Silicon tracking detectors

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HCPSS @ FNAL

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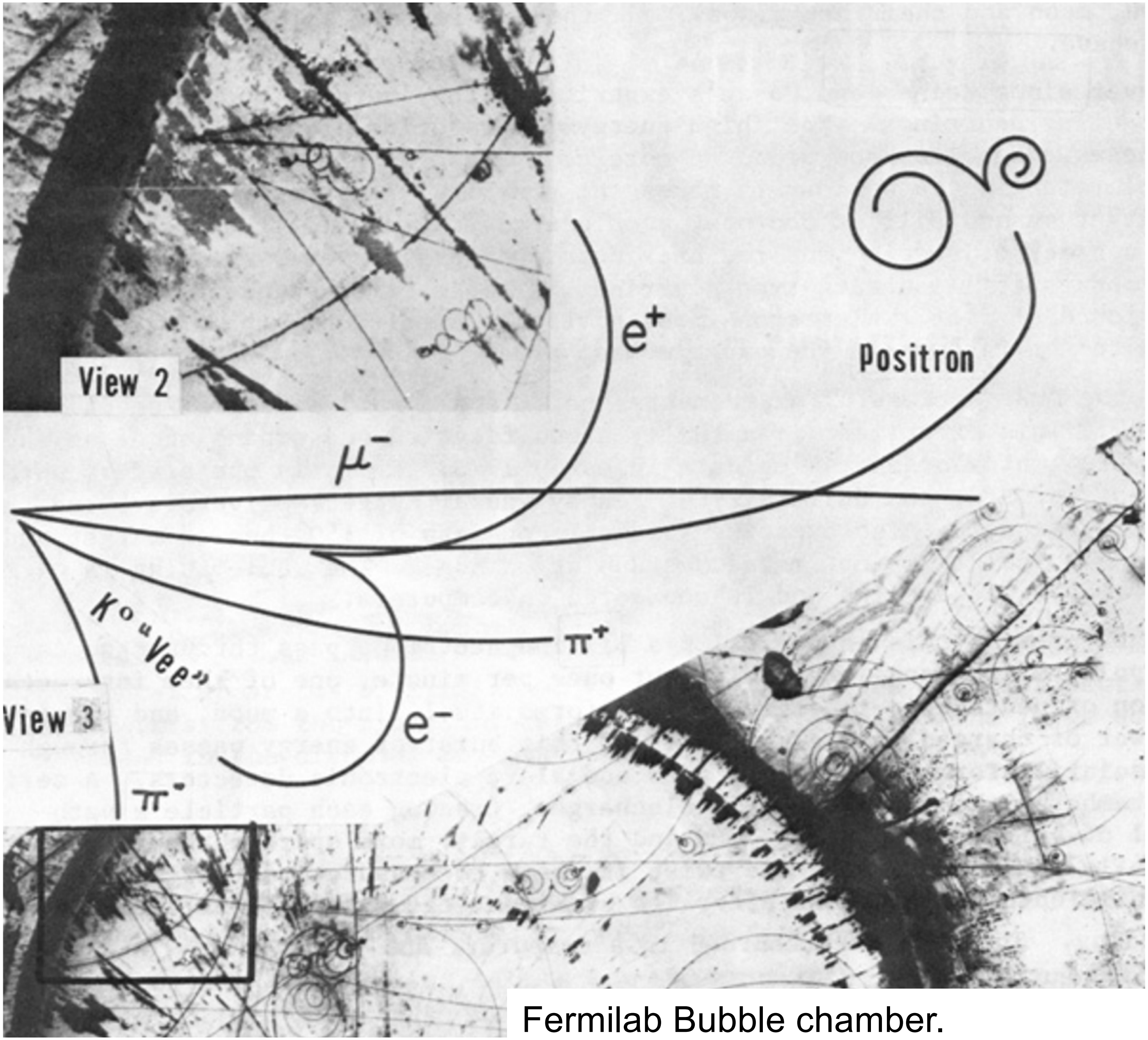
Introduction

- Strive for breadth rather than depth
  - → *Links to resources at the end of the slides*
- Today: from basic principles to tracks
  - → *What particle detectors do*
  - → *Semiconductors and signals from charged particles*
  - → *Local and global reconstruction*
- Tomorrow: devices in the real world
  - → *Radiation damage*
  - → *Operational considerations*
  - → *Real detectors*

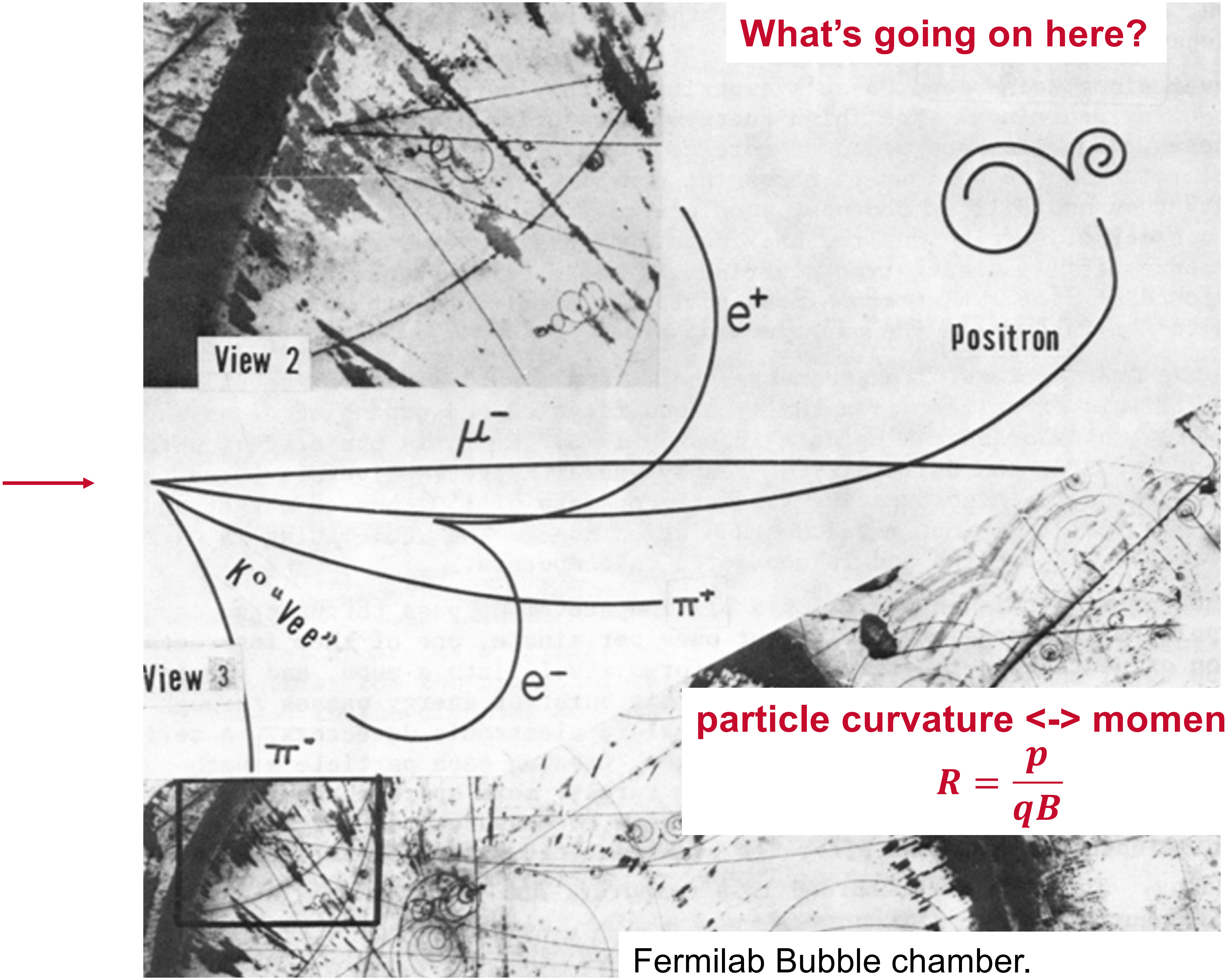
- Starting point: the basic project of experimental collider physics is to collide beams with matter (or other beams), identify and measure the particles that emerge to infer what happened.



Fermilab Bubble chamber.
Courtesy Fermilab Visual Media Services

https://history.fnal.gov/neutrino.html

What's going on here?



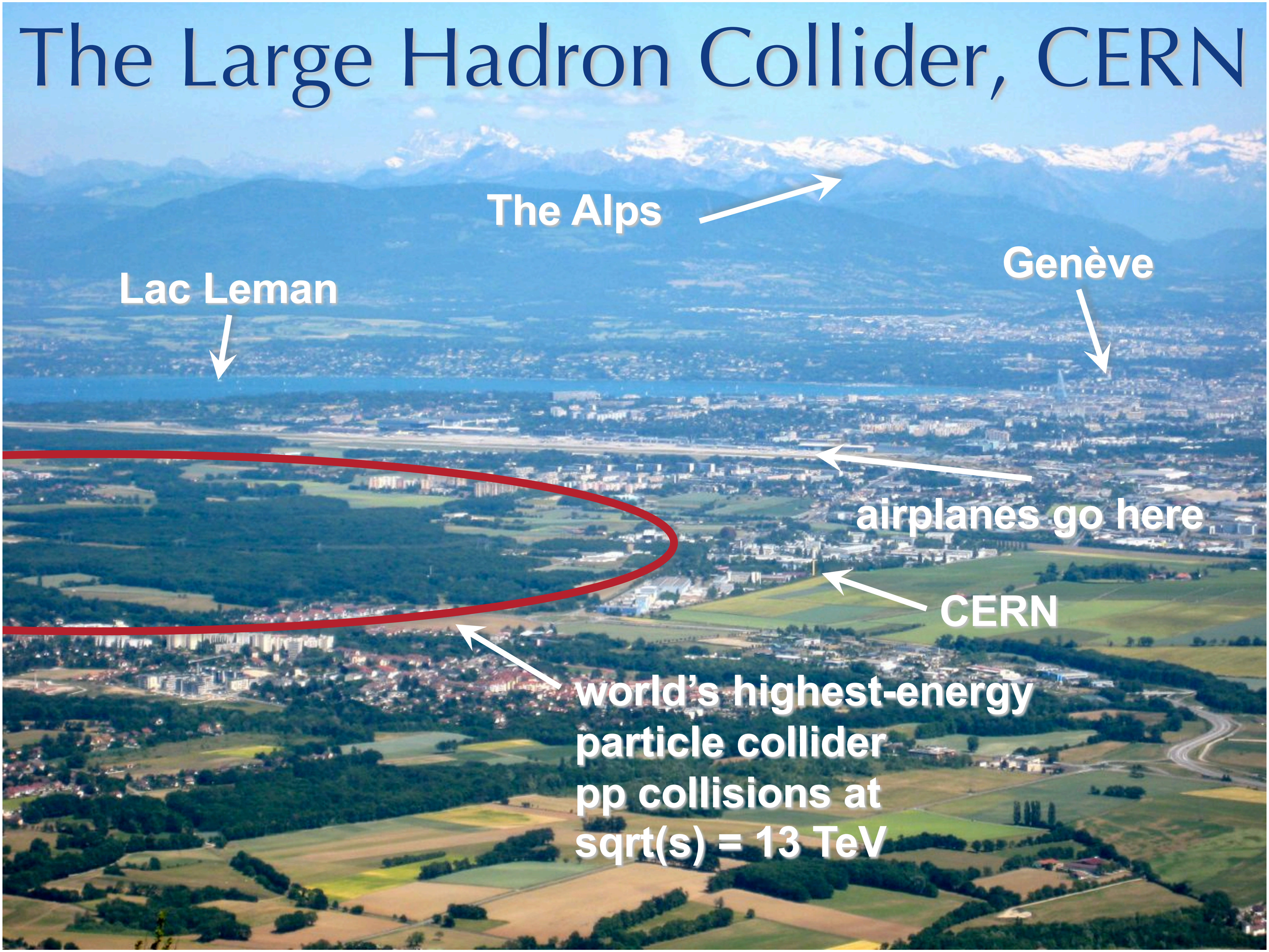
particle curvature <-> momentum

$$R = \frac{p}{qB}$$

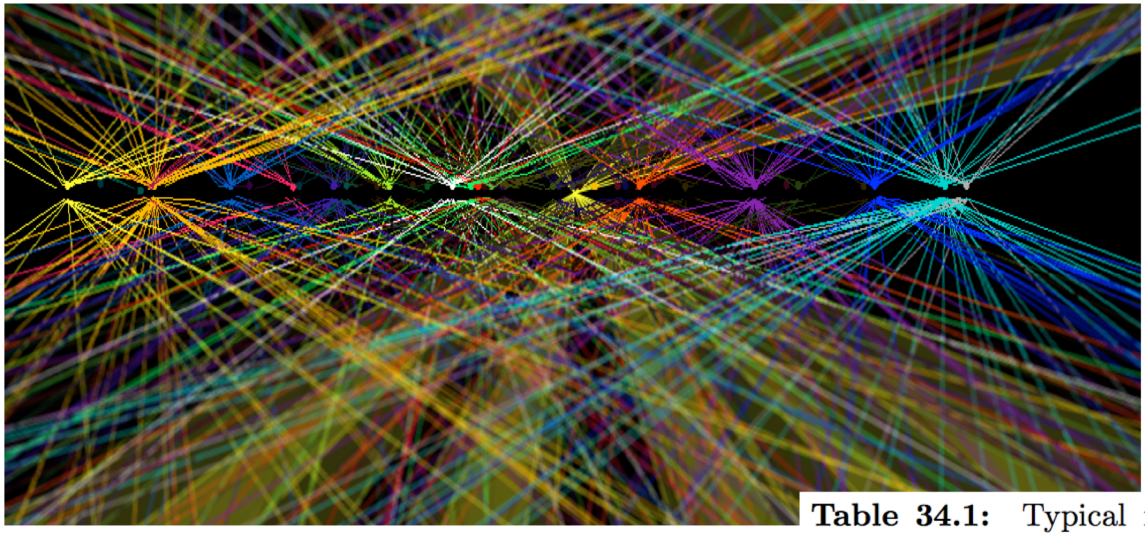
Fermilab Bubble chamber.
Courtesy Fermilab Visual Media Services

