d, s, c, b, t \end{cases}$$

detector:

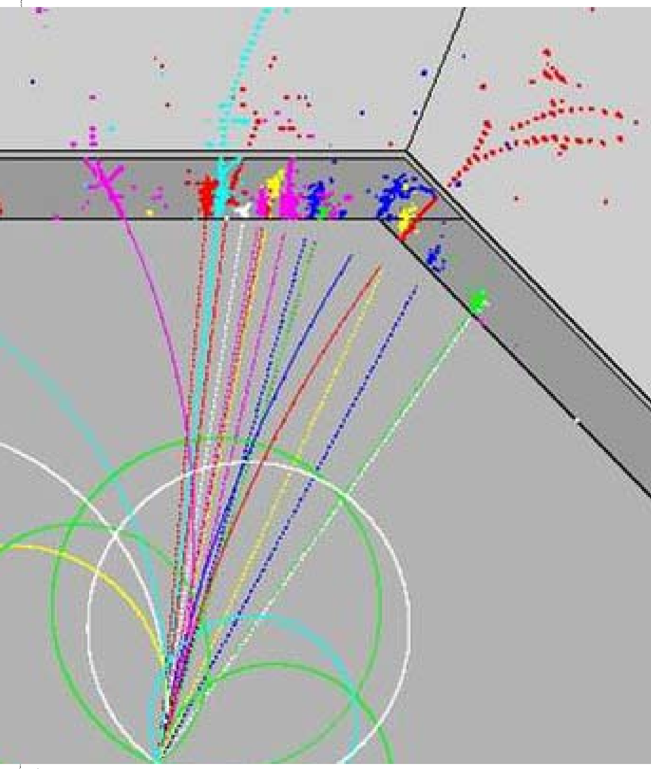


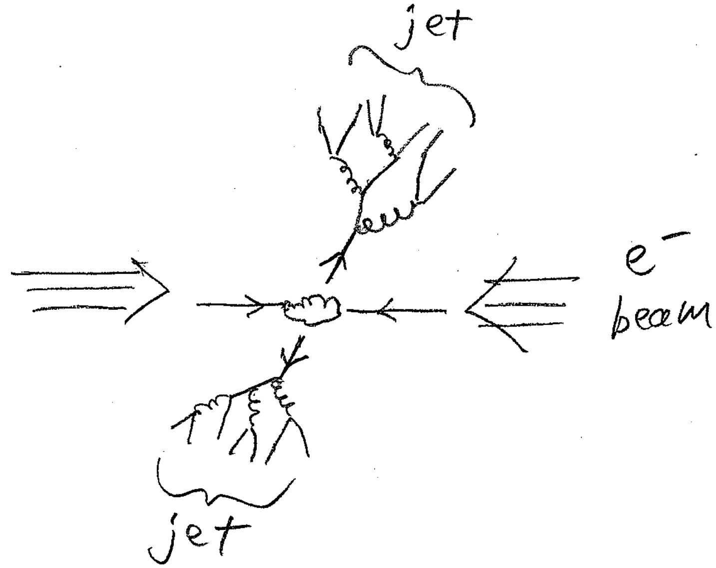
Fundamental:

(Feynman diagram)



$$e^+e^- \to f\bar{f}, \quad f = \begin{cases} e, \mu, \tau, \nu \\ u, d, s, c, b, t \end{cases}$$

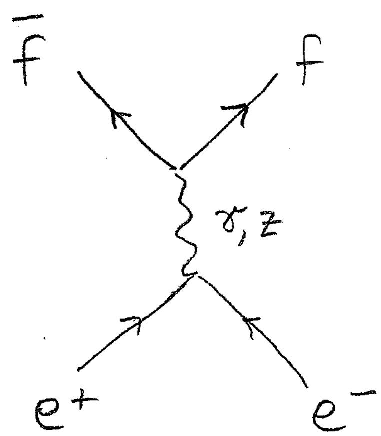


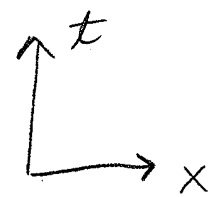


$\rightsquigarrow$ f has "color"

