An Introduction to Charged Particle Tracking

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Overview:

- *While we wish tracking were still this easy, real bubble chambers don't cut it for a 25ns cycle time*
- *Instead, we need the electronic version*
  - *More granular*
  - *Less resolution*
  - *More complicated*
- *How do we get there while satisfying*
  - *technical requirements*
    - *performance*
    - *operability*
    - *stability*
  - *spatial requirements*
    - *size, volume*
  - *cost requirements*

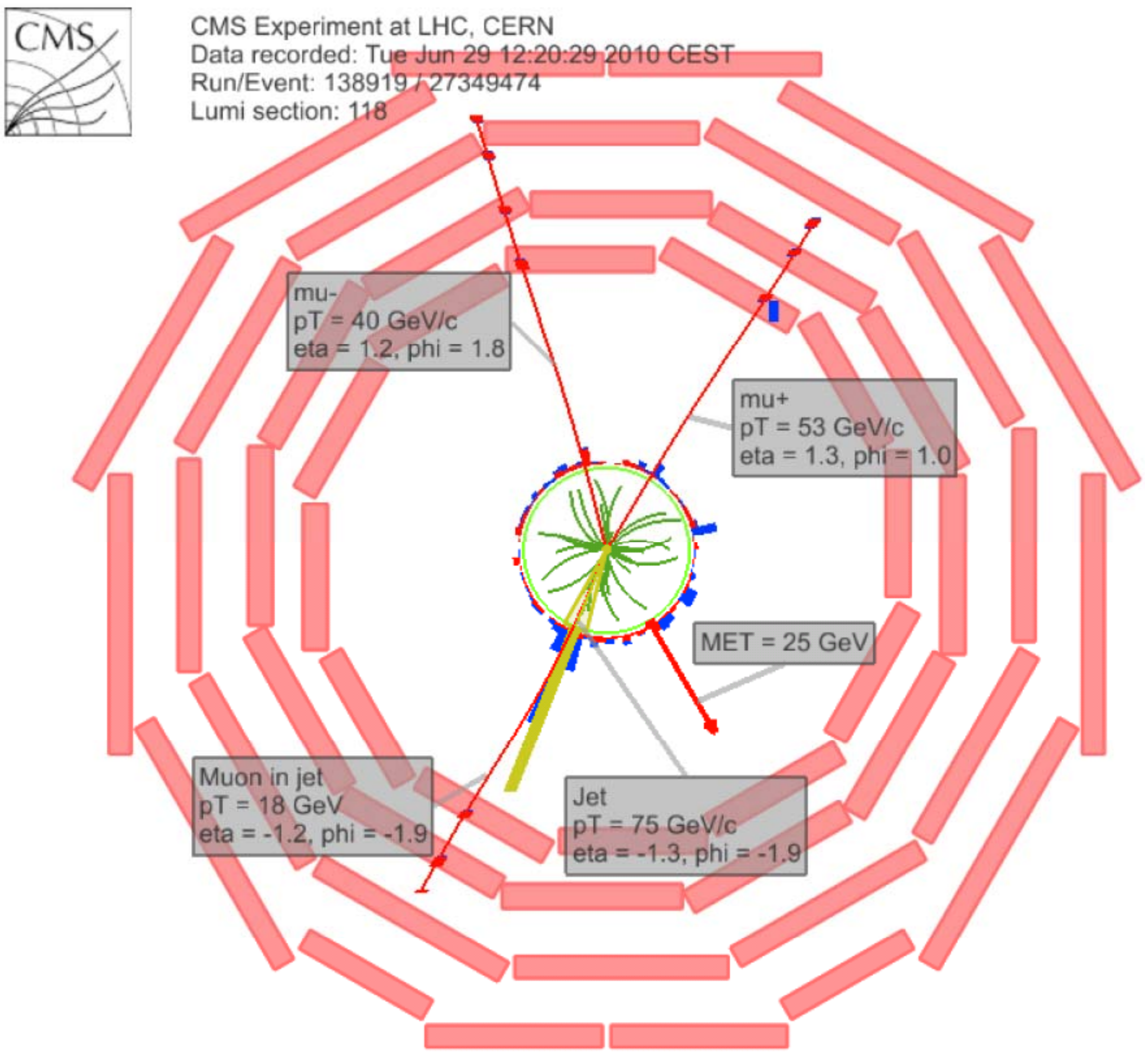
Overview:

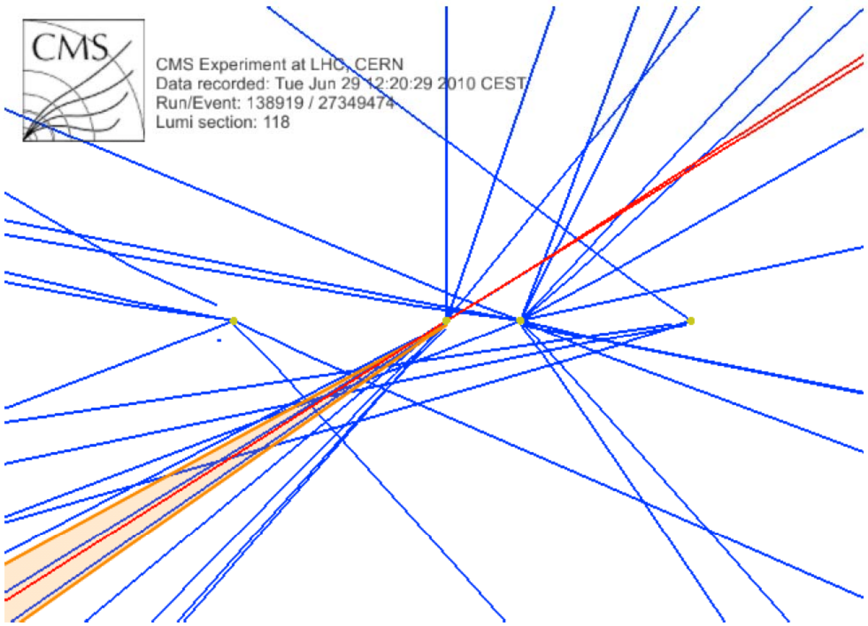
- *Outline for these lectures*
  - *Lecture 1:*
    - *Motivation*
    - *Tracking vocabulary*
    - *Detector Techniques*
  - *Lecture 2:*
    - *Algorithmic Techniques for Pattern Recognition, Fitting*
    - *Tracking system designs*
  - *Lecture 3:*
    - *Commissioning/Calibrating a tracking system*
    - *Environmental Challenges*
      - *Radiation damage, occupancy, etc.*
    - *Tracking information used in event triggers*
    - *Tracker upgrades*

Why Track?

- Basically, everything interesting happens within the first ~10^{-12} seconds after the beams collide
  - we can only see “final-state” particles
  - our physics knowledge is based on “working backwards in time” to infer what actually happened in the initial collision
  - the more precisely the final-state particles are measured, the more accurately we can determine the parameters of their parents
- Tracking provides precise measurements of
  - particle production positions
    - can reveal the presence of long-lived particles
  - particle momenta
    - complimentary to calorimeter at low energy
  - particle trajectories to the outer detectors
    - association with calorimeter energy deposits, muon hits
      - allows “global pattern recognition” of physics objects

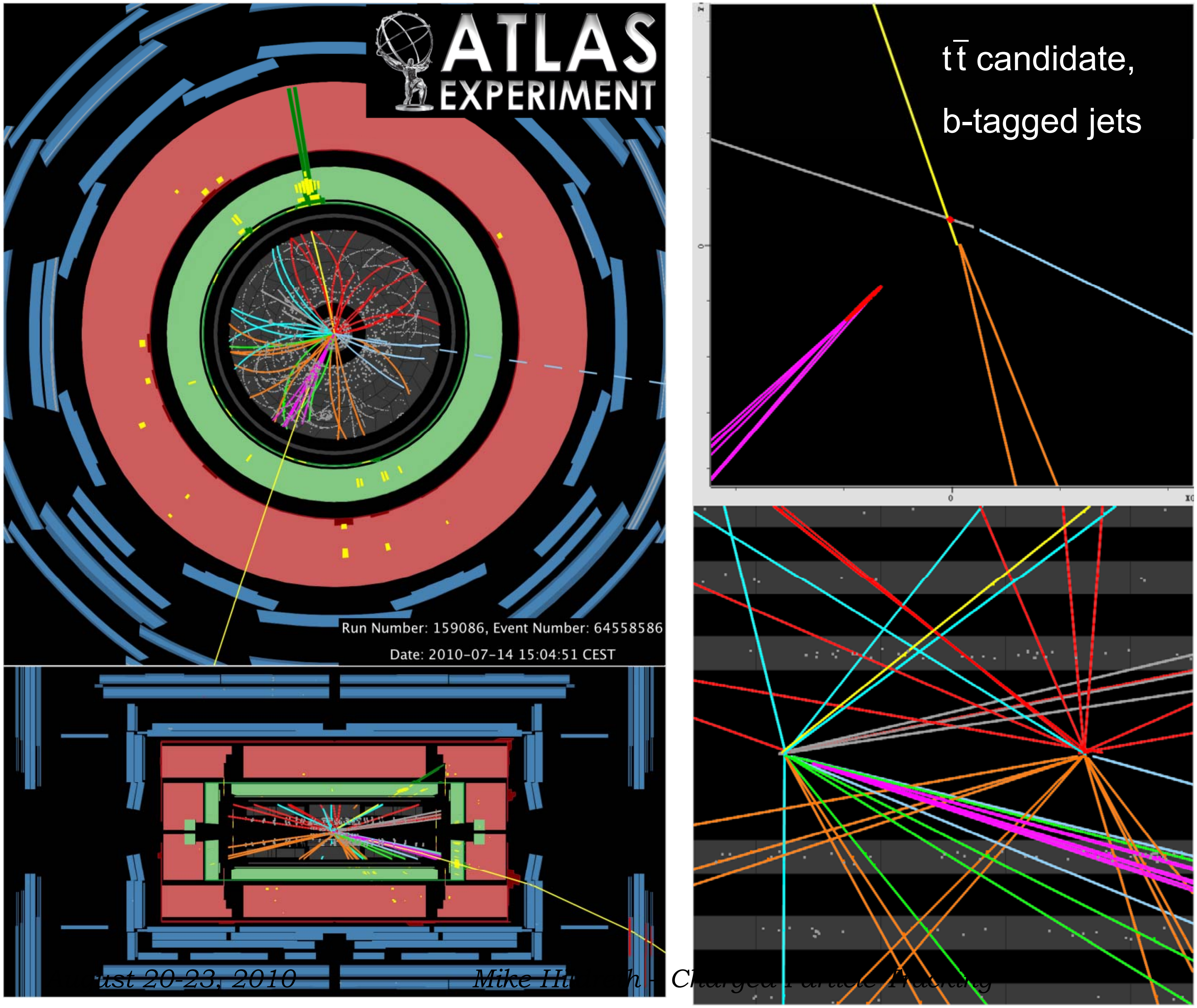
Tracking Provides: Production position



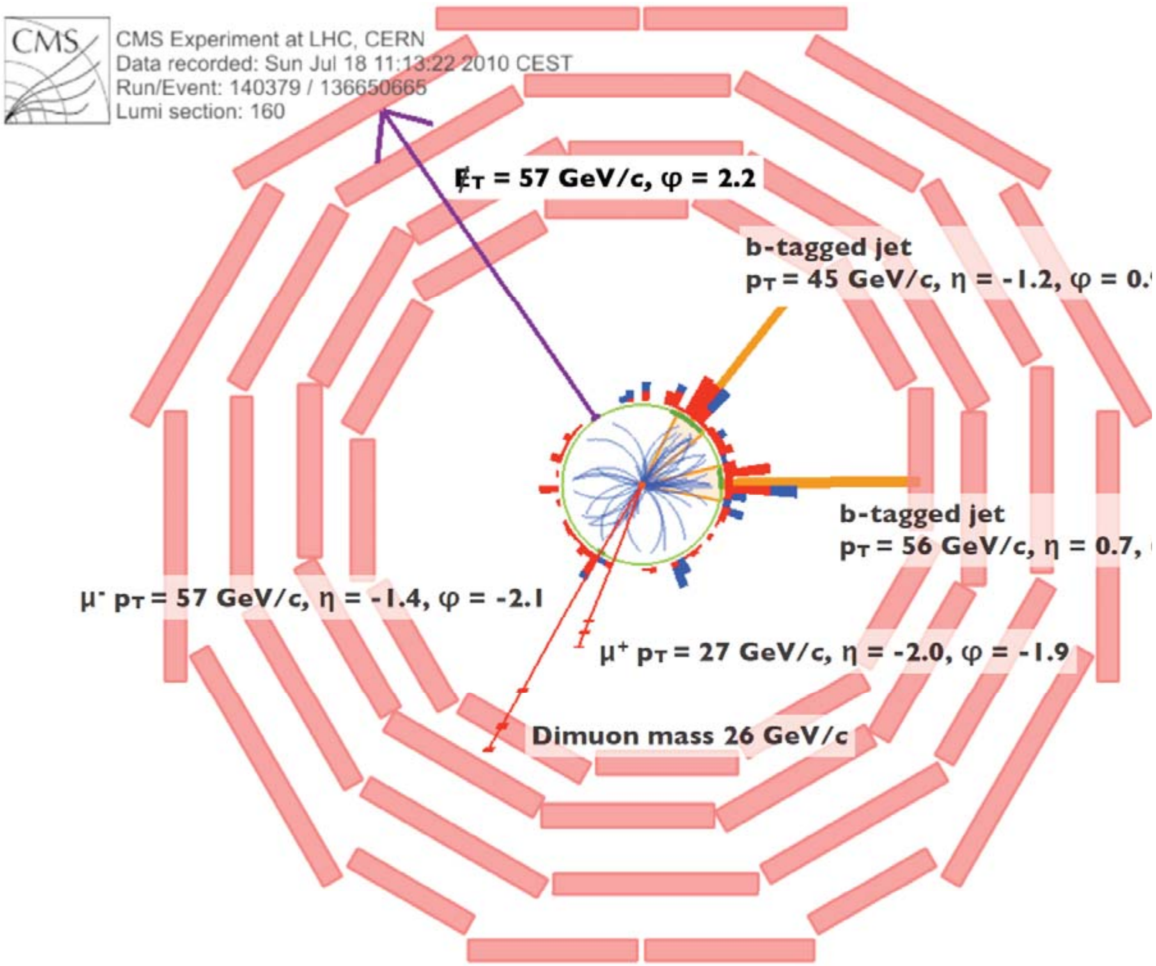


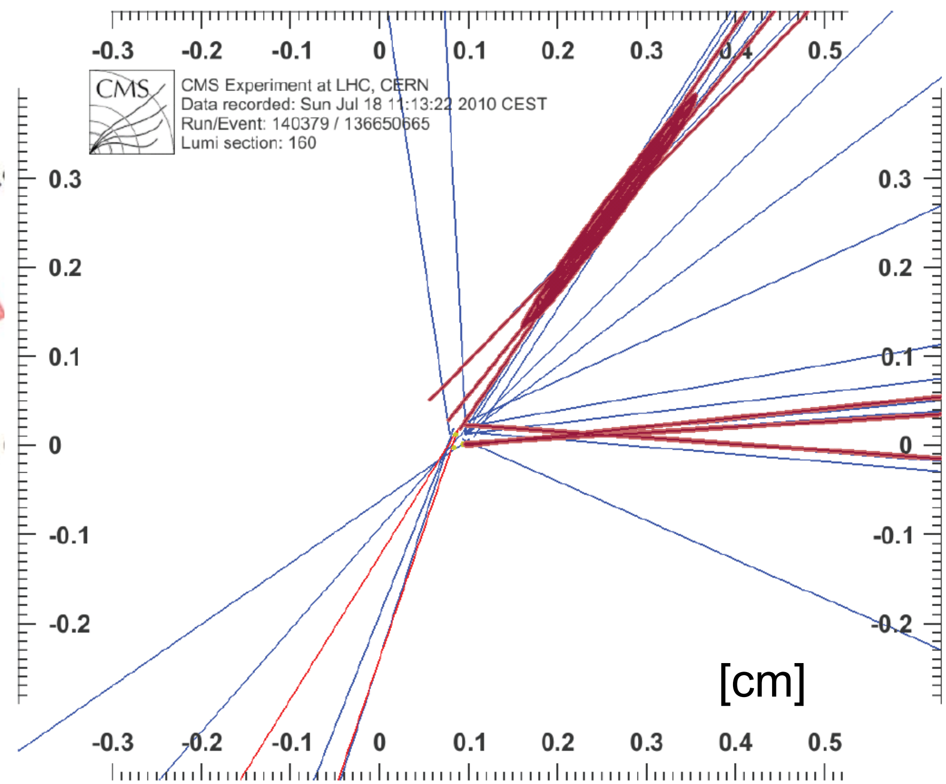
$t\bar{t}$ candidate, multiple interactions

Tracking Provides: Prod/decay position



Tracking Provides: Prod/decay position

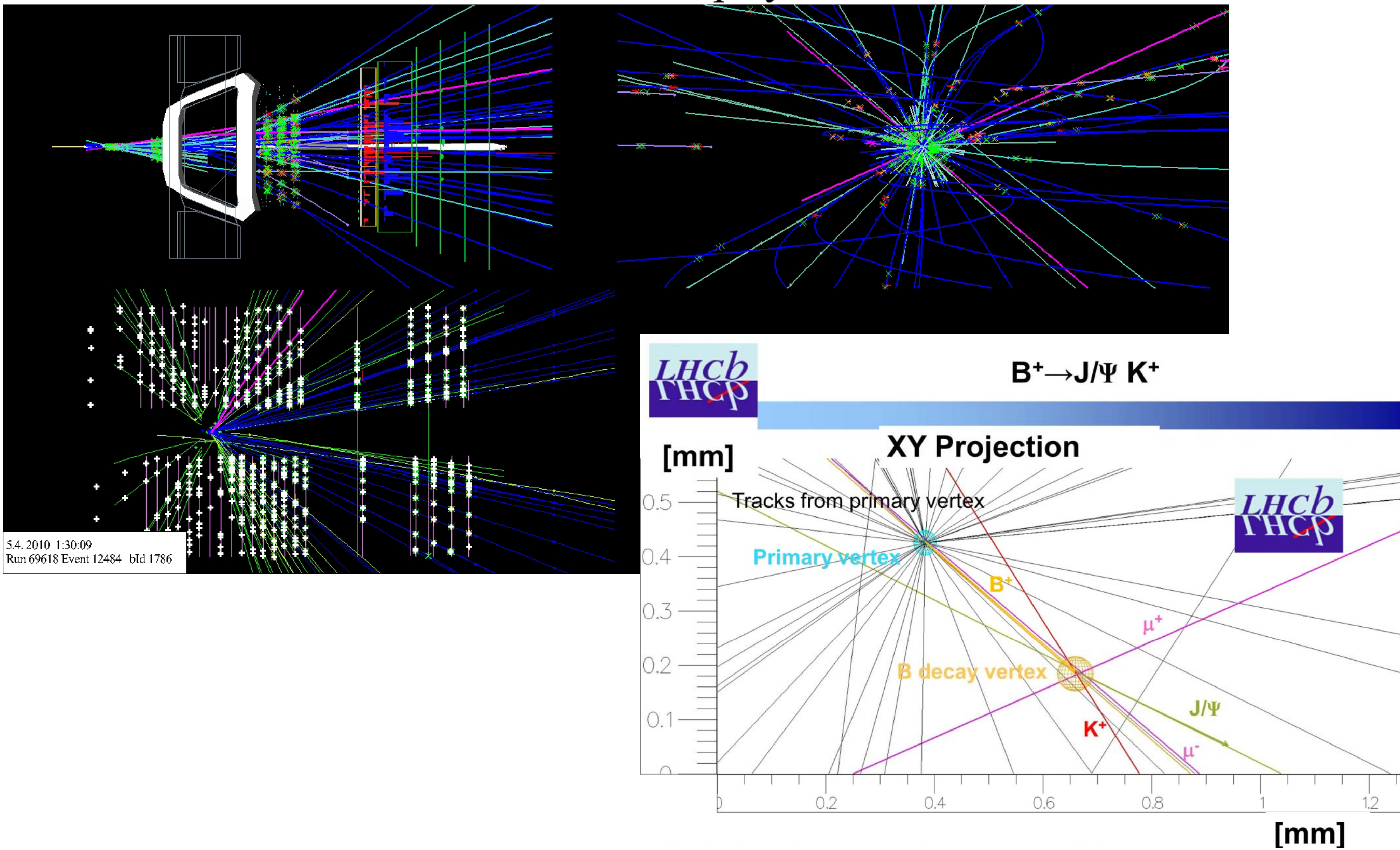




$t\bar{t}$ candidate, b-tagged jets

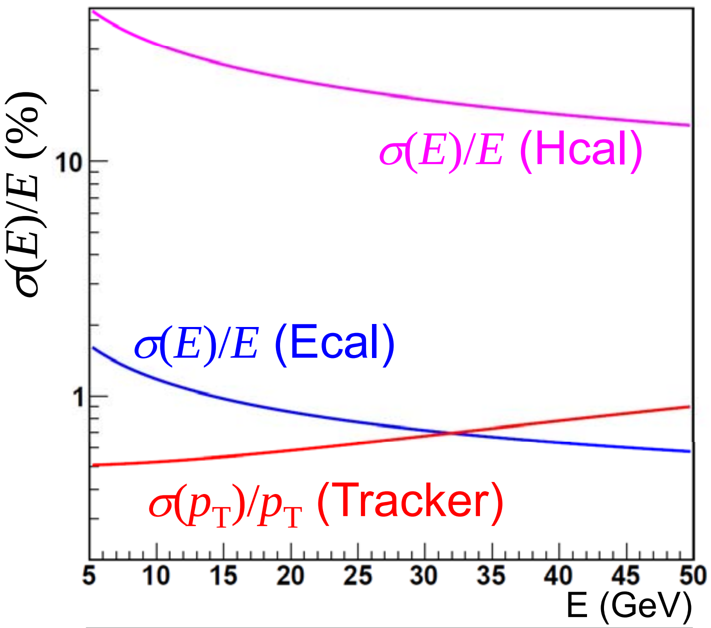
Tracking Provides: Prod/decay position

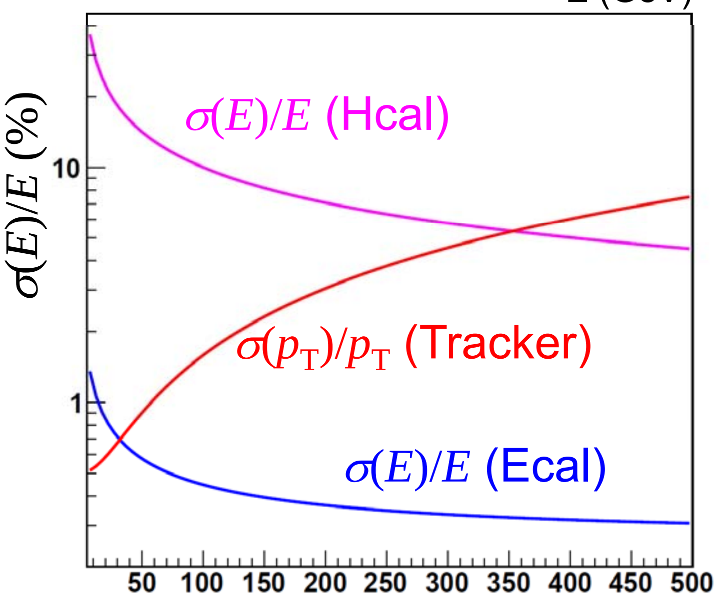
LHCb Event Display



Tracking Provides: momentum

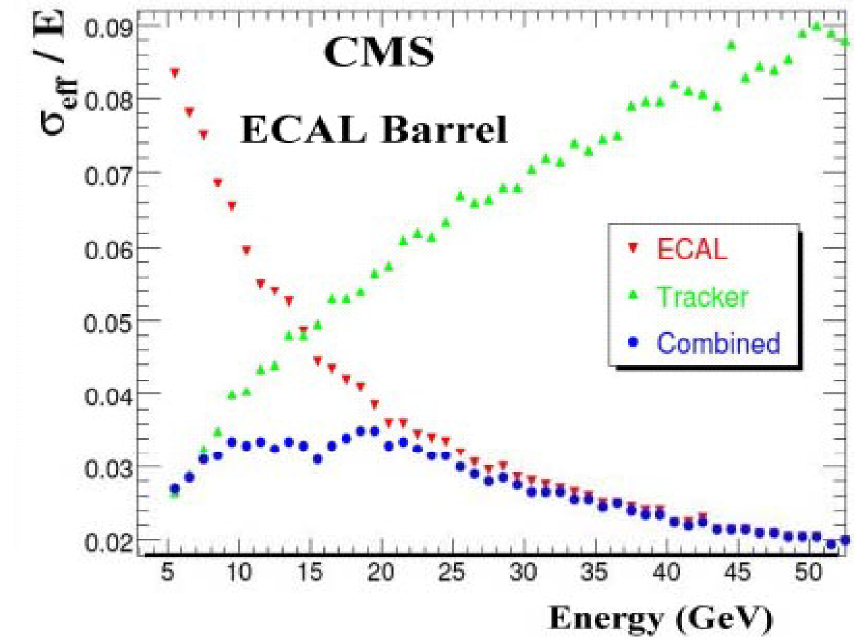
- Resolution complementary to calorimeters at low energies:

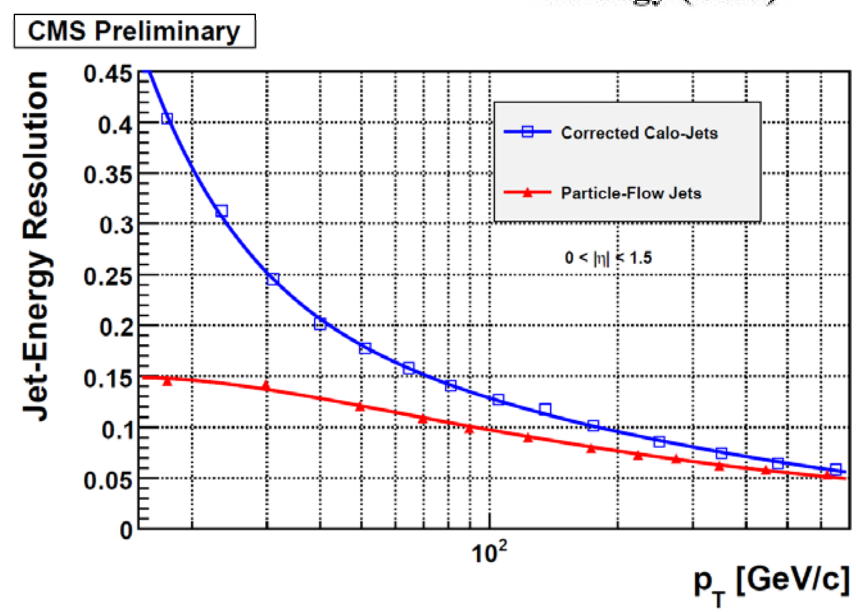




Resolutions from CMS Physics TDR

Basis of particle-flow algorithms to optimize resolution on final-state “objects” that are used for parton reconstruction

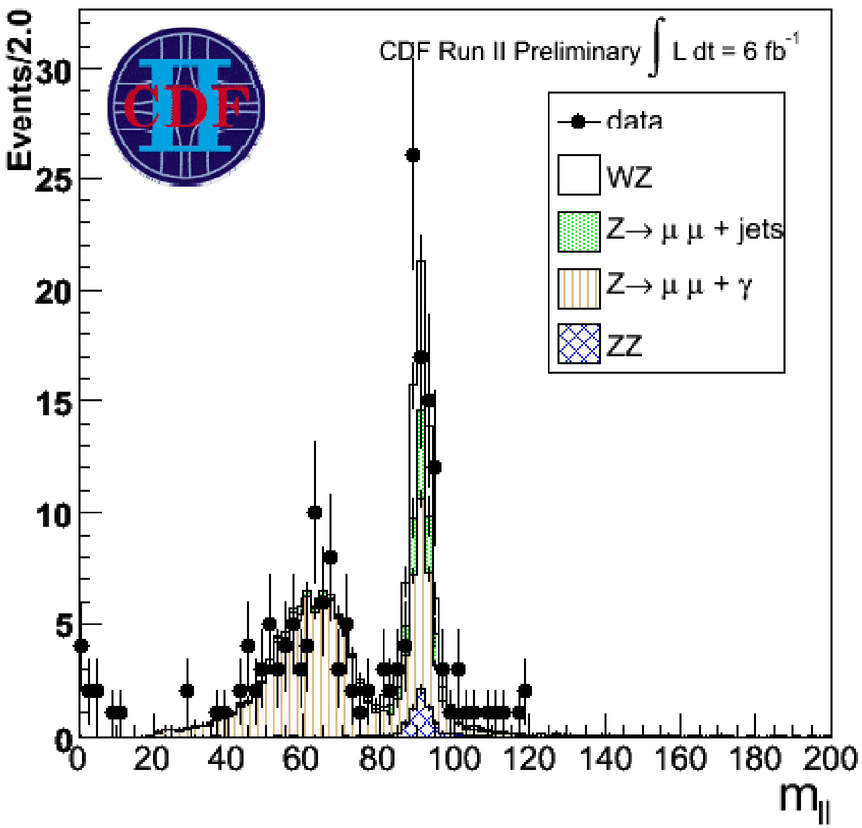




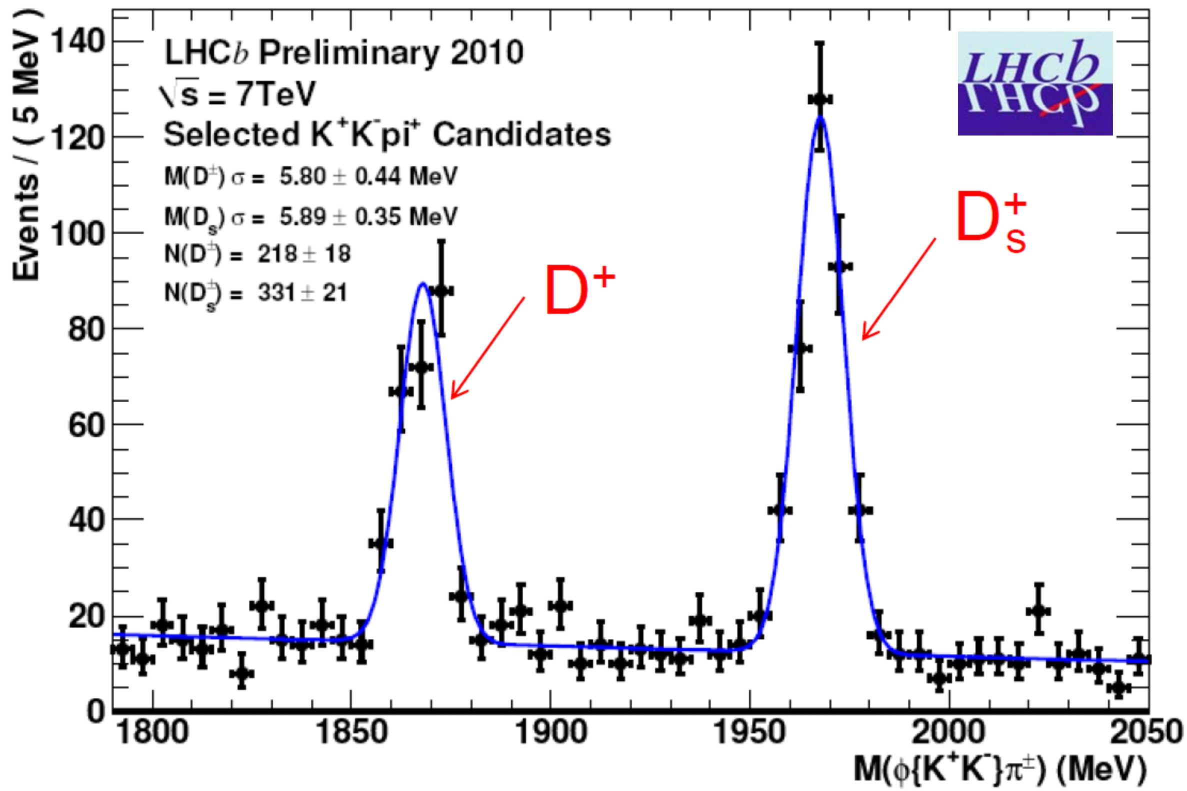
Tracking Provides: momentum

- Determination of particle four-vectors → resonances

CDF: WZ and ZZ analysis

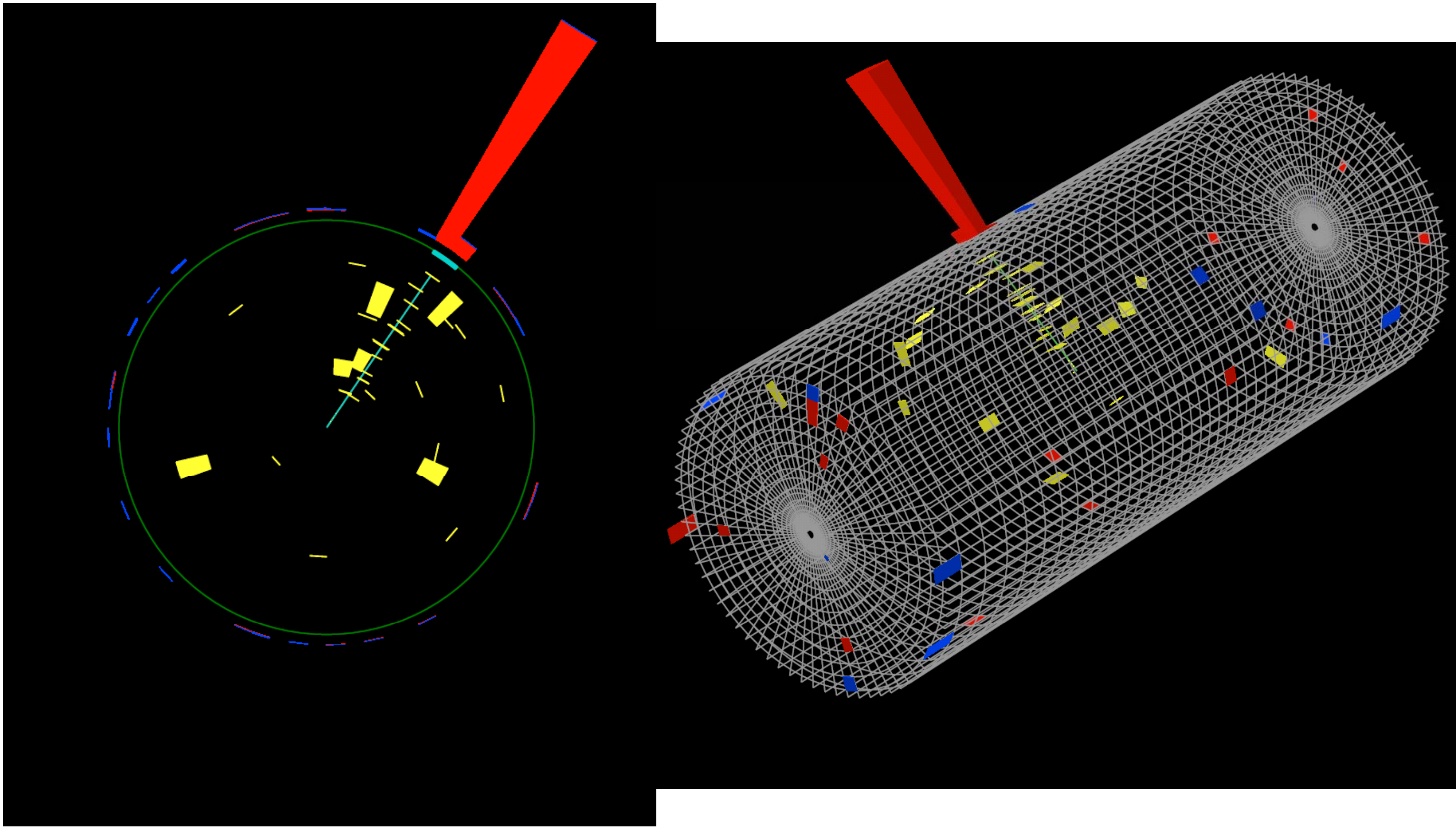


LHCb: exclusive charm reconstruction



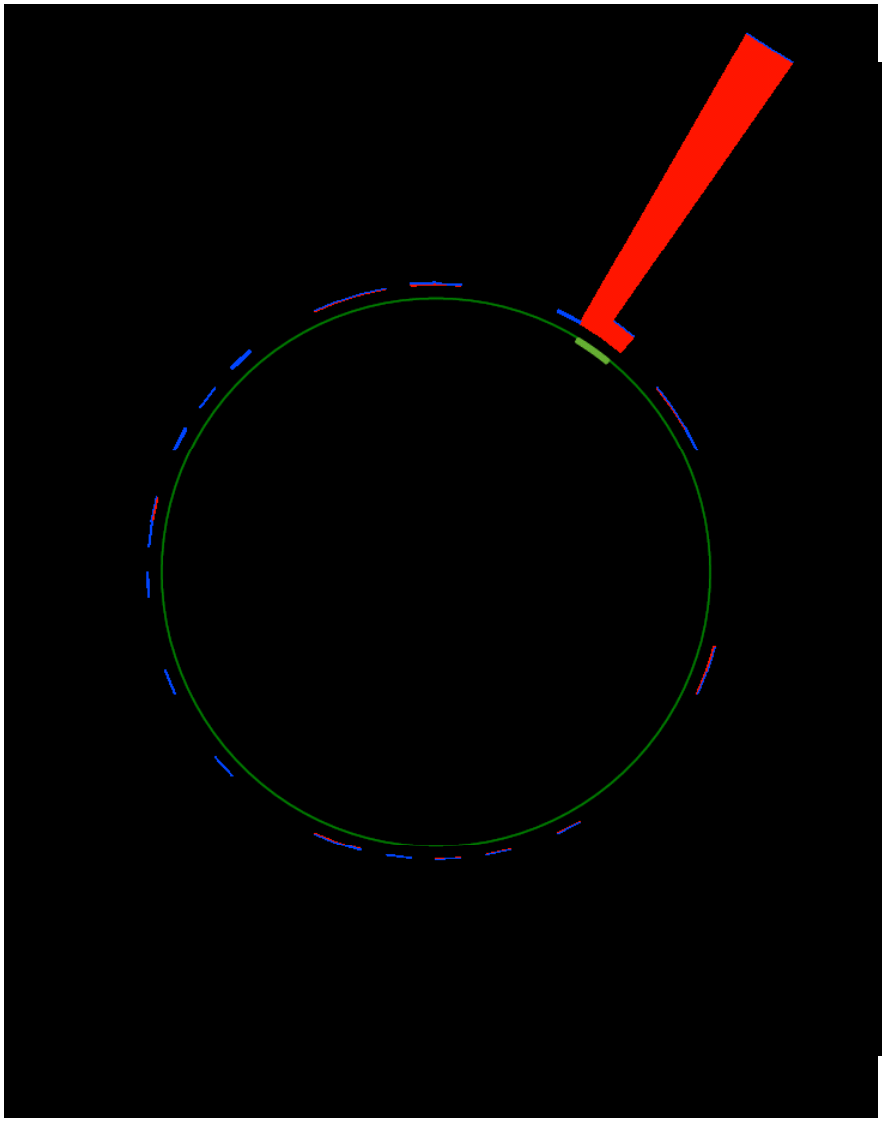
Tracking provides: Global objects

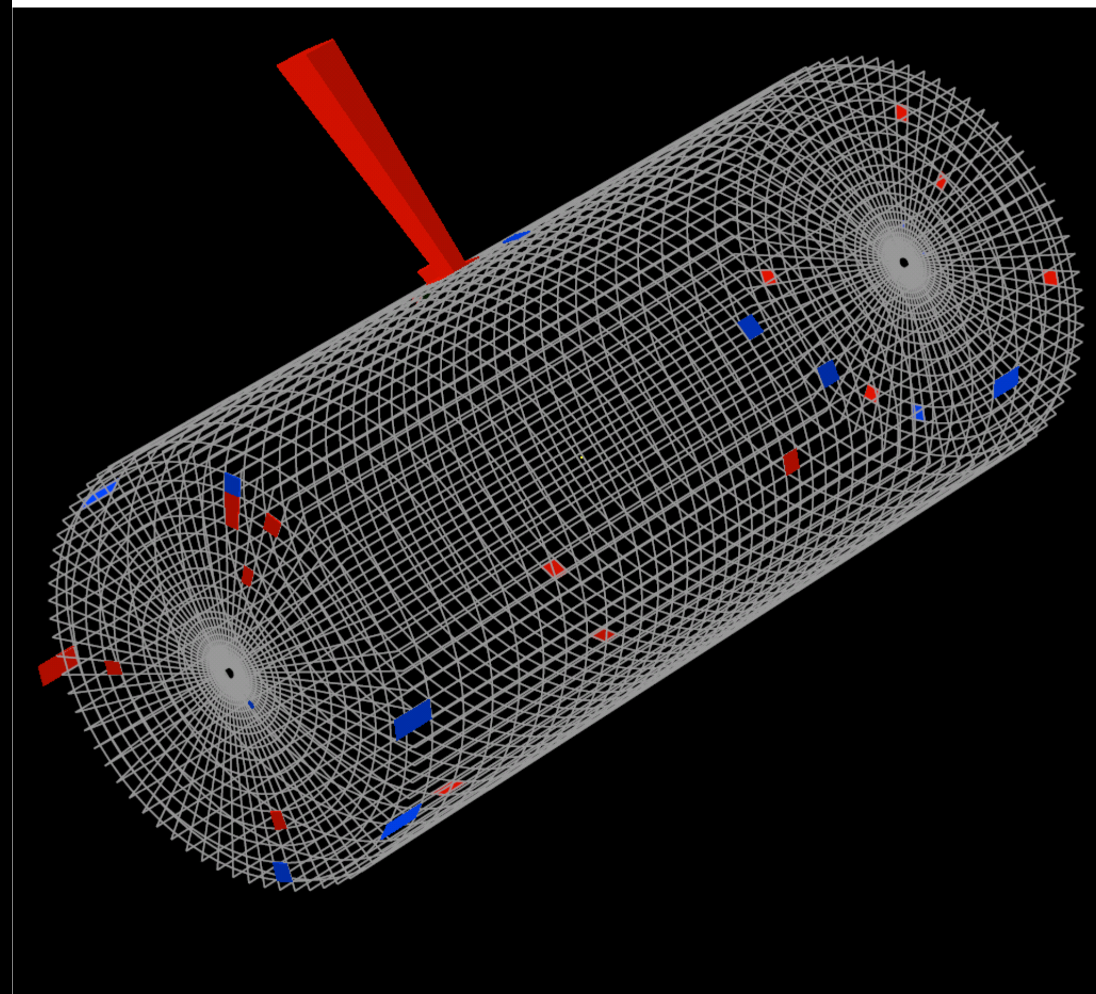
- Electron



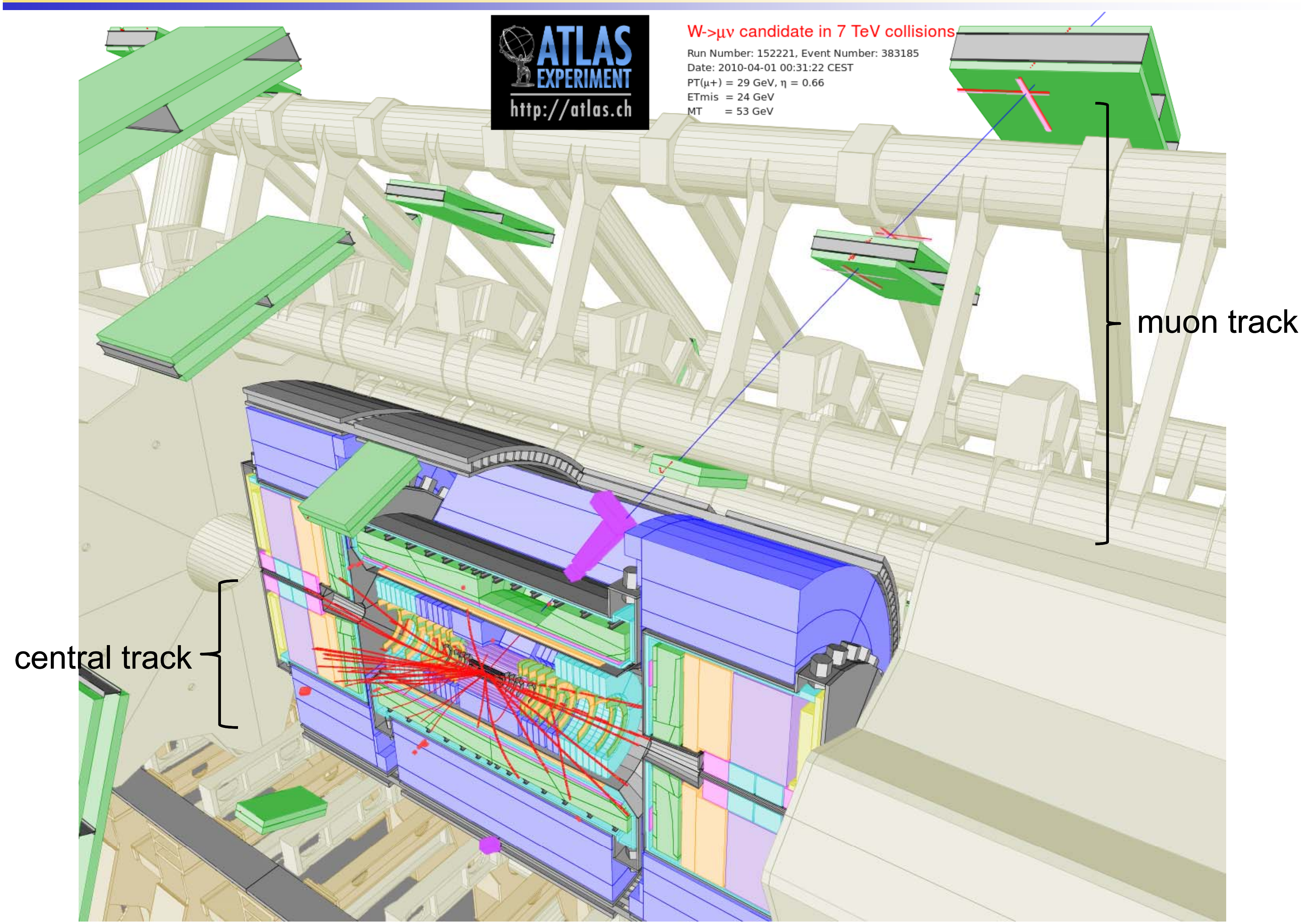
Tracking provides: Global objects

- or photon?



