An Introduction to Charged Particle Tracking & Detectors

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RAL & Oxford

RAL

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Target Audience & Participation

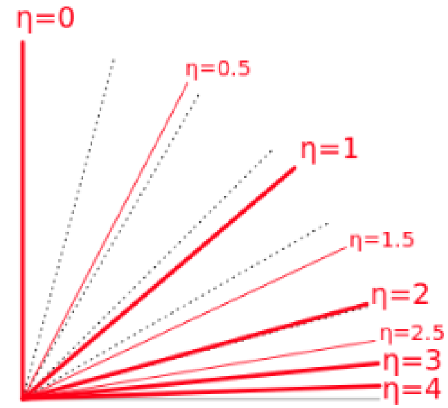
People who are quite new to Particle Physics and Particle Physics Detectors.

Feel Free to ask Questions as we go along. Do not wait until the end.

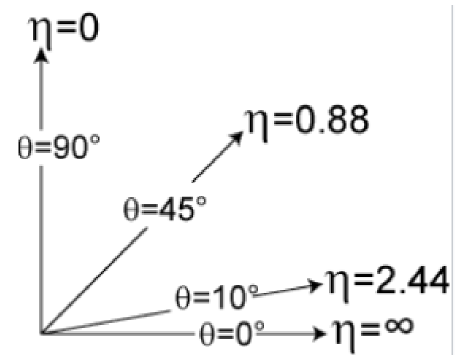
Before we get started

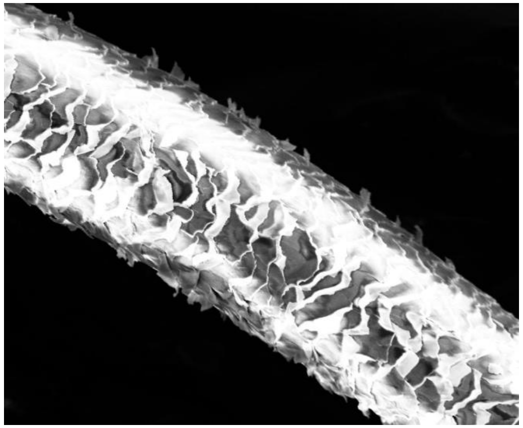
Some Mathematical & Other Pre-requistes

Pseudorapidity is commonly used as a measure of the angle of a particles 3-momentum with respect to the beam axis



$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$





Width of a human hair about 100 μm, 1,000 μm = 1mm

Tracking : An introduction

Tracking : An introduction

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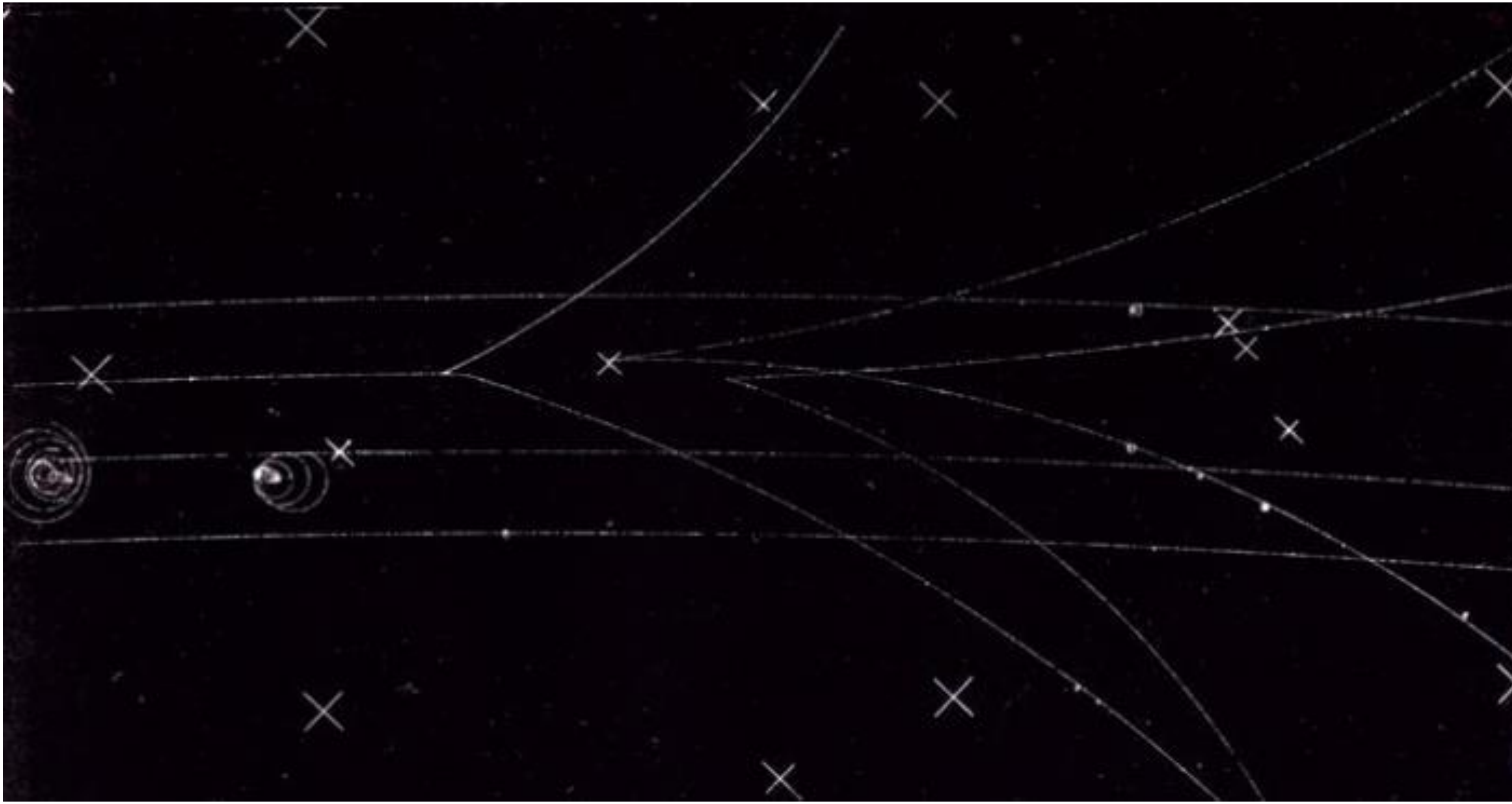
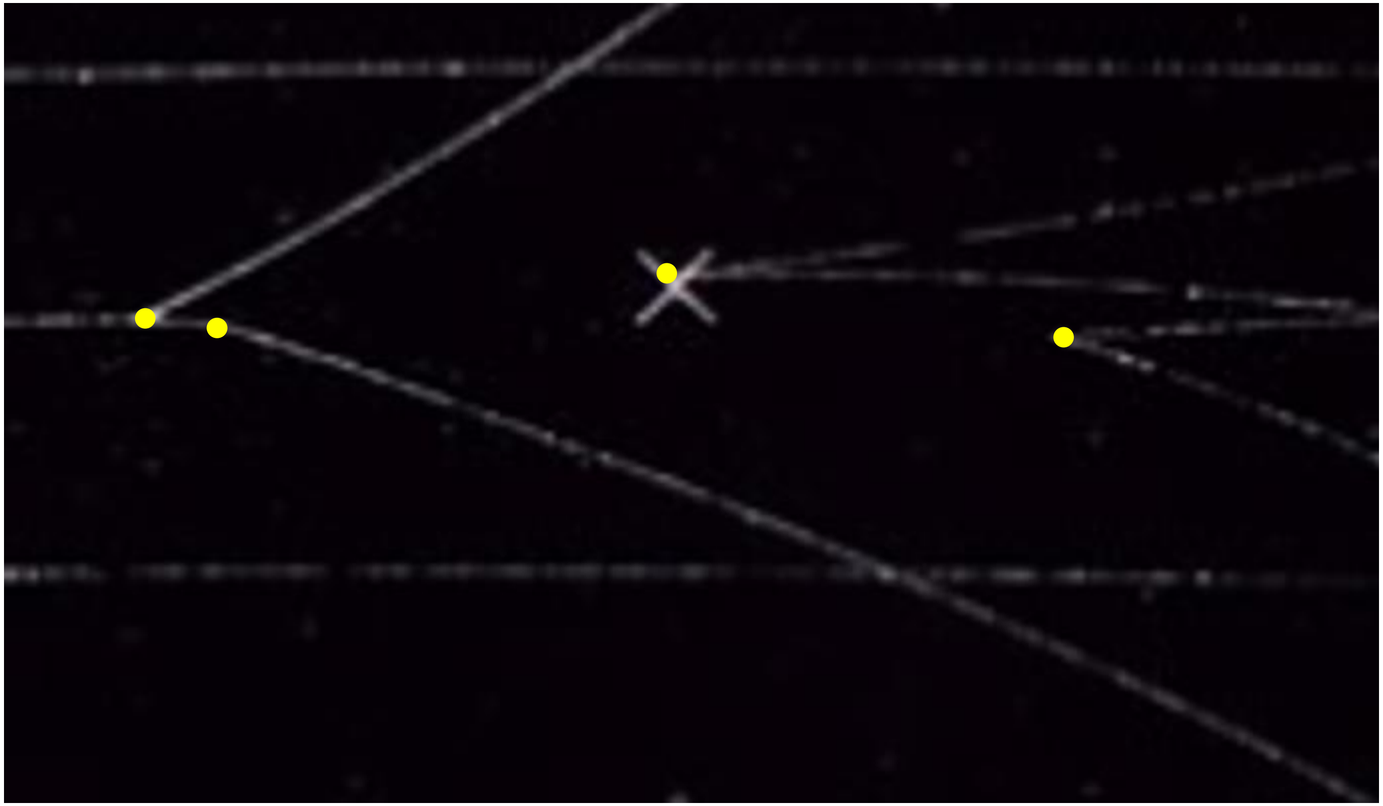
Tracking and Particle Interactions



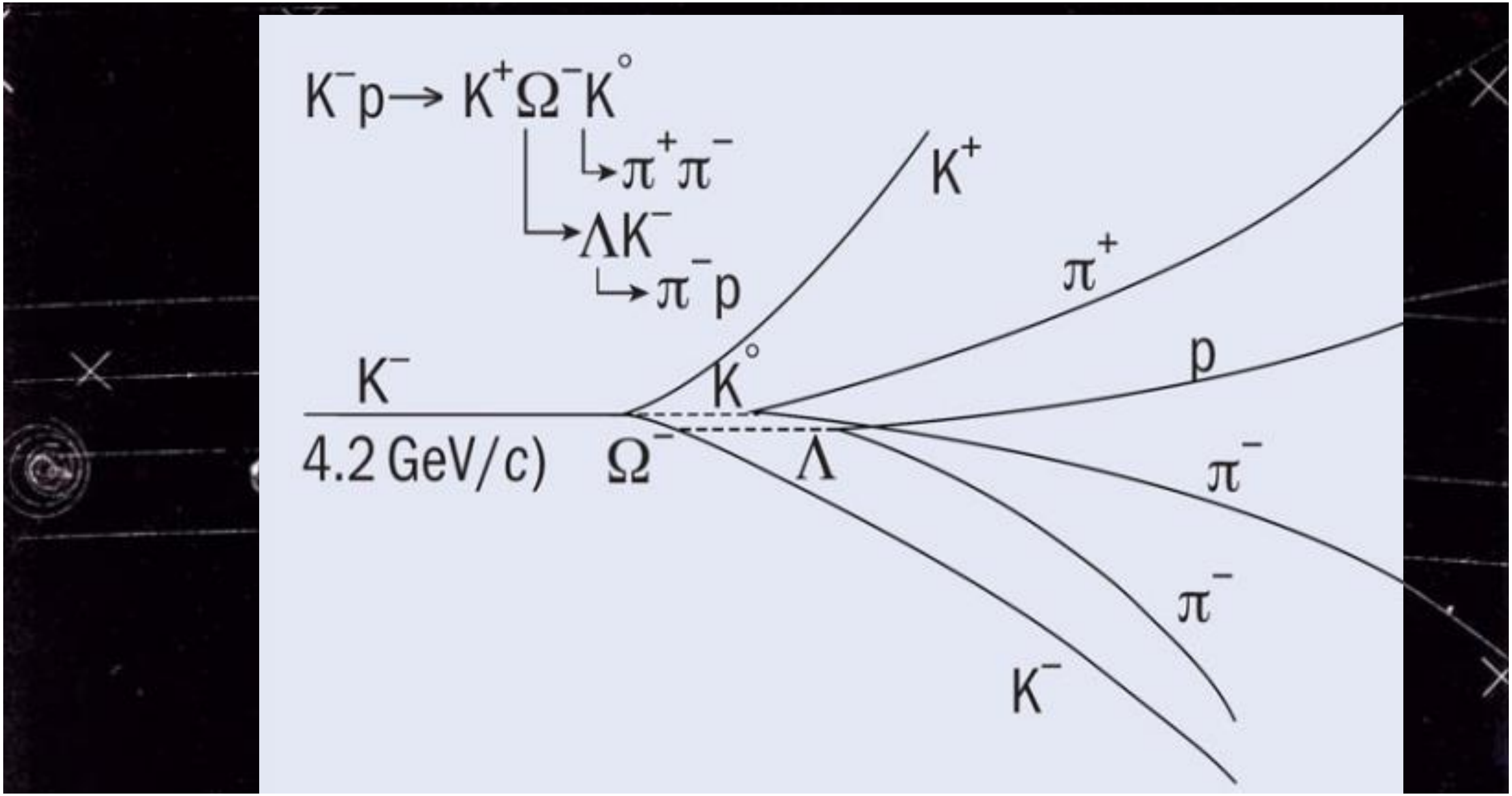
A bubble chamber photograph : particle physics technology of the 50s, 60s and …

Tracking and Particle Interactions



A bubble chamber photograph : particle physics technology of the 50s, 60s and …

Tracking and Particle Interactions



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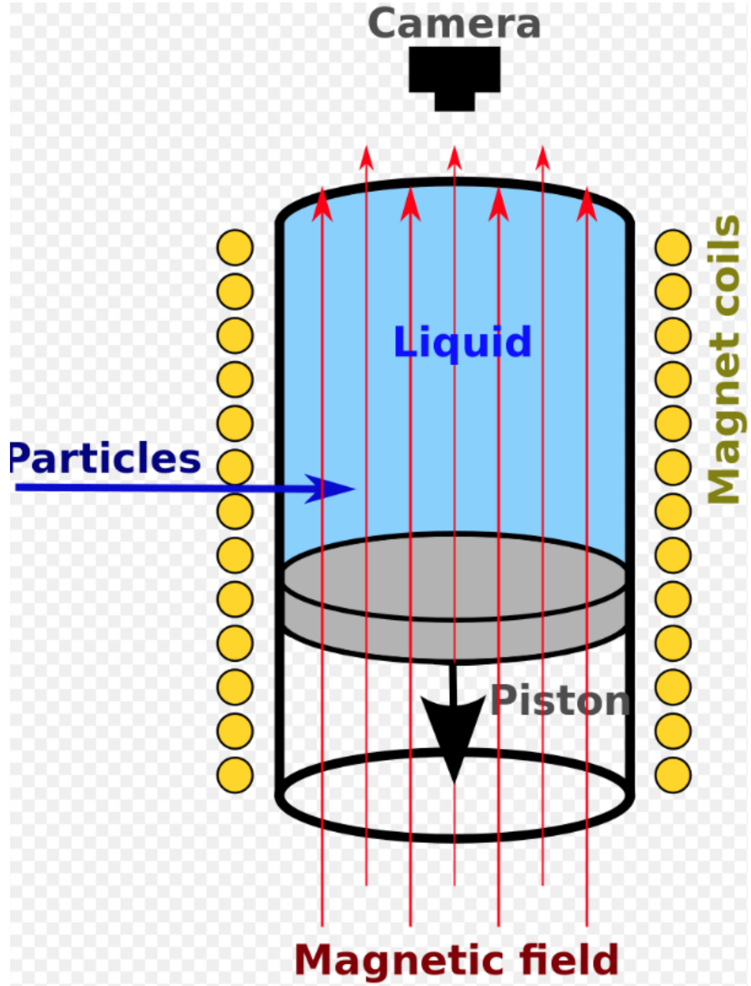
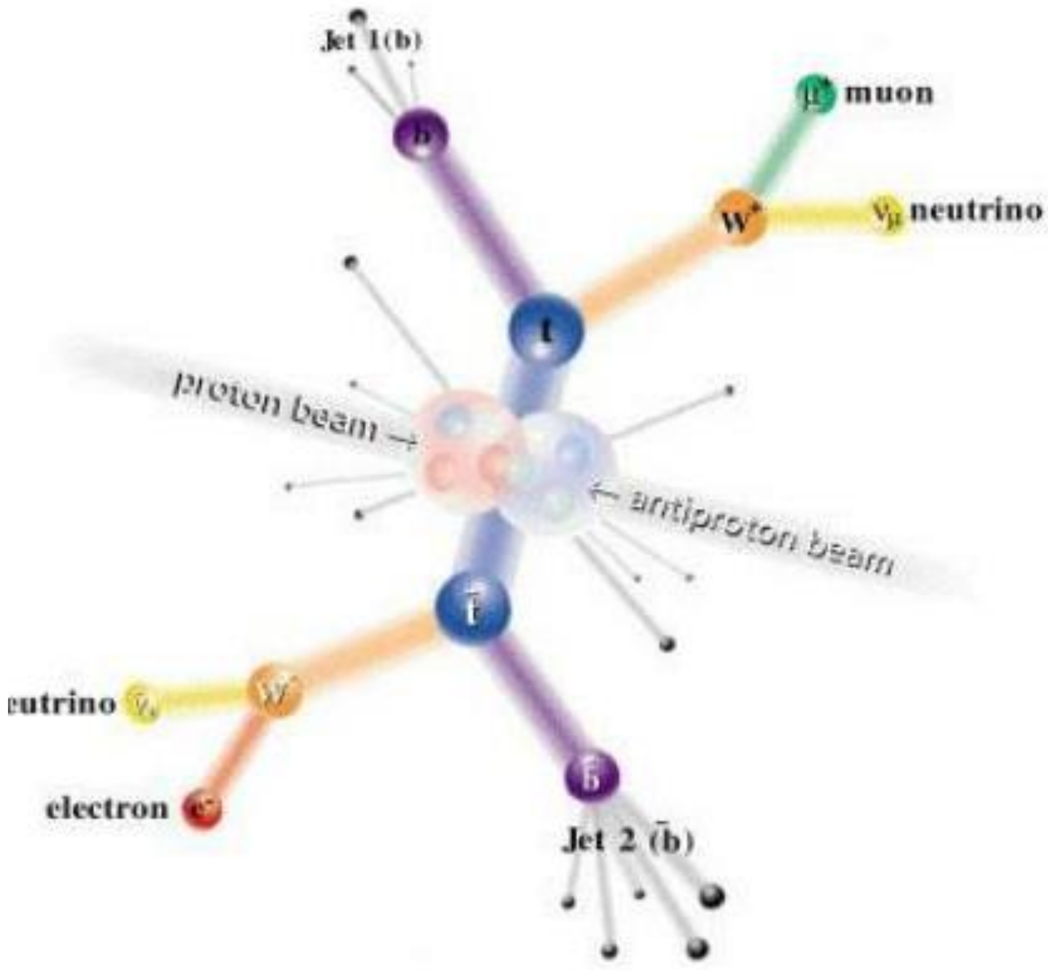
Tracking and Particle Interactions

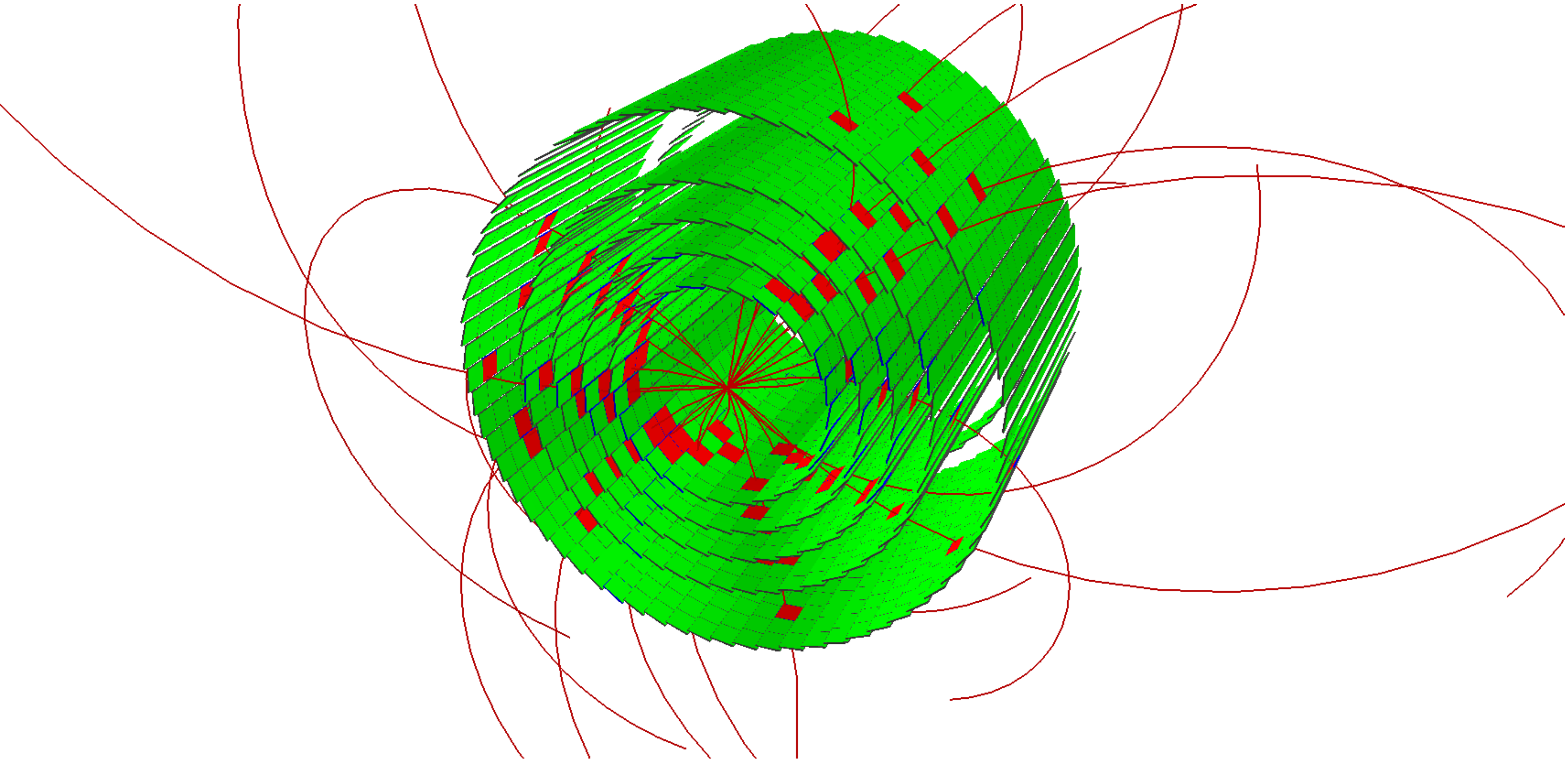


Superheated liquid (usually liquid hydrogen) just below boiling point
No triggering, need to record and develop ALL photographs and scan them. Rate limited