https://history.fnal.gov/neutrino.html

The Large Hadron Collider, CERN



Technology vs occupancy



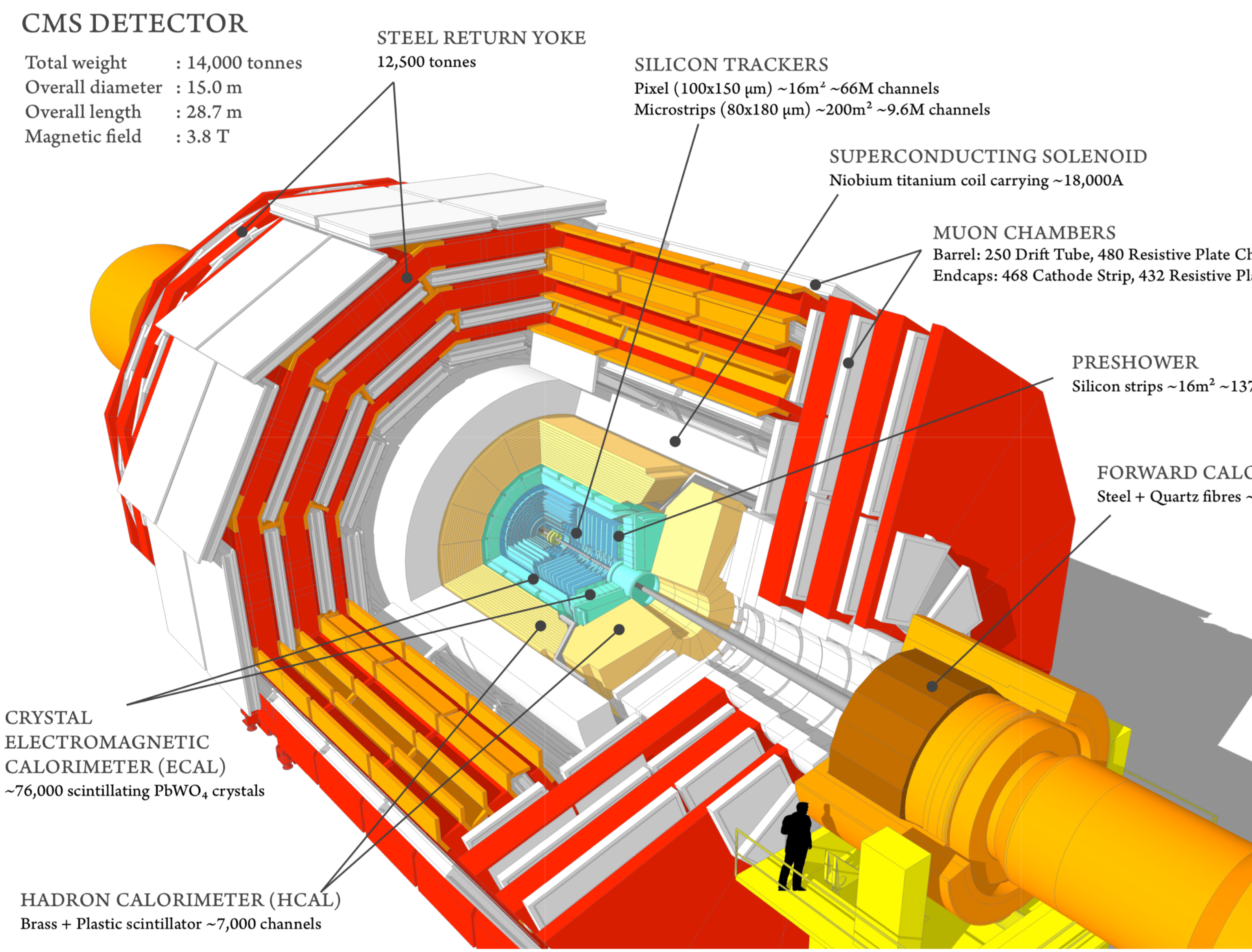
- Study of rare processes such as Higgs boson production require **ever-more-intense beams**

- 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

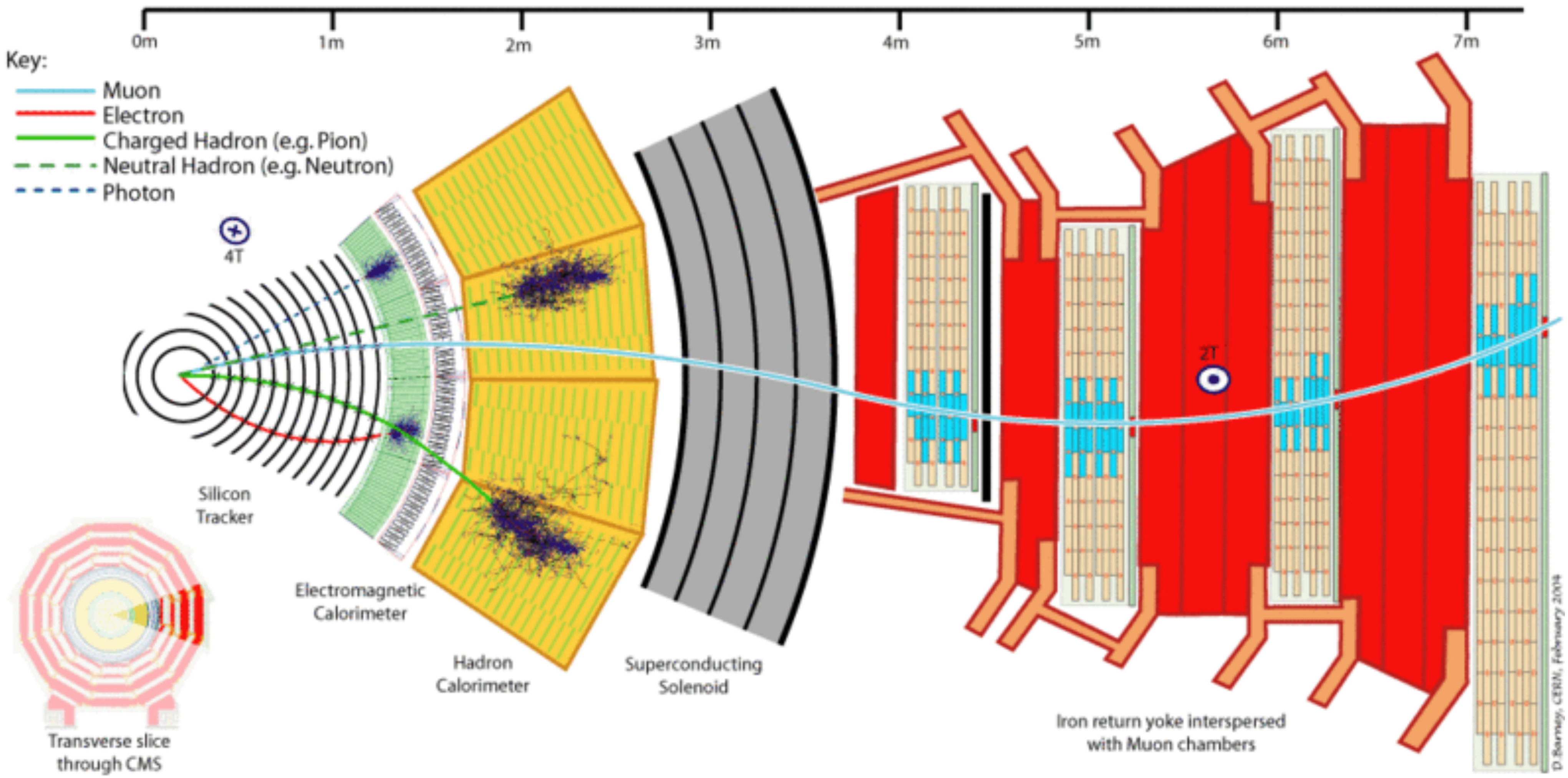
Table 34.1: Typical resolutions and deadtimes of common charged particle detectors. Revised November 2011.

Detector Type	Intrinsinc Spatial Resolution (rms)	Time Resolution	Dead Time
Resistive plate chamber	$\lesssim 10$ mm	1 ns (50 ps[a])	—
Streamer chamber	300 μm[b]	2 μs	100 ms
Liquid argon drift [7]	~175–450 μm	$\sim$ 200 ns	$\sim$ 2 μs
Scintillation tracker	~100 μm	100 ps/n[c]	10 ns
Bubble chamber	10–150 μm	1 ms	50 ms[d]
Proportional chamber	50–100 μm[e]	2 ns	20-200 ns
Drift chamber	50–100 μm	2 ns[f]	20-100 ns
Micro-pattern gas detectors	30–40 μm	$<$ 10 ns	10-100 ns
Silicon strip	pitch/(3 to 7)[g]	few ns[h]	$\lesssim 50$ ns[h]
Silicon pixel	$\lesssim 10$ μm	few ns[h]	$\lesssim 50$ ns[h]
Emulsion	1 μm	—	—

