Applications of Silicon Sensors in Tracking

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Outline

- Physics motivation for vertexing with silicon
- Limits on the hit resolution
- Alignment of silicon systems
- Pattern recognition and track fitting
  - Simple example of testbeam telescope
- Applications of precision detectors outside HEP

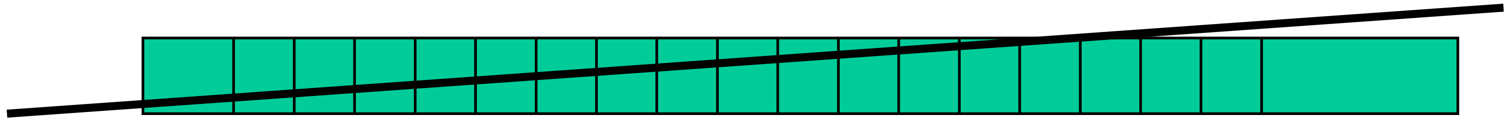
Solid State Tracking Detectors

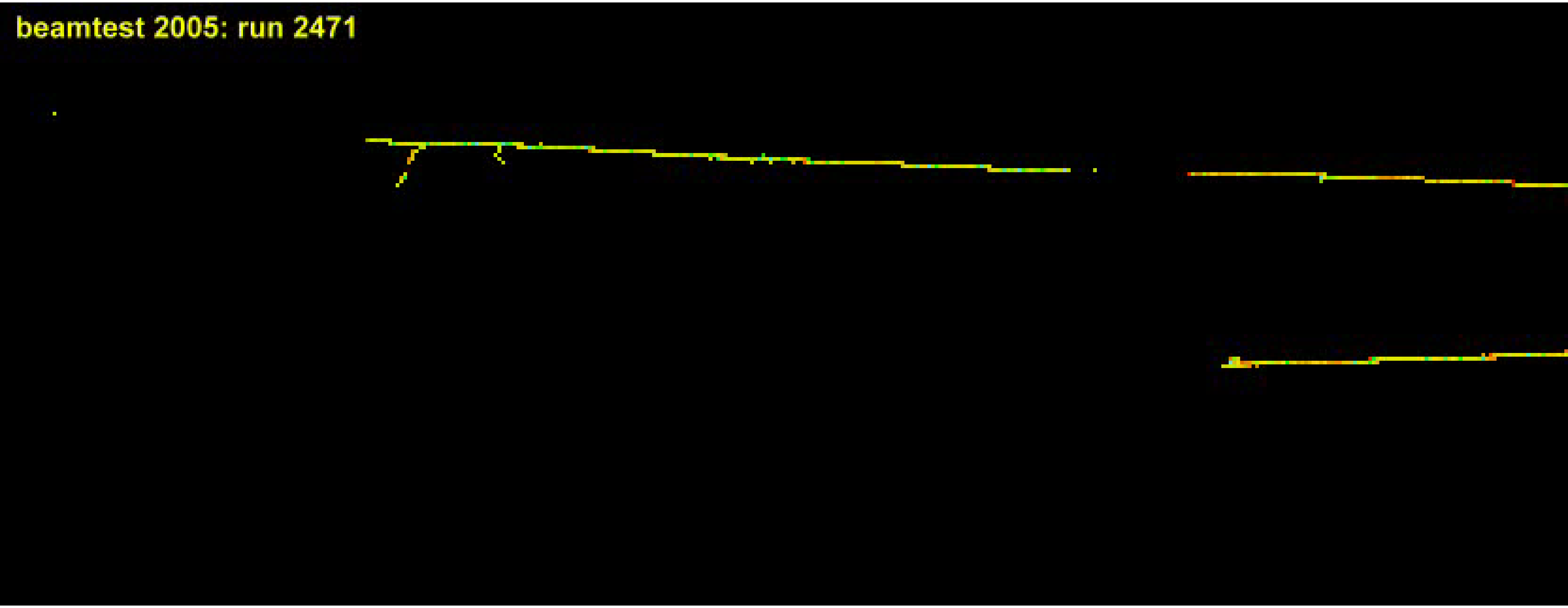
- Why Silicon?
  - Crystalline silicon band gap is 1.1 eV (small)
    - yields 80 electron-hole pairs/μm for minimum-ionizing track
      - (1 e-h pair per 3.6 eV of deposited energy)
    - 99.9% of ejected electrons have less than 1μm path length
      - fine-granularity devices possible
  - Integrated Circuit manufacturing techniques make just about any geometry possible, and at industrial prices
    - No need to “home-grow” these detectors

⇒ Tracker performance can be as good as bubble chamber

Silicon Pixel Detector

200 MeV protons hitting CMS pixel module at shallow angle (R.Horisberger)





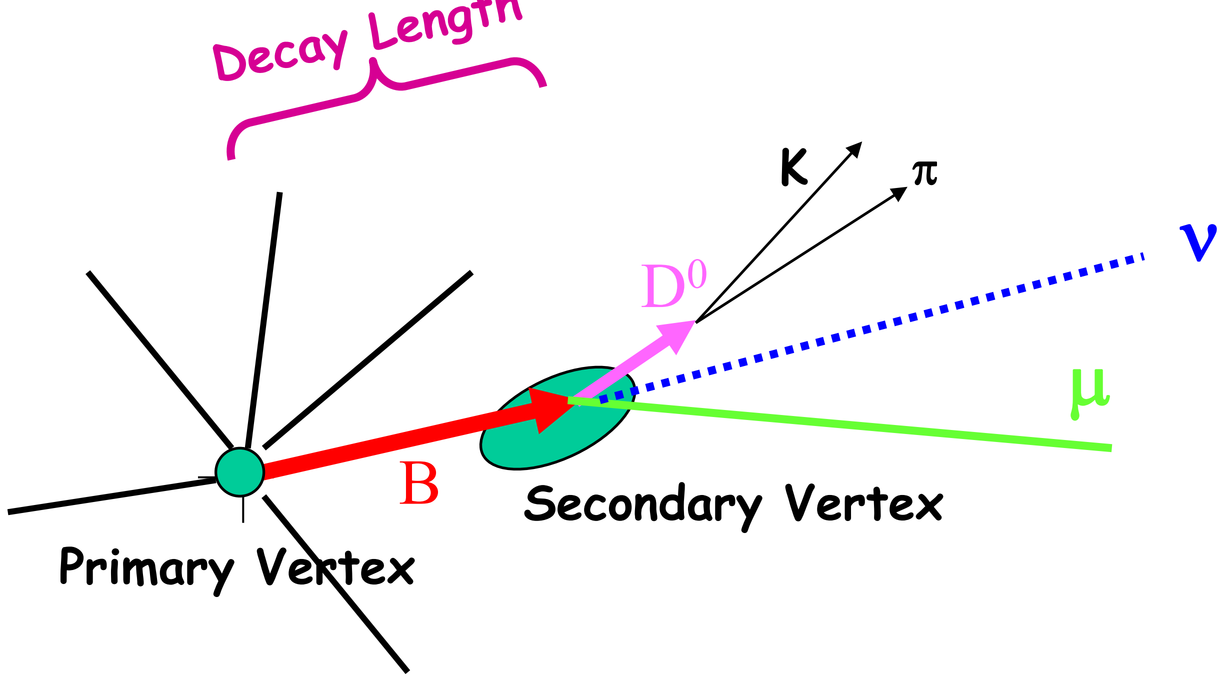
Physics Motivation

- Exclusive reconstruction of decays with secondary vertices
  - Physics of *b*-quark: lifetime, oscillations, CP violation

- *b*-tagging
  - Physics of top quark, Higgs and SUSY searches etc
  - More inclusive approach to keep efficiency high

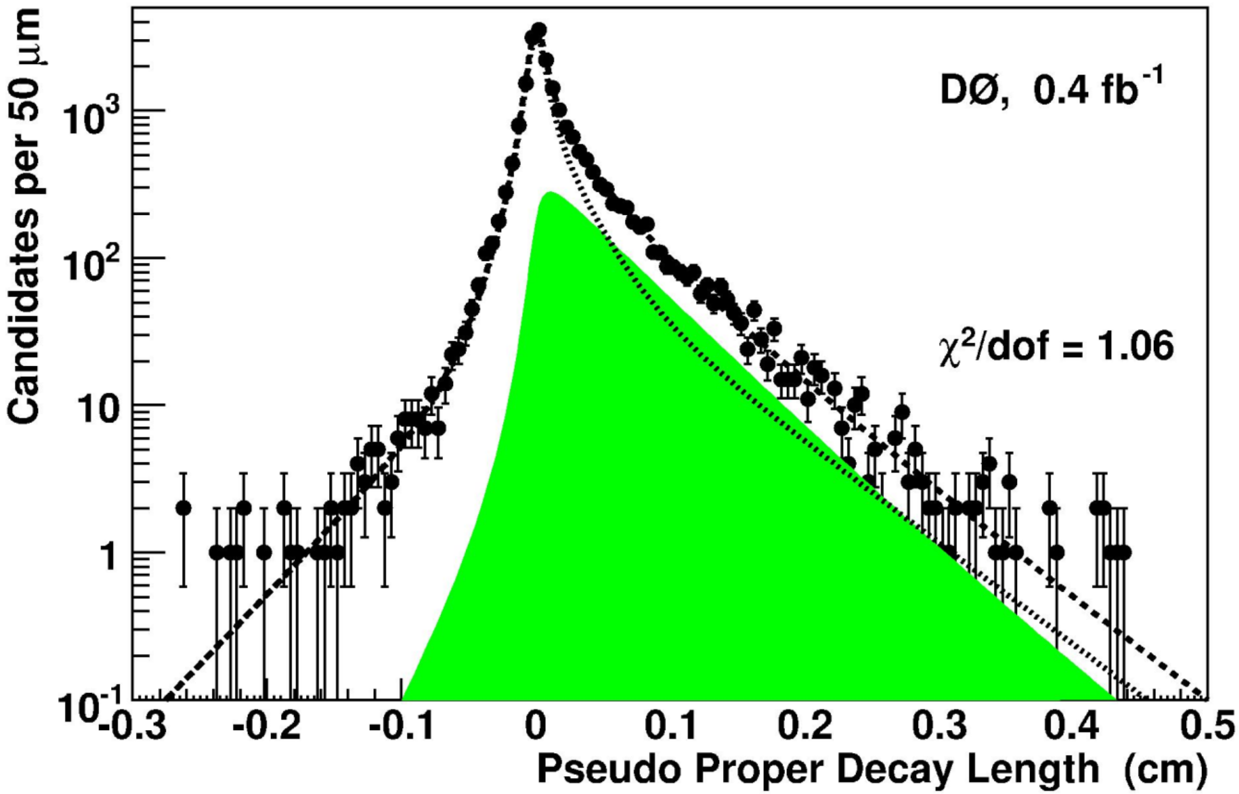
Example: Measurement of *B* Meson Lifetime

- Look for B vertex and measure decay length - distance between primary and secondary vertices
- Most of decays of B mesons happen within 1-2 mm of interaction point ($c\tau \sim 0.5$ mm, stretched by relativistic time dilation)
- Need vertex detectors with excellent position resolution ~ 10 μm
  - Even more important in Bs oscillations (cT~100 μm)

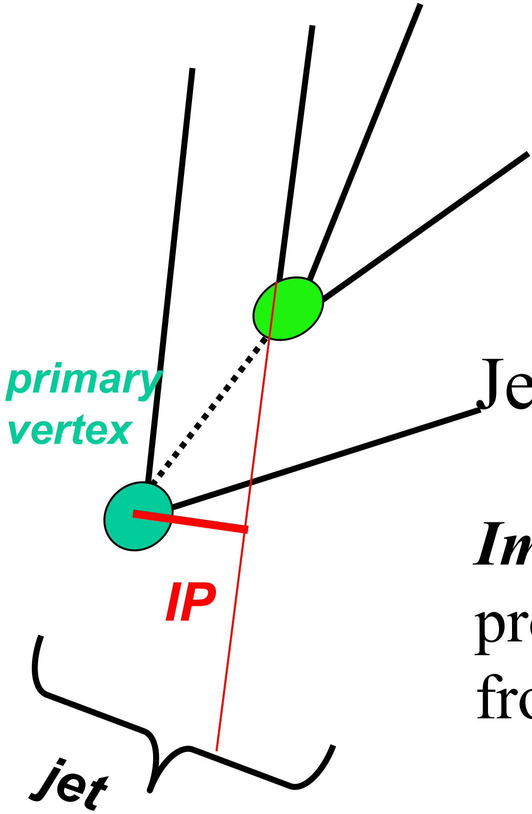


B_s^0 Meson Lifetime

- Proper lifetime : corrected for relativistic time dilation

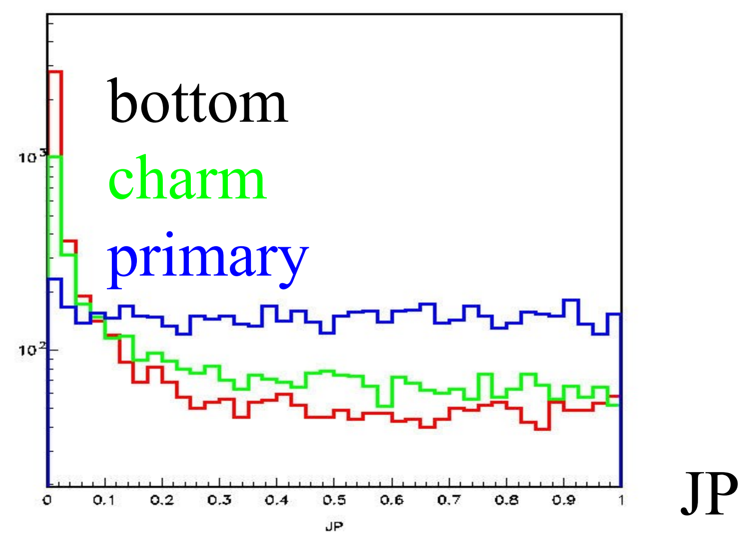


Example: *b*-tagging

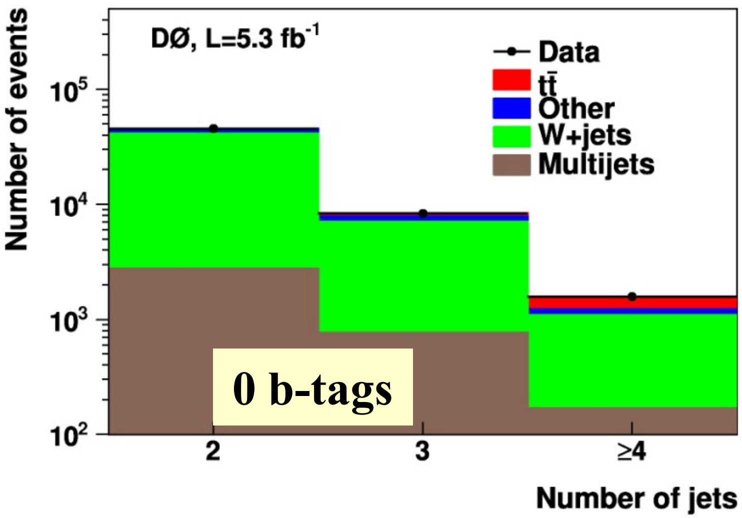


Jet Probability (JP) tagging algorithm

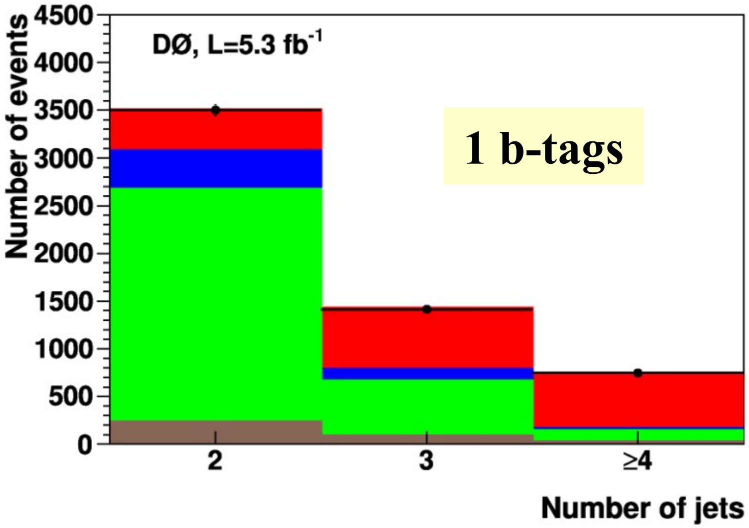
Impact parameter* => *Track probability
probability that track is consistent with coming from primary vertex.