LHC collider event structure

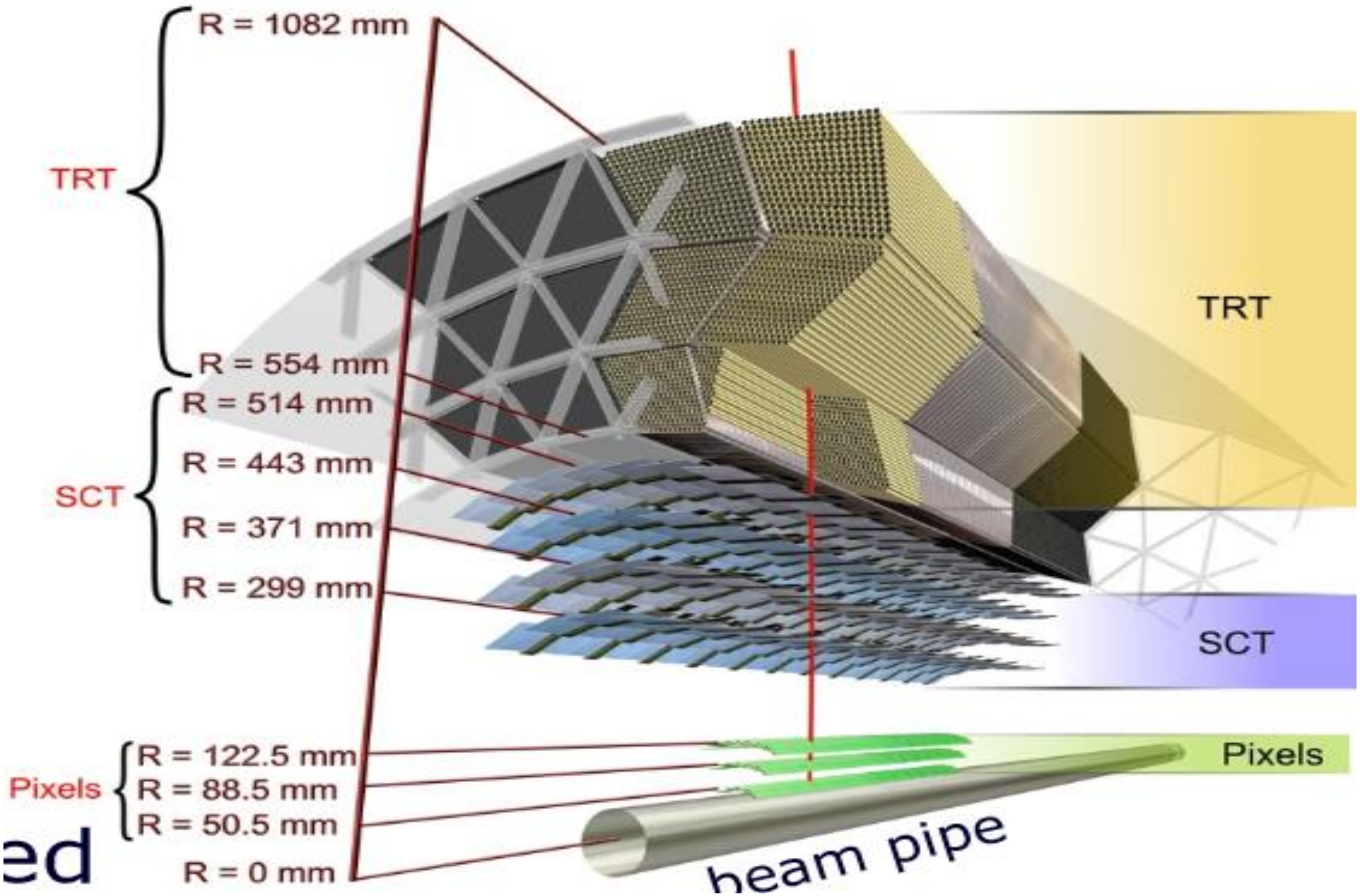


A Camera for taking pictures of high energy collisions

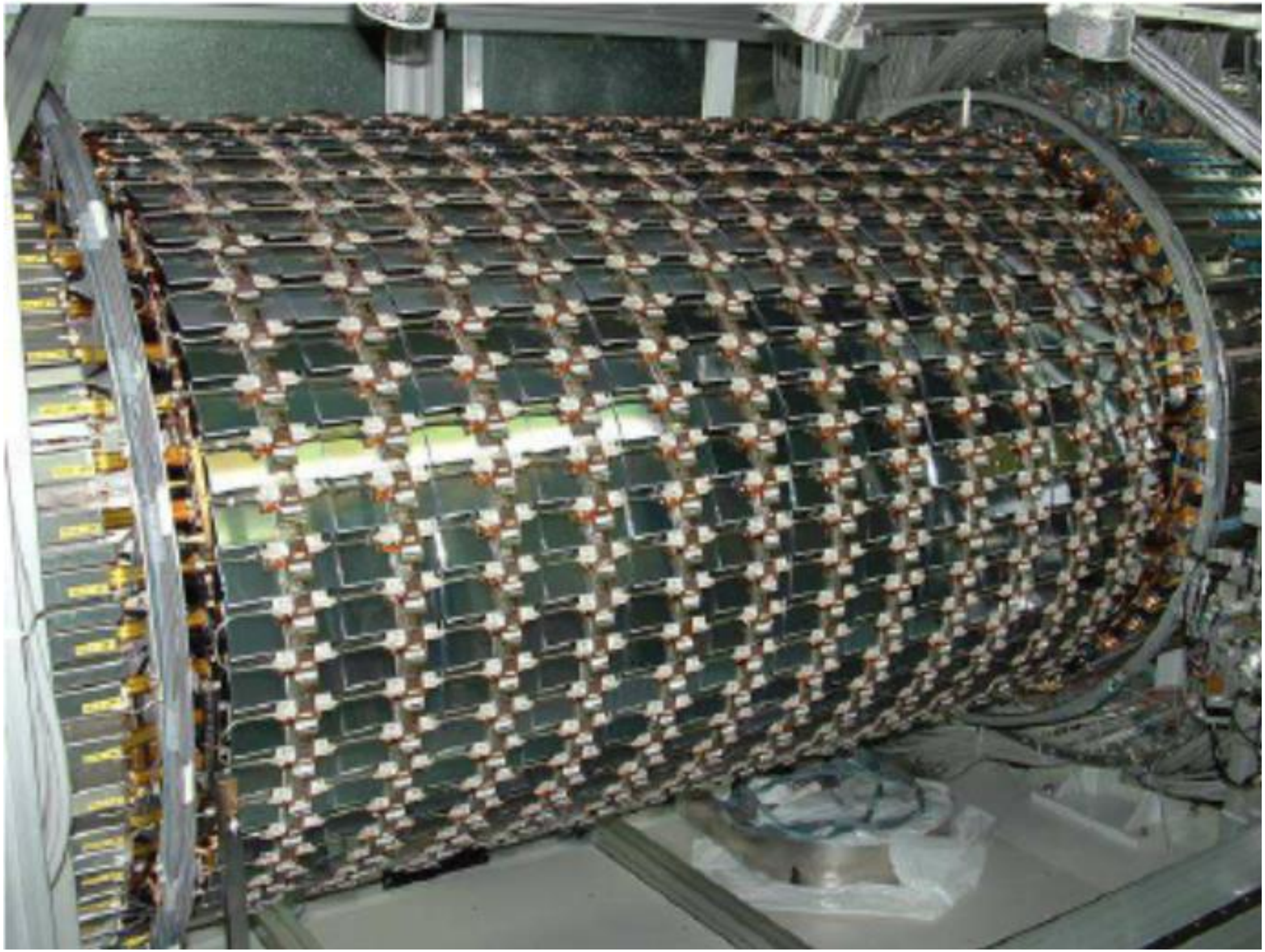


Sampling the trajectories of the particles as they fly from the collision point.

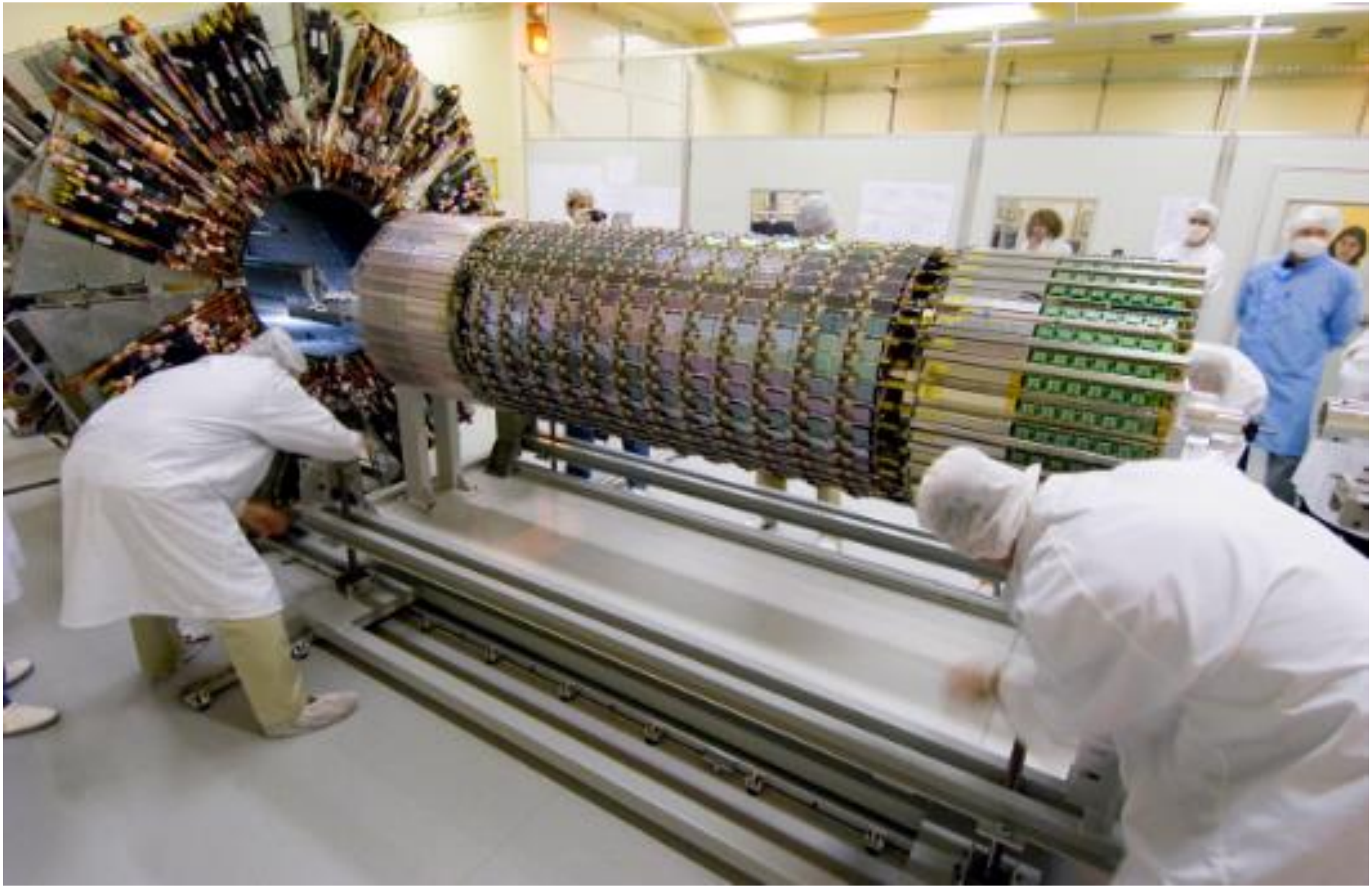
Section of old ATLAS Tracker



SCT Tracker Photographs



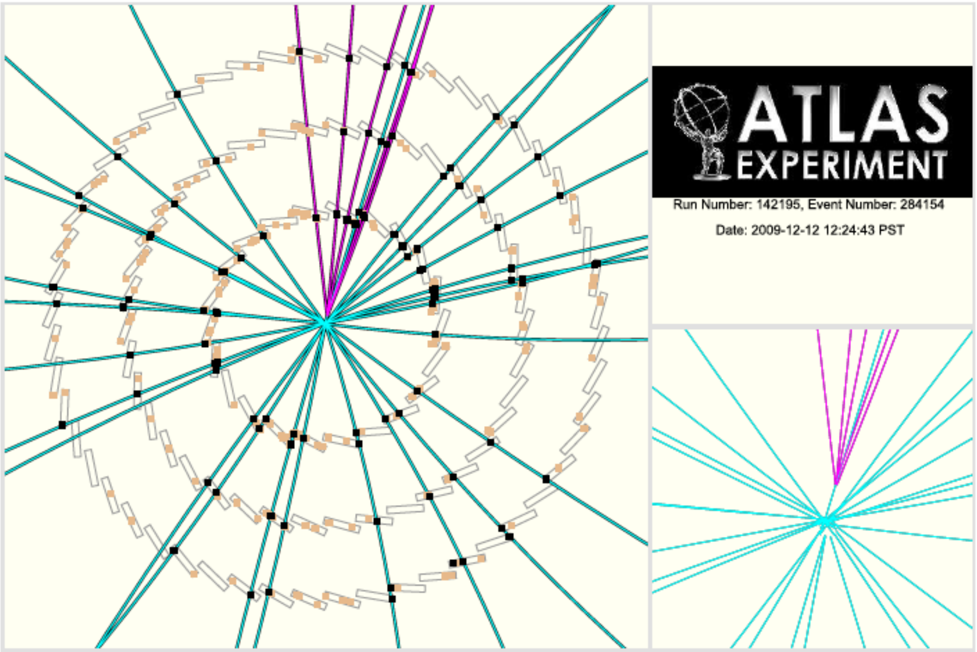
SCT Tracker Photographs

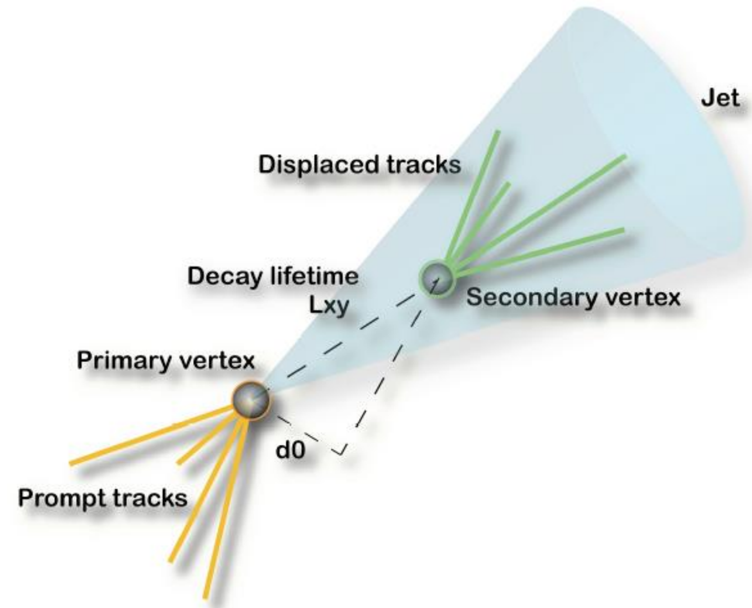


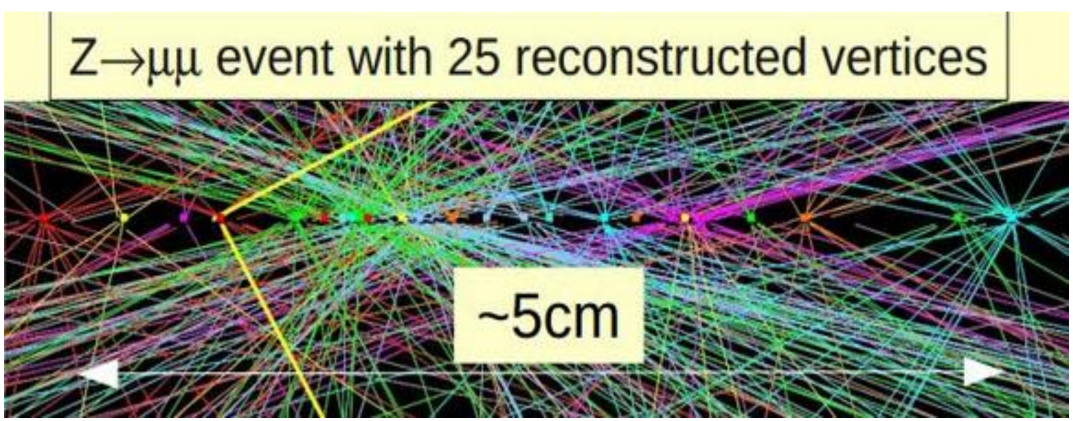
Pixel Tracker Photographs

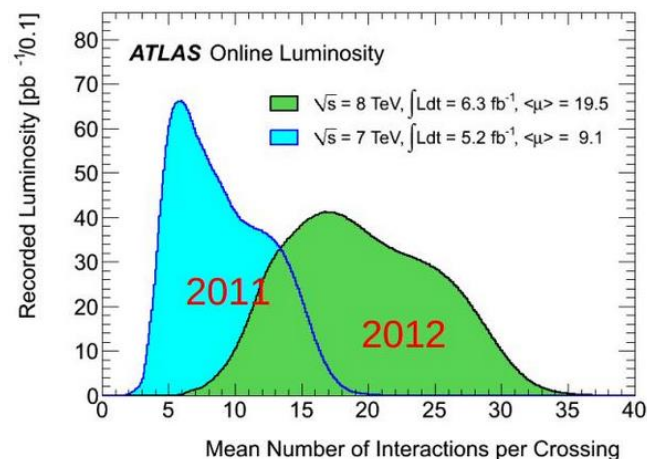
What do silicon trackers do well

- Charged particle track-reconstruction in magnetic field
  - Electric charge (+,-), transverse-momentum(P_T), direction (η,ϕ)
  - Vertex reconstruction (primary and secondary) and separation
  - Impact parameter determination,
  - Identification of tau leptons, b-tags, lifetime tagging
    - Measurement of proper time differences $\delta\tau$
  - Stand alone particle identification through dE/dX
  - Determine the point of impact into calorimeter
    - Important to be able to establish the absence of a track entering a calorimeter
  - High efficiency, low fake rates often in very crowded environments.
  - Important to be able to find photon-conversions and nuclear interactions
- Used in triggers and event filters
  - Can run and be read-out at very high rates (MHz)
  - Used in very crowded environments
  - Used in conjunction with other detector in PID (P, e,γ,μ..)



