An Introduction to Charged Particle Tracking

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• While we wish tracking were still this easy, real bubble chambers don’t cut it for a 25ns cycle time
• Instead, we need the electronic version
  – More granular
  – Less resolution
  – More complicated
• How do we get there while satisfying
  – technical requirements
    • performance
    • operability
    • stability
  – spatial requirements
    • size, volume
  – cost requirements
Overview:

• Outline for these lectures
  – Lecture 1:
    • Motivation
    • Tracking vocabulary
    • Detector Techniques
  – Lecture 2:
    • Algorithmic Techniques for Pattern Recognition, Fitting
    • Tracking system designs
  – Lecture 3:
    • Commissioning/Calibrating a tracking system
    • Environmental Challenges
      – Radiation damage, occupancy, etc.
    • Tracking information used in event triggers
    • Tracker upgrades
Why Track?

• Basically, everything interesting happens within the first $\sim 10^{-12}$ seconds after the beams collide
  – we can only see “final-state” particles
  – our physics knowledge is based on “working backwards in time” to infer what actually happened in the initial collision
  – the more precisely the final-state particles are measured, the more accurately we can determine the parameters of their parents

• Tracking provides precise measurements of
  – particle production positions
    • can reveal the presence of long-lived particles
  – particle momenta
    • complimentary to calorimeter at low energy
  – particle trajectories to the outer detectors
    • association with calorimeter energy deposits, muon hits
      – allows “global pattern recognition” of physics objects
Tracking Provides: Production position

CMS Experiment at LHC, CERN
Data recorded: Tue Jun 29 12:20:29 2010 CEST
Run/Event: 138919 / 27349474
Lumi section: 118

- Muon:
  - $p_T = 40 \text{ GeV/c}$
  - $\eta = 1.2$, $\phi = 1.6$

- Muon+:
  - $p_T = 53 \text{ GeV/c}$
  - $\eta = 1.3$, $\phi = 1.0$

- Muon in jet:
  - $p_T = 19 \text{ GeV}$
  - $\eta = -1.2$, $\phi = -1.9$

- Jet:
  - $p_T = 75 \text{ GeV/c}$
  - $\eta = -1.3$, $\phi = -1.9$

- MET = 25 GeV

$t\bar{t}$ candidate, multiple interactions
Tracking Provides: Prod/decay position

tt\bar{t} candidate, b-tagged jets
Tracking Provides: Prod/decay position

\[ \xi_T = 57 \text{ GeV/c}, \varphi = 2.2 \]

b-tagged jet
\[ p_T = 45 \text{ GeV/c}, \eta = -1.2, \varphi = 0. \]

b-tagged jet
\[ p_T = 56 \text{ GeV/c}, \eta = 0.7, \]

\[ \mu^+ p_T = 27 \text{ GeV/c}, \eta = -2.0, \varphi = -1.9, \]

Dimuon mass 26 GeV/c

t\bar{t} candidate, b-tagged jets
Tracking Provides: Prod/decay position

LHCb Event Display

B⁺→J/ψ K⁺

XY Projection
Tracks from primary vertex

Primary vertex
B⁺
B decay vertex
J/ψ
K⁺
Tracking Provides: momentum

- Resolution complementary to calorimeters at low energies:

\[ \sigma(E)/E \text{ (Hcal)} \]

\[ \sigma(E)/E \text{ (Ecal)} \]

\[ \sigma(p_T)/p_T \text{ (Tracker)} \]

Basis of particle-flow algorithms to optimize resolution on final-state “objects” that are used for parton reconstruction

- CMS Preliminary

Jet-Energy Resolution

Energy (GeV)

\[ \sigma_{\text{eff}} / E \]

reso
Tracking Provides: momentum

- Determination of particle four-vectors $\rightarrow$ resonances

CDF: WZ and ZZ analysis

LHCb: exclusive charm reconstruction
Tracking provides: Global objects

- Electron
Tracking provides: Global objects

• or photon?
Tracking provides: Global objects

W→μν candidate in 7 TeV collisions
Run Number: 35222, Event Number: 363185
Date: 2010-04-01 00:31:22 CEST
PT(μ+) = 29 GeV, η = 0.66
ETmiss = 24 GeV
MT = 53 GeV

central track
muon track
Visualizing particle trajectories

• Start with the basics: (more detail later)

