Tracking

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Overview:

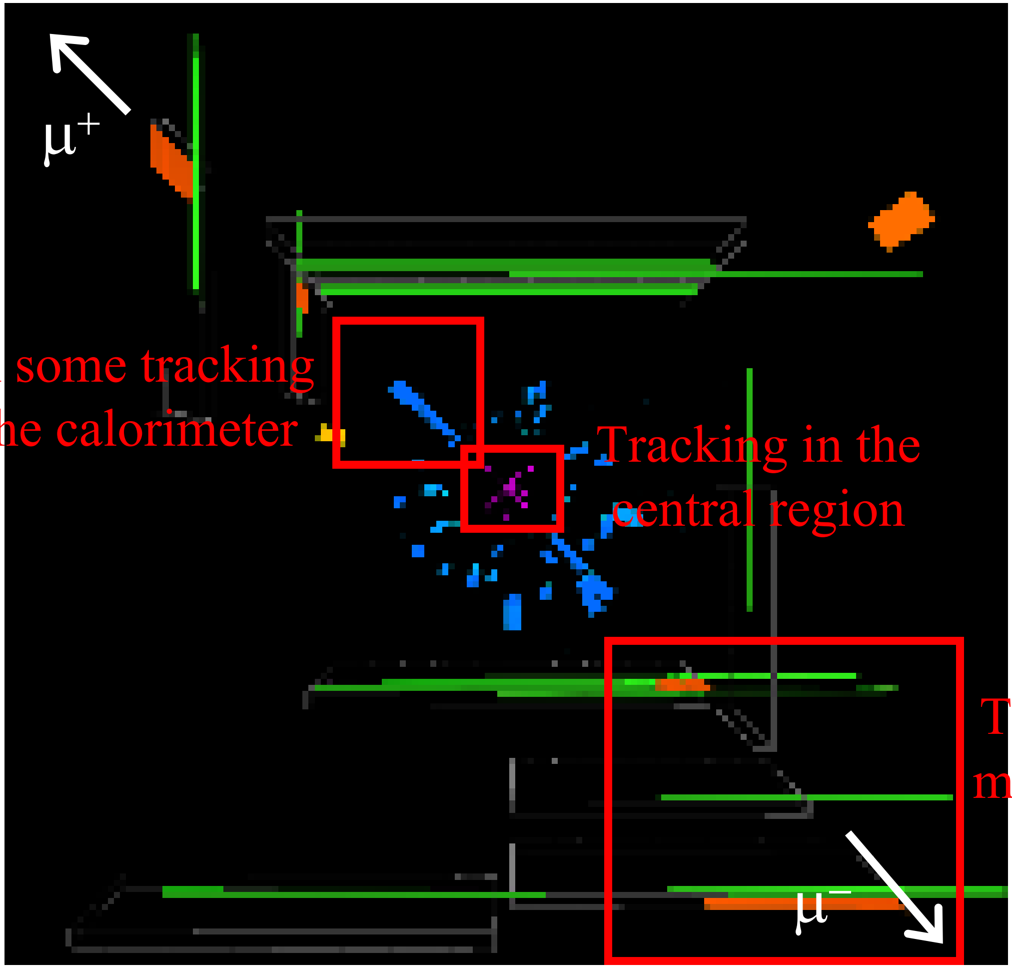
- Tracking detectors components.
- Example: the DØ tracking system.
- Tracking algorithms.
- Tracking performance (alignment, calibration).
- Examples of physics with tracking.

Why tracking?

- Momentum measurement of charged particles.
- Particle identification.
- Measurement of charged particles production and decay vertices.

Example (real collision)

A **Z**$\rightarrow\mu^+\mu^-$ event from a proton-antiproton collision in the DØ detector



Even some tracking in the calorimeter

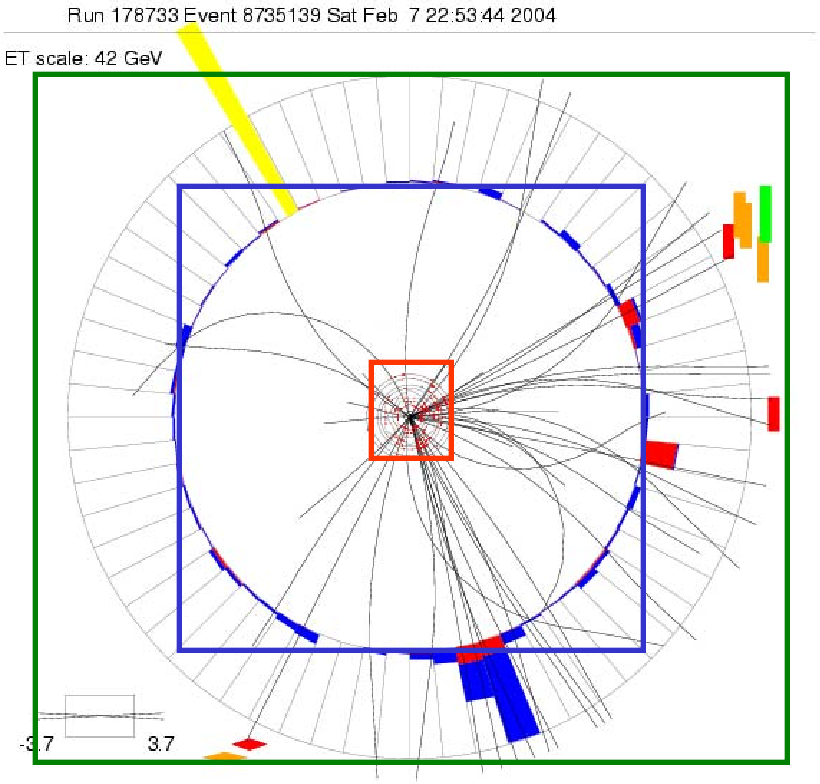
Tracking in the central region

Tracking in the muon chambers

Tracking detectors

- Devices which allow the tracking in position of a charged particle trajectory. They are arranged in a regular, repetitive structure of elements to allow "tracking" over a particular distance. A grid of electrodes is embedded in each element in order to reconstruct space points.
- A signal in each tracking detector is based on the interaction of the charged particle with the medium (most noticeably, ionization).
- If the detector, and the track, are immersed in a magnetic field, the trajectory and the value of the field gives a measure of the particle momentum.
- If the detector signal is analog, one can have a measure of the ionization loss dE/dx, and therefore identify the particle.

Typical detector suite of tracking elements



- Vertex detector: excellent position resolution

  __most common technology:__

  silicon μ-strips or pixels.
- Central tracking detectors: good momentum resolution, particle identification

  __most common technology:__

  gas wire chambers,

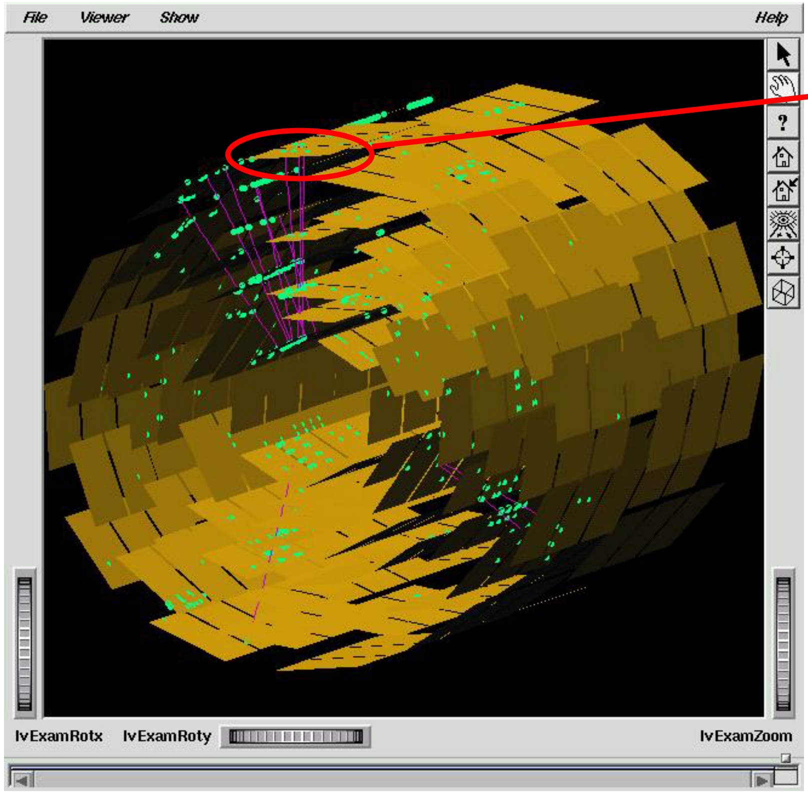
  scintillating fibers.
- Muon detectors: particle identification for muons, moderate momentum resolution

  __most common technology:__

  gas wire chambers.

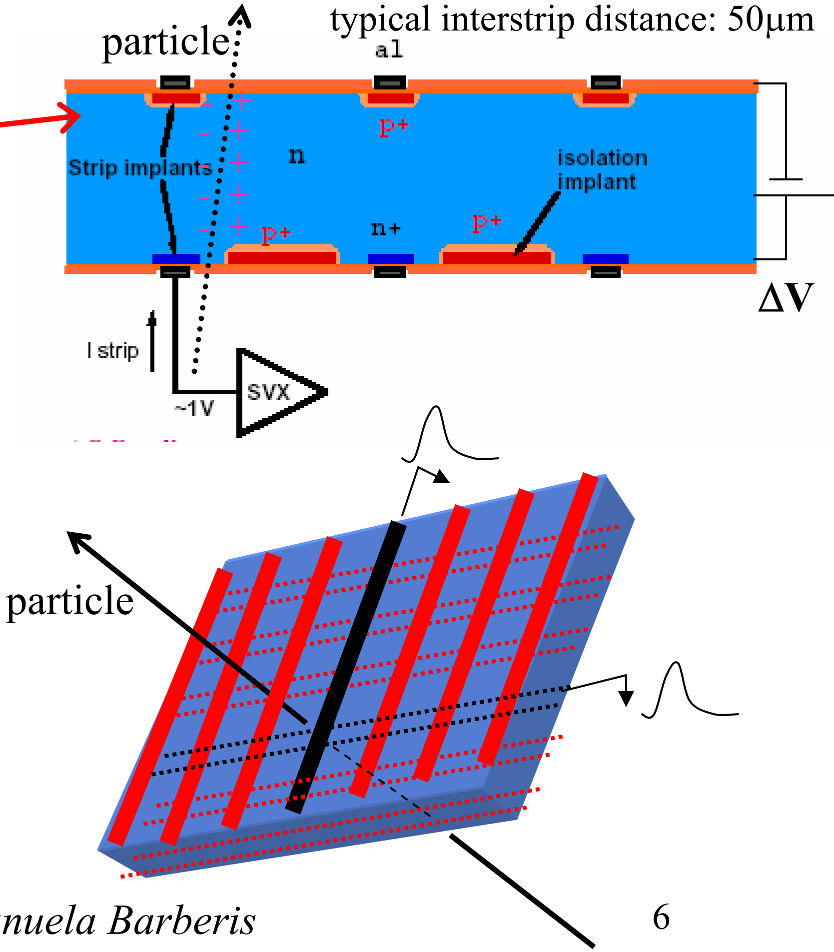
From particle to detector hits

- Example: Silicon μ-strips



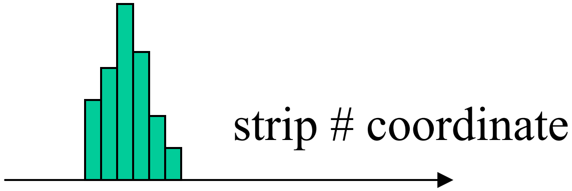
Cut-out of a Silicon μ-strip double-sided wafer

