9. Particle Identification

9.1 Introduction

9.2 Particle Identification via Time of Flight

9.3 Particle Identification via Ionization measurement (dE/dx)

9.4 Cherenkov Detectors

9.5 Transition Radiation Detectors
• In addition to tracking and calorimetry, detectors for particle identification are crucial elements in many particle physics experiments.

• Stable particles are identified by:
  
  (i) Their type of interaction with matter (e, γ, μ, hadrons)

  (ii) By measuring their mass (mass → particle)

• The second method is most relevant to separate hadrons (π, K, p, …)

  (their type of interaction is the same, no discrimination power)

• The measurement of the mass requires the measurement of either the velocity β (or Lorentz factor γ) in addition to the momentum measurement

\[ p = γmβc \]
• The measurement of velocity requires a second measurement, a second independent detector signature

• Various possibilities exist to identify/separate charged hadrons (see also Section 2):

  (i) Direct measurement of β (or γ):
      - Time of flight: \[ \Delta t \sim \frac{1}{\beta} \]
      - Cherenkov angle: \[ \cos \theta_C = \frac{1}{\beta n} \]
      - Transition radiation: \[ \sim \gamma \ (\gamma > 100) \]

  (ii) Energy loss (Bethe-Bloch)
      \[ \frac{dE}{dx} \propto \frac{z^2}{\beta^2} \ln(a/\beta \gamma) \]

• Neutral hadrons are more difficult to separate; stable are: \( n \) (→ calorimeter)

  Long-lived neutral strange hadrons: \( V_0 \) decays → reconstruct from decay kinematics (invariant mass)

→ The challenge is \( \pi^\pm, K^\pm, p \) separation
• The mass $m$ can be reconstructed from the momentum and $\beta$ measurement:

$$m = \frac{p}{c\beta\gamma}$$

• The uncertainty is given by:

$$\left( \frac{dm}{m} \right)^2 = \left( \frac{dp}{p} \right)^2 + \left( \gamma^2 \frac{d\beta}{\beta} \right)^2$$

• Since in most cases $\gamma >> 1$, the mass resolution is determined by the accuracy of the velocity measurement.
Armenteros plot from the ALICE experiment using data from \( \sqrt{s} = 900 \) GeV pp collisions. The different \( V_0 \) particles can be separated using the kinematic properties of their decay products.

\[ p_L^\pm : \text{Longitudinal momenta of the positively and negatively charged decay product in the direction of flight of the } V_0 \text{ (momentum vector)} \]

\[ q_T : \text{Transverse component of the momentum of the positive decay product} \]
Demonstration of the power of Particle Identification

Example 1: $\phi \rightarrow K^+ K^-$ decays

Search for $\phi \rightarrow K^+ K^-$ decays in the LHCb experiment
Left: Invariant mass of all pairs of tracks, without particle ID
Right: Invariant mass of all pairs of identified charged kaons using a Cherenkov detector

The inclusive decay $\phi \rightarrow K^+ K^-$ only becomes visible after particle (kaon) identification
Example 2: Measurement of rare B decays, e.g.: $B_d^0 \rightarrow \pi^+ \pi^-$

Reconstructed two-particle masses (Monte Carlo simulation, LHCb experiment)
Left: Without particle ID, assuming pion hypotheses
Right: With particle ID, using $p / K / p$ separation in a Ring Image Cherenkov Counter (RICH)

Rare decays become accessible after particle identification ($\pi$, K, p separation)
9.2 Time-of-flight measurement

- Basic idea: **measure the time difference** between the interaction and the passage of a particle through a Time-of-flight (TOF) counter (or the time difference between two detectors with a good time resolution)

- Traditionally: Plastic Scintillator + PMTs
  
  Typical resolution: $\sim 100$ ps $\pi/K$ separation up to $\sim 1.5$ GeV.