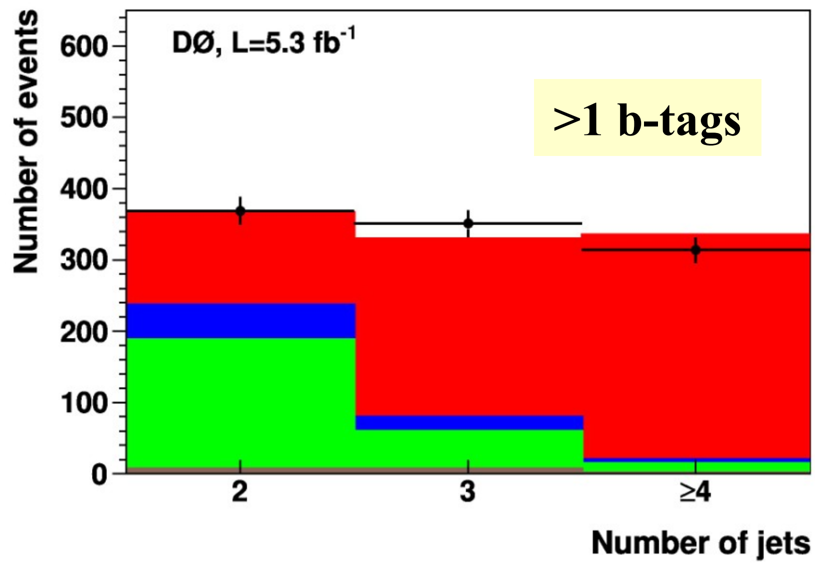


Example: *b*-tagging



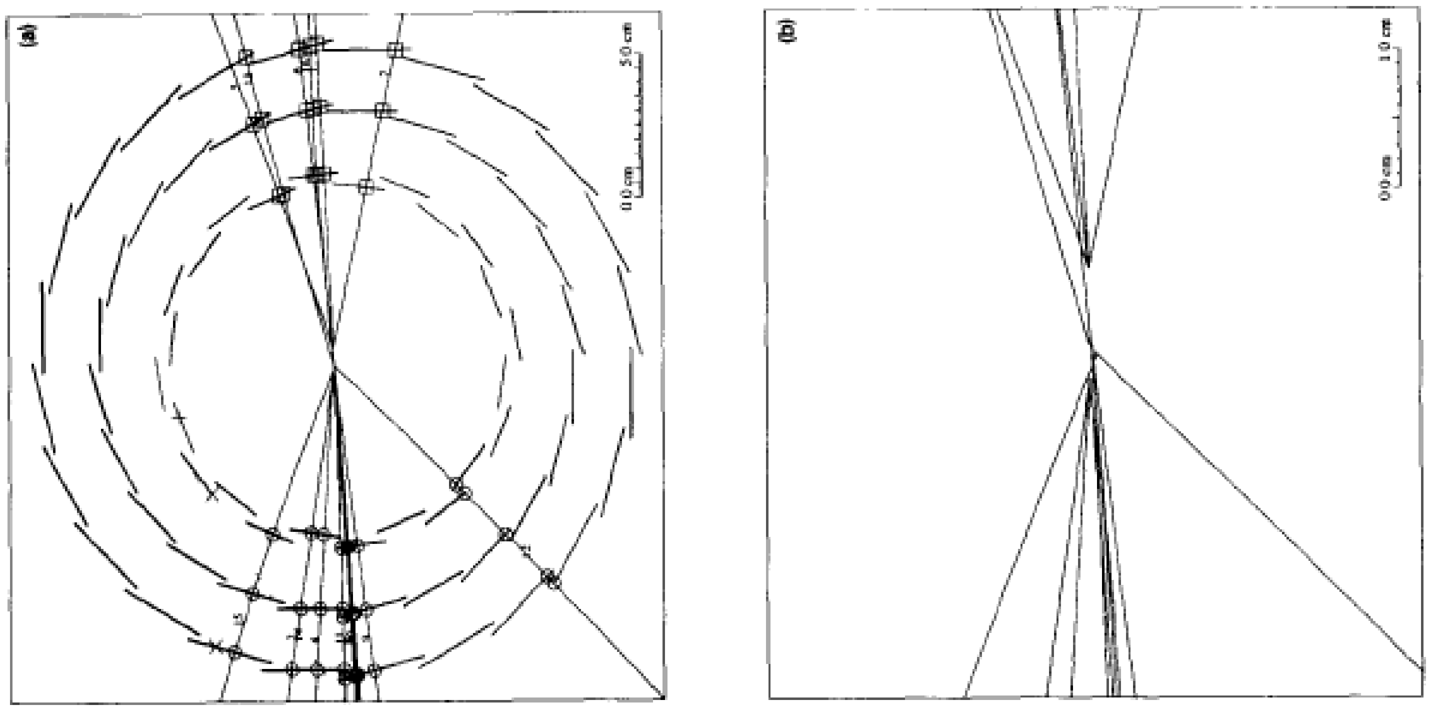
- Top sample at DZero, Tevatron
- tt→bbWW→lepton+jets
- Pure signal after two tags!





Vertexing

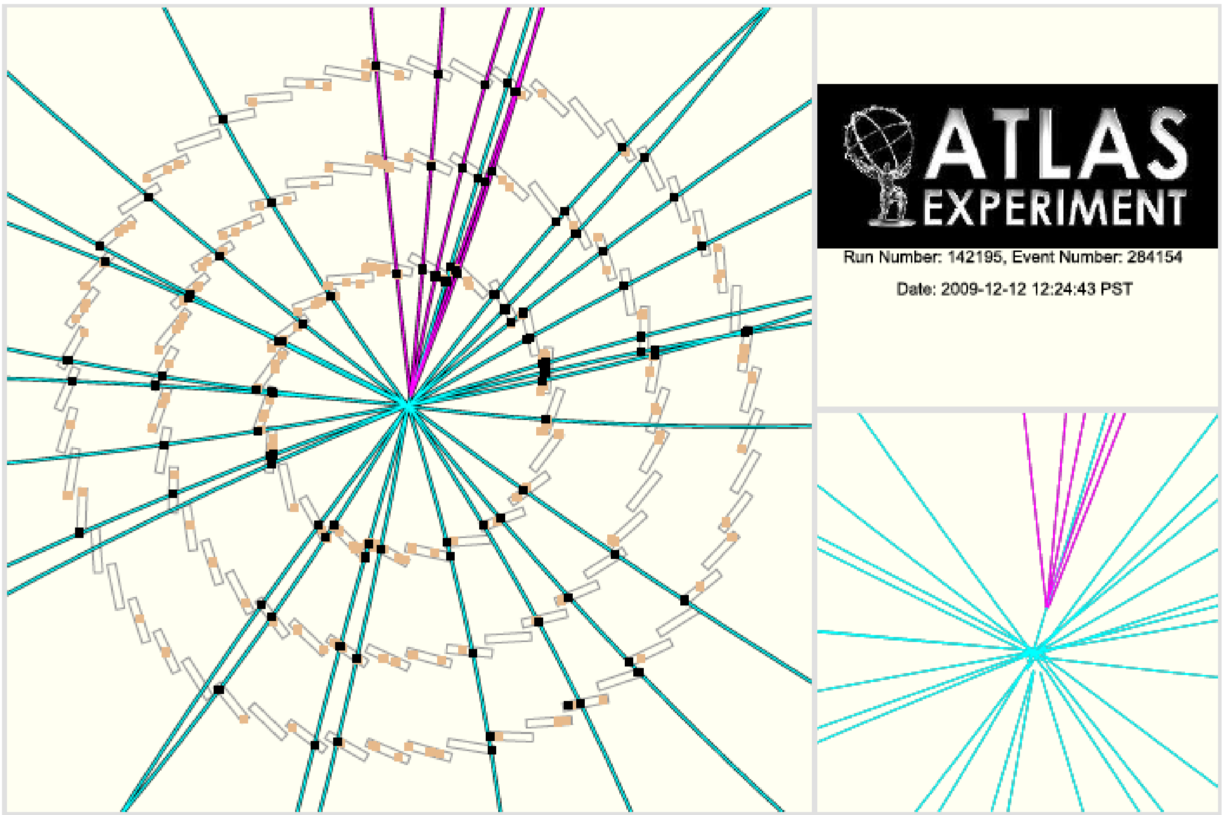
- DELPHI (e^+e^- collisions producing Z^0 bosons)



- Need precision for separation of vertices

Vertexing

- ATLAS (pp collisions)



- Silicon is viable *and* crucial at hadron colliders as well

Sensor Basics

Impact Parameter Resolution

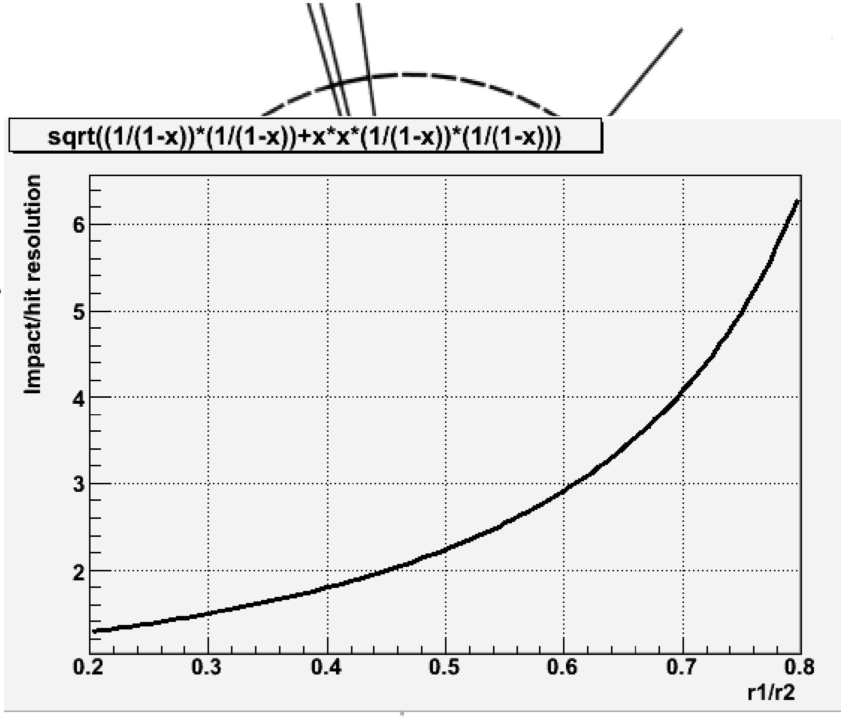
- For two layers: Error propagated to interaction point

$$\sigma_b^2 \approx \left(\frac{\sigma_1 r_2}{r_2 - r_1}\right)^2 + \left(\frac{\sigma_2 r_1}{r_2 - r_1}\right)^2 = \frac{1}{(r_2 - r_1)^2}\left[(\sigma_1 r_2)^2 + (\sigma_2 r_1)^2\right]$$

- Assuming equal resolutions

$$\left(\frac{\sigma_b}{\sigma}\right)^2 \approx \left(\frac{1}{1 - r_1/r_2}\right)^2 + \left(\frac{1}{r_2/r_1 -$$

- r_1/r_2 should be small
- σ=10 μm, r_1/r_2=0.5, σ_b = 22 μm



Some figures and examples here and later from
Helmuth Spieler "Semiconductor Detector Systems", 2005 Oxford University Press

Multiple Scattering

- In the above cannot make r_2 too large – need to account for multiple scattering
- For ex. Be beam pipe (ϕ 5 cm, thickness 1 mm)
  - X_0=35.3 cm; x/X_0=0.0028
  - Corresponds to 28 μm at IP for P = 1 GeV

Conclusions

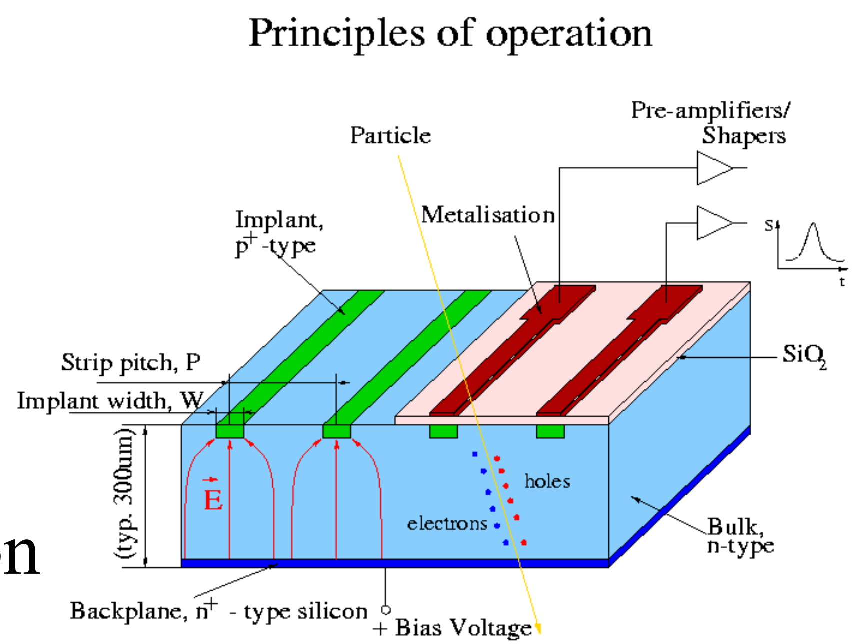
- Measure hits as precisely as possible
- First layer as close as possible to Interaction Point
- First layer as thin as possible

Position Resolution: Geometry

- Strip detectors are 100% efficient despite of gaps between strips – all field lines end on electrodes → electrical segmentation determined by pitch
- If tracks are distributed uniformly and every strip is readout:

