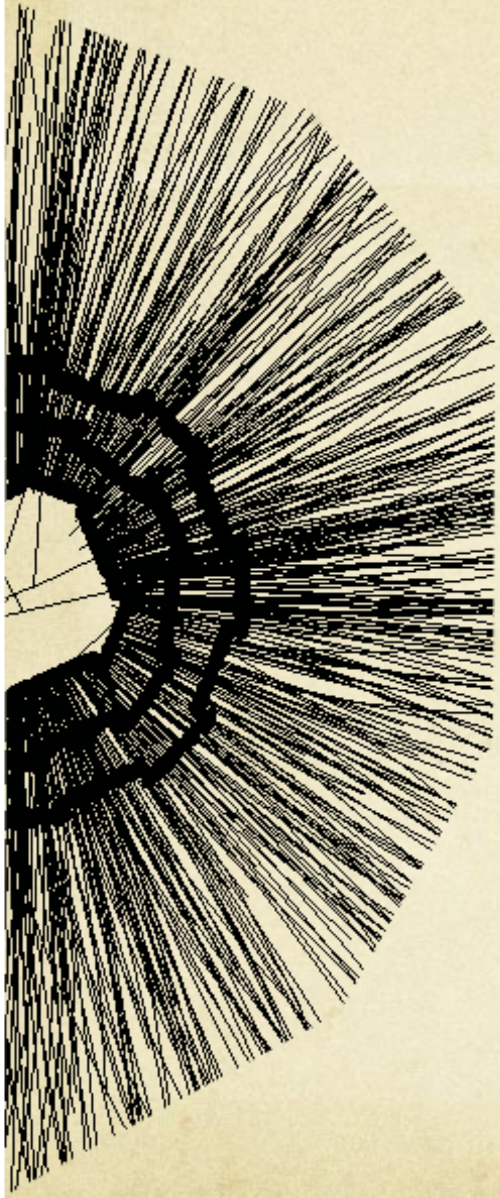
European School of Instrumentation
in Particle & Astroparticle Physics

2-3 February 2014, Archamps

Tracking



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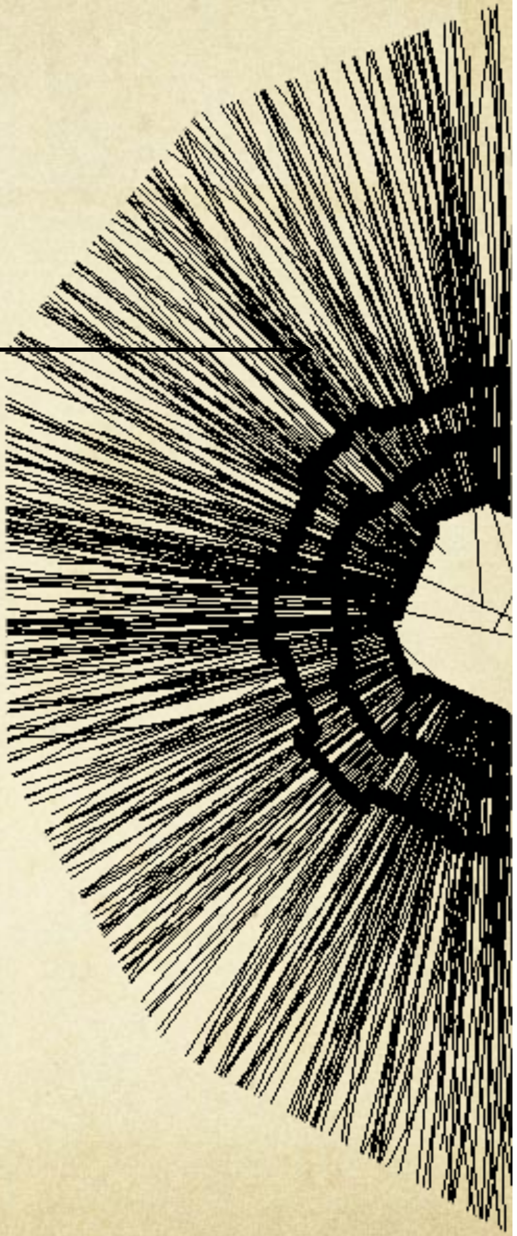
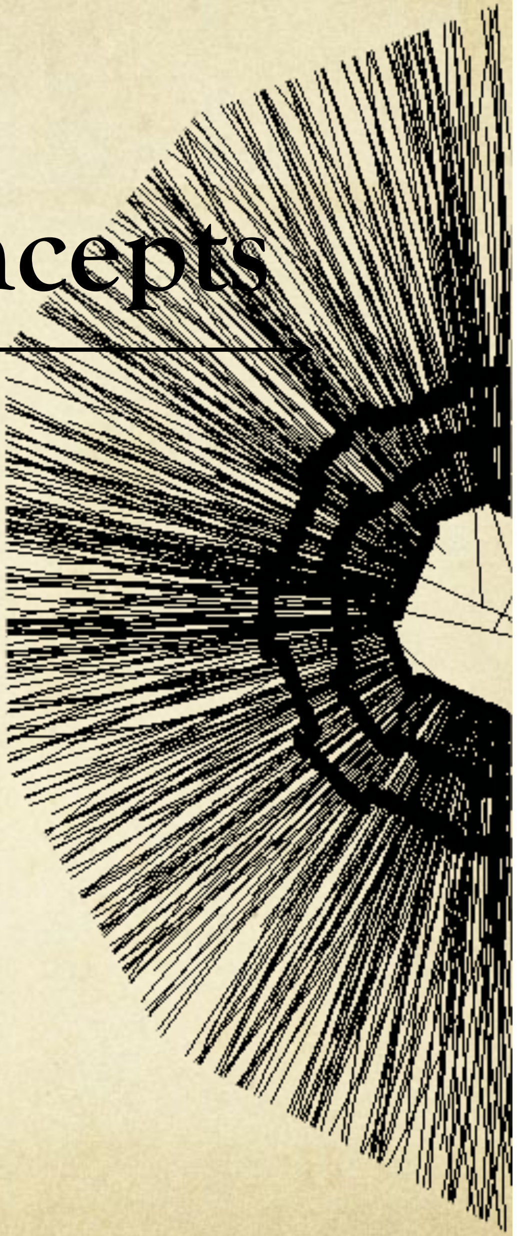
Lecture outline



