Instrumentation for High Energy Physics

Ludwik Dobrzynski
Laboratoire Leprince Ringuet - Ecole polytechnique - CNRS - IN2P3

Split 14-18 September 2015
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- Introduction
- Particle ID
- Particle momenta measurement
- Particle Energy measurement

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“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

“Instrumentation for the 21st century. No one does it better than physicists when it come to innovation for instrumentation, and thus the future of all scientific fields rests on our hands.”
Michael S. Turner
Basic particle interactions in detector processes

Every effect of particles or radiation can be used as a working principle for a particle detector. Claus Grupen
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Ionization:
- Charged Particle
- Electron

Pair production:
- Positron
- Nucleus
- Electron

Compton scattering:
- Photon
- Electron
- Electron

[Diagram showing various particle interactions]
By 1959: 20 particles

e⁻: fluorescent screen
n: ionization chamber

7 Cloud Chamber:
- e⁺
- μ⁺, μ⁻
- K⁰
- Λ⁰
- Ξ⁻
- Σ⁻

6 Nuclear Emulsion:
- π⁺, π⁻
- anti-Λ⁰
- Σ⁺
- K⁺, K⁻

2 Bubble Chamber:
- Ξ⁰
- Σ⁰

3 with Electronic techniques:
- anti-n
- anti-p
- π⁰
NOBEL PRIZES FOR INSTRUMENTATION

1927: C.T.R. Wilson, Cloud Chamber
1939: E. O. Lawrence, Cyclotron
1948: P.M.S. Blacket, Cloud Chamber
1950: C. Powell, Photographic Method
1954: W. Bothe, Coincidence Method

http://www.lhc-closer.es/php/index.php?i=1&s=9&p=2&e=0
<table>
<thead>
<tr>
<th>Year</th>
<th>Laureate</th>
<th>Invention/Innovation</th>
</tr>
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<tr>
<td>1960</td>
<td>Donald Glaser</td>
<td>Bubble Chamber</td>
</tr>
<tr>
<td>1968</td>
<td>L. Alvarez</td>
<td>Hydrogen Bubble Chamber</td>
</tr>
<tr>
<td>1992</td>
<td>G. Charpak</td>
<td>Multi Wire Prop. Chamber</td>
</tr>
<tr>
<td>2009</td>
<td>W. S. Boyle &amp; G. E. Smith</td>
<td>CCD sensors</td>
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**Caution**: These topics are very wide so it would be a non-sense to believe that they can be fully covered in 3 lectures. So a choice has been made.

OF COURSE, I (might) have some personal bias, so I apologize in advance if your expectations are not full field.
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*For a more complete set of lectures go for instance to:*

http://www.kip.uni-heidelberg.de/~coulon/Lectures/Detectors/
http://www.kip.uni-heidelberg.de/~coulon/Lectures/JCDet/
http://cds.cern.ch/collection/Summer%20Student%20Lectures (D. Bortoletto Oxford Univ.)
Start of a HEP experiment, one needs
Start of a HEP experiment, one needs a theory:
Start of a HEP experiment, one needs

A theory:
Start of a HEP experiment, one needs

A theory:

and a cafeteria
Start of a HEP experiment, one needs

A theory:

Clear and easy understandable drawings

and a cafeteria
Start of a HEP experiment, one needs

A theory:

and a cafeteria

and a tunnel for the accelerator and magnets and stuff

Clear and easy understandable drawings
Easy access to the experiment
Physicists to operate detector/analyze data

Easy access to the experiment
Easy access to the experiment

Physicists to operate detector/analyze data

and a Nobel prize
My lectures will just concentrate on the detectors.
HEP Experiment: Simplified View

Proton (quarks & gluons)

Proton (quarks & gluons)
HEP Experiment: Simplified View

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\[ E = mc^2 \]

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• For which Physics?
  – Higgs: photon and lepton reconstruction
  – Top: lepton and jets reconstruction
  – SUSY: soft leptons, jets and Missing transverse energy
  – B mesons....

• In which environment?
  – Radiation level
  – Accessibility limited sitting on the Collider

• A difficult compromise: look for the best performance within a given budget and feasibility
Which Concepts for the detector

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• **=> detector structure and organisation**

• **=> electronics, granularity, size …**
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• **=> Real detector**
Physics case 1: Higgs $\rightarrow$ 2 photons + 4 leptons

- Reconstruct and identify isolated photons and leptons in a huge hadronic background (large pileup).
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Questions:
- How to measure the photon energy with precision. Is a tracker necessary?
- Which is the dominant background and how do I get rid of it?
- What kind of calorimeter do I need?
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The response is straightforward: Best tracking system and Best Electromagnetic calorimeter.
Physics case 2: Susy

- In a cascade disintegration: look for soft leptons and large number of jets as well as “Missing ET”
Physics case 2: Susy

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- Other Physics and technical goals:
  - Blast of Higgs sector
  - Extra dimensions
  - Vector Boson fusion
  - Forward Physics …
  - tau lepton reconstruction algorithms
  - live at very high luminosity
Challenges

... or to discover a boson with ATLAS and CMS ...

- Inelastic: $10^9$ Hz
- Higgs (100 GeV/c$^2$): 0.1 Hz
- Higgs (600 GeV/c$^2$): $10^{-2}$ Hz
- Selection: $1:10^{10-11}$
- Operate in high radiation environment
- Resolve 20-25 superimposed events per BX
- High granularity detectors
- Fast electronics/detectors (25 ns)

Energy scale crucial!
Particle detector concept (1)

• All detector concept are based on basic knowledge of particle interactions with matter. Most involved processes are implying: electromagnetic interaction, ionisation, excitation, photo-electric effects, pair creation, bremsstrahlung, Cerenkov effect, transition radiation….

• The detector construction
  – result from a detailed study of all types of particles propagation through the detector
  – and the confirmation of the prediction by the results obtained in a test beam

• The detector should be as radiation hard as possible:
  – it’s a strong constraint on the detector material and on the electronics
What determines the Size, Material and Geometry of the Detector?

- Impact Parameter Measurement
- Momentum Measurement
- Energy Measurement
- Muon Measurement

Constraints

- Multiple scattering which has to be reduced as much as possible
- Impact Parameter resolution (Secondary Vertex)
- Lever arm and Magnetic Field for Momentum Measurement
- Material budget
LHC experimental challenge

- LHC detectors must have fast response
  - Otherwise will integrate over many bunch crossings \(\rightarrow\) large “pile-up”
  - Typical response time: 20-50 ns
    - \(\rightarrow\) integrate over 1-2 bunch crossings \(\rightarrow\) pile-up of 25-50 min-bias
    - \(\rightarrow\) very challenging readout electronics

- LHC detectors must be highly granular
  - Minimize probability that pile-up particles be in the same detector element as interesting object (e.g. \(\gamma\) from \(H \rightarrow \gamma\gamma\) decays)
    - \(\rightarrow\) large number of electronic channels
    - \(\rightarrow\) high cost

- LHC detectors must be radiation resistant:
  - High flux of particles from pp collisions \(\rightarrow\) high radiation environment e.g. in forward calorimeters:
    - up to \(10^{17}\) n/cm\(^2\) in 10 years of LHC operation
    - up to \(10^7\) Gy (1 Gy = unit of absorbed energy = 1 Joule/Kg)
Exemple : Atlas and CMS Detector
- Large volume for precise charged tracks measurement
- Strong magnetic field
- Hermetic
- Best stand alone muon chambers system
- Highly segmented
- Radiation hard
the largest and most complex “microscopes” we’ve ever built
The detectors together have 140 million data channels observing at 40 million times a second.
• **Protons are composite**
  Partons (valence+sea quarks, gluons) carry **longitudinal momentum fraction of the proton** \((x)\)

  *Longitudinal parton momenta are unknown*

• **Parton distribution functions** (PDFs): estimate the momentum fraction carried by a parton inside the proton
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What do we want to measure
Hadron Colliders

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### What do we want to measure

- **Number of particles**
- **Event topologie**
- **momentum / Energie**
- **Particle identity**
- **Transverse Missing energy/momentum**

Can’t be achieved with a single detector
Integrate detectors to a detector system
Particle detection
Particles characteristics are measured through different type of detectors and identified thanks to specific behaviours due to their interaction with matter.
Particle detection

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![Diagram of particle detection](image)
Particle detection

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<td>Electromagnetic calorimeters</td>
<td>Hadronic calorimeters</td>
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<tr>
<th>Photons</th>
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<th>$K^\pm, \pi^\pm, p$</th>
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<tr>
<td>B field</td>
<td>Low $\rho$</td>
<td>High $\rho$</td>
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<td>Tracking</td>
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$\gamma, e, \text{jets (q,g), missing energy (e.g. } \nu\text{), are detected with calorimeters}$
What can we access?

Measure stable and quasi-stable particles \((e, \gamma, \mu, \pi, K, p, n, \nu)\):

- Kinematics (momentum and/or energy)
- The way particle interacts with / passes through detectors

All other particles reconstructed via their decays to (quasi-) stable particles:
- Invariant mass of the system of daughter particles
- Decay vertex separated from production vertex for some particles decaying via weak interaction

Main goal of instrumentation for HEP:
- Precisely/fast measure kinematics of (quasi-) stable particles
- Unambiguously/fast identify them

For that:
- We study how particles interact with the matter
  and
- We choose the detector technologies that match the physics tasks
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How perform the measurements \((p,E)\)
• **Use of a magnetic field**
  *Obvious now* but UA2 (SPS) and D0 (run I) had no magnetic field!!!

