Tracking detectors at the LHC

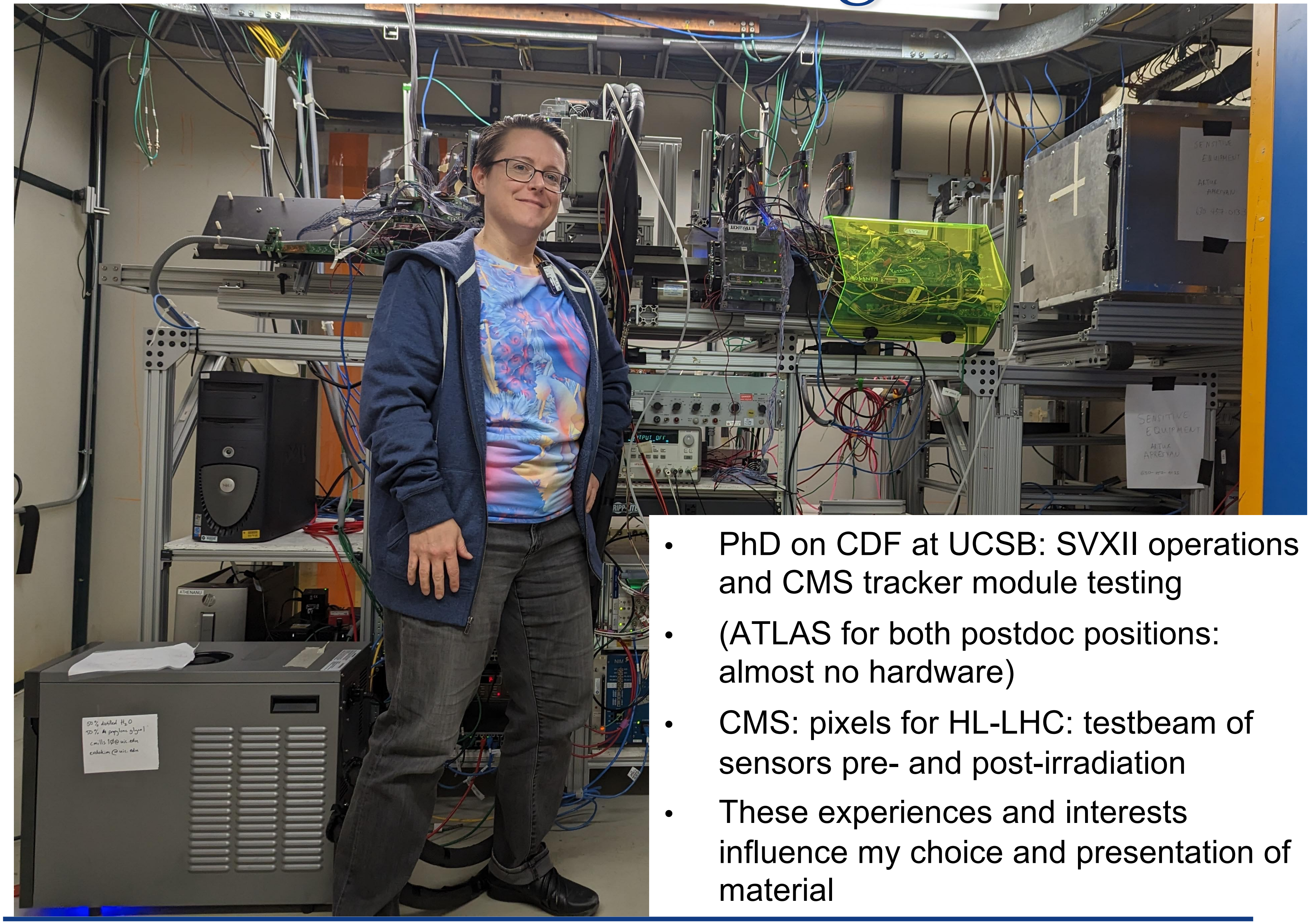
corrinne mills

July 2024

Overview

- Day 1: Depth, and the TRT
  - → *What are tracking detectors for?*
  - → *A gas-ionization-based detector: the TRT at ATLAS*
  - → *Physics of silicon detectors*
  - → *Radiation damage*
- Day 2: Breadth, and the future
  - → *The present: CMS, ATLAS, LHCb*
  - → *The current future*
    - Pixel and strip detector upgrades
    - LGAD timing detectors
  - → *The future future*
    - MAPS and flexible detectors

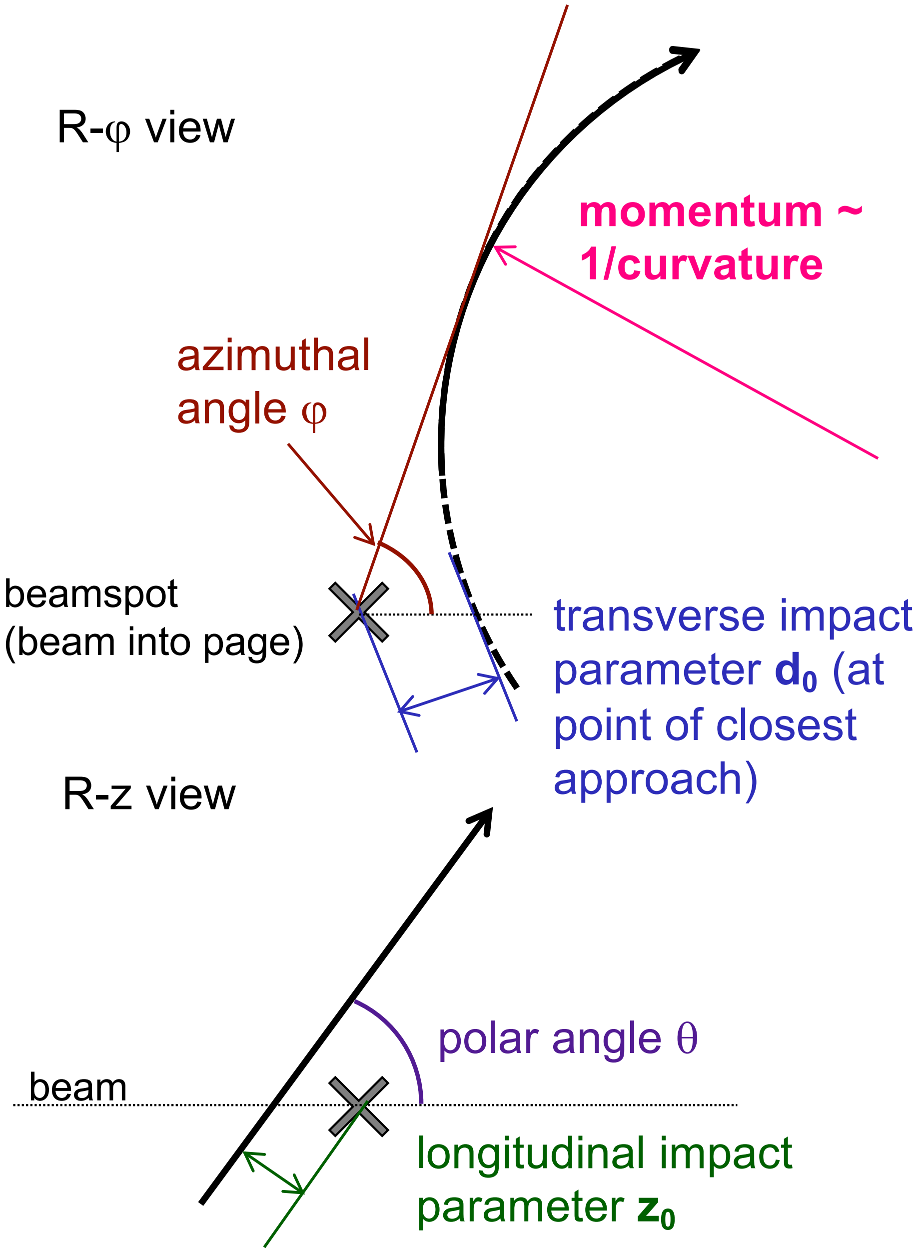
Where I'm coming from



- PhD on CDF at UCSB: SVXII operations and CMS tracker module testing
- (ATLAS for both postdoc positions: almost no hardware)
- CMS: pixels for HL-LHC: testbeam of sensors pre- and post-irradiation
- These experiences and interests influence my choice and presentation of material

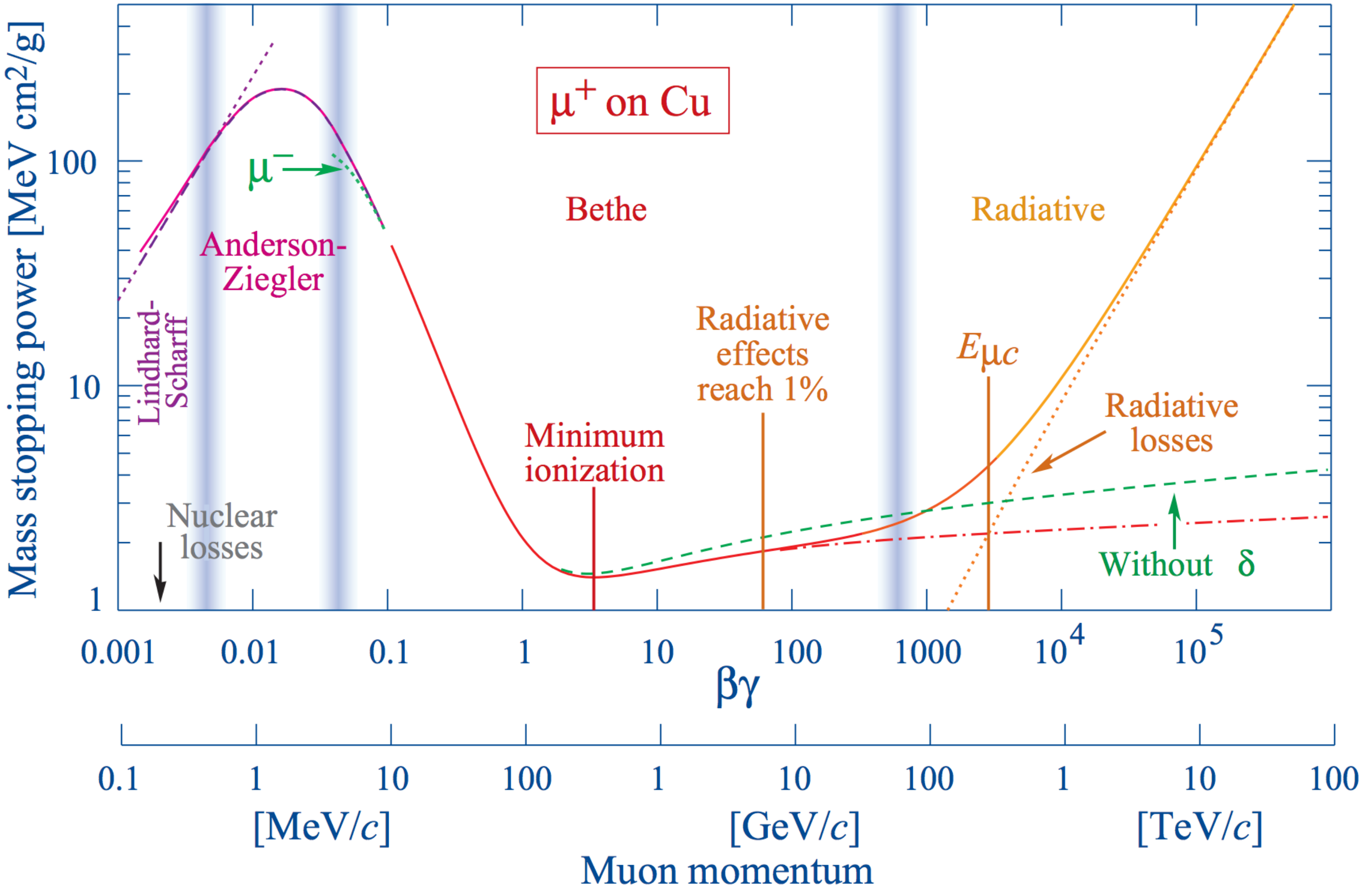
Tracking is helix-finding

- Tracking is fundamental to charged particle reconstruction + measurement
  - → *[Transverse] momentum*
    - kinematic selection
  - → *Impact parameter*
    - Displaced tracks from decay of particles such as b-quark hadrons
- Helical trajectory defined by 5 track parameters
  - → *2 impact parameters*
  - → *2 angles*
  - → *curvature/momentum*



Signals from charged particles

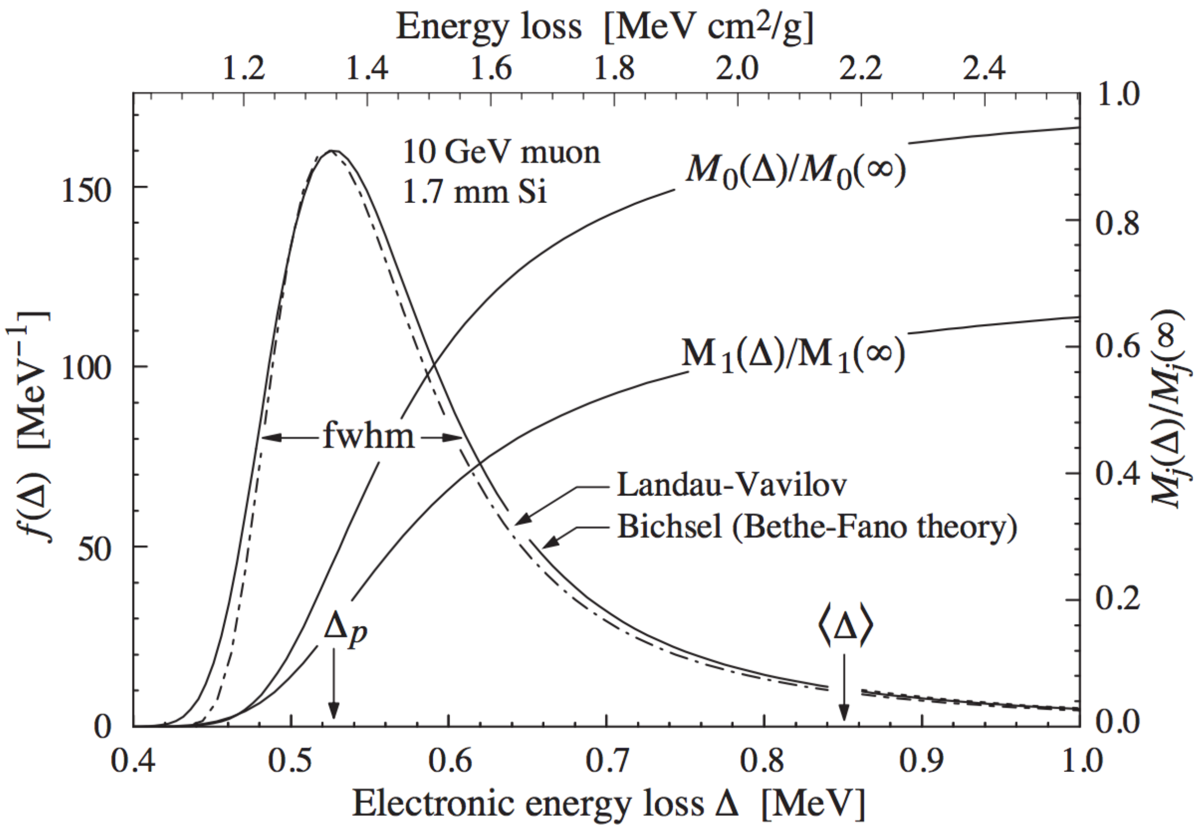
Bethe-Bloch equation describes interaction of particles with matter



$$\beta\gamma = \frac{p}{mc}$$

Signals from charged particles

- Signal in a *thin* detector such as a plane of silicon is **Landau-ish**



→ *Improved distribution described by Bichsel*

mean value != most probable value

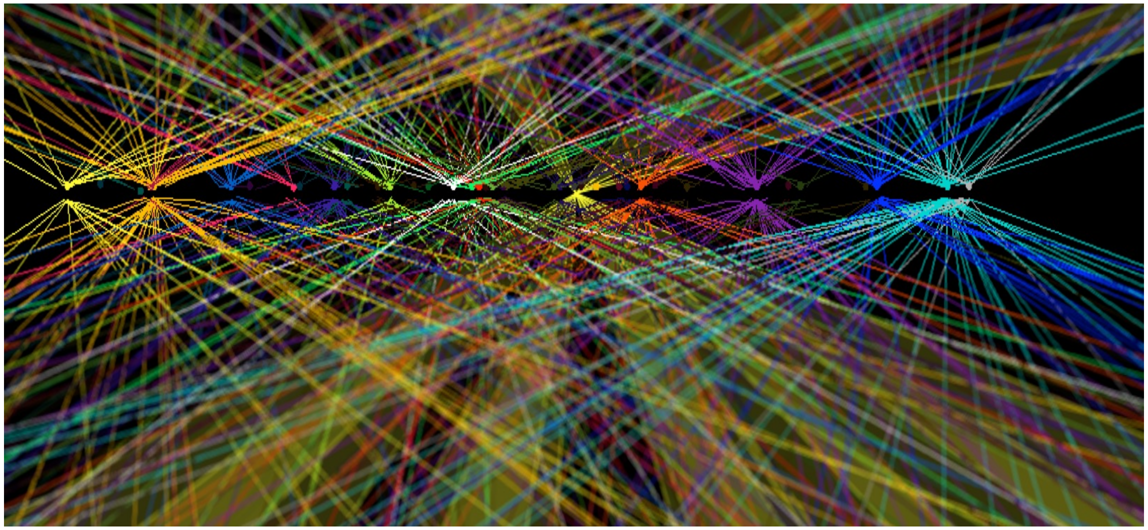
Silicon: 3.6 eV bandgap → 1 electron-hole pair

eh pairs per micron mpv 76 avg 108

poisson bulk (stochastic process)

long tail (delta rays)

