Experimental Methods of Particle Astrophysics

In these lectures we will focus on the experimental methods used to detect:

- ✓ Cosmic Rays 10^9 eV – 10^{20} eV
- ✓ Gamma Rays 10^4 eV – 10^{14} eV
- ✓ Neutrinos 10^5 eV – 10^{20} eV

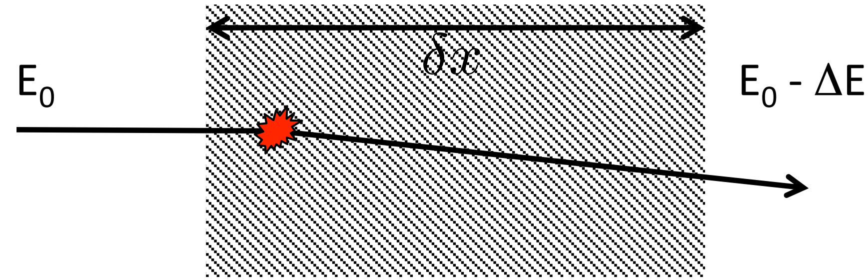
We will not discuss the science output of these techniques yet.

The detection of cosmic rays, gamma rays and neutrinos requires understanding of how these high energy particles interact with matter. It also requires understanding how secondary particles (low energy) interact with matter.

References:
Particle Data Group; J.D. Jackson “Classical Electrodynamics”

Stopping power

What is the energy lost by a particle by travelling through a material?



Single elastic scattering

The (differential) number of collisions resulting in energy loss between E and E+dE is:

$$N_t \delta x \frac{d\sigma}{d\Omega}(E) dE$$

N_t : target density

Define the following momenta:

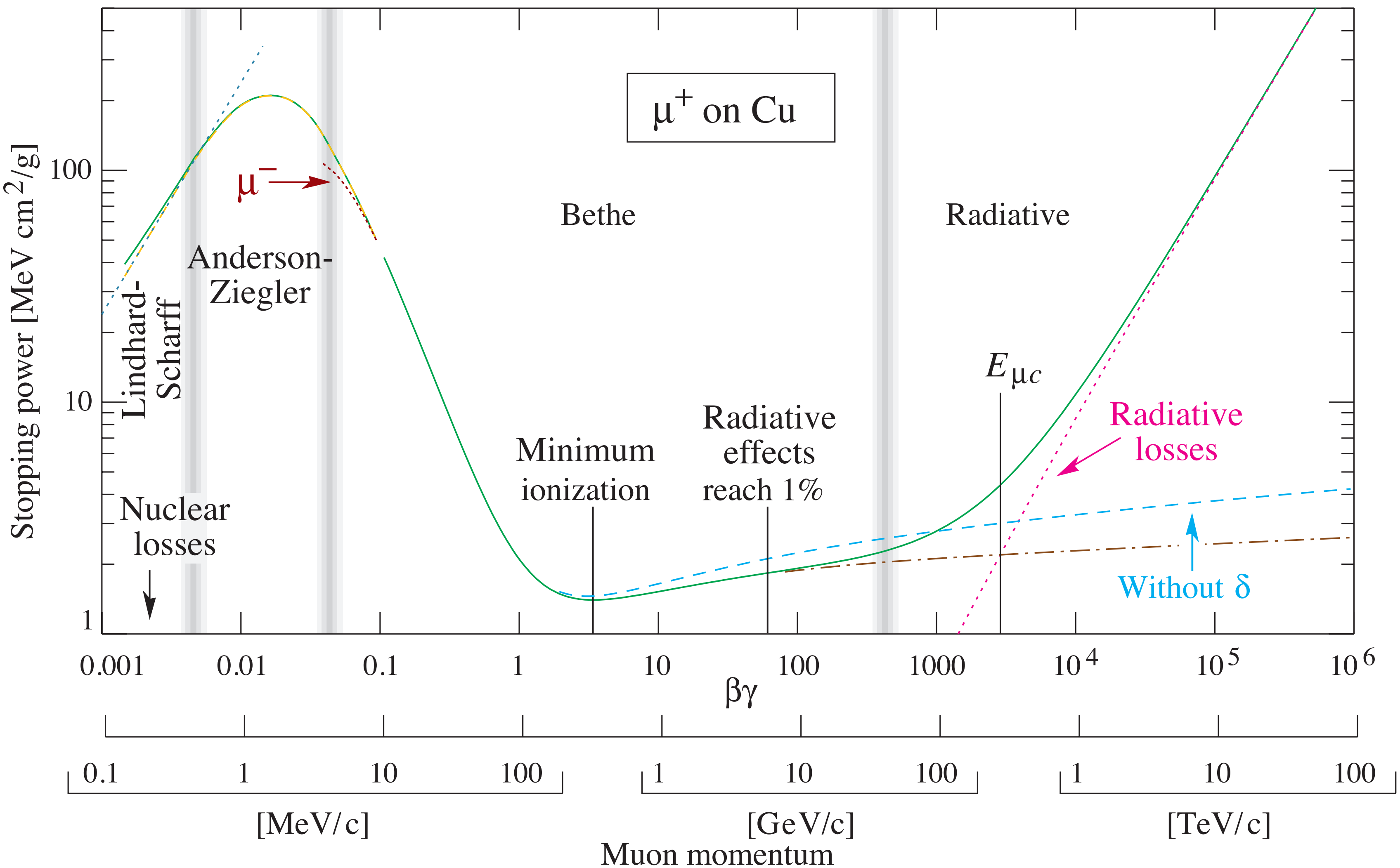
$$M_j(E_0) = N_t \delta x \int_0^{E_0} E^j \frac{d\sigma}{d\Omega} dE$$

M_0 is the number of collisions. M_1 is the mean energy loss in δx. Then:

Stopping Power

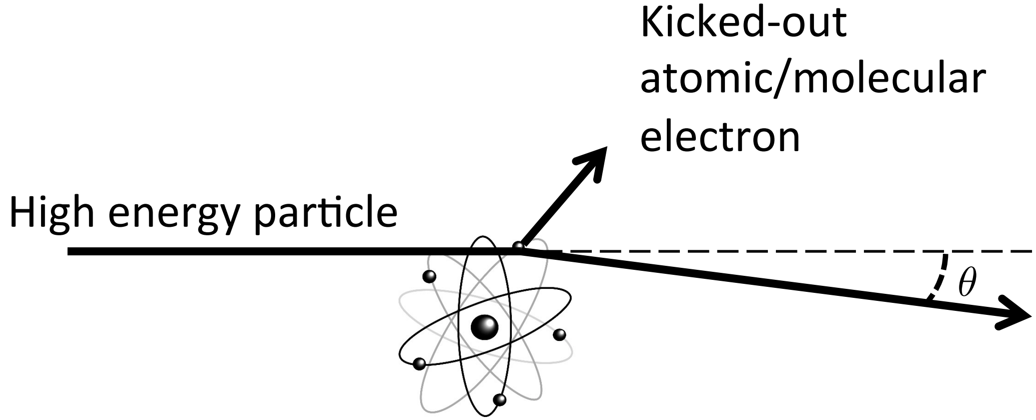
$$\frac{dE}{dx}(E_0) = \frac{dM_1}{d\delta x} = N_t \int_0^{E_0} E \frac{d\sigma}{d\Omega} dE$$

Example: Muon stopping power



Particle Data Group 2012

Ionization



Example:
$\mu^+ + atom \rightarrow \mu^+ + atom^+ + e^-$

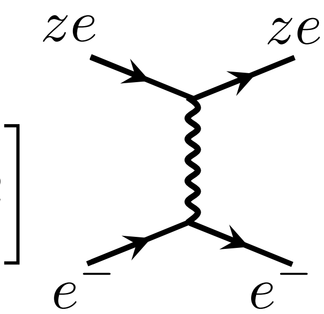
Atomic or molecular electrons are stripped off due to the Coulomb interaction of high energy radiation and the electrons. Typically the high energy deflection angle θ is very small. Also typically the atomic electron acquires energy < 100 eV.

Ionization is one of the most important energy loss mechanisms for charged particles. High-energy electrons, because of their small mass, must be treated differently than any other charged particle.

Ionization – Bethe Bloch

Energy loss per track length:

$$-\frac{dE}{dx} = \frac{4\pi n_e z^2 e^4}{m_e c^2 \beta^2}\left[\log\left(\frac{2m_e c^2\beta^2}{I^2(1-\beta^2)}\right) - \beta^2 - \delta/2\right]$$



Where:

$$n_e = \frac{ZN_A\rho}{M_u}$$ is the electron density in units of (e^-/cm^3)

N_A: Avogadro's number, Z: atomic number, ρ: density (gr/cm^3), M_u: Relative atomic weight (atoms/mol)

I: Average ionization potential (e.g. 13 eV for Hydrogen)

β is for the incident particle

$\delta(\beta\gamma)$: density correction (large $\beta\gamma$)

The equation above is not valid for electrons (limit $m_e/M << 1$). The equation above is in c.g.s. units.

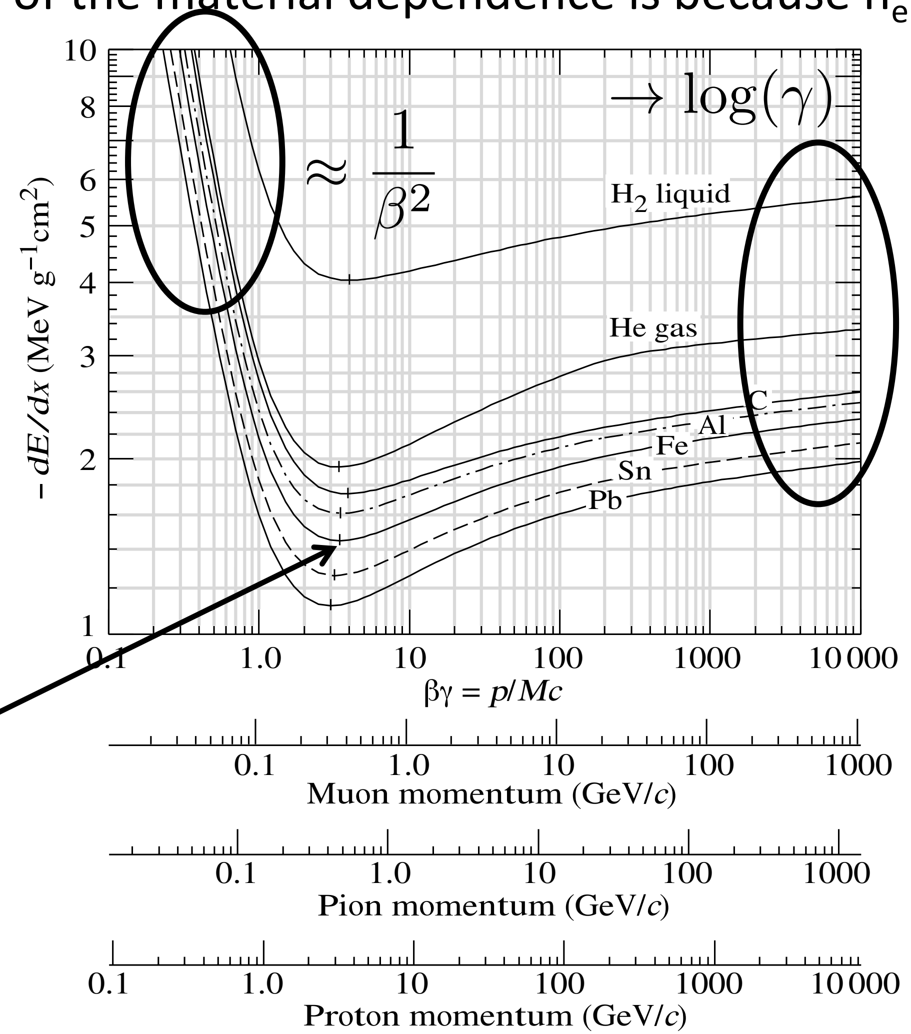
Ionization – Bethe Bloch

It is customary to rescale track length by density: $x \to \rho x$

So you end up measuring dE/dx in MeV.cm^2/g. This scale eliminates some of the material dependence. The rest of the material dependence is because n_e is proportional to Z/M_u and in the average ionization potential I

Bethe-Bloch is valid in the range $\beta\gamma \gtrsim 0.1$ $\beta\gamma < 10^4$

For low $\beta\gamma$, there's no good analytical description of ionization

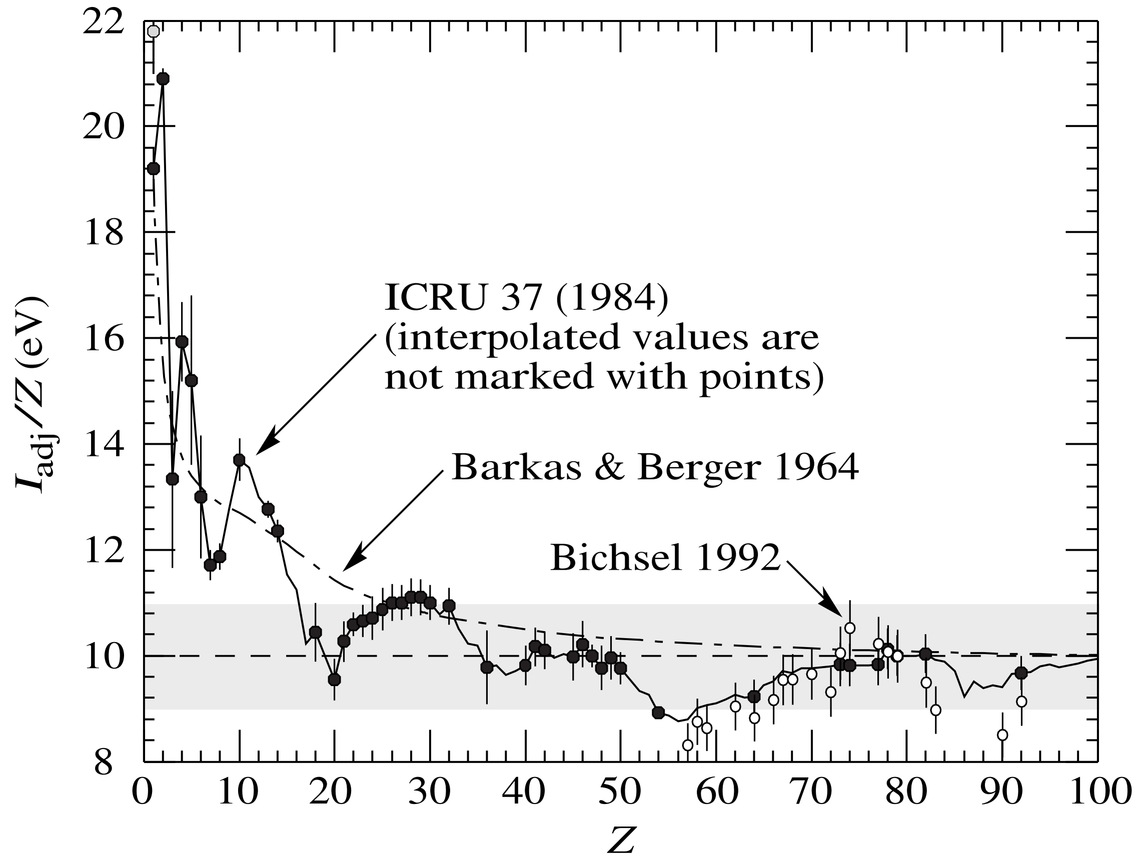


Ionization Minimum

Ionization – average ionization potential

Difference from material to material is in part due to average ionization potential.