typical wafer thickness: 300μm
typical interstrip distance: 50μm

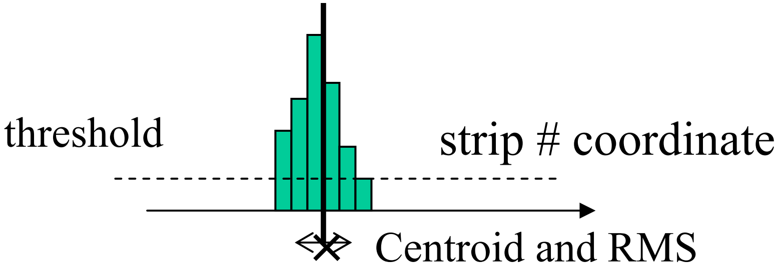


From particle to detector hits (2)

- Charge sharing, Lorentz drift → signal on multiple adjacent strips (1D cluster).



- Calibration: subtract signal obtained with not beam (pedestals), convert the electronic signal (ADC counts) to energy (gains). Flag and disable (from reconstruction) faulty strips (no counts, excessive counts).
- Set a minimum energy threshold, find centroid, and centroid error. Set minimum strip separation between clusters (usually, one strip). Make sure that disabled strips do not break a cluster.

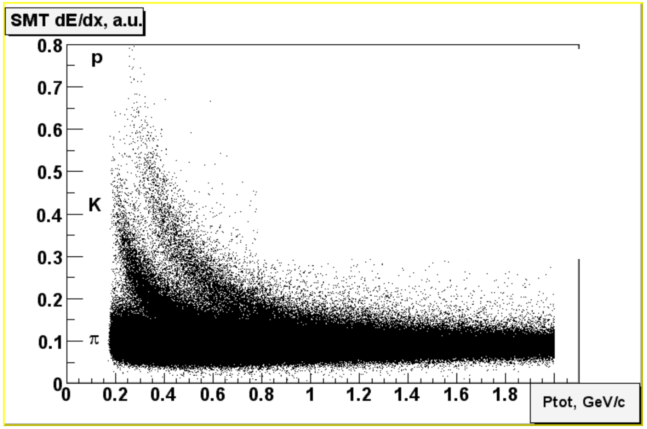


- Match centroids from opposite views of the Silicon wafer (2D cluster, local coordinates of the ladder). Define 2D error (ellipse).
- Use geometry description to translate the 2D cluster to 3D space point (hit).

From particle to detector hits (3)

- Pedestals, gains, disabled strips, geometry information (and alignment constants) are periodically checked and stored, and available to the reconstruction code (usually in database structures).
- Particle identification is possible in Silicon μ-strips detectors, but it is usually more effective with tracking detectors using a high pressure gas medium.

dE/dx



different particles can be “seen” in the Silicon, although not with good separation

momentum

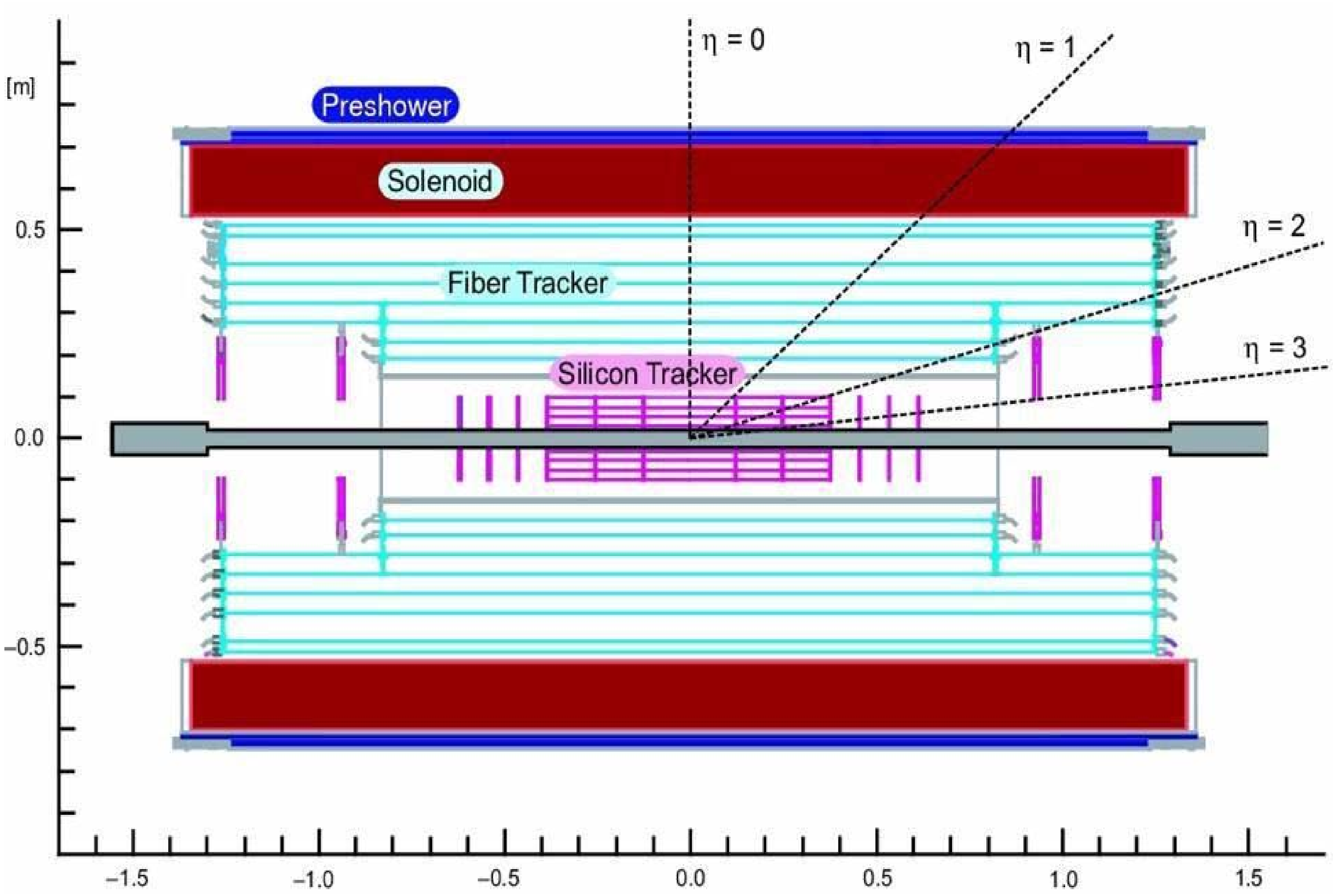
- The steps leading to hits-finding are similar for other types of tracking detectors. Let’s examine a real detector before going to the next steps in the determination of a particle trajectory.

Example: the D0 Tracking System

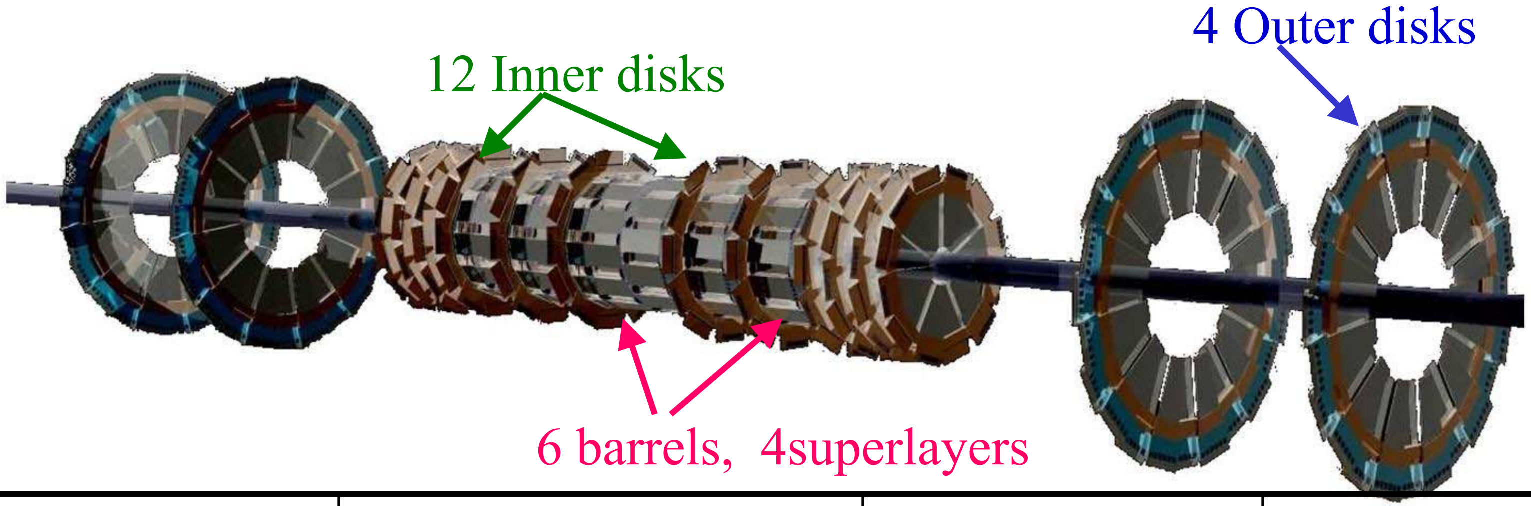
Inner tracking region

Features:

1) Small number of measurements per track (max 12)
2) Small lever arm (2-52 cm)
3) High |η| coverage
4) Small amount of material
5) 2T solenoidal field



DØ Vertex detector, SMT

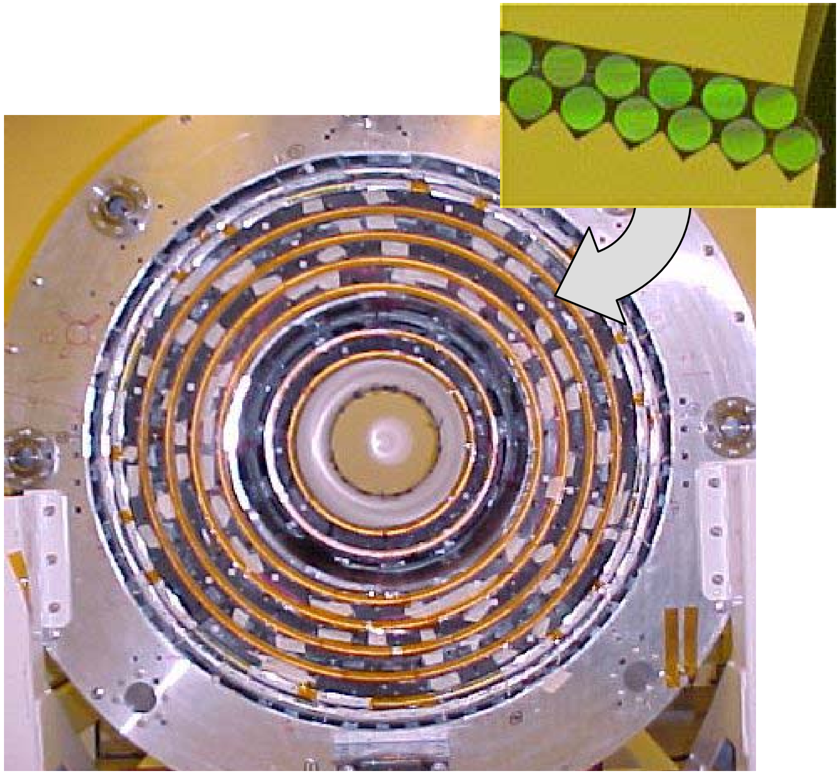


Silicon μ-strips	Barrels	Inner disks	Outer disks
Type of ladders	Single, double-sided	Double-sided	Double-sided
Stereo angle	0°, 2° and 90°	7.5°	15°
Inner radius	2.7 cm	2.6 cm	9.5 cm
Outer radius	9.5 cm	10.5 cm	26 cm
# of channels	400K	250K	150K

DØ Vertex detector, SMT (2)

- **SMT design has unique features:**
  - Barrel part is short (±38cm) compared to the z beam spot size (σ = 30 cm), so tracking in disks is crucial.
  - Disks are partially embedded between barrels, cannot really separate tracking in barrels and disks.
  - Hit and track pattern recognition at high $|\eta|$ has to be done entirely in SMT, without any external support.
  - $|\eta|$ coverage up to 3.
- **Hardware Performance:**
  - 88% of channels are currently working.
  - Running very stable – 99% uptime.

DØ Central Fiber Tracker, (CFT)



-835 μm diameter scintillating fibers arranged into precisely positioned ribbons of interlocked fiber doublets.

-256 fibers per ribbon.

- each barrel layer has axial and 3° stereo ribbons (XU, XV, XU…)

-VLPC readout

-Doublet position resolution ~ 100 mm, doublet efficiency > 98%

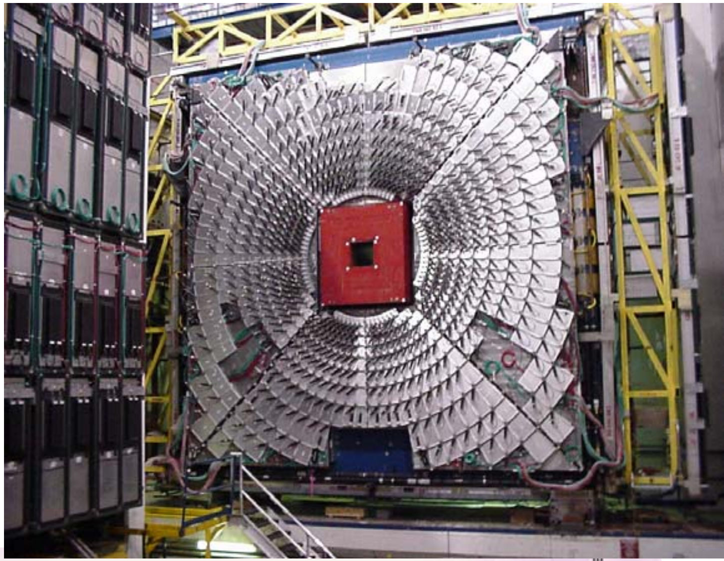
-Built in CMM, ribbons positioned within 30 mm of nominal

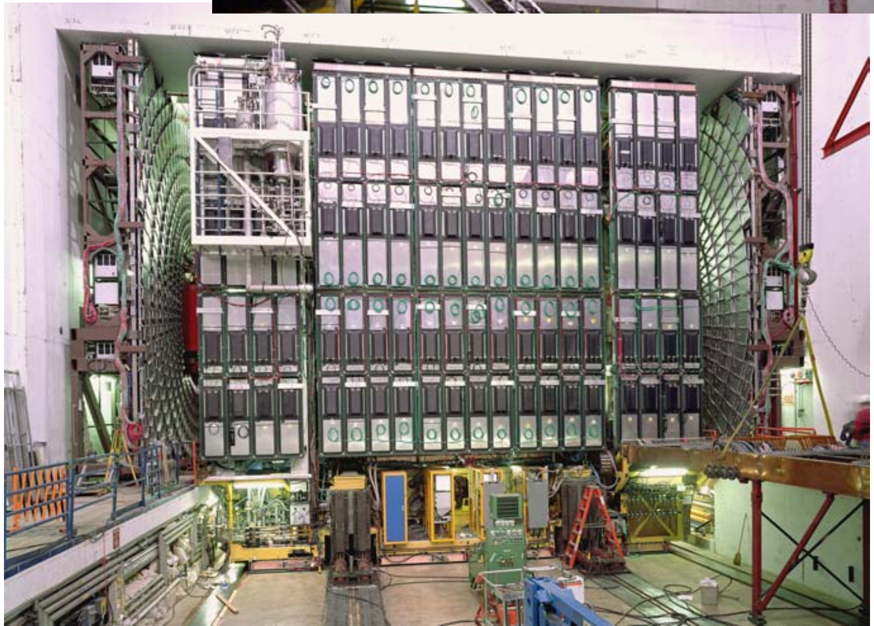
DØ Central Fiber Tracker, CFT (2)

- **CFT design**
  - 8 superlayers.
  - Each superlayer consists of axial/stereo layers.
  - $|\eta|$ coverage up to 2.0.
- **Hardware performance**
  - 98% of channels are working.
  - Running very stable.

DØ Muon detector

Outer tracking region





Features:

-Coverage to |η|<2.

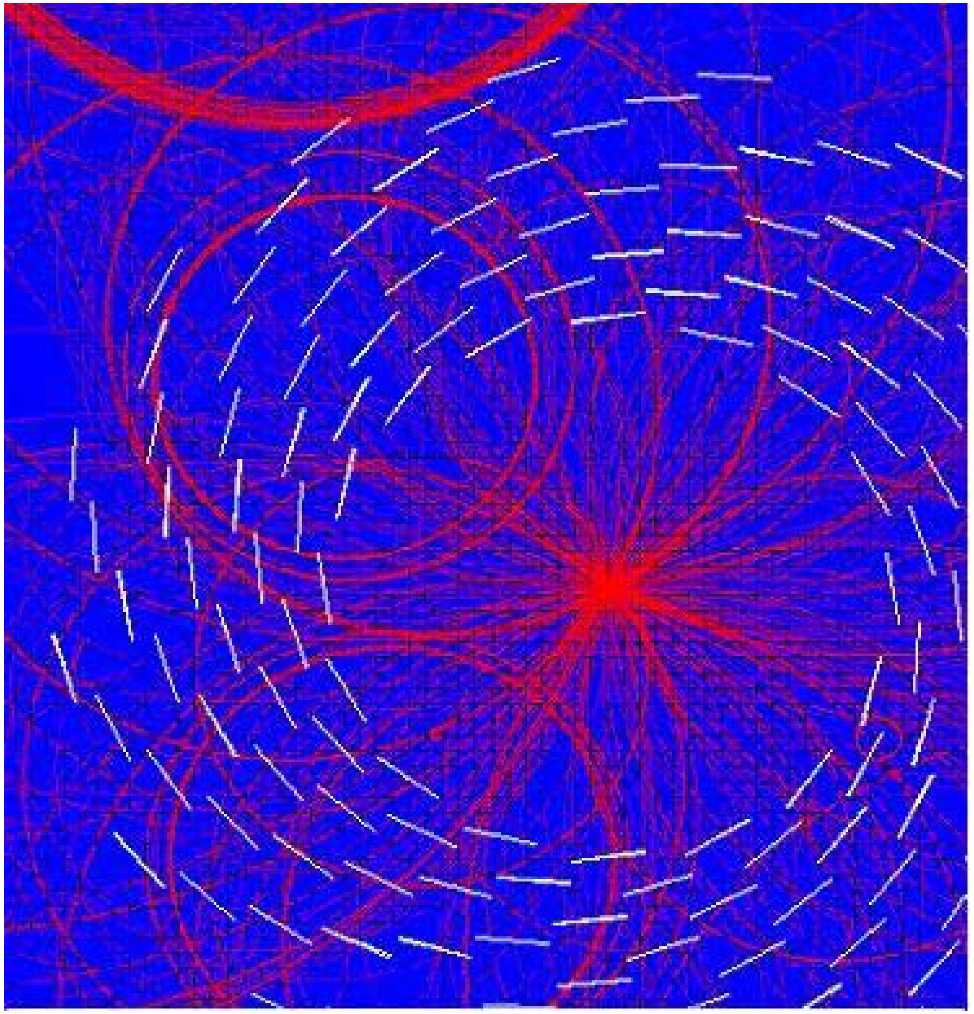
- Scintillator trigger planes (2 layers central, 3 layers forward) plus drift tubes (3 layers central/forward) for reconstruction.