Technology vs occupancy



- LHC: collisions every 25 ns and ~tens of collisions per bunch crossing (interaction region ~20 cm long, microns wide)
- Intense radiation environment and high particle density at the center

- Study of rare processes such as Higgs boson production require **ever-more-intense beams**

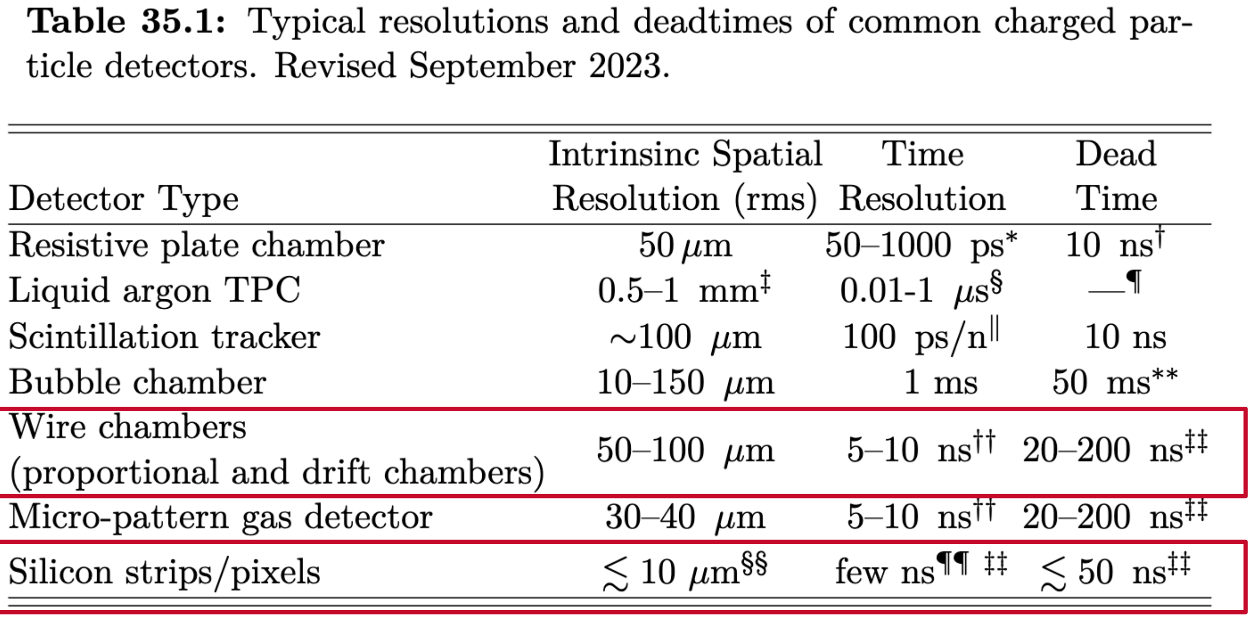
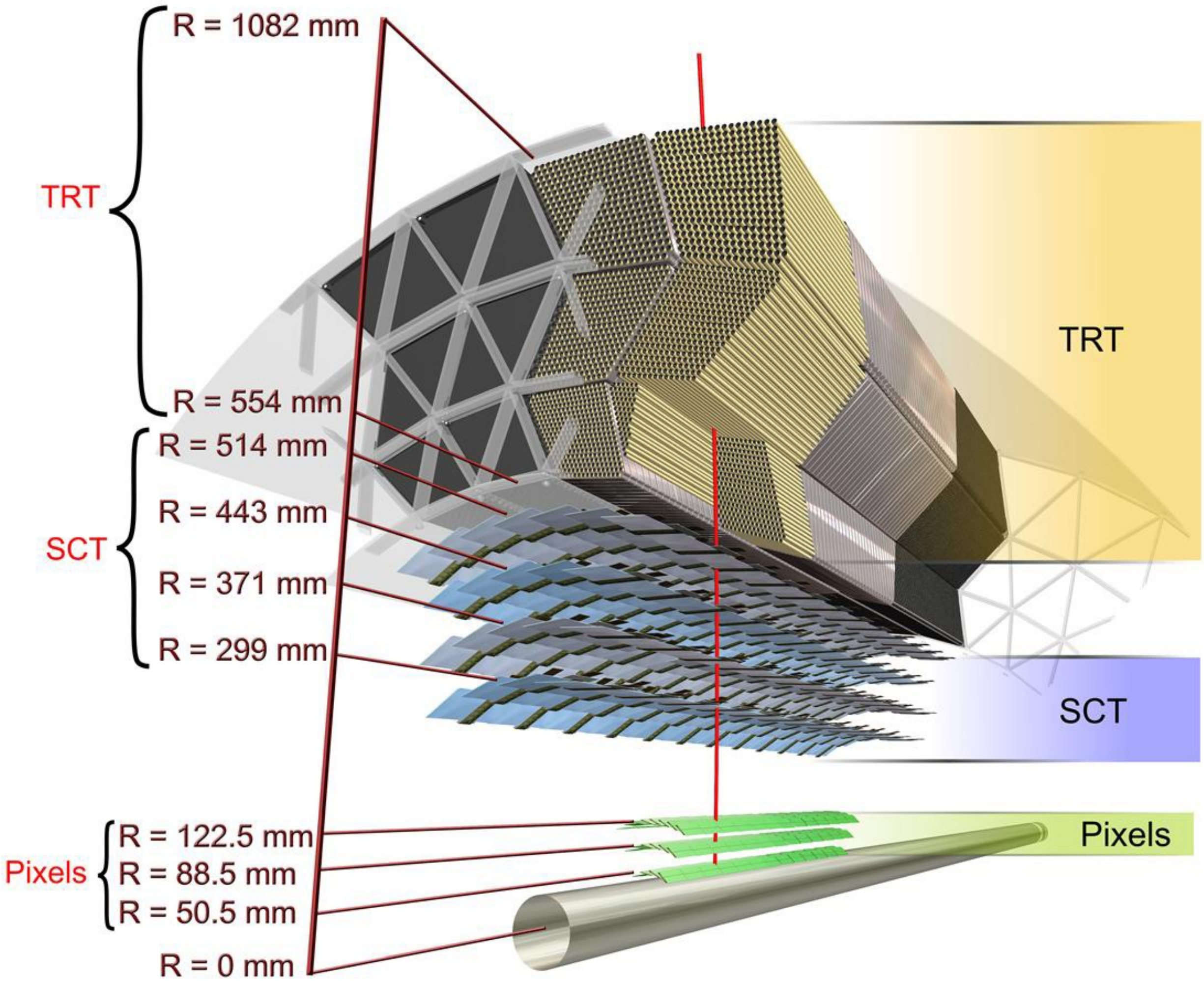


Table 35.1: Typical resolutions and deadtimes of common charged particle detectors. Revised September 2023.

Detector Type	Intrinsinc Spatial Resolution (rms)	Time Resolution	Dead Time
Resistive plate chamber	50 μm	50–1000 ps[*]	10 ns[†]
Liquid argon TPC	0.5–1 mm[‡]	0.01-1 μs[§]	—[¶]
Scintillation tracker	~100 μm	100 ps/n[‖]	10 ns
Bubble chamber	10–150 μm	1 ms	50 ms[**]
Wire chambers (proportional and drift chambers)	50–100 μm	5–10 ns[††]	20–200 ns[‡‡]
Micro-pattern gas detector	30–40 μm	5–10 ns[††]	20–200 ns[‡‡]
Silicon strips/pixels	$\lesssim$ 10 μm[§§]	few ns[¶¶] [‡‡]	$\lesssim$ 50 ns[‡‡]

these lectures

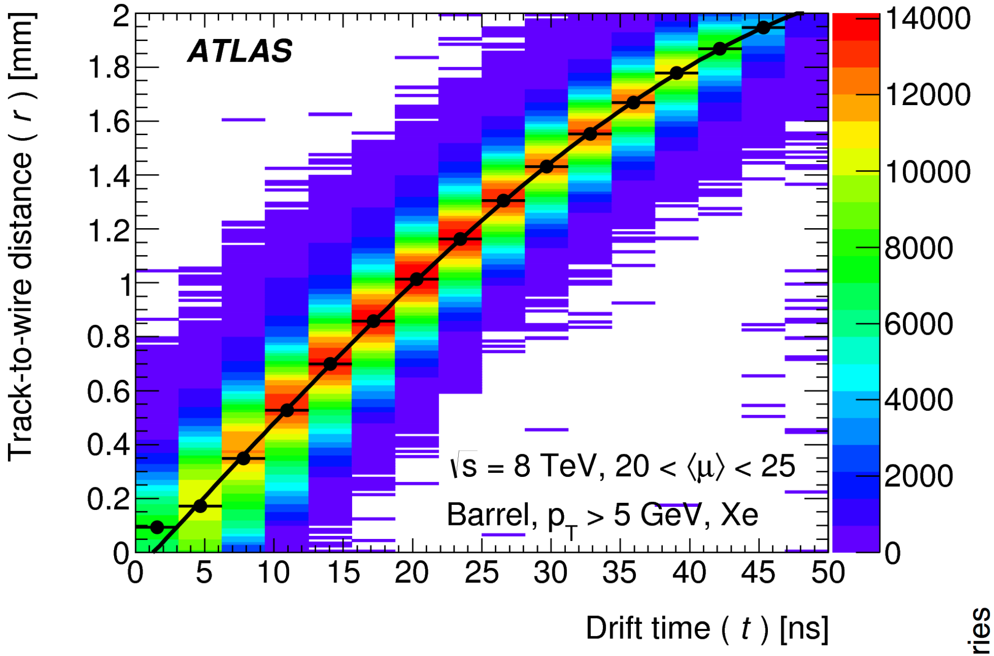
ATLAS Transition Radiation Tracker (TRT)



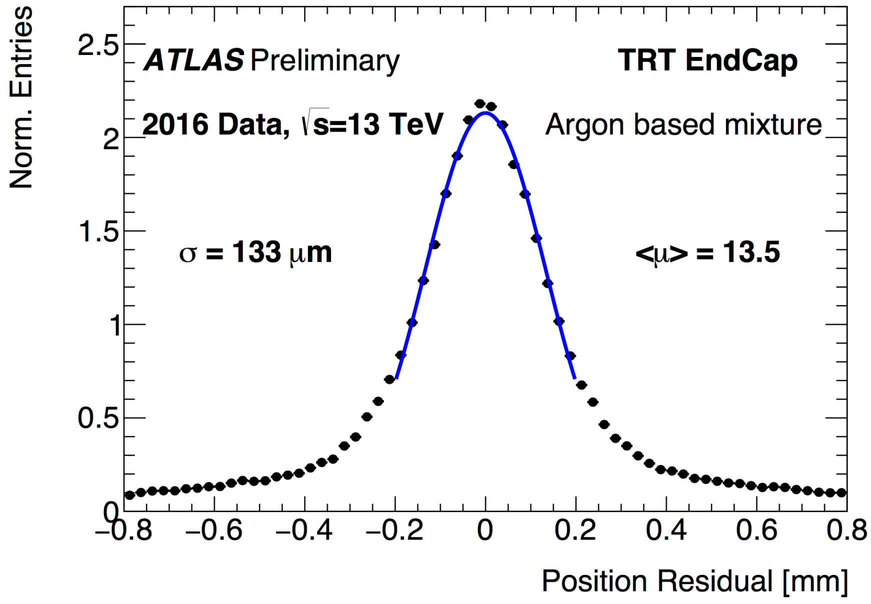
- Drift chamber of straw tubes
- Just under 300k straws 4 mm ID and 144 cm (37 cm) long in the barrel (endcaps)
- Wire running down the center measures signal
- 70% Xe or Ar gas absorbs TR (x-ray) photons, 27% CO_2 is a “quenching” gas (absorbs soft photons), 3% O_2 stabilizes high-voltage operations
- Xe-based gas mixture in Run 1, but gas system leaks in inaccessible places → switch to less-expensive Ar-based

TRT performance in Run 1: JINST 12 (2017) P05002

The TRT is a drift chamber



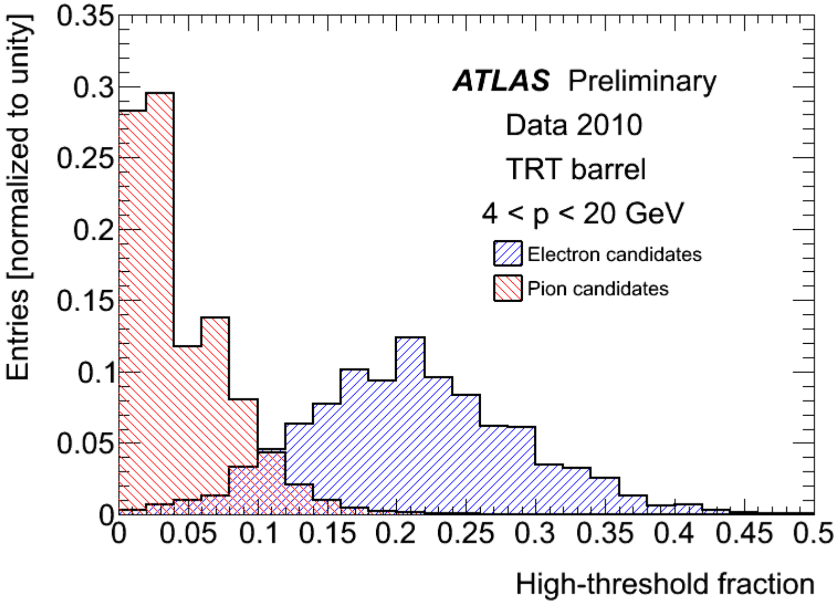
- Drift tubes measure distance to wire via drift time
  - → *Covered in muon detector lectures last week*
- Residuals show precision of the position measurement



- Xe-based gas mixture in Run 1, but gas system leaks in inaccessible places
- Switch to less-expensive Ar
  - → *Similar performance for tracking*
  - → *Reduced capabilities for particle ID*