For Z ≥ 16 (Sulphur) it's ok to assume I = Z 10eV

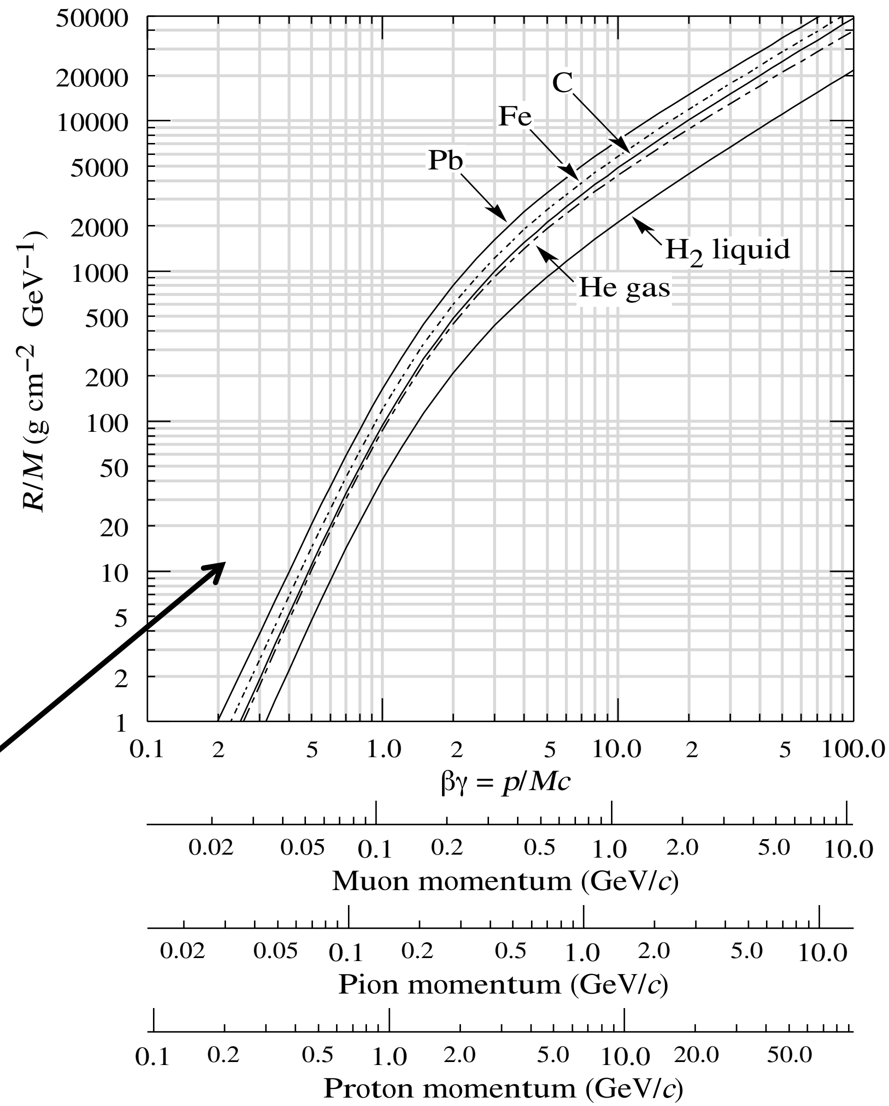


Particle Data Group 2012

Particle range

Given an energy loss mechanism (e.g. ionization), each particle has a range that is energy dependent.

$$R = \int_0^R dx = \int_0^E (-\frac{dE}{dx})^{-1} dE$$

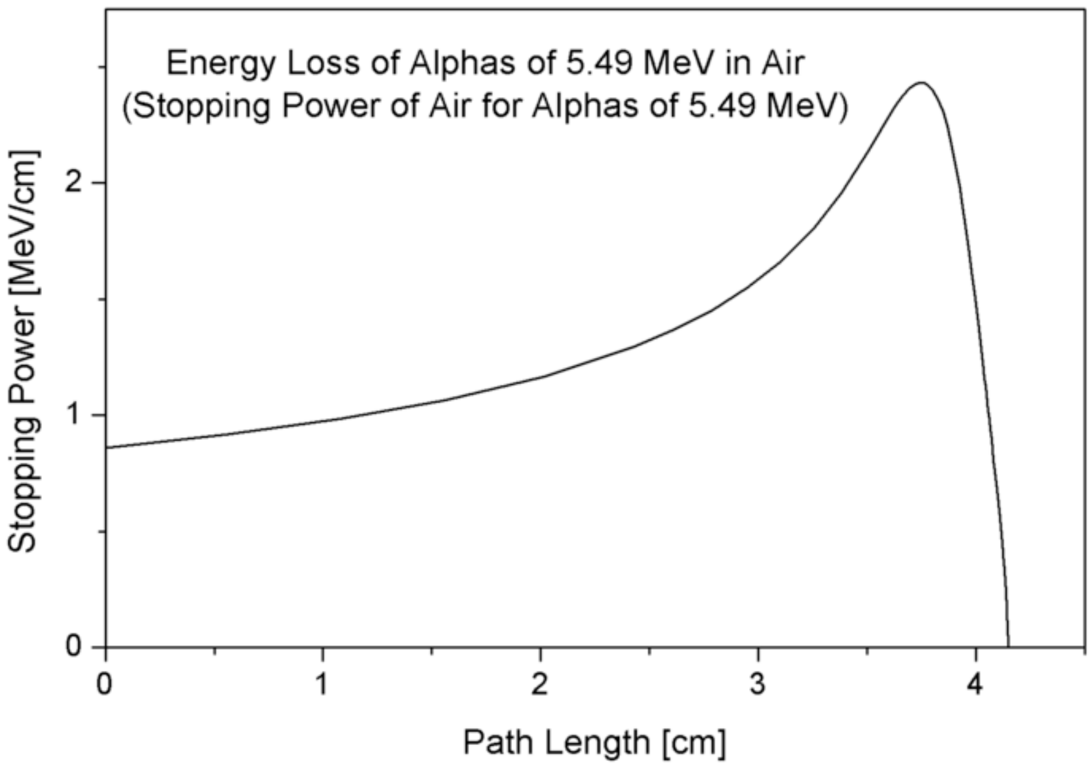


Note that we still assume that R has been rescaled by material density

(though this is not formally part of the integral above)

For any $M \gg m_e$ charged particle. Best example is the muon

Bragg peak



William H Bragg (1903)

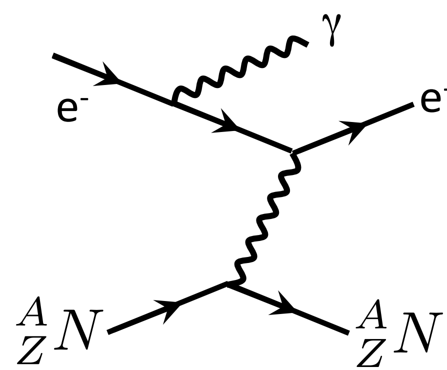
Ionization losses (for $m \gg m_e$) happen mostly just before the particle comes to a stop.

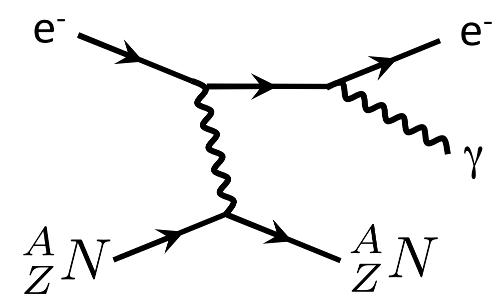
Electrons and photons: radiative losses

High-energy electrons loose energy primarily via Bremsstrahlung
High-energy photons loose energy primarily via pair-production.

Brem:

$$\sigma \sim O(Z^2\alpha^3)$$

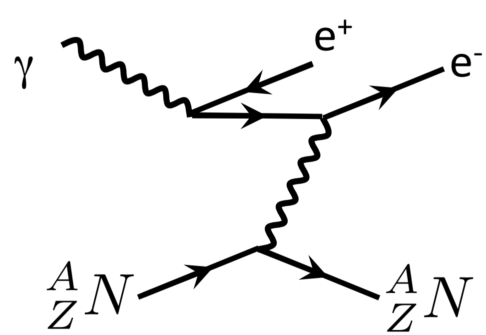


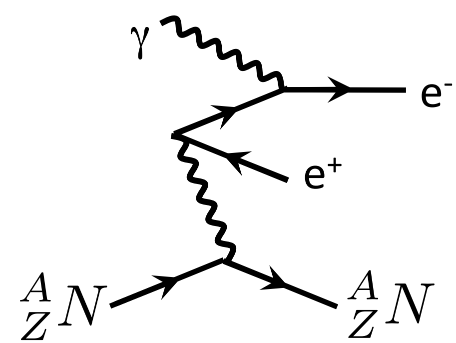


$$e^- + ^A_Z N \rightarrow \gamma + e^- + ^A_Z N$$

Pair production:

$$\sigma \sim O(Z^2\alpha^3)$$





$$\gamma + ^A_Z N \rightarrow e^- + e^+ + ^A_Z N$$

Electrons and photons: radiative losses

Note how brem and e-pair production are related by time reversal. This implies that (lowest order) Feynman diagram calculations are very similar. In both cases $-dE/dx \propto E$

For both brem and e-pair the incoming energy is (approximately) split among the two outgoing particles ($e^-+\gamma$ and e^-+e^+ respectively).

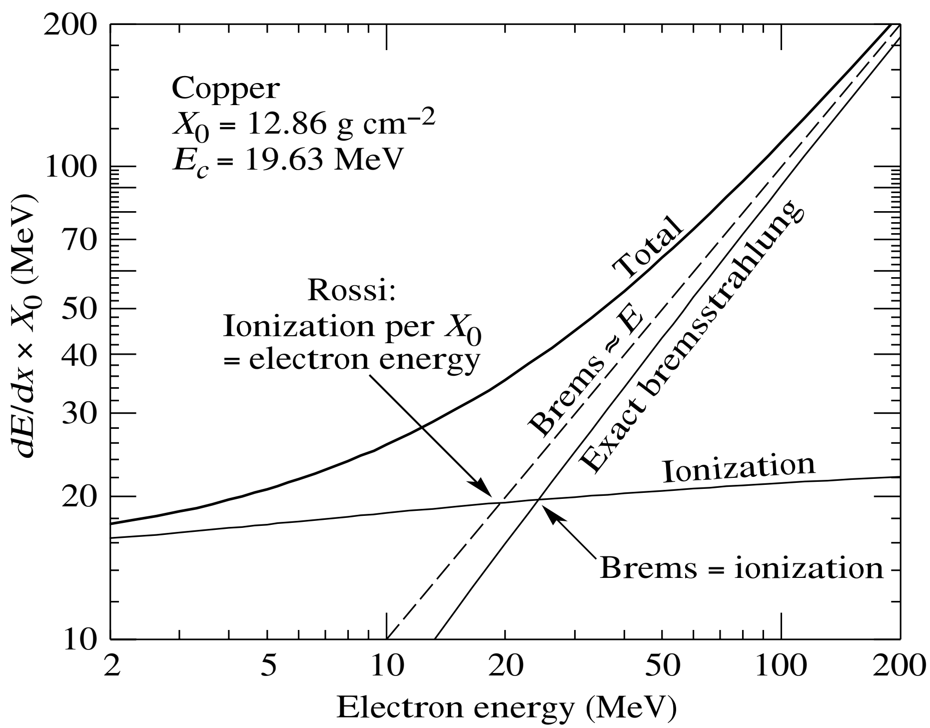
The characteristic distance over which an electron looses all but 1/e of its energy due to brem is the "Radiation length" X_0. For photons this distance is 7/9 X_0. A fit to the data of the radiation length for elements is:

$$X_0 = \frac{716.4\ A}{Z(Z+1)\log(287/\sqrt{Z})} [g \cdot cm^{-2}]$$

For a mixture of elements $1/X_0 = \sum w_j/X_j$, where w_j is the fraction by weight of each element.

Electrons: Ionization & brems

Ionization is also relevant for electrons – but not described properly by Bethe-Bloch. Ionization rises as logE for ionization, but as E for Brem. The critical energy E_c is that at which ionization losses equal brem losses. Alternative definition (Rossi): $-dE_{ion}/dx = E/X_0$



Element	Z	X_0 (cm)	Ec (MeV)
H_2 (*)	1	1000	340
C	6	18.8	103
Al	13	8.9	47
Fe	26	1.8	24
Cu	29	1.4	19.63
Pb	82	0.56	7

(*) Liquid H_2 @ 26 K.

Fit: $$E_c = \frac{800\ \mathrm{MeV}}{Z + 1.2}$$

Example: high energy electrons/photons in air

The atmosphere has density that changes with altitude:

$$X(h,i) = a(i) + b(i)e^{-\frac{h}{c(i)}} \quad [\mathrm{gcm}^{-2}]$$

Zone	h (km)	X (g cm^{-2})	a (g cm^{-2})	b (g cm^{-2})	c (m)
1	0 – 3.96	1079.5 – 582.6	146.66	932.8	5208
2	3.96 – 8.53	582.6 – 287.9	-110.33	1119.8	8255
3	8.53 – 17.68	287.9 – 59.73	-6.8	1182.0	6145
4	17.68 – 100	59.73 – 1.28x10^{-3}	0	1511.7	5472

Antarctic atmosphere profile
T.K. Gaisser, Cosmic Rays at Earth:
Researcher's Reference Manual and Data Book

X_0 (Nitrogen) = 38.2 g.cm^{-2}; X_0 (Oxygen) = 34.5 g.cm^{-2}

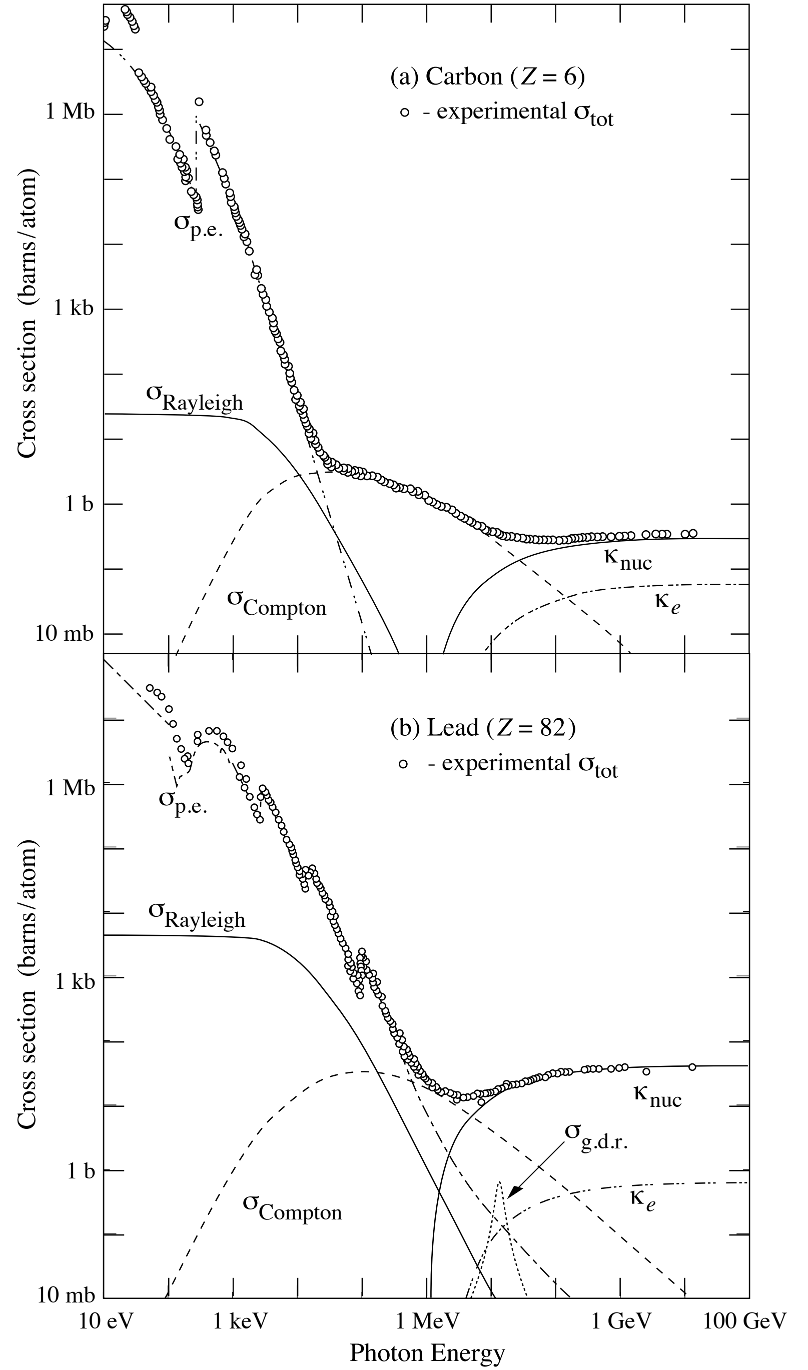
Air is 78% N_2 and 21% O_2 by Volume (but we need mass fractions) – let's use pure nitrogen in this example.

The atmosphere is (vertically) ≈28 radiations length thick.

Photon energy losses

p.e. : photo-electric effect
κ_{nuc}: e-pair of nucleus
κ_e: e-pair of electron field
g.d.r. : Photo-disintegration of nucleus via giant dipole resonance

Let's concentrate on Compton scattering and pair production.



Compton scattering

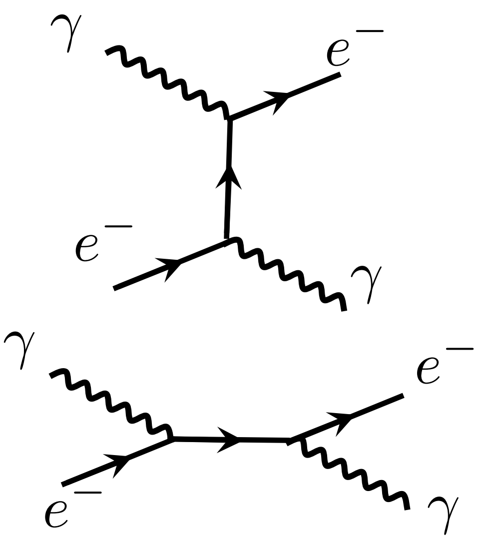
The Quantum Electrodynamics first order scattering cross section of free electrons with photons is given they Klein-Nishina formula

$$\frac{d\sigma}{d\Omega} = \alpha^2 \lambda_c^2 \frac{1}{2} P(E_\gamma, \theta)^2 \left[P(E_\gamma, \theta) + P(E_\gamma, \theta)^{-1} - 1 + \cos^2 \theta \right]$$

Where

λ_c is the Compton wavelength, $h/m_e c$

$$P(E_\gamma, \theta) = \frac{1}{1 + (E_\gamma / m_e c^2)(1 - \cos\theta)}$$



The final photon energy is $E'_\gamma = E_\gamma P(E_\gamma, \theta)$

θ: scattering angle of photon

Thomson scattering

In the low photon energy limit, $E_\gamma << m_e c^2$, this results in the classical Thomson scattering because $P(E_\gamma, \theta) \rightarrow 1$

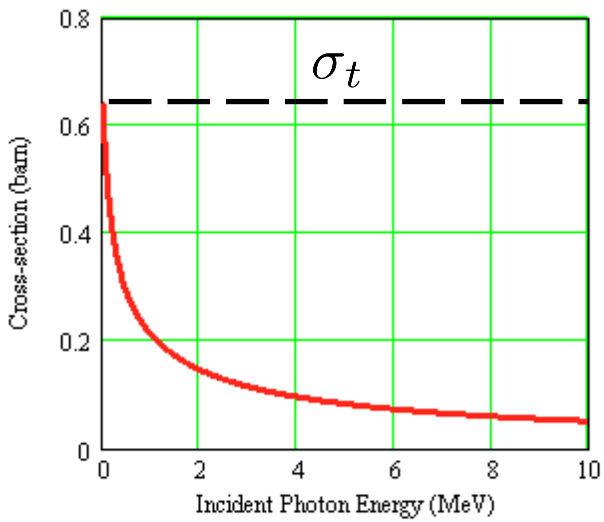
$$\frac{d\sigma}{d\Omega}_{Thomson} = \alpha^2 \lambda_c^2 \frac{1}{2} \left[1 + \cos^2\theta\right]$$

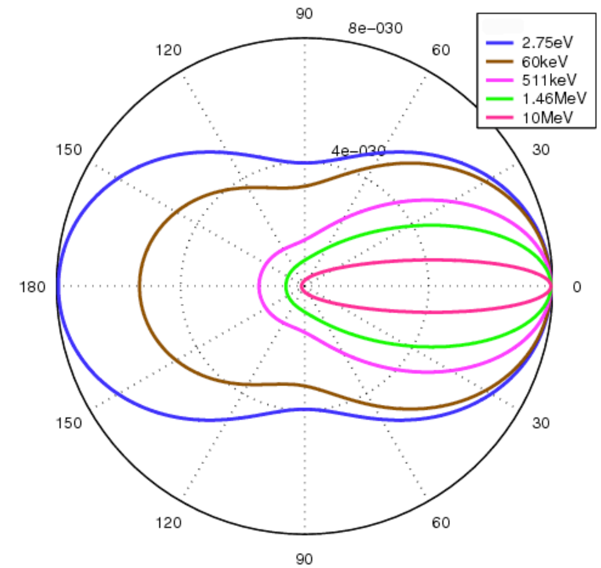
With $E_\gamma / mc^2 << 1$ $\quad \sigma \rightarrow \sigma_{\mathrm{Thomson}} = \frac{8}{3}\pi r_e^2 = \frac{8}{3}\left(\frac{e^2}{m_e c^2}\right)$

And the final photon energy matches the initial photon energy.

