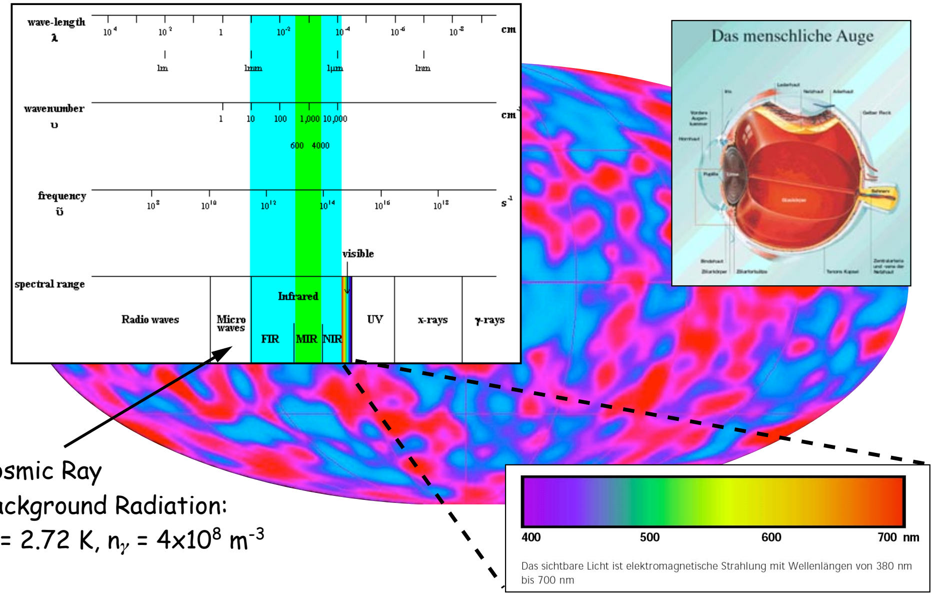
Detectors for Particle Physics

DESY Summer Student Lectures 2007

Carsten Niebuhr

Introduction



Cosmic Ray Background Radiation: $T = 2.72\ K$, $n_\gamma = 4\times10^8\ m^{-3}$

Topics of the Lecture

Part I

- Introduction
- Examples
- General Concepts
- Interaction of Charged Particles with Matter
  - Energy Loss: Bethe Bloch Formula
  - Multiple Scattering

Part II

- Use of Track Detectors for Momentum Measurement
- Gas Detectors
  - Proportional Chamber
  - Drift Chamber
  - TPC
  - MSGC, GEM
- Silicon Detectors
  - Strip Detectors
  - Pixel Detectors

Part III

- Scintillation Counters
- Photodetectors
- Cherenkov Counters
- Transition Radiation
- Calorimeters
  - Shower Development
  - electromagnetic
  - hadronic

Common lecture on Fr, 17.8. by Georg Steinbrück

- not covered
  - Trigger
  - DAQ

Literatur

Text books:

K.Kleinknecht: *Detektoren für Teilchenstrahlung*
Teubner, 1992

W.R. Leo: *Techniques for Nuclear and Particle Physics Experiments*
Springer 1994

G.F.Knoll: *Radiation Detection and Measurement*
Wiley, 3rd edition

C.Grupen: *Teilchendetektoren*
BI Wissenschaftsverlag 1993

W.Blum, L.Rolandi: *Particle Detection with Driftchambers*
Springer, 1994

Review articles:

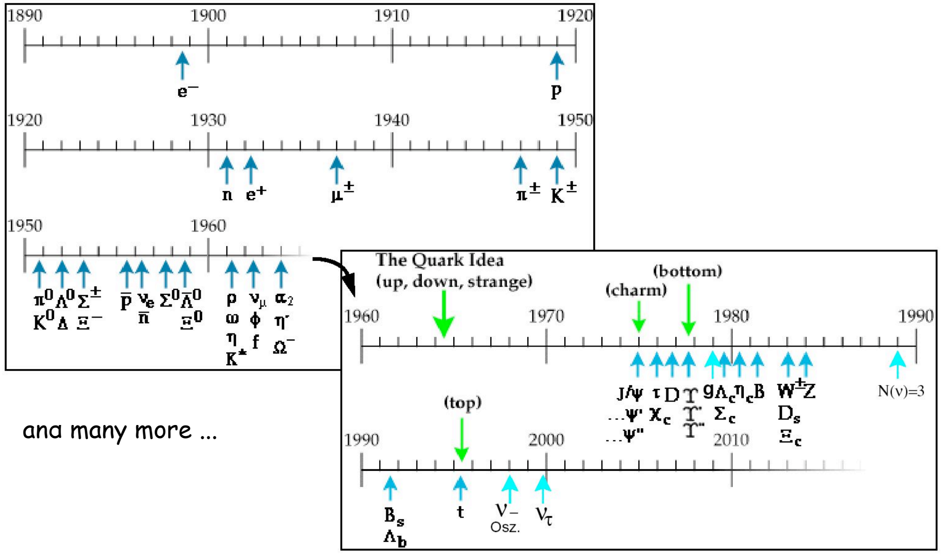
T.Ferbel: *Experimental Techniques in High Energy Physics*
Addison-Wesley 1987

Other sources:

Particle Data Group: *Review of Particle Physics*
Eur. Phys. J. C15, 1-878 (2000)

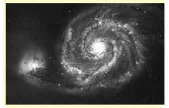
R.K.Bock, A.Vasilescu: *The Particle Detector BriefBook*
Springer, 1998 and //physics.web.cern.ch/Physics/ParticleDetector/BriefBook/

What are the Objects?

