8.882 LHC Physics

Experimental Methods and Measurements

Track Reconstruction and Fitting

[Lecture 8, March 2, 2009]

Organizational Issues

Due days for the documented analyses

- project 1 is due March 12

TWiki

- updated the documentation to include Monte Carlo instructions

Lecture Outline

Track reconstruction and fitting

- basics: alignment, particles in *B* field and matter
- real life tracking issues
- Monte Carlo methods and GEANT
- tracking strategies and fitting
  - inside-out and outside-in tracking
  - combining track algorithms
  - typical failures of tracking algorithms
- calibration of the tracking
  - efficiencies
  - momentum scale calibration
  - material calibration

Tracking – The Definition

In particle physics, the tracking is the act of measuring the direction and magnitude of charged particles momenta.

Taken from wikipedia.org: “Tracking (particle physics)”

Tracking also includes the act of determining the particle position.

Lesson: not everything found on the Web is complete

Detector Alignment

To perform tracking, detector has to be aligned

Alignment

- detector positions have to be known to micrometer level
- survey of each component is a must
- knowledge of possible component shifts crucial to simplify alignment model
- bootstrap: use tracks make them fit better by adjusting positions (careful effects have to be disentangled)
- alignment need to be redone regularly
  - detector opening and closing
  - temperature variations
  - detector sinking
  - detector breathes with magnetic field switching on and off, ...

Track Reconstruction: Outline

Reconstruct hits

- space points, sometimes called clusters
- determine space point uncertainties

Perform pattern recognition

- lay out all hits and find helical trajectories
- identify the hits which seem to belong to trajectory

Fit identified hits to expected trajectory (helix)

- use space points and their uncertainties and find helix which optimally describes those hits
- knowledge of detector material and detailed magnetic field crucial: think multiple scattering and energy loss

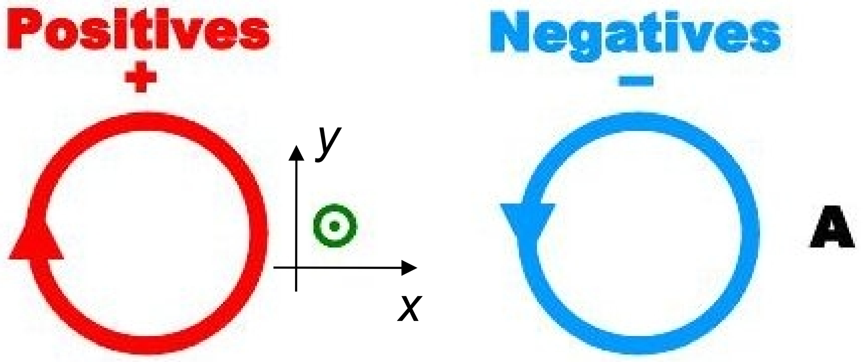
Often the steps are not separated but integrated for best performance

Charged Particles in Magnetic Field

Lorentz force

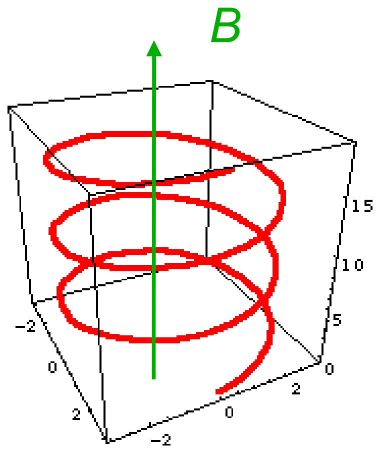
$$\vec{F} = \frac{d\vec{p}}{dt} = q\vec{E} + q(\vec{v} \times \vec{B})$$

- magnetic field: no change to momentum size, only changes direction
- electrical field irrelevant



Assume *B* field along *z*

- *xy*-plane motion: circle
- direction determines charge
- momentum component in z remains constant
- 3 dimensional: helix