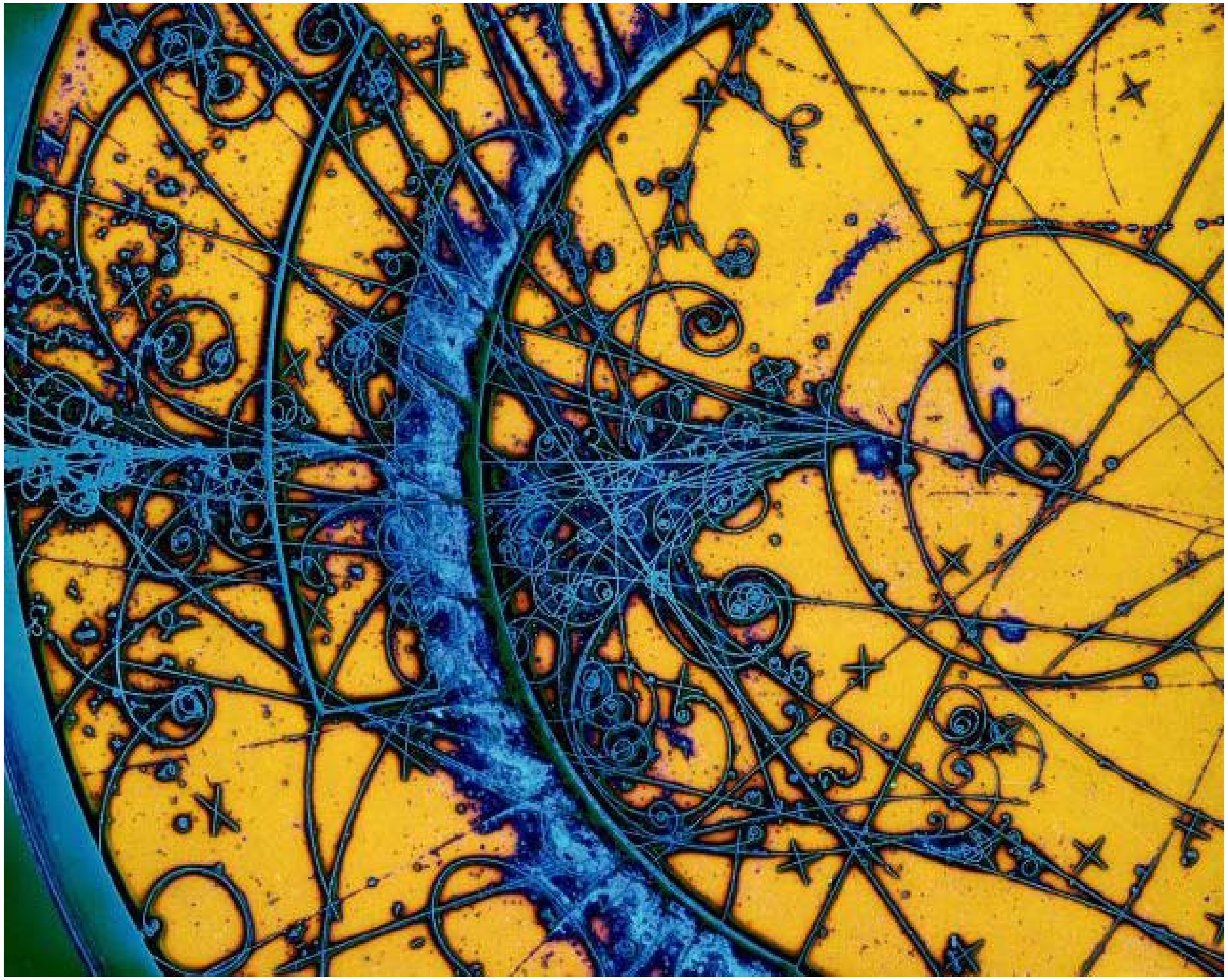


Tracking provides: Global objects



Visualizing particle trajectories

- Start with the basics: (more detail later)



Lorentz force: charged particles follow a curved trajectory in a magnetic field

- radius of curvature inversely proportional to momentum
- need to measure:
  - magnitude of B field
  - radius of curvature
- Radius measurement implies knowing where the particle is at several points along its trajectory
  - the particle must interact with a detection medium to leave a trace

  ⇒ Ionization

Ionization Loss: Bethe-Bloch Equation

- Relativistic Formula: Bethe (1932), others added more corrections later
- Gives "stopping power" (energy loss = dE/dx) for charged particles passing through material:

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

where

A, Z: atomic mass and atomic number of absorber

z: charge of incident particle

β,γ: relativistic velocity, relativistic factor of incident particle

$\delta(\beta\gamma)$: density correction due to relativistic compression of absorber

I: ionization potential

T_{max}: maximum energy loss in a single collision; $T_{max} = \frac{2m_ec^2\beta^2\gamma^2}{1+2\gamma m_e/M+(m_e/M)^2}$

$\frac{K}{A} = 4\pi N_A r_e^2 m_e c^2/A = 0.307075\ \text{MeV g}^{-1}\text{cm}^2,\ \text{for A} = 1\text{g mol}^{-1}$

dE/dx has units of MeV cm^2/g

x is ρs, where ρ is the material density, s is the pathlength

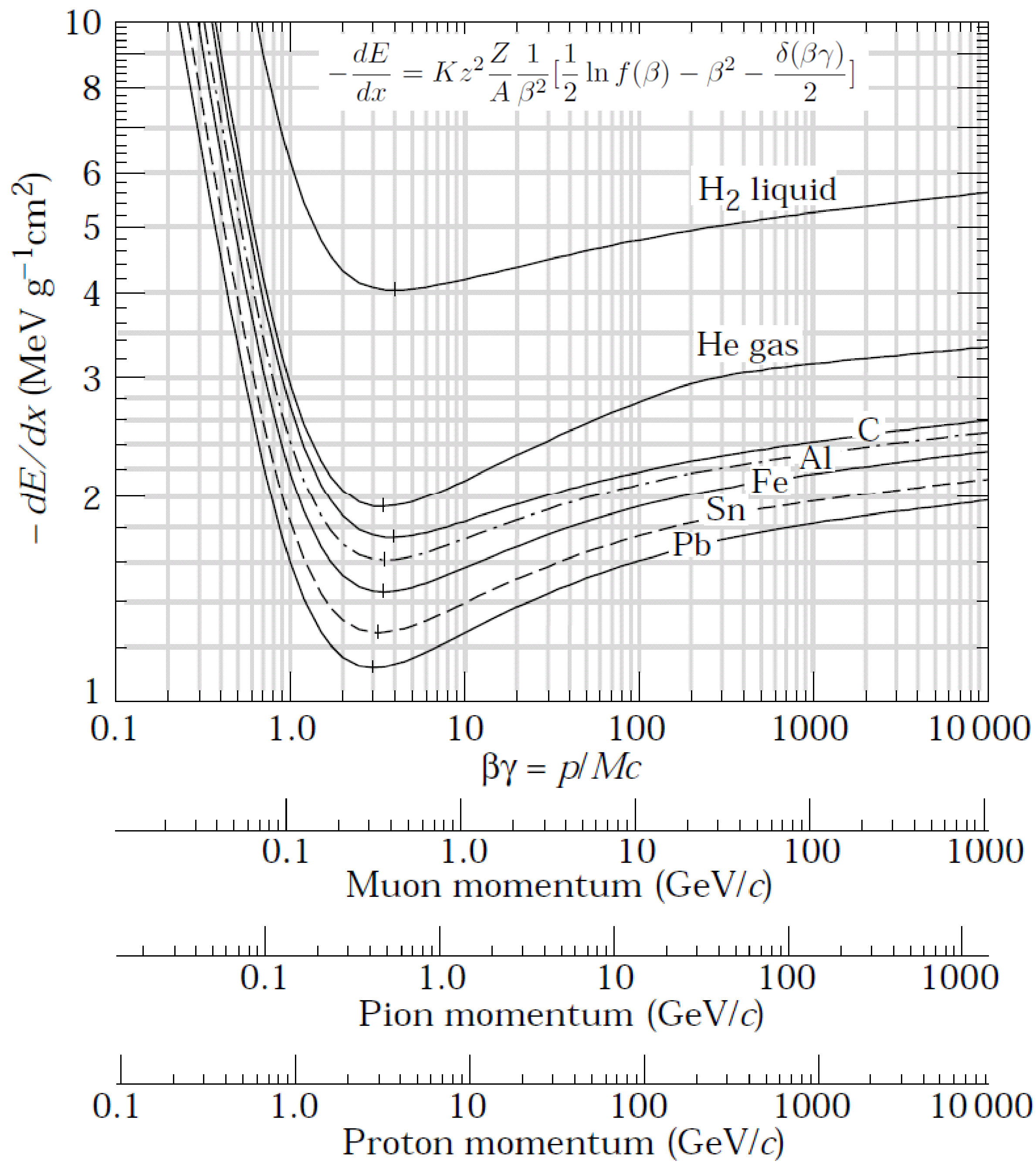
source for this and following: PDG

Ionization Loss: minimum ionization

- Position of minimum is a function of $\beta\gamma = p/Mc$
- occurs around p/Mc = 3-3.5
  ~ independent of material
- Characteristic shape of $1/\beta^2$ fall-off followed by relativistic rise

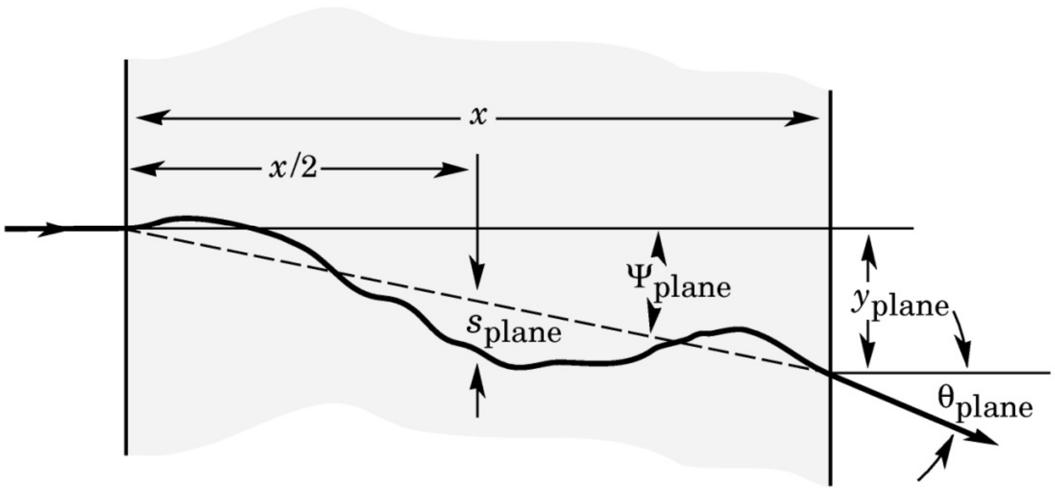
- "Rule of thumb":
  dE/dx ~ 2 MeV/cm $\times\rho$ (g/cm^3)
- Typical values:
  - liquids/solids:
    ~ few MeV/cm
  - gases:
    ~ few keV/cm

  ⇒ valid over range of most common momenta in collider experiments



First complication: Multiple Scattering

- Often called Multiple Coulomb Scattering: momentum transfer between particle and medium diverts particles from straight path
  - usually electromagnetic; hadronic interactions contribute, too
  - scattering angles well-described by Molière theory:



$$\psi_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{3}}\theta_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{3}}\theta_0$$

$$y_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{3}}x\,\theta_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{3}}x\,\theta_0\,,$$

$$s_{\text{plane}}^{\text{rms}} = \frac{1}{4\sqrt{3}}x\,\theta_{\text{plane}}^{\text{rms}} = \frac{1}{4\sqrt{3}}x\,\theta_0$$

Here θ_0 is a (mostly) gaussian distribution defined as $\theta_0 = \theta_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{2}}\theta_{\text{space}}^{\text{rms}}$ with a width of

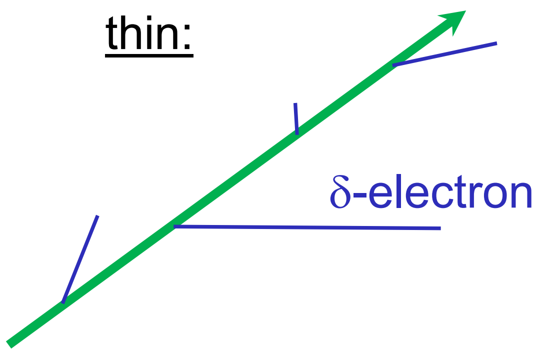
$$\theta_0 = \frac{13.6\ \text{MeV}}{\beta c p}\, z\,\sqrt{x/X_0}\Big[1 + 0.038\ln(x/X_0)\Big]$$

where X_0 = radiation length of material

Second Complication: Energy Loss

- Energy loss in material can be significant (c.f. ATLAS or CMS trackers): radius of curvature *increases* along path as p falls
- Fluctuations in Energy Loss in thin/thick samples of material:

thin:

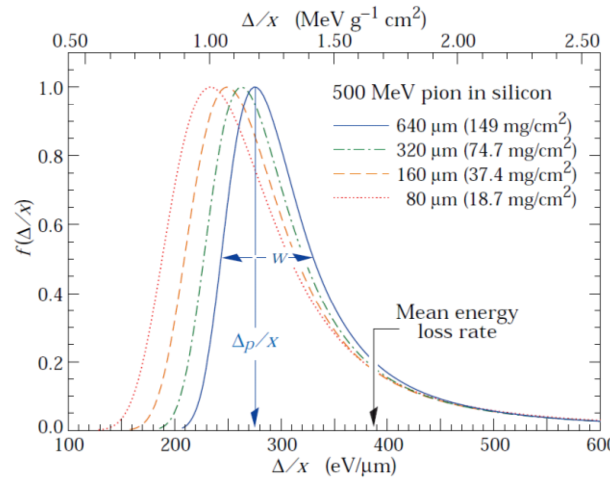


- Few collisions
- some with large energy transfer
- large fluctuations in energy loss

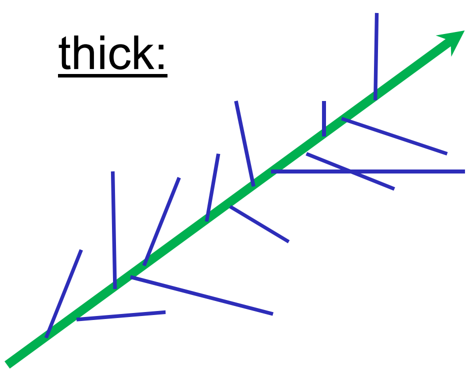
$\Rightarrow$ Landau distribution

- e.g.: 300um thick Si sensor:

ΔE_{mp} = 82 keV, $\langle \Delta E \rangle \sim$ 115 keV



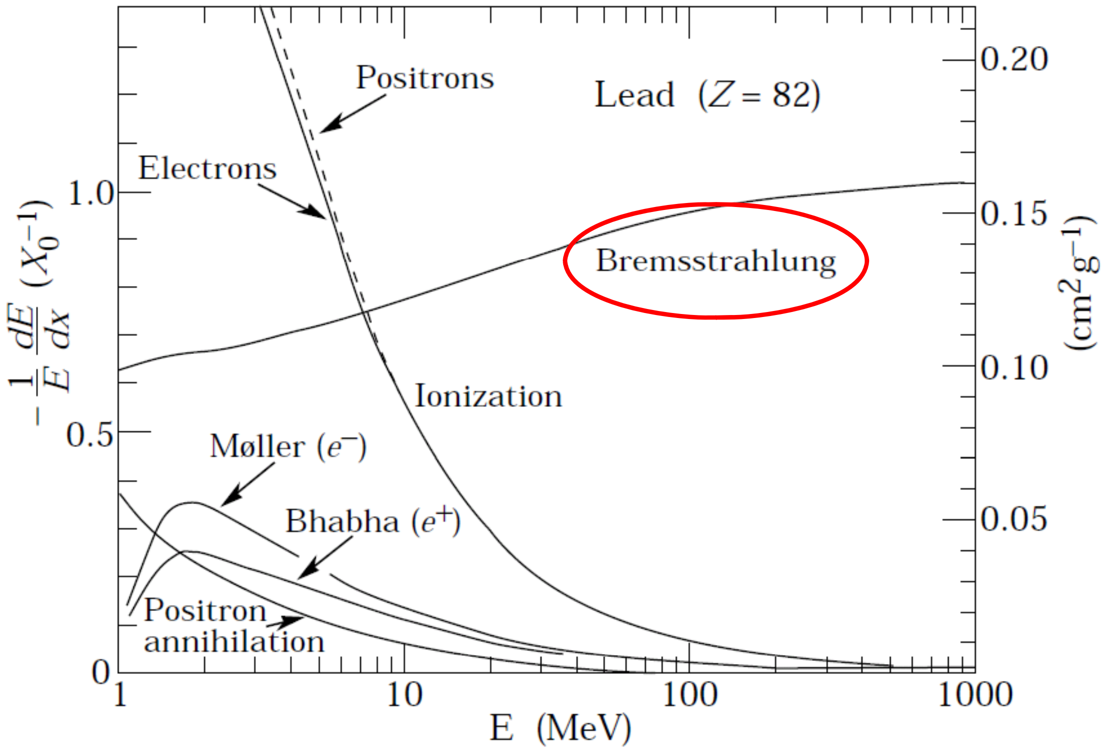
thick:



- Many collisions
- wide spectrum of energies
- distribution tends toward gaussian
- $\Delta E_{mp} \approx \langle \Delta E \rangle$

Third Complication: Bremsstrahlung

- Large (can be catastrophically so) discrete energy loss
- acceleration due to interaction with coulomb field of nuclei
- Dominant energy loss mechanism for electrons and positrons:



$$\frac{d\sigma}{dk} = \frac{A}{X_0 N_A k}\left(\tfrac{4}{3} - \tfrac{4}{3}y + y^2\right)$$

$$\propto Z^2\alpha^3$$

where

k = photon energy

y = k/E

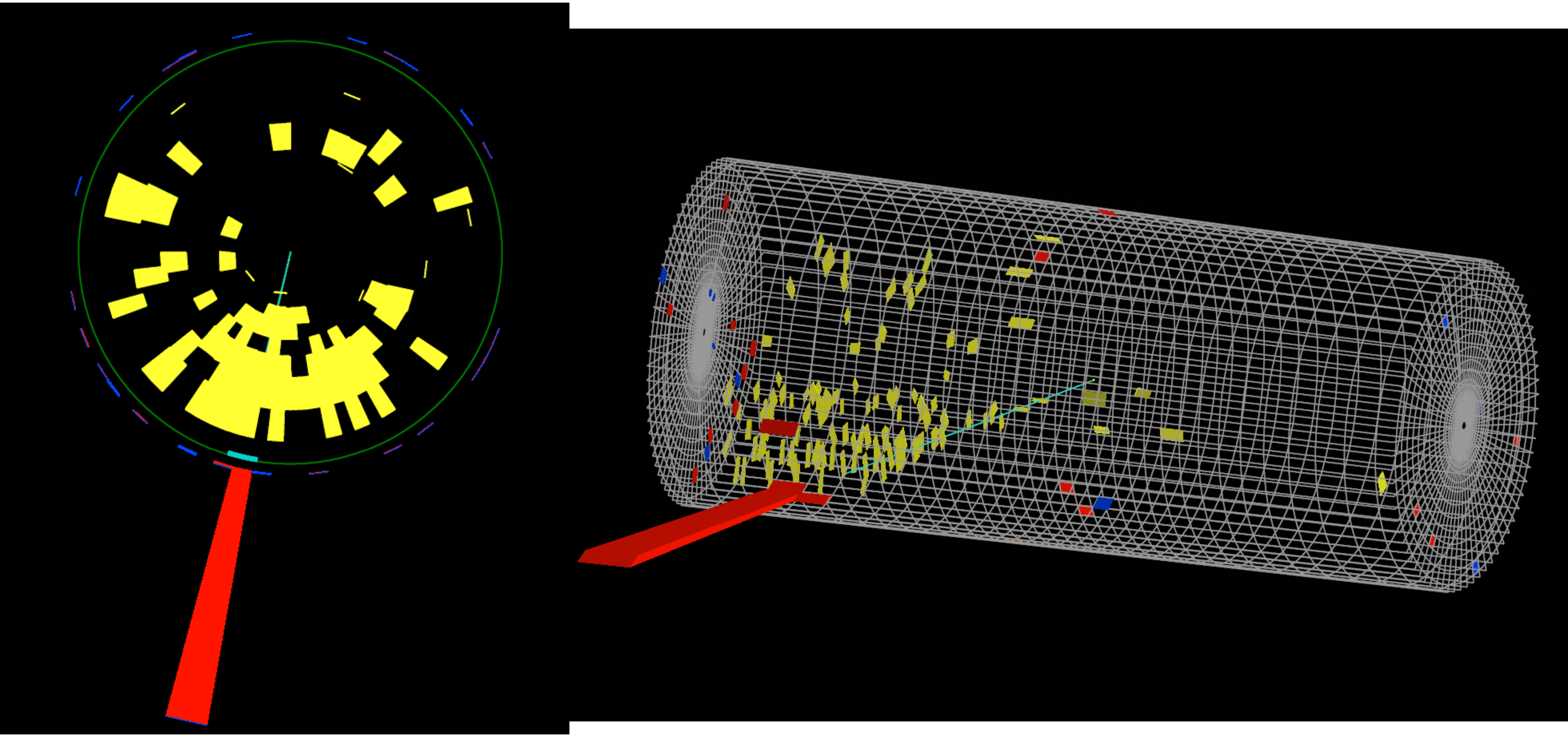
E = lepton energy

Overall probability of photon emission $\propto m^{-4}$

becomes important for high energy muons

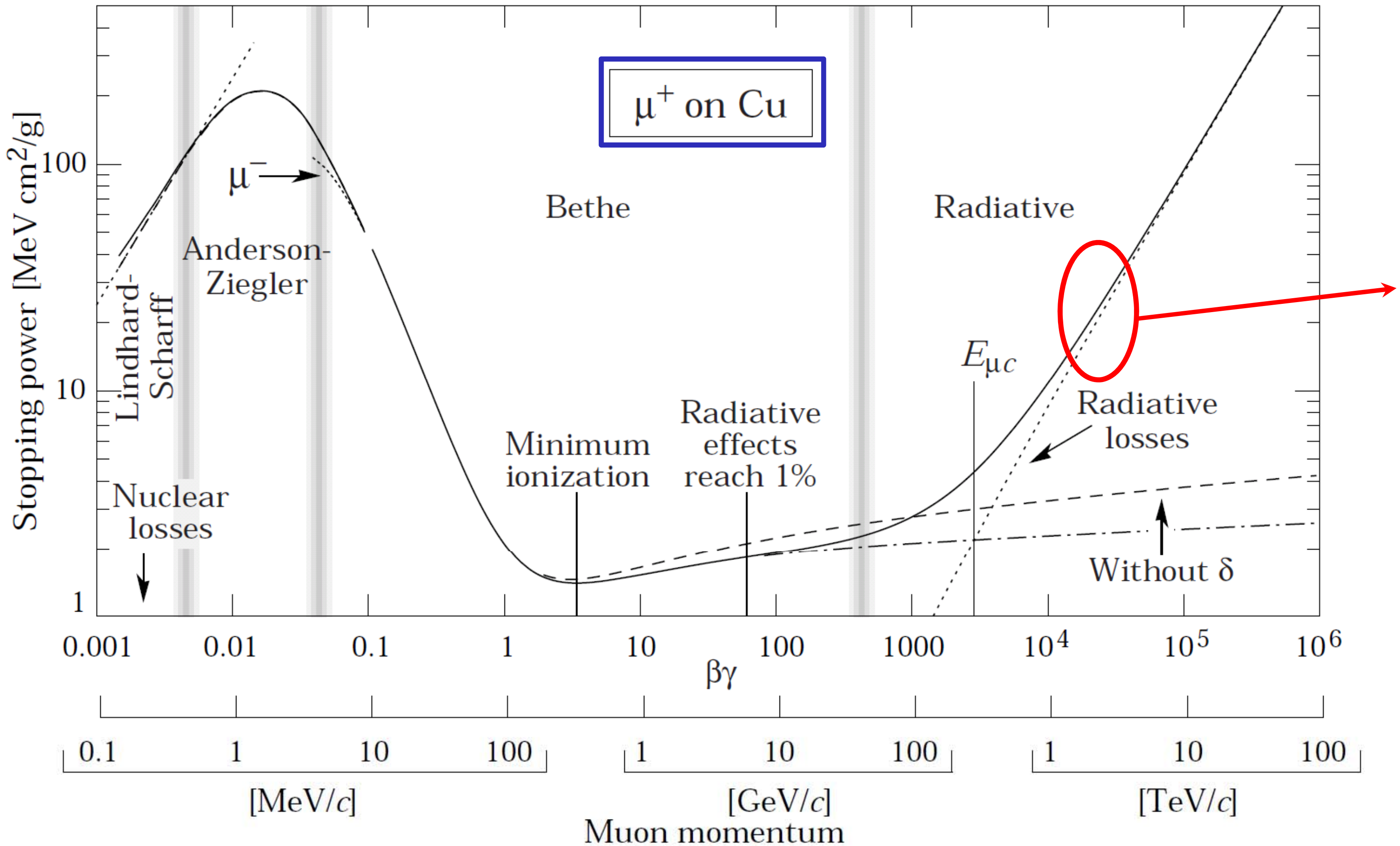
Third Complication: Bremsstrahlung

- Single 100 GeV electron in CMS tracker:



Ionization Loss: full spectrum

- Full *dE/dx* description includes many different effects



multi-TeV muons at LHC are NOT minimum ionizing!

