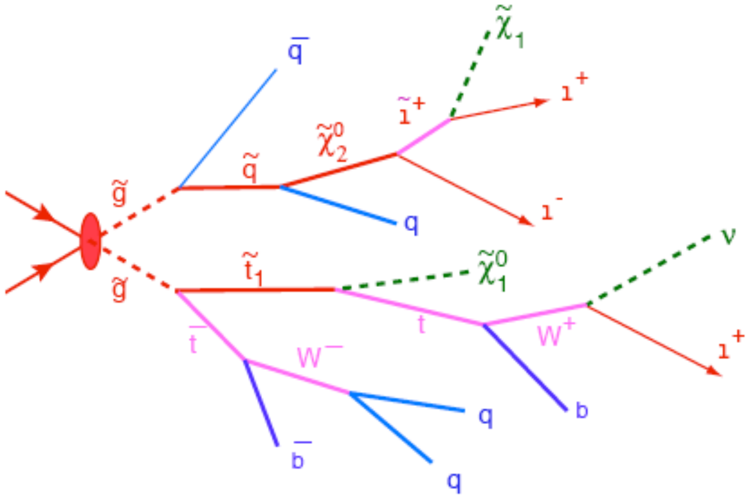
Instrumentation for the LHC Detectors

Jordan Nash – CLAS 2009

Outline

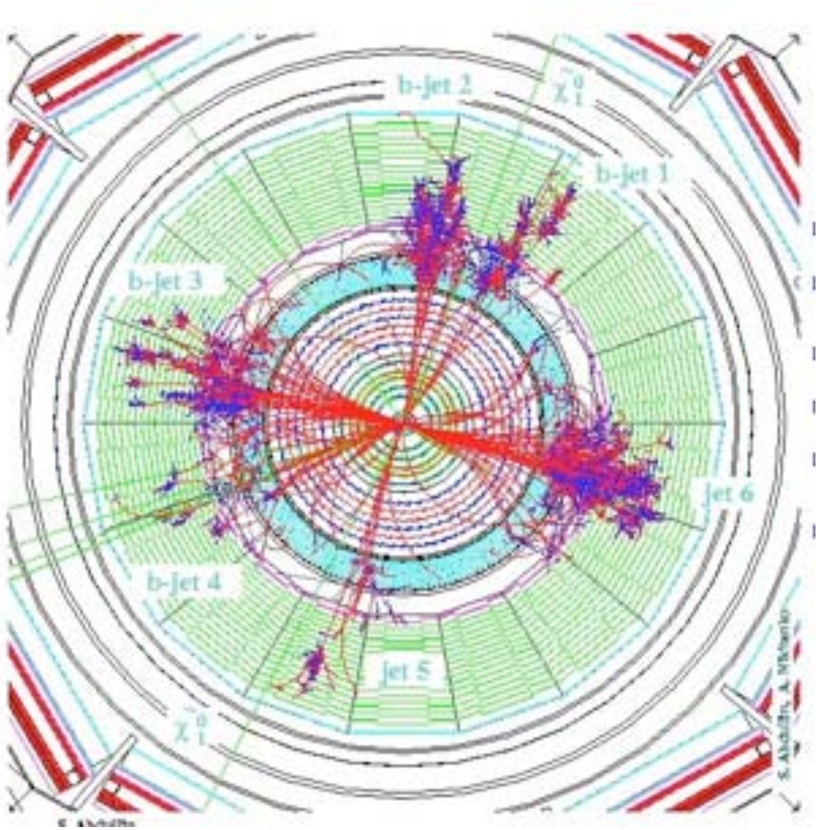
- What are the requirements for Detectors at the LHC?
  - The physics requirements
  - Coping with the LHC environment
- Particles passing through matter
- Tracking Detectors
- Calorimetry
- Muon Detection
- Detectors for triggering/timing/particle ID
- Preparing for the future - higher luminosity implications

What you want to see in a collision



- Identify all the final decay products from the collision
  - measure their charge
  - Momentum/energy
- Reconstruct the properties of the produced particles which have decayed

What you might actually see

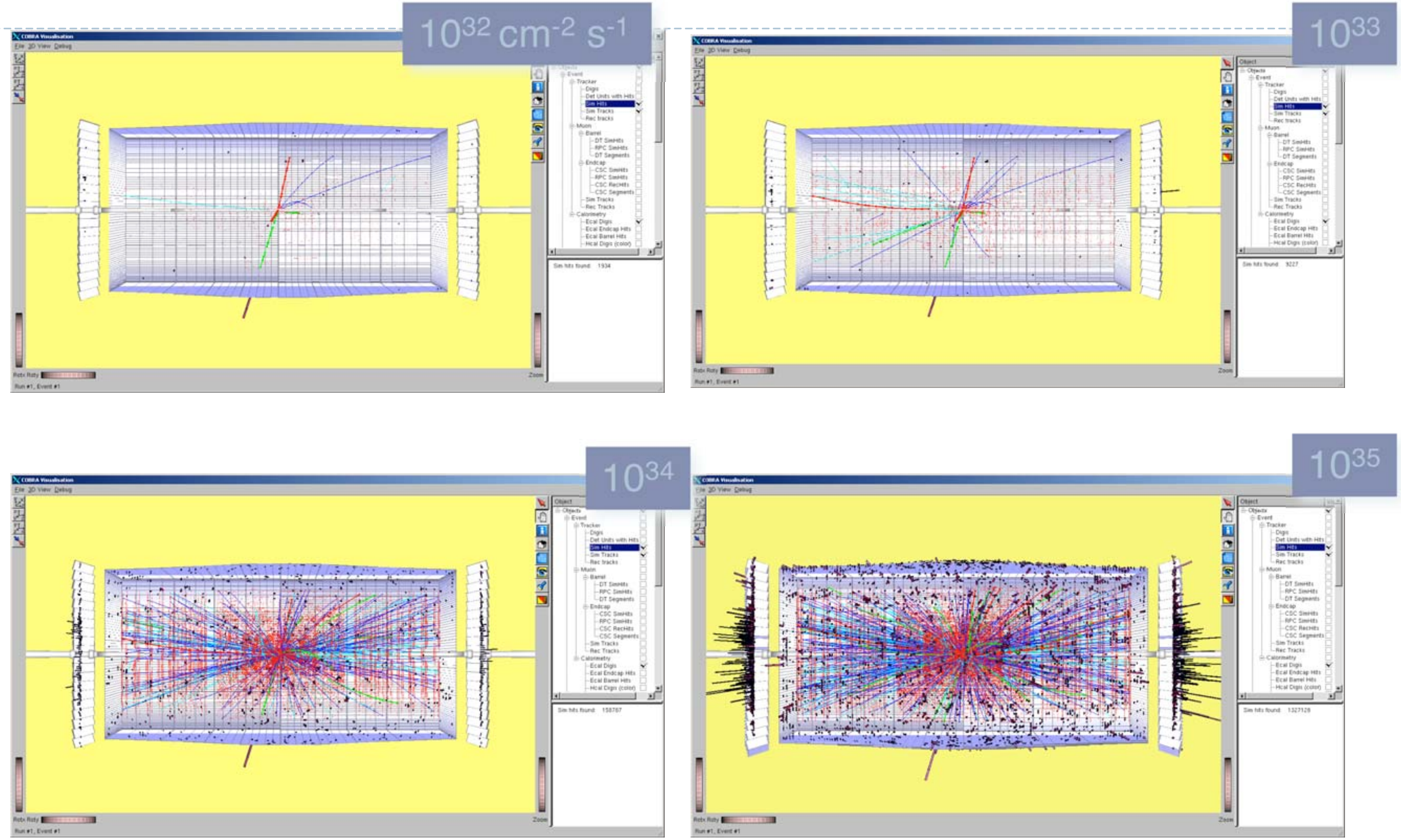


- Our main observables
  - Passage of charged particles through a tracking detector
  - Energy deposited by charged and neutral particles in a calorimetric detector
- "Missing" energy and momentum might give hints about weakly interacting particles
- Quarks appear as Jets of charged and neutral particles

The LHC Environment

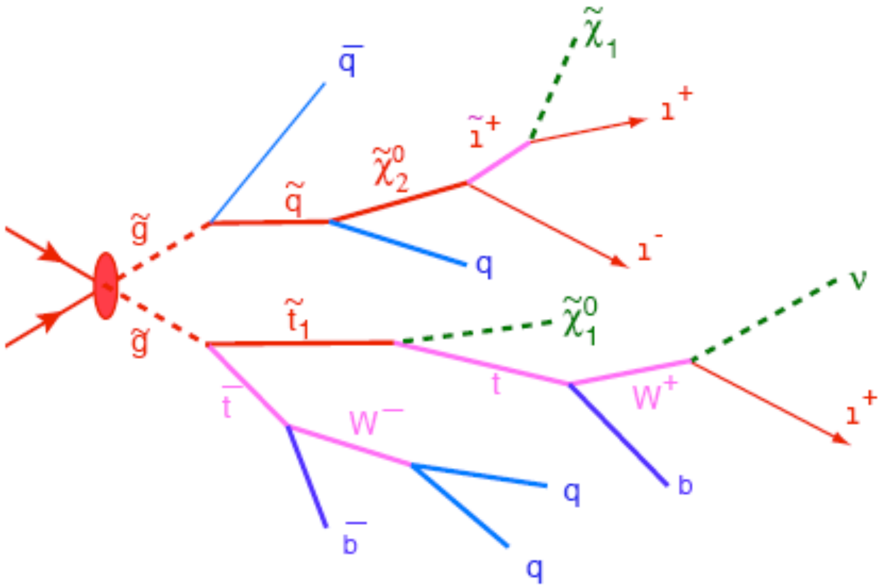
- The LHC beams collide in each of the detectors at a rate of 40 MHz
- At design luminosity of $10^{34} cm^{-2} s^{-2}$ There are 25 “underlying” events in every crossing of the LHC Beams
- These sit on top of the rare physics events we are looking for
- Implications for detectors
  - High radiation environment
  - High occupancy environment

Add in the LHC Environment

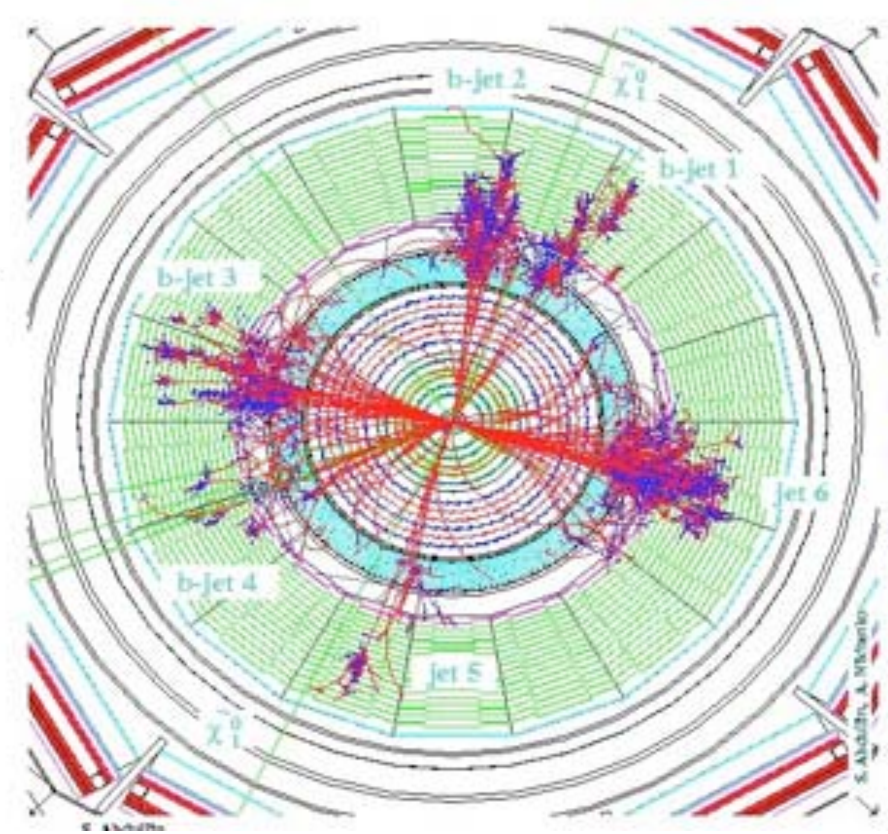


I. Osborne

Mapping measurements to Feynman Diagrams

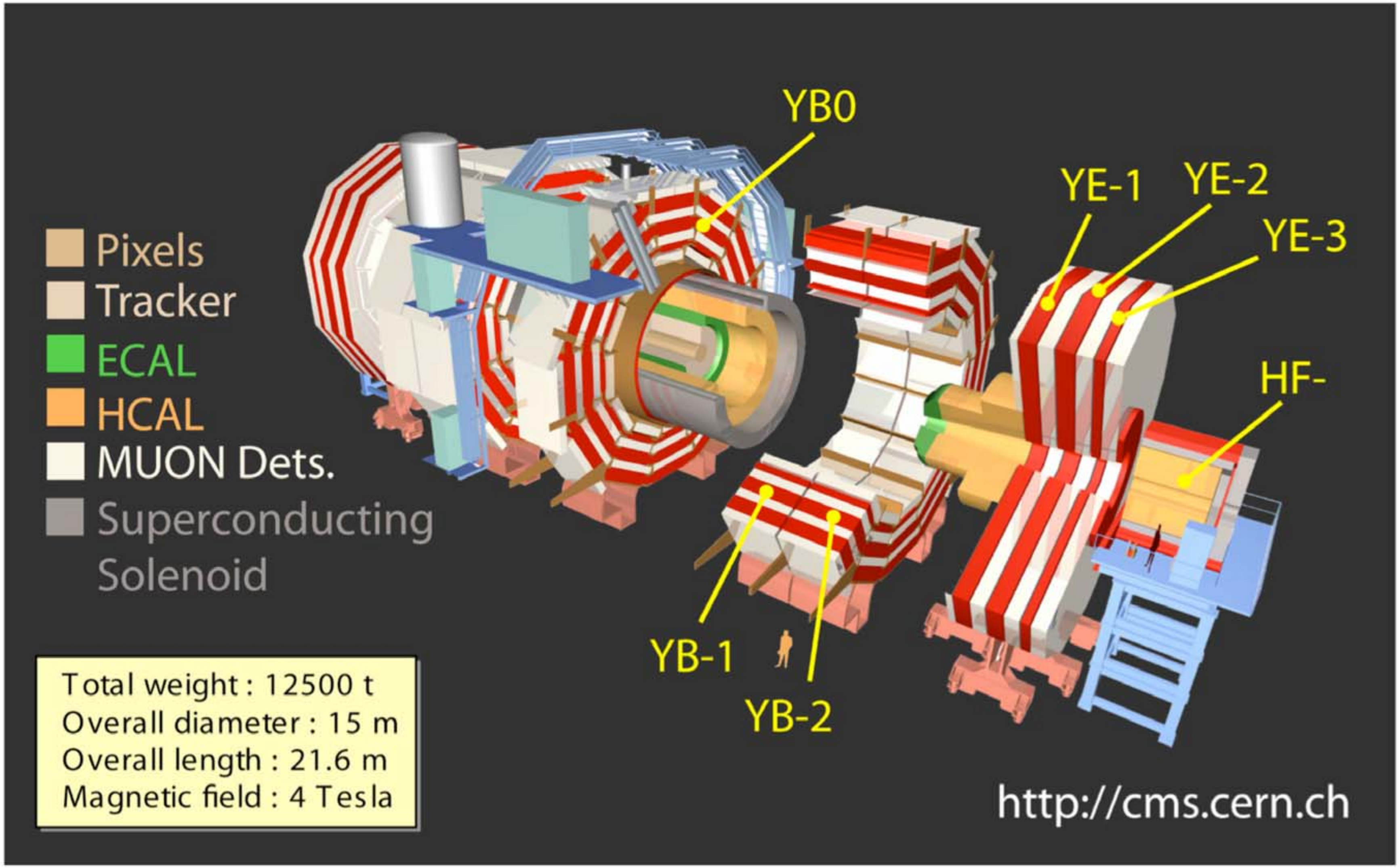


- Interesting Signatures to reconstruct
  - Leptons
  - Jets
  - Missing Energy

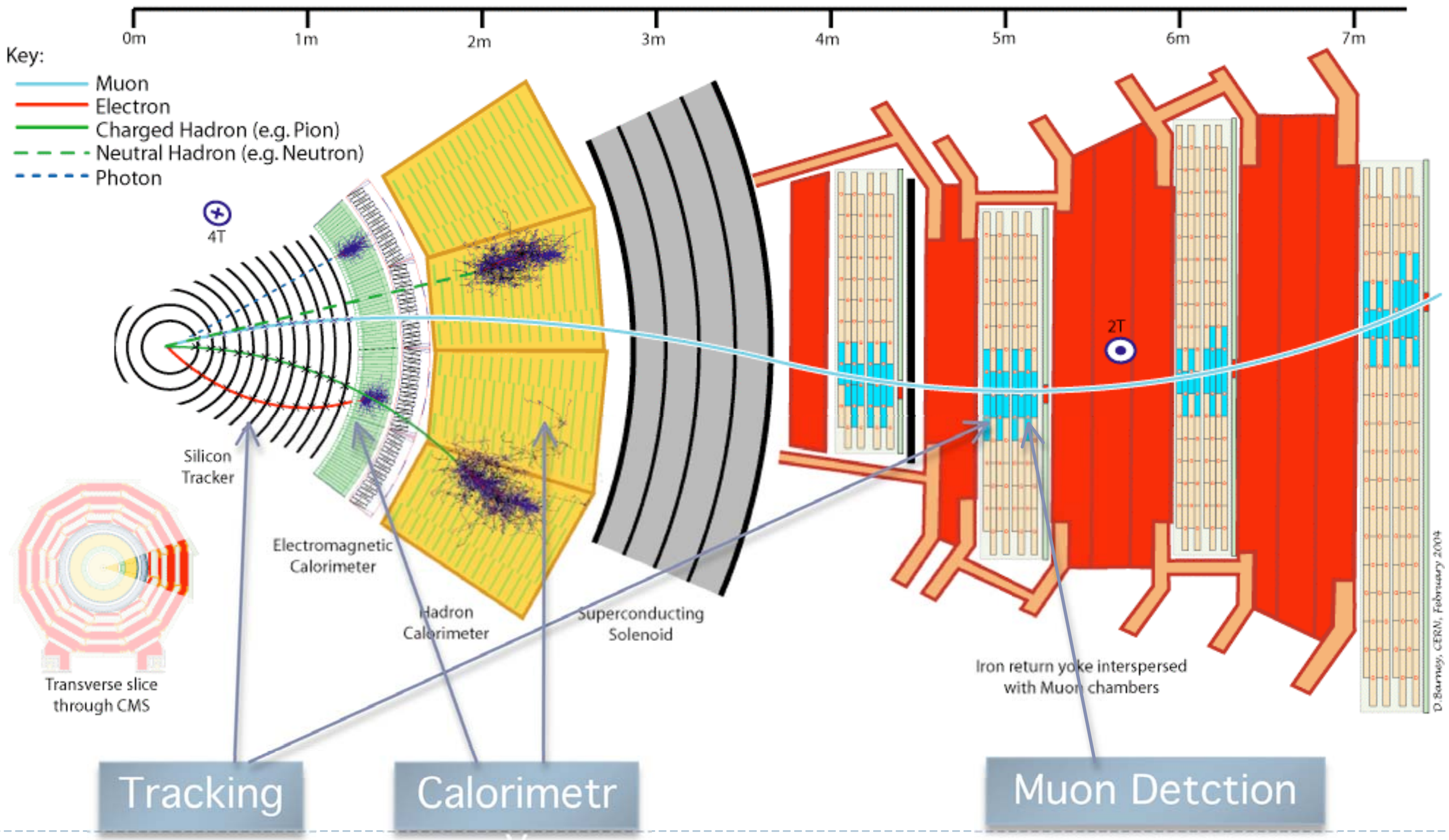


- Requires excellent understanding of the detector
- Additional interactions take place in the detector
  - The ideal detector would be
    - Massless
    - Have perfect resolution of particle properties

Real world detectors – certainly not massless!



How the detectors unravel the puzzle



Passage of particles through our detectors

Most likely interactions which will leave signals in our detectors

Particle	EM	Strong	Weak	None
Photon	✔			
Electron	✔			
Muon	✔			
Charged Hadron (pion…)	✔	✔		
Neutral Hadron		✔		
Neutrino or WIMP				✔