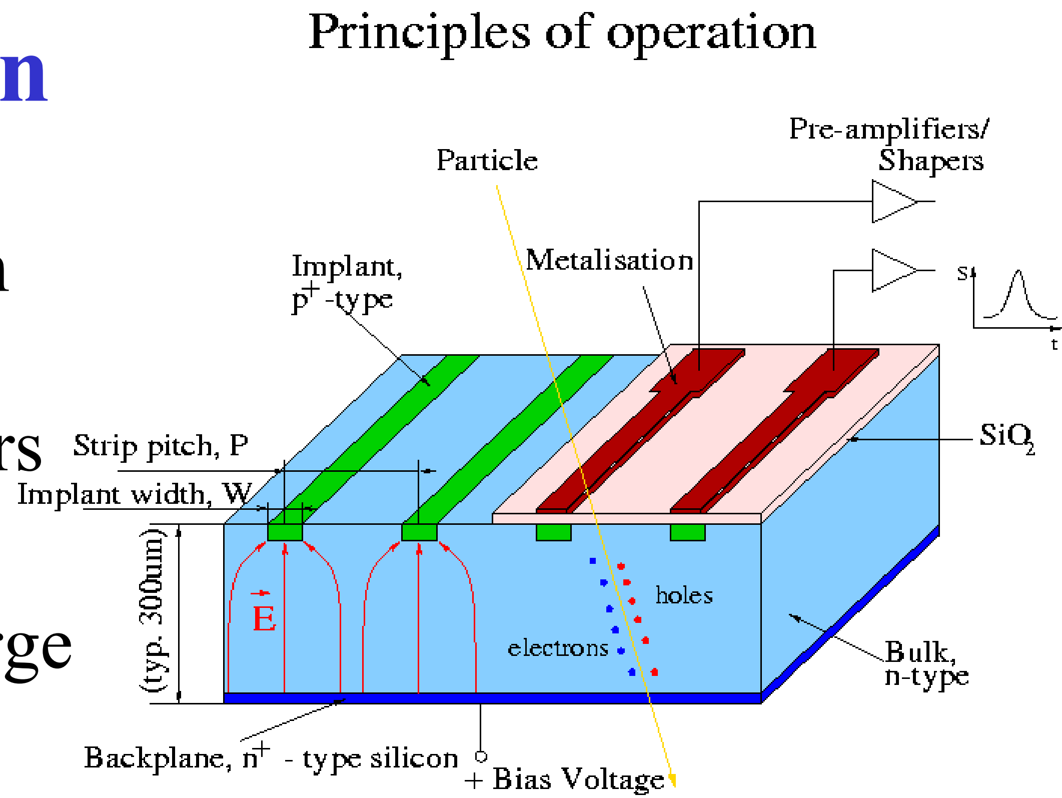
$$\sigma^2 = \int_{-p/2}^{p/2} \frac{x^2}{p} dx = \frac{p^2}{12}$$

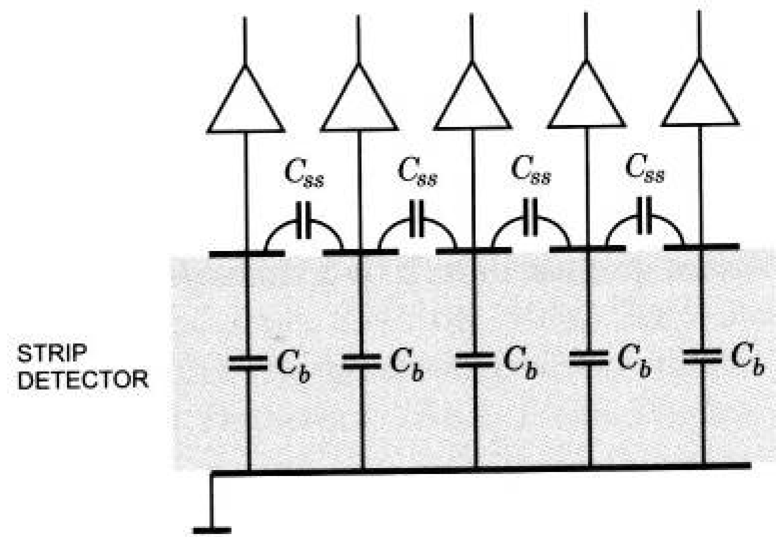
- If signal split across strips charge sharing can improve on this resolution



Signals in Silicon

- In a silicon detector each strip has capacitance to backplane and neighbours
- If amplifier input capacitance high all charge is collected
- If input capacitance low charge flows to neighbours → deteriorating position resolution





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Position Resolution: Diffusion

- Diffusion spreads charge transversely

$$\sigma_y = \sqrt{2Dt} \approx \sqrt{2\frac{kT}{e}\frac{d^2}{V_b}}$$

- Collection time

$$t_c \approx \frac{d}{v} = \frac{d}{\mu \overline{E}} = \frac{d^2}{\mu V}$$

25 ns in typical silicon sensors

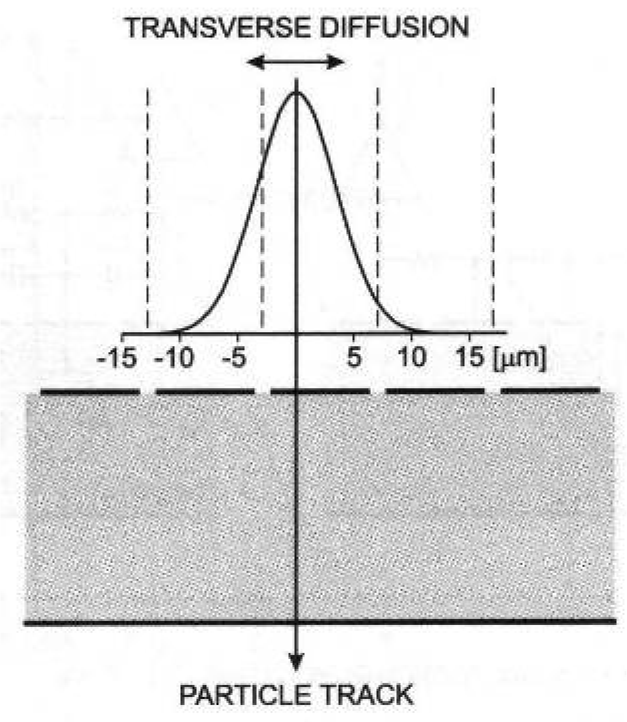
- Diffusion constant is linked to mobility as well

$$D = \frac{kT}{e}\mu$$

- Leads to diffusion of ~ 7 μm

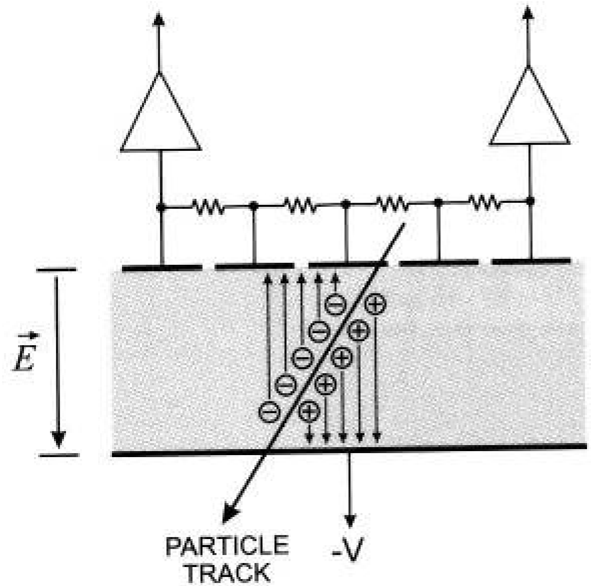
Charge Sharing

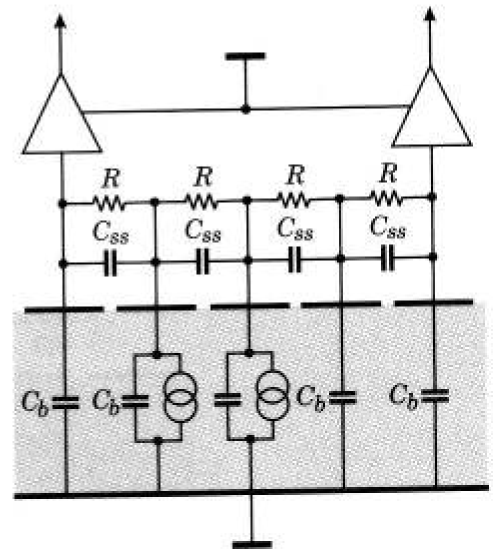
- Charge spreading improves resolution!
  - Centre of gravity interpolation
  - Resolution proportional to S/N
- Allows to beat sqrt(12) rule
  - Achieved resolutions 1.8 µm for 25 µm pitch (25/sqrt(12)=7 µm)
  - Requires S/N > 50 to achieve this
- Strip pitch should be comparable with diffusion



Intermediate Strips

- Charge division can be extended by introducing intermediate strips
- Strips are coupled capacitively to neighbours



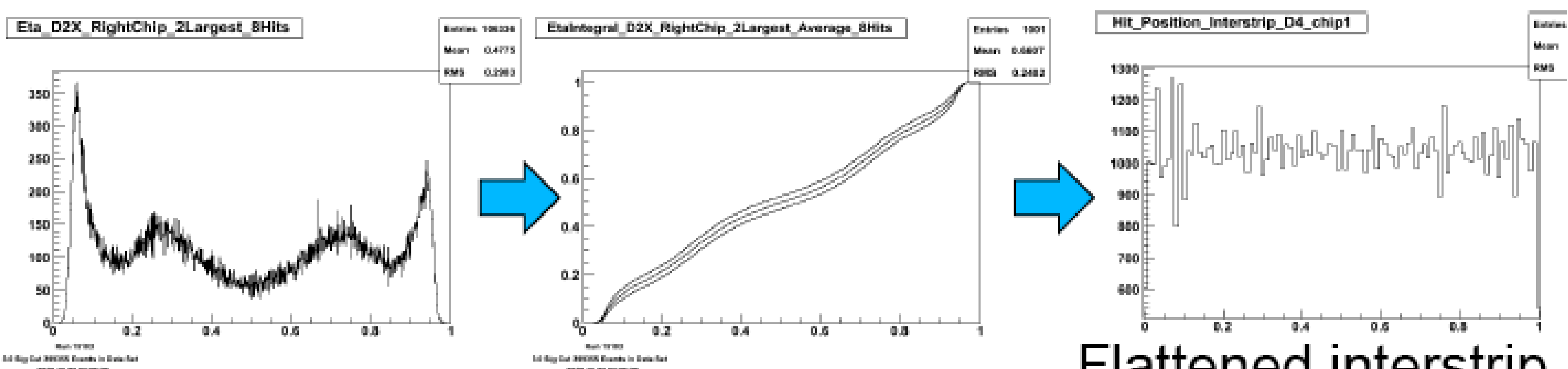


- Signal loss to backplane C_b/C_{ss}=0.1 → ~20% loss

Eta Algorithm

- Define η as PH_r / (PH_l+PH_r)
  - Electric field near implants biases response to uniform illumination
- Determine charged particle position by un-folding

$$x = P_s \int_0^{\eta} \frac{dN}{d\eta}(\eta)_n d\eta + X_0$$

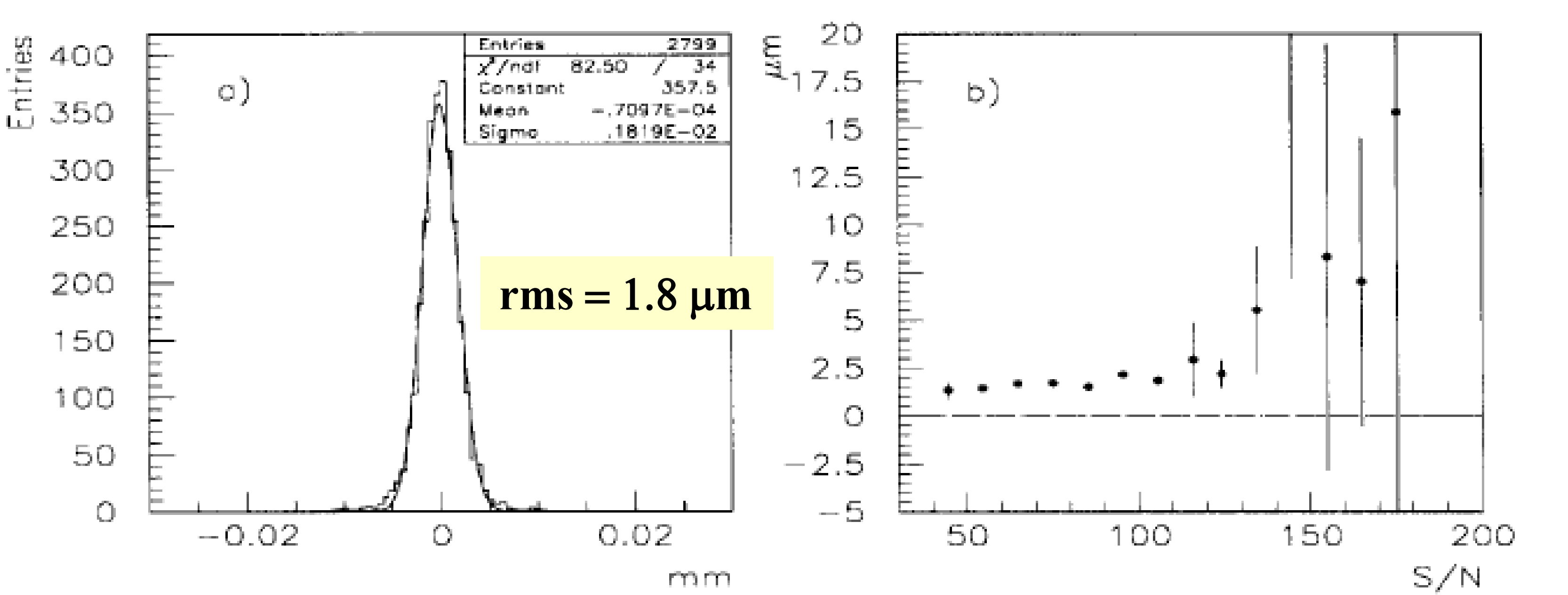


eta=qr/(ql+qr) integral Flattened interstrip occupancy

η η

Ultimate Position Resolution

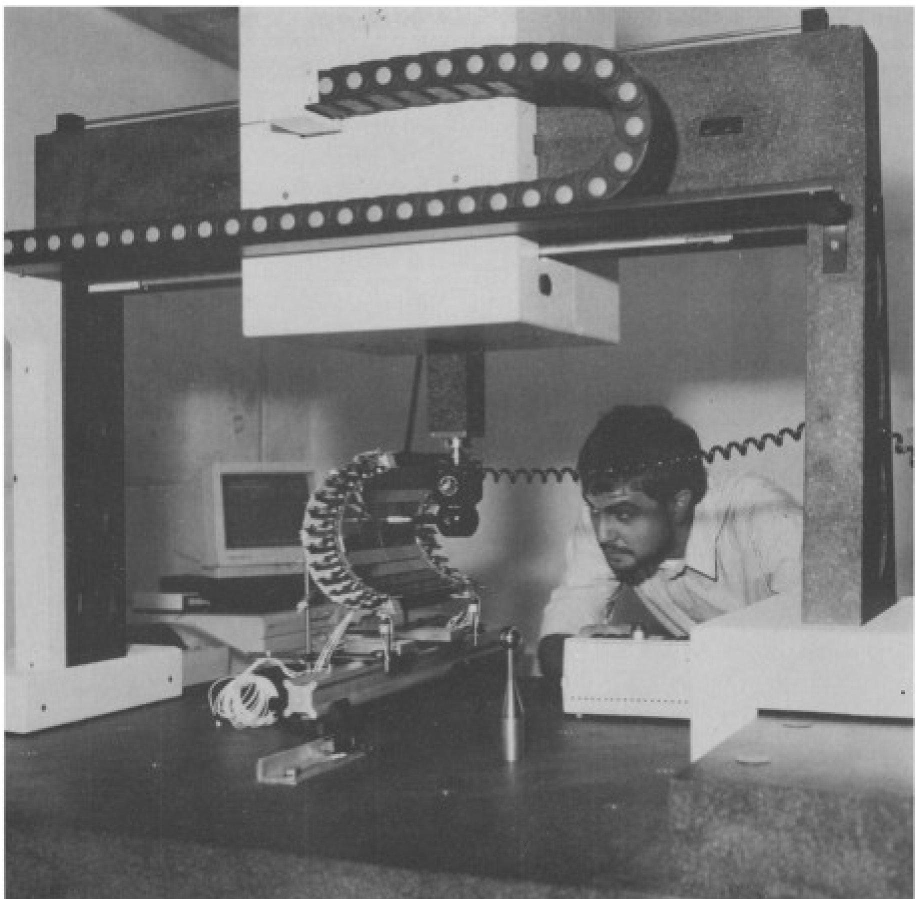
- Push all handles to the extreme
  - Minimise readout pitch (25 μm)
  - Shaping time to several μs (S/N ➡ 50, 70 or more)
  - Minimise diffusion/limit charge deposition (no δ-rays)
  - Use η algorithm



