Particle Identification PID
Introduction and historical development

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EURIZON Detector School 2023

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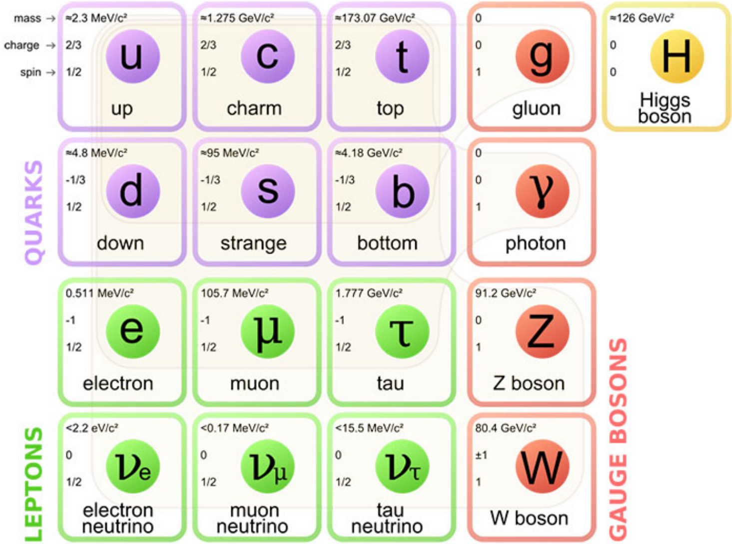
Particle Identities

Particles identified via lifetime, mass, charge, ...



Electron Discovery

- Example for particle identification (PID) by mass
- 1890: Arthur Schuster measuring charge-to-mass ratio
- Energy given by electric field:

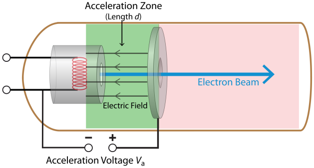
$$eE = \frac{1}{2}mv^2$$

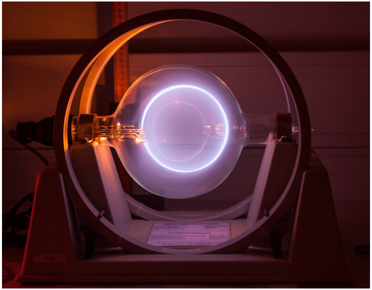
- Lorentz force resulting in centripetal force:

$$evB = \frac{mv^2}{R}$$

- Resulting in

$$\frac{e}{m} = 1.76 \cdot 10^{11}\,\frac{\mathrm{C}}{\mathrm{kg}}$$





Electron Discovery

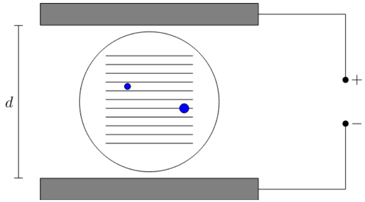
- Second measurement required to eliminate e (Millikan experiment in 1910)
- Electric force compensating gravitation and buoyancy:

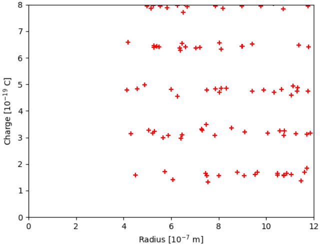
$$q = \frac{(\varrho_o - \varrho_a)\frac{4}{3}\pi r^3 g d}{U}$$

- Radius determined from falling speed of electron:

$$r = \sqrt{\frac{9 v \eta}{2(\varrho_o - \varrho_a) g}}$$

- Measurement results multiple of electron charge e



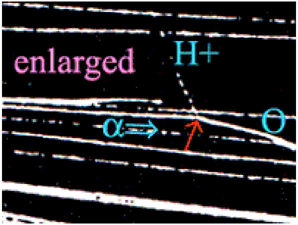


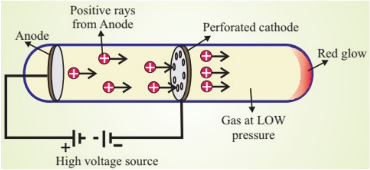
Proton Discovery

- 1925: Blackett's cloud chamber images show absorption of α-particles in a cloud chamber
- α-particle captured by nitrogen converting into oxygen (not carbon) and proton

$$^{14}N + \alpha \rightarrow {}^{17}O + p$$

- Thickness and length indications for energy loss per track length dE/dx and particle energy
- More detailed measurements using hydrogen in anode ray tubes $\rightarrow$ discovery of the proton



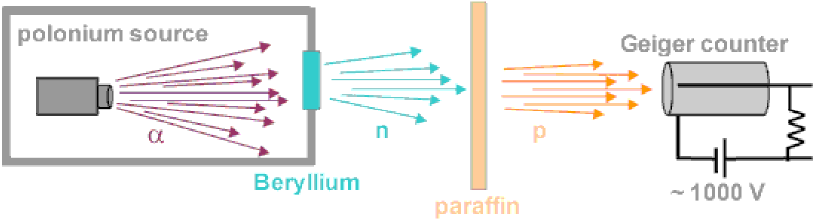


Neutron Discovery

- 1930: James Chadwick shooting α-rays into Beryllium target $\rightarrow$ neutral particles emitted

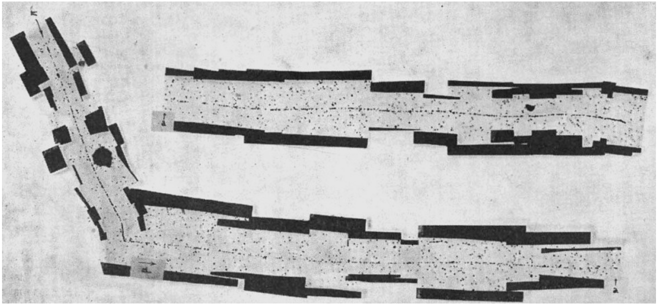
$$^{4}_{2}\alpha + ^{9}_{4}Be \rightarrow ^{12}_{6}C + ^{1}_{0}n$$