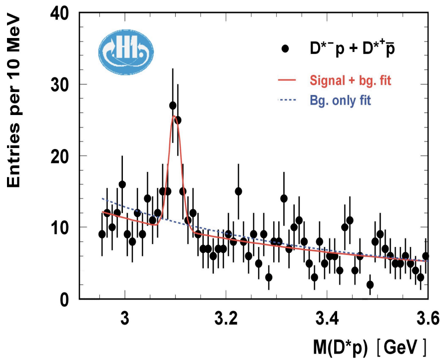


and many more ...

Fundamental Interactions

	Electro-weak force			
Forces	Strong force	Electro-magnetic force	Weak force	Gravity
Exchanged particles	Gluon	Photon	W,Z bosons	Graviton
Magnitude	1	0.01	10^{-5}	10^{-40}
	Nuclei Hadron Nuclear fusion Solar energy	Molecule, Atom Electronics Synchrotron rad. Aurora	Neutron decay Nuclei decay Neutrino Geothermy	Gravitation Galaxy Black Hole Stellar Pinwheel
				
Example	$\rho^0 \to \pi^+\pi^-$	$\pi^0 \to \gamma\gamma$	$K^0 \to \pi^+\pi^-$	
Lifetime [s]	$\approx 10^{-24}$	$\approx 10^{-16}$	$\approx 10^{-10}$	
cτ [mm]	$\approx 3 \times 10^{-13}$	$\approx 3 \times 10^{-5}$	≈ 30	

Example for Resonance at HERA



Pentaquark candidate:

$$\theta_c^0 \to D^{*-}p \to K^-\pi^+\pi^-p$$

minimal quark content: $uudd\bar{c}$

so far only „seen" by H1 ...

- is this a real signal ??
- or just a statistical fluctuation ?
- or a detector effect ?

=> very good understanding of detector response is required

- significance: signal/background
- resolution
- efficiency / acceptance

Detection of Particles and Radiation

The goal of experimental particle physics: measurement of

- particle properties
- reaction probabilities (→ cross sections)

This requires determination of:

- particle type (mass, charge, spin etc)
- momentum / energy of particle
- emission angles

Elements contributing to such measurements :

- position sensitive detectors → position, direction
- deflection in magnetic field → $|\vec{p}|$
- calorimetry: total energy absorption and measurement → E_{tot}
- mass determination → m
- Cherenkov radiation or time of flight → β
- transition radiation → γ

Criteria for an ideal Detector

Because in general there can be very complex event topologies one often aims at reconstruction of full event kinematics (background rejection)

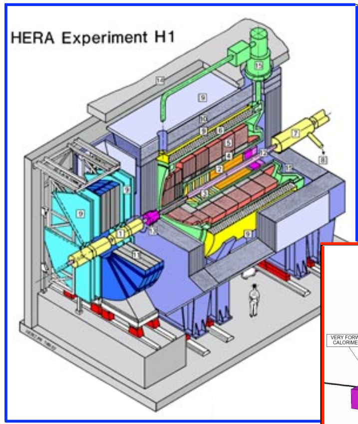
Most important:

- high efficiency
- high resolution
- high acceptance → try to cover full solid angle (4π)

also very important (partly conflicting demands):

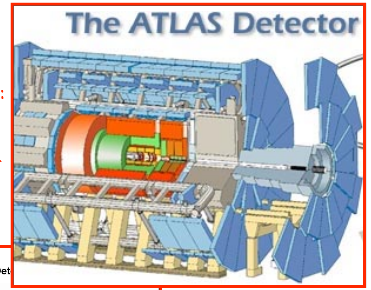
- particle identification capability
- fast response
- high rate capability
- small dead time
- hermeticity
- longevity of detector components
- high reliability
- good accessibility (for repairs)
- low cost

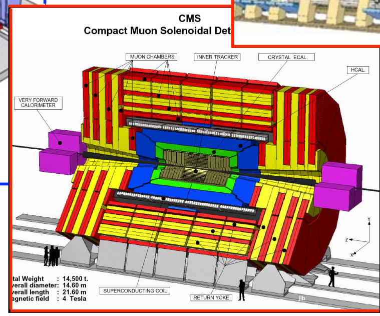
Modern Collider Detectors



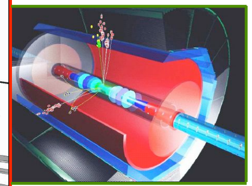
in operation: HERA/Tevatron

under construction: LHC





design phase: ILC



Example of Particle Physics Experiments

Besides the large collider detectors there are many other expts: www.hep.net/experiments/all_sites.html

Bates Linear Accelerator (MIT)
BLAST , OOPS , SAMPLE

Beijing IHEP
ARGO-YBJ , BES , Tibet ASgamma

Brookhaven
BRAHMS , Crystal Ball (E913/914) , E787 , E821/muon g-2 , E850 , E852 , E863/ EMU01 , E864 , E865 , E869 , E877 , E881 , E885 , E890 , E891 , E895 , E905 , E906 , E907 , E909 , E910 , E913/914 (Crystal Ball) , E917 , E923 , E926 , E927 , E949, E953 , EIC , EMU01/E863 , High Gain Harmonic Generation FEL , ICAE , IFEL , IMB , LEGS , MECO , Microundulator FEL , NuMass/E952 , PHENIX , PHOBOS , pp2pp , Smith-Purcell , STAR , Zero Degree Calorimeter