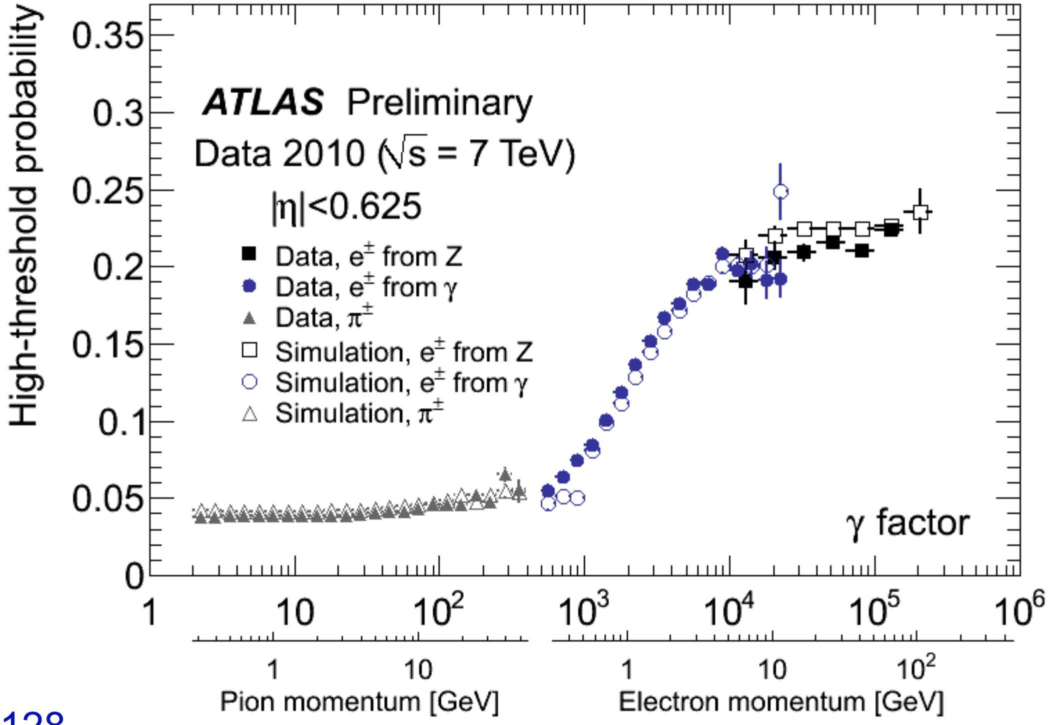
TRT performance in Run 1: JINST 12 (2017) P05002

Particle ID capabilities of the TRT



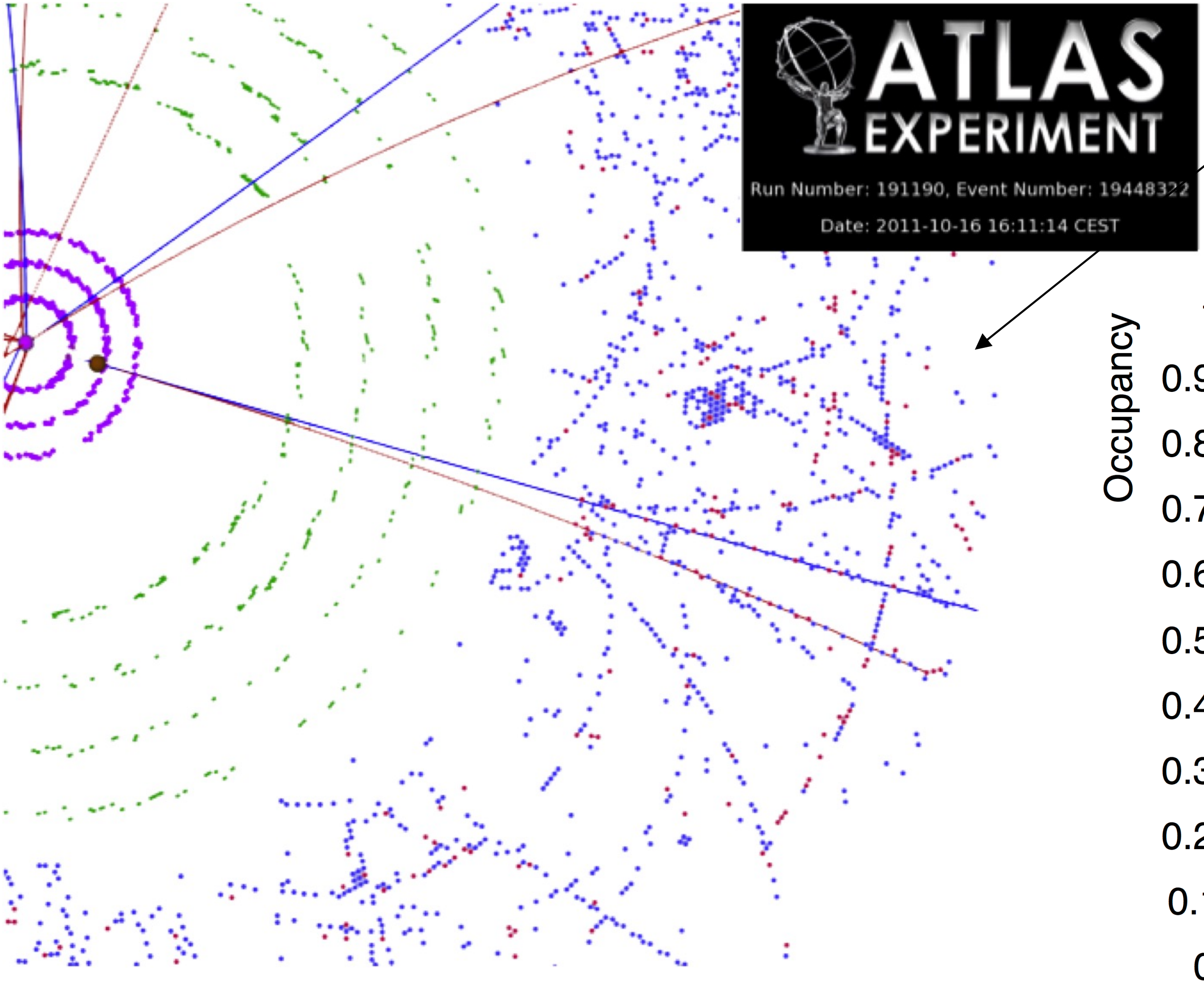
- Radiation of x-ray band photons aligned with particle direction by relativistic particles crossing boundary between materials with different dielectric constants

- Depends on γ → electron/pion discrimination up to ~100 GeV
  - → *Saturates above that momentum*
  - → $\gamma = E/m$ *so* $\gamma_e/\gamma_\pi = m_\pi/m_e \sim 280$
- Apply two charge thresholds (low and high) to detected charge in the readout electronics



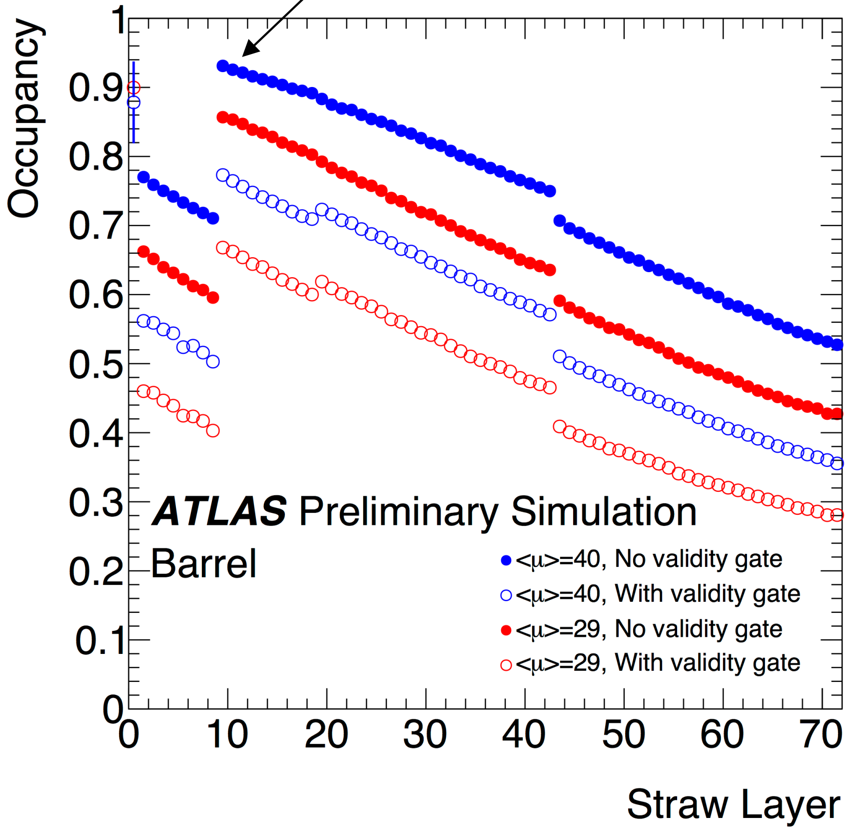
TRT performance note ATLAS-CONF-2011-128

High occupancy presents challenges



How it started

How it's going

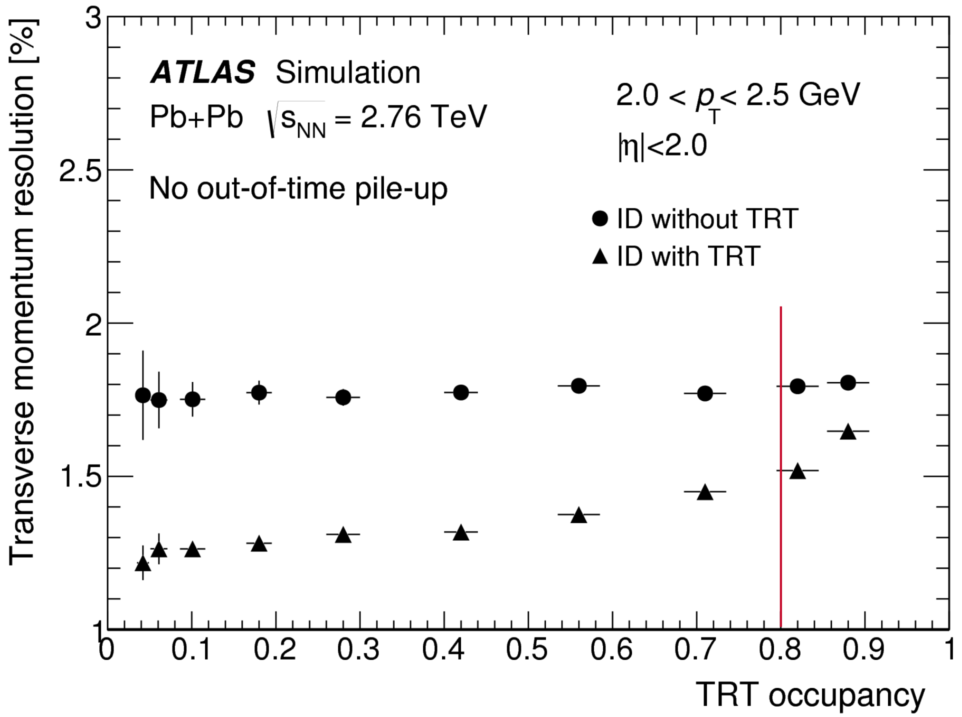


TRT performance in Run 1: JINST 12 (2017) P05002

TRT performance at sqrt(s) = 13 TeV TRT-2016-001

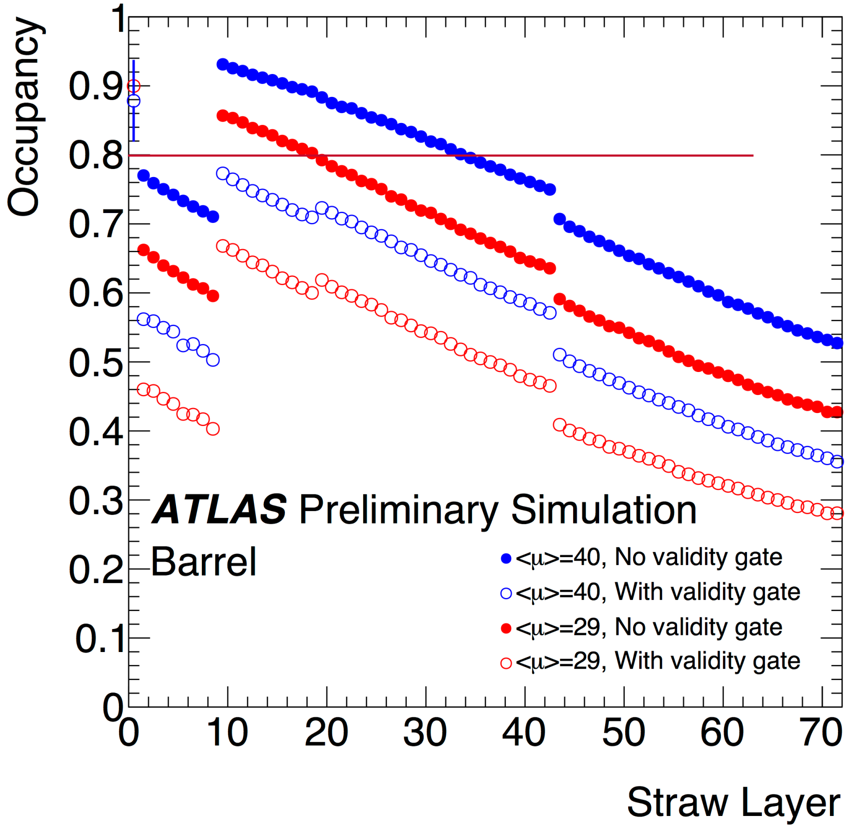
The TRT remains essential for p_T

But for the transverse momentum measurement the TRT still matters.
In Run 1, used heavy-ion data to study performance vs. occupancy:



TRT performance in Run 1: [JINST 12 (2017) P05002]

Reading out a shorter time window reduces the effective occupancy:



TRT performance at sqrt(s) = 13 TeV [TRT-2016-001]

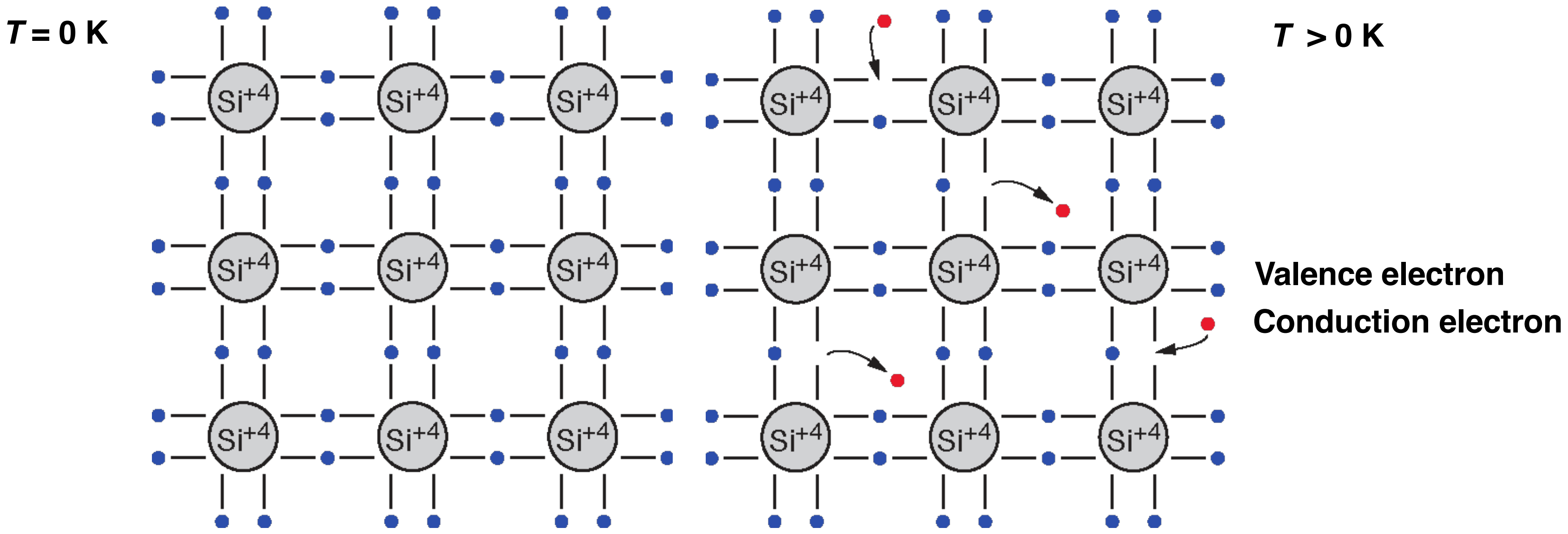
Silicon tracking detectors

Photo: CMS-PHO-TRACKER-2008-002-12

TIB integration activities in Florence and Pisa, May 2005

Semiconductors

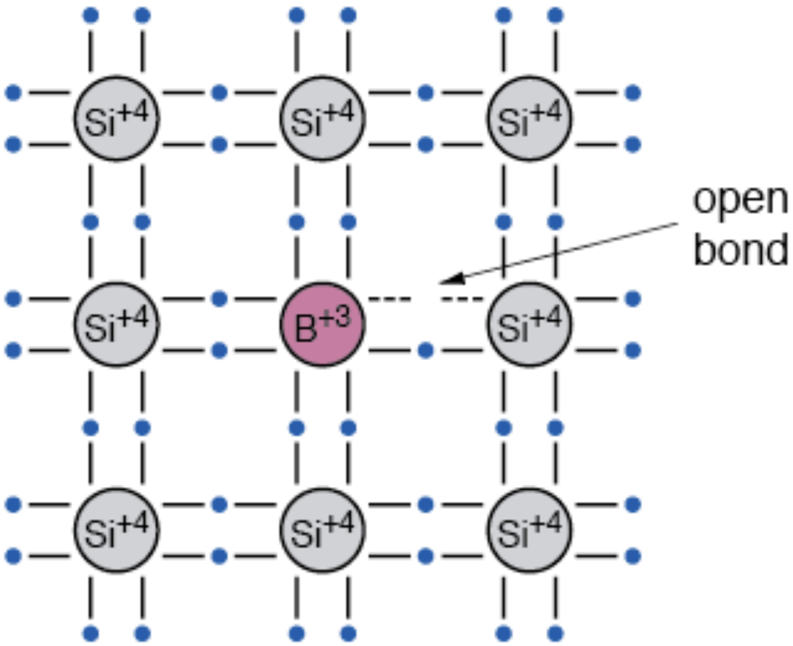
- Charged particle passing through semiconductor creates electron-hole pairs
- Charged-particle signal (10^4 electron-hole pairs) swamped by thermal production (10^8 e-h pairs at room temperature)

