Tracking and Vertexing
HCPSS 2006 (Fermilab)

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What We'll Cover Today

- Charged Particles
  - Helixes
  - Track parameterization
  - Energy loss
- Reconstructing Hits
  - Detectors: drift, Si, fiber
  - 2D points
  - 3D points
  - 4D points?
- Group activity! (5 mins)
- Track Reconstruction
  - Fitting: χ^2, Kalman filter
  - Multiple scattering
  - Alignment
  - Multiplicity and fakes
- Vertexing
- B-Tagging

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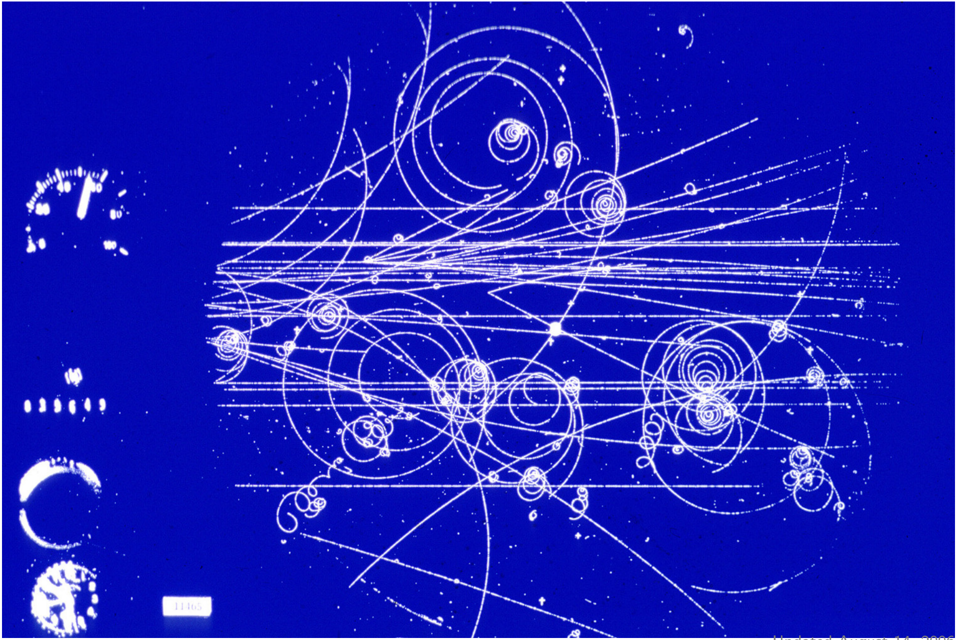
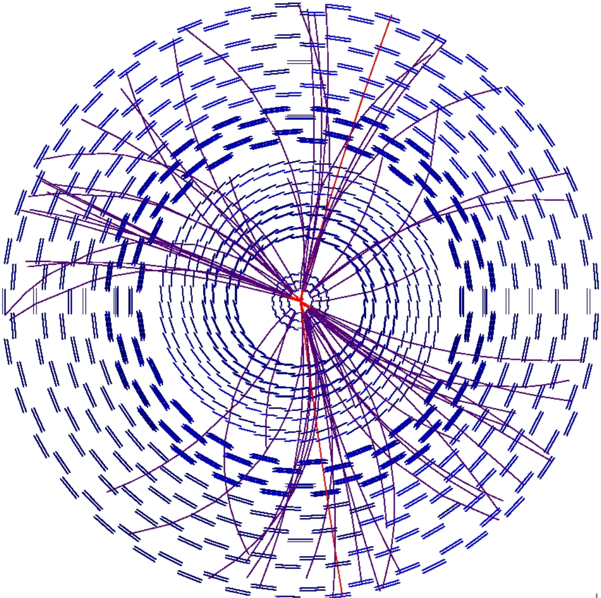
CERN Bubble Chamber



CMS Tracking Chamber



Basic Idea

When we talk about "tracking," we want to do the following:

- Measure the true path of the charged particle, which let's us know...
- The momentum (3-momentum) if we know the magnetic field
- The sign of the charge of the particle
- With other constraints or assumptions, the "origin" in space of the particle
- Without some other detector though, we can't measure the mass independently just with a tracker

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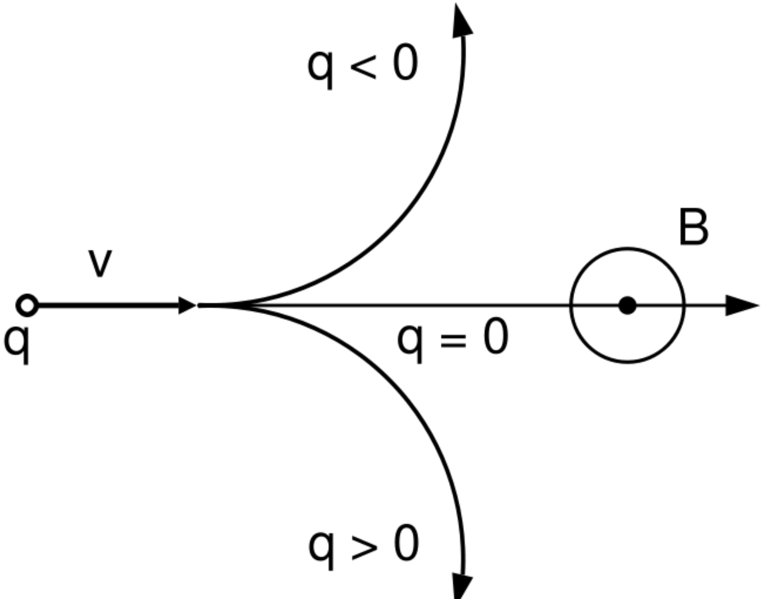
Lorentz Force: $q(\vec{v} \times \vec{B})$



Helicoidal Tracks

- For a solenoidal magnetic field (ie the main magnet), z is along the field direction
- The Lorentz force causes it to trace out a circle in the $x - y$ plane and move with constant velocity along z
- Displacement in z is proportional to the arclength (s) traversed in $x - y$
- We can think of a straight line in the $s - z$ plane

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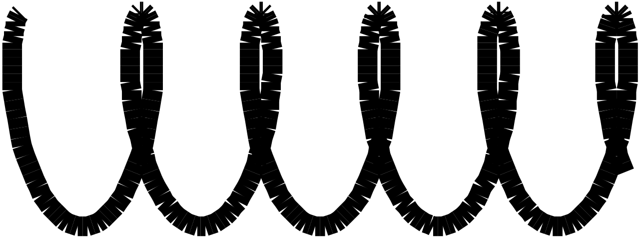

Helix Parameters

We can decompose the momentum of a track in spherical coordinates [1]:

$$p_x = p\cos\phi\sin\theta$$
$$p_y = p\sin\phi\sin\theta$$
$$p_z = p\cos\theta$$

Different experiments choose different ranges for the angles, it's important that you figure out what they are using:

$$\phi \in [-\pi, \pi] \qquad \theta \in [0, \pi]$$

There must also be some "reference point" in space to uniquely define our helix: (x_r, y_r, z_r)

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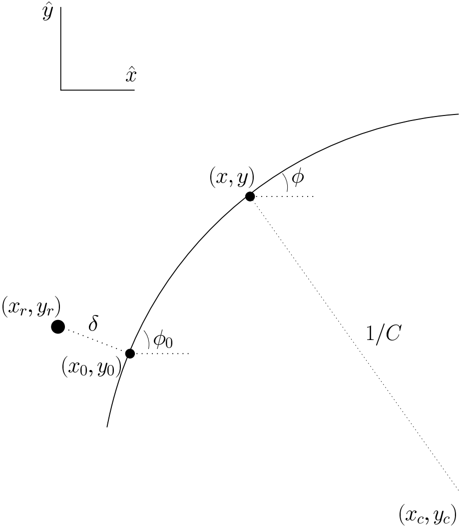
Helix Parameters in $x - y$ Plane

This parameterization is more closely related to things we actually measure with our trackers



- C: Curvature of the track. Signed with charge.
- ϕ_0: Azimuthal angle of the momentum at the point of closest approach
- δ: Distance of closest approach. (Also signed, but differently.)