CERN
ALEPH , ALICE , AMS , ANTARES , ASACUSA , ATHENA , Atlas (European) , ATRAP , CDHS neutrino experiment/WA1 , CERES/NA45 , CHORUS , CMS , CosmoLEP , CPLEAR/PS195 , Crystal Barrel/PS 197 , Crystal Clear/RD18 , DELPHI , EMU01 , FELIX , HARP , ICANOE , ISOLDE , L3 , LHC-B , MISTRAL , NTOF1, NTOF2, NTOF3 , NA45.2/IONS/EL.PAR , NA47/SMC , NA48, NA48.1, NA48.2 , NA49 , NA50 , NA51 , NA52/ Newmass , NA56/SPY , NA57 , NA58/COMPASS , NA59 , NA60 , NOMAD , OBELIX/PS201 , OPAL , OPERA , PAMELA , PS185 , PS205/HELIUMTRAP , PS210 , PS212/DIRAC , PS214/HARP , RD8 , RD11 , RD12/TTC , RD13 , RD27 , RD39/SMSD , RD41/ MOOSE , RD42 , RD44/Geant 4 , RD45 , RD46 , RD48/ ROSE , RD49/RADTOL , TOSCA , TOTEM , WA85 , WA92 (Beatrice) , WA94 , WA97 , WA98 , WA102

DESY
H1 , HERA-B , Hermes , TESLA , ZEUS

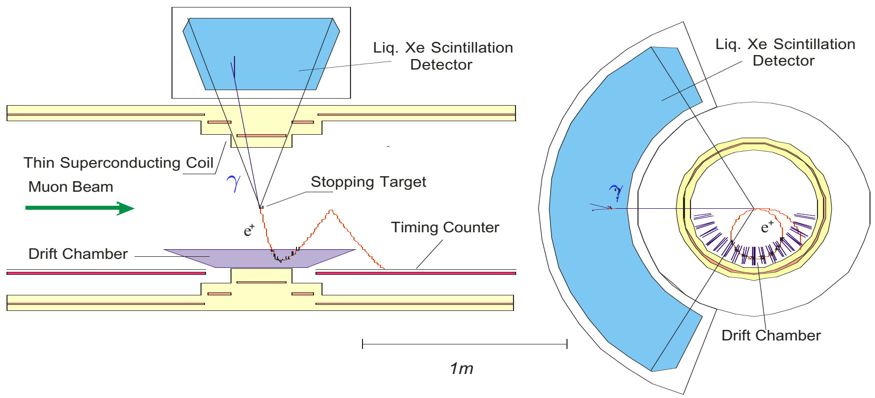
Fermilab
Antihydrogen/E862 , APEX/E868 , Auger Project , BooNE/E898 , BTEV/C0 , CDF/E830 , CDMS/E981 , CEX/E853 , Charmonium/E835 , CMS (US Server) , COSMOS/E803 , D0 (DZero)/E823 , Donut/E872 , E665 , E771 , E789 , Fermi III Project , FOCUS/E831 , HyperCP/E871 , KTEV/E799/E832 , MINOS/E875 , NuMI , NUSEA/E866 , NuTeV/E815 , SDSS , SELEX/ E781 , Zero Degrees/C0

Gran Sasso
BOREXino , CRESST , CUORICINO , DAMA , EASTOP, GALLEX(finished) , GENIUS , GNO , Heidelberg Dark Matter Search (HDMS) , Heidelberg-Moscow Experiment , ICARUS , LUNA , LVD , MACRO , MONOLITH , NOE , OPERA , USA

Search for Rare/Forbidden Decays

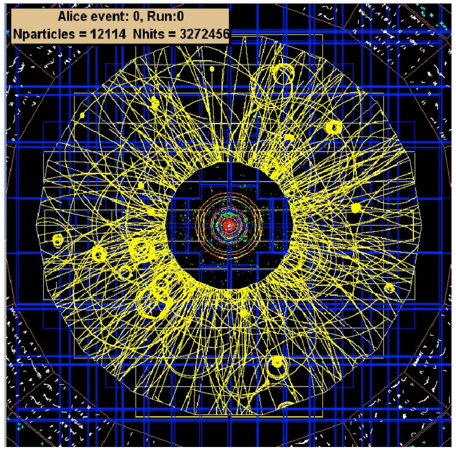
Experiment in preparation at Paul Scherrer Institut (PSI, Switzerland):

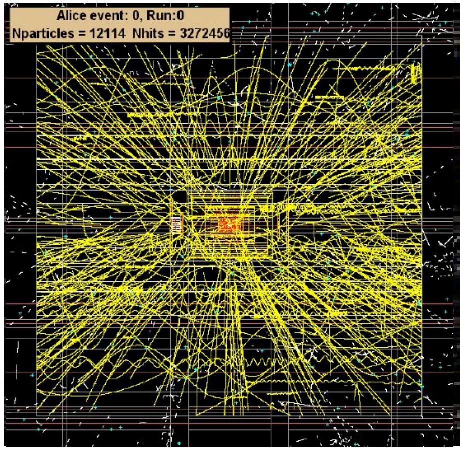
- search for lepton-number violating process: $\mu \to e\,\gamma$ sensitivity goal: 10^{-13} !
- needs excellent energy resolution, high event rate, but small track multiplicity per event
- start full data taking in 2007