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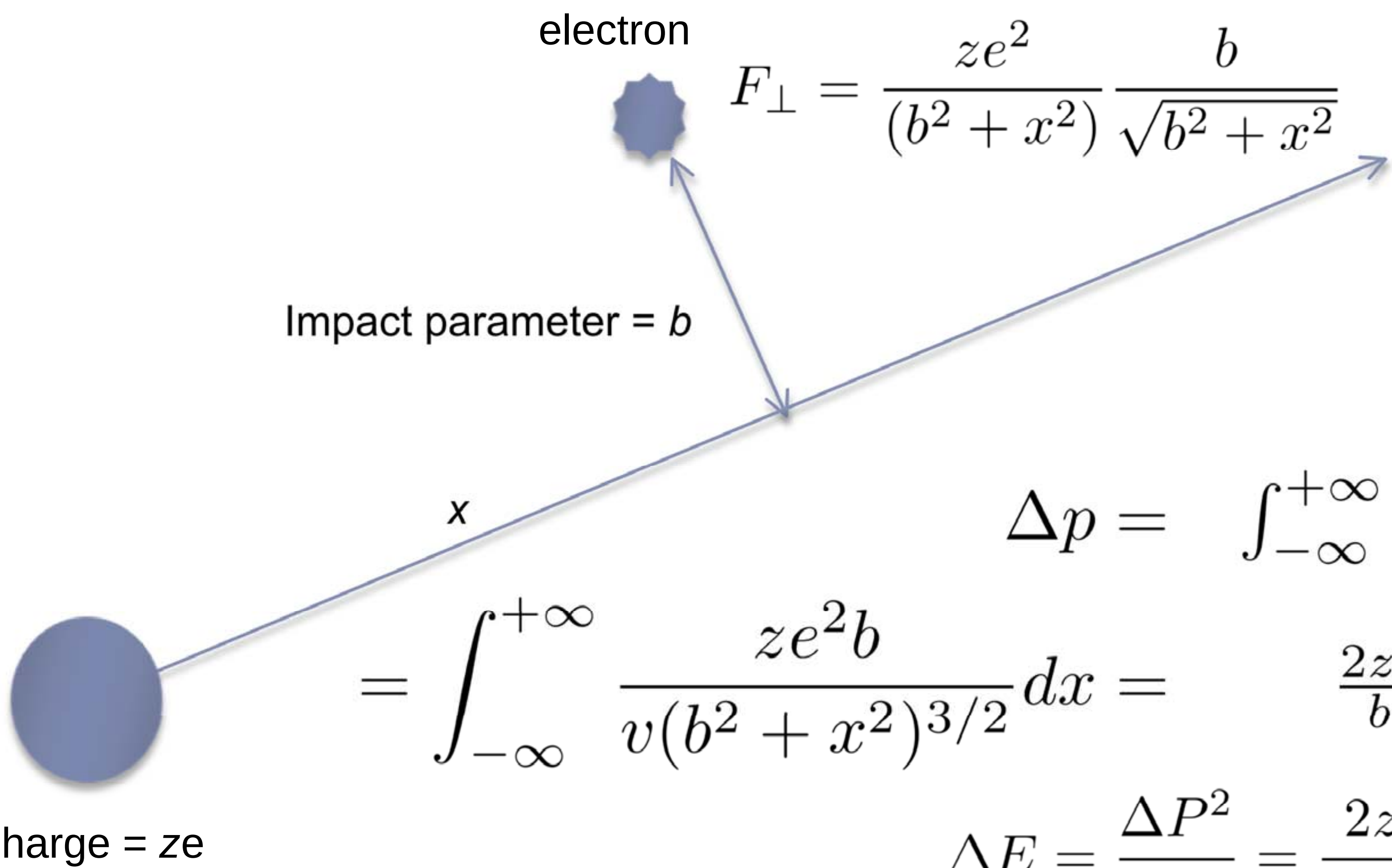
Passage of charged particles through matter



$$F_\perp = \frac{ze^2}{(b^2+x^2)} \frac{b}{\sqrt{b^2+x^2}}$$

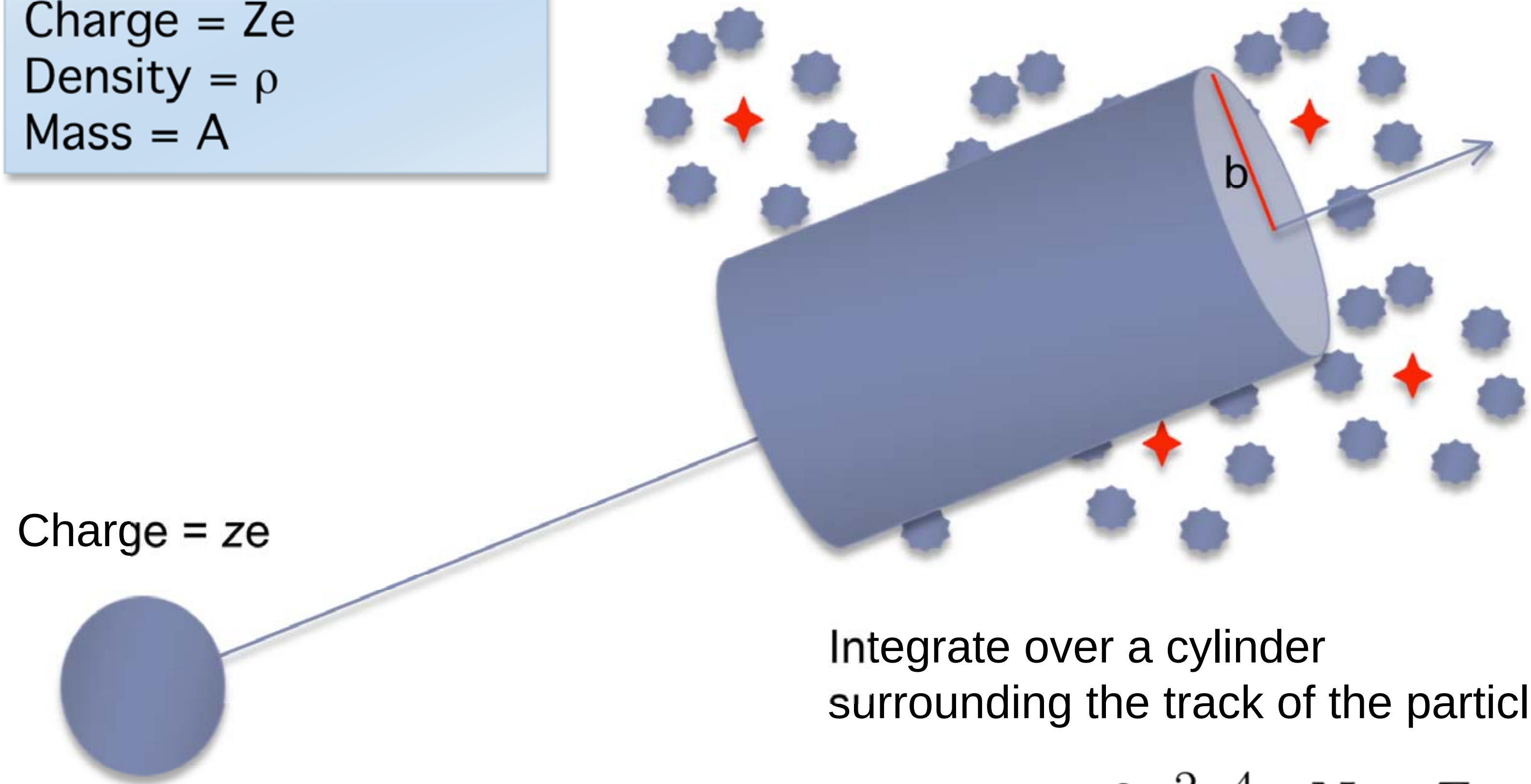
$$\Delta p = \int_{-\infty}^{+\infty} F_\perp \, dt$$

$$= \int_{-\infty}^{+\infty} \frac{ze^2 b}{v(b^2+x^2)^{3/2}} dx = \frac{2ze^2}{bv}$$

$$\Delta E = \frac{\Delta P^2}{2m_e} = \frac{2z^2e^4}{b^2v^2m_e}$$

Interaction with a Target

Target
Charge = Ze
Density = ρ
Mass = A



Integrate over a cylinder
surrounding the track of the particle

$$-dE = \Delta E N_e 2\pi b\, db\, dx = \frac{2z^2e^4}{b^2v^2m_e}\frac{N_A\rho Z}{A}2\pi b\, db\, dx$$

Energy Loss per unit length in material

$$
\begin{aligned}
-\frac{1}{\rho}\frac{dE}{dx} &= \frac{4\pi z^2 e^4 N_A Z}{v^2 m_e A}\int \frac{db}{b} = 4\pi N_A z^2 r_e^2 m_e c^2 \frac{Z}{A}\frac{1}{\beta^2}\ln\frac{b_{max}}{b_{min}} \\
&= K z^2 \frac{Z}{A}\frac{1}{\beta^2}\frac{1}{2}\ln\frac{E_{max}}{E_{min}}
\end{aligned}
$$

Ionization Energy

$$E_{min} = I$$

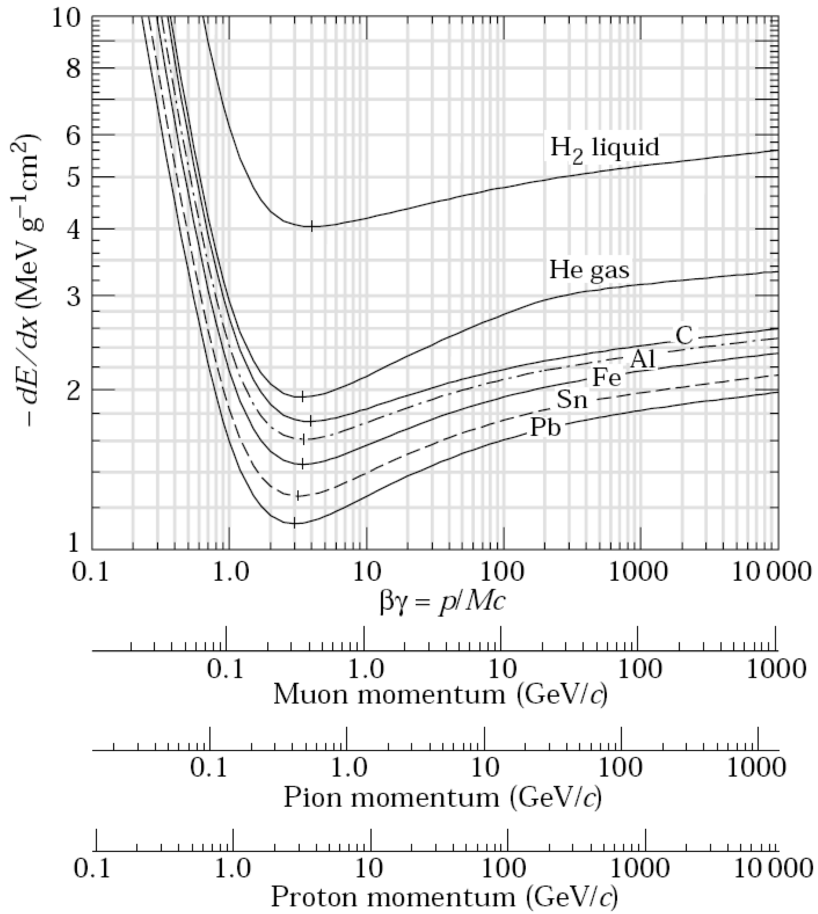
$$E_{max} = 2m_e c^2 \beta^2 \gamma^2 T_{max}$$

Head on Collision

$$r_e = \frac{e^2}{m_e c^2} \qquad K = 4\pi N_A r_e^2 m_e c^2$$

Average Energy Loss in Material
Bethe-Bloch

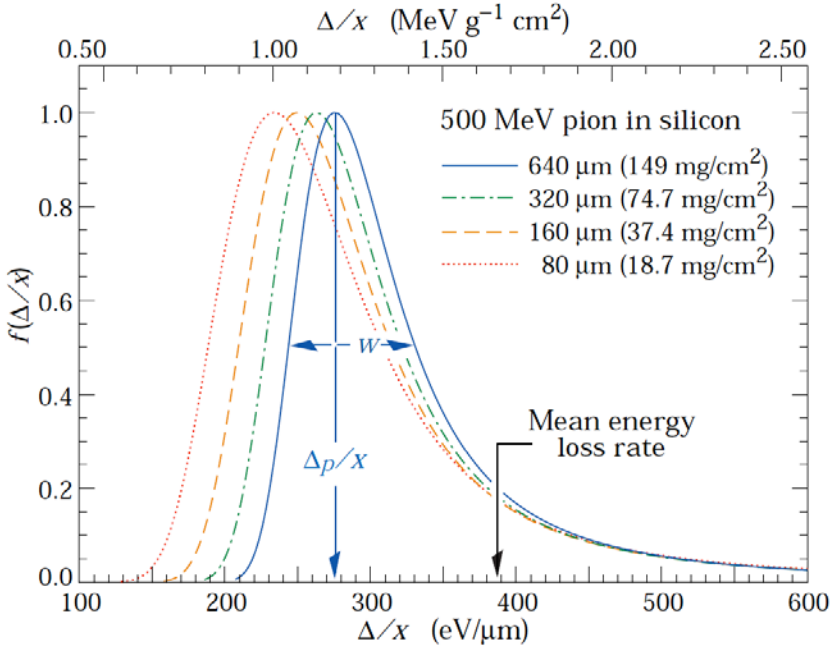
- In the full derivation, there are additional terms for the screening effect of the intermediate material
  - The material is polarized by the electric field of the particle passing through it
- The energy loss reaches a minimum, and then rises to a plateau



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

Energy loss in a thin layer
Landau Distribution

- Calculate the distribution of energy loss that is likely to be seen in a thin layer of a detector
- The distribution and most probable energy value depend on the material composition and thickness
- There is a long tail to the distribution



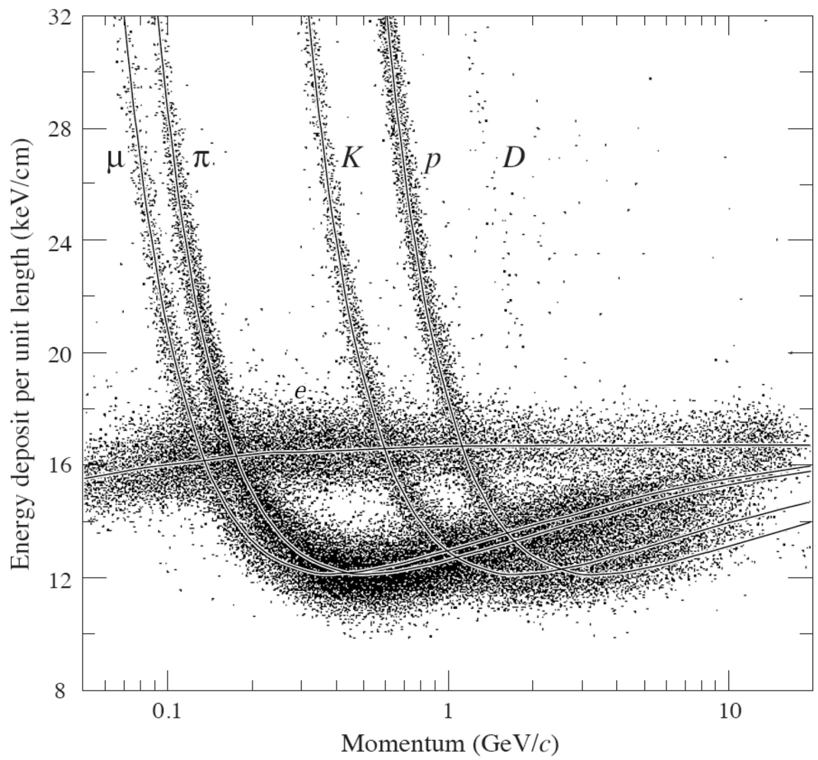
$$Q(\lambda) = \sqrt{\frac{e^{-(\lambda + e^{-\lambda})}}{2\pi}}$$

$$\lambda = A(E - E_p)$$

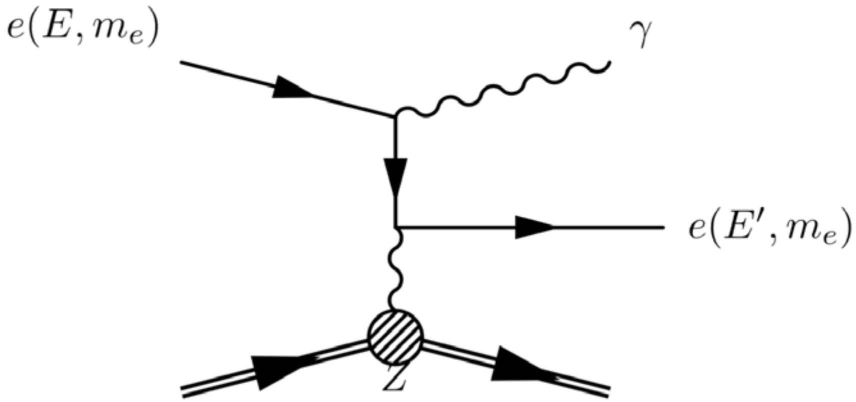
$$E_p \equiv \text{ most probable energy loss}$$

Identifying particles by energy loss

- The shape of the Bethe-Bloch curve is the same for any incoming particle on a given target, but depends on the particle velocity
- Different particle species will have different velocity for the same momentum
- Measuring both particle momentum, and dE/dx gives the possibility of an identification of different particle species
  - More effective at certain (low) momentum regions



Bremsstrahlung



$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} z^2 r^2 E \ln\frac{183}{z^{1/3}}$$

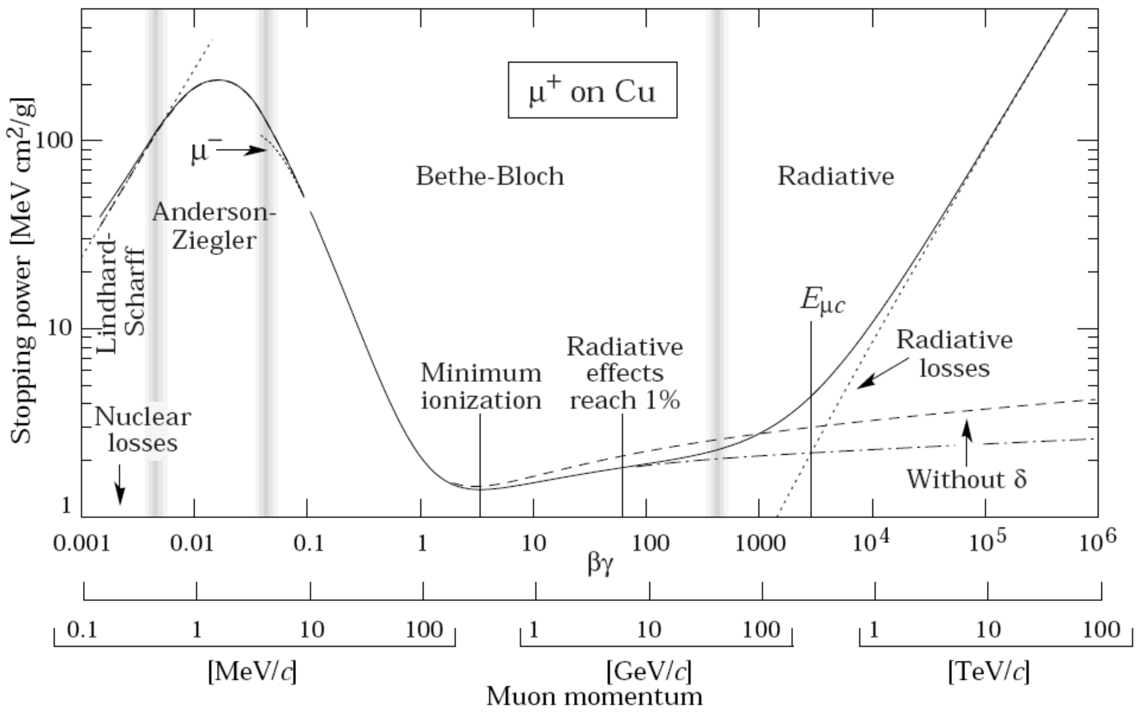
$$-\frac{dE}{dx} = \frac{E}{X_0}$$

$$E(x) = E_0 e^{-x/X_0}$$

$$X_0 = \frac{716.4A}{Z(Z+1)\ln(287/\sqrt{Z})} \; [g/cm^2]$$

$$r = \frac{e^2}{mc^2}$$

- Energy loss is proportional to the energy of the incoming particle
  - Compare to Ionization which is flat in Energy
- Energy loss is proportional to $1/m^2$ of the incoming particle
  - Muons radiate much less than electrons via Bremsstrahlung
- X_0 is the Radiation length which is a characteristic of the material
  - The incoming particle energy will decrease to E_0e^{-1} after travelling through one X_0 of material.

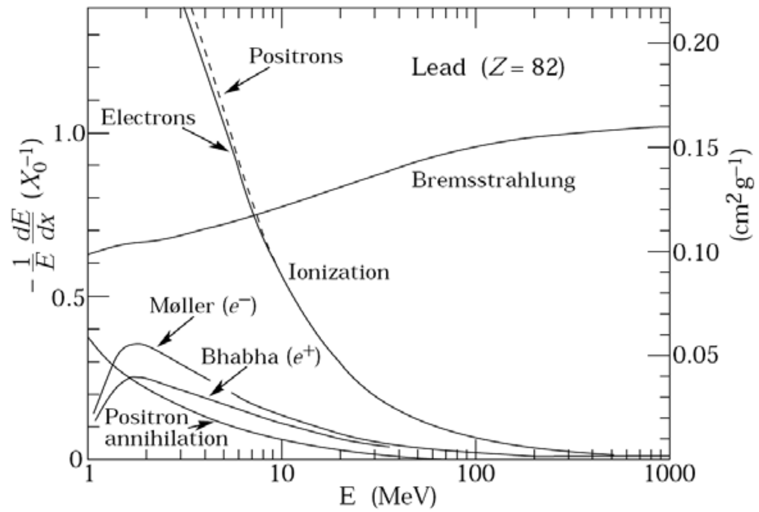


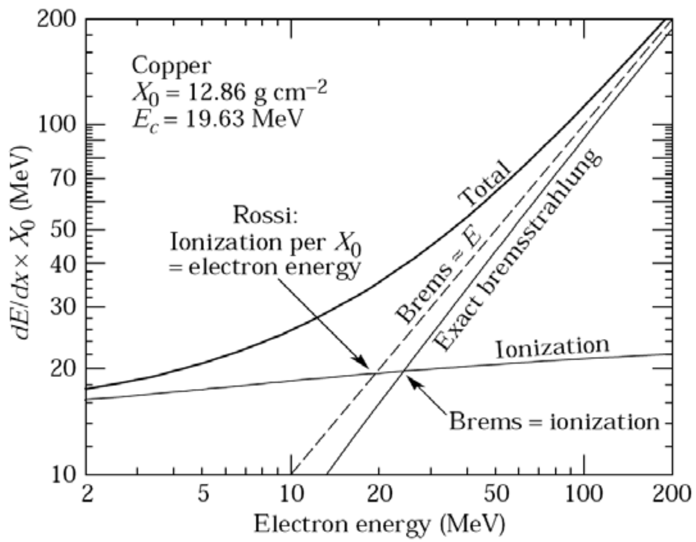
Muon Energy Loss

Dominated by Ionization losses at the energies of interest for LHC detectors

Ionization loss for muons is relatively constant for a given material at these energies

Electron energy loss



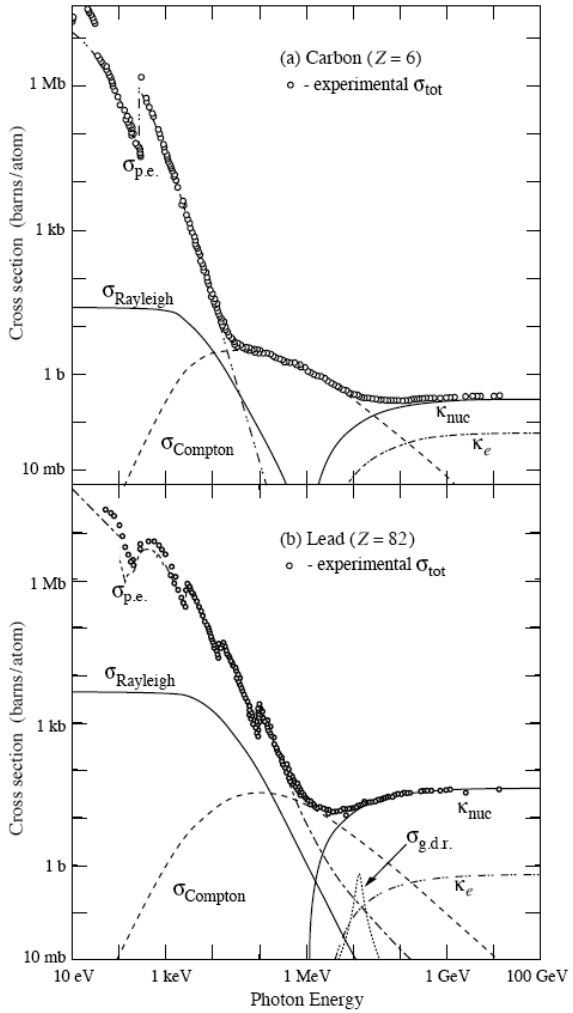


- Bremsstrahlung is the main mechanism for electron energy loss at energies above about 10 MeV
  - (Compare 400 GeV for Muons)
- Critical Energy
  - Where the ionization loss equals the loss from Bremsstrahlung

