The Physics of Particle Detectors

Lecture Notes
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On tools and instrumentation

“New directions in science are launched by new tools much more often than by new concepts.

The effect of a concept-driven revolution is to explain old things in new ways.

The effect of a tool-driven revolution is to discover new things that have to be explained”

Freeman Dyson

⇒ New tools and technologies will be extremely important to go beyond LHC
Nobel prices for instrumentation

1927: C.T.R. Wilson, Cloud Chamber
1939: E. O. Lawrence, Cyclotron & Discoveries
1948: P.M.S. Blackett, Cloud Chamber & Discoveries
1950: C. Powell, Photographic Method & Discoveries
1954: Walter Bothe, Coincidence method & Discoveries
1960: Donald Glaser, Bubble Chamber
1968: L. Alvarez, Hydrogen Bubble Chamber & Discoveries
1992: Georges Charpak, Multi Wire Proportional Chamber
Preliminary definition

The Physics of Particle Detectors

What is a Particle?

What is a Detector?

How to detect a particle?
What is a Particle?
Barions & mesons

Meson octet

Baryon octet

Baryon decuplet
Particle detection

• The detector sees only “stable” particles:
  – Electrons, muons, photons, pions, kaons, protons and neutrons

• In order to detect a particle, it has to interact - and deposit energy

• Ultimately, the signals are obtained from the interactions of charged particles

• Neutral particles (photons, neutrons) have to transfer their energy to charged particles to be measured
  ➔ calorimeters
A history of discoveries

... image and logic discoveries
The tools of discovery

John Aitken, *1839, Scotland:

Aitken was working on the meteorological question of cloud formation. It became evident that cloud droplets only form around condensation nuclei.

Aitken built the ‘Dust Chamber’ to do controlled experiments on this topic. Saturated water vapour is mixed with dust. Expansion of the volume leads to super-saturation and condensation around the dust particles, producing clouds.

From steam nozzles it was known and speculated that also electricity has a connection to cloud formation.
Charles Thomson Rees Wilson, * 1869, Scotland:

Wilson was a meteorologist who was, among other things, interested in cloud formation initiated by electricity.

In 1895 he arrived at the Cavendish Laboratory where J.J. Thompson, one of the chief proponents of the corpuscular nature of electricity, had studied the discharge of electricity through gases since 1886.

Wilson used a ‘dust free’ chamber filled with saturated water vapour to study the cloud formation caused by ions present in the chamber.
The cloud chamber

Wilson Cloud Chamber 1911
The tools of discovery

Conrad Röntgen discovered X-Rays in 1895.

At the Cavendish Lab Thompson and Rutherford found that irradiating a gas with X-rays increased its conductivity suggesting that X-rays produced ions in the gas.

Wilson used an X-Ray tube to irradiate his Chamber and found ‘a very great increase in the number of the drops’, confirming the hypothesis that ions are cloud formation nuclei.

Radioactivity (‘Uranium Rays’) discovered by Becquerel in 1896. It produced the same effect in the cloud chamber.

1899 J.J. Thompson claimed that cathode rays are fundamental particles \(\rightarrow\) electron [Nobel 1906].

Soon afterwards it was found that rays from radioactivity consist of alpha, beta and gamma rays (Rutherford).
The cloud chamber

X-rays, Wilson 1912

Alphas, Philipp 1926
Important particle discoveries

Positron discovery,
Carl Andersen 1933
[Nobel price 1936]

Magnetic field 15000 Gauss,
chamber diameter 15cm.

A 63 MeV positron passes through a
6mm lead leaving the plate with
energy 23MeV.

The ionization of the particle, and its
behaviour in passing through the foil
the same as those of an electron.
Important physics discovery

The picture shows an electron with 16.9 MeV initial energy. It spirals about 36 times in the magnetic field.

At the end of the visible track the energy has decreased to 12.4 MeV. From the visible path length (1030 cm) the energy loss by ionization is calculated to be 2.8 MeV.

The observed energy loss (4.5 MeV) must therefore be caused in part by Bremsstrahlung. The curvature indeed shows sudden changes as can most clearly be seen at about the seventeenth circle.