Transverse momentum

The component of the momentum in the $x - y$ plane, the transverse momentum p_T or $p_\perp$, is given by

$$p_\perp[\mathrm{GeV}] = \frac{B[\mathrm{kG}]\ c[\mathrm{mm/s}]\ 10^{-10}}{C[\mathrm{mm}^{-1}]} = \frac{B[\mathrm{T}]\ c[\mathrm{cm/s}]\ 10^{-13}}{C[\mathrm{cm}^{-1}]}$$

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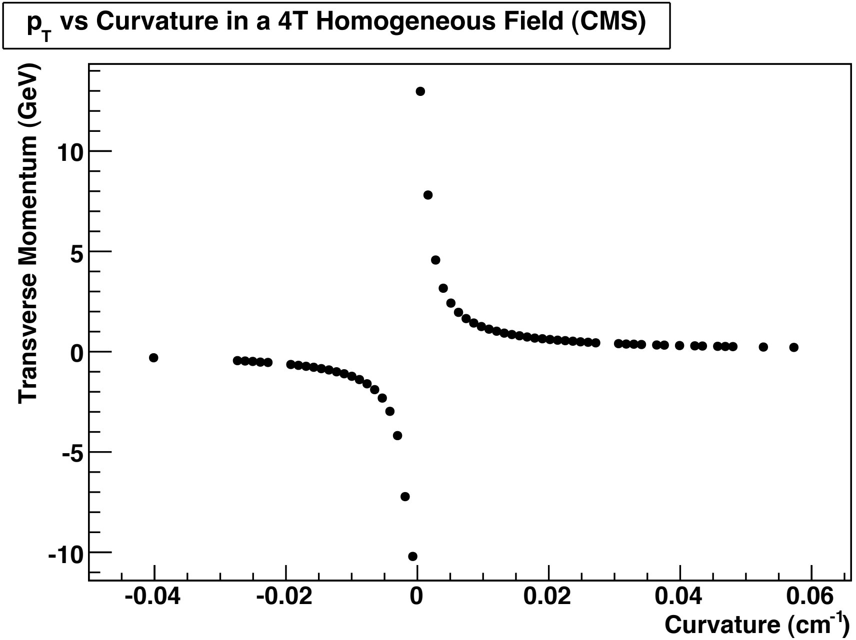


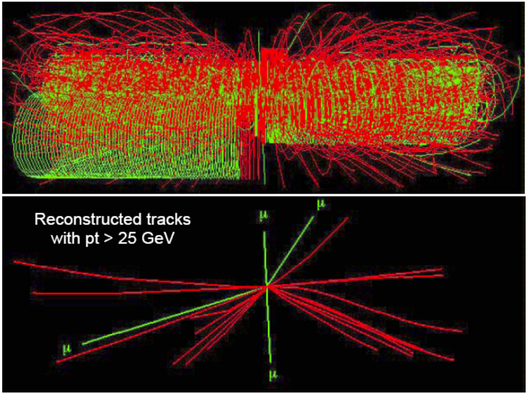
p_T vs Curvature in a 4T Homogeneous Field (CMS)
Transverse Momentum (GeV)
10
5
0
-5
-10
-0.04
-0.02
0
0.02
0.04
0.06
Curvature (cm^{-1})

Use p_T to separate wheat from chaff

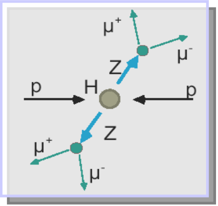
Minimum bias events

Luminosity = 10^{34} cm^{-2}s^{-1} = 10^{7} mb^{-1}Hz
Interaction rate = 10^{7}x80 = 8x10^{8} Hz
Interactions/crossing = 20

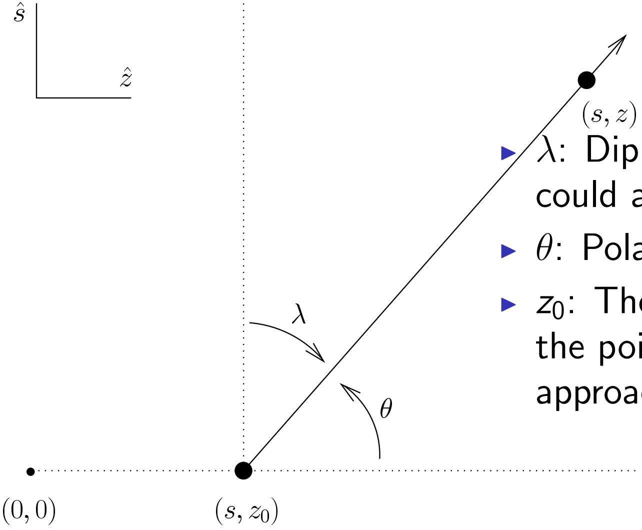
σ(pp) = 80 mb at 14 TeV
Bunch crossing = 25 ns = 2.5x10^{-8} s



Higgs event
+
~25 minimum bias events



$z = z_0 + s \tan \lambda$



- λ: Dip angle of track, or could also use
- θ: Polar angle of track
- z_0: The z of the track at the point of closest approach in $x - y$

Energy Loss

- If a charged particle passes through material, it can lose energy and slow down and change direction somewhat
- As a particle bends in the magnetic field, it can emit bremsstrahlung and slow down

Our model of the trajectory of the charged particle has to take these effects into account if they are important

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Tracking Detector

- Should have the least amount of material as possible
- Should have as many measurements of the trajectory as possible
- To measure p_T well, the longer the lever arm the better
- Measurement points should be as precise as possible

Some of the main technologies in use right now covert the energy lost by a charged particle with

- Gas and wire: ions in gas drift to wire under influence of electric field. Drift time and position must be precisely known
- Scintillating fibers
- Semiconductor: usually silicon, fully depleted. Charge is collected in precisely laid down strips or pixels

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CDF's COT

Figure 4. The COT during "stringing" of the wire planes and field sheets. The carbon composite inner cylinder, aluminum end plate (east) and aluminum outer cylinder are visible. Superlayers 1-5 have been strung and superlayer 6 is about half done. A wire plane is being inserted at 10:00 and a field plane at 4:00. Pre-tension fixtures are seen in superlayers 6 – 8.