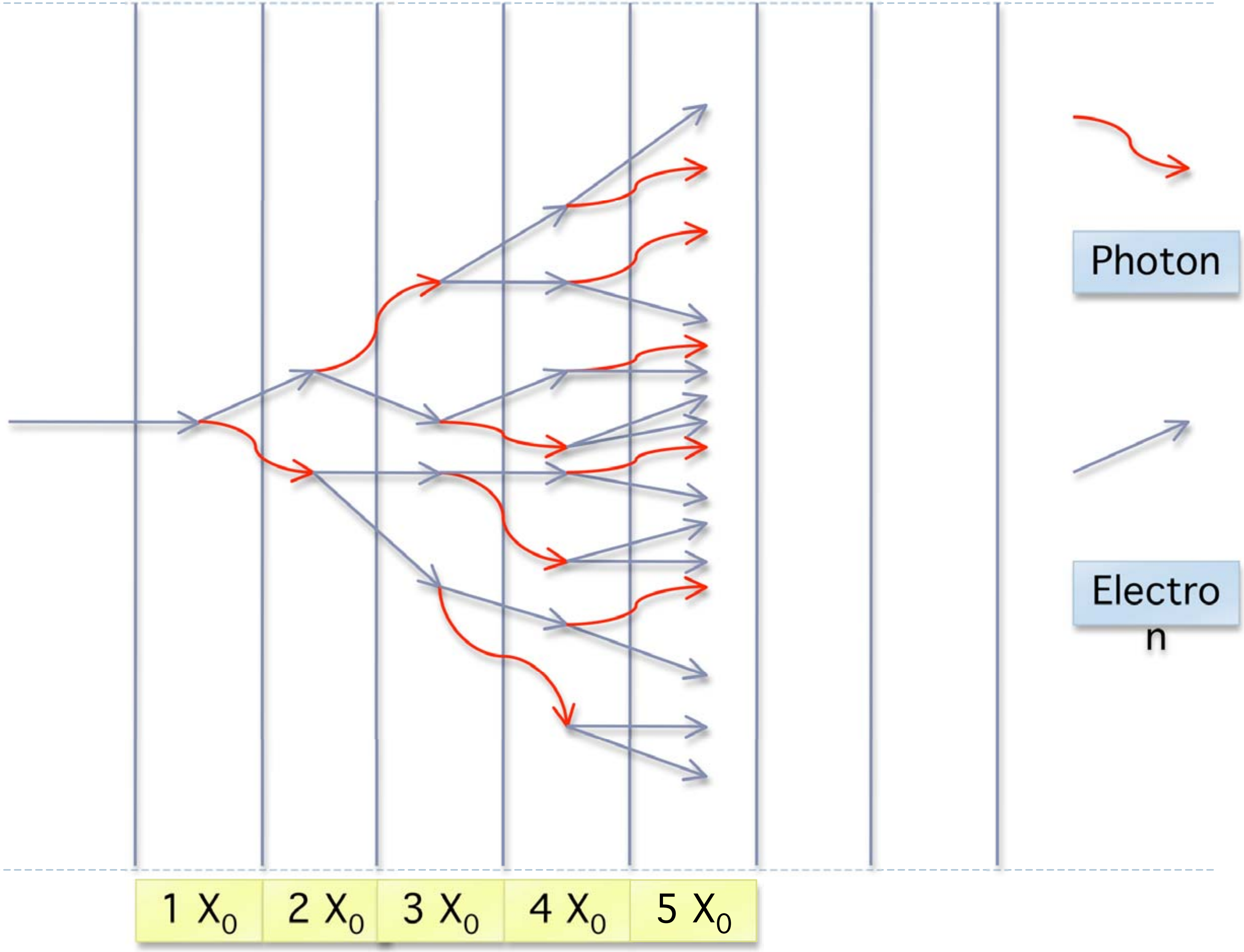
Photon Energy Loss

- For Photons, pair creation in the field of the nucleus is the dominant mechanism for energy loss at energies above an MeV.
- Compton scattering, then Rayleigh (and finally the photo-electric effect) dominate at lower energies

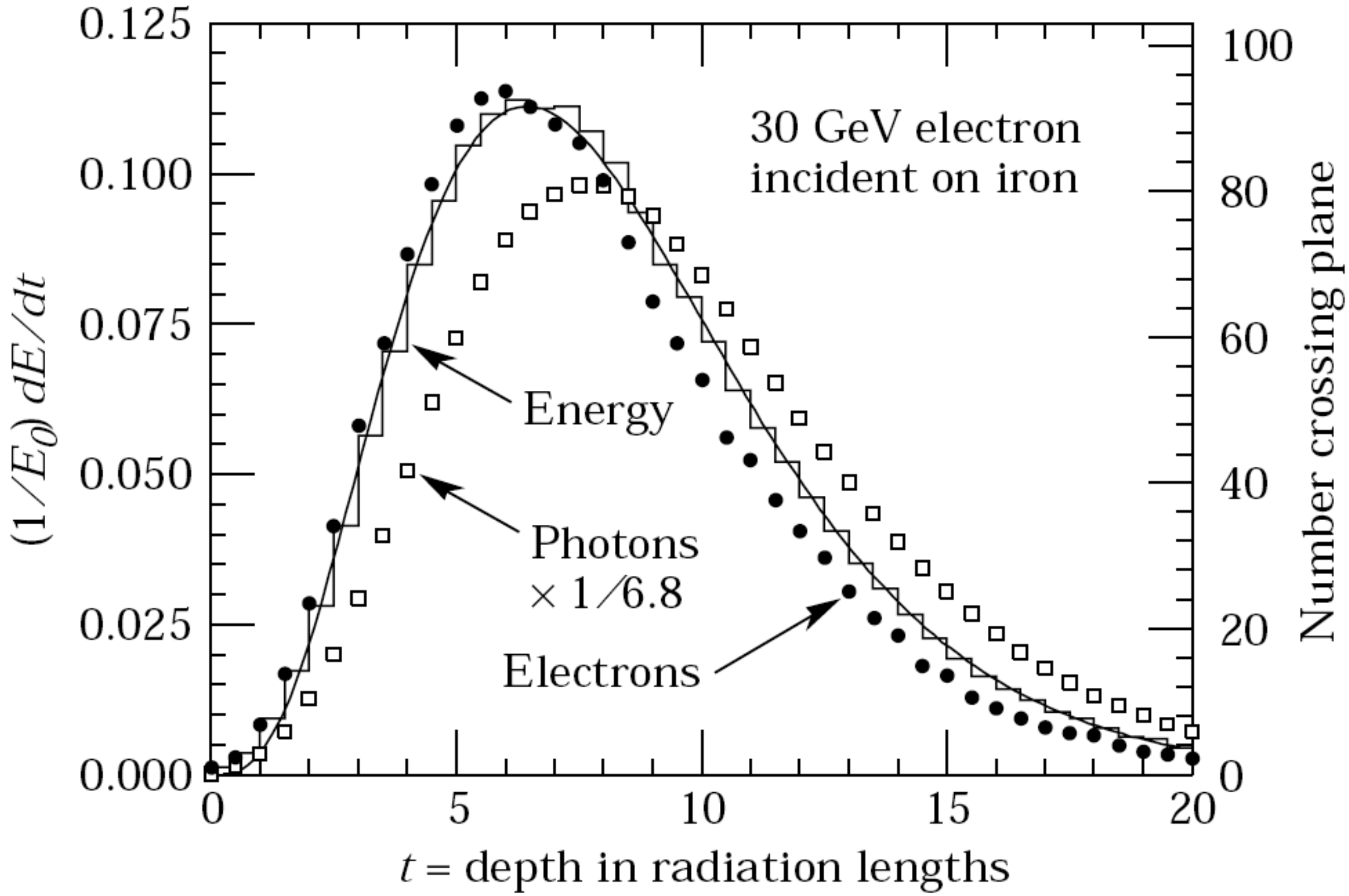
$$\sigma_{pair-creation} = \frac{7}{9}\frac{A}{N_A}\frac{1}{X_0}$$



Electromagnetic Showers



Electromagnetic Shower development



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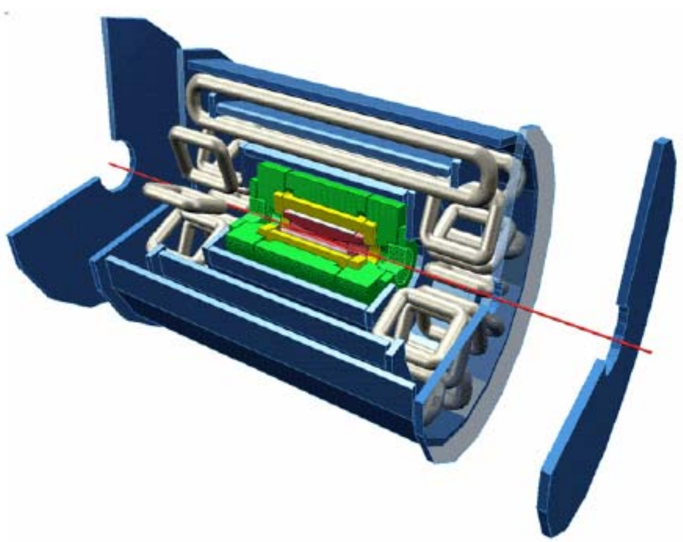
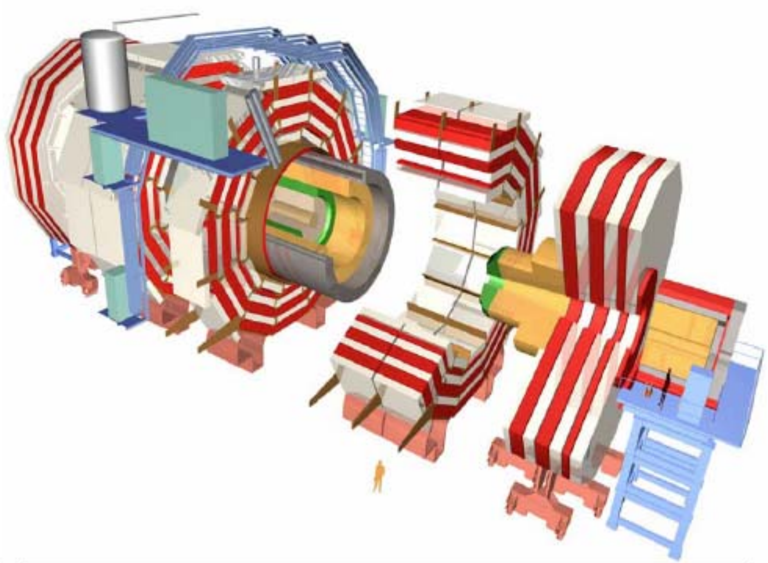
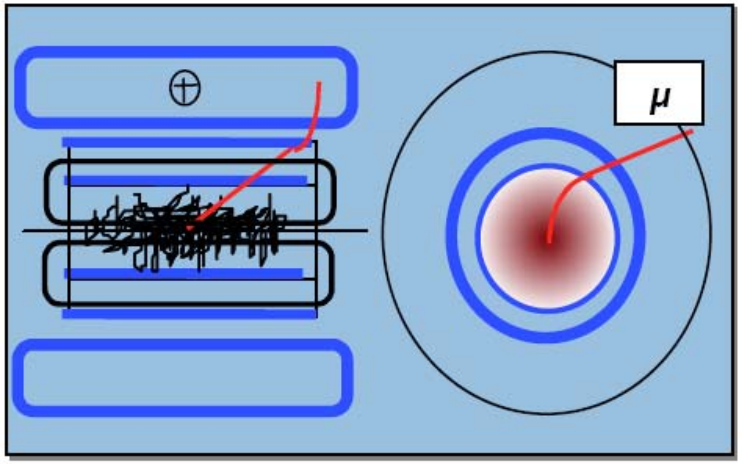
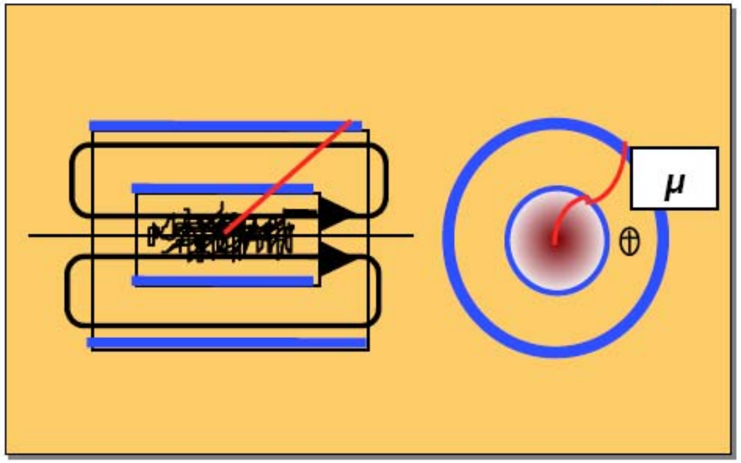
Basics of Tracking



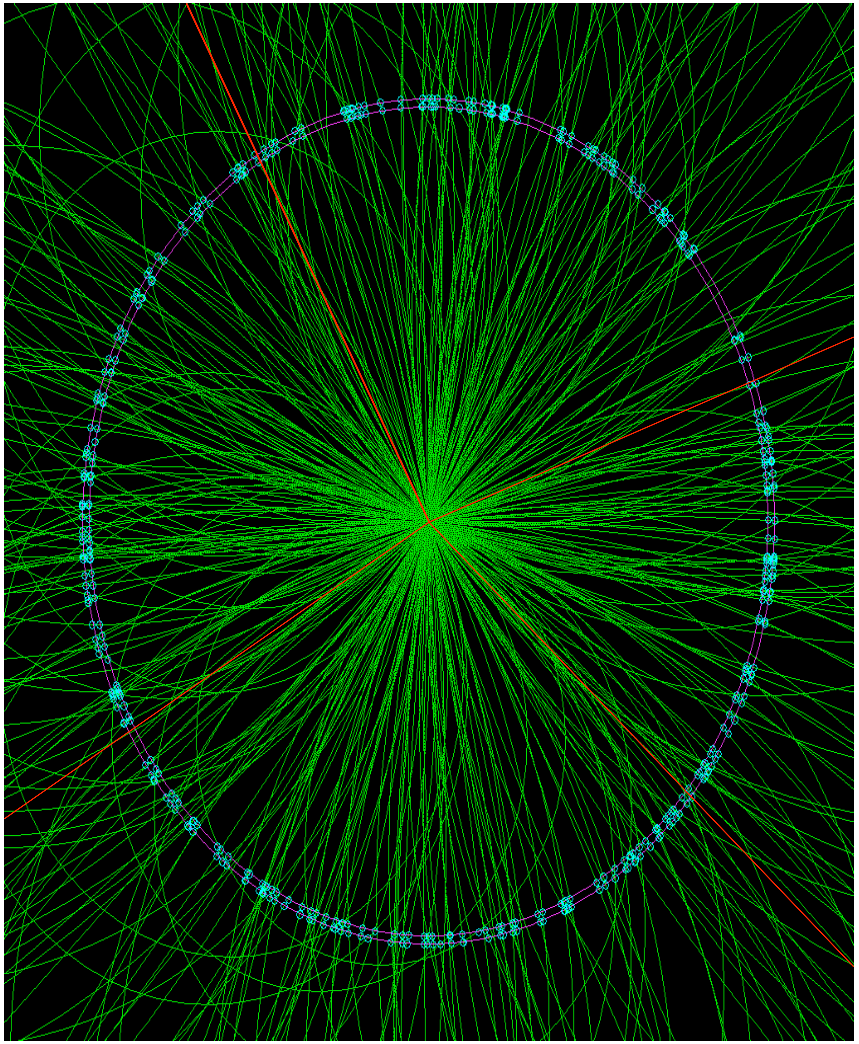




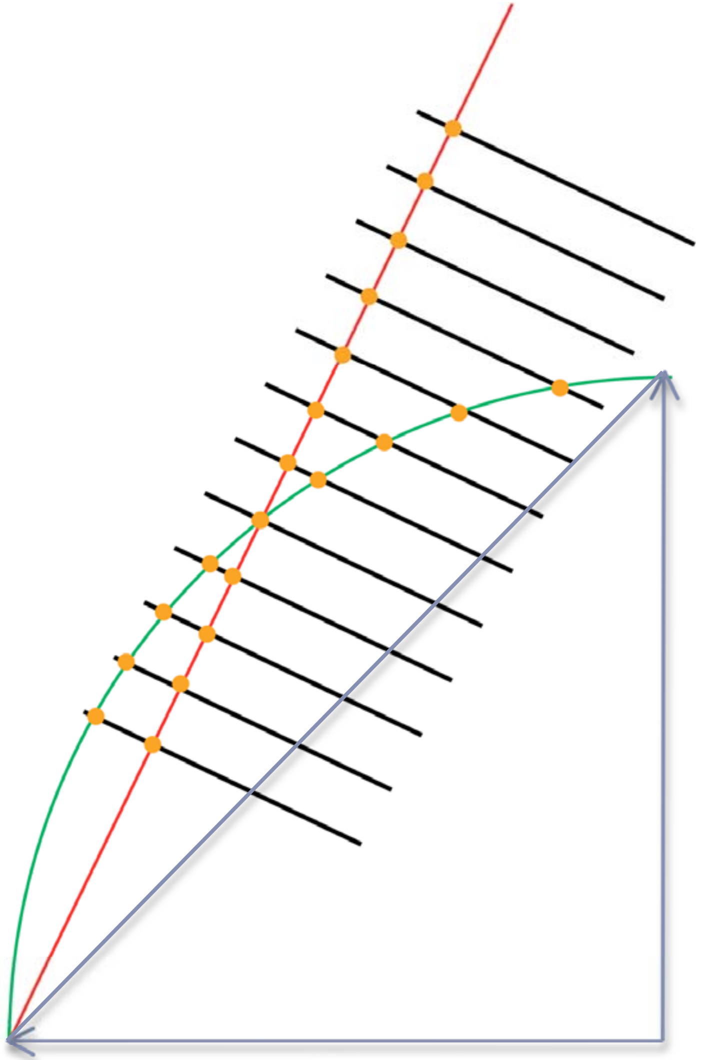


Finding and measuring charged particle properties

- Physics events at the LHC are full of a large number of charged particles.
- These pass through our detectors interacting with the detector material
- We want to
  - Measure the ionization from passing particles
  - Associate these "hits" with individual particles
  - Measure the trajectory of the particles



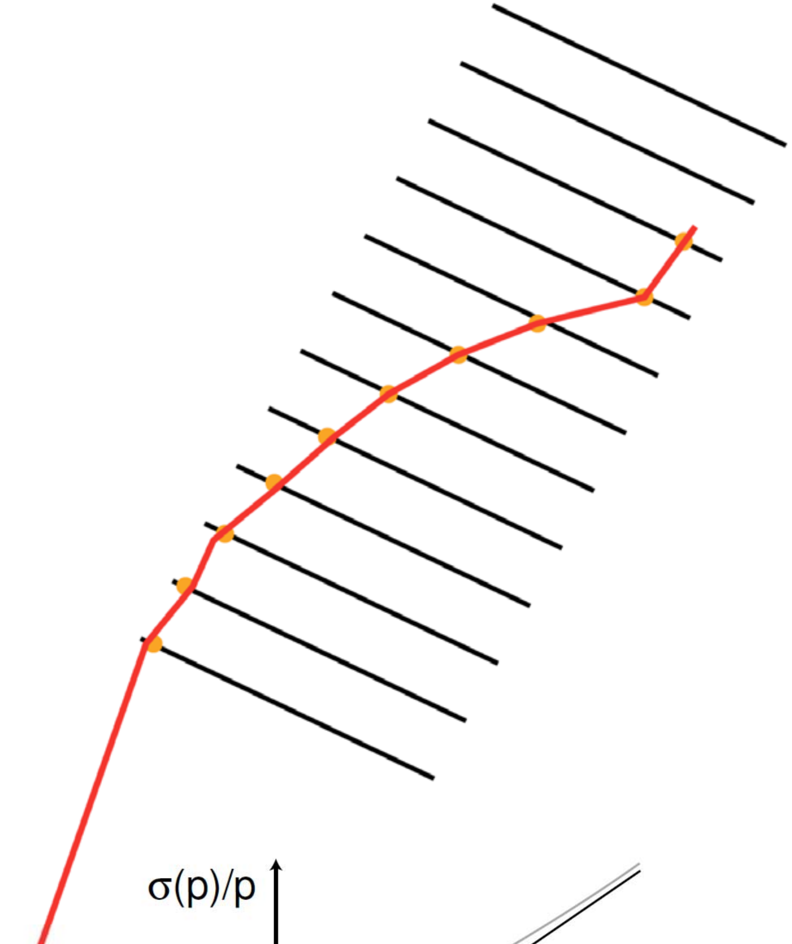
Tracking 101

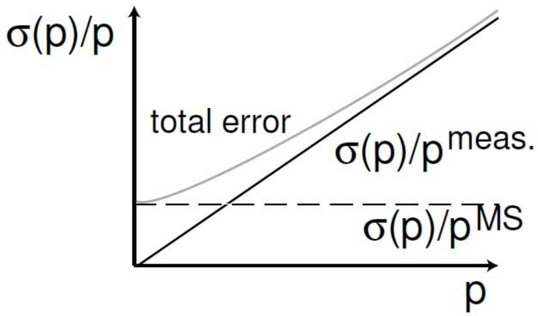


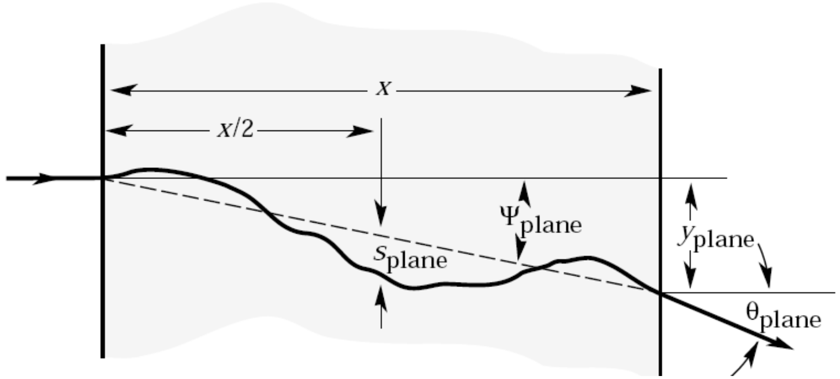
- Particles in a uniform magnetic field move in a circle
- The radius of the circle is proportional to the magnetic field
  - We fit the measured points to a helix to determine the momentum and point of origin
  - There is a global momentum determined for the track
- Limit at high momentum depends on how well we can measure the sagita
  - Low momentum should in principle continue to give better and better measurements of the track momentum
- We can also mis-measure tracks by not associating the correct hits to a given particle
  - Pattern recognition at the LHC is vital

$$p[GeV/c] = 0.3\,R[m]\,B[T]$$

Multiple scattering



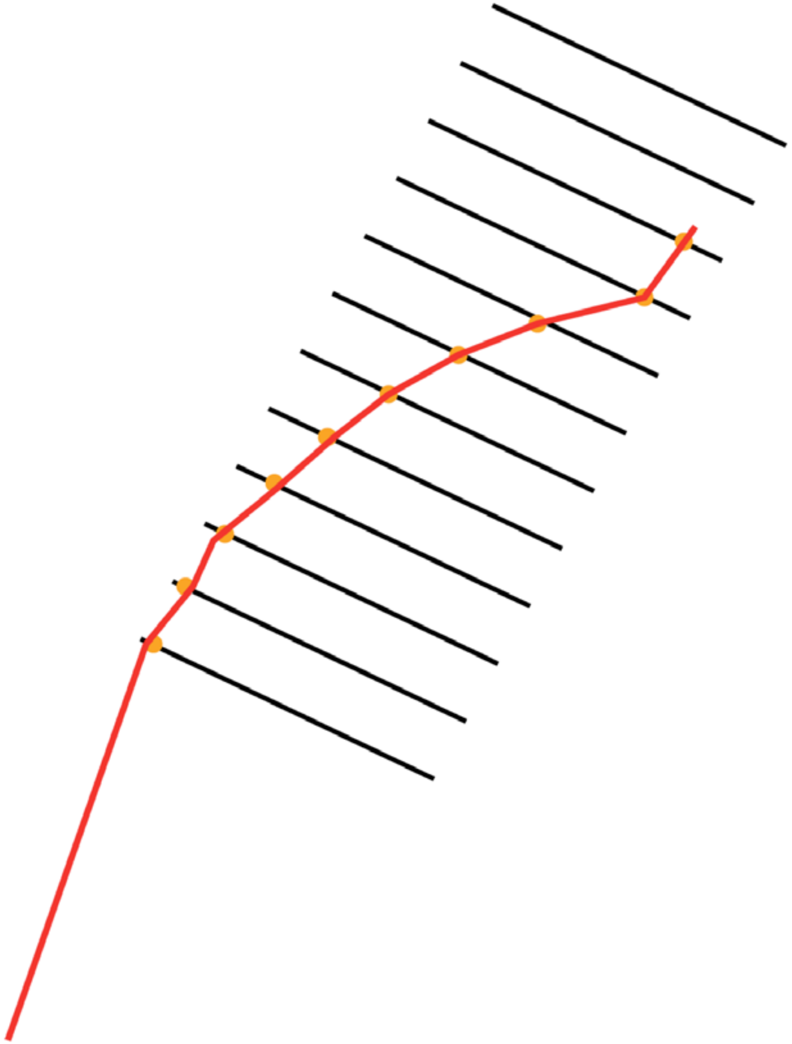




- Particles undergo multiple interactions as they pass through tracking detector material (and air or other material)
  - A bigger effect for lower momentum tracks
  - Multiple scattering limits resolution at low p
  - Tracks no longer follow a Helix
- Probability that after passing through a thickness x of a material with radiation length X_0 a particle is deflected by an angle θ is a gaussian distribution with sigma