- Standalone momentum measurement, to be used with inner tracking.

- Thorough shielding and good time resolution (1-2 ns).

-2T toroidal field.

From hits to tracks



Pattern recognition (i.e. track reconstruction) in the CMS inner tracker

From hits to tracks(2)

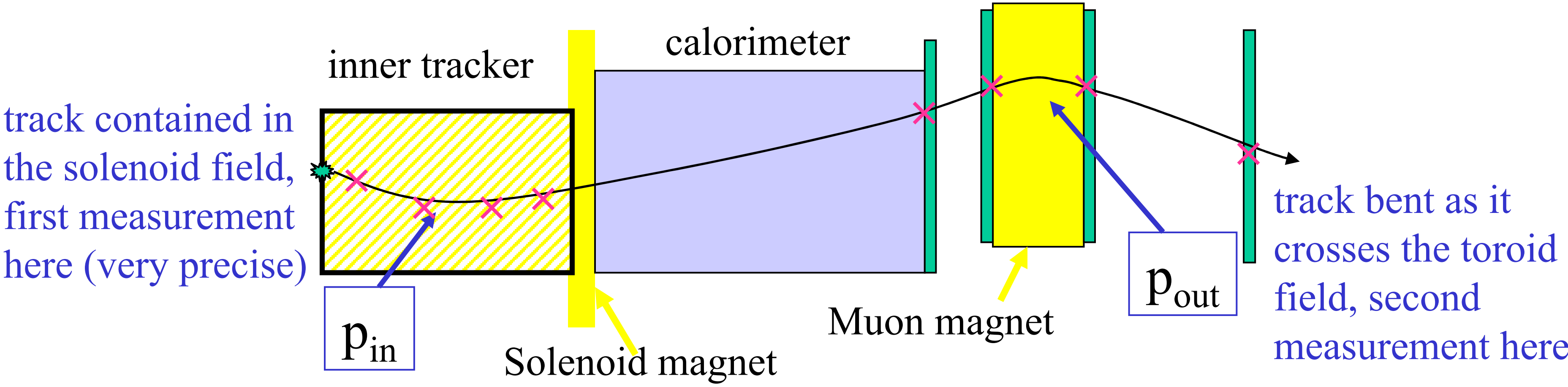
- Reconstructed hits constraint the trajectory in space (in the plane perpendicular to the direction of the field, the trajectory is a circle).Together with a magnetic field, B, this gives a measurement of the charged particle. **momentum**.

Momentum in the plane perpendicular to the direction of B

$$p_T(\text{GeV}/c)=0.3B(\text{T})\rho(\text{m})$$

Curvature

- Best example: a muon (it is tracked in the inner and outer tracking chambers).



track contained in the solenoid field, first measurement here (very precise)

track bent as it crosses the toroid field, second measurement here

Tracking algorithms

Track reconstruction

- The challenge of reconstructing the tracks in an event is to assign the reconstructed hits to a set of three-dimensional helices (if we are talking about the solenoidal magnetic field of a central tracker).

- Three steps:
  1. Presort tracks in the event.
  2. Which hits are to be associated with which tracks? Refit tracks.
  3. What are the parameters of the tracks?

- The second step is central to the problem, as there are, often, a large number of combinations of hits to be tried. The first question is addressed by defining track seeds, either with a first pass, rough combination of hits, or with histogramming methods.

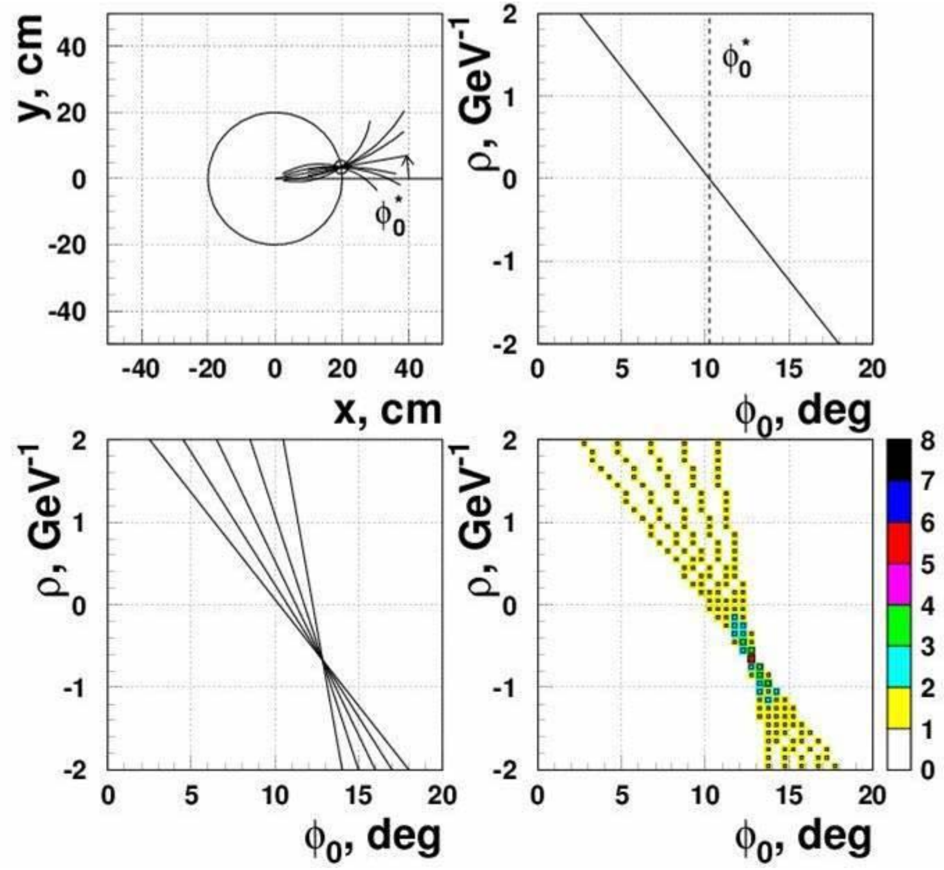
Track sorting

- Road-following technique:
  - Use the hits from a few tracking layers to form track seeds and continue to assign hits found in other layers to the track seeds.
  - Start from the innermost layers (inner-out) or the outermost (outer-in). Most commonly, start from the layers with lowest hits multiplicity.
  - Add each hit in the next layer to the track it matches best.
  - Refit the track and move to the next layer.

Track sorting(2)

- Histogram seeding:
  - Hits are organized in patterns and histogrammed in a chosen parameter space, where hits belonging to tracks will cluster in a peak.

  Example:
  - Each hit is a point in conventional (x,y) space and a line* in track parameter space (ρ,φ).
  - Lines in the (ρ,φ) space corresponding to hits from the same track intersect at one point – track parameter point.

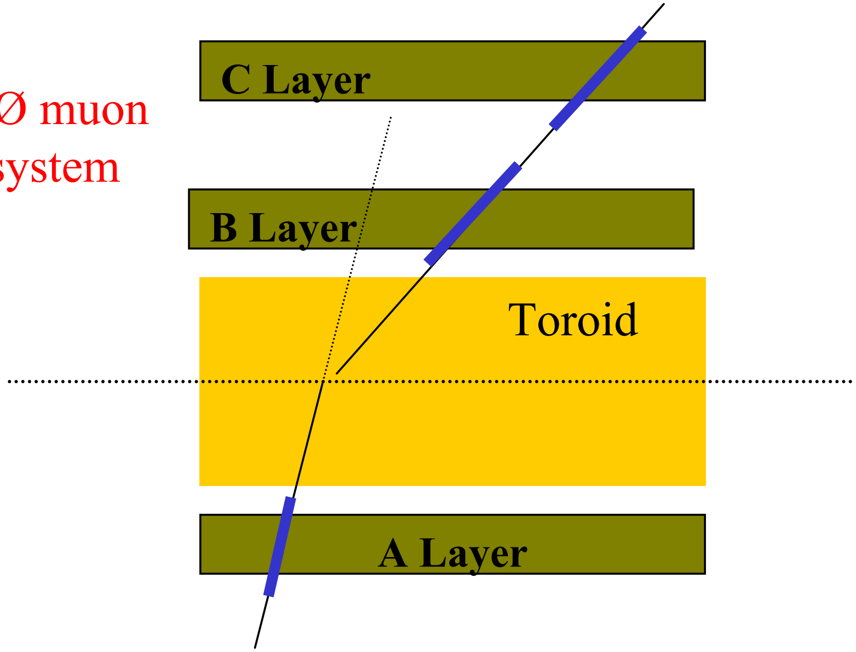


* valid for tracks with small impact parameter, where the three parameter of the circle reduce to two.

Track sorting(3)

- Track segments: in a muon system, for example, where some of the chambers are located before the magnet, and some after, one can look for local track segments as seeds to the track fitting algorithms.

DØ muon system



- Hits in the muon wire chambers are combined and a straight line, called **segment**, is fitted through the hits. Afterwards, the found segment is fitted with scintillators for timing information on the segment. B and C segments are combined, since they form a straight track.

- Segments are filtered, and serve as input to the muon track finding and fitting.

Track fitting

- Kalman fitter is the one most commonly used:
  - Well defined method of determining, from a set of measurements, the optimal track parameters, with errors, on any surface.
  - The tracks parameters, and error matrix are propagated to the surface of next measurement, creating a prediction on that surface.
  - The prediction can be used as aid to pattern recognition, as the incremental χ^2 can be used to filter the selection of the new candidate measurement (Kalman filter).
  - The Kalman fitting is complete only after the last surface is reached.
  - To obtain an optimal measurement at an intermediate surface, it is possible to use Kalman smoothing, i.e. do complimentary Kalman unidirectional fits from opposite directions, and combine the two estimates at the interior surface.