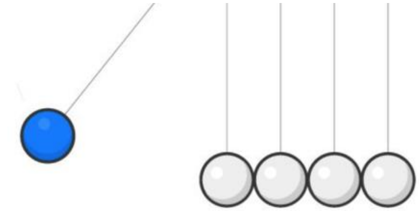






HL-LHC <μ> up to 200

Measuring momentum



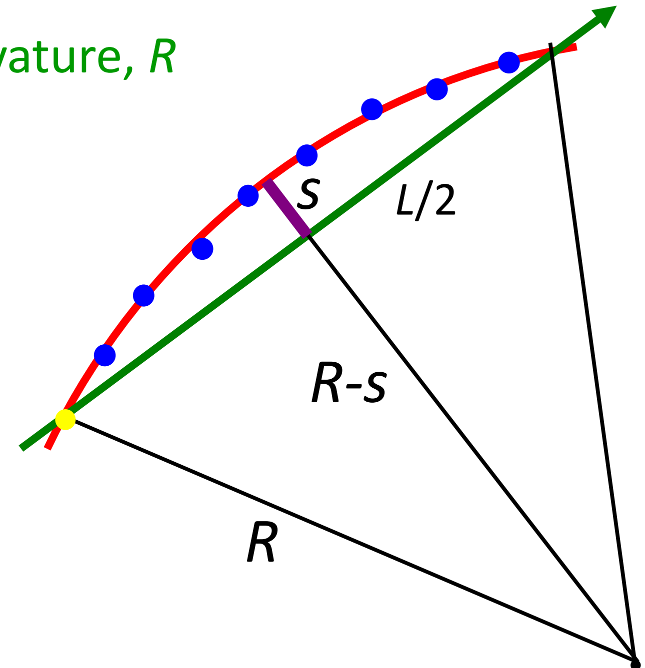
- Circular motion transverse to uniform B field:

$$p_T[\mathrm{GeV/c}] = 0.3 \cdot B[\mathrm{T}] \cdot R[\mathrm{m}]$$

- Measure sagitta, *s*, from track arc → curvature, *R*

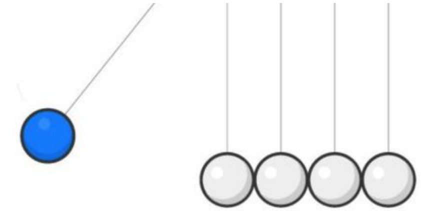
- $R = \frac{L^2}{2s} + \frac{s}{2} \approx \frac{L^2}{2s}$

- $\frac{\sigma_{p_T}}{p_T} = \frac{8 p_T}{0.3 B L^2} \sigma_s$



- Relative momentum uncertainty is proportional to p_T times sagitta uncertainty, σ_s. Also want strong B field and long path length, *L*

Measuring Momentum
A numerical example



P_T = 100 GeV/c

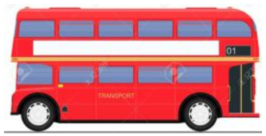
B = 2 T (ATLAS Solenoid)

L = 1 m (ATLAS Inner cryostat)

We find

R = 166.6 m

S = 3,000 μm



x 16

P_T = 101 GeV/c

B = 2 T

L = 1 m

We find

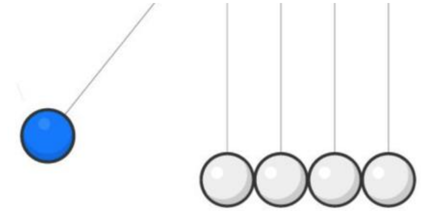
R = 168.3 m

S = 2,970 μm

***δS* (P_T = 100 - P_T = 101) = *30* μm**

Double decker busses are between 9.5m and 11.1m

Measuring momentum



- Sagitta uncertainty, σ_s, from N points, each with resolution $\sigma_{r\phi}$ is:

$$\sigma_s = \sqrt{\frac{A_N}{N+4}}\frac{\sigma_{r\phi}}{8}$$

- Statistical factor $A_N = 720$:

- The point error, $\sigma_{r\phi}$, has a constant part from intrinsic precision,

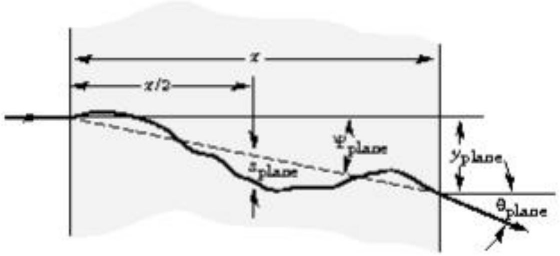
and a multiple scattering part.

- Multiple scattering contribution:
- (L is in the transverse plane)

$$\sigma_s \propto \frac{L}{p_T \sin^{1/2}\theta}\sqrt{\frac{L}{X_0}}$$

$$\frac{\sigma_{p_T}}{p_T} = \frac{8p_T \cdot \sigma_s}{0.3BL^2} \approx a \cdot p_T \oplus \frac{b}{\sin^{1/2}\theta}$$

Multiple (Coulomb) Scattering

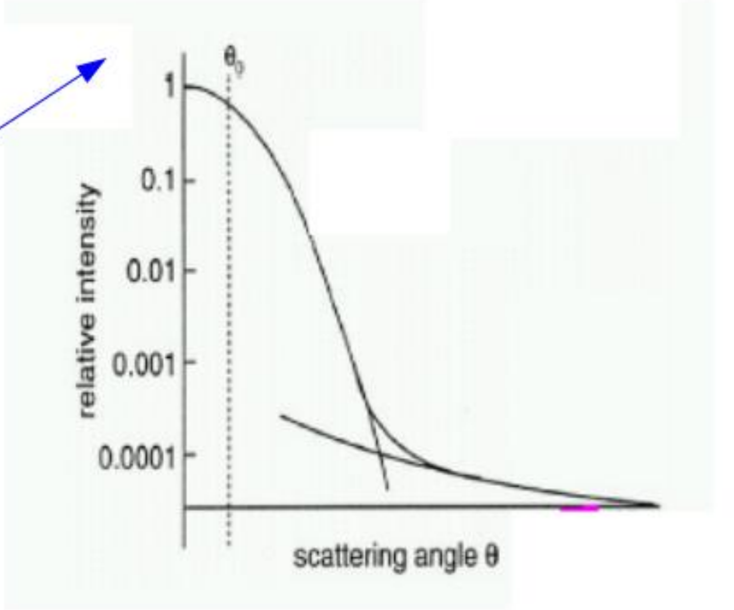


- 98% Gaussian around scattering angle 0
- 2 % large scattering angles

Approximation for standard deviation of projected angles (in plane) of scattering angle: Moliere theory

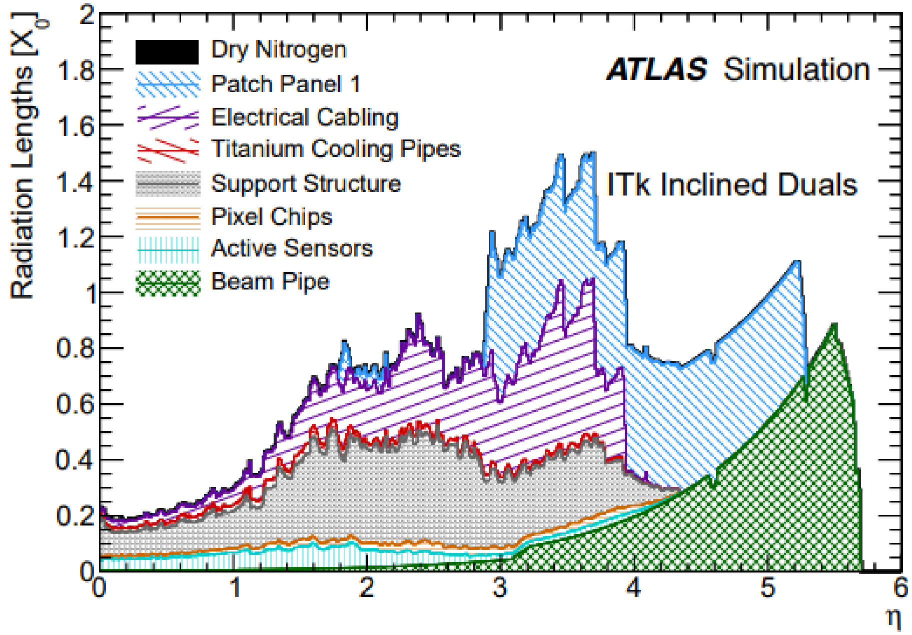
$$\Theta_{rms} = \frac{13.6\,MeV}{\beta c p} z \sqrt{x/X_0}\left(1 + 0.038 \ln(x/X_0)\right)$$

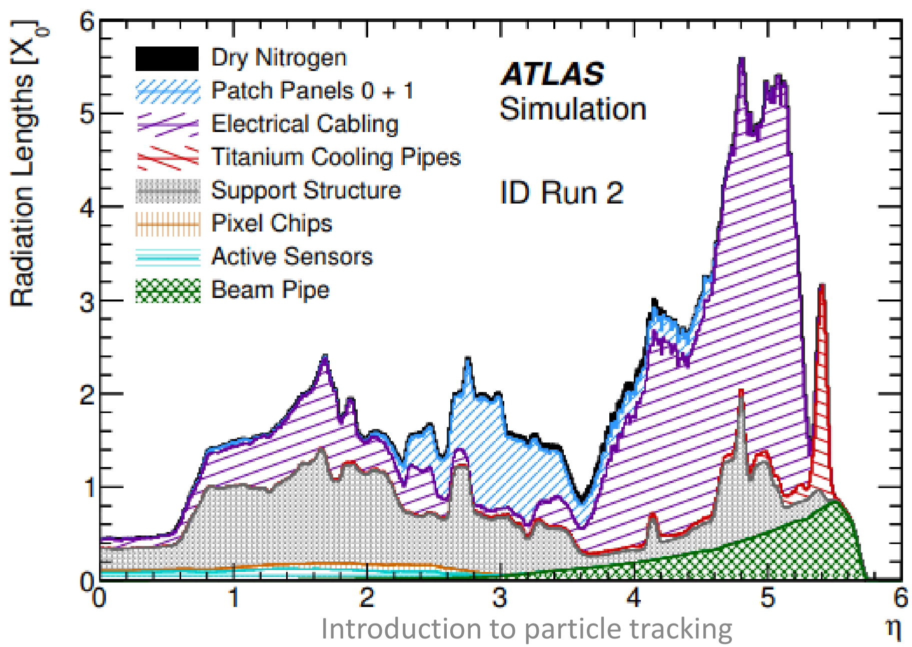
Radiation length $X_0 = \frac{716.4\, g\, cm^{-2} A}{Z(Z+1)\ln(287/\sqrt{Z})}$

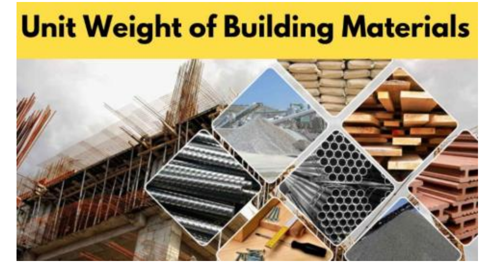


- strength of scattering depends on 1/p → large for small momenta
- limits mass resolution (momentum, direction)
- importance of detectors with very small material budget
- distribution of spacial scattering angle (diff. btw direction of incoming and outgoing particle)

How Much Material ?

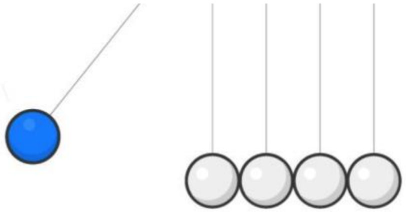




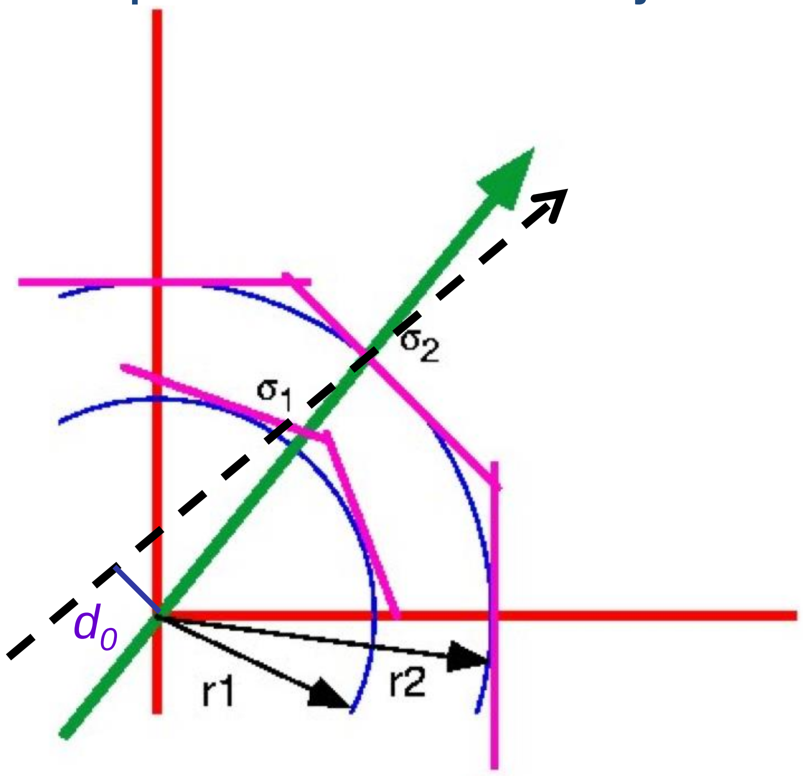


Taken from Pixel Technical Design Report in 2017

Impact parameter resolution



- Uncertainty on the transverse impact parameter, d_0, depends on the radii and space point precision.
- Simplified formula for just two layers:



$$\sigma_{d_0}^2 = \frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{(r_2 - r_1)^2}$$

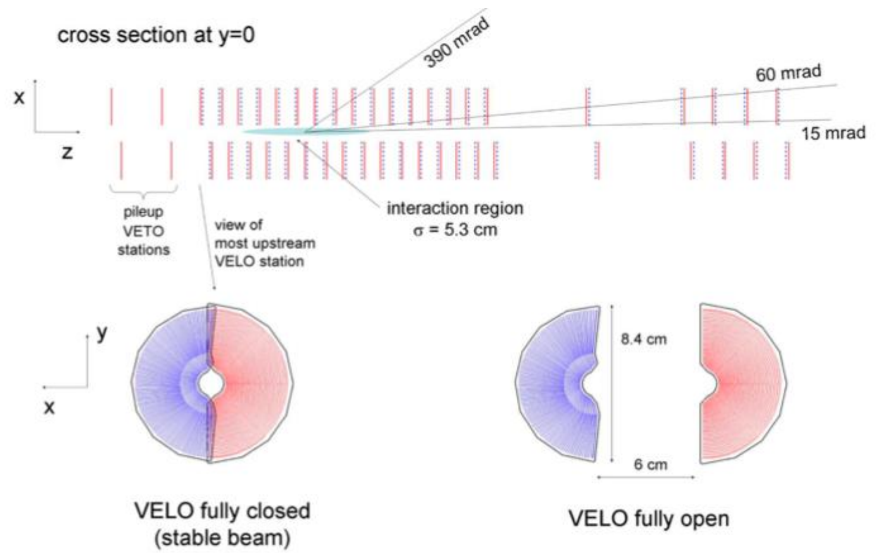
Suggests small r_1, large r_2, small σ_1, σ_2

But precision is degraded by multiple scattering…

Summary of some pixel results

	ALICE	ATLAS	CMS
Radii (mm)	39 – 76	50.5 – 88.5 – 122.5	44 – 73 – 102
Pixel size $r\phi$ x z (μm^2)	50 x 425	40 x 400	100 x 150
Thickness (μm)	200	250	285
Resolution $r\phi$ / z (μm)	12 / 100	10 / 115	~15-20
Channels (million)	9.8	80.4	66
Area (m^2)	0.2	1.8	1

The LHCb VELO: forward geometry strip detector with 42 stations along, inner radius of 7 mm. Moves close to beam when conditions are stable.



Tracking Efficiency in ITk

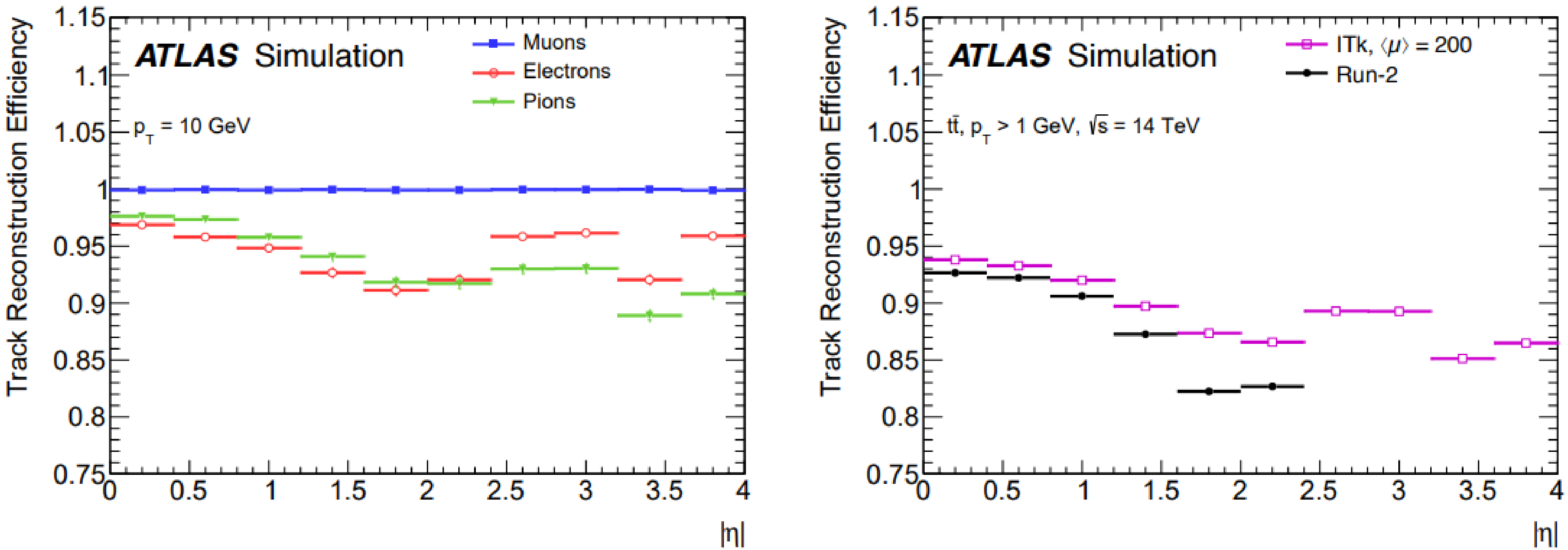


Figure 3.3: **Left**: Track reconstruction efficiency for single muons, pions and electrons with a constant transverse momentum of $p_T = 10$ GeV. **Right**: Track reconstruction efficiency for a top-pair sample with an average of 200 pile-up events. Overlaid are the results for the current Run 2 detector.