$$\Theta_0 = \frac{0.0136}{\beta c p\,[\mathrm{GeV}/c]} Z \sqrt{\frac{x}{X_0}}$$

Kalman filter fitting of tracks

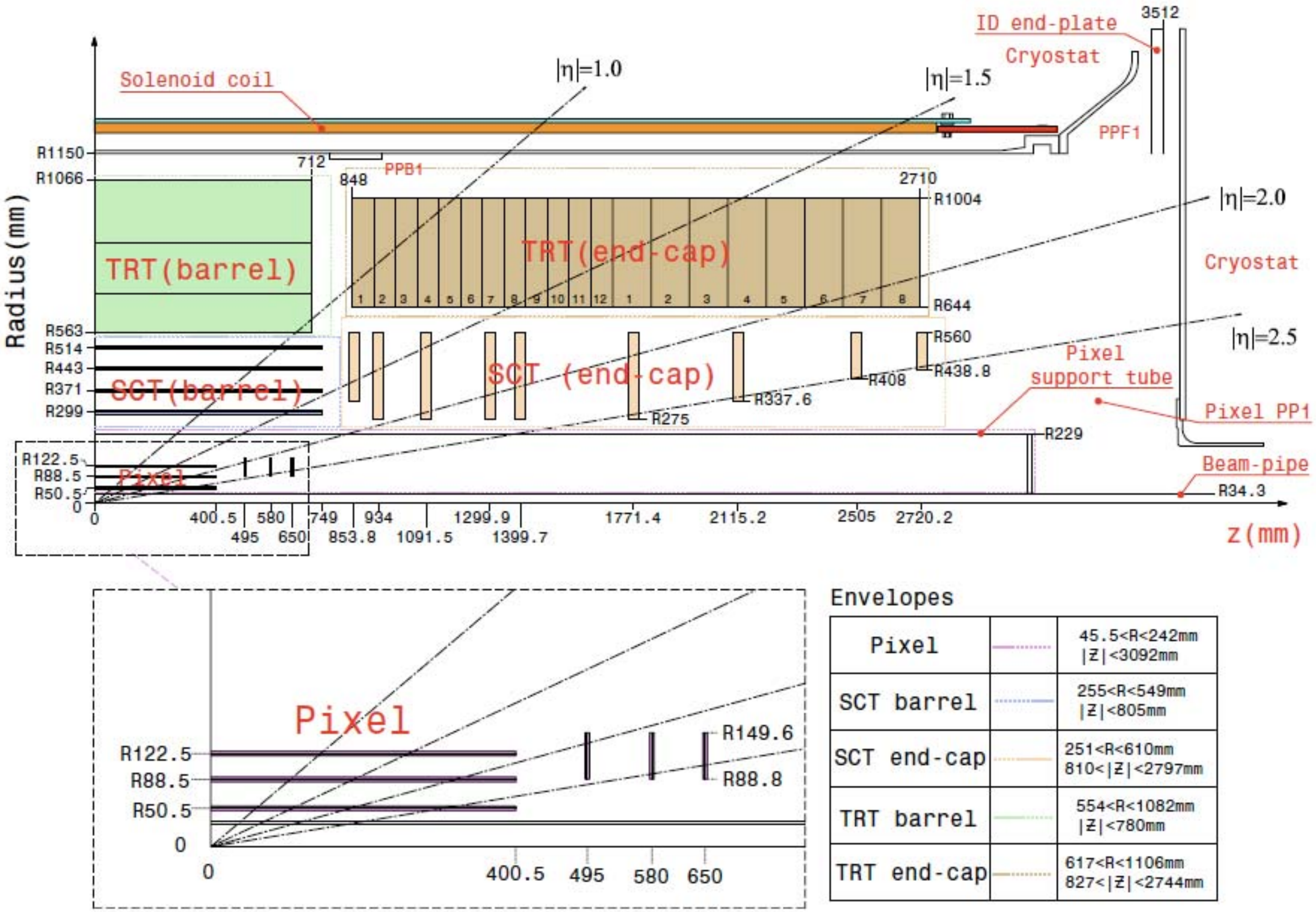


- In order to account for the effects of multiple scattering we need to modify our algorithms to allow for track deflection at each passage through material
- Tracks are propagated through material correcting for loss of momentum
  - The track momentum varies as a function of where it is measured
  - We need a good model of the material in the detector
  - There can be pattern recognition problems when there are large deflections

Properties of tracking devices

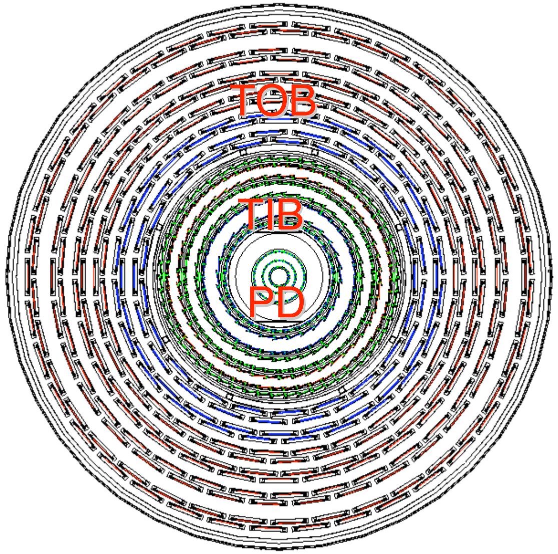
- Ideally we want to measure the passage of each charged track as accurately as possible
  - Better spatial resolution on hits helps us to separate the hits from closely spaced particles (pattern recognition)
    - We don't get a map to associate hits to particles, we have to figure it out…
  - Better measurement of the positions can give us a better precision on momentum resolution
    - There is a big premium on having extremely good spatial resolution very close to the interaction point of the beams
      - Separate underlying events which come from different locations in the beam spot
      - Look for long lived particles which decay of order mm from the primary interaction point
- However (think Heisenberg) we can't measure the particles coming out without disturbing them
  - Interaction in material in the detectors can cause particles to lose energy
    - Remember photons, electrons very sensitive to small amounts of material

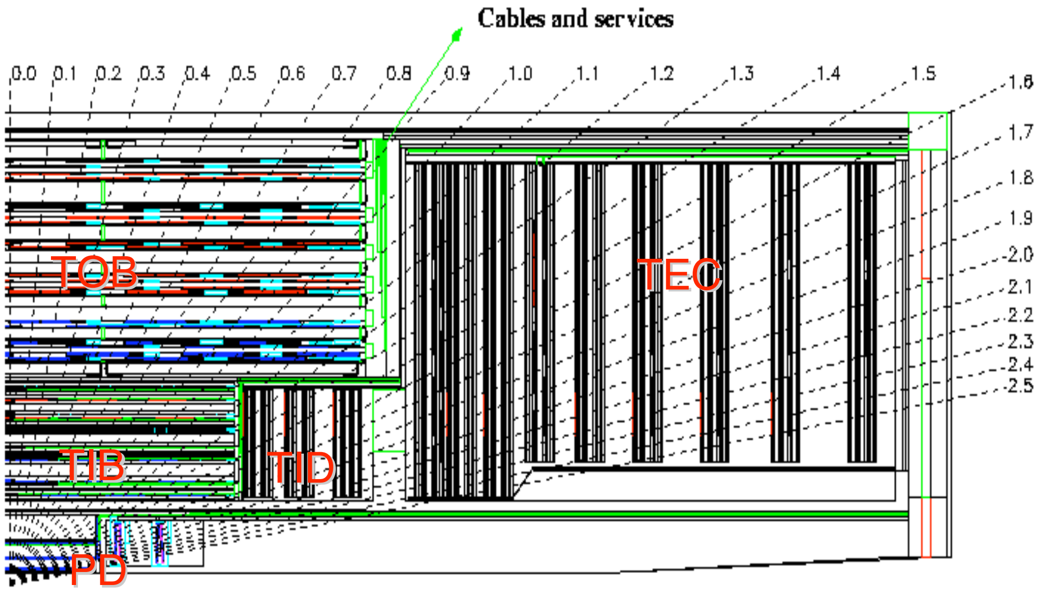
Covering the inner volume with tracking detectors - ATLAS

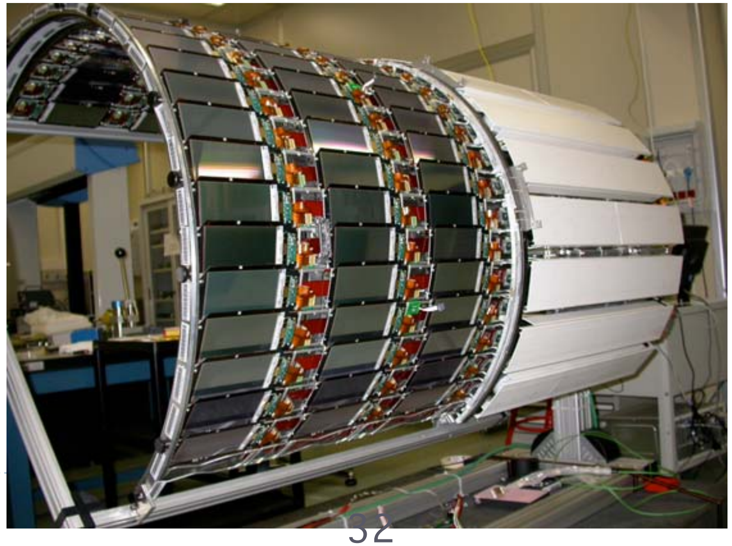


CMS Tracker

- All Silicon tracker
  - 200 m^2 of Silicon detectors
  - 50 Kw of power
  - 10,000,000 Channels strips
  - 60,000,000 Channels Pixels
- Cylindrical Barrels at low pseudo-rapidity
- Circular Disk Endcaps at higher pseudo-rapidity



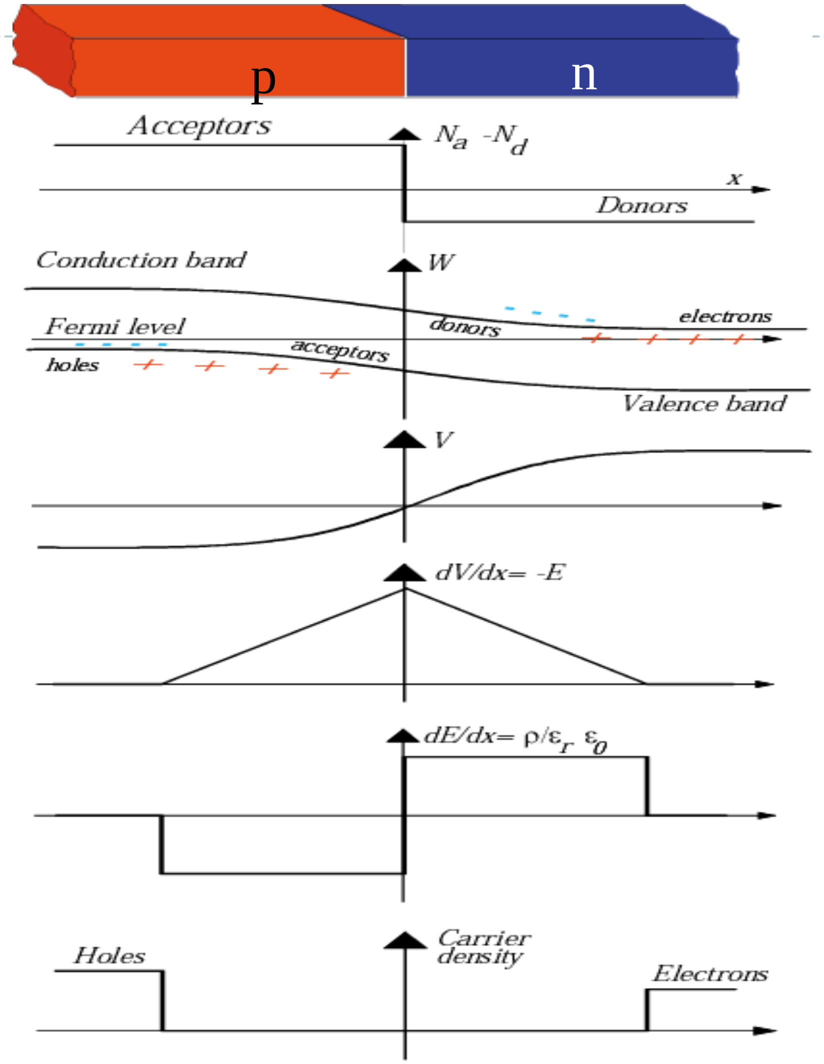




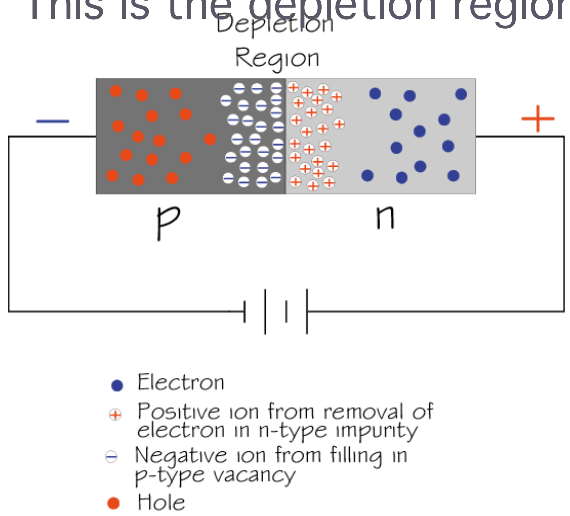
The innermost layers “Pixel” detectors

- Want smallest amount of material
- Highest density of channels
- 3D space points
- Able to withstand the high radiation environment close to the beam
- Silicon Pixel detectors are the choice
  - Localize each ionization signal to a small region
    - (~150μm x 150μm)
  - Small amount of material
  - Fast readout
  - Typically of order 60 M Pixels
    - but with 40MHz readout capability

How does a silicon detector work?

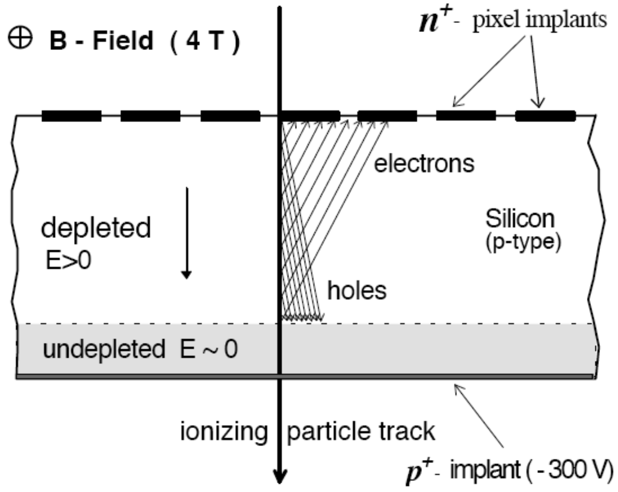


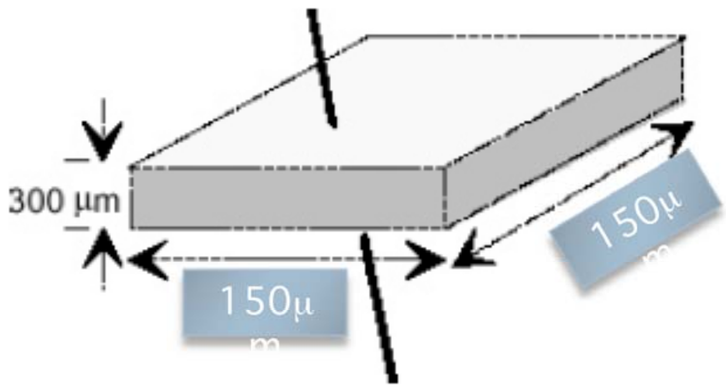
- Silicon is doped to create
  - Arsenic -N-type (more electrons)
  - Boron - P-type (more holes)
- A Diode is constructed by bringing together N-P material creating a junction
- At the junction there is a region with no charge carriers –
  - This is the depletion region



Charged particles in Silicon detectors

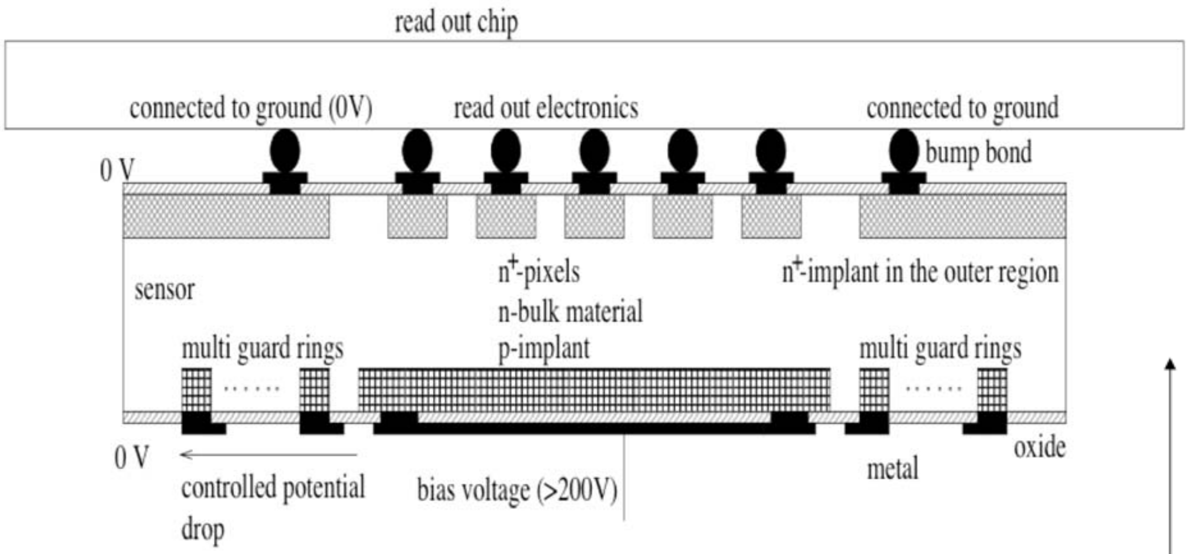
- A reverse bias is applied to the diode which extends the depleted region
- When a charged particle passes through a silicon diode, many electron-hole pairs are created in the depleted region
  - Silicon is dense
    - Energy loss 3.8 Mev/cm
  - The energy to create an e-h pair is much lower than the ionization energy
    - 3.6eV compared to 10's of eV for Ioniztion
  - ~9000 e- created in each 100μm thickness of Silicon
- The electrons drift in the electric field to the end of the detector where they create a signal which can be read out
  - Charge sharing between neighboring pixels or strips allows us to achieve a better single hit position resolution



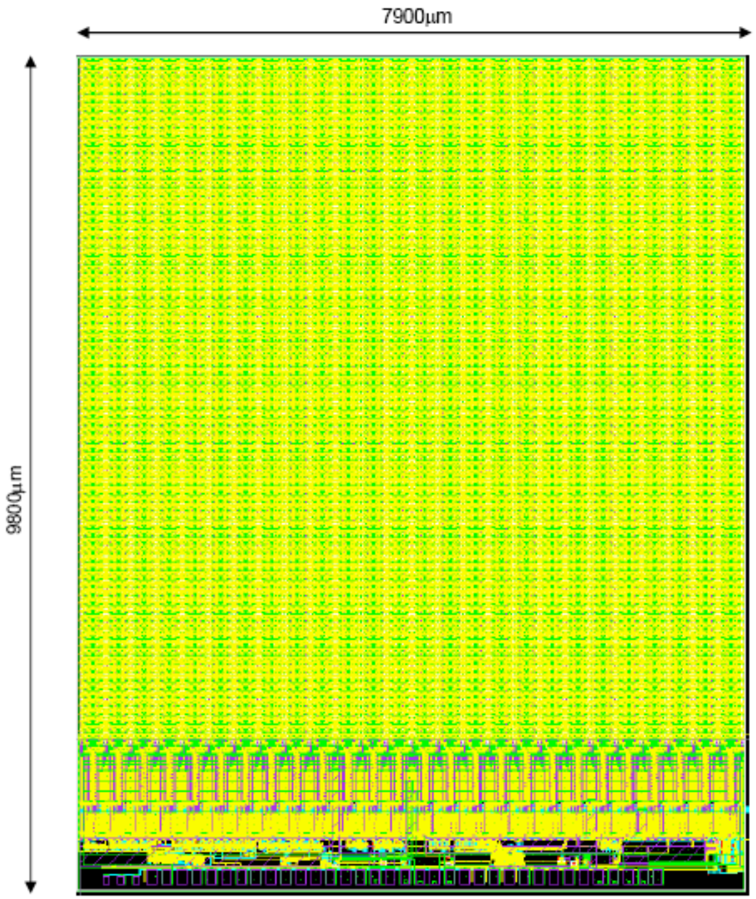


Typical Pixel

Readout of Pixel detectors

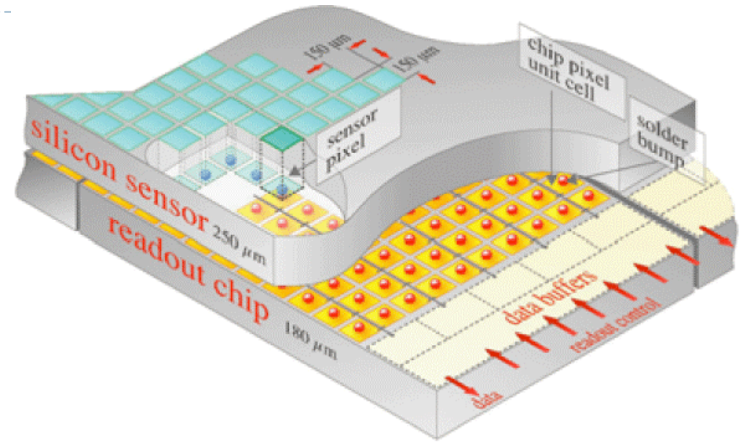


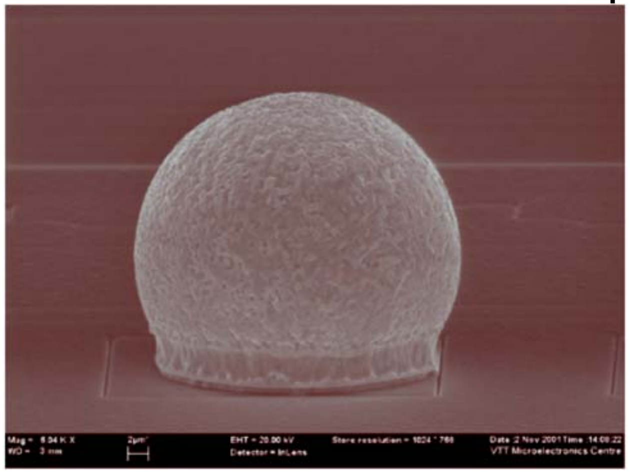
- One of the big difficulties is each how to read out each individual pixel
  - Large number of electronics channels (~60M)
  - Want to uniformly cover the surface area with sensitive detector
  - Difficult connectivity problem
- Electronics is bonded directly to the back of the Silicon Sensor
  - Channels are then read out in columns
  - End of the columns connected to external readout system