However, electrons can't always be assumed to be free, and Thomson scattering may not always be the best description.

Compton scattering





As energy increases, the total cross section decreases and behaves as

$$E_\gamma / m_e c^2 >> 1 \quad \sigma \to \frac{3}{8} \sigma_{\mathrm{T}homson} \frac{2 \log(2E_\gamma / m_e c^2) + 1}{E_\gamma / m_e c^2}$$

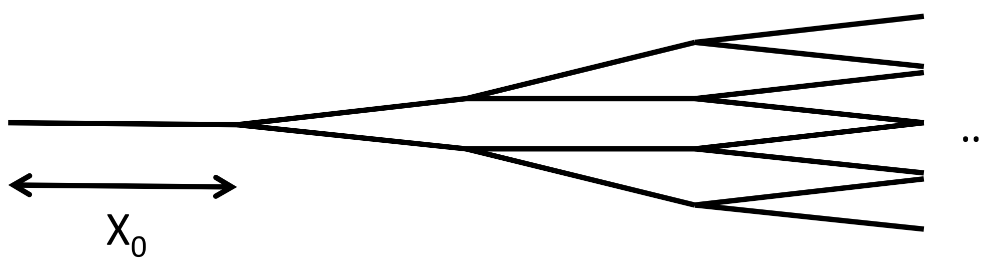
And as the energy increases the scattering angle is increasingly forward peaked.

We will study the related process of inverse compton scattering later in the course.

Electromagnetic Showers (cascades)

At high energy electrons and photons loose energy via radiative processes. This leads to an geometrical increase in the number of particles, with each generation of particles having ever lower energies. The shower stops when ionization, compton scattering, etc. become more important than radiative losses.

A simple model for a cascade



Rad. Lengths	t=1	t=2	t=3	t=4	…	t
Energy per particle	E	E/2	E/4	E/8	…	$E/2^t$

Electromagnetic Showers

In the simplistic model, the length of a cascade is found thus:

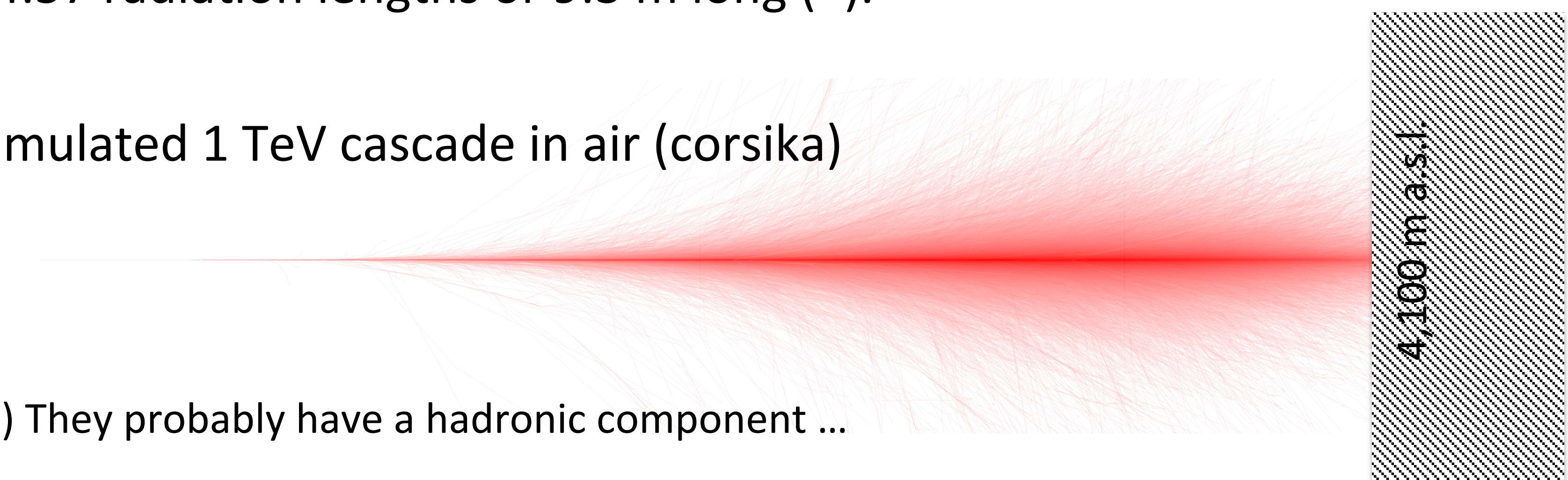
$$E/2^t = E_c$$

$$t = \log_2 E/E_c$$

$$L = tX_0$$

Example: In water, X_0 ≈ 38 cm and the critical energy is ≈80 MeV. IceCube has reported observing one cascade events of approximately 2 PeV energy. If they are electron initiated, the showers would be 24.57 radiation lengths or 9.3 m long (*).

Simulated 1 TeV cascade in air (corsika)

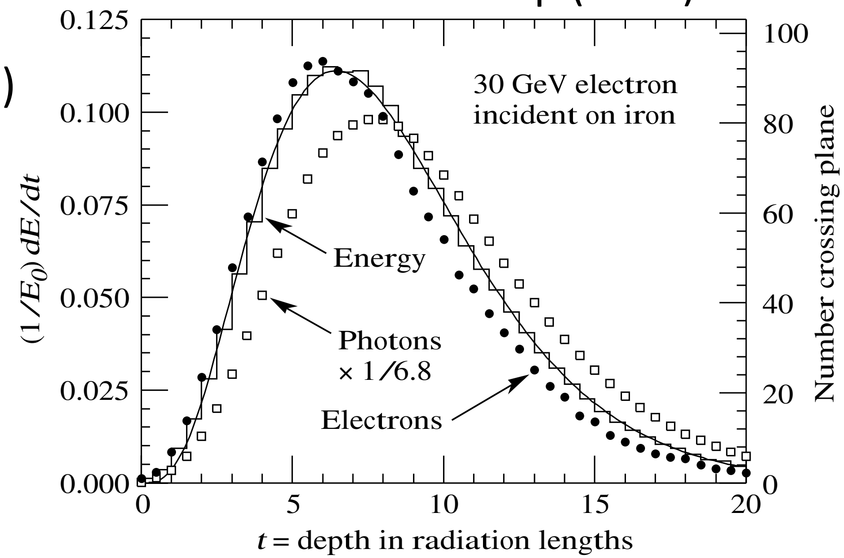


(*) They probably have a hadronic component …

Electromagnetic Showers

Simulated electron initiated shower.
Energy deposition (histogram+gamma function fit)
# of electrons (black circles)
# of photons (squares)

Particle Data Group (2012)



The transverse development of a shower described by the Moliere radius $R_M = X_0 E_s / E_c$, where E_s = 21 MeV. In a shower 90% of the energy is contained in one R_M and 99% within 3.5 R_M.

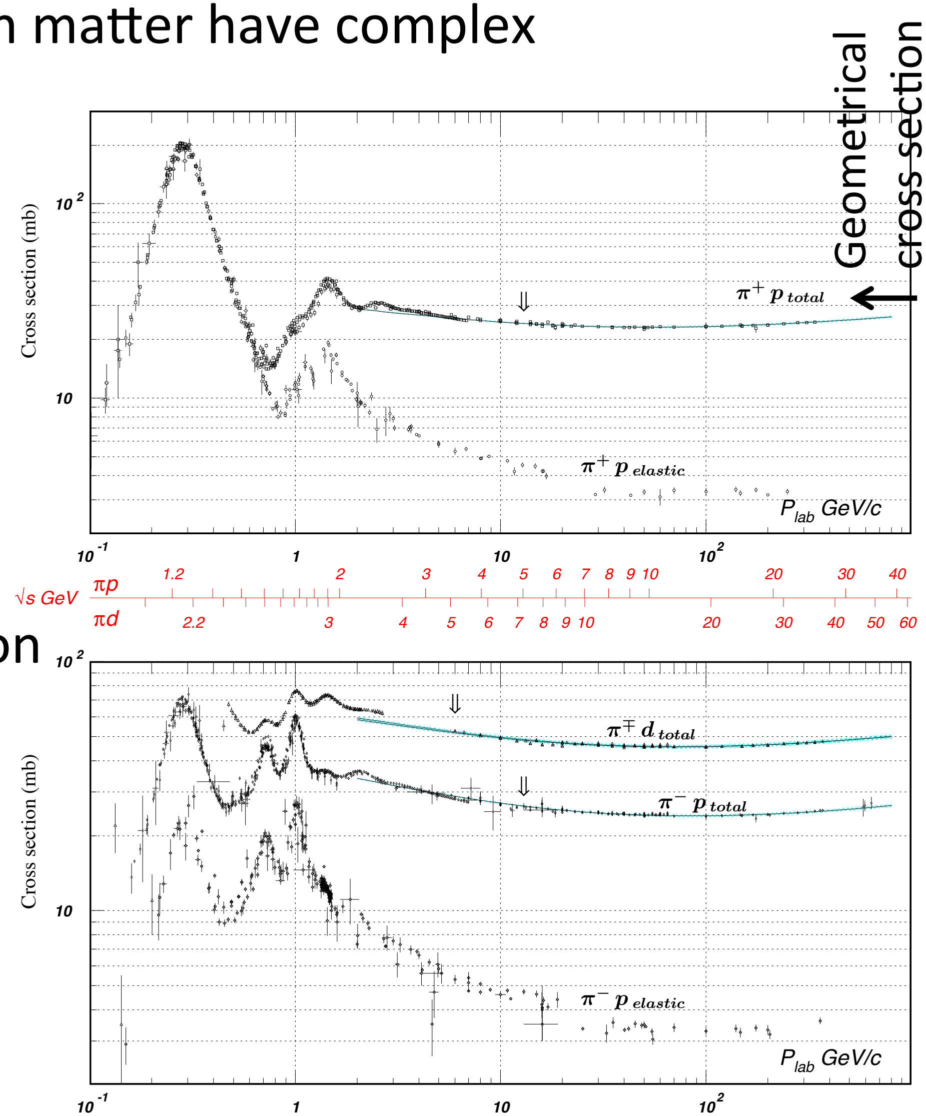
Example: air (sea level), X_0 = 300 m. E_c ~ 84 MeV; R_M = 75 m
(N.B. air showers broaden more than this because of variable density in air with altitude).
water, X_0 = 36 cm. E_c = 78,6 MeV; R_M = 9.6 cm

Hadron-nuclei interactions

Hadrons beams propagating through matter have complex interactions. Things to remember:

- ✓ Interactions can be both elastic and inelastic
- ✓ Resonances are critical over a specific energy range
- ✓ Short lived hadrons can decay in flight
- ✓ At large energies, the cross section is approximately the geometrical size of the target

$$R \approx 1.1 A^{1/3} \quad \mathrm{fm}$$



Hadron-nuclei interactions

The total cross section for hadron-nuclei interactions is of the form

$\sigma = \sigma_{\rm inel} + \sigma_{\rm elast}$

As a hadron crosses a material of width dx, it'll have an interaction probability of $n_t \sigma_t dx$, where n_t is the nuclei density. Thus the mean free path is $\lambda_c = 1/n_t\sigma_t$. For exclusively inelastic scattering, you can define the absorption length $\lambda_a = 1/n_t\sigma_{\rm inel}$. Note that for high beam energies, the cross section is dominated by inelastic processes and the collision length λ_c and absorption length are almost identical $\lambda_a \approx \lambda_c$.

Beams in the 80-300 GeV range. (*) Liquid H_2 @ 26 K.

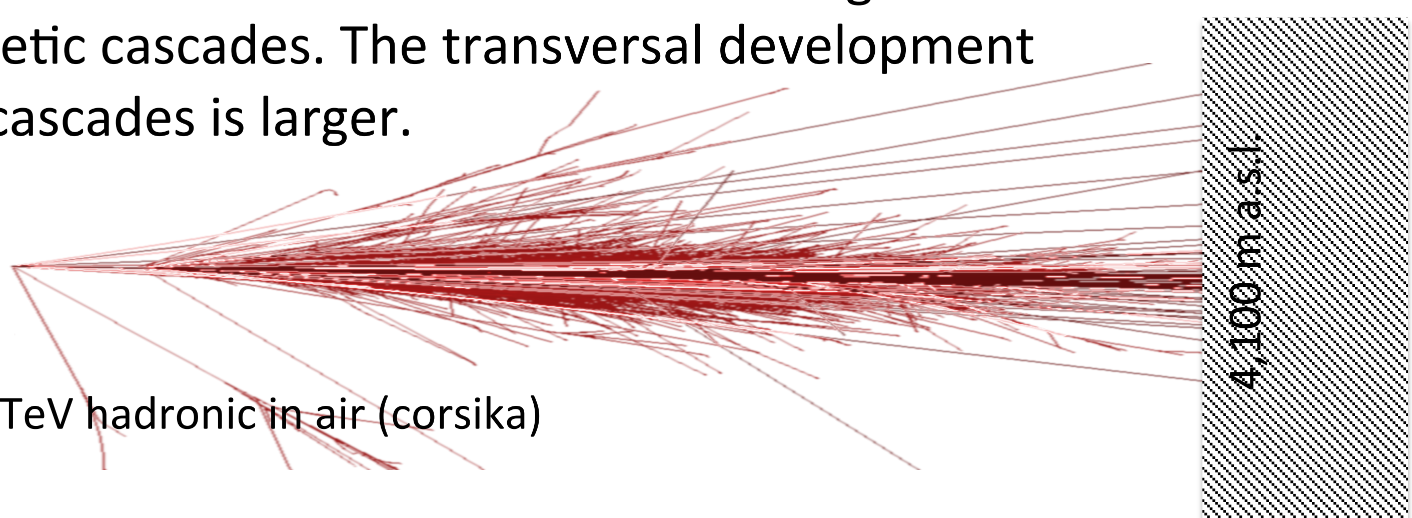
Element	Z	σ_t (mb)	σ_{inel} (mb)	λ_c (cm)	λ_a (cm)
H_2 (*)	1	39	33	687	806
C	6	331	231	26.6	38.1
Al	13	634	421	26.1	39.4
Fe	26	1120	703	10.5	16.8
Pb	82	2960	1770	10.2	17.1

Hadronic cascades (or showers)

Similar idea to electromagnetic cascades. When the cross section is dominated by inelastic processes and multi-pion (or multi meson) production, the number of particles with each interaction grows geometrically with each interaction.

Frequent generation of π^0, which decays $\pi^0 \rightarrow \gamma + \gamma$, results in hadronic cascades having a pure electromagnetic component.

Fluctuations in hadronic showers are far more significant than for electromagnetic cascades. The transversal development of hadronic cascades is larger.



Simulated 1 TeV hadronic in air (corsika)

Summary of passage of particles through matter

Photons and electrons: at high energy (> 0.1 – 1 GeV) radiative losses dominate, and these are the least penetrating particles.

Photons at intermediate energies (~ 10 – 100 MeV) Compton scattering is most important

Electrons at low energies: ionization.

Hadrons: radiative losses suppressed by $1/m^2$, hadronic showers develop.

Muons: long lifetime and low radiative losses, imply that these are the most penetrating particles (save for neutrinos)

Neutrinos: To be discussed later.

Properties for some materials

Material	Z	A	$\langle Z/A \rangle$	Nuclear [a] collision length λ_T {g/cm^2}	Nuclear [a] interaction length λ_I {g/cm^2}	$dE/dx\|_{\min}$ [b] $\left\{\frac{\text{MeV}}{\text{g/cm}^2}\right\}$	Radiation length [c] X_0 {g/cm^2}	{cm}	Density {g/cm^3} ({g/ℓ} for gas)	Liquid boiling point at 1 atm(K)	Refractive index n (($n-1$)×10^6 for gas)
H_2 gas	1	1.00794	0.99212	43.3	50.8	(4.103)	61.28 [d]	(731000)	(0.0838)[0.0899]		[139.2]
H_2 liquid	1	1.00794	0.99212	43.3	50.8	4.034	61.28 [d]	866	0.0708	20.39	1.112
D_2	1	2.0140	0.49652	45.7	54.7	(2.052)	122.4	724	0.169[0.179]	23.65	1.128 [138]
He	2	4.002602	0.49968	49.9	65.1	(1.937)	94.32	756	0.1249[0.1786]	4.224	1.024 [34.9]
Li	3	6.941	0.43221	54.6	73.4	1.639	82.76	155	0.534		—
Be	4	9.012182	0.44384	55.8	75.2	1.594	65.19	35.28	1.848		—
C	6	12.011	0.49954	60.2	86.3	1.745	42.70	18.8	2.265 [e]		—
N_2	7	14.00674	0.49976	61.4	87.8	(1.825)	37.99	47.1	0.8073[1.250]	77.36	1.205 [298]
O_2	8	15.9994	0.50002	63.2	91.0	(1.801)	34.24	30.0	1.141[1.428]	90.18	1.22 [296]
F_2	9	18.9984032	0.47372	65.5	95.3	(1.675)	32.93	21.85	1.507[1.696]	85.24	[195]
Ne	10	20.1797	0.49555	66.1	96.6	(1.724)	28.94	24.0	1.204[0.9005]	27.09	1.092 [67.1]
Al	13	26.981539	0.48181	70.6	106.4	1.615	24.01	8.9	2.70		—
Si	14	28.0855	0.49848	70.6	106.0	1.664	21.82	9.36	2.33		3.95
Ar	18	39.948	0.45059	76.4	117.2	(1.519)	19.55	14.0	1.396[1.782]	87.28	1.233 [283]
Ti	22	47.867	0.45948	79.9	124.9	1.476	16.17	3.56	4.54		—
Fe	26	55.845	0.46556	82.8	131.9	1.451	13.84	1.76	7.87		—
Cu	29	63.546	0.45636	85.6	134.9	1.403	12.86	1.43	8.96		—
Ge	32	72.61	0.44071	88.3	140.5	1.371	12.25	2.30	5.323		—
Sn	50	118.710	0.42120	100.2	163	1.264	8.82	1.21	7.31		—
Xe	54	131.29	0.41130	102.8	169	(1.255)	8.48	2.87	2.953[5.858]	165.1	[701]
W	74	183.84	0.40250	110.3	185	1.145	6.76	0.35	19.3		—
Pt	78	195.08	0.39984	113.3	189.7	1.129	6.54	0.305	21.45		—
Pb	82	207.2	0.39575	116.2	194	1.123	6.37	0.56	11.35		—
U	92	238.0289	0.38651	117.0	199	1.082	6.00	≈0.32	≈18.95		—
Air, (20°C, 1 atm.), [STP]			0.49919	62.0	90.0	(1.815)	36.66	[30420]	(1.205)[1.2931]	78.8	(273) [293]
H_2O			0.55509	60.1	83.6	1.991	36.08	36.1	1.00	373.15	1.33

The table uses different nomenclature than what I've used.