Lorentz force: charged particles follow a curved trajectory in a magnetic field
• radius of curvature inversely proportional to momentum
• need to measure:
  • magnitude of B field
  • radius of curvature
• Radius measurement implies knowing where the particle is at several points along its trajectory
  • the particle must interact with a detection medium to leave a trace
    ⇒ Ionization
Ionization Loss: Bethe-Bloch Equation

- Relativistic Formula: Bethe (1932), others added more corrections later
- Gives “stopping power” (energy loss = $dE/dx$) for charged particles passing through material:

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

where

- $A$, $Z$: atomic mass and atomic number of absorber
- $z$: charge of incident particle
- $\beta, \gamma$: relativistic velocity, relativistic factor of incident particle
- $\delta(\beta \gamma)$: density correction due to relativistic compression of absorber
- $I$: ionization potential
- $T_{max}$: maximum energy loss in a single collision; $T_{max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e / M + (m_e / M)^2}$
- $K/A = 4\pi N_A r_e^2 m_e c^2 / A = 0.307075$ MeV g$^{-1}$ cm$^2$, for $A = 1$ g mol$^{-1}$

$dE/dx$ has units of MeV cm$^2$/g

$x$ is $\rho s$, where $\rho$ is the material density, $s$ is the pathlength

source for this and following: PDG
Ionization Loss: minimum ionization

- Position of minimum is a function of $\beta \gamma = p/Mc$
- occurs around $p/Mc = 3-3.5$
  $\sim$ independent of material
- Characteristic shape of $1/\beta^2$ fall-off followed by relativistic rise
- “Rule of thumb”: $dE/dx \sim 2 \text{ MeV/cm} \times \rho \ (\text{g/cm}^3)$
- Typical values:
  - liquids/solids: $\sim$ few MeV/cm
  - gases: $\sim$ few keV/cm
  $\Rightarrow$ valid over range of most common momenta in collider experiments

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First complication: Multiple Scattering

- Often called **Multiple Coulomb Scattering**: momentum transfer between particle and medium diverts particles from straight path
  - usually electromagnetic; hadronic interactions contribute, too
  - scattering angles well-described by Molière theory:

\[
\begin{align*}
\psi_{\text{plane}} &= \frac{1}{\sqrt{3}} \theta_{\text{rms, plane}} = \frac{1}{\sqrt{3}} \theta_0 \\
y_{\text{plane}} &= \frac{1}{\sqrt{3}} x \theta_{\text{rms, plane}} = \frac{1}{\sqrt{3}} x \theta_0 \\
s_{\text{plane}} &= \frac{1}{4\sqrt{3}} x \theta_{\text{rms, plane}} = \frac{1}{4\sqrt{3}} x \theta_0
\end{align*}
\]

Here \( \theta_0 \) is a (mostly) gaussian distribution defined as with a width of

\[
\theta_0 = \theta_{\text{rms, plane}} = \frac{1}{\sqrt{2}} \theta_{\text{rms, space}}
\]

where \( X_0 = \) radiation length of material

\[
\theta_0 = \frac{13.6 \text{ MeV}}{\beta_c p} z \sqrt{x/X_0} \left[ 1 + 0.038 \ln(x/X_0) \right]
\]
Second Complication: Energy Loss

- Energy loss in material can be significant (c.f. ATLAS or CMS trackers): radius of curvature *increases* along path as $p$ falls
- Fluctuations in Energy Loss in thin/thick samples of material:

  thin:
  - Few collisions
  - some with large energy transfer
  - large fluctuations in energy loss
  $\Rightarrow$ Landau distribution
  - e.g.: 300um thick Si sensor:
  $\Delta E_{mp} = 82$ keV, $<\Delta E> \sim 115$ keV

  thick:
  - Many collisions
  - wide spectrum of energies
  - distribution tends toward gaussian
  - $\Delta E_{mp} \approx <\Delta E>$
Third Complication: Bremsstrahlung