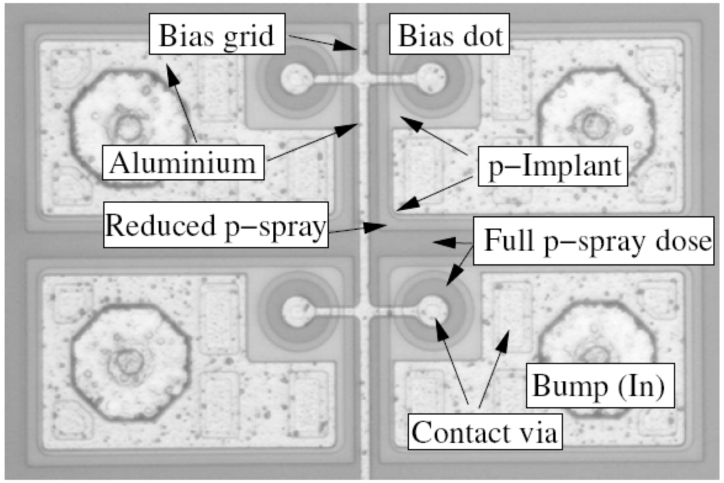


Pixel Detectors - Bump Bonding

- Electronics readout is "Bump Bonded" to the pixel sensor
- Indium bumps placed on the Sensor
- The electronics readout is aligned on top of the sensor so that the bumps line up with the connections to the amplifiers
- The layers are heated, the bump flows and creates a connection between the sensor and the readout chip

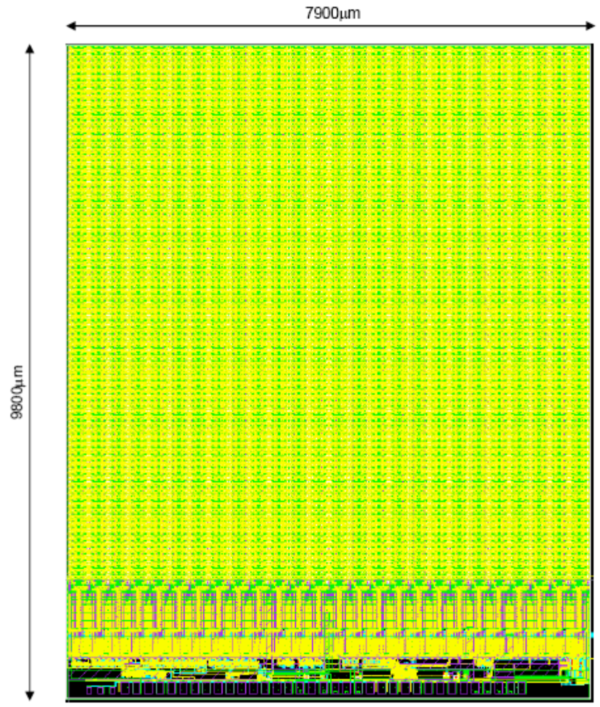




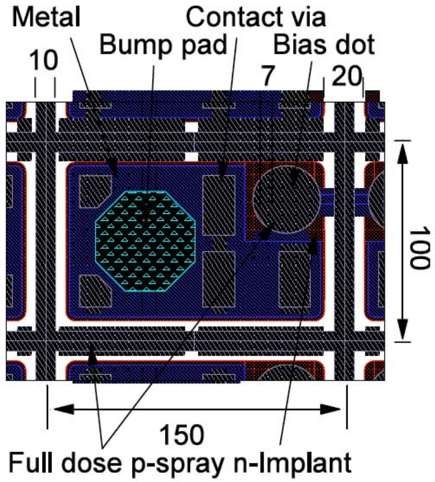


Pixel Sensors and ROC

- ROC (Read out Chip)
  - Farbricated in 0.25μm CMOS
  - Internal power regulation
  - Column Drain architecture
  - 1.3M transistors
  - 28 μW/pixel

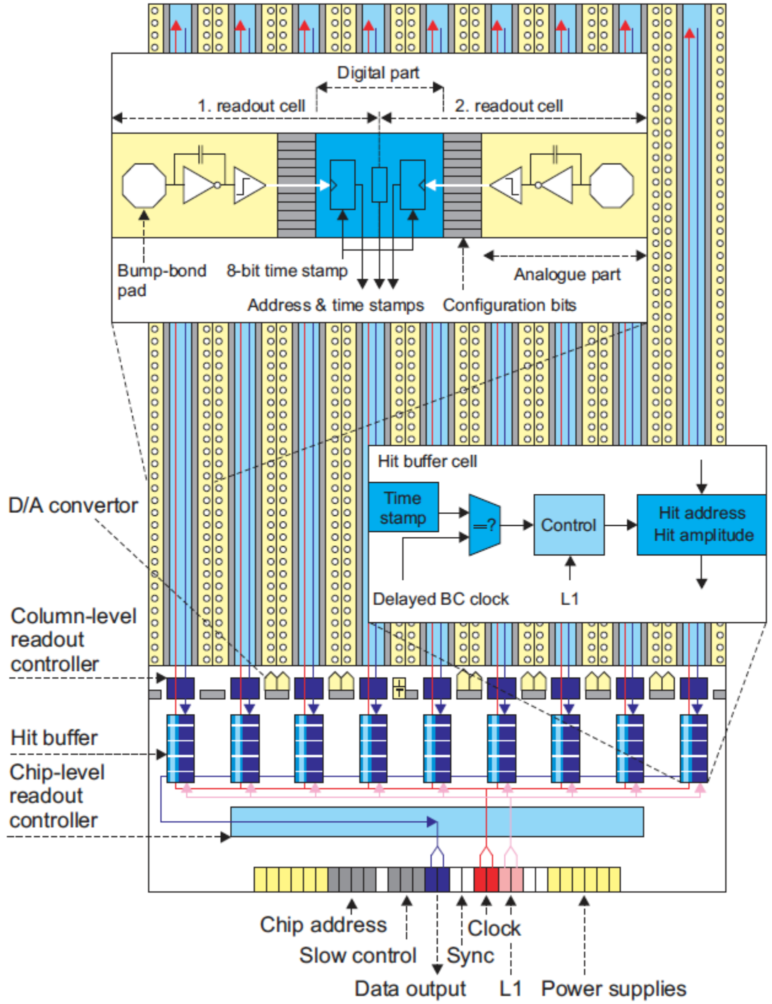


- Sensors 150μm x 100 μm
  - (ATLAS 400μm x 50μm)
  - P spray on oxygenated silicon
  - Radiation hard to 10^15 n /cm^2



Read out Chips for Silicon

- Individual Cells signal the column level controller that they have been hit
- The controller sends a token up and down the double column
  - Only hit cells receive the token
  - When a cell receives a token it sends its address and hit date to the column controller where it is stored in a buffer
- When a Level 1 Trigger is received, the data are removed from the column buffers



Data rates in the CMS pixel detector

Note factor 10

Radius [cm]	4	7	11
Luminosity $[10^{34}]$	0.1	1.0	1.0
Pixel hit rate [kHz]	7.6	13.0	6.9
Double column hit rate (2×53 pixels) [MHz]	0.47	0.77	0.44
Average number of hit pixels in a hit column	1.9	1.9	1.7
Readout chip hit rate (26 double columns) [MHz]	6.5	11	7.6
Average number of hit pixels in a hit chip	3.3	3.5	2.6
Barrel module hit rate (16 chips) [MHz]	36	40	38
Average number of hit pixels in a hit module	9.3	15	8.1
Pixel occupancy $[10^{-4}]$	1.9	3.3	1.7

Pixels are mostly empty
But still need to
process Millions of

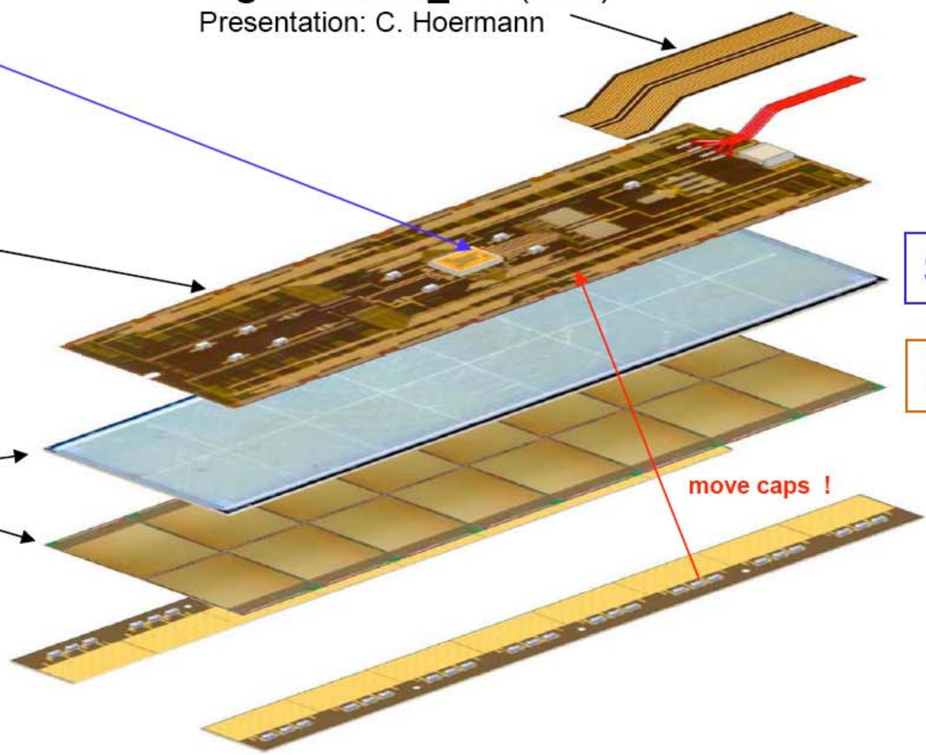
Assembly of a Pixel Module

Fabrication of modules with various glueing steps in assembly line (→ Talk: S. König)

TBM_V5 (final)
Presentation E. Bartz
Submission 9 Mai 05

Signal Cable_V3 (final)
Presentation: C. Hoermann

HDI_V3.1 (final)
Presentation C. Hoermann
Fabrication preseries (10%)
done by June 04



Sensor

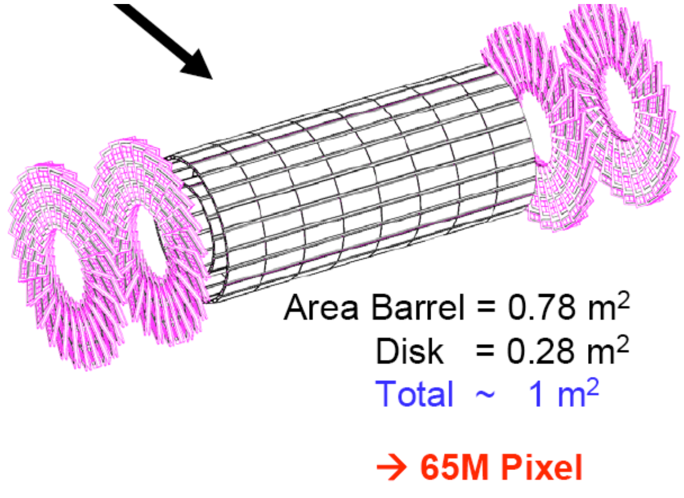
ROC

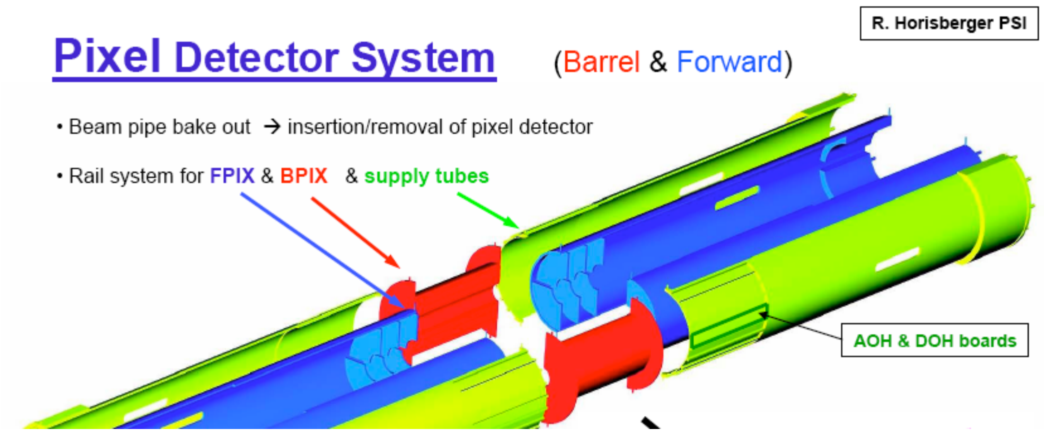
Bump bonding
at PSI, capacity now
3-4 modules /day
Presentation: H. Kästli

Si_3N_4 baseplate
move **caps** to HDI
simpler fabrication
150 substrates ordered
4” diameter, 250μ thick → delivery week 29

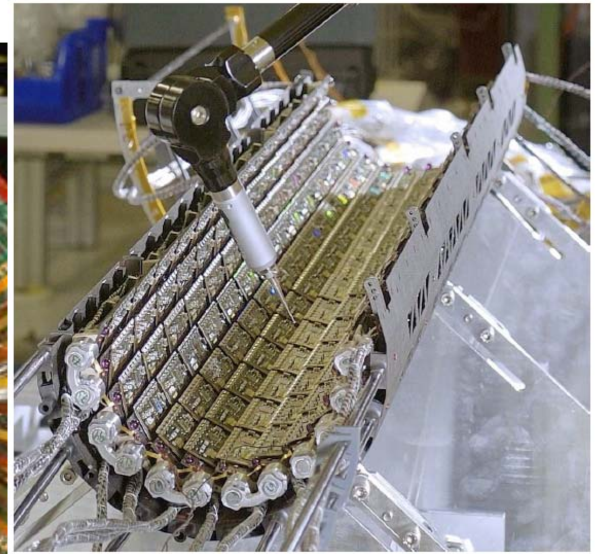
Pixel Detector

- Innermost tracking detector of CMS
  - 3 Barrel rings
  - 2 End disks
- Must withstand highest radiation doses/fluence
- Designed to be removed annually
- Largest number of channels in any CM detector



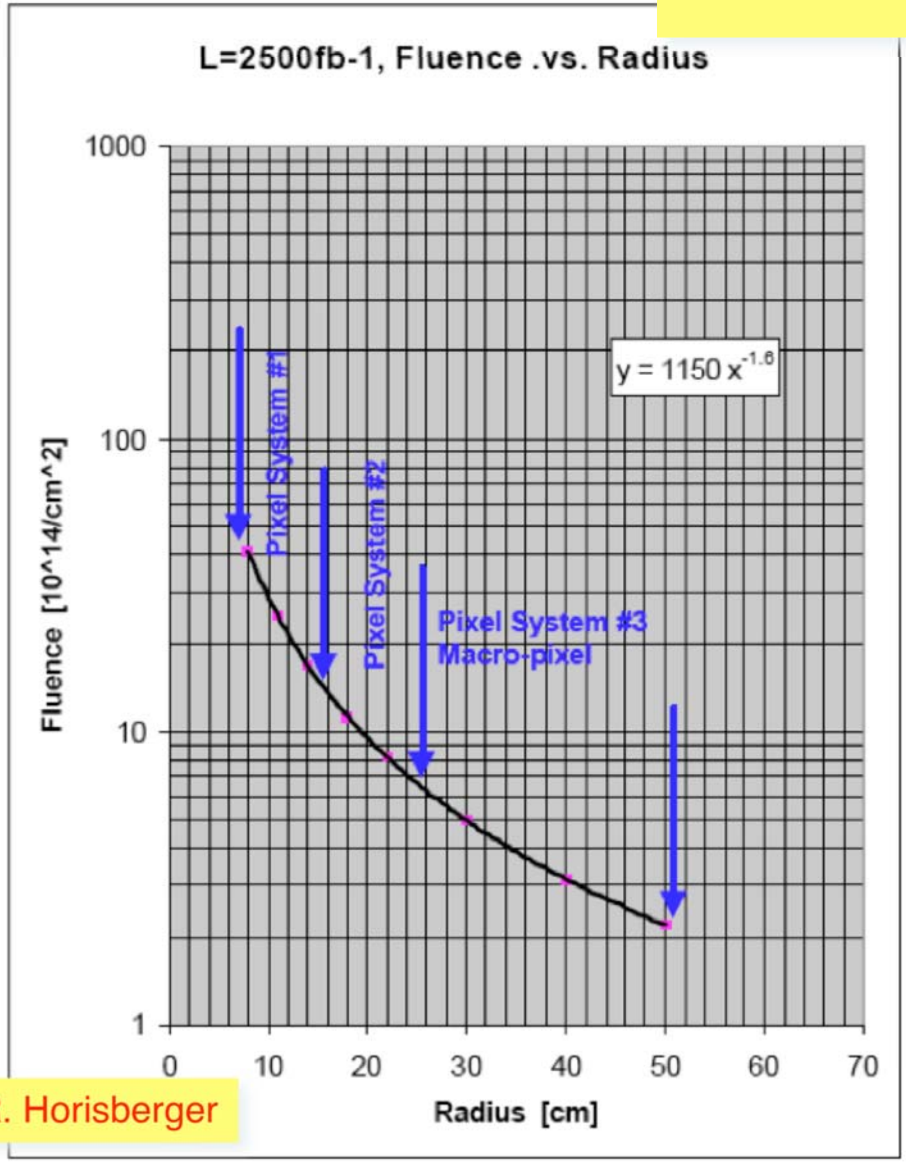


ATLAS and CMS Pixel Detectors

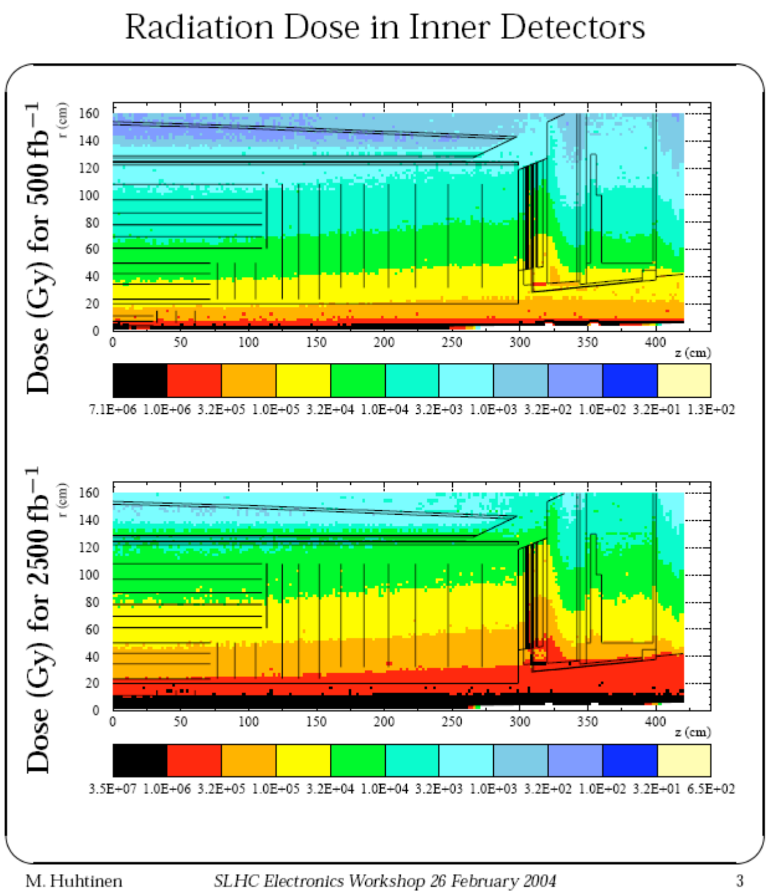


Radiation environment for trackers

Except for the very innermost layers many current technologies should survive SLHC

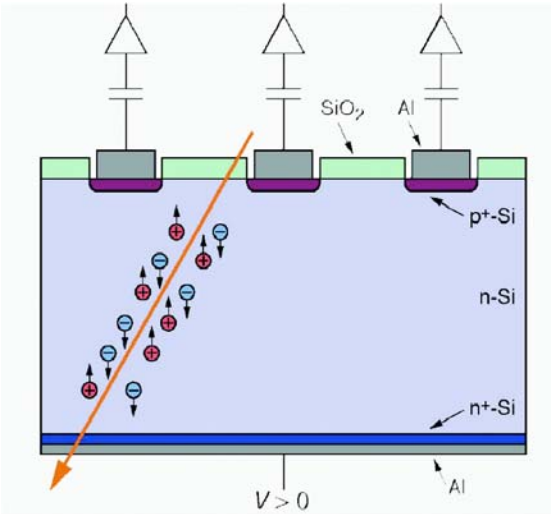


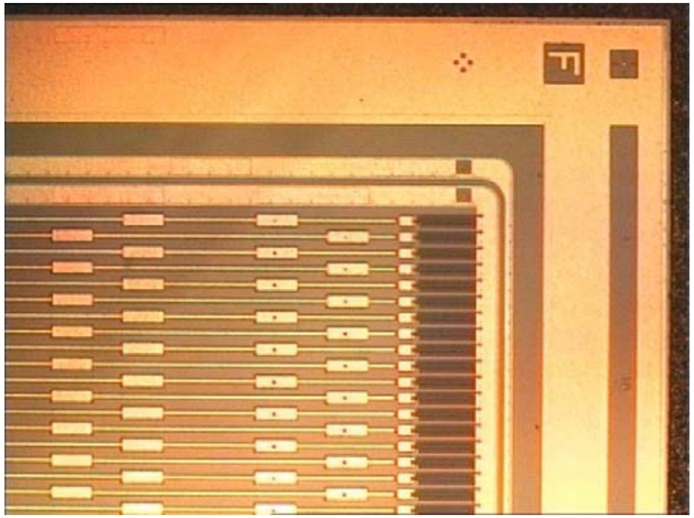
R. Horisberger



Silicon strip detectors

- Can't build an infinitely large pixel detector
  - Too many channels
  - Too expensive!
- Strip detectors can cover a larger area with less readout channels
  - Strips are placed separated by ~100μm
    - Metal of strip ~15μm
  - They are typically around 10cm long
  - Only a 2D resolution possible
    - Some 3D possible with "Stereo" layers