Detectors

This is an extensive topic. I will show a couple of examples for the detection of cosmic rays, gamma-rays and neutrinos.

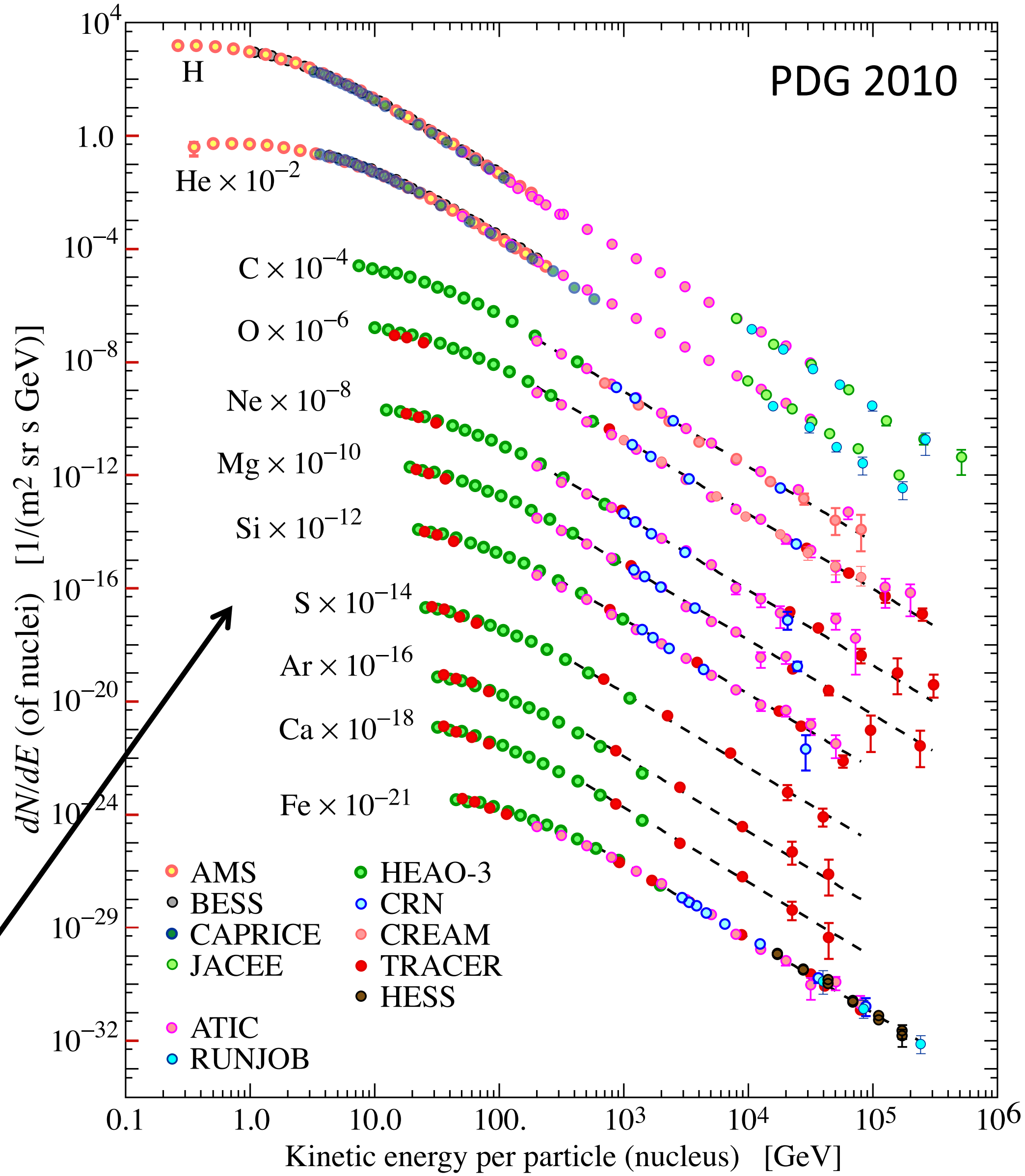
I will however describe other experimental techniques when describing specific experiments.

Cosmic Rays

Cosmic rays are charged particles that arrive at Earth with a wide range of energies with isotropic directions. Studies on cosmic rays focus on spectrum and elemental composition.

Highest energies: 10^{20} eV and particle fluxes of 1 particle per sq.km per century ...

Factor of 10^{-x} added for clarity



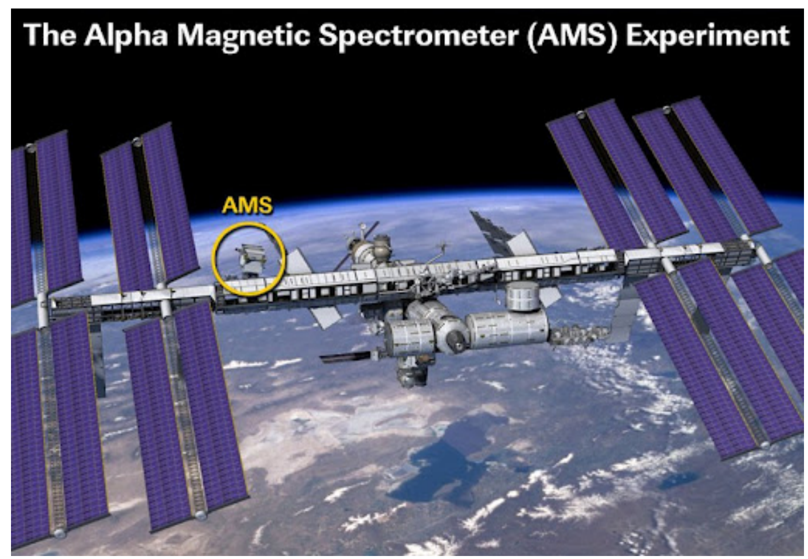
Balloon and Satellite detection of cosmic rays

Satellite and Balloons directly observe cosmic rays. Minimal CR-atmosphere interaction. Atmosphere is ~10^{-3} gr/cm^2 at 100 km. Detectors are small, observations are limited to low energy. Balloons, short flight, cheap. Satellites, long flight, expensive

Example balloon experiment: Cream
Example satellite experiment: AMS

Science objective of these experiments often goes beyond studying C.R.


CREAM (artist depiction)

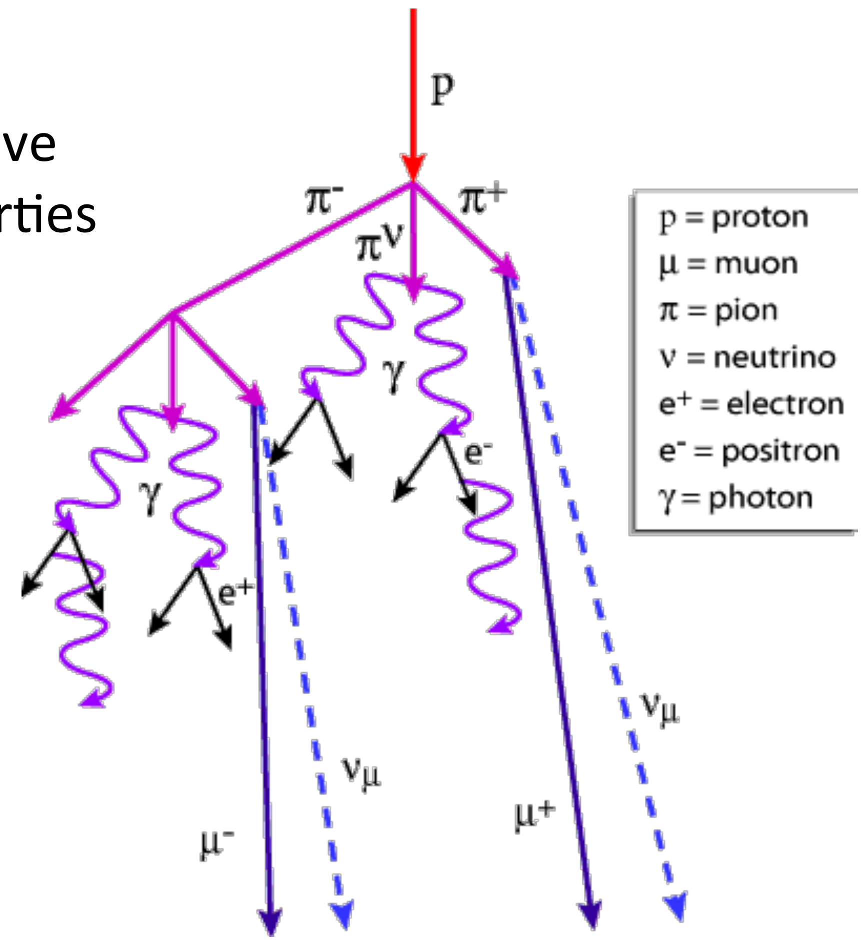


The Alpha Magnetic Spectrometer (AMS) Experiment

Example: Pierre Auger – Water Cherenkov

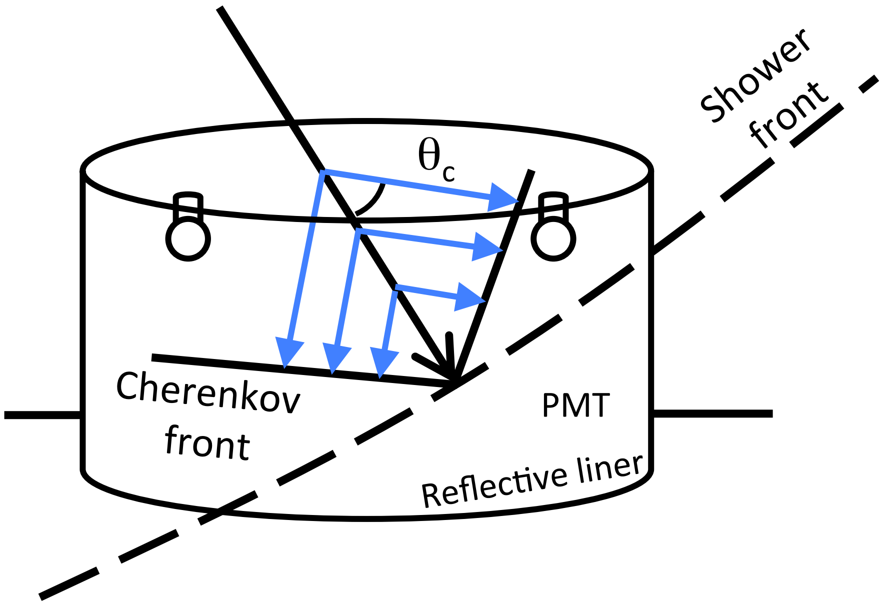
Air Showers: hadronic showers initiated by cosmic rays in the upper atmosphere. At ground level, the most common particles are electrons, positrons, gamma-rays, muons and neutrinos.

Pierre Auger detects particles that have reached the ground and infers properties of the initial cosmic ray.



Example: Pierre Auger – Water Cherekov

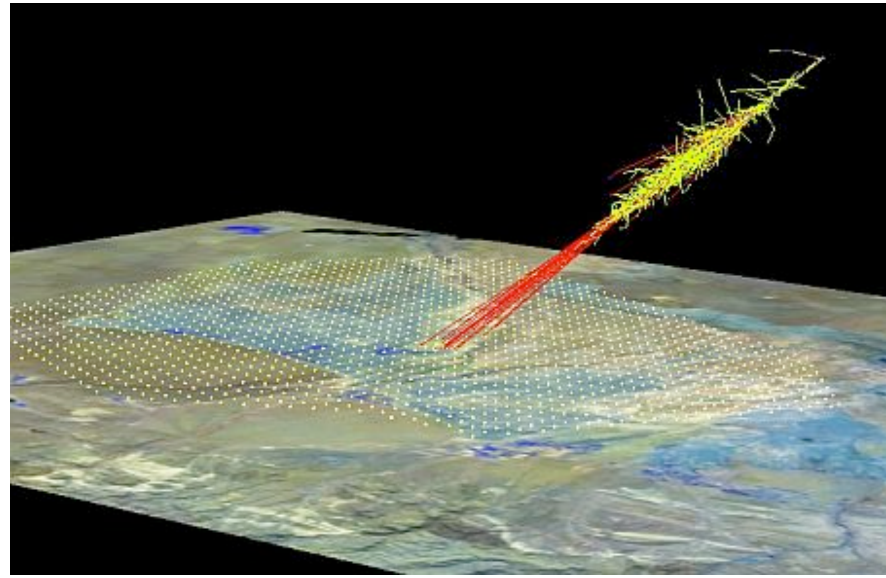
Charged particles that reach the ground produce Cherenkov radiation in water tanks. This is detected by PMTs. Photons (typical energies at ground are 100 MeV) may compton-scatter in water, leading to an electron, that also produces Cherenkov radiation.



Example: Pierre Auger – Water Cherenkov

Tank separation: 1.5 km

Area covered by tanks:
3000 km^2



Auger footprint, Argentina.

Air shower direction:

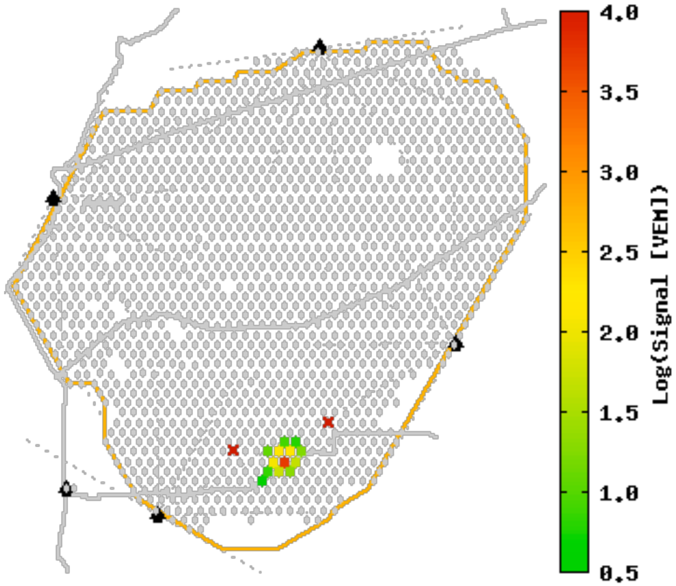
Relative time between tanks

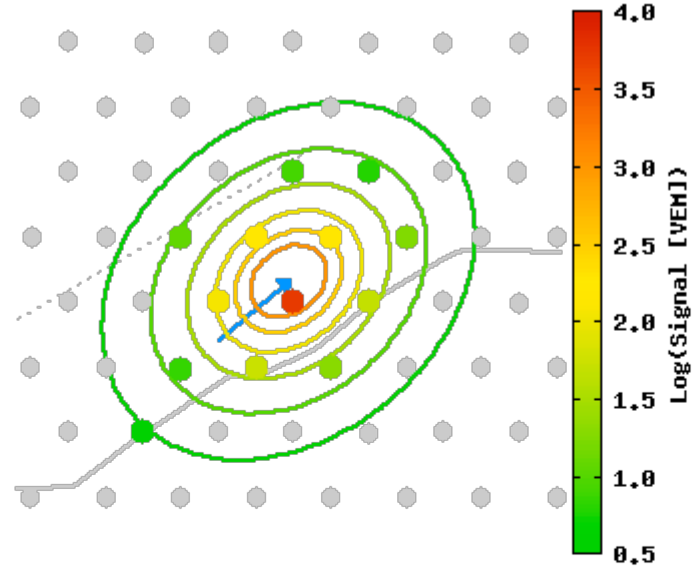
Shower maximum/height of
first interaction: curvature of shower front

Energy: Normalization of the lateral distribution function

N.B. Pierre Auger uses a second detection method, air fluorescence that I won't discuss.