- To go beyond that: one needs faster detectors:
  
  - Use Cherenkov light (prompt) instead of scintillations
  
  - Use fast gas detectors  
    e.g. **Resistive Plate Chambers (RPC)**
Calculation of time differences / required time resolutions

Distinguishing particles with ToF:
[particles have same momentum p]

\[
\Delta t = L \left( \frac{1}{v_1} - \frac{1}{v_2} \right) = \frac{L}{c} \left( \frac{1}{\beta_1} - \frac{1}{\beta_2} \right) \\
= \frac{L}{pc^2} (E_1 - E_2) = \frac{L}{pc^2} \left( \sqrt{p^2c^2 + m_1^2c^4} - \sqrt{p^2c^2 + m_2^2c^4} \right)
\]

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

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

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

Example:

Pion/Kaon separation ...
[m_k \approx 500 \text{ MeV}, m_n \approx 140 \text{ MeV}]

Assume:
\( p = 1 \text{ GeV}, \ L = 2 \text{ m} \)

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

\[
\approx 800 \text{ ps}
\]

For \( L = 2 \text{ m} \):

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

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

Separation power (in standard deviations) of Time-of-Flight measurements

For two particles with masses $m_1$ and $m_2$ with the same momentum $p$, the separation power in numbers of Gaussian Standard deviations is given by:

$$n_{\sigma_{\text{TOF}}} = \left| \frac{t_1 - t_2}{\sigma_{\text{TOF}}} \right| = \frac{Lc}{2p^2 \sigma_{\text{TOF}}} |m_1^2 - m_2^2|$$

→ separation power above $3\sigma$ in the low momentum range, e.g. $\pi/K$ separation with $> 3\sigma$ for $p < 1.6$ GeV ($2.3$ GeV) for a time resolution of $100$ ps ($50$ ps)

Particle separation with TOF measurements for three different system time resolutions ($\sigma_{\text{TOF}} = 50, 100, 150$ ps) and for a flight length of $L = 2m$) [no uncertainties on $p$ and $L$ assumed]
Calculation of mass resolution

\[ p = \beta \gamma m \]

\[ m^2 = p^2 \left( \frac{1}{\beta^2} - 1 \right) = p^2 \left( \frac{\tau^2}{L^2} - 1 \right) \]

Use:  \[ \beta = \frac{L}{\tau} \]

\[ \gamma = \left( 1 - \beta^2 \right)^{-1} \]

[\[ c = 1 \]]

\[ \frac{p^2 \tau^2}{L^2} = m^2 + p^2 = E^2 \]

\[ \delta(m^2) = 2p \, \delta p \, \left( \frac{\tau^2}{L^2} - 1 \right) + 2\tau \delta \tau \frac{p^2}{L^2} - 2 \frac{\delta L}{L^3} p^2 \tau^2 \]

\[ = 2m^2 \frac{\delta p}{p} + 2E^2 \frac{\delta \tau}{\tau} - 2E^2 \frac{\delta L}{L} \]

\[ \sigma(m^2) = 2 \left[ m^4 \left( \frac{\sigma_p}{p} \right)^2 + E^4 \left( \frac{\sigma_\tau}{\tau} \right)^2 + E^4 \left( \frac{\sigma_L}{L} \right)^2 \right]^{1/2} \]

Usually:

\[ \frac{\delta L}{L} \ll \frac{\delta p}{p} \ll \frac{\delta \tau}{\tau} \]

\[ \sigma(m^2) = 2E^2 \frac{\sigma_\tau}{\tau} \]

Uncertainty in time measurement dominates ...
Resistive Plate Chambers (RPC)

- For large systems the coverage with scintillators and photon readout is expensive.
- **Resistive Plate Chambers** provide an efficient and “cheaper” alternative. (Relatively simple construction, good time resolution)

**Layout:**

- Planar geometry, parallel plates with high resistivity form electrodes (glass, bakelite)
- Very High voltage, thin gap of typically a few mm, filled with gas → high gas gain
- Ionisation + very high voltage → avalanche or streamer mode (due to high resistivity, large signals or discharges are restricted to a well-localized area)
- Planar geometry, parallel plates with high resistivity form electrodes (glass, bakelite)

- Very High voltage, thin gap of typically a few mm, filled with gas. → high gas gain

- Ionisation + very high voltage → avalanche or streamer mode (due to high resistivity, large signals or discharges are restricted to a well-localized area)

- Strips in orthogonal directions give spatial information (position measurement)

- Accurate time measurement with resolutions of ~50 ns over large areas possible up to charged particle rates of a few kHz/cm²