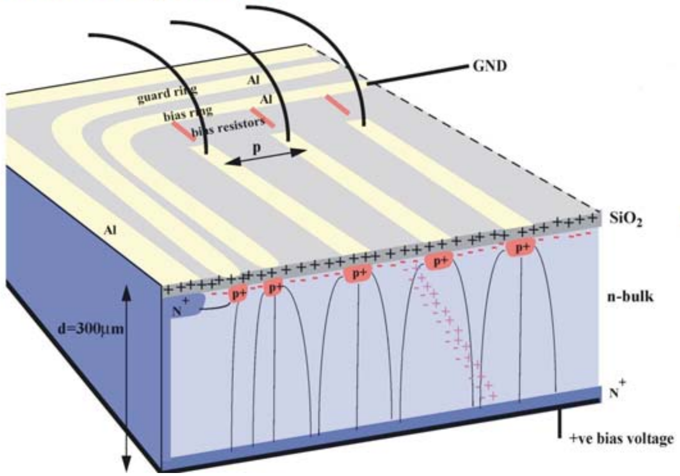


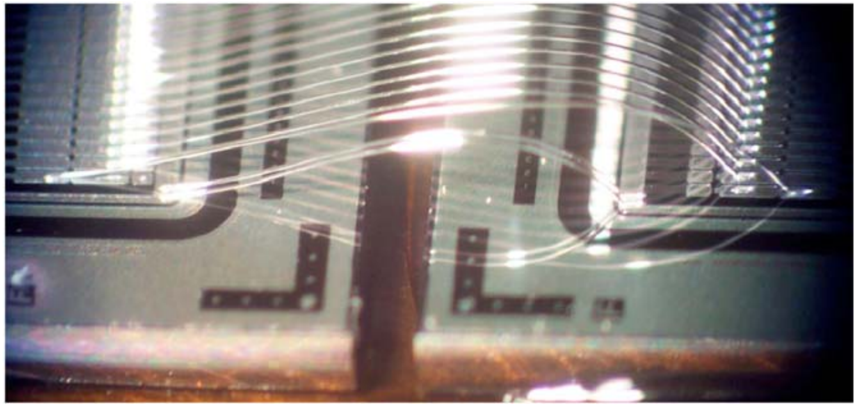


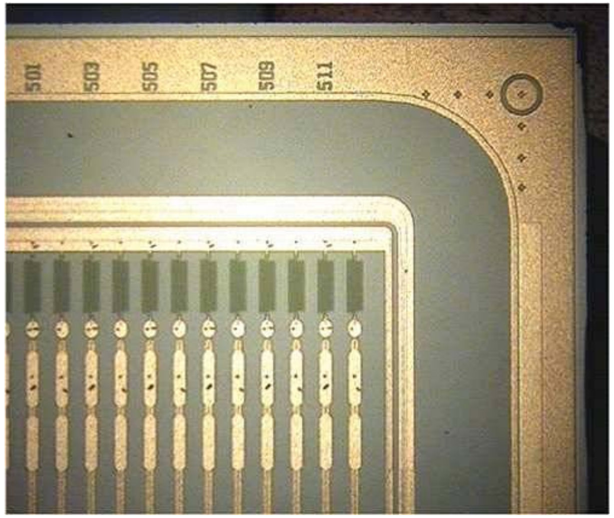
Connecting to the readout

- Connections to Silicon strips is done with ultrasonic wire-bonding
- This is a standard industry practice
  - Repairs can be made for badly made bonds
- Much easier to produce a detector that covers a large surface area

Sensor Design Baseline

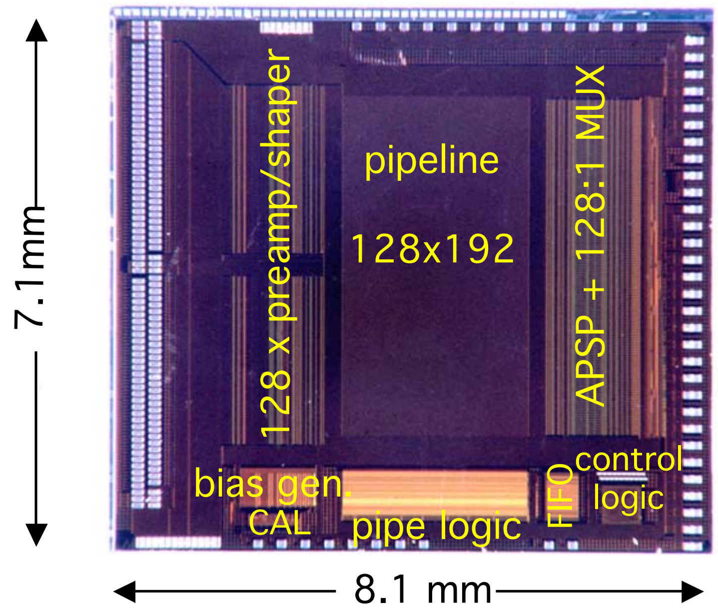


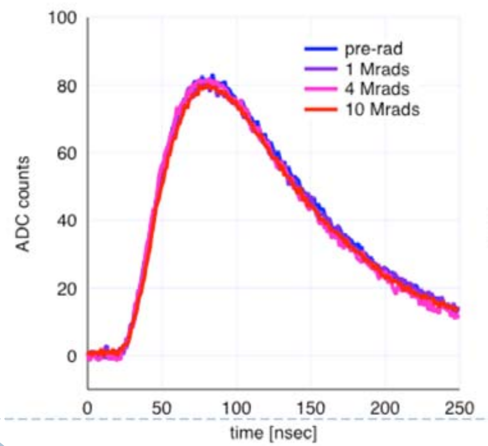


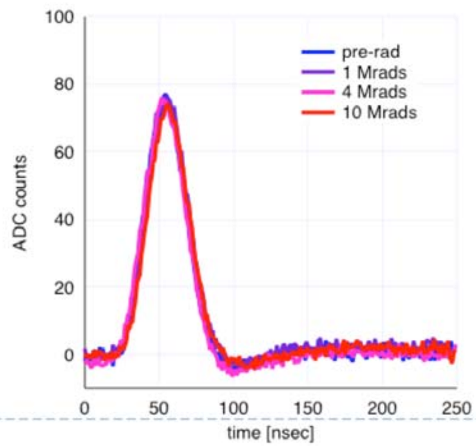


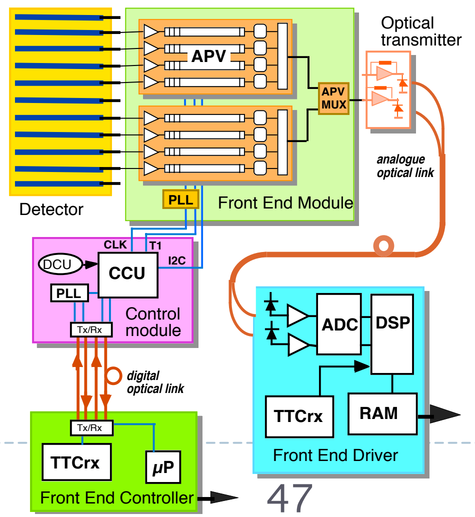
Readout electroncs

- Readout example APV25
  - One chip reads 128 strips
- Fast signal shaping
  - Sampled signal stored in a pipeline
- Pipeline takes up much of the chip – recall Nick’s lectures
  - Determines CMS Maximum level 1 latency
  - When a Level 1 Trigger arrives the data from all 128 strips are shipped out



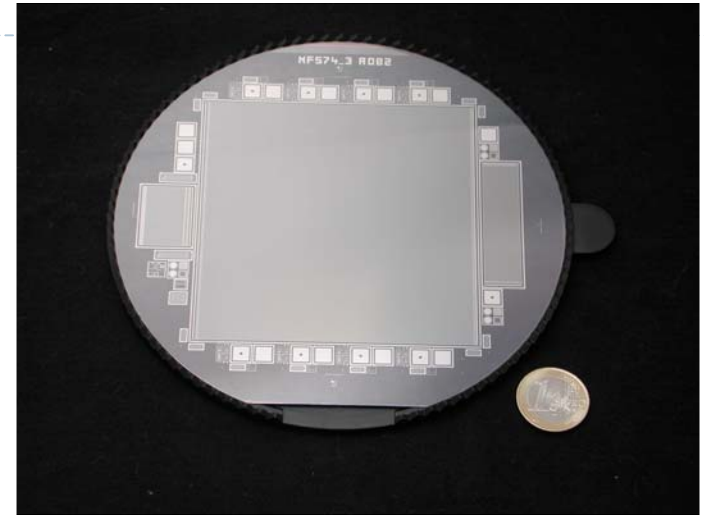


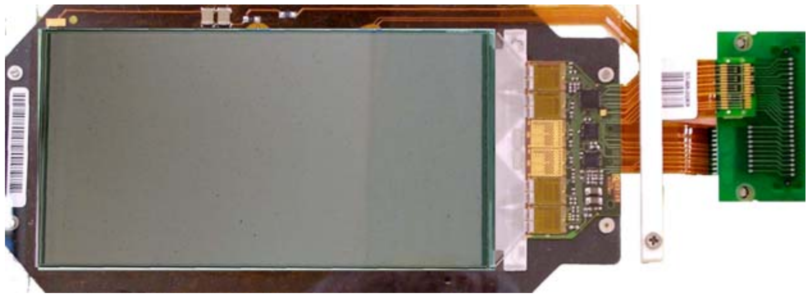




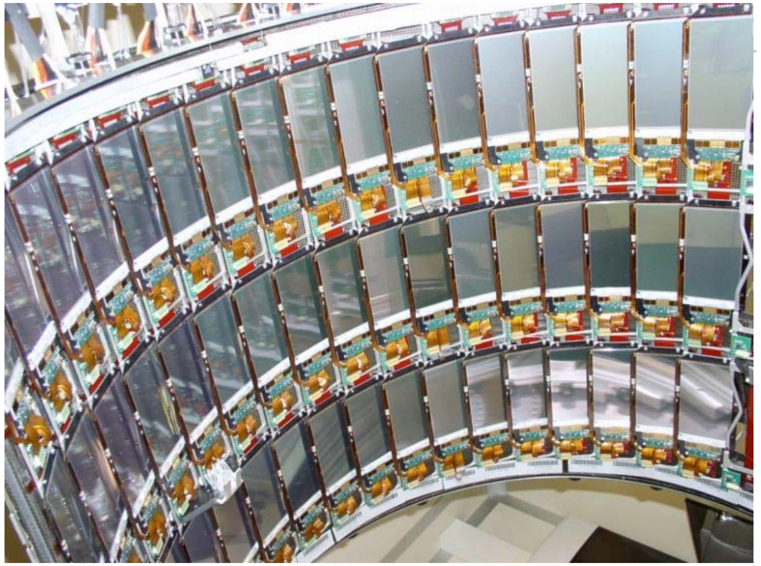
Building Silicon Modules

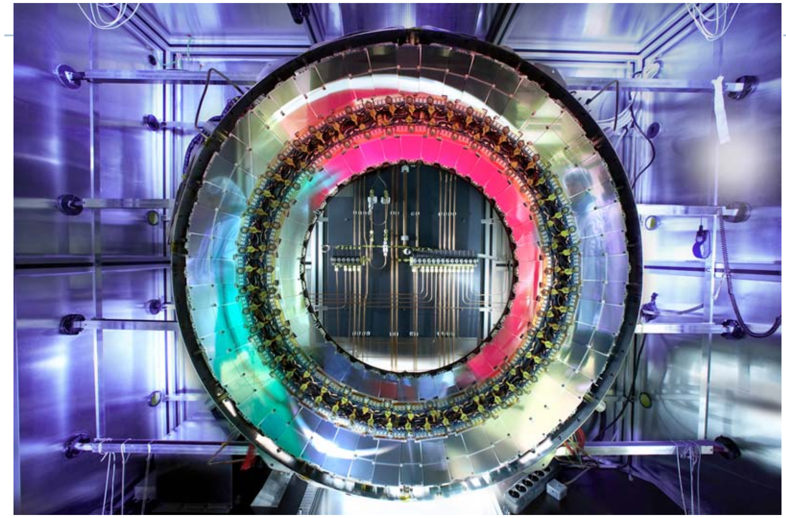
- Silicon Wafers are produced with strips on them
- Hybrids with readout chips and connections for power, readout are wire bonded to the strips
- A huge number and variety of these modules was require to build the LHC Silicon Strip detectors
  - CMS 16,000 Modules
  - 10,000,000 Strips

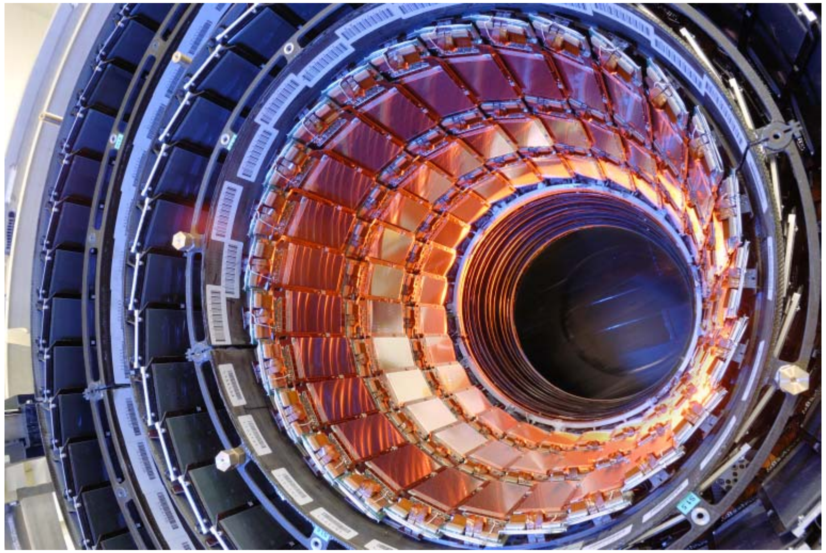


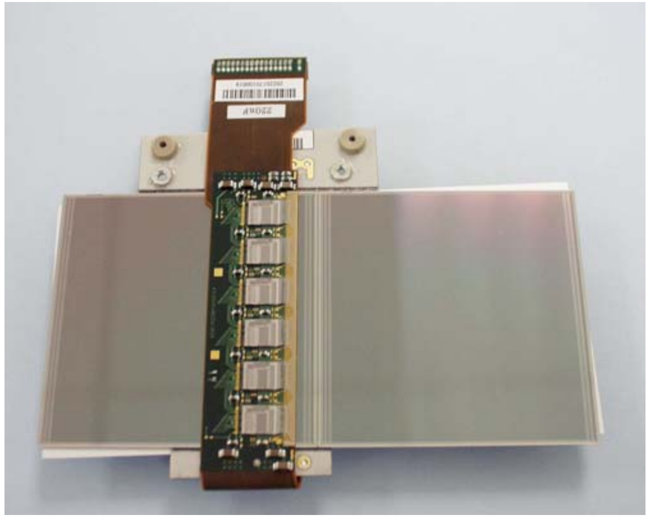


Building full size trackers



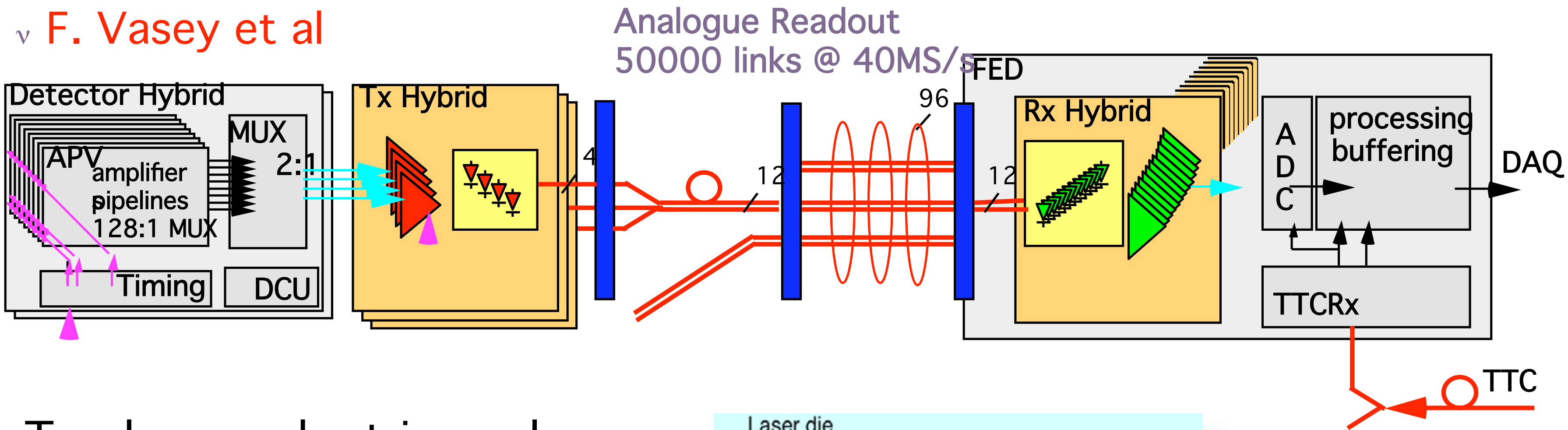




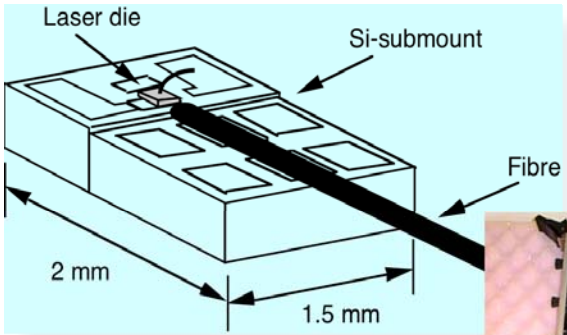


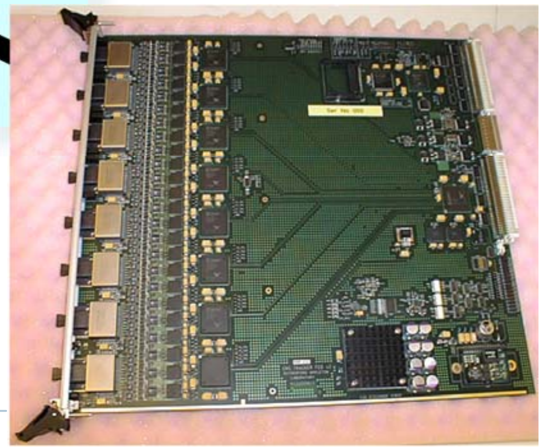
Tracker Readout

- F. Vasey et al

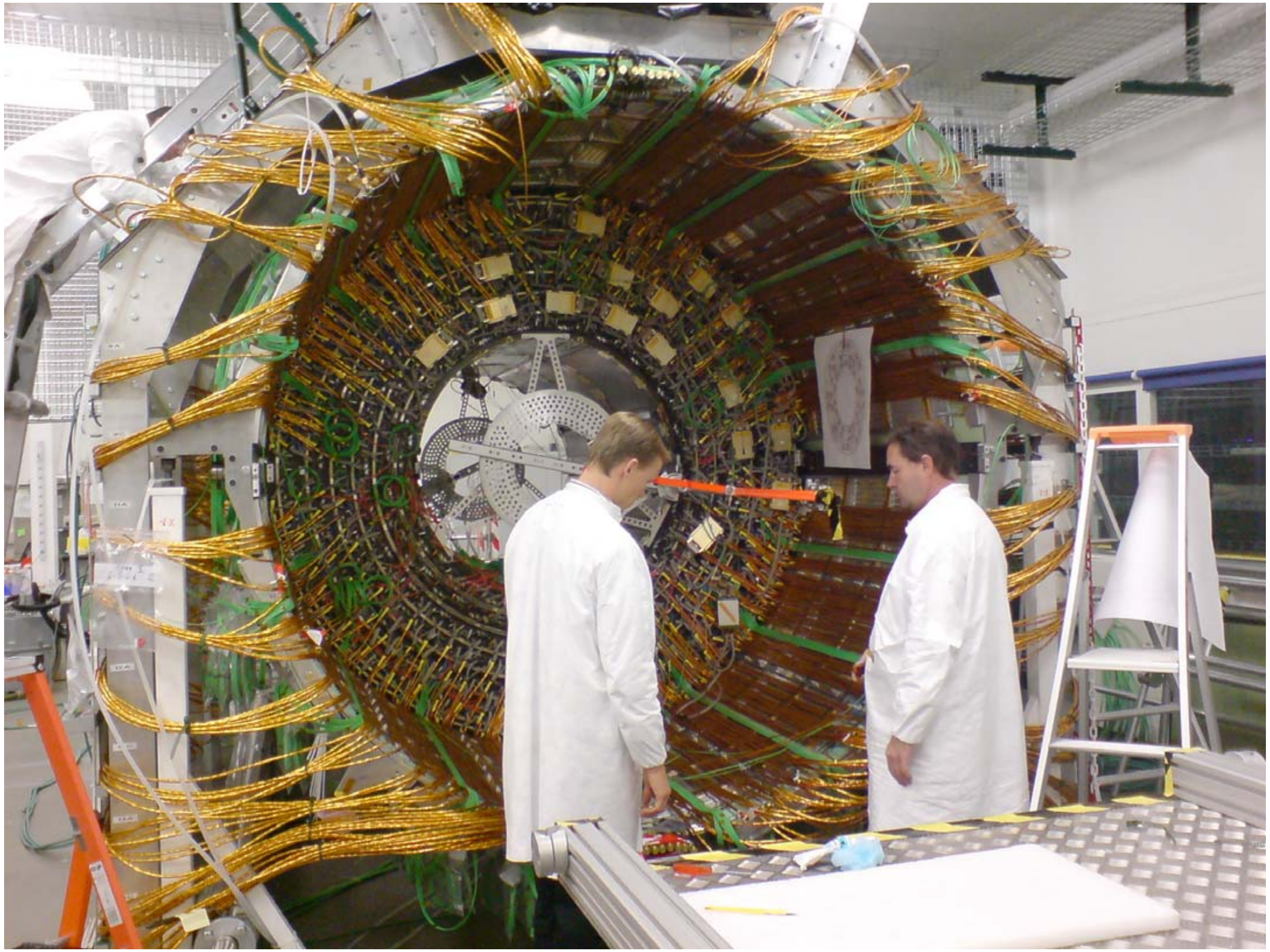


- Tracker readout is analogue signal from APV sent over optical fibre
- Edge emitting 1.3μm InGaAsP MQW laser diodes
  - single mode fibre ~50mW/256 detector channels
  - 50,000 optical links for tracker
- Analogue signal is digitized in off detector electroncis (FED)
  - Around 500 FEDs required



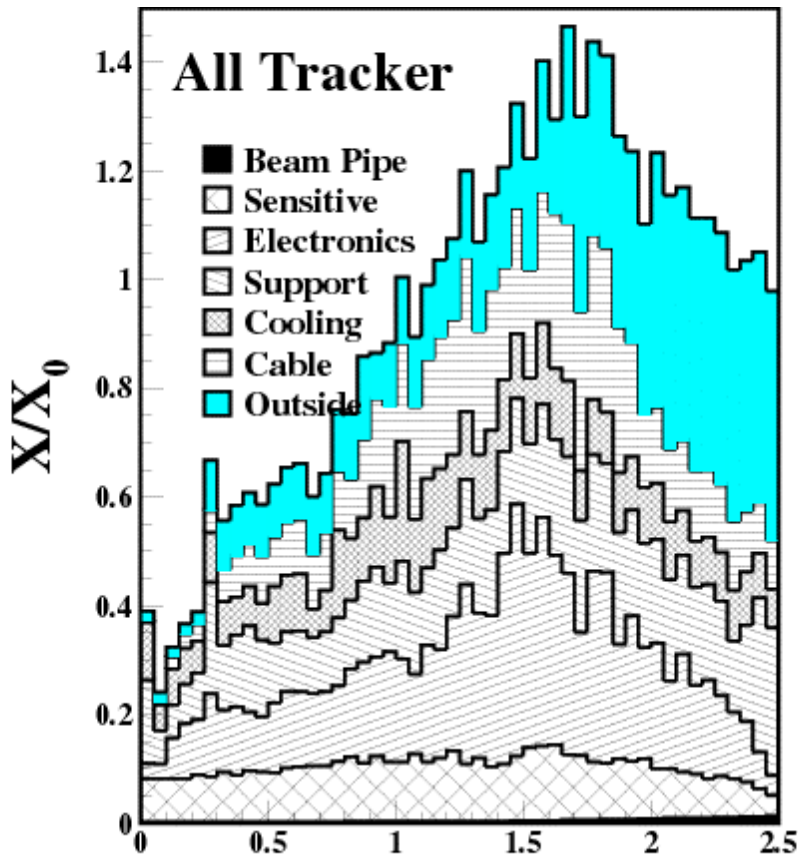


Full size tracker – a lot of cables!