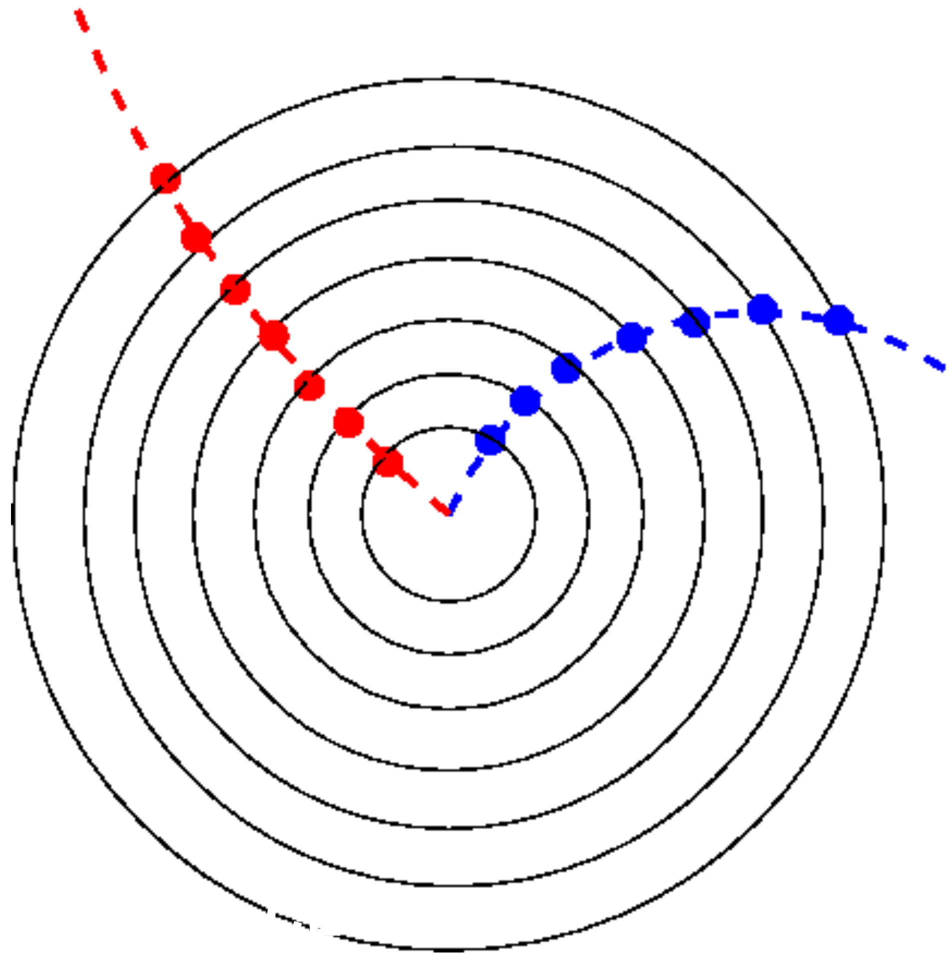
The CMS Detector



How we reconstruct particles

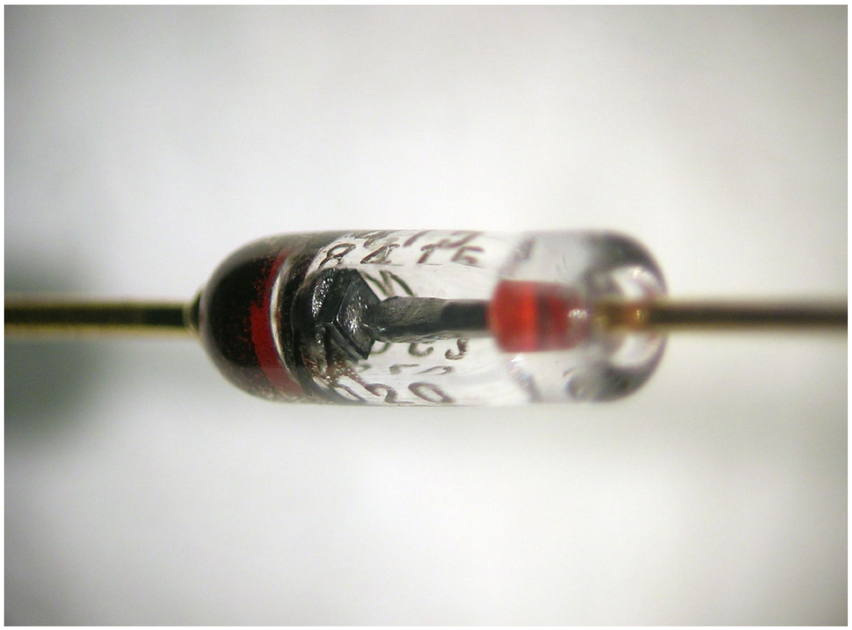


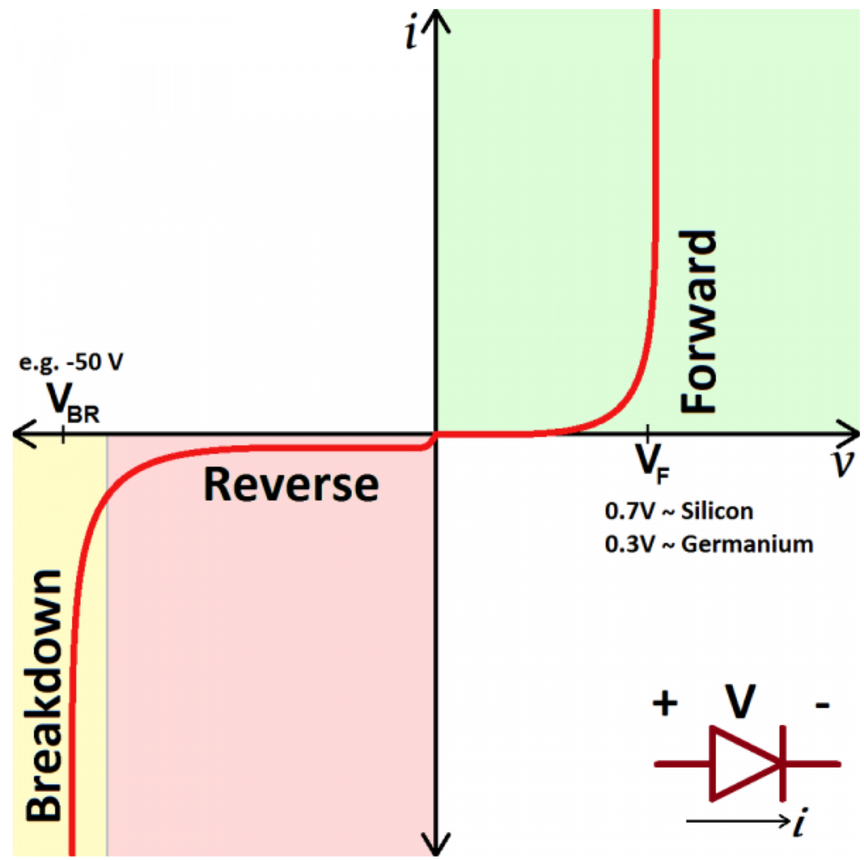
Silicon trackers at the heart of modern collider detectors, built at ever-increasing scale



Signals from charged particles

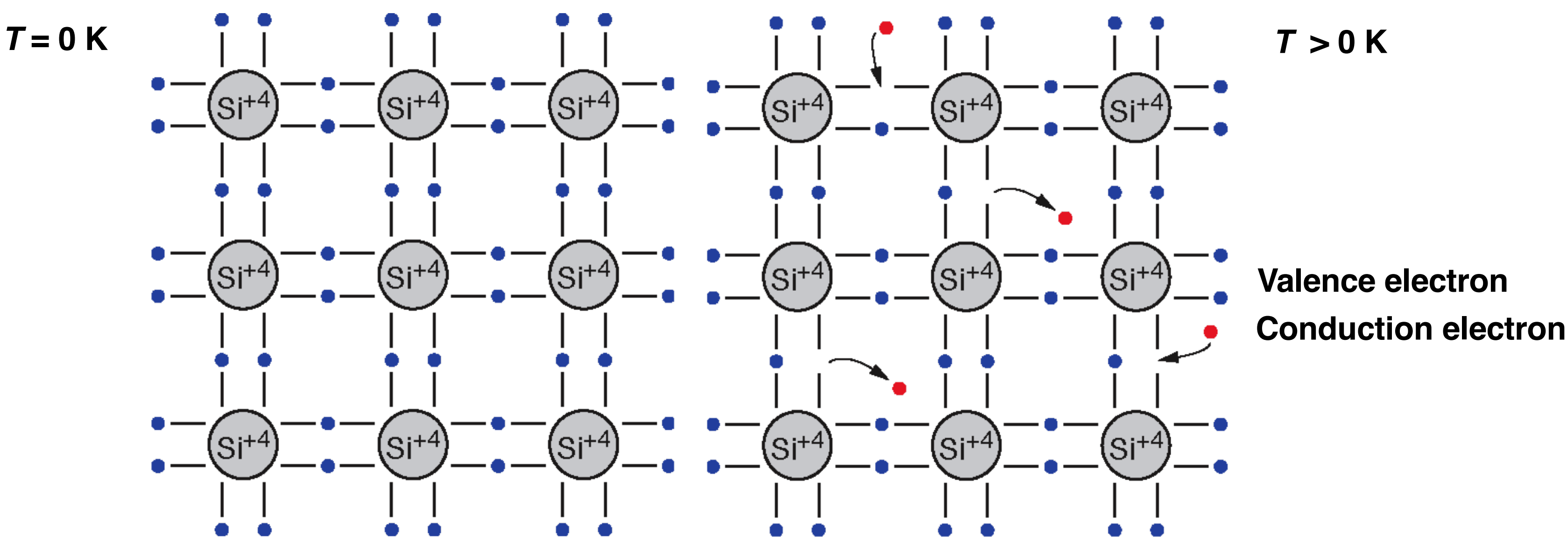
- A silicon detector is essentially a *reverse-biased diode*. Why?





Semiconductors

- Charged particle passing through semiconductor creates electron-hole pairs
- Thermal energy liberates charge conductors, but charged-particle signal (10^4 electron-hole pairs) swamped by thermal production (10^8 e-h pairs at room temperature)



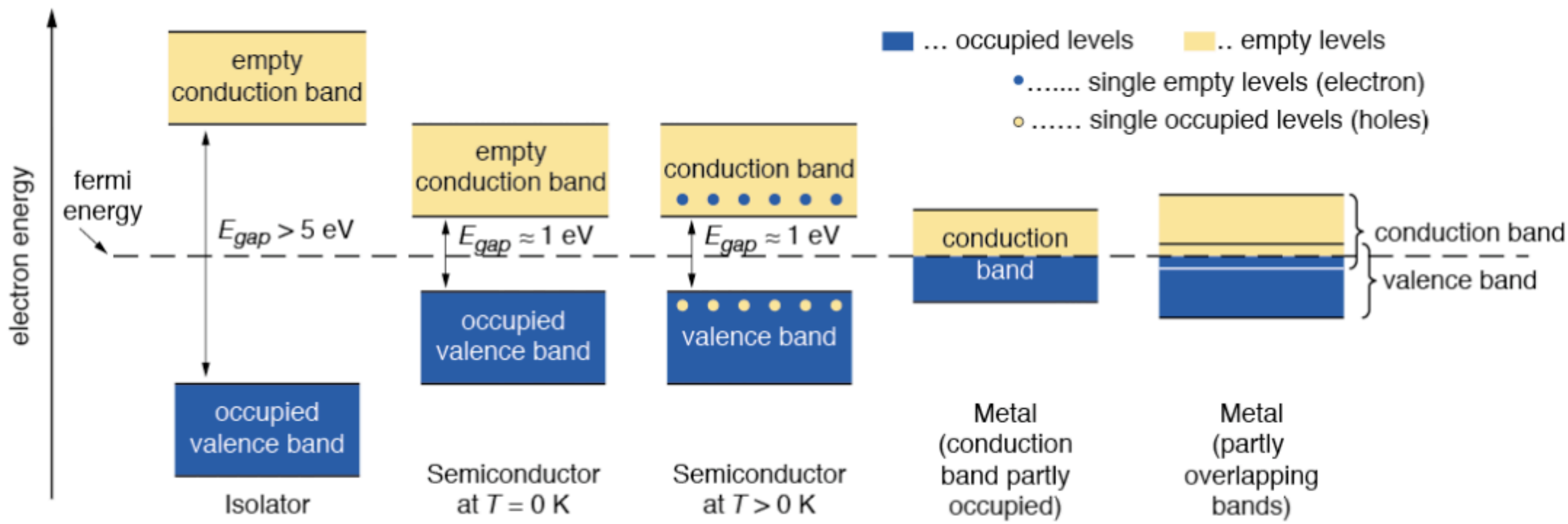
Semiconductors

- Single atom has discrete energy levels; in solids these become energy bands

→ ***Fermi level*** *= highest filled state at zero temperature*

→ *Thermal excitations move electrons to higher-energy states, leaving holes*

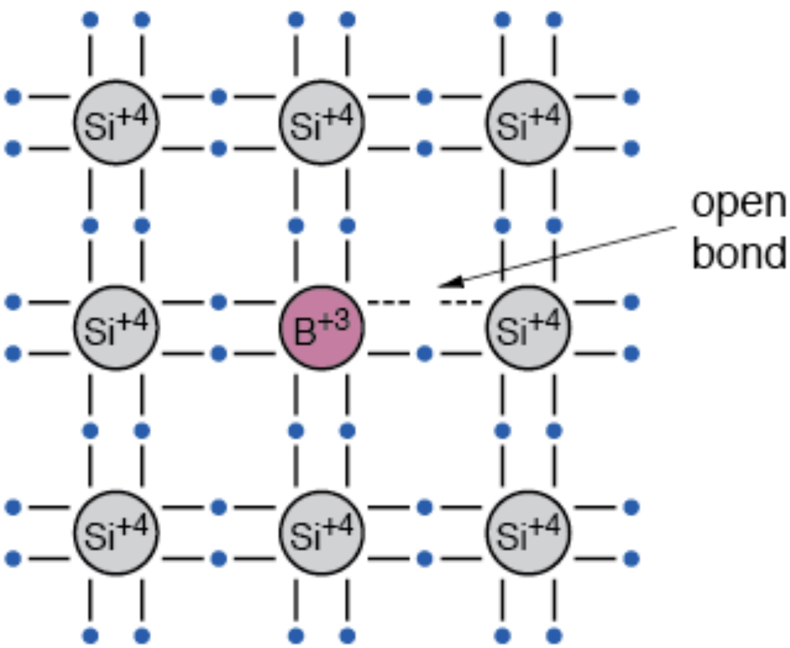
→ *A* ***hole*** *acts effectively as a positive charge carrier*

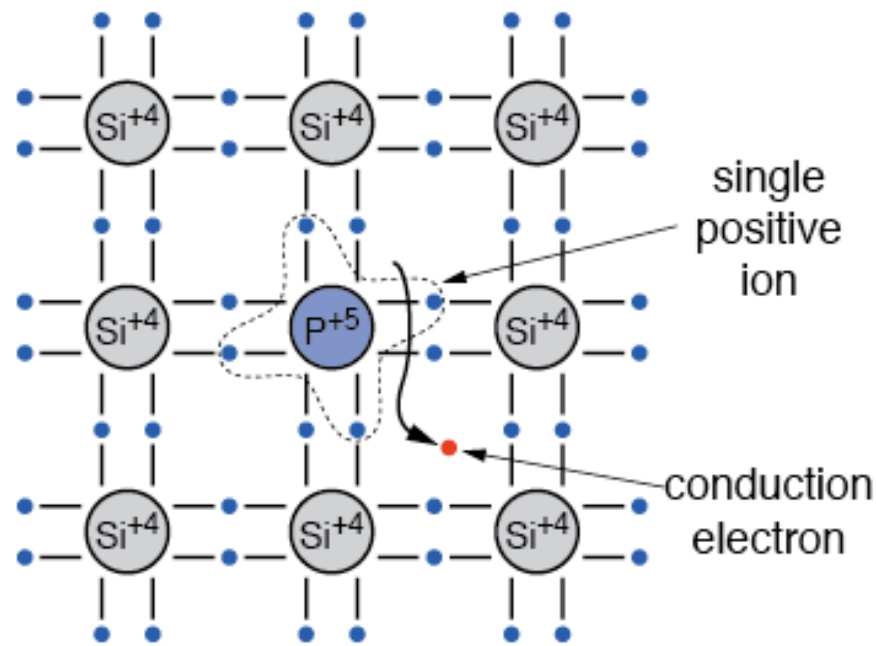


Semiconductors

- Semiconductors typically deliberately **doped** with impurities to alter their band structure