1. Basic concepts
2. Position sensitive detectors
3. Standard algorithms
4. Advanced algorithms
5. Optimizing a tracking system
6. References

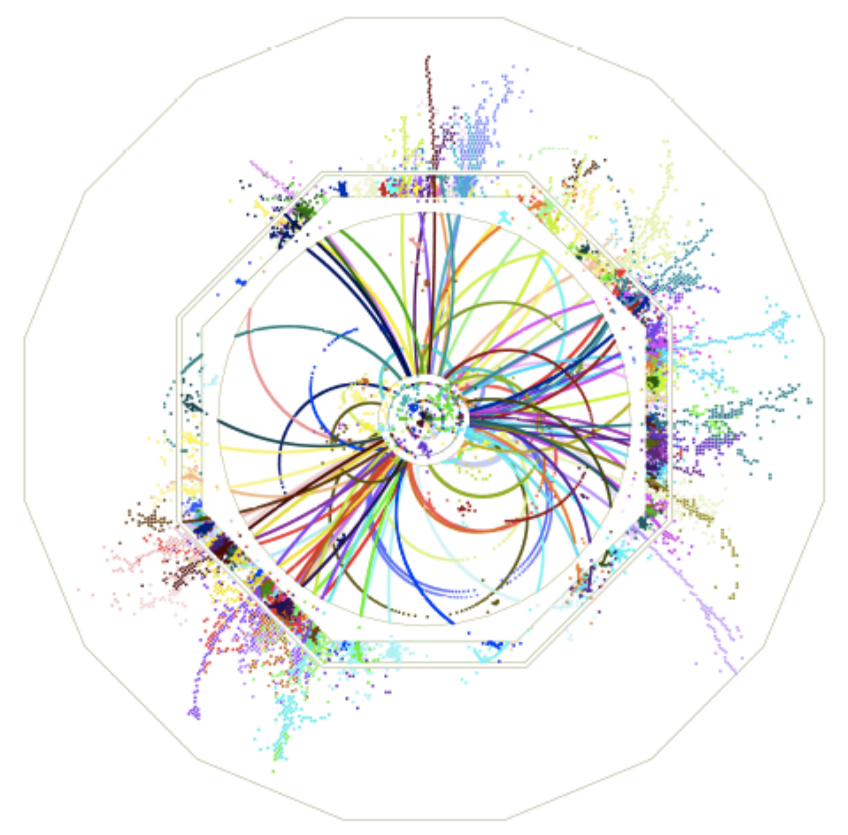
1. Motivations & basic concepts

- Motivations
- The 2 main tasks
- Environmental considerations



Motivations

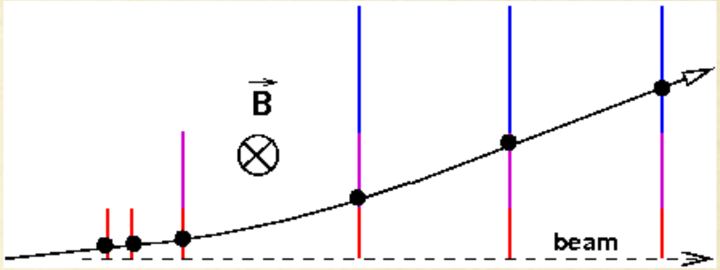
- Understanding an event
  - Individualize tracks ≃ particles
  - Measure their properties
  - LHC: ~1000 particles per 25 ns "event"
- Track properties
  - Momentum
    - Reconstruct invariant masses
  - Energy
  - Mass ⇔ identification
  - Origin ⇔ vertexing (track merging)
    - Identify decays
    - Measure flight distance

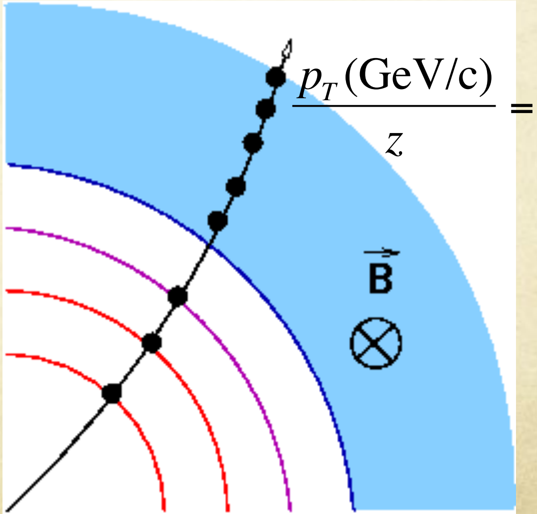


8 jets event (tt-bar h) @ 1 TeV ILC

Momentum measurement

- Magnetic field curves trajectories $\frac{\mathrm{d}\vec{p}}{\mathrm{d}t} = q\vec{v} \times \vec{B}$
  - Rewritten with position (x) and path length (l) = basic equation $\frac{\mathrm{d}^2\vec{r}}{\mathrm{d}^2 l} \propto \frac{q\vec{B}(\vec{x})}{\|\vec{p}\|}\frac{\mathrm{d}\vec{r}}{\mathrm{d}l}$
  - In B=4T a 1 GeV/c particle will get a sagitta of 1.5 mm
- Fixed-target experiments
  - Dipole magnet
  - Measurement of deflection (angle variation)
- Collider experiment
  - Barrel-type with axial B
  - Measurement of curvature (sagitta)
- Other arrangements
  - Toroidal B… not covered
- Two consequences
  - Position sensitive detectors needed
  - Any perturbation effects on trajectories is a pain





$$\frac{p_T(\mathrm{GeV/c})}{z} = 0.3 \cdot B(\mathrm{T}) \cdot R(\mathrm{m})$$

Multiple scattering - 1/2

- Reminder on the physics (see other courses)
  - Coulomb scattering mostly on nuclei
  - Molière theory description as a **centered** gaussian process
    - the thinner the material, the less true ➛ large tails