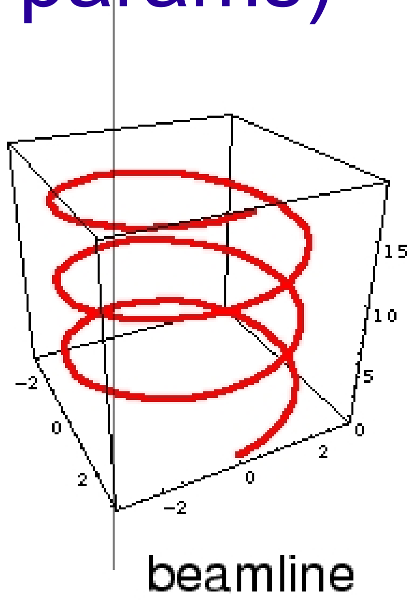
Real life

- magnetic fields never completely homogeneous

Helix Parameters

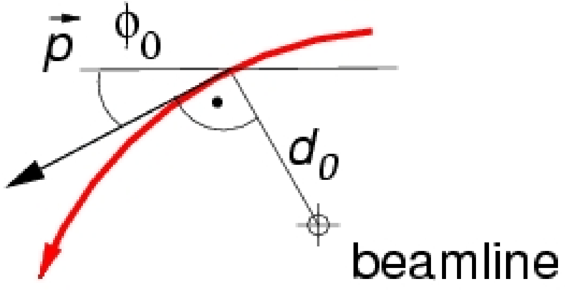
Description of particle in phase space (7 params)

- particle mass (m)
- creation point (x,y,z)
- momentum vector (p_x,p_y,p_z)



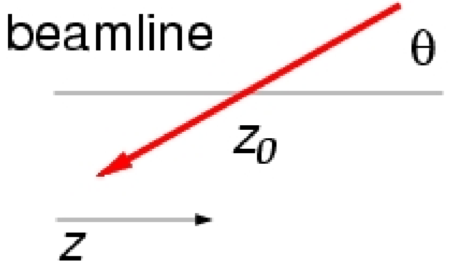
Tracking determines

- trajectory of the particle
- *per se* mass not included
- our cases of tracking: exact creation point not determined because of 1 dimensional ambiguity



Helix parameters must be 5

- 2 dim: curvature ρ ($\sim 1/p_T$), azimuthal angle φ_0, impact parameter d_0
- 3 dim: z_0 and cotθ ($=\lambda$)

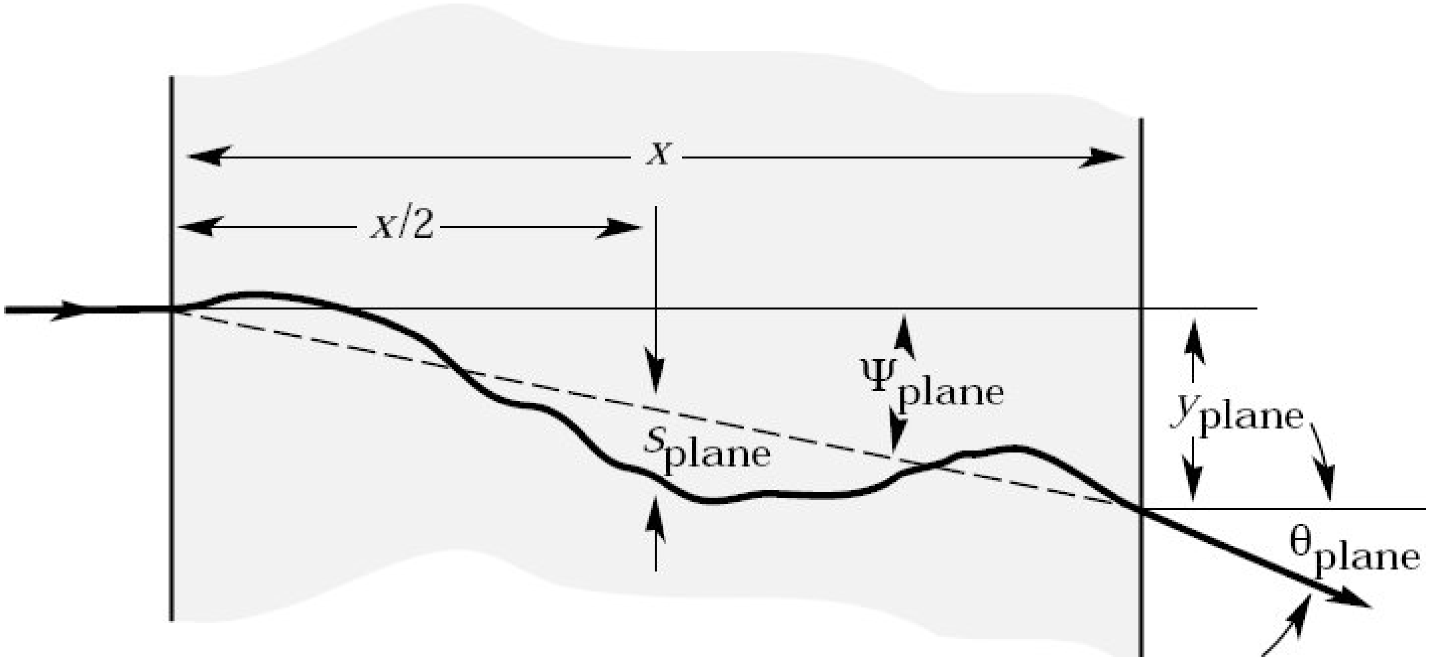


Particles Interactions in Matter

Multiple Scattering - Coulomb scattering approx.:

$$\left\langle \theta^2_{\text{proj}} \right\rangle = \left\langle \theta^2_{\text{space}}/2 \right\rangle = \frac{(21\,\text{MeV})^2(m^2+p^2)}{2p^4\beta^2}\frac{x}{X_0}\left(1+0.038\ln\frac{x}{X_0}\right)^2$$

x – traversed thickness, X_0 – material radiation length



always checkout PDG or GEANT implementation for reference

Particle Interactions with Matter

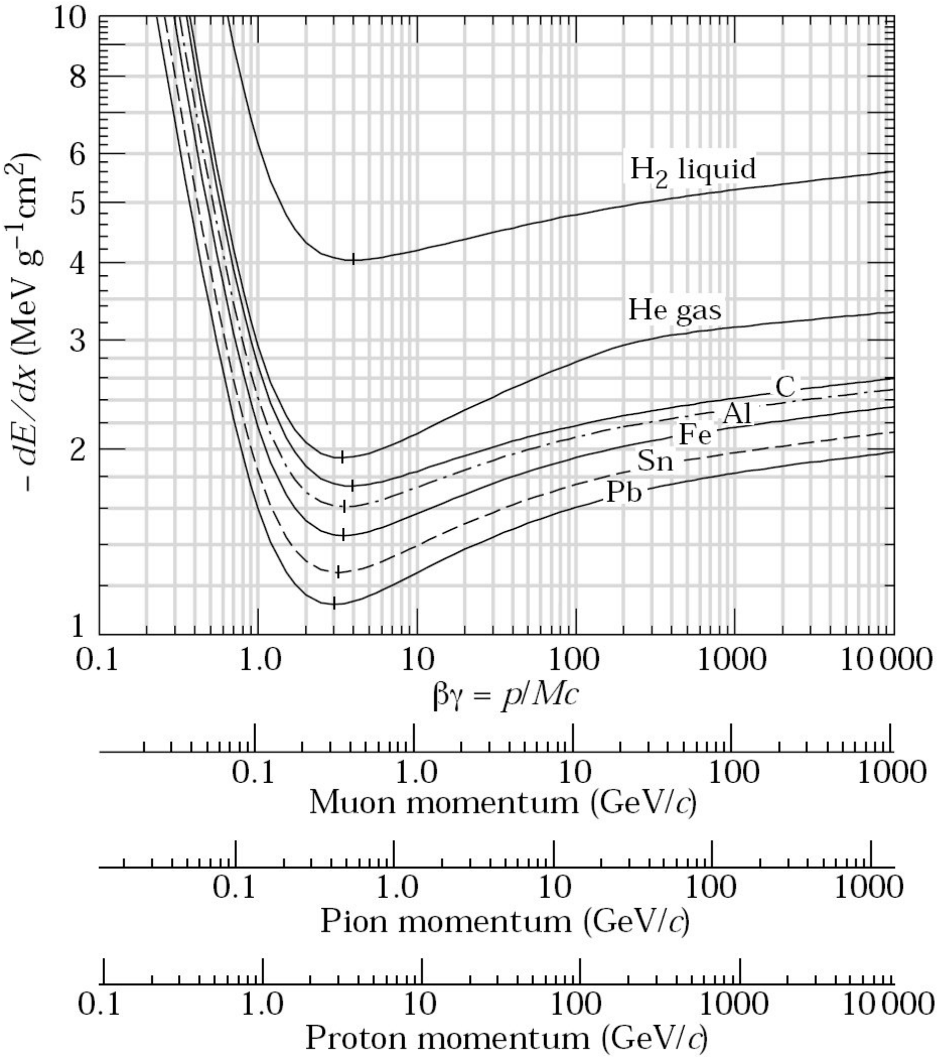
Energy loss (Bethe Bloch formula)

$$\frac{dE}{dx} = -Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\gamma^2\beta^2}{I^2}T^{\max} - \beta^2 - \frac{\delta}{2}\right]$$

- for moderately relativistic particles
- depends only on β

Very well studied effect

- theoretically complex
- measured in many materials
- good documentation
- useful for particle Id