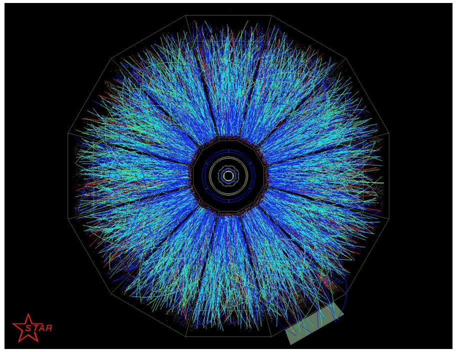
ALICE @ LHC

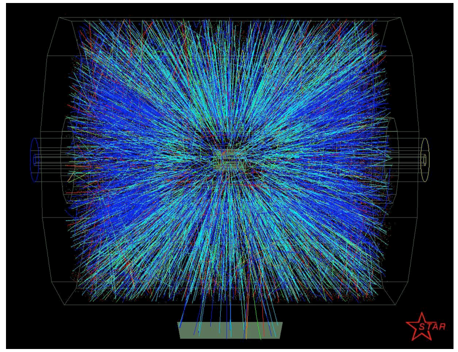
Heavy Ion Physics: this simulation shows 1/10 of all 10000-20000 expected tracks in a typical event. The separation of all these tracks puts very high demands on the position resolution and double hit seperation of the device.





Real Event in STAR at RHIC



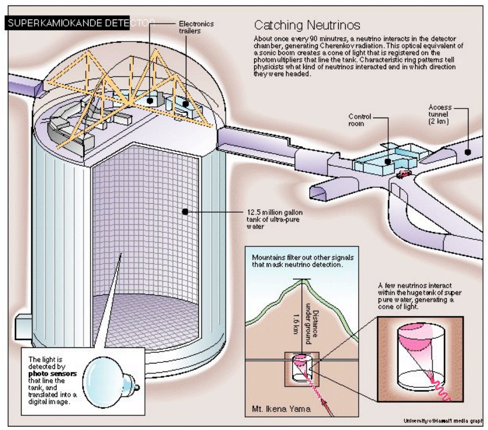


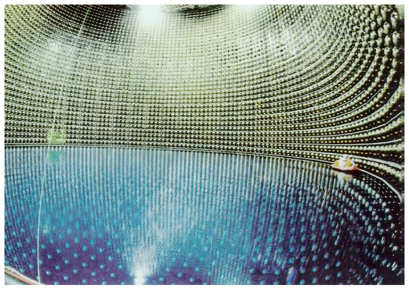
≈ 2000 tracks per event

Super Kamiokande (Japan)

Search for proton-decay and for neutrino oscillations

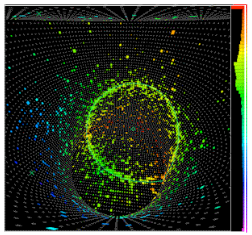
- 50000 tons of water
- 12000 photo tubes





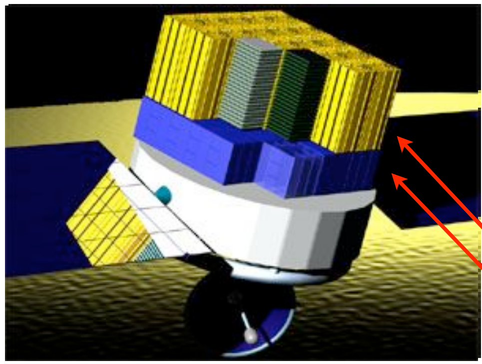
Reactions :

- $\nu_\mu N \to \mu N$ → Cherenkov
- $\nu_e N \to eN$ → shower



Satellite based Detectors

Liftoff scheduled for August 2007



GLAST Gamma-Ray observatory for high energy photons in the range 20MeV to >300 GeV

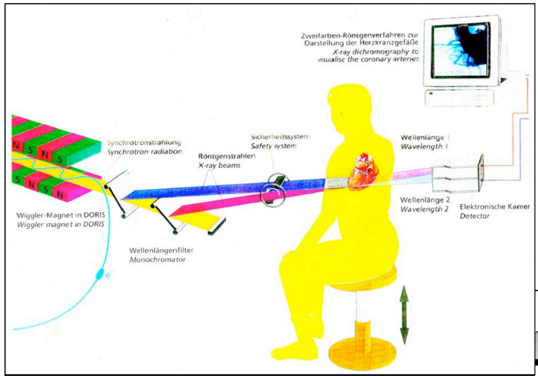
Astro particle physics

- history of star formation
- acceleration mechanism of AGN's
- sources of gamma ray bursts
- nature of dark matter

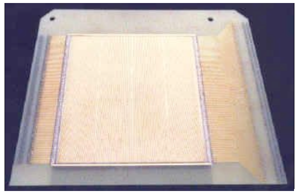
Components (need highest reliability !)