- In-plane description (defined by vectors $\mathbf{p}_{in}$, $\mathbf{p}_{out}$)
  - Corresponds to (ϕ, θ) with $\mathbf{p}_{in} = \mathbf{p}_z$ and $p_{out}^2 = p_{out,z}^2 + p_{out,T}^2$ $\begin{cases} p_{out,z} \cos\theta \approx p_{out,z} \\ p_{out,T} \sin\theta \approx p_{out,T}\theta \end{cases}$

$$\sigma_\theta = \frac{13.6\ (\mathrm{MeV/c})}{\beta p} \cdot z \cdot \sqrt{\frac{\mathrm{thickness}}{X_0}} \cdot \left[1 + 0.038\ \ln\left(\frac{\mathrm{thickness}}{X_0}\right)\right]$$

- In-space description (defined by fixed x/y axes)
  - Corresponds to (θ_x, θ_y) with $p_{out,T}^2 = p_{out,x}^2 + p_{out,y}^2$ $\begin{cases} p_{out,x} \sin\theta_x \approx p_{out,T}\theta_x \\ p_{out,y} \sin\theta_y \approx p_{out,T}\theta_y \end{cases}$ ➡ $\theta^2 = \theta_x^2 + \theta_y^2$
  - θx and θy are independent gaussian processes $\sigma_\theta^2 = \sigma_{\theta x}^2 + \sigma_{\theta y}^2$ and $\sigma_{\theta y} = \sigma_{\theta y} = \frac{\sigma_\theta}{\sqrt{2}}$

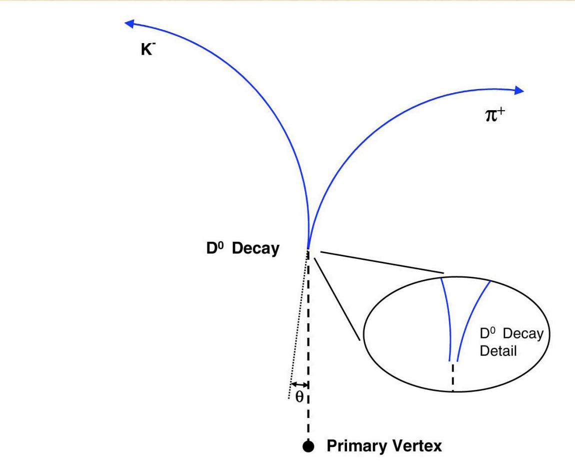
Multiple scattering - 2/2

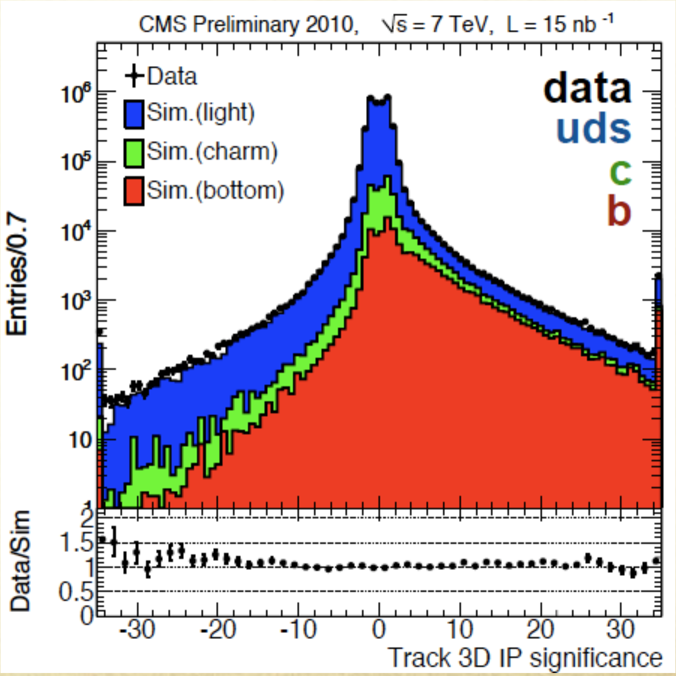
- **Important remark when combining materials**
  - Total thickness T = Σ T_i, each material (i) with $X_0(i)$
  - Definition of effective radiation length ➡ $X_{0,eff} = \frac{\sum T_i \times X_0(i)}{T}$
  - Consider single gaussian process $\sigma_{eff} \propto \sqrt{\frac{T}{X_{0,eff}}}$

and never do variance addition $\xcancel{\sigma_{eff} = \sqrt{\sum \frac{T_i}{X_0(i)}}}$

Vertexing

- Identifying through topology
  - Short-lived weakly decaying particles
    - Charm $c\tau$ ~ 120 µm
    - Beauty $c\tau$ ~ 470 µm
  - Exclusive reconstruction
    - Decay topology with secondary vertex
  - Inclusive reconstruction
    - Flavor tagging partly based on impact parameter
    - σ_{IP} ~ 20-100 µm requested
- Finding the origin
  - Where did the collision did occur?
    - Primary vertex (could be multiple)
  - (life)Time dependent measurements
    - CP-asymmetries @ B factories (Δz≈60-120 µm)
- Remarks:
  - Usually no measurement below 1-2 cm / vertex
  - Requires extrapolation