• **Use of position detectors**:
  • *Gaseous*: multi wires chambers, Time Projection chambers, drift tube ....
  • *Solid*: Silicium detectors
  • *Try to do if possible a non destructive measurement*
    => minimize the amount of material in the detector itself

• **Use calorimetry for the Energy measurement**
Detector requirements
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  - test of prototypes in beam lines are keys elements of the conception of a detector
Particle identification
(for details clic)
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• There are four main processes that depend on the velocity of a particle:
  1. Most direct is to measure the Time Of Flight (TOF) of the particles over a fixed distance
  2. Alternatively one can look at the detail of their interaction with matter
     The main source of energy loss is via Ionization \( (dE/dx) \)
  3. If the velocity of the particle changes compared to the local speed of light it will radiate photons, detected as Transition radiation
  4. If a particle travels at greater than the local speed of light, it will radiate Cherenkov radiation

(for details clic)
• For low-momentum—typically up to a few GeV
  • charged particles can be identified by processes that depend on their velocity ($\beta$).
  • A simultaneous measurement of $p = \beta \gamma m$ and $\beta$ allows extracting the mass.
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Objects for Top Quark identification

- Mainly produced in pairs via strong interactions: $\text{ttbar}$
- Top quark decays via the electroweak interactions
- Final state characterized by the decay of the W boson
- **Dilepton** (lepton = e or $\mu$) (7%): 2 leptons, 2 b quarks, 2 neutrinos
- **Lepton+Jets** (lepton = e or $\mu$) (34%): 2 b quarks, 2 light quarks, 1 lepton, 1 neutrino
- **All-Jets** (44%): 2 b quarks, 4 light quarks
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- electrons
- muons
- b quarks
- Jets
- ETmiss
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Object reconstruction
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  – **Tracking**
    • finding path of charged particles through the detector
  – **Calorimeter reconstruction**
    • finding energy deposits in calorimeters from charged and neutral particles
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Combined reconstruction: tracker + calorimeter informations
- Electron/Photon identification
- Muon identification
- Jet finding
Object reconstruction

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  - finding energy deposits in calorimeters from charged and neutral particles
- **Combined reconstruction**: tracker + calorimeter informations
  - Electron/Photon identification
  - Muon identification
  - Jet finding
- **Calibrations and alignments applied at nearly every step** (see lectures 2 and 3)
Vertex detectors: $b$ quarks ID
Requirements based on b-jets parameters
- B hadrons lifetime: average of \(\sim 1.6\) ps
- Semi-leptonic fraction \(\sim 10\% e,\) and \(10\% \mu\)
- \(c\tau = 470\) microns \(\rightarrow\) impact parameter \(d \sim 100\) microns
- Need accuracy: \(< 20\) microns on \(d\)
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Accuracy limited by
- lever arm,
- granularity,
- number of layers

Solution:
- 3 layer pixel detector
- first layer as close as possible to beam pipe
- single hit accuracy < 15 microns in \(r\phi\)
- equipped with fast electronics

Beware
- of radiation damage
- multiple scattering in material
- power dissipation
Objects: Electrons ID

Must extract lepton signal from much larger jet background

Requires correlation of information among detectors

Selected based on properties of each lepton species

More in Roger Forty’s talk
Objects: Electrons ID

**Signature**

- Energy deposited in EM Calorimeter
- Track pointing at the energy deposition and with momentum consistent with calorimeter energy
- Little or no energy in hadronic calorimeter
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- **Signature**
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  - Track pointing at the energy deposition and with momentum consistent with calorimeter energy
  - Little or no energy in hadronic calorimeter

- **Backgrounds**
  - Jets
  - Early showering charged pions
  - Conversions: $\pi^0 \rightarrow \gamma\gamma \rightarrow ee + X$
  - Semileptonic b-decays
  - Photon conversions
  - Photons similar to electrons

More in Roger Forty's talk
Objects: Muons ID

Must extract lepton signal from much larger jet background.

Requires correlation of information among detectors.

Selected based on properties of each lepton species.

More in Roger Forty’s talk.
Objects: Muons ID

**Signature**

- Track passes through all the detectors and is reconstructed in muon spectrometer
- Minimum ionizing energy deposits in EM ad HAD calorimeter
- Track match between inner tracker and muon spectrometer

More in Roger Forty's talk
Objects: Muons ID

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- Punchthrough
- Cavern background (LHC)
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- **Performance**
  - Measured using Z’s
  - 60-100% depending on $|\eta|$
Measurement of the kinematics of a hard parton emission requires reconstruction: best matching to hard parton and the identified jets is necessary. Many algorithms available: cone, midpoint, K_{T} scale: calibration of the energy response, minimizing the measurement error resolution: different reconstruction algorithms provide varied performance in the precision of the energy measurement. Reconstruction and scale are fundamental for precision measurements. Resolution is critical for the successful identification of low S/B signal.
Measurement of the kinematics of a hard parton emission requires

Reconstruction:

- Cone, midpoint, K_T
- Scale: calibration of the energy response, minimizing the measurement error
- Resolution: different reconstruction algorithms provide varied performance in the precision of the energy measurement

Reconstruction and Scale are fundamental for precision measurements. Resolution is critical for the successful identification of low S/B signal

2/3 charged hadrons, 1/3 neutral hadrons
Objects: Jets ID

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Objects: Neutrino ID
• **Signature**
  
  • No interaction in the detector
Objects: Neutrino ID

- **Signature**
  - No interaction in the detector

- **Reconstruction**
  - Look for momentum imbalance and assign the missing momentum to the $\nu$
  - But in hadron colliders, limited to using only the 2 transverse components of the momentum \( \rightarrow p_T \)
  - \( ET_{\text{miss}} \) Resolution depends on calorimeter resolution
  - Degrades with detector imperfection (cracks) and pile up
• **Efficiency**
  
  – how often do we reconstruct the object – e.g. tracking efficiency

\[
\text{Efficiency} = \frac{\text{Number of Reconstructed Tracks}}{\text{Number of True Tracks}}
\]
Important figures of merit for reconstructed objects

- **Efficiency**
  - how often do we reconstruct the object – e.g. tracking efficiency

- **Resolution**
  - how accurately do we reconstruct it – e.g. energy resolution

Energy resolution = \( \frac{\text{Measured\_Energy} - \text{True\_Energy}}{\text{True\_Energy}} \)
Important figures of merit for reconstructed objects

• **Efficiency**
  - how often do we reconstruct the object – e.g. tracking efficiency

• **Resolution**
  - how accurately do we reconstruct a quantity – e.g. energy resolution

• **Fake rate**
  - how often we reconstruct a different object as the object we are interested in – e.g. a jet faking a electron

Fake rate = \( \frac{\text{Number of jets reconstructed as an electron}}{\text{Number of jets}} \)
Important figures of merit for reconstructed objects

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- **Fake rate**
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- For physics analysis it is important to have high efficiency, good resolution, and low fake rates
- to be able to measure the efficiencies, resolutions and fake rates and their uncertainties is not easy
- Robust against detector problems
  - Noise
  - Dead regions of the detector
- Be able to run within the computing resources limitations
  - CPU time per event
  - Memory use

![Graph showing fake rate before and after isolation cut]
Particle identification is a crucial aspect of most high energy physics experiments, in addition to tracking and calorimetry.
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*Short-lived particles* are reconstructed from their decay products.
ID summary

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• Distinguishing the different long-lived charged hadrons ($\pi$, $K$, $p$) is more challenging, and usually requires dedicated detectors

• Their identification is based on four main processes: TOF, $dE/dx$, Transition radiation and the Cherenkov effect
Towards detector definition

Lets look how were build the LHC detectors
Configuration of HEP Detectors
Configuration of HEP Detectors

Fixed target geometry

“Magnet spectrometer”

interaction point
tracking
muon filter

LHCb

beam magnet (dipole) calorimeter

Collider geometry

“4π multi purpose detector”

ATLAS CMS

ALICE (both geometries)

endcap barrel endcap
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**Fixed target geometry**
- "Magnet spectrometer"
- interaction point
- tracking
- muon filter

**Collider geometry**
- "4π multi purpose detector"
- barrel
- endcap

**LHCb**
- beam magnet (dipole)
- calorimeter

**ALICE**
- (both geometries)
- endcap

**ATLAS CMS**
detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
Status of ATLAS
ATLAS Cavern
Split, 29-Sep-2008, P. Jenni

Status of ATLAS
The Compact Muon Solenoid (CMS)

Total weight: 12,500 t
Overall diameter: 15 m
Overall length: 21.6 m
Magnetic field: 4 Tesla

Silicon Microstrips
Pixels

Drift Tube Chambers (DT)
Resistive Plate Chambers (RPC)
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)
Detector Characteristics
Length: 20 m
Width: 12 m
Height: 12 m
Weight: 2000 tons
Summary

- Particle physics, ‘born’ with the discovery of radioactivity and the electron at the end of the 19th century, has become ‘Big Science’ during the last 100 years.
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- Through the electronic revolution and the development of new detectors, both traditions merged into the ‘electronics image’ in the 1970ies.

- Particle detectors with over 100 million readout channels are operating now at LHC.
Questions (1)

- which particles are the most penetrating? depending on energy?
- what particle qualities (mass, charge,..) are the most important for the interaction with matter
- how to distinguish photons and electrons at 100 GeV in matter?
Questions (2) for home

❖ compare decay and interaction probability for GeV pion
❖ compare $\lambda_{\text{hadr}}$ and $x_0$ sizes of e.m. and hadronic showers
❖ multiple scattering angle vs. momentum of particle, vs. thickness of absorber
❖ compare ratio of particle energies to masses in hadronic and e.m. showers
❖ draw $dE/dx$ from Bethe-Bloch for muons in iron in the range of 0.1 to 100 GeV
Text books (a selection)

- C. Grupen, B. Shwartz, Particle Detectors, 2nd ed., Cambridge University Press, 2008
- R.S. Gilmore, Single particle detection and measurement, Taylor&Francis, 1992

Review Articles

- Many excellent articles can be found in Ann. Rev. Nucl. Part. Sci.