- Rate limitations due to large charges (distortion of the electric field, and local drop of the electric field in the gas gap → hit spot of the detector becomes insensitive to further traversing particles; rest of the detector still o.k.)
• On the Rate Limitation of RPCs:

a) Ionisation of a charged particle
b) Drift inside the electric field, avalanche process
c) Electrons reach anode faster than positive ions
d) Charges on electrodes distort the field, field strength drops below the critical value needed for avalanche creation
   → dead time, due to high resistivity

C. Lippmann, PhD thesis, Frankfurt
• RPCs can be operated in **Avalanche** or **Streamer mode**

- **Avalanche mode**: normal Townsend avalanche multiplication

- **Large number of charge carriers influences** the electric field in the gap and thereby the own amplification

- **Higher initial electric fields ( ~40 kV/cm)**
  → higher gas gain
  → larger photon contributions

- **Streamer can be formed, conductive channel between the two electrodes**

- **Streamer mode**: large current signals, no amplifying electronics needed

  Typical charges: a few nC, high efficiency, time resolutions of a few ns, however: larger dead time / rate limitation at a few 100 Hz/cm²

C. Lippmann, PhD thesis, Frankfurt
Multi-Gap Resistive Plate Chambers

Main advantages:
Increase of efficiency

- Stack of equally spaced resistive plates with voltage applied to external surfaces → avalanche signals in each gap
- Internal plates are electrically floating
- Electrodes on external surfaces (resistive plates are transparent to induced signals)
Applications of RPCs

Resistive Plate Chambers are heavily used in LHC experiments

(i) ATLAS and CMS:
Fast Muon Trigger Chambers

(ii) ALICE:
Time-of-Flight System

Particle ID in high multiplicity environment requires …

ToF system with high granularity and coverage of the full ALICE barrel
ATLAS RPC Fast Muon Trigger system
ALICE (Detector for Heavy Ion Collisions at the LHC)

Some focus on Particle Identification (TPC (dE/dx), RPC-based TOF system and a Transition Radiation Detector)
ALICE RPC-based Time-of-Flight system

ToF array arranged as barrel with radius 3.7 m
[Divided into 18 sectors]

→ Large L, good expected separation
ALICE RPC-based Time-of-Flight system

ALICE MRPC
[Time-of-Flight System]

Double stack;
each stack with 5 gaps
[i.e. 10 gaps in total]

250 micron gaps separated
by standard fishing lines

Resistive plates
from soda lime glass
[commercially available]

400 micron internal glass
550 micron external glass

Area: 160 m²
Channels: 160 k [size: 2.5 x 3.5 cm²]
Performance of the ALICE RPC-based Time-of-Flight system

Velocity $\beta = v/c$, as measured with the ALICE TOF detector as a function of the particle momentum $p$ multiplied with the sign of the electric charge for a data sample taken at $\sqrt{s} = 7$ TeV pp collisions (from C. Lippmann, arXiv:1101.3276).

Why are there no data for $|q| < 0.3$ GeV ??
Performance of the ALICE RPC-based Time-of-Flight system

Overlap between $\pi$, $K$, and $p$ for a selected momentum range of $1.0 < p_T < 1.1$ GeV in the ALICE experiment (from C. Lippmann, arXiv:1101.3276).

Measured time resolution of the ALICE ToF system (from data 2010).
9.3 Particle Identification via Ionization measurement (dE/dx)
Basic idea: the universal (Bethe-Bloch) energy loss curve ($dE/dx$ vs. $\beta\gamma$) splits into mass-dependent bands, if plotted as function of the particle momentum [see Chapter 2, these lectures]

$$p = \gamma m \beta c$$

→ The combined measurement of $p$ and ionization ($<dE/dx>$) provides particle identification
Overlap of curves leads to “blind spots” for certain particle-ID combinations

- The separation power can be defined as:
  (Depends on the achievable resolution on $\sigma_E / \langle dE/dx \rangle$)

- To improve the resolution, multiple measurements of the specific energy loss are performed → Landau / Gauss fit

Typical values: $\sigma_E / \langle dE/dx \rangle \sim 3-5\%$
Overlap of curves leads to “blind spots” for certain particle-ID combinations

Major conclusions:

• Hadron identification works well in the low momentum region
• Problem in region of minimum ionization ($\beta\gamma \approx 3.5$)
• Moderate identification capabilities in region of relativistic rise
Example: Particle identification using dE/dx measurements

Measured quantities: 
- particle momentum $p$ (magnetic field)
- deposited energy in a detector $\text{d}E/\text{dx}$

The measured values in detectors show statistical fluctuations, described by Landau / Gauss distributions, depending on the absorber thickness.