- First thought: γ-rays emitted by beryllium (not deflected by the magnetic field and extremely penetrating)
- Unlike γ-rays not charging electroscope $\rightarrow$ new particle
- Analyzing kinematics reveals the same mass as proton $\rightarrow$ neutron



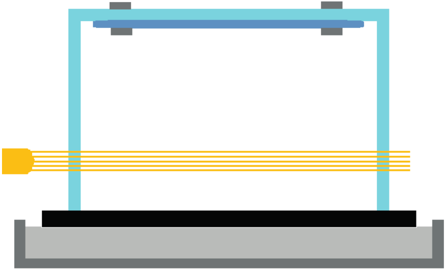
Pion Discovery

- Pion containing 1 up- and 1 down-quark
- Range too large (no electron)
- Scattering too large (no proton)
- Frequently captured by nuclei (no muon)
- $\pi^{\pm}$ decaying into $\mu^{\pm}$ (two-body decay $\rightarrow$ equal kinetic energy)
- PID using tracking, energy loss, and particle decay

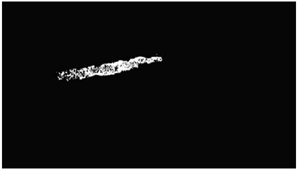


Cloud Chambers

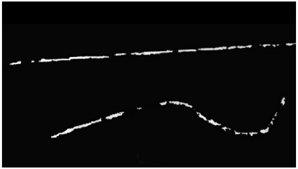
- Commonly filled with isopropanol
- Thermal gradient between top and bottom
- Thin layer of saturated vapor
- Charged particle followed by condensation track



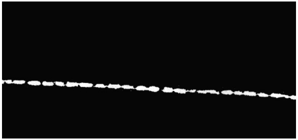
α particle



fast and slow $e^{\pm}$

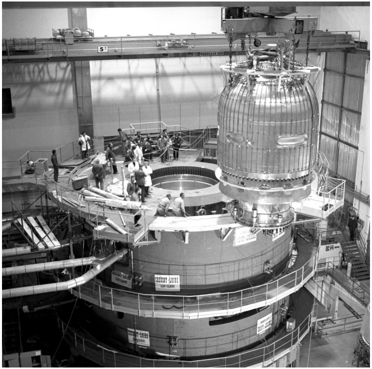


muon (MIP)



Bubble Chambers

- Studying particle physics with the Big European Bubble Chamber (BEBC)
- Installed in Proton Synchrotron at CERN in 1977
- Stainless steel vessel filled with 35 m^3 superheated liquid hydrogen/deuterium
- Operating temperature: 27 K
- Operating pressure: 5 bar



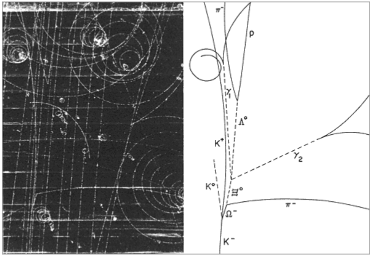
Omega Baryon

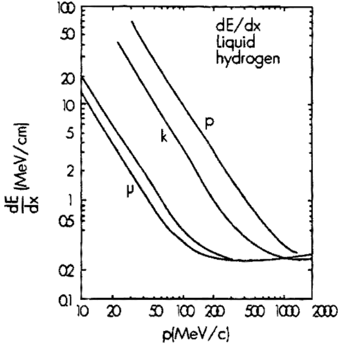
- Discovery of Ω^{--} baryon in 1964 at Brookhaven National Lab (BNL) in bubble chamber:

$$K^- + p \to \Omega^- + K^+ K^0$$

- Neutral particles not interacting with matter
- Number of bubbles per centimeter of track inversely proportional to the square of the particle velocity
- Rest mass calculated from momentum and energy of decay products

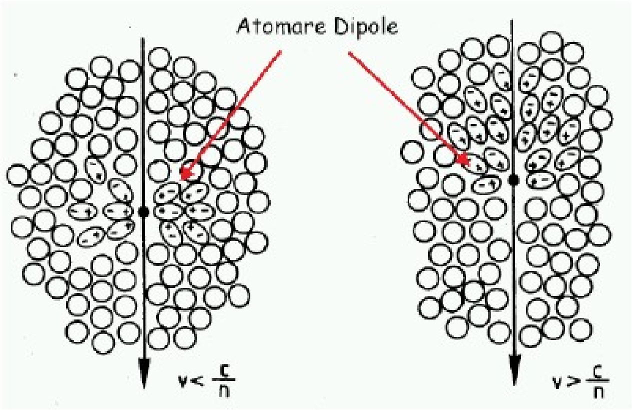
$$m = \sqrt{E^2 - p^2}$$





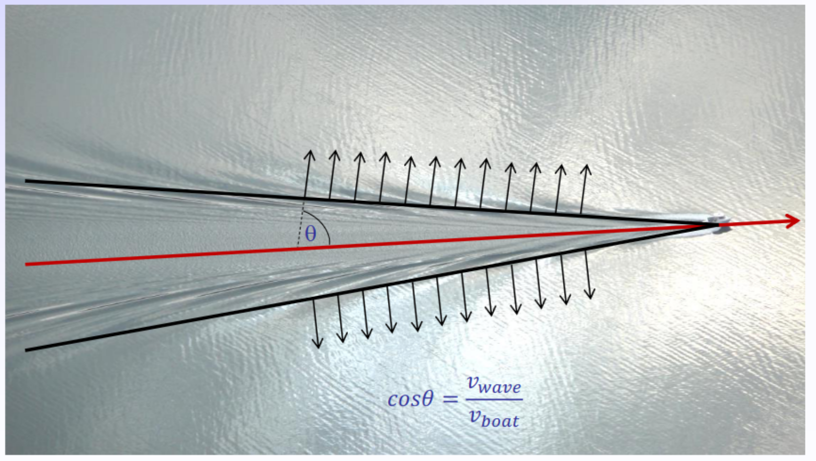
Cherenkov Effect

- Cherenkov radiation: Charged particle traversing medium faster than phase speed of light in medium
- Smaller velocities: Destructive interference of waves

