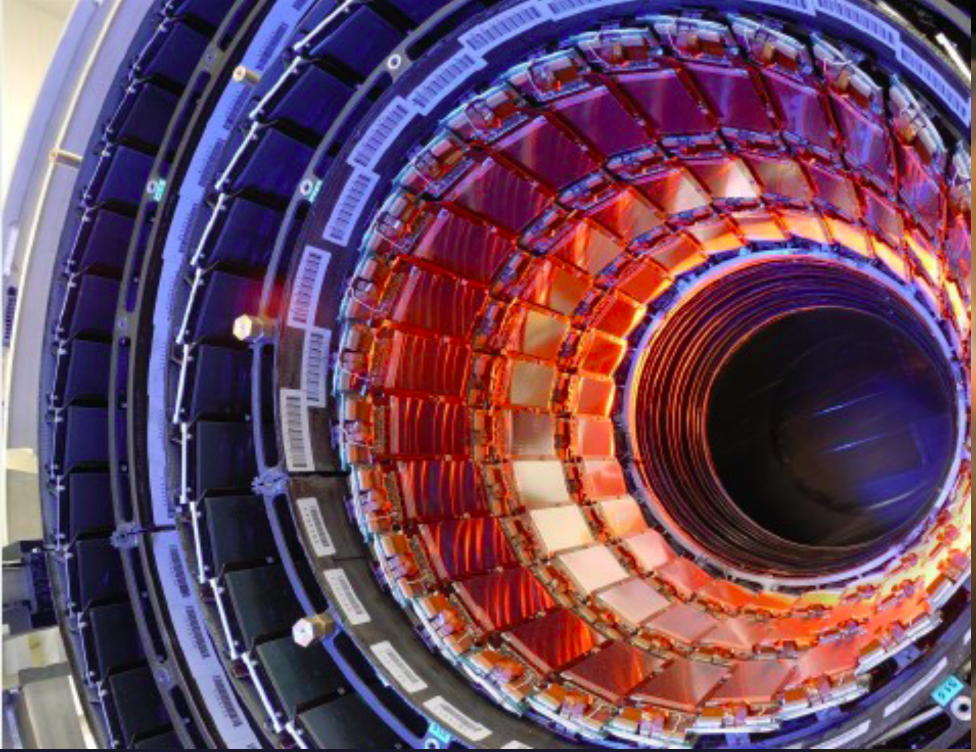
 

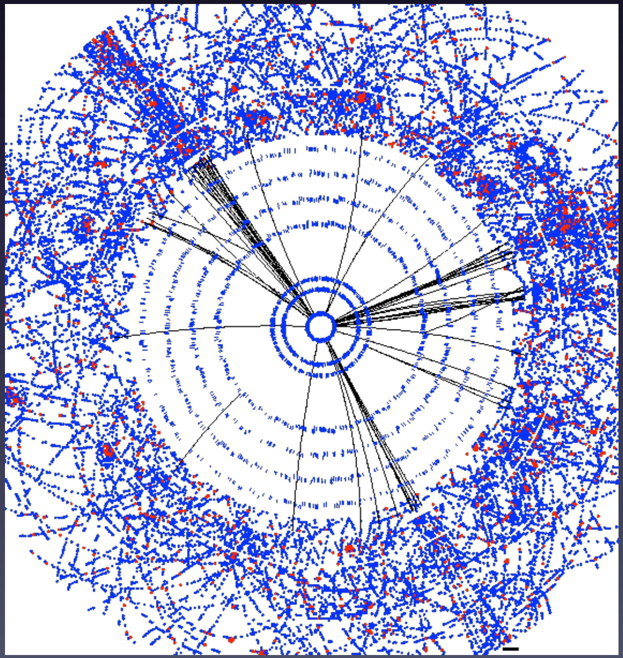
Tracking

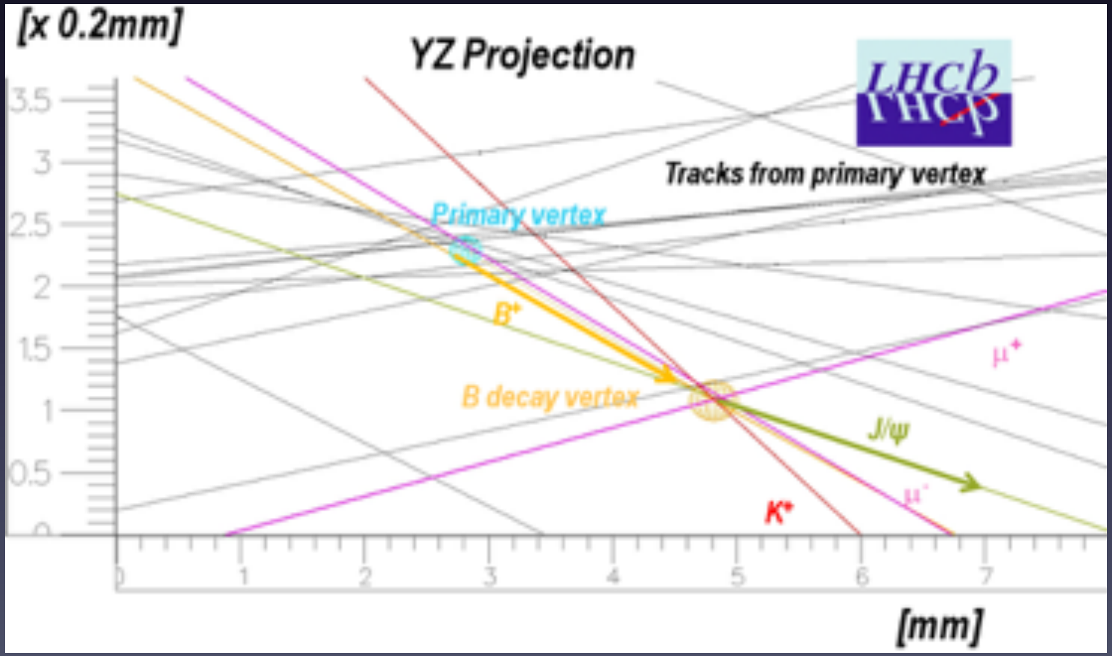
- Fundamental issues in tracking or how to design a tracker ?
- Silicon detectors
- New ideas and developments for the HL-LHC

D. Bortoletto **University of Oxford**

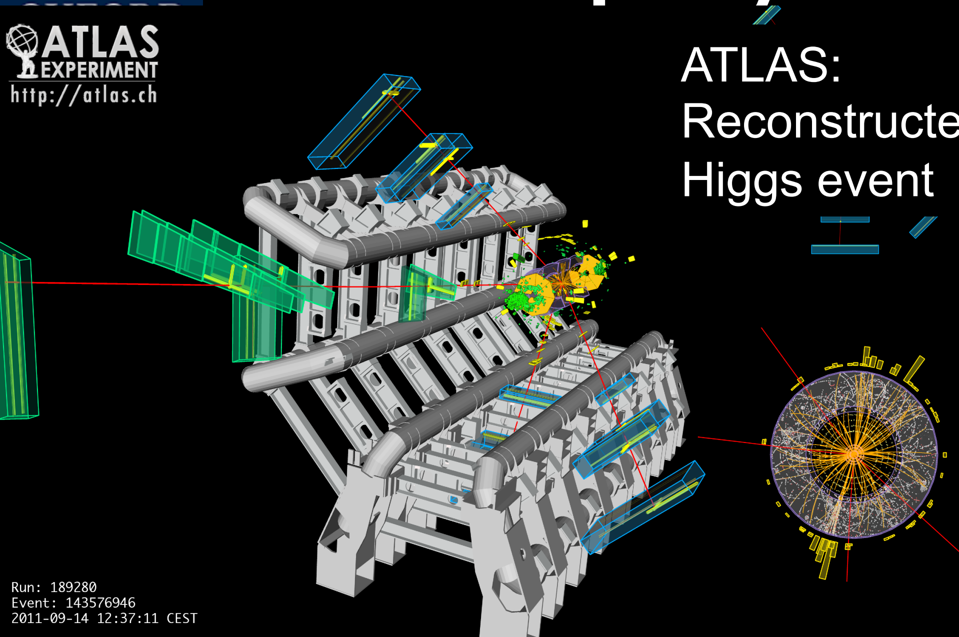
Tracking detectors

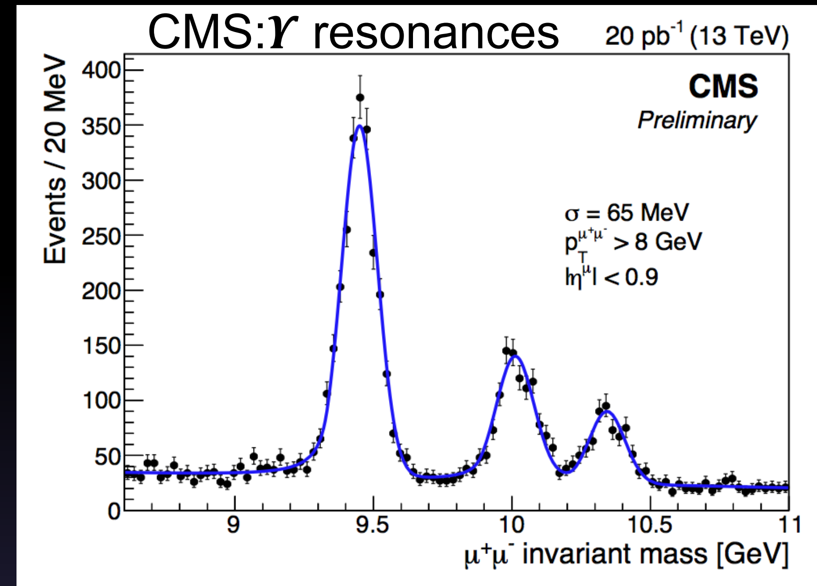
- High granularity detectors close to the interaction region providing precise measurements of the position of charged particles
  - Measure the trajectory using “hits” to determine the momentum of charged particles from their curvature in a magnetic field
  - Extrapolate to the origin and reconstruct
    - Primary vertices and identify the vertex associated with the “hard” interaction
    - Secondary vertices to identify tau-leptons, b and c-hadrons by lifetime tagging
  - Reconstruct strange hadrons, which decay in the detector volume
  - Identify photon conversions and nuclear interactions

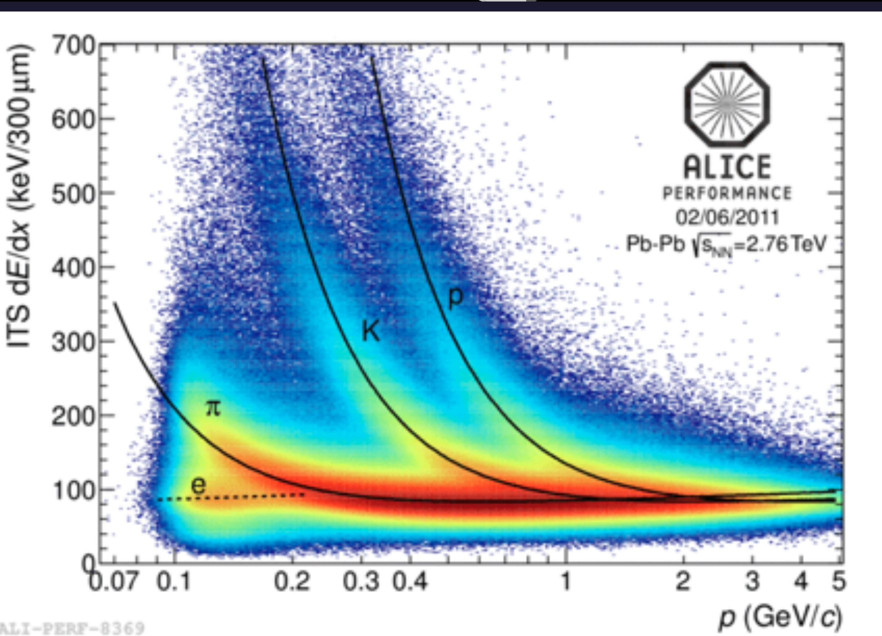


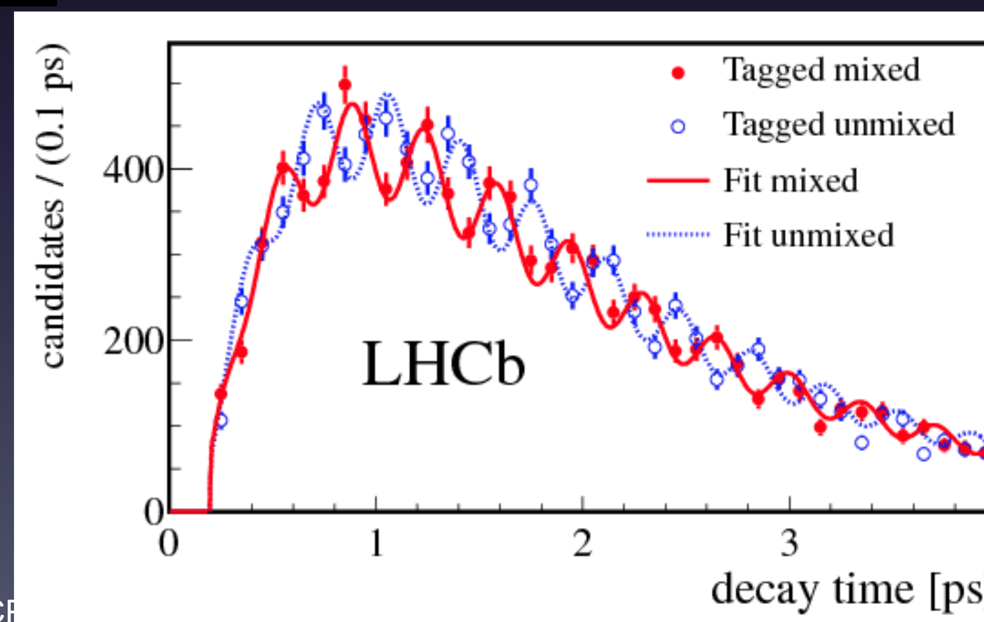


LHC physics program









Momentum Measurements

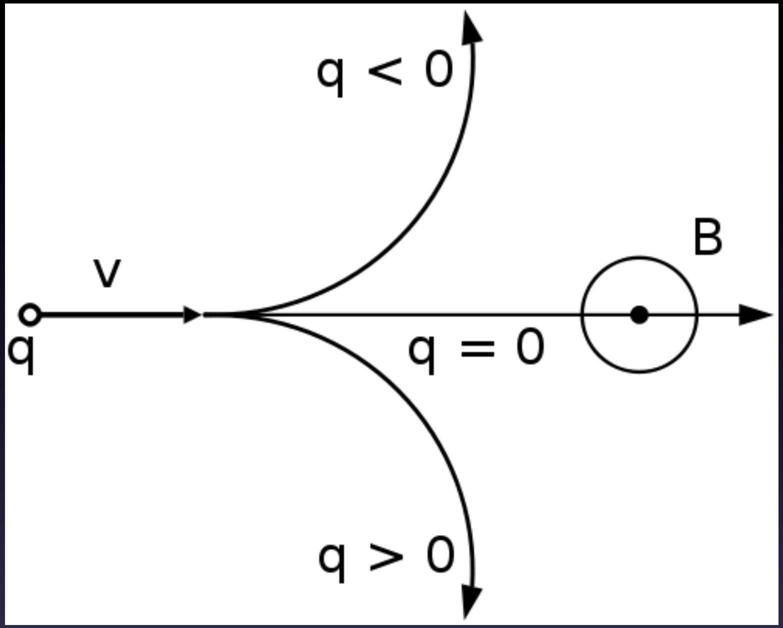
- The determination of the momentum (and charge) of charged particles can be performed by measuring the bending of a particle trajectory (track) in a magnetic field

Lorentz Force

$$\vec{\mathbf{F}} = q\vec{v} \times \vec{\mathbf{B}}$$

Motion transverse to an uniform B field

$$\frac{mv^2}{r} = qvB$$



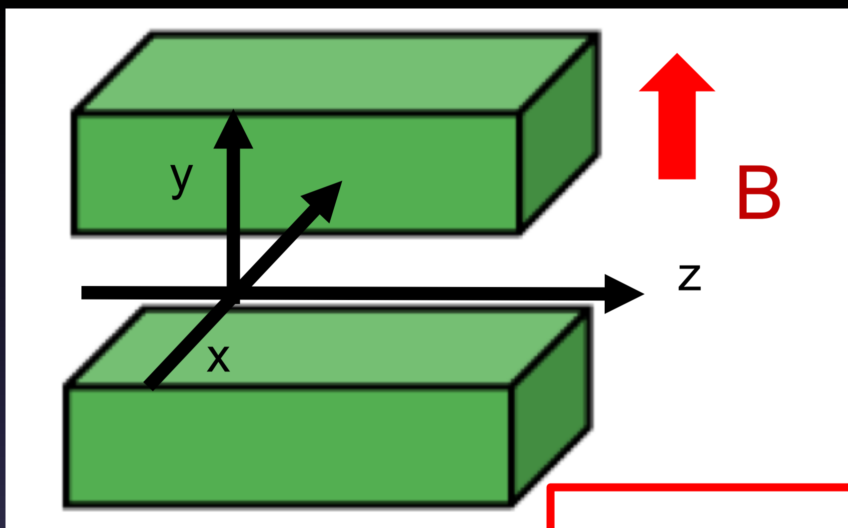
$$p_T\,[GeV/c] = 0.3B\,[T]\,R\,[m]$$

- Use layers of position sensitive detectors before and after or inside a magnetic field to measure a trajectory and determine the bending radius
- The tracker configuration depends critically on the choice of the magnet

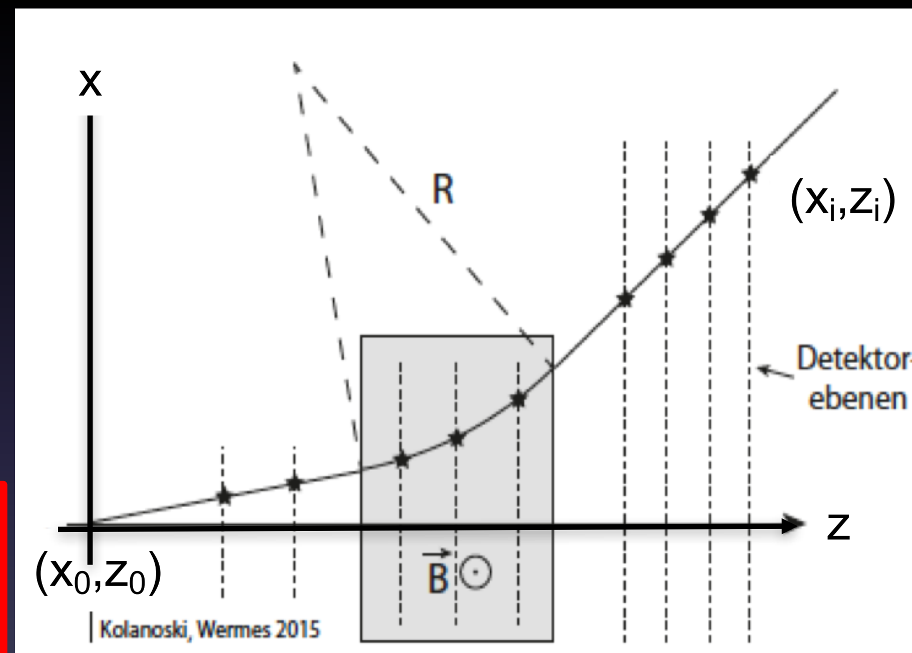
Forward Spectrometers

Dipole LHCb NI = 4Tm

Plane symmetry

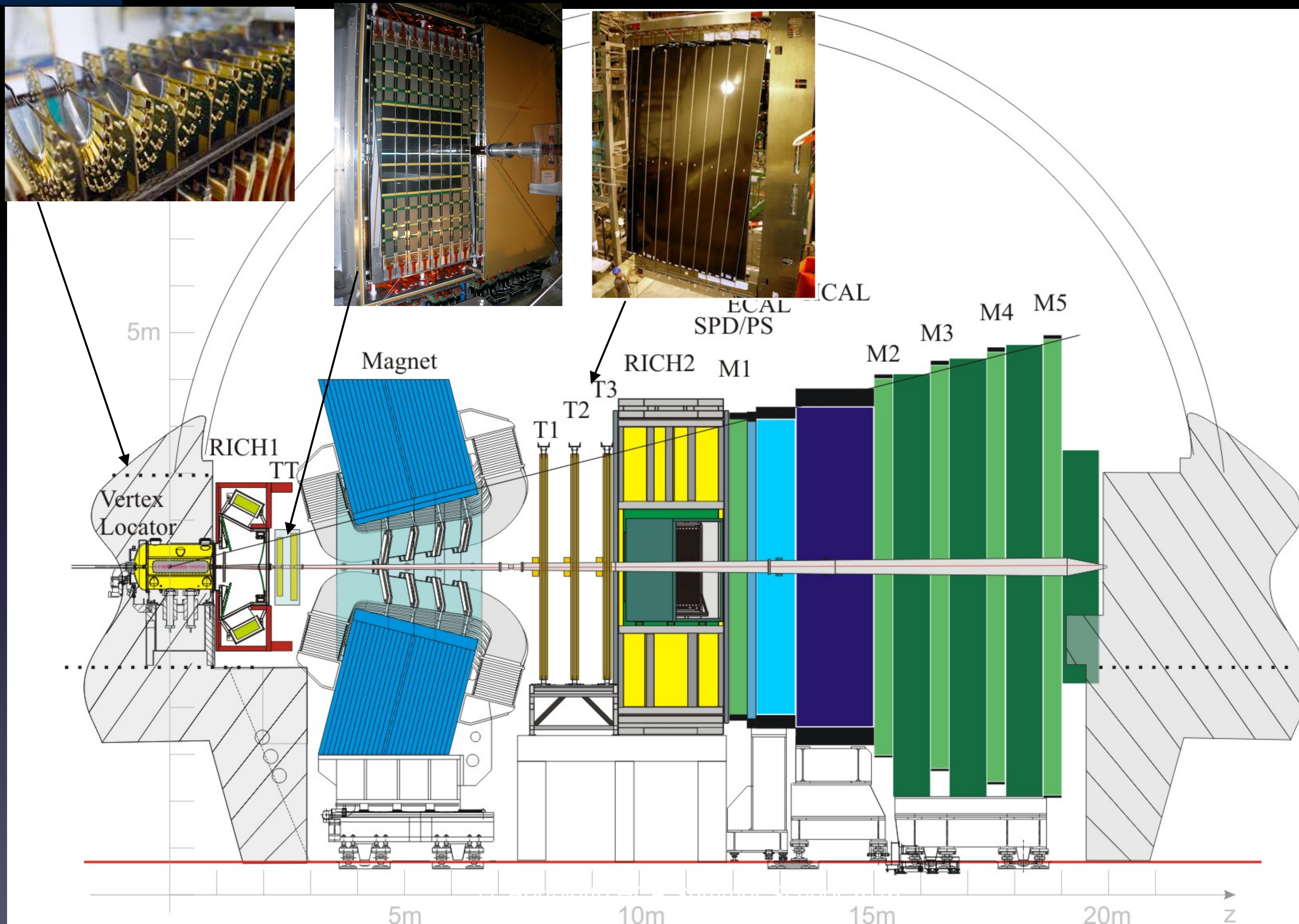


$$B \approx \frac{\mu_0 N I}{h}$$

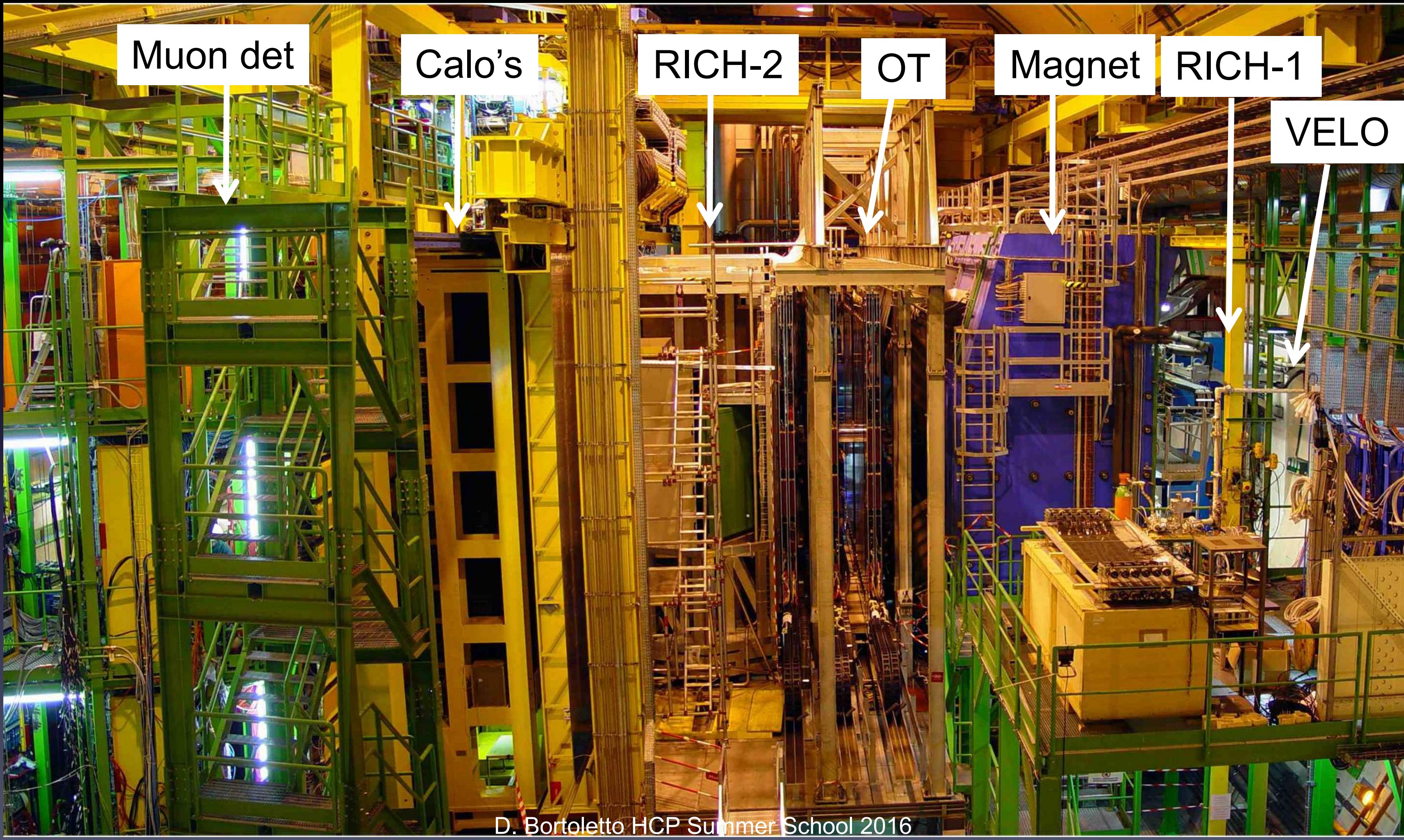


- Particle deflected in x - z plane
- Tracking detectors are arranged in parallel planes along z
- Bending from difference of the slopes before and after magnet