- precision tracker (Si-strips)
- calorimeter (CsI(Tl))
- data acquisition system
- anticoincidence detector

Applications in Medicine

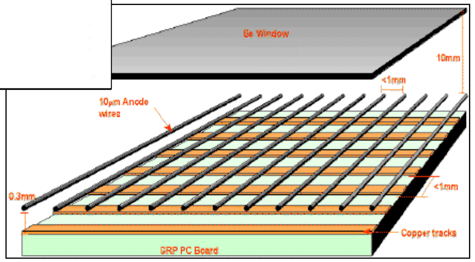


Non-invasive Koronary Angiography
using synchrotron radiation



Imaging microgap detector:

Photon rates ≈ $10^6\ mm^{-2}\ s^{-1}$



Interplay between Physics and Technology

Almost all effects used in particle detectors are based on the electromagnetic interaction only. Most modern detectors convert the absorbed energy into an electrical signal.

The detection sensitivity and detector performance depends on

- statistical processes in the detector
- fluctuations in the electronics

To maximize detection sensitivity and resolution one must consider and optimize

- signal formation in the detector
- coupling of the detector to the readout electronics
- noise generated in the electronics

Understanding of e.g. a modern tracking detector in high-energy physics or a medical imaging system thus requires knowledge of

- solid state physics
- semiconductor device physics
- semiconductor fabrication technology
- low-noise electronics techniques
- analog and digital microelectronics
- high-speed data transmission
- computer-based data acquisition systems

Interaction of Radiation with Matter

Charged Particles

heavy charged particles

electrons

Neutral Particles

neutrons

gamma radiation

neutrinos

Coulomb-Interaction with electrons of medium
→ electrical signal in detector

Mainly "singular" interactions, resulting in energy transfer to charged particles

Cross Section of a typical Collider Detector

Particle type:

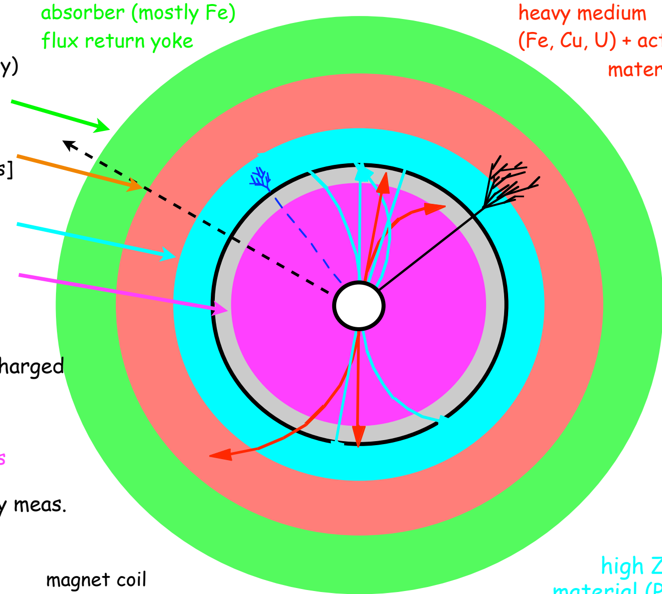
neutrinos (missing energy)

muons μ

hadrons: p, π, K ...
[quarks, gluons → jets]

electrons, photons

charged particles



absorber (mostly Fe)
flux return yoke

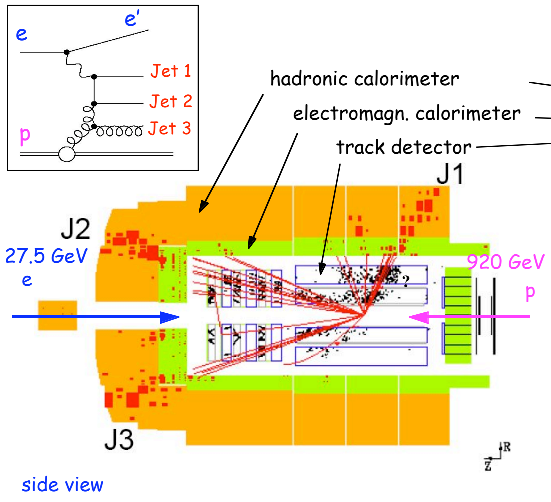
heavy medium
(Fe, Cu, U) + active material

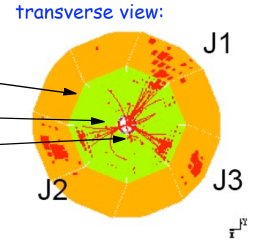
- Track detectors for charged particles
  - gas detectors
  - solid state detectors
- Calorimeter for energy meas. (neutral & charged)
  - electromagnetic
  - hadronic

magnet coil
(solenoid, field || beam axis)

high Z material (Pb)