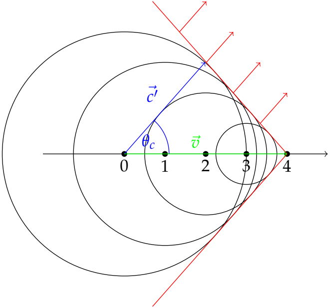


Cherenkov Effect

Classical analogue: boat on the water



Cherenkov Effect



- Deriving Cherenkov angle

$$\cos\theta_c = \frac{v}{c} \Rightarrow \boxed{\cos\theta_c = \frac{1}{n\beta}}$$

- Condition

$$v > \frac{c}{n} \Rightarrow \beta = \frac{1}{n}$$

- Using important relativistic correlation

$$\beta = \frac{p}{E} = \frac{p}{\sqrt{p^2 + m^2}}$$

- Threshold momentum for Cherenkov radiation:

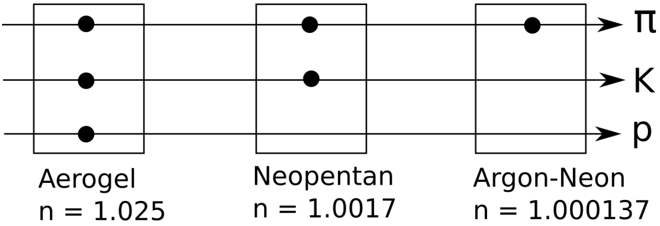
$$\boxed{p_{\text{th}} = \frac{m}{\sqrt{n^2 - 1}}} \approx 0.8m$$

Threshold Cherenkov Counters

- Maximum refractive index (derived from previous formula)

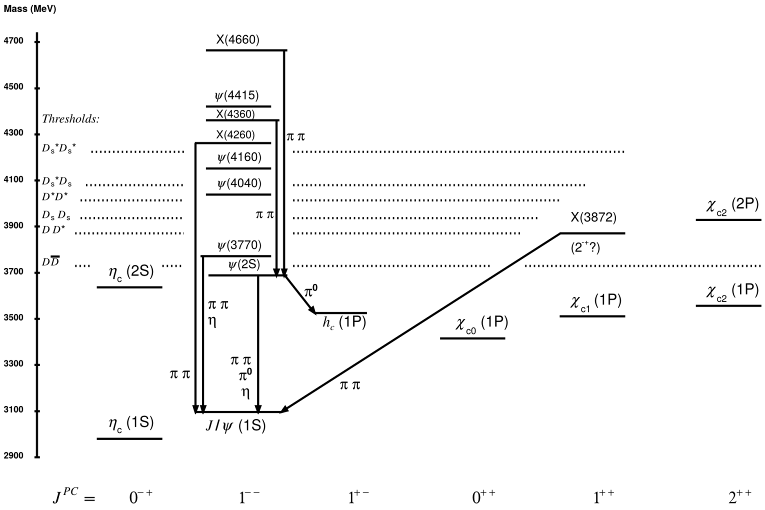
$$n = \sqrt{\frac{m^2}{p^2} + 1}$$

- Momentum $p = 12\,\mathrm{GeV/c}$
- p: $n > 1.0035$, $K^{\pm}$: $n > 1.000843$, $\pi^{\pm}$: $n > 1.000129$
- Electrons visible in all counters
- Other Cherenkov detector concepts: DIRC, RICH



Charmonium Discovery

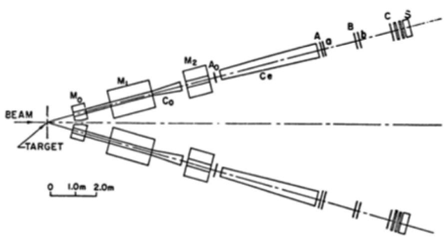
- First charmonium discovery of $J/\Psi(1S)$ in 1974 with mass in 3096 MeV $\rightarrow$ November revolution in particle physics



Brookhaven Experiment

- Discovery of J by Samuel Ting
- Goal: finding new particles decaying into e^+/e^- and μ^+/μ^-
- Two Cherenkov threshold counters C_0 and C_e
- Observed Reaction

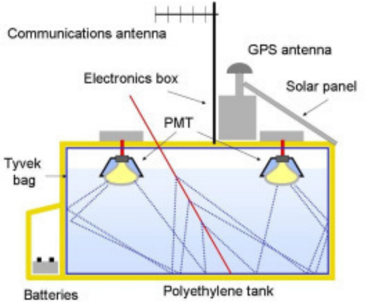
$$p + Be \to J + X \to e^+ + e^- + X$$

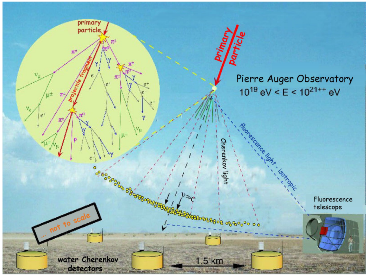


a) Plan view

Pierre Auger Experiment

- 1,660 surface detector stations (distance 1,5000 m)
- Diameter: 3.6 m
- Water depth: 1,2 m
- Volume: 12 m^3
- 3 PMTs per water tank
- Filling: highly purified water
- Detection of Cherenkov light
- Number of secondary particles depending on shower energy
- Amount of Cherenkov light proportional to number of particles



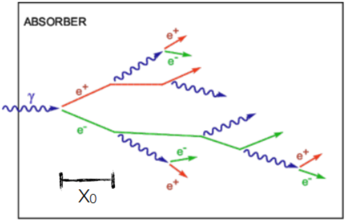


Particle Showers

Reminder:

Dominant processes
at high energies ...