LHCb A Forward Spectrometer



LHCb A Forward Spectrometer

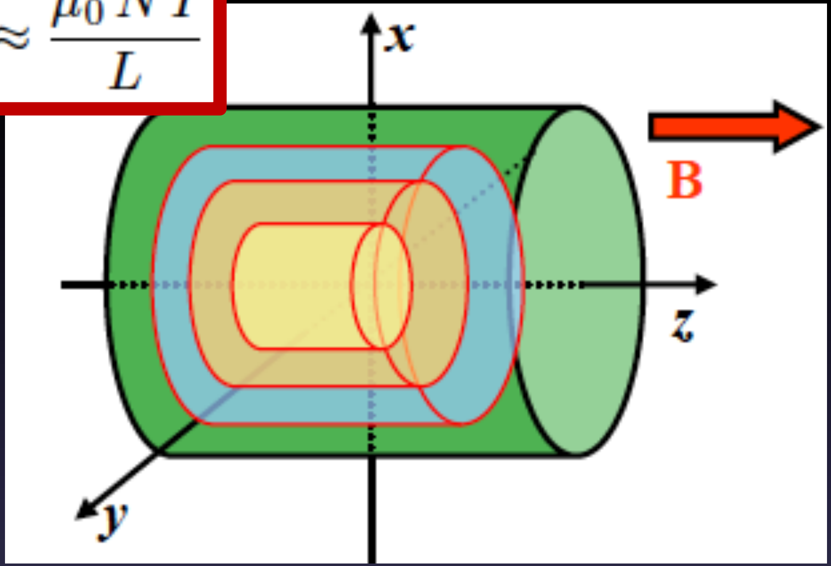


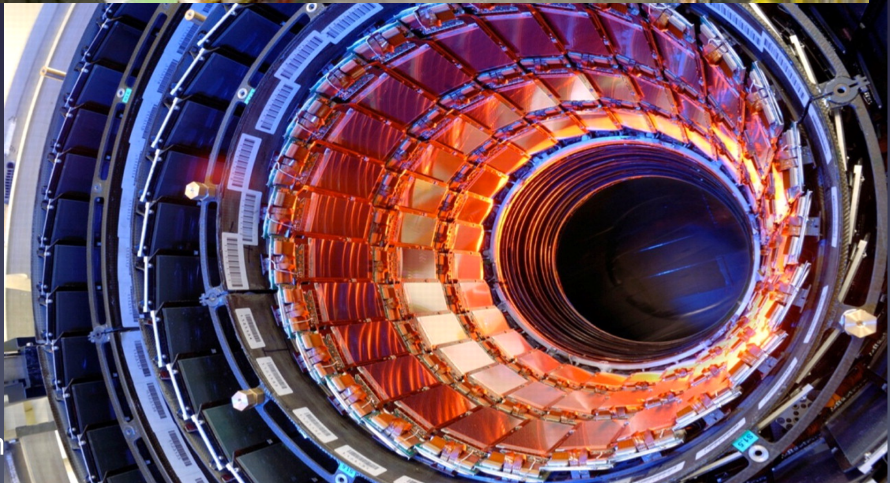
Central Detectors

Solenoid CMS 4T, Atlas 2T

Cylindrical symmetry

$$B \approx \frac{\mu_0 N I}{L}$$



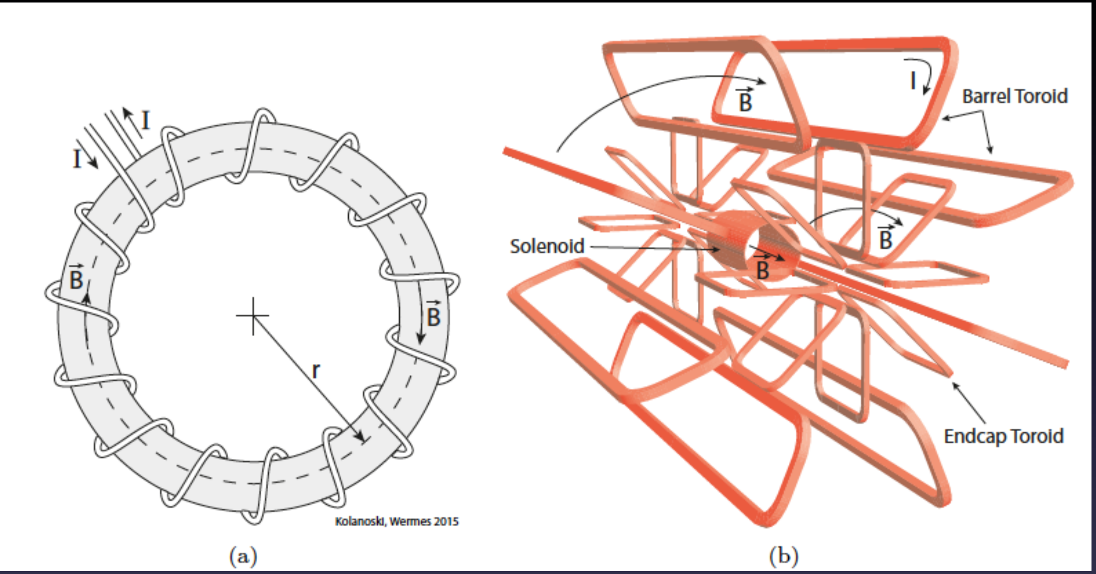


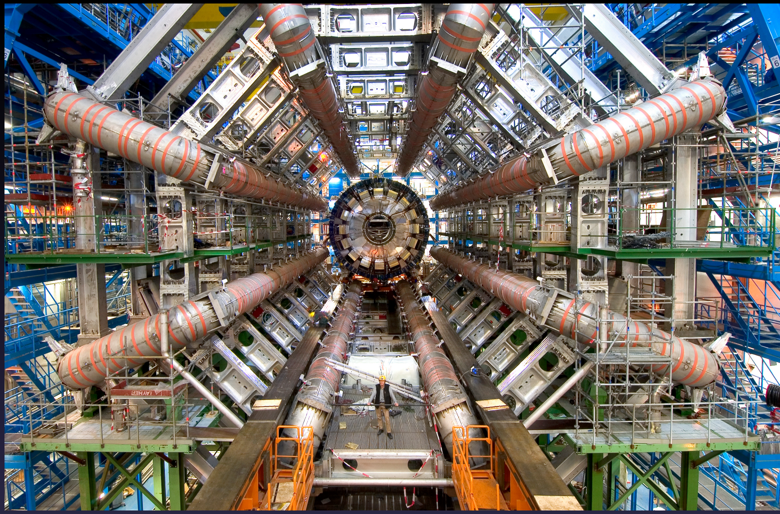
- Magnetic field along the beam
- Particle deflected in x –y (r - ϕ) plane
- Tracking detectors are arranged in cylindrical shells along r
- Measurement of curved trajectories on r- ϕ planes at fixed r

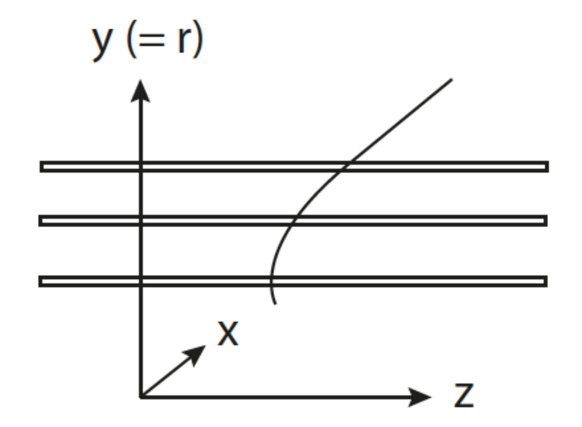
Magnetic Spectrometers

Toroid Atlas 0.5T

Azimuthal symmetry

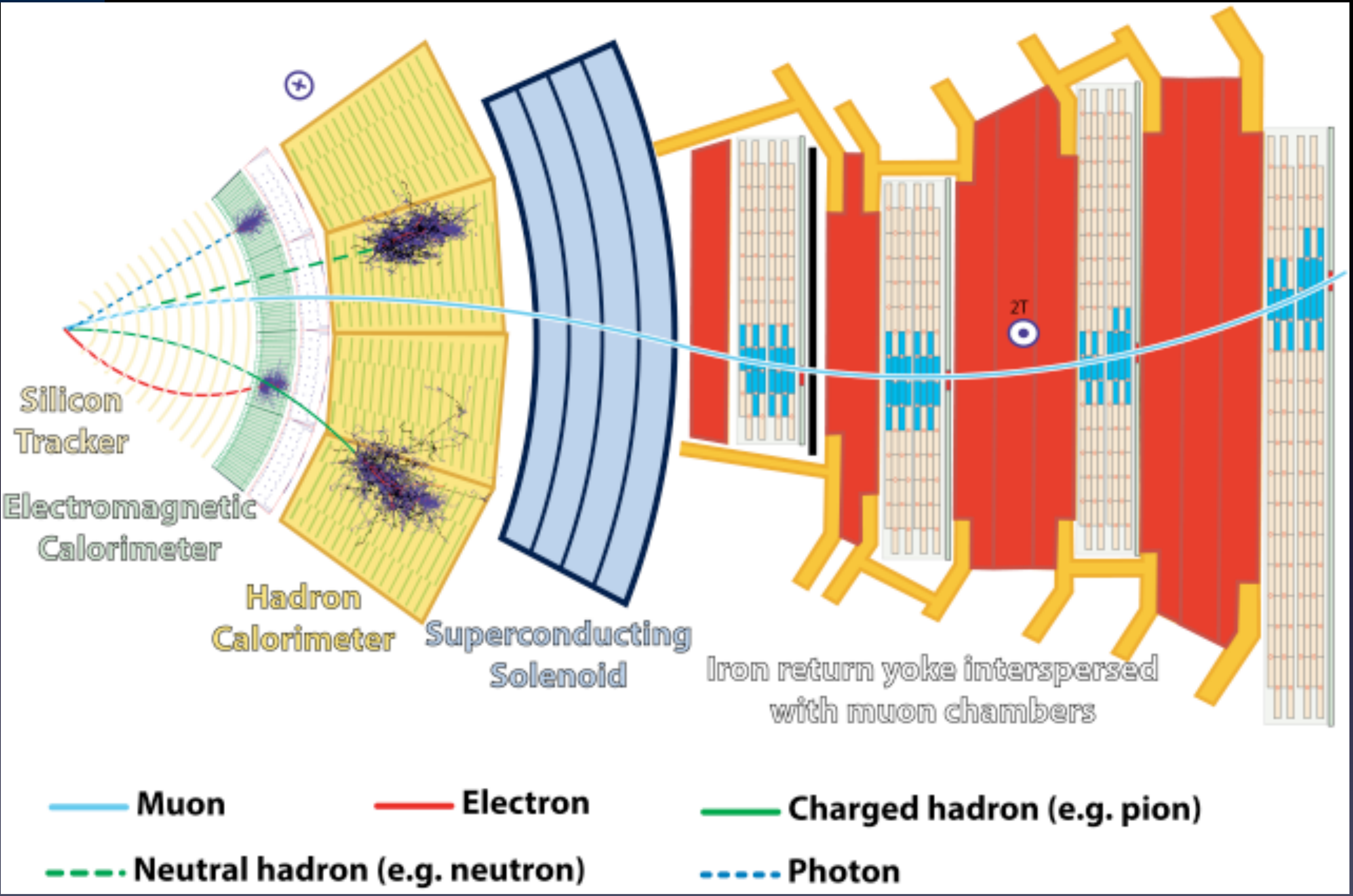




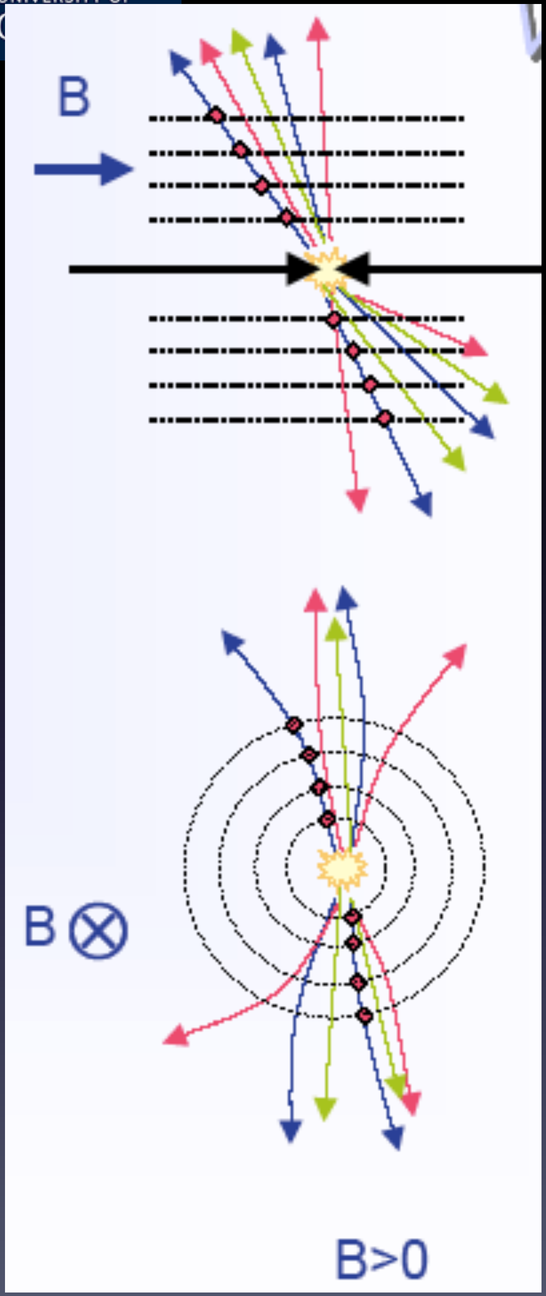


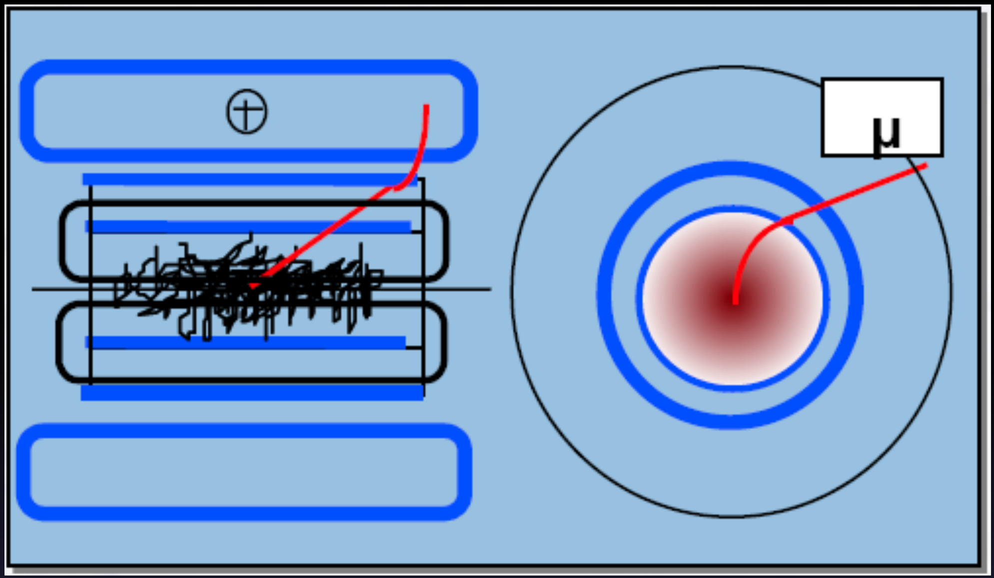
- Deflection in (r - z) – plane
- Tracking detectors are arranged in cylindrical shells providing measurement of curved trajectories in r-z planes at fixed r

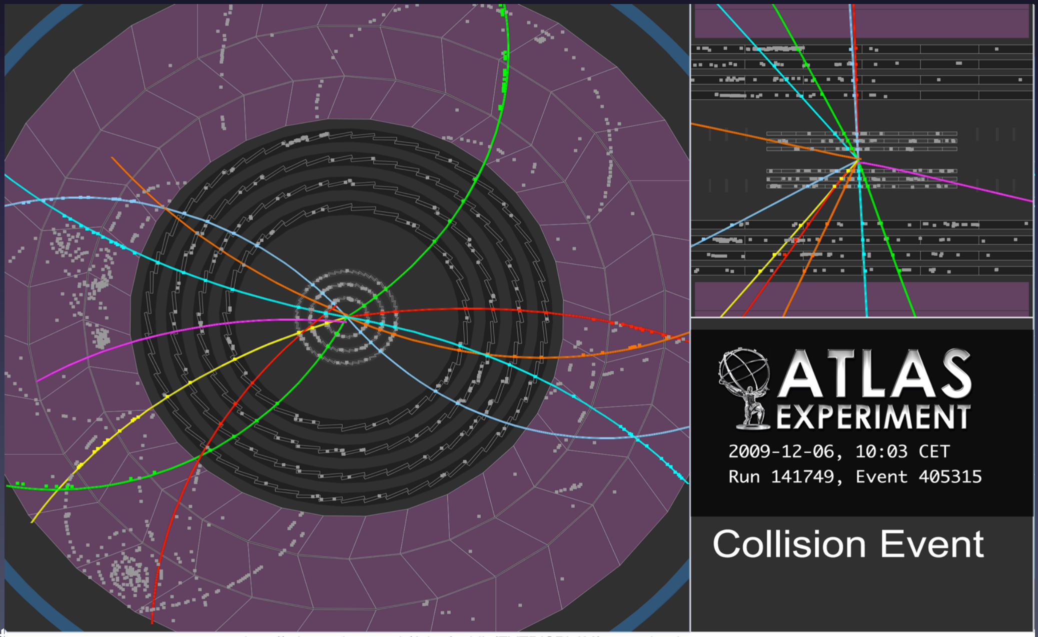
CMS


2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with muon chambers
Muon
Electron
Charged hadron (e.g. pion)
Neutral hadron (e.g. neutron)
Photon

Tracking in ATLAS



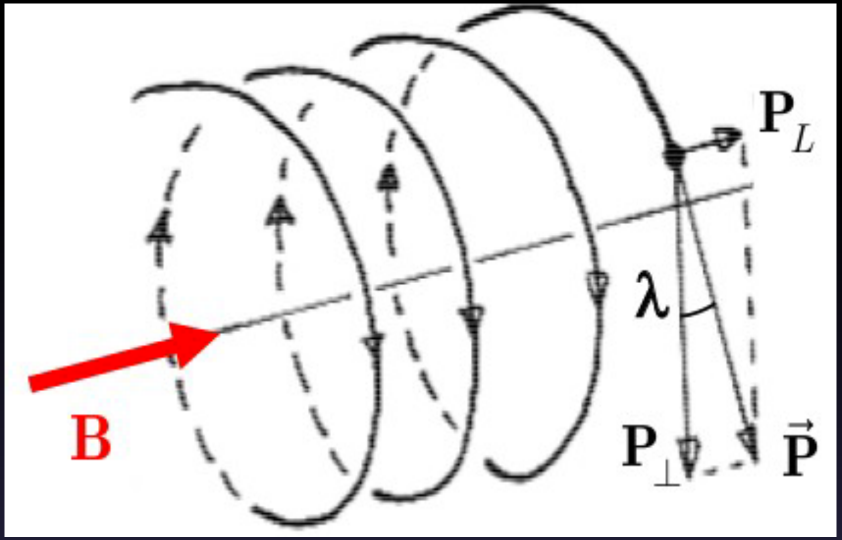


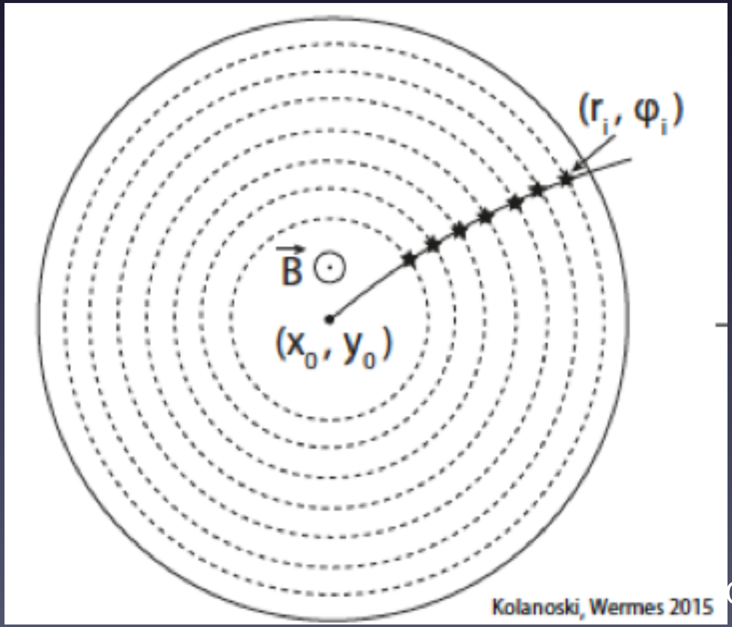


http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

Tracking in a solenoidal B

- The trajectory of a charged particle in a uniform B field along the beamline is a helix
  - Transverse (xy) and Longitudinal (rz) projections.
  - Φ=azimuthal angle is measured in transverse plane
  - θ=polar angle is measured from z axis
  - Dip, $\lambda = \pi/2 - \theta$
  - Pseudorapidity, $\eta = -\ln \tan(\theta/2)$
  - Transverse momentum, $p_T = p \sin\theta$