Rate of Fake Tracks in ITk

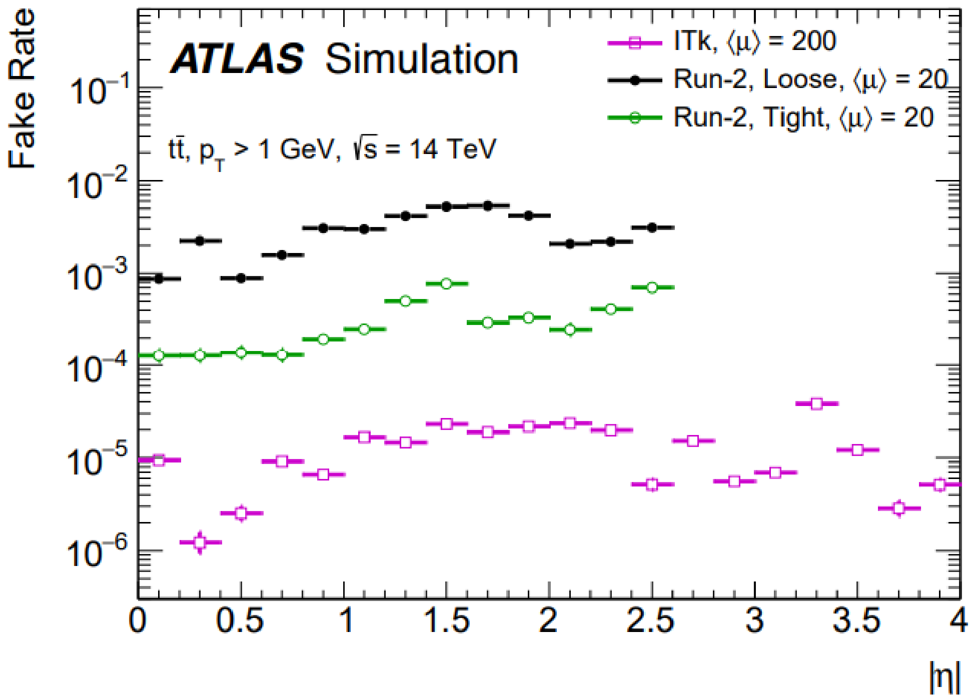
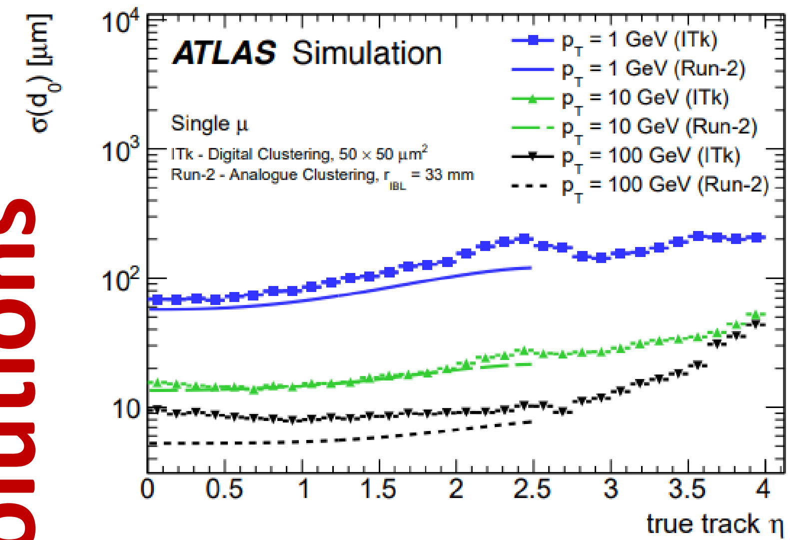
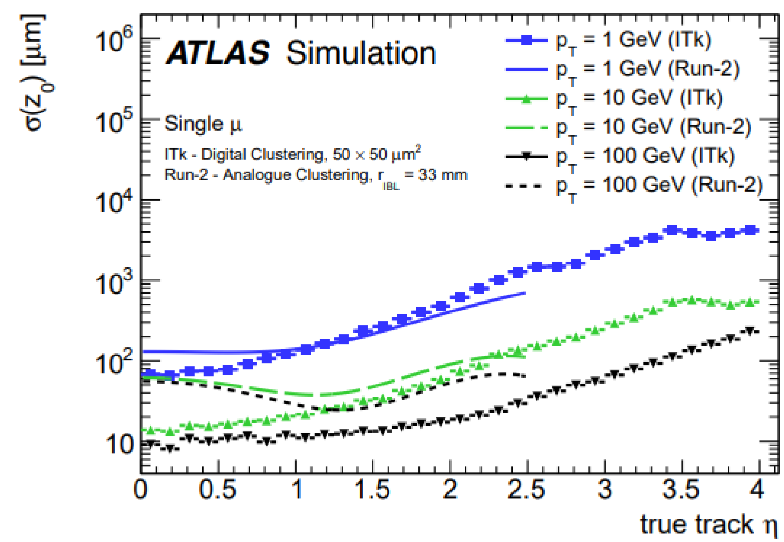
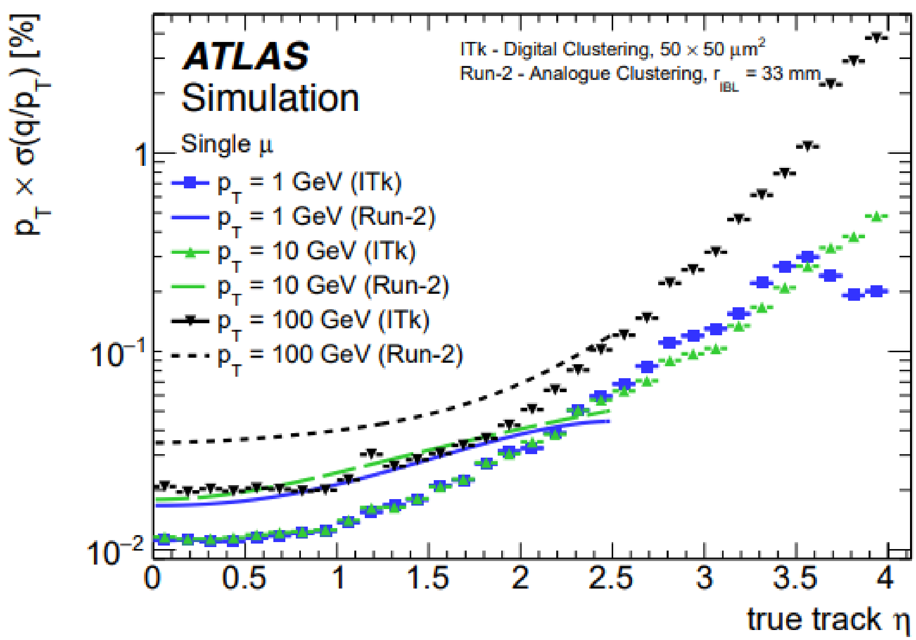


Figure 3.5: Fake rate for reconstructed tracks in $t\bar{t}$ events with $\langle\mu\rangle = 200$ using the truth particle matching criterion P_{match} as define in the text. ITk is compared to the Run 2 detector results for two different levels of track selection (loose and tight, see text for details).

Track Parameter Resolutions





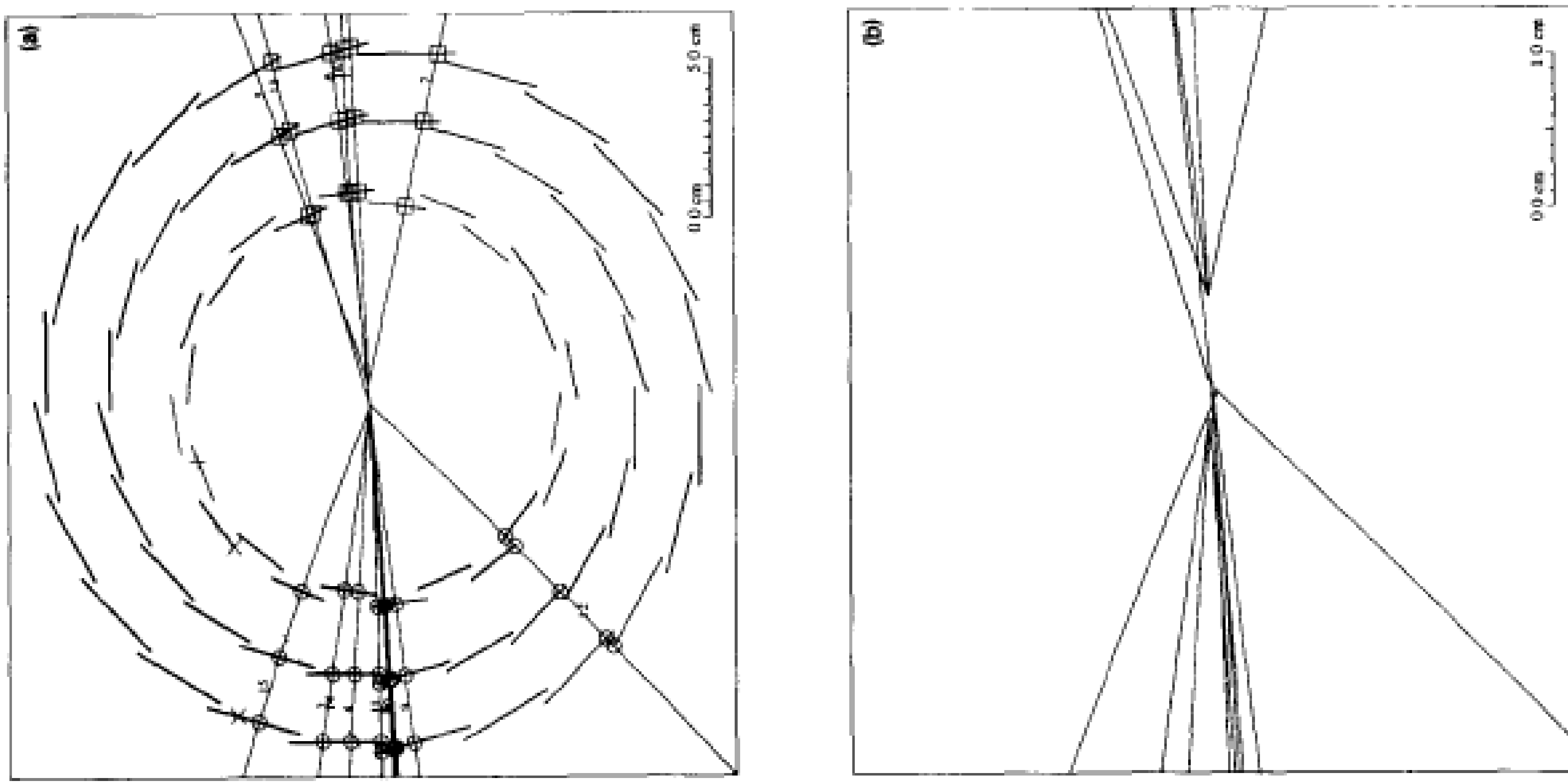


Parameter

Vertexing at LEP (1990)

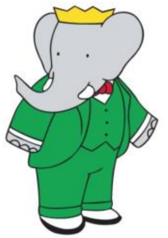
DELPHI

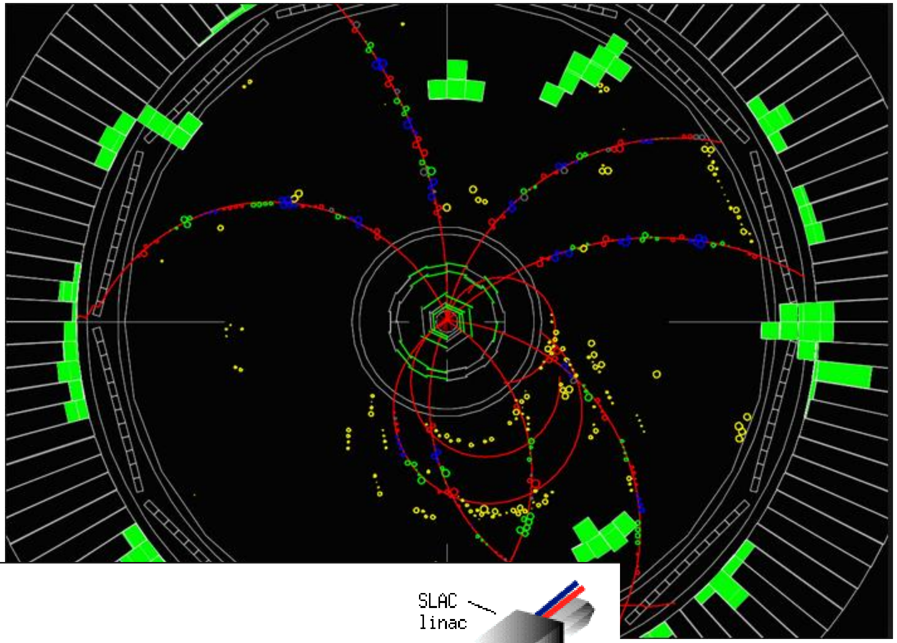
- DELPHI (symmetric e^+e^- collisions producing Z^0 bosons)
- LEP - 45 GeV per beam

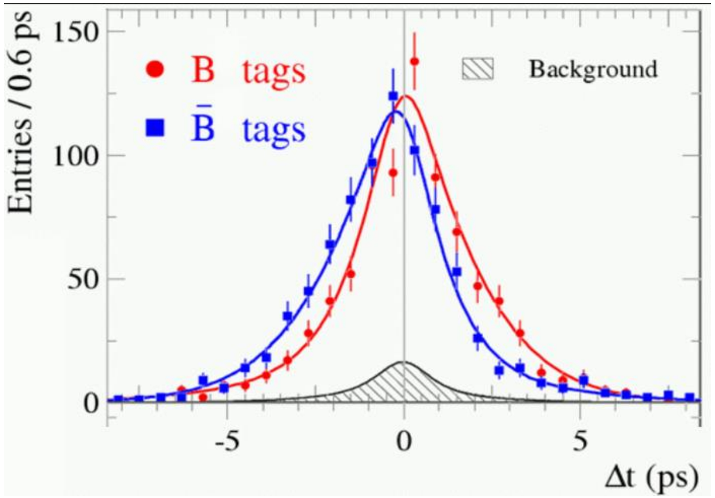


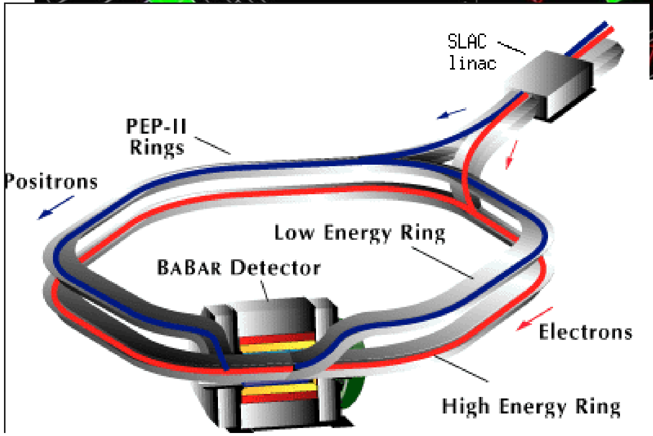
- Need ~10 micron precision for separation of vertices

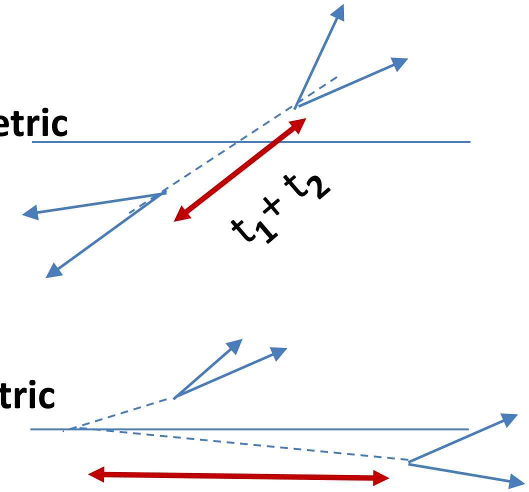
- **Vertexing in BaBar (2000)**
- BaBar asymmetric collider at SLAC (9GeV e^- on 3.1 e^+)
- Running at the Upsilon(4S) resonance, decaying to $B^0\overline{B^0}$ and B^+B^-



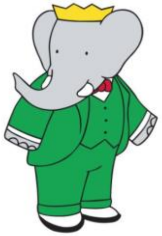








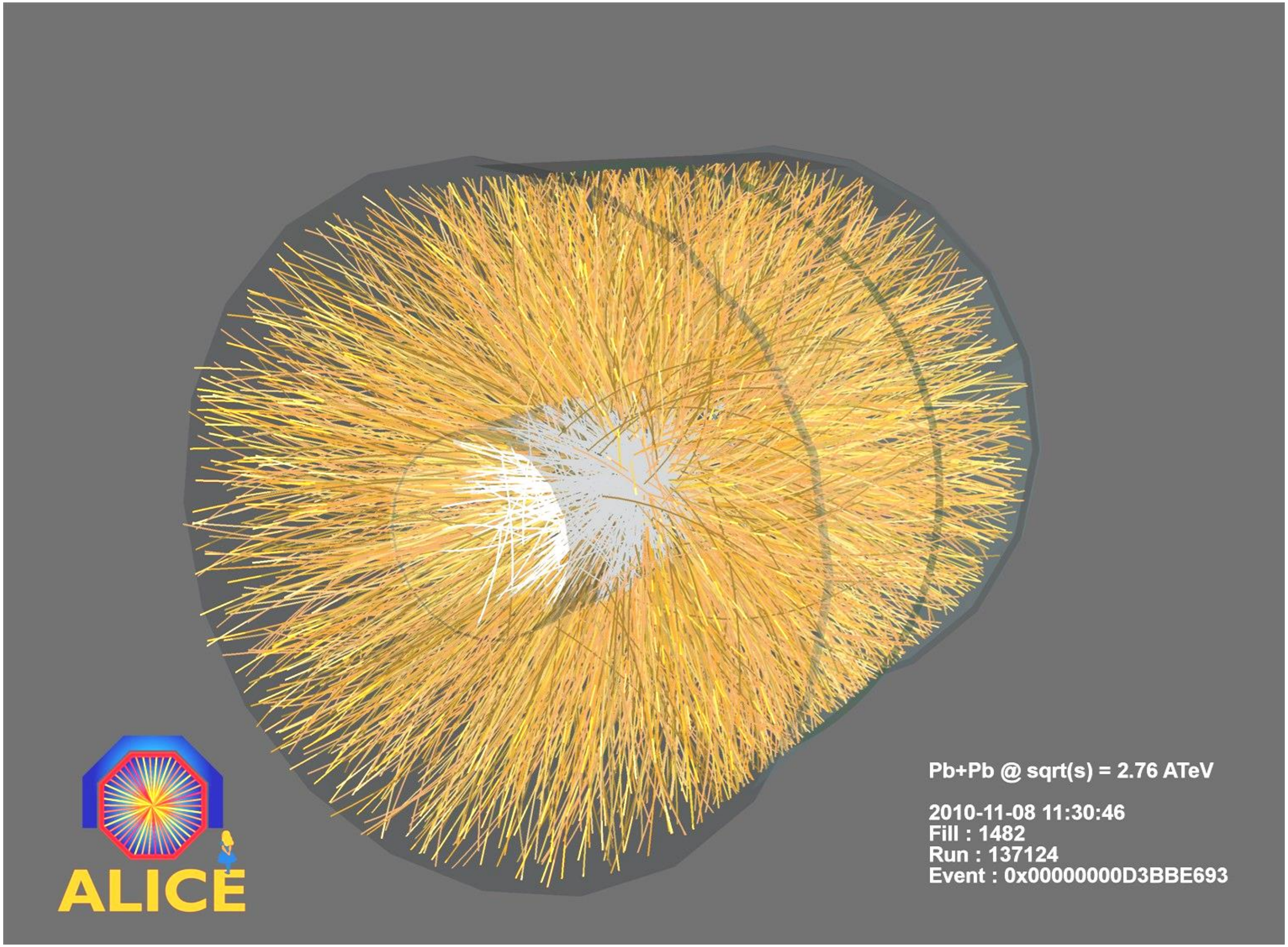
Vertexing in BaBar (2000)



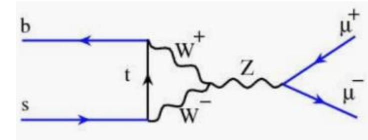
- 5 layers
- two-sided silicon strip
- 300µm thick
- pitch: 50-200 µm

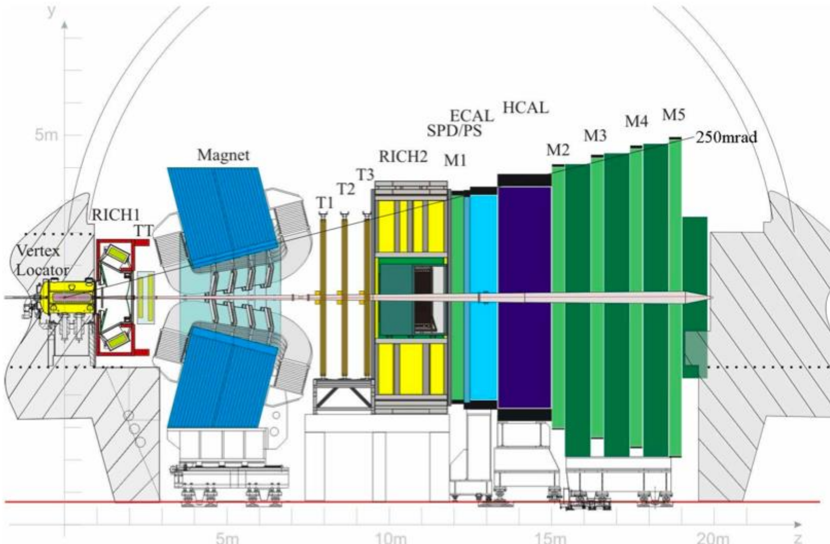
- space resolution:
  10-30 µm

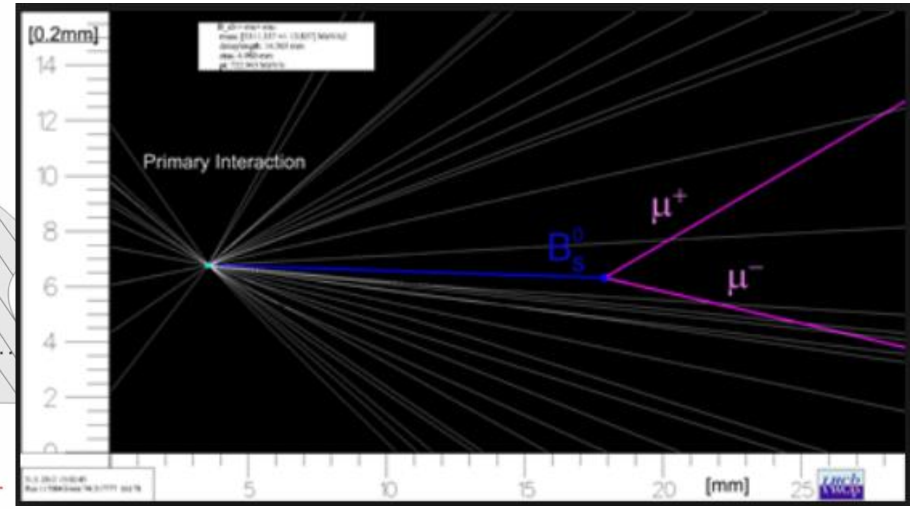
Tracking at ALICE on the LHC

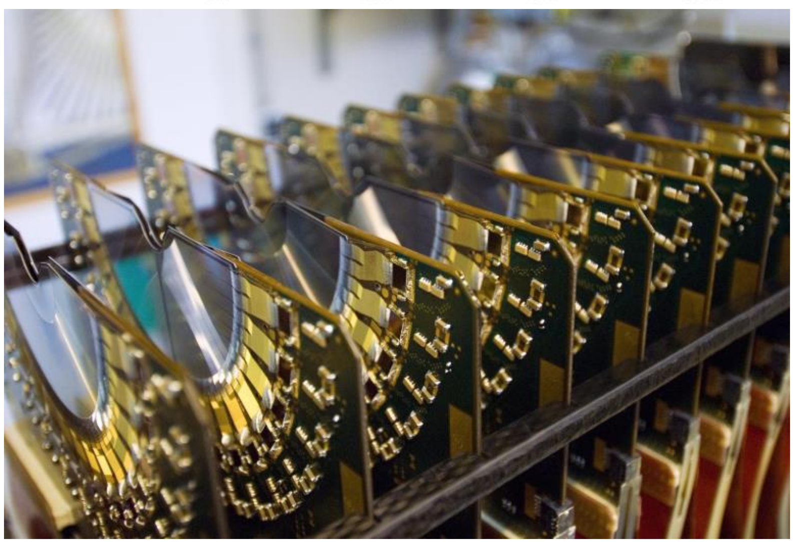


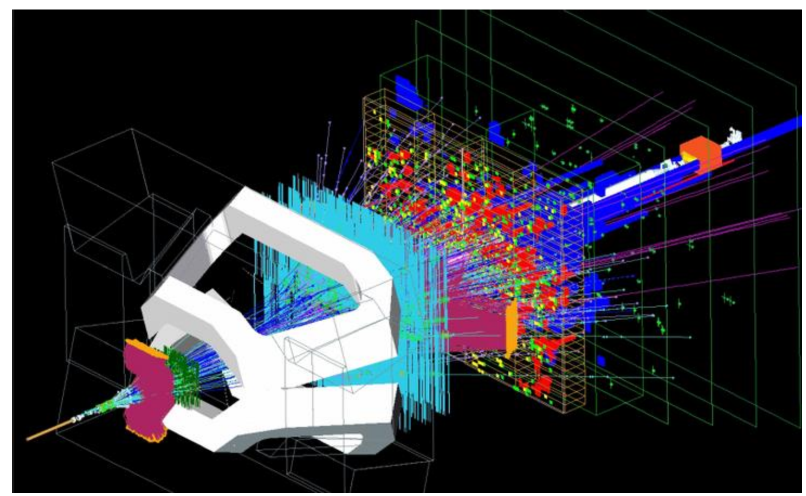
Charged particle Tracking at LHCb on the LHC