Tracking Basics

- Assuming we can make hits now, what do we do with them?
- Charged particles curve in an axial magnetic field:
  - transverse momentum p_T (Gev/c) = 0.3 B R
    - R is the radius of curvature (m), B is field strength (T)
- What matters is how well we can measure the radius R
  - we actually measure the sagitta s
  - A little algebra

$$\frac{L/2}{R} = \sin\frac{\theta}{2} \approx \frac{\theta}{2}$$ for small angles; $$\theta \approx \frac{L}{R} = \frac{0.3BL}{p_T}$$

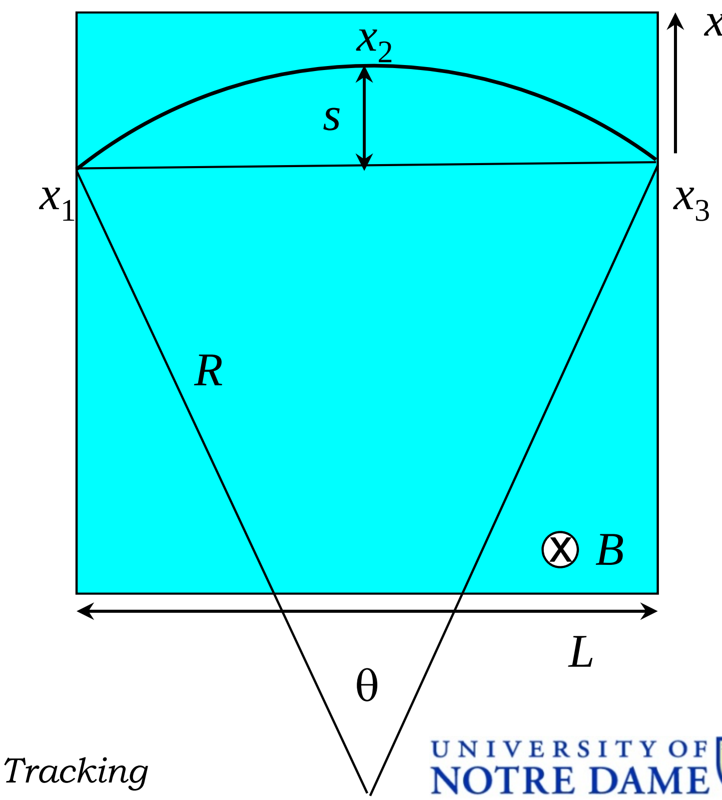
$$s = R\left(1-\cos\frac{\theta}{2}\right) \approx R\left(1-(1-\frac{\theta^2}{8})\right) = R\frac{\theta^2}{8} \approx \frac{0.3BL^2}{8p_T}$$

For three points, $s = x_2 - \frac{1}{2}(x_1+x_3)$

$\rightarrow ds = dx_2 - dx_1/2 - dx_3/2$

assuming $\sigma(x) \equiv dx$ (uncorrelated errors)

$\sigma^2(s) = \sigma^2(x) + 2(\sigma^2(x)/4) = 3/2\ \sigma^2(x)$



Tracking Basics

- Putting all of this together (for a three-hit tracker):

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma_s}{s} = \frac{\sigma_x}{s}\sqrt{3/2} = \frac{\sigma_x \cdot p_T}{0.3\cdot BL^2}\sqrt{96}$$

  where σ_x is the single-hit resolution.

  – Note that this quantity $\sigma(p_T)/p_T$
    - degrades linearly with σ_x and p_T
    - improves linearly with B
    - improves quadratically with L

- For N (N >10) equally-spaced points,

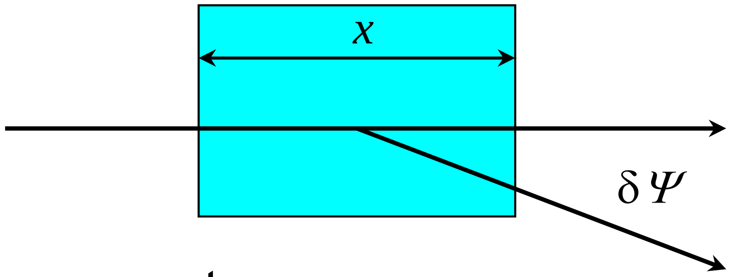
Gluckstern, NIM **24** (1963) 381

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma_x \cdot p_T}{0.3\cdot BL^2}\sqrt{720/(N+4)}$$

So, $\dfrac{\sigma(p_T)}{p_T^2}$ is a measure of performance for a given tracker

Effects of Complications

- multiple coulomb scattering in material
  - scattering in a thin layer of material introduces random angular errors
  - this adds an additional error to the p_T measurement:

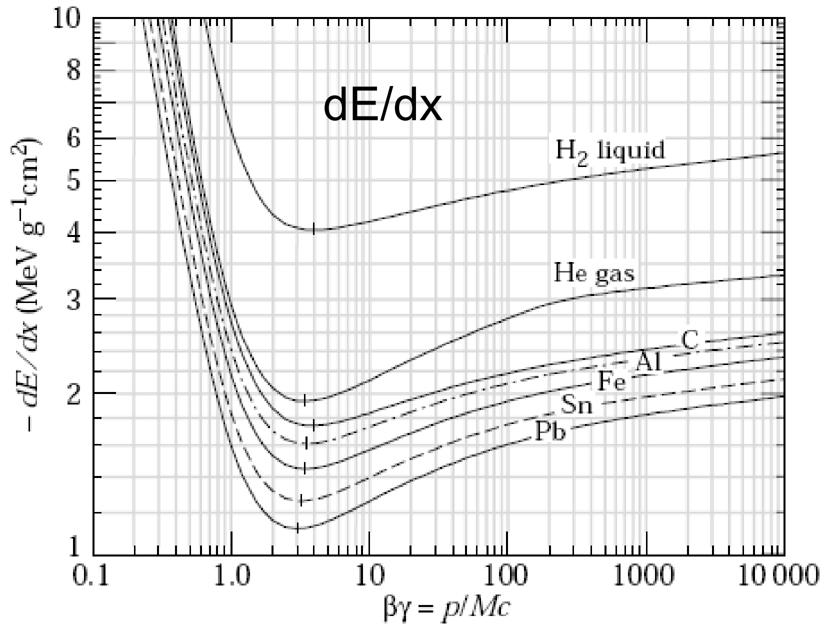


$$\left.\frac{\sigma(p_T)}{p_T}\right|^{ms} = \frac{28\ MeV}{0.3 \cdot BL}\sqrt{x / X_0}\,\frac{p_T}{\beta c p}$$

X_0 = radiation length of material

- Ionization Energy Loss
  - curvature decreases with pathlength
  - fluctuations in energy loss can be large if there is a lot of material:

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{Eloss} \sim \frac{x / X_0}{p}$$



$\Rightarrow$ Both effects *decrease* with p_T

Detector Techniques

- Now that we have a bit of theory, let's take a look at how one can use ionization loss to provide the hits used in track fitting.
- Three basic groups of tracking detectors:
  - gaseous
  - solid state
  - scintillating
- Each converts the ionization left by the passing of a charged particle into an electrical signal
  - charge collection
  - light collection/conversion with photo-cathode
- Ideally, we would build a fast electronic bubble chamber with sub-micron hit resolution and infinite three-dimensional granularity
  - unfortunately, reality intervenes and we have to actually be able to pay for it, never mind actually build it
  - many compromises and optimizations are required

Some Detector Physics Basics

- Reminder:

  Ionization Energy loss: on average ~ 2 MeV/cm ρ/(g cm^{-3})

  – liquids/solids: ~ few MeV/cm

  – gases: ~ few keV/cm

- Ionization potential for materials:

  – primary ionization potential (~10-15 eV) plus some additional energy to separate electron and ion: total of ~30eV per atom

  – So, for 1 cm of gas, 3000 eV lost ⇒ 100 primary electron/ion pairs

  – these ionize further, so add another factor 2-3 ⇒ 200-300 e^-/cm

  – (Note: *not* a very big signal!)

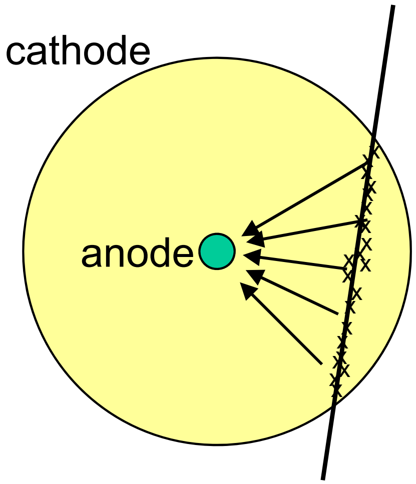
    - detectors based on ionized gas need Multiplication
    - solid-state detectors are ok in this regard

      – can't be too thick, though

        » problems with multiple scattering

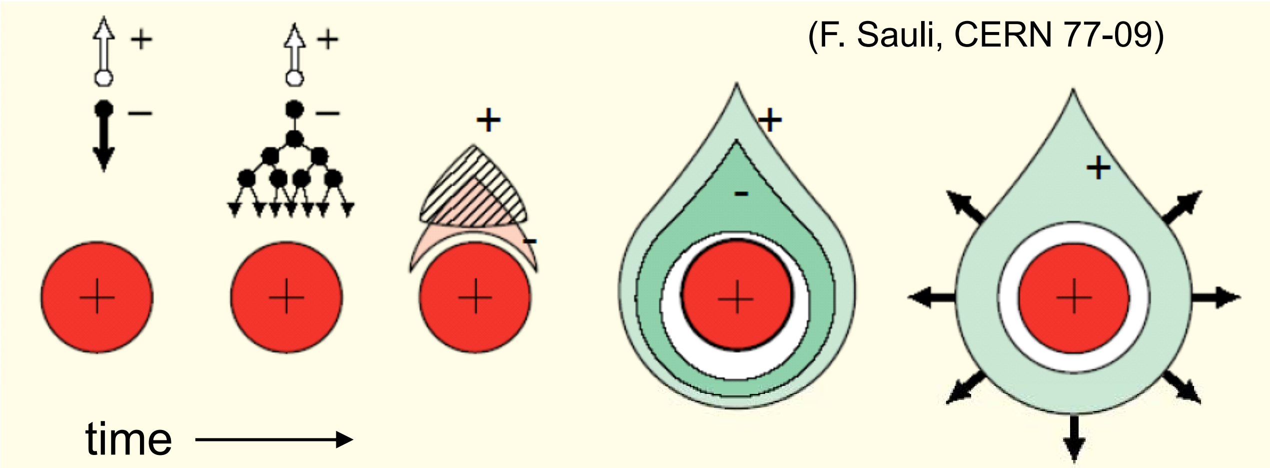
Charge Multiplication

- Small radius wires with large voltage; ionized electrons drift in:



- because E∝1/r, fields near wire become very large (>10V/μm = 10kV/cm)
- electrons reach energies sufficient to ionize gas
- secondary electrons also accelerated

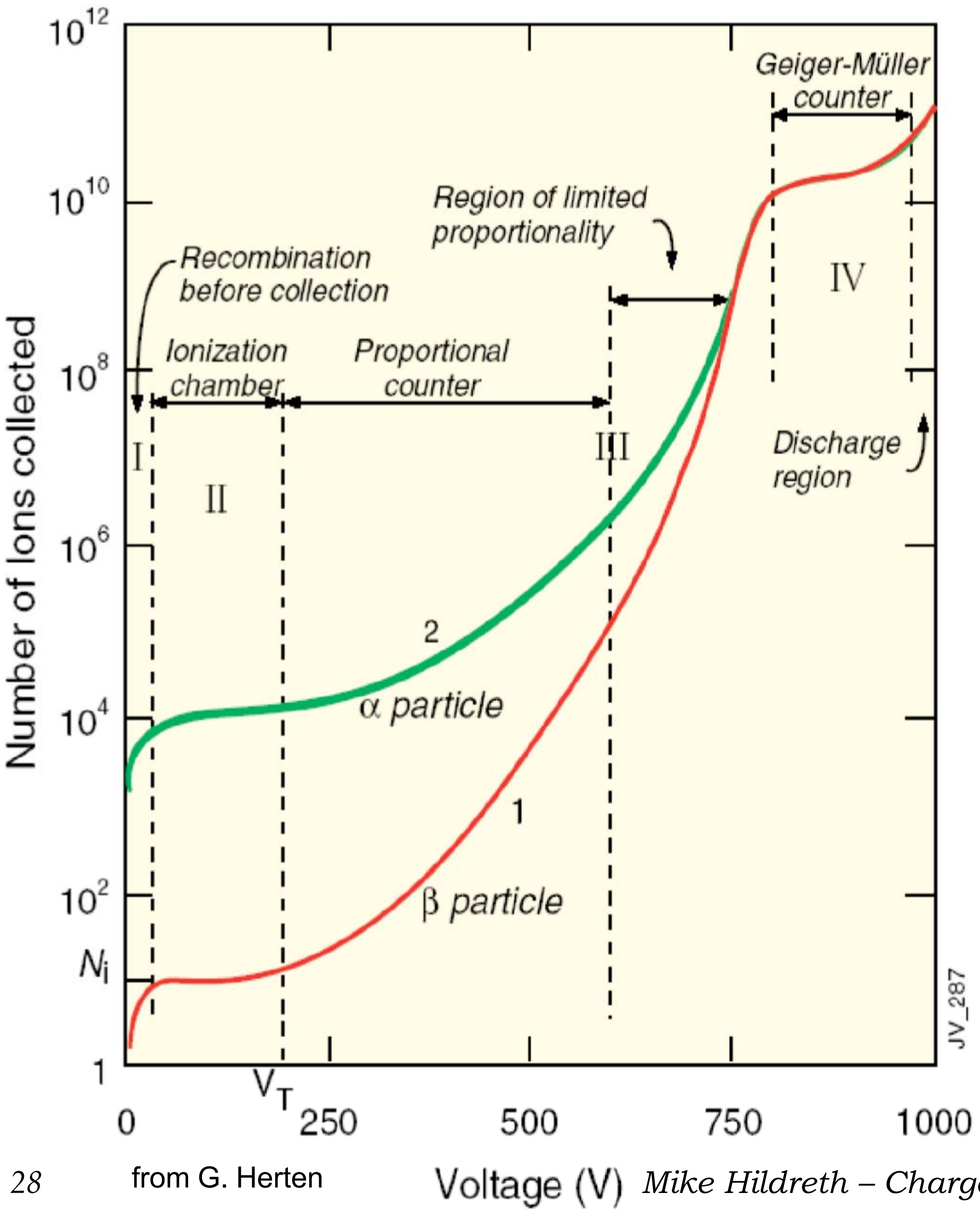
- For sufficiently large fields, an avalanche forms ⇒ large amount of charge deposited on anode (sense) wire



(F. Sauli, CERN 77-09)

gas must contain quenching agents to absorb photons generated in avalanche

SWPC Operational Modes

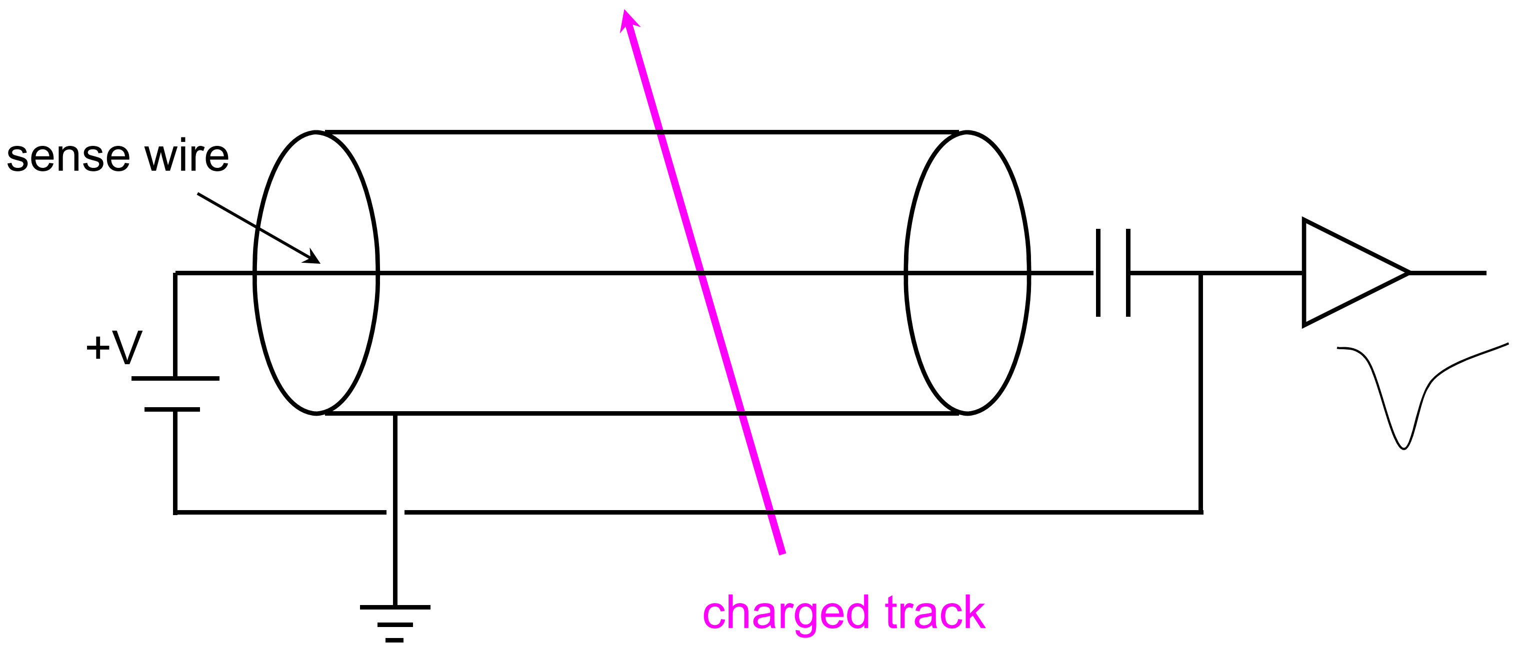


- ionization mode
  - full charge collection
  - no multiplication, gain ~ 1
- proportional mode
  - multiplication of ionization
  - signal proportional to dE/dx
  - secondary avalanches must be quenched
  - gain ~ $10^4 – 10^5$
- limited proportional mode
  - (saturated, streamer)
  - strong photoemission
  - secondary avalanches require strong quenching or HV pulsing
  - gain ~ 10^{10}
- Geiger mode
  - massive photoemission over full length of anode wire
  - discharge stopped by HV cut

from G. Herten

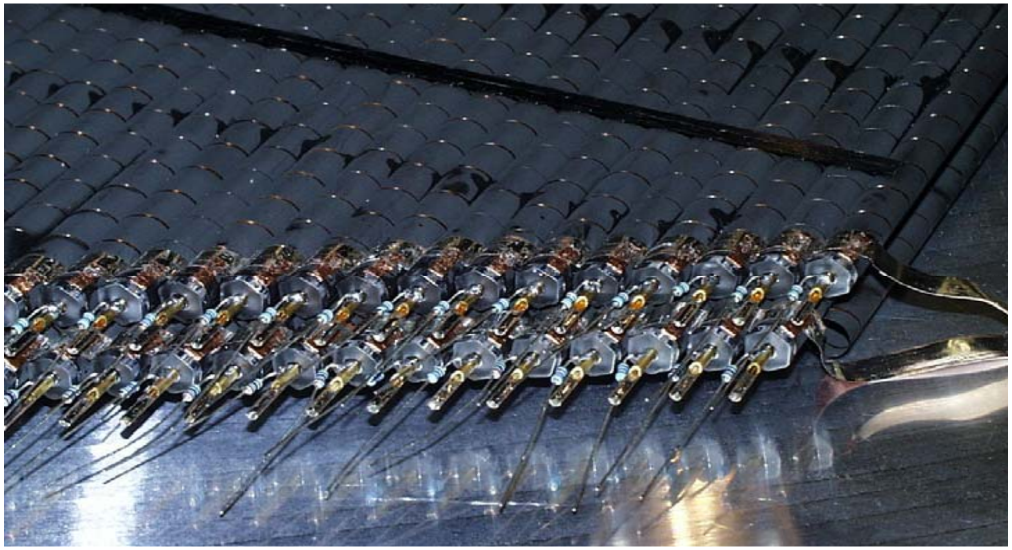
Gaseous Tracking Detectors: Geiger

- Simplest possible device
- Central (anode) sense wire
- Large voltage difference causes electrons to drift
- Charge avalanche occurs due to large fields near wire surface
- Binary (hit or not) – no attempt to measure timing, pulse height, etc.
- huge signals (given correct gas and voltage) $\Rightarrow$ simple electronics