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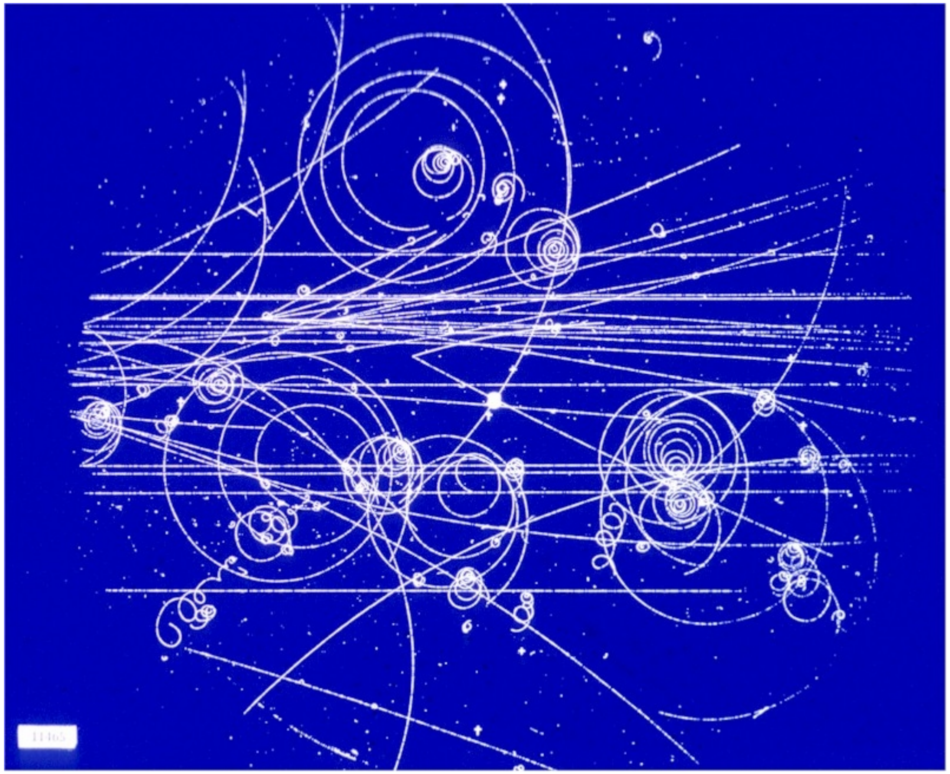
Real Life Issues for Tracking

Particle follow helix, but ....

- inhomogeneous *B* field: helix gets bend out of shape
- multiple scattering: blurs helix, momentum up and down
- energy loss: helix radius decreases

Tracking should be precise to micrometer level:

- those effects have to be taken into account in details
- detector simulation programs are used to implement all those issues in detail



Monte Carlo Method

They [Monte Carlo methods] are distinguished from other simulation methods (such as molecular dynamics) by being stochastic, that is nondeterministic in some manner – usually by using random numbers (or, more often, pseudo-random numbers) – as opposed to deterministic algorithms.

as usual from wikipedia.org: “Monte Carlo method”

In High Energy physics complex systems with many components need to be simulated .... Monte Carlo technique is a must in modern HEP and is only adequate since the advent of large computers.

Detector Simulation: GEANT

GEometry ANd Tracking software package

- originally developed in Fortran at CERN (1974) for HEP experiments, now available as Geant4 in C++
- based on Monte Carlo methods

Features

- allows complex detector descriptions: definitions of volumes of certain material(s)
- implements detailed particle interaction with material
- multiple scattering, energy loss, particle decay, particle creation, motion of charged particles in magnetic field
- various plugins: digitization, hadronic showers *etc.*

Output of GEANT simulation

- usually – fully digitized detector response, *i.e.* hits

GEANT Basic Tracking

GEANT tracks particle through given detector

- any particle and their “children” can be tracked
- track is not calculated as a whole but rather in fine grained steps
  - many effects can be linearized
  - account for inhomogeneous magnetic field
  - particle interaction and decay can be stochastically introduced
- step size is optimized depending on detector material
  - keeps computing time hopefully reasonable
  - always accounts for material boundaries
- particle shower in calorimeter
  - very complex processes: many particles are created
  - hadronic showers through special programs: FLUKA, GEISHA
  - potentially very time consuming: shower cut off

Tracking Algorithms

There is no one tracking algorithms which does it all

Tracking process is highly complex and has many ways it can be adjusted (tuned)

Considerations

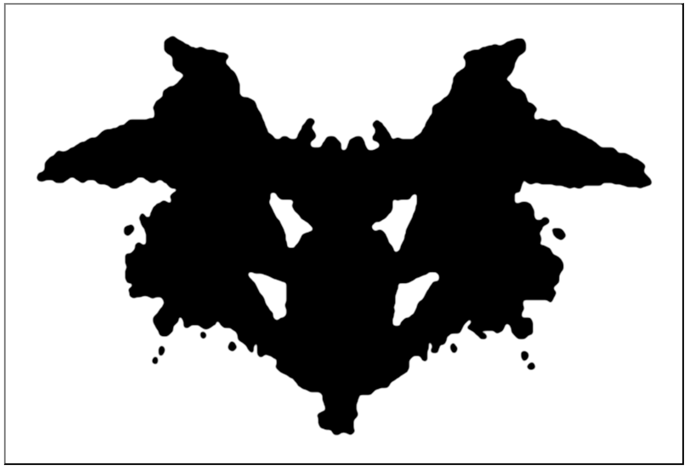
- tracker type, geometry and hits it produces
- magnetic field
- event environment
- physics analysis requirements
- computing time available

In the following I will give you the key words and explain them.