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



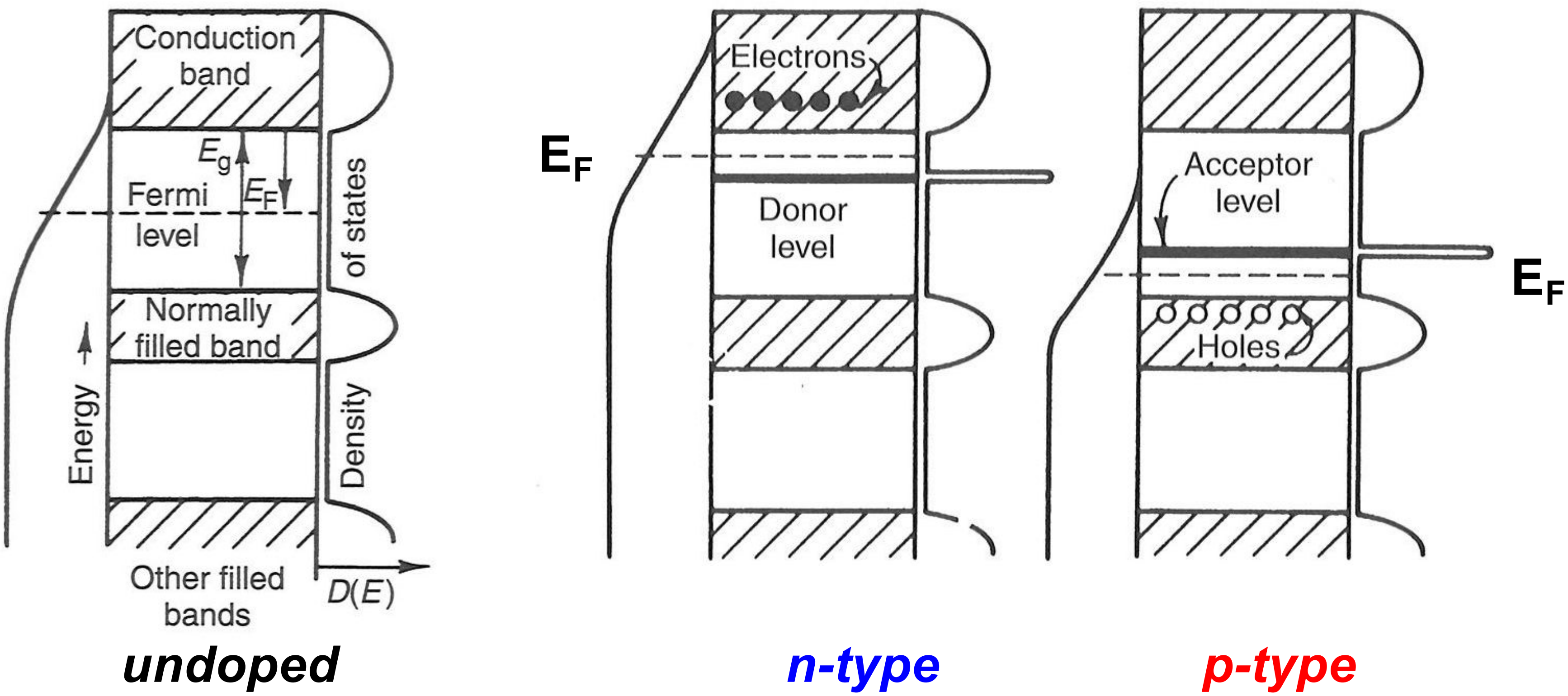


p-type
charge carrier positive
stationary nucleus effectively negative

n-type
charge carrier negative
stationary nucleus effectively positive

Semiconductors

- Doping alters the band structure and Fermi Level



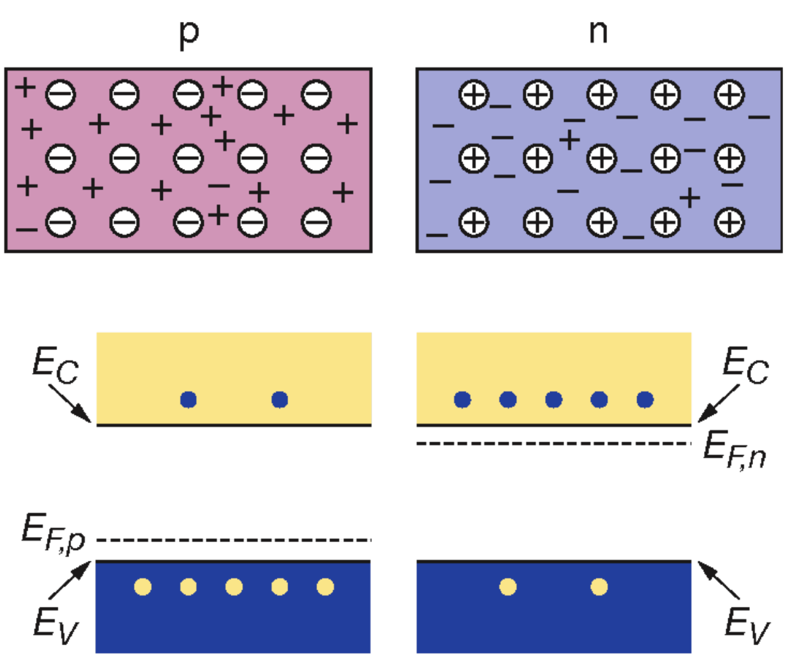
from Melissinos & Napolitano

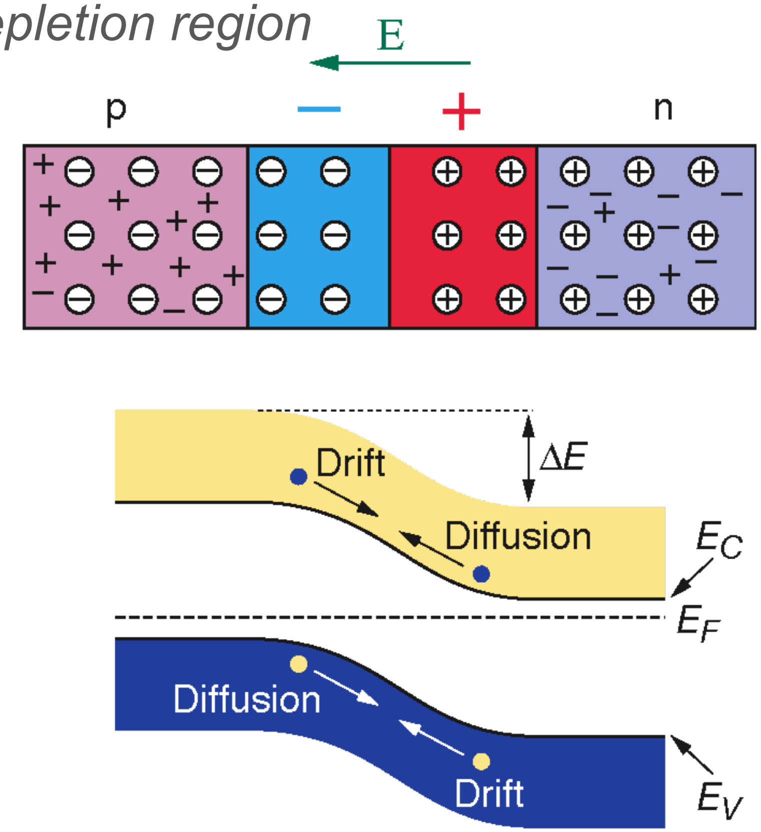
The p-n junction

- 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: internal electric field and depletion region*

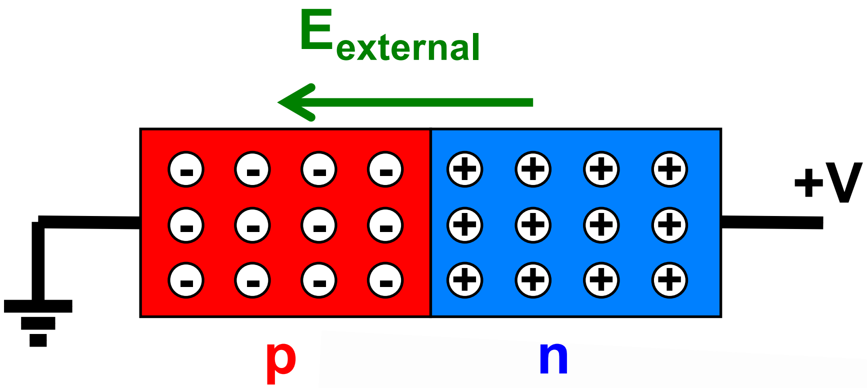




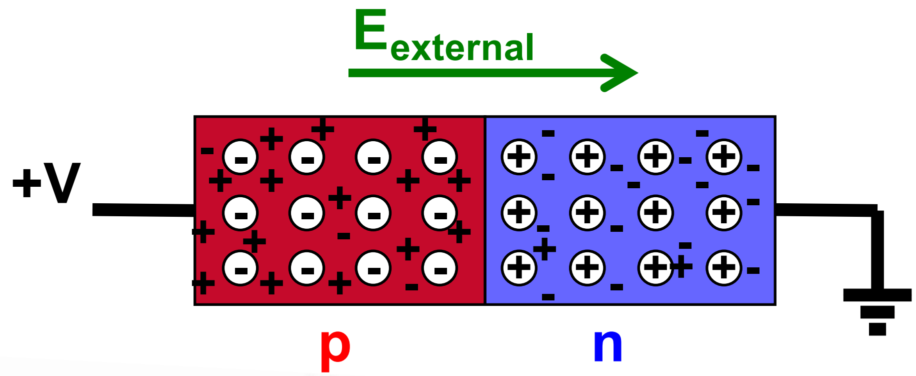
from F. Hartmann lectures on semiconductor particle detectors