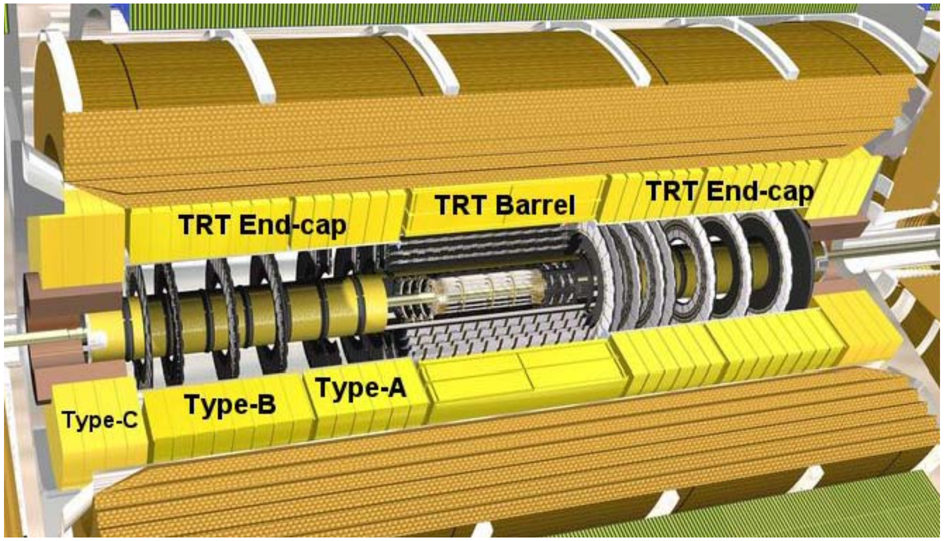
GTDs: Straw Tube

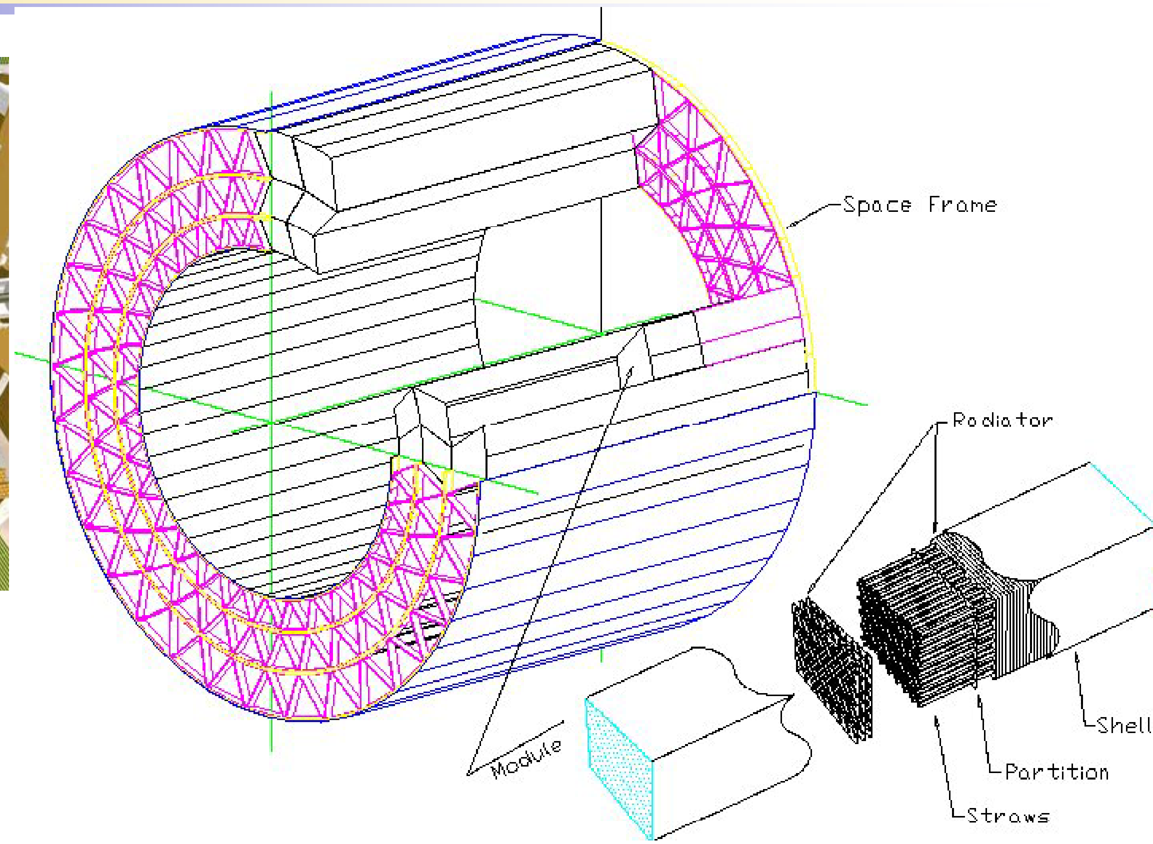
- Next step up from Geiger counter
  - operates in "proportional mode" where total charge detected is proportional to the number of incident electrons
  - timing information gives radial position information
- Construction:
  - each tube has small central wire (15-50 μm radius), typically small radius (5mm-1cm) outer cylinder of stiff, thin material (100-200 μm)
  - built into arrays of tubes to provide multiple hits along trajectory



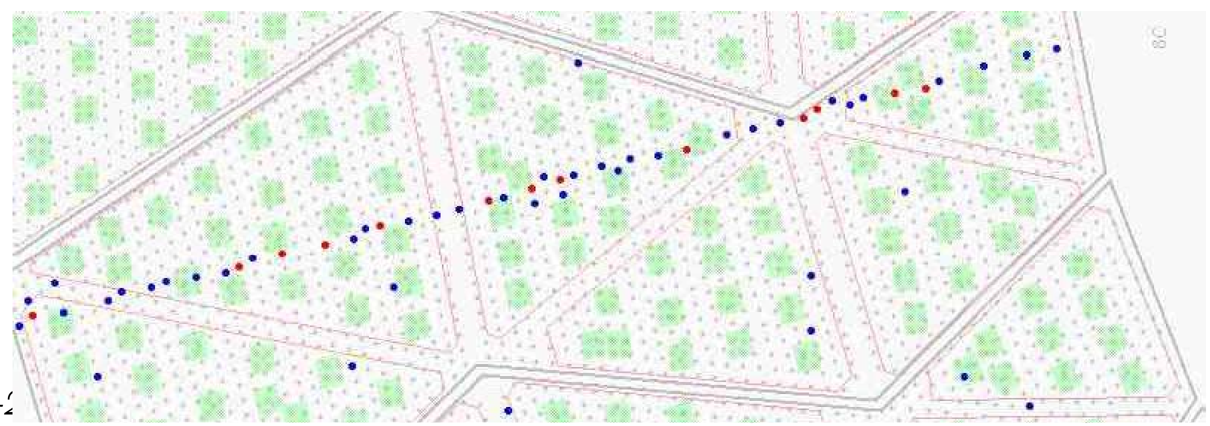
Zeus Tracker

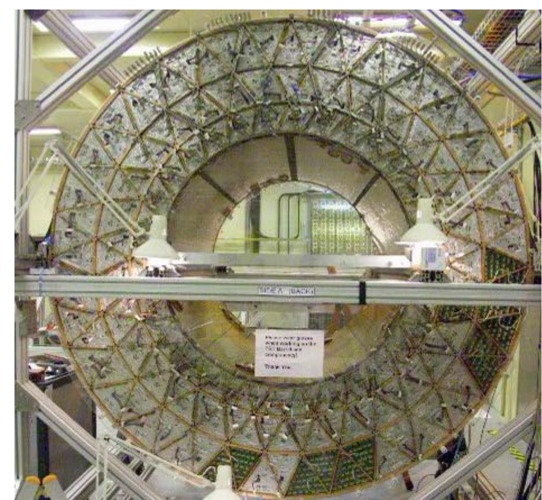
GTDs: Atlas Straw Tubes (TRT)





- 4mm straws, 31μm wires
- fast charge collection: ~45ns
- gain of 25,000
- particle ID (e/π separation) using transition radiation





GTDs: Atlas – Why Straws?

Choice of optimization point:

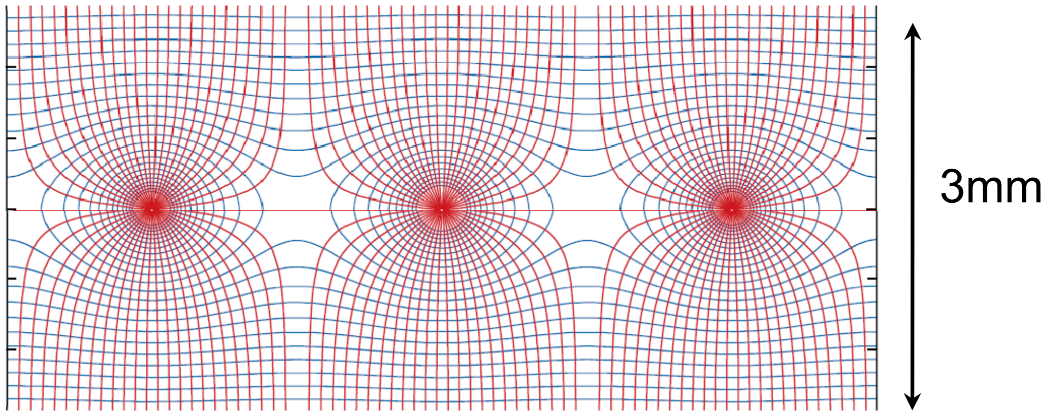
- decided a large number of hits/track is desirable
  - driven to some sort of gas-based detector for fabrication cost reasons
  - more hits with worse resolution/hit
- individual element volume is a compromise between
  - maximum signal collection time (occupancy/multi-hit issue)
    - smaller volume is better (Atlas arrived at ~40-50ns)
  - channel count
    - smaller volumes $\Rightarrow$ more channels $\Rightarrow$ more cost

Straws vs. Open Drift Cell structure

- mostly a question of robustness
  - physical structure of straws more robust than free wires
  - damage from wire breakage limited to individual straw tube
  - cross-talk minimized: cathode acts as ground shield
- However: any gas detector in this environment faces serious ageing issues
  - 10 Mrad expected dose in 10 years (10 C/cm total charge!)

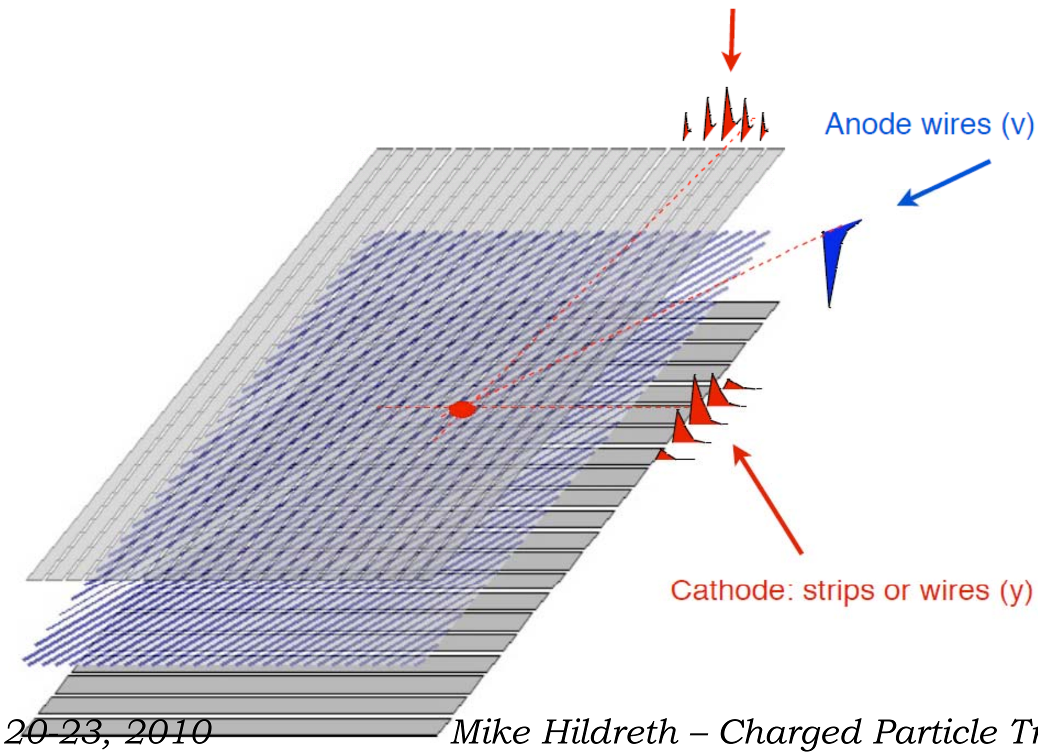
GTDs: Multi-Wire Proportional Chambers

- Replicate single wire geometry in large arrays



1mm cell width gives single hit resolution of ~ 300 μm

- Can have 2-D information:



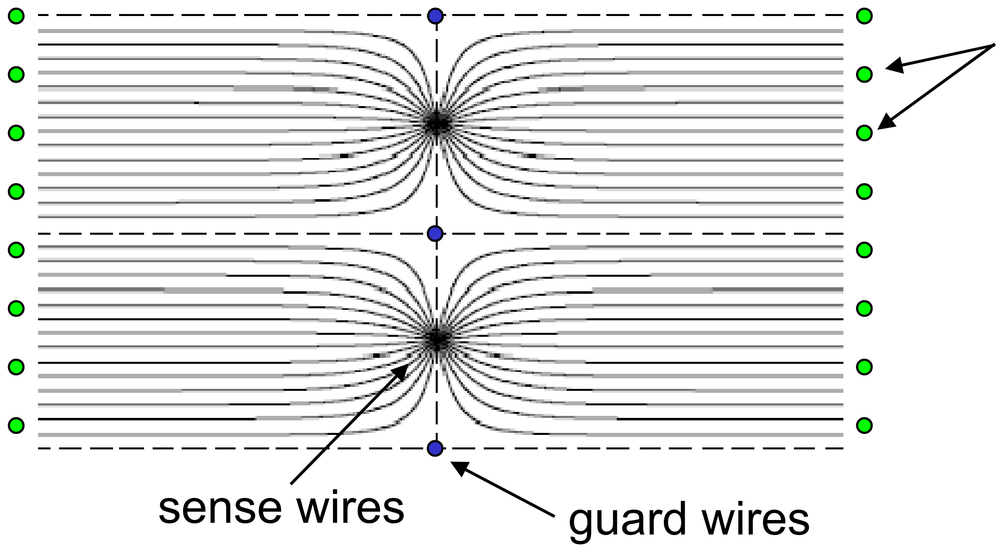
Many different ways to use this basic concept:

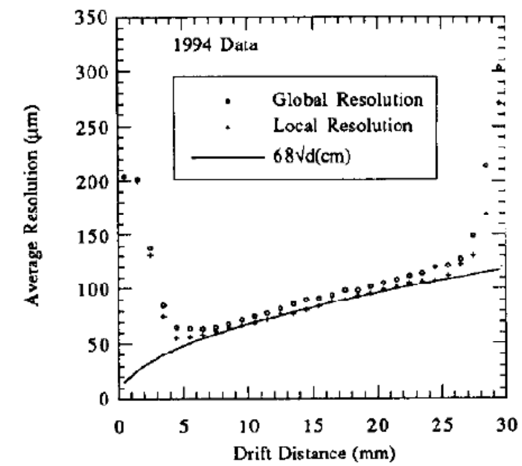
e.g. Cathode Strip Chambers, Resitive Plate Chambers, Small Gap Chamber, Monitored Drift Tubes, Streamer tubes, (insert favorite muon detection technology here)

from G. Herten

GTDs: Drift Chamber

- "Open" MWPC
  - arrays of cathode "field" wires used to create uniform electric field

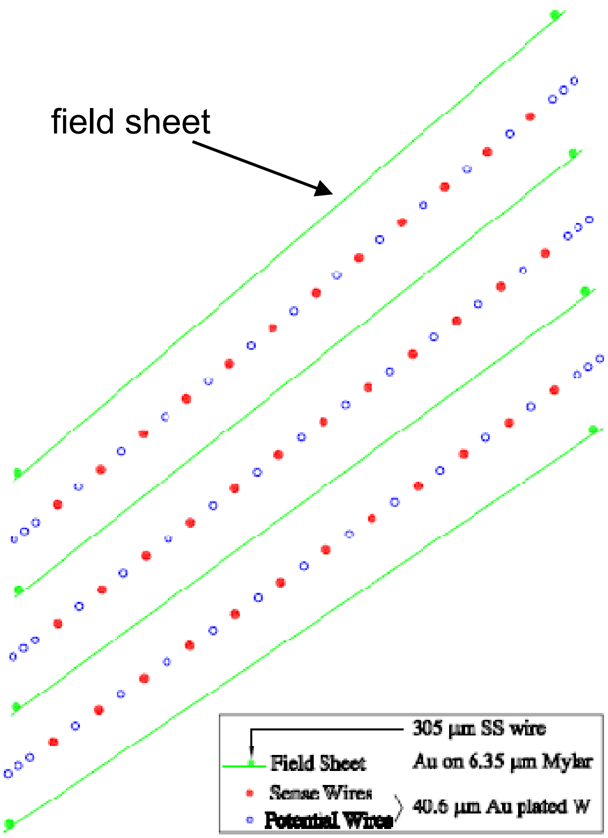




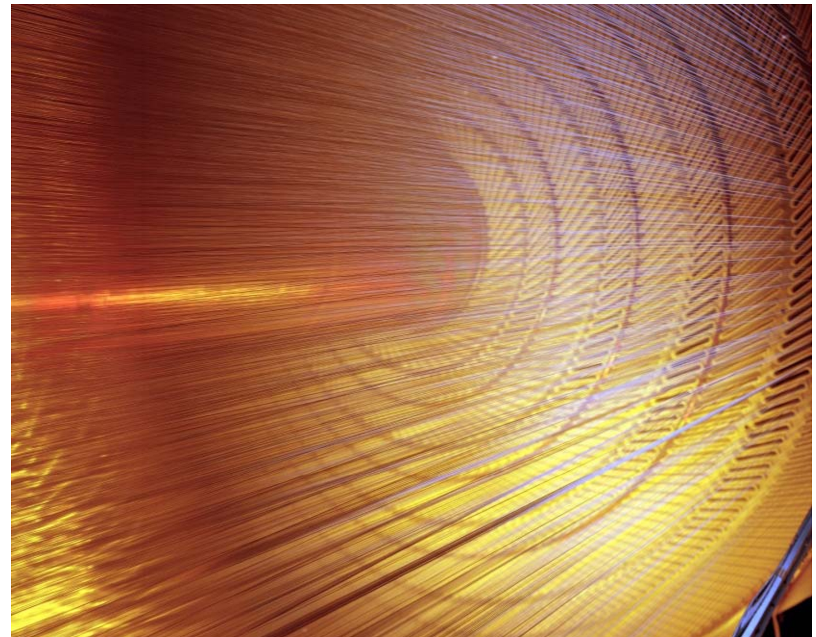
  - uniform electric field creates uniform drift velocity, so position can be determined by time measurement
    - modulo edge and near-wire corrections (detailed field map)
    - with appropriate gas, drift distances can be very long
  - detector is inherently "thin": many measurements and large volumes possible without adding a huge amount of material

GTDs: CDF COT

- optimized for “high”-luminosity tracking

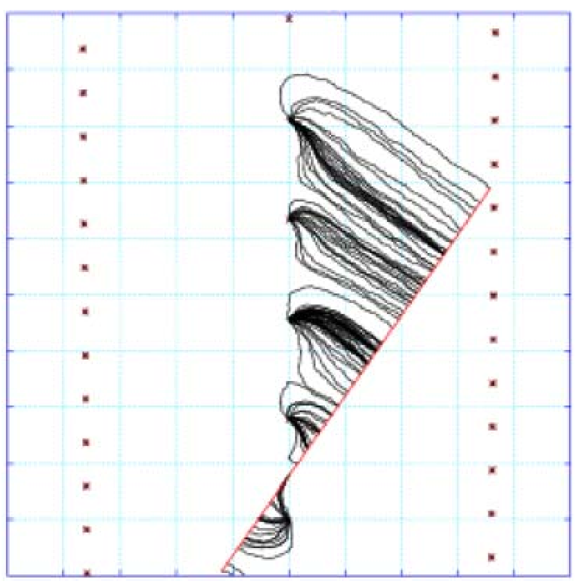


- narrow drift cells insure short collection times: trigger input
- tilted cells insure well-separated hits for radial tracks, limit multiple tracks/wire, limit left-right ghosts
- Note: stereo wires



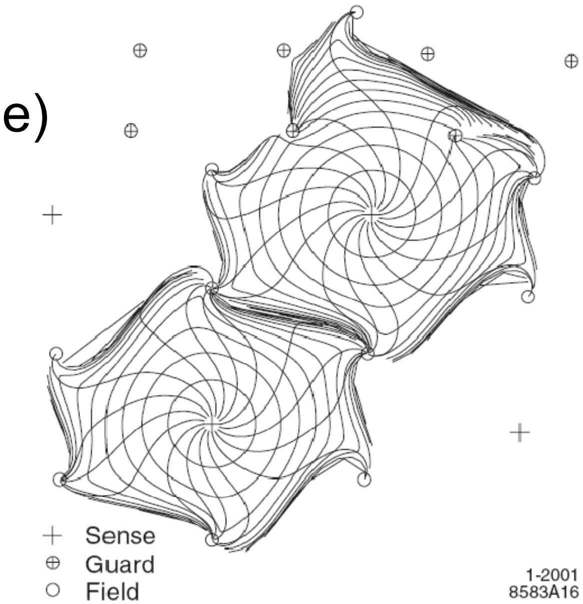
typical resolutions: σ_{xy} ~100μm

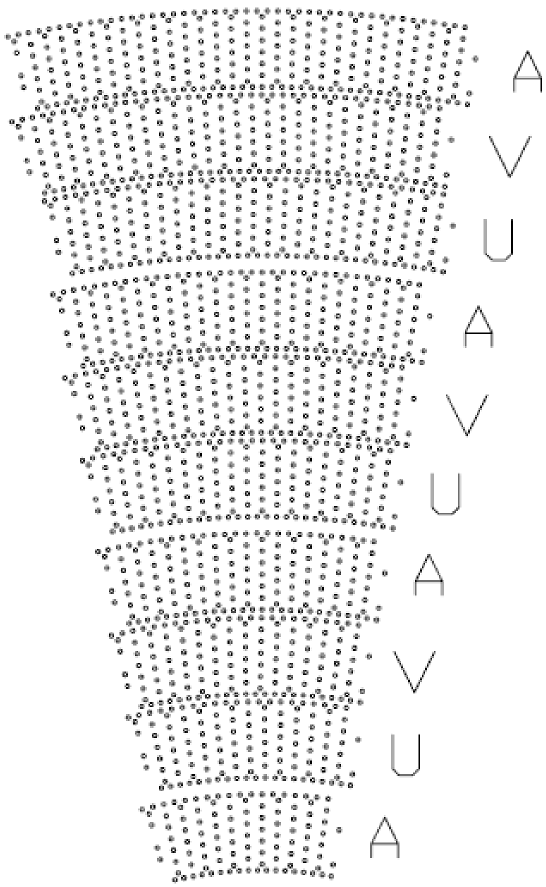
σ_z~<1mm



GTDs: BaBar Drift Chamber

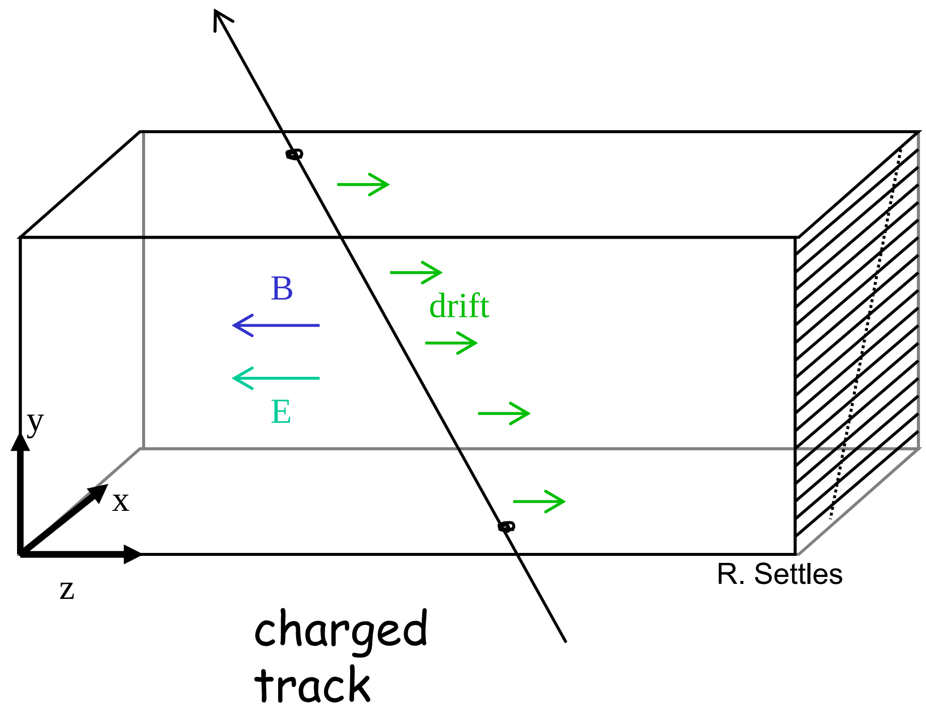
- Optimized for high-rate *and* low-mass
  - helium-based gas mixture (80% He, 20% isobutane)
  - gas + wires only gives 0.3% X_0 at 90
  - small cells (short drift times) allow use in trigger
  - also used for dE/dx measurement