Alignment

Mechanical Survey During Construction

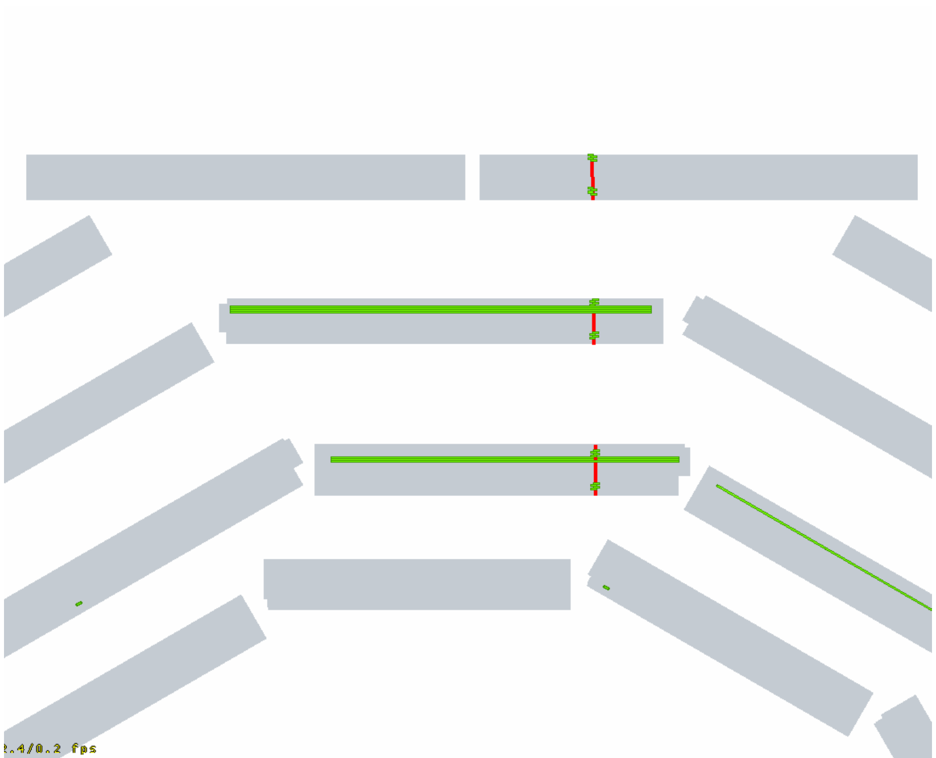
- Constrain sub-assembly alignment during fabrication
- Survey whole tracker prior to installation

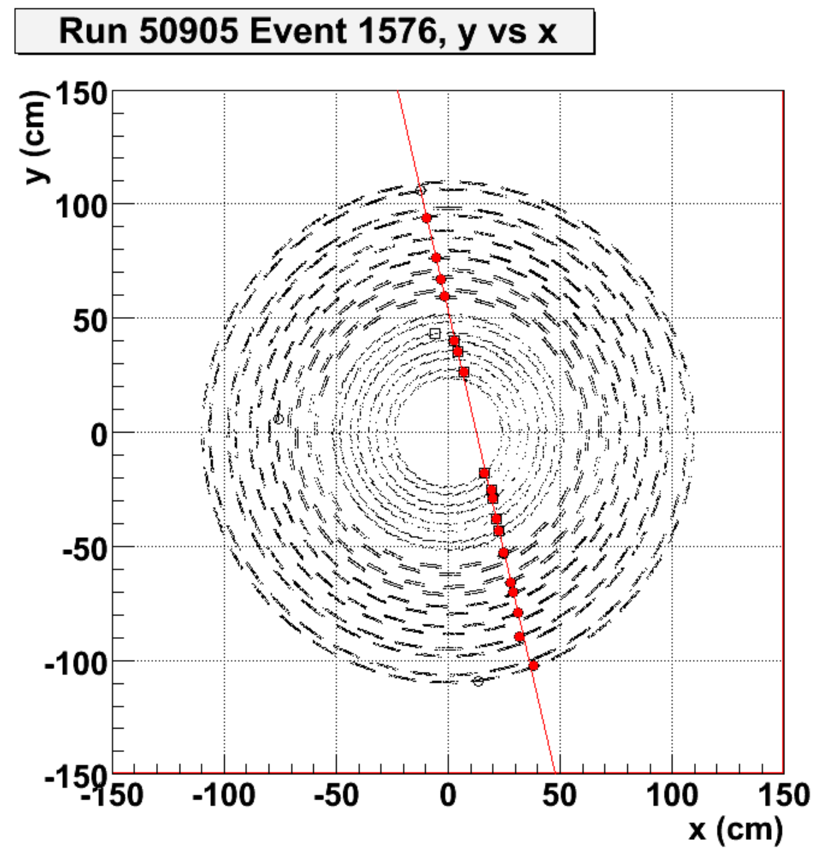


- 3D coordinate measm’t
  - Few μm precision over $1m^3$ volumes
  - Lots of systematics to understand before this data is useful

Alignment with Cosmic Rays

- After tracker is installed, have two sources of particles to use for calibration: cosmics and collisions
  - movies from CMS: Cosmics muon spectrometer and hits in silicon tracker

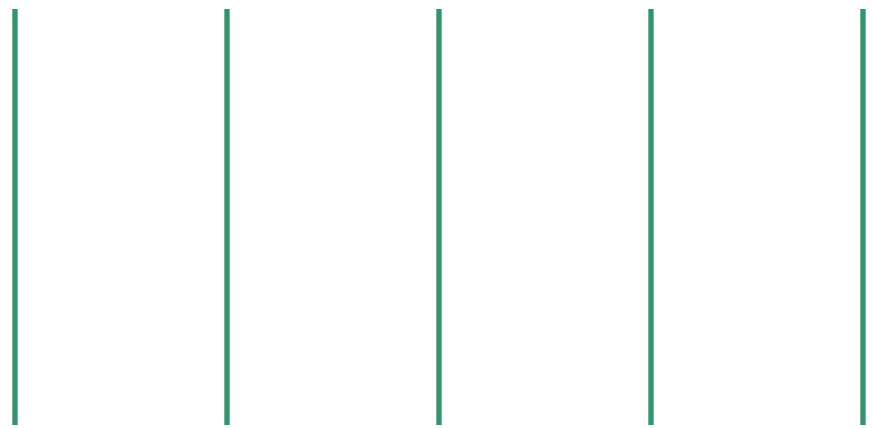




(movies in .ppt version)

Tracker Alignment

How do you fix this?

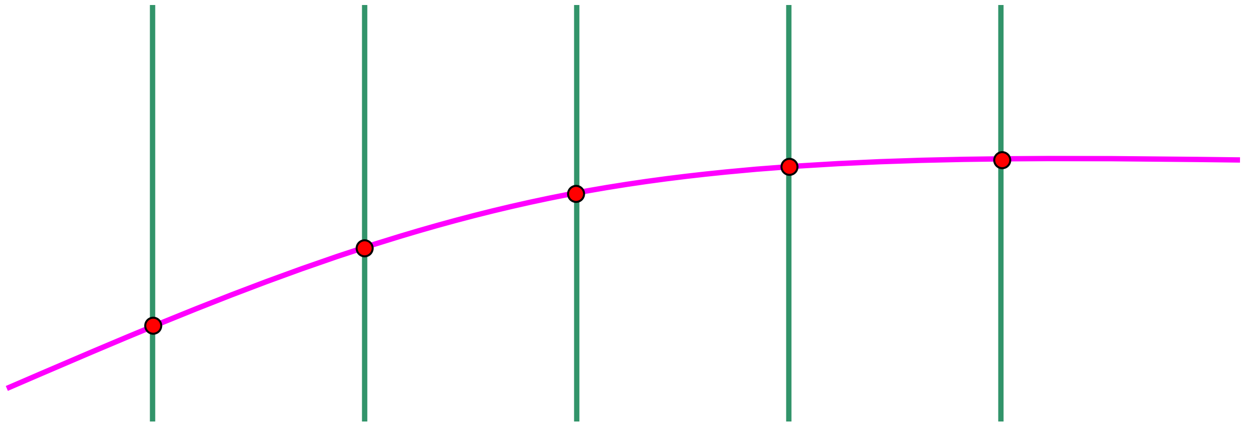


Consider a five-layer tracker

borrowed from F. Meier

Tracker Alignment

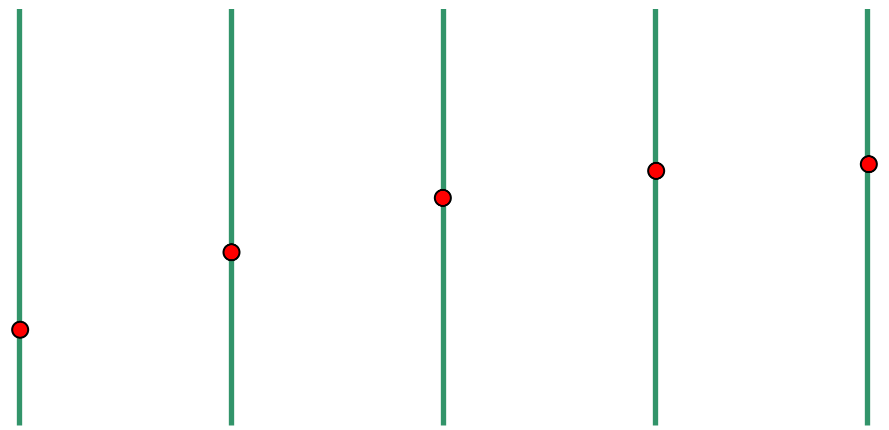
How do you fix this?



A track goes through, leaving hits

Tracker Alignment

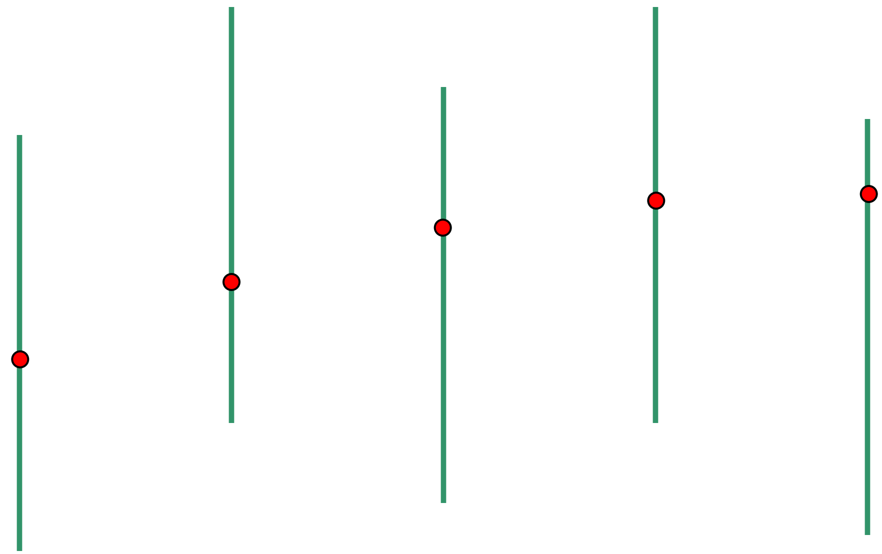
How do you fix this?



All you really see are the hits, actually

Tracker Alignment

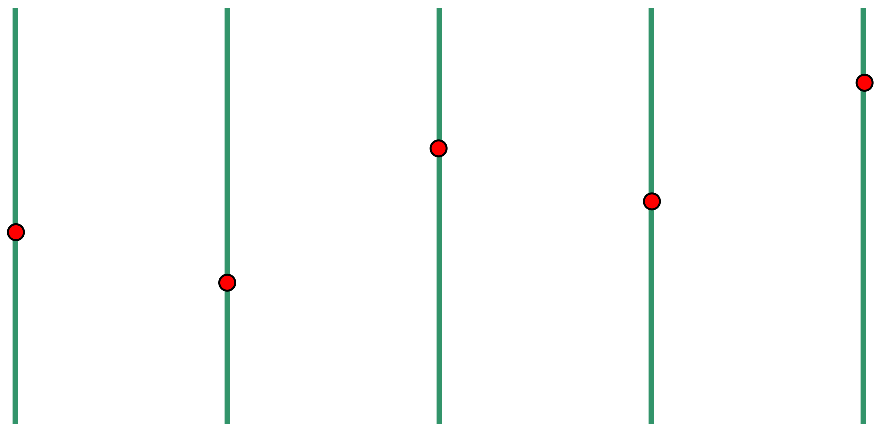
How do you fix this?



Now, if your tracker is misaligned, the hits positions really look like this

Tracker Alignment

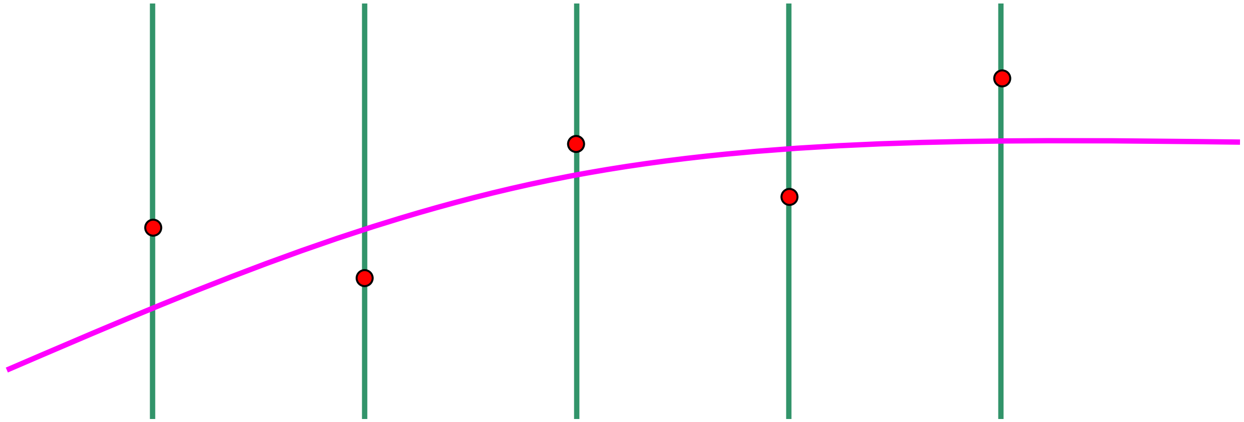
How do you fix this?