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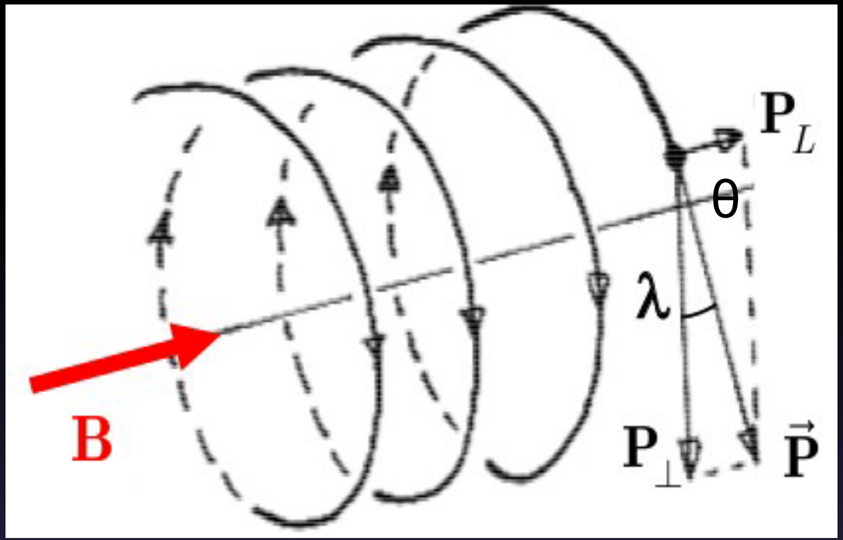
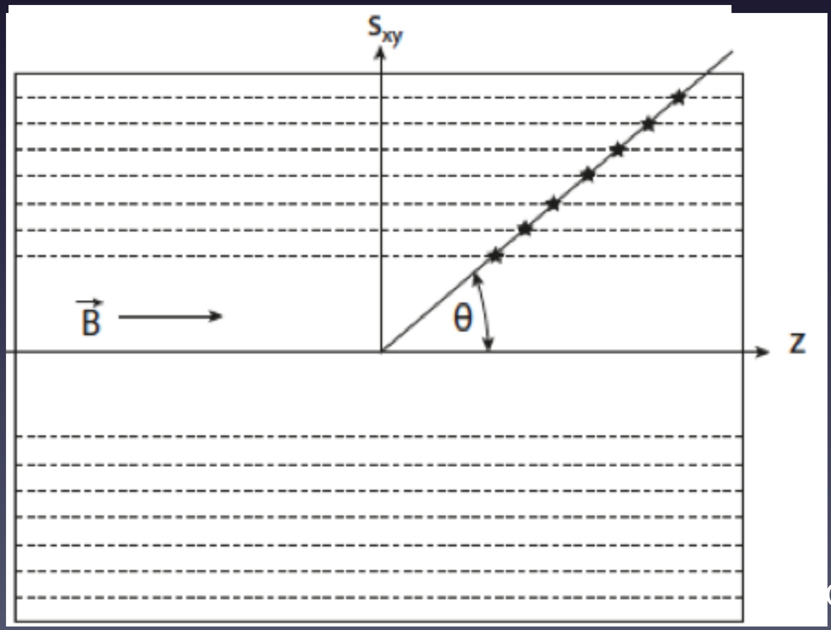
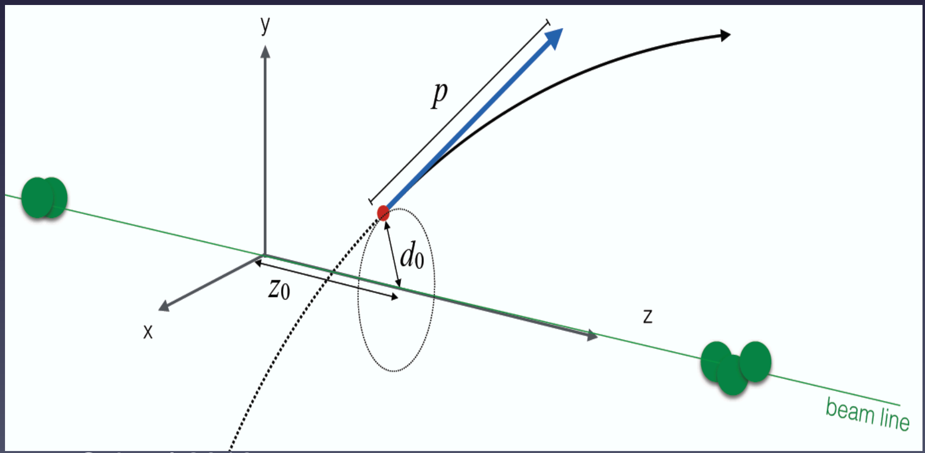
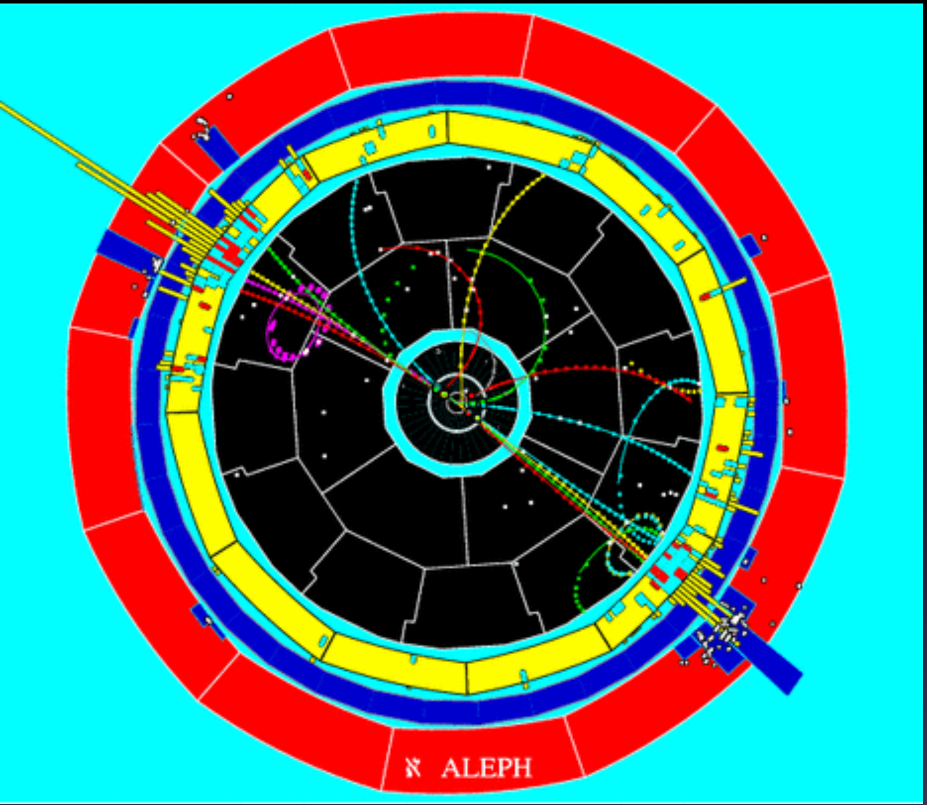


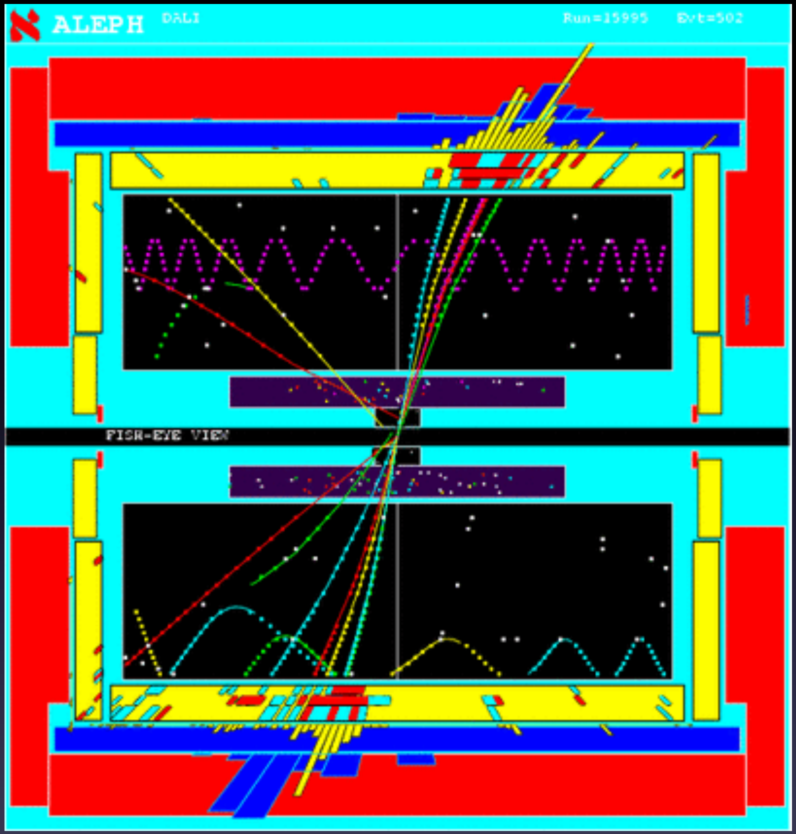


- Impact parameter d_0



The Helix … seen in an experiment





- For small momenta y is a periodic function of z
- For large momenta we have a straight line as a function of z

What we need to do?

- Measure the transverse momentum and the dip angle λ

$$P = \frac{P_\perp}{\cos\lambda} = \frac{0.3BR}{\cos\lambda}$$

- The error on the momentum is given by the measurement errors on the curvature radius R and the dip angle λ

$$\frac{\partial P}{\partial R} = \frac{P_\perp}{R}$$

$$\frac{\partial P}{\partial \lambda} = -P_\perp \tan\lambda$$

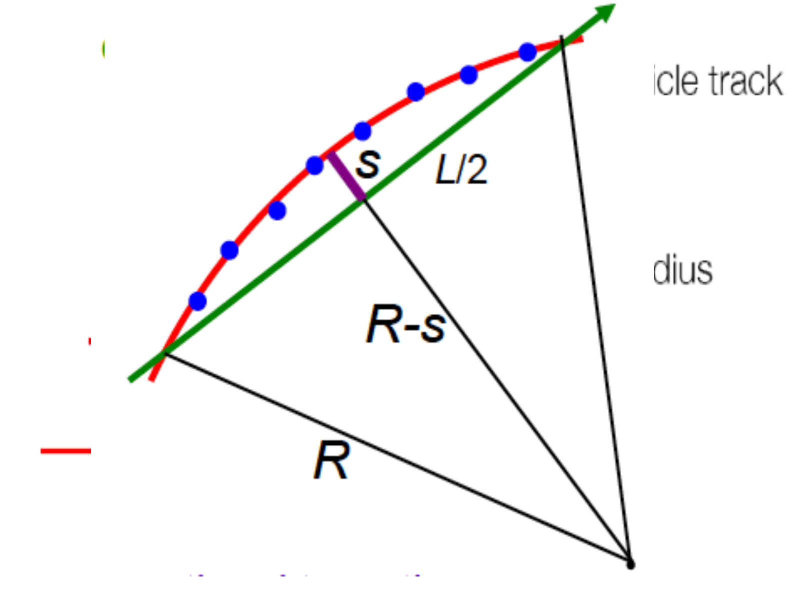
$$\left(\frac{\Delta P}{P}\right)^2 = \left(\frac{\Delta R}{R}\right)^2 + (\tan\lambda\Delta\lambda)^2$$

- For central detector configurations with solenoid magnets
  - the error on the radius measured in the bending plane r – φ
  - the error on the dip angle in the r - z plane
  - The contribution of multiple scattering to the the momentum resolution
- In a hadron collider like LHC the main emphasis is on transverse momentum measurement

Momentum measurement

- Motion transverse to uniform B field

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



Measure the sagitta, s, from radius of curvature, R. If s<<L

$$R = \frac{L^2}{8s} + \frac{s}{2} \approx \frac{L^2}{8s}$$

$$\frac{\Delta p_T}{p_T} = \frac{\Delta R}{R}$$

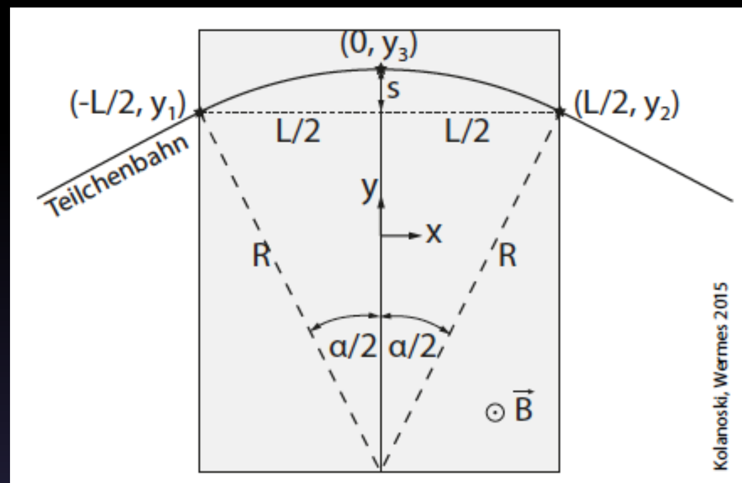
$$\frac{\sigma_{p_T}}{p_T} = \frac{8p_T}{0.3BL^2}\sigma_s$$

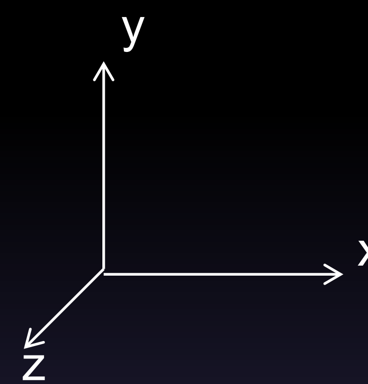
Good relative momentum requires small σ_s, strong B field, long path length L (as L^2 ➠ often use beam constraint).

Momentum resolution gets worse at large p_T

Momentum resolution

- Let us assume that we have 3 measurements of the position of the particle





$$s = y_3 - \frac{y_1 + y_2}{2}$$

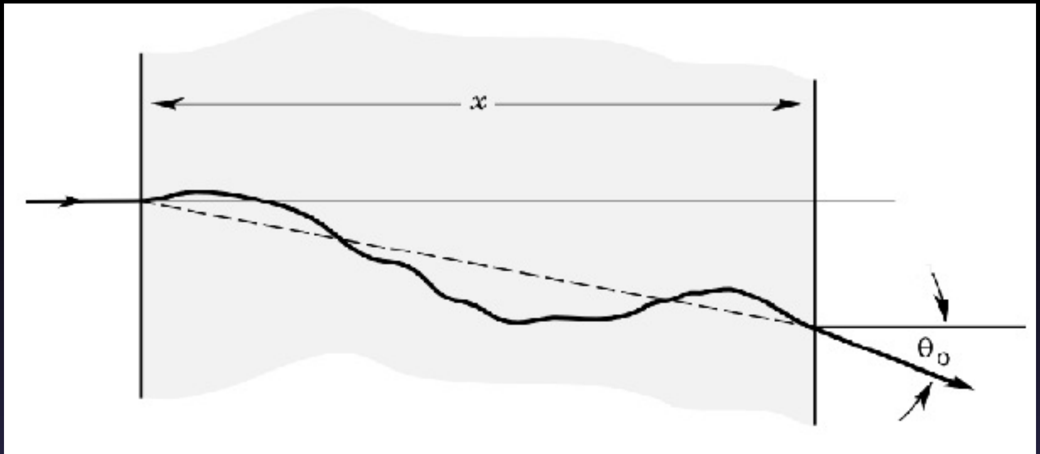
$$\sigma_s = \sqrt{\sigma_{r\phi}^2 + \frac{1}{4} 2\sigma_{r\phi}^2} = \sqrt{\frac{3}{2}}\sigma_{r\phi}$$

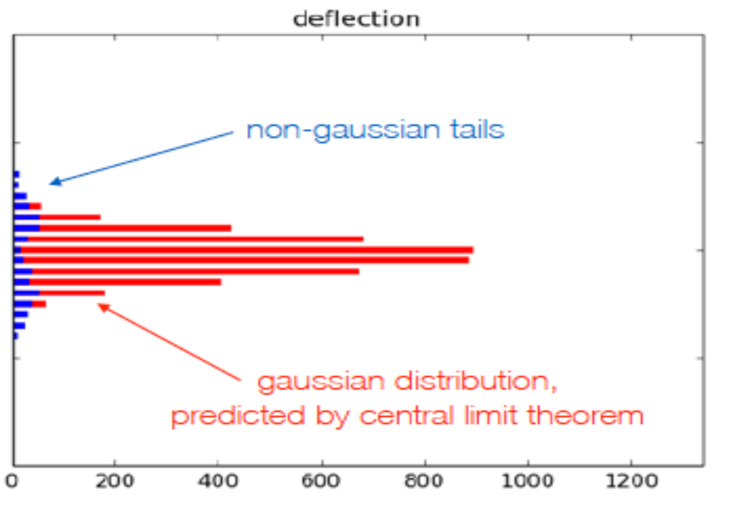
- For N measurements all with the uncertainty

Small σ_s ➠ small $\sigma_{r\phi}$ and large N (many measurement points, but only as √N)

Multiple scattering

- A charged particle in medium undergoes random deflections caused:
  - by multiple (Coulomb) scattering off the core of atoms
  - single large (Rutherford) scattering





$$\theta_0 = \frac{13.6\ MeV/c}{p\beta} Z \sqrt{\frac{x}{X_0}} \left(1 + 0.038 \ln \frac{x}{X_0}\right)$$

- This introduces an error on the sagitta
- Multiple scattering is reduced by: low Z, thin materials, long X_0

Momentum resolution

- The point error, $\sigma_{r\phi}$, has a part from intrinsic measurement precision and a multiple scattering part. Therefore:

$$\frac{\sigma_{p_T}}{p_T} = \sqrt{\left(\frac{\sigma_{p_T}}{p_T}\right)^2_{r\phi} + \left(\frac{\sigma_{p_T}}{p_T}\right)^2_{MS}}$$

$$\left(\frac{\sigma_{p_T}}{p_T}\right)_{r\phi} = \frac{p_T}{0.3L^2B}\sqrt{\frac{720}{N+4}}\,\sigma_{r\phi}$$

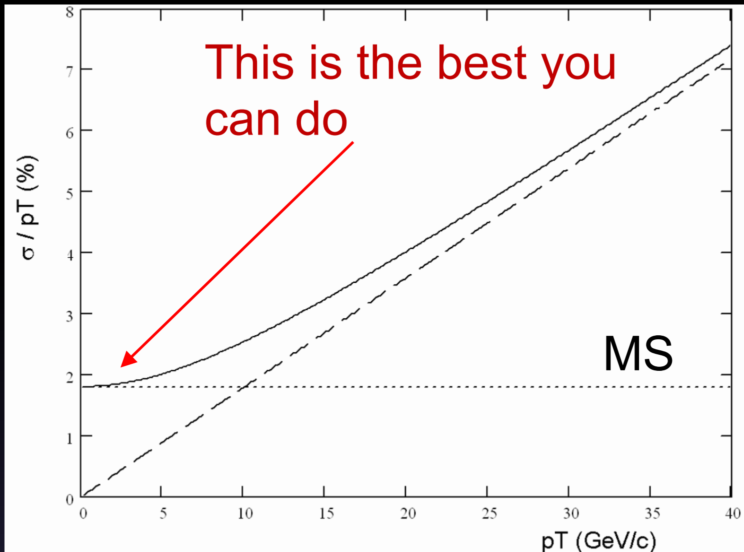
$$\left(\frac{\sigma_{p_T}}{p_T}\right)_{MS} = \frac{0.054}{LB\beta}\sqrt{\frac{L}{X_0}\sin\theta}$$

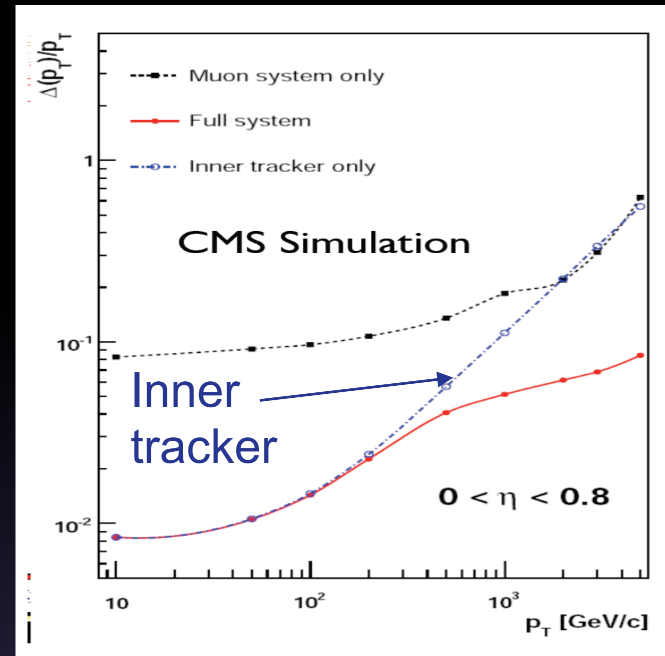
Radiation length=mean length of a material to reduce the energy of an electron by 1/e. It can be approximated as:

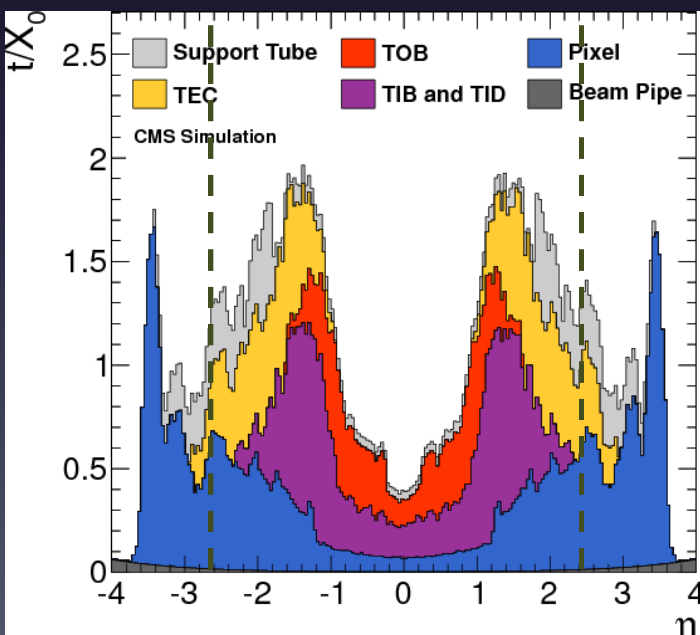
- Thickness of detector often expressed in 'fraction of radiation length' x/X_0:

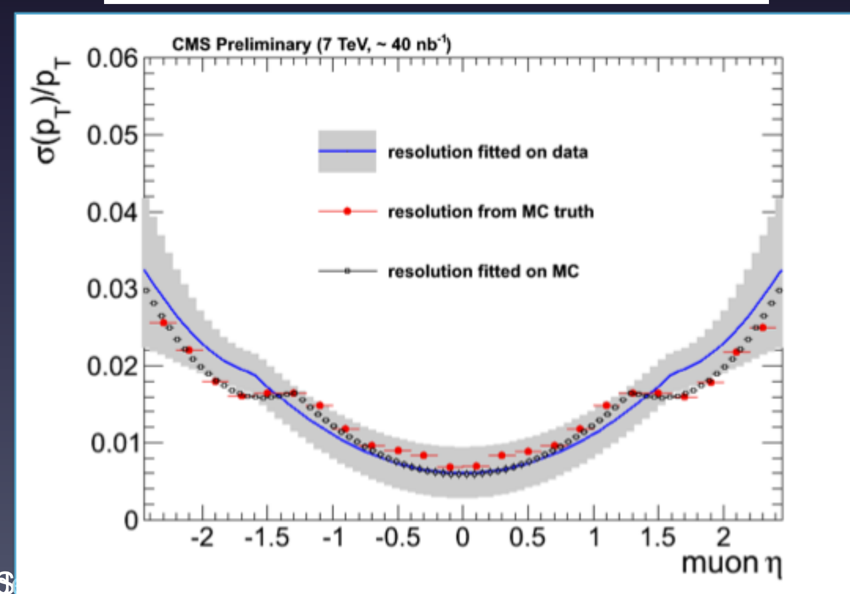
Good momentum resolution requires long X_o, and therefore small Z and thin materials

Total momentum resolution



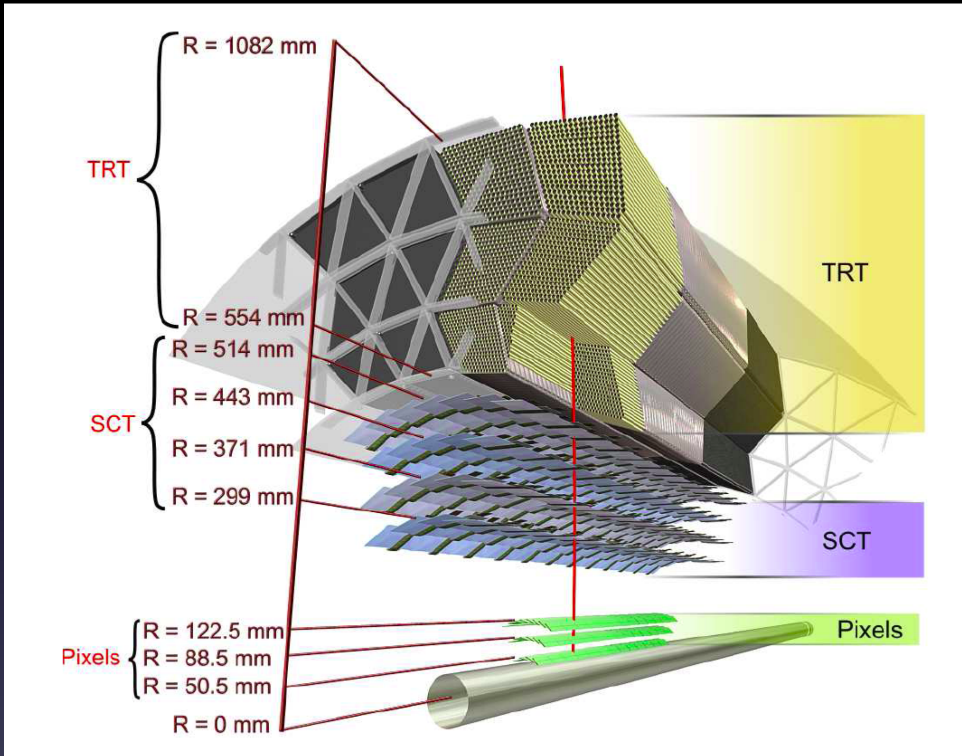






Estimate the ATLAS momentum resolution

- Simplification:
  - Assume high momenta (no MS)
  - R_{min} = 5.05 cm, R_{max} = 1082cm
  - Pixels (5cm to 12cm)
    - N=3 (up to 2012), σ = 12μm
  - SCT (30cm to 55cm)
    - N=4 layers, σ = 16 μm
  - TRT (55cm to 105 cm)
    - N = 36, σ = 170 μm
    - Use as a single point with σ = 28 μm at R = 80 cm (= R_{max} ⇒ L = 75 cm)
  - N = 3 + 4 + 1 = 8
  - σ = 12, 16, 28 μm ➠ < σ > ~16 μm
  - L=75 cm



$$\left(\frac{\sigma_{p_T}}{p_T}\right)_{r\phi} = \frac{p_T}{0.3L^2B}\sqrt{\frac{720}{N+4}}\,\sigma_{r\phi} = 7.74\frac{p_T}{0.3L^2B}\sigma_{r\phi}$$

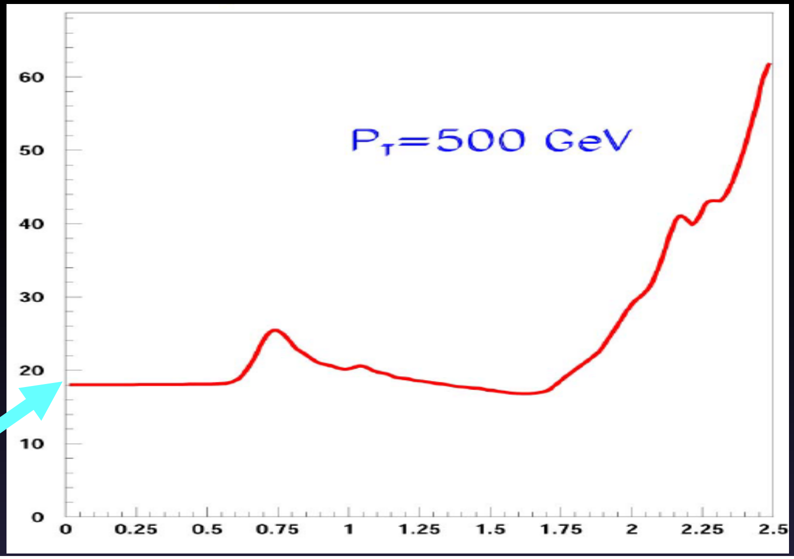
Estimate: ATLAS momentum resolution

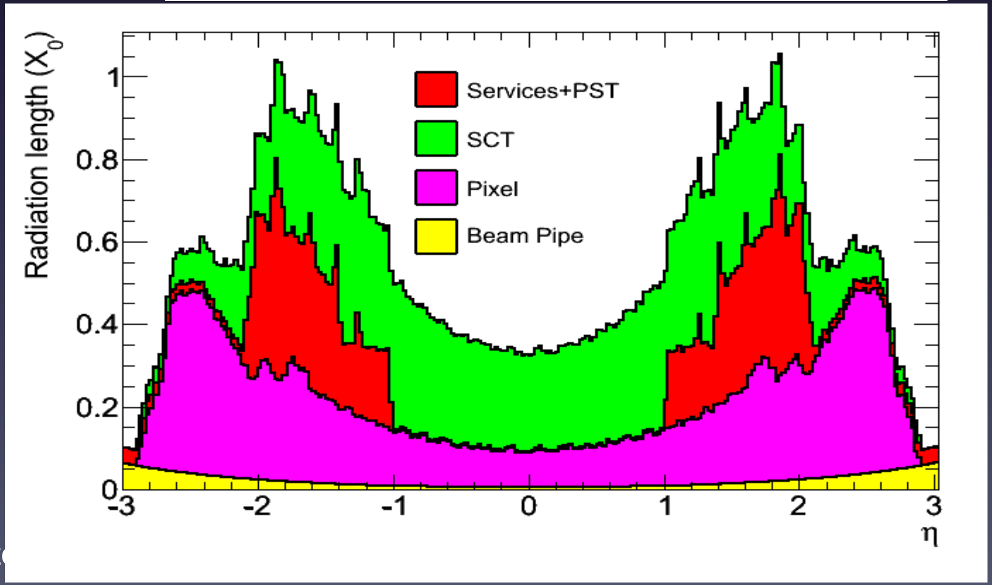
- B=2T, L=0.75m

$$\left(\frac{\sigma_{p_T}}{p_T}\right)_{r\phi} = 7.74\frac{p_T}{0.3L^2B}\sigma_{r\phi}$$
$$= 3.6\times10^{-4}\,p_T\,[GeV]$$

- At p_T=500 GeV

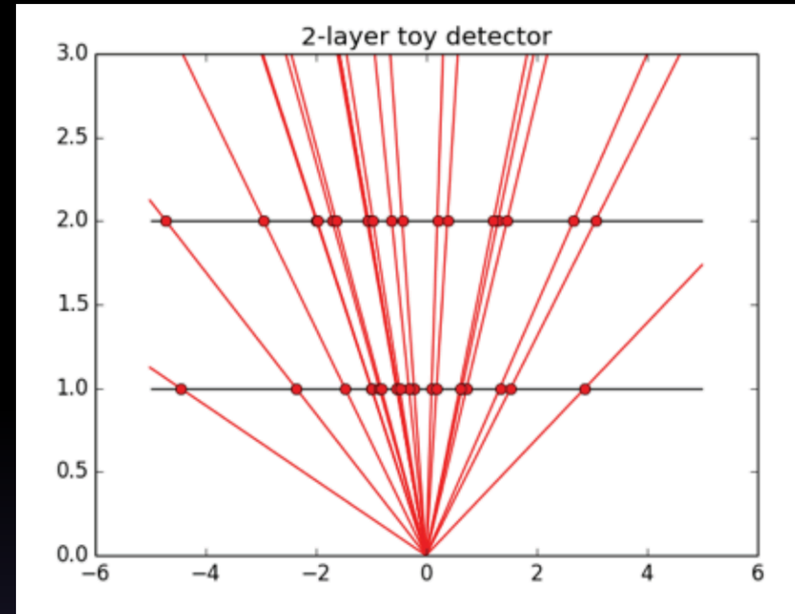
$$\frac{dp}{p} = 18\%$$

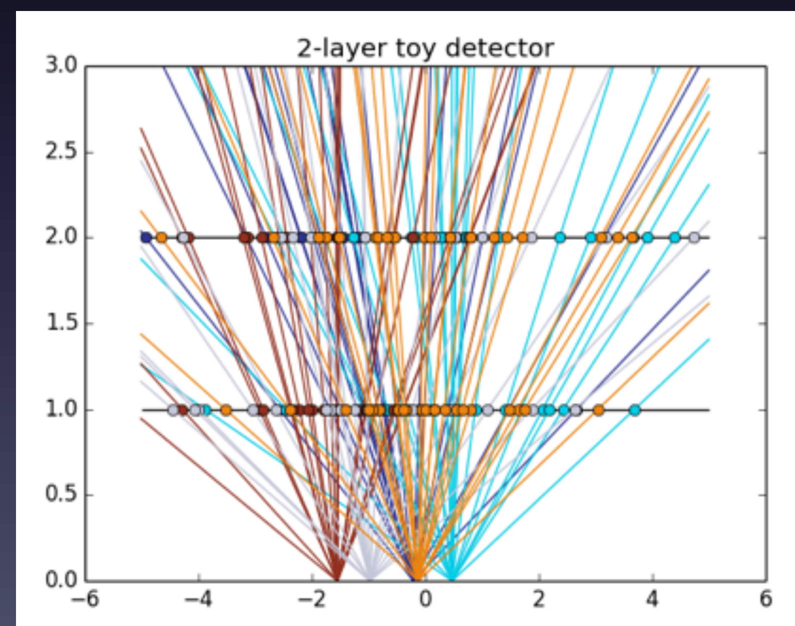


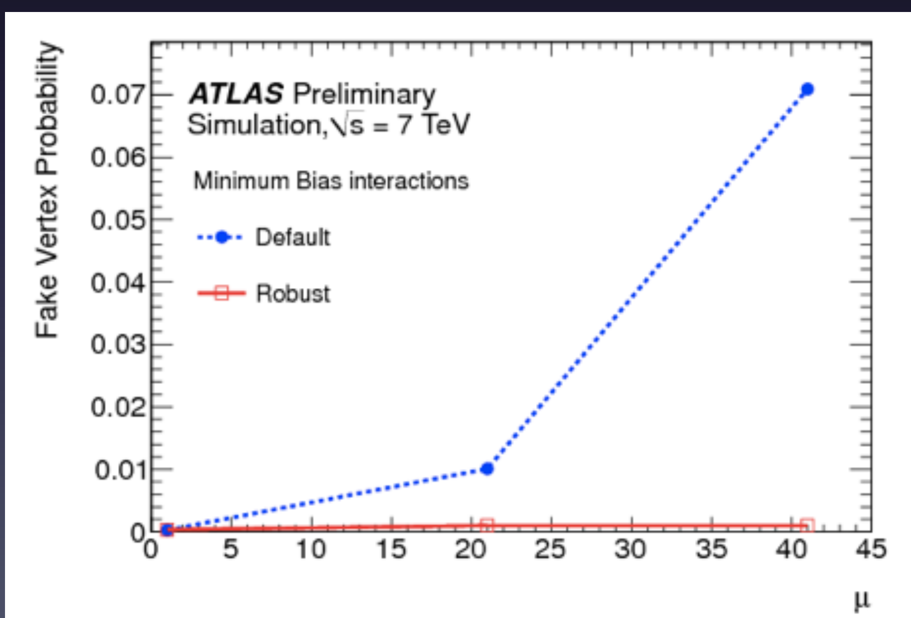


Vertex reconstruction

- Use reconstructed tracks, to extrapolate back and find the primary vertex
- To maximise the physics potential, LHC runs in a regime of multiple instantaneous collisions: pile-up
- Pile-up renders tracks reconstruction and vertex finding more complex: more seeds and CPU time explodes

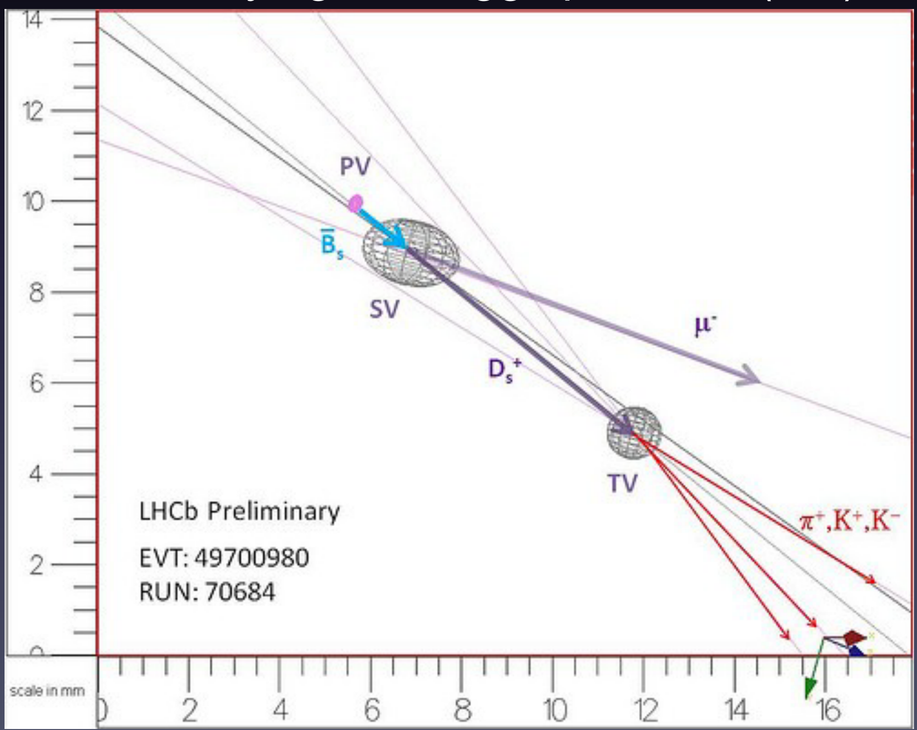


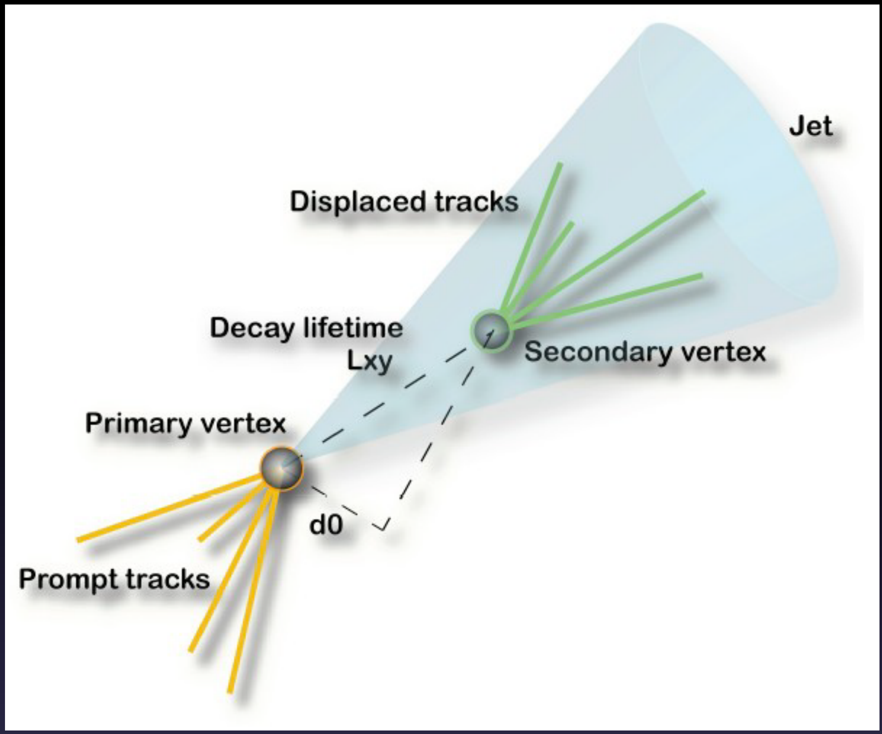




Lifetime tagging

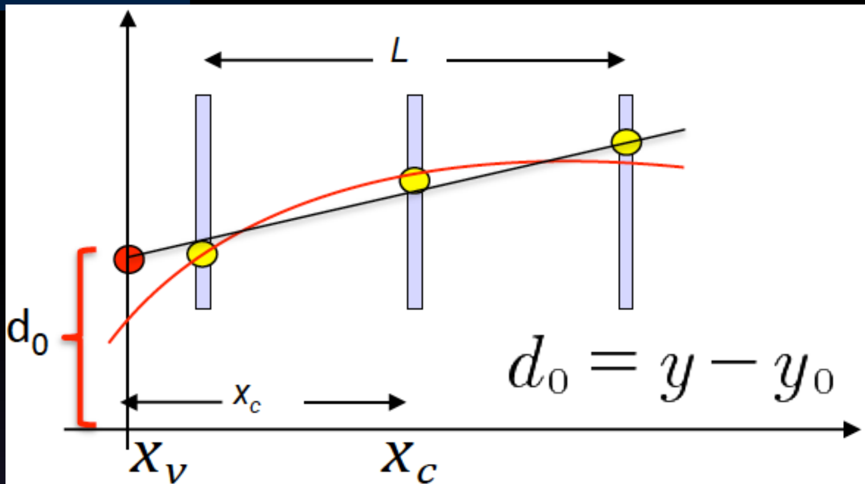
- Tracks with significant impact parameter, d_0, can be used to form a reconstructed secondary vertex
  - Essential to study the heavy quarks (t, b, c)
  - Tagging the Higgs since BR(H→ $b\bar{b}$) ≈ 58%
  - Studying the Higgs potential (HH)





Example of a fully reconstructed event from LHCb, with primary, secondary and tertiary vertex.

Impact parameter resolution



- Vertex extrapolation
  - Linear (B=0)

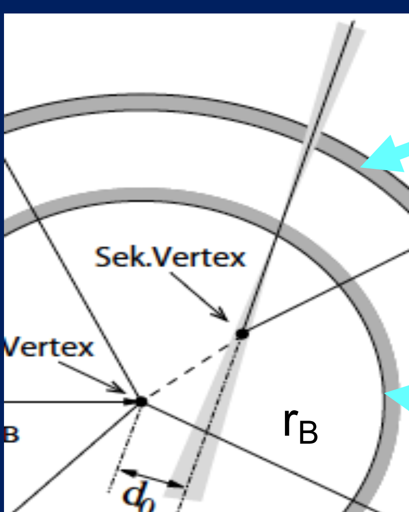
$$y = a + bx$$

  - Parabolic (with B field)

$$y = a + bx + \frac{1}{2}cx^2$$

- Linear approximation

$$\sigma_{d_0}^{meas} = \sqrt{\sigma_a^2 + x_0^2\sigma_b^2} = \frac{\sigma_{meas}}{\sqrt{N}}\sqrt{1 + \frac{12(N-1)}{(N+1)}r^2}$$



First Layer

MULTIPLE SCATTERING

$$\sigma_{d_0}^{MS} = \theta_0 r_B$$

Beam Pipe

r= extrapolation length

$$r = \frac{x_0}{L}$$

Impact parameter resolution

- In the linear case

$$r = \frac{x_0}{L}$$

$$\sigma_{d_0} = \sigma_{d_0}^{meas} \oplus \sigma_{d_0}^{MS} = \frac{\sigma_{meas}}{\sqrt{N}} \sqrt{1 + \frac{12(N-1)}{(N+1)} r^2} \oplus \theta_0 r_B$$

- To have good impact parameter resolution:
  - Small measurement errors σ_{meas}
  - Large lever arm L ➠ r
  - Place measurement plane as near as possible to the production point: small x_0 ➠ r
  - Limit multiple scattering ➠ Low Z thin beam pipe and measurement layers
  - Increasing number of points also improves the d_0 resolution (1/√N)

Example ATLAS

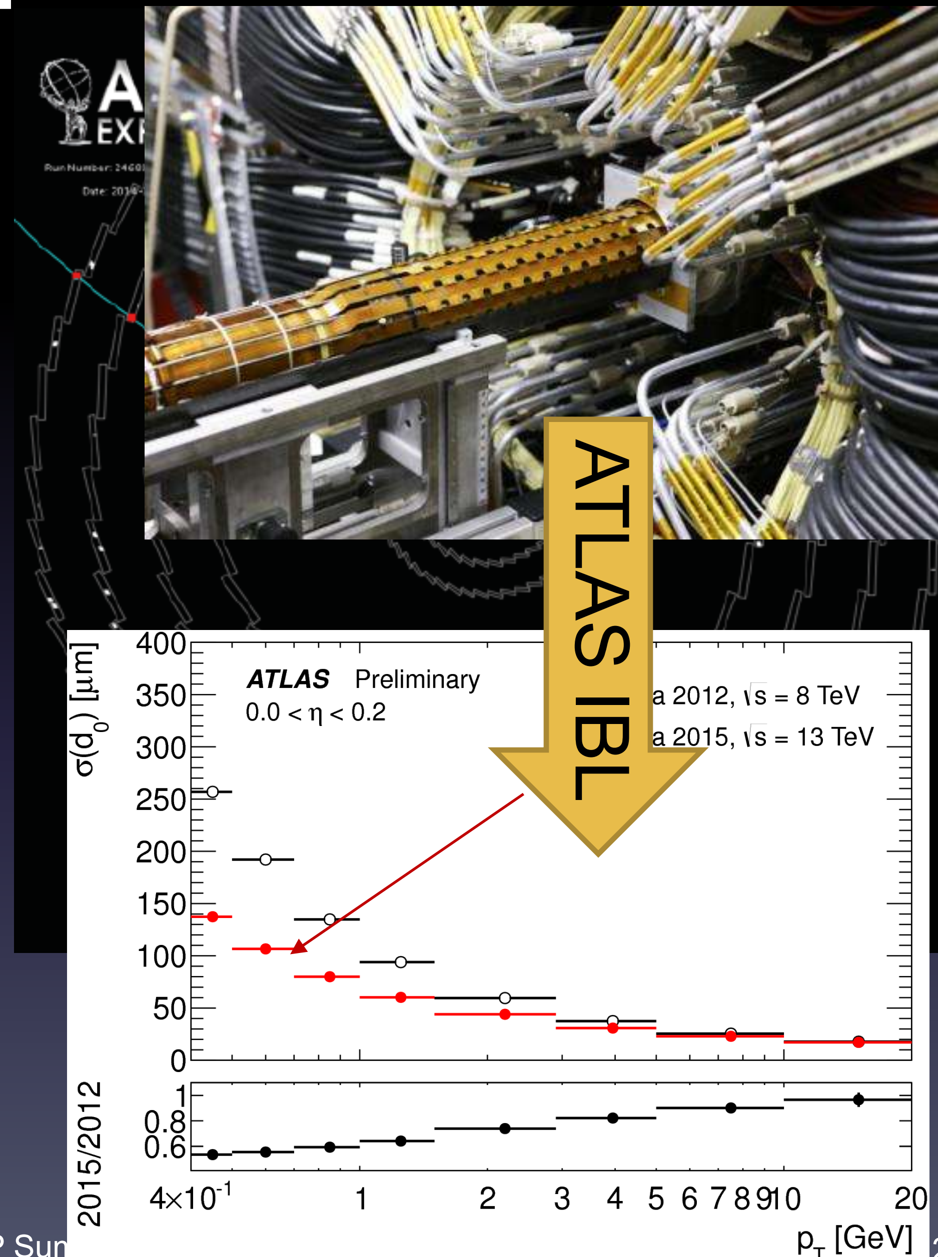
- ATLAS Pixel detector
  - N = 3, σ = 10 μm
  - x_1 = 5.05 cm
  - x_2 = 8.85 cm
  - x_3 = 12.25 cm
  - L = 7.2 cm
  - r = x_2/L = 1.22