Track fitting (2)

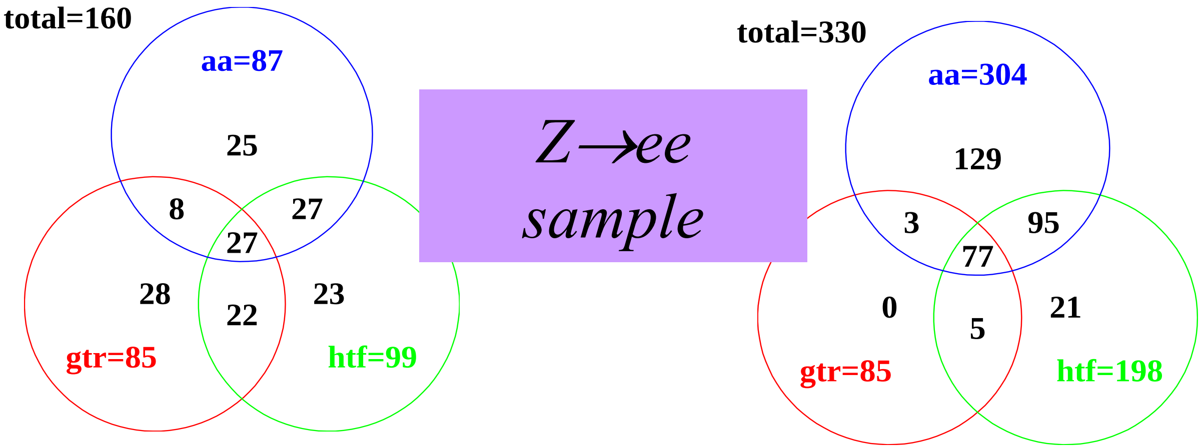
- One alternative to Kalman fitting:
  - Elastic arms algorithm: track seeds are fitted dynamically, i.e. they continuously change their probabilities of being connected with each hit, as their parameters evolve. Uses mean-field annealing to associate tracks with hits and tracks with vertices. The minimization of an "energy" variable, which defines the goodness of the fit, is driven by an external parameter equivalent to a temperature. Local minima are avoided.

DØ's evolution of inner tracking algorithms

- Initially, 3 different algorithms combinations (plus a 4th algorithm which used elastic arms rather than Kalman filter)
  - They differed in sorting algorithms, starting points, handling of missed hits in detector elements, and shared hits.
  - All 3 were used to debug the event reconstruction on data.
- We have now settled on a combination of histogram sorting+Kalman filter

Started with:

Came to:



What do you need to know
about your detector to do good tracking?

- Where is it (alignment).
- Detector and electronics response to particles (calibration).
- Description of all the material along the track.
- Magnetic field.

Alignment

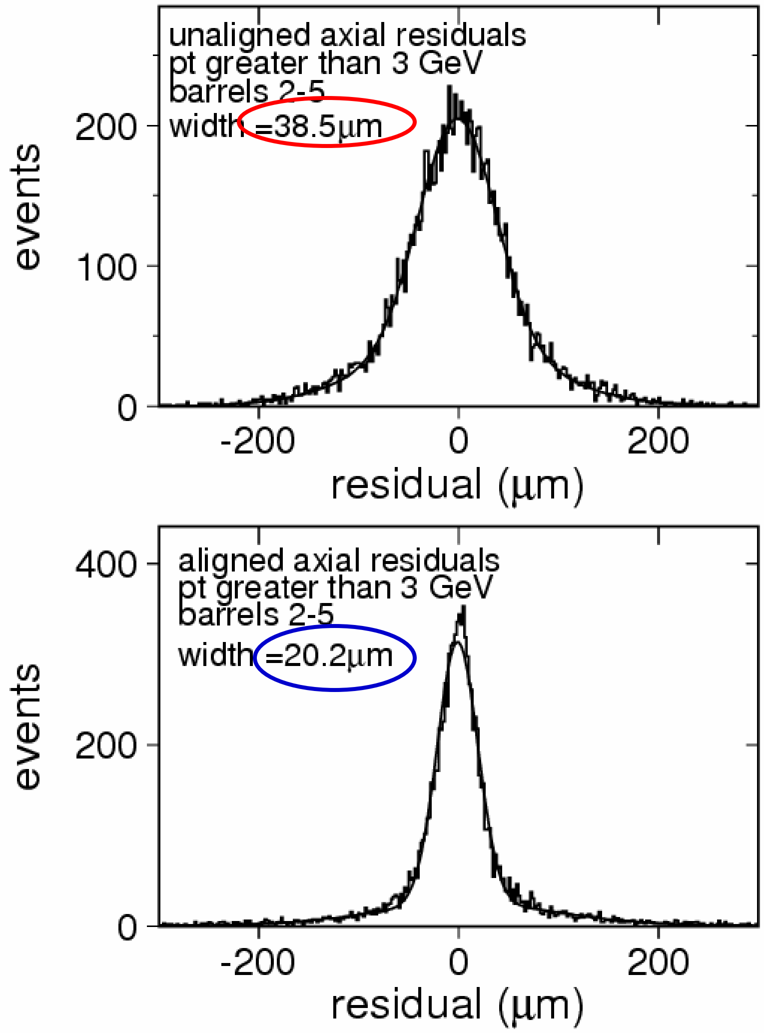
- In order to measure tracks with high precision, one needs to know precisely where the detector elements are located. Variations in position can occur because of:
    - temperature variations.
    - movements of large structures under mechanical stress (e.g. weight of cables, etc.).
- Ways to align a detector are:
    - passive alignment: the detector location is determined before the run by means of an (optical) survey of each detector elements. The data from survey measurements have to be translated from the local coordinate system of the survey to the global detector coordinate system.
    - active alignment (1): continuous monitoring of the location of the detector elements by means of a system of sensors (e.g. a system of laser beams for the CMS muons chambers).
    - active alignment (2): tracks are used to determine the position of the detector elements.

Alignment with tracks

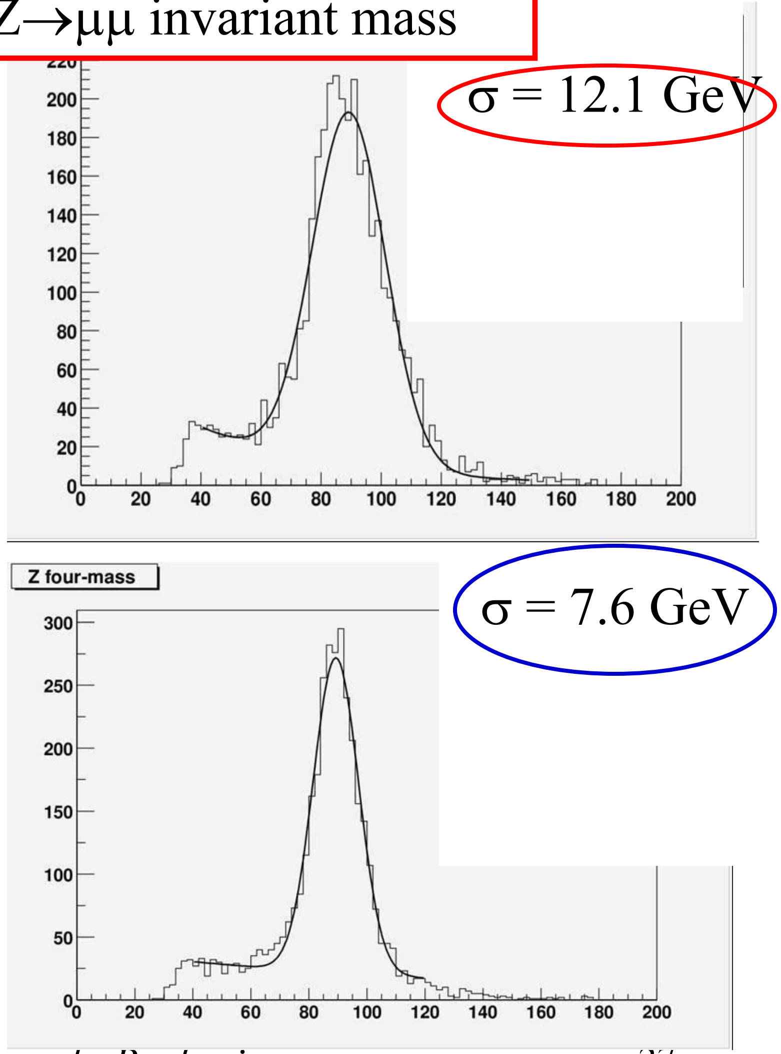
- Alignment is iterative process
  - Minimization of residuals of reconstructed hit position resolution and reconstructed track intersection with the detector plane.
- Example: DØ Silicon Vertex
  - Started from geometry provided by construction survery
    - Impact parameter (i.e. distance of closest approach to the beam line, in 2D, or to (0,0), in 3D) resolution for high- p_T tracks was ~120 μm.
  - Used 500K data with B = 0 magnetic field to align the tracker ;
  - For the check of the alignment, use:
    - Number of track found in the same run before and after alignment
    - Impact parameter resolution of tracks, require:
      - p_T>3 GeV;
      - Coming from primary vertex;
      - With at least 3 SMT hits;
    - $Z \rightarrow \mu^+\mu^-$ mass peak resolution

Alignment with tracks(2)