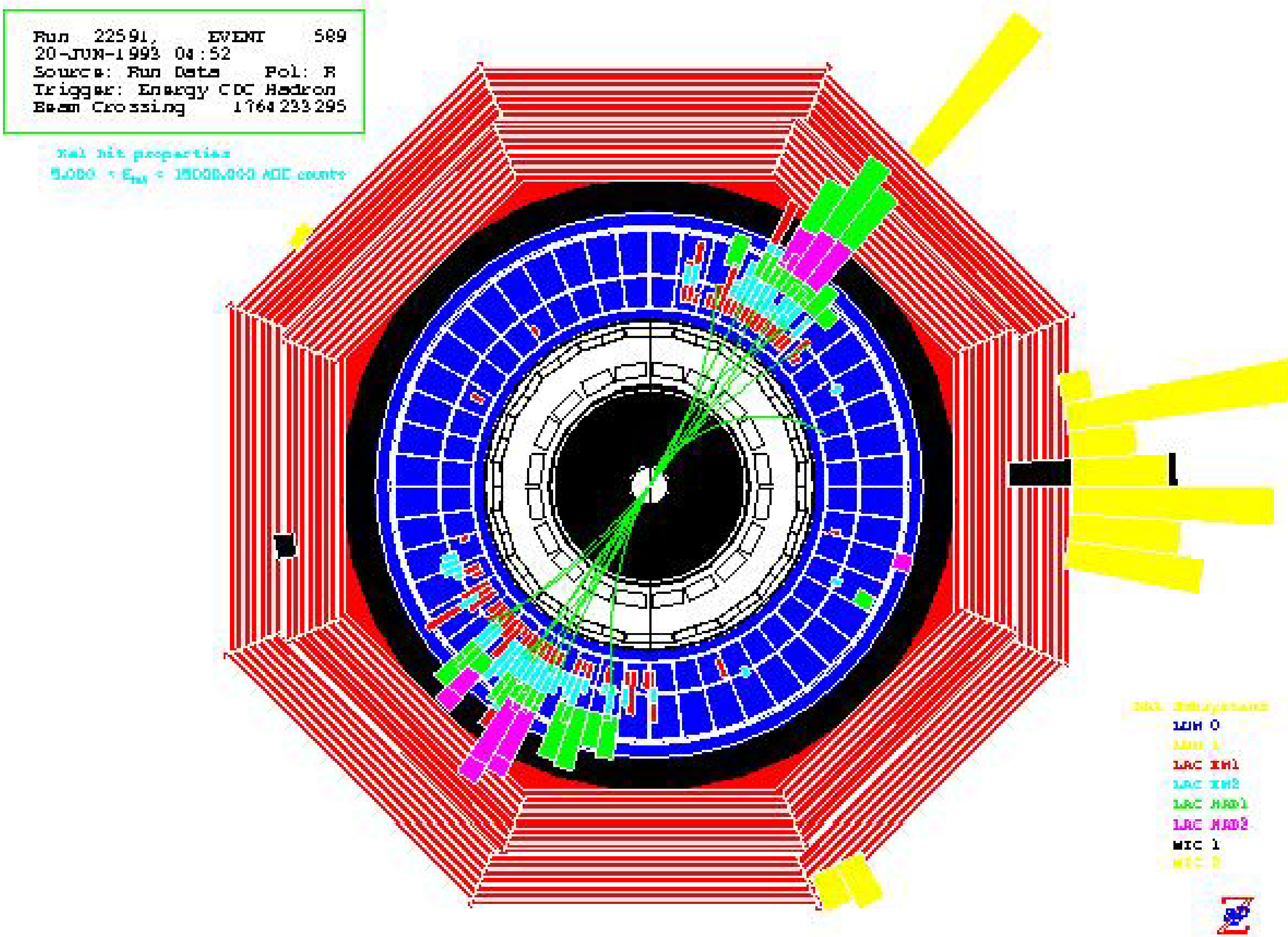
Fundamental:

(Feynman diagram)