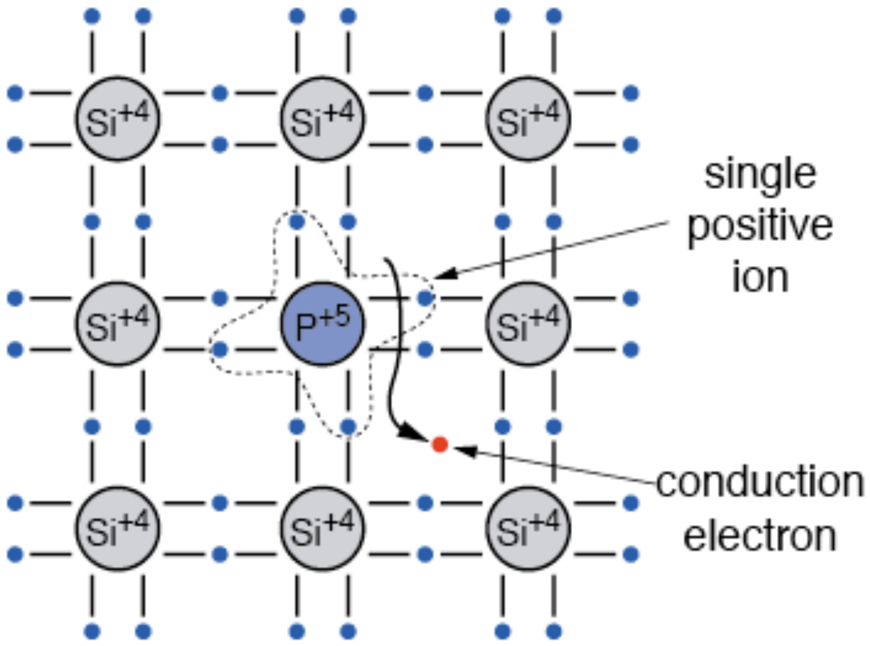


Semiconductors

- Semiconductors typically deliberately **doped** with impurities to alter their band structure – introduces **relatively mobile** charge carriers

→ *type V or III, typically boron or phosphorus*



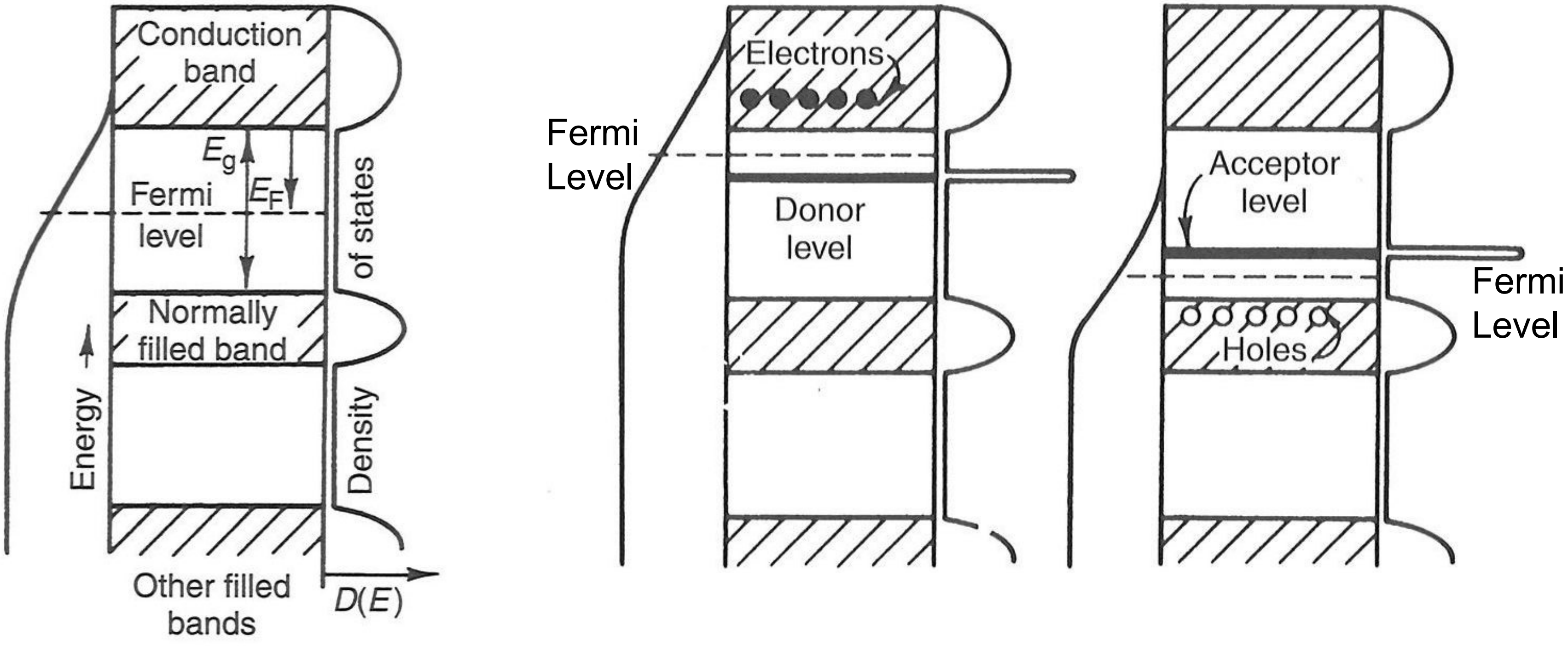


p-type
charge carrier positive
stationary nucleus effectively negative

n-type
charge carrier negative
stationary nucleus effectively positive

Semiconductors

- Doping alters the band structure and Fermi Level = energy at which 50% of states are occupied



undoped

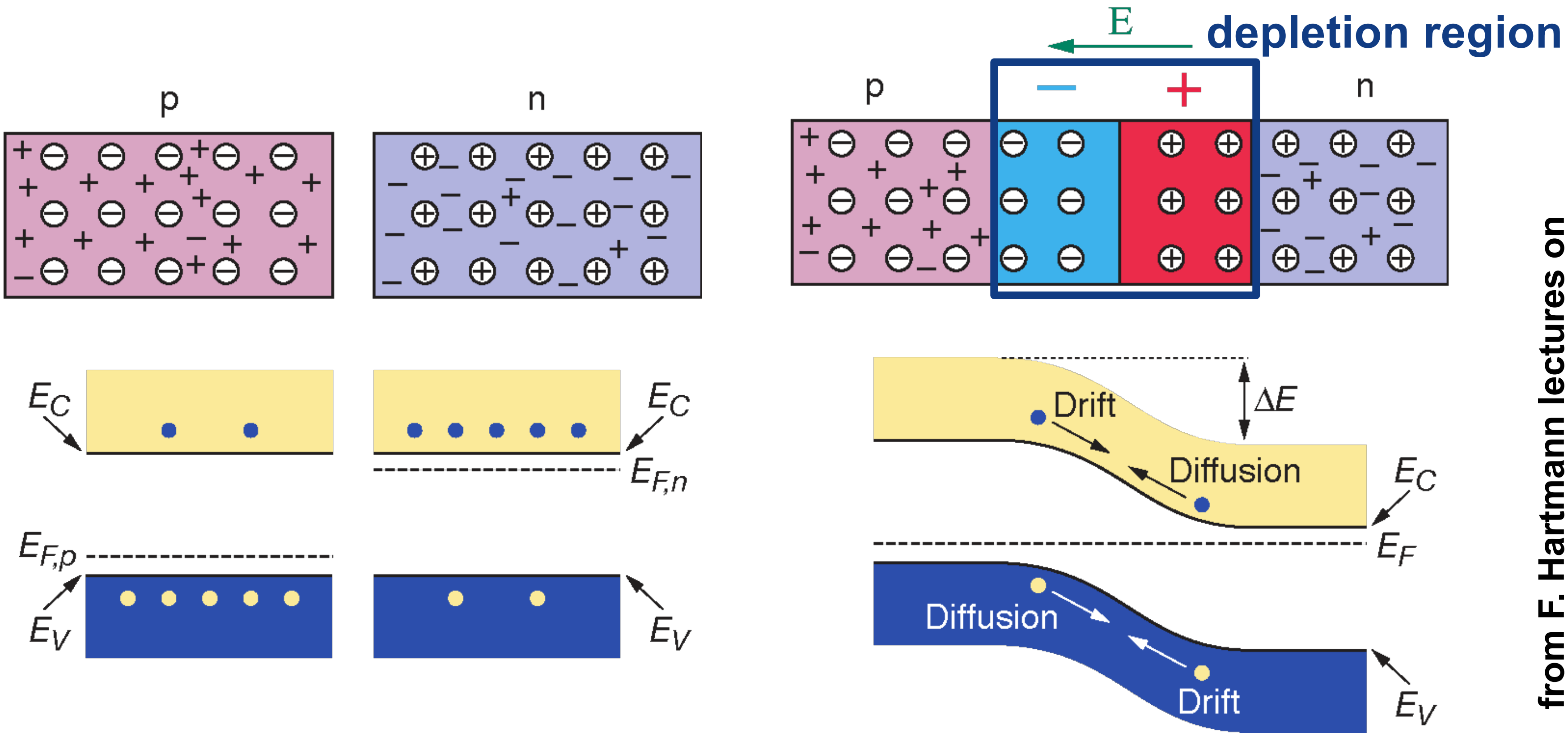
n-type

p-type

from Melissinos & Napolitano

The p-n junction

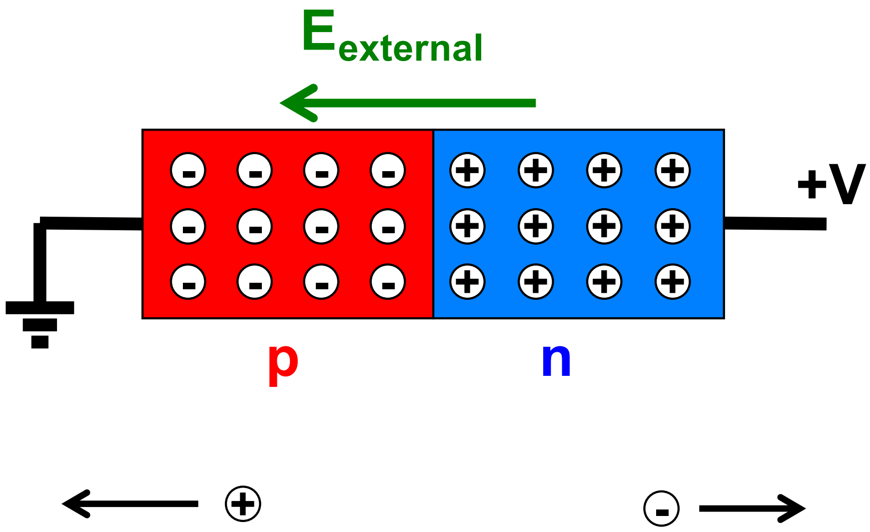
- At thermal equilibrium with no external E field
- Fermi level must be the same throughout material
  - → *Diffusion of surplus charge carriers across the boundary at the interface until thermal equilibrium is reached.*
  - → *Result: depletion region with space charge → internal electric field*



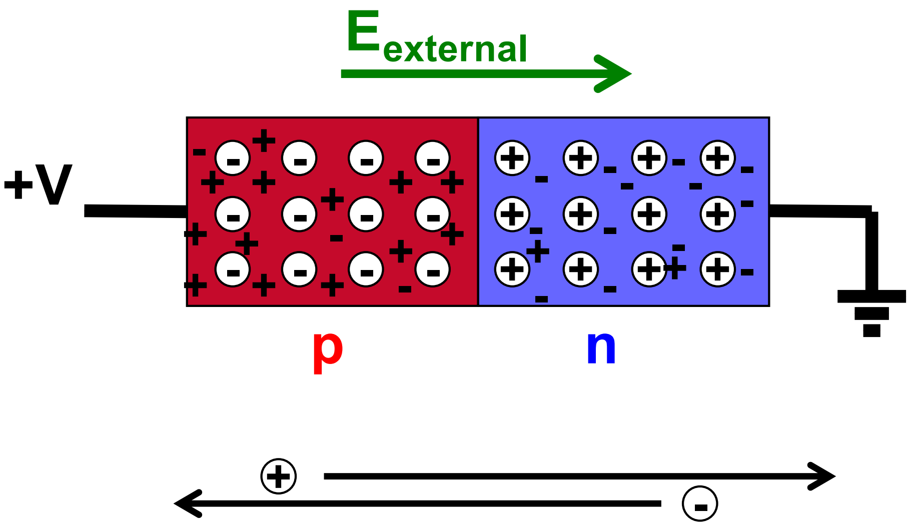
from F. Hartmann lectures on semiconductor particle detectors

The p-n junction

Reverse bias: depletion region expands



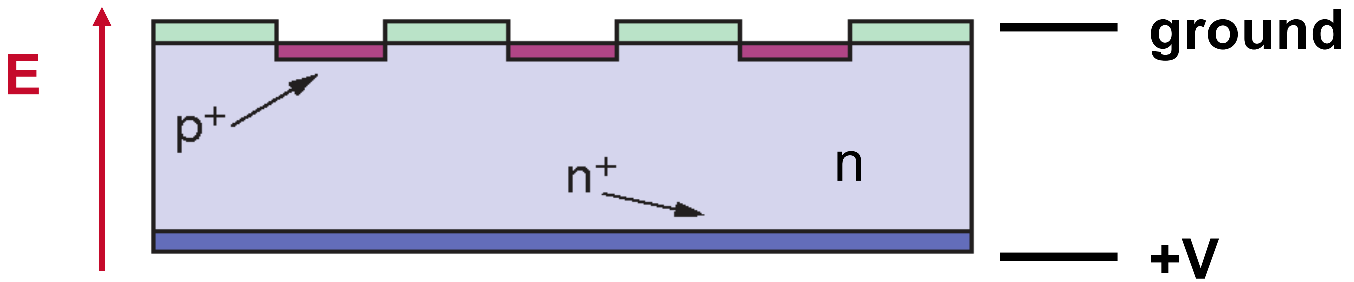
Forward bias: current flows



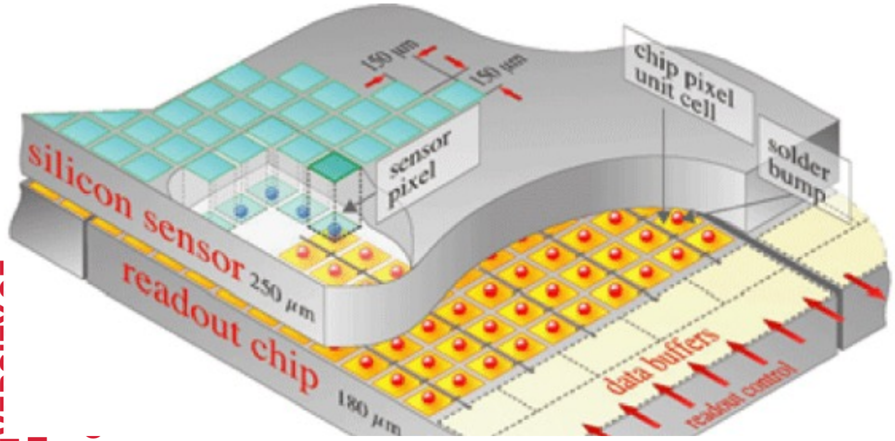
This is how we operate the detectors

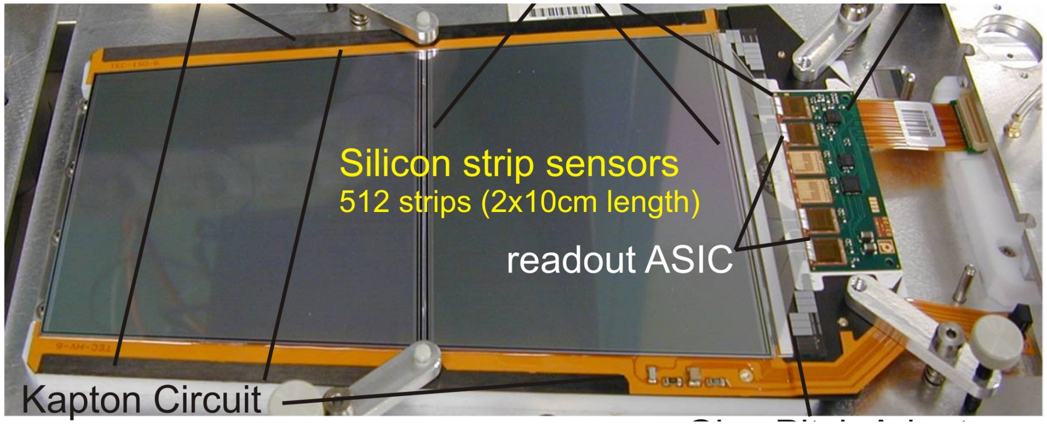
Basic Si detectors are “just” diodes

- Segmented implants with different doping than bulk
- Classically p-in-n detector, but n^+-in-n and n-in-p also possible
- Reverse bias **depletes** the bulk