Other sources

- R. Bock, A. Vasilescu, Particle Data Briefbook http://www.cern.ch/Physics/ParticleDetector/BriefBook/
  - ICFA schools lectures : http://www.ifm.umich.mx/school/ICFA-2002/
- Proceedings of detector conferences (Vienna VCI, Elba, IEEE, Como)

Trigger and DAQ

CERN-Latin American Schools of Physics : Usually an article on trigger and DAQ
Useful material & acknowledgments

I have taken part of the content of these lecture from Werner Riegler’s summer student lectures in 2011 and Erika Garutti’s DESY lecture notes

Useful books

– Detector for particle radiation, Konrad Kleinknecht
– Techniques for Nuclear and Particle Physics Experiments, W. R. Leo
– Particle Detectors, Claus Grupen
– Introduction to Experimental Particle Physics, R. Fernow
– The Physics of Particle Detectors, D. Green
– Review in data particle book on Passage of particles through matter
– Review in data particle book on Particle Detectors at accelerators
To extend your knowledge (2)

- P. Rice-Evans: *Spark, Streamer, Proportional and Drift Chambers* (Richelieu, 1974)
- F. Sauli: *Principles of Operation of Multiwire Proportional and Drift Chambers* (CERN 77-16)
- Th. Ferbel, Editor: *Techniques and Concepts of High-energy Physics* (Plenum, 1983)
- R.C. Fernow: *Introduction to Experimental Particle Physics* (Cambridge Univ. Press, 1988)
- K. Kleinknecht: *Detectors for Particle Radiation* (Cambridge Univ. Press 1998)
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Some important definitions and units

\[ E^2 = p^2c^2 + m^2_0c^4 \]

- energy \( E \): measure in eV
- momentum \( p \): measure in eV/c
- mass \( m_0 \): measure in eV/c^2

\[ \beta = \frac{v}{c} \quad (0 \leq \beta < 1) \quad \gamma = \frac{1}{\sqrt{1 - \beta^2}} \quad (1 \leq \gamma < \infty) \]

\[ E = m_0\gamma c^2 \quad p = m_0\gamma \beta c \quad \beta = \frac{pc}{E} \]

1 eV is a tiny portion of energy. 1 eV = 1.6 \cdot 10^{-19} \text{ J}

\[ m_{\text{bee}} = 1g = 5.8 \cdot 10^{32} \text{ eV/c}^2 \]
\[ v_{\text{bee}} = 1\text{ m/s} \rightarrow E_{\text{bee}} = 10^{-3} \text{ J} = 6.25 \cdot 10^{15} \text{ eV} \]
\[ E_{\text{LHC}} = 14 \cdot 10^{12} \text{ eV} \]

To rehabilitate LHC…

Total stored beam energy: \( E_{\text{total}} = 10^{14} \text{ protons} \cdot 7 \cdot 10^{12} \text{ eV} \approx 7 \cdot 10^{26} \text{ eV} \approx 1 \cdot 10^8 \text{ J} \]

this corresponds to a \( m_{\text{truck}} = 100 \text{ T} \)
\( v_{\text{truck}} = 120 \text{ km/h} \)

Stored energy in LHC magnets \( \sim 1 \text{ GJ} \)

\( m_{747} = 400 \text{ T} \)
\( v_{747} = 255 \text{ km/h} \)
Time Of Flight

• Simple concept: measure the time difference between two detector planes

\[ \beta = \frac{d}{c} \Delta t \]

• At high energy, particle speeds are relativistic, closely approaching to c

• For a 10 GeV K, the time to travel 12 m is 40.05 ns, whereas for a π it would be 40.00 ns, so the difference is only 50 ps

• Modern detectors + readout electronics have resolution \( \sigma_t \sim 10 \) ns, fast enough for the LHC (bunch crossings 25 ns apart) but need \( \sigma_t < 1 \) ns to do useful TOF

• TOF gives good ID at low momentum

  Very precise timing required for \( p > 5 \) GeV
Ionization

- Charged particles passing through matter can knock out electrons from atoms of the medium: ionization
- Energy loss described by the Bethe-Bloch formula, which gives the universal velocity dependence: \( \frac{dE}{dx} \propto \log(\beta^2 \gamma^2) / \beta^2 \)
- This can be used to identify particles, particularly at low momentum where \( \frac{dE}{dx} \) varies rapidly

**Advantage:**
uses existing detectors needed for tracking

**Note:** these techniques all provide signals for charged leptons e, \( \mu \) as well as \( \pi, K, p \)
But \( m_\mu \approx m_\pi \), so they are not well separated
Transition radiation

- Local speed of light in a medium with refractive index $n$ is $c_p = c/n$
- If its relative velocity $v/c_p$ changes, a particle will radiate photons:
  1. Change of direction $v$ (in magnetic field) $\rightarrow$ Synchrotron radiation
  2. Change of $|v|$ (passing through matter) $\rightarrow$ Bremsstrahlung radiation
  3. Change of refractive index $n$ of medium $\rightarrow$ Transition radiation

- **Transition radiation** is emitted whenever a relativistic charged particle traverses the border between two media with different dielectric constants ($n \sim \sqrt{\varepsilon}$)
- The energy emitted is proportional to the boost $\gamma$ of the particle
  $\rightarrow$ Particularly useful for electron ID
  Can also be used for hadrons at high energy

- Named after the Russian scientist P. Cherenkov who was the first to study the effect in depth (Nobel Prize 1958)
Particle Detection Principle

In order to detect a particle
- it must interact with the material of the detector
- transfer energy in some recognizable fashion

i.e. The detection of particles happens via their energy loss in the material it traverses ...

Possibilities:

- Charged particles: Ionization, Bremsstrahlung, Cherenkov ...
- Hadrons: Nuclear interactions
- Photons: Photo/Compton effect, pair production
- Neutrinos: Weak interactions

Energy loss by multiple reactions
Total energy loss via single interaction ➔ charged particles
Particle Interactions – Examples

Ionization:

Pair production:

Compton scattering:
Energy Loss by Ionization – $dE/dx$

For now assume: $M c^2 \gg m_e c^2$

i.e. energy loss for heavy charged particles

$[dE/dx$ for electrons more difficult ...]

Interaction dominated by elastic collisions with electrons ...

Bethe-Bloch Formula

$$-\langle \frac{dE}{dx} \rangle = K Z^2 \frac{1}{A \beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{T^2} - \beta^2 - \frac{\delta(\beta \gamma)}{2} \right]$$

$\propto \frac{1}{\beta^2} \cdot \ln(\text{const} \cdot \beta^2 \gamma^2)$

Energy Loss of Electrons

Bethe-Bloch formula needs modification

Incident and target electron have same mass $m_e$

Scattering of identical, undistinguishable particles

$$-\langle \frac{dE}{dx} \rangle_{\text{el.}} = K Z \frac{1}{A \beta^2} \left[ \ln \frac{m_e \beta^2 \gamma^2 T}{2T^2} + F(\gamma) \right]$$

$[T$: kinetic energy of electron$]$

$W_{max} = \frac{1}{2} T$

Remark: different energy loss for electrons and positrons at low energy as positrons are not identical with electrons; different treatment ...
Bethe-Bloch – Classical Derivation

Particle with charge $ze$ and velocity $v$ moves through a medium with electron density $n$.

Electrons considered free and initially at rest.

Momentum transfer:

$$\Delta p_\perp = \int F_\perp \, dt = \int F_\perp \frac{dt}{dx} \, dx = \int F_\perp \frac{dx}{v}$$

$$= \int_{-\infty}^{\infty} \frac{ze^2}{(x^2 + b^2)} \cdot \frac{b}{\sqrt{x^2 + b^2}} \cdot \frac{1}{v} \, dx = \frac{ze^2 b}{v} \left[ \frac{x}{b^2 \sqrt{x^2 + b^2}} \right]_{-\infty}^{\infty} = \frac{2ze^2}{bv}$$

Symmetry!

More elegant with Gauss law:

[infinite cylinder; electron in center]

$$\int E_\perp (2\pi b) \, dx = 4\pi (ze) \rightarrow \int E_\perp \, dx = \frac{2ze}{b}$$

and then ...

$$F_\perp = eE_\perp$$

$$\Delta p_\perp = e \int E_\perp \frac{dx}{v} = \frac{2ze^2}{bv}$$
Bethe-Bloch – Classical Derivation

Energy transfer onto single electron for impact parameter $b$:

$$\Delta E(b) = \frac{\Delta p^2}{2m_e}$$

Consider cylindric barrel $\Rightarrow N_e = n \cdot (2\pi b) \cdot db \cdot dx$

Energy loss per path length $dx$ for distance between $b$ and $b+db$ in medium with electron density $n$:

Energy loss!

$$-dE(b) = \frac{\Delta p^2}{2m_e} \cdot 2\pi nb \cdot db \cdot dx = \frac{4z^2e^4}{2b^2v^2m_e} \cdot 2\pi nb \cdot db \cdot dx = \frac{4\pi n z^2e^4}{m_e v^2} \cdot \frac{db}{b} \cdot dx$$

Diverges for $b \to 0$; integration only for relevant range $[b_{\min}, b_{\max}]$:

Bohr 1913

$$-\frac{dE}{dx} = \frac{4\pi n z^2e^4}{m_e v^2} \cdot \int_{b_{\min}}^{b_{\max}} \frac{db}{b} = \frac{4\pi n z^2e^4}{m_e v^2} \ln \frac{b_{\max}}{b_{\min}}$$
Bethe-Bloch – Classical Derivation

Bohr 1913

Determination of relevant range \([b_{\text{min}}, b_{\text{max}}]\):
[Arguments: \(b_{\text{min}} > \lambda_e\), i.e. de Broglie wavelength; \(b_{\text{max}} < \infty\) due to screening ...]

\[
b_{\text{min}} = \lambda_e = \frac{\hbar}{p} = \frac{2\pi \hbar}{\gamma m_e v}
\]

\[
b_{\text{max}} = \frac{\gamma v}{\langle v_e \rangle}; \quad \left[ \gamma = \frac{1}{\sqrt{1 - \beta^2}} \right]
\]

Use Heisenberg uncertainty principle or that electron is located within de Broglie wavelength ...