Fast electron in a magnetic field at the Bevatron, 1940
The muon was discovered in the 1930ies and was first believed to be Yukawa’s meson that mediates the strong force.

The long range of the muon was however causing contradictions with this hypothesis.

In 1947, Powell et. al. discovered the Pion in nuclear emulsions exposed to cosmic rays, and they showed that it decays to a muon and an unseen partner.

The constant range of the decay muon indicated a two body decay of the pion.
Particle momenta are measured by the bending in the magnetic field.

‘... The V0 particle originates in a nuclear interaction outside the chamber and decays after traversing about one third of the chamber. The momenta of the secondary particles are $1.6\pm0.3$ BeV/c (now GeV/c) and the angle between them is 12 degrees ...’

By looking at the specific ionization one can try to identify the particles and by assuming a two body decay on can find the mass of the V0.

‘... if the negative particle is a negative proton, the mass of the V0 particle is $2200 \text{ m}_e$, if it is a $\pi$ or $\mu$ Meson the V0 particle mass becomes about $1000\text{ m}_e$ ...’

Rochester and Wilson
Important particle discoveries

Pions from AGS (Brookhaven) decay in flight into muon and neutrino. 5,000-ton steel wall stops muons. Neutrinos detected as spark trails due to the impact on aluminum plates in a neon-filled detector.

Discovery of the muon neutrino (1962)

Leon M. Lederman
Melvin Schwartz
Jack Steinberger

[Nobel prize 1988]
Important particle discoveries

Discovery of the W/Z boson (1983)

Carlo Rubbia
Simon Van der Meer

[Nobel prize 1984]

$Z_0 \rightarrow e^+e^-$
Important particle discoveries

Discovery of the Higgs boson (20XX)
ATLAS and CMS collaborations
[P. Higgs, Nobel 20YY]

“This is not exactly, what theory predicted for the Higgs decay!”
Preliminary definition

### The Physics of Particle Detectors

#### What is a Particle?

A particle detector is an instrument to measure one or more properties of a particle ...

<table>
<thead>
<tr>
<th>Properties of a particle:</th>
<th>Type of detection principle:</th>
</tr>
</thead>
<tbody>
<tr>
<td>- position and direction</td>
<td>- position and tracking</td>
</tr>
<tr>
<td>- momentum</td>
<td>- tracking in a magnetic field</td>
</tr>
<tr>
<td>- energy</td>
<td>- calorimetry</td>
</tr>
<tr>
<td>- mass</td>
<td>- Spectroscopy and PID</td>
</tr>
<tr>
<td>- velocity</td>
<td>- Cherenkov radiation or time of flight</td>
</tr>
<tr>
<td>- transition radiation</td>
<td>- TRD</td>
</tr>
<tr>
<td>- spin, lifetime</td>
<td></td>
</tr>
</tbody>
</table>
Fundamental questions

• Which kind of “particle” we have to detect?
• Which is the required dimension of the detector?
• Which “property” of the particle we have to know?
  – Position
  – Time
  – Number with which resolution?
  – Energy
  – Polarity

• Which is the maximum count rate?
• Which is the “events time distribution”? 
Quality of measurements: resolution

Resolution generally defined as 1 standard deviation ($1\sigma$) for a Gaussian distribution. Sometimes use FWHM instead:

$$\text{FWHM} = 2.355 \, \sigma_{\text{Gauss}}$$

What if the distribution is not Gaussian? (RMS, RMS$_{90}$, Quartiles)
The detector zoo
History of detectors (ex. trackers)

• **Cloud Chambers** dominating until the 1950s
  ➔ now very popular in public exhibitions related to particle physics

• **Bubble Chambers** had their peak time between 1960 and 1985
  ➔ last big bubble chamber was BEBC at CERN (Big European Bubble Chamber), now in front on the CERN Microcosm exhibition

• **Wire Chambers** (MWPCs and drift chambers) started to dominate since 1980s

• Since early 1990s solid state detectors are in use
  ➔ started as small sized vertex detectors
  ➔ now ~200 m² silicon surface in CMS tracker
Future of detectors (the jewelry gallery)