Photons : Pair production
Electrons : Bremsstrahlung



Pair production:

$$\sigma_{\text{pair}} \approx \frac{7}{9}\left(4\,\alpha r_e^2 Z^2 \ln\frac{183}{Z^{\frac{1}{3}}}\right)$$

$$= \frac{7}{9}\frac{A}{N_A X_0}$$

[X_0: radiation length]
[in cm or g/cm^2]

Absorption
coefficient:

$$\mu = n\sigma = \rho\frac{N_A}{A}\cdot\sigma_{\text{pair}} = \frac{7}{9}\frac{\rho}{X_0}$$

Bremsstrahlung:

$$\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 \cdot E\,\ln\frac{183}{Z^{\frac{1}{3}}} = \frac{E}{X_0}$$

$$\rightarrow E = E_0 e^{-x/X_0}$$

After passage of one X_0 electron
has only (1/e)$^{\text{th}}$ of its primary energy ...
[i.e. 37%]

Particle Showers

Principle:

Alternating layers of absorber and active material [sandwich calorimeter]

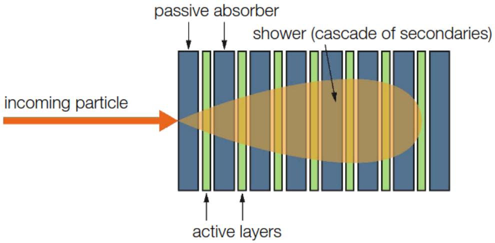
Absorber materials:
[high density]

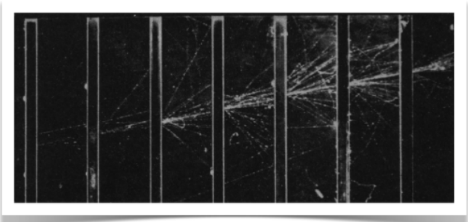
Iron (Fe)
Lead (Pb)
Uranium (U)
[For compensation ...]

Active materials:

Plastic scintillator
Silicon detectors
Liquid ionization chamber
Gas detectors

Scheme of a sandwich calorimeter

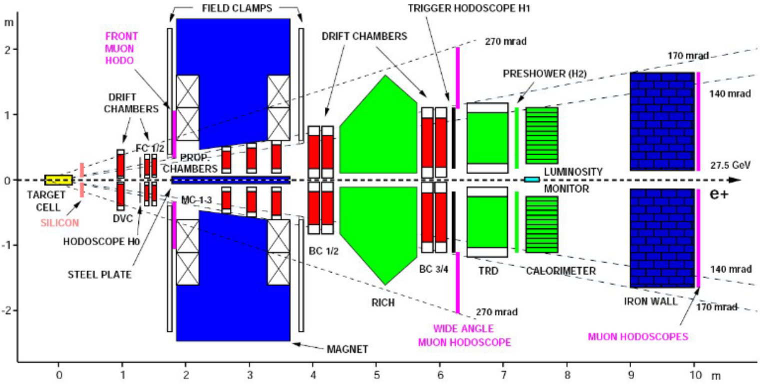




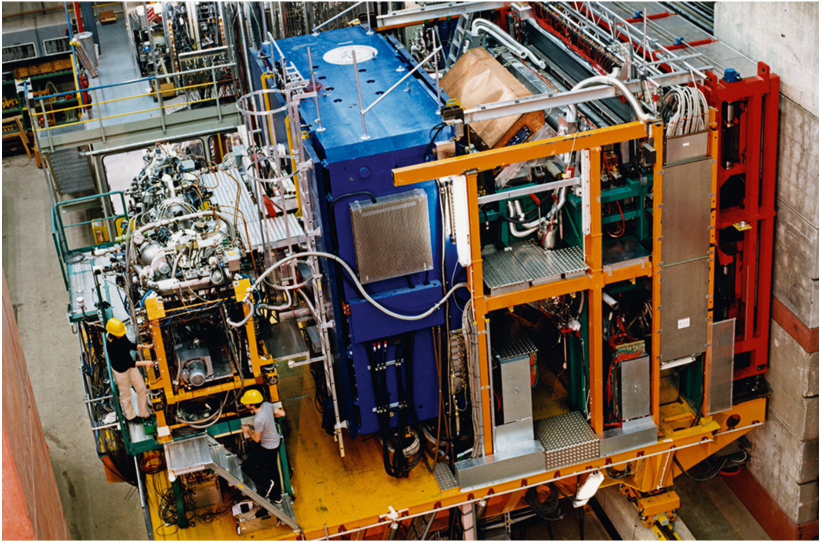
Electromagnetic shower

HERMES Detector

Main purpose: measuring spin structure of the nucleons

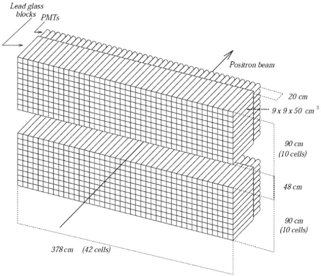


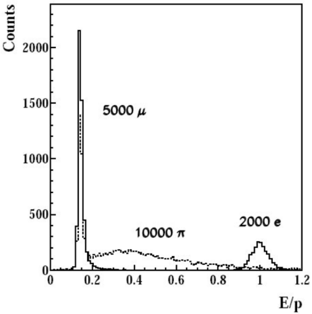
HERMES Detector



HERMES Calorimeter

- 840 identical radiation hard F101 lead-glass blocks
- Area of each block: $9 \times 9\,\mathrm{cm}^2$
- Length of each block: 50 cm (corresponding 18 X_0)
- Block size chosen to contain 99% of EM shower inside 3×3 blocks
- Wrapped in aluminum (mirrror)
- Block length optimized to improve energy resolution
- PMTs glued to end of blocks
- Particle identification
  - Muons: minimum ionizing particles
  - Pions: minimum ionizing peak with long tail due to hadronic showers
  - Electrons lose nearly all energy



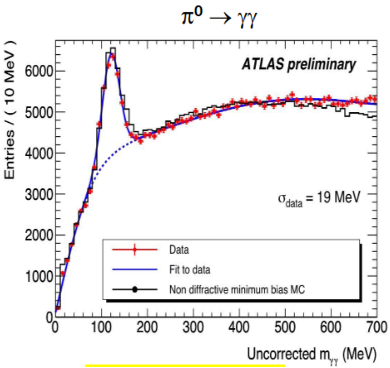


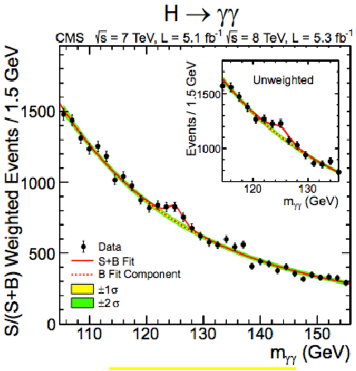
Modern PID Motivation

- Identifying different particle species
- Long-living (but still decaying) neutral particles: Λ^0 or Ξ^0
- Short-living particles: τ, mesons with charm and bottom quarks
- Determination of 4-vector momentum of all decay products required to calculate the invariant mass of the original particle
- PID reduces to identify all stable particles in the final state: p, n, $K^{\pm}$, K_L^0, $\pi^{\pm}$, $e^{\pm}$, $\mu^{\pm}$, γ
- 3-momentum of particle measured: second observable required
  - Total energy: $E = \gamma m_0 c^2$
  - Energy loss (Bethe-Bloch) $\frac{dE}{dx} \propto \frac{1}{\beta^2} \ln\left(\beta^2\gamma^2\right)$
  - Time of Flight (ToF) $\tau \propto \frac{1}{\beta}$
  - Cherenkov angle $\cos\theta = \frac{1}{n\beta}$
  - Transition radiation $\gamma > 1000$

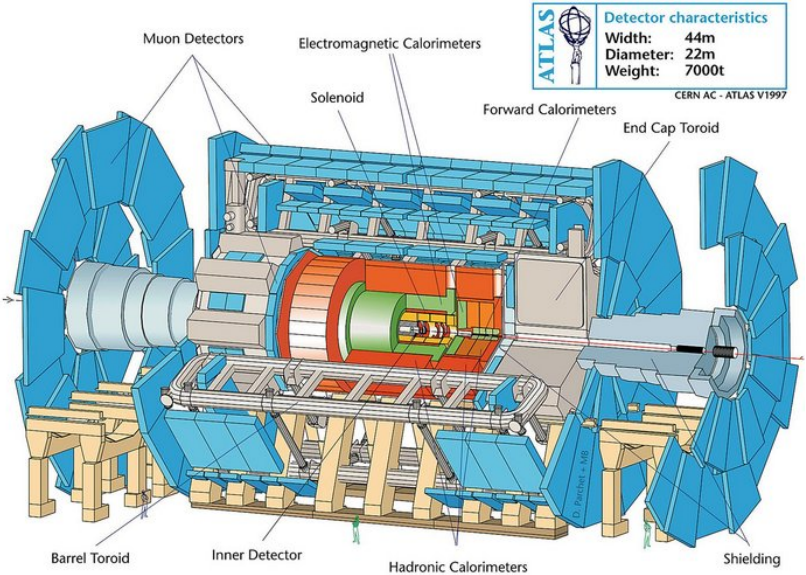
Mass Reconstruction

- Typical example of reconstruction of a particle decay: $\pi^0 \to \gamma\gamma$ (one of the first composite particles reconstructed in the LHC experiments)
- Technique also used to search for more exciting signals, like the Higgs boson (Last missing piece of the Standard Model, discovered 5 years ago at the LHC)





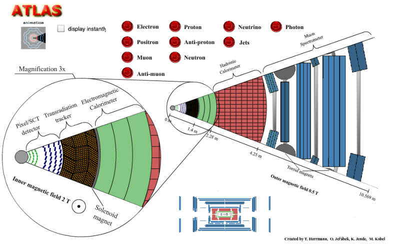
Recent Particle Detectors

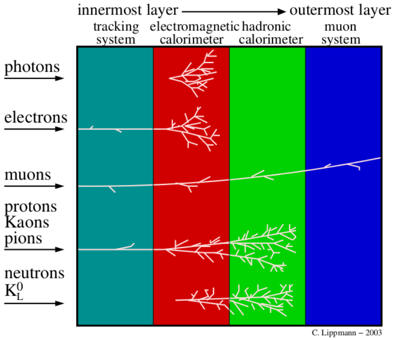


Interaction with Matter

- Charged kaon decay visible in tracking detector via characteristic "kink"
- Sampling calorimeters (lead-scintillator) and homogenous (Lead-Tungsted) calorimeters available
- Neutrinos do not interact with matter (missing energy)
- Quark flavor tagging identifies flavor of jet responsible for jet
- Hadrons with beauty quarks having large lifetime (secondary vertex)
- K_S^0 and Λ known as V^0 particles due to characteristic decay vertices:

$$K_S^0 \to \pi^+\pi^-$$





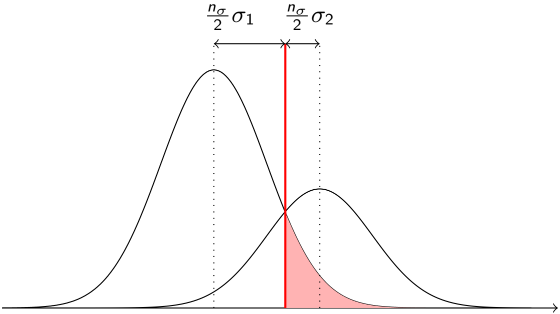
Separation Power

Definition of separation power:

$$n_\sigma = \frac{\mu_2 - \mu_1}{\frac{1}{2}(\sigma_1 + \sigma_2)}$$

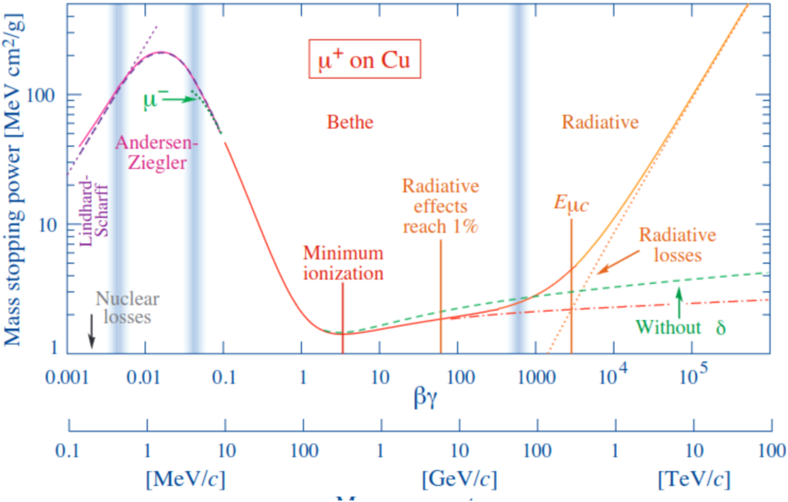
Probability for misidentification:

$$P_{\mathrm{misid}}(n_\sigma) = \frac{1}{2}\left[1 - \mathrm{erf}\left(\frac{n_\sigma}{2 \cdot \sqrt{2}}\right)\right]$$



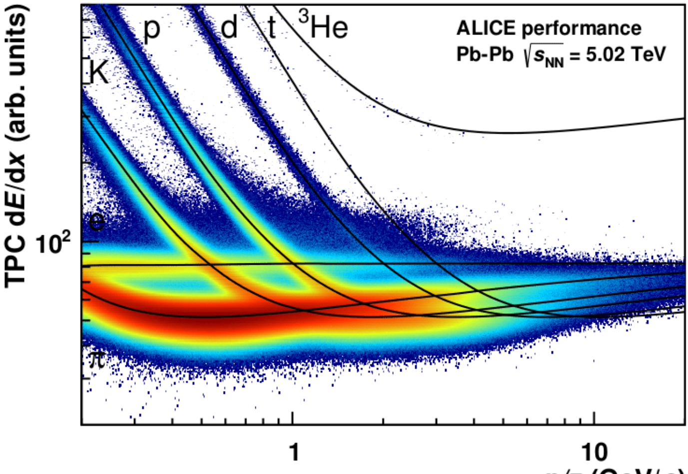
Energy Loss

Energy loss of μ^+ as function of its momentum



Energy Loss

- Energy Energy loss dE/dx depending on particle mass
- Height of measured signal directly correlated with energy loss
- Particle identification (PID) especially for small momenta
- Smearing from detector resolution and Landu distribution



Time of Flight

- Time difference between particles

$$\Delta t = L\left(\frac{1}{v_1} - \frac{1}{v_2}\right) = \frac{L}{c}\left(\frac{1}{\beta 1_1} - \frac{1}{\beta_2}\right)$$

- Inserting

$$\beta = \frac{p}{E} = \frac{p}{\sqrt{p^2 + m^2}}$$

leads to

$$\Delta t = \frac{L}{pc^2}(E_1 - E_2) = \frac{L}{pc^2}\left(\sqrt{p^2 + m_1^2} - \sqrt{p^2 + m_2^2}\right)$$

- Using $E \gg m \Rightarrow E \approx m$:

$$\boxed{\Delta t = \frac{L}{2pc^2}(m_1^2 - m_2^2)}$$

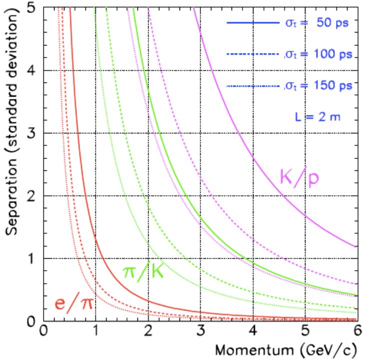
Time of Flight

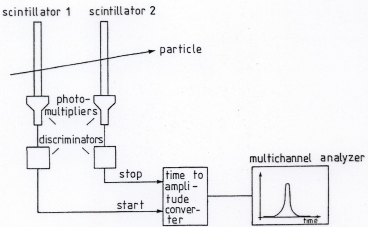
- Separating K/π at $p = 1\,\text{GeV/c}$ for $L = 2\,\text{m} \Rightarrow \sigma_t \approx 800\,\text{ps}$
- Error propagation

$$\sigma_{m^2} = 2\left[m^4\left(\frac{\sigma_p}{p}\right)^2 + \right.$$
$$\left. + E^4\left(\frac{\sigma_t}{t}\right)^2 + E^4\left(\frac{\sigma_L}{L}\right)^2\right]^{\frac{1}{2}}$$