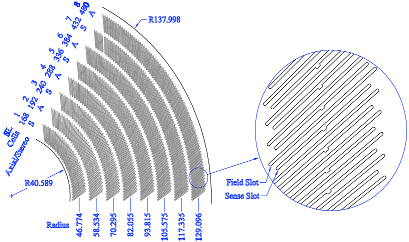
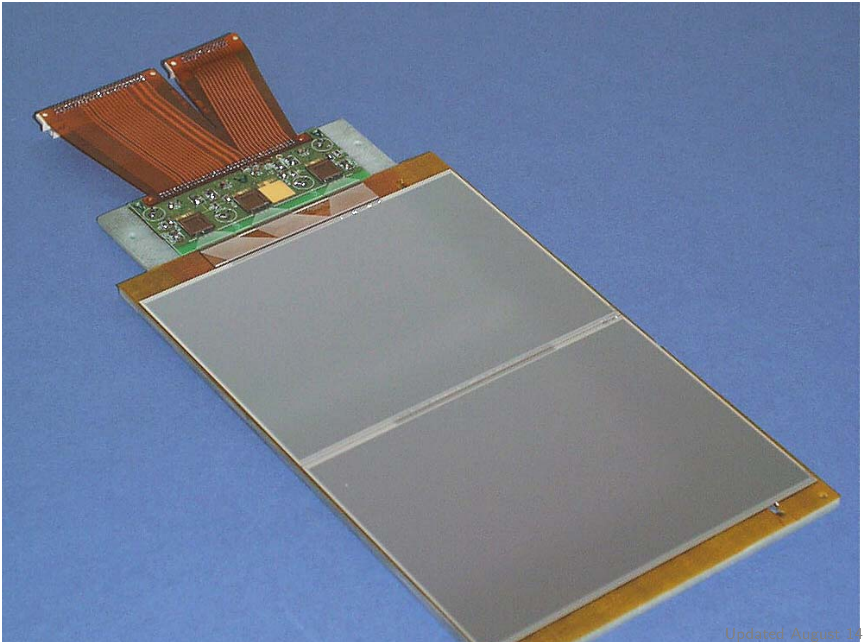
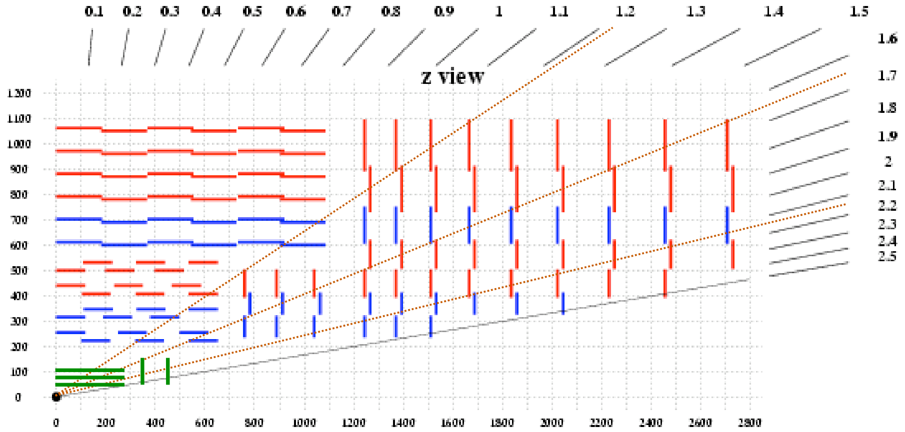


Figure 2. 1/6 section of the COT end plate. For each superlayer is given the total number of supercells, the wire orientation (axial or stereo), and the average radius. The enlargement shows the sense and field slot geometry in detail. Dimensions are in cm.

Silicon Strip Module



CMS All Silicon Tracker



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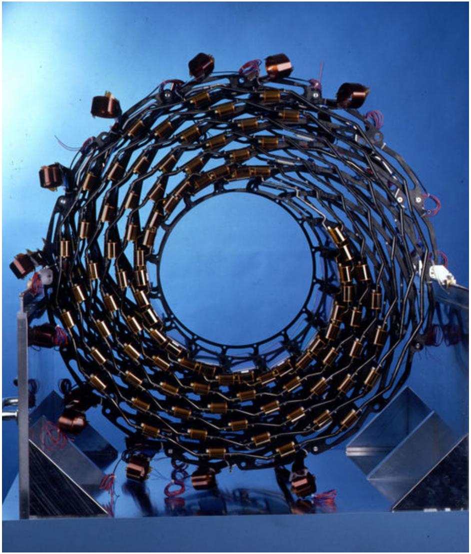
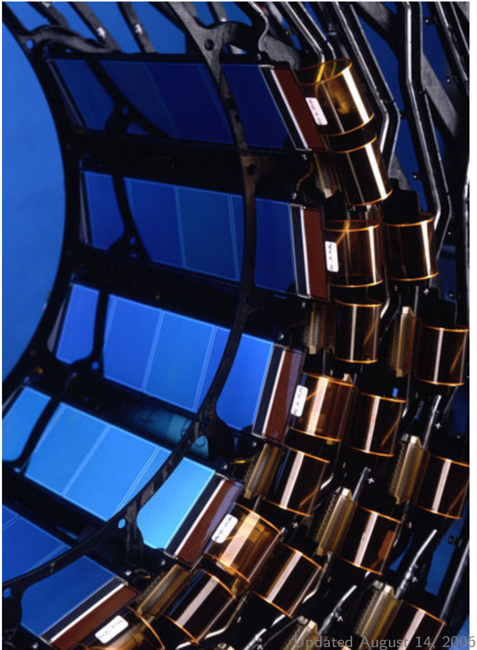
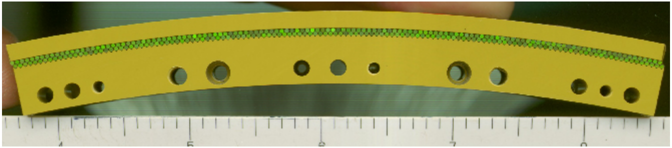
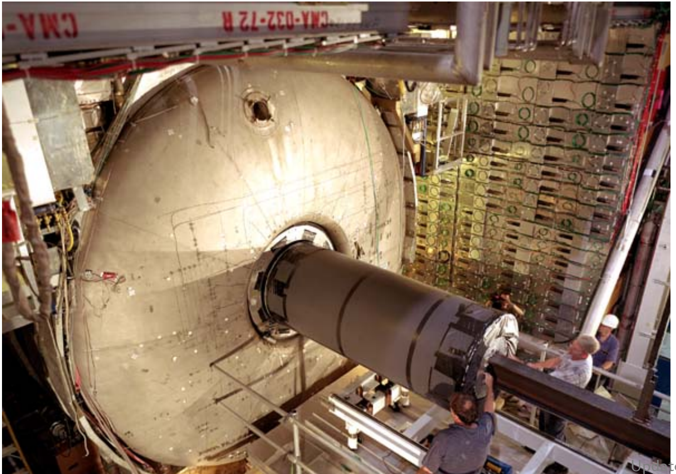