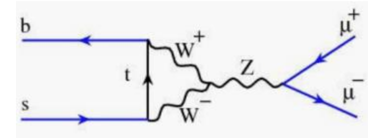











b
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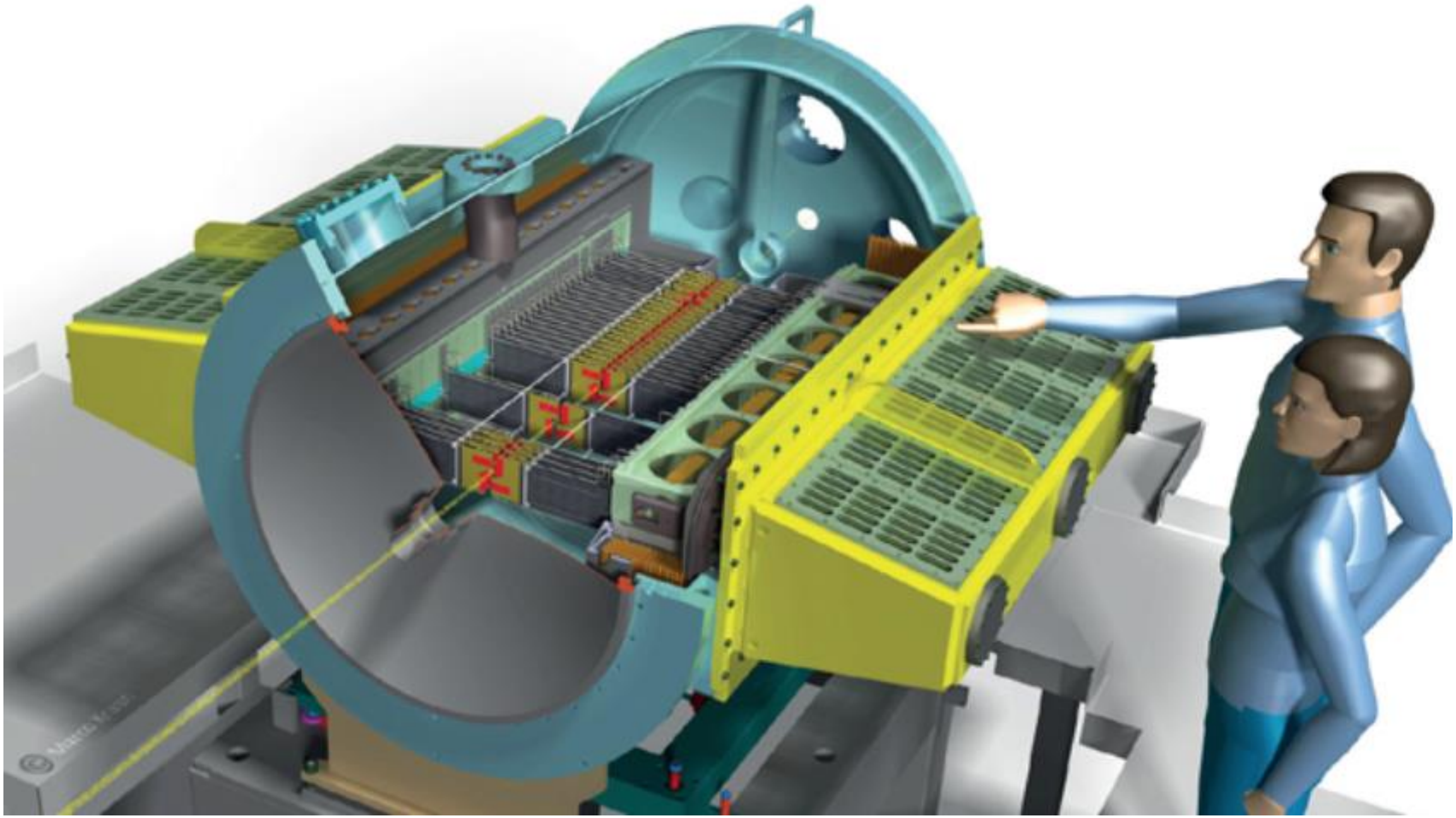
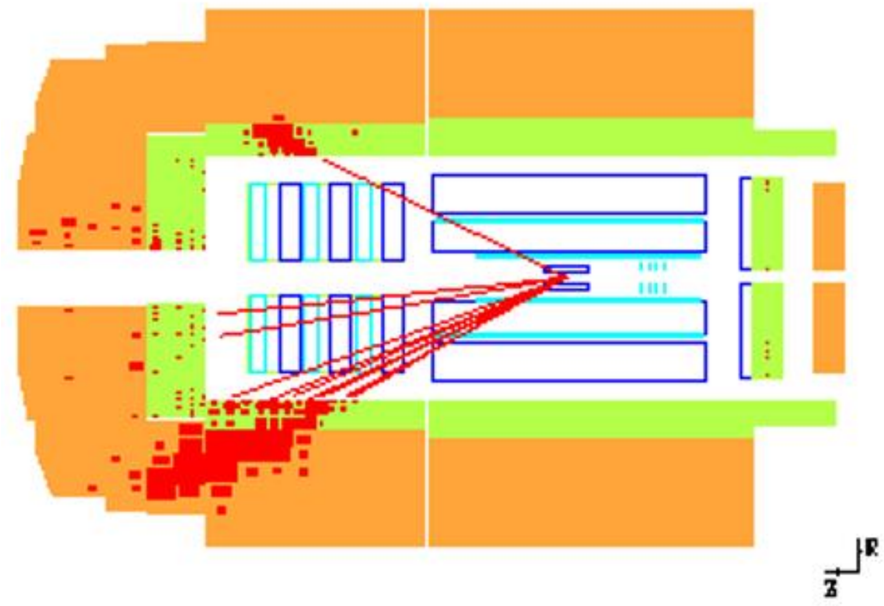
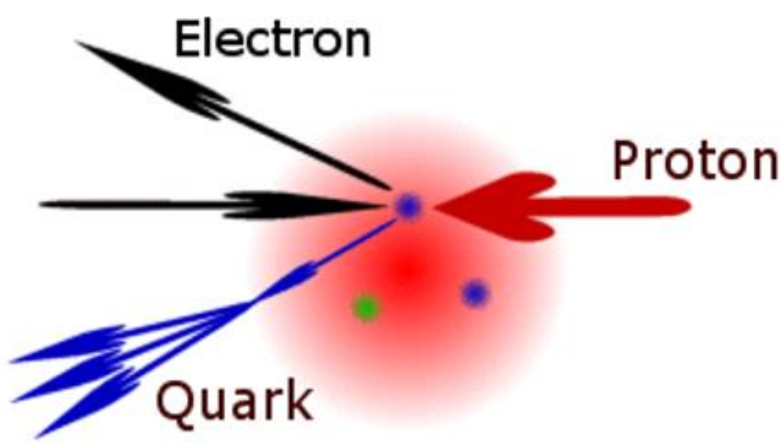


Tracking in H1 at DESY

Asymmetric electron-proton machine colliding 30 GeV electroncs with 820 GeV protons
Also note the unique capability of doing Transition Radiation Tracking in forward region





Tracker Requirements

Measurements

charge, transverse momentum, primary-vertices, secondary-vertices, vtx seperation

Data Rates and volume

40Mhz beam crossing, Hierarchy of trigger rates and latencies: 1Mhz L0, 400Khz L1

Pattern Recognition

Ability to pick out the parts of the track and «stitch» them together.

Need High intrinsic detector and reconstruction efficiency & Low fake rates.

Track Triggering

Provide input to a Level-1 track trigger

Radiation tolerance

Ionizing Radiation, hadronic radiation

Ease of construction

Relatively short construction times. Distributed production

Ease of maintenance

Need to be able to access and replace inner layers close to the beam

Robustness

No significant deterioration in performance for modest losses of detector system

Other environmental issues

protection of electronics against accidental beam loss

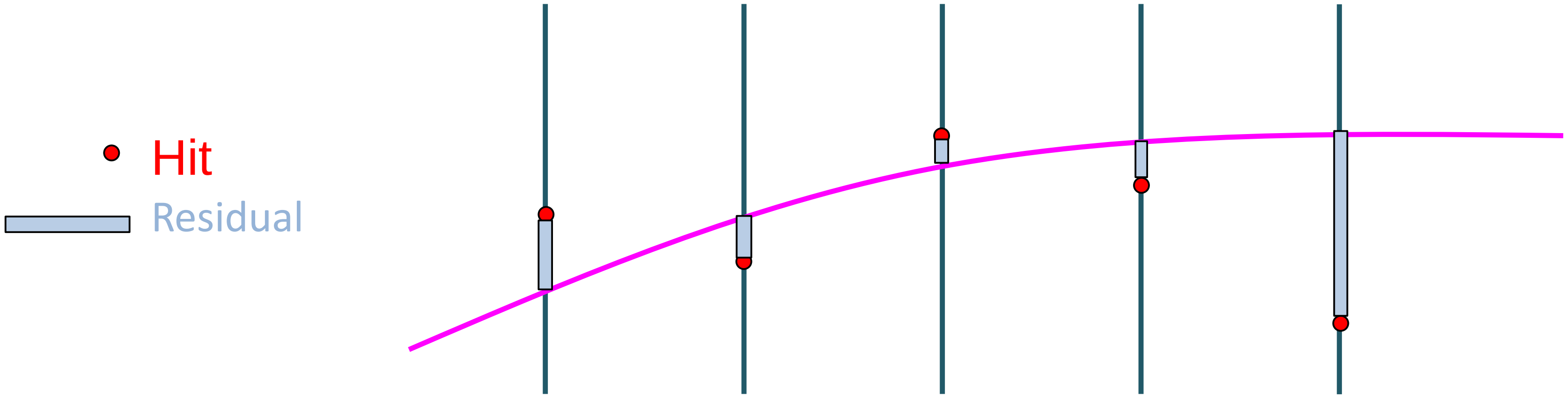
Engineering

Demanding mechanical, vibrational, thermal requirements

Modest Cost …

Alignment performance: Strong

- Track based alignment minimizes residuals for a sample of tracks, by adjusting position of sensitive elements.
- Position and width of known mass objects allows momentum resolution measurement.



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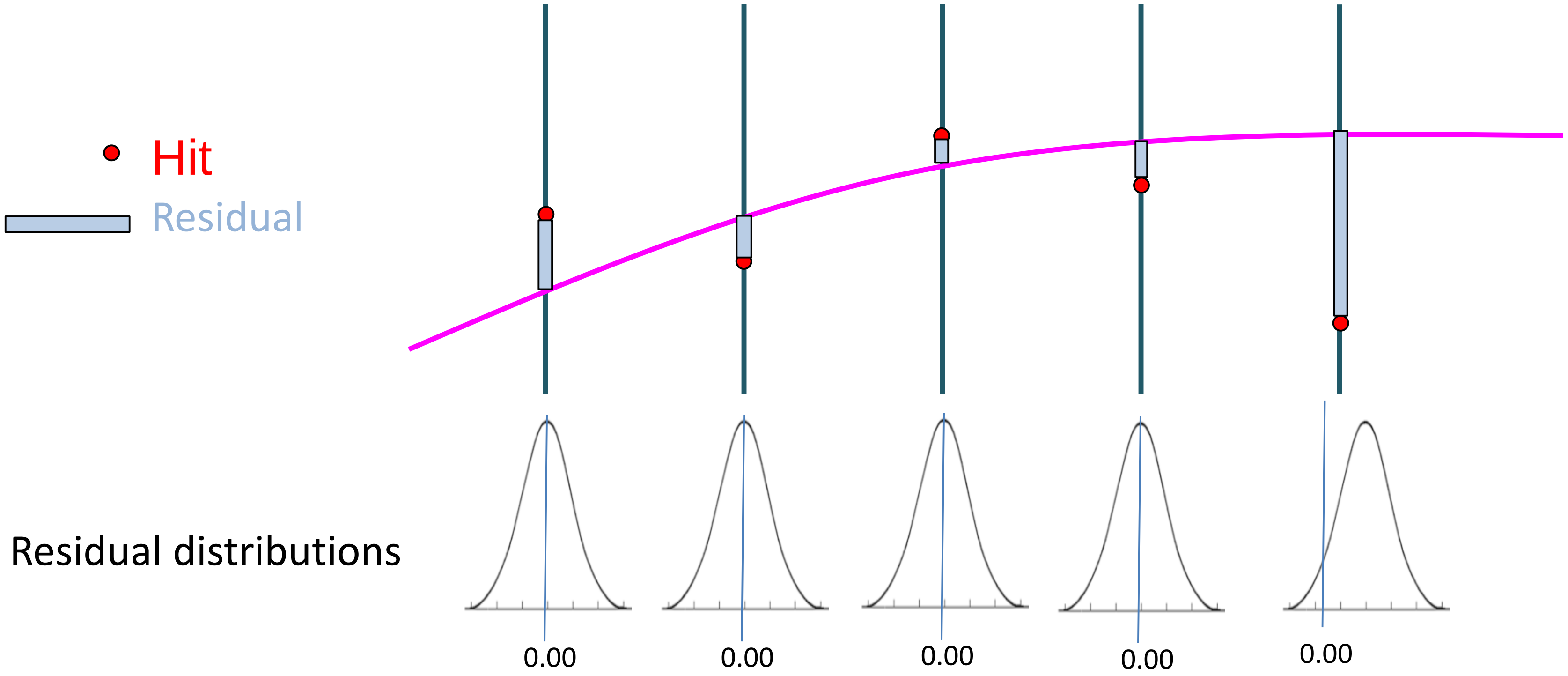


Effect of misalignment on IP resolution

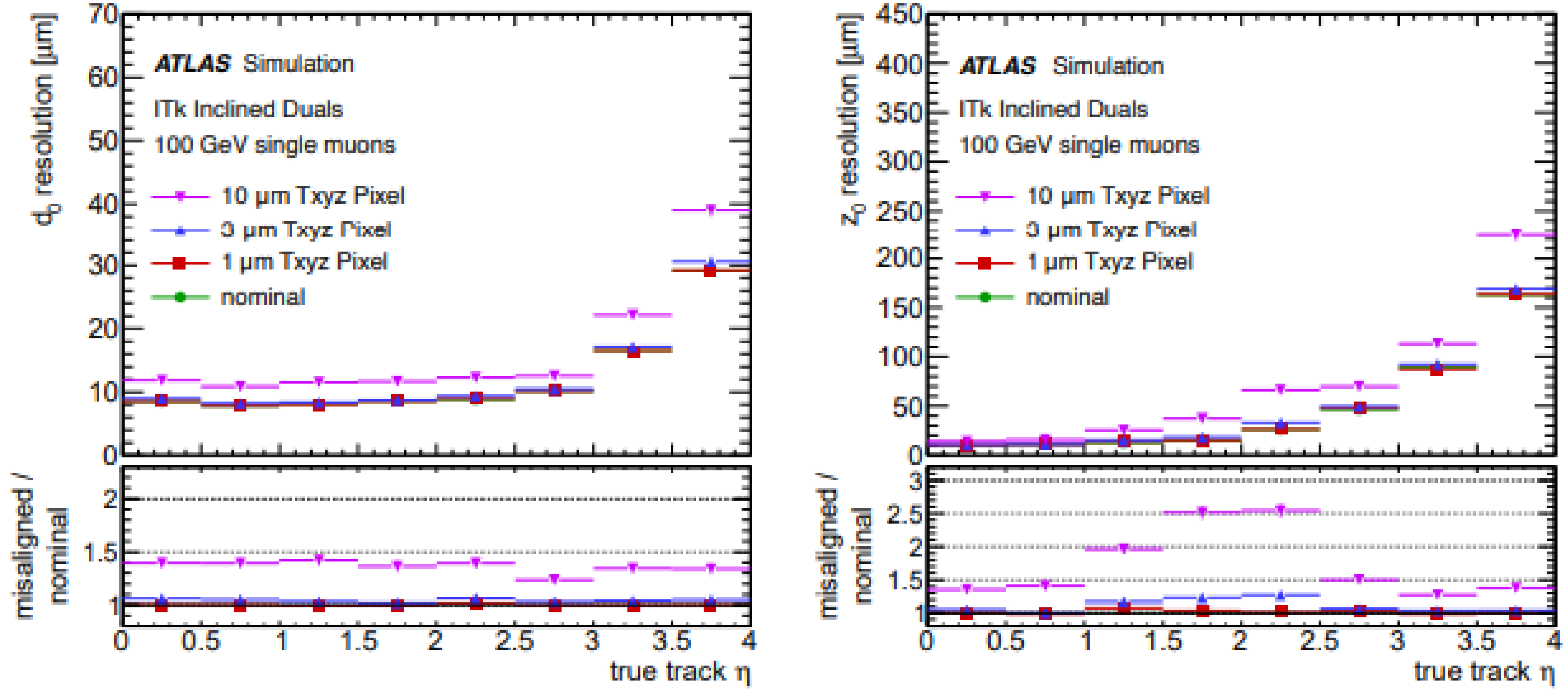


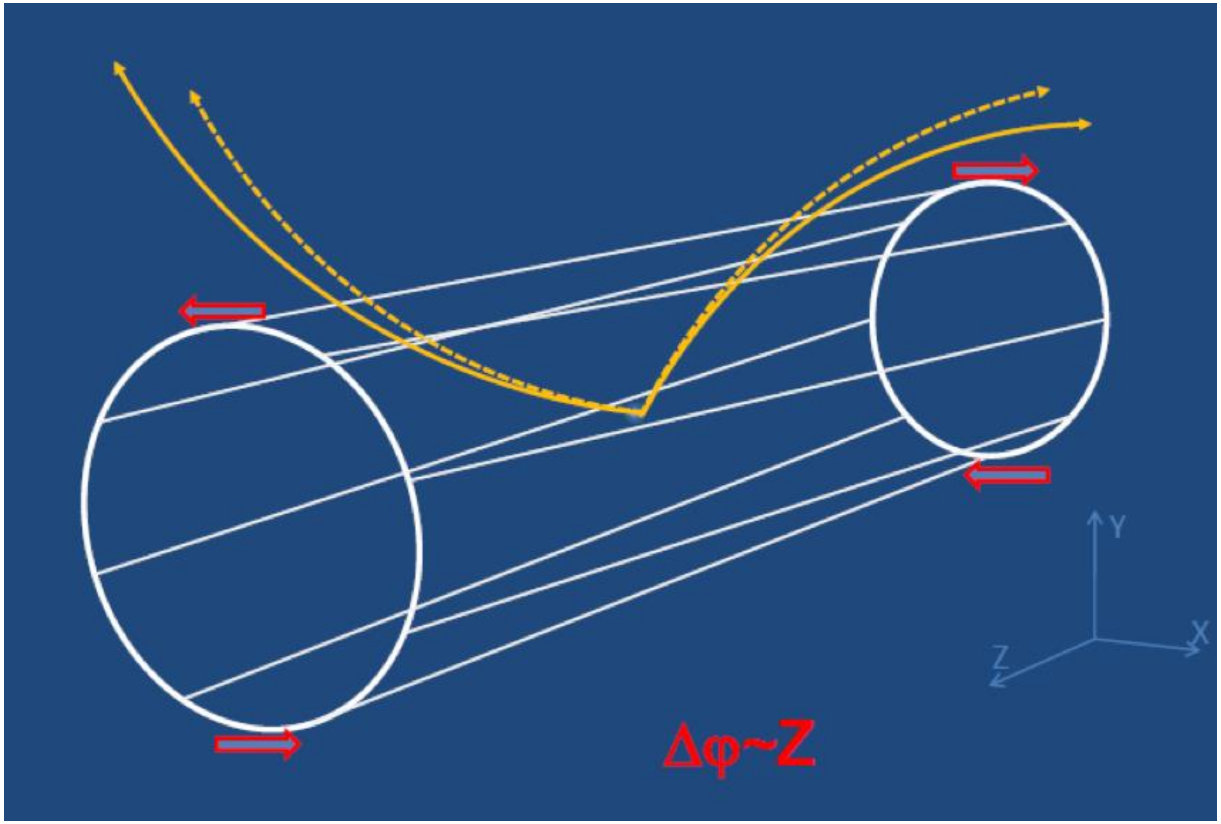
Figure 3.8: Change in impact parameter resolution for single muons with $p_T = 100$ GeV, applying a random misalignment of 1, 3, and 10 μm RMS to all pixel modules in all three local module dimensions. **Left**: Change of transverse impact parameter resolution $\sigma(d_0)$. **Right**: Change in longitudinal impact parameter resolution $\sigma(z_0)$.

in ALIGNMENT

out of ALIGNMENT

Alignment performance: Weak Modes

- Systematic distortions, example a twist, are hard to detect.
- Track residuals can be minimized but p_T is biased.