Pattern Recognition

Bubble chamber days

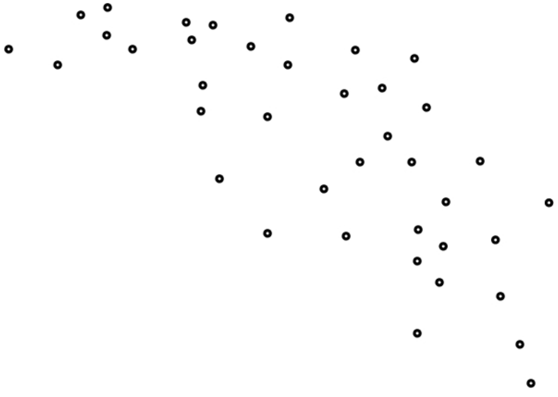
- scanning team looked at photograph
- recognition straight forward



what pattern do you recognize?

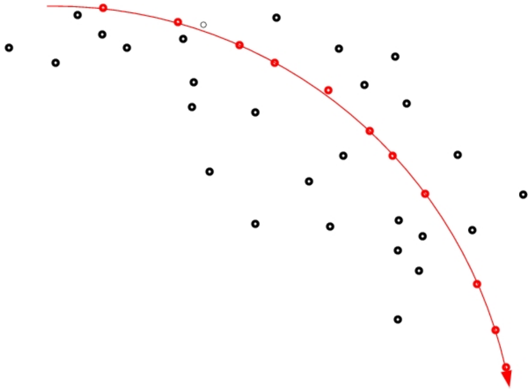
Electronically read out detectors

- less hits per track length
- environment got more dense (more hits)
- algorithms needs to replace 'look at'

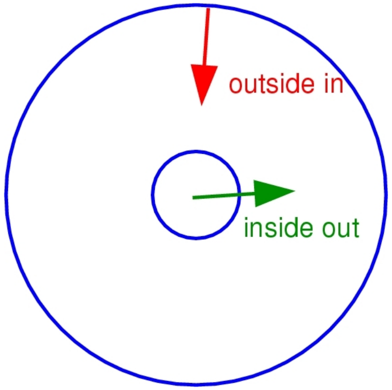


Algorithm (time consuming)

- usually start from a 'seed' in 2 dim
  - set of three points on a line in *rz* projection
  - a pixel (CMS), a segment (CDF superlayer) ....
- permutations, book keeping essential
- 3 dim hits added in next step



Tracking Algorithms



Outside in

- start with seed at outer end of tracking volume
- swim in general direction of the beamline
- advantage: low occupancy outside, easy pattern reco, add hits moving in one knows already where to look

Inside out

- follow natural particle direction, least MS
- detector cutoff in pseudorapidity has minimal effect
- seeding difficult because of high occupancy

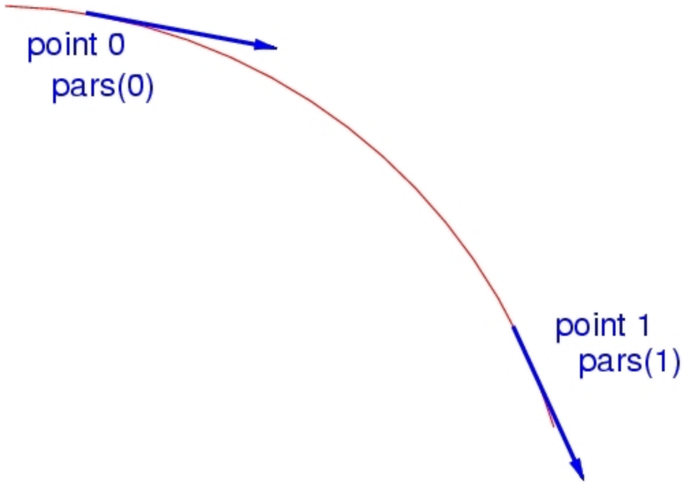
Difficulties

- bias towards beamline has to be avoided as best as possible, most algorithm work better if they know where to look (duh!)