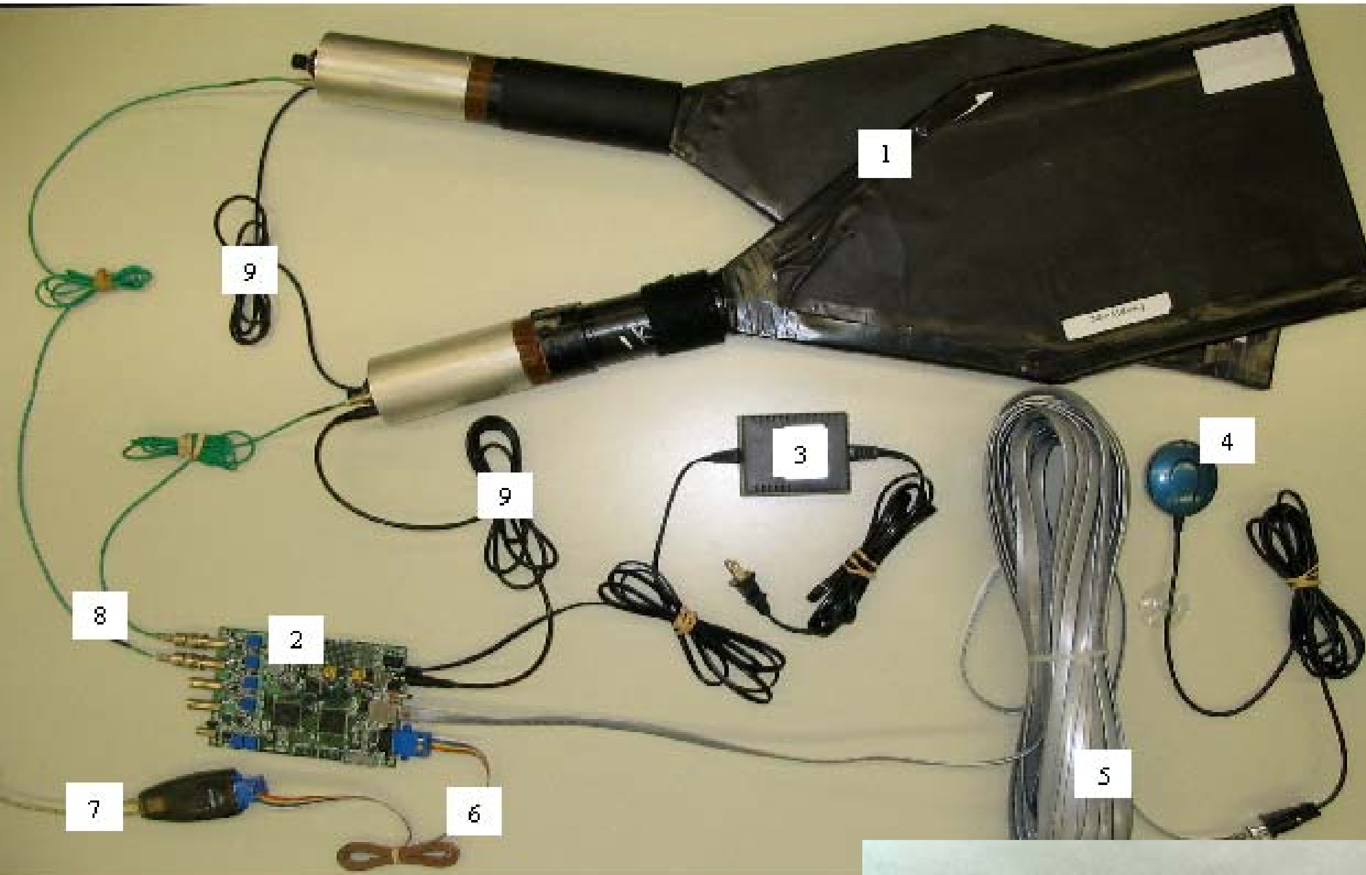




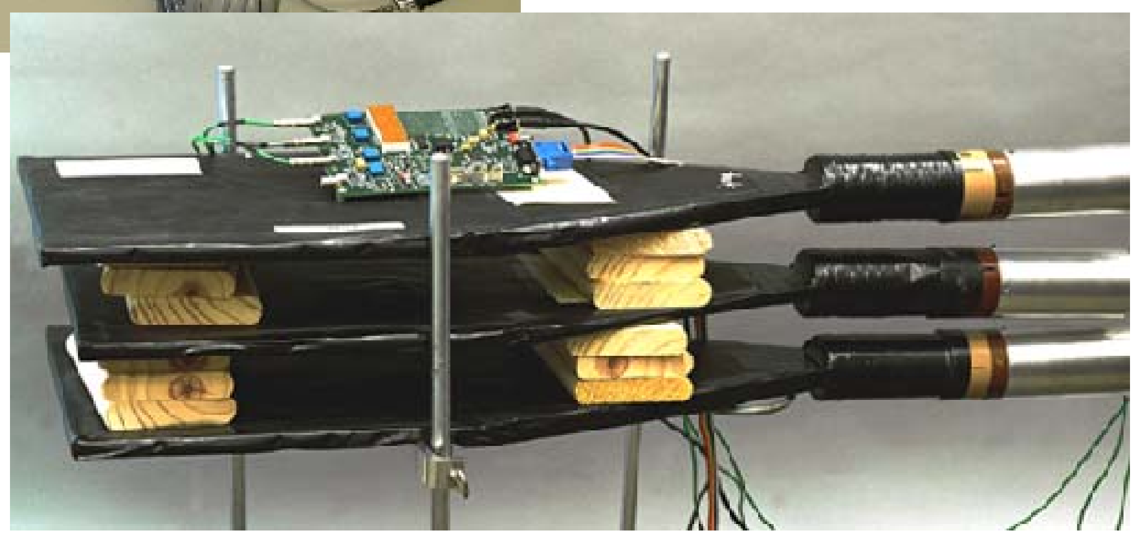
e+e- → q anti-q   at E=91 GeV



QuarkNet cosmic ray detectors



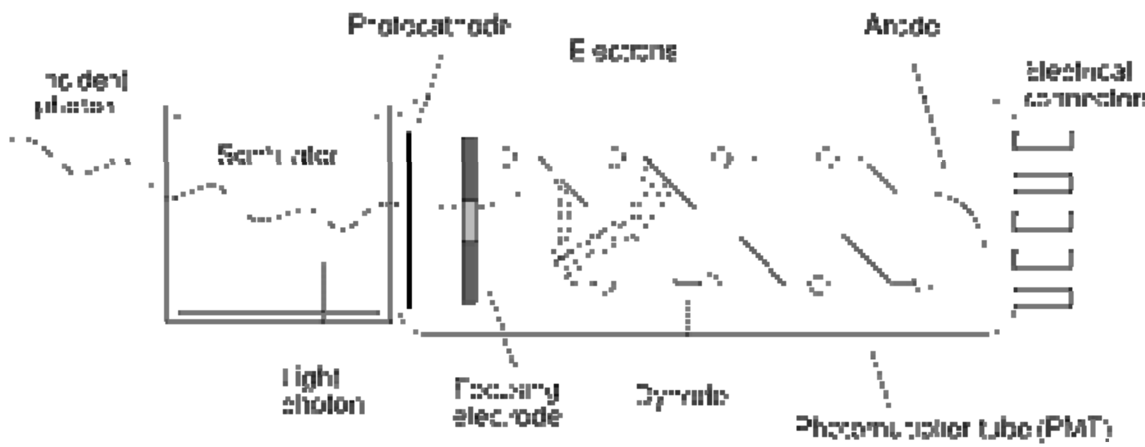
- 4 scintillator paddles and photomultiplier tubes
- requires only wall plug power
- GPS receiver
- electronics card and computer interface



- measure cosmic ray rates in various configurations
- datasets written to computer
- combine with other setups
- muon lifetime experiment

CRD principle in a nutshell

- A “minimum ionizing particle” (MIP), e.g. a typical cosmic ray muon, passes through a plastic scintillator, depositing (on average) about 2 MeV / cm (ionization of the plastic)
- Typically, the scintillation yield is $\sim$1 photon per 100 eV of ionization $\Rightarrow$ $\underline{2\times10^4 \text{ photons/ cm}}$ for each muon
- Some fraction of the photons are collected at the photomultiplier tube (PMT) – depends on geometry and indices of refraction
- The photocathode of the PMT converts a blue photon to an electron with efficiency of $\sim$10%
- The PMT multiplies an electron by a factor $\sim 10^6$
  - depends on high voltage setting, number of stages N (N=10 to 12 typically), and geometry
  - Gain $\propto$ (few)^N

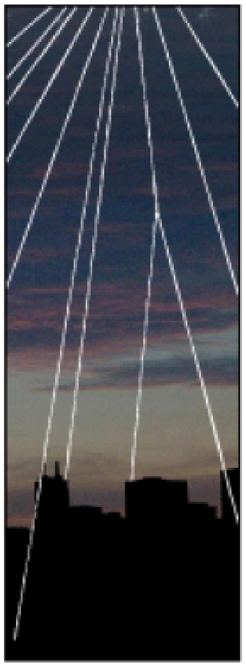


a community of cosmic experimenters

Cosmic Ray e-Lab

Teacher Home | Student Home

High school students use cutting-edge tools to do scientific investigations.



The Cosmic Ray e-Lab provides an online environment in which students experience the excitement of scientific collaboration in this series of investigations into high-energy cosmic rays. Schools with cosmic ray detectors upload data to a "virtual data grid" portal where ALL the data resides. This approach allows students to analyze a much larger body of data and to share analysis code. Also, it allows schools that do not have cosmic ray detectors to participate in research by analyzing shared data.

Students learn what cosmic rays are, where they come from and how they hit the Earth. While scientists understand cosmic rays with low to moderate energies, some cosmic rays have so much energy that scientists are not sure where they come from. A number of research projects are looking at this question. Students will have a chance to gain their own understanding of cosmic rays and may be fortunate enough to capture a rare highly-energetic cosmic ray shower on their classroom detector and analyze their results with this e-Lab.

Information common for all e-Labs

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