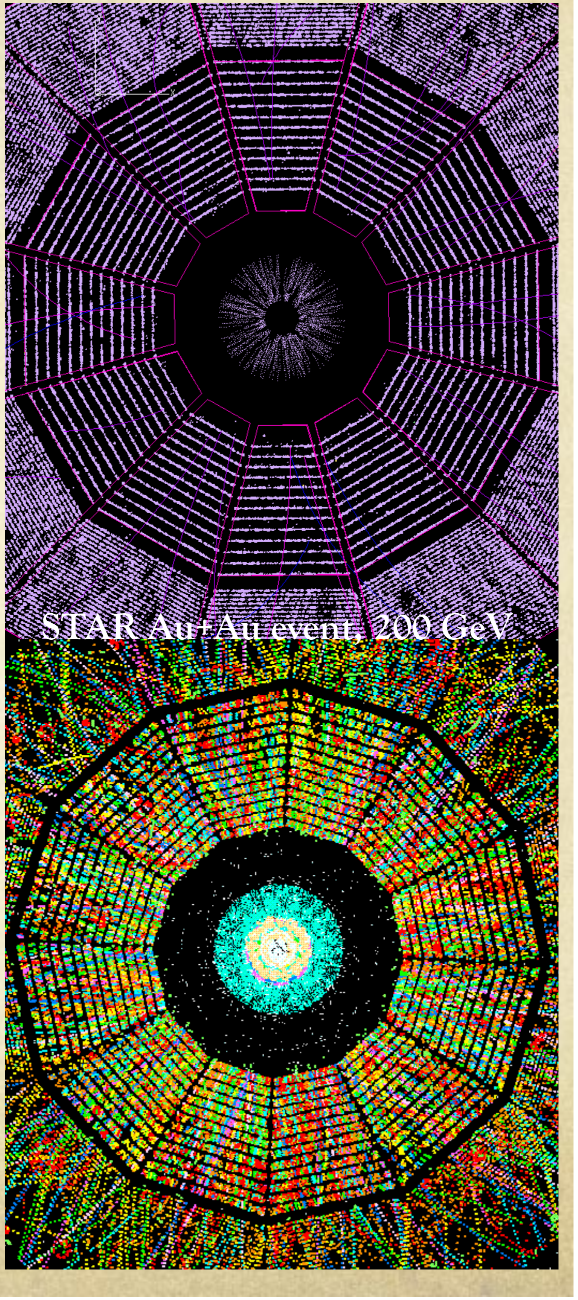
Energy measurement

- Usually not a tracker task
  - ➛ CALORIMETERs (see lecture by Isabelle)
  - ➛ Indeed calorimeters gather material to stop particles while trackers try to avoid material (multiple scattering)
  - ➛ however…calorimetry tries to improve granularity
- Particle flow algorithm
  - ➛ LHC / ILC
- Energy evaluation by counting particles
  - ➛ Clearly heretic from calorimetry experts
  - ➛ Required to separate Edeposit in dense environment
- Range measurement for low energy particles
  - ➛ Stack of tracking layers
  - ➛ Modern version of nucelar emulsion

NOT COVERED

The two man tasks

- Basic inputs from detectors
  - Succession of 2D or 3D points (or track segments)
  - Who's who ?
- 2 steps process
  - Step 1: track identification = **finding** = pattern recognition
    - Associating a set of points to a track
  - Step 2: track **fitting**
    - Estimating trajectory parameters ➛ momentum
- Both steps require
  - Track model (signal, background)
  - Knowledge of measurement uncertainties
  - Knowledge of materials traversed (Eloss, mult. Scattering)
- Vertexing needs same 2 steps
  - Identifying tracks belonging to same vertex
  - Estimating vertex properties (position + 4-vector)



STAR Au+Au event, 200 GeV

Environmental conditions – 1/2

- Life in a real experiment is tough (for detectors of course)
  - Chasing small cross-sections ➞ large luminosity and/or energy
  - Short interval between collisions
    - LHC: 25 ns
    - CLIC: 5 ns (but not continuous)
  - Large amount of particles ➡ background, radiation
    - makes the finding more complicated
  - Vacuum could be required (space, very low momentum particles (CBM, LHCb))

- Radiation tolerance
  - Two types of energy loss
    - Ionizing (generate charges): dose in Gy = 100 Rad
    - Non-ionizing (generate defects in solid): fluence in $n_{eq}(1MeV)/cm^2$
  - The more inner the detection layer, the harder the radiation ($radius^2$ effect)
  - Examples for most inner layers:
    - LHC: 10^{15} to $<10^{17}$ $n_{eq}(1MeV)/cm^2$ with 50 to 1 MGy
    - ILC: $<10^{12}$ $n_{eq}(1MeV)/cm^2$ with 5 kGy

Environmental conditions – 2/2

Timing consideration

- ➛ Readout speed limits dead time
- ➛ Time resolution offers time-stamping of tracks
  - Tracks in one “acquisition event” could be associated to their proper collisions event if several have piled-up