Gold bump bonding

Diamond as beam monitor and future Pixel detector

Cadmium zinc telluride bolometers for neutrino-less double beta decay

Sapphire as calorimeter
HEP detectors

A perfect detector should reconstruct any interaction of any type with 100% efficiency and unlimited resolution (get “4-momenta” of basic physics interaction)

Efficiency: not all particles are detected, some leave the detector without any trace (neutrinos), some escape through not sensitive detector areas (holes, cracks for e.g. water cooling and gas pipes, electronics, mechanics)
Particle detector: detector system @ colliders
Astro-particle physics
Particle detector: Cosmic rays detector

HESS telescope, Namibia
Particle detector: positron emission tomography
Particle detector: photon science

- photon energy: 3-12 keV
- wavelength: 0.1-0.3 nm
- pulse duration (FWHM): 100 fs
- average flux of photons: $3.6 \times 10^{16}$/s
- number photon per pulse: $1.2 \times 10^{12}$
- peak power: 24 GW
Fundamental questions

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• Which is the required dimension of the detector?
• Which “property” of the particle we have to know?
  – Position
  – Time
  – Number with which resolution?
  – Energy
  – Polarity

• Which is the maximum count rate?
• Which is the “events time distribution”?
BACKUP
Measuring particles

Particles are characterized by

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>eV/c^2 or eV</td>
</tr>
<tr>
<td>Momentum</td>
<td>eV/c or eV</td>
</tr>
<tr>
<td>Energy</td>
<td>eV</td>
</tr>
<tr>
<td>Charge</td>
<td>e</td>
</tr>
</tbody>
</table>

(+ Spin, Lifetime ...)

Relativistic kinematics:

\[ E^2 = \vec{p}^2 c^2 + m^2 c^4 \]

\[ \beta = \frac{v}{c}, \quad \gamma = \frac{1}{\sqrt{1 - \beta^2}} \]

\[ E = m\gamma c^2 = mc^2 + E_{\text{kin}} \]

\[ \vec{p} = m\gamma \beta c \]

\[ \vec{\beta} = \frac{\vec{p}c}{E} \]

\[ eV = 1.6 \cdot 10^{-19} \text{ J} \]

\[ c = 299 792 458 \text{ m/s} \]

\[ e = 1.602176487(40) \cdot 10^{-19} \text{ C} \]

Particle Identification via measurement of

e.g. (E, \vec{p}, Q) or (\vec{p}, \beta, Q) (\vec{p}, m, Q) ...
# Measuring particles [Units]

<table>
<thead>
<tr>
<th>Quantity</th>
<th>HEP units</th>
<th>SI Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>length</td>
<td>1 fm</td>
<td>$10^{-15}$ m</td>
</tr>
<tr>
<td>energy</td>
<td>1 GeV</td>
<td>$1.602 \cdot 10^{-10}$ J</td>
</tr>
<tr>
<td>mass</td>
<td>1 GeV/c$^2$</td>
<td>$1.78 \cdot 10^{-27}$ kg</td>
</tr>
<tr>
<td>$\hbar=h/2$</td>
<td>$6.588 \cdot 10^{-25}$ GeV s</td>
<td>$1.055 \cdot 10^{-34}$ Js</td>
</tr>
<tr>
<td>c</td>
<td>$2.988 \cdot 10^{23}$ fm/s</td>
<td>$2.988 \cdot 10^8$ m/s</td>
</tr>
<tr>
<td>$\hbar c$</td>
<td>$0.1973$ GeV fm</td>
<td>$3.162 \cdot 10^{-26}$ Jm</td>
</tr>
</tbody>
</table>

### Natural units ($\hbar = c = 1$)

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</tr>
</thead>
<tbody>
<tr>
<td>mass</td>
<td>1 GeV</td>
<td></td>
</tr>
<tr>
<td>length</td>
<td>1 GeV$^{-1}$ = $0.1973$ fm</td>
<td></td>
</tr>
<tr>
<td>time</td>
<td>1 GeV$^{-1}$ = $6.59 \cdot 10^{-25}$ s</td>
<td></td>
</tr>
</tbody>
</table>
Bethe-Bloch