- Large (can be catastrophically so) discrete energy loss
- Acceleration due to interaction with coulomb field of nuclei
- Dominant energy loss mechanism for electrons and positrons:

\[
\frac{d\sigma}{dk} = \frac{A}{X_0 N_A k} \left( \frac{4}{3} - \frac{4}{3} y + y^2 \right)
\]

\[\propto Z^2 \alpha^3\]

where

- \( k \) = photon energy
- \( y = k/E \)
- \( E = \) lepton energy

Overall probability of photon emission \( \propto m^{-4} \) becomes important for high energy muons
Third Complication: Bremsstrahlung

- Single 100 GeV electron in CMS tracker:
Ionization Loss: full spectrum

- Full $dE/dx$ description includes many different effects

multi-TeV muons at LHC are NOT minimum ionizing!
Tracking Basics

• Assuming we can make hits now, what do we do with them?
• Charged particles curve in an axial magnetic field:
  – transverse momentum \( p_T \) (Gev/c) = 0.3 \( BR \)
  • \( R \) is the radius of curvature (m), \( B \) is field strength (T)
• What matters is how well we can measure the radius \( R \)
  – we actually measure the sagitta \( s \)
  – A little algebra

\[
\frac{L/2}{R} = \sin \frac{\theta}{2} \approx \frac{\theta}{2} \quad \text{for small angles;} \quad \theta \approx \frac{L}{R} = \frac{0.3BL}{p_T}
\]

\[
s = R \left(1 - \cos \frac{\theta}{2}\right) \approx R \left(1 - (1 - \frac{\theta^2}{8})\right) = R \frac{\theta^2}{8} \approx \frac{0.3BL^2}{8p_T}
\]

For three points, \( s = x_2 - \frac{1}{2} (x_1 + x_3) \)

\[
\rightarrow ds = dx_2 - dx_1/2 - dx_3/2
\]

assuming \( \sigma(x) \equiv dx \) (uncorrelated errors)

\[
\sigma^2(s) = \sigma^2(x) + 2(\sigma^2(x)/4) = 3/2 \sigma^2(x)
\]
• Putting all of this together (for a three-hit tracker):

\[
\frac{\sigma(p_T)}{p_T} = \frac{\sigma_s}{s} = \frac{\sigma_x}{s} \sqrt{\frac{3}{2}} = \frac{\sigma_x \cdot p_T}{0.3 \cdot B L^2} \sqrt{96}
\]

where \( \sigma_x \) is the single-hit resolution.

- Note that this quantity \( \sigma(p_T)/p_T \)
  - degrades linearly with \( \sigma_x \) and \( p_T \)
  - improves linearly with \( B \)
  - improves quadratically with \( L \)

• For \( N (N > 10) \) equally-spaced points,

\[
\frac{\sigma(p_T)}{p_T} = \frac{\sigma_x \cdot p_T}{0.3 \cdot B L^2} \sqrt{720/(N + 4)}
\]

So, \( \frac{\sigma(p_T)}{p_T} \) is a measure of performance for a given tracker.

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Gluckstern, NIM 24 (1963) 381
Effects of Complications

• multiple coulomb scattering in material
  – scattering in a thin layer of material introduces random angular errors
  – this adds an additional error to the $p_T$ measurement:

$$\frac{\sigma(p_T)}{p_T} = \frac{28 \text{ MeV}}{0.3 \cdot BL} \frac{\sqrt{x / X_0}}{\beta c p}$$

$X_0$ = radiation length of material

• Ionization Energy Loss
  - curvature decreases with pathlength
  - fluctuations in energy loss can be large if there is a lot of material:

$$\frac{\sigma(p_T)}{p_T} \sim \frac{x / X_0}{p}$$

$\Rightarrow$ Both effects decrease with $p_T$
Detector Techniques

- Now that we have a bit of theory, let’s take a look at how one can use ionization loss to provide the hits used in track fitting.
- Three basic groups of tracking detectors:
  - gaseous
  - solid state
  - scintillating
- Each converts the ionization left by the passing of a charged particle into an electrical signal
  - charge collection
  - light collection/conversion with photo-cathode
- Ideally, we would build a fast electronic bubble chamber with sub-micron hit resolution and infinite three-dimensional granularity
  - unfortunately, reality intervenes and we have to actually be able to pay for it, never mind actually build it
  - many compromises and optimizations are required
Some Detector Physics Basics