If you assume the module positions are "ideal", you see this

Tracker Alignment

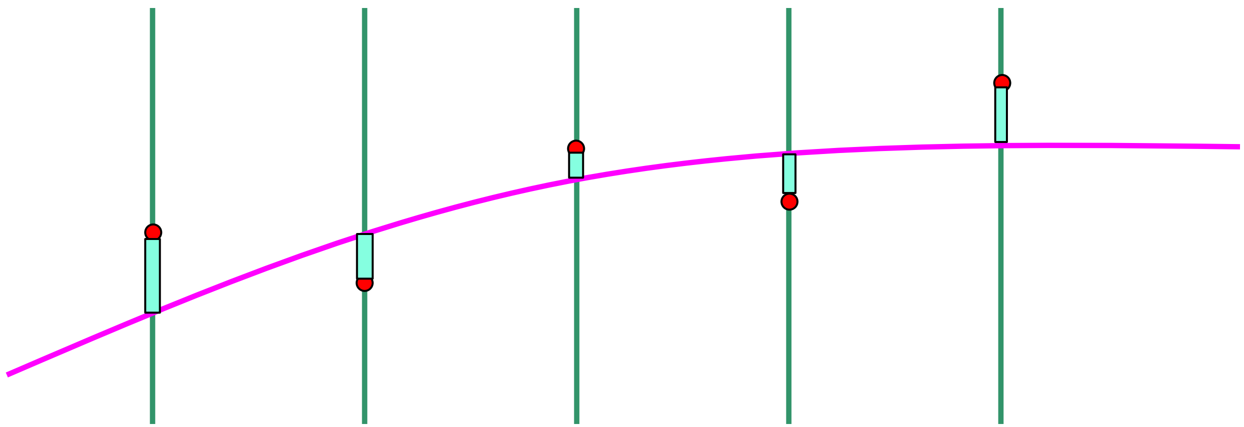
How do you fix this?



So your track really looks like this

Tracker Alignment

How do you fix this?



To "align", we keep track of the "residuals" between the hits and the projected track positions (shown as) for many tracks, then adjust the positions of the actual detectors to minimize the residuals across the whole tracker.

Tracker Alignment: In 3D

χ^2 minimization: $$\chi^2(\mathbf{p},\mathbf{q}) = \sum_j^{\text{tracks}} \sum_i^{hits} \mathbf{r}_{ij}^T(\mathbf{p},\mathbf{q}_j)\,\mathbf{V}_{ij}^{-1}\,\mathbf{r}_{ij}(\mathbf{p},\mathbf{q}_j)$$

where $\mathbf{p}$ parametrize the tracker geometry, $\mathbf{q}_j$ are the track parameters, and $\mathbf{r}_{ij}$ are the residuals: $\mathbf{r}_{ij} = \mathbf{m}_{ij} - \mathbf{f}_{ij}(\mathbf{p},\mathbf{q}_j)$, $\mathbf{m}$ are measured hits and $\mathbf{f}$ are predicted hits.

Scale of Problem: (CMS Tracker)

- Each module:6 degrees of freedom:
  - 16588 modules x 6 = ~10^5 parameters
- Each track has 5 degrees of freedom,

  need 10^6 tracks or more

⇒ Not easy!

Alignment Techniques

1. Global (e.g. "Millepede-II" for CMS)
   - Matrix inversion determines module parameters only:
     - ~10^5x10^5 matrix
     - Correlations between modules included
     - simplified tracking parameterization: no E_{loss}, Multiple Scattering
     - few iterations
2. Local
   - Local minimization of residuals: ~10 parameters at a time
   - Incorporate survey data as a constraint
   - Full track extrapolation with Scattering and E_{loss}
   - Includes local correlations between adjacent modules

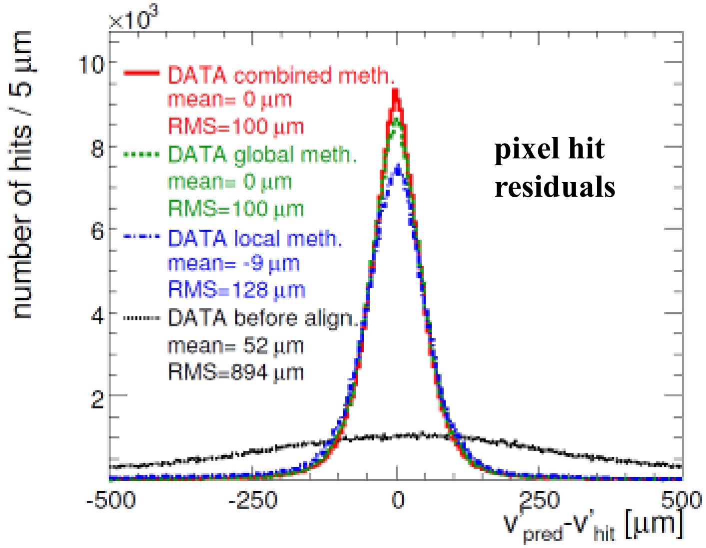
ATLAS Tracker Alignment

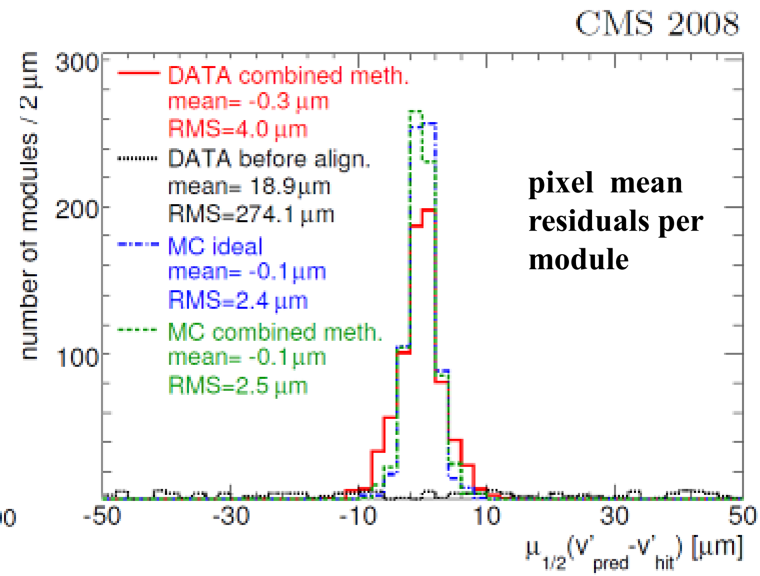
- In practice proceed hierarchically
  - Build on mechanical survey constraints
  - Align larger objects relative to one another first

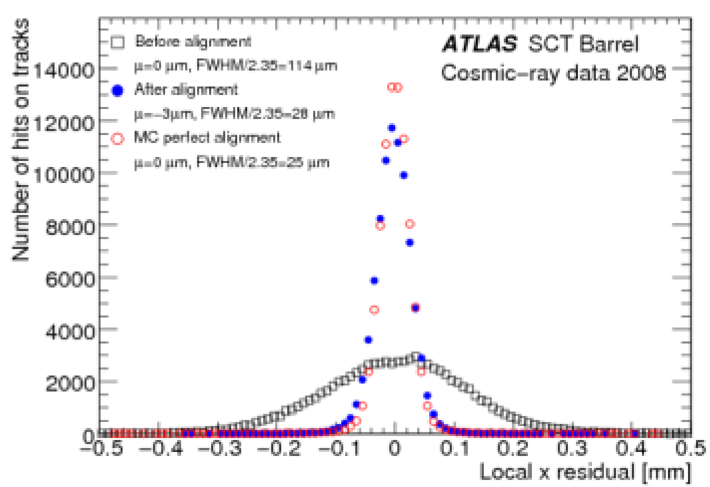
Level	Brief description		Structures	Degrees of freedom
0		Total:	7	41
	Whole Pixel detector		1	6
	SCT barrel and 2 endcaps		3	18
	TRT barrel (except T_z) and 2 endcaps		3	17
1		Total:	14	84
	Pixel barrel layers split into upper and lower halves plus 2 endcaps		6+2	48
	SCT barrel split into 4 layers plus 2 endcaps		4+2	24
2		Total:		2472
	Pixel barrel layers split into staves plus 2 endcaps		112+2	684
	SCT barrel layers split into staves plus 2 endcaps		176+2	1068
	TRT barrel modules (except T_z)		96	480
	TRT endcap wheels (only T_x, T_y and R_z)		40×2	240
3		Total:	3568	7136
	Pixel barrel modules (only T_x and R_z)		1456	2912
	SCT barrel modules (only T_x and R_z)		2112	4224

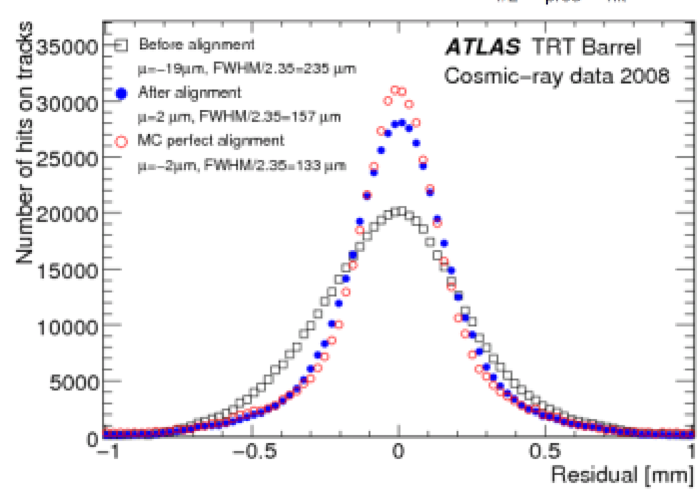
‘Only’ 10^4 parameters determined in ATLAS

Alignment Results (cosmics)





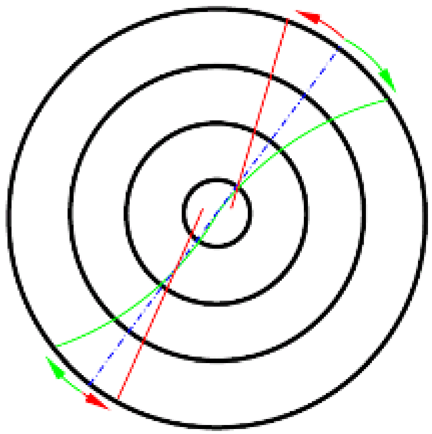




⇒ **Basically, all detectors reached near-optimal alignment before collisions**

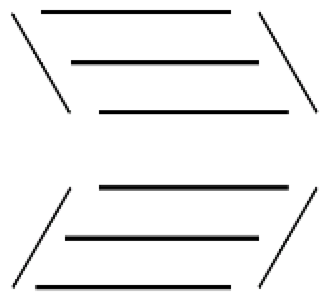
Alignment Pitfalls

- Exist modes of detector deformation with no change in total χ^2, yet physical locations not "ideal"

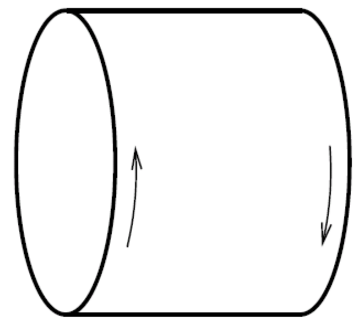


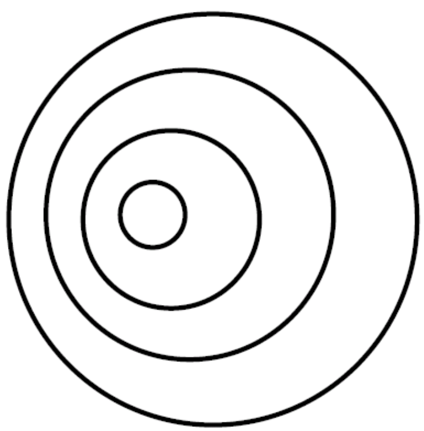
shear (red) or bend (green) in r–ϕ

z shear

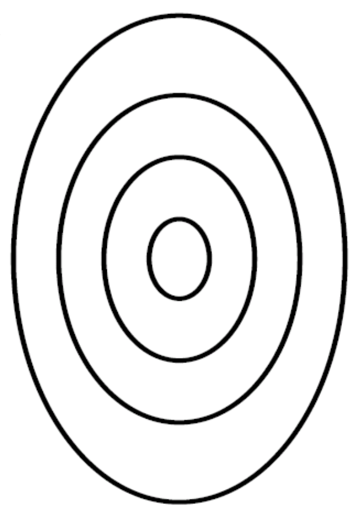


z twist





r–$r\phi$ mode 1



r–$r\phi$ mode 2

This is tricky…

Need orthogonal sets of tracks to constrain these modes:

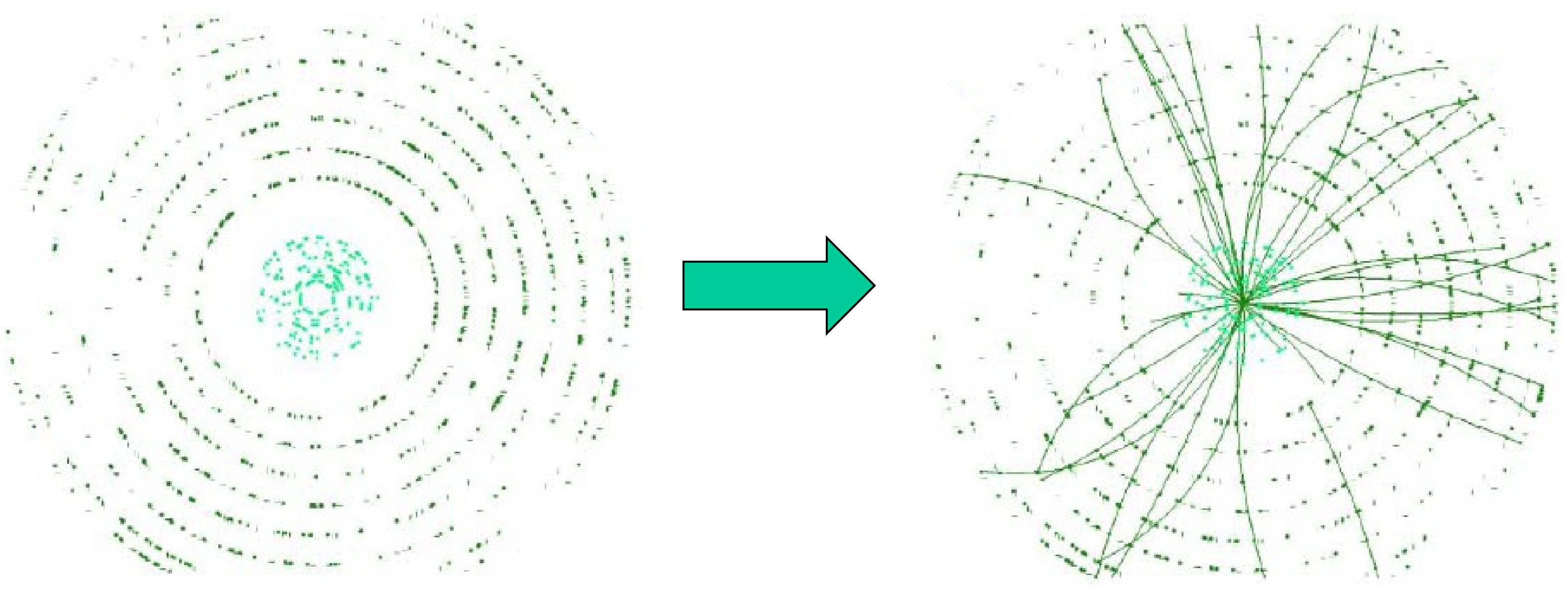
•cosmics, which don't pass through the tracker origin