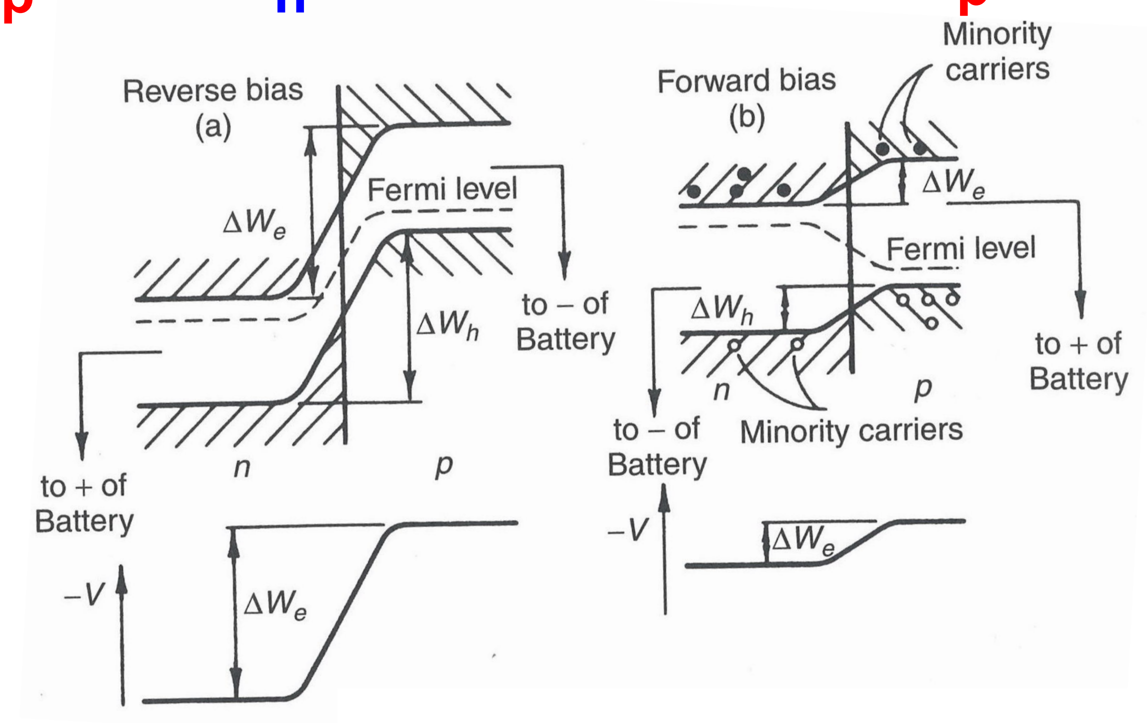
The p-n junction

Reverse bias: depletion region expands



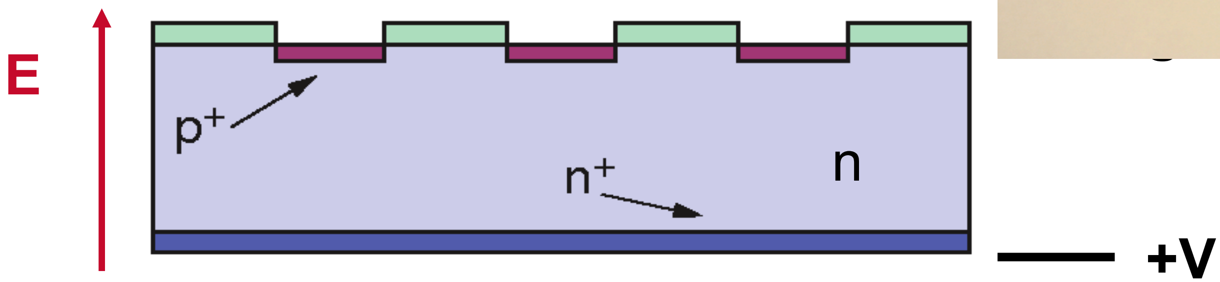
Forward bias: current flows



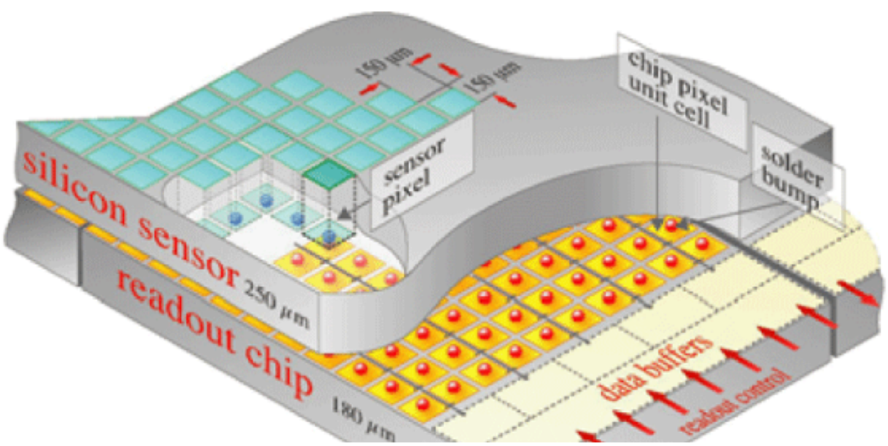


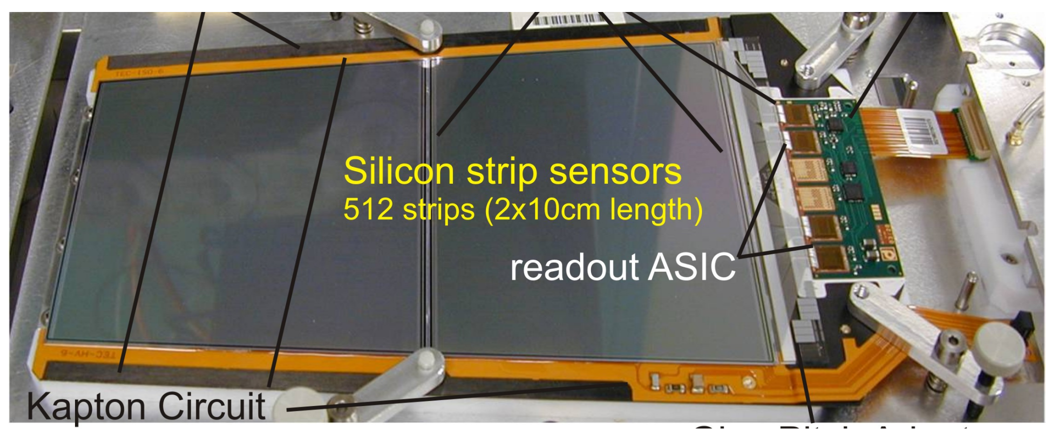
Detector from diodes

- Segmented implants with different doping tha
- Classically p-in-n detector, but n⁺-in-n and n-
- Apply reverse bias to deplete the bulk



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





Depletion zone in Si detector

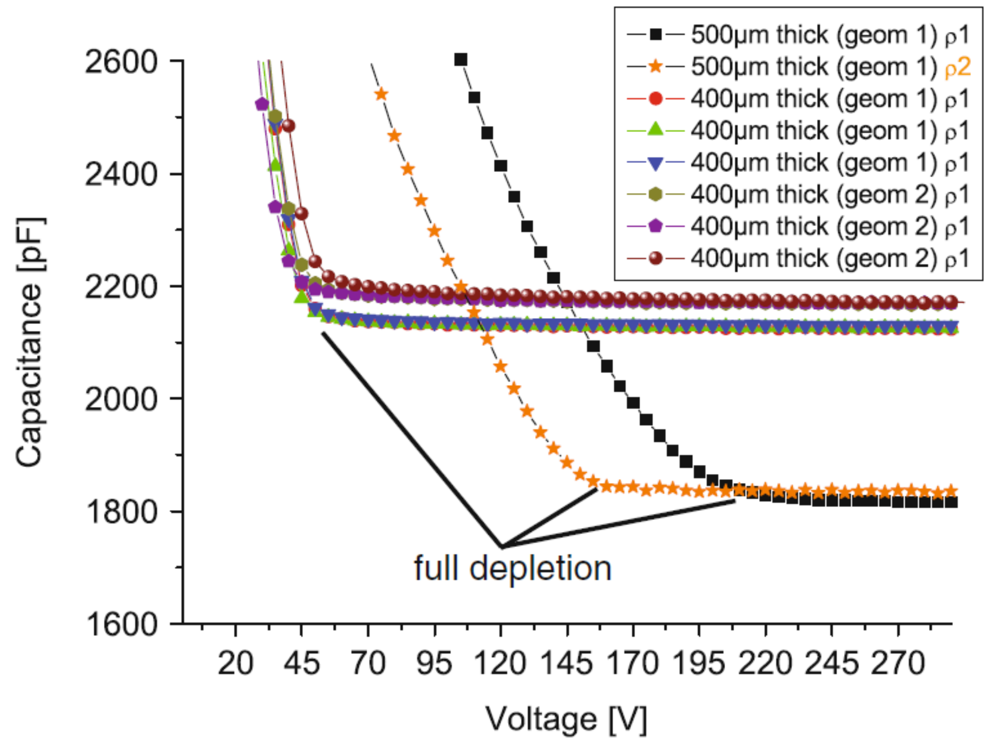
- The **depletion voltage** is the minimum voltage at which the bulk of the sensor is fully depleted. The operating voltage is usually chosen to be slightly higher (overdepletion).
- High resistivity material (i.e. low doping) requires low depletion voltage.

$$V_{FD} = \frac{D^2}{2\varepsilon\mu\rho}$$

For a typical Si p-n junction ($N_a >> N_d >> n_i$) the detector capacitance is given as:

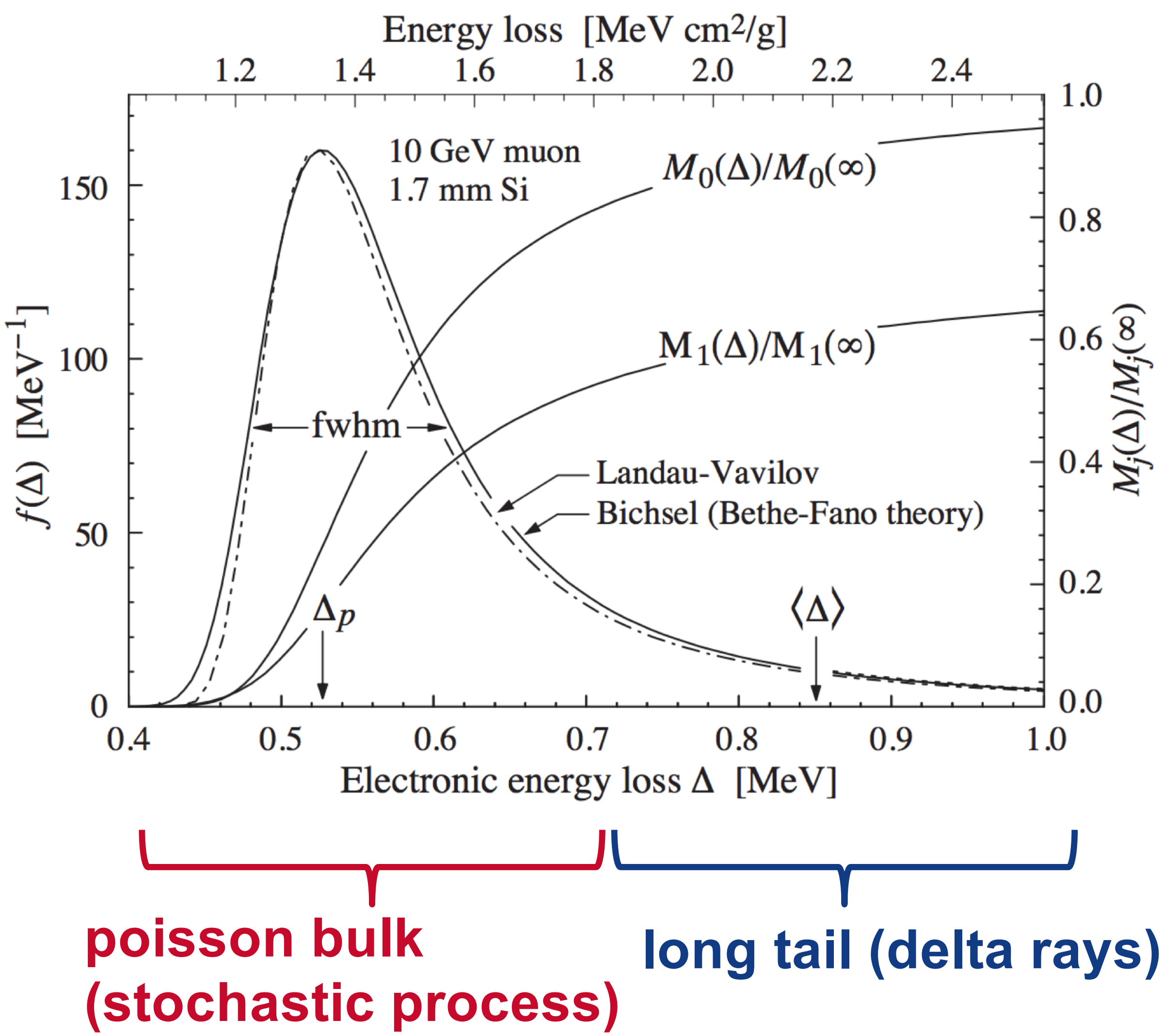
$$C = \sqrt{\frac{\varepsilon_0\varepsilon_r}{2\mu\rho|V|}} \cdot A$$

ρ … specific resistivity of the bulk
μ … mobility of majority charge carrier
V … bias voltage
A … detector surface
D … detector thickness



Signals from charged particles

- Signal in a *thin* detector such as a plane of silicon is Landau-ish
  → *True distribution described by Bichsel*