Track Fitting

Input to the fit

- hits identified to be part of the track
- helix trajectory model
- transport mechanism to adjust helix parameters and their uncertainties (covariance matrix)
  - multiple scattering
  - energy loss
  - magnetic field (use a detailed map)



Fit output

- full set of helix parameter at point 0 (ideally particle production point)
- full covariance matrix (later essential for vertex fits)

Kalman Filtering / Road Search

Wikipedia says

The Kalman filter is an efficient recursive filter which estimates the state of a dynamic system from a series of incomplete and noisy measurements.

Applied to track reconstruction:

- use a track seed or 'tracklet' perform a fit and extrapolate to attach one or more hits
- add hit(s) based on some criteria, refit, extrapolate and add more hits *etc.*
- at some point the recursive algorithm has finished and a final track fit can be applied to the attached hits (intermediate fits can neglect many aspects for speed)

Road search

- based on a tracklet you can define a road where to look for more hits

Combining Track Algorithms

General truth about tracking algorithms

- never 100% efficient, have large overlaps
- they better be complementary in some way
- final fit in most cases the same
- why do it? track algorithm inefficiency reduces the data sample for the analysis

Combination brings issues

- identify the tracks found with both algorithms (prune)
- choose the 'best' of the two tracks
- complicates efficiency measurement
- testing Monte Carlo simulations becomes more complex
- organizational overhead: history of track origin
- computational overhead: some tracks tried multiple times

Typical Tracking Problems

Too many hits

- bad silicon hit (noise or real) on the track will seriously distort vertex determination, not so important in drift chamber

Too many tracks

- ghost track: track which is not really there – mirror image because ambiguity in wire plane was not resolved
- split tracks: tracks which originate from one particle but where identified as separate tracks (alignment, algorithm)

Missing tracks

- track is at the limit of the fiducial volume
- too few hits (hit efficiency too low, *ex.* aging chamber)
- misalignment, hit too far from 'expected' position

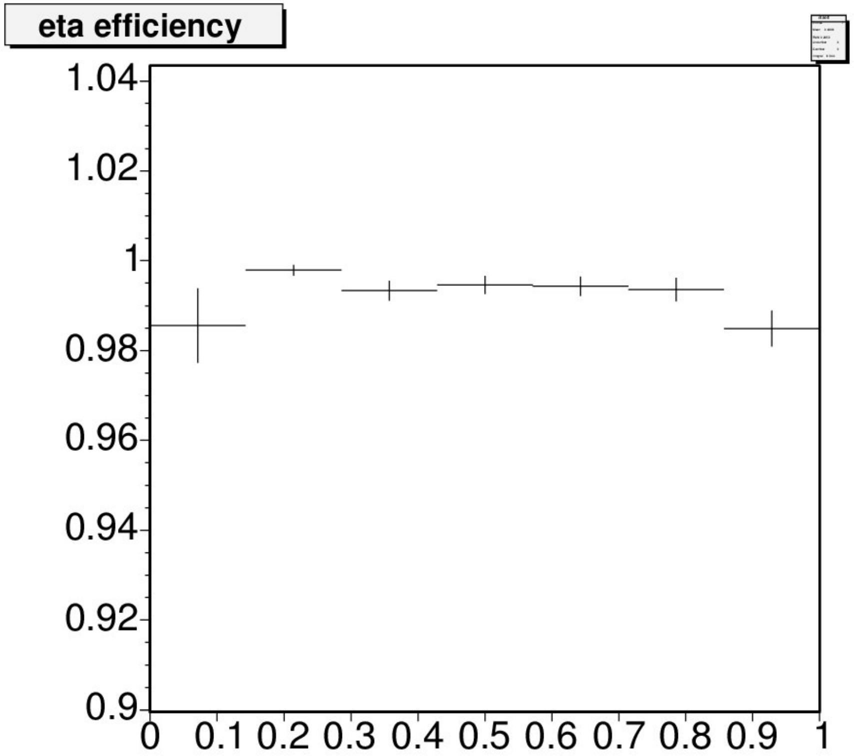
CDF COT Efficiency

The Dream

- determine efficiency from MC

Why it does not work!

