Cross Section of Typical Collider Detector

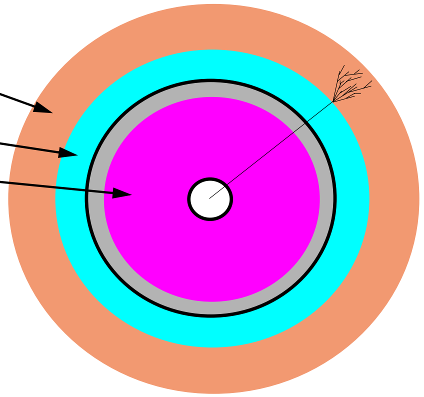
Particle type:

- neutrinos (missing energy)
- muons μ
- hadrons: p, π, K ...
  [quarks, gluons $\rightarrow$ jets]
- electrons, photons
- charged particles

Rough classification

- track detectors for charged particles:
  - gas detectors
  - solid state detectors
- calorimeter for energy measurement
  - electromagnetic
  - hadronic

"massless" detectors



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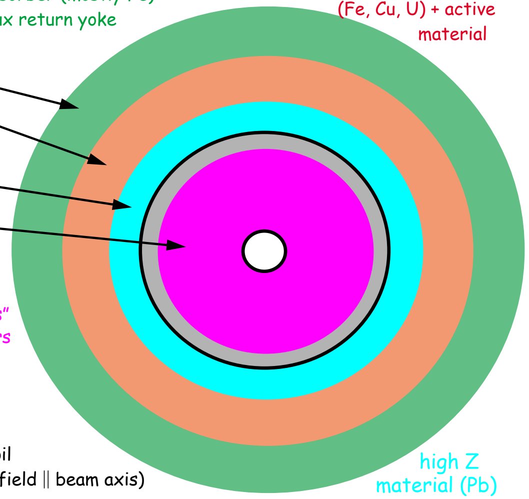

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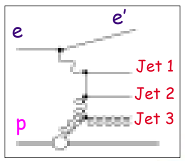
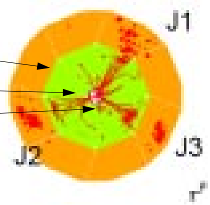
Example 1: HERA ep 3-Jet Event



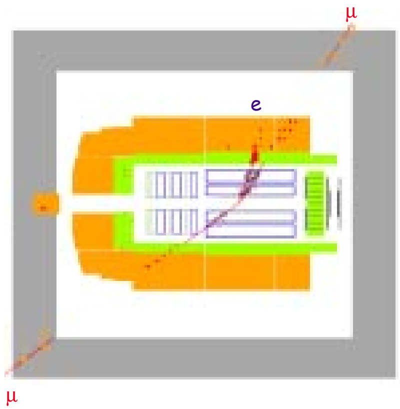


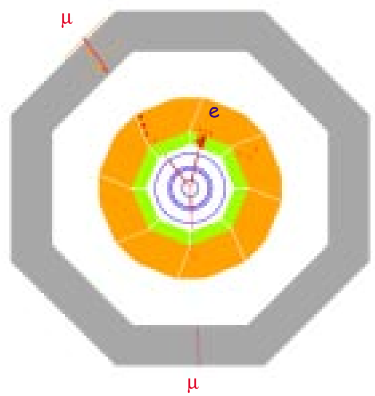
$$\sum_i \vec{p}_{trans} = 0$$

- almost hermetic detector
- $\Rightarrow$ detection of nearly all produced particles
- exploit energy- and momentum conservation

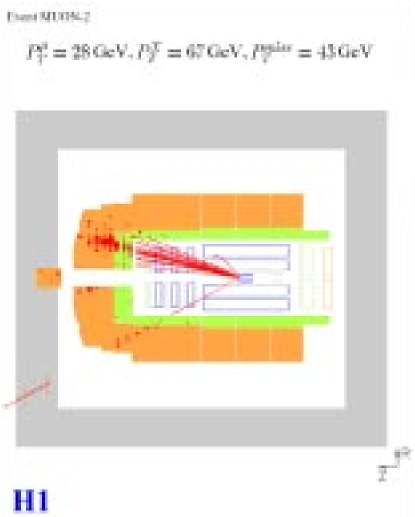
Example 2: Muon Detection

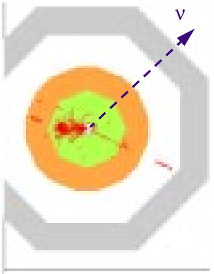
Because muons do not interact strongly and because of their large mass (compared to electrons) they don't shower so easily and thus can penetrate calorimeter and iron yoke