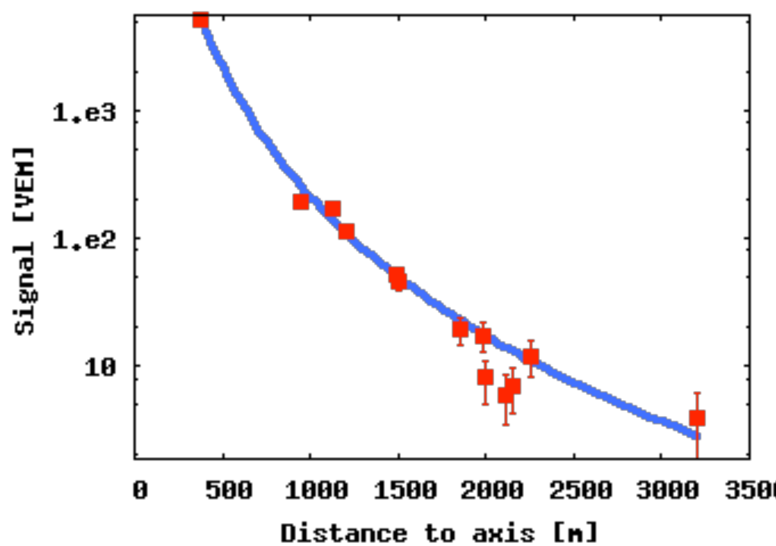
Sample Pierre Auger event



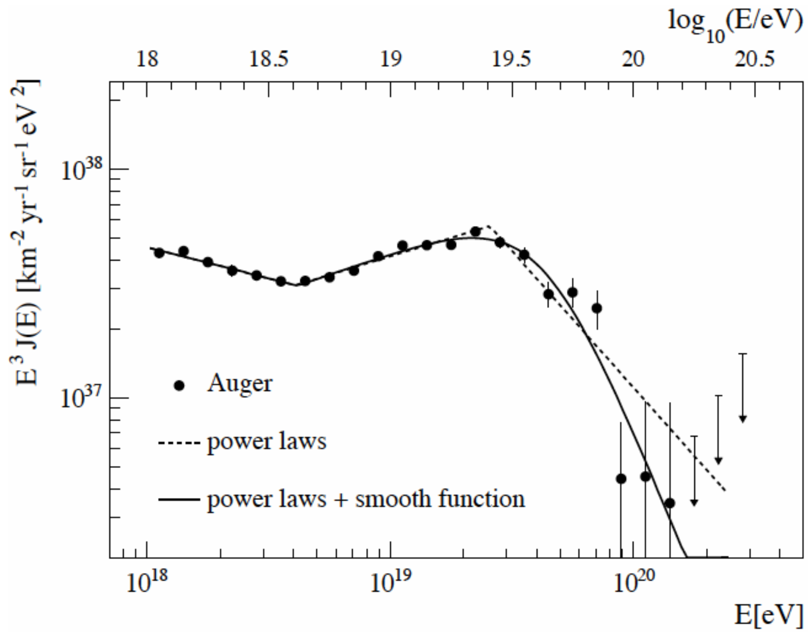


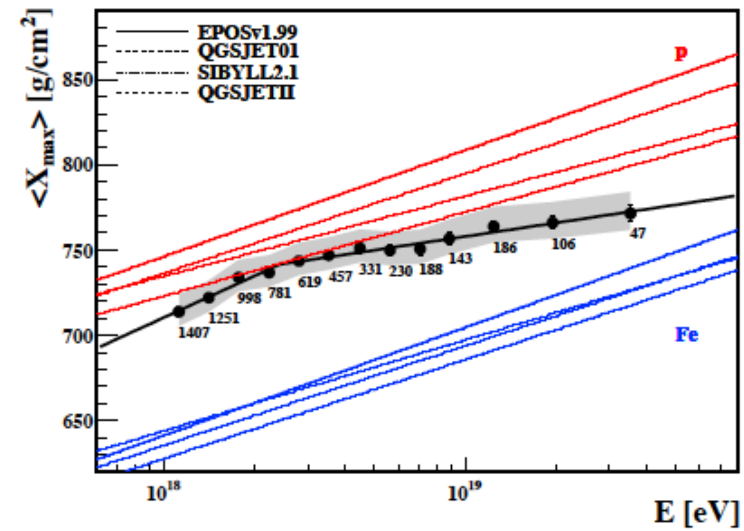
Event information
Date: Tue Oct 26 17:39:16 2010
# of stations 13

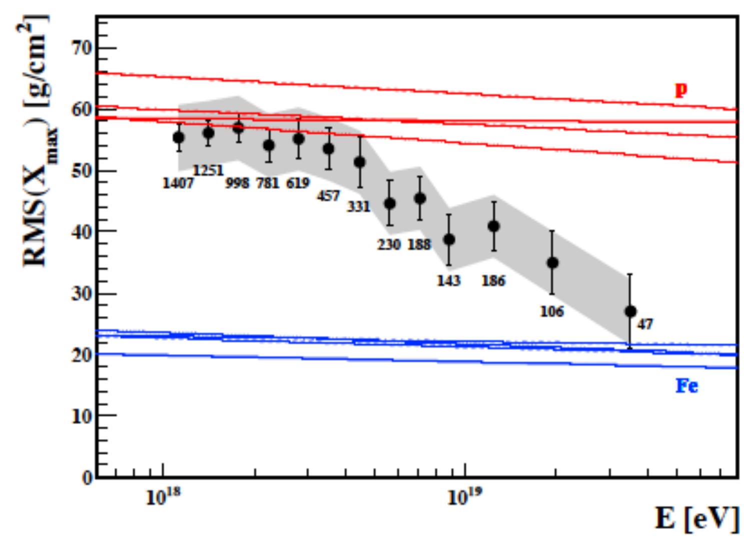
Energy	$4.99 \pm 0.19\ 10^{19}$ eV
θ	40.3 ± 0.1 deg
ϕ	-139.5 ± 0.2 deg
Curvature	12.2 ± 0.6 km



Pierre-Auger: spectrum and composition







We will return to these plots when we study cosmic rays.

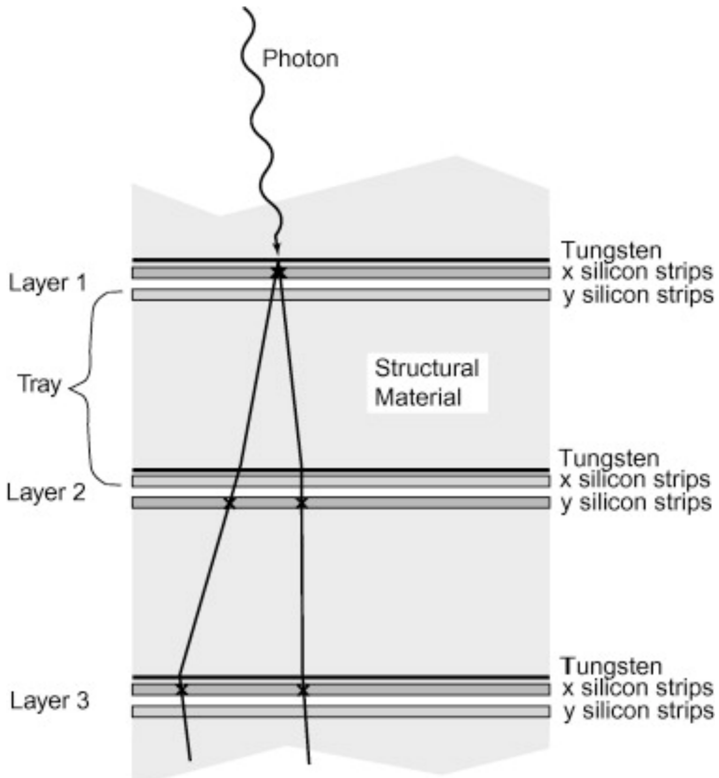
Satellite detection of gamma rays

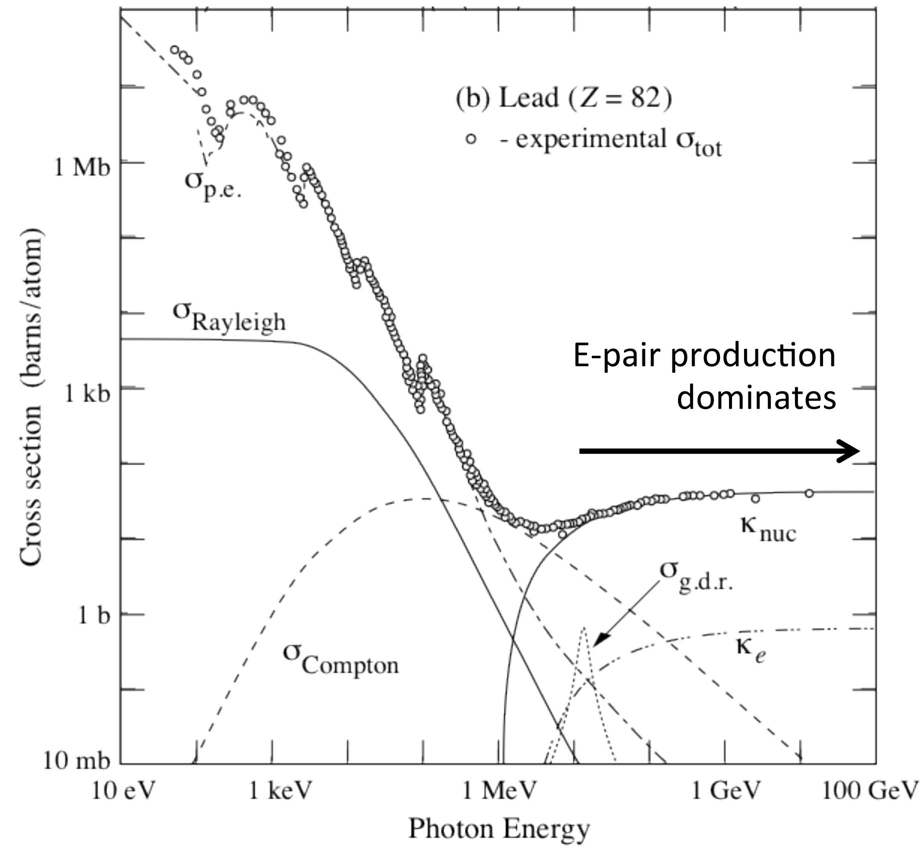
Satellite directly observe gamma rays. Minimal gamma-atmosphere interaction. Atmosphere is ~10^{-3} gr/cm^2 at 100 km. Detectors are small, observations are limited to < 30 GeV. Satellites, long flight, expensive.

Example satellite experiment: Fermi LAT – e-pair conversion. E-pair conversion is not the only relevant technique. At lower energy Compton telescopes, scintillators, etc are also used.

EGRET (part of CGRO) also worked as an e-pair conversion detector

Pair-Conversion Telescope (tracker)





Note that the actual target is tungsten

Thickness of target foils is a compromise between thin (good for angular resolution) and thick (good for effective area).

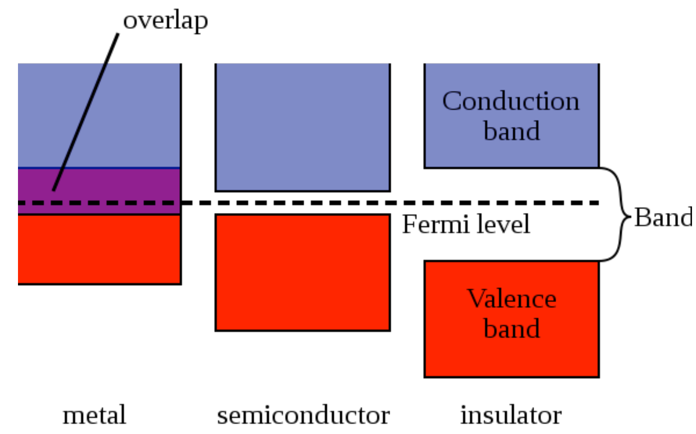
First 12 Tungsten foils are 2.7% rad lengths, final four are 18% rad lengths.

LAT: Silicon strips

A charged particle passing through a semi-conductor will promote an electron from the valence band to the conduction band.

The result is an electron-hole pair.

The band gap is only ~1 eV (for semiconductors). And only 3-4 eV energy loss are needed to create the electron-hole pair. So a particle passing through a silicon strip will release create many electron-hole pairs, even if the strip is very thin (400 μm in LAT). A voltage across the strip allows the measurement of a current pulse related to the passage of ionizing radiation. Both holes and electrons produce current.