- Monte Carlo usually not reliable enough at full detail of the hit simulation
- track efficiency depends on environment: many hits around or few

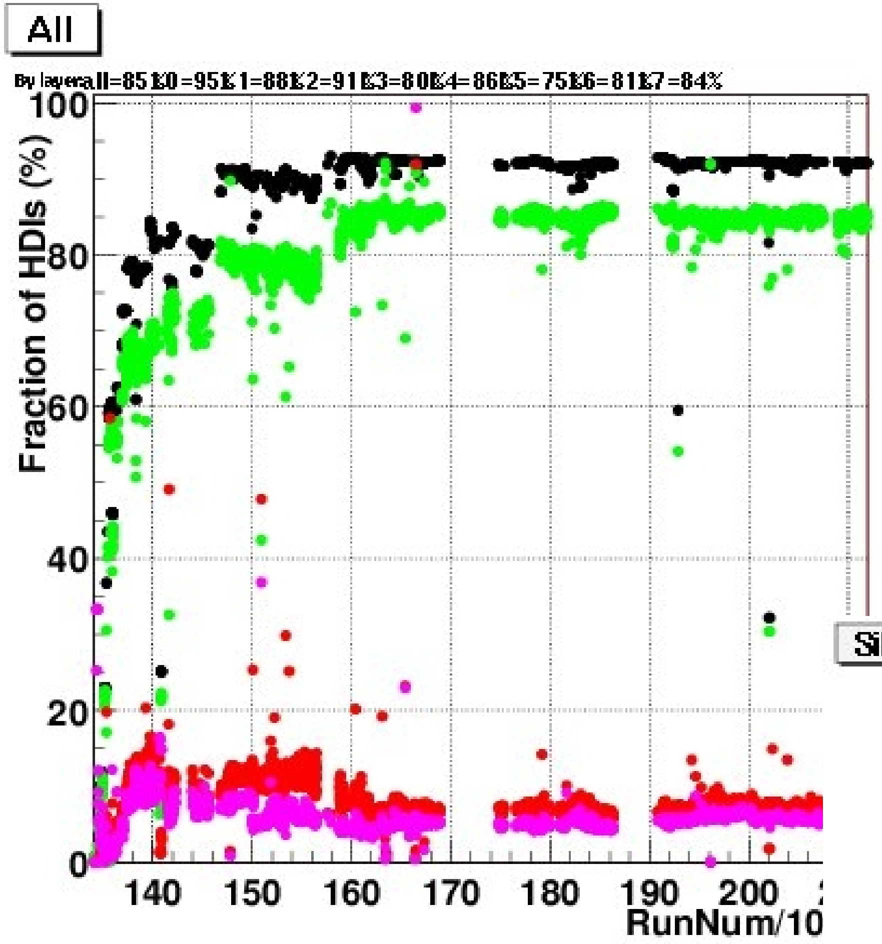


COT efficiency measured from data *W*-no track sample

Solution

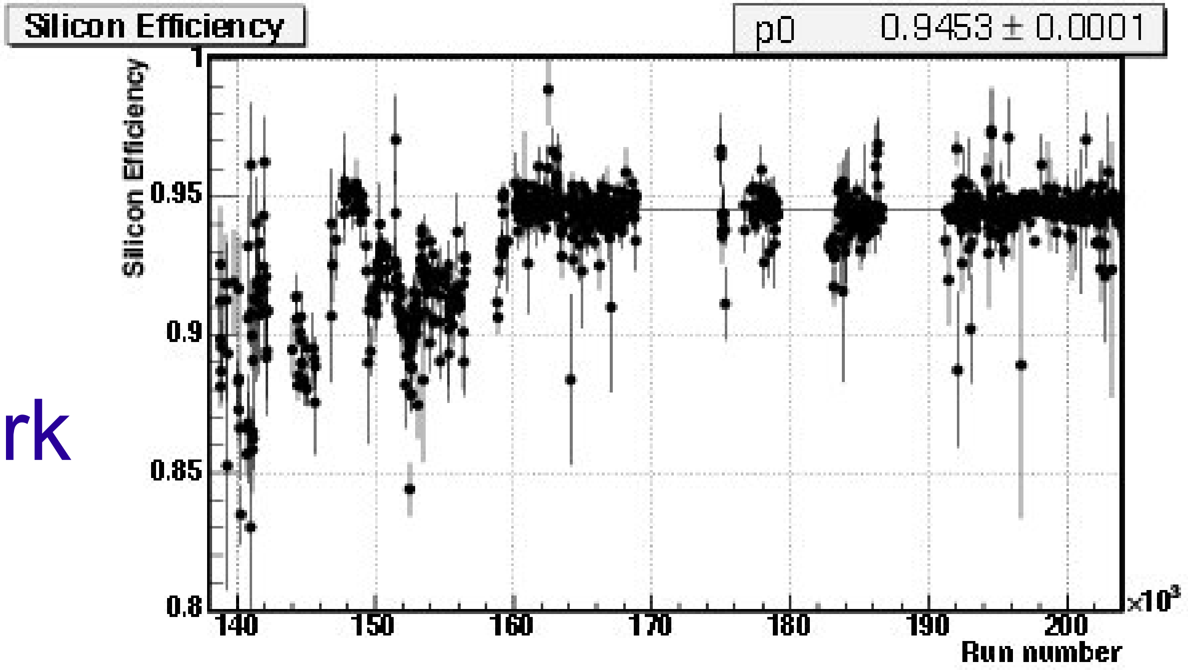
- use well selected data samples and measure it directly
- embed Monte Carlo tracks into the data environment at the hit level