Example 3: Neutrinos



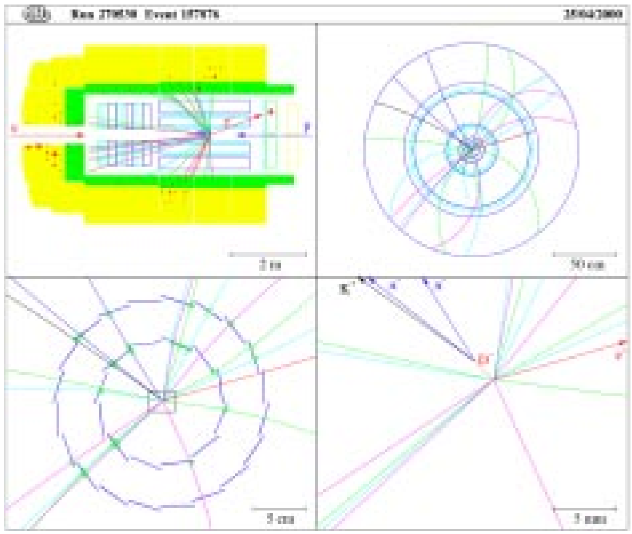


Missing transverse energy and transverse momentum:

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

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

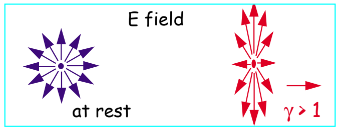
Energy loss by ionisation:

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

- 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 (⇒ saturation of relativistic rise)
- other constants
  - N_A Avogadro's number
  - $r_e = 2.8\, fm$ classical electron radius
  - m_e electron mass

Properties:

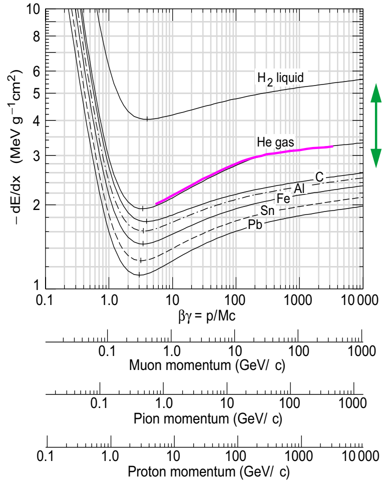
- dependence only on particle velocity not on particle mass
- at small energies
  - drops like $\propto 1/\beta^2$
- at relativistic energies i.e. $\beta\gamma \gg 1$
  - logarithmic rise $\propto \ln\beta\gamma = \ln E$



- approximate range of validity:

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

Material Dependence

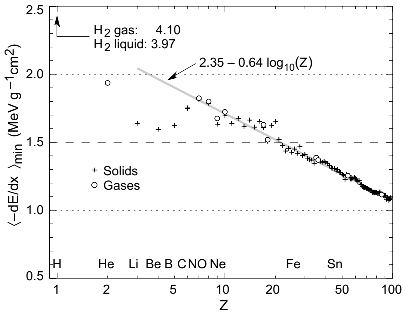


Energy loss is a function of Z/A, I, and the density ρ . Hence use instead :

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

⇒ dE/dX essentially a function of Z/A

"Stopping Power"



- logarithmic rise more pronounced for gases (He)

Energy Loss of Electrons

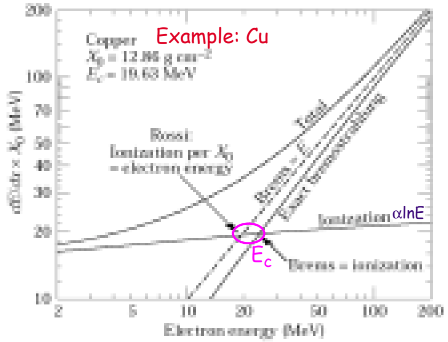
In addition to energy loss by ionisation high energy particles also loose energy due to interaction with the Coulomb field of the nuclei: Bremsstrahlung