•collision tracks

•collision tracks with B=0

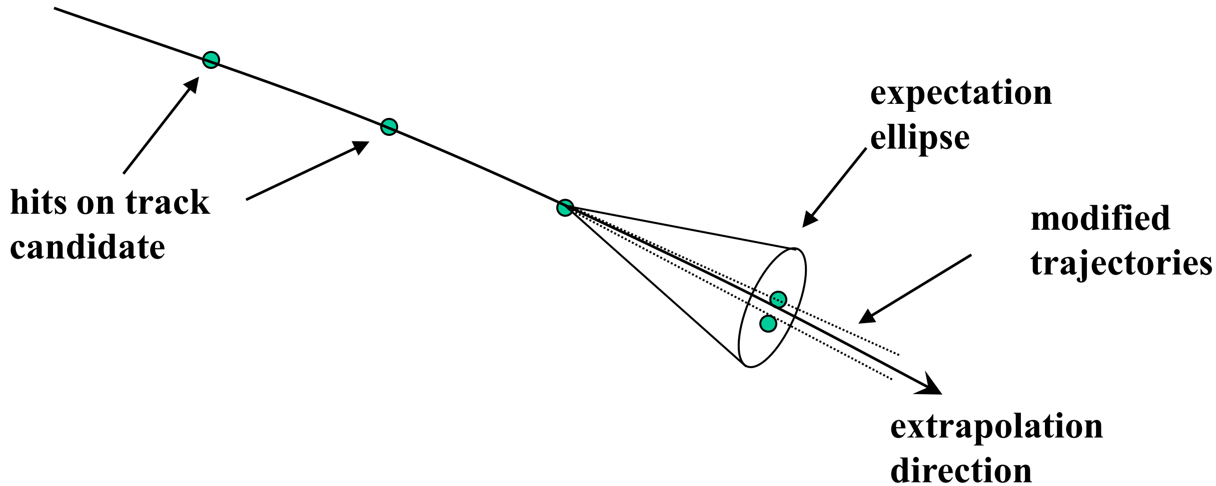
Putting it All Together: Tracking

- First, find track candidates:
  - "Pattern Recognition"
- Then (or simultaneously) estimate the track parameters
  - "Fitting"
- The Trick:



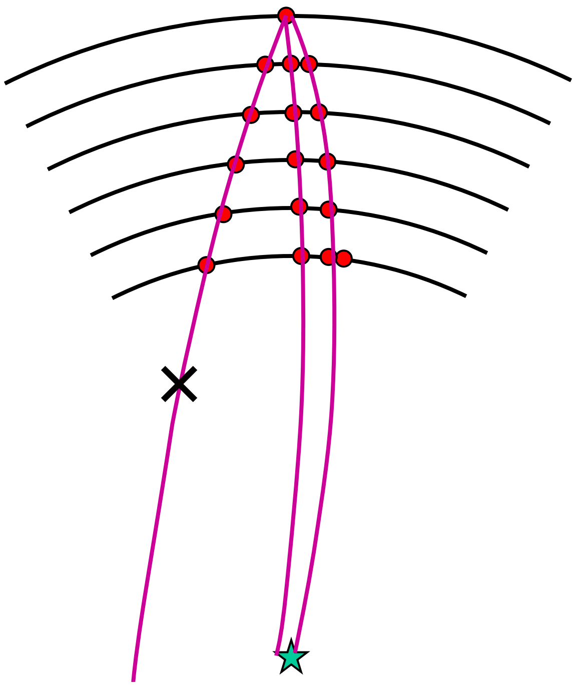
Pattern Recognition: Road-Following

- Simplest to understand, not optimal in some cases
- Subset of well-separated hits (and possibly a beam spot) are used to create initial track hypotheses
- Candidate tracks extrapolated to next layers to add potential new hits, refine track parameters, continue

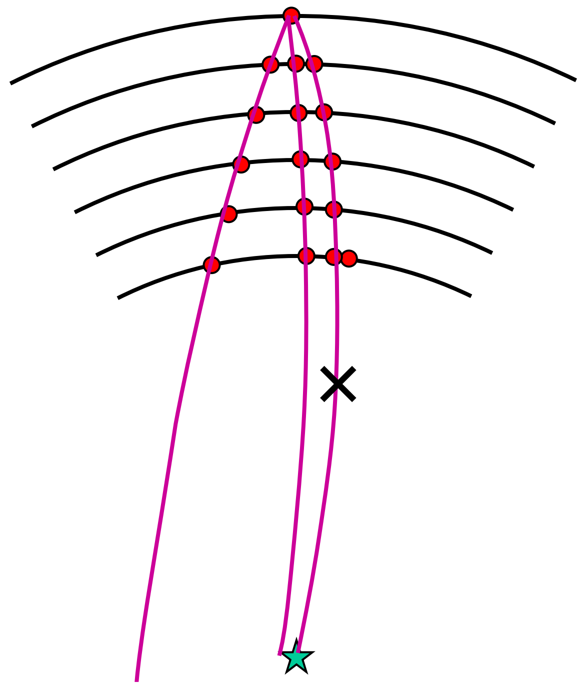


Pattern Recognition: Simplifications

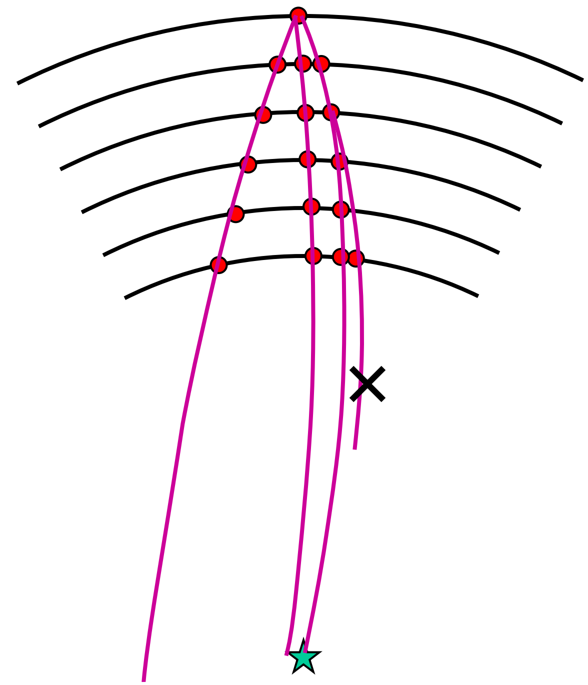
- Track finding struggles in high-occupancy environments
  - too many fakes, or takes way too long…
- Compromises to efficiency necessary to speed things up:



Accept tracks that originate near the IP



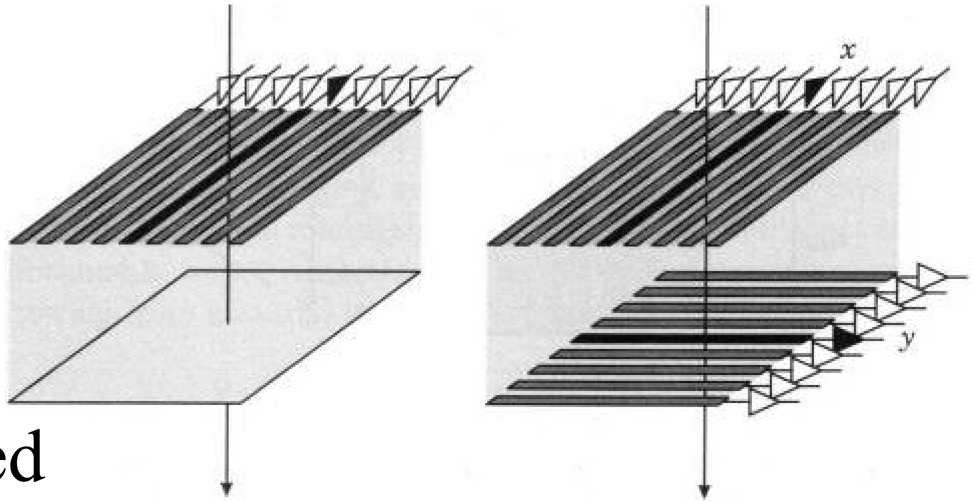
Prefer higher momentum tracks (min p_T cut)

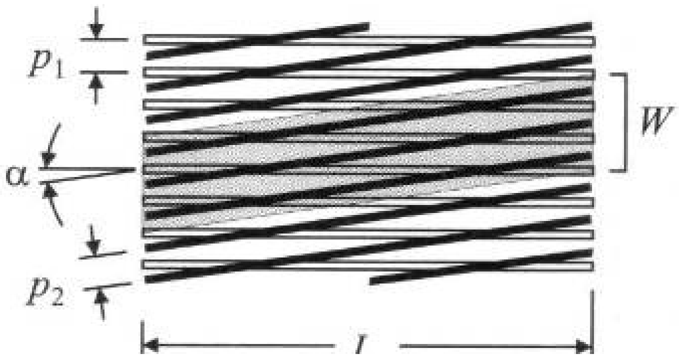


Limit number of misses or extrapolation residual

Two Dimensional Information

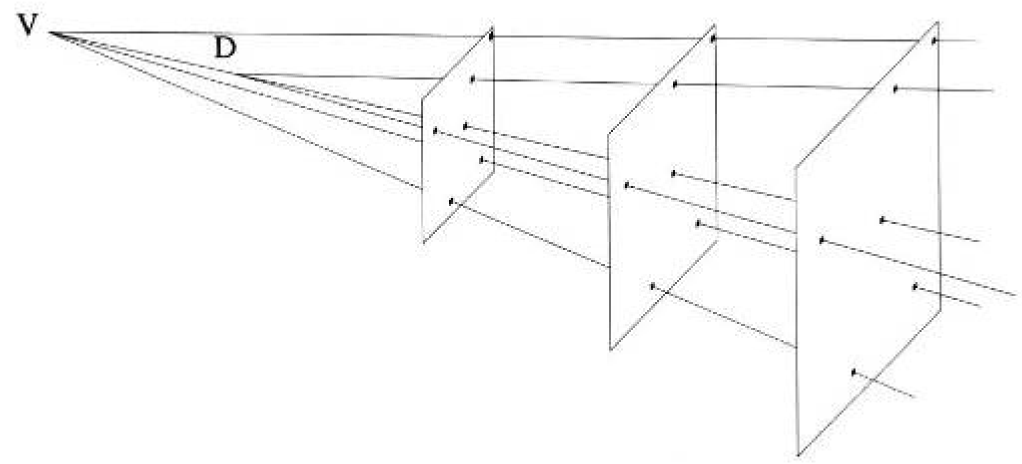
- 2D information allows to reconstruct 3D points – advantageous for track reconstruction
    - ◆ Good for both precision and pattern recognition
- Pixel detector vs double sided strip detectors
- Segment other side of the sensor in orthogonal direction
    - ◆ Gives best resolution
- Small angle stereo
    - ◆ Resolution in orthogonal direction ~ pitch / sin α

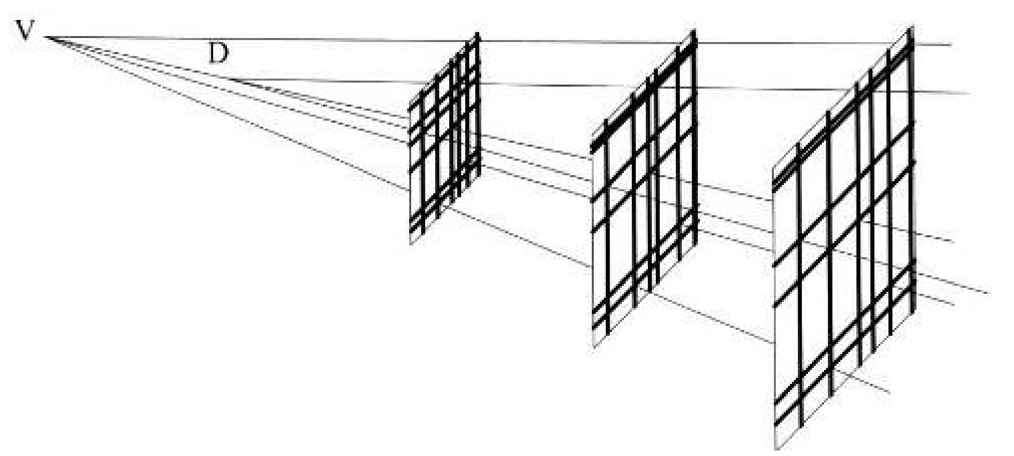




Ghosts in Tracking

- Ghosts appear in multi-track environment when more than one particle hit the sensor
- N^2-N ghost tracks for strip detectors with orthogonal strips





Track Fitting: Least Squares (I)

following P. Avery

- Once you've determined a set of measurements y_l use them to estimate track parameters α such that $y_l = f_l(\alpha)$.
- If we take an initial guess α_A at the parameters and make a linear expansion around that solution, we get

$$y_l = f_l(\alpha_A) + (\partial f_l/\partial\alpha_i)(\alpha_i - \alpha_{A\,i})$$

- This allows us to define a χ^2 measure

individual measurement errors

$$\chi^2 = \sum_l (y_l - f_l(\alpha_A) - A_{li}(\alpha_l - \alpha_{A\,l}))^2/\sigma_l^2$$

$$= (\mathbf{y} - \mathbf{f}(\alpha_A) - \mathbf{A}(\alpha - \alpha_A))^T \mathbf{V}_y^{-1} \; (\mathbf{y} - \mathbf{f}(\alpha_A) - \mathbf{A}(\alpha_A - \alpha))$$

$$\equiv (\Delta\mathbf{y} - \mathbf{A}(\alpha - \alpha_A))^T \mathbf{V}_y^{-1} \; (\Delta\mathbf{y} - \mathbf{A}(\alpha - \alpha_A))$$

where $\Delta\mathbf{y} = \mathbf{y} - \mathbf{f}(\alpha_A)$ and $A_{li} = \partial f_l(\alpha)/\partial\alpha_i|_{\alpha_A}$ is a matrix of constant derivatives. $\mathbf{V}_y$ is covariance matrix of the measurements.

