Detectors for Particle Physics

Lecture 2:
Drift detectors
Muon detectors
MWPC, CSC, RPC, TRT, TPC, Cherenkov
Outline

• Lecture 1:
  ▶ Collider detectors
  ▶ Charged particles in a magnetic field
  ▶ Silicon detectors

• Lecture 2:
  ▶ Drift tubes
  ▶ Muon systems
  ▶ MWPCs, CSCs, RPCs, TRTs, TPCs, Cherenkovs

• Lecture 3:
  ▶ Electromagnetic showers and calorimeters
  ▶ Photon detectors
  ▶ Hadronics showers and calorimeters
  ▶ Particle flow technique

• Discussion session:
  ▶ Your questions, please
Track ionises gas atoms
✦ electrons drift towards anode: $v_D$
✦ Amplify
✦ Measure drift time: $\Delta t = t_1 - t_0$
✦ Reconstruct radius: $\Delta s = v_D \Delta t$.
✦ $v_D$ depends on gas, voltage, pressure, temperature, field: need calibration.
Drift velocity

- Drift velocity depends on electric field, pressure, gas, temperature, magnetic field.
- Want stable operation point: just above maximum.
- Trade-off:
  - Slower gas = higher resolution.
  - Faster gas better in a high-rate environment.
ATLAS drift tubes

tube wall: 0.4 mm Al
wire: 50 µm W-Re at +3300V
endplug

Gas: Ar (91%) CH4 (5%) N2 (4%) at 3 bar

Length up to 6 m
30 mm diameter

Drift velocity: 30 µm/ns

Distance from time:

Resolution [µm]: 80 µm

Resolution [µm]:

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CMS drift cells

*Extra electrode for field shaping: more uniform drift.*
*Left/right ambiguity remains.*

**time synchronization:**

\[ t_{\text{meas}} = t_{\text{elecr}} + t_{\text{of}} + t_{\text{prop}} + t_{\text{drift}} \]

- time pedestal \((t_{\text{trig}})\)

**time spectrum:**

- **time box**
  - Entries: 318611
  - \(\chi^2/\text{ndf}\): 127.2/32
  - Constant: 2595 ± 14.1
  - Mean: 1905 ± 0.1
  - Sigma: 7.933 ± 0.095

**drift velocity calibration:**

\[ v_{\text{drift}} = \frac{L}{2 \times \langle T_{\text{max}} \rangle} \]

**resolution**

\[ \text{resolution} = v_{\text{drift}} \times \langle \sigma_{T_{\text{max}}} \rangle \]
Choice of Gas 1: ionization and drift

- Drifting electrons should not be trapped:
  - Use noble gas, e.g. Ar.

- Want large primary ionization yield:
  - Ar gives 25 ions/cm at normal T, p for a minimum ionizing particle.

- The primary electrons may ionize further atoms:
  - $\times 3$ or $\times 4$ increase.

- Xe and/or higher pressure are even better (and more expensive).
Signal amplification near the wire

For cylindrical geometry:

\[ E(r) \propto \frac{1}{r} \quad \text{and} \quad V(r) \propto \ln \frac{r}{a} \]

- the primary electrons drift towards the positive anode
- due to \(1/r\) dependence the electric field close to very thin wires reaches values of \(E > \text{kV/cm}\)
- \(\Rightarrow\) in between collisions with atoms electrons gain enough energy to ionize further gas molecules
- \(\Rightarrow\) exponential increase in number of electron-ion pairs very close (few \(\mu\text{m}\)) to the wire

Amplification by \(10^5\) possible
The Avalanche

- Amplification depends on:
  - Anode voltage
  - Wire radius
  - Gas composition
  - Pressure
  - Temperature

Receding ion cloud induces signal on the wire
Choice of Gas 2: high gain, stable operation

- Want large gain at low voltage:
  - Ar is mono-atomic gas
  - No vibrational or rotational modes, only excitation and ionization.

- Excited Ar atoms may emit UV photons (11.6 eV):
  - UV photons may reach the cathode and produce photoelectrons.
  - Photoelectrons drift back towards the wire and may start a new avalanche
    - Continuous discharge!