GTDs: Time Projection Chamber (TPC)

- Set up a situation where E ∥ B
  - electrons drift along the z axis
    - looong drift distances
  - measure time and arrival position
- True 3-D detectors
- Many measurements/track
  - allows good particle ID with dE/dx
- Only gas in active volume
  - very little material
  - Large track densities possible



Alice

Very long drift (typically > 2 m) implies/requires:

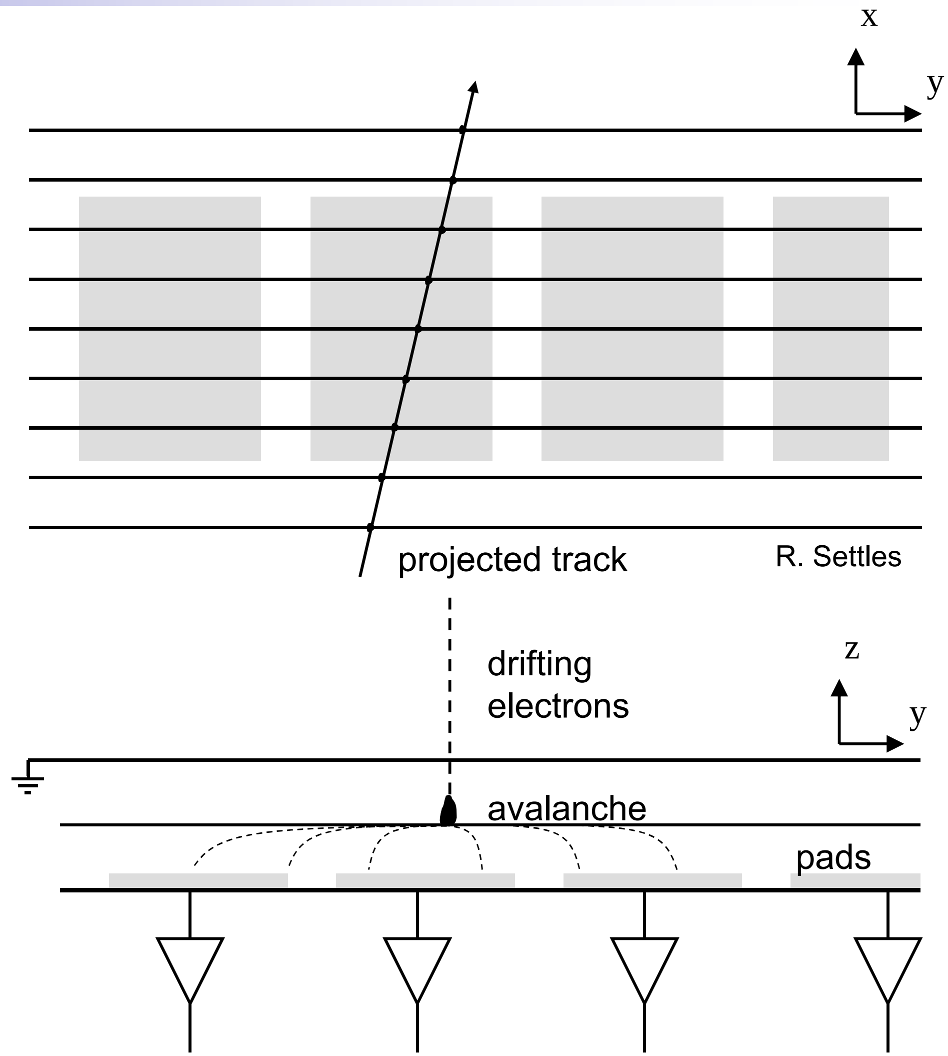
- slow detector (~40 μs)
- no impurities in gas
- uniform E-field
- strong & uniform B-field

GTDs: TPCs

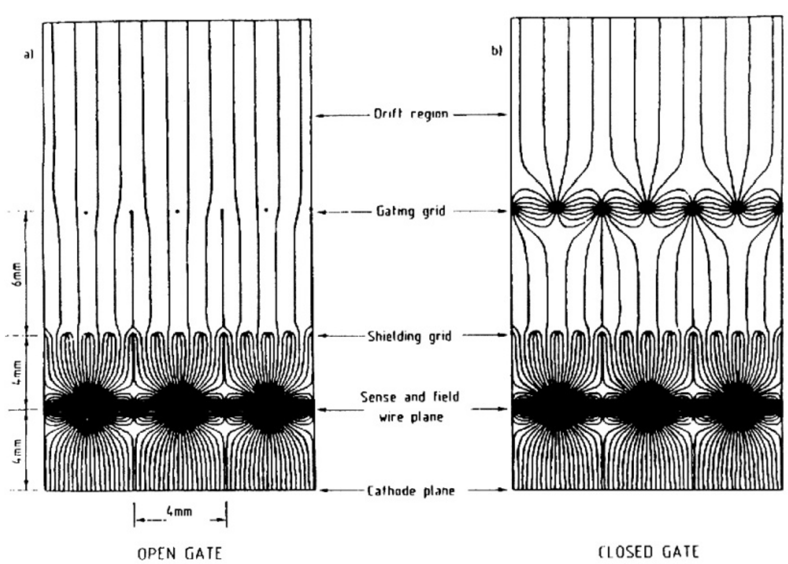
- wires on end plane only measure one coordinate

⇒ special cathode geometry

  - cathode pads used to measure orthogonal coord.
  - granularity key for single hit resolution
  - ion clearing/gating:
    - special precautions to get rid of avalanche remnants



typical resolutions: σ_{xy} ~200μm, σ_z~<1mm



GTDs: TPCs

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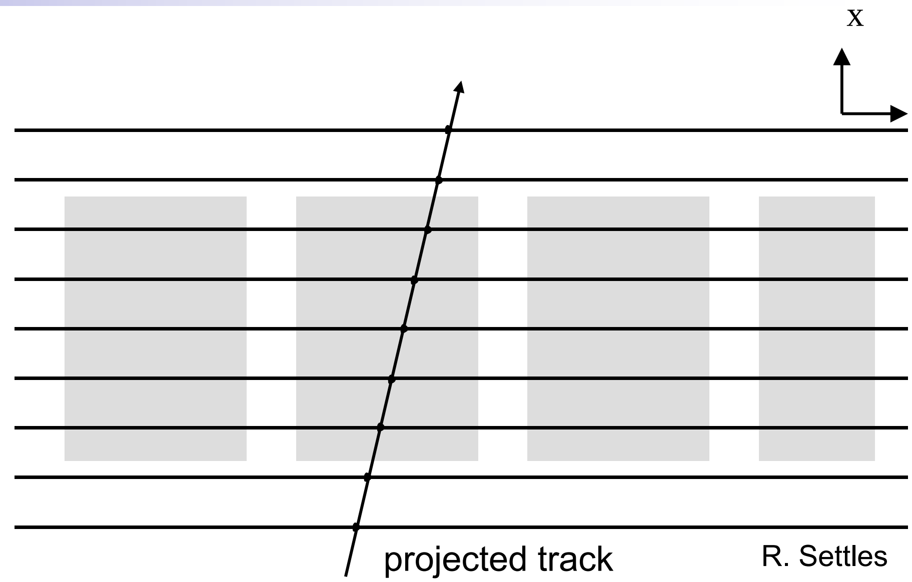
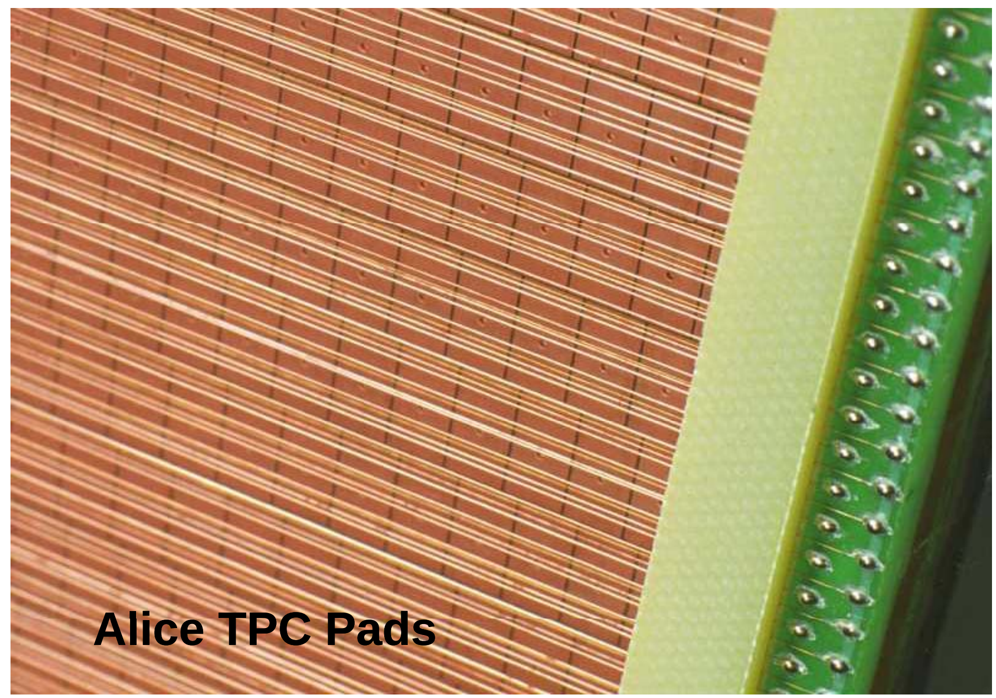
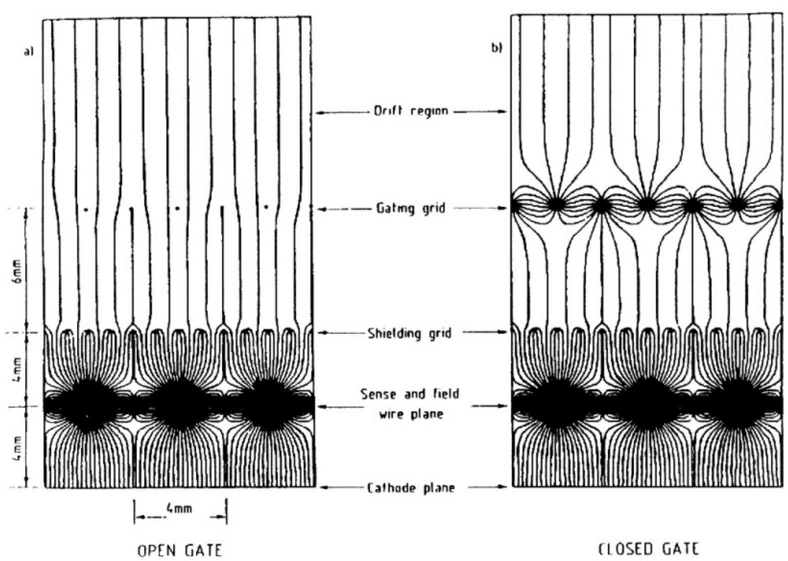
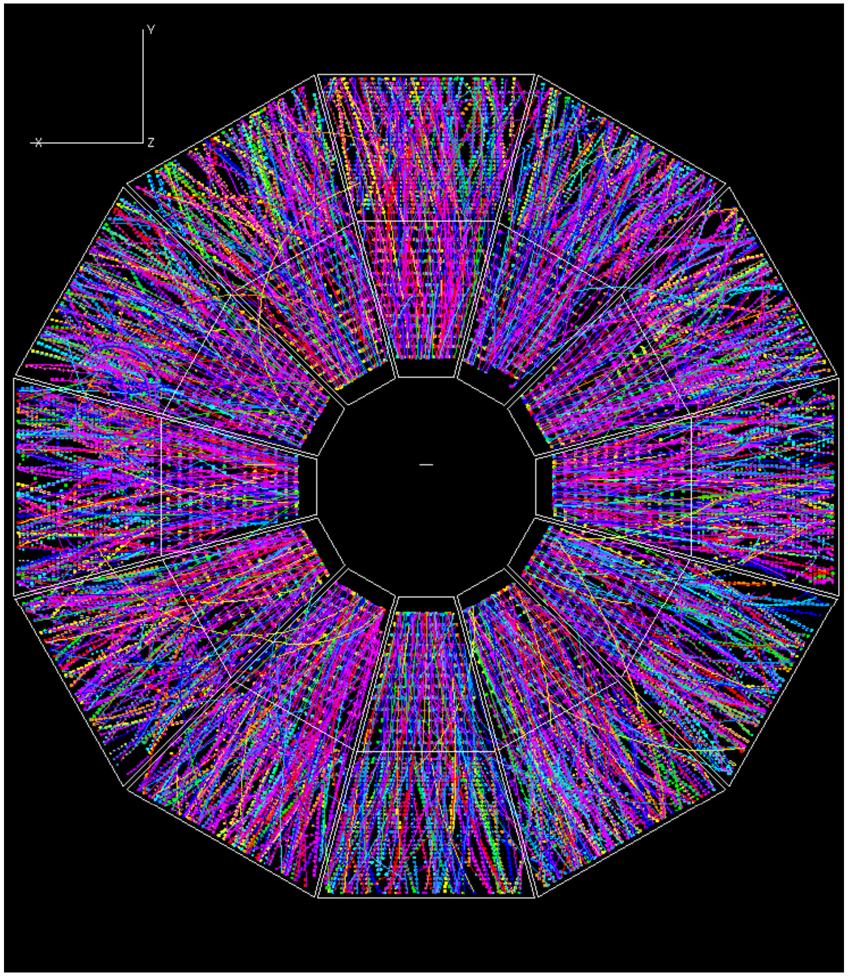


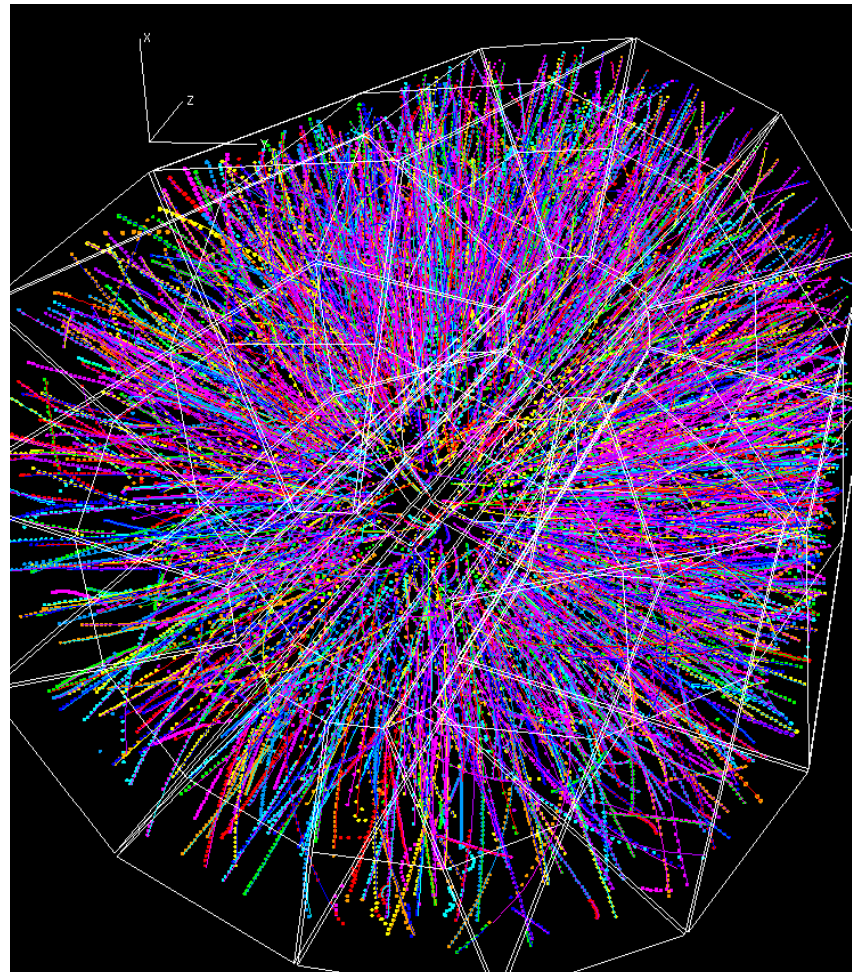




GTDs: TPCs

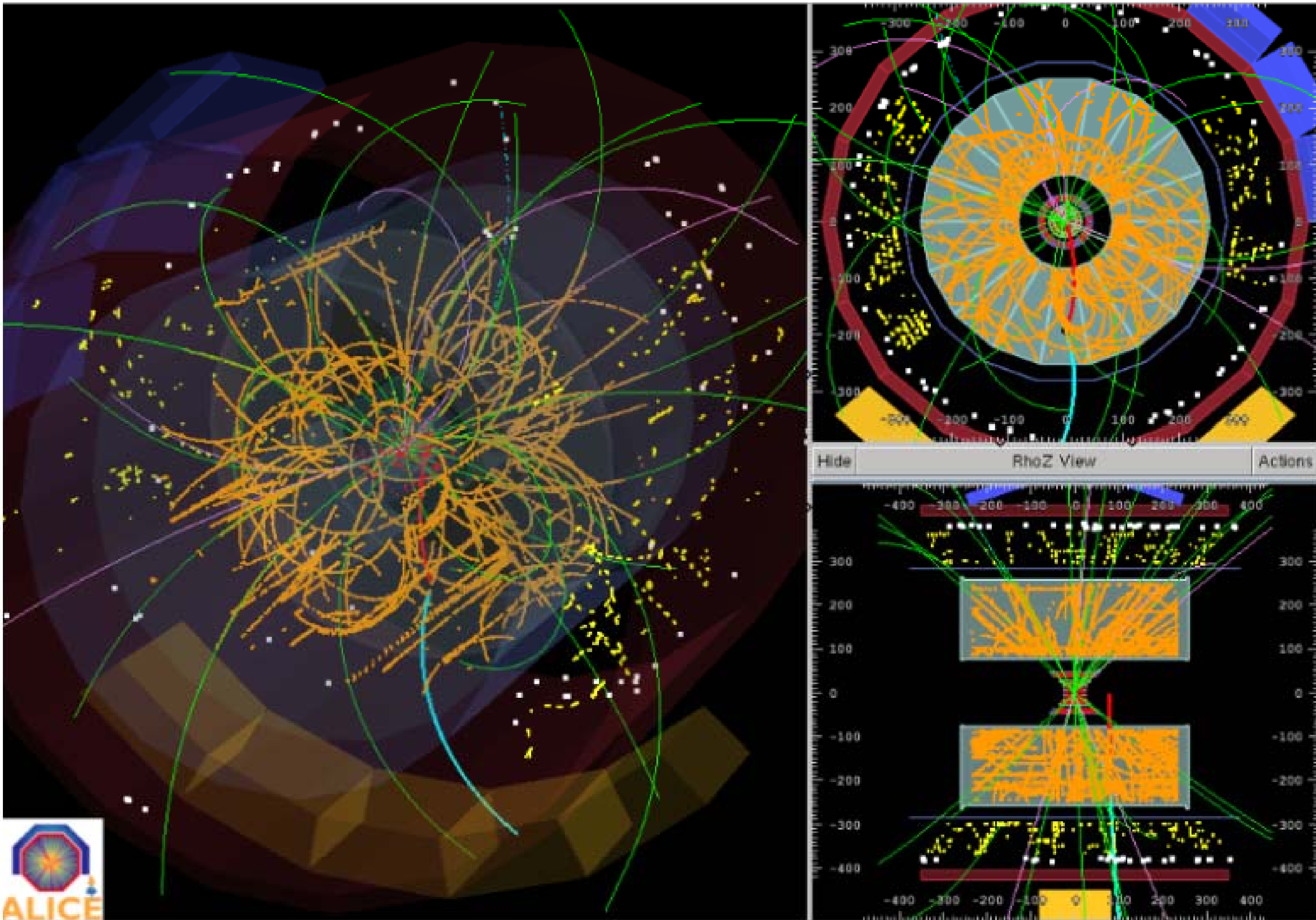
- Large track densities *are* possible!