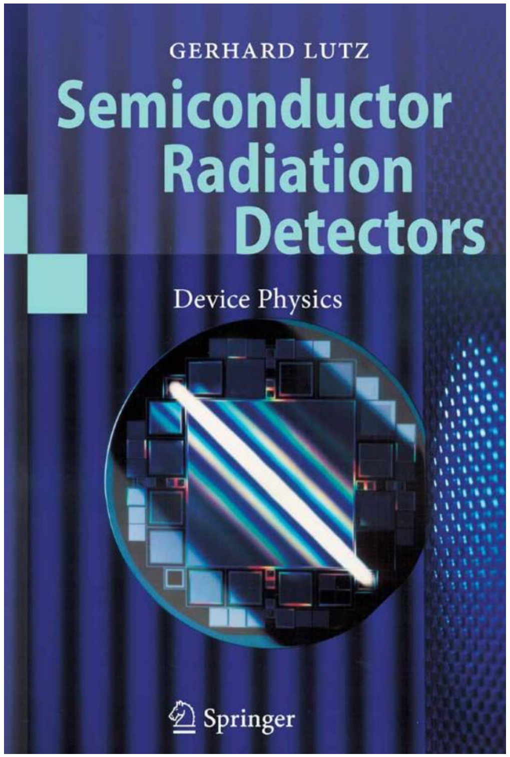
from P. Brückman de Renstrom

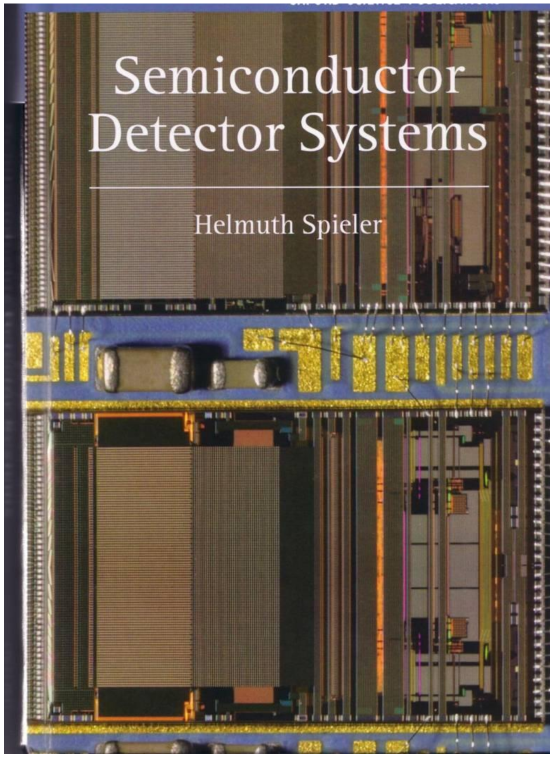
What do silicon trackers do well

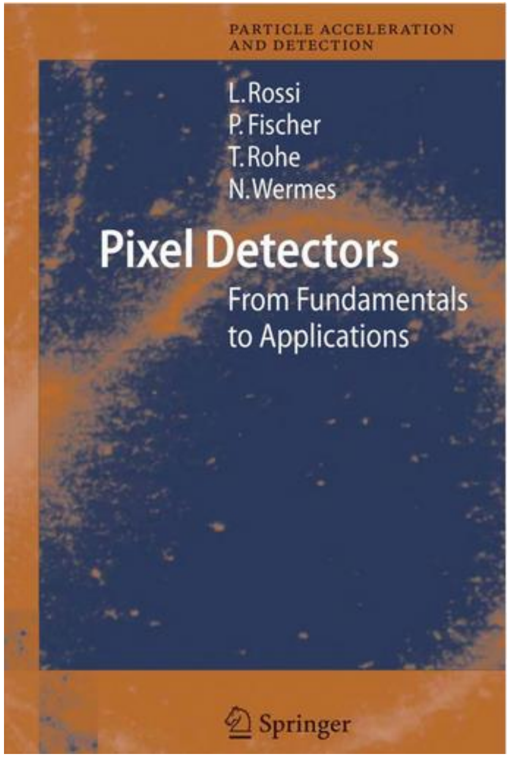
- Advantages of semi-conductor (silicon) detectors
  - Small feature size - good space point precision
    - *Note that in tracking not all co-ordinates are equal, this in the bending plane are more important. This is easily accommodated in silicon technology.*
  - Fast collection times (<20ns over $300\mu m$ of silicon) (depending on h or e)
  - Thin detectors give large signals
  - Thin detectors implies less multiple scattering
  - Radiation tolerant for both ionizing and non-ionizing radiation
  - Used in conjunction with wire chambers further away from beam
  - Accurate momentum measurement
    - depends on a lot of factors: alignment, layout, construction, stability
  - *The exact requirements on the performance of the silicon detector (which in turn drive the design) all come from the physics under study and will be different from case to case.*

Some Books on silicon systems

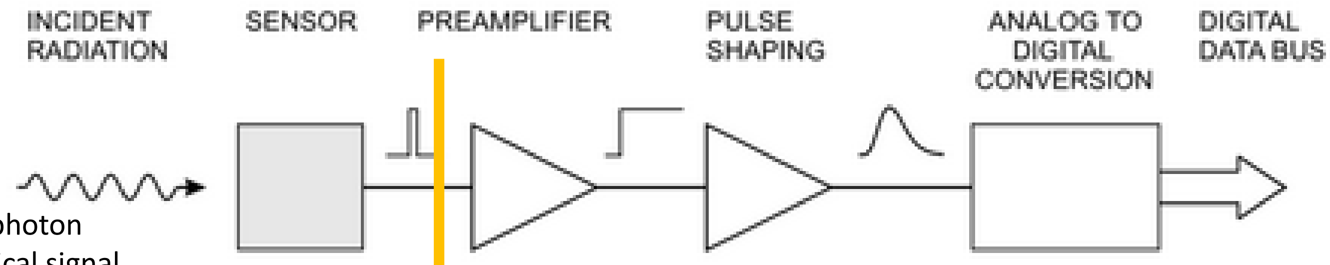
- Gerhard Lutz “Semiconductor Radiation Detectors”
- Helmuth Spieler “Semiconductor Detector Systems”
- L. Rossi et al “Pixel Detectors”
- A.S. Grove “Physics and technology of semiconductor devices”





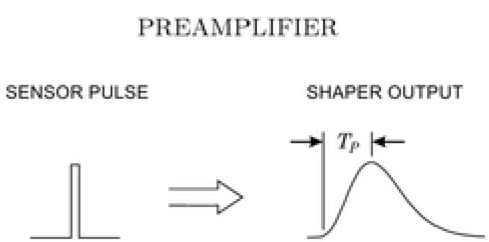


Detector: end-to-end



Energy of particle/photon
converted to electrical signal

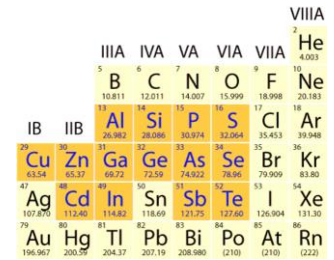
SENSOR | **READ-OUT CHIP ASIC**



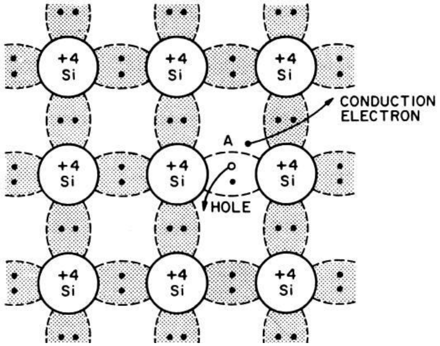
Combined sensor and pre-amplifier are designed to minimize electronics noise.
minimize capacitance at the input

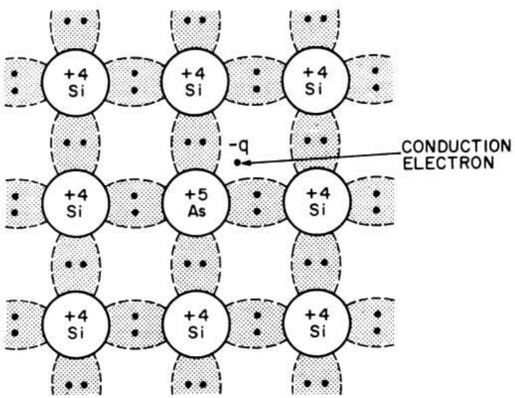
Pulse shaping: optimize S/N
Frequency spectra of the signal and the noise not the same. This means we can optimize (filter) the S/N.
This also changes the shape of the pulse and typically lengthens it.
Sometimes low noise is critical
Sometimes high speed critical balance required
Shapers: upper bound frequency -> rise time
lower bound frequency -> duration

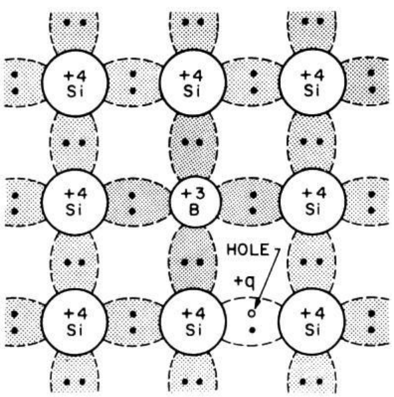
Semiconductors: Electrons & Holes



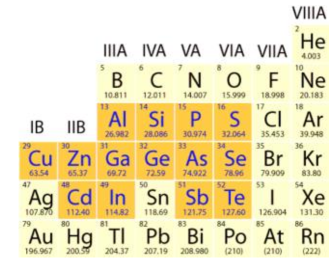
- Intrinsic semiconductors
  - Similar to dielectrics but smaller gap between valence and conductive bands
  - Some conductivity due to temperature
- Doped semiconductors
  - Have diluted impurities
  - n-type (electrons), Phosphor, 5 valence e-
  - p-type (holes), Boron, 3 valence e-
  - Doping is achieved by diffusion or ion implantation
- Doped semiconductors can have much higher conductivity than intrinsic semiconductors







Semiconductors



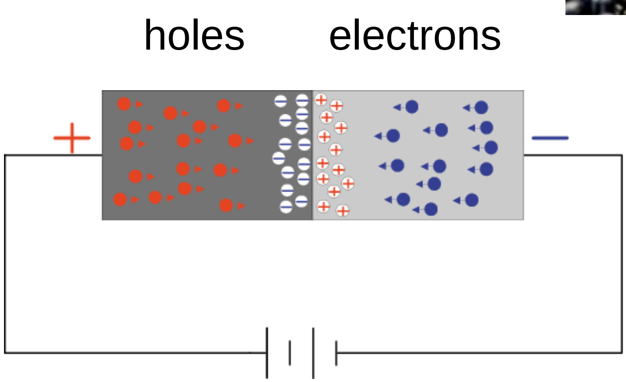
- In semiconductor detectors electrical charge is formed directly by ionization → electron-hole pairs
- Different from other detection mechanisms

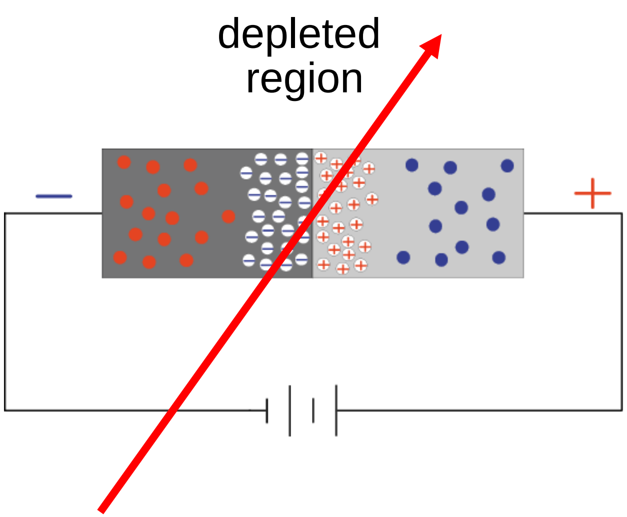
Ionization in gases	30 eV
Ionization in semiconductors	1 – 5 eV
Scintillation	10 – 200 eV
Phonons	meV
Breakup of Cooper pairs	meV

- Phonon or Cooper pairs can be used only at low temperatures
- At room temperatures semiconductors yield largest signal

Silicon detectors

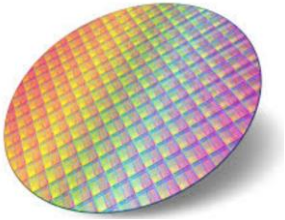
- Silicon detector is a p-n diode
  - p-type (more holes)
  - n-type (more electrons)
  - Current can flow if forward biased

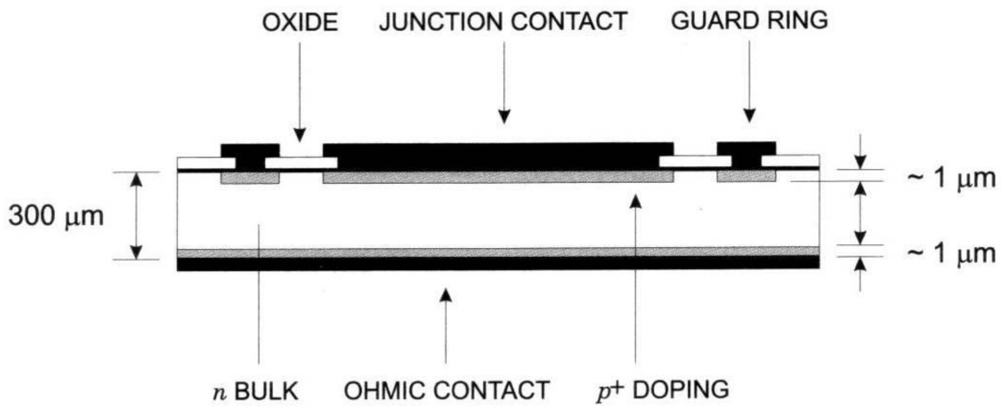




- Reverse bias to create a depletion layer with no mobile charge carriers
  - Passage of a charged particle releases electron-hole pairs by ionisation
  - 20,000 to 30,000 pairs in 300 μm
  - Signal > 10 times more than background noise
  - High enough resistivity to allow full depletion (i.e. full depth of sensor) with a few 100V

Typical Silicon Sensor Section

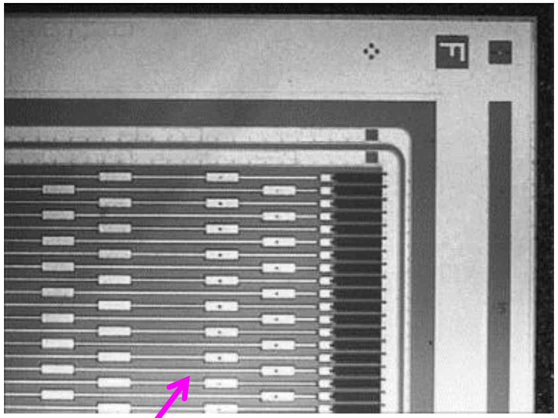




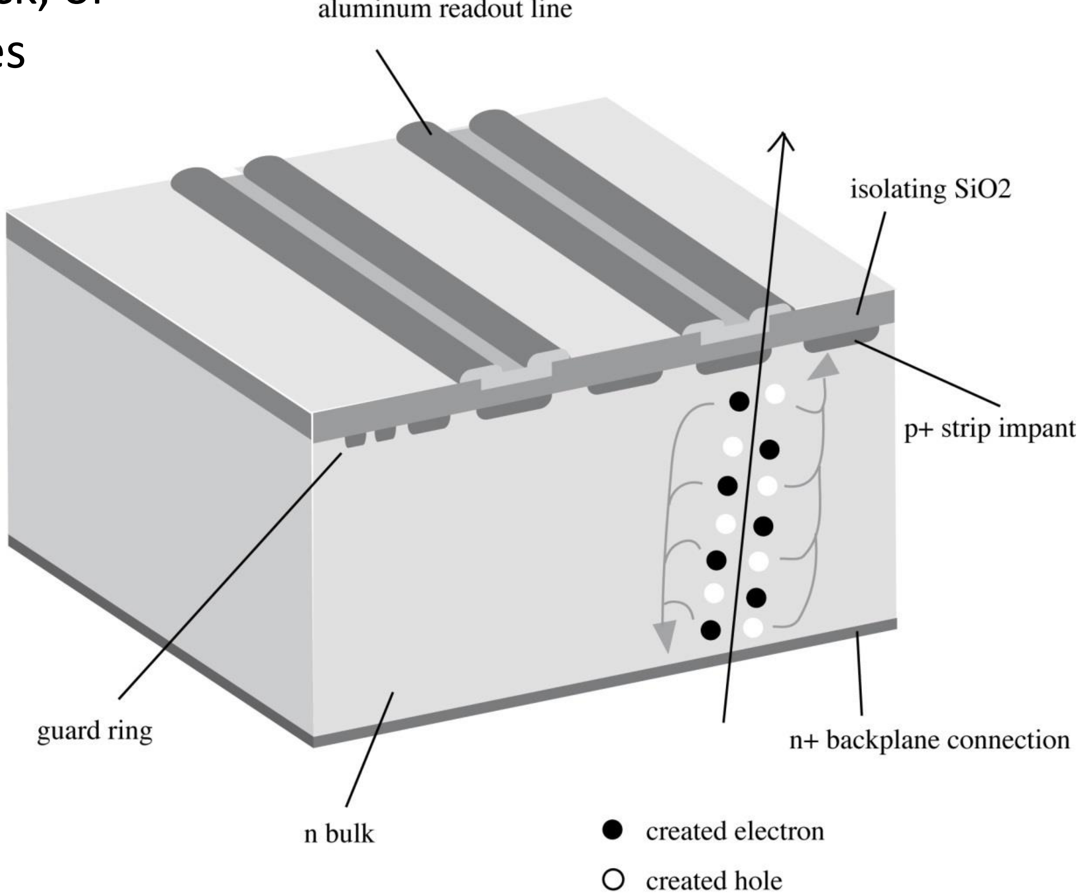
- Cross section of a typical silicon strip sensor
- Junction is asymmetric with highly doped surface layer and lightly doped bulk
- With a reverse bias the junction depletes into the bulk
- The SiO2 protect the silicon surface.
- Guard ring to protect from surface leakage current due to mechanical damage during dicing

Silicon Microstrip Sensors

- Make many diodes on one wafer
  - ~50 μm strip pitch (possible with planar fabrication process)
  - Glue wafers back-to back, or make strips on two sides
  - eg. p strips in n bulk

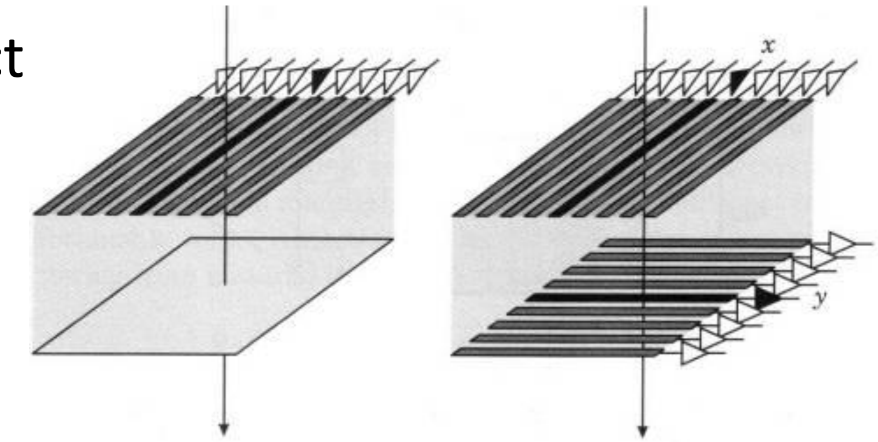


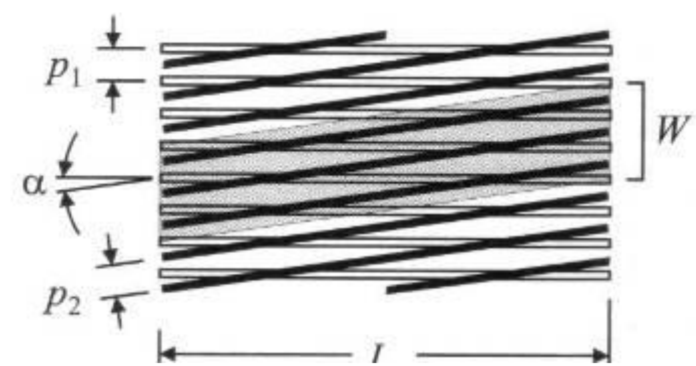
Metalisation above strips, with bond pads