Track Fitting: Least Squares (II)

- We want the parameter estimation that minimizes the distance between the measured points and the fitted track, so we set $\partial\chi^2/\partial\alpha_i = 0$ which gives us the solution

$$\alpha = \alpha_A + \mathbf{V}_A \mathbf{A}^T \mathbf{V}_y^{-1} \Delta\mathbf{y} \quad \text{where} \quad \mathbf{V}_A = (\mathbf{A}^T \mathbf{V}_y^{-1} \mathbf{A})^{-1}$$

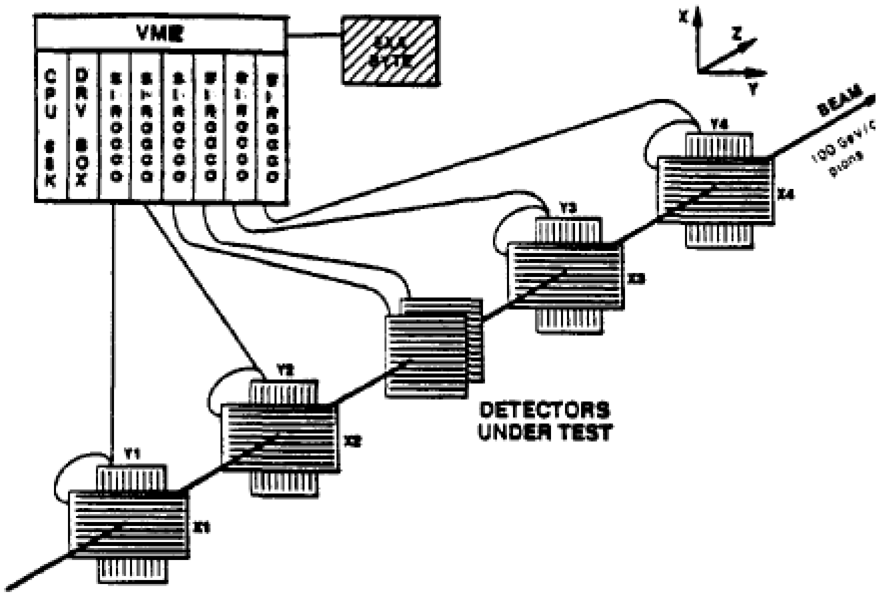
covariance matrix of *A*

- Ideally, iterate to get best estimate of the parameters α
- This method has several short-comings:
  - Only works well if all of the points are independent
  - All of the points have equal weight

- More sophisticated techniques exist (Kalman filters…)

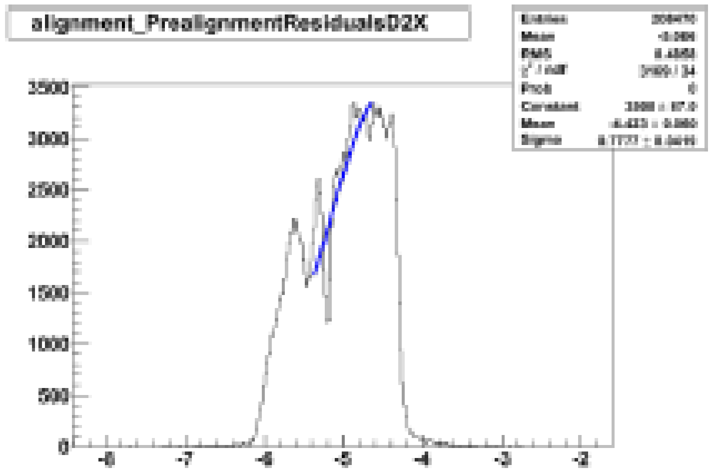
Application in a Testbeam

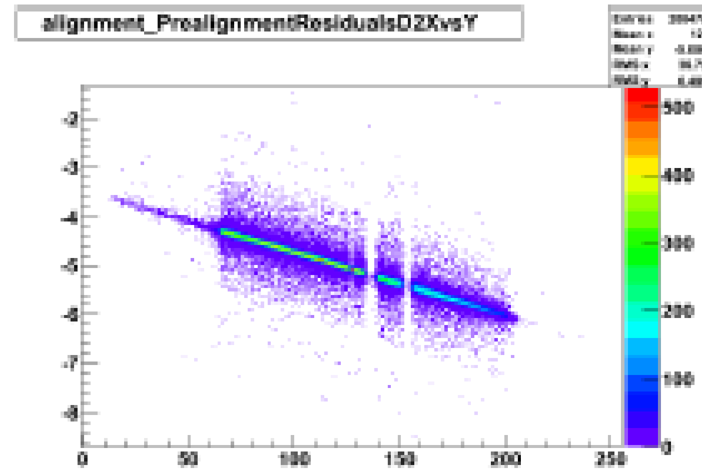
- Typically see all of these steps in a testbeam
  - Study eta algorithm, determine un-folding
  - Quantify S/N, evaluate readout electronics
  - Align reference planes
  - Simplest pattern recognition
  - Do track fitting



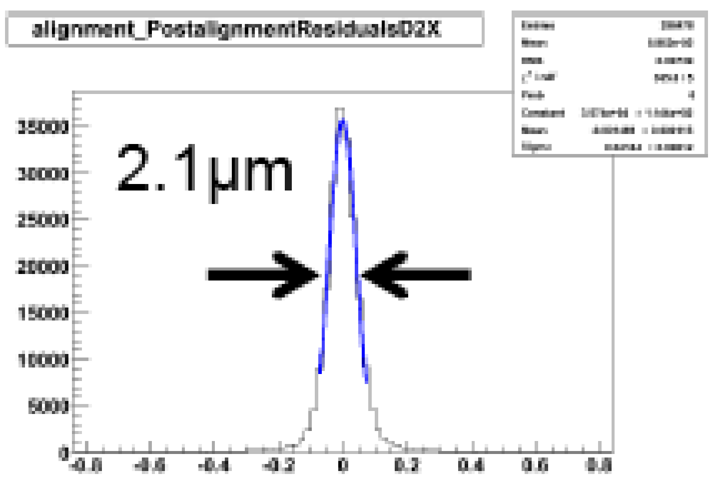
Alignment of Testbeam Telescope

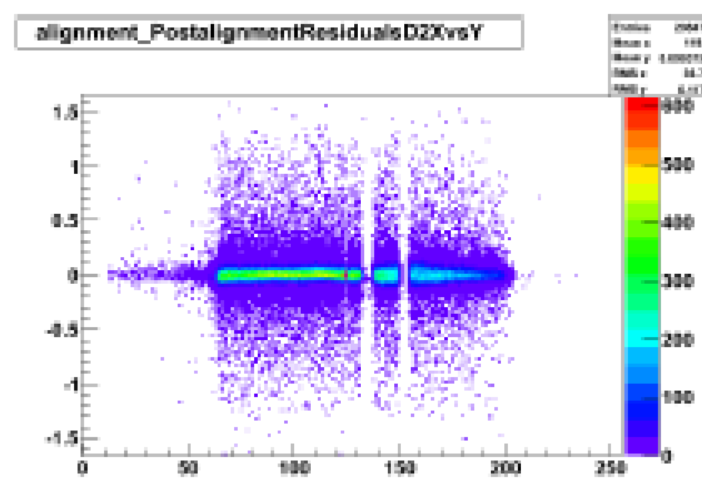
Before alignment





After alignment





Alignment Stability

Offset	Run 15101	Run 15103	Run 15208	Run 15212
D1X	0.528	0.539	0.534	0.537
D2X	-3.51	-3.49	-3.52	-3.52
D3X	1.68	1.70	1.69	1.69
D1Y	-0.484	-0.487	-0.502	-0.498
D2Y	-9.26	-9.26	-9.21	-9.20
D3Y	1.52	1.52	1.55	1.562
D1X phi	0.00339	0.00331	0.00338	0.00335
D2X phi	0.0126	0.0126	0.0126	0.0126
D3X phi	-0.000222	-0.000145	-0.000188	-0.000196
D1Y phi	0.00210	0.00211	0.00211	0.00210
D2Y phi	-0.0113	-0.0113	-0.0114	-0.0115
D3Y phi	0.000150	0.000160	6.21e-05	6.95e-06

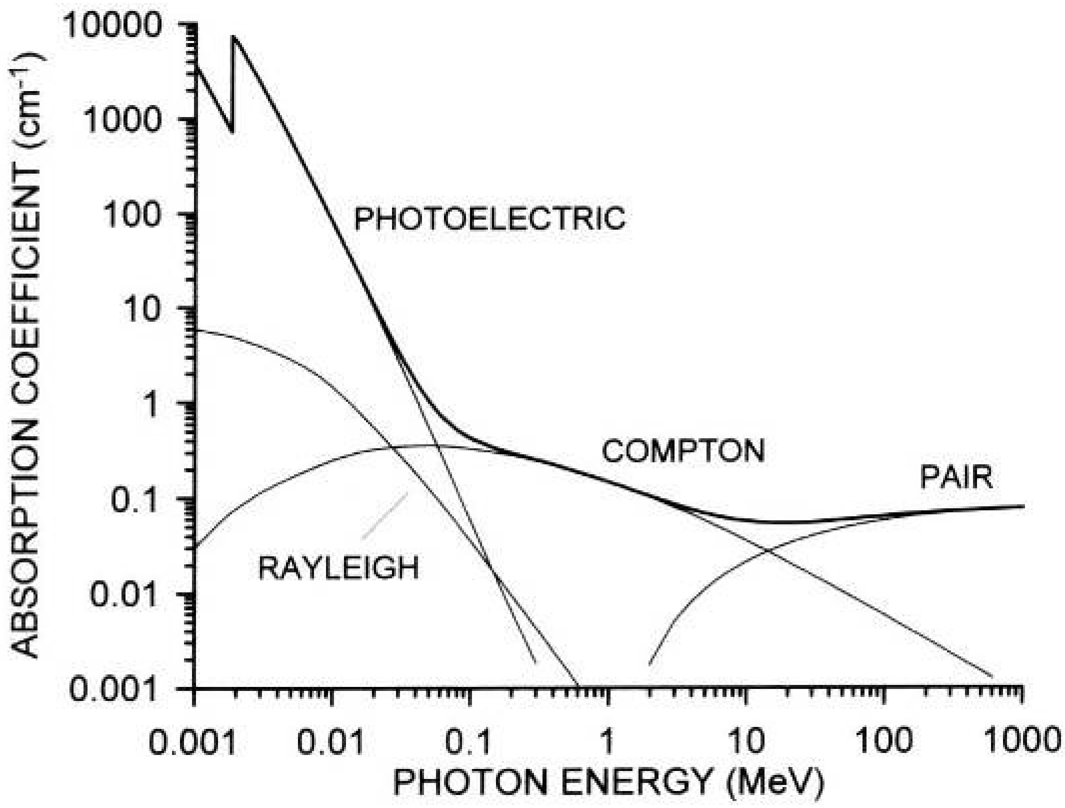
Applications Outside Particle Physics

- Broad area, overlap with fast/medical imaging
- Include here a couple of examples

  - Fast radiography
  - Sound preservation

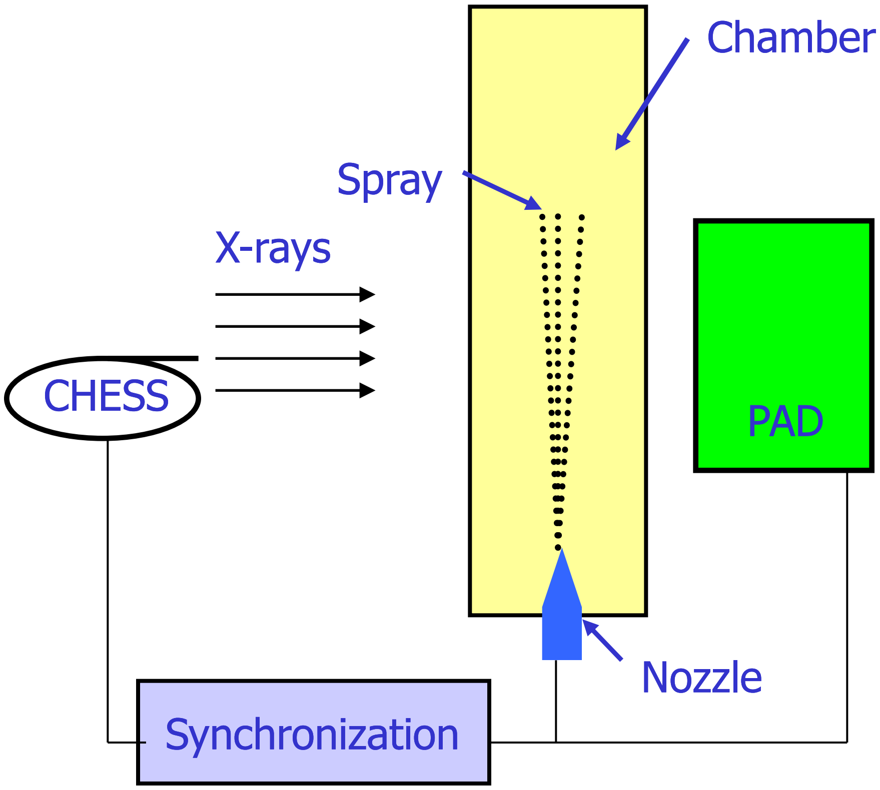
X-Rays in Silicon

- Visible photon range ~ μm
- 20 keV X-ray range 5 μm
- 100 keV X-ray range 80 μm

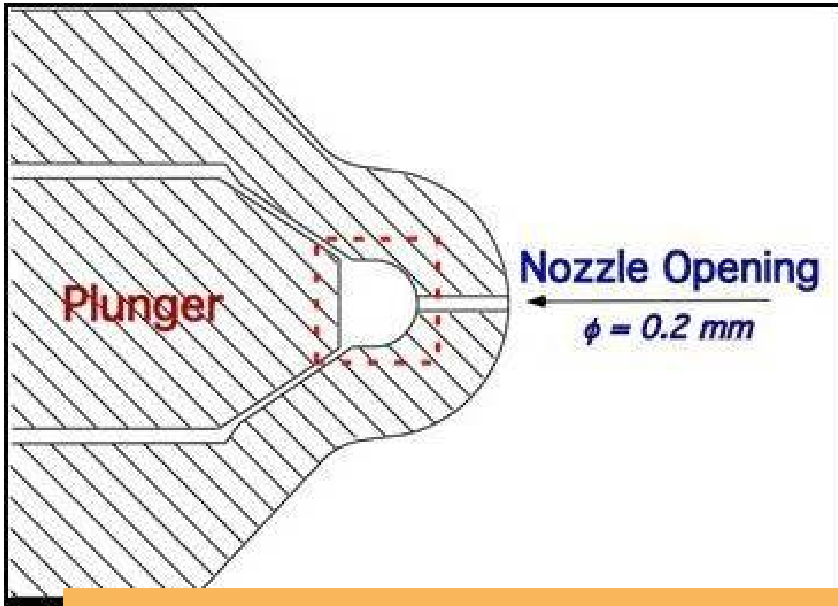


High Speed Radiography

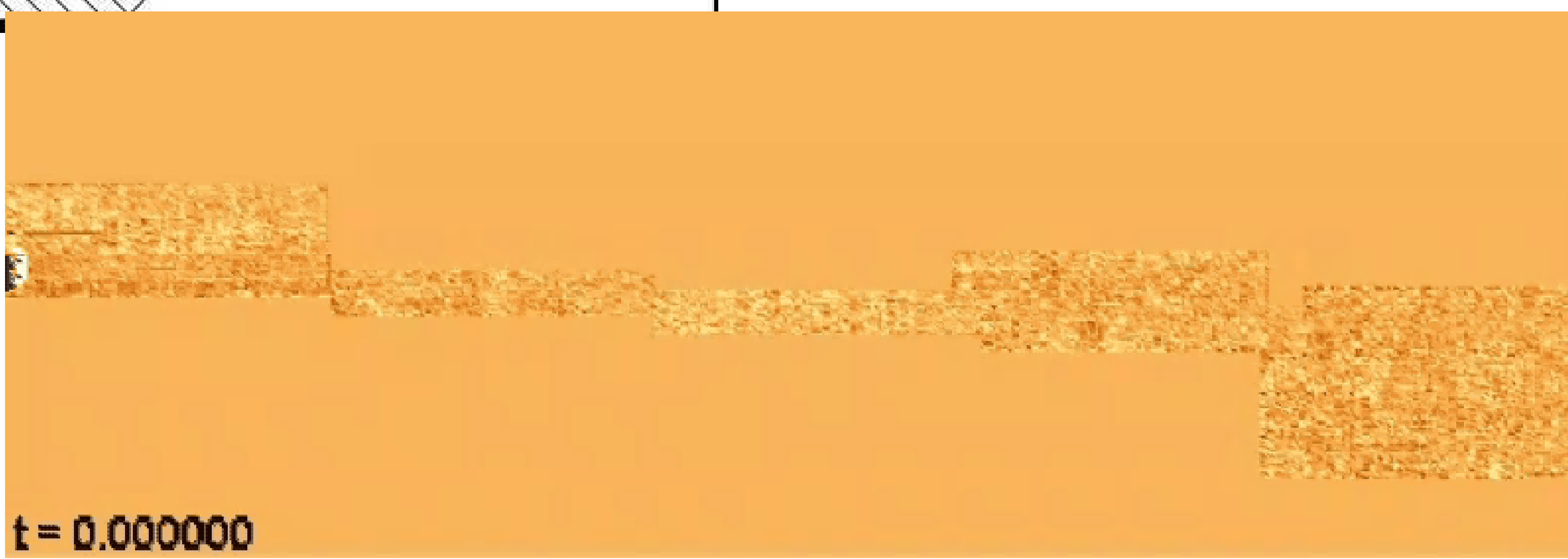
- Supersonic spray from Diesel Fuel Injection System
  - Impossible to observe in visible light
- 6 keV X-ray beam recorded by fast silicon pixel detector