CDF Silicon Detector and Hit Attaching



Starting from COT track

- attaching silicon in road search
- efficiency about 95%



Detectors do not work perfectly: 7% of Si readout dead/shaky

Material and Magnetic Field

Correct material budget? Magnetic field is precisely determined?

- use standard candle ($J/\psi \rightarrow \mu\mu$) and measure it

Effect on the reconstructed mass

- magnetic field shifts overall scale up and down
- material as well.... hmmm?

Energy loss

- depends on momentum of tracks
- reconstructed mass will be momentum dependent
- not the case for magnetic field

CDF material budget of tracker at startup

- simulation: 25 kg, weight of detector on scale: 128 kg

Momentum Scale / Material Calibration

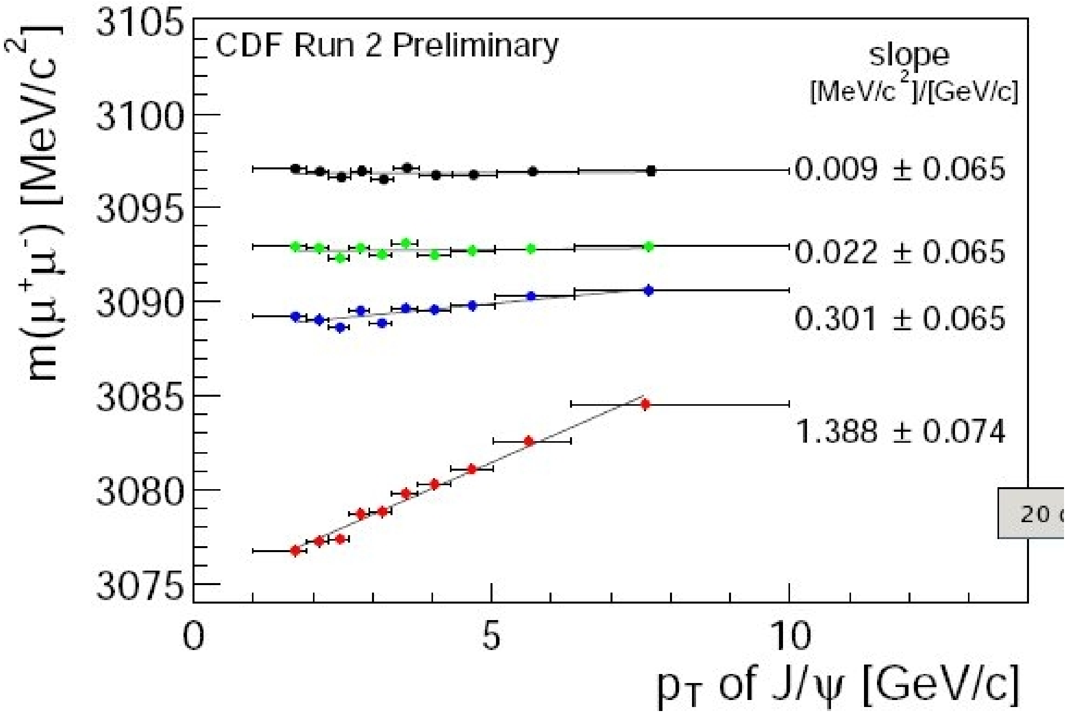
Momentum mostly from COT

- $\Delta p_T / p_T = (0.7 \oplus 0.1 \cdot p_T)\%$

Calibration of the tracking

- use: $J/\psi \to \mu^+\mu^-$ (500k)
- measure material in detector
- measure momentum scale
  $\to$ adjust B field
- new method invented for Run II
- more sophisticated than Run I
- more material than in Run I

Building up tools step by step



Calibration procedure

- raw tracks
- nominal E loss corrections
- fine tuned E loss corrections
- adjust overall scale (B field)

Conclusion

Charged particle tracking

- a well established process in particle physics
- very complex with many parameters to play with
- needs specific implementation at each detector

Components

- prerequisite: detector alignment
- hit reconstruction (space points with uncertainties)
- pattern recognition
- track fitting

in most cases integrated for best performance

Properties

- tracking efficiency and resolution
- momentum scale, material budget

Next Lecture

Analysis tips – Charge Multiplicity