Heat concerns

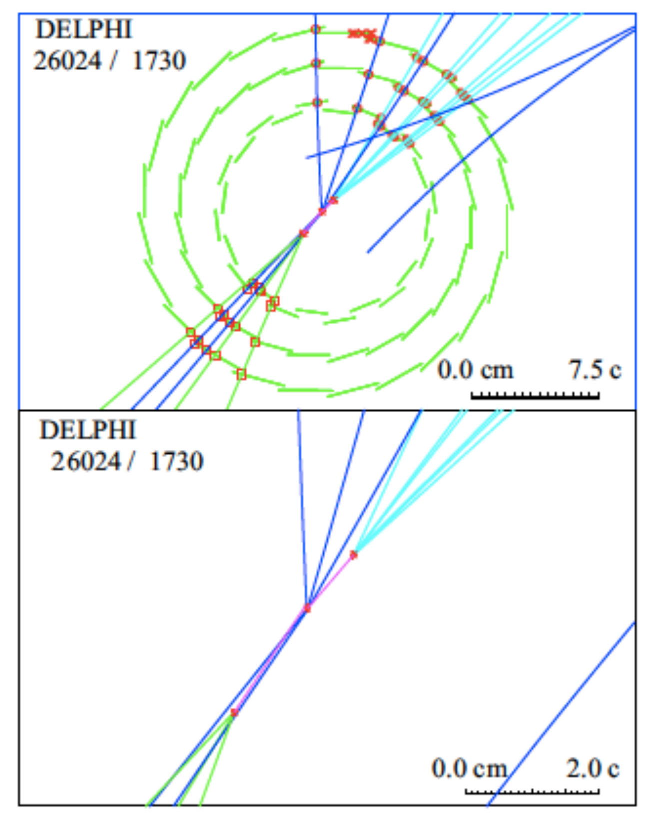
- ➛ Spatial resolution ➞ segmentation
  Readout speed ➞ power dissipation/channel } Hot cocktail!
- ➛ Efficient cooling techniques exist BUT add material budget and may not work everywhere (space)

Conclusion

- ➞ Tracker technology driven by environmental conditions: hadron colliders (LHC)
- ➞ Tracker technology driven by physics performances: lepton colliders (B factories, ILC)
- ➞ Of course, some intermediate cases: superB factories, CLIC

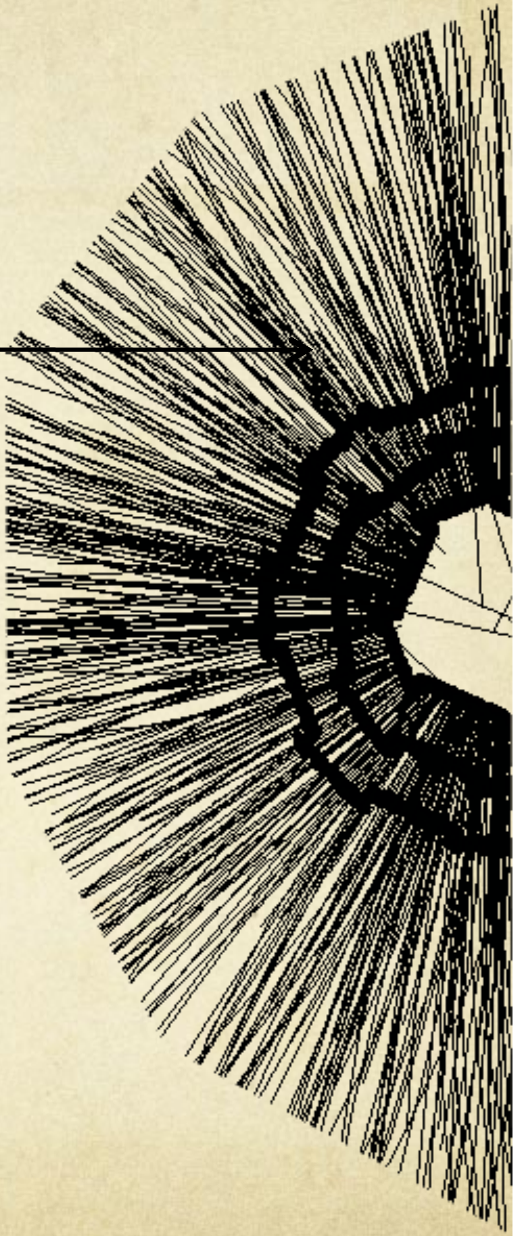
Figures of Merit

- For detection layer
  - Detection efficiency
    - Mostly driven by Signal/Noise
    - Note: Noise = signal fluctuation ⊕ readout (electronic) noise
  - Intrinsic spatial resolution
    - Driven by segmentation (not only)
    - Useful tracking domain $\sigma < 1$mm
  - Material budget
  - "Speed" (integration time, count rate, ...)



- Two-track resolution
  - Ability to distinguish to nearby trajectories
  - Mostly governed by signal spread
- Momentum resolution $\frac{\sigma(p)}{p}$
- Impact parameter resolution
  - Sometimes called "distance of closest approach" to a vertex

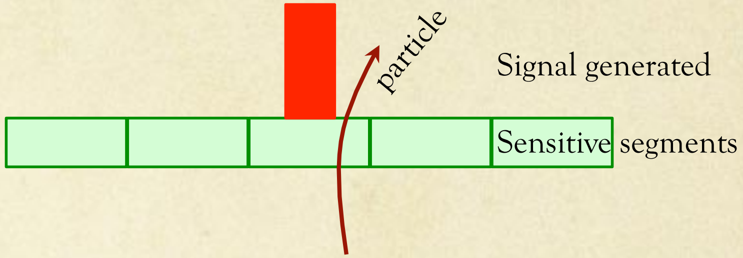
2. Detection technologies



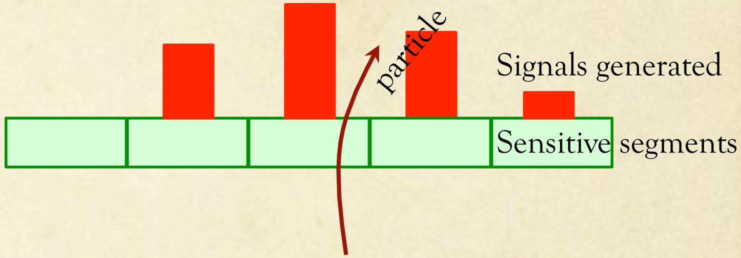
- Intrinsic resolution
- Single layer systems
  - Silicon, gas sensors
- Multi-layer systems
  - Drift chamber and TPC
- Tentative comparison
- Magnets
- Leftovers