- Need 'quencher' molecules that absorb UV photons without creating photoelectrons:
  - CH$_4$, C$_2$H$_6$, CO$_2$, ...
Signal Induced by a Moving Charge

Choice of Gas 3: prevent ageing

deposits on the wire:

- Impurities in the gas (or in the chamber) may form deposits on the wire and reduce the gain.
- 'Whiskers' lead to HV instabilities.
- Prevention:
  - Build chamber in a clean room.
  - Use clean gas.
  - Add ~1% alcohol, water, or oxygen.

'whiskers':
ATLAS Drift Tube Chambers

- 6 drift tube layers, arranged in 2 multilayers glued to a spacer frame
- length: 1 – 6 m, width: 1 – 2 m
- optical system to monitor chamber deformations
- gas: Ar:CO$_2$ (93:7) to prevent aging, 3 bar
- chamber resolution: 50 µm
  - single tube resolution: 100 µm
  - required wire position accuracy: 20 µm
Assembly of MDT Chambers (Frascati, IT)
ATLAS muon spectrometer

"Excellent stand-alone capabilities and coverage in open geometry

"Complicated geometry and field configuration (large fluctuations in acceptance and performance over full potential $\eta \times \phi$ coverage ($|\eta| < 2.7$)
ATLAS Barrel muon system in the toroid field

Detailed field map needed!
"Superior combined momentum resolution in the central region with silicon tracker."
"Limited stand-alone resolution and trigger (at very high luminosities) due to multiple scattering in iron."
"Degraded overall resolution in the forward regions (|η| > 2.0) where solenoid bending power becomes insufficient."
Pseudo-rapidity

\[ p_t = \sqrt{p_x^2 + p_y^2} \]
\[ p = \sqrt{p_x^2 + p_y^2 + p_z^2} \]
\[ \varphi = \arctan \left( \frac{p_y}{p_x} \right) \in [-\pi, \pi] \]
\[ \theta = \arccos \left( \frac{p_z}{p} \right) \in [0, \pi] \]

Pseudo-rapidity: \( \eta = -\ln \left( \tan \left( \frac{\theta}{2} \right) \right) \)

(soft hadron production: \( \frac{dN}{d\eta} \approx \text{const.} \) 'central rapidity plateau')

<table>
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<th>( \eta )</th>
<th>( \theta )</th>
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<td>0</td>
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<tr>
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Rapidity: \( y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right) \)
\( y \approx \eta \) for \( p \gg m \)
CMS Muon chambers

cosmic ray muon track

iron

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ATLAS and CMS: muon momentum resolution

ATLAS barrel standalone

CMS barrel standalone

Estimated contribution to resolution (%) vs. $p_t$ (GeV/c)
low-\(p_T\) muons

Requirements for muon identification and reconstruction at low \(p_T\)

" Identify track stub in first layer of muon system
" Check for minimum ionising signals in last layers of hadron calorimeter
" Match as precisely as feasible (within limitations due to large MS and energy loss in calorimetry) measured track in inner detector with track stub in muon system
Multi-wire proportional chambers MWPCs

String many anode wires between cathode planes:

- ±3 mm. max. drift time can be < 50 ns. Fast!
- 2 mm wire spacing, resolution ~ 0.5 mm

Signals can be extracted from the wire and both cathode planes. Cathodes can be segmented.

Georges Charpak, CERN Nobel prize 1992
CMS Cathode Strip Chambers

- Cathode strips: 0.1 mm resolution.
- Wires: 4 ns timing for the trigger.
- 6 planes/chamber
- 468 chambers
- 6000 m²
- 450k channels
ATLAS muon chamber wheel

Ø25m
**RPC Resistive plate chambers**

no wires!

2 Bakelite plates separated by a gas gap and 8kV.

a particles causes **local** discharge which induces signals in the readout strips.

RPCs are fast and stable at high rate. Used as trigger chambers.