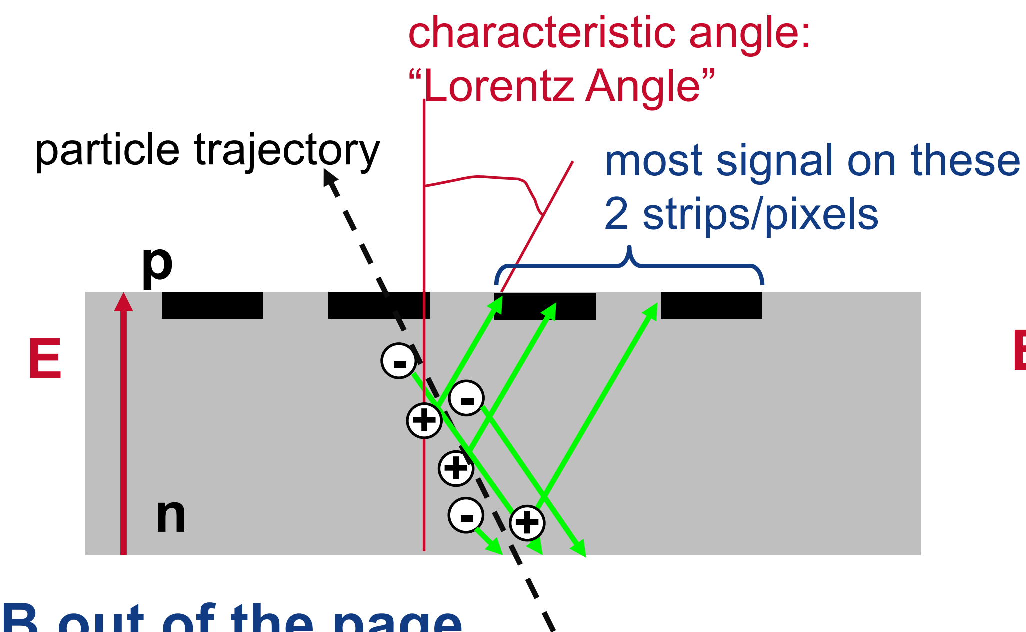
mean value != most probable value

Silicon: 3.6 eV to create 1 electron-hole pair
eh pair per micron
mpv 76 avg 108

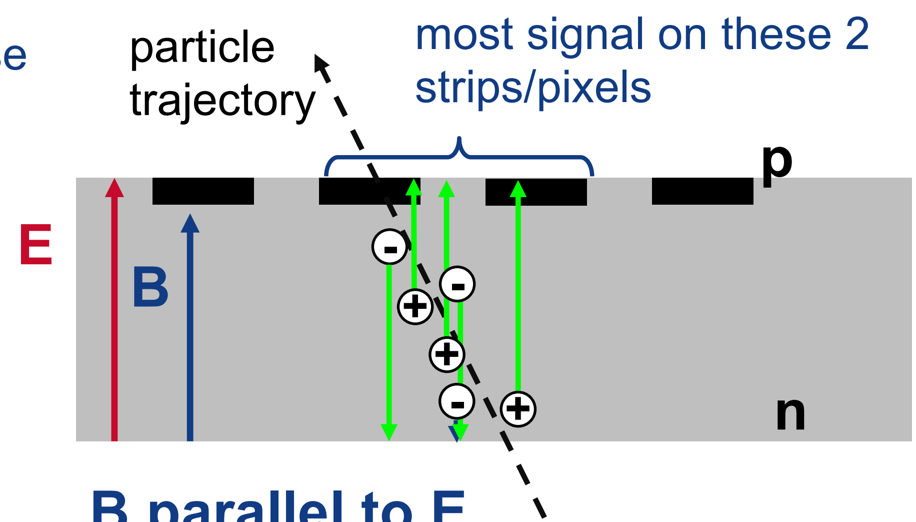
Electron-hole pairs drift

- 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



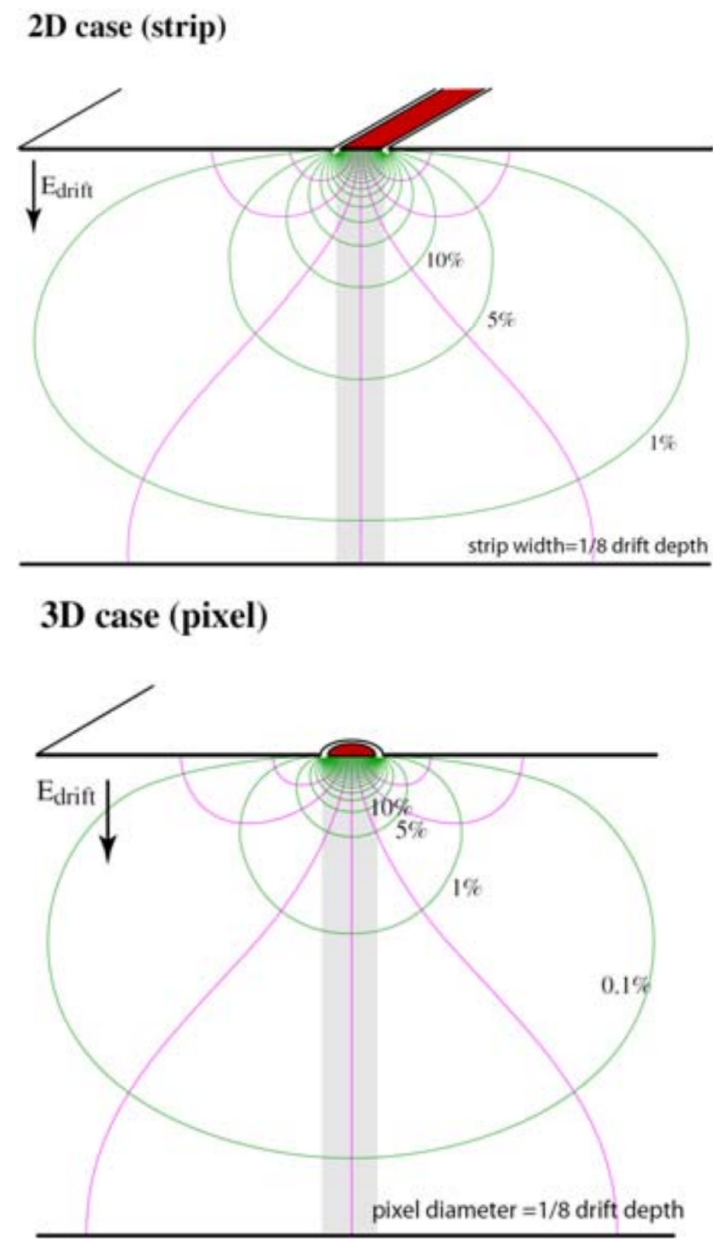
B parallel to E
typical of forward

Drifting charge induces signal

- **Signal is actually *induced* on the electrodes on the sensor surface rather than collected directly**
  - → *Shockley-Ramo theory: instead of calculating the effect of the field of the moving charge, current can be inferred from the velocity of the charge and the weighting field of the electrode if it is at a potential of 1, other electrodes are a ground, and the drifting charge is absent*

$$\boldsymbol{i = -q\vec{E}_W \cdot \vec{v}}$$

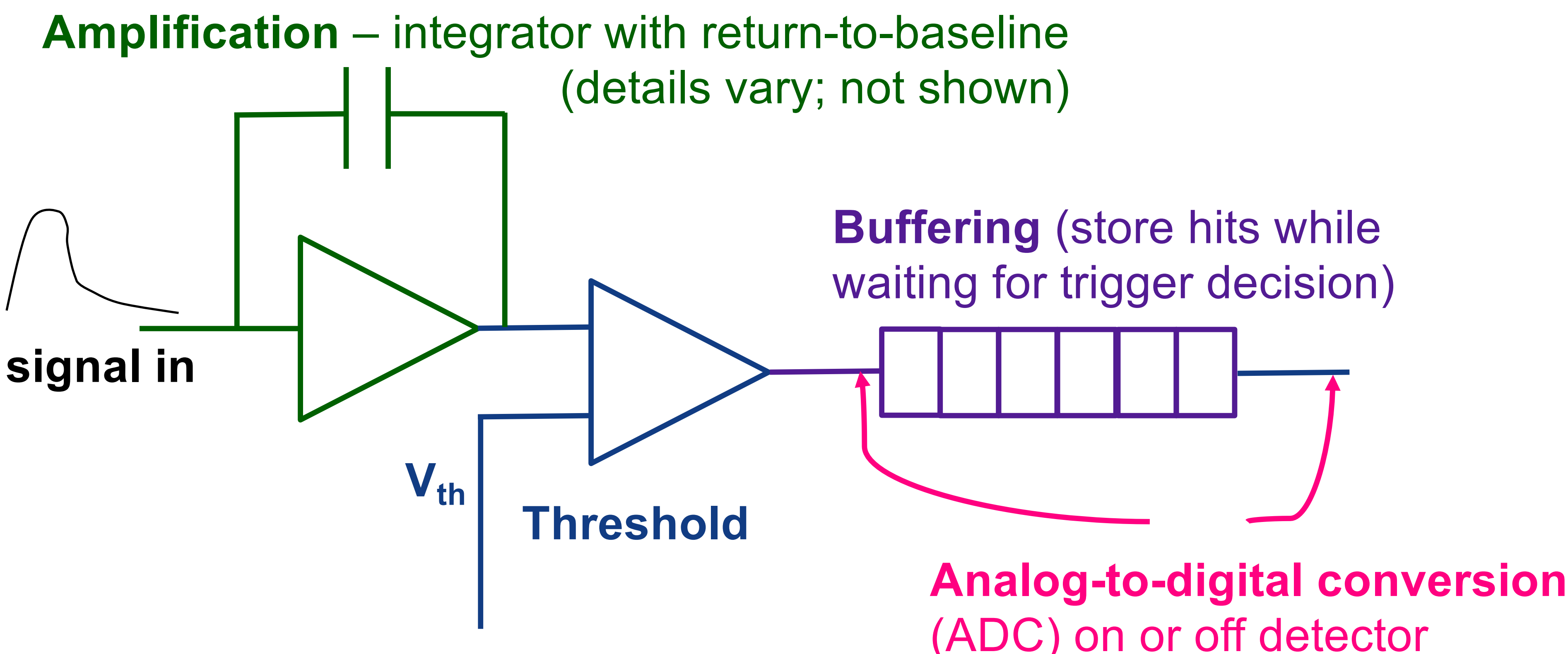
  - → *Holds in the presence of space charge and/or constant magnetic field*
  - → *Total induced charge found using potential difference* $Q = -q\Delta V$
- **Both electrons and holes induce signal**



V. Radeka via Hartmann

Electronics

- Readout via dedicated ASIC (Application-Specific Integrated Circuit)
- Pulses are small
  → *80 e+h pairs per micron * 150 um detector = 12,000 electrons = 2 fC*
- Measure time-over-threshold or just presence of charge (binary)
- Zero-suppression: only read out pixels/strips with charge



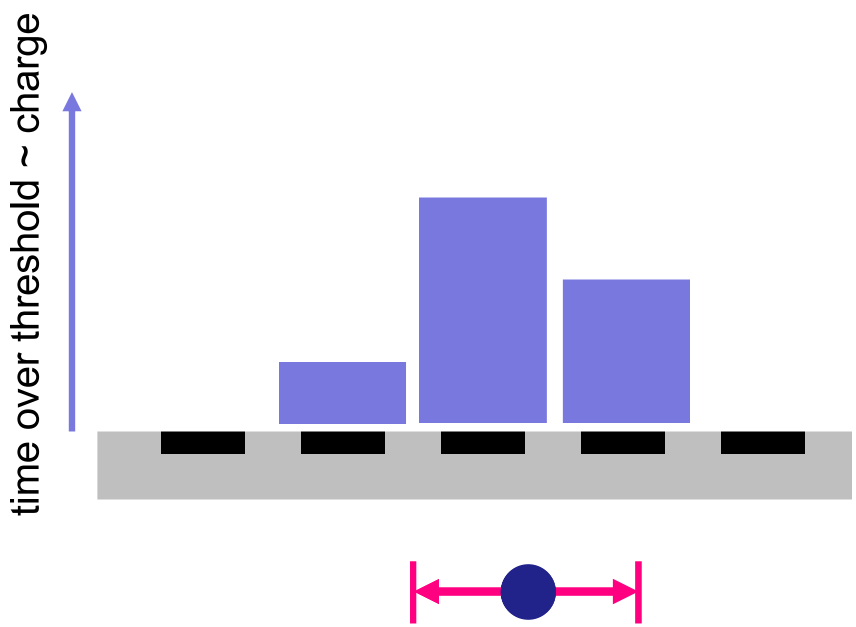
Building clusters

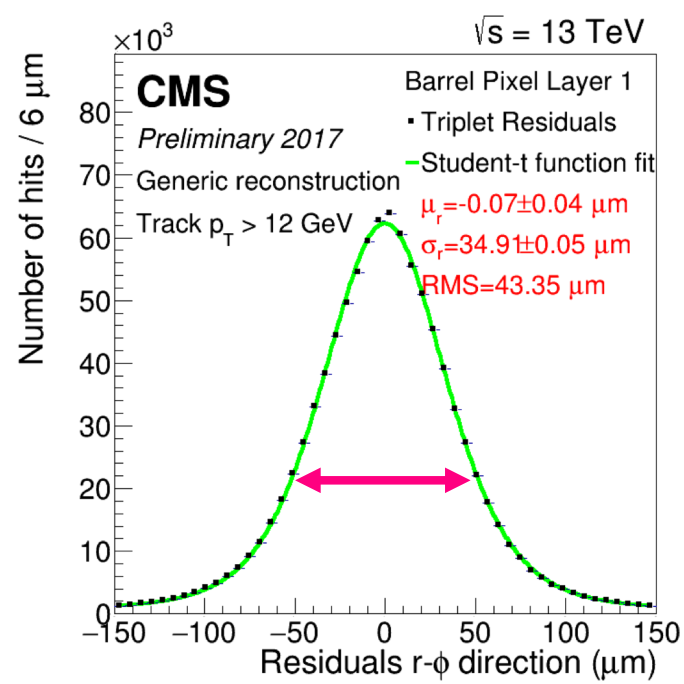
- From detector pulses to a particle trajectory
- Start from charge information: cluster centroid

→ *Interpolate from edges or make a template fit (latter has significant advantage after irradiation*

- But need *resolution* of hit location for track fit

→ ***Resolution*** *= width of (Gaussian) distribution of* residuals *(difference between track position and estimated cluster centroid)*