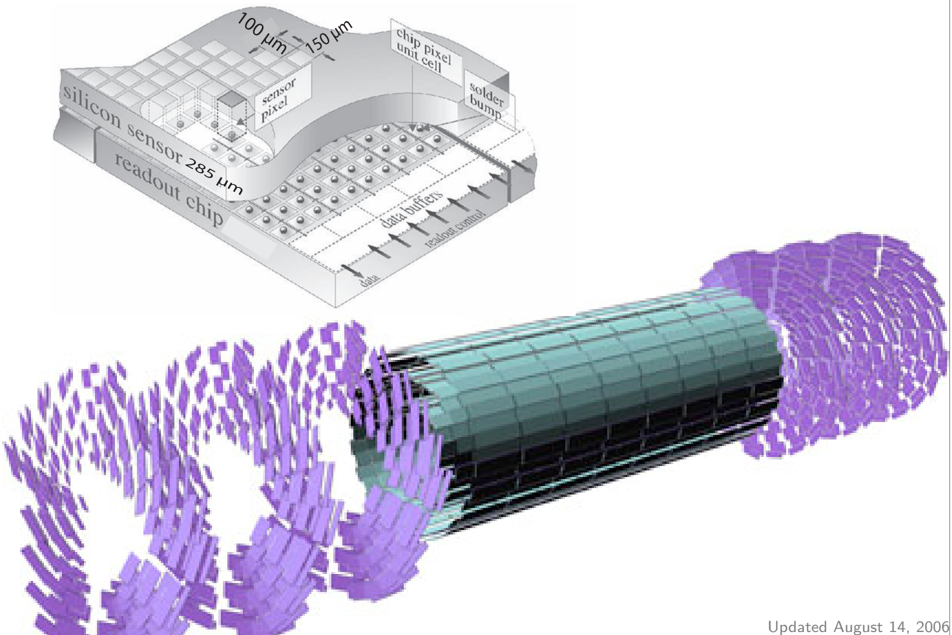


D0 Fiber Tracker

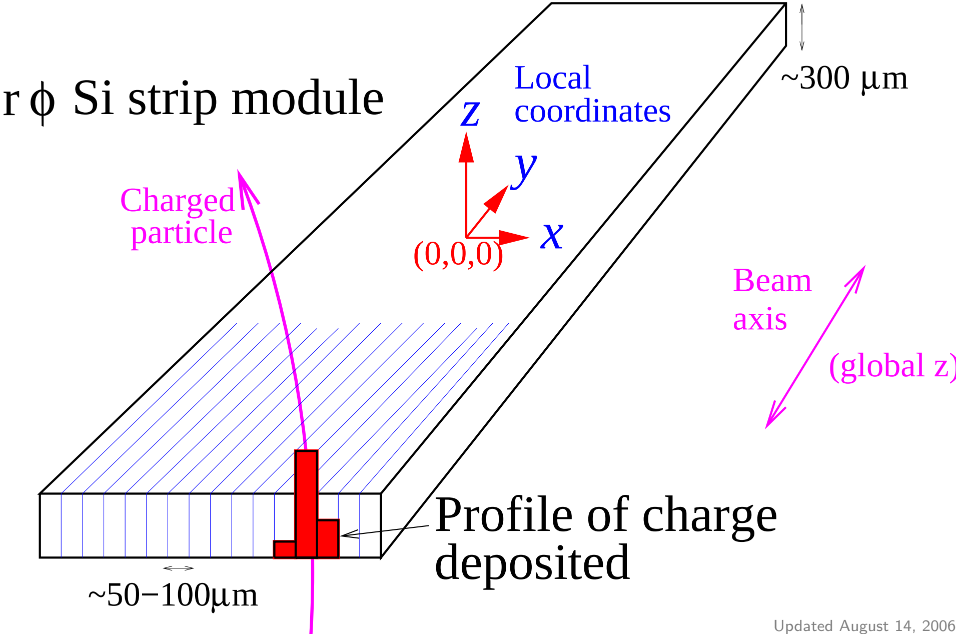




CMS Pixel Detector



2D Point ($r\phi$ or rz): $\bar{x} = (\sum i * q_i) / \sum q_i$



Resolution of Si Strip Detector

- The resolution of a Si hit depends on the number of strips in the cluster (2-strip most precise)
- Charge drifts with Lorentz force: $q(\vec{E} + \vec{v} \times \vec{B})$
- Thin material: Landau distribution of charge [2]
- Track impact angle & position makes a difference [3]
- Delta rays (hard knock e^-) can bias charge distribution
- Dead channels, noise, V_{dep}, temperature all could affect this too
- Radiation damage changes
- Pileup from previous event
- Multiple particles passing through same strips

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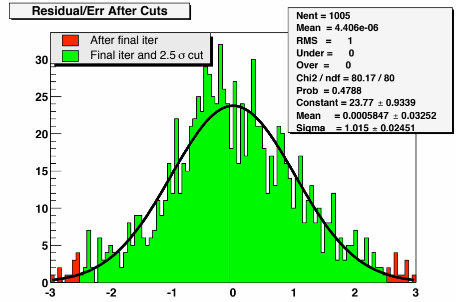
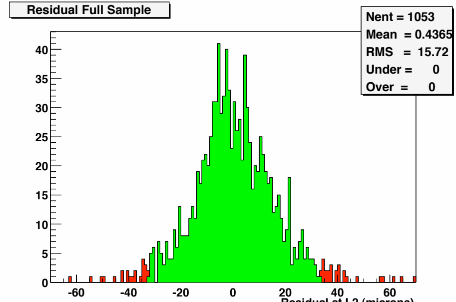
- The resolution of a Si hit depends on the number of strips in the cluster (2-strip most precise)
- Charge drifts with Lorentz force: $q(\vec{\boldsymbol{E}} + \vec{\boldsymbol{v}} \times \vec{\boldsymbol{B}})$
- Thin material: Landau distribution of charge [2]
- Track impact angle & position makes a difference [3]
- Delta rays (hard knock e^-) can bias charge distribution
- Dead channels, noise, V_{dep}, temperature all could affect this too
- Radiation damage changes
- Pileup from previous event
- Multiple particles passing through same strips

Typical Resolution of 50 μm Strips (CDF)





Cluster Width	Resolution
1	12 μm
2	9 μm
3	14 μm
4+	22 μm

- *rz* strips are either shallow stereo (2°), or 90° stereo but larger pitch
- Intrinsic resolution of larger pitch stereo usually factor of 2+ worse than $r\phi$

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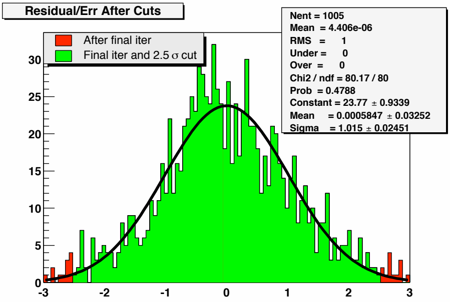