Tracker Material

- Although the tracker is made of silicon, there is a large amount of material required for the electronics
  - Sensors
  - Support
  - Cooling
  - Power Cables
- Minimizing this was a big task, and taking this a step further would be a big goal of any upgraded tracker
- Consider how many photons produced convert before they escape the volume of the tracking devices
  - Electrons also will have a high probability of losing energy via Bremsstrahlung

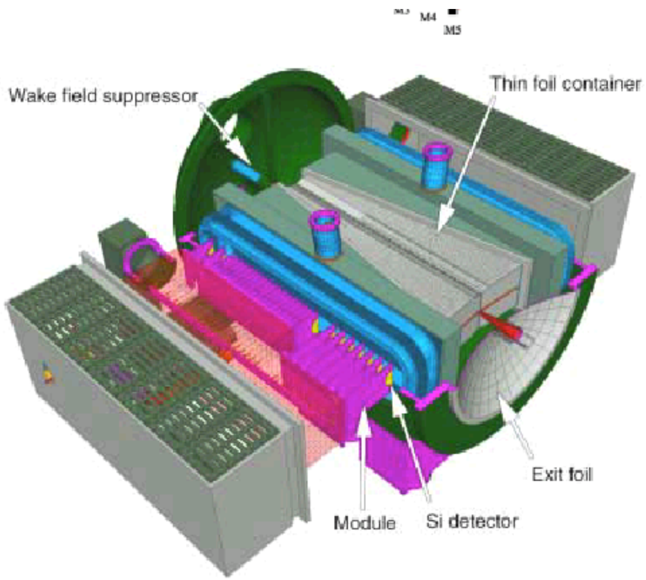


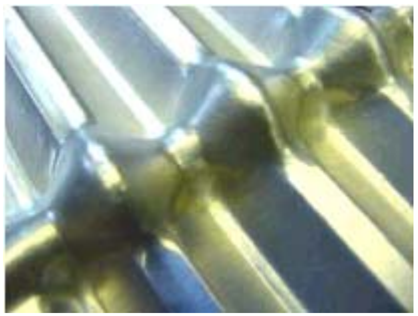
Intrinsic performance of tracking

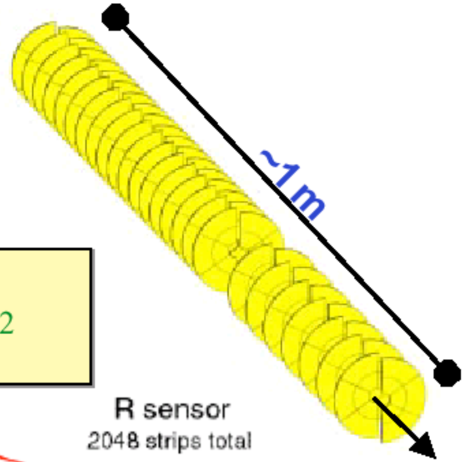
Item	Intrinsic accuracy (μm)	Alignment tolerances (μm)		
		Radial (R)	Axial (z)	Azimuth (R-ϕ)
Pixel				
Layer-0	10 (R-ϕ) 115 (z)	10	20	7
Layer-1 and -2	10 (R-ϕ) 115 (z)	20	20	7
Disks	10 (R-ϕ) 115 (R)	20	100	7
SCT				
Barrel	17 (R-ϕ) 580 (z)[1]	100	50	12
Disks	17 (R-ϕ) 580 (R)[1]	50	200	12

- Pixels give the most detailed information
  - Including the best information in Z (Along the beam line)
- The 2D strip detectors give some Z information when they are read out in stereo pairs
  - Two parallel layers back to back with a small angle between them
  - correlation between the hit strips can determine where the particle went through the detector in Z
- Intrinsic position resolution is very good on a single Silicon module
  - Silicon is very precisely manufactured
- However all the individual modules need to be aligned with respect to each other in order to have a global understanding of where the particles have travelled
  - See Andreas' talk

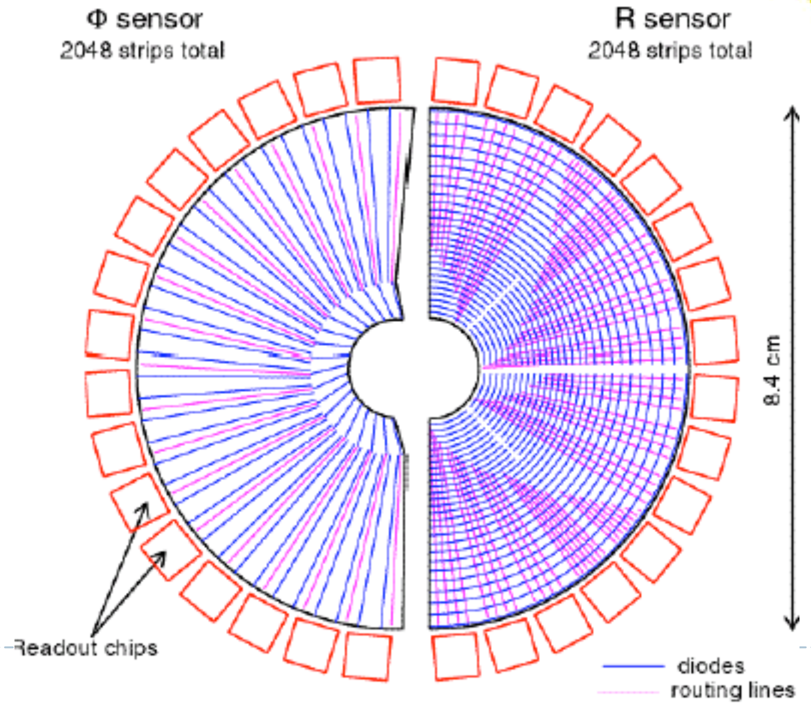
LHCb
Vertex Detector - VELO



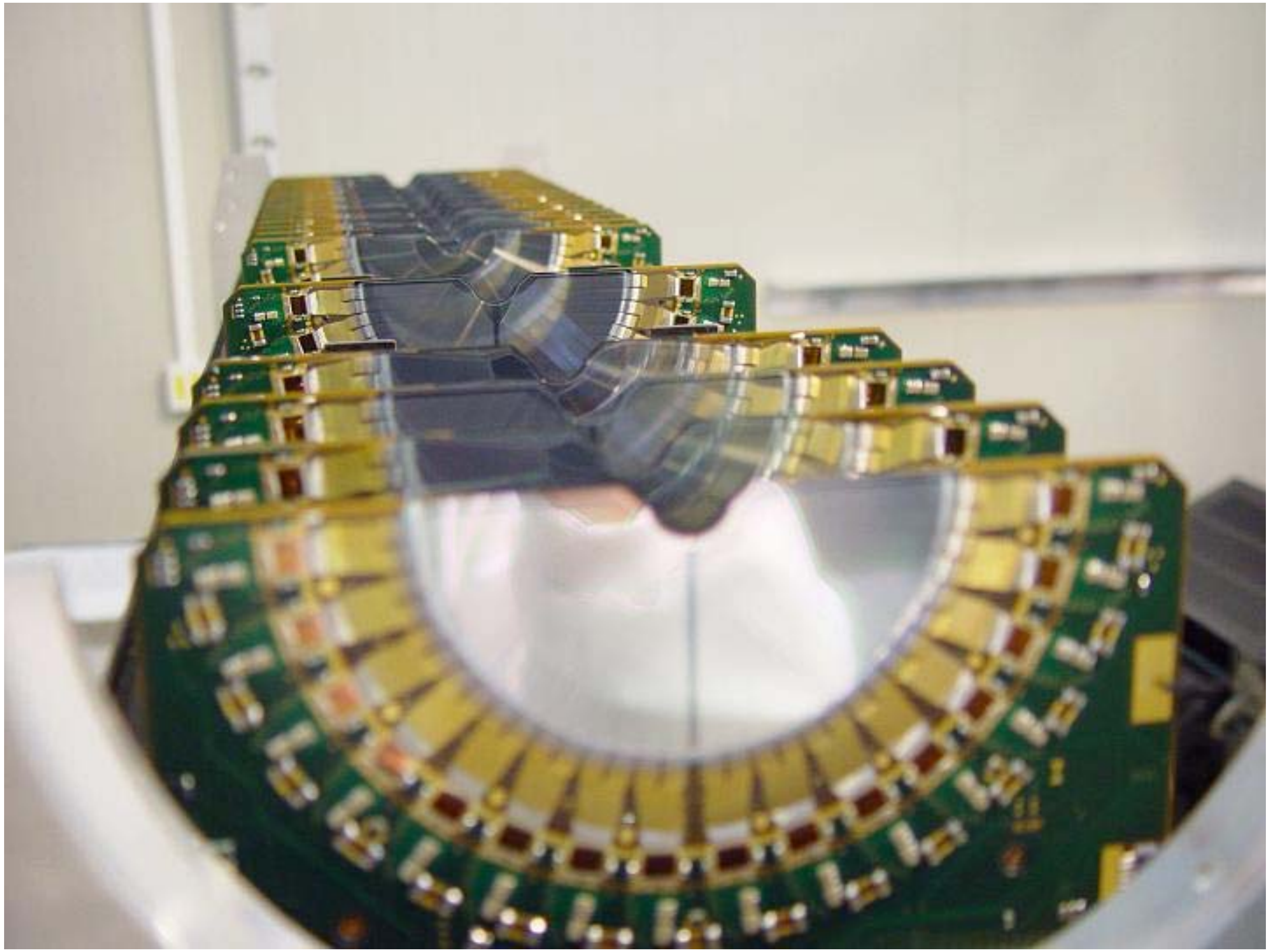




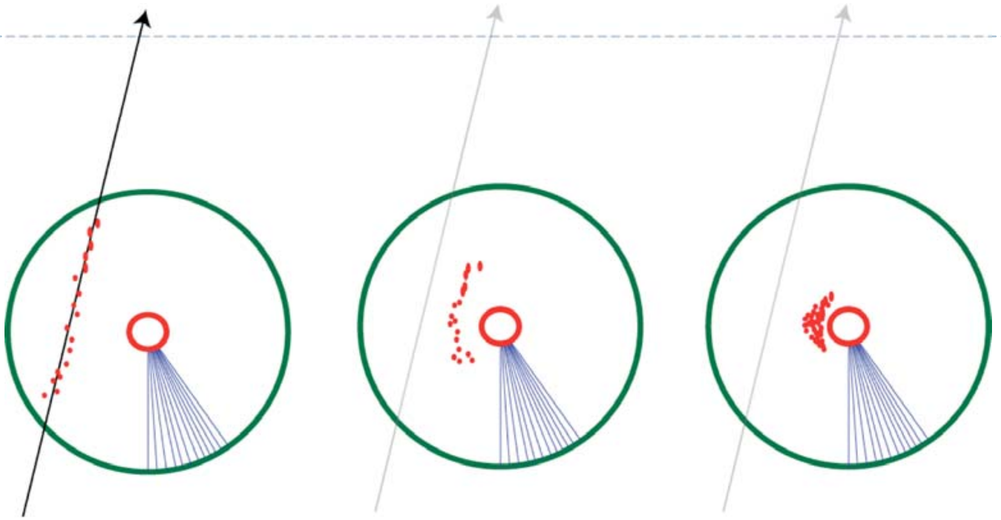
Number of silicon sensors: 100
Area of silicon: $0.32 m^2$
Number of channels: 204,800



Velo



Wire chambers and Avalanches



Chamber consists of an inner wire held at a positive Voltage (anode) of radius a, and outer cylinder (cathode) of radius b which is filled with gas

Charged particle passes through gas ionizing gas molecules

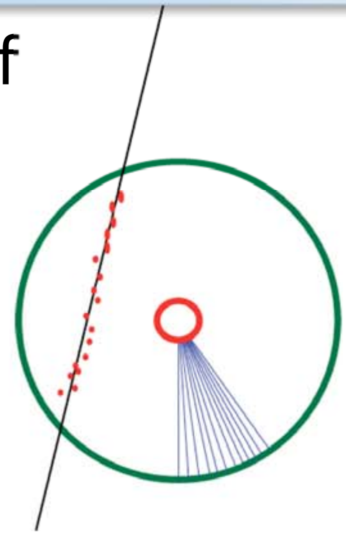
Electrons drift towards the central wire (anode) along the

The electric field value gets very high near the anode – drifting electrons create more ionization. This causes an *Amplification* of

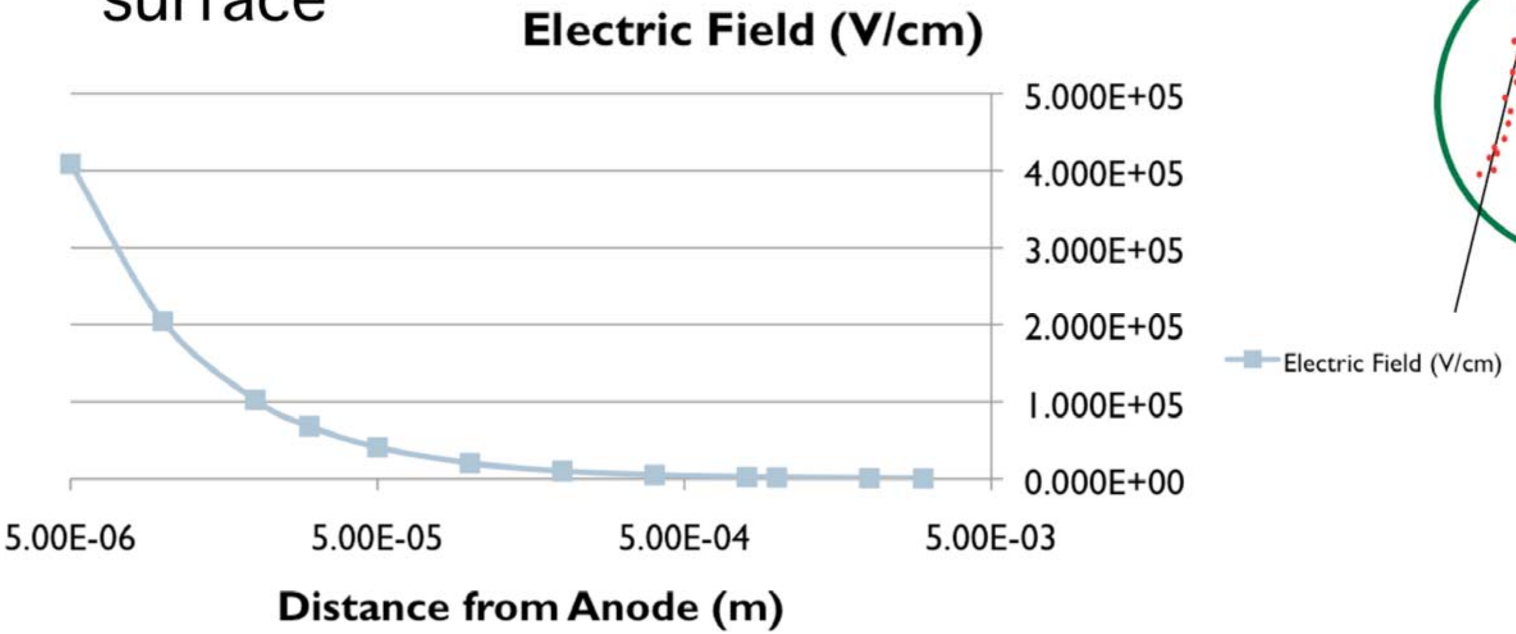
Electric Field

$$E(r) = \frac{\lambda}{2\pi\varepsilon_0}\frac{1}{r} = \frac{V_0}{\ln\frac{b}{a}}\frac{1}{r}, \qquad V(r) = \frac{V_0}{\ln\frac{b}{a}}\ln\frac{r}{a},$$

Wire of radius a
outer cylinder of
radius b



- For a wire with radius 30μm in a cylinder of 4mm fields reach 400Kv/cm near the wire surface

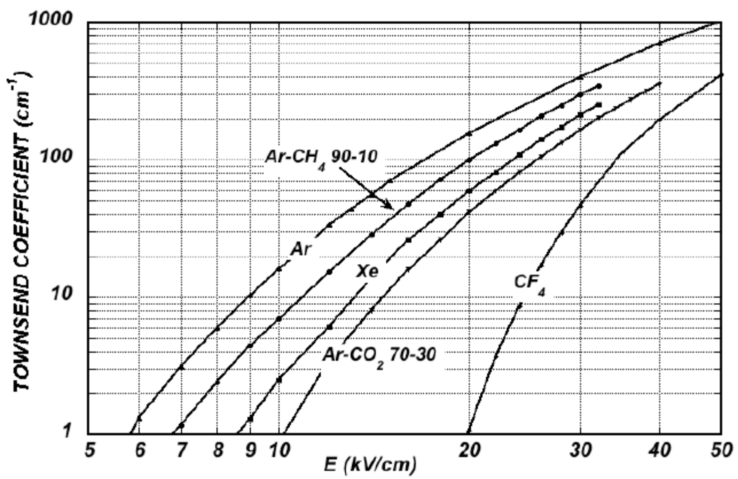


Avalanche Characteristics

- As the electrons approach the anode, the field grows very rapidly
- Electrons create more electrons by collision with a mean free path which gets shorter as the electrons approach the anode and the Electric field grows
- Townsend coefficient estimates the mean free path as a function of field (or radius)
- Can calculate the Multiplication factor
  - The number of electrons reaching the anode compared to how many were produced in the initial ionization

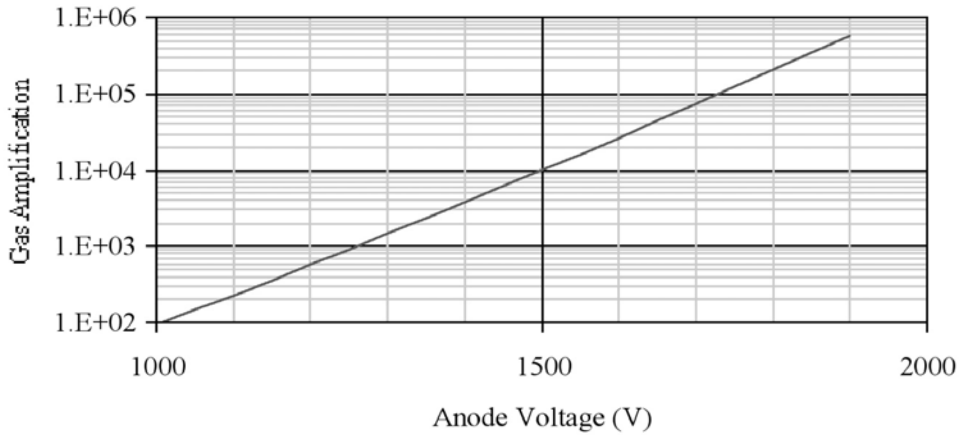
Avalanche Multiplication Factor

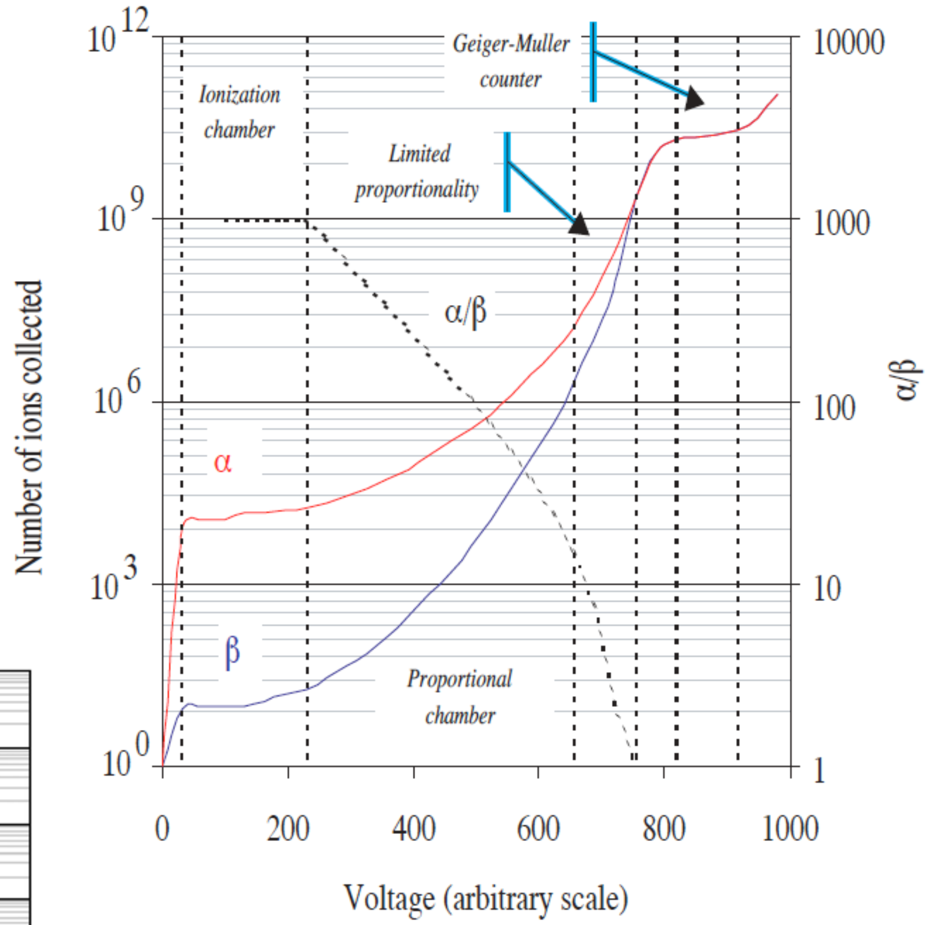
$$1/\alpha \equiv \text{ mean free path}$$
$$n_0 = \text{ number of electrons}$$
$$dn = n\alpha dr$$
$$n = n_0 e^{\alpha r}$$
$$M = n/n_0$$
$$M = e^{\int_a^r \alpha(r)\,dr}$$



Avalanche Modes

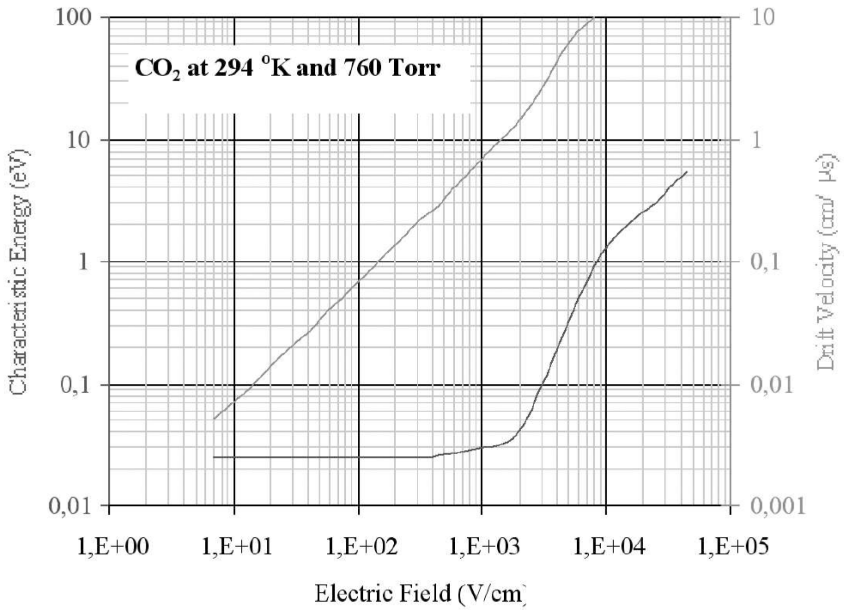
- Wire chambers can operate at many different gas gains
  - Proportional mode M = 10^3-10^4 –
  - the number of ions measured is proportional to the ionization
- Up to Geiger mode
  - $M=10^9$
  - Avalanches propagated by products of initial avalanche
  - No relation of the signal to the primary ionization