- “Pixel” and “strip” detectors distinguished by segmentation and readout: at edge for strips, overlaid for pixels

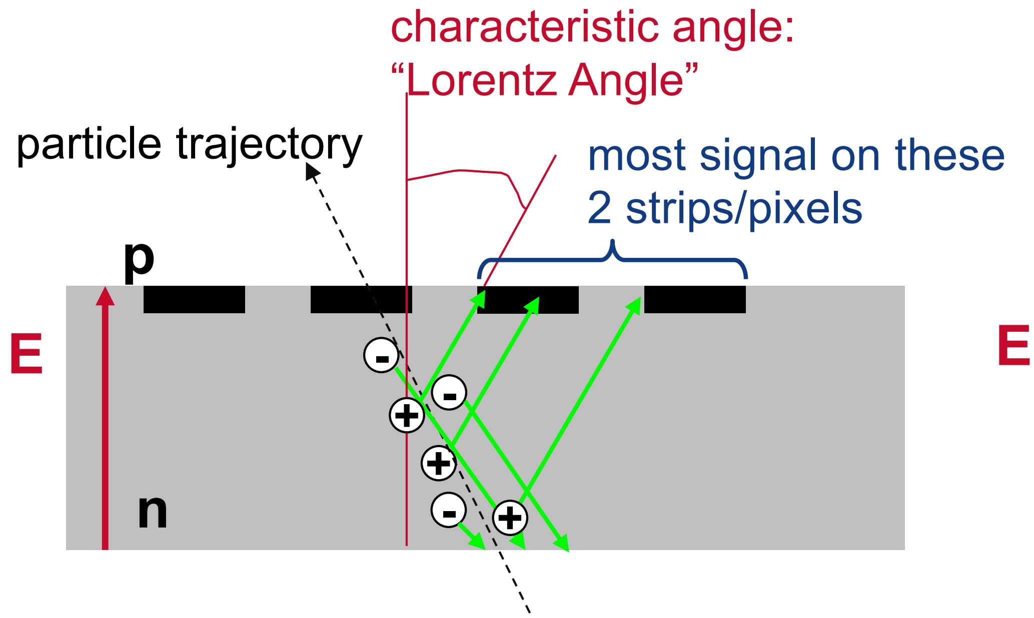




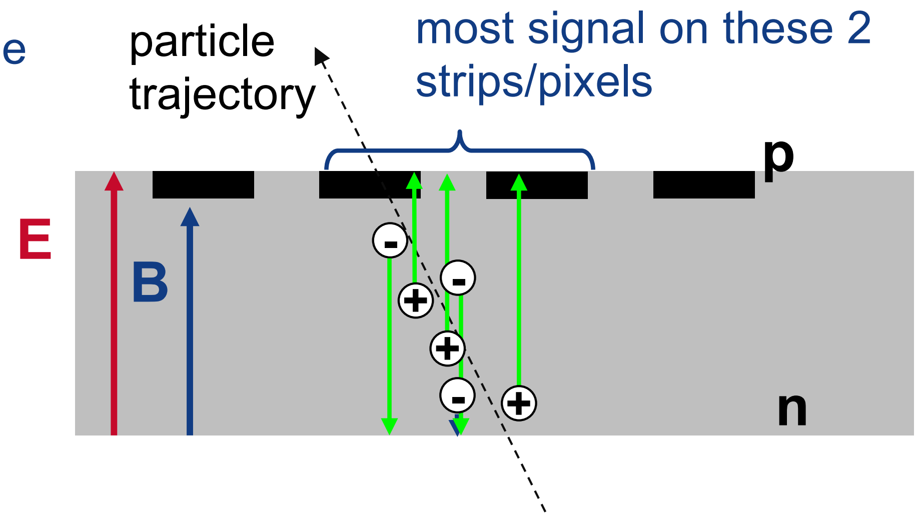
Electron-hole pairs drift

- Charges drift under the influence of the E and B fields
  - → ***Lorentz angle*** *= angle of charge drift relative to the E field*
  - → *Drift direction offset the same for positive and negative*

$$\vec{F} = q\vec{E} + q\vec{v}\times\vec{B}$$



B out of the page
typical of barrel



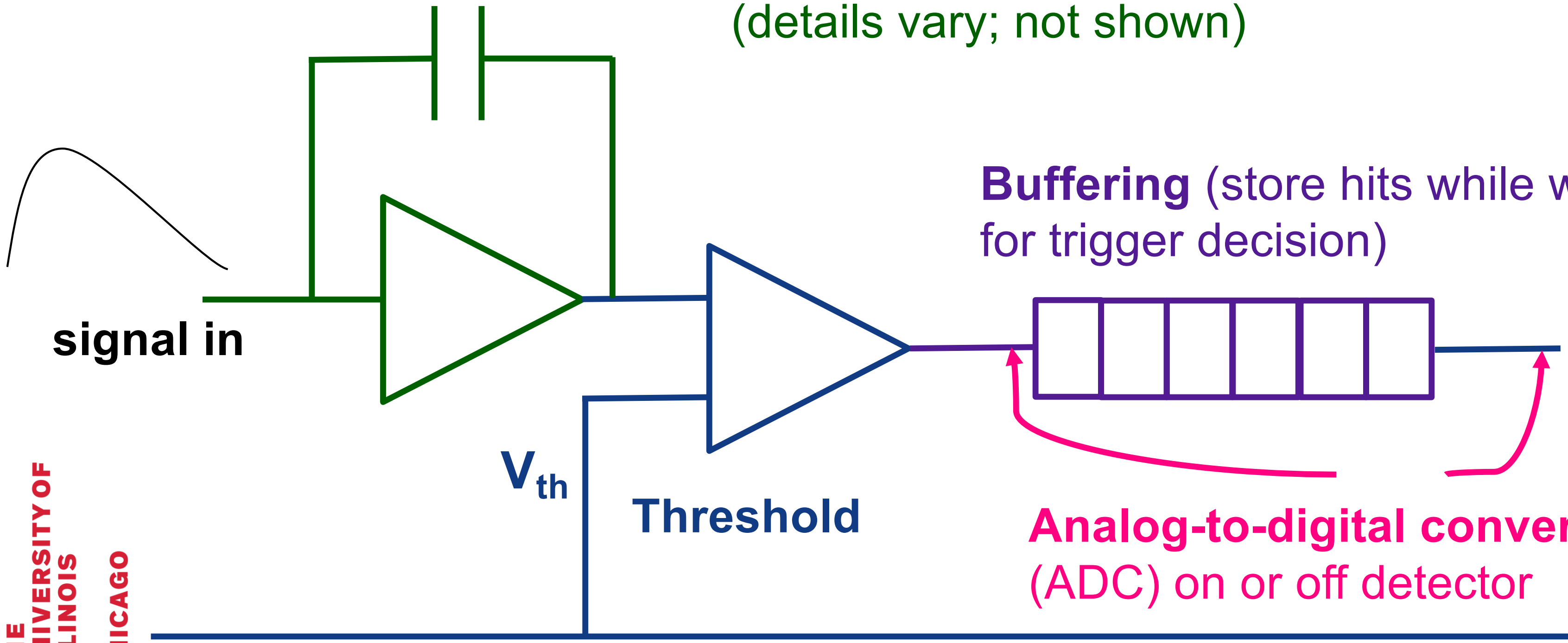
B parallel to E
typical of forward/disks

Electronics amplify and digitize

- Readout via dedicated ASIC (Application-Specific Integrated Circuit)
- Pulses are small – *must be amplified*

→ *80 e+h pairs per micron * 150 um detector = 12,000 electrons = 2 fC*

- Zero-suppression: only read out pixels/strips with charge over pre-defined threshold – *don't spend bandwidth on noise*
- Measure time-over-threshold or just presence of charge (binary)



Amplification – integrator with return-to-baseline (details vary; not shown)

signal in

V_{th}

Threshold

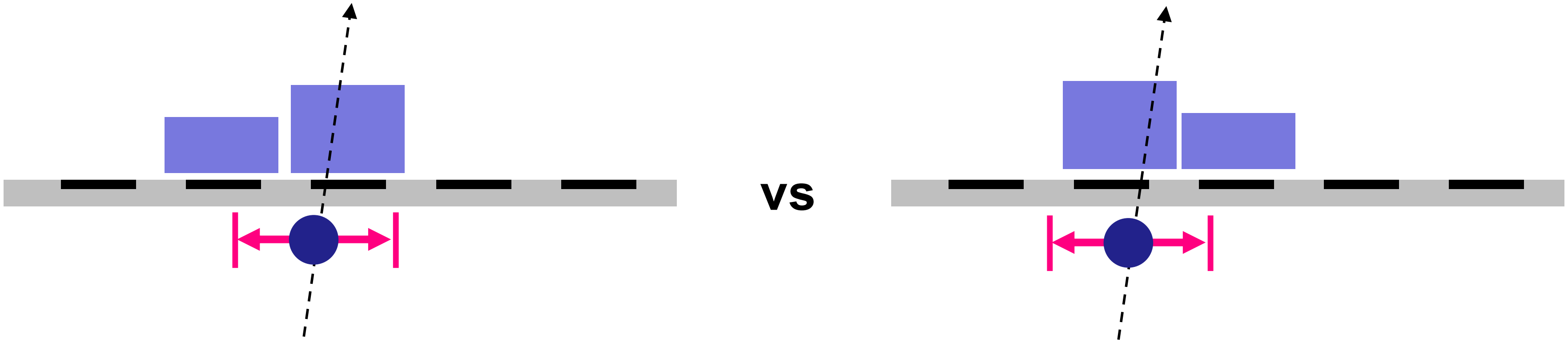
Buffering (store hits while waiting for trigger decision)

Analog-to-digital conversion (ADC) on or off detector

Resolution and cluster size

- Single pixel clusters are effectively *binary*: all the information we have is that the track hit in the pixel

  → *Results in resolution of pitch/sqrt(12)*
- With two or more pixels, charge distribution between adjacent pixels carries information about track location

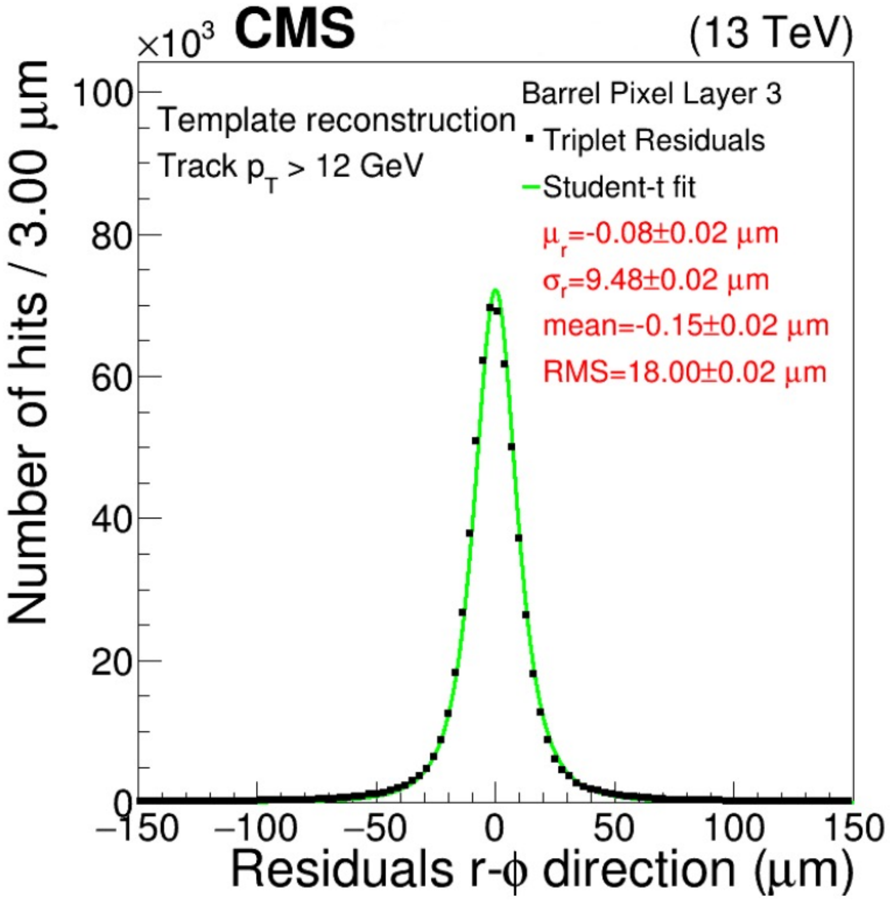


- Position resolution is determined by combination of pitch and charge measurement granularity (Δq/q)
- Two-pixel clusters have best position resolution

  → *Larger clusters: charge of edge pixels most important*
- On CMS, a template fit is used to infer position from cluster shape

Key metric: Position Resolution

- **Resolution** quantifies how well we can measure the position of a particle passing through the detector
- In one event, measure a **residual** = difference between extrapolated track position and position measured by the detector
- Reference track from beam telescope at testbeam, or track reconstructed in situ without layer being characterized
- Make a distribution of residuals for all events
  - → *Approximately Gaussian (usually...)*
  - → *Mean should be zero*
  - → *Width is the resolution*