STAR

GTDs: Alice TPC

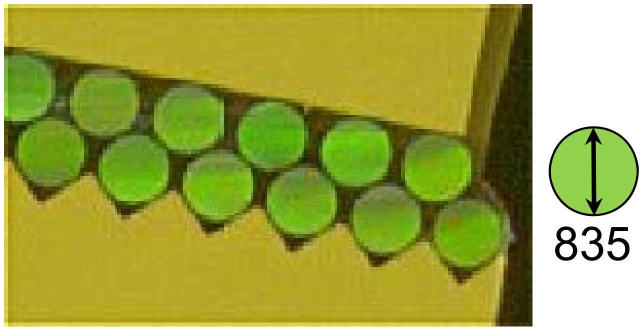


Issues for GTDs

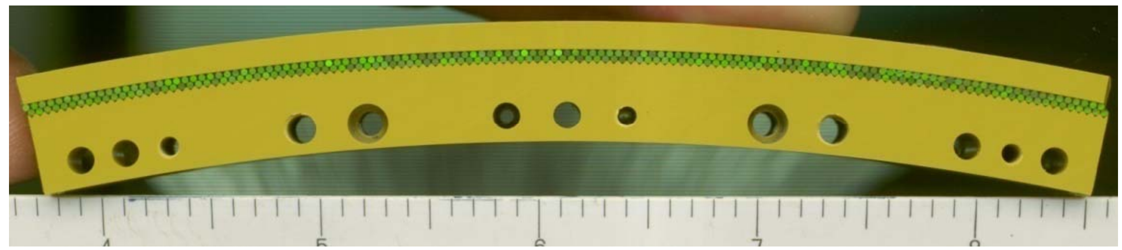
- cover large volumes relatively cheaply
- nearly 100% sensitive volume
- Gas composition/stability/contamination
  – basically a black art
  – need gases that give good multiplication, but not too much
  – need gases with low electron diffusion for good resolution
  – need components to quench the avalanches
  – need to avoid contaminants that ruin the performance
  – sometime contaminants can be beneficial (c.f. CDF and H_20)
  – all of this must be monitored constantly
- electric field mapping (with data)
  – distortion corrections important for ultimate resolution
- limited single hit resolution
  – unavoidable given drift/diffusion/avalanche considerations
    - best resolution achieved was ~30-40 μm/hit (Mark II DCVD)

Solid Detectors: Scintillating Fibers

- Small, multi-clad fibers doped with scintillating dye & waveshifter can function as a tracking device



835 µm



- DØ Central Fiber Tracker: ~77k fibers
- 8 Barrels: each barrel layer has axial and 3˚ stereo ribbons (XU, XV, XU…)
- Light collection: visible light photon counters (VLPCs)

  - solid state photodetectors
  - high-gain (~40,000)
  - high quantum efficiency
  - fast – use in trigger

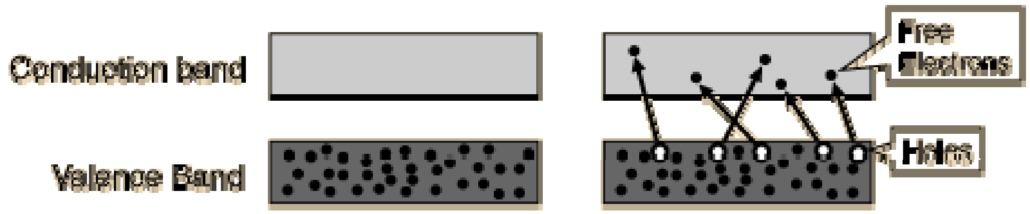
Solid State Tracking Detectors

- Why Silicon?
  - crystalline silicon band gap is 1.1 eV (c.f. ~20eV for typical gases)
    - yields 80 electron-hole pairs/μm for minimum-ionizing track
      - (1 e-h pair per 3.6 eV of deposited energy)
    - 99.9% of ejected electrons have less than 1μm path length
      - fine-granularity devices can easily be made

  ⇒ detector performance could be as good as emulsion/bubble chamber
  - Integrated Circuit manufacturing techniques make just about anything possible, and at industrial prices
    - no real need to "home-grow" these detectors
    - just buy what you need…

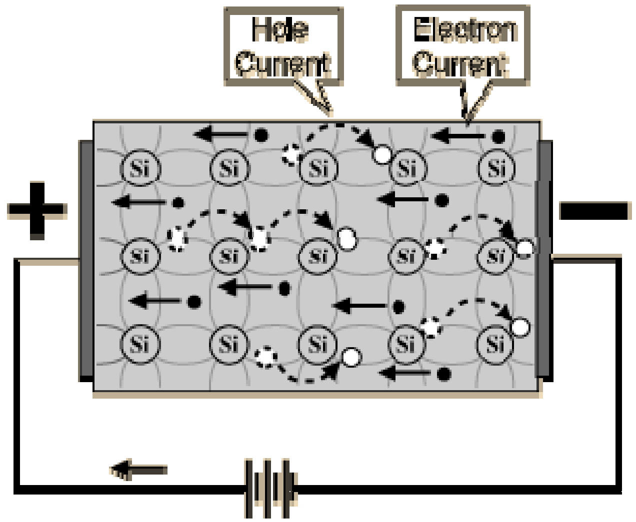
Silicon Basics

- Detection still based on collecting electrons from dE/dx in material
- semiconductor structure:



http://hyperphysics.phy-astr.gsu.edu

electrons excited (thermally or otherwise) into Conduction band become mobile



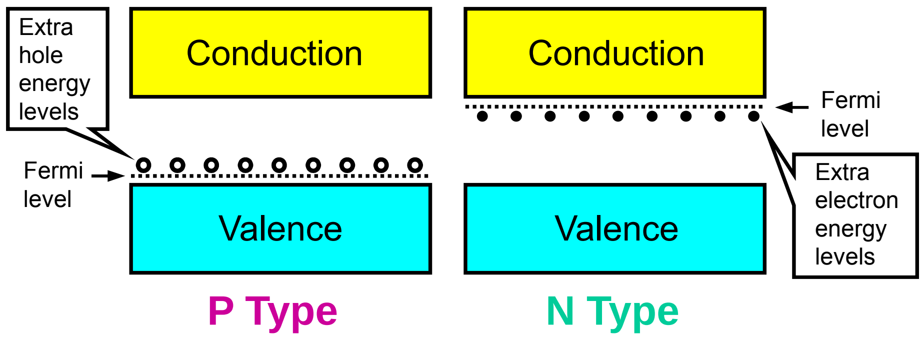
Liberated electrons will drift under the influence of an applied voltage

- the problem: recombination
  - many, many more free charge carriers in a semiconductor than what is liberated through ionization $\Rightarrow$ electrons re-combine with holes

Silicon Basics: Doping and PN

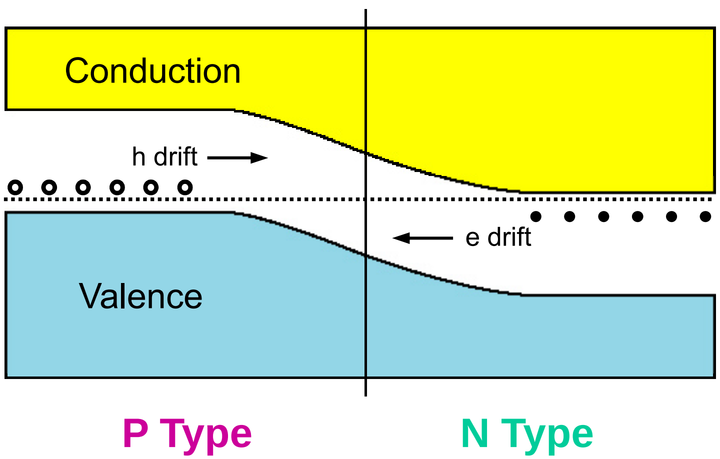
- The solution(s): 1. modify material structure

P-type silicon has electron acceptor (hole donor) atoms (B) added to create additional hole states

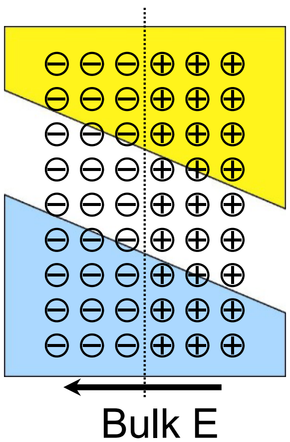


N-type silicon has electron donor atoms (P) added to create additional electron states

2. Modify charge structure: put P and N together (PN Junction)
   – in thermal equilibrium, Fermi levels become equal due to drift of electrons/holes across junction

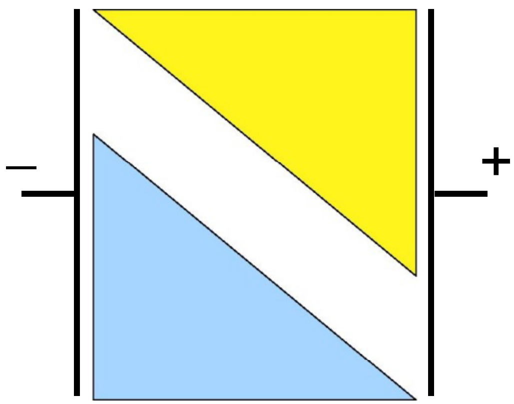


Near junction, electrons bind to hole sites, creating negative ions, leaving positive ions behind. Bulk E-field stops motion of more particles ⇒ Depletion region: no free charge carriers!



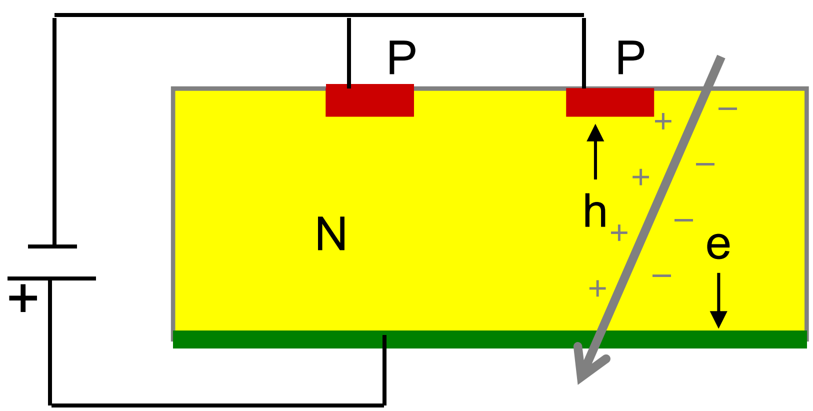
Silicon Basics: PN Junction, Bias

3. Apply a voltage to suppress bulk E field, increase size of depletion layer to encompass entire volume: "Reverse Bias"

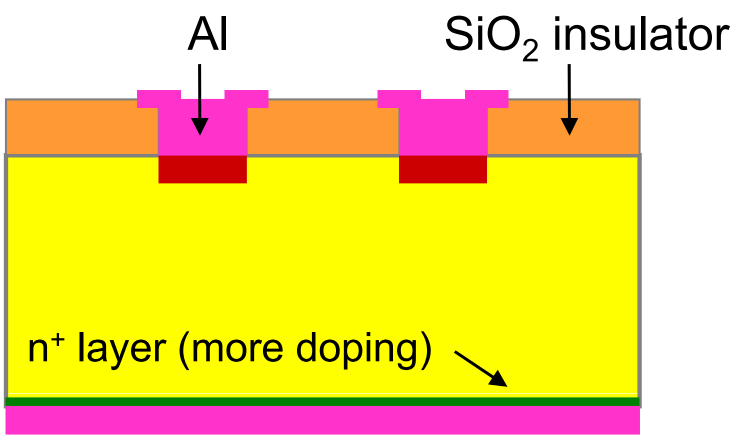


At the depletion voltage, no more free charge carriers exist in the semiconductor; any additional e-h pairs generated can drift to the edges

In reality, use bulk silicon of one type, make "electrodes" out of the other type:



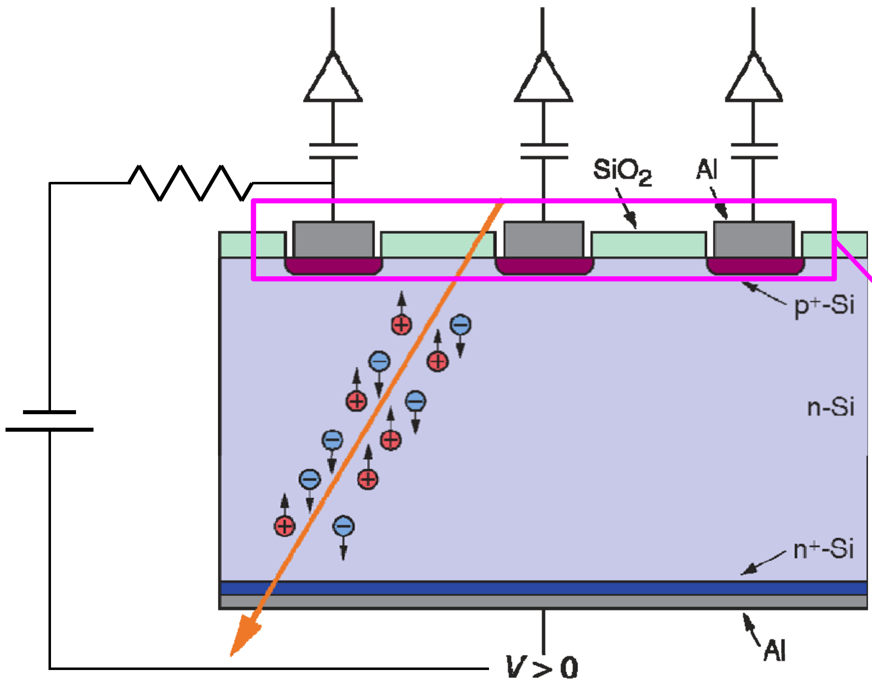
"Real" detectors necessarily more complicated

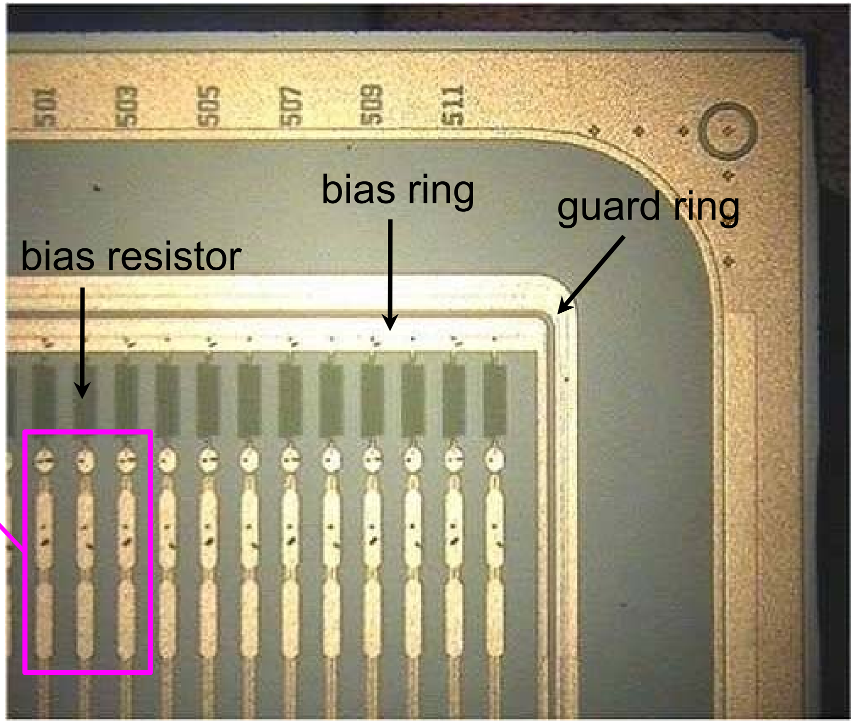


R. Wallny

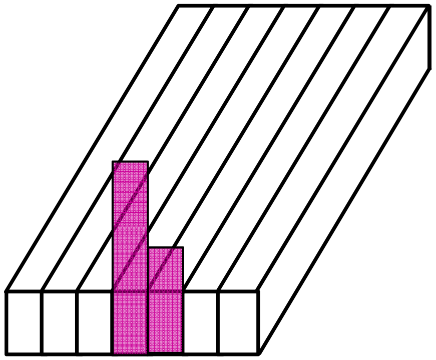
SSTDs: Silicon Microstrips

- The easiest thing to do is put down sensor lines, read out at end





- Charge sharing improves position resolution:

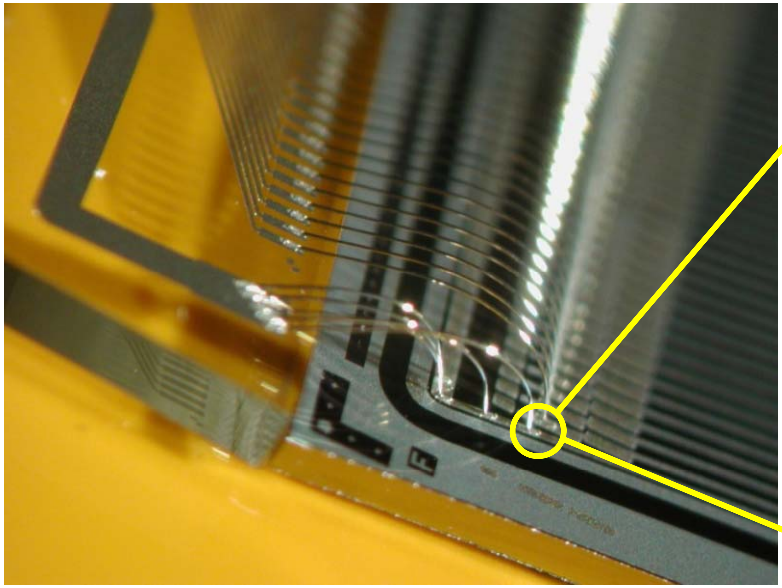


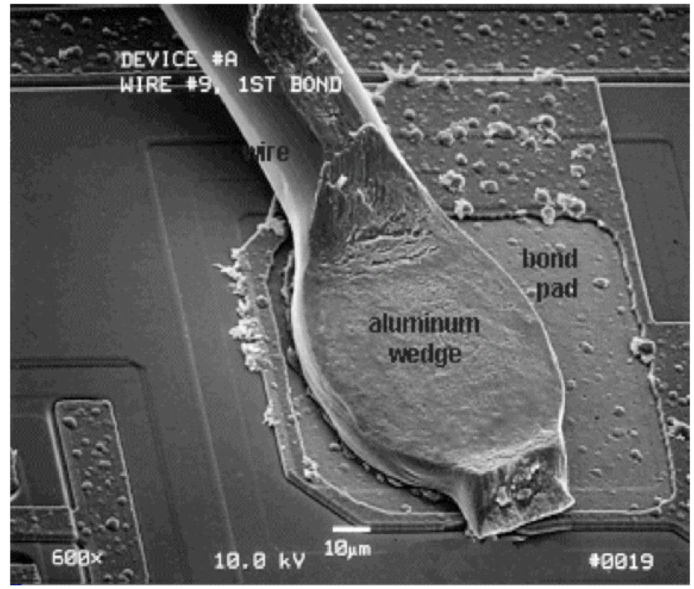
$$\bar{x} = \frac{\sum x_i q_i}{\sum q_i}$$

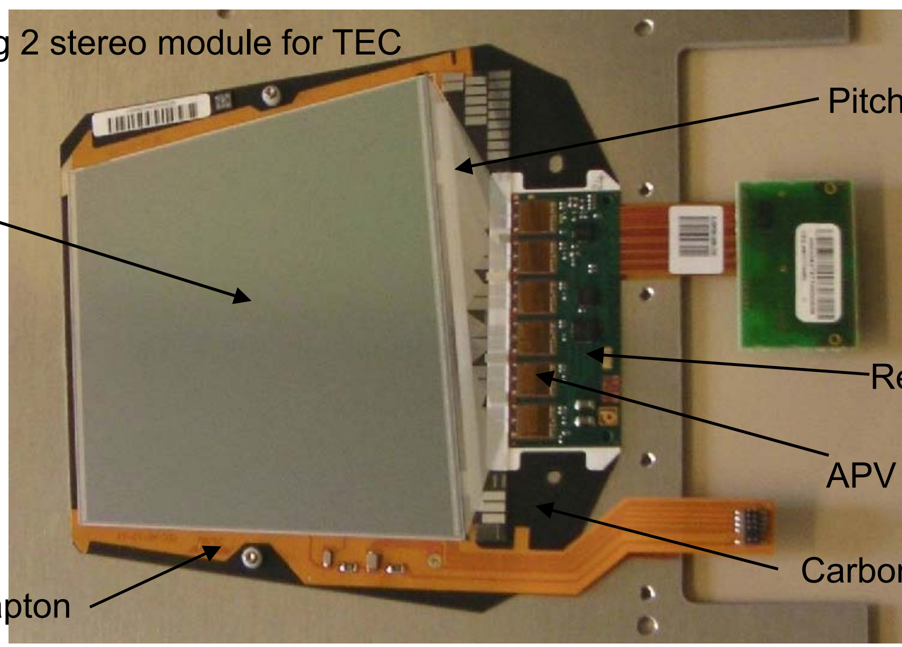
- Typical pitch width: 50μm – 200μm
  - one strip: width/$\sqrt{12}$
  - two stips: width/4
  - more than two: width/2

SSTDs: Silicon Microstrips

- Exquisitely complicated micro-mechanical construction





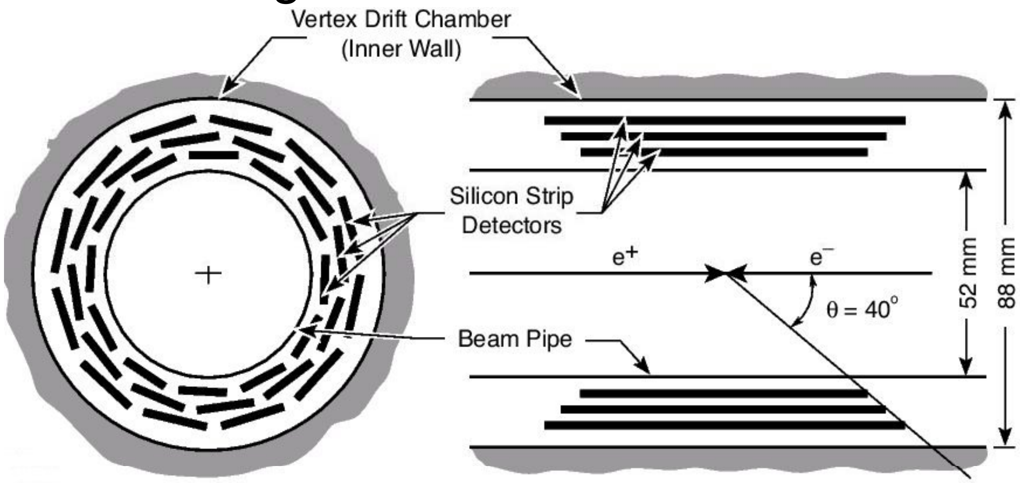


SSTDs: Silicon Microstrips

- inherently 2-D: go to double-sided (or glue sensors at an angle for stereo) for r-z, but still 2-D devices
- “shingle” geometry common
  - full azimuthal coverage