• Reminder:
  Ionization Energy loss: on average ~ 2 MeV/cm $\rho/(g \ cm^{-3})$
  – liquids/solids: ~ few MeV/cm
  – gases: ~ few keV/cm

• Ionization potential for materials:
  – primary ionization potential (~10-15 eV) plus some additional energy to separate electron and ion: total of ~30eV per atom
  – So, for 1 cm of gas, 3000 eV lost $\Rightarrow$ 100 primary electron/ion pairs
  – these ionize further, so add another factor 2-3 $\Rightarrow$ 200-300 e$^-$/cm
  – (Note: not a very big signal!)
    • detectors based on ionized gas need Multiplication
    • solid-state detectors are ok in this regard
      – can’t be too thick, though
        » problems with multiple scattering
Charge Multiplication

• Small radius wires with large voltage; ionized electrons drift in:

  - because \( E \propto 1/r \), fields near wire become very large
    (>10V/\( \mu \)m = 10kV/cm)
  - electrons reach energies sufficient to ionize gas
  - secondary electrons also accelerated

• For sufficiently large fields, an avalanche forms \( \Rightarrow \) large amount of charge deposited on anode (sense) wire

(F. Sauli, CERN 77-09)

gas must contain quenching agents to absorb photons generated in avalanche
SWPC Operational Modes

- **ionization mode**
  - full charge collection
  - no multiplication, gain ~ 1

- **proportional mode**
  - multiplication of ionization
  - signal proportional to \( \frac{dE}{dx} \)
  - secondary avalanches must be quenched
  - gain ~ \(10^4 – 10^5\)

- **limited proportional mode**
  - (saturated, streamer)
  - strong photoemission
  - secondary avalanches require strong quenching or HV pulsing
  - gain ~ \(10^{10}\)

- **Geiger mode**
  - massive photoemission over full length of anode wire
  - discharge stopped by HV cut
Gaseous Tracking Detectors: Geiger

- Simplest possible device
- Central (anode) sense wire
- Large voltage difference causes electrons to drift
- Charge avalanche occurs due to large fields near wire surface
- Binary (hit or not) – no attempt to measure timing, pulse height, etc.
- Huge signals (given correct gas and voltage) ⇒ simple electronics
GTDs: Straw Tube

• Next step up from Geiger counter
  – operates in “proportional mode” where total charge detected is proportional to the number of incident electrons
  – timing information gives radial position information

• Construction:
  – each tube has small central wire (15-50 μm radius), typically small radius (5mm-1cm) outer cylinder of stiff, thin material (100-200 μm)
  – built into arrays of tubes to provide multiple hits along trajectory

Zeus Tracker
GTDs: Atlas Straw Tubes (TRT)

- 4mm straws, 31μm wires
- fast charge collection: ~45ns
- gain of 25,000
- particle ID (e/π separation) using transition radiation
GTDs: Atlas – Why Straws?

Choice of optimization point:

• decided a large number of hits/track is desirable
  – driven to some sort of gas-based detector for fabrication cost reasons
  – more hits with worse resolution/hit
• individual element volume is a compromise between
  – maximum signal collection time (occupancy/multi-hit issue)
    • smaller volume is better (Atlas arrived at ~40-50ns)
  – channel count
    • smaller volumes ⇒ more channels ⇒ more cost

Straws vs. Open Drift Cell structure

• mostly a question of robustness
  – physical structure of straws more robust than free wires
  – damage from wire breakage limited to individual straw tube
  – cross-talk minimized: cathode acts as ground shield

• However: any gas detector in this environment faces serious ageing issues
  – 10 Mrad expected dose in 10 years (10 C/cm total charge!)
GTDs: Multi-Wire Proportional Chambers