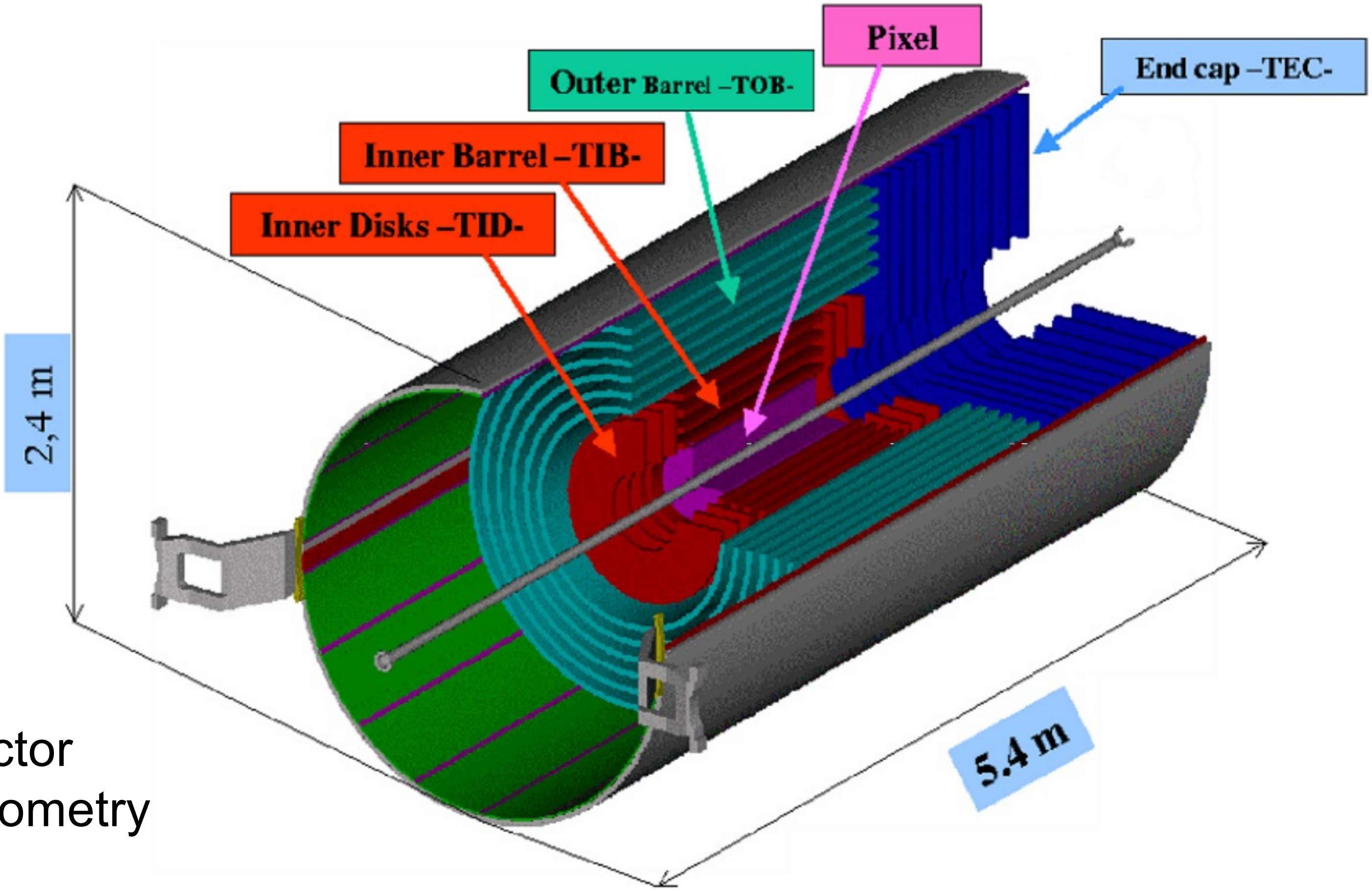


Nested cylindrical layers form tracking systems

- Pixels at smallest radii, strips at large radii
- Strip direction aligned with beam (or radially outward on disks)

→ *Best measurement R-φ*

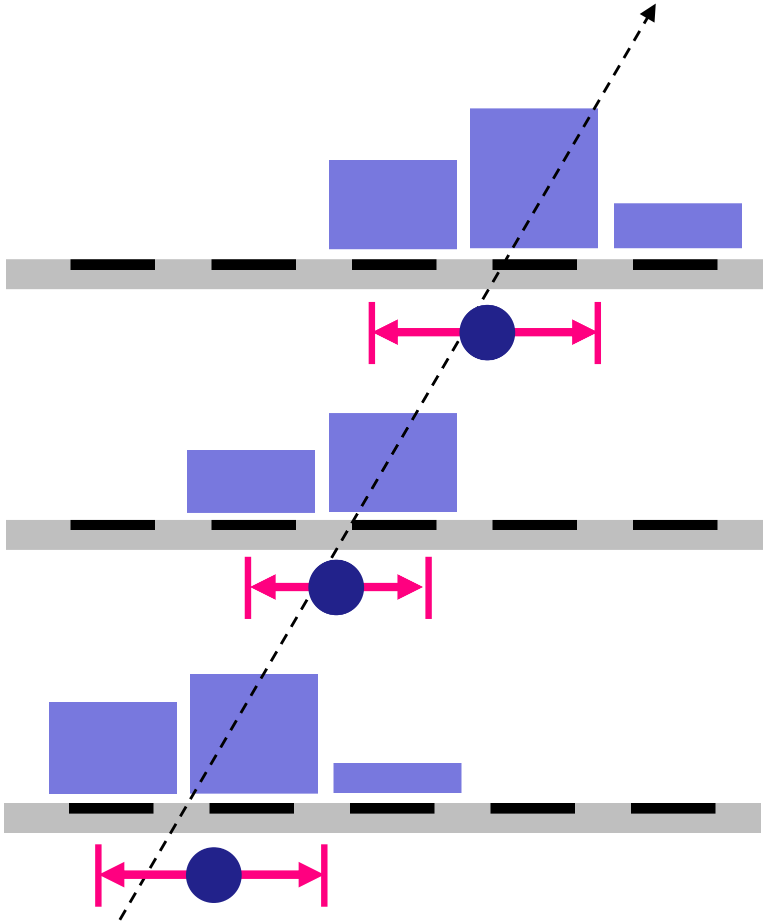
- Pixels: greater longitudinal segmentation



CMS detector
original geometry

Building tracks

- From detector pulses to a particle trajectory
- Seed tracks built with 3-4 hits in pixel detector
- Kalman filter for track extrapolation and subsequent fit to helical trajectory



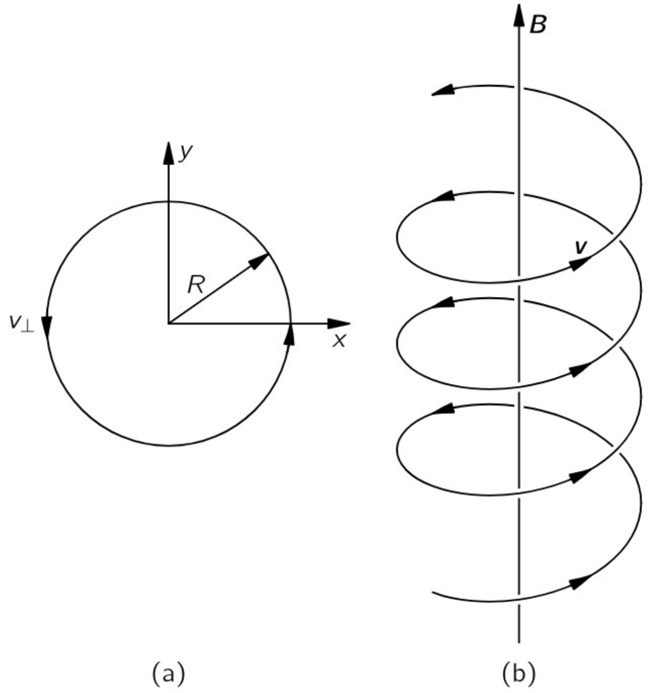
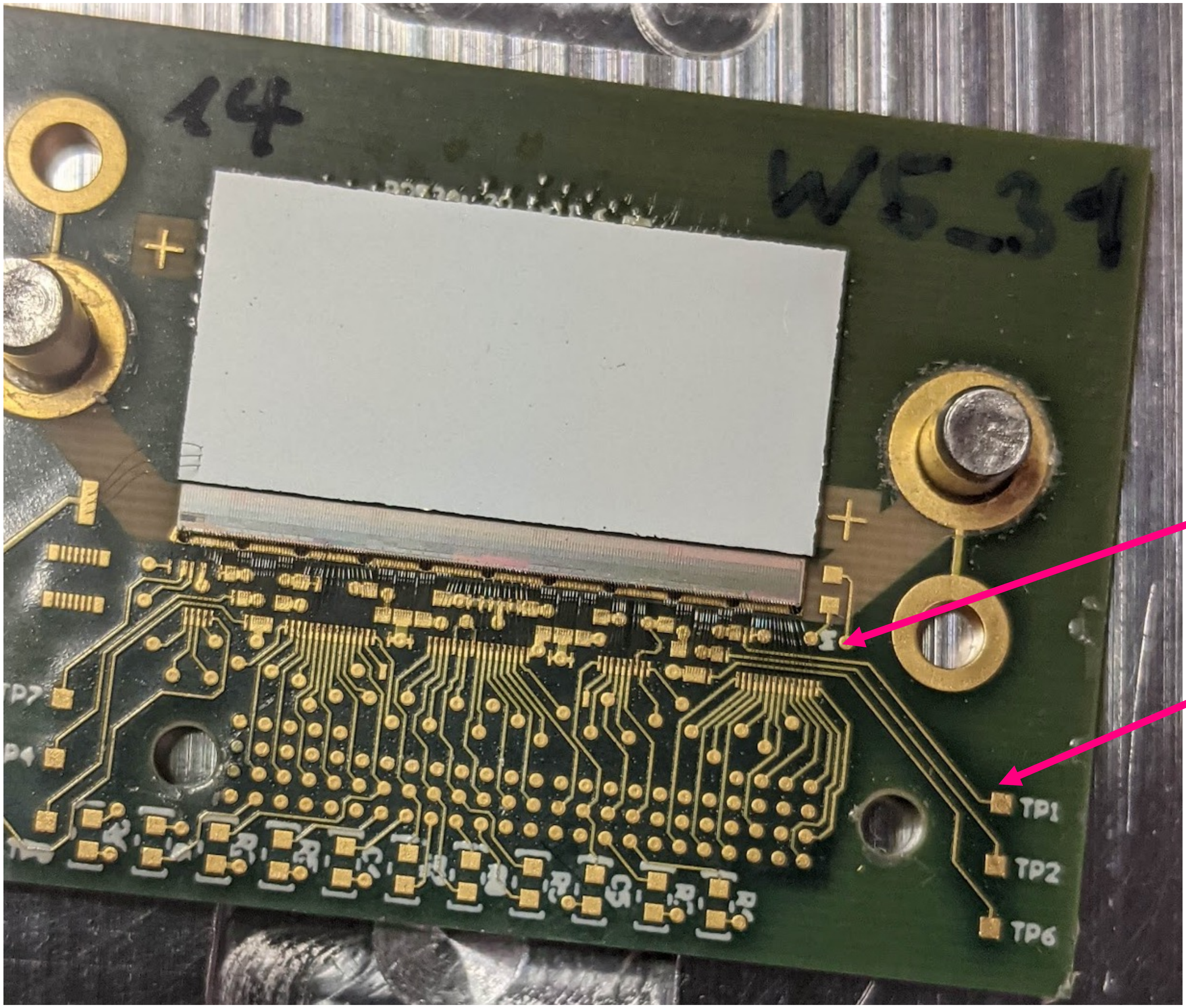


Fig. 29–1. Motion of a particle in a uniform magnetic field.

Up-close view of a test device



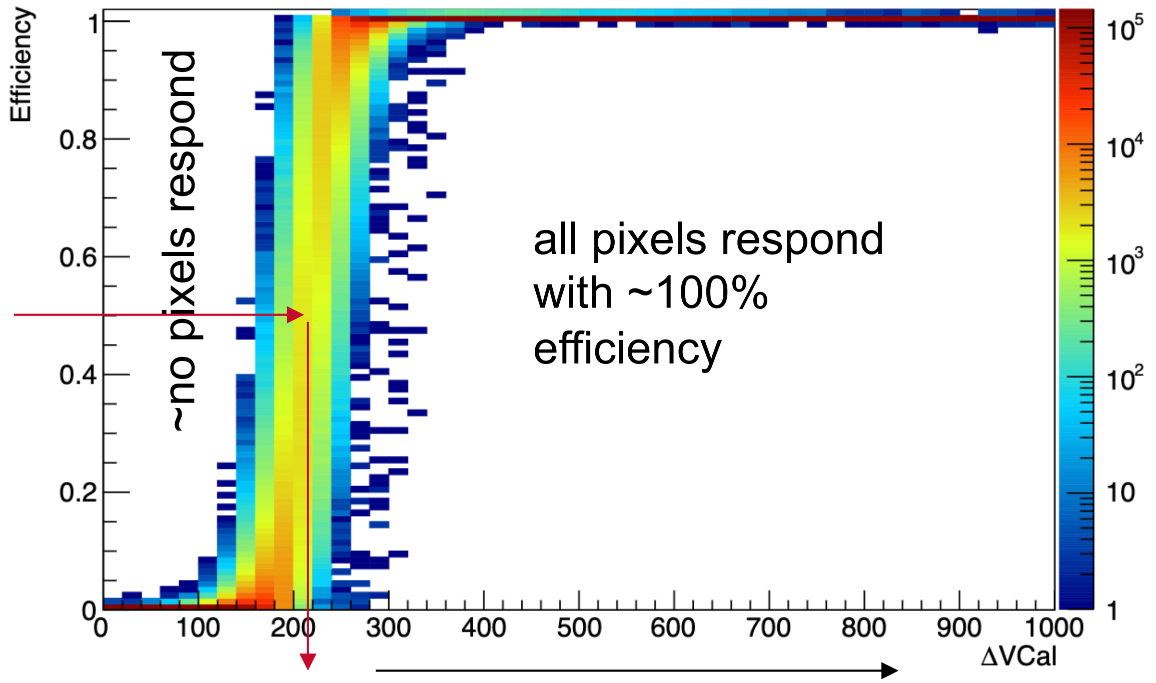
Close-up of a CMS Phase 2 pixel sensor prototype bump-bonded to an RD53A sensor

note the delicate wirebonds

and test points for checking voltages

Low voltage and ASIC tuning

- LV = low voltage, powers the *ASIC* (readout chip)
- ASIC has numerous *registers* that control threshold (global and per-pixel or per-strip), gain (DAC output → electrons map), etc
- Use internal charge injection circuits to calibrate the response
- Example: threshold tuning for a CMS Phase 2 pixel prototype



50% efficiency = threshold

~no pixels respond

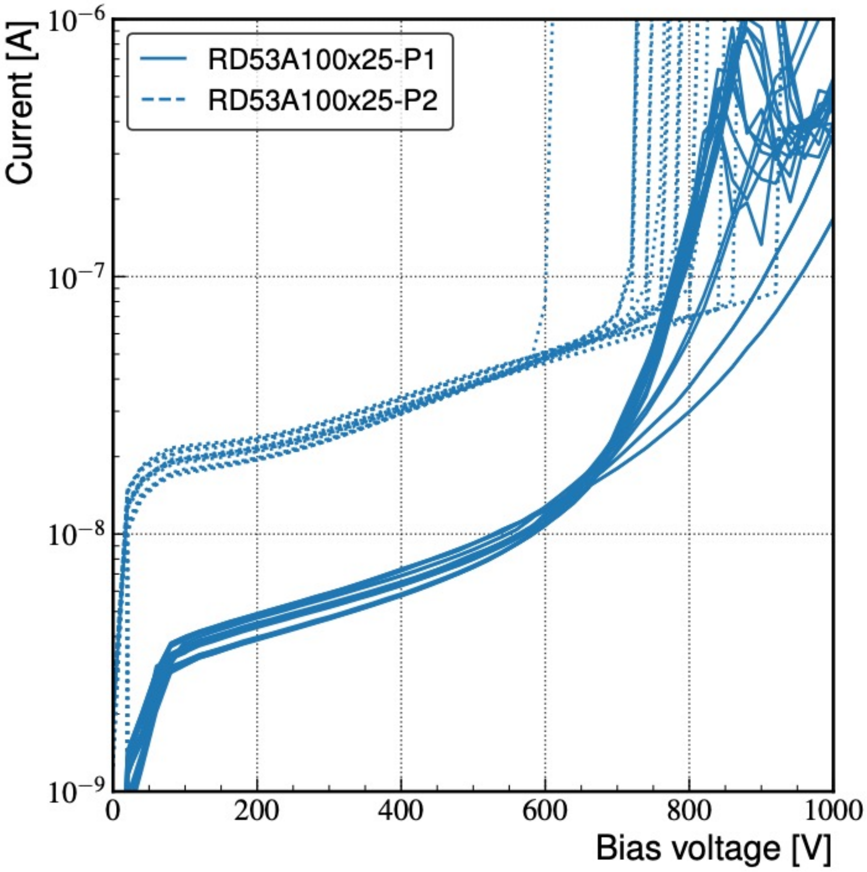
all pixels respond with ~100% efficiency

One entry per pixel per injected charge point

scan **injected charge** (ΔVCal maps to electrons)