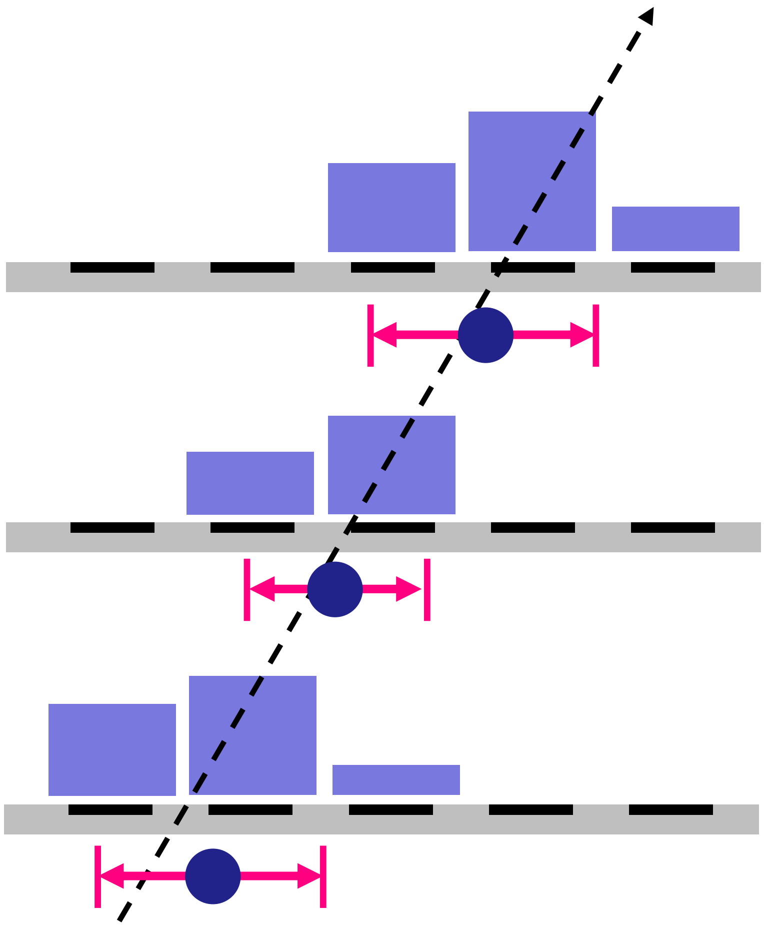




https://twiki.cern.ch/twiki/bin/view/CMSPublic/PixelOfflinePlotsAugust2017

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



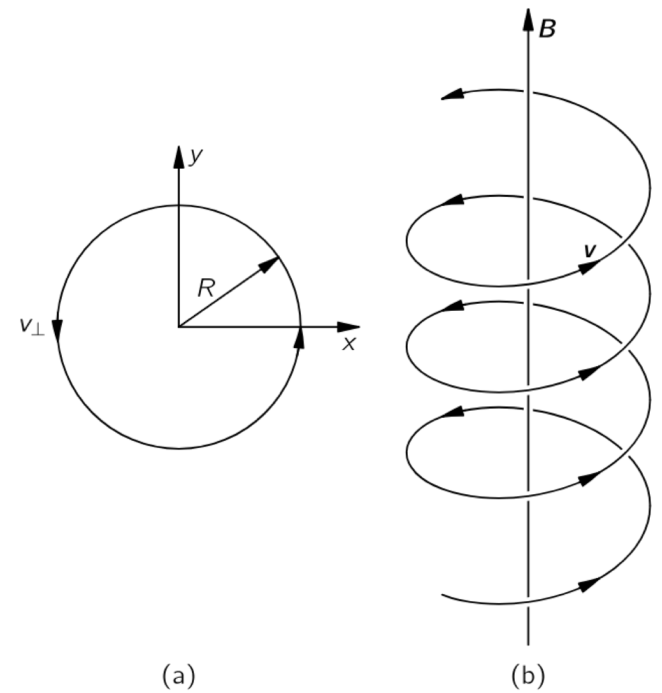
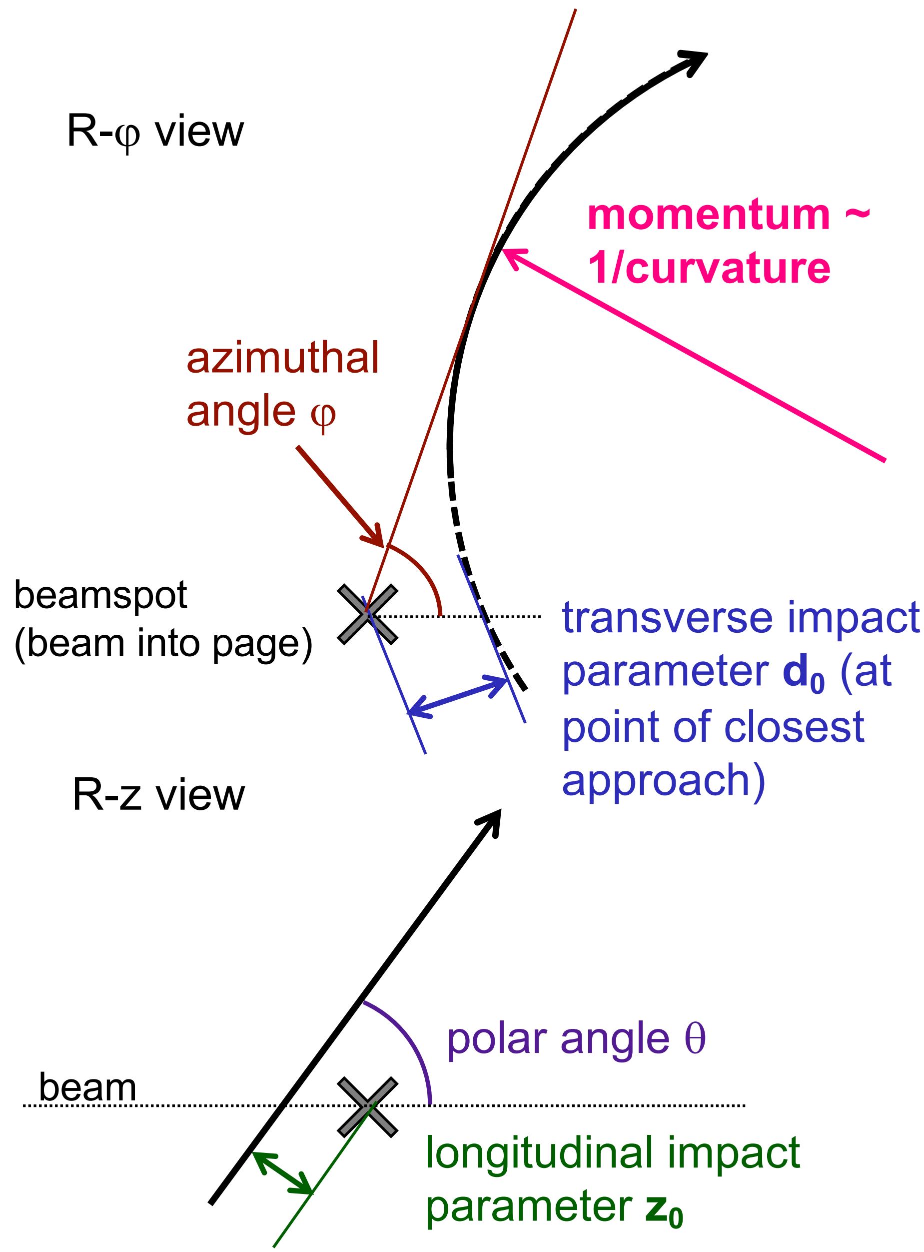


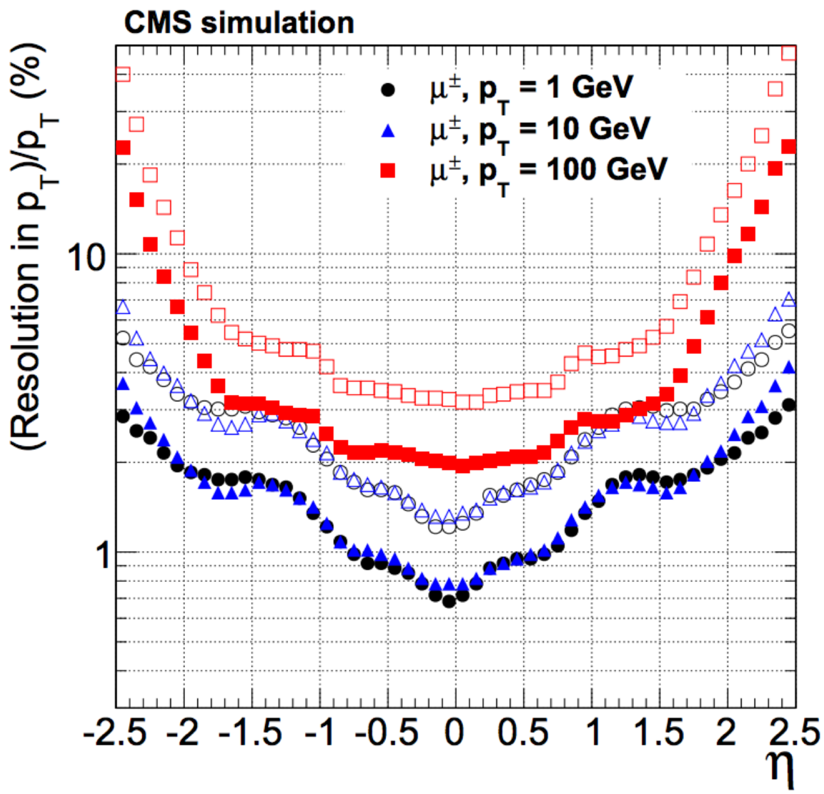
Fig. 29–1. Motion of a particle in a uniform magnetic field.

Tracking performance at CMS

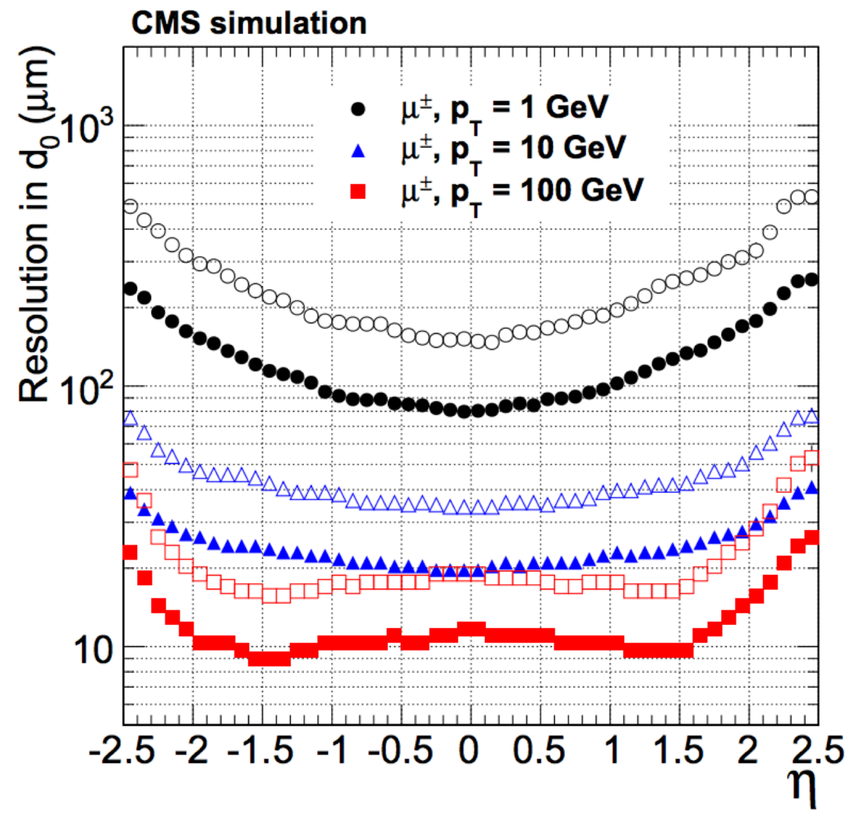
- Tracking is fundamental to charged particle reconstruction + measurement
  - → *[Transverse] momentum*
    - kinematic selection
  - → *Impact parameter*
    - Displaced tracks from decay of particles such as b-quark hadrons
- Helical trajectory defined by 5 track parameters
  - → *2 impact parameters*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



Tracking performance at CMS



Harder to measure curvature of straighter (higher-momentum) tracks



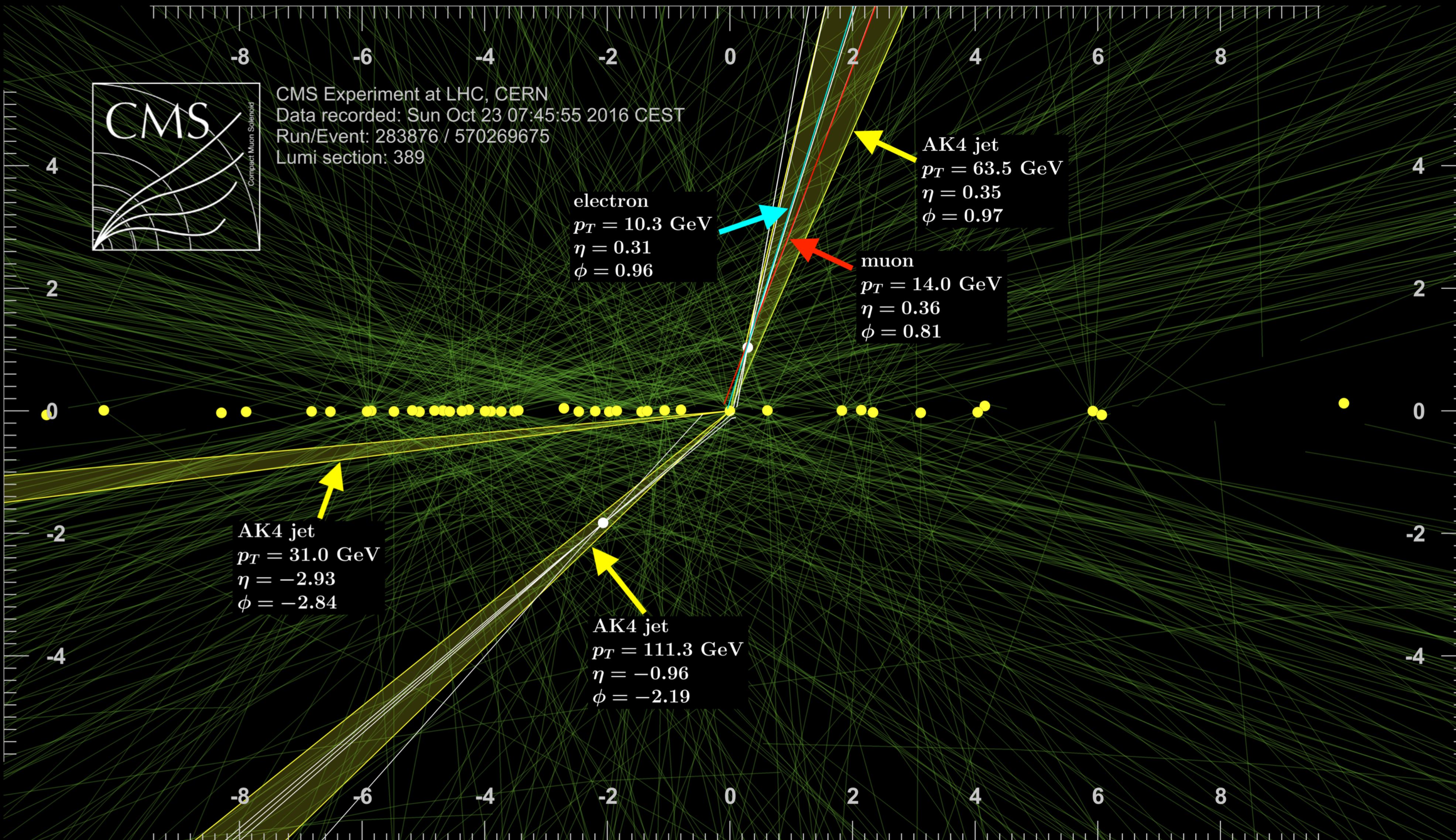
Harder to extrapolate lower-momentum tracks: scattering in material matters