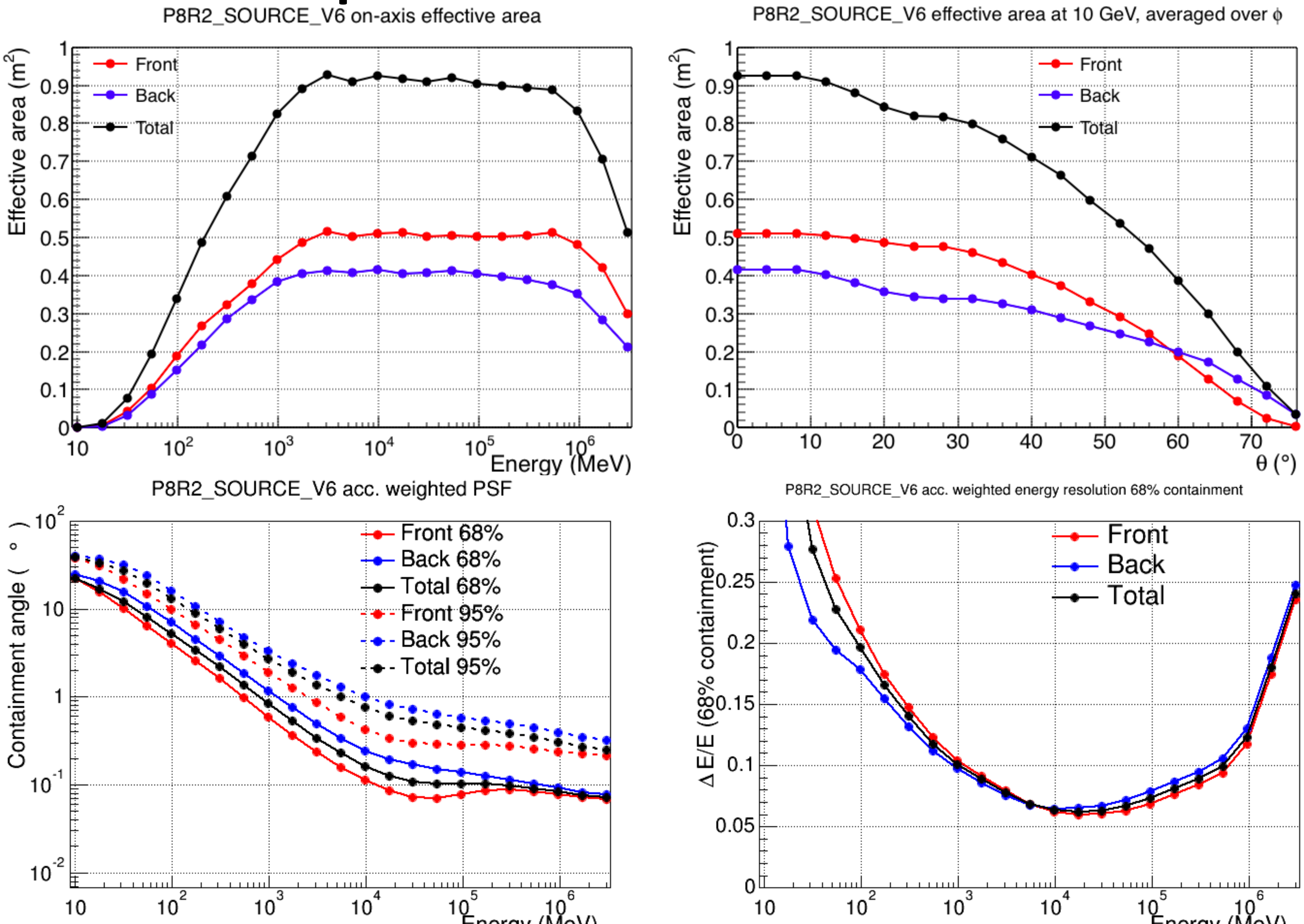


The current is simply

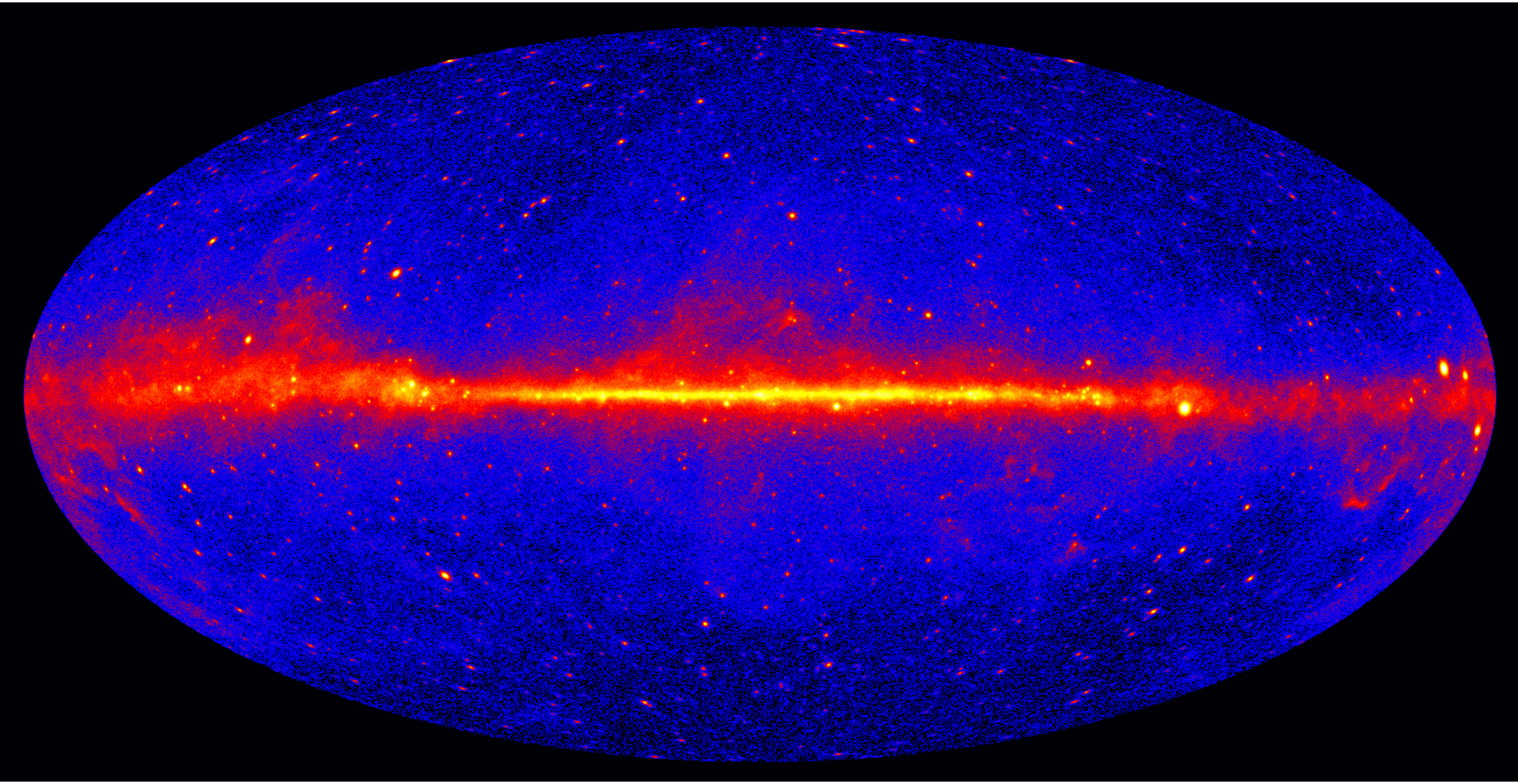
$$I = E_v q v$$

LAT Si strip pitch: 228 μm

Fermi LAT performance



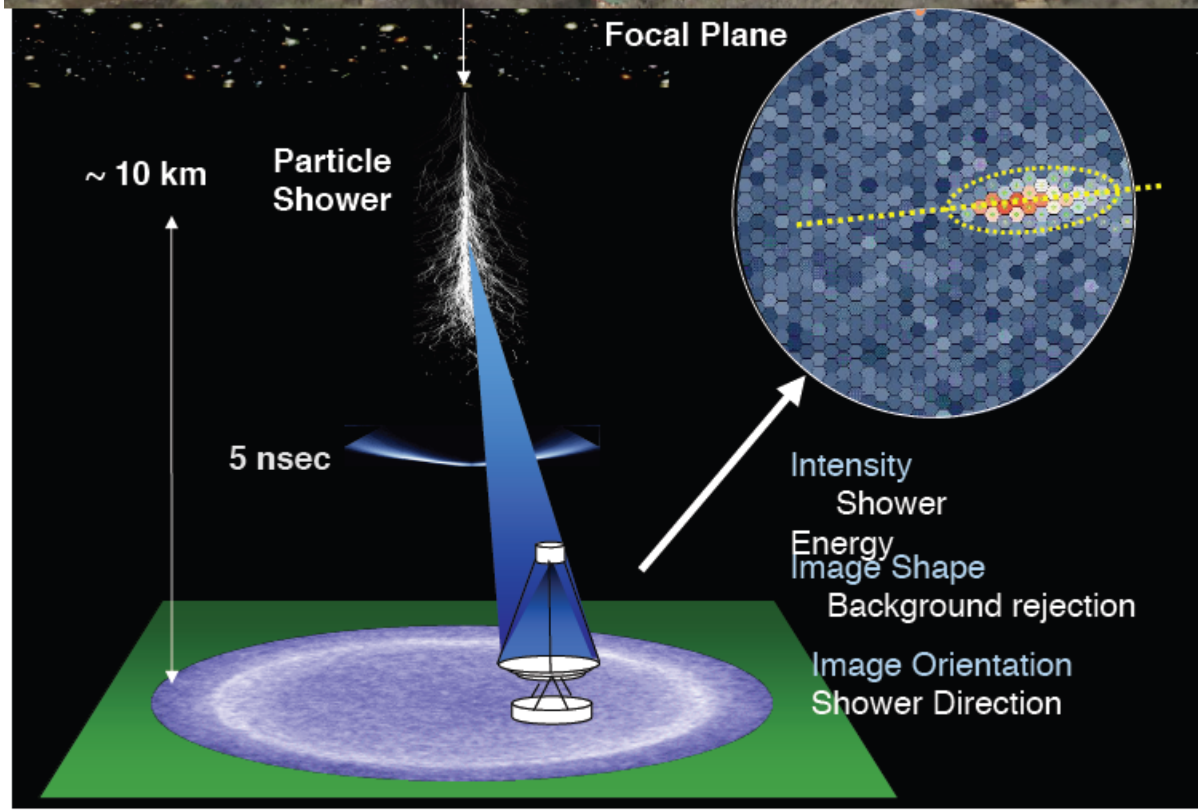
Fermi LAT sky map (> 1 GeV)



5 year Fermi sky map above 1 GeV

Over 2000 sources + diffuse emission. More later …

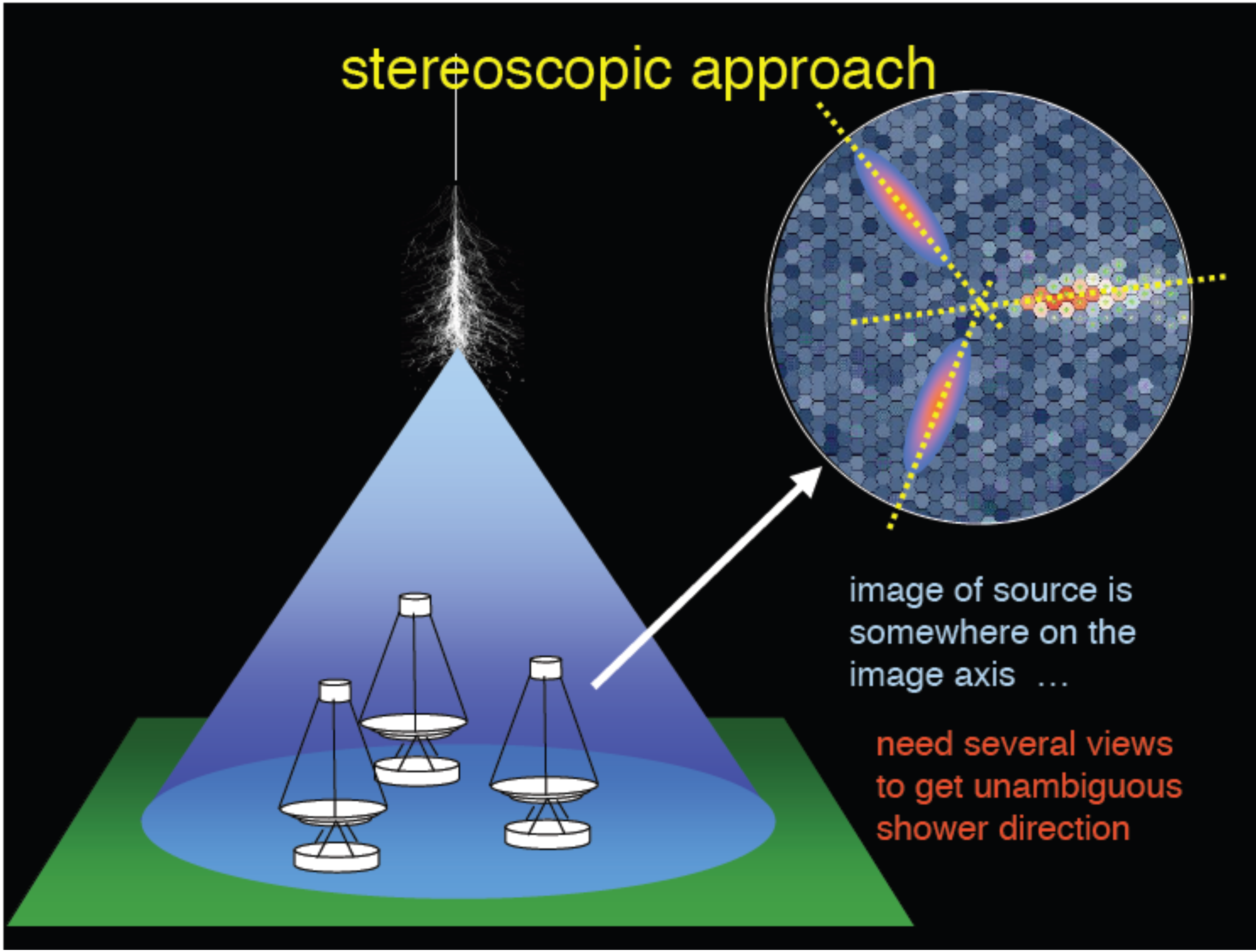
Ground detection of gamma rays - IACT



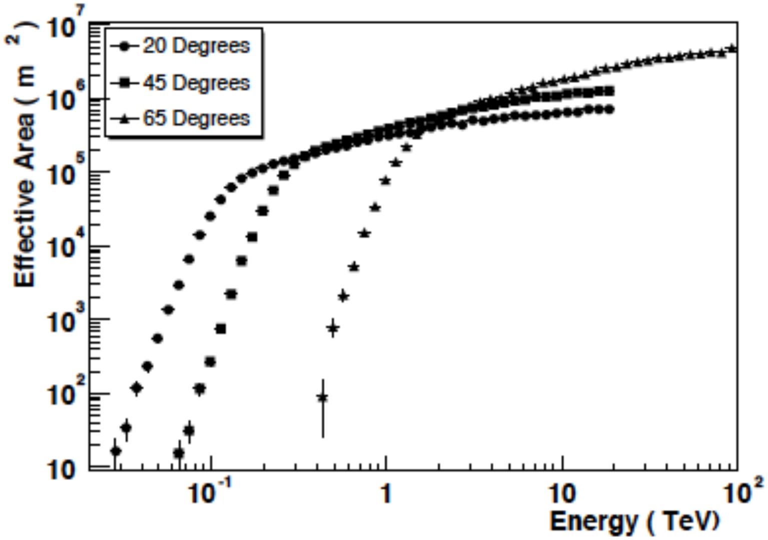
For a 10 km high shower max and 1° Cherenkov angle, the Cherenkov pool at the ground is 175 m in radius.

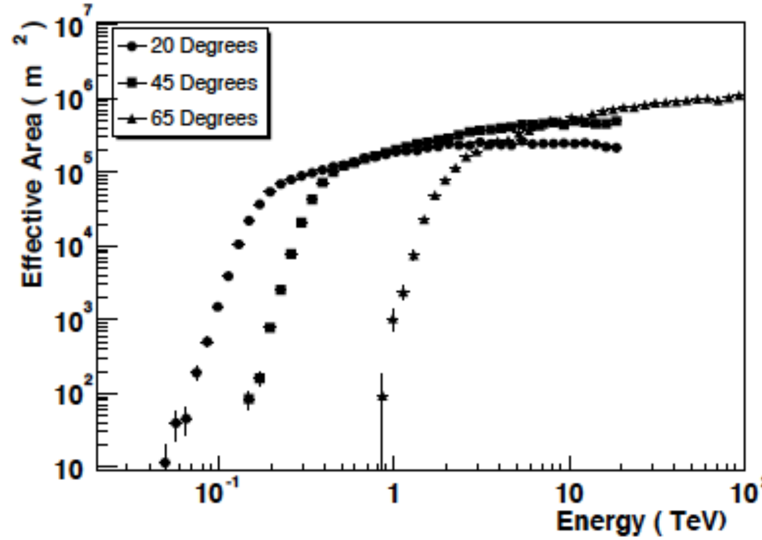
With a single telescope you know the plane that contains the shower, but not the actual shower max location.

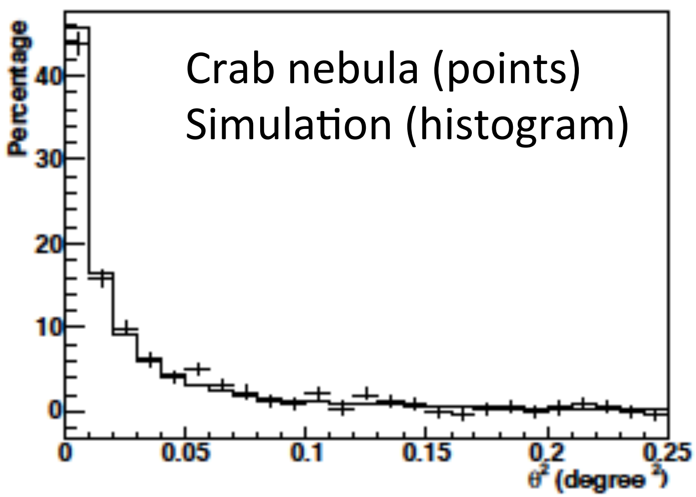
Other IACTs: Veritas, Magic, etc


stereoscopic approach
image of source is somewhere on the image axis ...
need several views to get unambiguous shower direction

HESS performance





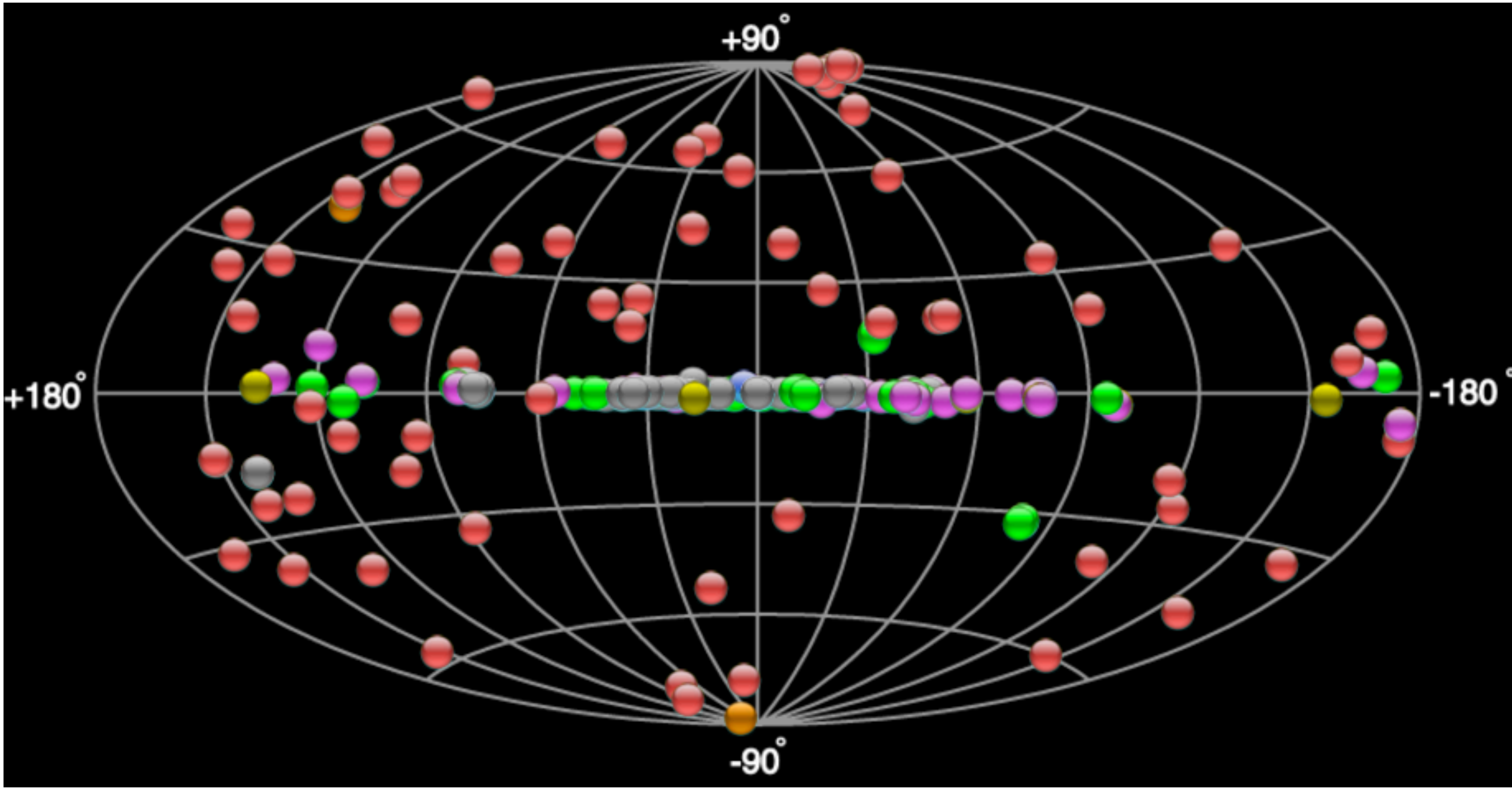


Crab nebula (points)
Simulation (histogram)

Field of view: about 5 degrees

Duty cycle: about 10 % (700 hours/year)
+ 5% (350 hours/year partial moon

The Gamma ray sky (>100 GeV)



tevcat.uchicago.edu

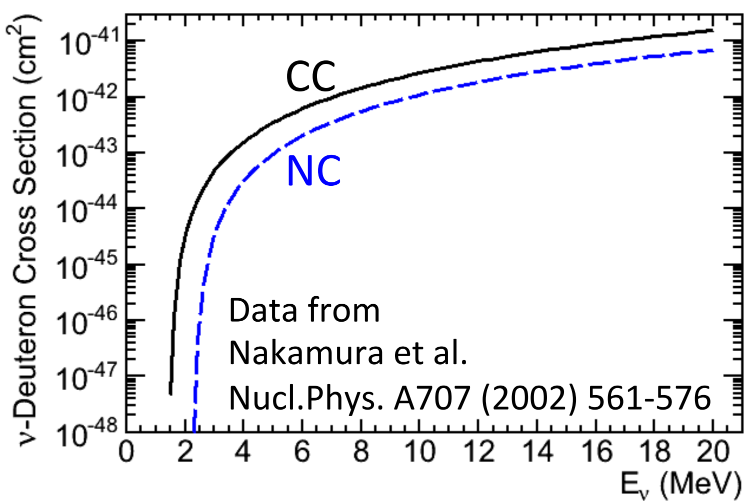
Approximately 180 known sources
More later …

Neutrino-matter cross section low energy

Electron scattering

$$\sigma_{\nu_e+e^-\to\nu_e+e^-} = 1\times 10^{-44} E_\nu/\mathrm{MeV}\ [\mathrm{cm}^2]$$ $E_\nu \sim 7 - 50$ MeV

Deuteron-neutrino

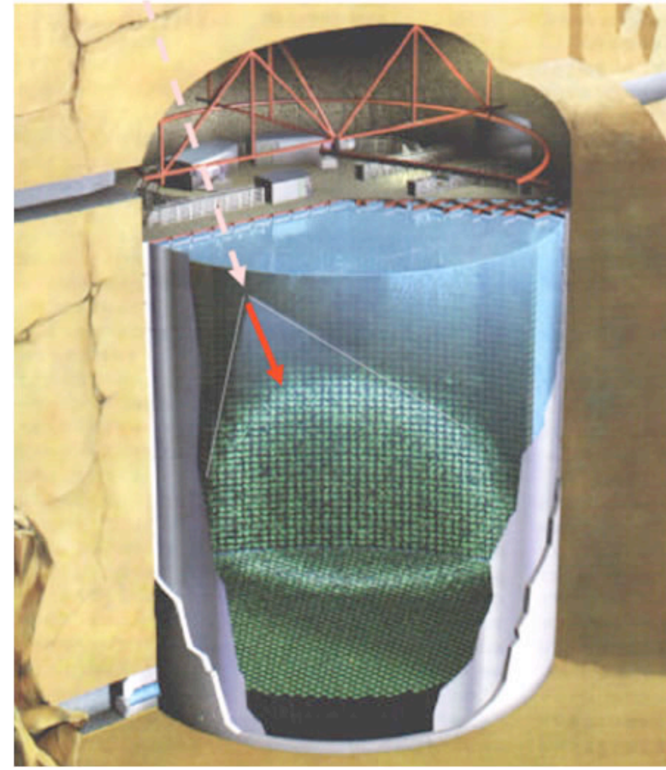


$$\nu_e + d \to p + p + e^-$$ CC

$$\nu_e + d \to n + p + \nu_e$$ NC

Neutrino – matter interactions depend on the channel. Only a couple of examples given.