- Assuming small errors in L in p:
- Mass resolution:

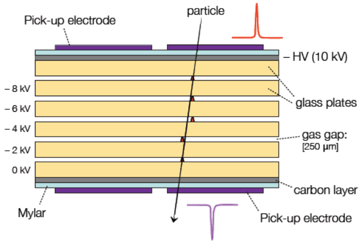
$$\sigma_{m^2} \approx 2E^2\frac{\sigma_t}{t}$$

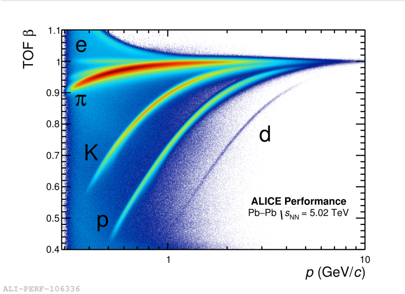


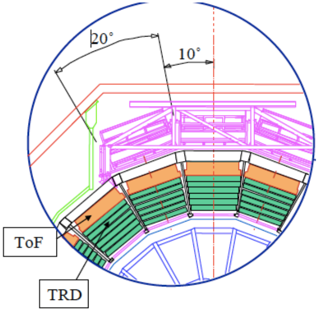


Time of Flight

- ALICE Multi Resistive Plate Chamber (Time of Flight system)
- Particle ID in high multiplicity environment → ToF with very high granularity and coverage of full ALICE barrel
- Gas detector only choice





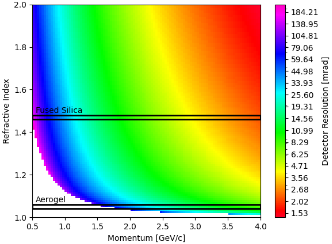


Modern Cherenkov Detectors

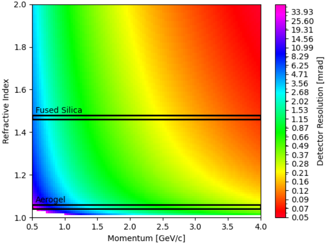
- Required Resolution: Difference of Cherenkov angles

$$\sigma_{\theta_c} = \arccos\left(\frac{\sqrt{m_1^2 + p^2}}{np}\right) - \arccos\left(\frac{\sqrt{m_2^2 + p^2}}{np}\right)$$

π/K separation



μ/π separation

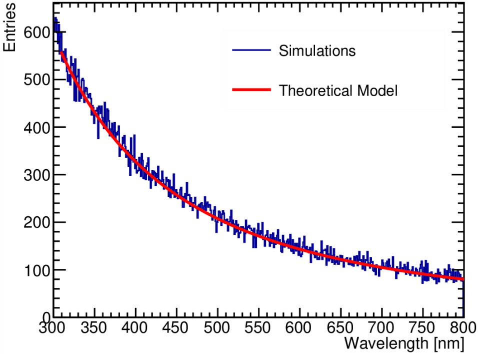


Photon Yield

- Number of photons described by Frank Tamm equation:

$$\frac{\mathrm{d}N}{\mathrm{d}x} = 2\pi\alpha z^2 \int_{\lambda_1}^{\lambda_2} \left(\frac{1}{\lambda^2} - \frac{1}{n^2\beta^2\lambda^2} \right) \mathrm{d}\lambda$$

- Fused Silica: 50 photons/mm for $(300 < \lambda < 800\,\mathrm{nm})$
- Photon yield per wavelength for 1000 simulated events



Dispersion Relation

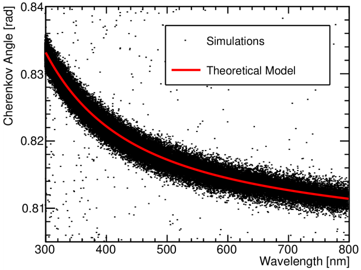
- Chromatic error due to dispersion

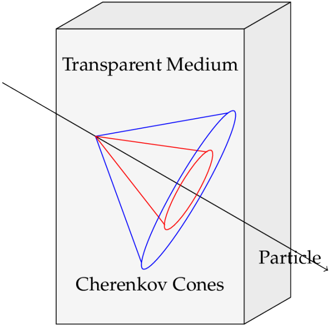
$$n = n(\lambda)$$

- Sellmeier equation:

$$n^2(\lambda) = 1 + \sum_{i=1}^{3} \frac{B_i \lambda^2}{\lambda^2 - C_i}$$

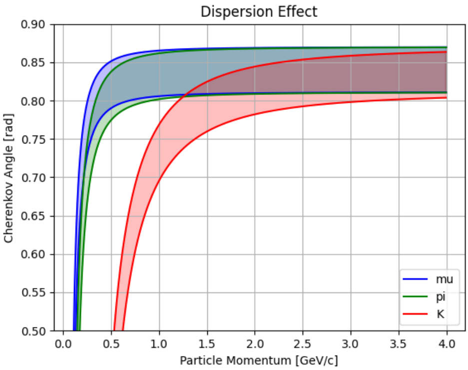
- Example for fused silica





Dispersion Effects

Cherenkov angle in fused silica:

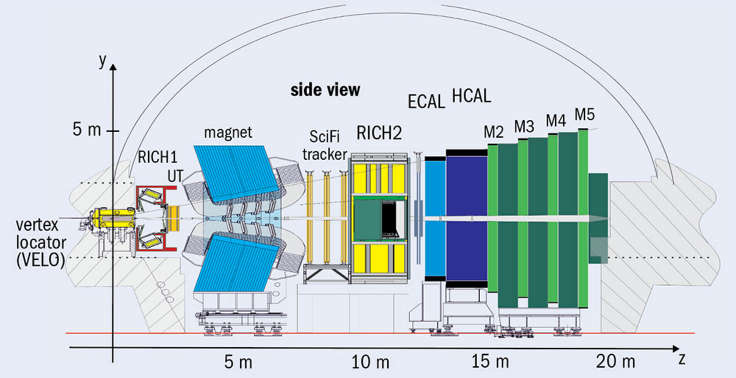


Possible solutions for band width reduction:

- Higher photon statistics
- Reduction of wavelength acceptance (optical filter)
- Correction of dispersion by achromatic optics
- Correction by means of photons time of propagation

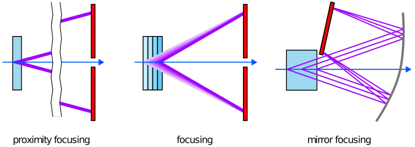
RICH Detectors

- Example: LHCb Detector designed for study bottom and charm quarks
- containing tracking detectors (VELO/SciFi tracker), calorimeters, and 2 RICH detectors
  - RICH1 for small particle momenta
  - RICH2 for large momenta

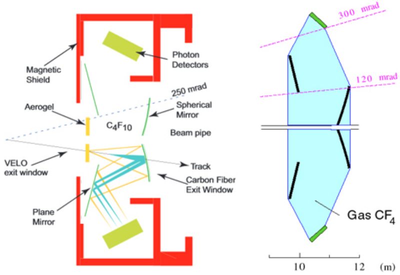


RICH Detectors

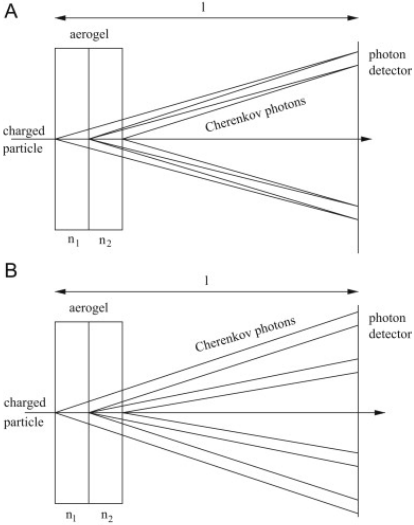
RICH: Ring Imaging Detectors



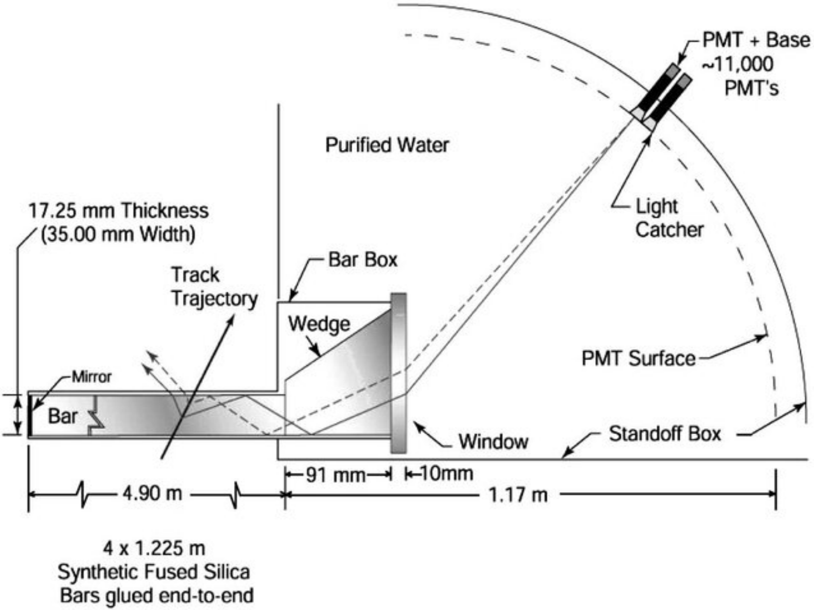
2x RICH in LHCb:



$n_2 > n_1$: Focusing
$n_2 < n_1$: Defocusing



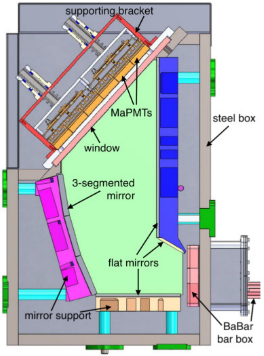
DIRC Detectors



Other DIRCs

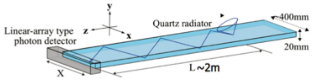
GlueX DIRC

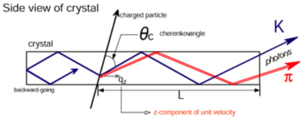
- Horizontally placed BaBar boxes containing 48 fused silica bars in total
- Mainly pion/kaon separation
- Up to 4 GeV/c particle momentum
- Polar angle range: up to approx. 11°



Belle II ToP

- Large Plates in barrel shape around interaction point
- Mainly pion/kaon separation
- Up to 5 GeV/c particle momentum
- Polar angle range: 32° – 120°





Thank you very much for your attention!