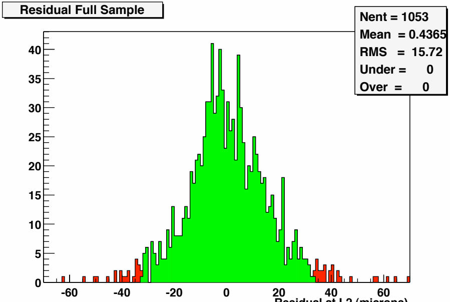

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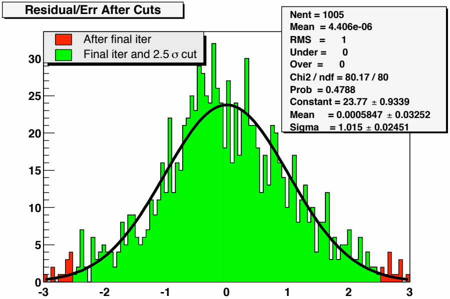

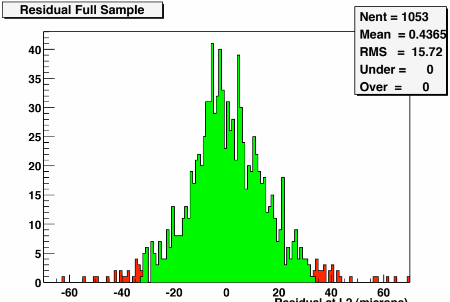

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3D Points

A three dimensional point is reconstructed if we know both the local x and y coordinate on the detector element and we know the detector's location in space precisely.

- If we have two simultaneous measurements in orthogonal coordinates on a double-sided silicon detector, or in a wire chamber or fiber tracker with axial and stereo elements. We match the $r\phi$ and rz measurements and make a 3D space point – the problem is the matching can be hard to do
- Si pixel detectors! These are little rectangles of silicon which automatically give us 3D information without matching info from axial and stereo components.

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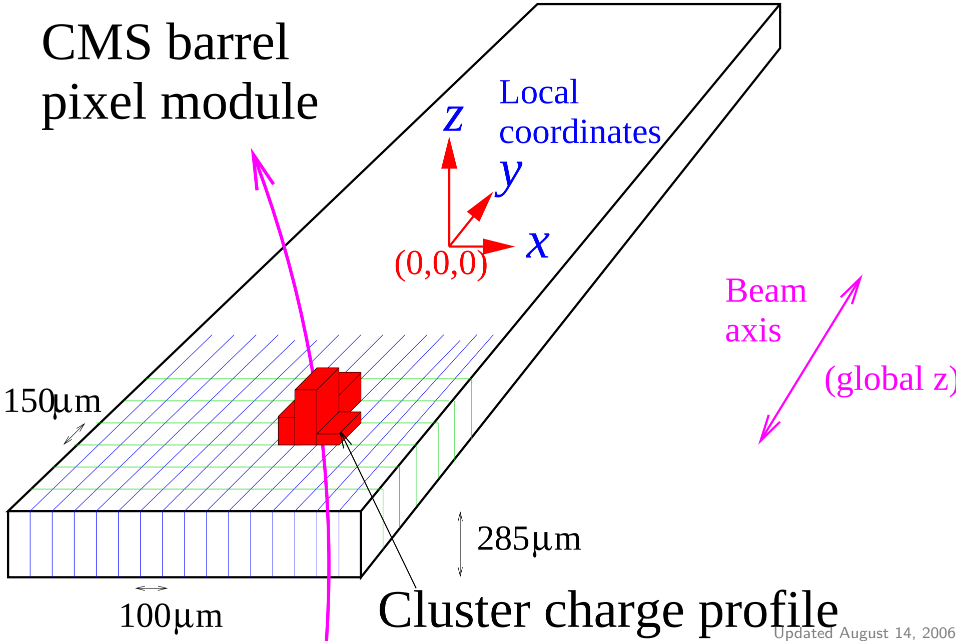
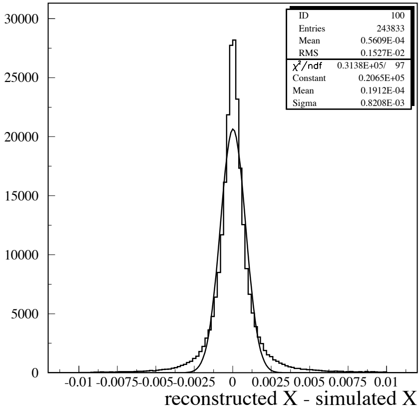
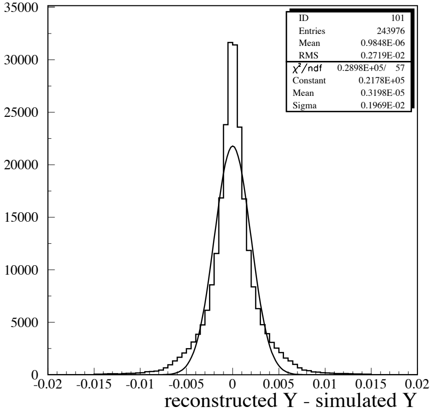
3D Space Point from Pixel Detector

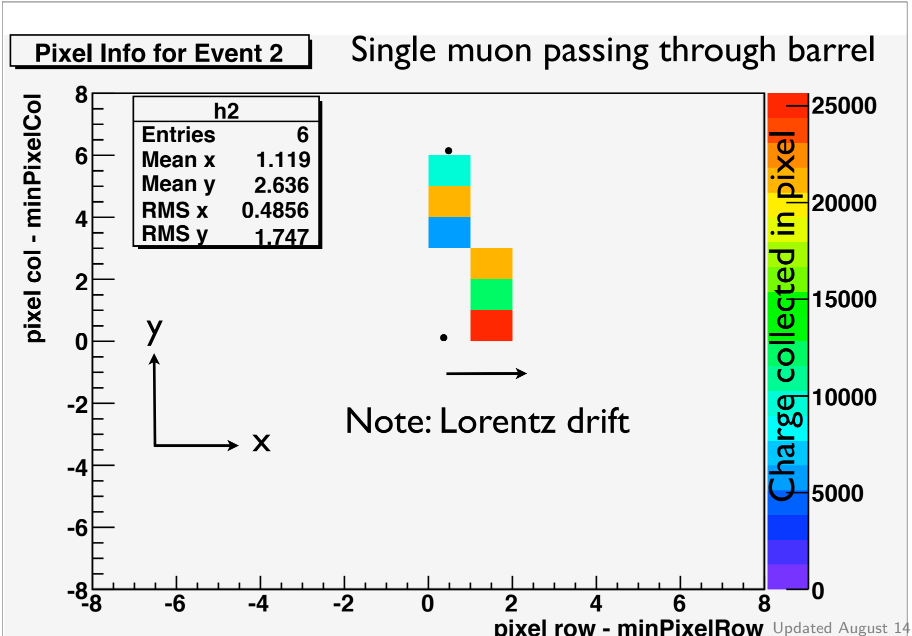


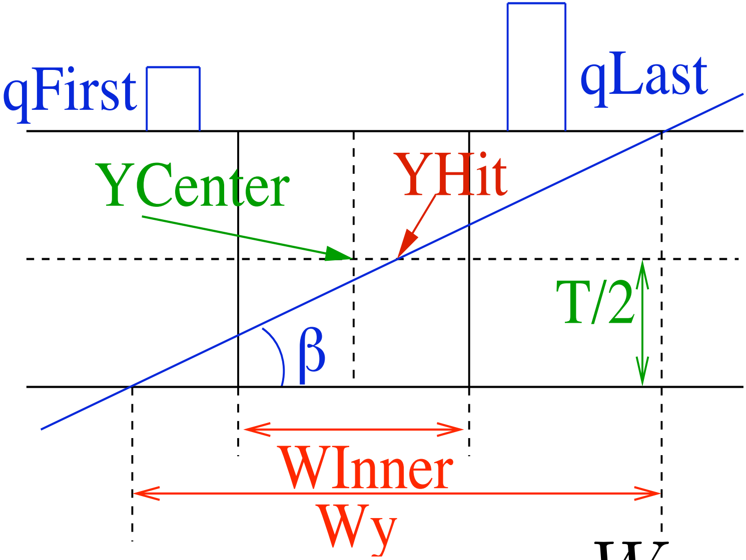
Typical Pixel Resolution (CMS): $8 - 20\ \mu\text{m}$