Interaction time \((b/v)\) must be much shorter than period of the electron \((\gamma/v_e)\) to guarantee relevant energy transfer ...

[adiabatic invariance]

\[
- \frac{dE}{dx} = \frac{4\pi z^2 e^4}{m_e c^2 \beta^2} \quad n \cdot \ln \frac{m_e c^2 \beta^2 \gamma^2}{2\pi \hbar \langle v_e \rangle}
\]

Deviates by factor 2 from QM derivation

Electron density: \(n = N_A \cdot \rho \cdot Z/A \) !!

Effective Ionization potential: \(l \sim \hbar \langle v_e \rangle\)
Bethe-Bloch Formula

\[
- \left( \frac{dE}{dx} \right) = K \frac{Z^2}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} - \beta^2 - \frac{\delta(\beta \gamma)}{2} \right]
\]

\[ K = 4\pi N_A r_e^2 m_e c^2 = 0.307 \text{ MeV} \, \text{g}^{-1} \, \text{cm}^2 \]
\[ T_{\text{max}} = 2m_e c^2 \beta^2 \gamma^2 / (1 + 2\gamma m_e / M + (m_e / M)^2) \]

\[ r_e = e^2 / 4\pi \varepsilon_0 m_e c^2 = 2.8 \text{ fm} \]
\[ m_e = 511 \text{ keV} \]
\[ N_A = 6.022 \cdot 10^{23} \]

\[ \beta = v/c \]
\[ \gamma = (1 - \beta^2)^{-1/2} \]

\[ \delta : \text{Density correction [transv. extension of electric field]} \]

\[ Z : \text{Charge number of medium} \]
\[ A : \text{Atomic mass of medium} \]
\[ I : \text{Mean excitation energy of medium} \]
\[ \text{Validity: } 0.05 < \beta \gamma < 500 \]
\[ M > m_\mu \]

[see e.g. PDG 2010]
Energy Loss of Charged Particles

Dependence on

- **Mass A**
- **Charge Z**

of target nucleus

Minimum ionization:

- ca. 1 - 2 MeV/g cm$^{-2}$
- [H$_2$: 4 MeV/g cm$^{-2}$]
Bremsstrahlung

Bremsstrahlung arises if particles are accelerated in Coulomb field of nucleus

\[
\frac{dE}{dx} = 4\alpha N_A \frac{Z^2 Z^2}{A} \left( \frac{1}{4\pi \epsilon_0} \frac{e^2}{mc^2} \right)^2 E \ln \frac{183}{Z^{1.3}} \propto \frac{E}{m^2}
\]

i.e. energy loss proportional to \(1/m^2\) → main relevance for electrons ...

... or ultra-relativistic muons

Consider electrons:

\[
\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 \cdot E \ln \frac{183}{Z^{1.3}}
\]

\[
\frac{dE}{dx} = \frac{E}{X_0} \quad \text{with} \quad X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln \frac{183}{Z^{1.3}}}
\]

\[ E = E_0 e^{-x/X_0} \]

After passage of one \(X_0\) electron has lost all but \((1/e)^{th}\) of its energy

[i.e. 63%]
Total Energy Loss of Electrons

Fractional energy loss per radiation length in lead as a function of electron or positron energy.

Electrons

Positrons

Møller (e−)

Bhabha (e+)

Bremsstrahlung

Ionization

Annihilation

Fractional energy loss per radiation length in lead as a function of electron or positron energy.
Energy Loss – Summary Plot for Muons

Fig. 27.1: Stopping power (\(\langle -dE/dx \rangle\)) for positive muons as a function of \(\beta\gamma = p/Mc\) over nine orders of magnitude in momentum (12 orders of magnitude in kinetic energy). Solid curves indicate the total stopping power. Data below the break at \(\beta\gamma \approx 0.1\) are from ICRR\(^4\), and data at higher energies are from Ref. 5. Vertical bands indicate boundaries between different approximations discussed in the text. The short dotted lines labeled \(\mu^-\) illustrate the effect, the dependence of stopping power on projectile charge at very low energies \([6]\).

27.2.2. Stopping power at intermediate energies: The mean rate of energy loss by moderately relativistic charged heavy particles, \(\delta x\), is well described by the Bethe-Bloch equation,

\[
\langle -dE/dx \rangle = K_2 Z A^{1/3} \beta^2 \left[ \frac{1}{2} \ln \frac{2 m e c^2}{\beta^2 \gamma^2 T_{\text{max}}} \right].
\]

(27.3)

It describes the mean rate of energy loss in the region \(0.1 < \beta\gamma < \sim 1000\) for intermediate-\(Z\) materials with an accuracy of a few %. At the lower limit the projectile velocity becomes comparable to atomic electron "velocities" (Sec. 27.2.3).
dE/dx and Particle Identification

Measured energy loss

[ALICE TPC, 2009]

Remember:

$\frac{dE}{dx}$ depends on $\beta$!
Cross Section - Definition

Incoming flux:

\[ \Phi = \frac{1}{A} \cdot \frac{\Delta N}{\Delta t} = \frac{\dot{N}_{\text{in}}}{A} \]

Reaction rate:

\[ \dot{N}_{\text{reac}} = \dot{N}_{\text{in}} \frac{A_{\text{tar}}}{A} = \Phi \cdot A_{\text{tar}} = \Phi \cdot N_{\text{tar}} \cdot \sigma \]

Cross section:

\[ \sigma = \frac{\text{Number of reactions (of given type) per unit time}}{\text{Incoming flux} \cdot \text{Number of target particles}} \]

\[ = \frac{\dot{N}_{\text{reac}}}{\Phi \cdot N_{\text{tar}}} = \frac{\dot{N}_{\text{reac}}}{\dot{N}_{\text{in}} \cdot N_A \cdot \rho \cdot d/m_{\text{mol}}} \]

Absorbing target area

\[ A_{\text{tar}} = \sigma \cdot N_{\text{tar}} \]

\[ = \sigma \cdot \rho \cdot A_d \cdot m_{\text{mol}} \cdot N_A \]

with

\[ \rho : \text{target density} \]
\[ m_{\text{mol}} : \text{molar mass} \]
\[ N_A : 6.022 \cdot 10^{23} \text{ mol}^{-1} \]

Transition rate \( W_{fi} \)

Unit: \([\sigma] = \text{cm}^2\)
\[ W_{\text{fi}} = 2\pi |M_{\text{fi}}|^2 \cdot \frac{dN}{dE_f} \]

\[
M_{\text{fi}} = -i \int j^{(1)}_{\mu} \cdot \left( \frac{1}{q^2} \right) \cdot j^{(2)}_{\mu} \, d^4x
\]

\[
\sigma \sim |M_{\text{fi}}|^2 \\
\sim g^4 \cdot \left( \frac{1}{q^4} \right)
\]
**Cross Section - Magnitude and Units**

Standard cross section unit: \( [\sigma] = \text{mb} \)  

or in natural units: \( [\sigma] = \text{GeV}^{-2} \)

with \( 1 \text{ mb} = 10^{-27} \text{ cm}^2 \)

and \( 1 \text{ GeV}^{-2} = 0.389 \text{ mb} \)

\( 1 \text{ mb} = 2.57 \text{ GeV}^{-2} \)

Estimating the proton-proton cross section:

Proton radius: \( R = 0.8 \text{ fm} \)

Strong interactions happen up to \( b = 2R \)

\[
\sigma = \pi (2R)^2 = \pi \cdot 1.6^2 \text{ fm}^2
\]

\[
= \pi \cdot 1.6^2 \cdot 10^{-26} \text{ cm}^2
\]

\[
= \pi \cdot 1.6^2 \cdot 10 \text{ mb}
\]

\( = 80 \text{ mb} \)
Proton-Proton Scattering Cross Section

Figure 40.11: Total and elastic cross sections for $pp$ and $pp$ collisions as a function of laboratory beam momentum and total center-of-mass energy. Corresponding computer-readable data files may be found at http://pdg.lbl.gov/current/xsect/.

(Courtesy of the COMPAS group, IHEP, Protvino, August 2005)
Proton-Proton Scattering Cross Section

$10^9$ Events/sec
[1 Mbyte/Event]

$\sim 10^{10}$

10 Events/min
[m$_H \approx$ 100 GeV]

with 0.2% H $\rightarrow$ $\gamma\gamma$
1.5% H $\rightarrow$ ZZ

Trigger!