- Neglecting Multiple scattering

$$\sigma_{d0}^{meas} = \frac{\sigma_{meas}}{N}\sqrt{1+\frac{12(N-1)}{(N+1)}r^2} = 18\mu m$$

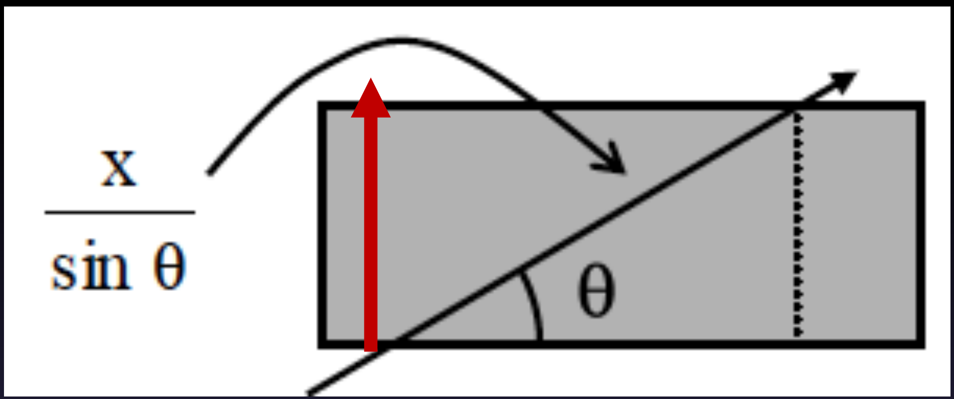
  - With IBL: N = 3, σ = 10 μm and x_1 = 3.55 cm

$$\sigma_{d0}^{meas} \approx 10\mu m$$



Tracker resolution with MS

- For low p_T tracks the momentum resolution and the impact parameter resolution are dominated by multiple scattering
- The amount of material traversed by the particles depends on polar angle



- Momentum resolution:

$$\frac{\sigma_p}{p^2} \rightarrow k_p \frac{\sqrt{x/X_0}}{p\sqrt{\sin\theta}}$$

- Impact parameter resolution:

$$\sigma_{d_0} \rightarrow k_{d_0} \frac{\sqrt{x/X_0}}{p\sqrt{\sin\theta}}$$

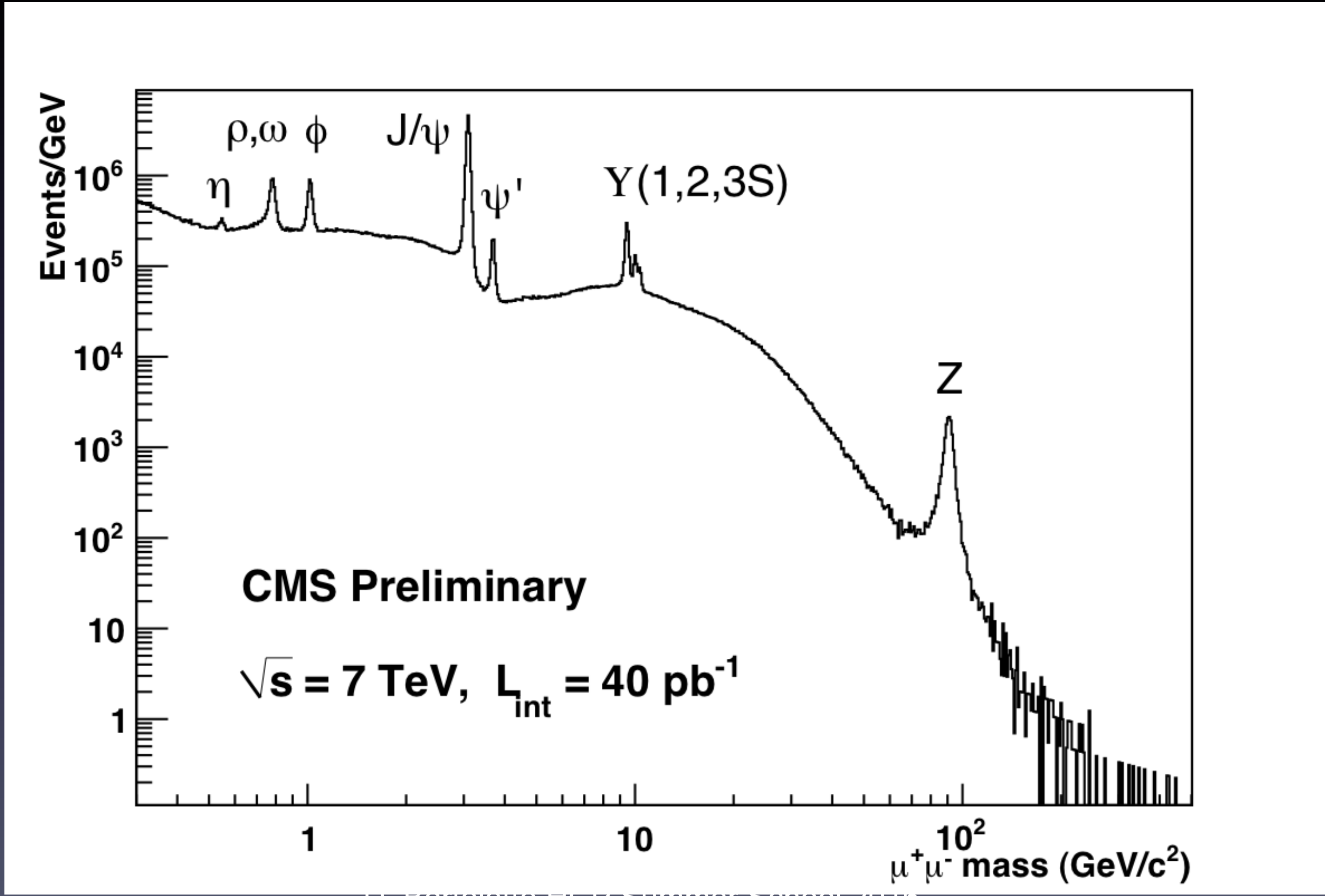
- The MS error and the point measurement error are independent of each other,
- The total error is the sum in quadrature of the 2 terms
- ATLAS detector Monte Carlo studies show:

$$\frac{\sigma_{p_T}}{p_T^2} = 0.00036 \oplus \frac{0.013}{p_T\sqrt{\sin\theta}}(1/GeV)$$

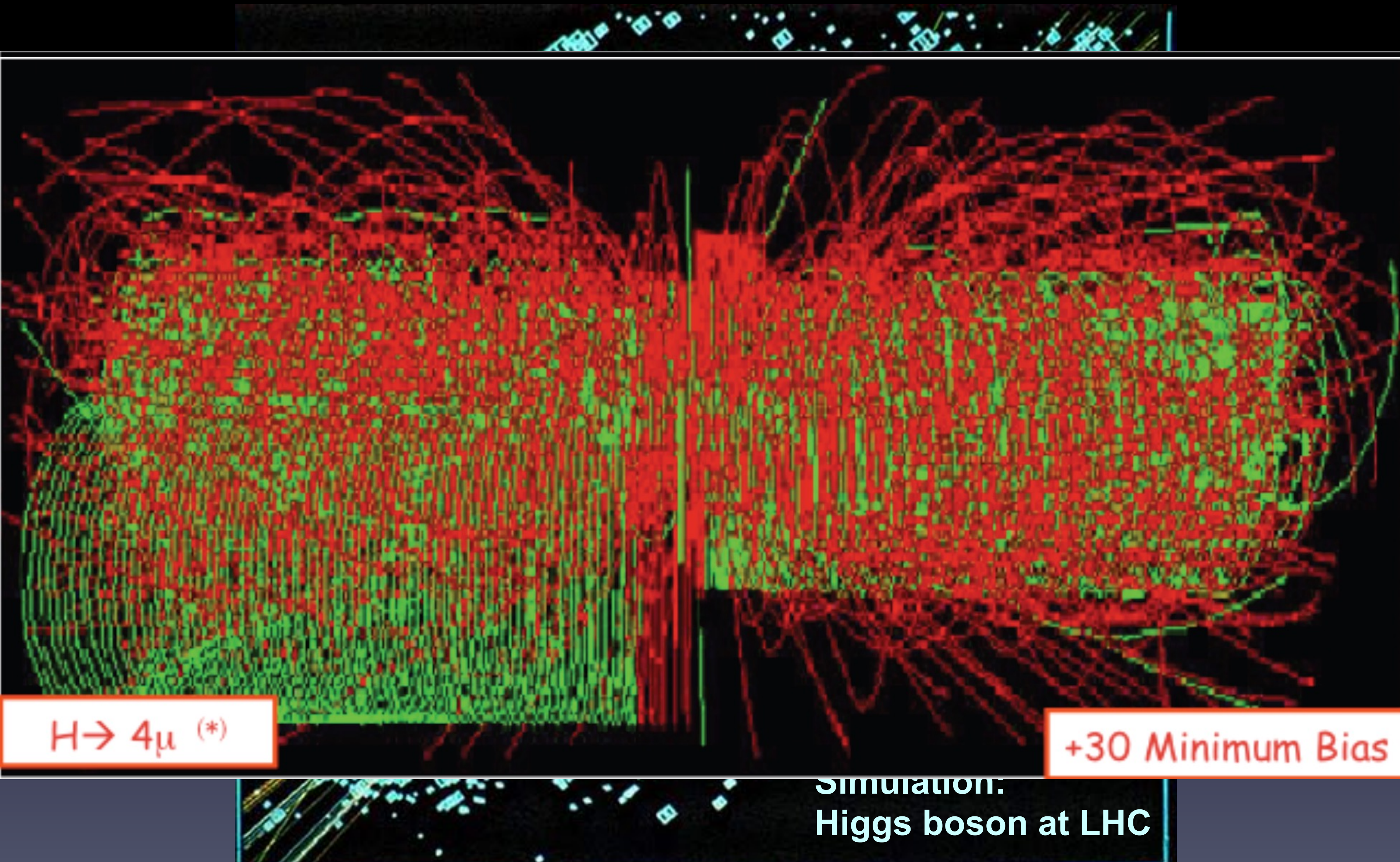
$$\sigma_{d_0} = 11\mu m \oplus \frac{73\mu m}{p_T\sqrt{\sin\theta}}$$

Systematic effects

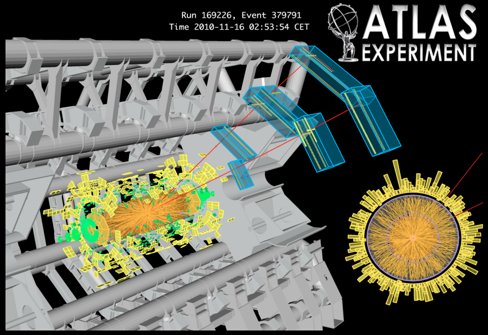
- Alignment
- Knowledge of the B field
- Material



Tracking is more challenging



Tracking at the LHC



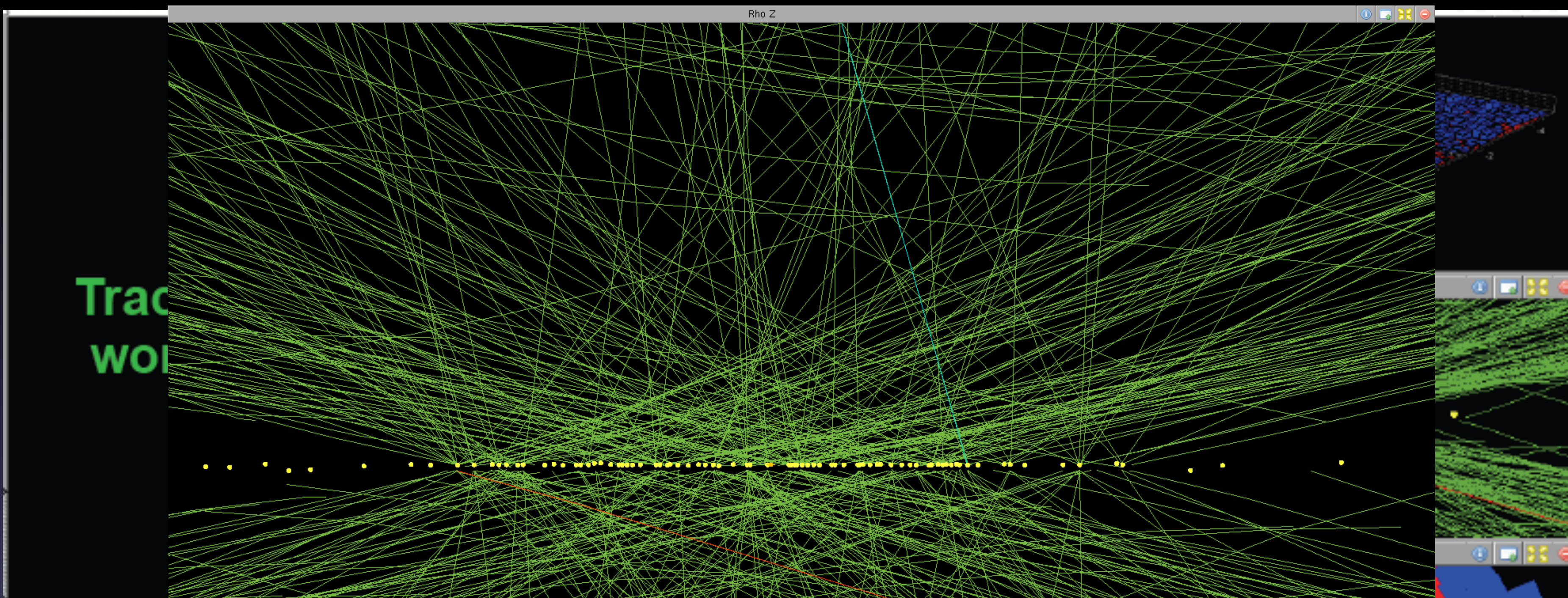
- ~1200 tracks every 25 ns or ~ 10^{11}/second
  - high radiation dose 10^{15} n_{eq} / cm^2 / 10 yrs
  - 600 kGy (60 Mrad) through the ionisation of mips in 250 μm bulk silicon

Requiements:

- Response times of the detector elements and their read-out electronics must be fast enough to process the event in less than 25 ns to minimize the pile-up to one bunch crossing;
- High granularity to keep the occupancy low;
- All elements of the detector, including active material, read-out electronics and cables must be rad-hard.

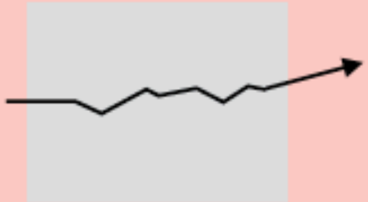
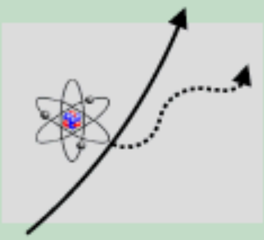
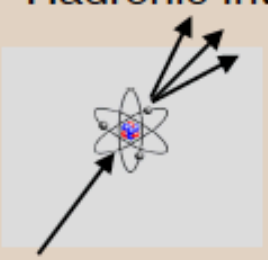
Tracking and Vertex Detectors

- Solid state detectors especially silicon offer high segmentation
- Determine position of primary interaction vertex and secondary decays



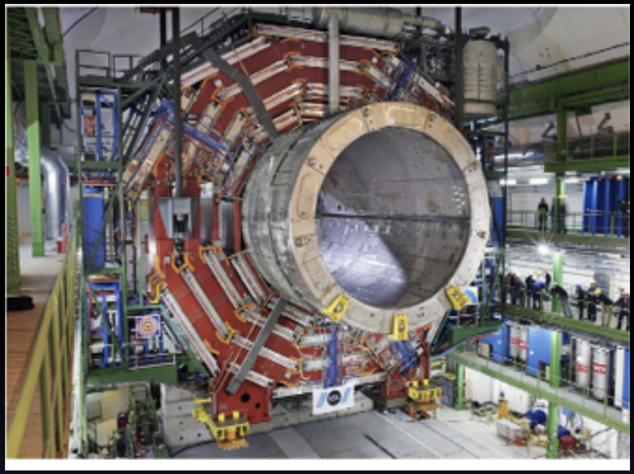
This would have not been possible without semiconductor (pixel and strip) trackers

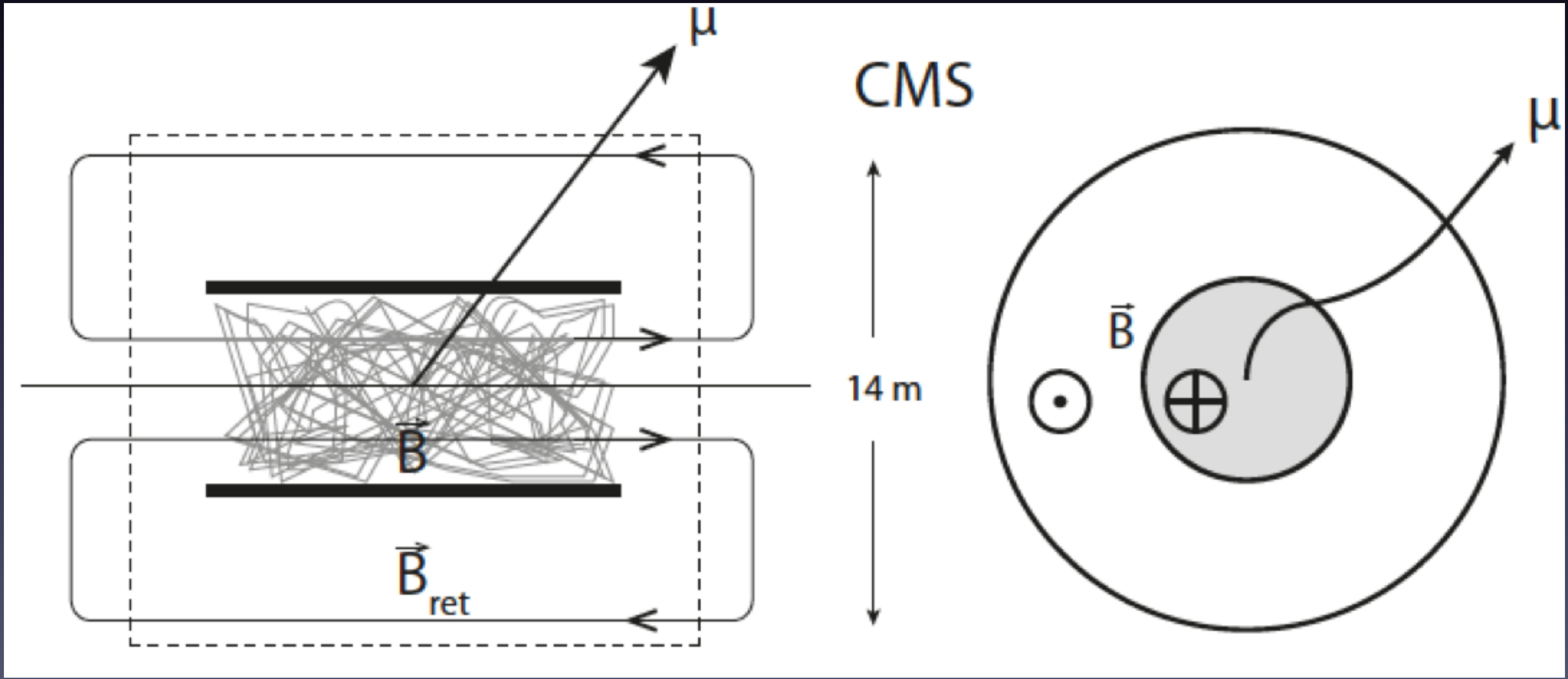
- The interaction of a particle with matter can be used as a working principle for a particle detector.
- The interaction of a particle with matter impact the precision of the measurement

Type	particles	fund. parameter	characteristics	effect
Multiple Scattering 	all charged particle	radiation length X	almost gaussian average effect 0 depends $\sim 1/p$	deflects particles, increases measurement uncertainty
Ionisation loss 	all charged particle	effective density $A/Z^* \rho$	small effect in tracker, small dependence on p	increases momentum uncertainty
Bremsstrahlung 	all charged particle, dominant for e	radiation length X	highly non-gaussian, depends	introduces measurement bias
Hadronic Int. 	all hadronic particles	nuclear interaction length Λ	destroys particle, rather constant effect in p	main source of track reconstruction inefficiency

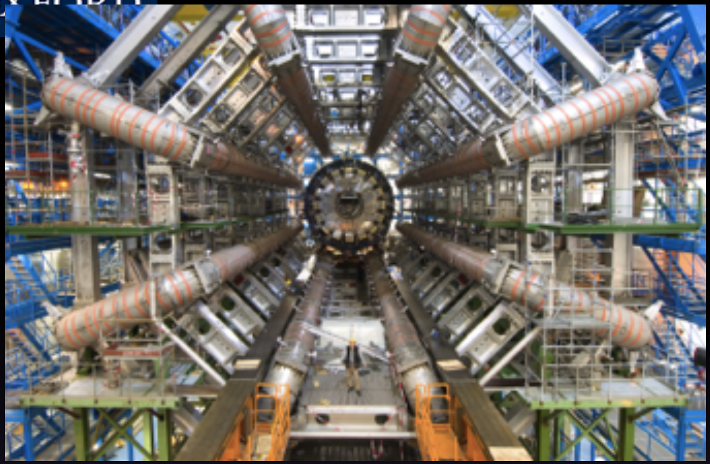
Measuring Muons

CMS:
- measurement of momentum in tracker and B return flux;
- Solenoid with Fe flux return
- Property: μ tracks point back to vertex in r-z plane