Intrinsic resolution

- Position measurement comes from segmentation
  - Pitch
- Digital resolution $\sigma = \frac{\text{pitch}}{\sqrt{12}}$



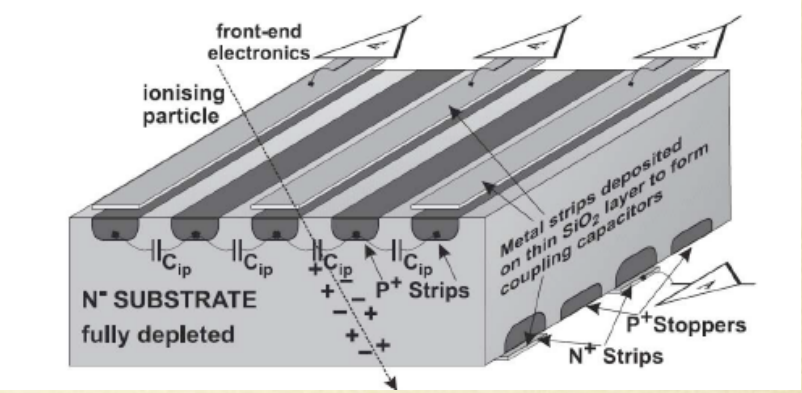
- Improvement from signal sharing
  - Position = charge center of gravity
  - Effects generated by $\sigma \propto \frac{\text{pitch}}{\text{signal/noise}}$
    - Secondary charges spread inside volume
    - Inclined tracks (however, resol. limited at large angles)
  - Potential optimization segmentation / sharing
  - Warnings:
    - Lorentz force from B mimick the effect
    - counterproductive / 2-track resolution



Silicon sensors: strips

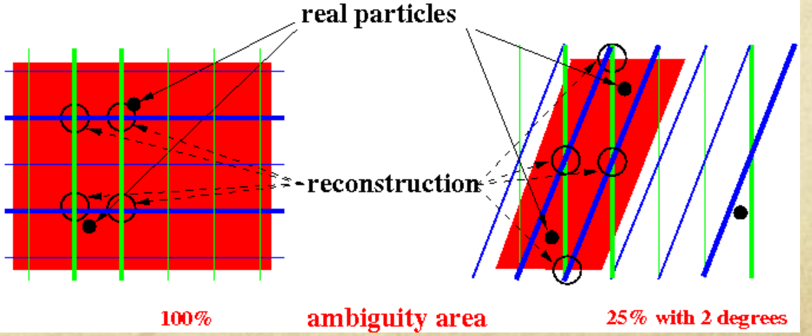
Basic sensitive element

- E-h pairs are generated by ionization in silicon
  - 3.6 eV needed
  - 300 µm thick Si generates ~22000 charges for MIP BUT beware of Landau fluctuation
- Collection: P-N junction = diode
  - Depletion (10 to 0.5 kV) generates a drift field (10^4 V/cm)
  - Collect time ~ 15 ps/µm