To Backup
Electromagnetic Shower Development

Detecting a signal:

→ The contribution of an electromagnetic interaction to energy loss usually depends on the energy of the incident particle and on the properties of the absorber

→ At “high energies” ($> \sim 10 \text{ MeV}$):
  → electrons lose energy mostly via Bremsstrahlung
  → photons via pair production

→ Photons from Bremsstrahlung can create an electron-positron pair which can radiate new photons via Bremsstrahlung in a process that last as long as the electron (positron) has energy $E > E_c$

→ At energies $E < E_c$, energy loss mostly by ionization and excitation

→ Signals in the form of light or ions are collected by some readout system

Building a detector

→ $X_0$ and $E_c$ depends on the properties of the absorber material

→ Full EM shower containment depends on the geometry of the detector
A simple shower model (Rossi-Heitler)

Considerations:

→ Photons from bremsstrahlung and electron-positron from pair production produced at angles $\theta = mc^2/E$ ($E$ is the energy of the incident particle) → jet character

Assumptions:

→ $\lambda_{pair} \approx X_0$
→ Electrons and positrons behave identically
→ Neglect energy loss by ionization or excitation for $E > E_c$
→ Each electron with $E > E_c$ gives up half of its energy to bremsstrahlung photon after $1X_0$
→ Each photon with $E > E_c$ undergoes pair creation after $1X_0$ with each created particle receiving half of the photon energy
→ Shower development stops at $E = E_c$
→ Electrons with $E < E_c$ do not radiate → remaining energy lost by collisions
Electromagnetic Shower Development

A simple shower model

Shower development:

Start with an electron with $E_0 \gg E_c$

→ After $1X_0$: 1 $\gamma$ and 1 $\gamma$, each with $E_0/2$

→ After $2X_0$: 2 $e^-$, 1 $e^+$ and 1 $\gamma$, each with $E_0/4$

→ After $tX_0$:

\[ N(t) = 2^t = e^{t \ln 2} \]

\[ E(t) = \frac{E_0}{2^t} \]

→ Number of particles increases exponentially with $t$

→ Equal number of $e^+$, $e^-$, $\gamma$

\[ t(E') = \frac{\ln(E_0/E')}{\ln 2} \]

→ Depth at which the energy of a shower particle equals some value $E'$

\[ N(E > E') = \frac{1}{\ln 2} \frac{E_0}{E'} \]

→ Number of particles in the shower with energy $> E'$

Maximum number of particles reached at $E = E_c$:

\[ t_{\text{max}} = \frac{\ln(E_0/E_c)}{\ln 2} \]

\[ N_{\text{max}} = e^{t_{\text{max}} \ln 2} = \frac{E_0}{E_c} \]
Electromagnetic Shower Development

A simple shower model

Concepts introduce with this simple mode:

→ Maximum development of the shower (multiplicity) at $t_{\text{max}}$

→ Logarithm growth of $t_{\text{max}}$ with $E_0$:

  → implication in the calorimeter longitudinal dimensions

→ Linearity between $E_0$ and the number of particles in the shower
Electromagnetic Shower Development

**A simple shower model**

What about the energy measurement?

Assuming, say, energy loss by ionization

→ **Counting charges:**

→ Total number of particles in the shower:

\[
N_{all} = \sum_{t=0}^{t_{\text{max}}} 2^t = 2 \times 2^{t_{\text{max}}} - 1 \approx 2 \times 2^{t_{\text{max}}} = \frac{2E_0}{E_c}
\]

→ Total number of charge particles (e\(^+\) and e\(^-\) contribute with 2/3 and γ with 1/3)

\[
N_{e^+e^-} = \frac{2}{3} \times 2 \frac{E_0}{E_c} = \frac{2}{3} \frac{E_0}{E_c} \quad \Rightarrow \text{Measured energy proportional to } E_0
\]
A simple shower model

What about the energy resolution?

Assuming Poisson distribution for the shower statistical process:

$$\sigma(E) = \frac{1}{\sqrt{E}}$$

Resolution improves with $E$

Example: For lead (Pb), $E_c \approx 6.9$ MeV:

$$\frac{\sigma(E)}{E} = \frac{7.2\%}{\sqrt{E} \text{ [GeV]}}$$

More general term:

$$\frac{\sigma(E)}{E} = a \frac{1}{\sqrt{E}} \oplus b \oplus c \frac{1}{E}$$

Statistic fluctuations
Constant term (calibration, non-linearity, etc)
Electromagnetic Shower Development

**A simple shower model**

Simulation of the energy deposit in copper as a function of the shower depth for incident electrons at 4 different energies showing the logarithmic dependence of $t_{\text{max}}$ with $E$.

EGS4* (electron-gamma shower simulation)

*EGS4 is a Monte Carlo code for doing simulations of the transport of electrons and photons in arbitrary geometries.

Longitudinal profile of an EM shower.

Number of particle decreases after maximum.

Figure 2.9: The energy deposit as a function of depth, for 1, 10, 100 and 1000 GeV electron showers developing in a block of copper. In order to compare the energy deposit profiles, the integrals of these curves have been normalized to the same value. The vertical scale gives the energy deposit per cm of copper, as a percentage of the energy of the showering particle. Results of EGS4 calculations.
Electromagnetic Shower Development

**Shower Profile**

- Longitudinal development governed by the radiation length $X_0$
- Lateral spread due to electron undergoing multiple Coulomb scattering:
  - About 90% of the shower up to the shower maximum is contained in a cylinder of radius $< 1X_0$
  - Beyond this point, electrons are increasingly affected by multiple scattering
  - Lateral width scales with the **Molière radius** $\rho_M$

\[ \rho_M = X_0 \frac{E_s}{E_c} \left[ \frac{g}{cm^2} \right], \quad E_s \approx 21\text{MeV} \]

| 95% of the shower is contained laterally in a cylinder with radius $2\rho_M$ |
Electromagnetic Shower Development

Shower profile

From previous slide, one expects the longitudinal and transverse developments to scale with \(X_0\):

\[ X_0 \propto A/Z^2, \quad E_c \propto 1/Z \Rightarrow \rho_M \propto A/Z \]

\(\rightarrow \rho_M\) less dependent on \(Z\) than \(X_0\):
Electromagnetic Shower Development

Energy deposition

The fate of a shower is to develop, reach a maximum, and then decrease in number of particles once $E_0 < E_c$.

Given that several processes compete for energy deposition at low energies, it is important to understand how the fate of the particles in a shower.

→ Most of energy deposition by low energy $e^\pm$'s.

Ionization dominates

EGS4 calculation

To Backup
In absence of other effects, at thermal energies, the mean speed of the charges (given by the Maxwell distribution of the energies) is:

\[ v = \sqrt{\frac{8kT}{\pi m}} \]

where \( k \) is Boltzmann’s constant, \( T \) the temperature and \( m \) the mass of the particle.

The charges diffuse by multiple collisions, and a local distribution follows a Gaussian law:

\[
\frac{dN}{dx} = \frac{N_0}{\sqrt{4 \pi D t}} \exp \left( -\frac{x^2}{4Dt} \right)
\]

where \( N_0 \) is the total number of charges, \( x \) the distance from the point of creation and \( D \) the diffusion coefficient.

Then the linear and volume r.m.s. of the spread are:

\[
\sigma_x = \sqrt{2Dt}
\]

\[
\sigma_v = \sqrt{6Dt}
\]

For instance, the radial spread of ions in air in normal conditions is about 1 mm after 1 second.
Drift and mobility in gas

* In the presence of an electric field, electrons and ions will drift in the gas. The drift velocity for electrons can be much higher w.r.t. ions since they are much lighter.

* \( \mu = \frac{v}{E} \) is the mobility of a charge where \( v \) is the drift velocity and \( E \) the electric field.

* Ions:
  - Mean velocity \( v^+ \) is proportional to \( \frac{E}{P} \)
  - Mobility \( \mu^+ \) is constant (average energy of ions almost unmodified up to very high electric fields)

* Electrons:
  - Drift velocity \( v^- = \left( \frac{e}{2m} \right) E \tau \) where \( \tau \) is the mean time between collision
  - Typical value around 5 cm/\( \mu \)s are obtained (ions thousand times slower)
Electrons drift and diffusion

Drift velocity and diffusion of electrons vary in a wide range, depending on the gas mixture.

Relation between mobility and diffusion: \[ \frac{D}{\mu} = \frac{kT}{e} \approx 0.026 \text{ eV} \]

The minimum diffusion at a given field is given by the thermal value: \[ \sigma_x = \sqrt{\frac{2kT}{e} \frac{x}{E}} \]

Drift velocity:

Diffusion:
Magnetic field

The drifting electrons cloud is rotated by an angle $\theta_B$ in the plane perpendicular to $E$ and $B$.

$$\tan \theta_B = \omega \tau$$

$\tau$ : mean collision time

$$v_B = \frac{E}{B} \frac{\omega \tau}{\sqrt{1 + \omega^2 \tau^2}}$$

$\omega = eB/m \rightarrow$ Larmor frequency

$\star E \perp B \star$

$\star E \parallel B \star$

$$v_B = v_0$$

$$\sigma_L = \sigma_0$$

Drift velocity unchanged

$$\sigma_T = \frac{\sigma_0}{\sqrt{1 + \omega^2 \tau^2}}$$

Transverse diffusion is reduced
Transverse diffusion in magnetic field

In some gases the transverse diffusion is strongly reduced

→ improves the precision of the projected coordinate measurement in Time Projection Chambers
Avalanche phenomenon

- One electron drifts towards the anode wire:
  - Electric field is increasing
  - Ionizing collisions $\rightarrow$ pair multiplication

- Due to lateral diffusion and difference of velocity of electrons-ions, a drop-like avalanche develops near the wire

- UV photons are emitted $\rightarrow$ risk of uncontrolled amplification (spark)

- Electrons are collected in a very short time (few ns) and ions drift slowly towards the cathode
Charge multiplication

– $\alpha = 1/\lambda$ is the probability of ionization per unit length with $\lambda$ the mean free path of the electron for a secondary ionizing collision

– For $n$ electrons, there will be $dn = n\alpha dx$ new electrons created in a path $dx$

– Then $n = n_0 e^{\alpha x}$ with $\alpha$: first Townsend coefficient

– And we can define a multiplication factor $M$:

$$M = \frac{n}{n_0} = \exp \left[ \int_{r_1}^{r_2} \alpha(x) \, dx \right]$$

$\alpha$ is a function of $x$ (non-uniform electric fields)

– Limitation of $M$: above $10^8$, sparks occur (Raether limit)

– Calculating $\alpha$ (or gas gain) for different gases (model by Rose and Korff):

$$\frac{\alpha}{p} = A \exp \left( -\frac{Bp}{E} \right)$$

where $A$ and $B$ depend on the gas

To Backup
We have decided now to identify the particle species by a bar code.
HEP detector: Measures particle momenta ... by means of a spectrometer (tracker and magnetic field)

Need second observable to identify particle type:

- Velocity: Time-of flight, Cherenkov angle, Transition radiation
- Energy loss: Bethe-Bloch
- Total energy: Calorimeter

\[ p = \gamma m_0 \beta c \]

With \( p, \gamma, \beta \) calculate particle mass \( m_0 \) ...
Special signatures for neutrals:

- **Photons**: Total energy deposited in electromagnetic shower; use energy measurement, shower shape and information on neutrality (e.g. no track) ...