MeV-GeV Neutrino detection: Super Kamiokande



SuperK works via:

$$\nu_l + e^- \rightarrow \nu_l + e^-$$

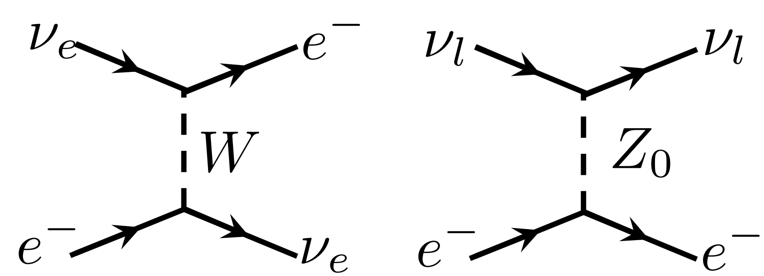
(let's ignore anti-neutrinos)

50 ktons of water (33.8 m high, 36.2 m diam inner detector). Walls covered with 11,456 large (51 cm diam) PMTs looking inward and 1885 (20 cm diam) PMTs in the outer detector.

Energy is measured by number of Cherenkov photons (proportional to e^- track in water)

For MeV energies, electrons travel ~1 cm/MeV.

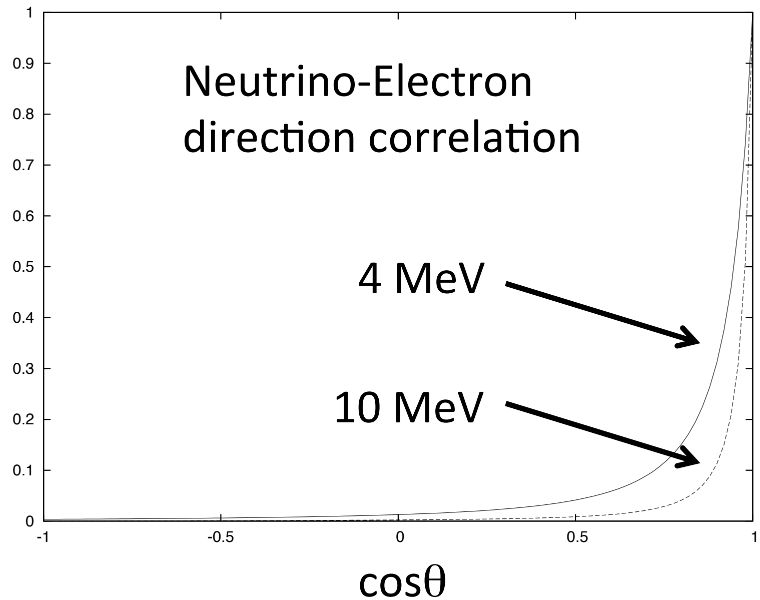
Electron direction is obtained from Cherenkov ring on the wall.

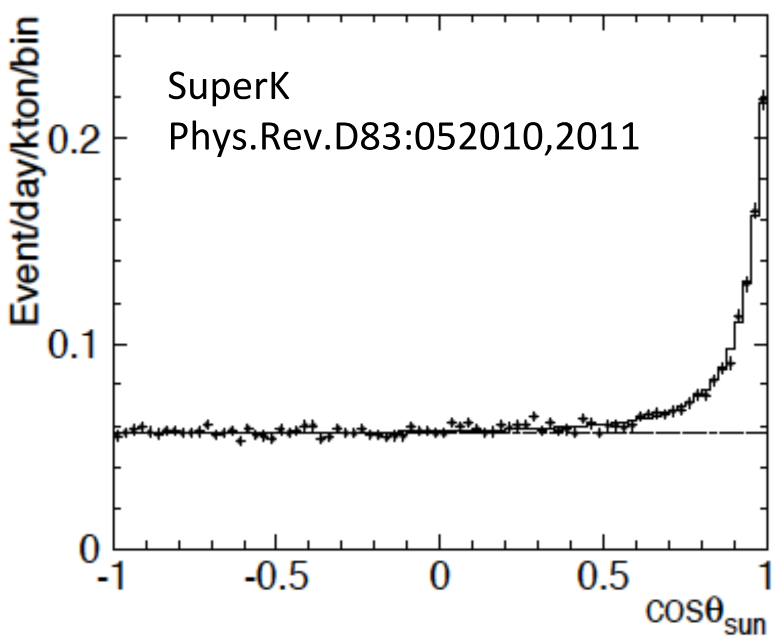


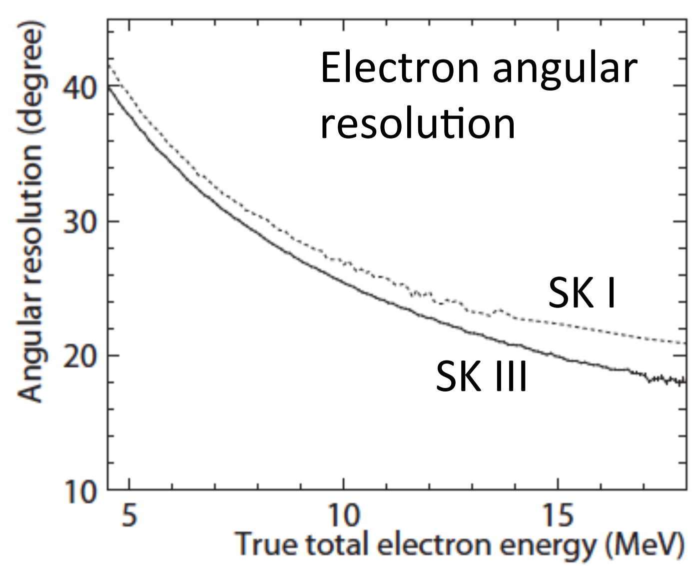
Super K Performance

For $\nu_e + e^- \rightarrow \nu_e + e^-$ in the C.M. the cross section is isotropic in scattering angle. In the lab frame:

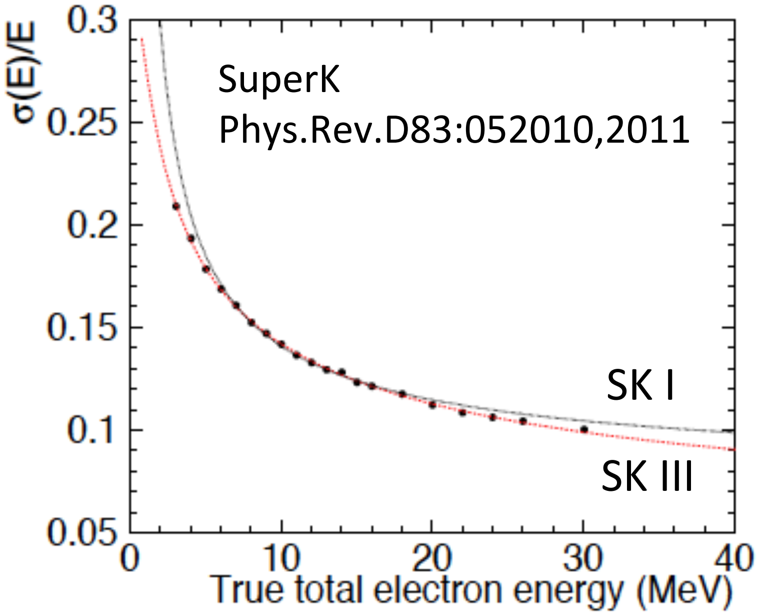
$$\frac{d\sigma}{d\cos\theta} \propto \frac{1}{1 + \frac{E_\nu}{m_e c^2}(1 - \cos\theta)}$$





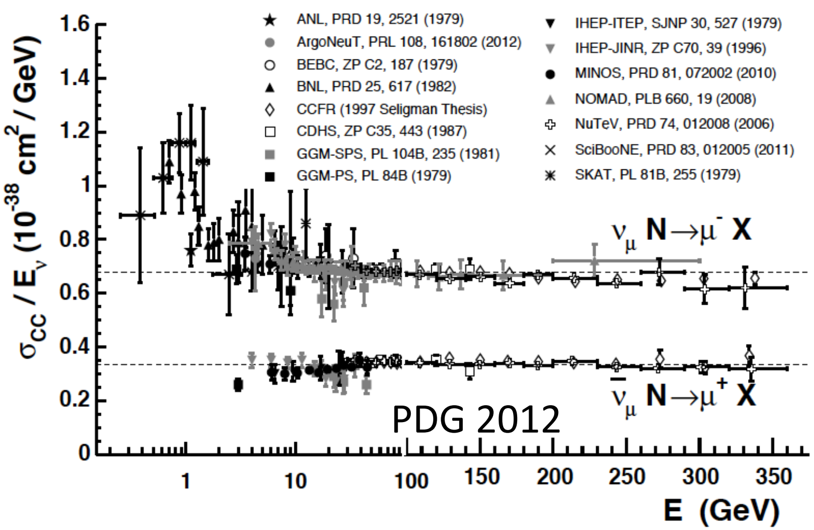


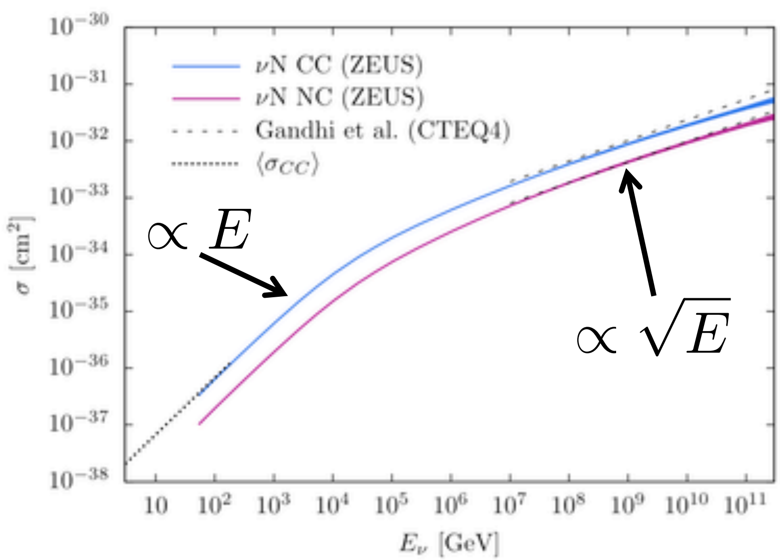
Super K Performance

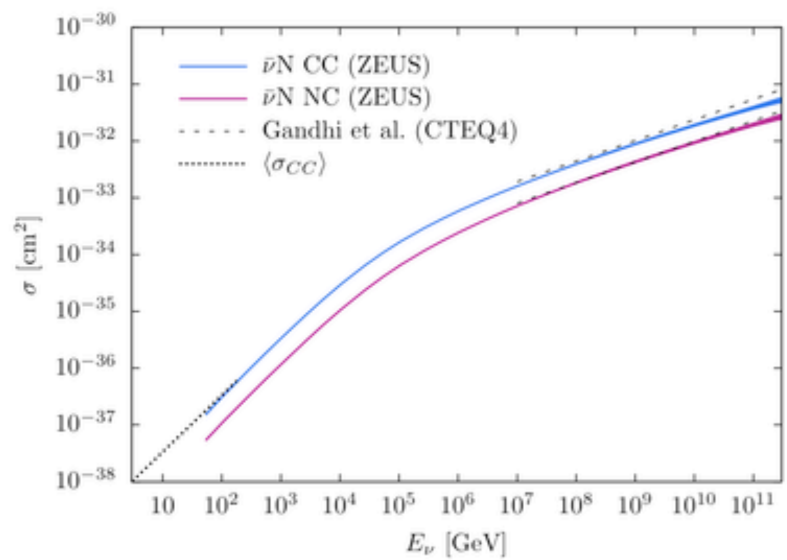


Neutrino and electron energy are perfectly correlated as it is a 2 body result.

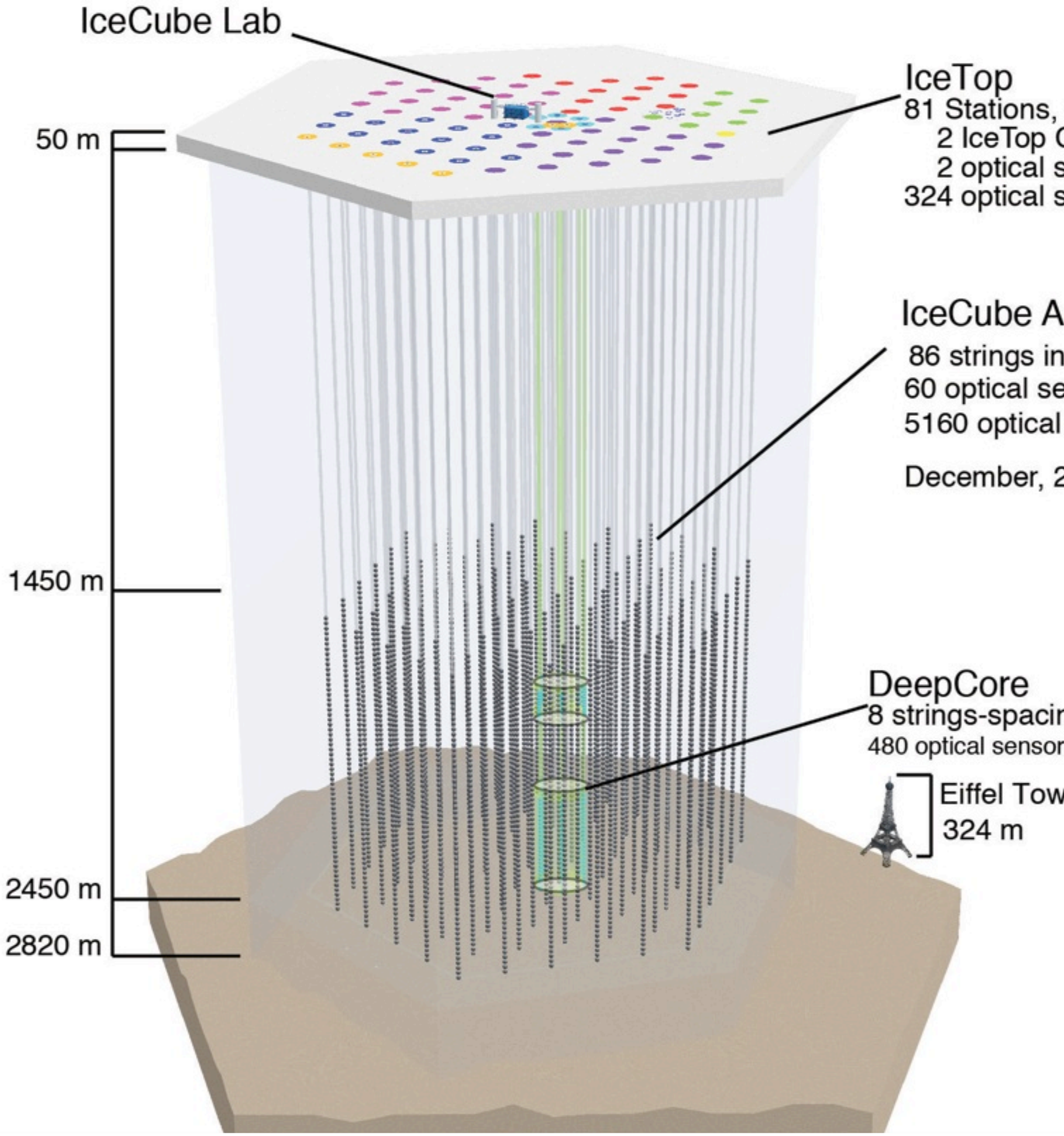
neutrino - matter cross-section E > 1 GeV

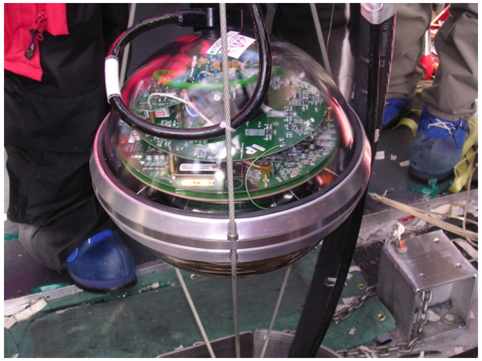






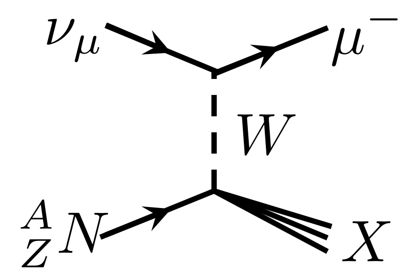
TeV neutrino detection: IcEcube





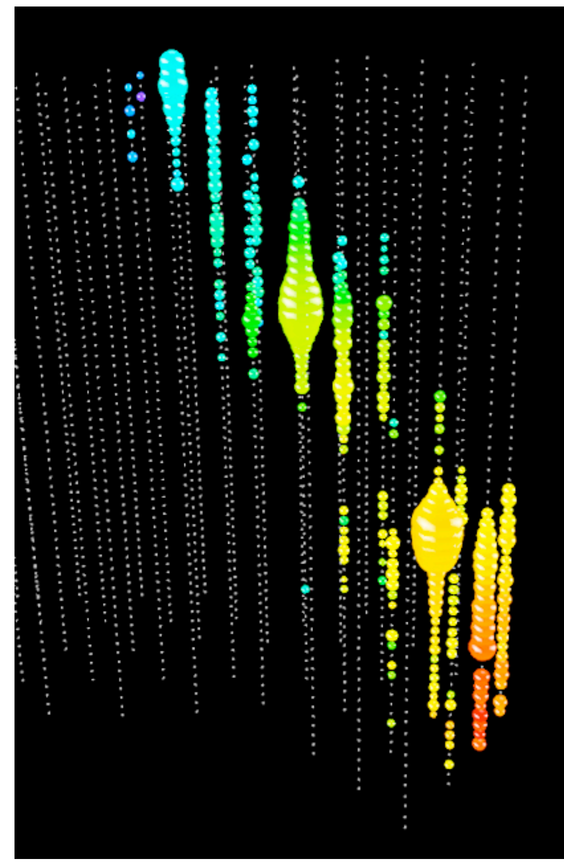
TeV neutrino detection: IceCube

Main detection mode (but not the only one) is muon neutrino charged current interaction.