- Replicate single wire geometry in large arrays

1mm cell width gives single hit resolution of ~ 300 μm

- Can have 2-D information:

Many different ways to use this basic concept:

- e.g. Cathode Strip Chambers, Resitive Plate Chambers, Small Gap Chamber, Monitored Drift Tubes, Streamer tubes, (insert favorite muon detection technology here)
GTDs: Drift Chamber

• “Open” MWPC
  – arrays of cathode “field” wires used to create uniform electric field
  – uniform electric field creates uniform drift velocity, so position can be determined by time measurement
    • modulo edge and near-wire corrections (detailed field map)
    • with appropriate gas, drift distances can be very long
  – detector is inherently “thin”: many measurements and large volumes possible without adding a huge amount of material
GTDs: CDF COT

- optimized for “high”-luminosity tracking

- narrow drift cells insure short collection times: trigger input

- tilted cells insure well-separated hits for radial tracks, limit multiple tracks/wire, limit left-right ghosts

- Note: stereo wires

**typical resolutions:** $\sigma_{xy} \sim 100\mu m$

$\sigma_z \sim 1 mm$
GTDs: BaBar Drift Chamber

• Optimized for high-rate and low-mass
  – helium-based gas mixture (80% He, 20% isobutane)
  – gas + wires only gives 0.3% $X_0$ at 90
  – small cells (short drift times) allow use in trigger
  – also used for dE/dx measurement
GTDs: Time Projection Chamber (TPC)

- Set up a situation where \( E \parallel B \)
  - Electrons drift along the \( z \) axis
    - Long drift distances
    - Measure time and arrival position
- True 3-D detectors
- Many measurements/track
  - Allows good particle ID with \( dE/dx \)
- Only gas in active volume
  - Very little material
  - Large track densities possible

Very long drift (typically > 2 m) implies/requires:

- Slow detector (~40 \( \mu s \))
- No impurities in gas
- Uniform E-field
- Strong & uniform B-field
GTDs: TPCs

- wires on end plane only measure one coordinate

⇒ special cathode geometry
  - cathode pads used to measure orthogonal coord.
  - granularity key for single hit resolution
  - ion clearing/gating:
    - special precautions to get rid of avalanche remnants

![Diagram of TPC setup with wires and pads]

**Typical resolutions:**

\[ \sigma_{xy} \sim 200 \mu m, \quad \sigma_z \sim <1 \text{mm} \]
GTDs: TPCs

- wires on end plane only measure one coordinate

⇒ special cathode geometry
- cathode pads used to measure orthogonal coord.
- granularity key for single hit resolution
- ion clearing/gating:
  - special precautions to get rid of avalanche remnants

Alice TPC Pads
GTDs: TPCs

• Large track densities are possible!

STAR
GTDs: Alice TPC
Issues for GTDs

• cover large volumes relatively cheaply
• nearly 100% sensitive volume
• Gas composition/stability/contamination
  – basically a black art
  – need gases that give good multiplication, but not too much
  – need gases with low electron diffusion for good resolution
  – need components to quench the avalanches
  – need to avoid contaminants that ruin the performance
  – sometime contaminants can be beneficial (c.f. CDF and H₂0)
  – all of this must be monitored constantly
• electric field mapping (with data)
  – distortion corrections important for ultimate resolution
• limited single hit resolution
  – unavoidable given drift/diffusion/avalanche considerations
    • best resolution achieved was ~30-40 μm/hit (Mark II DCVD)
Solid Detectors: Scintillating Fibers

- Small, multi-clad fibers doped with scintillating dye & waveshifter can function as a tracking device

- **DØ Central Fiber Tracker:** ~77k fibers
- 8 Barrels: each barrel layer has axial and 3° stereo ribbons (XU, XV, XU…)
- Light collection: visible light photon counters (VLPCs)
  - solid state photodetectors
  - high-gain (~40,000)
  - high quantum efficiency
  - fast – use in trigger
Solid State Tracking Detectors