- **Neutrons**: Energy in calorimeter or scintillator (Li, B, $^3$He) and information on neutrality (e.g. no track) ...

- **$K_0$, $\Lambda$, ...**: Reconstruction of invariant masses ...

- **Neutrinos**: Identify products of charged and neutral current interactions ...

**Muons:**

Minimum ionizing particles; penetrates thick absorbers; measure signal behind complete detector ...
Introduction

Particle ID [CMS Detector Slice]
Basic idea:

Measure signal time difference between two detectors with good time resolution [start and stop counter; also: beam-timing & stop counter]

Typical detectors:

- Scintillation counter
- Resistive Plate Chamber (RPC)

Coincidence setup or TDC measurement with common start/stop from interaction time
Distinguishing particles with ToF:
[particles have same momentum \( p \)]

Particle 1: velocity \( v_1, \beta_1 \); mass \( m_1 \), energy \( E_1 \)
Particle 2: velocity \( v_2, \beta_2 \); mass \( m_2 \), energy \( E_2 \)
Distance \( L \): distance between ToF counters

\[
\Delta t = L \left( \frac{1}{v_1} - \frac{1}{v_2} \right) = \frac{L}{c} \left( \frac{1}{\beta_1} - \frac{1}{\beta_2} \right)
\]

\[
= \frac{L}{pc^2} (E_1 - E_2) = \frac{L}{pc^2} \left( \sqrt{p^2c^2 + m_1^2c^4} - \sqrt{p^2c^2 + m_2^2c^4} \right)
\]

Relativistic particles, \( E \simeq pc \gg m_i c^2 \):

\[
\Delta t \approx \frac{L}{pc^2} \left[ (pc + \frac{m_1^2c^4}{2pc}) - (pc + \frac{m_2^2c^4}{2pc}) \right]
\]

\[
\Delta t = \frac{Lc}{2p^2} (m_1^2 - m_2^2)
\]

For \( L = 2 \) m:

Requiring \( \Delta t \approx 4\sigma_t \) K/π separation possible up to \( p = 1 \) GeV if \( \sigma_t \approx 200 \) ps ...

Cherenkov counter, RPC : \( \sigma_t \approx 40 \) ps ...
Scintillator counter : \( \sigma_t \approx 80 \) ps ...

Example:

Pion/Kaon separation ...
\([m_K \approx 500 \text{ MeV}, m_\pi \approx 140 \text{ MeV}]\)

Assume:
\( p = 1 \) GeV, \( L = 2 \) m ...

\[
\Rightarrow \quad \Delta t \approx \frac{2 \text{ m} \cdot c}{2 (1000)^2 \text{ MeV}^2/c^2} (500^2 - 140^2) \text{ MeV}^2/c^4
\]

\[
\approx 800 \text{ ps}
\]
Use relativistic rise of $dE/dx$ for particle identification ...

Key problem: Landau fluctuations

Need to make many $dE/dx$ measurements and truncate large energy-loss values ...
[determination of 'truncated mean']

Average energy loss in a 1 cm layer of argon-methane

$\mu/\pi$ separation impossible, but $\pi/K/p$ generally achievable

Energy loss distribution; 50 GeV pions and kaons ...
[1 cm layer Ar/Methane]
Particle ID - Specific Energy Loss

Remember: $dE/dx$ depends on $\beta$!
Truncated energy loss distributions for various momenta ...

[ALPEH TPC]
Reminder:

Polarization effect ...
Cherenkov photons emitted if \( v > c/n \) ...

Cherenkov angle:

\[
\cos \theta_c = \frac{1}{n \beta}
\]

Simple Geometric derivation:

\[
\begin{align*}
\overrightarrow{AB} &= \beta c \cdot t \\
\overrightarrow{AC} &= c/n \cdot t
\end{align*}
\]

\[
\cos \theta = \frac{\overrightarrow{AC}}{\overrightarrow{AB}} = \frac{c/n \cdot t}{(\beta c \cdot t)} = \frac{1}{n \beta}
\]

To Backup
Threshold detection:
Observation of Cherenkov radiation $\Rightarrow \beta > \beta_{\text{thr}}$

Choose $n_1, n_2$ in such a way that for:

- $n_2 : \beta_\pi, \beta_K > 1/n_2$ and $\beta_p < 1/n_2$
- $n_1 : \beta_\pi > 1/n_1$ and $\beta_K, \beta_p < 1/n_1$

Light in $C_1$ and $C_2$ $\Rightarrow$ identified pion
Light in $C_2$ and not in $C_1$ $\Rightarrow$ identified kaon
Light neither in $C_1$ and $C_2$ $\Rightarrow$ identified proton
Differential Cherenkov detectors:
Selection of narrow velocity interval for actual measurement ...

Threshold velocity:
\[ [\cos \theta = 1] \]
\[ \beta_{\text{min}} = \frac{1}{n} \]

Maximum velocity:
\[ [\theta = \theta_{\text{max}} = \theta_t] \]
\[ \sin \theta_t = \frac{1}{n} \]
\[ \cos \theta_{\text{max}} = \sqrt{1 - \sin^2 \theta_t} = \frac{1}{n \beta_{\text{max}}} \]
\[ \beta_{\text{max}} = \frac{1}{\sqrt{n^2 - 1}} \]

Example:
Diamond, \( n = 2.42 \) \( \Rightarrow \) \( \beta_{\text{min}} = 0.413, \beta_{\text{max}} = 0.454 \),
i.e. velocity window of \( \Delta \beta = 0.04 \) ...

Suitable optic allows \( \Delta \beta/\beta \approx 10^{-7} \)
Ring Imaging Cherenkov Counter

Optics such that photons emitted under certain angle form ring ...

Focal length of spherical mirror: $f = R_s/2$ ...
Cherenkov light emitted under angle: $\theta_C$ ...
Radius of Cherenkov ring: $r = f \cdot \theta_C = R_s/2 \cdot \theta_C$ ...

$$\beta = \frac{1}{n \cos(2r/R_s)}$$

Determination of $\beta$ from $r$ ....

Photon detection:
Photomultiplier, MWPC
Parallel plate avalanche counter ...
Gas detectors filled with photosensitive gas ...
[e.g. vapor addition or TMAE (C$_5$H$_{12}$N$_2$)]
Transition radiation occurs if a relativist particle (large $\gamma$) passes the boundary between two media with different refraction indices ...

[predicted by Ginzburg and Frank 1946; experimental confirmation 70ies]

Effect can be explained by rearrangement of electric field ...

Energy loss distribution for 15 GeV pions and electrons in a TRD ...
Historical examples

Cathode ray tube

J. Plücker 1858 \[\rightarrow\] J.J. Thomson 1897

Philosophical Magazine, 44, 293 (1897).
Historical Development

First Detection of α-, β- and γ-rays

Image of Becquerel’s photographic plate which has been fogged by exposure to radiation from a uranium salt.