Track residuals



Z→µµ invariant mass



σ = 12.1 GeV

σ = 7.6 GeV

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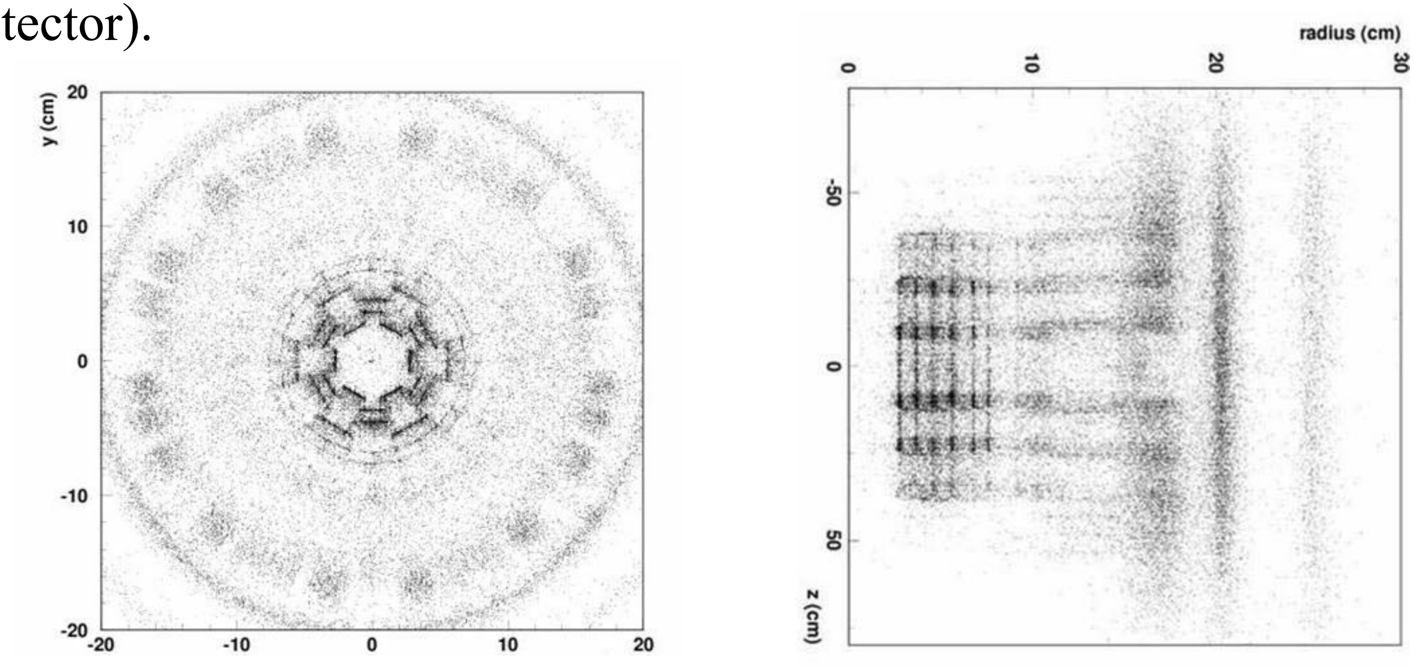
Calibration

- Which calibration constants are needed depends on the type of detector technology and electronics involved. Different detector and electronics parameters might also vary in time faster than others. With current detectors (many, many channels of electronics) the volume of calibration data is quite large and calibration data is stored in database structures (often, commercial products are used).
- Alignment constants are often regarded as part of the calibration data.

Material Studies

- Find photon ($\gamma \rightarrow e^+e^-$) conversions (almost an X-ray picture of the detector).



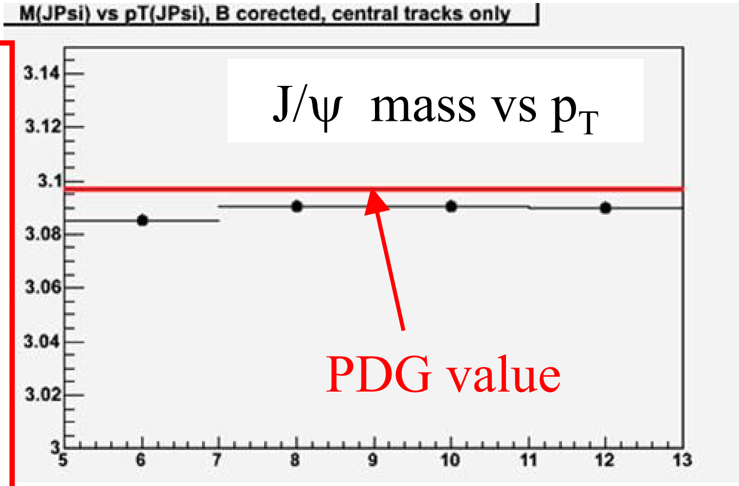
DØ Silicon Vertex

- Use photon conversions to calibrate the amount of material in the Monte Carlo to the amount of material in the data.

Material studies (2)

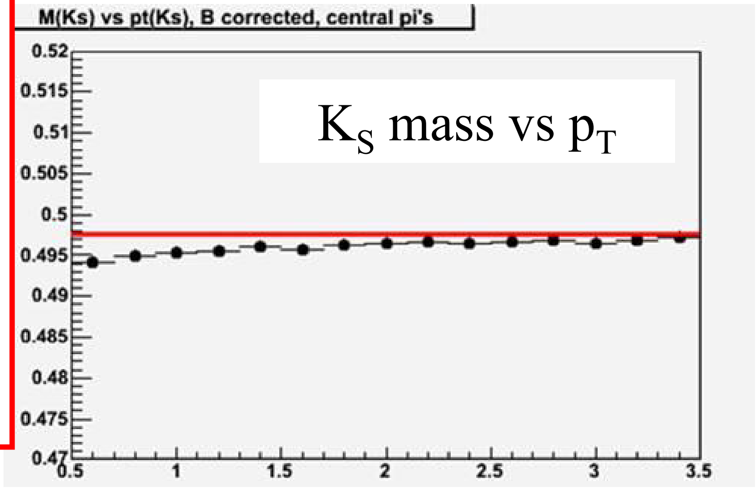
First pass of corrections with tuned material representation (this also contains field map corrections).

Before corrections



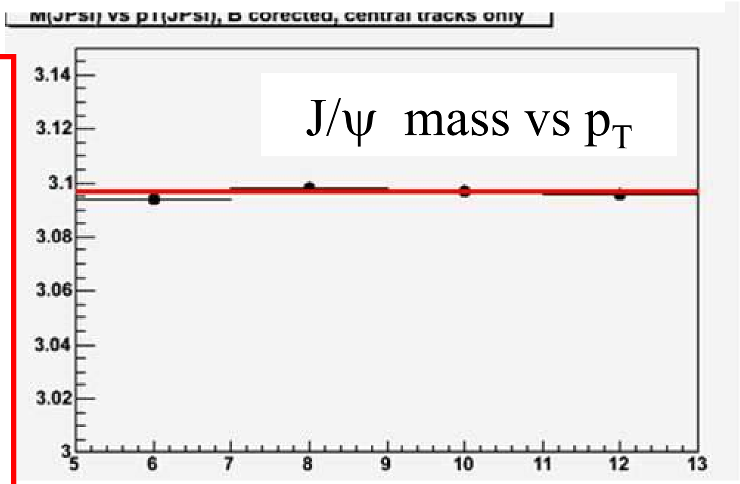
J/ψ mass vs p_T

PDG value

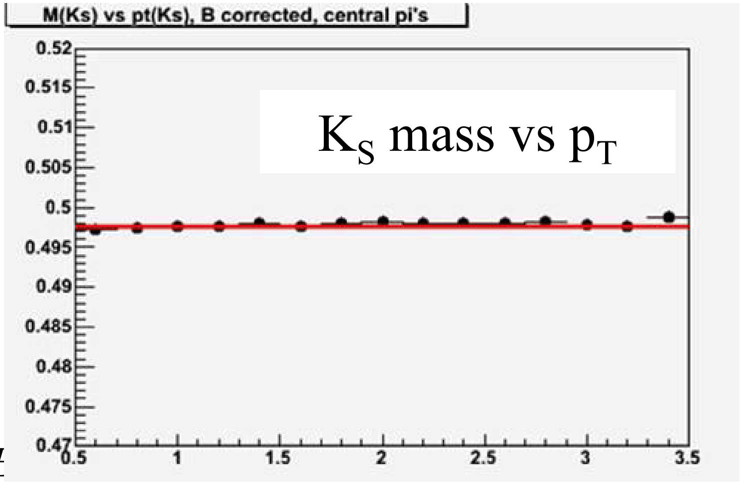


K_S mass vs p_T

After corrections



J/ψ mass vs p_T



K_S mass vs p_T

Magnetic field

- Surveying and monitoring with magnetic probes (Hall and NMR). Both during shutdown periods and during running.
- Physics analysis of known processes (such as resonances mass) can also lead to corrections in the field map.

Tracking Performance

- How to: measure efficiency and resolutions in data

  Example: DØ tracking – use a muon sample
  - Select as clean muons as possible using local muon chambers information;
  - Look how often a global track can be found in a window around muon;
  - To the first order, $\varepsilon = N_{tracks} / N_{muons}$
  - If muon track is missed but another track is reconstructed, efficiency measurement would be biased high:

$$\varepsilon_M = \varepsilon_T + (1 - \varepsilon_T)\varepsilon_R$$

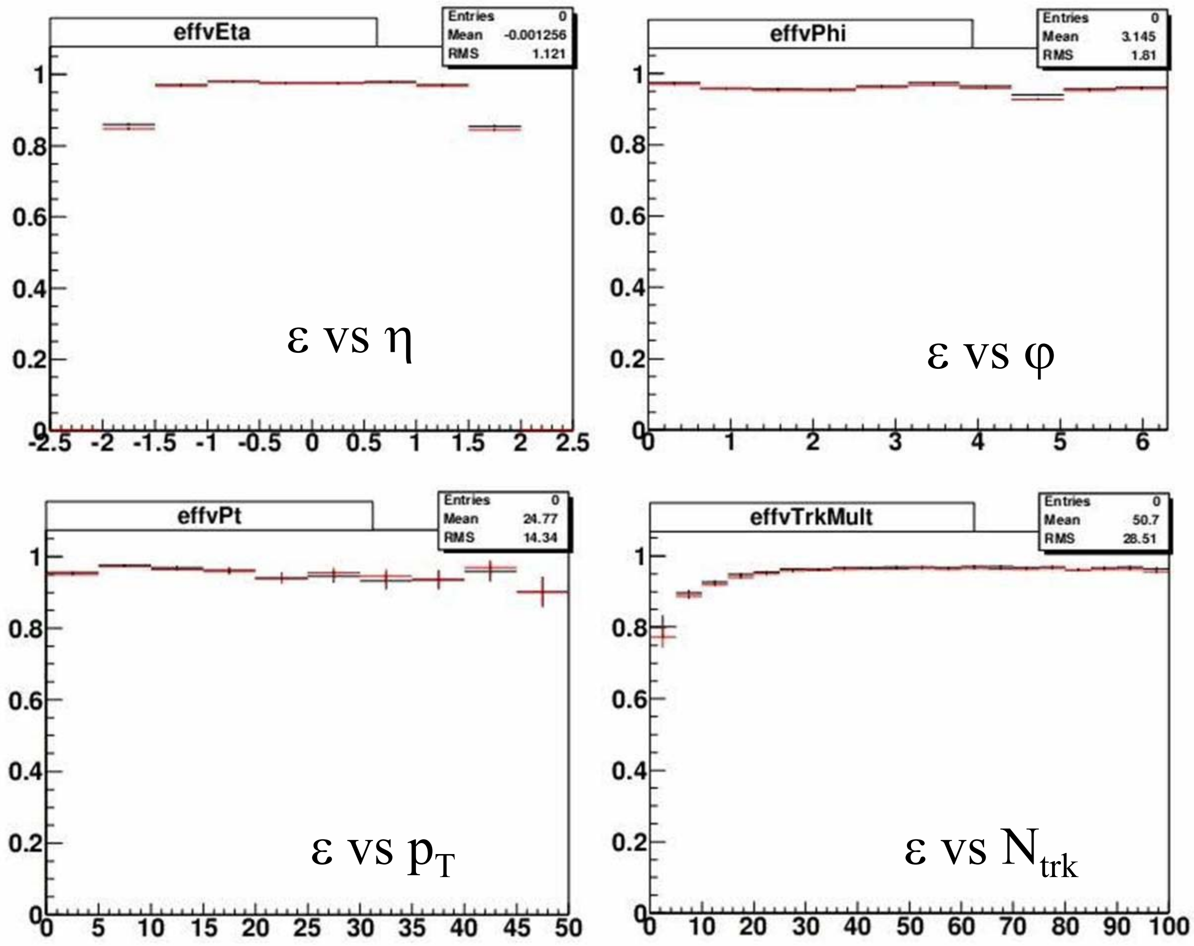
Measured efficiency ***True efficiency*** *Random probability*

  - Measure $\varepsilon_R \sim 5\%$ in control window of the same size but adjacent in φ.