• Why Silicon?
  – crystalline silicon band gap is 1.1 eV (c.f. ~20 eV for typical gases)
    • yields 80 electron-hole pairs/\(\mu\)m for minimum-ionizing track
      – (1 e-h pair per 3.6 eV of deposited energy)
    • 99.9% of ejected electrons have less than 1\(\mu\)m path length
      – fine-granularity devices can easily be made
    \(\Rightarrow\) detector performance could be as good as emulsion/bubble chamber
  – Integrated Circuit manufacturing techniques make just about anything possible, and at industrial prices
    • no real need to “home-grow” these detectors
    • just buy what you need…
**Silicon Basics**

- Detection still based on collecting electrons from dE/dx in material
- Semiconductor structure:
  
  ![Diagram of semiconductor structure](http://hyperphysics.phy-astr.gsu.edu)
  
  Electrons excited (thermally or otherwise) into Conduction band become mobile

  Liberated electrons will drift under the influence of an applied voltage

- The problem: recombination
  - Many, many more free charge carriers in a semiconductor than what is liberated through ionization \( \Rightarrow \) electrons re-combine with holes
Silicon Basics: Doping and PN

• The solution(s): 1. modify material structure

P-type silicon has electron acceptor (hole donor) atoms (B) added to create additional hole states

N-type silicon has electron donor atoms (P) added to create additional electron states

2. Modify charge structure: put P and N together (PN Junction)
   – in thermal equilibrium, Fermi levels become equal due to drift of electrons/holes across junction

Near junction, electrons bind to hole sites, creating negative ions, leaving positive ions behind. Bulk E-field stops motion of more particles ⇒ Depletion region: no free charge carriers!
Silicon Basics: PN Junction, Bias

3. Apply a voltage to suppress bulk E field, increase size of depletion layer to encompass entire volume: “Reverse Bias”

At the depletion voltage, no more free charge carriers exist in the semiconductor; any additional e-h pairs generated can drift to the edges.

In reality, use bulk silicon of one type, make “electrodes” out of the other type:

“Real” detectors necessarily more complicated
SSTDs: Silicon Microstrips

- The easiest thing to do is put down sensor lines, read out at end

- Charge sharing improves position resolution:

- Typical pitch width: 50µm – 200µm
  - one strip: width/√12
  - two strips: width/4
  - more than two: width/2

\[ \bar{x} = \frac{\sum x_i q_i}{\sum q_i} \]
SSTDs: Silicon Microstrips

- Exquisitely complicated micro-mechanical construction
SSTDs: Silicon Microstrips

- inherently 2-D: go to double-sided (or glue sensors at an angle for stereo) for r-z, but still 2-D devices
- “shingle” geometry common
  - full azimuthal coverage

Mark II
18.4k ch

Type II

CMS
9.6M ch
SSTDs: Pixels

- CCDs (charge-coupled devices) (what’s in your digital camera)
  - how do they work?

Thin depletion layer; active p-type epitaxial layer of \( \sim 20 \mu m \); generated charge reflected off of p\(^+\) substrate and eventually collected

C. Dammerell

SLD VXD3:
- \( 3 \times 10^8 \) pixels
- world-record for collider detector hit resolution: \( \sim 4 \mu m \)

Complicated pixel structure built on surface; Readout is serial – I shifts move each row down, R-\( \phi \) shifts read out the columns. Can take 100ms to read out a large detector

technology still advancing...
SSTDs: Hybrid Pixels

- Use fast, intelligent, rad-hard devices for high-occupancy environments
  - sensors separate from readout electronics – bonded together

Read-out (HDI) Design:
Pixel Modules and systems

- layer assembly

Signal Cable
LV& HV Cable

HDI
Bump bonding
SiN baseplate

ATLAS Pixels:
50x400 μm
1x10^8 channels

CMS Pixels:
100x150 μm
7x10^7 channels

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SSTDs: Issues

- Support infrastructure
  - even with miniature electronics, lots of power dissipated
  - cooling necessary in active volume
  - detectors tend to be “thick” — lots of material from supports, sensors

- $$$/\mu m^3
  - even with miniaturization, channels cost money

(CMS is similar or worse)
SSTDs: “services”