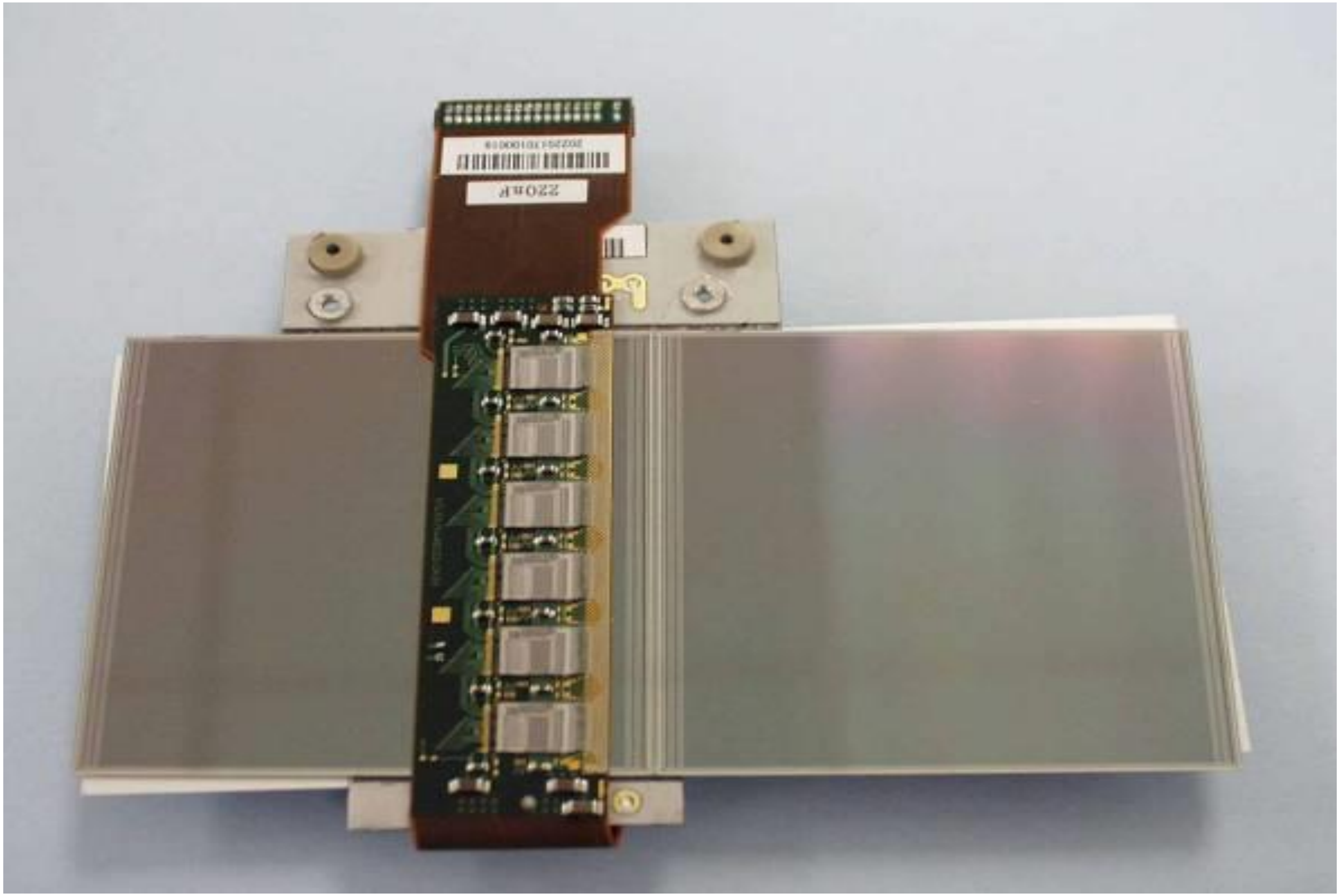
Constructing Two Dimensional Information

- 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





The ATLAS Silicon-Strip Modules

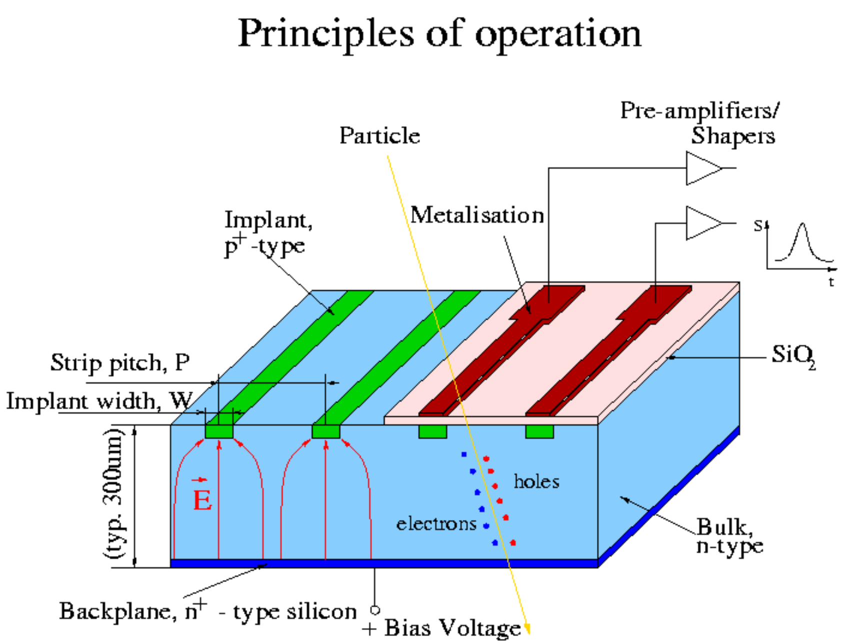


Position Resolution: Geometry

- 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:

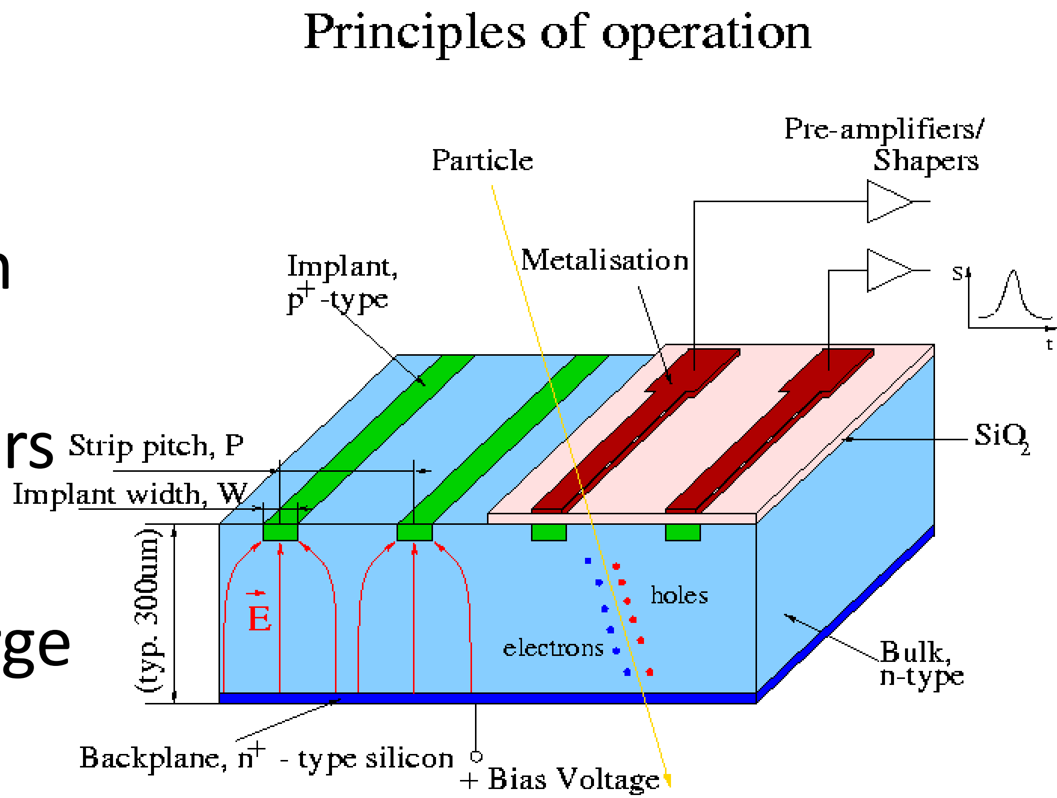
$$\sigma^2 = \int_{-p/2}^{p/2} \frac{x^2}{p} dx = \frac{p^2}{12}$$

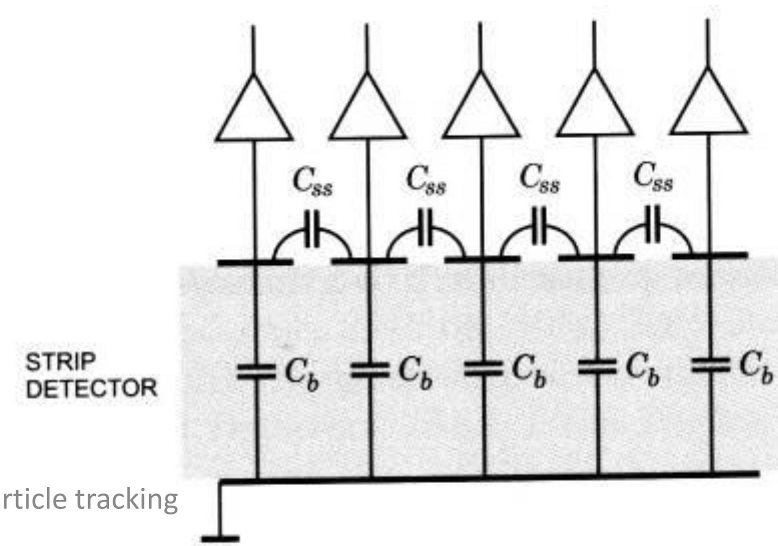
- If signal is split across strips, charge sharing can improve the resolution



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





Position Resolution: Diffusion

- Diffusion spreads charge transversely

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

- Collection time

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

Depends on holes or electrons mobility

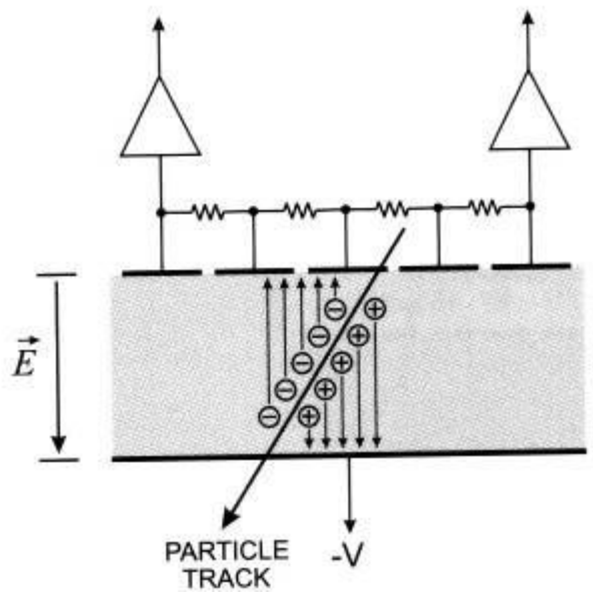
- Diffusion constant is also linked to mobility

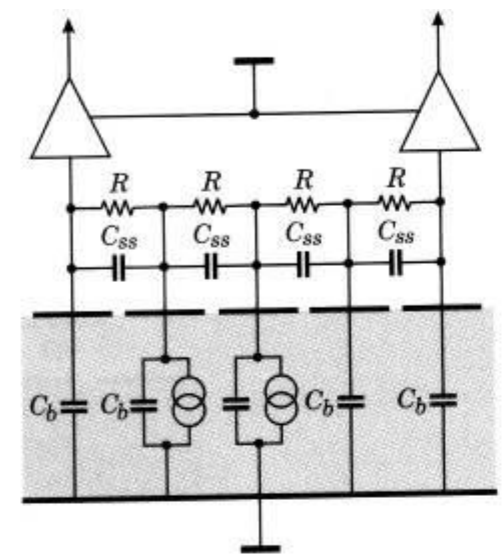
$$D = \frac{kT}{e}\mu$$

- Leads to diffusion of ~ 7 μm

Intermediate Strips

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

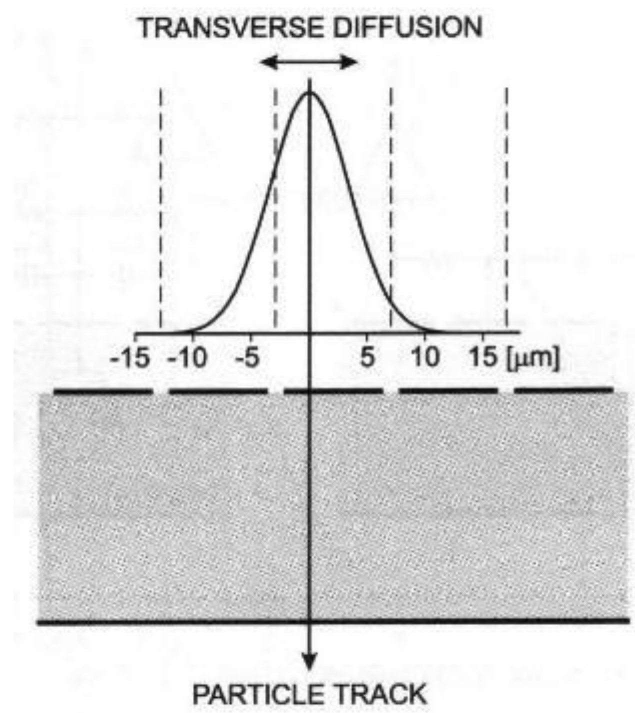




- Signal loss to backplane C_b/C_{ss}=0.1 → ~20% loss

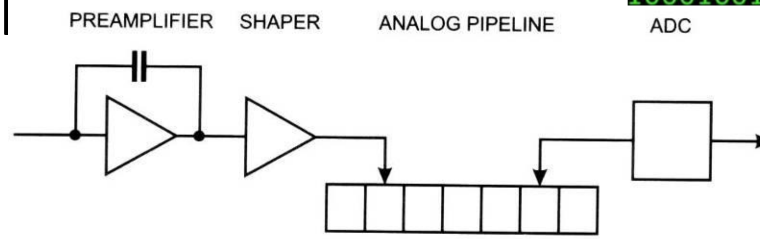
Charge Sharing

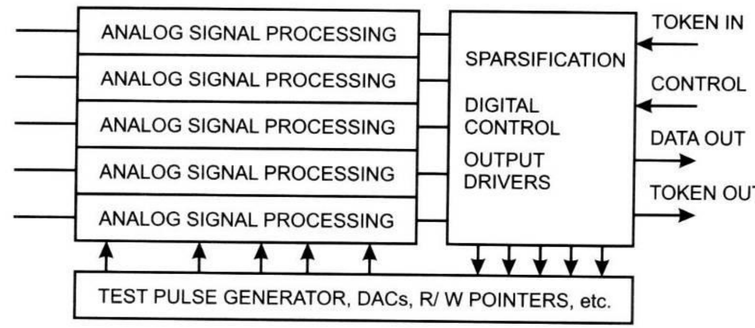
- Charge spreading improves resolution!
  - Centre of gravity interpolation
  - Resolution proportional to S/N
- Allows to beat sqrt(12) rule
  - Achieved resolutions 1.2 μm for 25 μm pitch (25/sqrt(12)=7 μm)
  - Requires S/N > 50 to achieve this
- Strip pitch should be comparable with diffusion

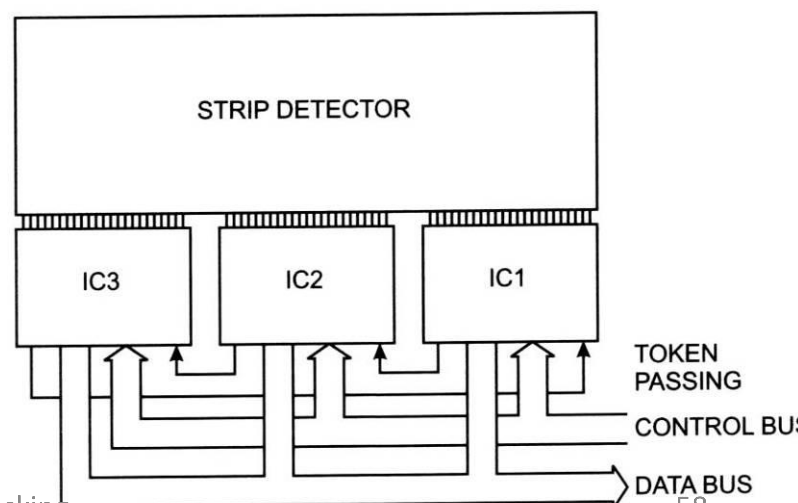


Silicon Systems : Binary readout

- Small readout pitch → need special readout IC
- Typically each channel has
  - Front-end amplifier and shaper
  - Analogue pipeline to wait for trigger decision
  - ADC
  - Analogue processing
  - Sparcification (zero suppression)
- All the above in parallel
- Multiple ICs are connected to a common control and data bus
  - Unique address
  - Token passing so bus is used by a single IC
- Data format: header+data+trailer – many variations possible

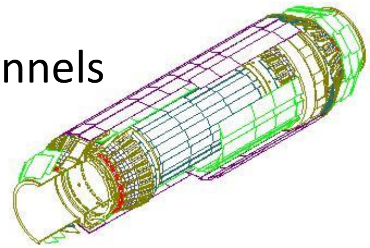




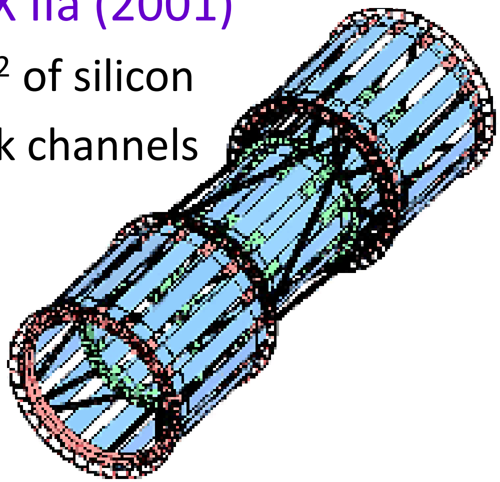


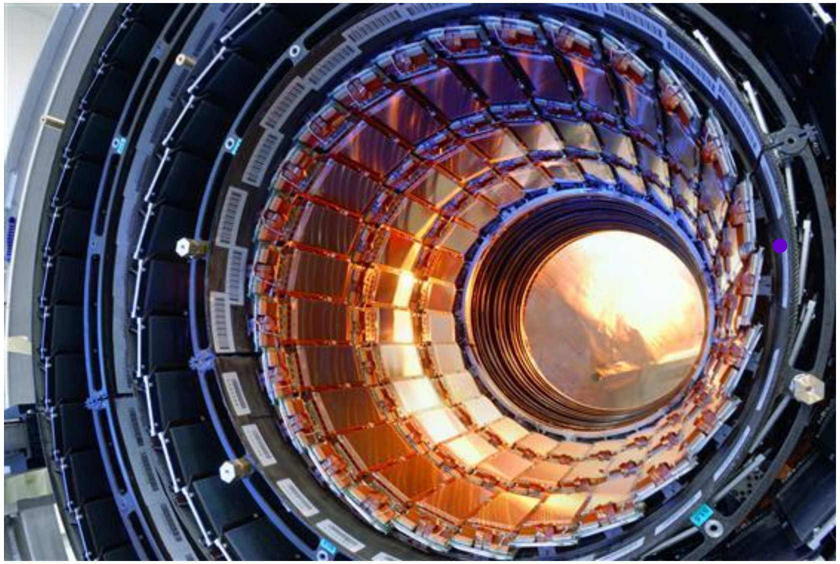
Evolution of silicon strip detectors

- LEP eg. DELPHI (1996)
  - 1.8 m^2 of silicon
  - 175k readout channels



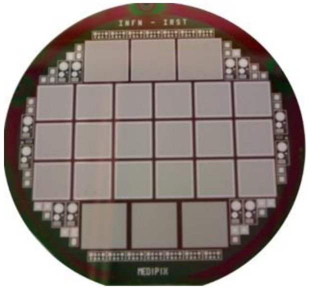
- CDF SVX IIa (2001)
  - 6 m^2 of silicon
  - 175k channels





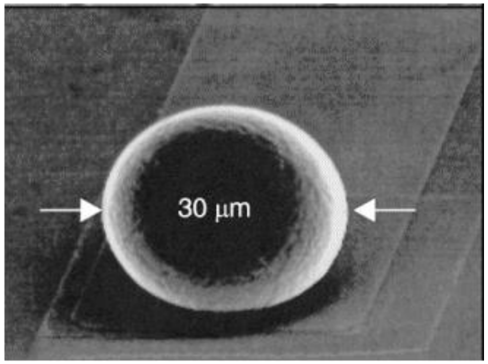
- CMS tracker
  - Full Silicon Tracker
  - 210 m^2 of silicon
  - 10.7 M channels