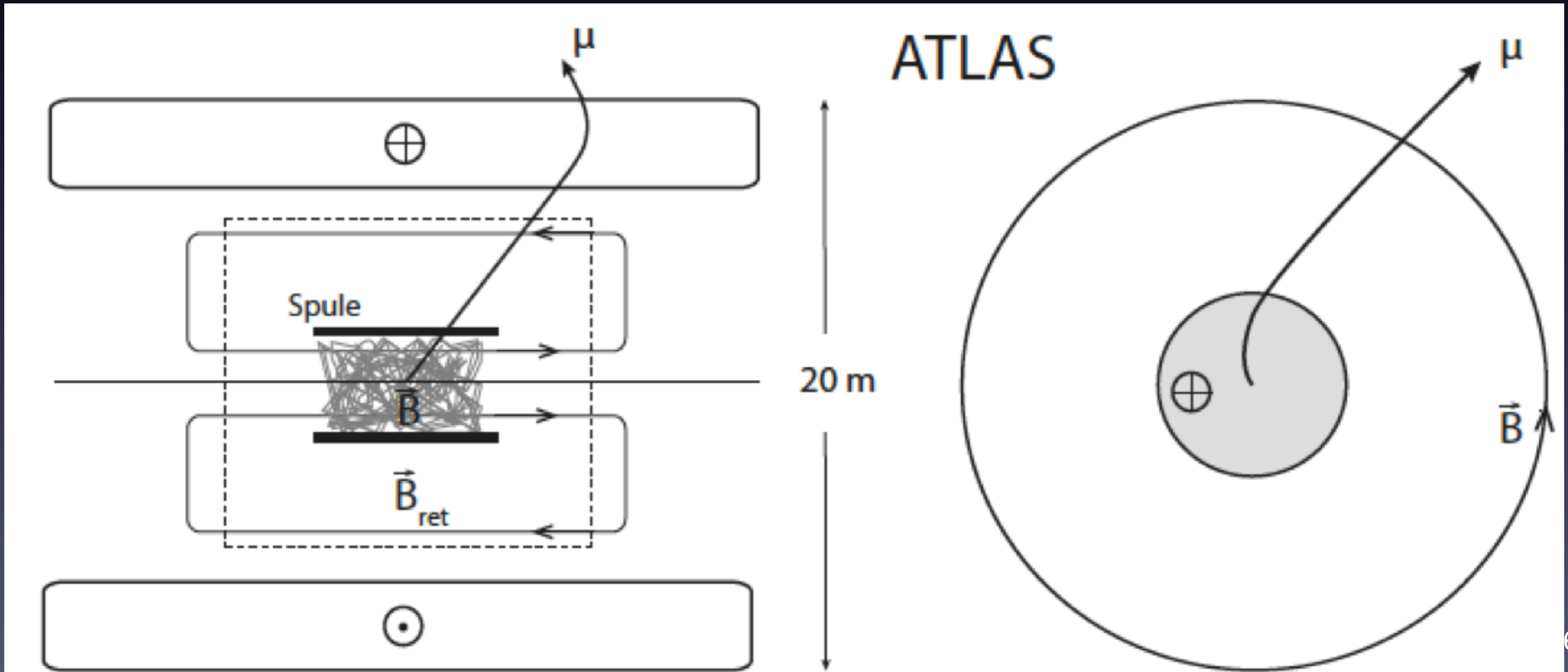


Measuring Muons



ATLAS

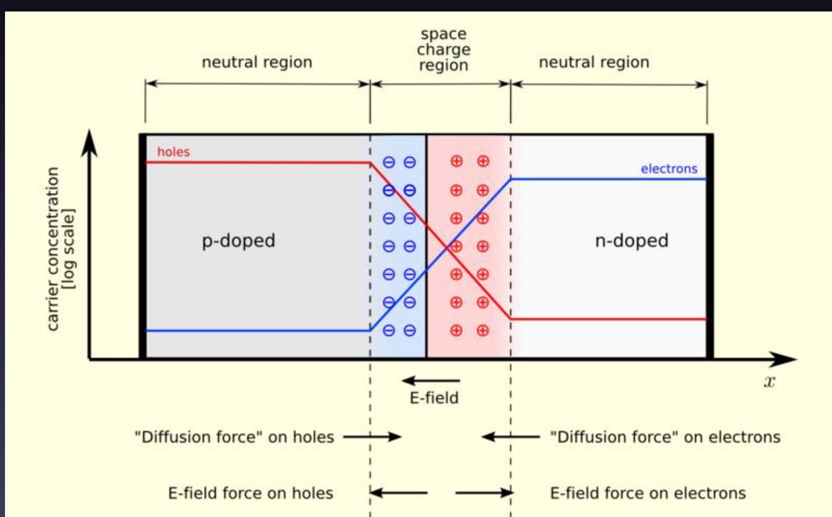
- standalone μ momentum measurement
- Air-core toroid safe for high multiplicities
- Property: σ_p flat with η

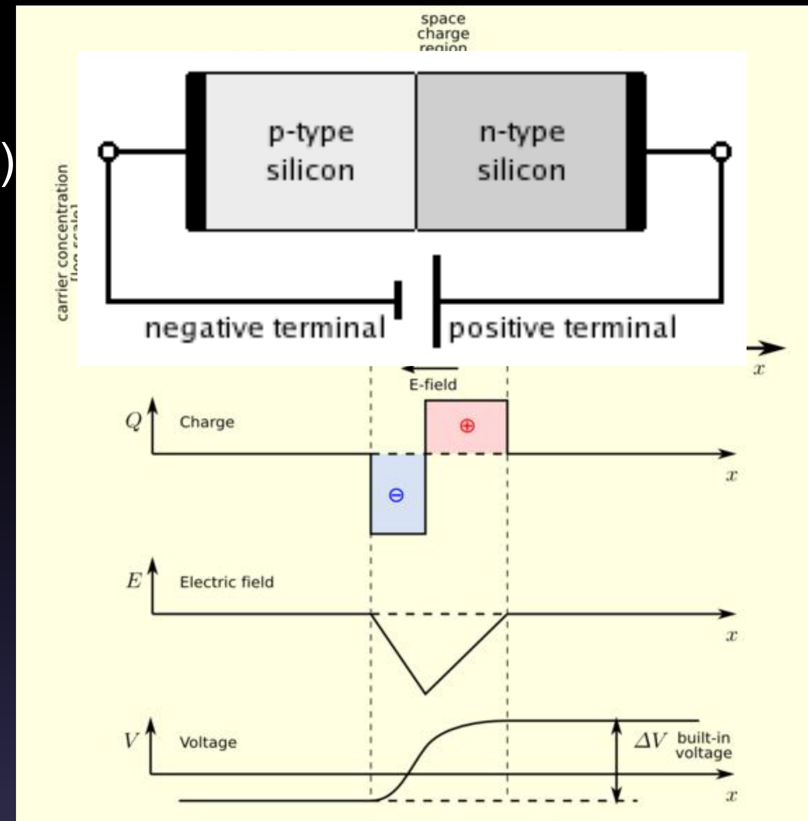


Silicon Detectors

- A silicon detector is a p-n diode
  - n-type (P, As, Sb doping ➠ more electrons)
  - p-type (B, Al, Ga doping➠ more holes)

- p-n junction without external voltage
  - Free charges diffuse until equilibrium is reaches and create the built-in potential





The W of the depletion region can be found by applying Poisson equation and depends on V

$$W = W_p + W_n = \sqrt{\frac{2\varepsilon}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)(V_{bi}+V)}$$

- The space charge (depletion) region can be made bigger by applying a reverse bias voltage

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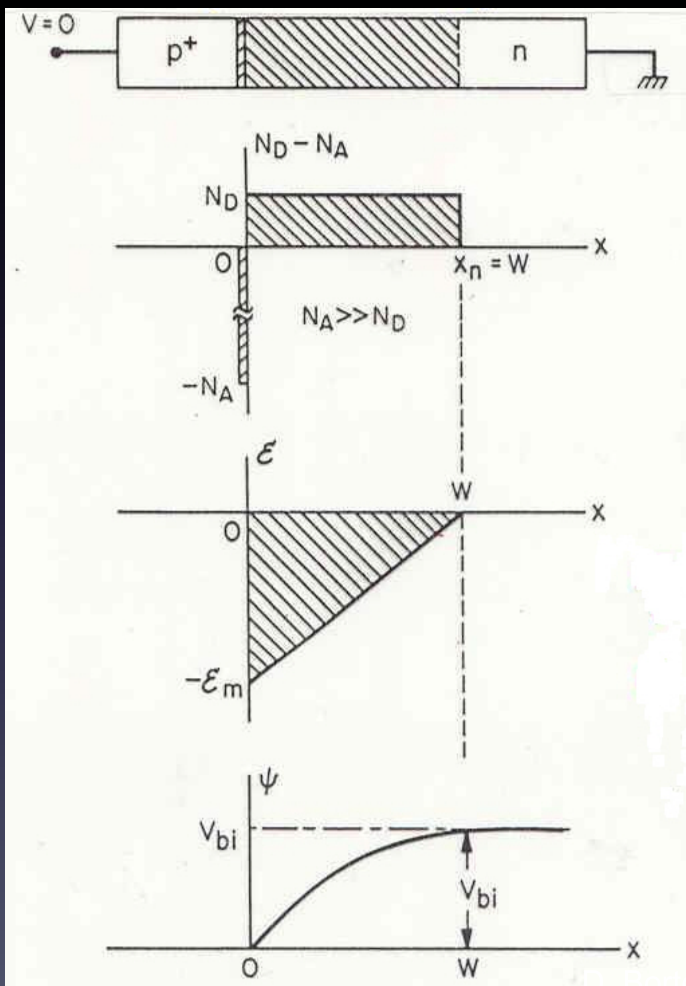
p+-n sensors

- P+-n sensors consists of a thin (~µm), highly doped p+ (~10^{19} cm^{-3}) layer on lightly doped n- (~10^{12} cm^{-3}) substrate
- Since N_A>>N_D most of the n-type silicon is depleted



$$W = \sqrt{\frac{2\varepsilon}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_{bi} + V)}$$
$$\approx \sqrt{\frac{2\varepsilon}{q}\frac{1}{N_D}V}$$

$$W \sim \sqrt{2\varepsilon_0\varepsilon_r\mu\rho|V|}$$

$$\rho = \frac{1}{e\mu N_D}$$

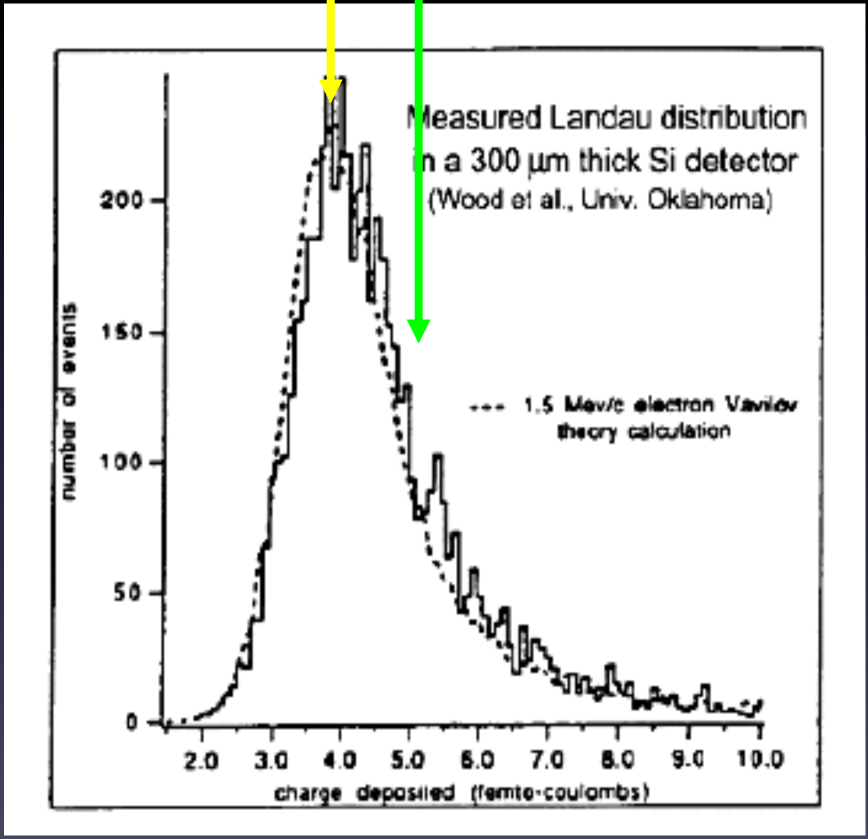
V ... External voltage
ρ..... resistivity
µ ... mobility of majority charge carriers
N_{eff}..effective doping concentration

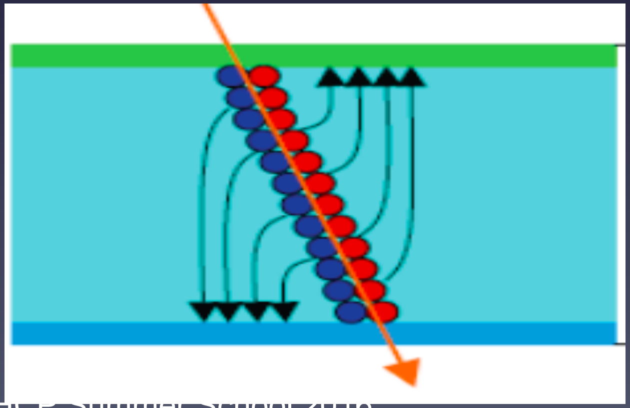
Signal

- The signal generated in a silicon detector depends on the thickness of the depletion zone and on the dE/dx of the particle.
  - The distribution is given by the Landau distribution
  - In silicon the most probable dE/dX of a MIP is 300 eV/μm and the mean ionization energy I_0 = 3.62 eV. Therefore a charged particle creates ≈80 e^-h^+/ μm.
  - For 300 μm silicon the most probable charge is ≈ 24000 e-/h pairs

Most probable charge ≈ 0.7× mean

Mean charge

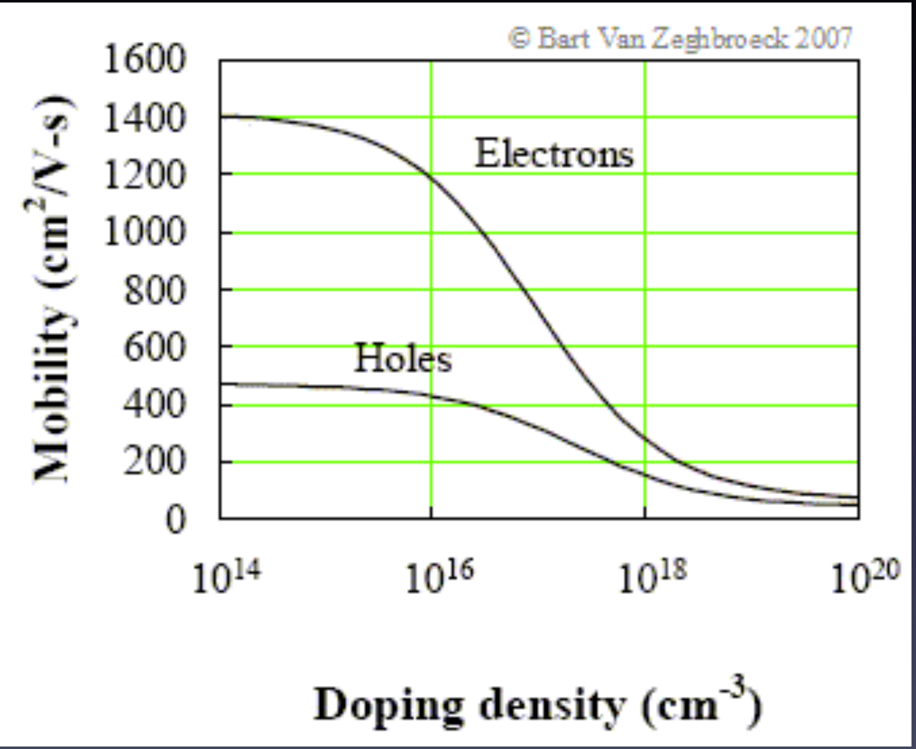




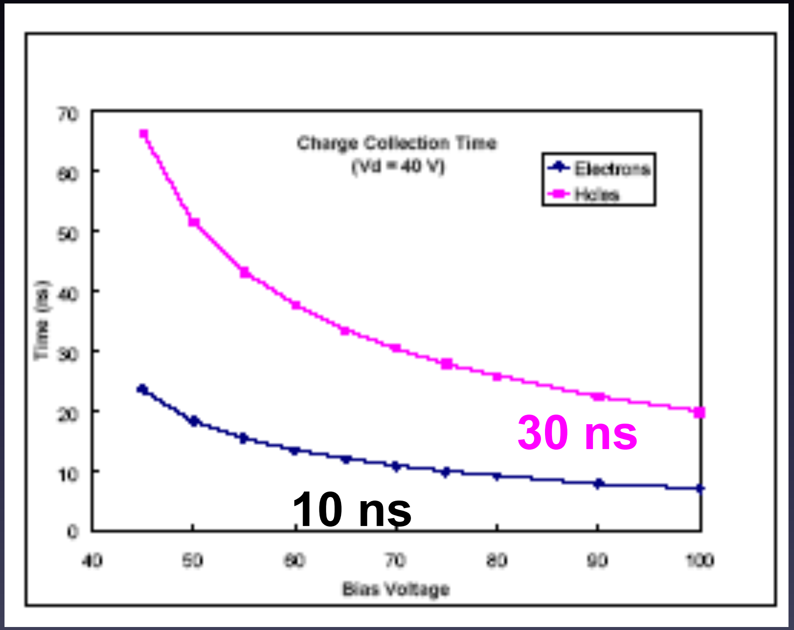
Collection by drift

- Electrons an holes move in an E field F=qE

$$v_{e,h}=\mu_{e,h} E$$



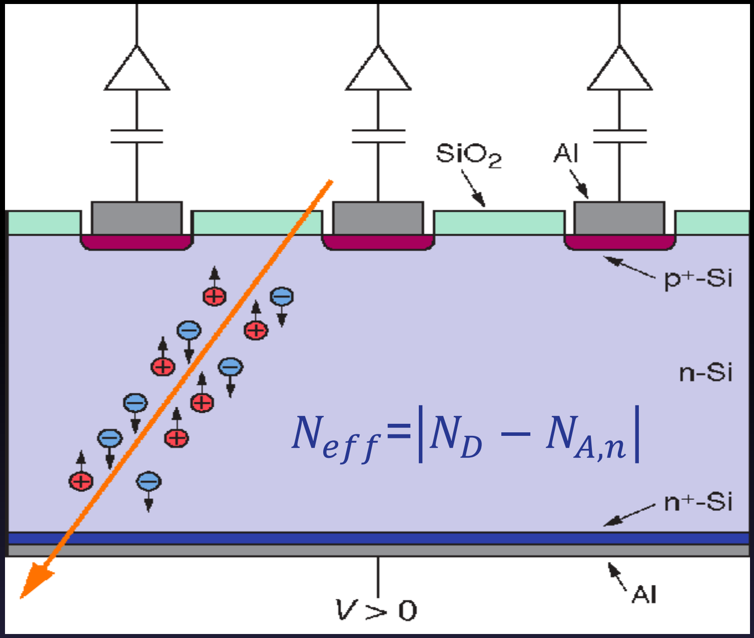
- The time required for a carrier to traverse the sensitive volume is the collection time.

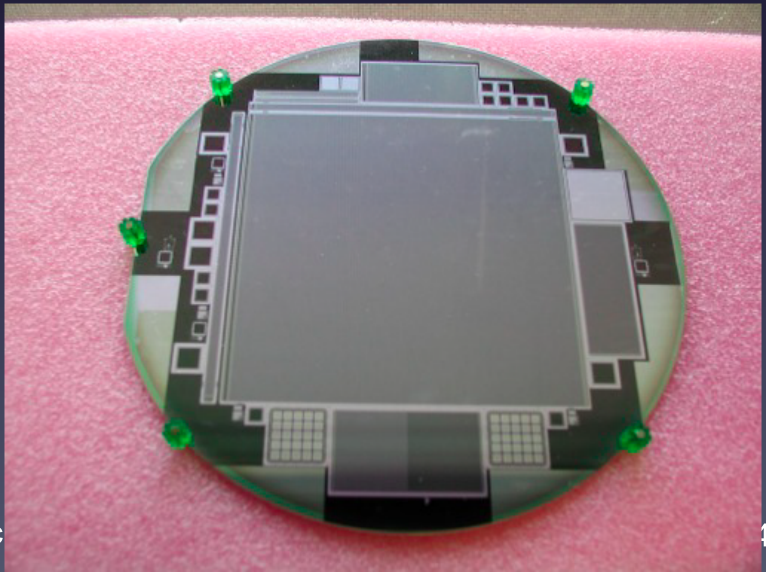


- The collection time can be reduced by over-biasing the sensor

DC Silicon Strip Detectors

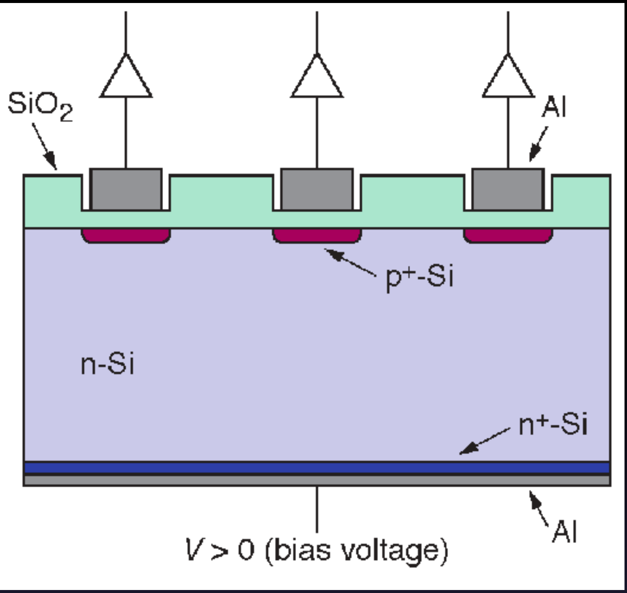
- The drift (current) creates a signal which is amplified by an amplifier connected to each strip allowing precise position determination
- Standard configuration:
  - p^+n junction: $N_A \approx 10^{19}$ cm^{-3}, $N_D \approx 1$–$5{\cdot}10^{12}$ cm^{-3}
  - Substrate n doped (~2-10 kΩcm) and ~300μm thick
  - n^+ layer on backplane to improve ohmic contact
  - Aluminum metallization