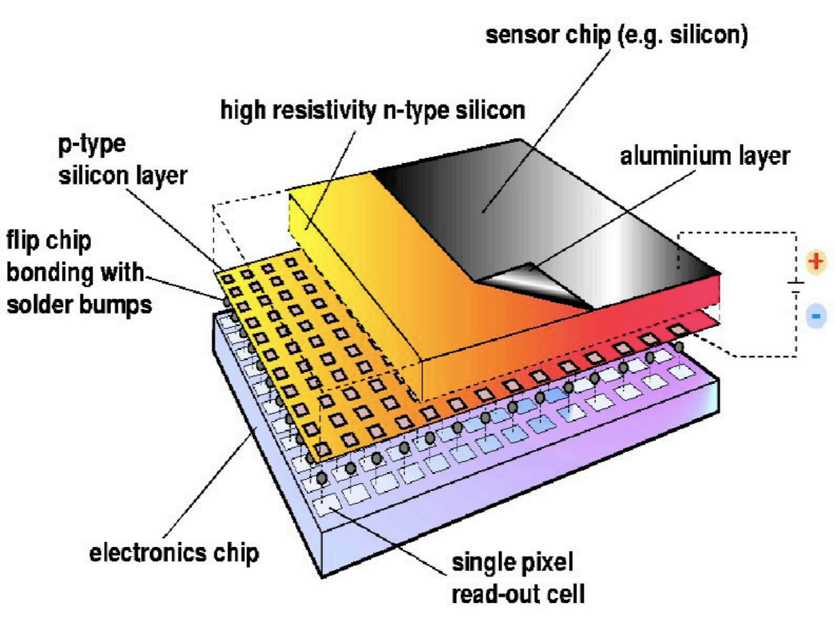
Silicon strip detectors

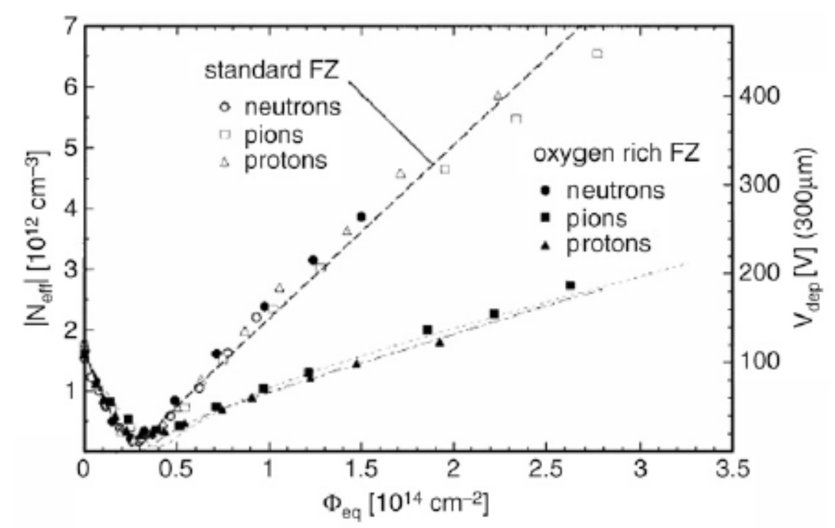
- sensor"easily" manufactured with pitch down to ~25 µm
- 1D if single sided
- Pseudo-2D if double-sided
  - Stereo-angle useful against ambiguities
- Difficult to go below 100 µm thickness



Silicon sensors: hybrid-pixels

- Concept
  - Strips → pixels on sensor
  - One to one connection from electronic channels to pixels
- Performances
  - Real 2D detector & keep performances of strips
    - Can cope with LHC rate (speed & radiation)
  - Pitch size limited by physical connection and #transistors for treatment
    - minimal (today): 50x50 μm^2 typical: 100x150/400 μm^2
    - spatial resolution about10 μm
  - Material budget
    - Minimal(today): 100(sensor)+100(elec.) μm
  - Power budget: 10 μW/pixel

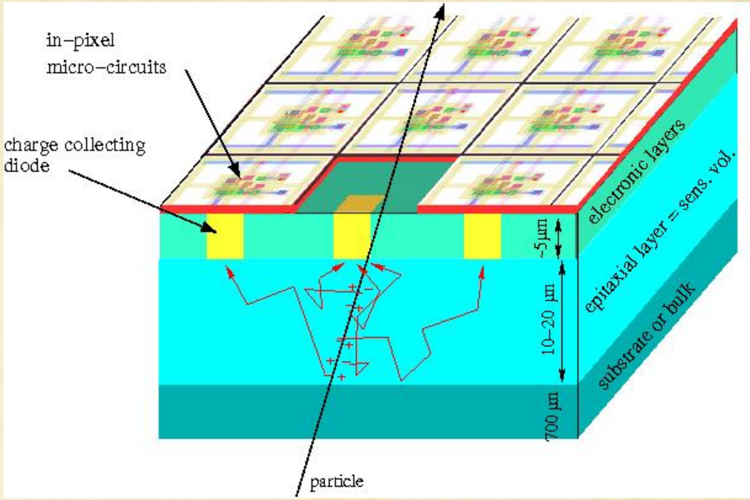




CMOS Pixel Sensor

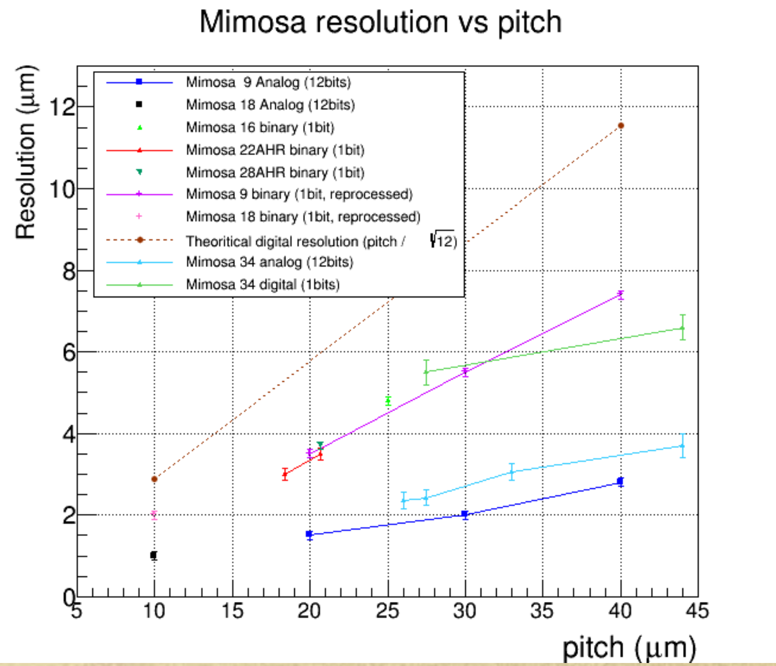
Concept

- Use industrial CMOS process
  - Implement an array of sensing diode
  - Amplify the signal with transistors near the diode
- Gain in granularity: pitch down to ~10 µm
- Gain in sensitive layer thickness ~ 10-20 µm
- BEWARE: depletion not systematically available
  - Slow (100 ns) thermal drift



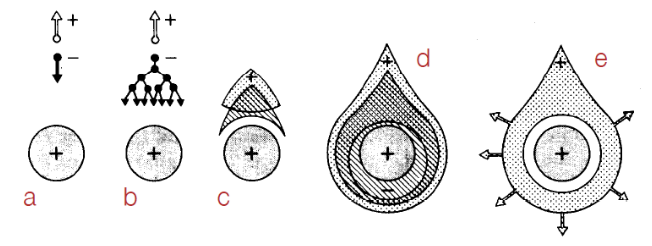
Performances

- Spatial resolution 1-10 µm (in 2 dimensions)
- Material budget: ≲ 30 µm
- Power budget: 1-5 µW/pixel
- Integration time ~ 50-100 µs demonstrated
  - 1 µs in development