High voltage and I-V curves

- HV = high voltage, depletes the *sensor*
  - → *Planar devices: up to 120V unirradiated, up to 800V irradiated*
  - → *3d devices: up to 30-40V unirradiated, up to ~120V irradiated*
- Current is called a “leakage current’
  - → *range nA (unirradiated planar sensor) to 10s of μA (irradiated sensors)*
- Leakage currents are strongly temperature dependent
  - → *A good way to test the HV connection is to see if the leakage current changes with the temperature.*



unirradiated CMS prototype planar pixel sensor (temp unknown) from NIM A1053 (2023) 168326

"NIEL hypothesis" of lattice damage

- Silicon detectors still susceptible to radiation damage
- Primary effect in sensors from *damage to the silicon crystal lattice*
- *Studied by hadron (usually p) bombardment of devices as a function of flux Φ*
- *Scale to units of* ***95 MeV neutron equivalent per cm²***

→ *Abbreviated to n_{eq}/cm^2*

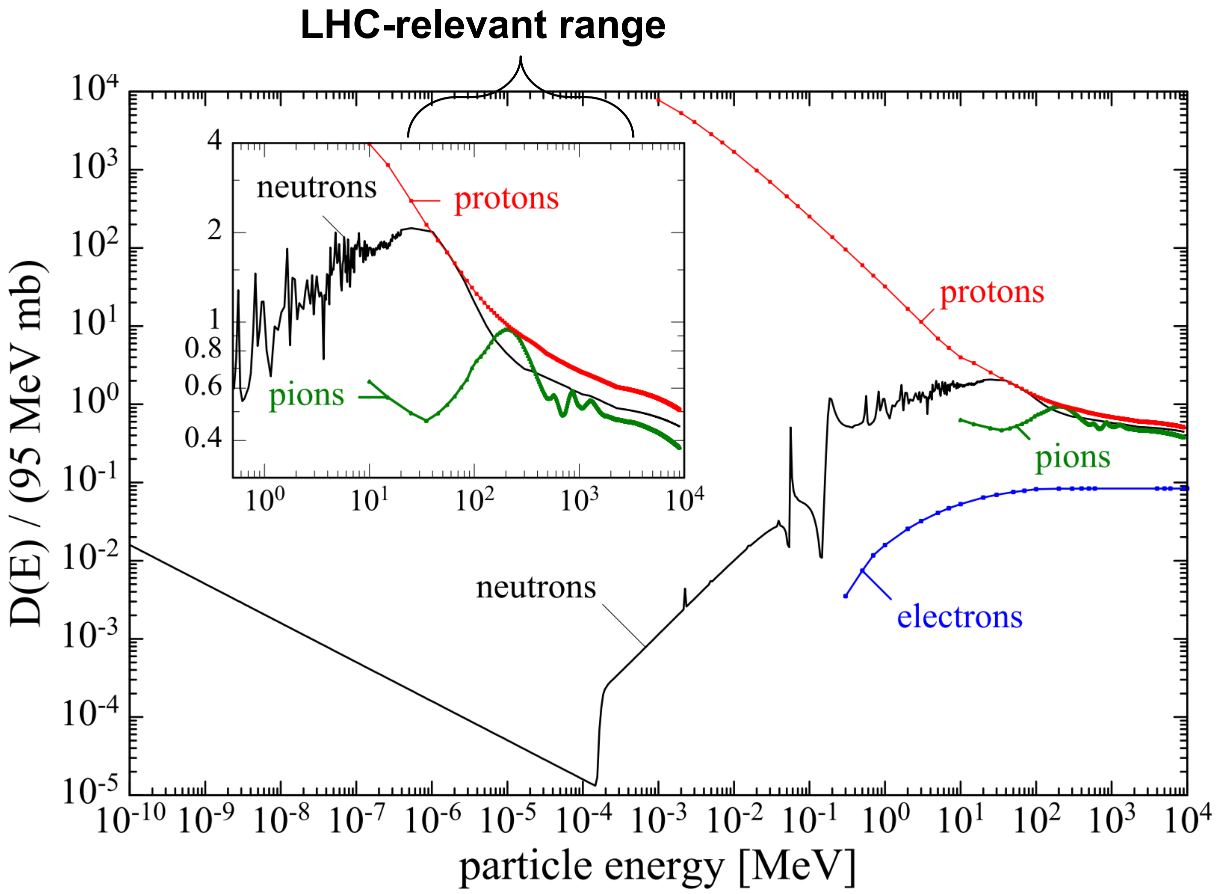
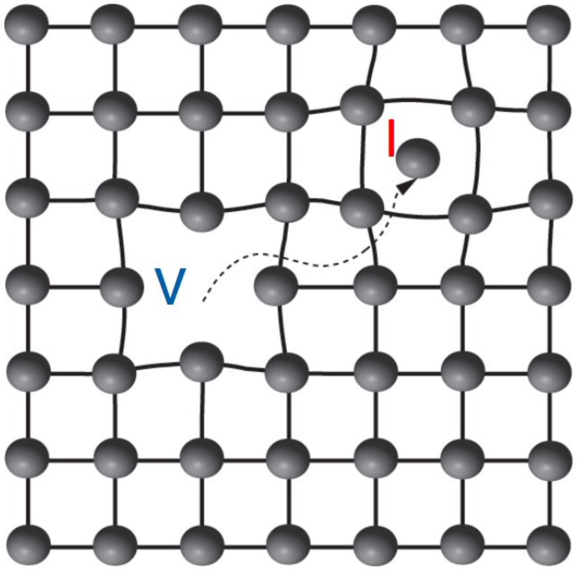

LHC-relevant range

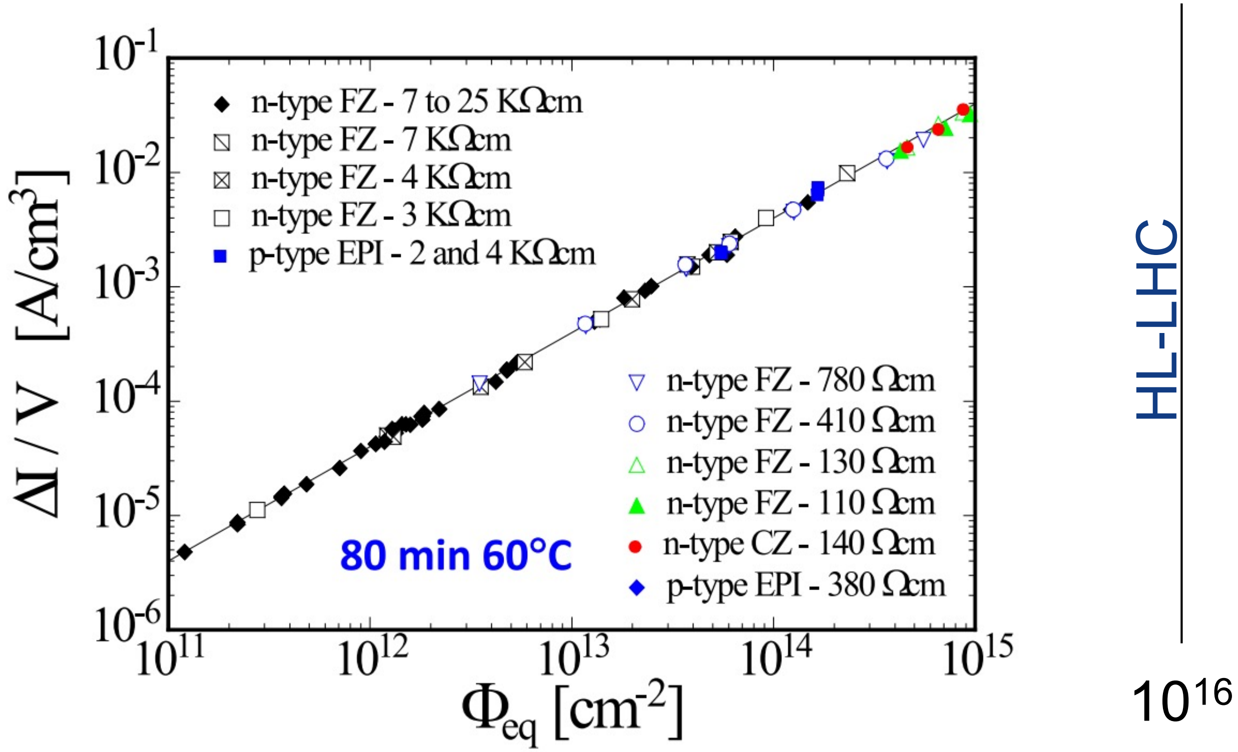
Fig. 3. NIEL cross sections normalized to 95 MeV mb. Data collected by A. Vasilescu and G. Lindstroem [22] based on [23]–[26] and private communications.

This and graphs on the following slides from Moll review on radiation damage, IEEE TNS (2018)

Leakage current increases

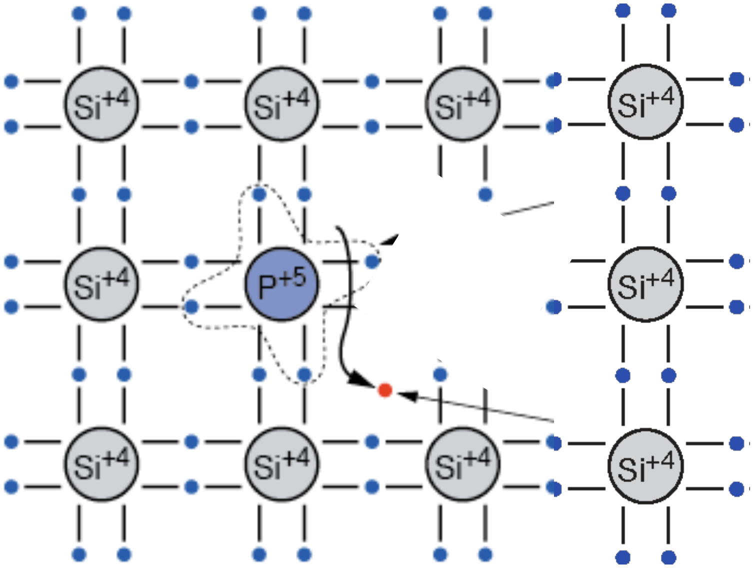
- Damage to crystal lattice complicates the band structure with intermediate states
  - → *Trapping centers reduce charge collection efficiency*
  - → *Generation centers increase leakage current (proportional to fluence)*

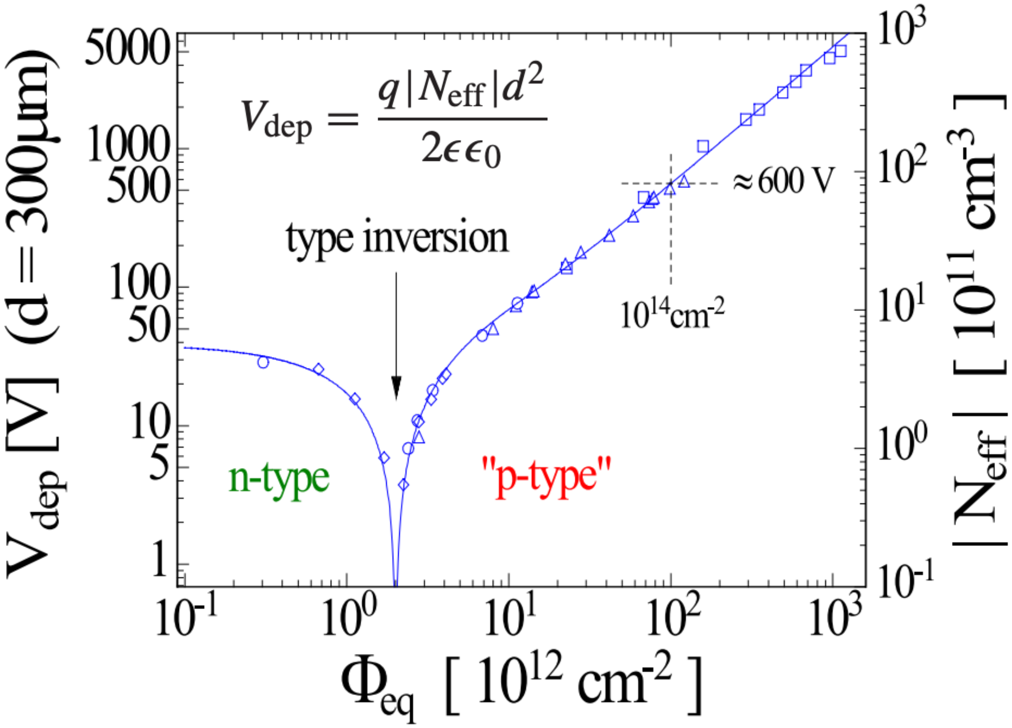




Depletion requires more voltage

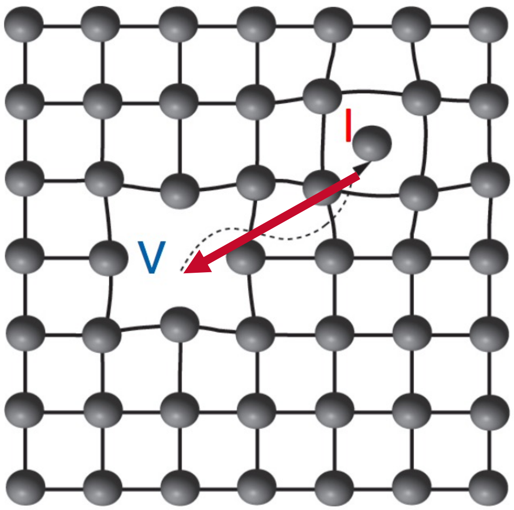
- Lattice structure damage also changes effective doping concentration
  - → *Example: Vacancy + phosphorous removes the donor property of P*
  - → *Many competing effects*
  - → *Space charge sign inversion, sometimes referred to as "type inversion"*
- Primary effect is on depletion voltage → much more required to operate sensor at full efficiency

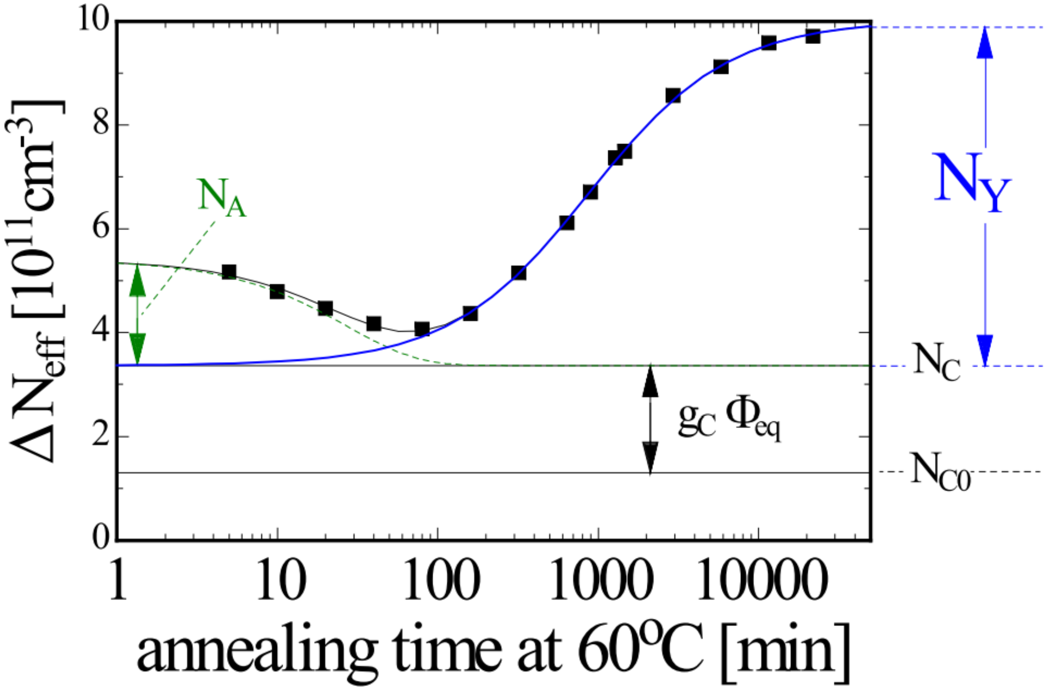




Annealing helps (and then hurts)