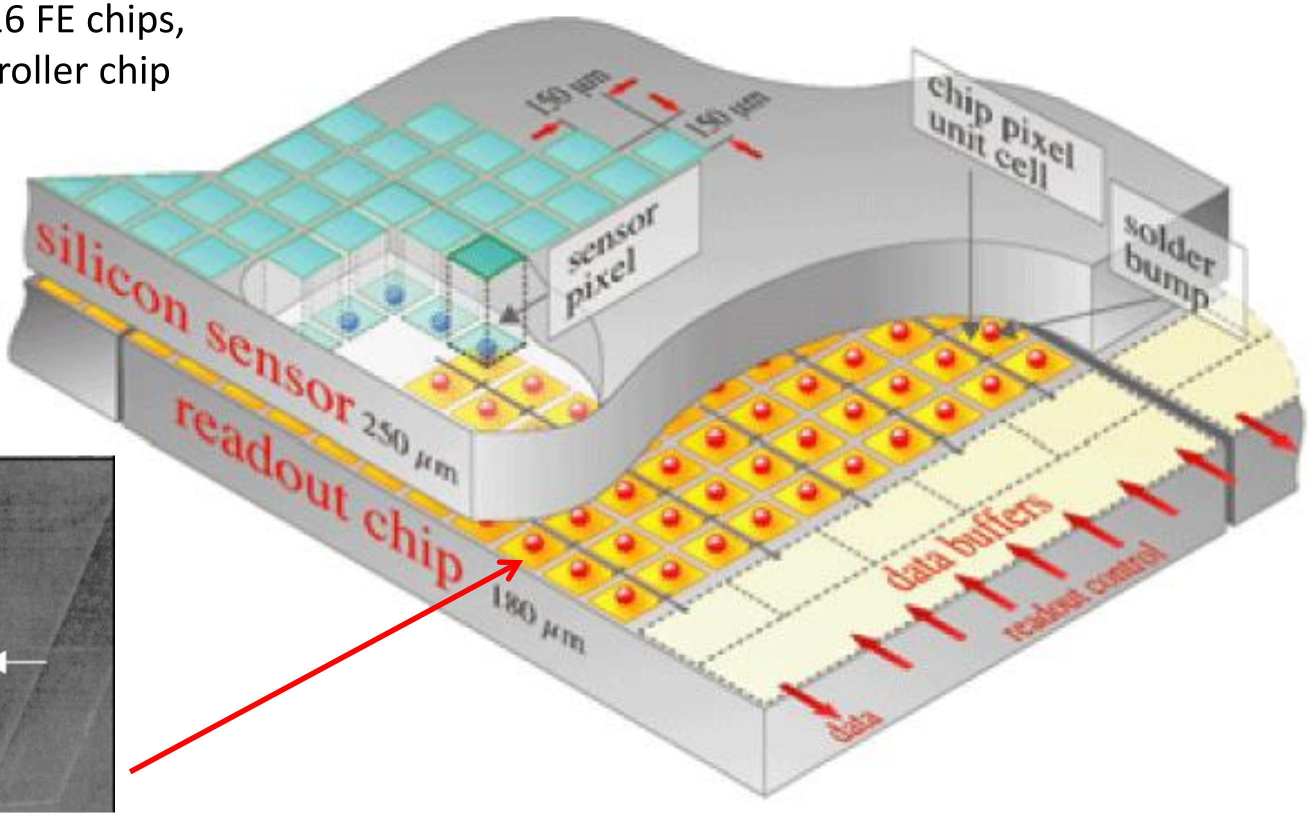
Si Pixel detectors



- 2-d position information with high track density.
  - Back-to-back strips give “ghost” hits. Pixels give unambiguous space-point
- Hybrid pixel detectors with sensors and readout chips bump-bonded together in a module
  - eg. one sensor, 16 FE chips, one master controller chip

bump bond

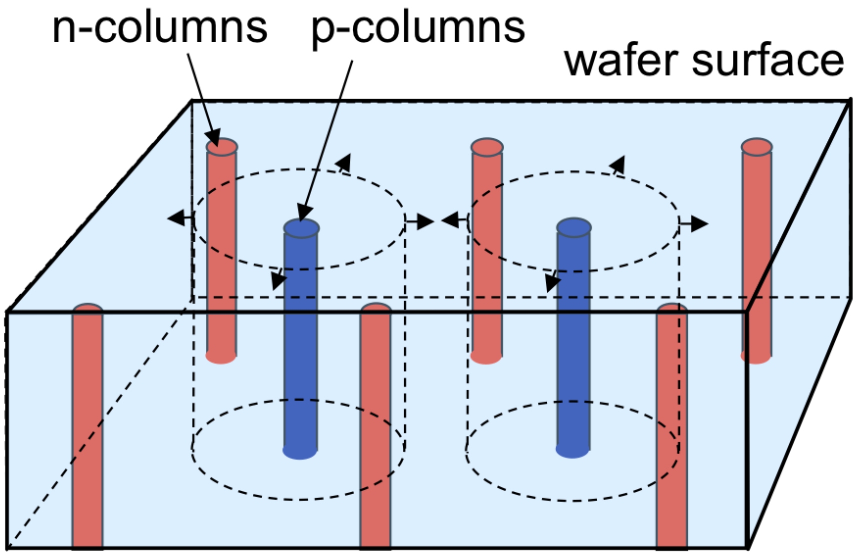




ATLAS Pixel Barrel

Technology Variants – 3D

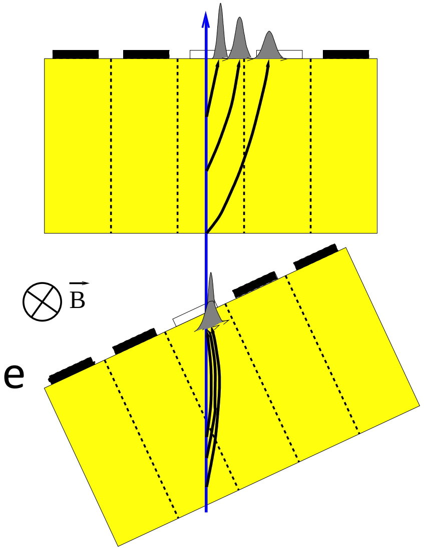
- HL-LHC – larger occupancy and radiation dose
  - Will need higher granularities at larger radius (eg. short strips) for 200 events per bunch crossing.
  - Active R&D programs for improved sensor technology, eg. 3d detectors – deplete between columns → short distance, low depletion voltage and fast signal.
  - Continue to study alternative materials (RD50 for silicon, RD42 for diamond)
  - New interconnects (fuse sensor and FE chip without bump bonds)



Some odds and sods that should not be left out

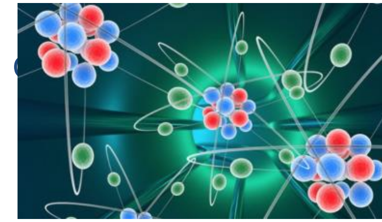
Silicon systems

- Sensors have high intrinsic accuracy and mechanical rigidity
  - Tilt detectors to reduce charge spreading by Lorentz effect in B-field
  - Lightweight support structures – must be stable

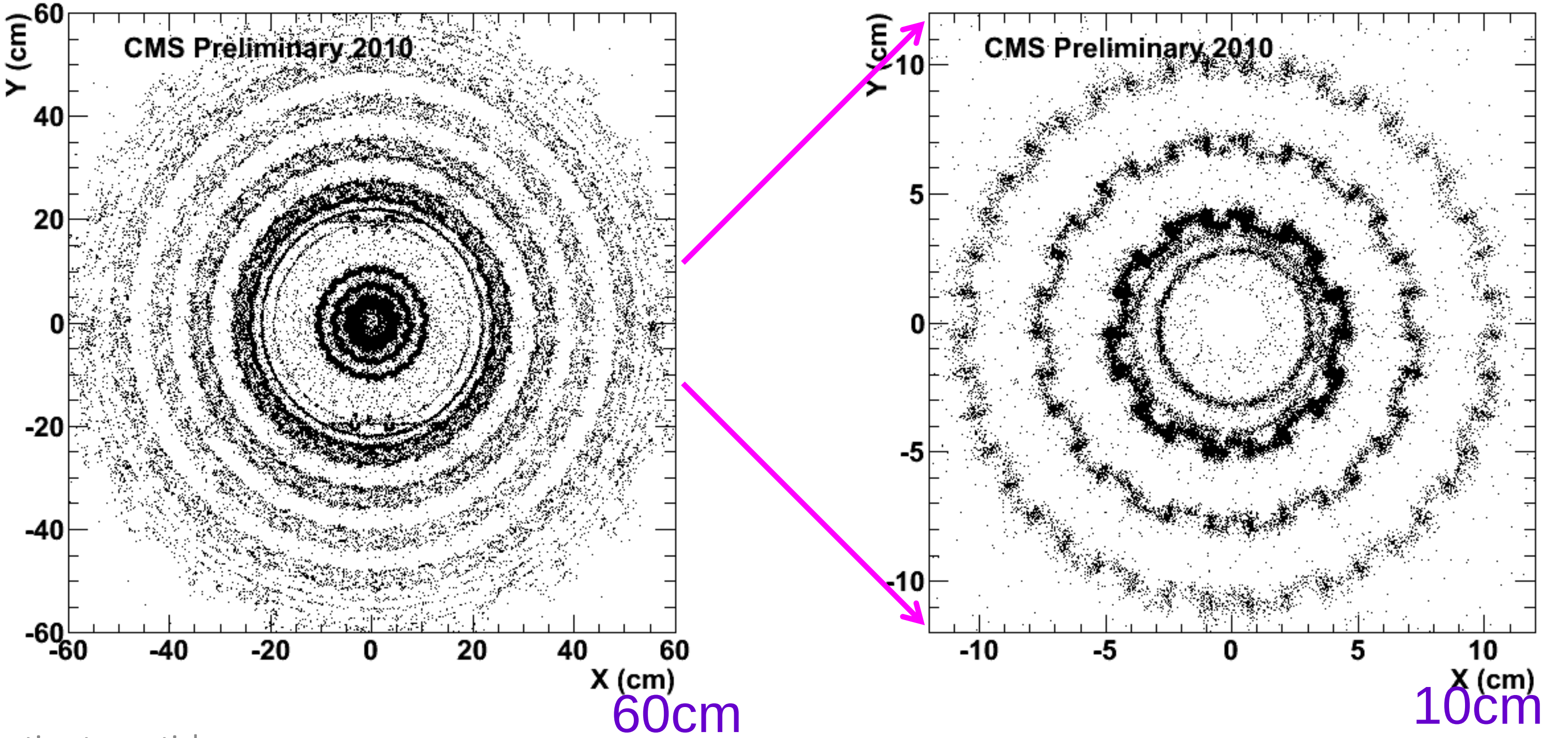


- HL-LHC Innermost layers must withstand >2x10^{16} neq over ~10 years
  - Increased noise and heat load from increased leakage current – risk of thermal runaway
  - May not be able to fully deplete the sensor
  - Type inversion (n-type bulk becomes p-type bulk, so depleted region develops from the opposite side of the sensor)
  - Keep the detectors at −10 °C to reduce leakage current and to reduce reverse annealing (further degradation without irradiation)
  - Low radiation dose received to date – only just starting to see evolution of leakage currents

Photon conversions

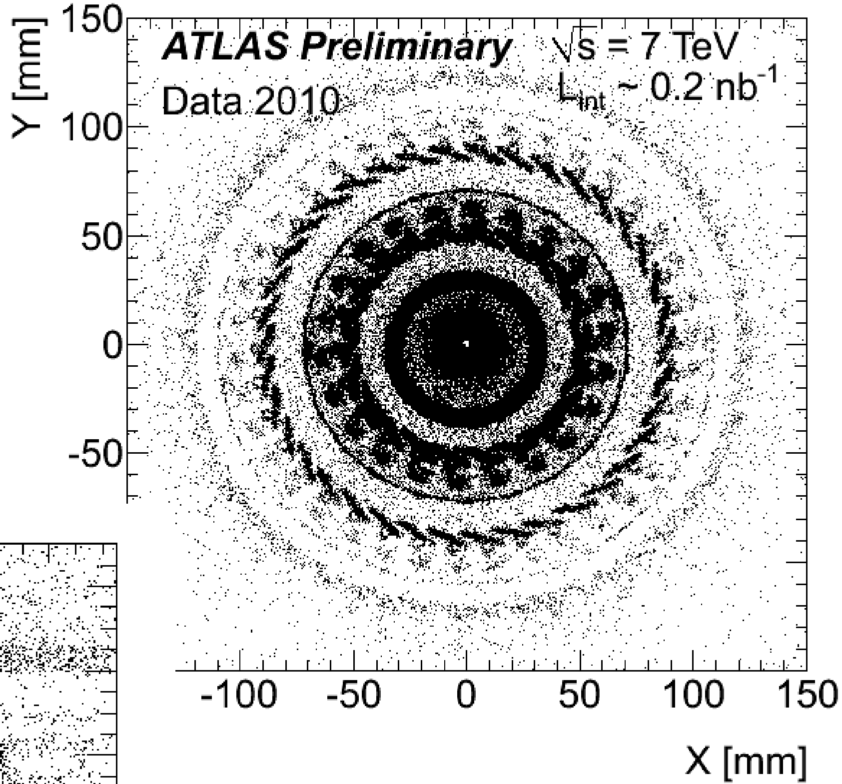


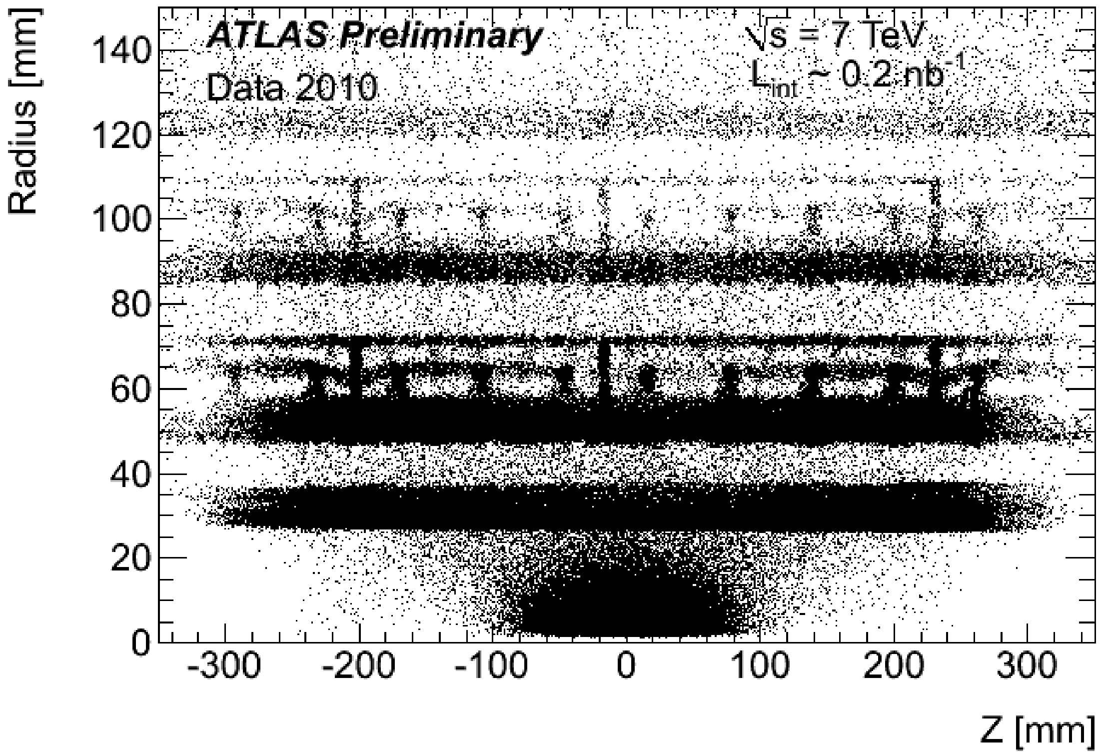
- Conversions, $\gamma \rightarrow e^+e^-$, example from CMS
  - Two oppositely charged tracks
  - Consistent with coming from the same point
  - Consistent with fit to a common vertex, imposing zero mass



Nuclear interactions

- ATLAS example
  - Tracks with d_0>2mm w.r.t





- x-y view for |z|< 300mm
- Sensitive to interaction lengths instead of radiation lengths

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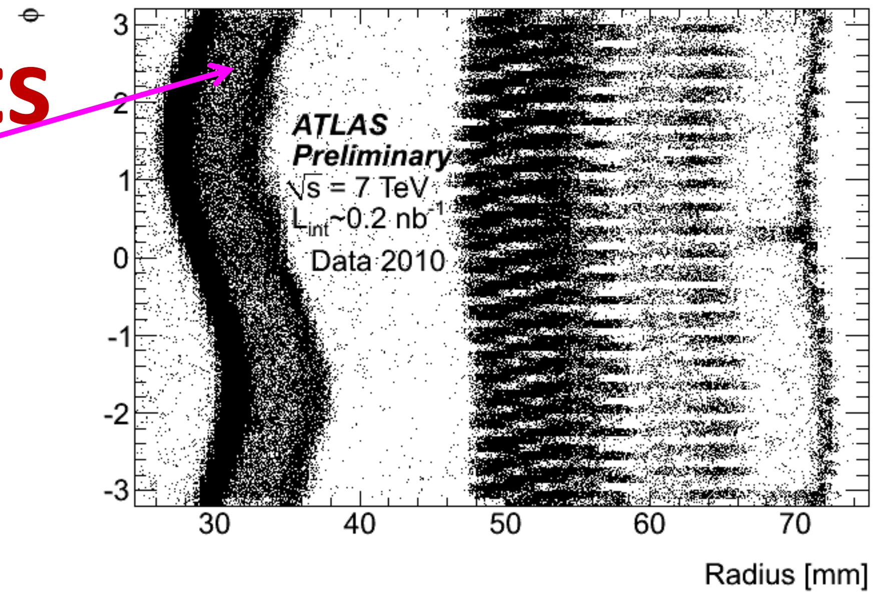
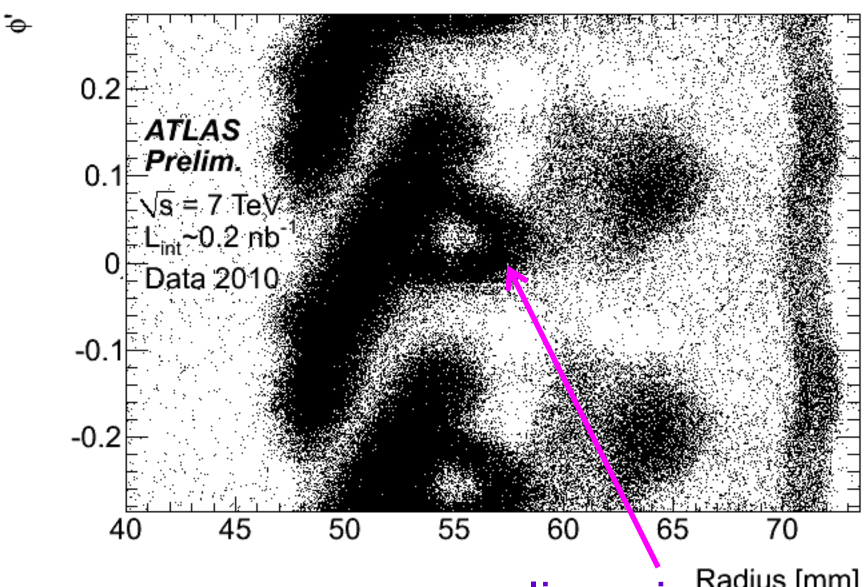
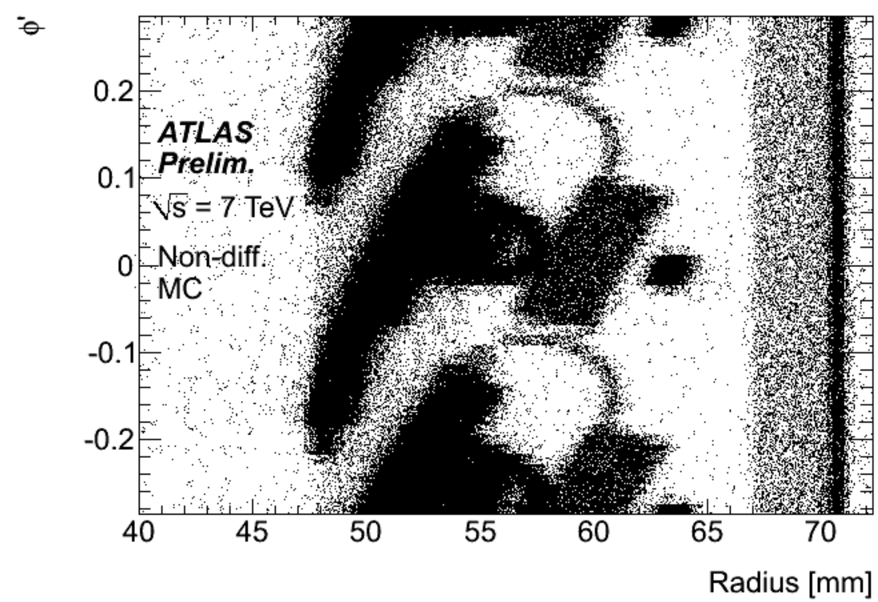
Interactions rϕ plots

- Full ϕ range shows displaced beam pipe(i.e. r varies with ϕ)
- Zoom in, and plot pixel inner layer local ϕ (i.e. pile all modules on one picture)
- Some features more spread out in data than MC.





cooling pipe



Stop Here