Diesel Fuel Injector Spray

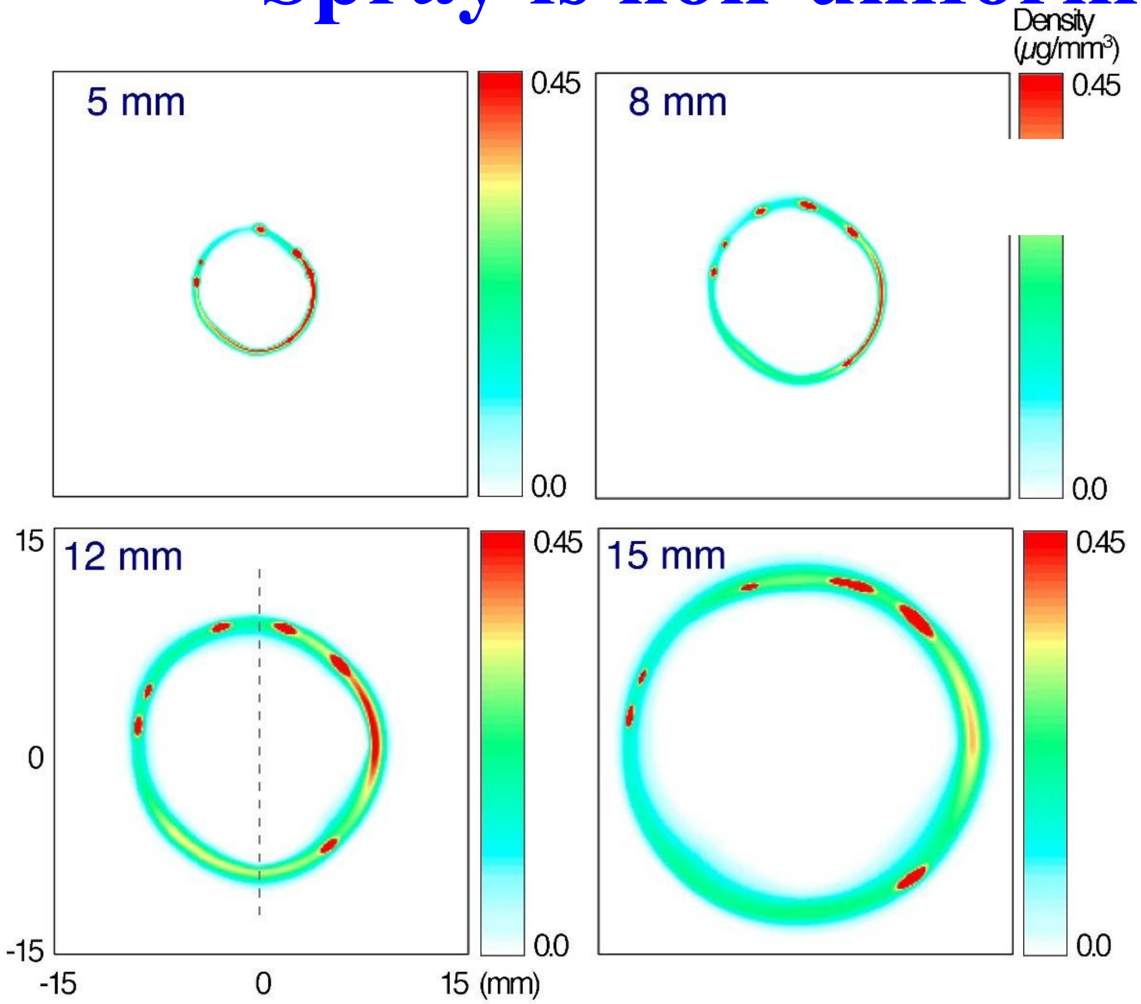


- **Total exposure time 1.3 ms**



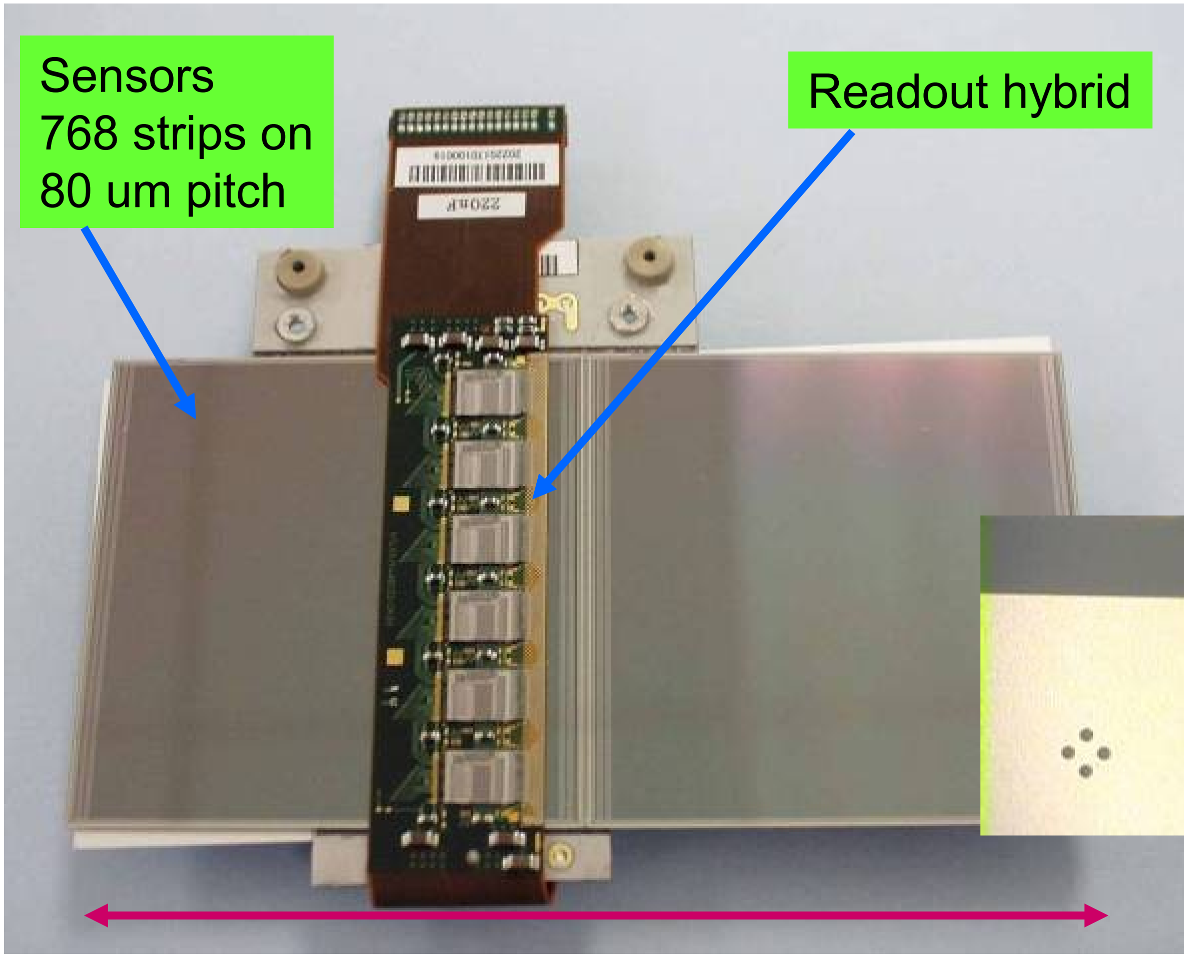
A. MacPhee, *et al*, Science (2002), **295**, 1261-1263.

Spray is non-uniform



These measurements provided unexpected information: shock waves, oscillations – used to optimize engines

Optical Metrology of ATLAS Modules



12 cm

SmartScope

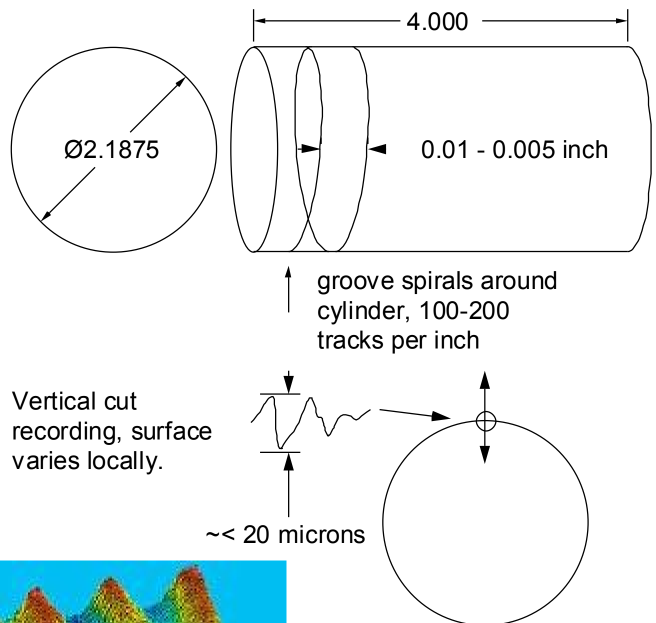
Corner
fiducial mark

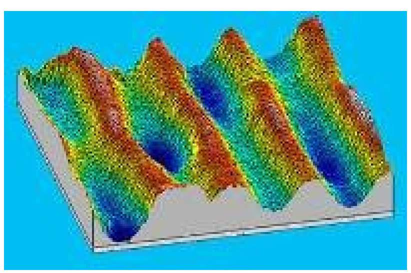
Can locate detector position with ~micron precision

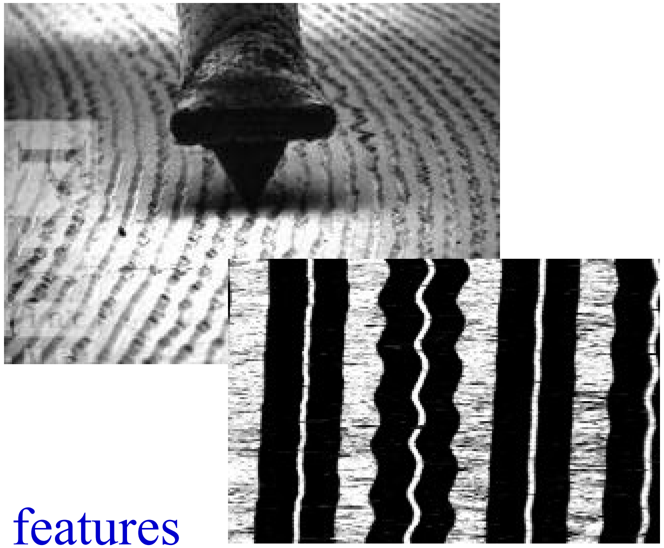
Preservation of Mechanical Recording

Cylinder: groove varies in depth (Vertical Cut)

Disc: groove moves from side to side (Lateral Cut)



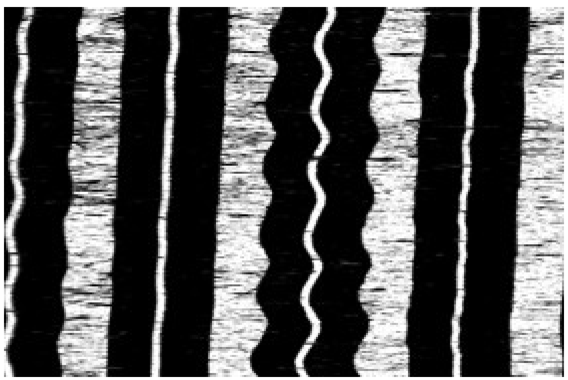


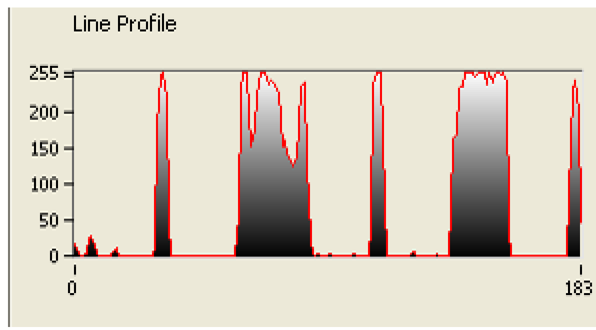


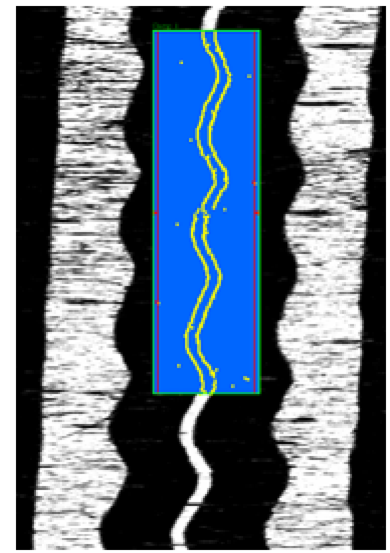
Audio is encoded in micron scale features which are >100 meters long

Sound Preservation: Image Analysis

Used ATLAS silicon module survey camera for scanning (Carl Haber and co-authors)







Now being used to generate digital record of all recordings in Smithsonian collection in Washington DC

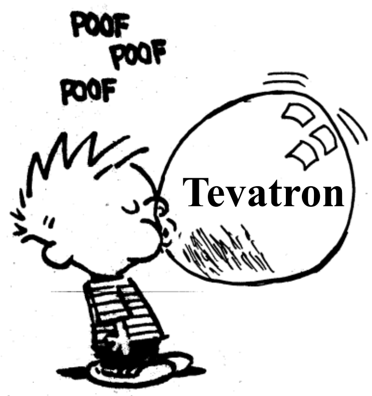
Summary

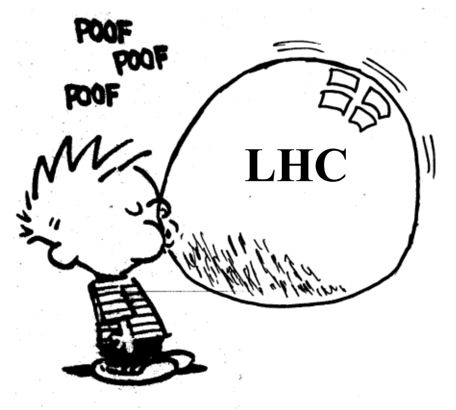
- Silicon detectors offer un-paralleled hit precision
- Critical for B physics and ID of long–lived particles
- Need combination of:
  - Large, well localised, signal in stable detector mechanics
  - Low noise readout electronics
  - Clever alignment algorithms
  - Ultimate granularity and pattern recognition

  to realise the ultimate precision of these systems
- This precision + LHC collisions will drive discoveries

Silicon technology finding applications beyond particle physics

As Long As This Doesn't Happen





Whoops…

P.Collins, ICHEP 2002