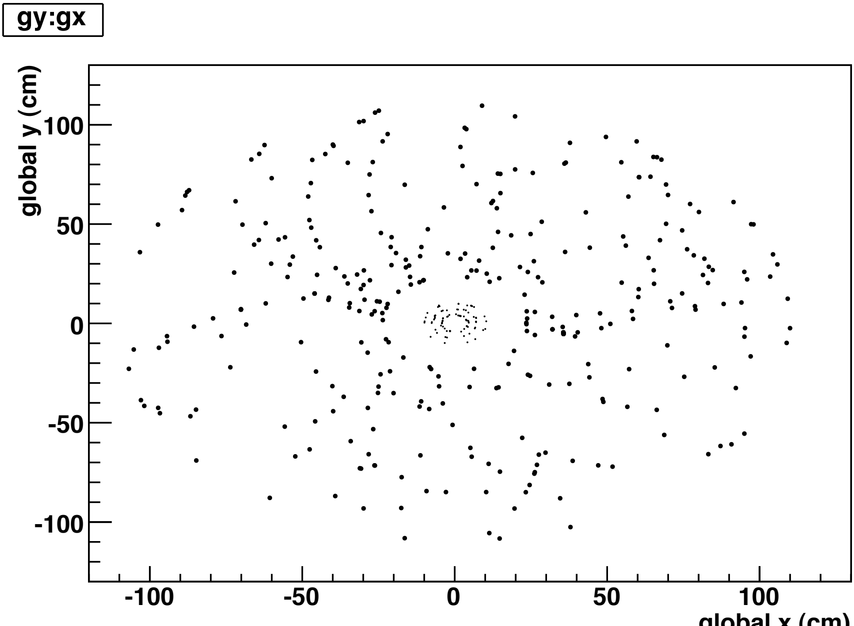
Pixel Stub! Impact angle (θ) from shape





$$\tan(\pi/2 - \beta) = \frac{W_y}{T}$$

Can you find the 50 GeV p_T Track?



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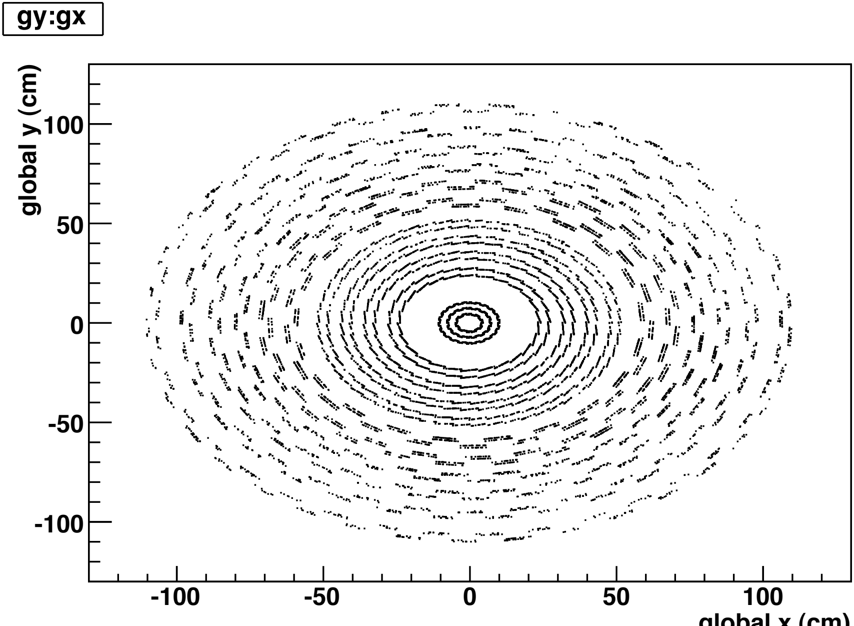

Pattern Recognition & Track Fitting

Typically, pattern recognition algorithms are either "inside-out" or "outside-in."

- You have to start with some idea of the path of the particle to bootstrap your algorithm: a track seed
- Then you take this candidate, this seed, can try to find compatible hits in other layers
- Continue this process until you've met some criteria for what a "good track" should have
- Once you've got your hits for your track, try to do a good job of fitting your pseudohelix
- Psuedohelix because there is energy loss and multiple scattering
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Alignment is Crucial!

- Before you have a hope of matching hits from one layer to the next to make a helix, your detector elements' positions must be known to the level of your intrinsic resolution
- But how can you align your detector without tracks?
- This is the subject of part of Nick Hadley's talks on calibrations
- But it is always an iterative procedure, bootstrapped by a very good optical survey during construction and installation
- Here's an example (from ATLAS) of what needs to be done...

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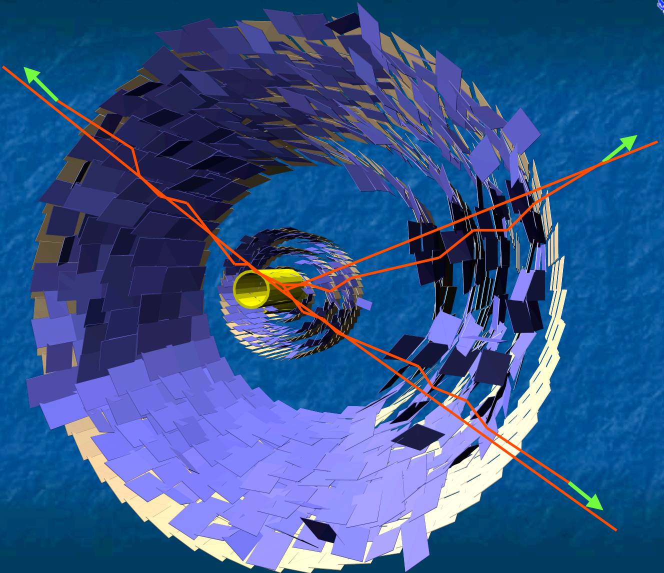
Global χ^2 fit – the idea