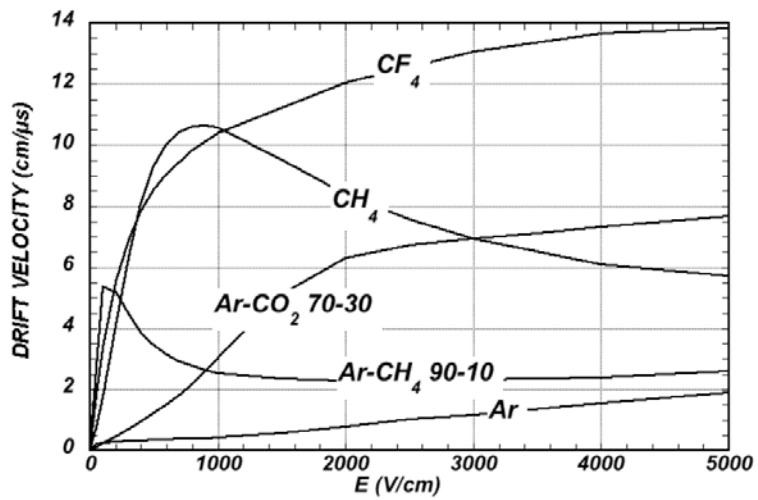




Drift Velocity

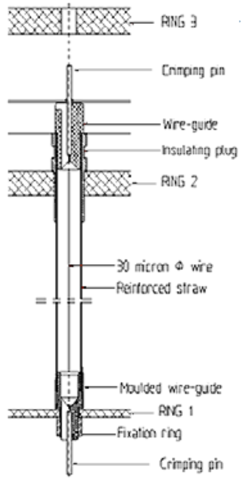
- Electrons undergo many collisions and drift at a relatively slow velocity towards the anode
  - *Drift Velocity (top curve)*
- The electron *characteristic energy* (bottom curve) stays well below ionization energies up to a certain threshold in field value
  - Depends on gas composition
- Look to operate wire chambers with gasses where the drift velocity is relatively stable with varying Electric field

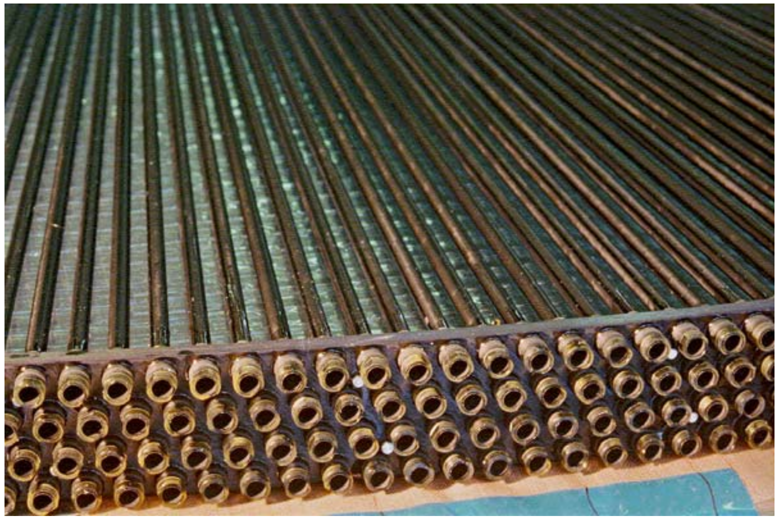




ATLAS TRT – Wires for inner detector

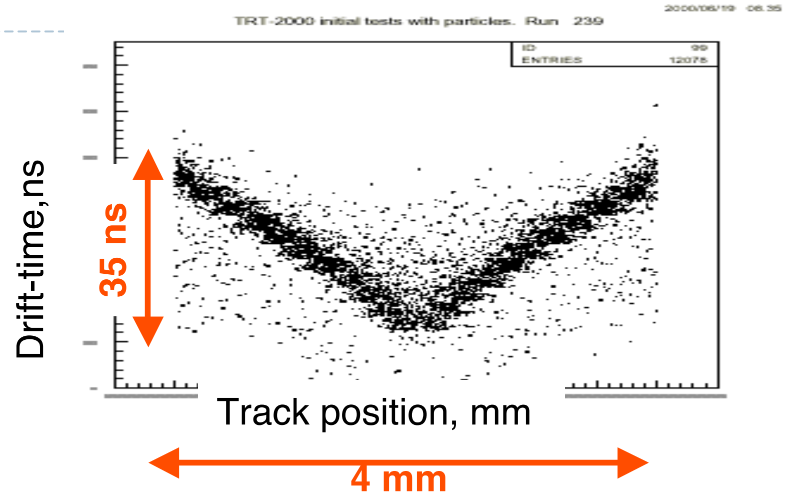
- The outer part of the ATLAS Inner Detector consists of "Straw" tubes.
- These are 4 mm diameter tubes with a 30 μm wire inside
  - Aluminium on the inside of the straw-tube covered with highly insulating Kapton
  - Stiffened with carbon fibre
- Gas gain 2×10^4
  - limited streamer mode
- All detector components designed to operate in the high radiation environment that the Inner Detector requires

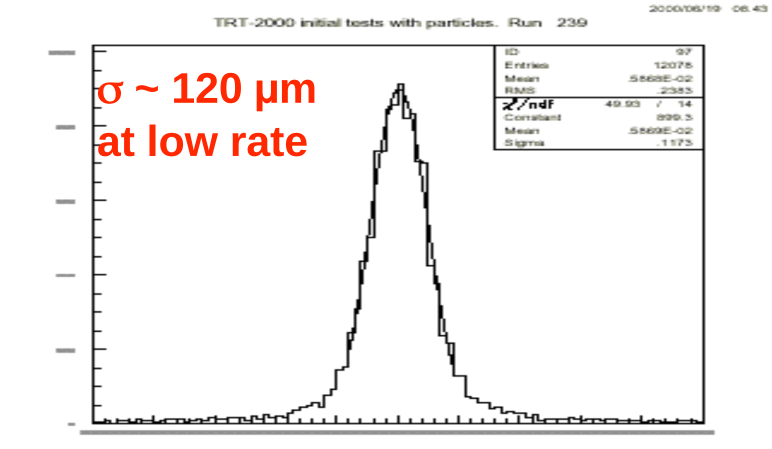




TRT performance

- Particles drift to the anode
- Drift time is quite rapid
  - Maximum drift distance is only 2mm
- Can operate at high rates
  - Up to 20 MHz
- Measuring the drift time allows us to determine the position of passage of the charged track through the straw
  - Uncertainty in the drift time gives an uncertainty in the position measured
- This detector also contains a radiator so that Transition Radiation can be detected
  - (We will discuss this when we talk about Particle Identification)

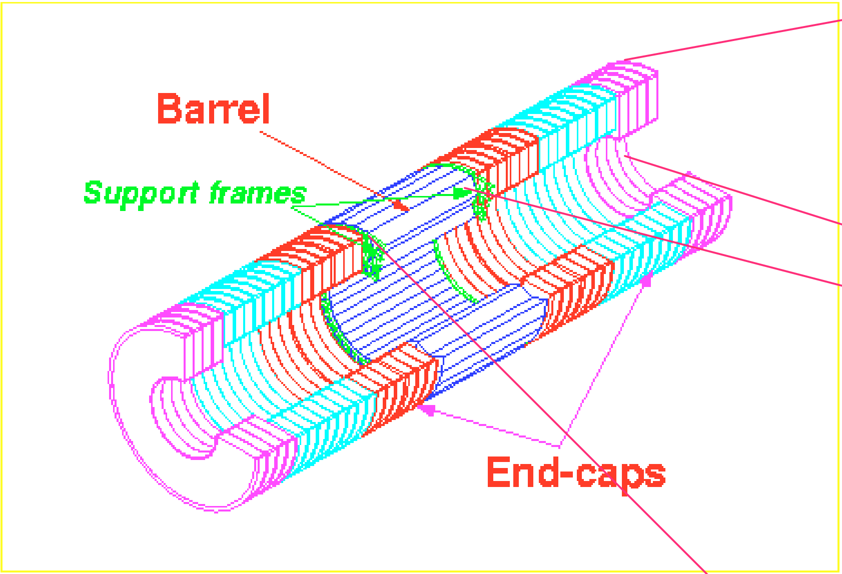


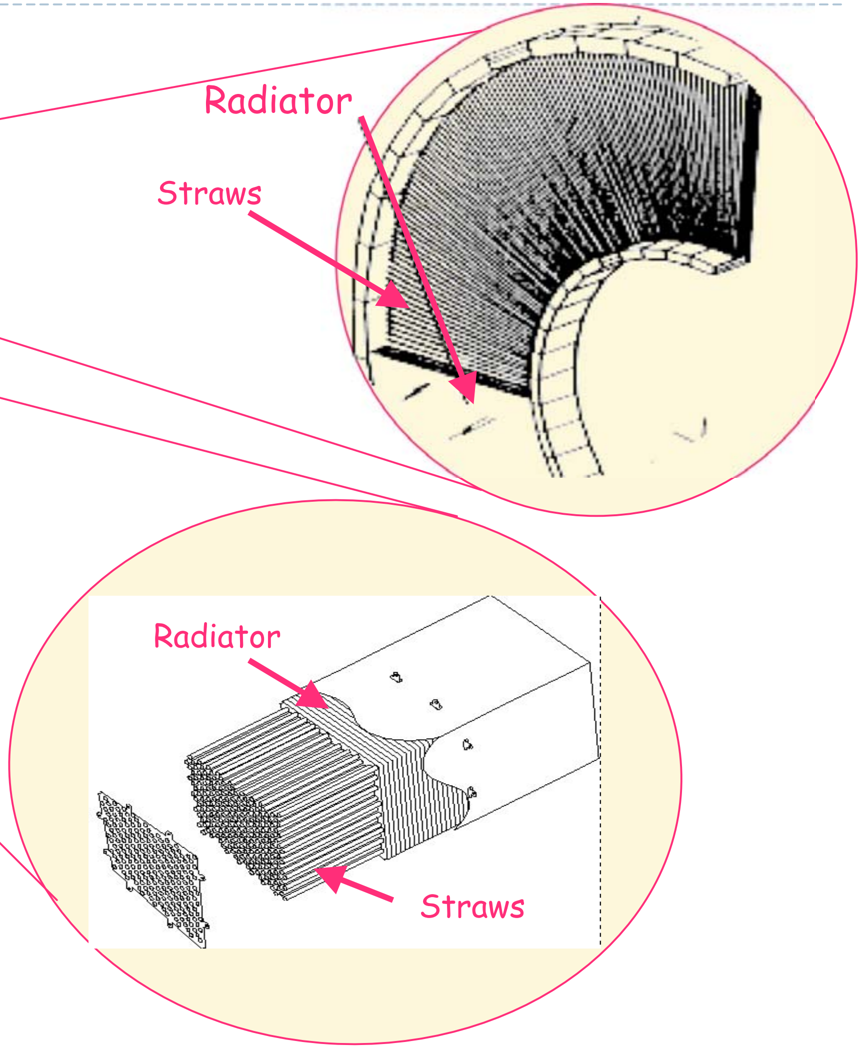


Track-to-measured position residual, mm

TRT Detector

TRT global parameters





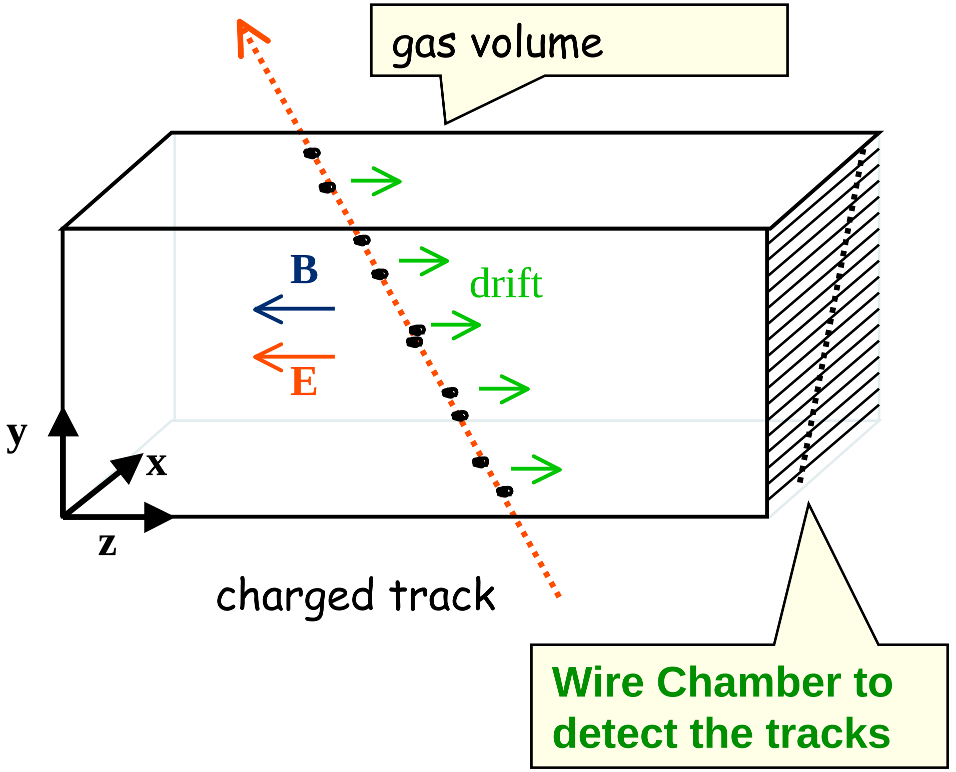
Length: Total		6802 cm
	Barrel	148 cm
	End-cap	257 cm
Outer diameter		206 cm
Inner diameter		96-128 cm

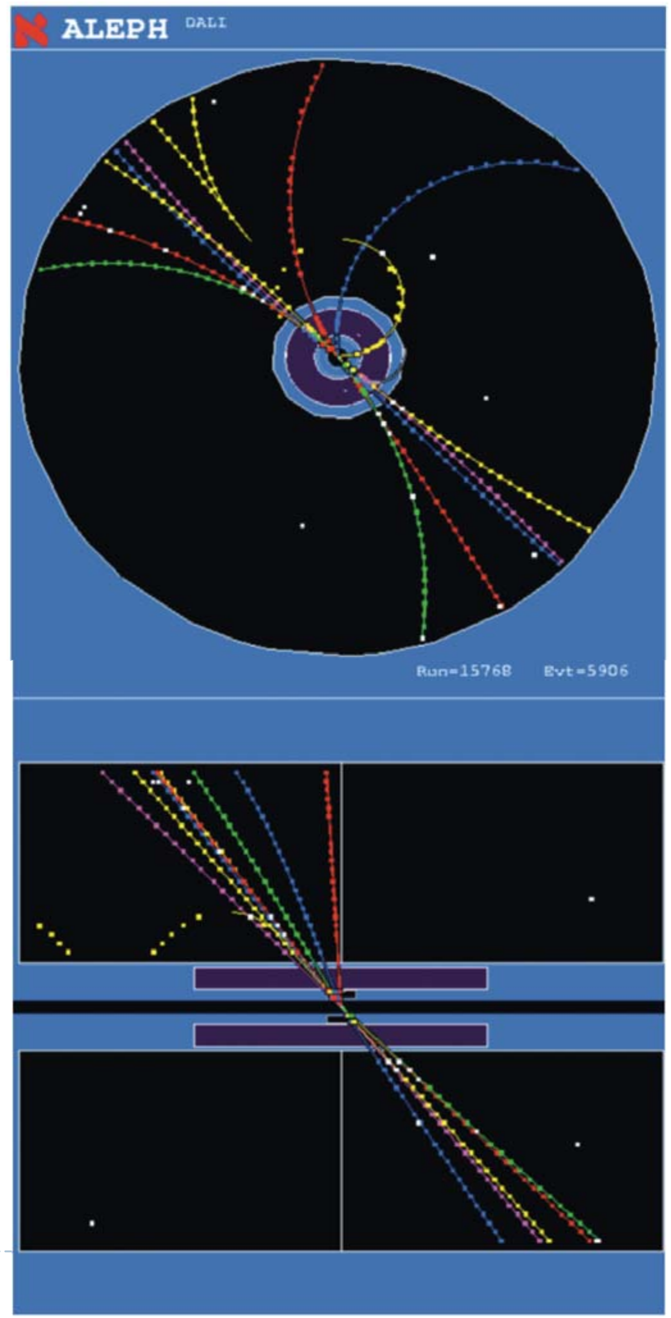
N straws: Total		372032
	Barrel	52544
	End-cap	319488
N electronics channels		424576
Weight		~ 1500 kg

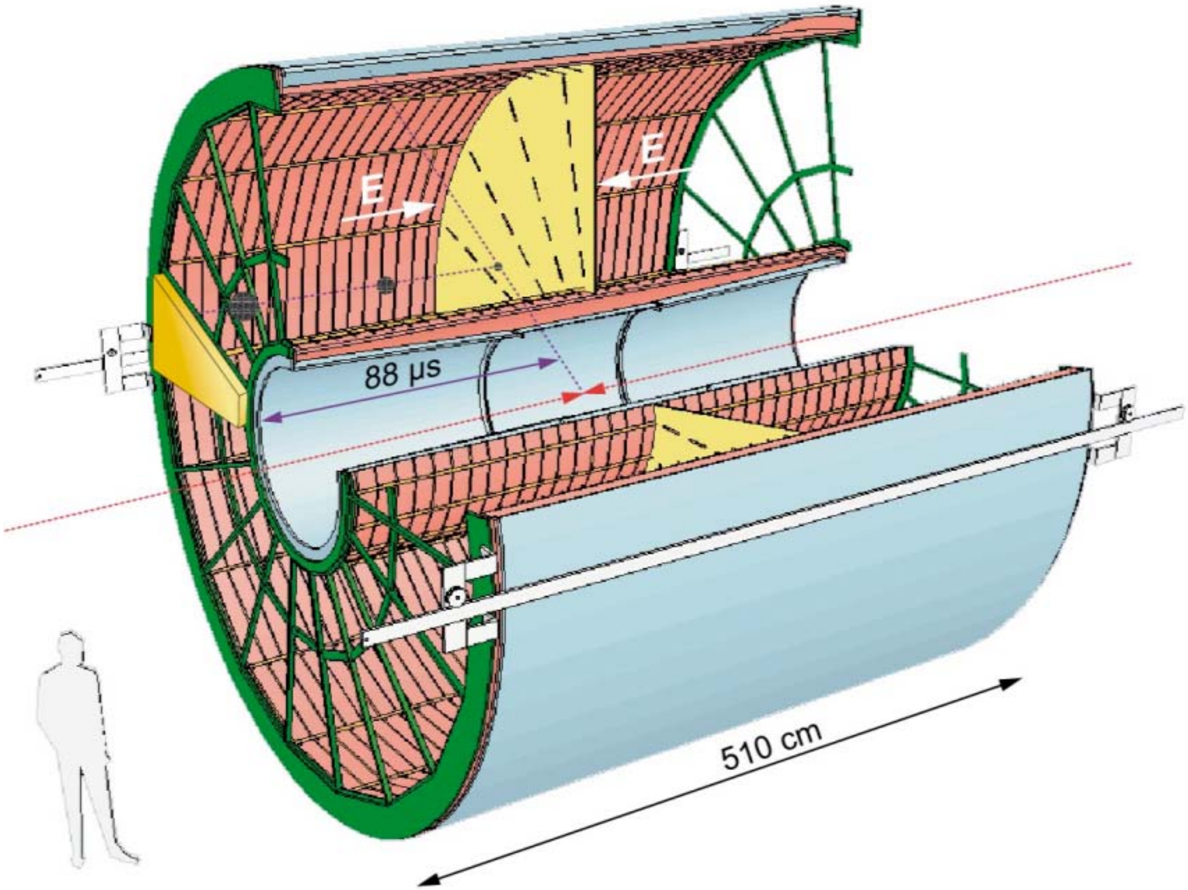
Time Projection Chamber (TPC):

Gas volume with parallel E and B Field.
B for momentum measurement. Positive effect:
Diffusion is strongly reduced by E//B (up to a factor 5).

Drift Fields 100-400V/cm. Drift times 10-100 μs.
Distance up to 2.5m !







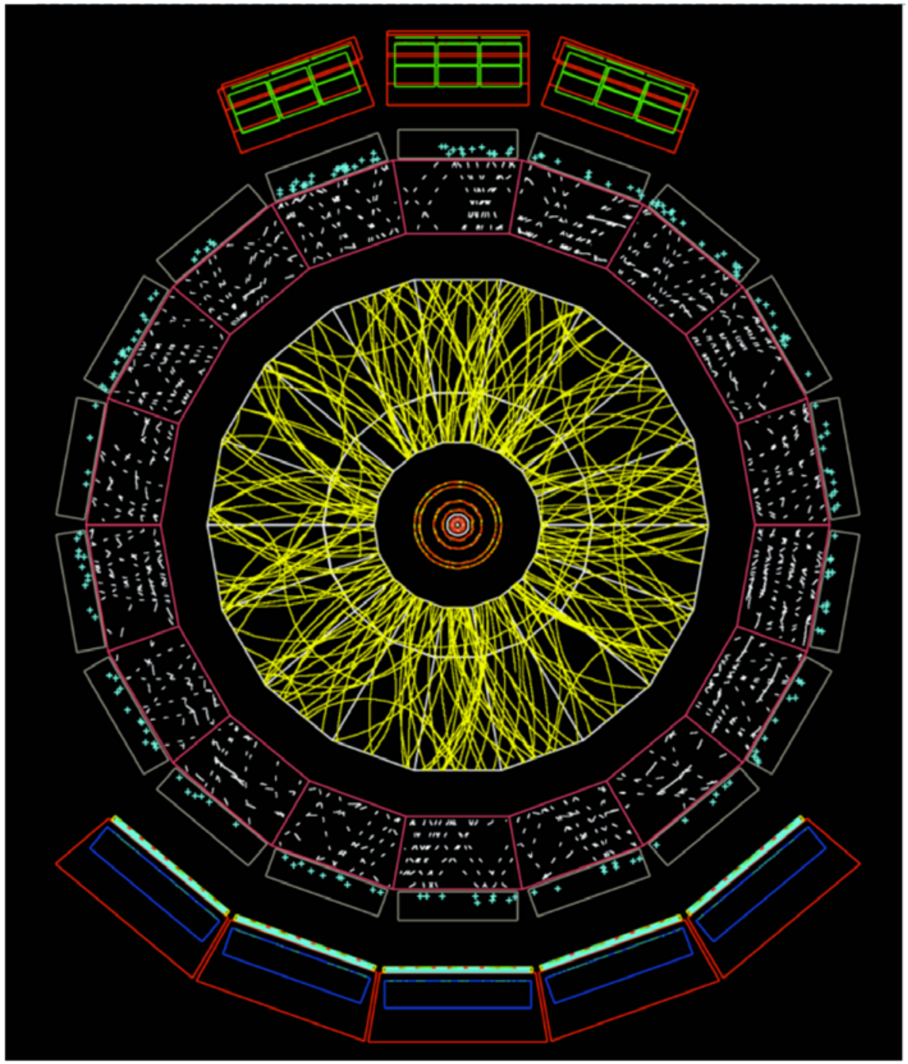
ALICE TPC

TPCs offer the advantage of very low material (only the gas inside) as well as three dimensional resolution of hits

The TPC is impractical for the GPD detectors (ATLAS and CMS) as they don't handle the high rate of interactions of the high luminosity detectors

Heavy Ion collisions have a much lower rate in ALICE and so the TPC can be used

TPC



- 100,000 V on the cathode plane in the middle of the gas volume
- 32m^2 of detectors at the ends of the TPC
  - 570,000 channels
- The TPC will have to handle up to 40,000 tracks per event

Tracking - fin

- This ends our brief tour of the inner tracking devices of the LHC detectors
- The collaborations have prepared devices that can give extremely good spatial resolution on the passage of ionizing particles
  - Attempted to keep material low to
    - Give better tracking performance
    - Avoid too much energy loss from photons/electrons
- We will come back to discuss tracking detectors when we cover Muon detectors
- Next we will discuss how we catch the neutral particles which are created as well as trying to identify electrons