Example 1: HERA ep Event with 3 Jets





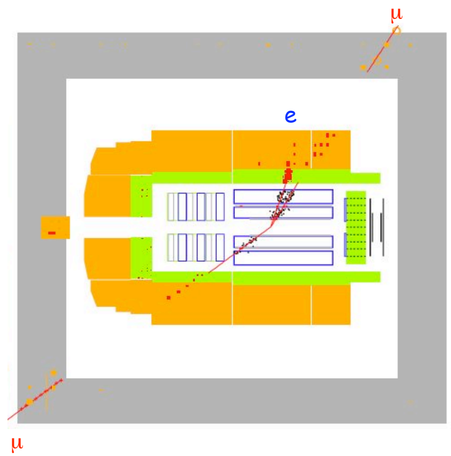
almost hermetic detector

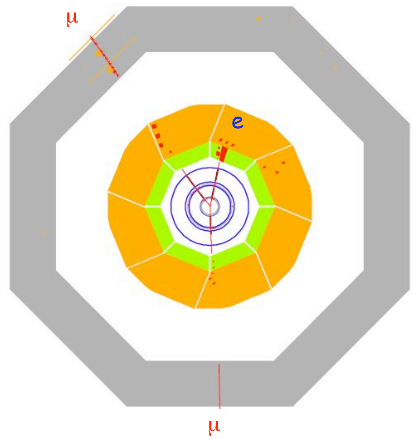
⇒ detection of nearly all produced particles

exploit energy- and momentum conservation

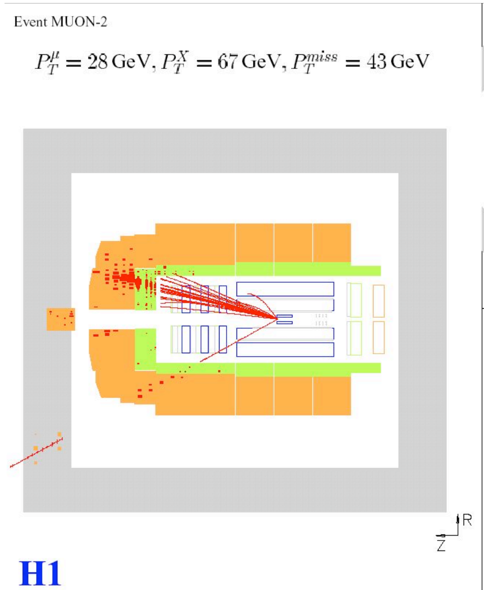
Example 2: Muon Detection

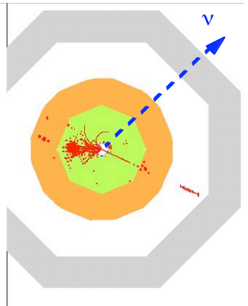
Because muons do not interact strongly and because of their large mass (compared to electrons) they don't shower so easily and thus can penetrate calorimeter and iron yoke





Example 3: Neutrinos



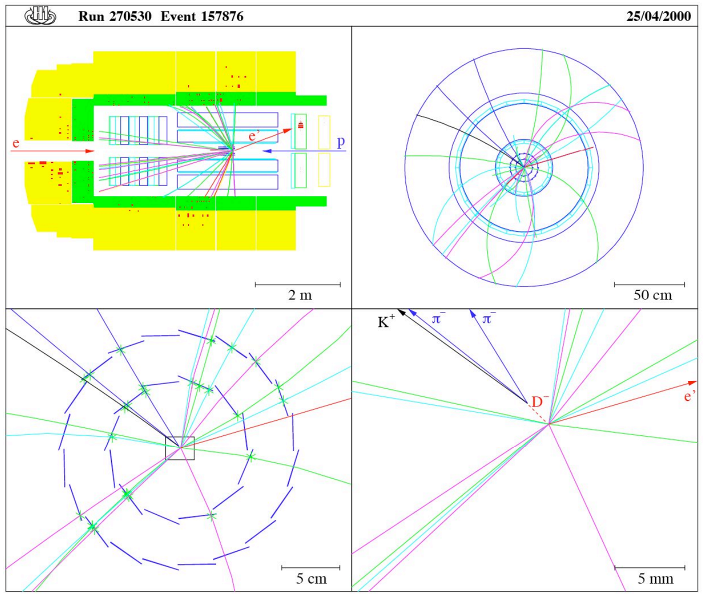


Missing transverse energy and transverse momentum:

$$\sum_i \vec{p}_{trans} = 43\text{GeV}$$

carried away by neutrino ?

Example 4: Secondary Vertices



Some mesons containing heavy quarks (charm or beauty) only decay via the weak interaction.

example: $D^- \rightarrow K^+ \pi^- \pi^-$

Resulting lifetimes are relatively long:

$\tau \approx O(10^{-12}s)$ or

$c\tau \approx 100 - 500\ \mu m$

With the help of high precision track detectors one can distinguish if particles originate from secondary or primary vertex:

⇒ vertex detectors [in most cases based on silicon]

Interaction of Charged Particles

There are two principal effects which characterize the passage of charged particles through matter:

- energy loss
- change of direction

both effects result from the following electromagnetic processes:

- inelastic collisions with shell electrons of medium
- elastic scattering off nuclei

relevant is the statistical sum of many such interactions.

In addition there are the following processes:

- bremsstrahlung
- emission of Cherenkov radiation
- nuclear reactions
- emission of transition radiation

which however in general occur much less frequent than atomic collisions.

For charged particles one must distinguish light particles (i.e. e^+, e^-) and heavy particles (i.e. all the rest: μ, π, p, α, light nuclei, ...)