Kalman Filter

- The Kalman Filter [4] is an iterative procedure
- You start with a seed track. For example, a pair of hits in the pixel detector that line up within 5σ of the primary interaction region
- Then you add points on successive layers, taking into account projected error from current hypothesis track and multiple scattering
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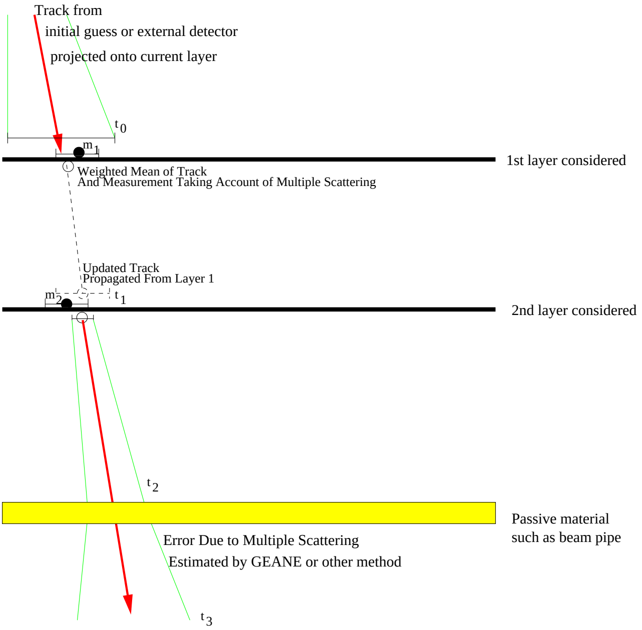
Kalman Filter in Action



Tracking Resolution

The resolution of the various helix parameters depends on a number of things

- The number of hits used from various subdetectors (hopefully, more is better)
- The momentum of the particle. Higher momentum particles deflect less from multiple scattering
- The polar angle of the track (η)
- Quality of alignment
- Presence of other tracks!
- Detector noise

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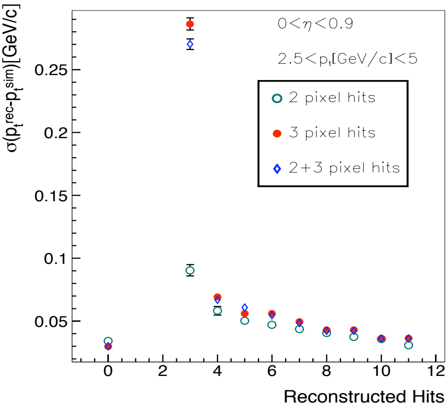
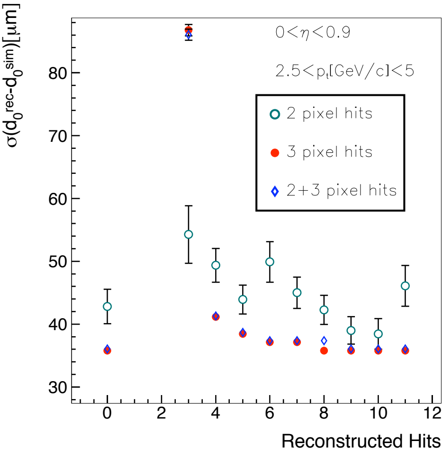
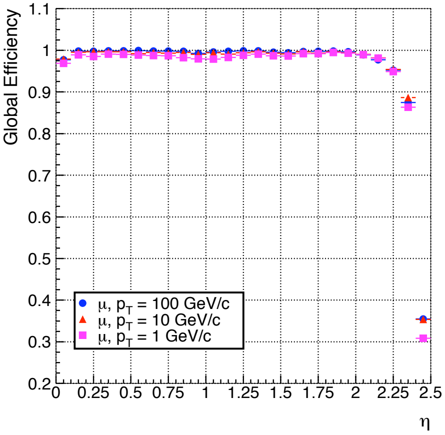
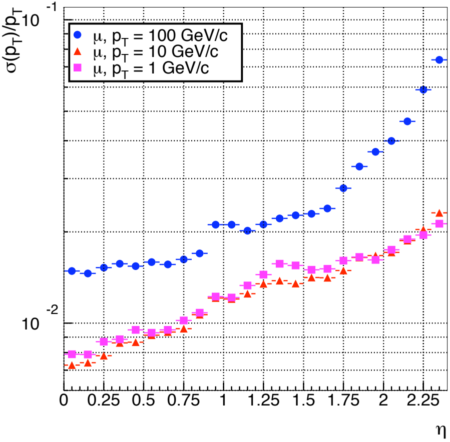
p_T and d_0 Resolution (CMS)



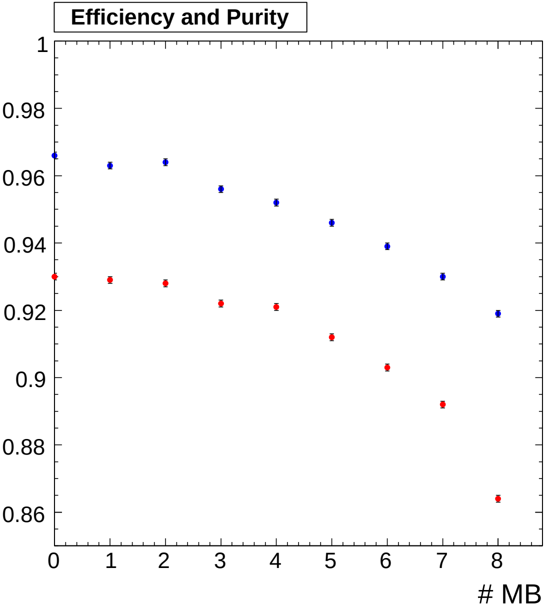


Single Track Reconstruction Efficiency (CMS)





Mult. Interactions Degrade Track Eff (D0)

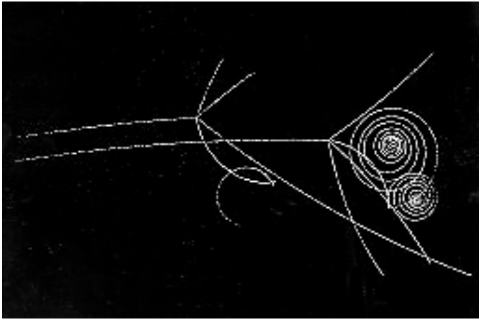


High Multiplicity Strategies

- If your inner layers are being swamped, use an outside-in algorithm instead of an inside-out algorithm
- Try to boost efficiency for higher p_T tracks by reconstructing them first, and then remove these hits from consideration
- Upgrade your detector

Vertexing: Basic Idea

The basic idea of vertexing is to figure out where the particles came from. We can associate tracks to particle decays and interactions this way.