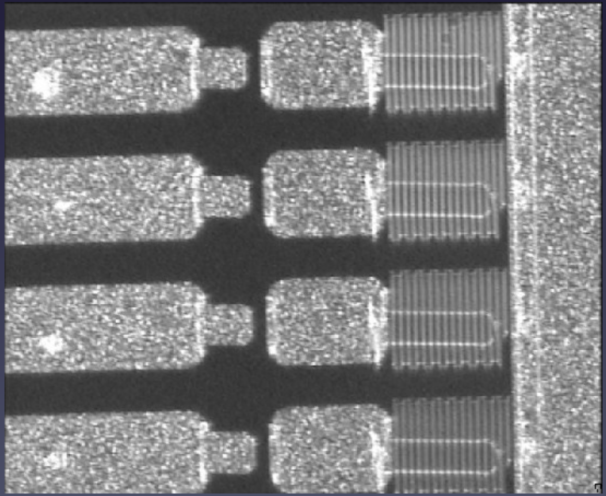


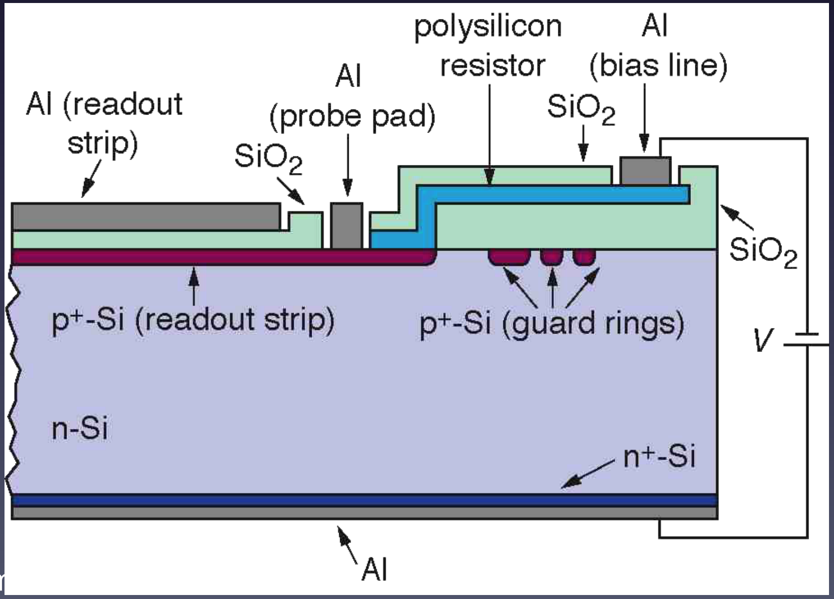


AC coupled Strip Detector

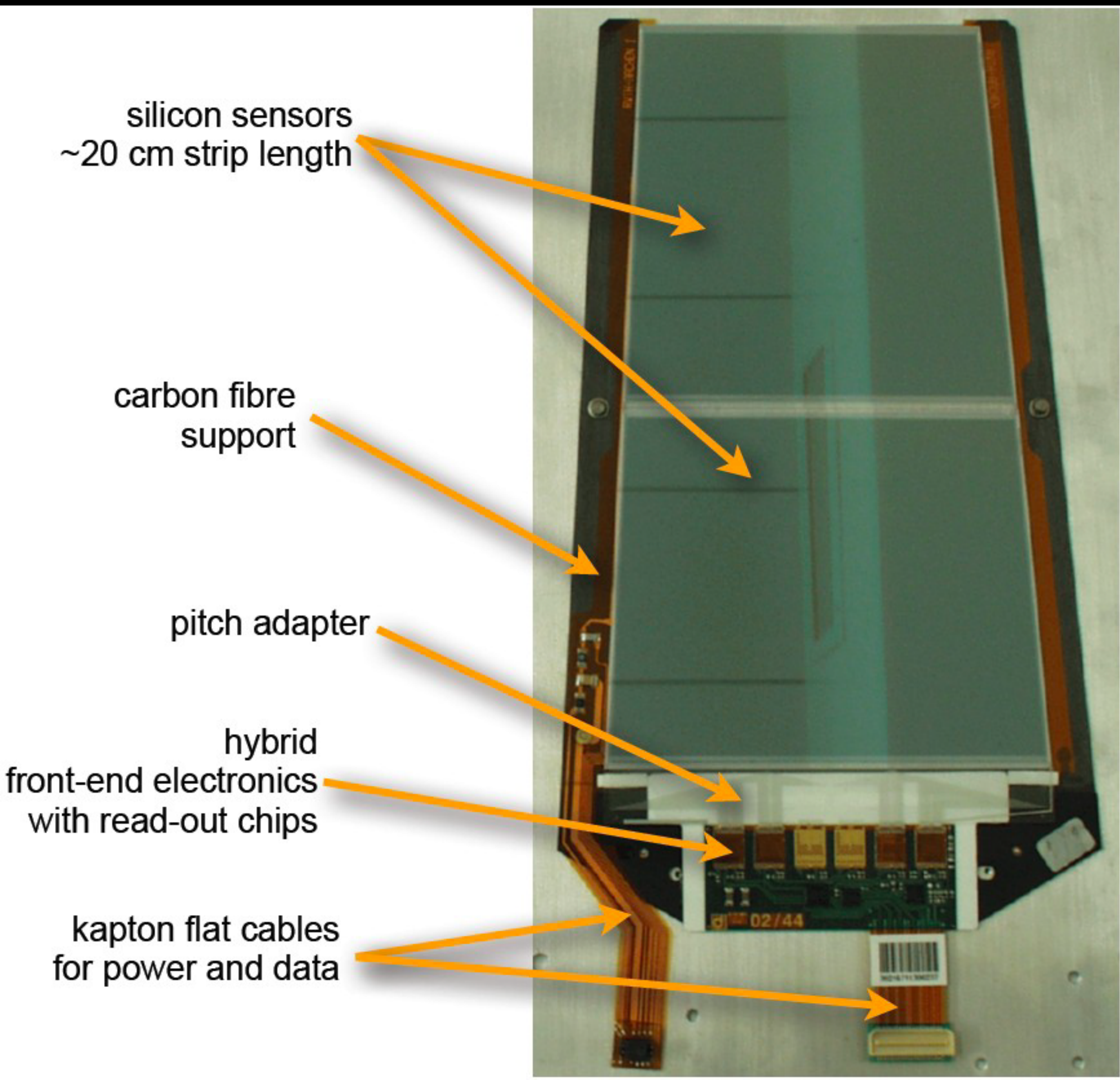
- AC coupling blocks DC leakage current
- Integration of coupling capacitances in standard planar process.
  - Deposition of SiO_2 with a thickness of 100–200 nm between p+ and aluminum strip
  - Increase quality of dielectric by a second layer of Si_3N_4.
- Coupling capacitance ≈ 8–2 pF/cm
- Long poly silicon resistor with R>1MΩ to connect the bias voltage to the strips:

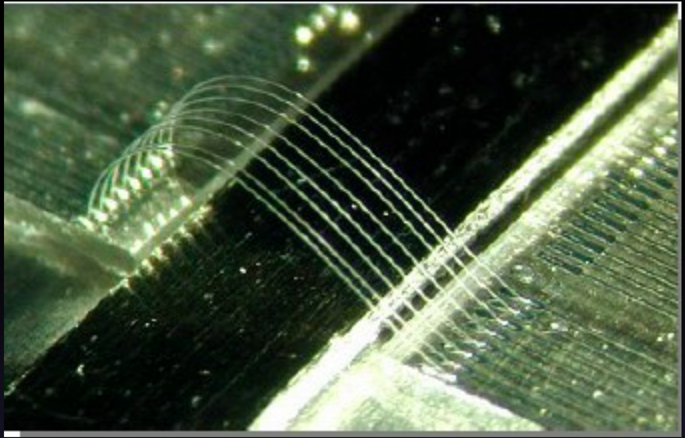


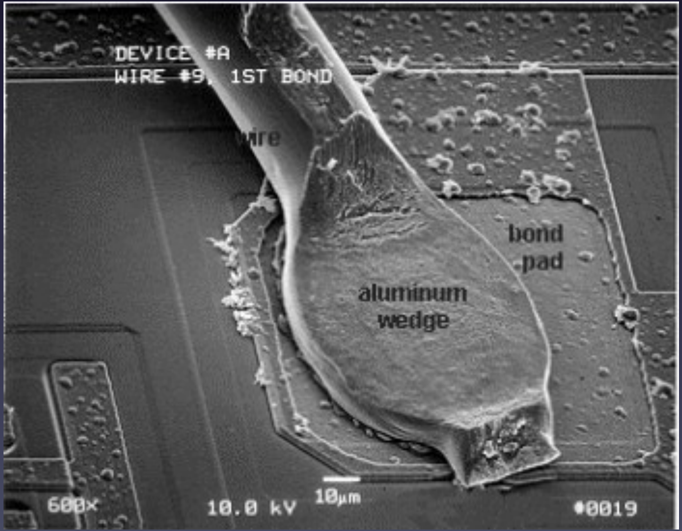




A typical strip module (CMS)

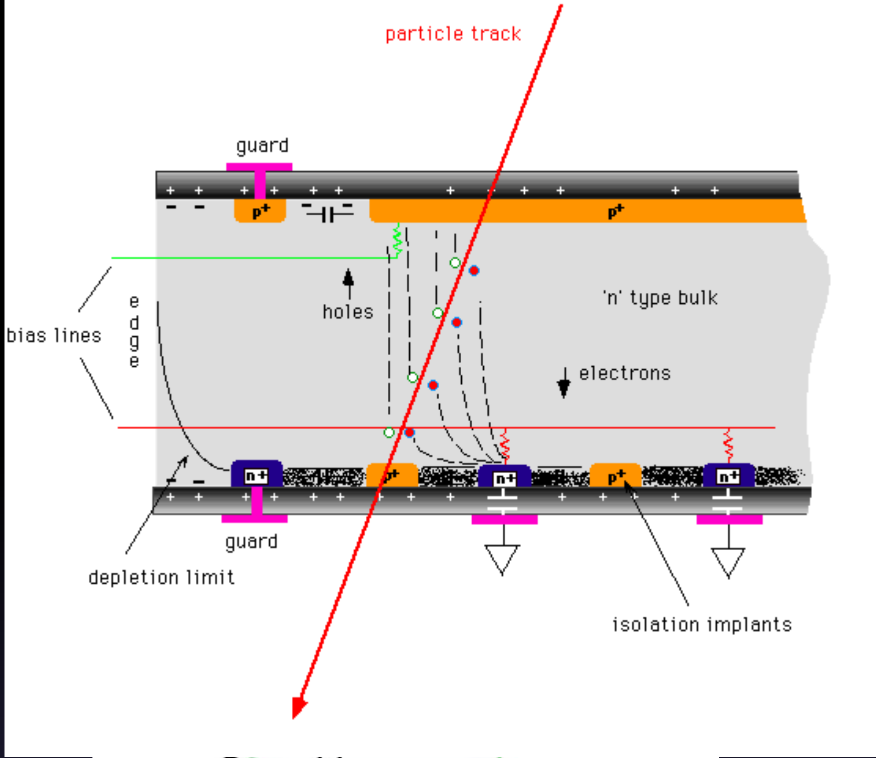


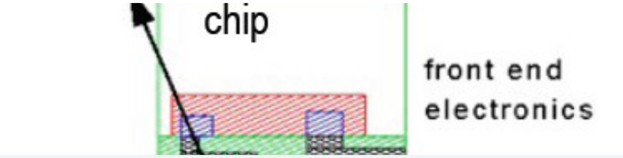


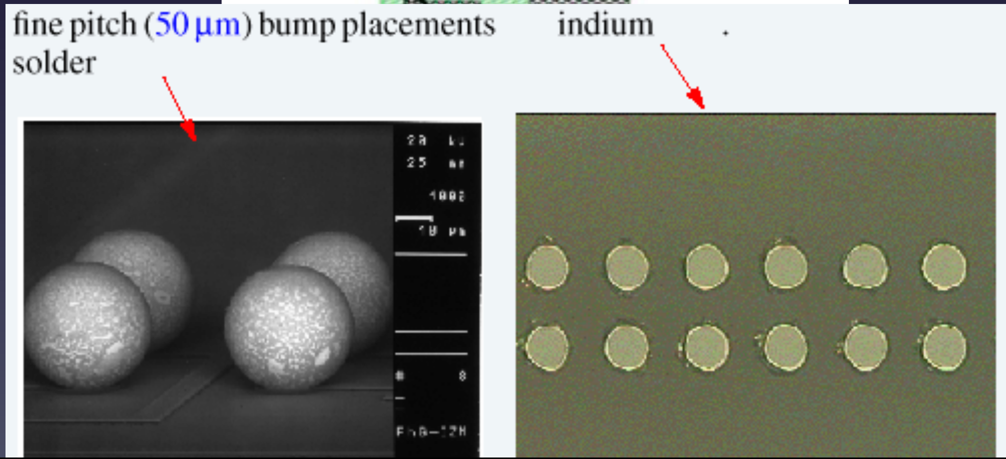


Pixel detector

- Advantages
  - Pixel detectors provides space-point information removing hit ambiguities
- Small pixel area
  - low detector capacitance (≈1 fF/Pixel)
  - large signal-to-noise ratio (e.g. 150:1).
- Small pixel volume
  - low leakage current (≈1 pA/Pixel)
- n^+-on n for the LHC
  - Electron have faster collection time
- **Disadvantages:**
  - Large number of readout channels
  - Large bandwidth
  - Large power consumption
  - Bump bonding is costly and complex



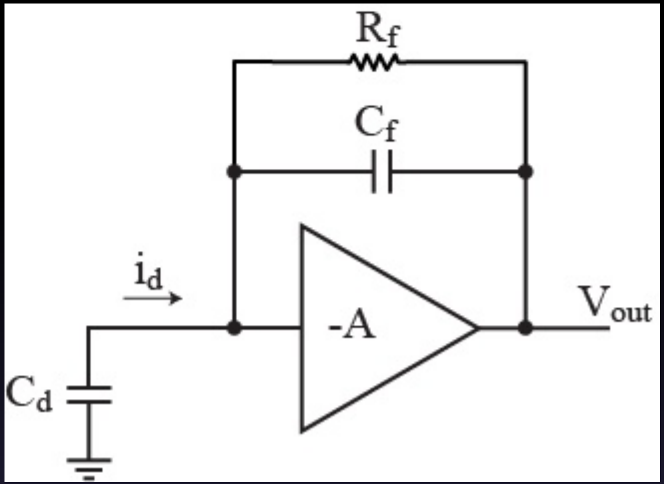




https://www.youtube.com/watch?v=ojeVwQxOrGo&feature=youtu.be

Readout

- The signal of a silicon detector is readout by a charge sensitive amplifier



$$V_O = \frac{Q_D}{C_f}$$

$$\tau_f = R_f C_f$$

- The most simple CSA has a feedback capacitor C_f between the input and output stores the charge from the detector.
- The gain of the preamplifier is $1/C_f$.
- The resistor in parallel with the feedback capacitor can be used to reset the CSA
- Each pulse of current from the detector causes on output voltage proportional to the integral of the detector current

$$V_{out}(t) \propto Q(t) = \int^{t} i_d \, d\tau$$

Readout Noise

- Noise is given as "equivalent noise charge" ENC.

$$\mathrm{ENC} = \frac{\text{noise output voltage (rms)}}{\text{signal output voltage for the input charge of } 1e^-}$$

Reference
Rossi, Fischer, Rohe, Wermes
Pixel Detectors

$$ENC_{tot}^2 = ENC_{shot}^2 + ENC_{therm}^2 + ENC_{1/f}^2$$

$$ENC_{\mathrm{shot}} = \sqrt{\frac{I_{\mathrm{leak}}}{2q}\tau_f} = 56e^- \times \sqrt{\frac{I_{\mathrm{leak}}}{\mathrm{n}A}\frac{\tau_f}{\mu s}}$$

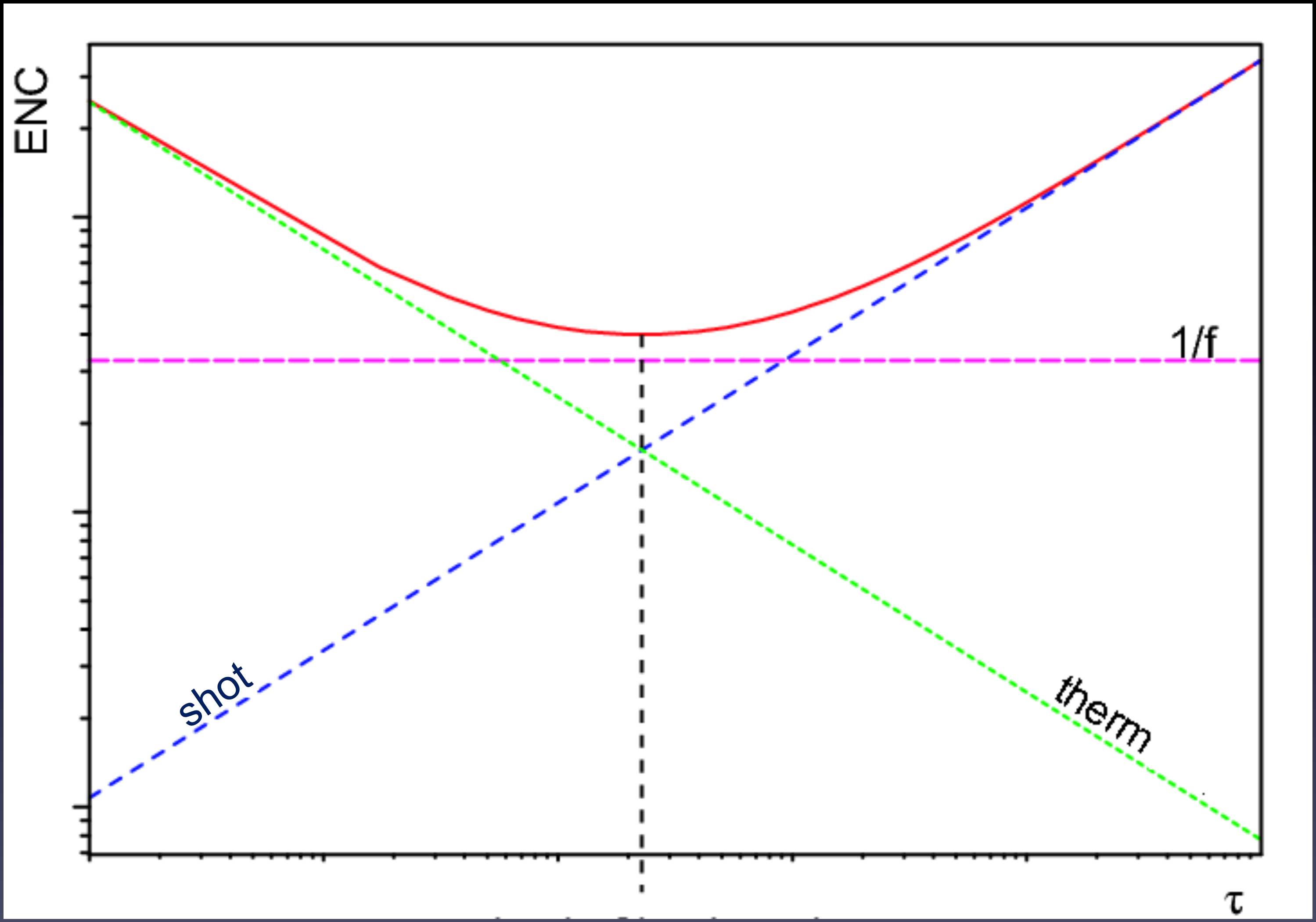
$$ENC_{\mathrm{therm}} = \frac{C_f}{q}\sqrt{\langle v_{\mathrm{therm}}^2\rangle} = \sqrt{\frac{kT}{q}\frac{2C_D}{3q}\frac{C_f}{C_{load}}} = 104e^- \times \sqrt{\frac{C_D}{100\,\mathrm{fF}}\frac{C_f}{C_{load}}}$$

$$ENC_{1/\mathrm{f}} \approx \frac{C_D}{q}\sqrt{\frac{K_f}{C_{ox}WL}}\sqrt{\ln\left(\tau_f \frac{g_m}{C_{load}}\frac{C_f}{C_D}\right)} = 9e^- \times \frac{C_D}{100\,\mathrm{fF}}(\text{for NMOS trans.})$$

W, L = width and length of trans. gate
K_f = 1/f noise coefficient
C_{ox} = gate oxide capacitance

C_f = feedback capacitance
C_{load} = load capacitance
C_D = detector capacitance
τ_f = feedback time constant

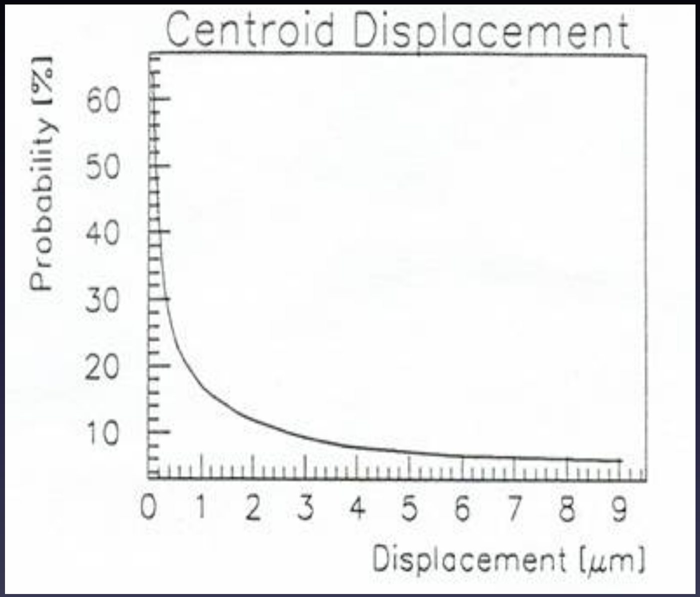
Noise



Position resolution

The position resolution depends on various factors

- Physics processes:
  - Diffusion of charge carriers
  - Statistical fluctuations of the energy loss



Low probability δ(E) release additional electrons drifting perpendicularly to the track and spoiling position resolution

- External parameters
  - Binary readout or read out of analogue signal value
  - Distance between strips/pixels (pitch)
  - Signal to noise ratio

- Strip detector with binary readout

$$\sigma_X = \frac{p}{\sqrt{12}}$$

- Typical pitch (distance between strips) 100-50 μm ➡ $\sigma_x \simeq$ 10-30 μm

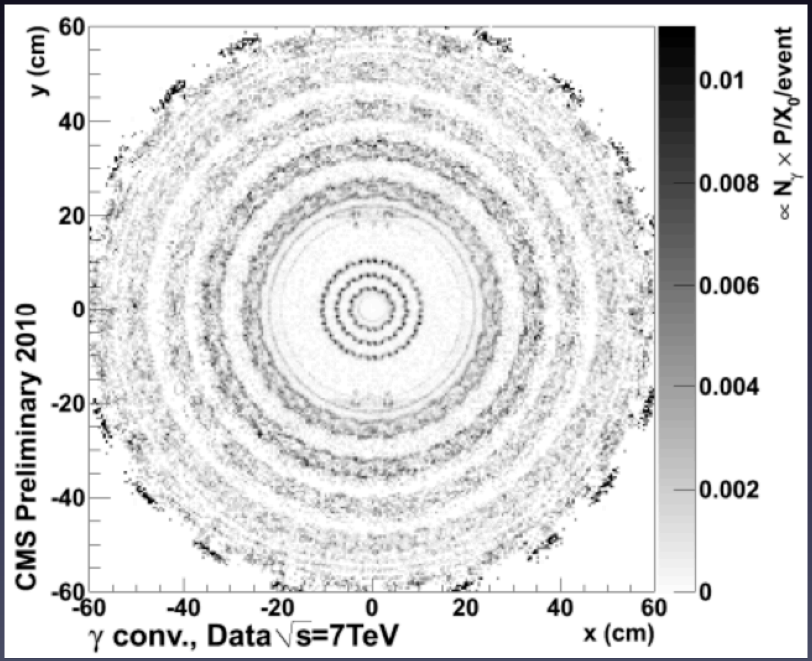
- One can do better with analog readout

$$\sigma_X \propto \frac{p}{SNR}$$

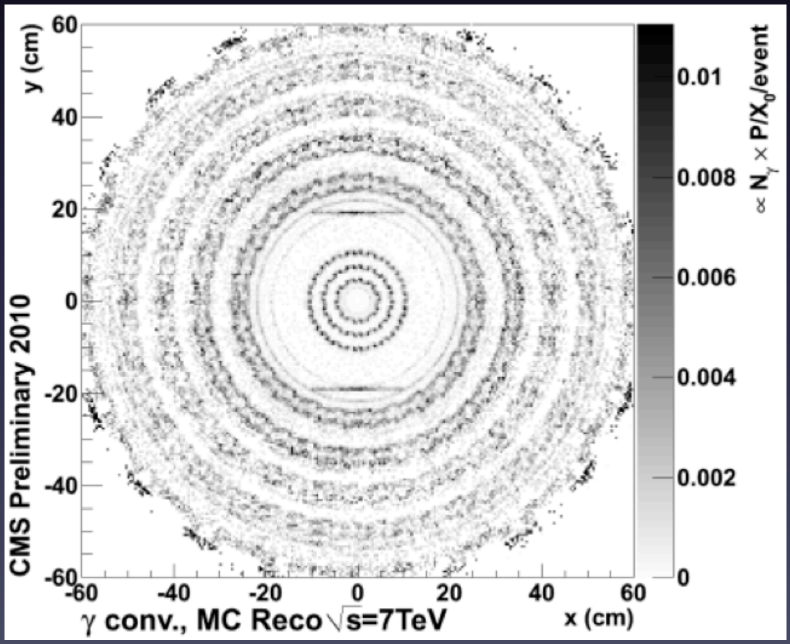
Material

- Reconstruction of photon conversions ($\gamma \rightarrow e^+e^-$) can provide precise map of the material
  - The number of photon conversion in a volume ≈ amount of material x reconstruction efficiency
  - The reconstructed vertices can be used to build detailed maps of the Tracker material