Bethe-Bloch Formula

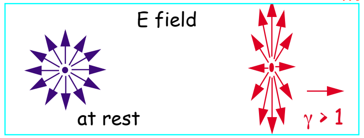
Energy loss by ionisation:

$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \cdot \frac{1}{\beta^2} \cdot \left[\ln\frac{2m_e c^2\beta^2\gamma^2}{I} - \beta^2 - \frac{\delta}{2}\right] \quad \text{[MeV/cm]}$$

- incident particle
  - $\beta = v/c$ velocity of particle
  - z charge of particle
- medium
  - Z, A of medium
  - $I \cong 16 \cdot Z^{0.9}$ average ionisation potential in [eV]
  - δ describes density effect due to polarisation of medium ($\Rightarrow$ saturation of relativistic rise)
- other constants
  - N_A Avogadro's number
  - $r_e = 2.8\,fm$ classical electron radius
  - m_e electron mass

Properties:

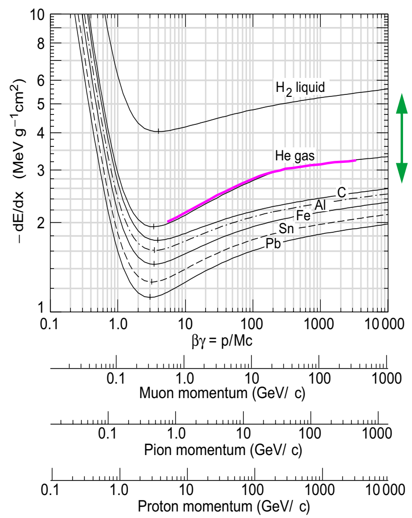
- dependence only on particle velocity not on particle mass
- at small energies
  - drops like $\propto 1/\beta^2$
- at relativistic energies i.e. $\beta\gamma \gg 1$
  - logarithmic rise $\propto \ln(\beta\gamma) = \ln\frac{p}{m}$



- approximate range of validity:

$$10\,\text{MeV/c} \le p \le 50\,\text{GeV/c}$$

Material Dependence



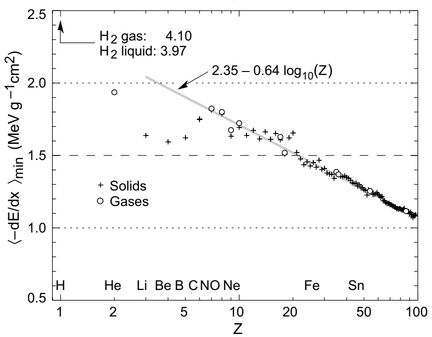
- logarithmic rise more pronounced for gases (He)

Energy loss is a function of Z/A, I, and the density ρ. Hence use instead :

$$X = x \cdot \rho \quad \Rightarrow \quad \frac{dE}{dX} = \frac{1}{\rho} \cdot \frac{dE}{dx} \quad [\text{MeV g}^{-1}\text{cm}^2].$$

$\Rightarrow$ dE/dX essentially a function of Z/A

"Stopping Power"



Energy Loss of Electrons

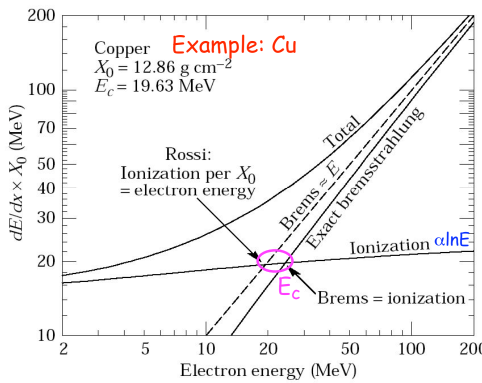
In addition to energy loss by ionisation high energy particles also loose energy due to interaction with the Coulomb field of the nuclei: Bremsstrahlung

Due to their small mass this effect is especially prominent for electrons (positrons):

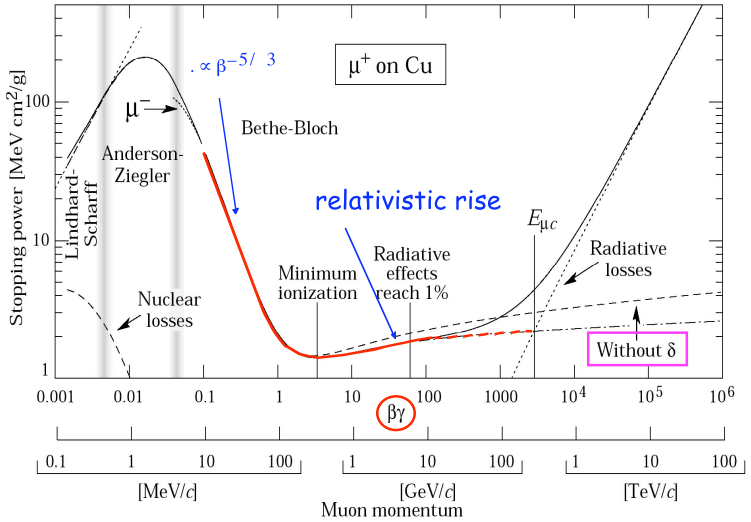
- $-dE/dx \propto Z^2 \cdot E/m^2$
- it is useful to introduce radiation length X_0
- energy attenuation: $E = E_0 \exp\left(\frac{-x}{X_0}\right)$
- approx.: $X_0 = \dfrac{716\,\text{g cm}^{-2} A}{Z(Z+1)\,\ln(287/\sqrt{Z})}$
- critical energy E_c:

$$\frac{dE_{Brems}}{dx} = \frac{dE_{collision}}{dx}$$

- approximately: $E_c = \dfrac{610\,\text{MeV}}{Z + 1.24}$



Energy Loss of Muons



MIP = minimum-ionising particles

dE/dx Applications for different Detector Types

Gas

- ionisation ⇒ proportional or drift chamber

Liquid

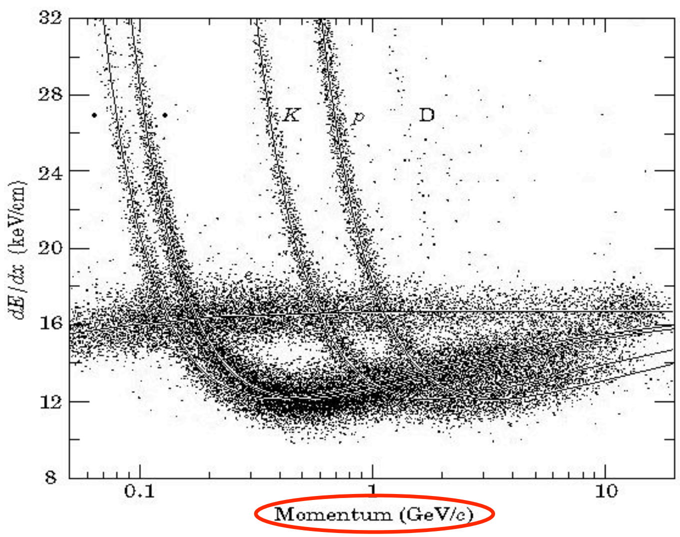
- local heating ⇒ bubble chamber
- ionisation ⇒ calorimeter (Liquid Argon or Krypton)

Solid

- excitation of electrons → conversion into light ⇒ scintillators
- creation of electron-hole pairs ⇒ solid state detectors

dE/dx in a TPC

Measurements in PEP4/9-TPC (Ar-CH_4 = 80:20 @ 8.5atm)



If dE/dx is plotted versus momentum of particle the curves are shifted horizontally for different masses

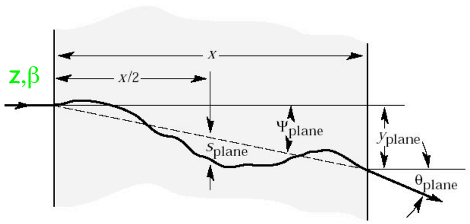
Application: if also the momentum of the particle is known the measurement of the specific ionisation can be used for particle identification

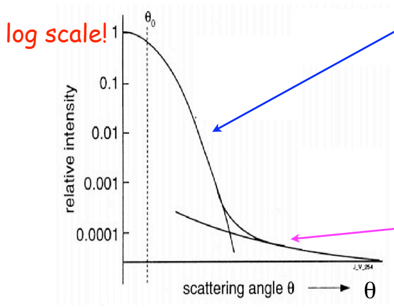
In this example each dot represents ≈185 single measurements in a drift chamber

Properties of some Materials (PDG)

Material	Z	A	$\langle Z/A\rangle$	Nuclear [a] collision length λ_T {g/cm²}	Nuclear [a] interaction length λ_I {g/cm²}	$dE/dx\|_{min}$ [b] {MeV/(g/cm²)}	Radiation length [c] X_0 {g/cm²}	X_0 {cm}	Density {g/cm³} ({g/ℓ} for gas)	Liquid boiling point at 1 atm(K)	Refractive index n ((n−1)×10⁶ 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
CO_2 gas			0.49989	62.4	89.7	(1.819)	36.2	[18310]	[1.977]		[410]

Multiple Scattering





Scattering of charged particles off the atoms in the medium causes a change of direction:

the statistical sum of many such small angle scatterings results in a gaussian angular distribution with a width given by:

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

example: p = 1 GeV/c, d = 300μm Si, X_0=9.4cm
⇒ $\theta_0 \approx$ 0.8 mrad. For 10cm distance this corresponds to 80μm, which is significantly larger than typical resolution of Si-strip detector

the less likely scattering off the atomic nuclei causes large scattering angles resulting in a deviation from a gaussian distribution at large angles

Summary Part I

- properties of different particles require many different types of detectors
- rough classification
  - track/position detectors (non destructive) → Part II
  - calorimeters (destructive) → Part III
- basically all detectors based on electromagnetic interaction
- detectors also more and more used for other applications (e.g. medical appl.)

- energy loss of charged particles: Bethe-Bloch describes loss due to ionisation
  - $z^2/\beta^2 \rightarrow \ln E$ → Fermiplateau
  - minimum at $\beta\gamma \approx 3$: 1-2 MeV per gcm^{-2}
  - however light particles (electrons, muons) at high energies lose energy predominantly by bremsstrahlung: $-dE/dx \propto Z^2 \cdot E/m^2$

- multiple scattering
  - gaussian core of distribution with angular spread: $\theta_0 \sim \frac{1}{p}\sqrt{\frac{x}{X_0}}$
  - deviation from gaussion distributiun at large angles due to Rutherford scattering (nuclei)

Part II

- Use of Track Detectors for Momentum Measurement

- Gas Detectors
  - Proportional Chamber
  - Drift Chamber
  - TPC
  - MSGC, RPC, GEM

- Solid State Detectors
  - Strip Detectors
  - Pixel Detectors

→ Common lecture on Fr, 10.8. by Georg Steinbrück