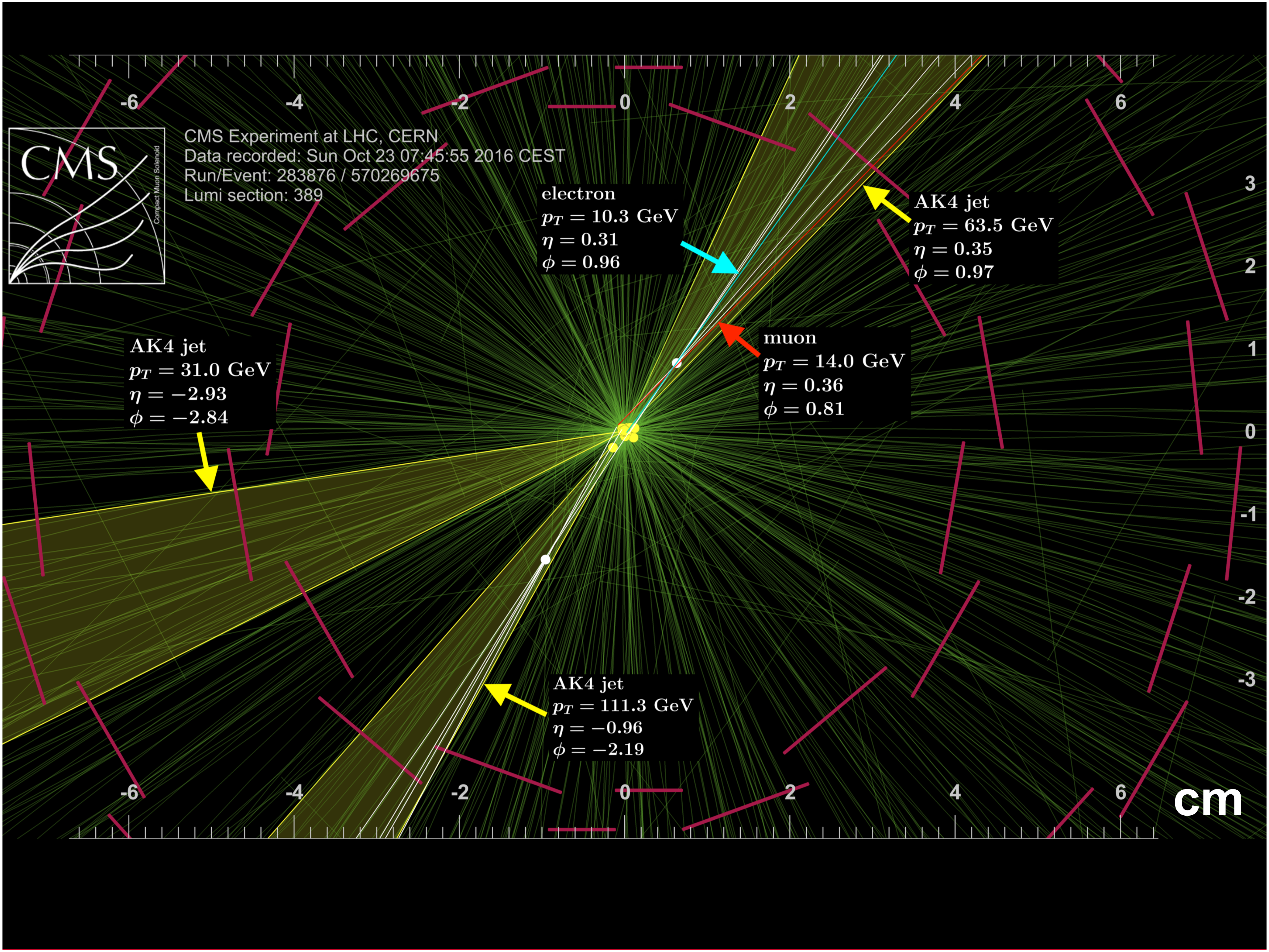
$$\left(\frac{\sigma_{p_T}}{p_T}\right)^2 \propto c_1 \cdot \left(\frac{p_T}{BL^2}\sqrt{\frac{720}{N+4}}\right)^2 + c_2 \cdot \left(\frac{1}{B\sqrt{LX_0}}\right)^2$$

curvature — **multiple scattering**

For CMS:
magnetic field **B** = 3.8 T
tracker radius **L** = 1.2 m
number of measurements **N** >10

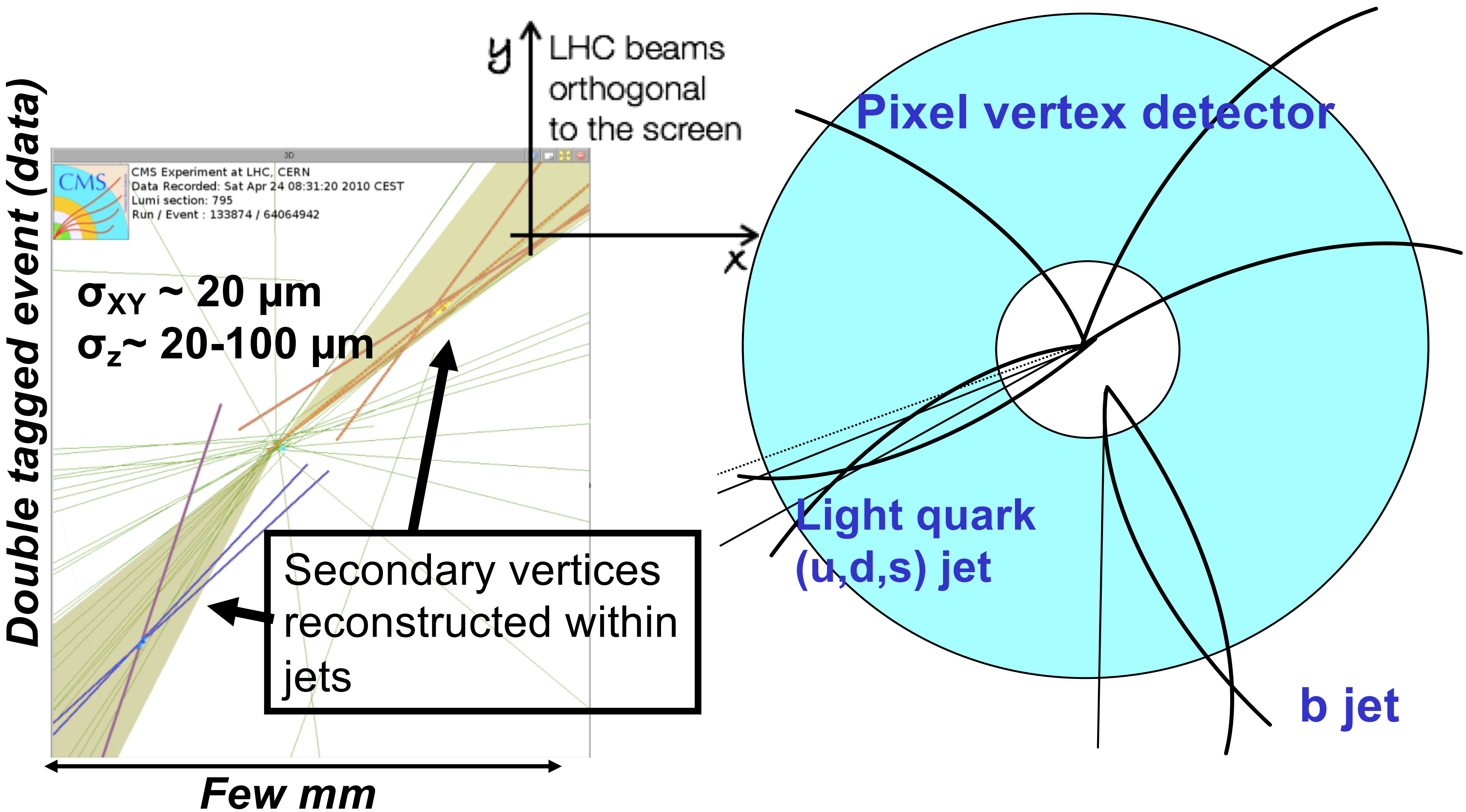
Identifying particles and vertices




CMS
CMS Experiment at LHC, CERN
Data recorded: Sun Oct 23 07:45:55 2016 CEST
Run/Event: 283876 / 570269675
Lumi section: 389
electron
$p_T = 10.3$ GeV
$\eta = 0.31$
$\phi = 0.96$
AK4 jet
$p_T = 63.5$ GeV
$\eta = 0.35$
$\phi = 0.97$
muon
$p_T = 14.0$ GeV
$\eta = 0.36$
$\phi = 0.81$
AK4 jet
$p_T = 31.0$ GeV
$\eta = -2.93$
$\phi = -2.84$
AK4 jet
$p_T = 111.3$ GeV
$\eta = -0.96$
$\phi = -2.19$
-6
-4
-2
0
2
4
6
3
2
1
0
-1
-2
-3
cm

Identifying b-quark jets

- Identify jets originating from b- quark by long lifetime of B hadrons



- For H to bb, typically 70% b-tagging efficiency

Acknowledgements & References

- To Julia Thom for her notes, slides, and resources

- Frank Hartmann's summer school lectures (LPC 2014 etc)
- *Evolution of Silicon Sensor Technology in Particle Physics*, Second Edition (2017), Frank Hartmann, Springer Tracts in Modern Physics
- http://pdg.lbl.gov/2018/reviews/rpp2018-rev-passage-particles-matter.pdf
- Charge deposition (energy loss) in thin materials (Bischsel) https://journals.aps.org/rmp/pdf/10.1103/RevModPhys.60.663
- Shockley-Ramo Theorem: NIM A Volume 463, Issues 1–2, 1 May 2001, Pages 250-267
- CMS Run1 tracking: https://arxiv.org/pdf/1405.6569.pdf
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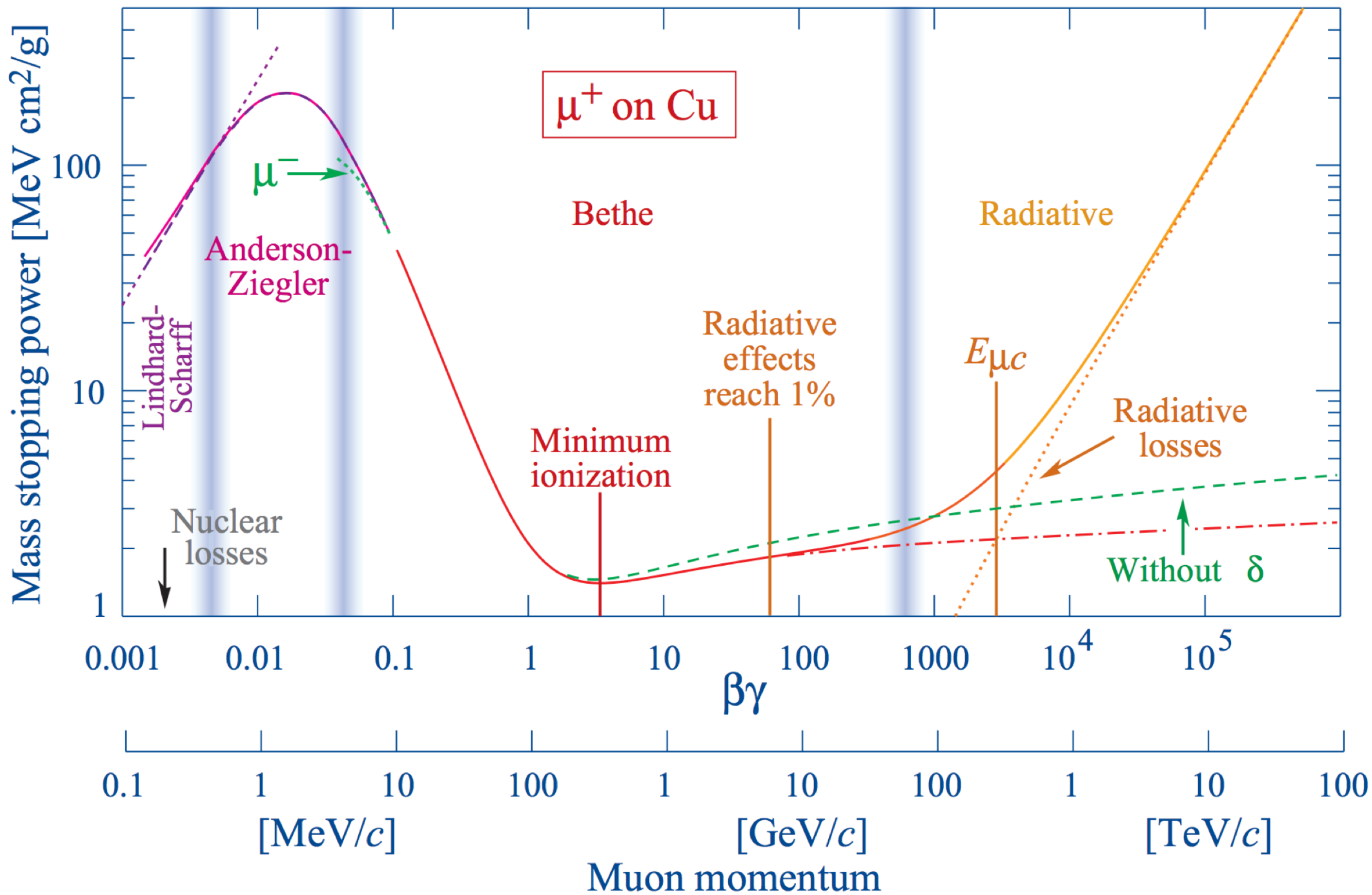
Signals from charged particles

Bethe-Bloch equation describes interaction of particles with matter



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