An x-ray picture taken by Wilhelm Röntgen of Albert von Kölliker’s hand at a public lecture on 23 January 1896.
Historical Development

Rutherford's scattering experiment

1911

Schematic view of Rutherford experiment

Rutherford's original experimental setup

Microscope + Scintillating ZnS screen

Rutherford's original experimental setup

Historical Development

Rutherford's scattering experiment

1911

Schematic view of Rutherford experiment

Rutherford's original experimental setup

Microscope + Scintillating ZnS screen
The Geiger counter, later further developed and then called Geiger-Müller counter

First electrical signal from a particle

H. Geiiger and W. Müller, Phys. Zeiits. 29 (1928) 839
Historical Development

Detection of cosmic rays
[Hess 1912; Nobel prize 1936]

1912
Victor F. Hess before his 1912 balloon flight in Austria during which he discovered cosmic rays.
The general procedure was to allow water to evaporate in an enclosed container to the point of saturation and then lower the pressure, producing a over-saturated volume of air. Then the passage of a charged particle would condense the vapor into tiny droplets, producing a visible trail marking the particle’s path, their number per unit of length being proportional to the density of ionization (dE/dx).

was used at discovery of the positron
(1932 by Carl Anderson, Noble Prize 1936)
Discovery of antimatter
[Anderson 1932; Nobel prize 1936]

63 MeV positron passing through lead plate emerging as 23 MeV positron.

The length of this latter pass is at least ten times greater than the possible length of a proton path of this curvature.
Historical Development

Discovery of the pion
Nuclear emulsion technique
[Powell 1947; Nobel prize 1950]

\[ \pi \rightarrow \mu \nu \]
\[ \mu \rightarrow e \nu \nu \quad \text{[not seen]} \]
Similar principle as cloud chamber:

- **Bubble chamber (1952 by Donald Glaser, Noble Prize 1960)**
  - (4.8 x 1.85 m²) chamber with liquid (e.g. H₂) at boiling point ("superheated")
  - charged particles leave trails of ions
    - formation of small gas bubbles around ions

---

was used at discovery of the "neutral current" (1973 by Gargamelle Collaboration, no Noble Prize yet)
First observed $\Omega^-$ event
[BNL Bubble Chamber]
Historical Development

Discovery of the muon neutrino (1962)

Leon M. Lederman
Melvin Schwartz
Jack Steinberger

[Nobel prize 1988]

The spark chamber is shown in Figure 3 and 4. It consisted of ten modules, each of 9 aluminum plates, 44 in. x 44 in. x 1 in. thick separated by 3/8 in. Lucite spacers. Anticoincidence counters covered the front, top and rear of the assembly, as shown, to reduce the effect of cosmic rays and muons which penetrate the shielding wall. Forty triggering counters were inserted between modules and at the end of the assembly. Each triggering counter consisted of two sheets of scintillator separated by 3/4 in. of aluminum. The scintillators were put in electronic coincidence.

Melvin Schwartz in front of the spark chamber used to discover the muon neutrino

Single muon event from original publication
Geiger - Müller tube just good for single tracks with limited precision (no position information) → in case of more tracks more tubes are needed or...

Multi Wire Proportional Chamber → 1968 by Georges Charpak, Nobel Prize 1992

The Nobel Prize in Physics 1992

The Royal Swedish Academy of Sciences awards the 1992 Nobel Prize in Physics to Georges Charpak for his invention and development of particle detectors, in particular the multiwire proportional chamber.

Georges Charpak
CERN, Geneva, Switzerland

F. Sauli, http://www.cern.ch/GDD
Historical Development

Discovery of the W/Z boson (1983)

Carlo Rubbia
Simon Van der Meer

[Nobel prize 1984]
Historical Development

Some relevant Nobel Prizes

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<th>Year</th>
<th>Category</th>
<th>Name(s)</th>
<th>Discovery/Invention (Year)</th>
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<td>1901</td>
<td>Physics</td>
<td>Wilhelm C. Röntgen</td>
<td>X-rays (1896)</td>
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<td>1903</td>
<td>Physics</td>
<td>Antoine H. Becquerel, Marie Curie, Pierre Curie</td>
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<td>1905</td>
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<td>Philipp Lenard</td>
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<td>[Phosphorescent material]</td>
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<td>1908</td>
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<td>Ernest Rutherford</td>
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<td>[Scintillating crystals]</td>
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<td>1927</td>
<td>Physics</td>
<td>Charles T. R. Wilson</td>
<td>Cloud chamber (1912)</td>
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<td>1935</td>
<td>Physics</td>
<td>James Chadwick</td>
<td>Neutron discovery (1932)</td>
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<td>[Ionization chamber]</td>
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<td>1936</td>
<td>Physics</td>
<td>Victor F. Hess, Carl D. Anderson</td>
<td>Cosmic rays (1912)</td>
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<td>Positron discovery (1932)</td>
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## Historical Development

### Some relevant Nobel Prizes

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<th>Year</th>
<th>Field</th>
<th>Laureate(s)</th>
<th>Discovery/Invention</th>
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<tr>
<td>1948</td>
<td>Physics</td>
<td>Patrick M. S. Blackett</td>
<td>$e^+e^-$ Production ... (1933)</td>
<td>[Advanced cloud chambers]</td>
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<td>1950</td>
<td>Physics</td>
<td>Cecil F. Powell</td>
<td>Pion discovery (1947)</td>
<td>[Photographic emulsion]</td>
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<td>1953</td>
<td>Physics</td>
<td>Walter Bothe</td>
<td>Coincidence method (1924)</td>
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<td>1958</td>
<td>Physics</td>
<td>Pavel A. Cherenkov</td>
<td>Cherenkov effect (1934)</td>
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<tr>
<td>1959</td>
<td>Physics</td>
<td>Emilio G. Segrè, Owen Chamberlain</td>
<td>Antiproton discovery (1955)</td>
<td>[Spectrometer; Cherenkov counter ...]</td>
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<td>1960</td>
<td>Physics</td>
<td>Donald A. Glaser</td>
<td>Bubble chamber (1953)</td>
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<td>1976</td>
<td>Physics</td>
<td>Burton Richter, Samuel C.C. Ting</td>
<td>$J/\psi$ discovery (1974)</td>
<td>[AGS Synchrotron; pBe collisions] [SLAC $e^+e^-$ collider; MARK I]</td>
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<tr>
<td>1980</td>
<td>Physics</td>
<td>James Cronin, Val Fitch</td>
<td>CP violation (1963)</td>
<td>[Spark chamber; spectrometer]</td>
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Historical Development

Some relevant Nobel Prizes

<table>
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<tr>
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<td>1984</td>
<td>Physics</td>
<td>Carlo Rubbia, Simon Van der Meer</td>
<td>W/Z discovery (1983)</td>
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<td>[SPS; 4π multi-purpose detector]</td>
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<td>[Neutrino beam; spark chambers]</td>
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<td>[ep scattering; spectrometer]</td>
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<tr>
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<td>[Ion trap technique]</td>
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<td>1992</td>
<td>Physics</td>
<td>Georges Charpak</td>
<td>Multi-Wire Chamber (1968)</td>
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<td>2002</td>
<td>Physics</td>
<td>Raymond Davis Jr., Masatoshi Koshiba</td>
<td>Cosmic neutrino (1986)</td>
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Applications

To Backup
Application 1

1/ Explain the difference between electrons and heavy ions when they interact with matter. Why the trajectory is different from the range in the case of electrons?

2/ Which effect arises when an electron beam is passing through an absorber?

3/ What is the critical energy for electrons in Pb (Z=82)? Are such electrons relativists?

4/ Below which energy the Bremsstrahlung is <5%? In order to have a good protection against relativist electrons, is it worth to use light or heavy materials?

5/ Calculate $E_c$ for Carbon (Z=6). Calculate Bremsstrahlung ratio for 10 MeV electrons in carbone and compare with Pb. Then for 300 MeV.
1/ Heavy ions: collisions with electrons (no deviation, distance depending on the energy and material) then atomic collisions at low energy. The trajectory is almost equal to the path in the matter.

Electrons: collisions with electrons (deviation, numerous collisions when energy decreasing). Atomic collisions (radiative losses) arise at high E. Due to the high number of deviations, the trajectory of electrons is larger than their range.

2/ Bremsstrahlung is the major effect to take into account (for radioprotection purposes for instance). It is proportional to E and \( Z^2 \).

3/ \[ E^e_c = \frac{800 \text{ MeV}}{82 + 1.2} = 9.62 \text{ MeV} \]
   \[ E = (\gamma - 1) m_0 c^2 \Rightarrow \gamma = 19.8 \]
   \[ \beta = \frac{v}{c} = \sqrt{1 - 1/\gamma^2} = 0.9987 \]
4/ If \( r \) is the Bremsstrahlung ratio then \( r = \frac{\text{brem}}{\text{brem+coll}} \) and 
\[
\frac{1}{r} = 1 + \frac{\text{coll}}{\text{brem}} = 1 + \frac{700}{\text{ZE}}
\]
\( \Rightarrow E = 449 \text{ keV} \)

In any case, it is better to minimize the Bremsstrahlung and so to use a low Z material.

5/ \( Z=6 \) so \( E_c = 111.1 \text{ MeV} \).

For 10 MeV electrons the Brem. ratio is 7.9% in carbone and 54% in lead.

For 300 MeV electrons the Brem. ratio is 72% in carbone and 97% in lead.
Application 2

1/ In water, what is the minimum kinetic energy for an electron to undergo a Cherenkov effect?

2/ Calculate this energy for a proton and an alpha.

Water index of refraction: $n = \frac{4}{3}$

\[
m_0^e c^2 = 0.511 \text{ MeV}
\]

\[
m_0^p c^2 = 938.3 \text{ MeV}
\]

\[
m_0^n c^2 = 939.6 \text{ MeV}
\]
The velocity of the charged particle must be \( v > \frac{3}{4} \cdot c \).

Electron kinetic energy is:

\[
T = mc^2 - m_0 c^2 \quad \text{with} \quad m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}
\]

So \( E_e > 0.26 \text{ MeV} \); \( E_\beta > 480 \text{ MeV} \); \( E_\alpha > 1.922 \text{ GeV} \)
Application 3

Photons detection:

A gamma source is located behind an aluminium plate of 0.5 cm thickness and detected by a counter at a distance of 4 cm with an effective detection area of 5 cm$^2$.

The source is emitting 3700 photons/sec with an energy of 0.95 MeV.

For such photons, the mass attenuation coefficient of aluminium is 0.1 cm$^2$/g.

If the detection efficiency of the counter is 90%, calculate the number of counts per second in the detector.