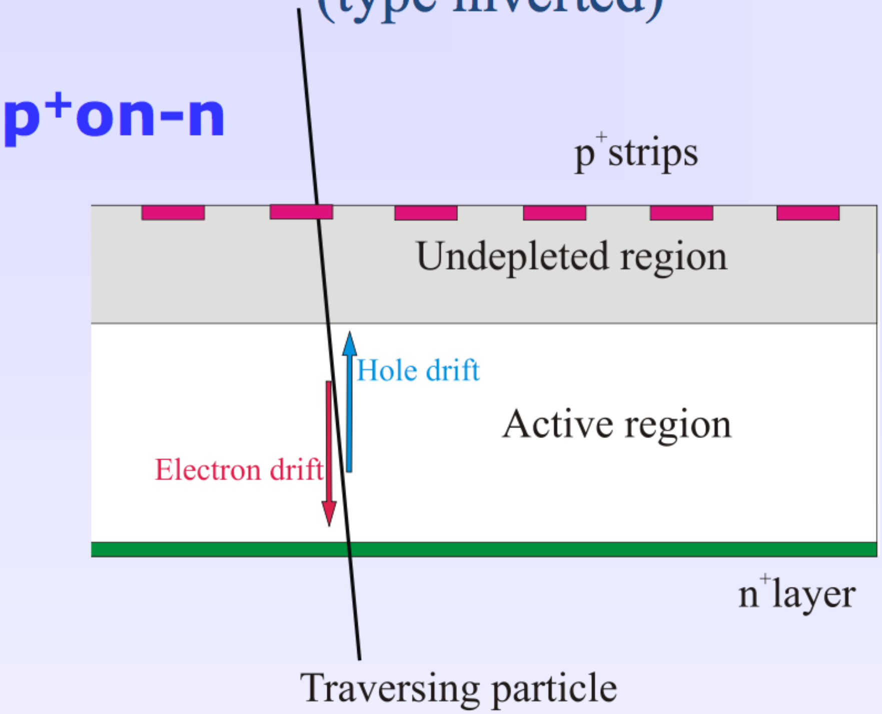
- Annealing effects complicate the issue
- Competing effects with different time constants
  - → *"Beneficial" annealing: recombination of vacancy and interstitial (τ ~ hours)*
  - → *"Reverse" annealing: more complex defects can combine (τ ~ days)*
    - V+V → double vacancy (charge trapping), vacancy + impurity
- Thermal process: vacancies and interstitials are *mobile*
  - → *Reason to keep silicon detectors **cold** (-20C -> -35C)*



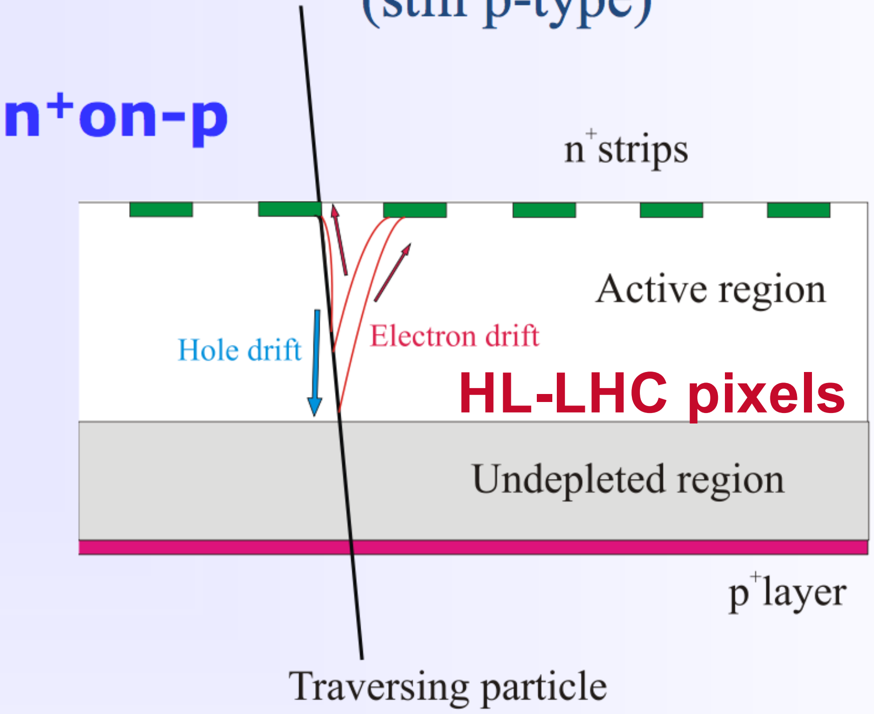


Sensor doping and radiation

n-type silicon after high fluences:
(type inverted)



p-type silicon after high fluences:
(still p-type)



p-on-n silicon, under-depleted:

- **Charge spread – degraded resolution**
- **Charge loss – reduced CCE**

n-on-p silicon, under-depleted:

- **Limited loss in CCE**
- **Less degradation with under-depletion**
- **Collect electrons (3 x faster than holes)**

Comments:
- Instead of n-on-p also n-on-n devices could be used

Michael Moll

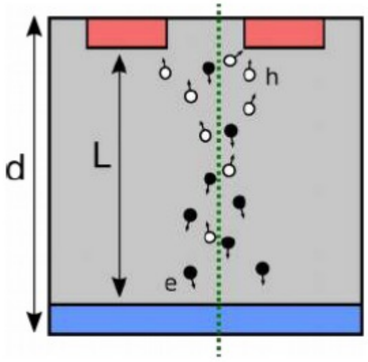
***as they are in current CMS pixels**

Rad-hard design: planar and 3D

- Reduce the drift length through the sensor geometry to mitigate radiation damage
  - → *Thinner planar sensors (CMS Phase 2 is 150 μm)*
  - → *Change the drift path from **transverse** to **parallel** to sensor surface*
    - Maintain signal amplitude, which is proportional to sensor depth

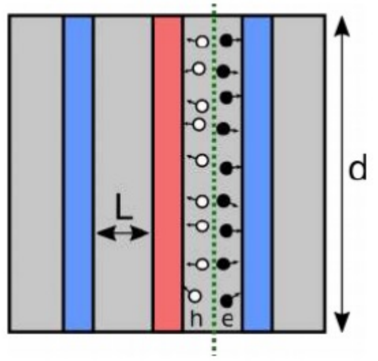
thin-planar sensor

- drift length L<200μm (now: 300μm)
- n-in-p (e signal)
- **outer** and **possibly also innermost layers/rings**



3D sensor

- shorter drift length L
- lower depletion voltage
- technically more challenging
- **inner layer (at most one)**

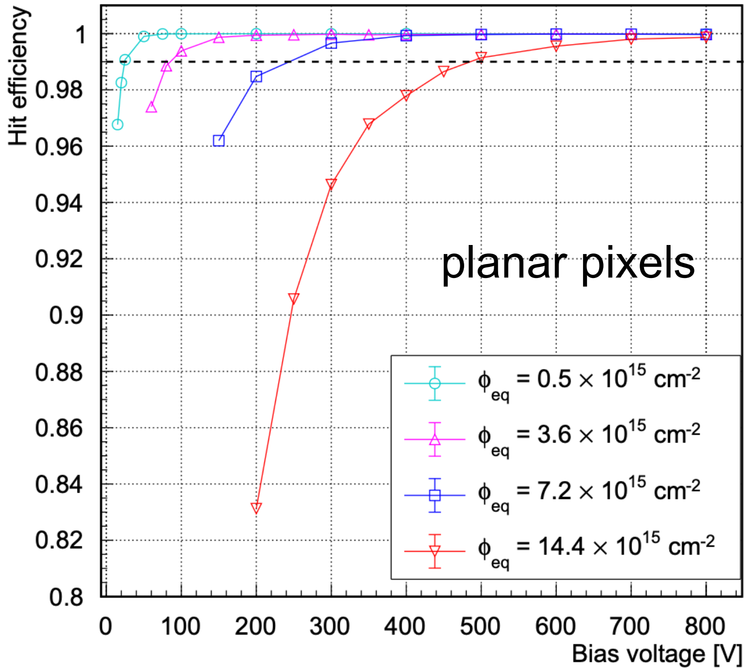


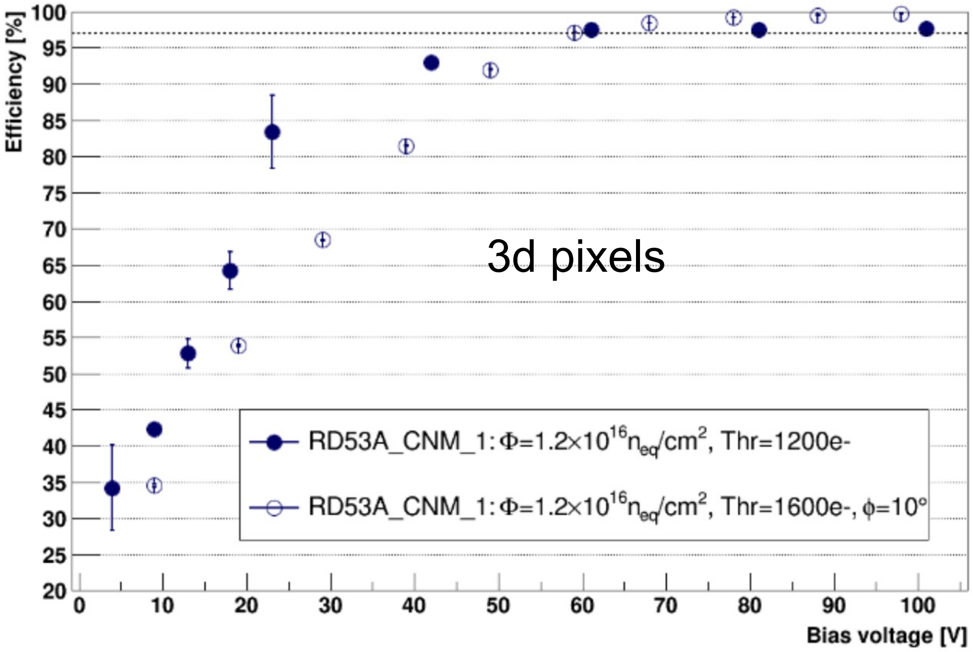
Key metric: Efficiency

$$\text{Efficiency} = \frac{N(\text{tracks with matched clusters})}{N(\text{tracks})}$$

- Answers the question: if there should be a hit there, is there one?
- Should be > 99% for unirradiated devices
- Increases with bias voltage

→ *unirradiated planar devices can be nearly fully efficient at 0V*

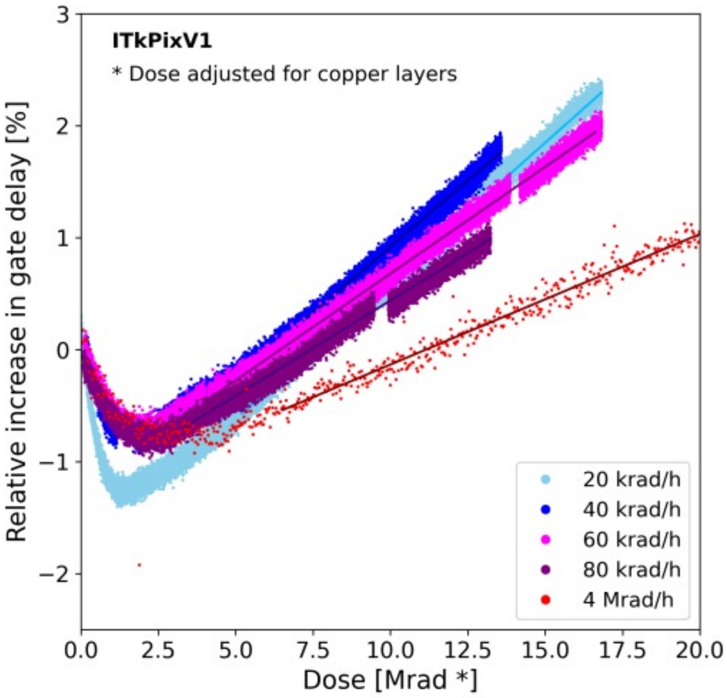




publication forthcoming

Radiation and electronics

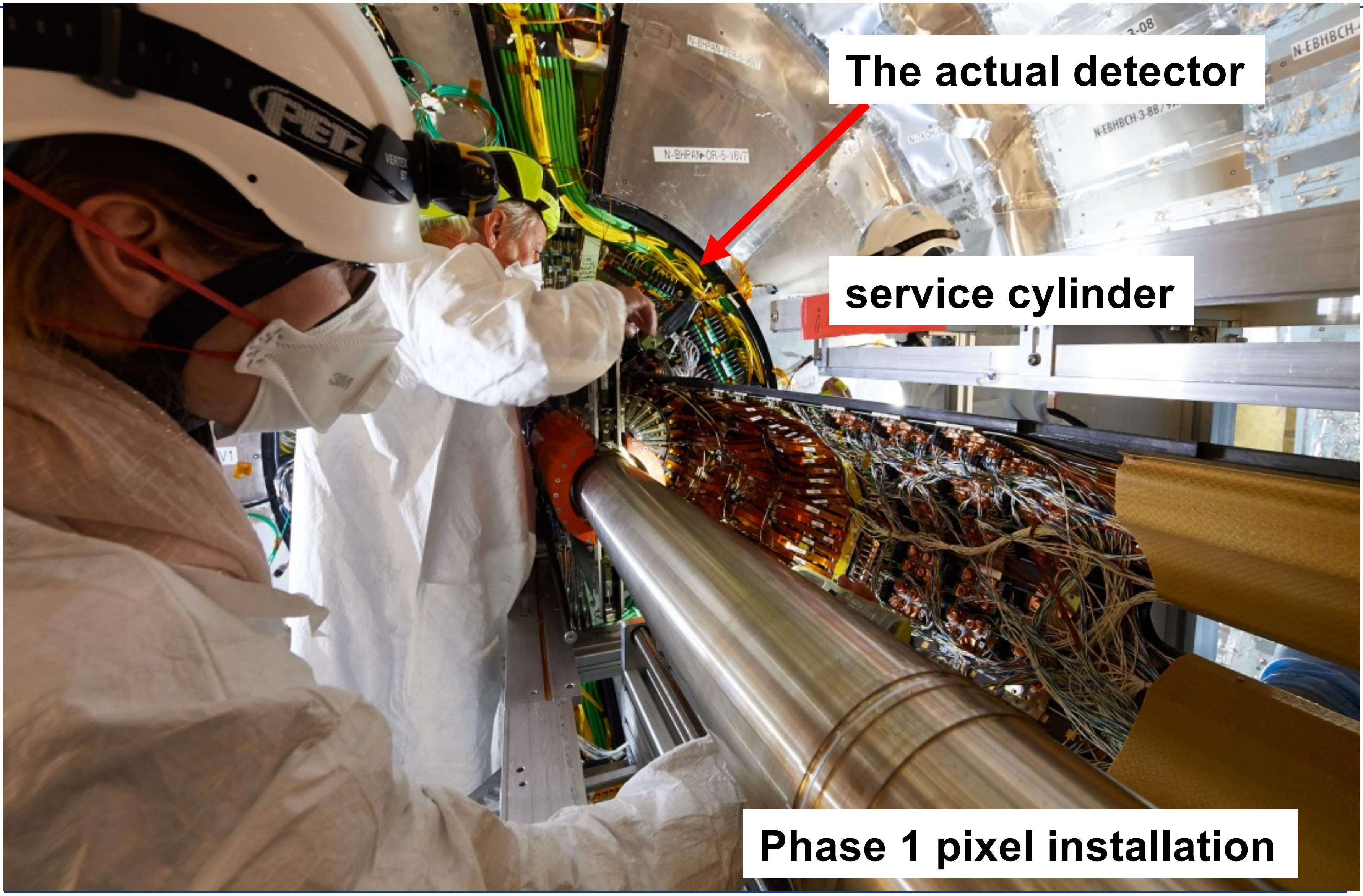
- Electronics are also sensitive to radiation, but differently so
  - → *EM damage = the "dose", vs. fluence for the sensors*
  - → *Typically tested through exposure to x-ray and gamma photons*
- Single-event upset (SEU) – flipped bit
  - → *Guard against through "triple modular redundancy" for important registers: majority vote of three replicas*
- Damage to transistors: shrink transistor size (130 nm → 65 nm)



ATLAS pixel chip in X-ray irradiations

arXiv:2404.10963 [physics.ins-det]

Tomorrow: LHC tracking now and in the near future


The actual detector

service cylinder

Phase 1 pixel installation