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Transition Radiation

- Relativistic particles passing through an interface radiate.

\[ \langle \mathcal{P} \rangle \approx \frac{1}{\gamma} \]

\[ \hbar \omega_p = 20 \text{ eV} \]
\[ \hbar \omega_p = 0.7 \text{ eV} \]

polypropylene \((C_3H_6)_x\)

\[ \omega_p^2 = \frac{n_e e^2}{m_e \varepsilon_0} \]

\[ \gamma = \frac{E}{m} \]

\[ \theta \approx 1/\gamma \]

\[ \hbar \omega \approx 10-30 \text{ keV} \]

for \( \gamma \approx 10^4 \)

N \( \sim \gamma \hbar \omega_p \)

depends on particle!

\[ \frac{d^2W}{d\Omega d\theta} = \frac{2\alpha \theta^3}{\pi} \left( \frac{1}{\gamma^2 + \theta^2 + \omega^2} - \frac{1}{\frac{1}{\gamma^2} + \theta^2 + \frac{\omega^2}{\omega^2}} \right)^2 \]

1% probability per foil

Xe gas to absorb X-ray.
e/π separation using TRT

ATLAS 20-GeV electrons
- beam-test data
- Monte-Carlo simulation

20-GeV pions
- beam-test data
- Monte-Carlo simulation

pion reduction by factor 75 for 90% electron efficiency
ATLAS Transition Radiation Tracker

Straw gas mixture:
Xe(70%) CO2(27%) O2(3%)

Radiator foils are placed between the straws

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First cosmic ray event seen in the Barrel TRT!

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ATLAS inner tracking: silicon and straws

red = tracks found in the silicon layers.

white = hits in the straw tubes.
36 hits/track: good for pattern recognition.
Time Projection Chamber in a solenoid field

Separate two regions:
- Drift along z: 20-30 µs/m.
- Amplify at the end plate

No material inside drift volume!

\[ E \parallel B: \text{drifting electrons curl around B field lines: limited spread.} \]

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ALICE TPC

max. drift time 88 µs.
LHC operates with low luminosity at ALICE (pp and PbPb).

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Detectors 2.31
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TPC

Time Projection Chamber (TPC)

- Charged particle track
- Drift volume
- Gating grid (-100V)
- Cathode plane (GND)
- Sense wire plane (+1.5kV)
- Pad plane

$z = v_0 t$

ALICE TPC has 557568 Channels

Pad signal

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Detectors 2.32

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Energy loss of charged particles in matter

- Charged particles loose energy in collisions with electrons in matter:

Bethe-Bloch:

\[
\frac{1}{\rho} \frac{dE}{dx} = -4 \pi N_A r_e^2 m_e c^2 \frac{Z^2}{A} \left[ \ln \left( \frac{2 m_e c^2 \beta^2 \gamma^2}{\langle I \rangle} \right) - \beta^2 - \frac{\delta}{2} \right]
\]

\(\frac{dE}{d\rho x}\)

~\(1/\beta^2\)

Relativistic rise \(\sim \ln(\gamma)\)

Minimum at \(p/m \approx 3.5\) for all particles

In iron (\(\rho\)=7.9 g/cm\(^3\)):

\(\frac{dE}{dx} = 1.3\) GeV/m.
$\langle dE/dx \rangle$ averaged over many samplings:  
$\sigma \sim \sqrt{N}$.  

Good for particle identification at low momenta.
Cerenkov Radiation

Cerenkov-Effect:
A charged particle moving faster than the speed of light in a medium $v > c/n$ emits Cerenkov radiation.

Emission of a coherent wave front: $\cos \theta_c = 1/(\beta n)$
LHCb Cerenkov Detector

The Cerenkov cone is imaged into a ring at a position-sensitive photon detector. Ring radius \( \rightarrow \) Cerenkov angle \( \rightarrow \) particle velocity. Together with momentum measurement: determine particle mass. Good for \( \pi \) – \( K \) – \( p \) separation.

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\[ C_4F_{10}, \quad n=1.03 \]
\[ \text{aerogel} \]
\[ n=1.0014 \]
\[ \text{mirror} \]
\[ 330 \text{ mrad} \]

\[ \text{Beam pipe} \]
\[ \text{low } \nu \]
\[ \text{high } \nu \]

\[ \theta_c \]

LHCb
Hybrid photon detector HPD

- A Cherenkov photon reaches the multialkali-coated quartz window of an HPD.
- A photoelectron is released, and is accelerated toward the silicon array by a 20kV potential.
- The photoelectron creates around 5,000 electron-hole pairs in the silicon.
- The silicon array has 1024 pixels for position measurement.
- Readout is by a bump-bonded amplifier and discriminator chip.
Summary

- Drift detectors
- muons systems
- MWPC, CSC, RPC
- transition radiation
- TPCs
- Bethe-Bloch dE/dx
- Cherenkov and HPDs