DATA

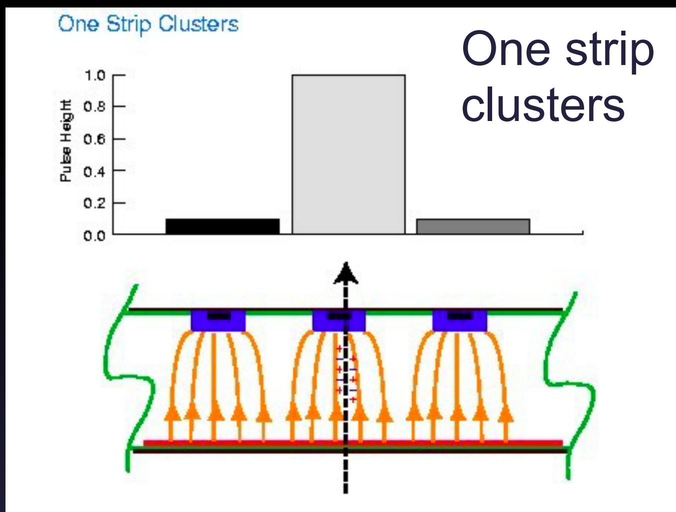


MC

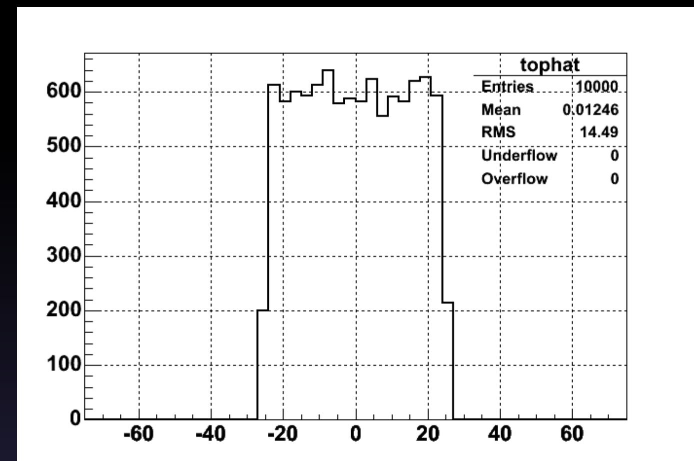


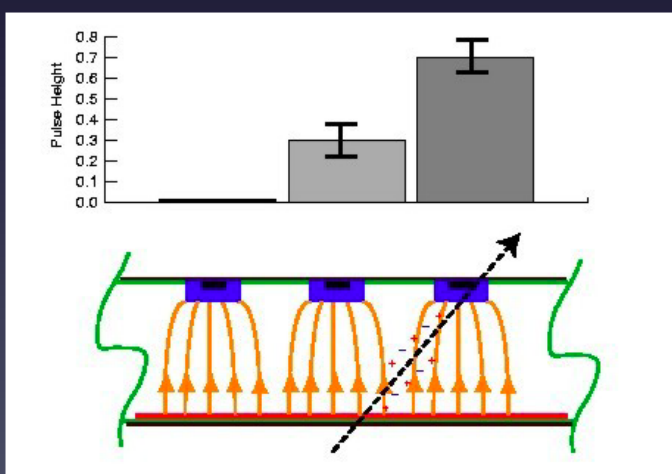
Position resolution

- Resolution is the spread of the reconstructed position minus the true position



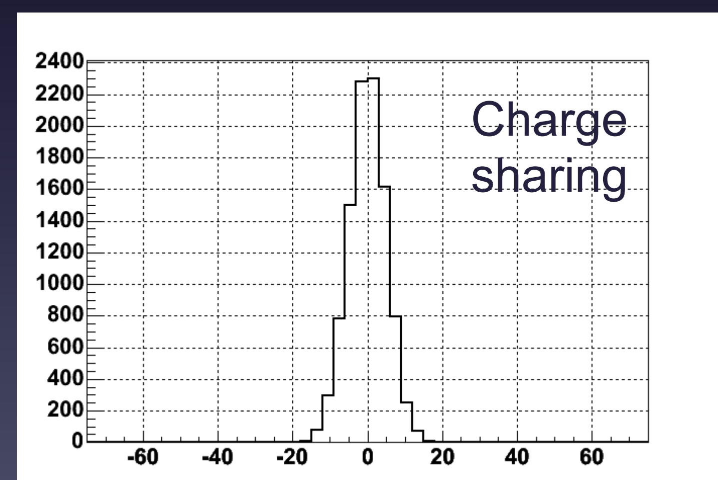
$$\sigma = \frac{pitch}{\sqrt{12}}$$



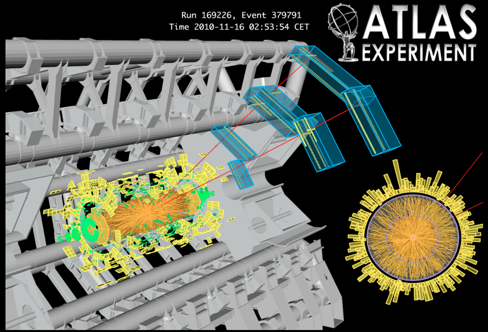


$$\sigma \approx \frac{pitch}{1.5 \cdot \sqrt{12}}$$

$$= \frac{PH_R}{PH_L + PH_R}$$

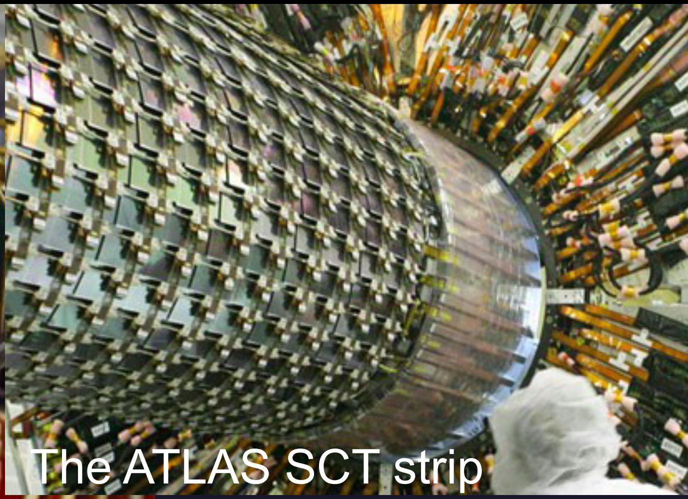


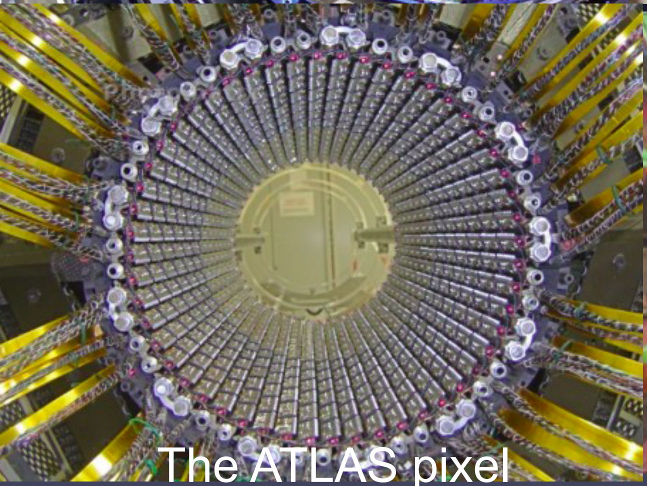
Tracking at the LHC



- ~1200 tracks every 25 ns or ~ 10^{11}/second
  - high radiation dose 10^{15} n_{eq} / cm^2 / 10 yrs
  - 600 kGy (60 Mrad) through the ionisation of mips in 250 μm bulk silicon
- Vertexing is critical to distinguish high p_T collision from pile up:
  - LHC has a Gaussian sigma along the beam direction of ~ 8 cm
  - Vertices of the different inelastic collisions are separated by ≈1 cm on average
- Tracker must deal with very complex pattern recognition
  - Many measurement layers
- Complexity increases as a function of the occupancy (<number of hits>/ event in one elementary detector element)
  - Need to have occupancy <1%
- Most particles are inside the detector in the next bunch crossing
  - high p_T particles travel ≈7 m from the interaction point in 25 ns
  - low p_T particle may curl 2–3 times inside the tracker

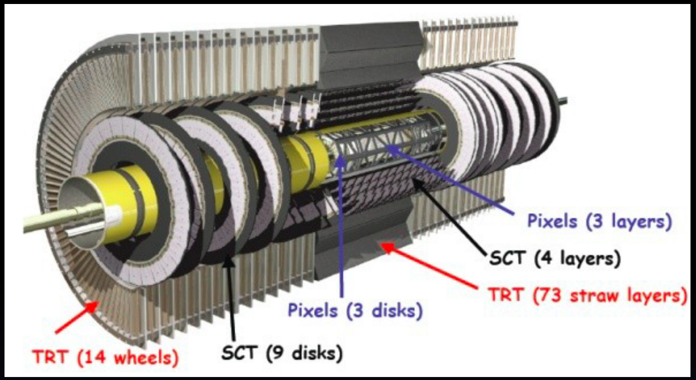
The LHC detectors



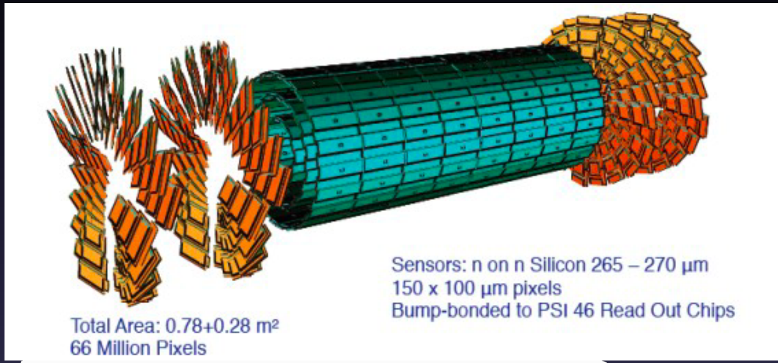


The LHC silicon detectors

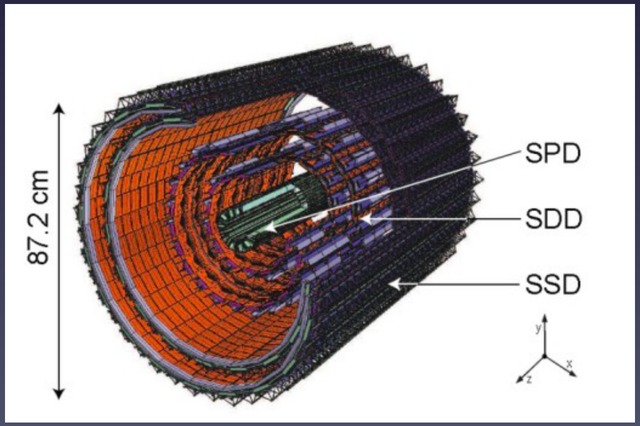
- **ATLAS** Strips: 61 m^2 of silicon, 4088 modules, $6x10^6$ channels Pixels: 1744 modules, 80 x 10^6 channels



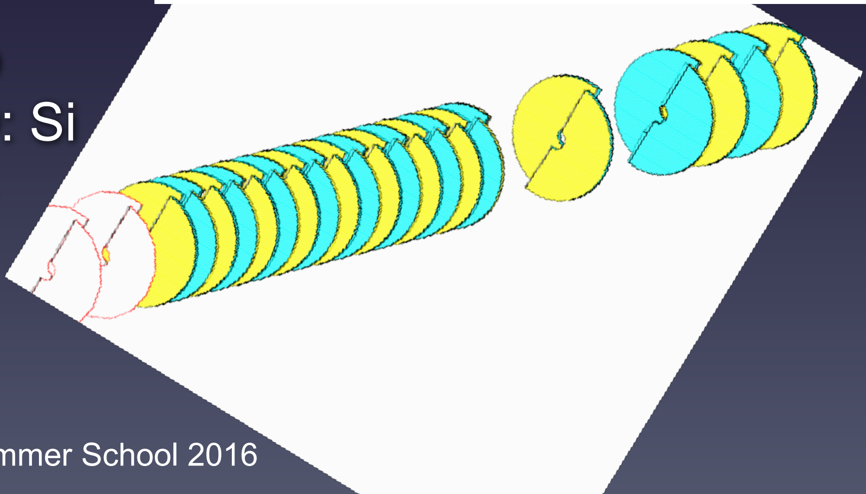
- **CMS** the world largest silicon tracker 200 m^2 of strip sensors (single sided) 11 x 10^6 readout channels ~1m^2 of pixel sensors, $60x10^6$ channels



- **ALICE** Pixel sensors, Drift detectors Double sided strip detectors



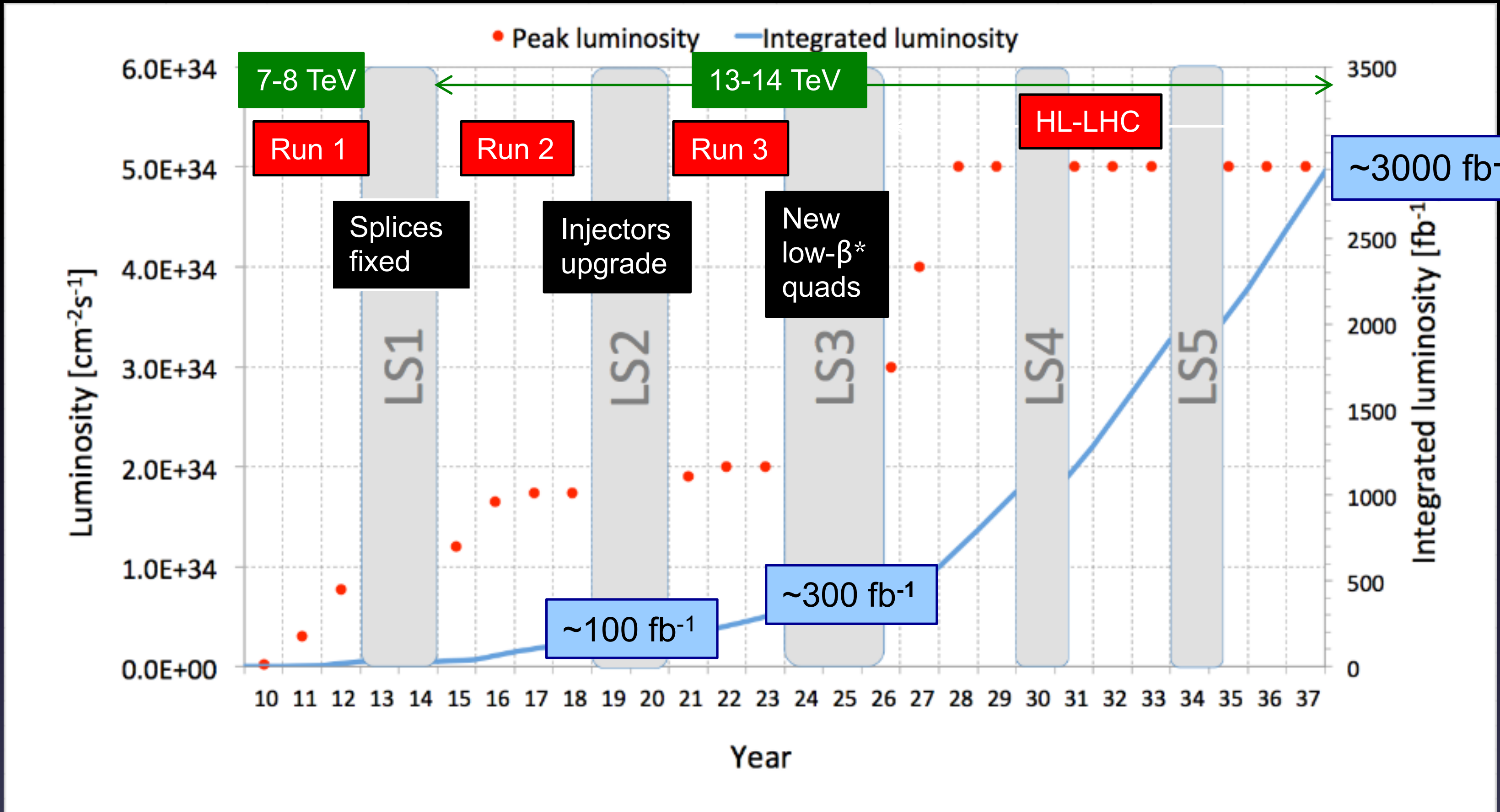
- **LHCb** VELO: Si Strips



Comparison of LHC trackers

	ALICE	ATLAS	CMS
R inner	3.9 cm	5.0 cm	4.4 cm
R outer	3.7 m	1.1 m	1.1 m
Length	5 m	5.4 m	5.8 m
$\|\eta\|$ range	0.9	2.5	2.5
B field	0.5 T	2 T	4 T
Total X_0 near η=0	0.08 (ITS) + 0.035 (TPC) + 0.234 (TRD)	0.3	0.4
Power	6 kW (ITS)	70 kW	60 kW
rϕ resolution near outer radius	~ 800 μm TPC ~ 500 μm TRD	130 μm per TRT straw	35 μm per strip layer
p_T resolution at 1GeV and at 100 GeV	0.7% 3% (in pp)	1.3% 3.8%	0.7% 1.5%

The LHC Future

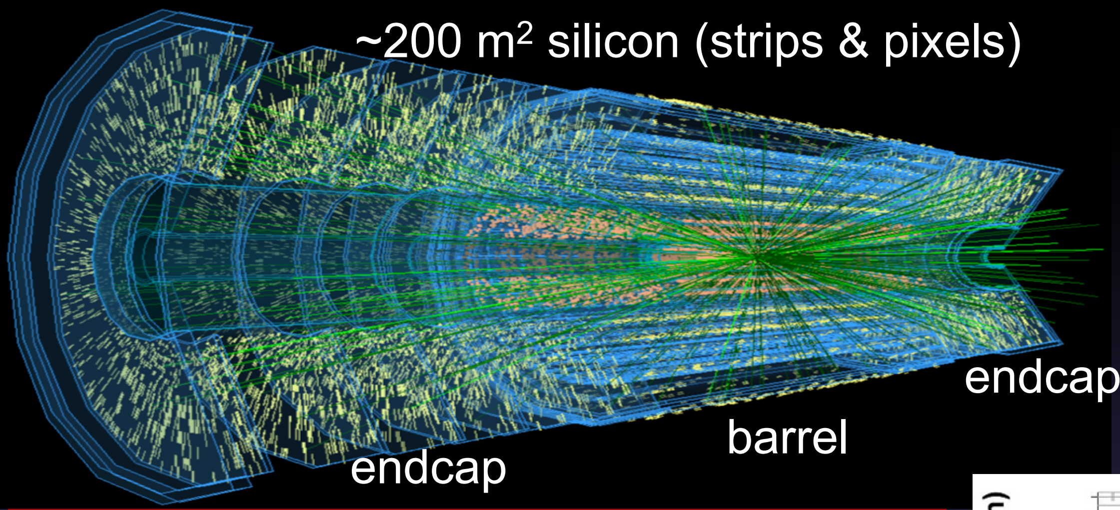


- ❑ LIU/HL-LHC Cost & Schedule reviews in March 2015 and October 2016
- ❑ ATLAS and CMS: "scoping documents" presented to Resources Review Board October 2015 → scale of funding defined, now proceeding to TDRs
- ❑ ALICE and LHCb: major upgrades under construction for installation in LS2

Fabiola Gianotti

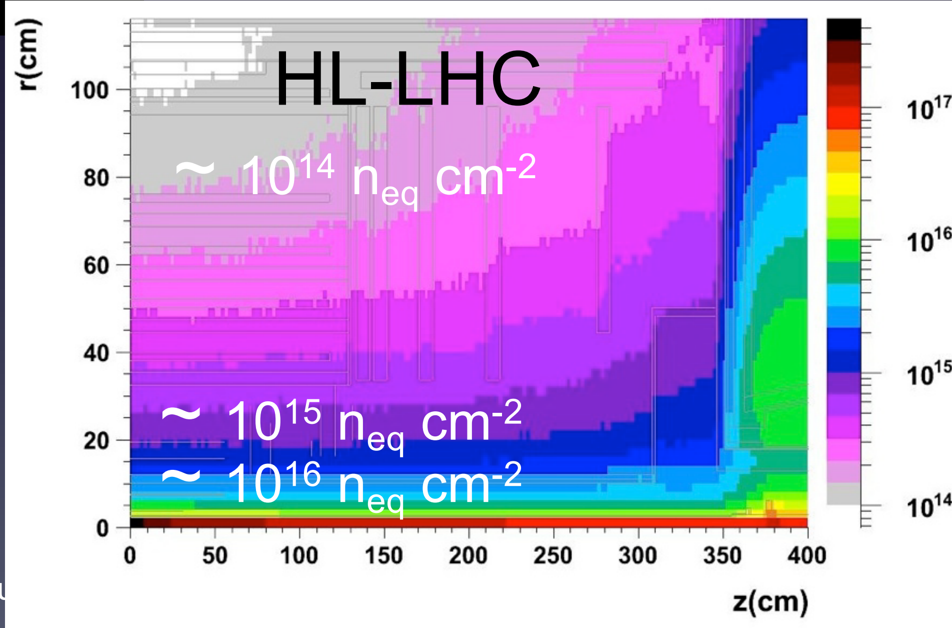
HL-LHC tracker upgrades

- New all-silicon trackers for ATLAS and CMS



- Increased luminosity and larger area require
  - Higher hit-rate capability
  - Increased granularity
  - Higher radiation tolerance
  - Lighter detectors
  - Cheaper price tag !!

- Radiation hardness and rate performance must increase compared to LHC Run I
  - Run 2 (2015) ≈ x5
  - Run 3 (2018) ≈ x 5-10
  - HL-LHC (>2025) ≈ x 10-30
- In the inner pixel layers:
  - 10^{16} n_{eq} cm^{-2} and TID > 1 Grad



References

- Interaction with Matter & detectors:
  - CERN Summer school lectures (D. Bortoletto, W. Reigler): https://indico.cern.ch/event/387976/
  - The Physics of Particle detectors- DESY- organized by E. Garutti http://www.desy.de/~garutti/LECTURES/ParticleDetectorSS12/Lectures_SS2012.ht
  - CERN-Fermilab Hadron Collider Physics Summer School: http://hcpss.fnal.gov/hcpss14/
- Silicon: Manfred Krammer http://www.hephy.at/fileadmin/user_upload/Lehre/Unterlagen/Praktikum/Halbleiterdetektoren.pdf
- CMOS:
  - I. Peric :https://indico.cern.ch/event/237380/
  - W.Snoyes https://agenda.infn.it/getFile.py/access?contribId=62&resId=0&materialId=slides&confId=8834
- Tracking
  - Excellent lectures on tracking algorithms by A. Saltzburger at HCPSS2014
  - Previous CERN academic lecture by P. Wells https://indico.cern.ch/event/526765/
- New ideas for silicon detectors:
  - Great summary by Norbert Wermes at VCI 2016: https://indico.cern.ch/event/391665/sessions/160850/#20160215
  - TWEPP: Topical Workshop on electronic for Particle Physics. Excellent talk by F. Faccio on radiation effects on electronics
  - VCI, VERTEX, PIXEL, Trento workshops

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