Tracking Performance (2)

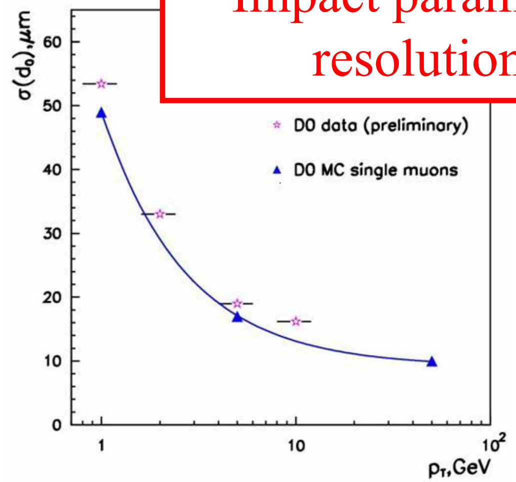
Tracking performance for muons with p_T>1.5 GeV, data

‘True’ efficiency

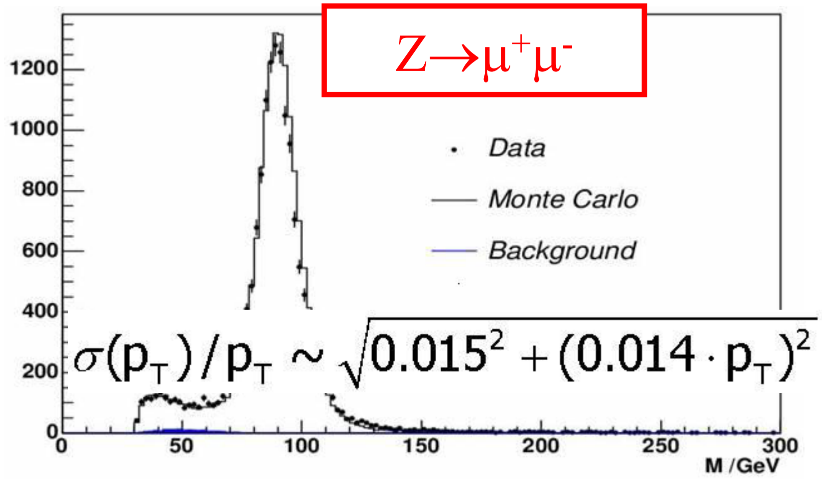


Tracking Performance (3)

Impact parameter resolution

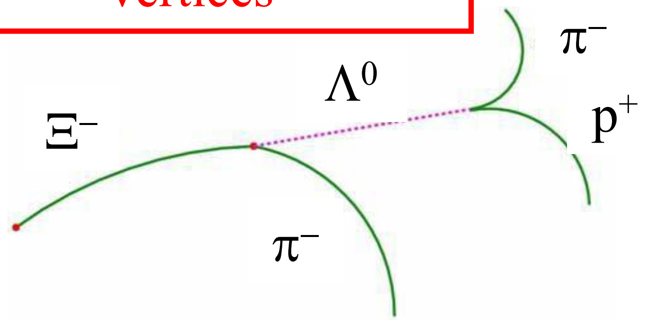


$Z\to\mu^+\mu^-$

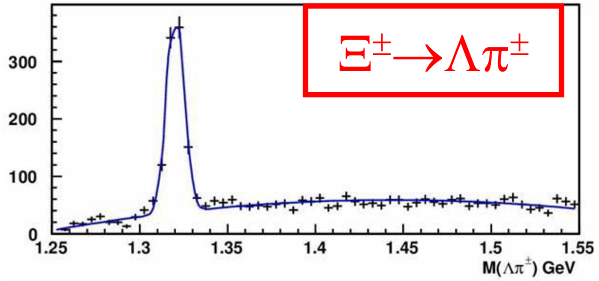


$$\sigma(p_T)/p_T \sim \sqrt{0.015^2 + (0.014 \cdot p_T)^2}$$

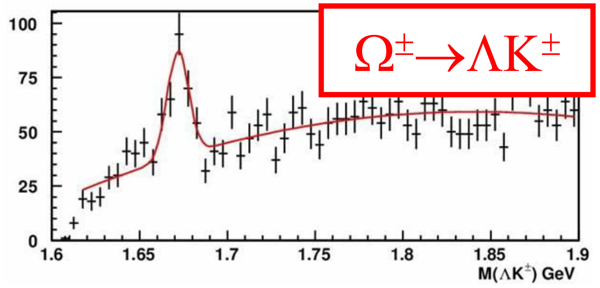
Tracks from secondary vertices



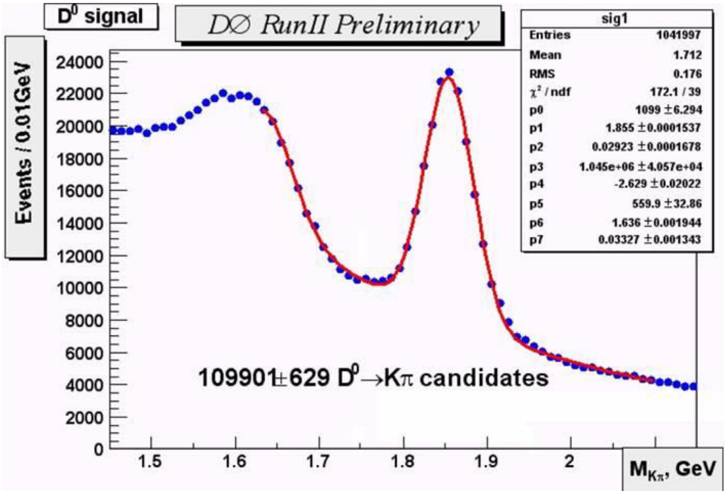
$\Xi^\pm\to\Lambda\pi^\pm$



$\Omega^\pm\to\Lambda K^\pm$



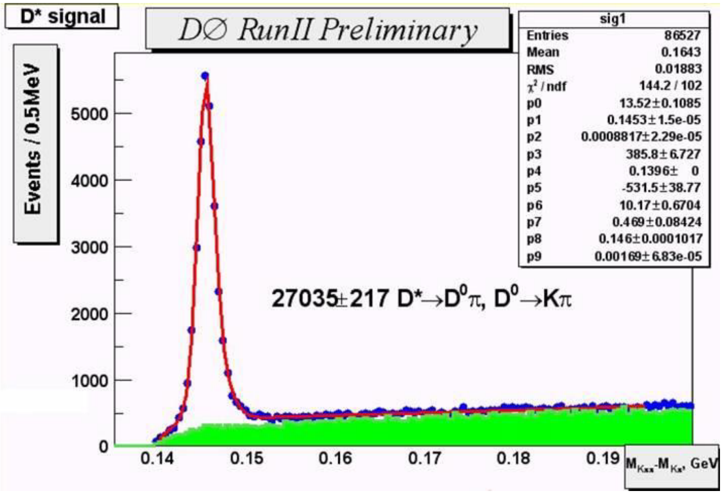
Physics with tracks at DØ (1)

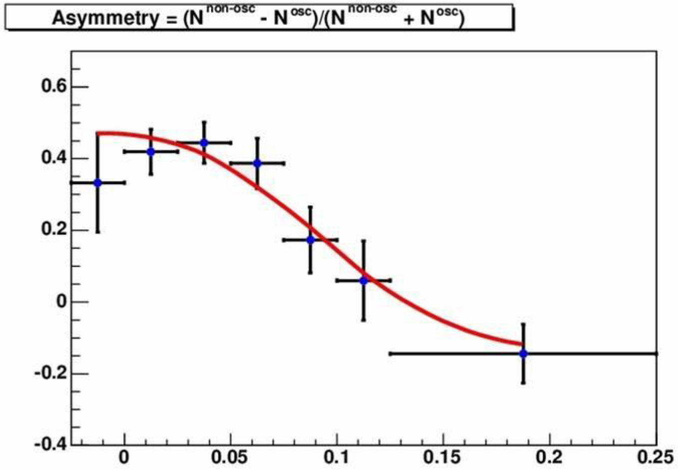


Exclusively reconstructed B→ D (D^0, D*) final states

Opposite side muon used to determine initial b flavor

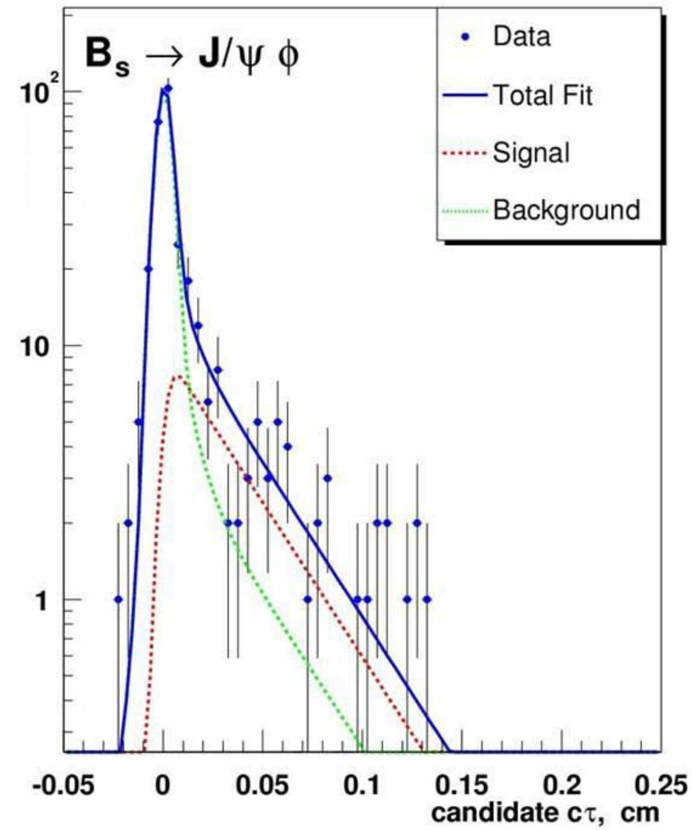
$$\Delta m_d = 0.506 \pm 0.055(stat) \pm 0.049(syst) ps^{-1}$$