- Problem for particle identification: large overlap between the $\pi$ and $p$ distribution, in particular due to the asymmetric Landau distribution (large tails).
- Bethe-Bloch formula describes $\langle \text{d}E/\text{dx} \rangle$; multiple repeated measurements can be used to get a better estimate of the mean $\text{d}E/\text{dx}$ value.

Example: distribution of the measured energy loss of a beam of pions and protons with a momentum of 600 MeV in a 3 mm thick silicon detector (from Ref. [3]).

Note: pions close to mip, larger signals for 600 MeV protons due to $1/\beta^2$ dependence.
• Multiple, repeated measurements of $dE/dx$ (samplings) in consecutive detector layers $\rightarrow$ effect of Landau tail can be reduced

• Example: 100 measurements in gas detectors $\rightarrow$ mean value can be reconstructed with a relative uncertainty of $\sigma(dE/dx) / (dE/dx) \sim 2\%$

• Likelihood ratio methods can be used to exploit full information;

• Use Landau probability distributions and calculate likelihood for different particle hypotheses

Energy loss distributions for pions and kaons with $p = 50$ GeV in 1 cm (argon/methane = 80/20) gas
Example: Five dE/dx measurements in an argon/methane gas detector, particle momentum 50 GeV

Calculate probabilities for the pion and kaon hypotheses

Pion hypothesis: \[ P_1 = \prod_{i=1}^{N} P_{\pi}^i(x_i) \]

p-values in example:
(0.031, 0.236, 0.192, 0.108, 0.047)

Kaon hypothesis: \[ P_2 = \prod_{i=1}^{N} P_{K}^i(x_i) \]

p-values in example:
(0.124, 0.061, 0.025, 0.013, 0.006)

Probability for pion: \[ P = \frac{P_1}{P_1 + P_2} \]

for example considered here: \( P = 0.998 \)
Particle Identification performance of the ALICE TPC

- Impressive performance for low momenta

- Separation on statistical basis even possible at high momenta (relativistic rise)

→ probability assignments possible
Particle Identification performance of the ALICE TPC

- A plot from heavy ion collision data-
Combined ALICE Particle Identification performance
9.4 Particle Identification via Cherenkov Radiation
Cherenkov radiation:

Reminder:

Polarization effect ...
Cherenkov photons emitted if $v > c/n$ ...
Cherenkov angle:

$$\cos \theta_c = \frac{1}{n\beta}$$

Simple Geometric derivation:

$$AB = \beta c \cdot t$$
$$AC = c/n \cdot t$$

$$\cos \theta = \frac{AC}{AB} = \frac{c/n \cdot t}{(\beta c \cdot t)}$$

$$= \frac{1}{n\beta}$$

A: $v < c/n$
Induced dipoles symmetrically arranged around particle path; no net dipole moment; no Cherenkov radiation

B: $v > c/n$
Symmetry is broken as particle faster the electromagnetic waves; non-vanishing dipole moment; radiation of Cherenkov photons
Dependence of the Cherenkov angle on $\beta$:

$$\cos \theta_c = \frac{1}{n \cdot \beta}$$

$$\theta_c^{\text{min}} = 0 \quad \beta = \frac{1}{n}$$

$$\frac{1}{n} < \beta < 1$$

$$\theta_c^{\text{max}} = \arccos \frac{1}{n} \quad \beta = 1$$

Application for Particle Identification

(i) **Threshold counters**: measure the intensity of Cherenkov radiation and discriminate light particles that emit radiation from heavier ones that don’t

(ii) **Differential Cherenkov counter**: focus only Cherenkov photons with a certain emission angle onto the detector $\rightarrow$ detect particles in a narrow $\beta$ interval

(iii) **Imaging Cherenkov counters**: Measurement of the Cherenkov angle $\rightarrow$ $\beta$ (particle velocity)

In conjunction with add. measurements of $p$ $\rightarrow$ particle mass
Light output:

• As already discussed in Chapter 2, the energy loss of charged particles due to Cherenkov radiation is much smaller than the ionization energy loss.