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

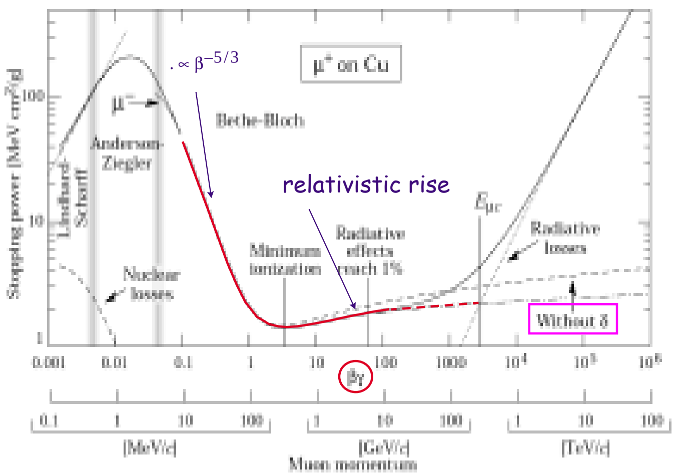
- $-dE/dx \propto Z^2 \cdot E/m^2$
- it is useful to introduce radiation length X_0
- energy attenuation: $E = E_0 \exp\left(\frac{-x}{X_0}\right)$
- approx.: $X_0 = \frac{716 \text{g cm}^{-2} A}{Z(Z+1)\ \ln(287/\sqrt{Z})}$
- critical energy E_c:

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

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



Energy Loss for Muons



MIP = minimum-ionising particles

dE/dx Applications in different Detector Types

Gas

- ionisation ⇒ proportional or drift chamber

Liquid

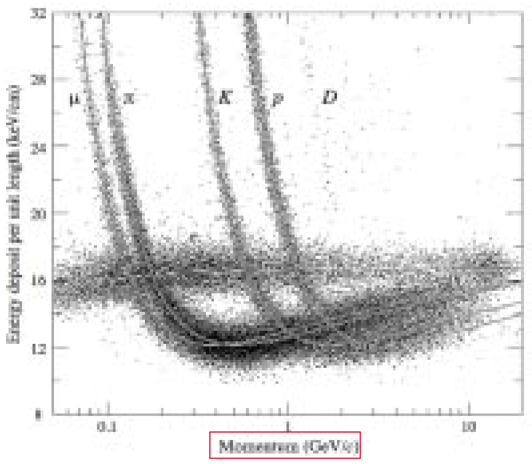
- local heating ⇒ bubble chamber
- ionisation ⇒ calorimeter (Liquid Argon or Krypton)

Solid

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

dE/dx in a TPC for different Particle Species

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



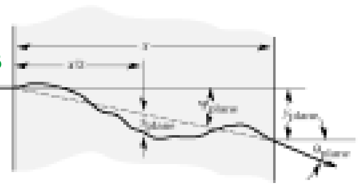
- If dE/dx is plotted versus momentum of particle the curves are shifted horizontally for different masses
- Application: if also the momentum of the particle is known the measurement of the specific ionisation can be used for particle identification
- In this example each dot represents 185 single measurements in a TPC

Properties of some Materials (PDG)

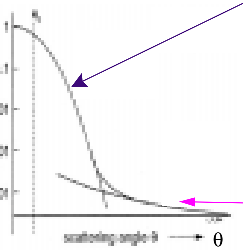
Material	Z	A	$\langle Z/A \rangle$	Nuclear [a] collision length λ_T {g/cm^2}	Nuclear [a] interaction length λ_I {g/cm^2}	$dE/dx\|_{min}$ [b] {MeV/(g/cm^2)}	Radiation length [c] X_0 {g/cm^2}	X_0 {cm}	Density {g/cm^3} ({g/ℓ} for gas)	Liquid boiling point at 1 atm(K)	Refractive index n (($n-1$)×10^6 for 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
CO_2 gas			0.49989	62.4	89.7	(1.819)	36.2	[18310]	[1.977]		[410]

Multiple Scattering

z,β



log scale!



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:

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

- 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 a 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 of Part I

- properties of different particles requires 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
  - $z^2/\beta^2 \to \ln E$ → 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)