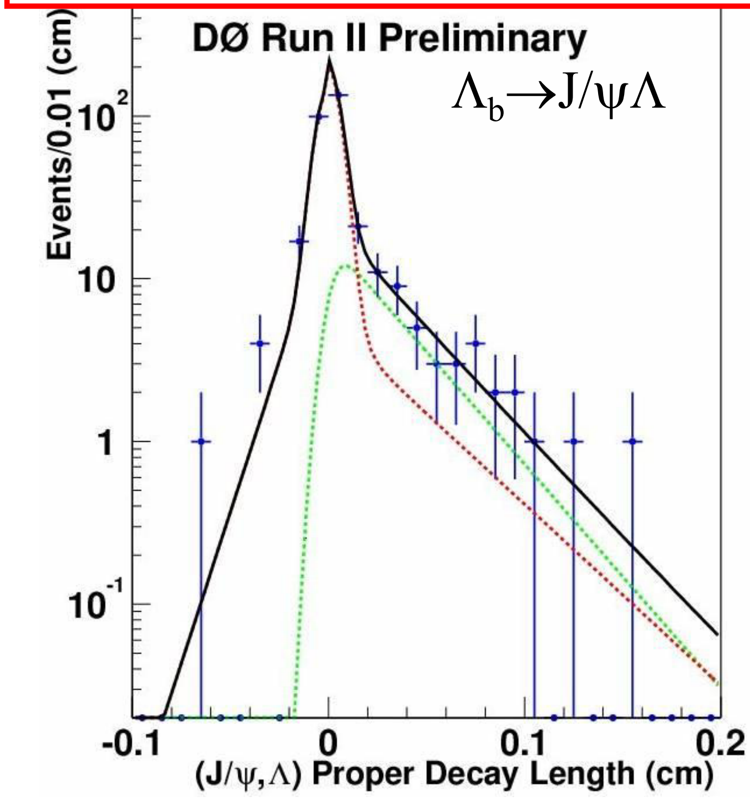




Physics with tracks at DØ (2)

Can be studied only at the Tevatron





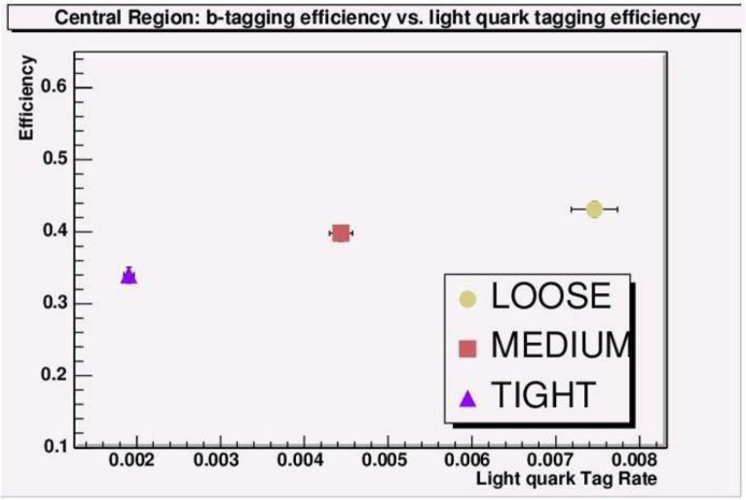
$\tau(B_s) = 1.19^{+0.19}_{-0.16}(stat) \pm 0.14(syst)\mathrm{ps}$

$\tau(\Lambda_b) = 1.05^{+0.21}_{-0.18}(stat) \pm 0.12(syst)\mathrm{ps}$

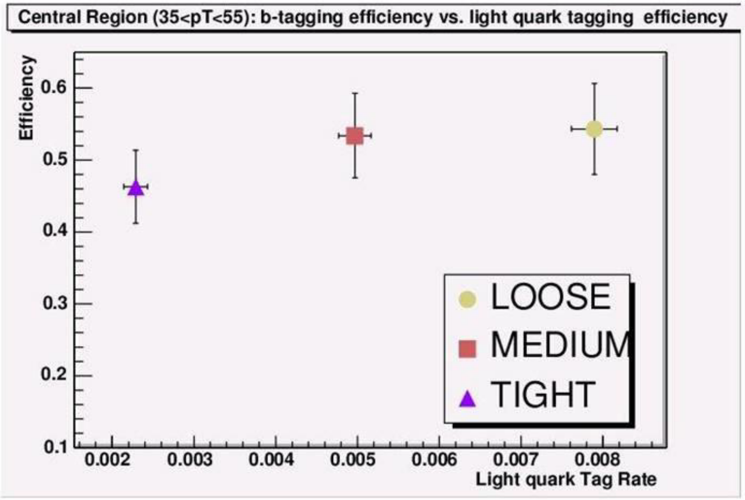
Physics with tracks at DØ (3)

Displaced vertices (b-tagging)

- Three algorithms used:
  - Secondary Vertex (SVT)
  - Jet Lifetime Probability (JLIP)
  - Counting Signed Impact Parameter (CSIP)
- Performance measured on data
- Probability of tagging a $t\bar{t}$ event: $P(n_{tags} \geq 1) \sim 60\%$; $P(n_{tags} \geq 2) \sim 15\%$



Central Region: b-tagging efficiency vs. light quark tagging efficiency

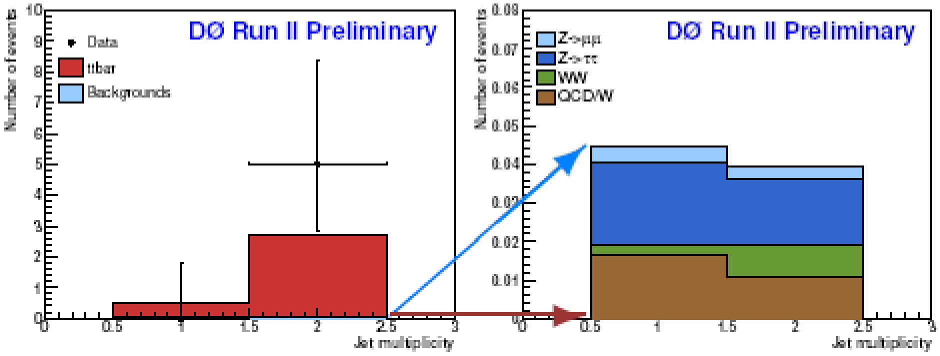


Central Region (35<pT<55): b-tagging efficiency vs. light quark tagging efficiency

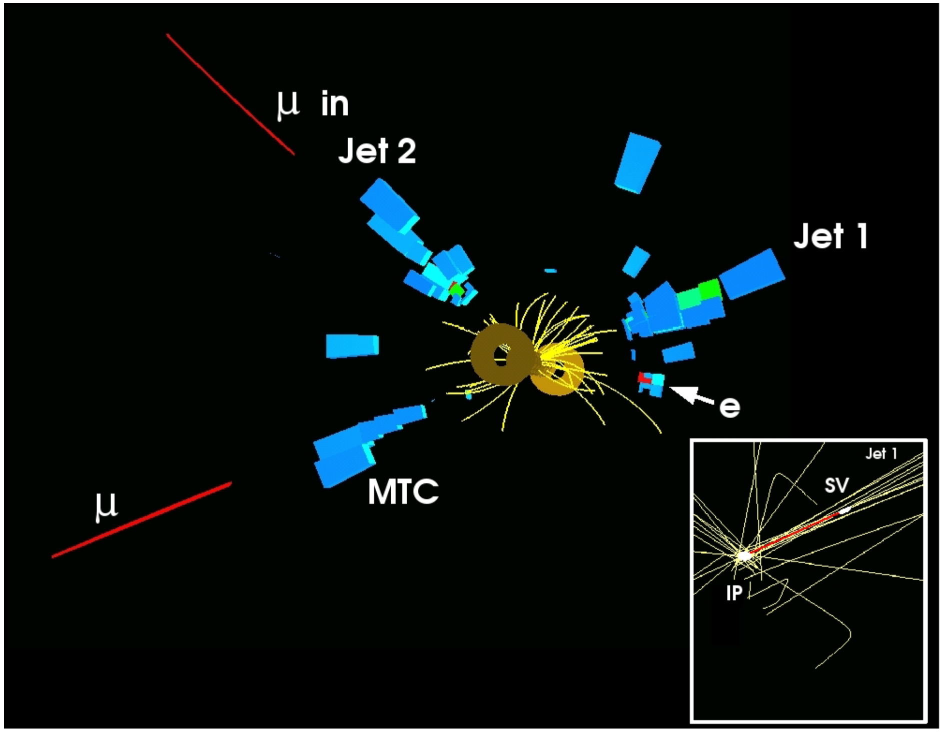
Physics with tracks at DØ (4)

$t\bar{t} \rightarrow e\mu + \text{jets}$

with two b-tagged jets (very clean signature for Top quark pair production



Number of b-tagged events vs. jet multiplicity



References

- Fitting theory (by Paul Avery):

http://www.phys.ufl.edu/~avery/fitting.html

- Everything you might want to know about Silicon detectors, and more (by Helmut Spieler):

http://www-physics.lbl.gov/~spieler/

- One reference on Elastic Arms algorithms:

  M. Lindstrom, "Track Reconstruction in the ATLAS Detector using Elastic Arms", *Nuclear Instruments and Methods in Physics Research A* **357**, 129-149 (1995).

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And now, the challenge!

W→μν in high
Luminosity
at the LHC