Vertexing Strategy

- A vertex is a point where more than one particle comes from
- If there is more than one track coming from the same place, then the helixes should cross each other, right?
- Look for places where helixes cross
- Caveat: The track parameters $\vec{p}_i = (C, \phi, d_0, \tan\lambda, z_0)$ are different in different parts of the helix

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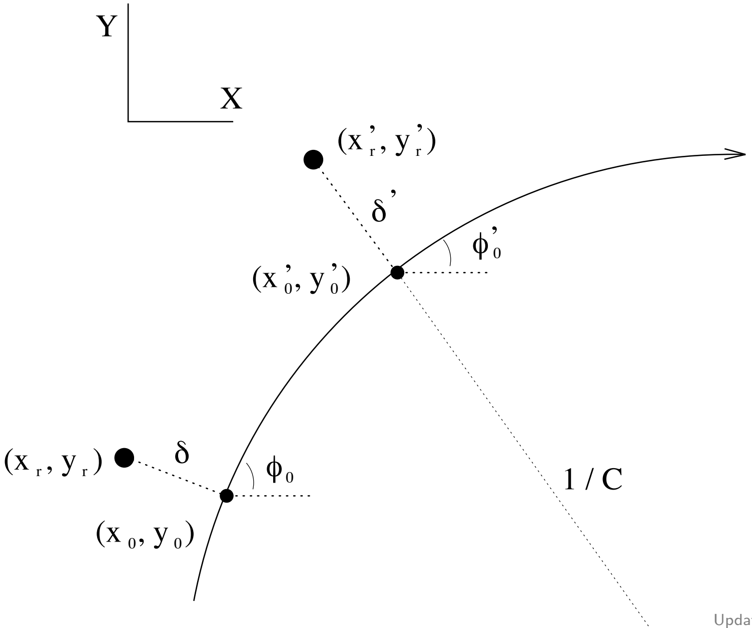
Track Parameters Depend on Reference



Vertexing Algorithm

- If helixes cross, that means the track parameters must be the same at some point
- In 2D, this is as simple as looking for crossing circles
- But you can take full advantage of full track parameterization and covariance matrix to look for vertexes
- Most methods [5] are built on some kind of χ^2 of track parameters

$$\chi^2 = \sum_{i}^{N_{\mathrm{trk}}} (\vec{x} - \vec{g}(\vec{p}_i))^{\mathrm{T}} \mathbf{J}^{\mathrm{T}} \mathbf{M}_i^{-1} \mathbf{J} (\vec{x} - \vec{g}(\vec{p}_i))$$

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Vertex Algorithm Continued

- Again, we have a problem of pattern recognition
- The χ^2 can be defined for any collection of tracks
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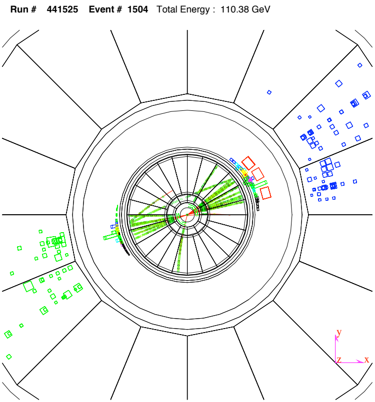
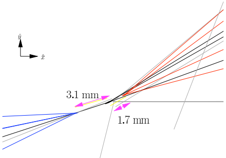
Vertex Resolution (CMS)

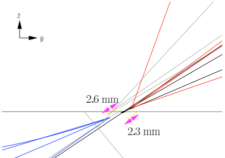
Filter	x-coordinate σ [μm]	x-coordinate Tails [μm]	x-coordinate Pull	z-coordinate σ [μm]	z-coordinate Tails [μm]	z-coordinate Pull
$t\bar{t}H$						
Kalman	16.7	102	1.41	20.1	117	1.31
Adaptive	12.2	28.0	0.97	16.2	41.8	0.97
Trimmed	12.4	28.8	0.98	16.6	43.0	1.00
$B_s^0 \to J/\psi\,\phi$- primary vertex						
Kalman	44.1	176	1.11	54.3	224	1.07
Adaptive	38.4	94.9	0.94	48.7	140	0.94
Trimmed	39.4	98.7	0.97	49.5	144	0.95
$B_s^0 \to J/\psi\,\phi$- secondary vertex						
Kalman	54.8	164	1.08	73.8	471	1.08
Adaptive	53.6	155	1.02	73.0	440	1.02
Trimmed	54.0	174	1.04	75.0	502	1.05

B-Tagging: Basic Idea



Transverse Imbalance :	.0290		Longitudinal Imbalance :	-.2966	
Thrust :	.9175	Major :	.2847	Minor :	.0800
Event DAQ Time :	800000	1			





- B hadrons have lifetimes and decay lengths distinct from other species
- Decay length is measurable in a given event by finding a vertex ("secondary") and taking the distance to the "primary" vertex
- Can look for B hadrons by finding these vertexes which are compatible with known properties of B hadrons

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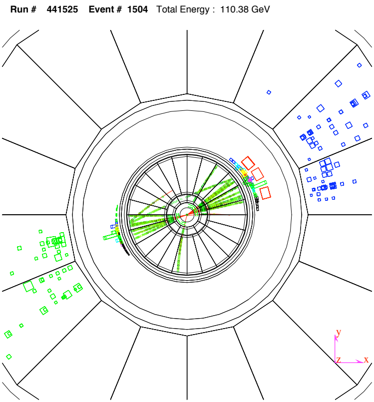

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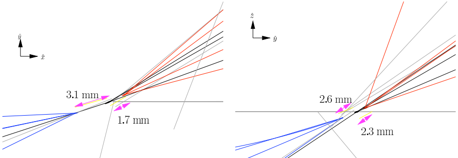

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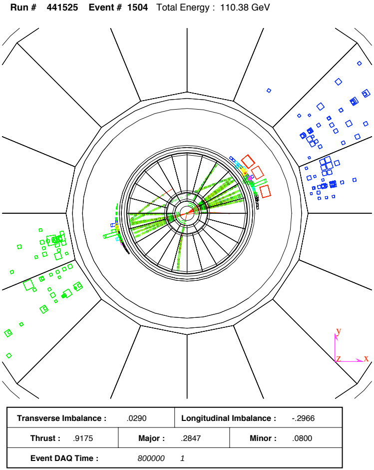

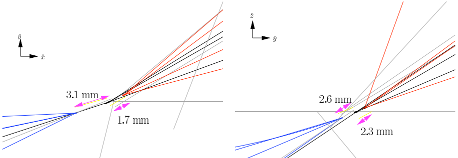

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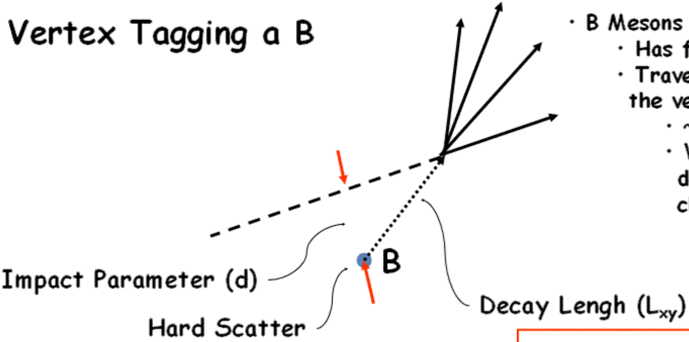
Example B-Tag (D0)

Vertex Tagging a B



- B Mesons
  - Has finite life time
  - Travels some distance from the vertex before decaying
    - ~ 1mm
    - With charm cascade decay, about 4.2 charged tracks

Impact Parameter Resolution	$d/\sigma(d)$
Decay Length Resolution	$L_{xy}/\sigma(L_{xy})$

Several algorithms under active development

Summary

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