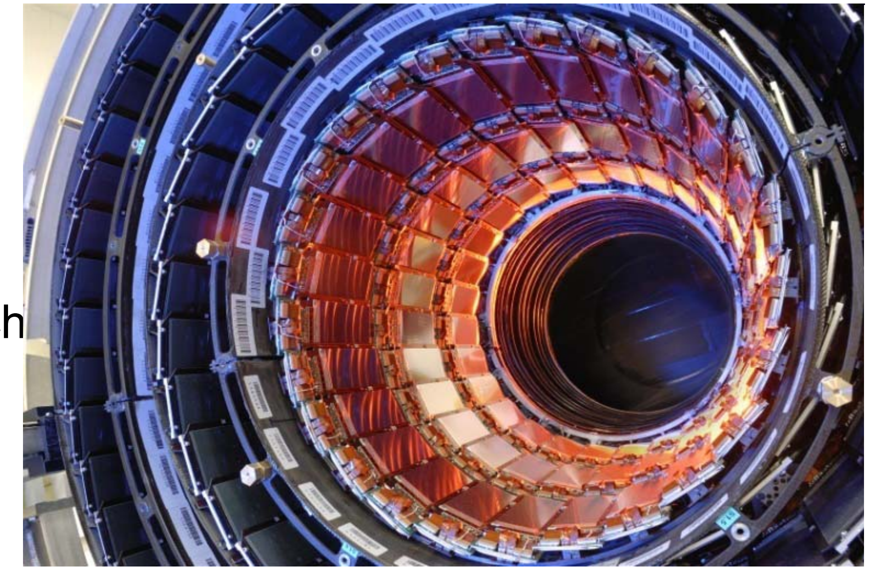
Mark II

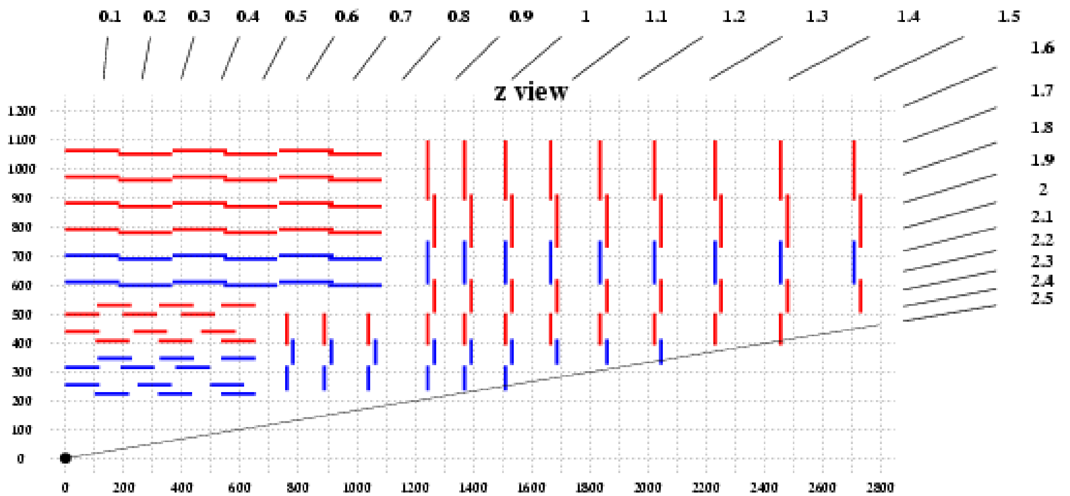
18.4k ch



CMS

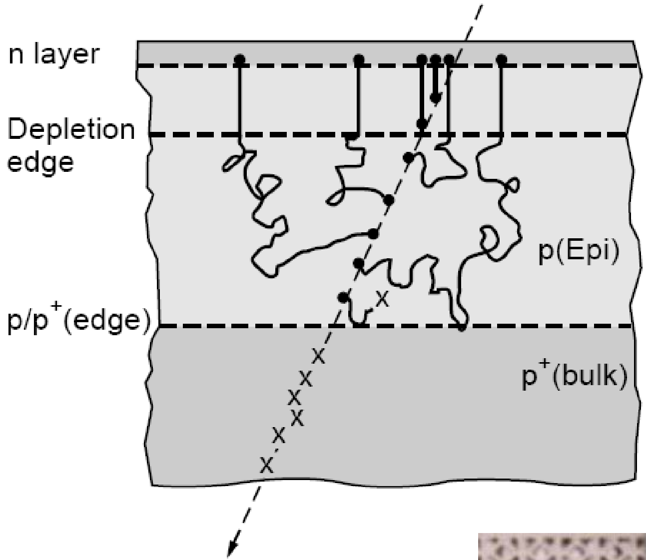
9.6M ch





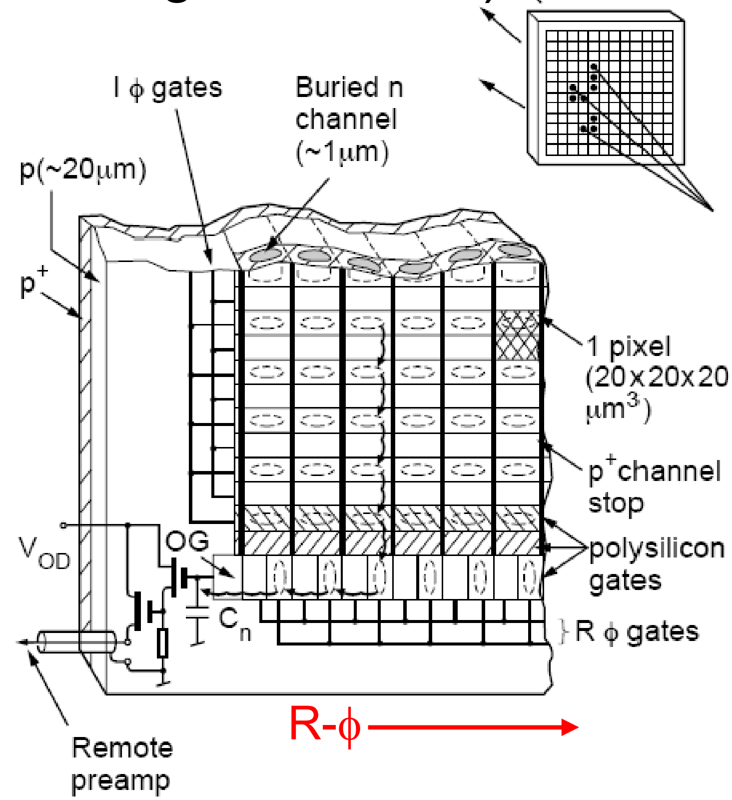
SSTDs: Pixels

- CCDs (charge-coupled devices) (what's in your digital camera)
  - how do they work?



Thin depletion layer; active p-type epitaxial layer of ~20μm; generated charge reflected off of p+ substrate and eventually collected

C. Dammerell



SLD VXD3:

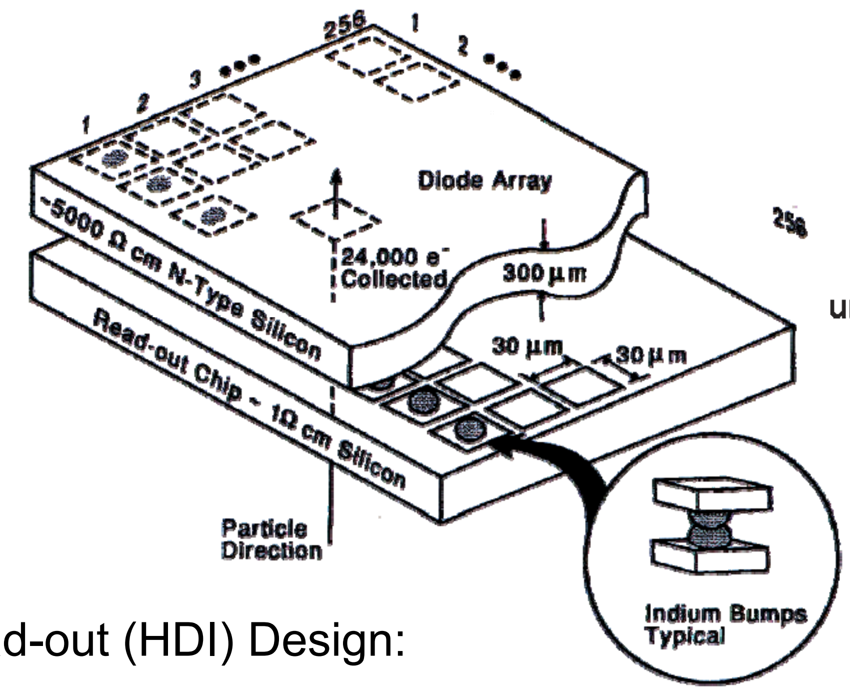
- 3x10[8] pixels
- world-record for collider detector hit resolution: ~4μm

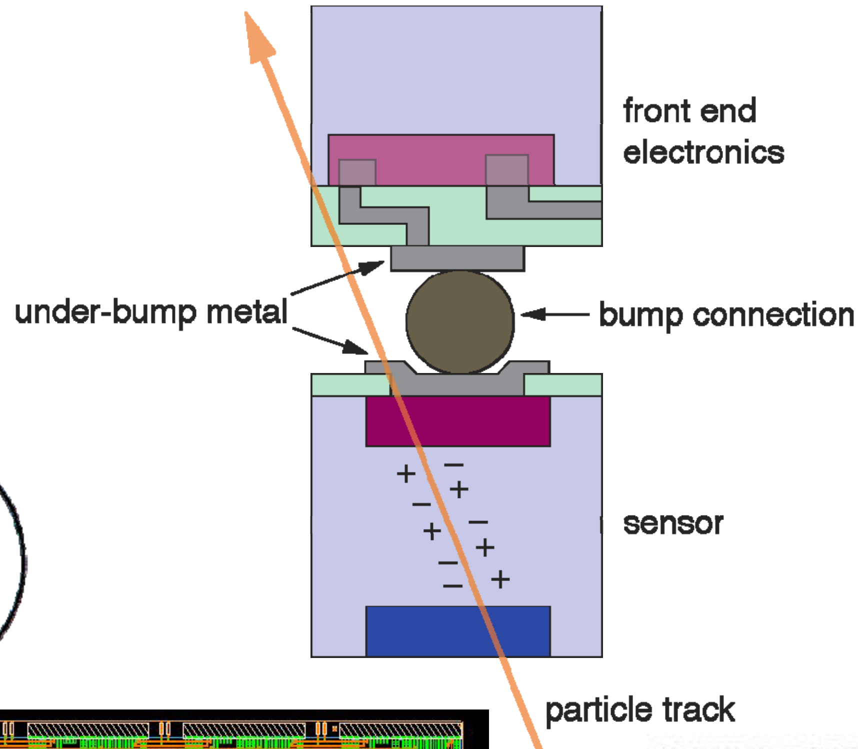
Complicated pixel structure built on surface; Readout is serial – I shifts move each row down, R-ϕ shifts read out the columns. Can take 100ms to read out a large detector

technology still advancing...

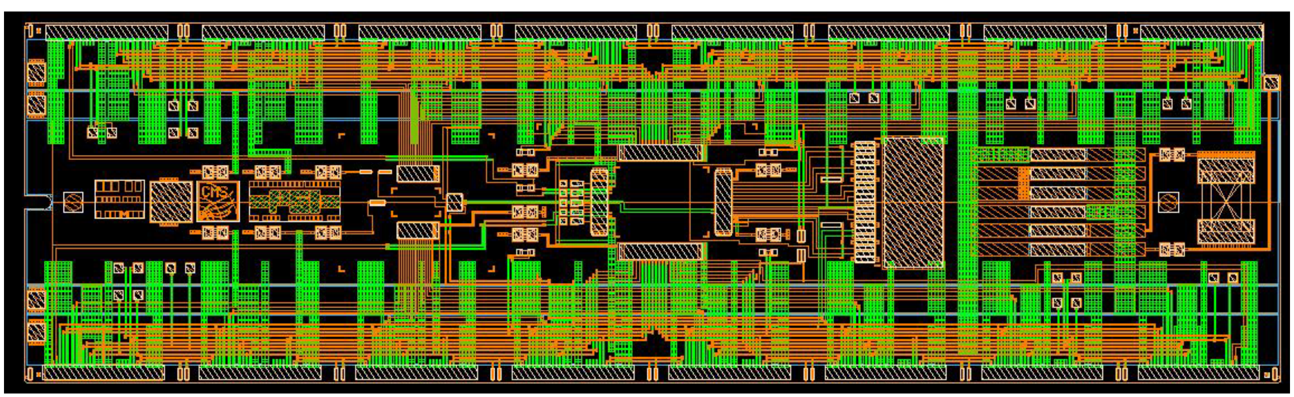
SSTDs: Hybrid Pixels

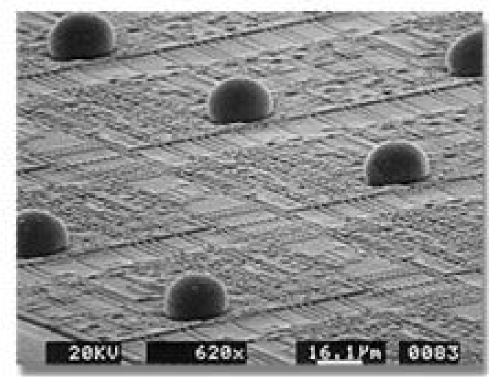
- Use fast, intelligent, rad-hard devices for high-occupancy environments
  - sensors separate from readout electronics – bonded together





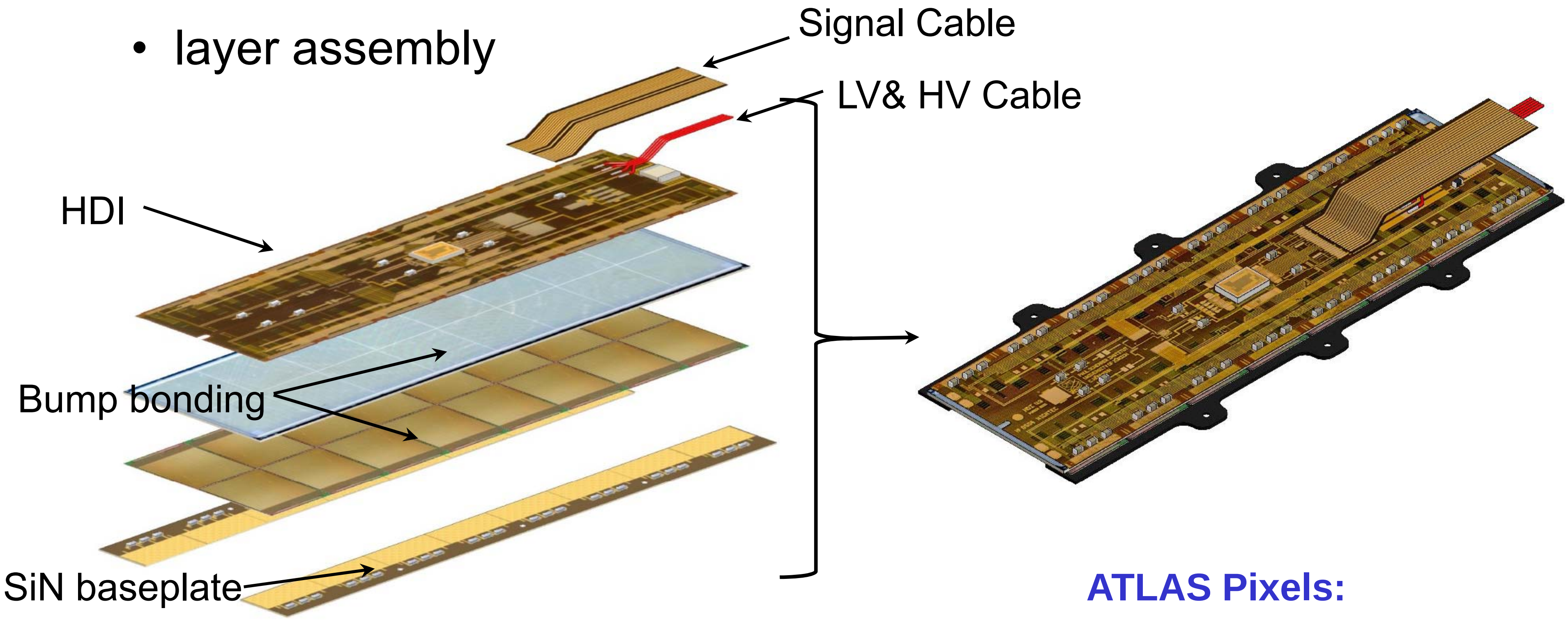
Read-out (HDI) Design:





Pixel Modules and systems

- layer assembly



ATLAS Pixels:

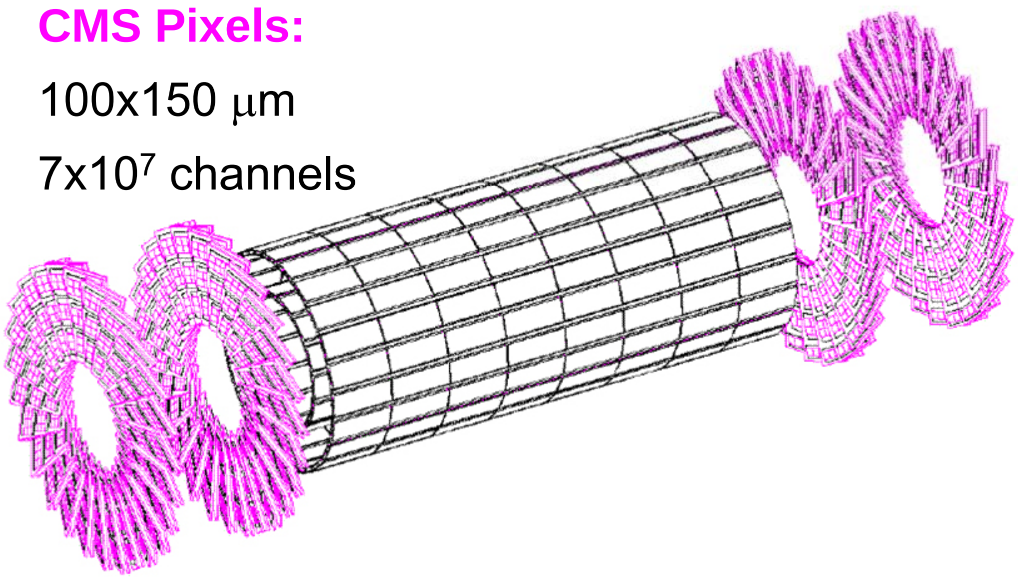
50x400 μm

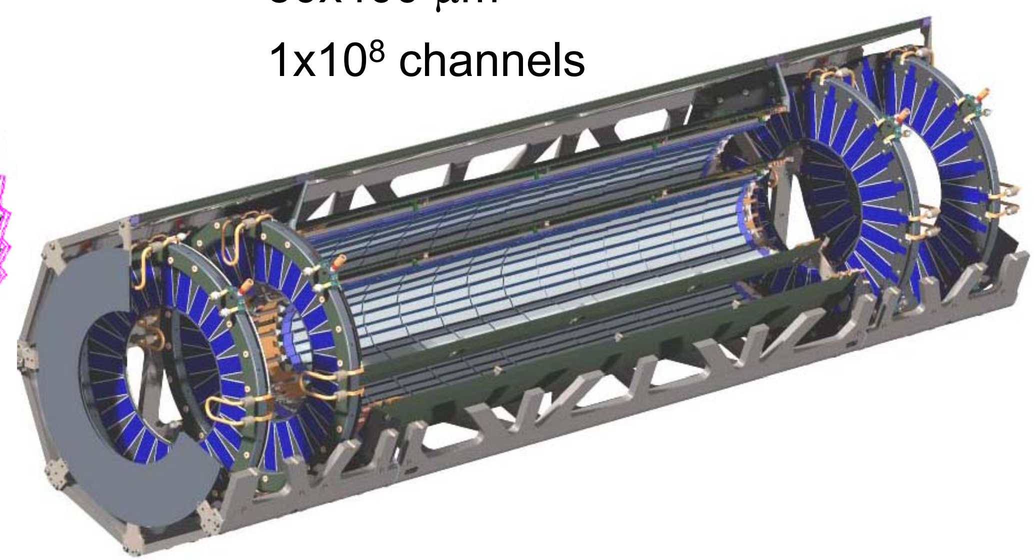
1×10^8 channels

CMS Pixels:

100x150 μm

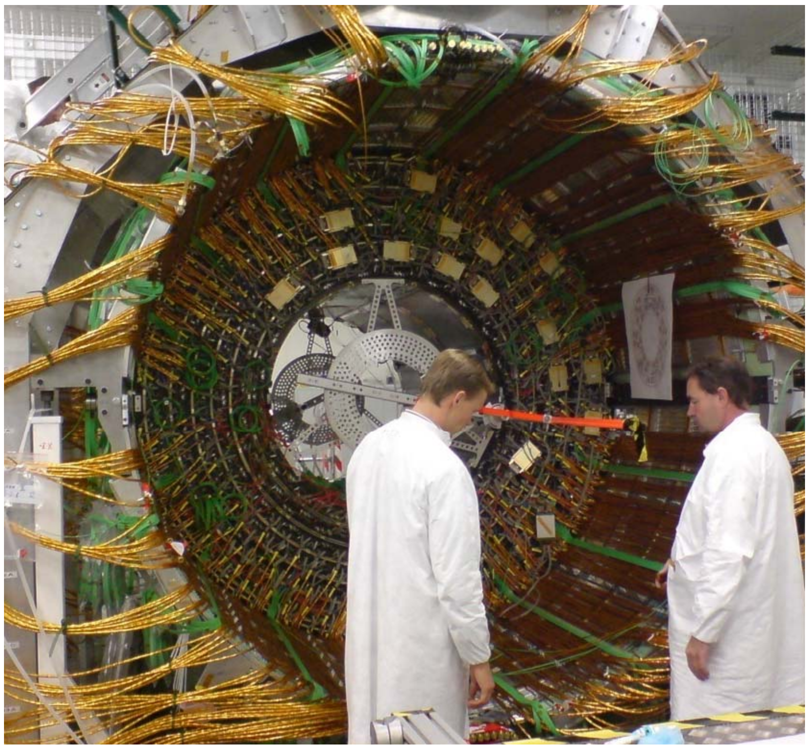
7×10^7 channels

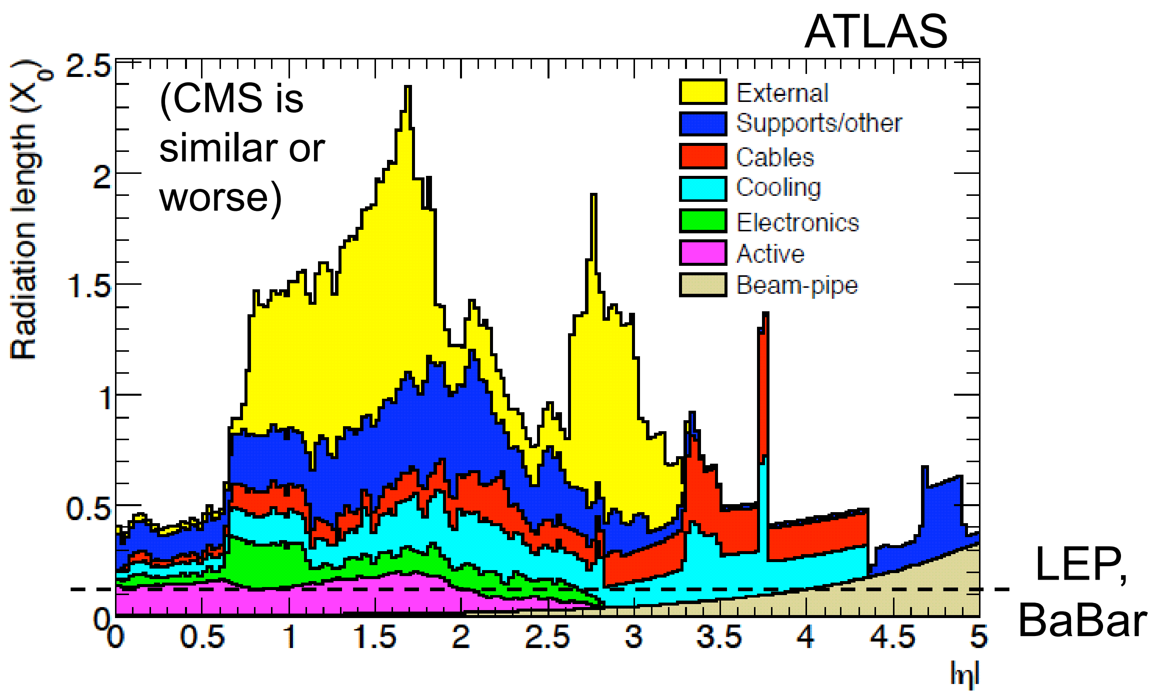




SSTDs: Issues

- Support infrastructure
  - even with miniature electronics, lots of power dissipated
    - cooling necessary in active volume
  - detectors tend to be “thick” – lots of material from supports, sensors





- $$$/μm^3
  - even with miniaturization, channels cost money

SSTDs: “services”