Muon track length is hundreds of meters to several km long in IceCube energy range.

$$\theta_{\nu_\mu - \mu} \sim \frac{0.7^\circ}{\sqrt{E_\mu/\mathrm{TeV}}}$$



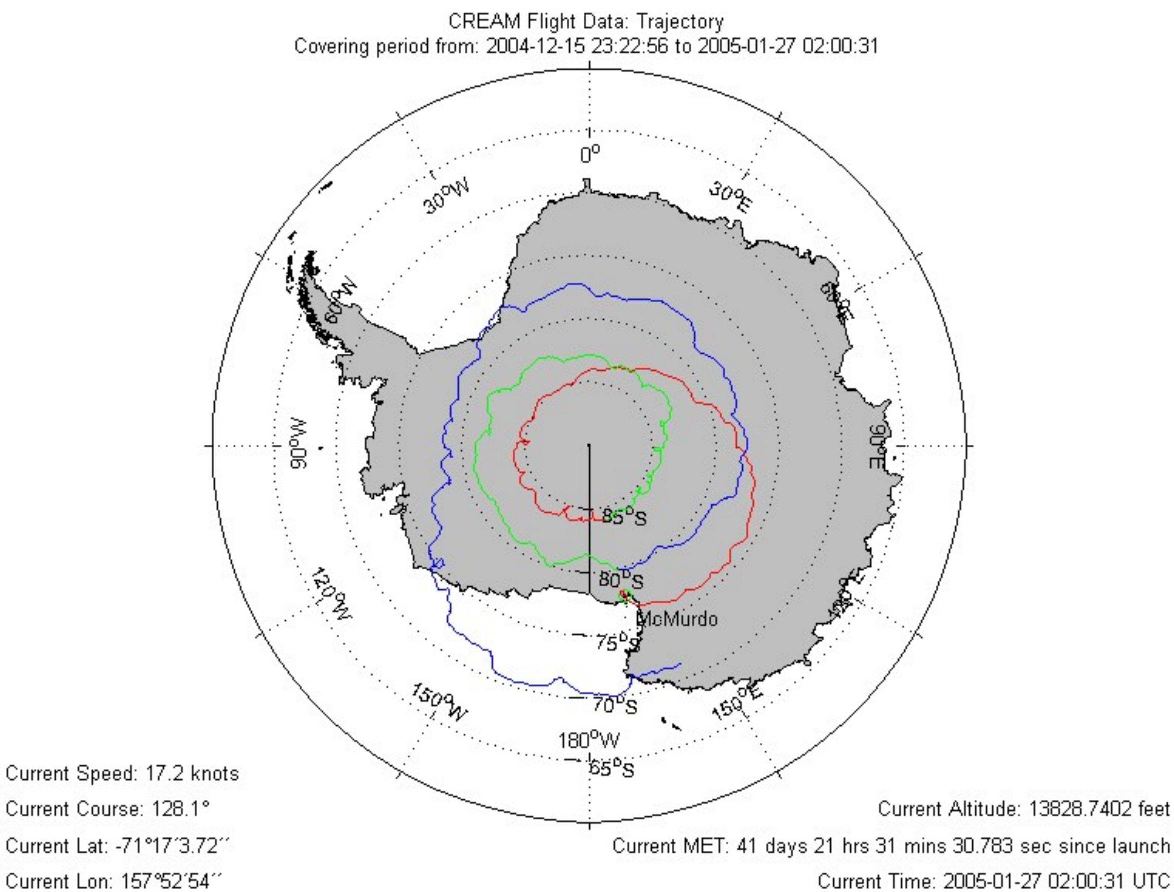
Muon directional reconstruction is based on long lever arm of track in the detector and on relative timing of PMTs.

Muon energy reconstruction is based on dE/dx (brems+ionization) of muon <u>inside</u> the detector. Neutrino-muon energy are correlated but not perfectly.

Example balloon experiment: CREAM

Modern balloon experiments are often launched from McMurdo, Antarctica to maximize flight duration.

Cream 1st flight trajectory



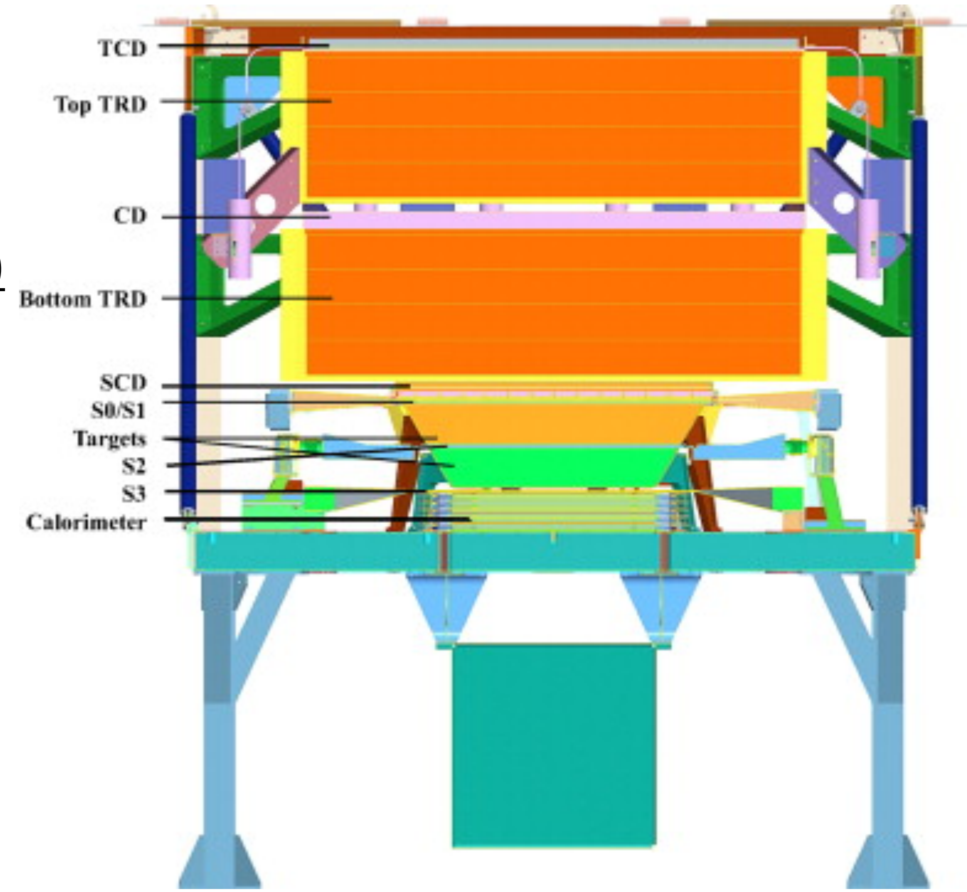
Cream flights
(1)12/16/04 – 1/27/05
(2) 12/16/05 – 1/13/06
(3) 12/19/07 – 1/17/08
(4) 12/19/08 – 1/7/09
(5) 12/1/09 – 1/8/10
(6) 12/20/10 – 12/26/10
(7) 2012 ?
(8) ?

Example balloon experiment: CREAM

CREAM objective: measure energy and species with high accuracy.

Multiple particle detectors

- Timing Charge Detector (TCD)
- <u>Transition Radiation Detector (TRD)</u>
- Cherenkov Detector (CD)
- Silicon Charge Detector (SCD)
- Scintillator hosdoscopes (S1,S2,S3)
- Calorimeter



H.S. Ahn et al (CREAM collab.)
NIMPA 579, (2007), 1034–1053

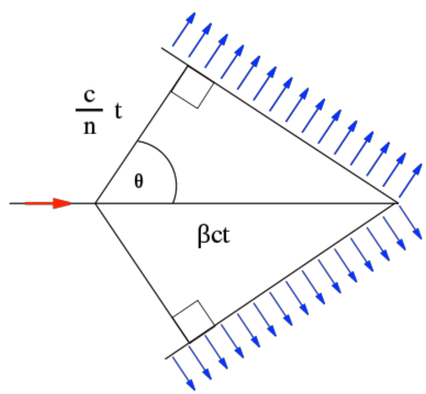
Let's focus on understanding the transition radiation detector. CREAM's

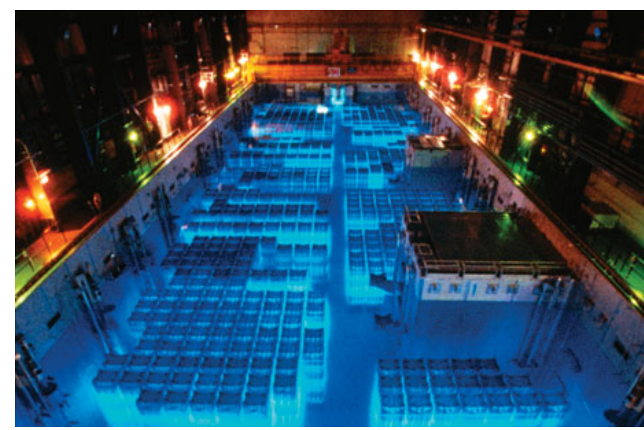
Transition Radiation Detector works in in the X-ray range.

Cherenkov Radiation

A charged particle traveling through a homogeneous dielectric with a speed faster than the speed of light in the medium produces Cherenkov radiation. The energy loss is insignificant, but it's easy to detect optical photons.

The wave front of Cherenkov is $\cos\theta = \dfrac{1}{n\beta}$ where n is the index of refraction. The threshold is $\beta = 1/n$





Nuclear Reactor Pond

The number of photons produced is

$$\frac{d^2N}{dEdx} = \frac{\alpha z^2}{\hbar c}\sin^2\theta_c = \frac{\alpha^2 z^2}{r_e m_e c^2}\left(1 - \frac{1}{\beta^2 n^2(E)}\right)$$

$$\approx 370\sin^2\theta_c(E) \quad [\mathrm{eV}^{-1}\mathrm{cm}^{-1}]$$

Transition Radiation

Transition radiation is related to Cherenkov radiation. When a particle of charge ze crosses from vacuum to a medium with plasma frequency ω_p, the energy radiated is $I = \alpha z^2 \gamma \hbar \omega_p / 3$

Here $\hbar\omega_p = \sqrt{4\pi n_e r_e^3} m_e c^2/\alpha = \sqrt{\rho\,[\mathrm{gr/cm^3}] Z/A} \times 28.81\ [eV]$

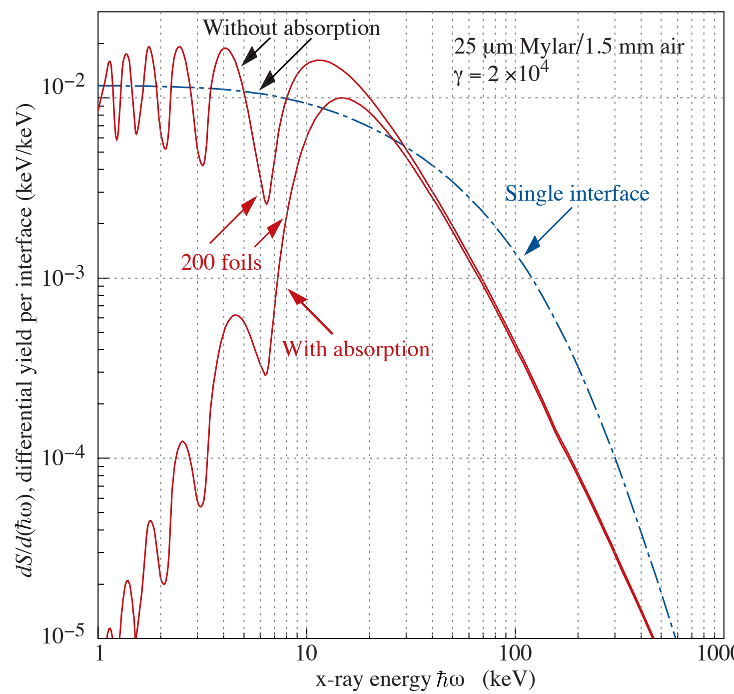
The number of photons above $\hbar\omega_0$ is:

$$N_\gamma(\hbar\omega > \hbar\omega_0) = \frac{\alpha z^2}{\pi}\left[\left(\log\frac{\gamma\hbar\omega_p}{\hbar\omega_0} - 1\right)^2 + \frac{\pi^2}{12}\right]$$

So for $\hbar\omega_0 << \gamma\hbar\omega_p$

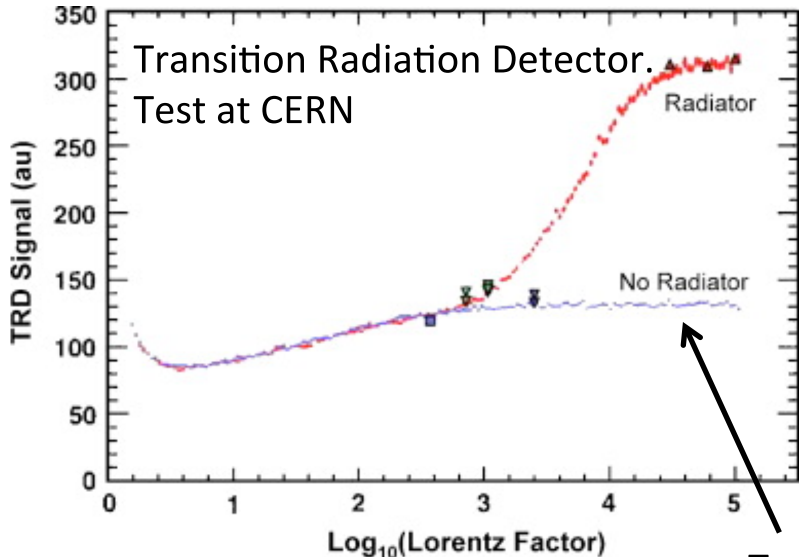
$$N_\gamma \to (\log\gamma)^2$$

Photon counting measures γ.
(but note dependence on z.

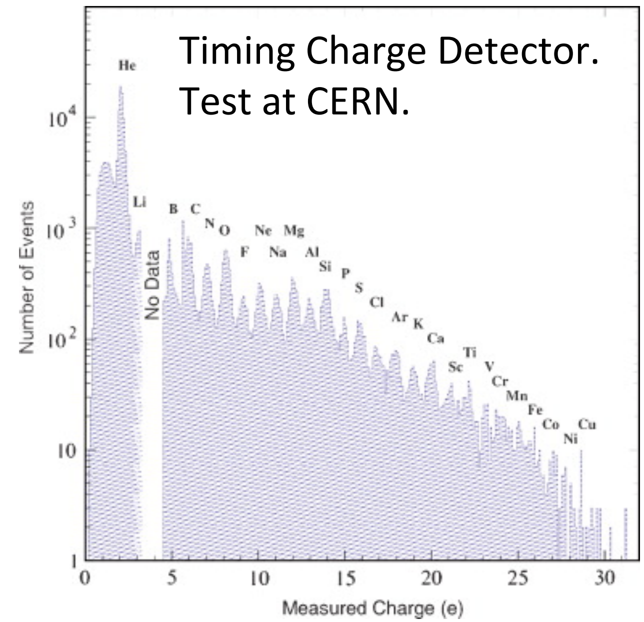


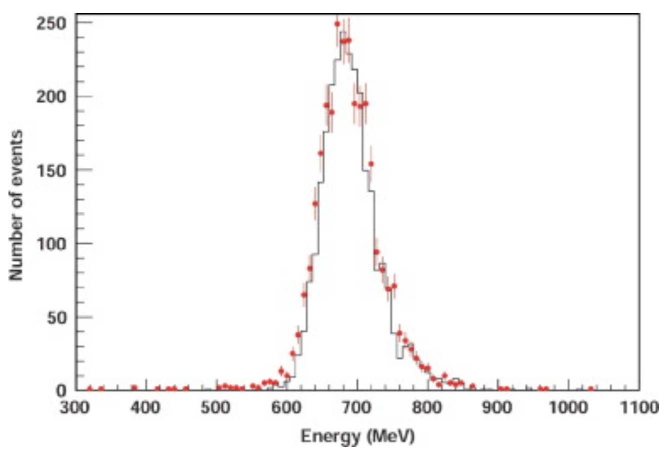
PDG 2010

CREAM Performance Transition



Test without
radiator foam





Calorimeter response to 150 GeV electrons
Test at CERN

H.S. Ahn et al (CREAM collab.)
NIMPA 579, (2007), 1034–1053

Electromagnetic Showers

The longitudinal profile of a cascade is well described by a gamma function. The energy deposited in the medium is:

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

The maximum energy deposition happens at $t_{max} = (a-1)/b$

The values a & b can be fitted to data. An alternative is to assume b=0.5 (good for a wide range of elements) and then find a from equating t_{max} with the shower length in the simplistic model:

$$t_{max} = (a-1)/b = \log_2 E/E_c$$

Cosmic Rays

Cosmic rays are charged particles that arrive at Earth with a wide range of energies with isotropic directions. Studies on cosmic rays focus on spectrum and elemental composition.