Aluminium mass density: 2.7 g/cm$^3$
Number of photons detected is related to the solid angle fraction, the photons attenuation in the aluminium and the detection efficiency.

\[ N = N_0 \times \frac{S_{\text{eff}}}{4\pi r^2} \times \exp(-\mu_m \rho x) \times \text{efficiency} \]

\[ N = 3700 \times \frac{5}{4\pi 4^2} \times \exp(-0,1 \times 2,7 \times 0,5) \times 0,9 = 72,4 \ \gamma \cdot s^{-1} \]
Energy loss for photons \( \rightarrow \) three major physics mechanisms:

- **Photo electric effect**: absorption of a photon by an atom ejecting an electron

  \[
  \sigma = Z^5 \alpha^4 \left( \frac{m_e c^2}{E_\gamma} \right)^n \quad n = 7/2 \text{ for } E \ll m_e c^2 \quad \text{and} \quad \rightarrow 1 \text{ for } E \gg m_e c^2
  \]

  Strong dependence with Z, dominant at low photon energy

- **Compton scattering**

  \[
  \sigma_C^e \propto \frac{\ln E_\gamma}{E_\gamma} \quad \text{and atomic compton} = Z \sigma_C^e
  \]

- **Pair creation** (similar to bremsstrahlung): dominant for \( E \gg m_e c^2 \)

  \[
  \sigma_{\text{pair}} \approx 4\alpha r_e^2 Z^2 \left( \frac{7}{9} \ln \frac{183}{Z^3} \right) = \frac{A}{N_A} \left( \frac{7}{9} \frac{1}{X_0} \right) \quad \text{Independent of energy!}
  \]

  Probability of pair creation in 1 \( X_0 \) is \( e^{-7/9} \), mean free path of a photon before creating a \( e^+e^- \) pair is \( \Lambda_{\text{pair}} = 9/7 X_0 \).
Energy loss for photons

(a) Carbon ($Z = 6$)
- experimental $\sigma_{\text{tot}}$

(b) Lead ($Z = 82$)
- experimental $\sigma_{\text{tot}}$

\[
\begin{align*}
\sigma_{\text{p.e.}} &= \text{Atomic photoelectric effect (electron ejection, photon absorption)} \\
\sigma_{\text{Rayleigh}} &= \text{Rayleigh (coherent) scattering–atom neither ionized nor excited} \\
\sigma_{\text{Compton}} &= \text{Incoherent scattering (Compton scattering off an electron)} \\
\kappa_{\text{nuc}} &= \text{Pair production, nuclear field} \\
\kappa_{e} &= \text{Pair production, electron field} \\
\sigma_{\text{g.d.r.}} &= \text{Photonuclear interactions}
\end{align*}
\]
Electron (positron) interaction with matter

Define Radiation Length $X_0$ as the Radiative Mean Path:

i.e. the distance over which the energy of electron/positron is reduced by a factor $\epsilon$ by Bremsstrahlung.

Measured in units of [g/cm$^2$]

Bethe-Bloch for heavy particles

$\text{Stopping Power} \equiv \frac{dE}{dx} \equiv E \cdot \rho \frac{1}{X_0}$
Energy (kinetic) loss by Coulomb interaction of charged particles with the atoms/electrons:

- **Excitation**: the atom (or molecule) is excited to a higher level
  \[
  \text{atom}^* \rightarrow \text{atom} + \gamma
  \]
  low energy photons of de-excitation
  - **light detection**

- **Ionization**: the electron is ejected from the atom
  \[
  \text{electron / ion pair}
  \]
  - **charge detection**

- **Instead of ionization/excitation** real photon can be produced under certain conditions
  - **Cerenkov or Transition radiation**
  Contribute very little to the energy loss (< 5%), can be neglected but they are used for particle ID
Stopping power (\langle -\frac{dE}{dx} \rangle) for positive muons in copper as a function of \( \beta\gamma = p/Mc \) over nine orders of magnitude in momentum (12 orders of magnitude in kinetic energy). Solid curves indicate the total stopping power.
Minimum Ionizing Particle:

- Minimum at $\beta\gamma \sim 3 ... 4$
- Similar for all elements $\sim 2$ MeV/(g/cm²)
Cherenkov radiation detectors

Unique tool to identify charged particles with a high separation power over a range of momentum from few hundred MeV/c up to several hundred GeV/c

A charged particle with velocity $\beta = v/c$ in a medium with refractive index $n = n(\lambda)$ may emit light along a conical wave front.

**Radiator**

+ **Photon detector**

The angle of emission is given by:

$$\cos \Theta_C = \frac{1}{\beta \cdot n} \quad \cos \theta_{\text{max}} = \frac{1}{n} \quad \beta_{\text{min}} = \frac{1}{n}$$

➡ Particle ID: Threshold (detect Cherenkov light) and Imaging (measure Cherenkov angle) techniques

➡ Fast particle counters, tracking detectors, performing complete event reconstruction,
Neutrino detectors
Stopping power

- We have seen that to stop a 450 GeV muon beam one needs 900m of concrete.
- Muons interact mostly by electromagnetic interaction.
- Neutrino are neutral and interact only through the weak interaction
  => most of them will go through a 900m block of concrete without interacting (and even through the earth)!
- There is no detector capable of detecting all neutrinos from a beam.
  => we can only sample a fraction of the neutrinos passing through a detector
Super Kamiokande

• One of the most successful neutrino observatory (Nobel prize 2002)
• 50 000 tonne of pure water
• Located under Mount Kamioka in Japan.
Sudbury Neutrino Observatory

- 1000 tonnes of heavy water.
- Located in Ontario, Canada.
- Because heavy water contains a lot of neutrons, SNO is sensitive to both neutral currents and charged currents => unique in the world.
  => Confirmed solar neutrinos oscillations
Antares / IceCube

- Because neutrinos are (almost) unaffected by matter, they may give a different picture of the Universe than photons or cosmic rays
  => Neutrino telescopes in sea, lake (Baikal) or ice!
Invariant mass

- From relativistic kinematics, the relation between energy $E$, momentum $p$, and (rest) mass $m$ is: $E^2 = p^2 + m^2$

- Consider a particle that decays and gives two daughter particles:
  - The invariant mass of the two particles from the decay:
    \[ M^2 = m_1^2 + m_2^2 + 2 (E_1 E_2 - p_1 \cdot p_2 \cos \theta) \]
    → to reconstruct the parent mass a precise knowledge of the momentum and the angle $\theta$ of decay products is needed, there are obtained:
    - from the tracking system,
    - and their particle type, which determines their masses $m_1$ and $m_2$
Example: find Higgs boson via its decay:

\[ p + p \rightarrow H X \rightarrow Z^0 Z^{0*} X \rightarrow e^+ e^- \mu^+ \mu^- X \]

Compute (from the measured kinematics):

\[
m_H^2 = (E_{Z^0} + E_{Z^{0*}})^2 - (\vec{p}_{Z^0} + \vec{p}_{Z^{0*}})^2
\]

Also for each \( Z^0 \) compute (e.g. for \( Z^0 \rightarrow \mu^+ \mu^- \)):

\[
m_{Z^0}^2 = (E_{\mu^+} + E_{\mu^-})^2 - (\vec{p}_{\mu^+} + \vec{p}_{\mu^-})^2
\]

The same for the other Higgs decay mode: \( H \rightarrow \gamma\gamma \)

In all cases we have to reconstruct tracks (EM clusters for photons) and measure momenta, energies and identify particles (charge and mass hypothesis).
Given the characteristics of the collisions let us define some useful variables:

- **Transverse momentum,** \(p_T\) (very useful)
  - Particles that escape detection \((\theta < 3°)\) have \(p_T \approx 0\)
  - Transverse momentum conserved imply \(\sum p_T i \approx 0\)
  - **Longitudinal momentum and energy,** \(p_z\) (not useful)
  - If particles that escape detection have large \(p_z\)
  - It implies that the visible \(\sum p_T i\) is not conserved

- **Polar angle,** \(\theta\) (very useful)
  - Not Lorentz invariant
  - Rapidity: \(y\)

- **Pseudorapidity:** \(\eta\)

- **Azimuthal angle,** \(\phi\) (very useful)
  - Well measured since detectors have complete coverage and are azimuthally symmetric at a given \(\eta\)
Example of particle interactions

- **Ionization**
- **Pair production**
- **Compton scattering**

Delta-electrons
## Non-destructive methods: charged particles

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<th>Measure:</th>
<th>Example</th>
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<td>hit and/or drift time</td>
<td>Position resolution: ~ 50 µm</td>
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<td>Tracks reconstruction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+ Magnetic field</td>
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<tr>
<td></td>
<td></td>
<td>Momentum</td>
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<td></td>
<td>energy losses dE/dx</td>
<td>Particle ID</td>
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<tr>
<td><strong>Silicon detectors</strong></td>
<td>hits and/or amplitude</td>
<td>Position resolution: ~ 5 µm</td>
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<td>Tracks &amp; <strong>Vertices</strong> reconstruction</td>
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<tr>
<td><strong>Cherenkov detectors</strong></td>
<td>Cherenkov photons</td>
<td>Particle ID</td>
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<tr>
<td><strong>Transition radiation detectors, ...</strong></td>
<td></td>
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</table>
Destructive methods

Calorimeters: electromagnetic and hadronic

Measure: shower energy and/or shower shape
- Energy resolution
- Position resolution: ~few mm
- Particle ID

Muon detectors

Measure: hits
- Muon track reconstruction after absorber
  - Particle ID
Detector Systems

Typical arrangement of subdetectors

- Low density
- High precision
- High granularity
- Track density \( \propto \frac{1}{r^2} \)

vertex location
(Si detectors)
main tracking
(gas or Si detectors)
particle identification
e.m. calorimetry
magnet coil
hadron calorimetry / return yoke
muon identification / tracking

\( \mu^+ \)

ATLAS and CMS require high precision tracking also for high energetic muons \( \Rightarrow \) large muon systems with high spatial resolution behind calorimeters.
IN A P-P COLLISION