\[-\frac{dE}{dx}\bigg|_{CH} \sim 0.01 - 0.02 \text{ MeV} / \text{g} \cdot \text{cm}^{-2} \text{ (gases)}\]

• The number of radiated photons is given by (see Jackson, Classical Electrodynamics):

\[
\frac{dN}{dx} = 2\pi \alpha z^2 \int_{\lambda_1}^{\lambda_2} \left(1 - \frac{1}{n^2 \beta^2}\right) \frac{d\lambda}{\lambda^2}
\]

• For \(\lambda_1 = 400\) nm and \(\lambda_2 = 700\) nm and for \(z = 1\), one obtains (see Grupen): (dispersion neglected, i.e. \(n(\lambda) = \text{const}\))

\[
\frac{dN}{dx} = 490 \sin^2 \theta_c \text{[cm}^{-1}]\]

• Realistic case: An additional efficiency factor \(\varepsilon_{\text{det}}\), which takes into account losses in the photon collection and detection efficiencies of the photon detector; Typical values: \(\varepsilon_{\text{det}} \approx 0.10 - 0.40\)
The number of photons produced by Cherenkov light emission per cm in liquids and solid state materials (left) and per m in gases (right) as a function of the particle velocity $\beta$ (from Ref. [3])
Experimental requirements for Cherenkov detectors:

• **Radiator** chosen such that the Cherenkov angle varies with velocity, from threshold to the highest anticipated momentum;

  The **thickness L of the radiator** has to be chosen such that a sufficient number of photons is radiated in the particle momentum / $\beta$ range of interest

• **High quality light collecting system**
  (light guides, mirrors)
  Focusing system for (Ring) Imaging Cherenkov counters

• **High quality photon detection system**

  Typically a low number of photons is converted in photocathodes (CsI, bialkali)
(i) Threshold Cherenkov counters:

Main application:  
- fixed target experiments  
- Separate particles based on whether they emit Cherenkov radiation or not

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
(ii) Differential Cherenkov counter (an example)

Main application:
- fixed target experiments
- testbeams, particle separation

Differential Cherenkov detectors:
Selection of narrow velocity interval for actual measurement ...

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

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

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 \( \Delta \beta/\beta = 10^{-7} \)

Working principle of a differential Cherenkov counter
(iii) Ring Imaging Cherenkov counter (an example)

Main application: Collider experiments (DELPHI, LHCb, ....)

Ring Imaging Cherenkov Counter
Optics such that photons emitted under certain angle form ring ...

Focal length of spherical mirror: \( f = \frac{R_s}{2} \) ...
Cherenkov light emitted under angle: \( \theta_C \) ...
Radius of Cherenkov ring: \( r = f \cdot \theta_C = \frac{R_s}{2} \cdot \theta_C \) ...

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

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 (C₅H₁₂N₂)]
- Ring Imaging Cherenkov Counters can be used at colliders. They allow to extend the particle ID to a much higher momentum range: \( 10 < p < 100 \text{ GeV} \)

- The particle mass can be reconstructed from the measured Cherenkov angle:

\[
m = \frac{p}{c} \sqrt{n^2 \cos^2(\theta_C) - 1}
\]

- Two-particle separation: two particles with the same momentum \( p \) and masses \( m_1 \) and \( m_2 \); measured Cherenkov angles \( \theta_1 \) and \( \theta_2 \)

The resolution of the angle measurement determines the mass separation power:

\[
n_{\sigma_{\theta_C}} = \frac{\theta_{C,1} - \theta_{C,2}}{\langle \sigma_{\theta_C} \rangle}
\]

For \( \beta \approx 1 \) the separation power can be approximated by [Particle Data Book]:

\[
n_{\sigma_{\theta_C}} \approx \frac{c^2}{2p^2 \langle \sigma_{\theta_C} \rangle \sqrt{n^2 - 1}} |m_1^2 - m_2^2|
\]
Example: The LHCb Ring Imaging Cherenkov detector

Two RICH detectors

Goal: $\pi/K$ separation in the momentum range $2 < p < 100$ GeV
Example: The LHCb Ring Imaging Cherenkov detector
Example: The LHCb Ring Imaging Cherenkov detector

Features:

• Photon detectors are placed outside of the acceptance (250 mrad) of the LHCb detector
  (limit degradation of the momentum resolution of the tracking system)

• A set of spherical and flat mirrors projects the Cherenkov light onto the detector plane
  (carbon fibre material, to minimize material of mirrors in acceptance)

• Radiator: gas radiator C$_4$F$_{10}$; Additional aerogel radiator in RICH-1
  $\rightarrow$ the three radiators cover the targeted momentum range

• Photon detector: (large area 4 m$^2$, high granularity 2.5 x 2.5 mm$^2$, fast readout)
  $\rightarrow$ Hybrid Photon detectors

Quartz window with bialkali photocathode, 20 kV acceleration + silicon pixel detector
Some parameters of the LHCb RICH detectors

<table>
<thead>
<tr>
<th></th>
<th>RICH1</th>
<th>RICH2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Silica aerogel</td>
<td>$C_4F_{10}$</td>
</tr>
<tr>
<td>Momentum range [GeV/c]</td>
<td>$\leq 10$</td>
<td>$10 \lesssim p \lesssim 60$</td>
</tr>
<tr>
<td>Angular acceptance [mrad]</td>
<td>vertical</td>
<td>$\pm 25$ to $\pm 250$</td>
</tr>
<tr>
<td></td>
<td>horizontal</td>
<td>$\pm 25$ to $\pm 300$</td>
</tr>
<tr>
<td>Radiator length [cm]</td>
<td>5</td>
<td>95</td>
</tr>
<tr>
<td>Refractive index $n$</td>
<td>1.03 (1.037)</td>
<td>1.0014</td>
</tr>
<tr>
<td>Maximum Cherenkov angle [mrad]</td>
<td>242 (268)</td>
<td>53</td>
</tr>
<tr>
<td>Expected photon yield at $\beta \approx 1$</td>
<td>6.7</td>
<td>30.3</td>
</tr>
<tr>
<td>$\sigma_{\Theta_i}$ [mrad]</td>
<td>expected</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>measured</td>
<td>$\sim 7.5$</td>
</tr>
</tbody>
</table>

Cherenkov angles as a function of momentum for different particles for the three LHCb radiators
Simulated LHCb event in the RICH-1 detector
(The two photon detector planes are shown in the upper and lower halves)
Particle separation power achievable in the LHCb RICH detectors
LHCb published performance plot of the RICH detectors
9.5 Particle Identification via Transition Radiation
Transition Radiation:

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 ...

Rearrangement of electric field yields transition radiation

Energy loss distribution for 15 GeV pions and electrons in a TRD ...
Detection principle of Transition Radiation:
ALICE Transition Radiation detector:
ALICE Transition Radiation detector:

Transition Radiation [TR]
for charged Particles with $\gamma > 1000$
**Combining Tracking with particle ID: ATLAS TRT**

- $e/\pi$ separation via transition radiation: polymer (PP) fibres/foils interleaved with DTs

**Diagram:**
- **Barrel TRT Module**
  - Radiator
  - Straws
  - Total: 370,000 straws
  - Barrel ($|\eta| < 0.7$): 36 $r$-$\phi$ measurements / track
  - Resolution $\sim 130 \, \mu m / straw$
  - 18 end-cap wheels ($|\eta| < 2.5$): 40 or less $z$-$\phi$ points

**Key Points:**
- Electrons radiate $\rightarrow$ higher signal
- Particle Identification by counting the number of high-threshold hits

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The ATLAS Inner Tracking System

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**Charged particle**
- Anode wire (HV+)
- Cathode (HV–)
- Noble Gas
- Transition radiation

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**Electrons radiate $\rightarrow$ higher signal**

Particle Identification by counting the number of high-threshold hits
ATLAS Transition Radiation Tracker (TRT):

• Straw tube tracker
• Inter-space filled with foam
• Different thresholds in readout:
  high threshold hits → higher probability for transition radiation
• Main purpose: Tracking + improved electron ID
Performance of the ATLAS TRT:

Electrons clearly visible in first LHC data (2009) (Larger fraction of high-threshold hits)

... confirmed later by reconstructed electron candidates from conversions (good agreement between data and Monte Carlo simulation)
Summary on Particle Identification

π/K Separation
[Comparison of different PID methods]