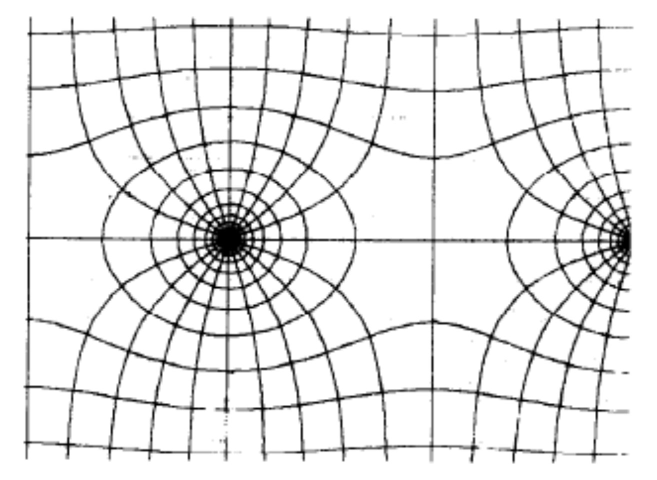


Wire chambers

- ## Basic sensitive element
  - Metallic wire, 1/r effect generated an avalanche
  - Signal depends on gain (proportional mode) typically 10^4
  - Signal is fast, a few ns



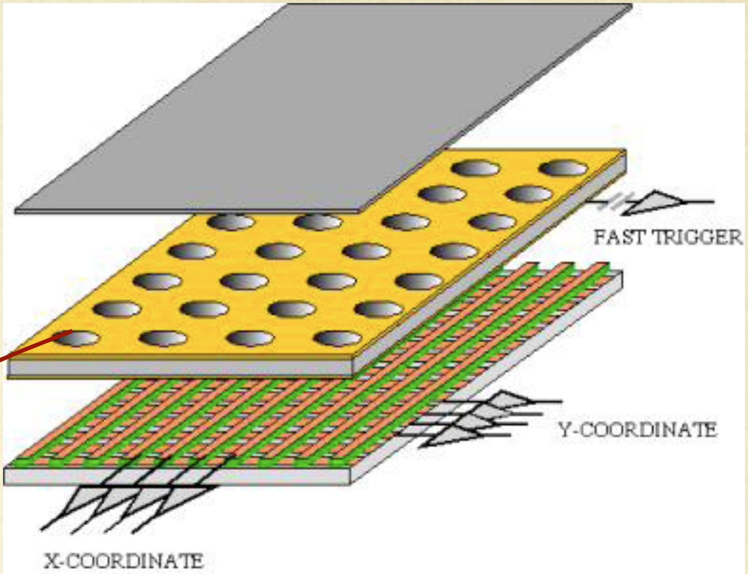
- ## Gas proportional counters
  - Multi-Wire Proportional Chamber
    - Array of wires
    - 1 or 2D positioning depending on readout
    - Wire spacing (pitch) limited to 1-2 mm
  - Straw or drift tube
    - One wire in One tube
    - Extremely fast (compared to Drift Chamber)
    - Handle high rate
    - Spatial resolution <200 μm
    - Left/right ambiguity

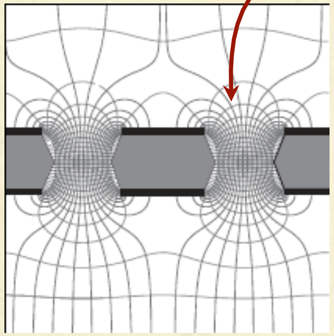


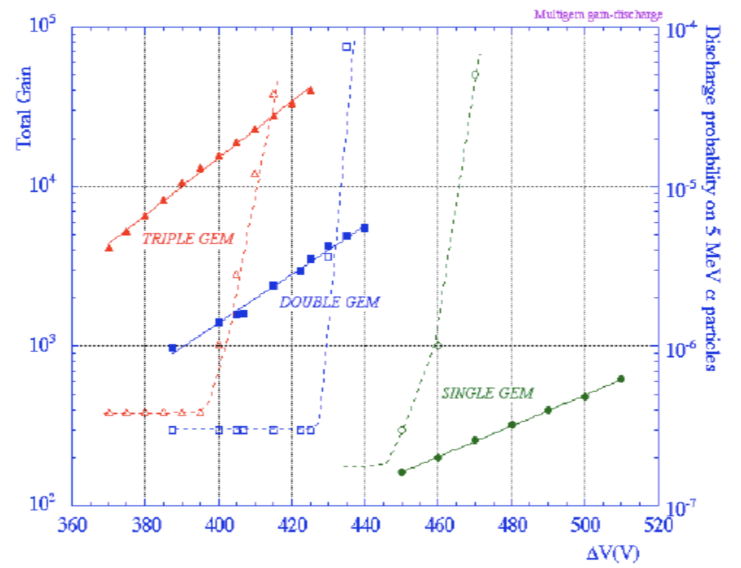
Electric fields line
around anode wires

Wire chambers “advanced”

- **Micro-pattern gas multipliers**
  - MSGC
    - Replace wires with lithography micro-structures
    - Smaller anodes pitch 100-200 µm
    - BUT Ageing difficulties due to high voltage and manufacturing not so easy
  - GEM
    - Gain 10^5
    - Hit rate 10^6 Hz/cm2
  - MICROMEGAS
    - Even smaller distance anode-grid
    - Hit rate 10^9 Hz/cm2
  - More development
    - Electron emitting foil working in vacuum!







Drift chambers

Basic principle

- Mix field and anode wires
  - Generate a drift
- Pressurize gas to increase charge velocity (few atm)
- 3D detector
  - 2D from wire position
  - 1D from charge sharing at both ends

Spatial Resolution

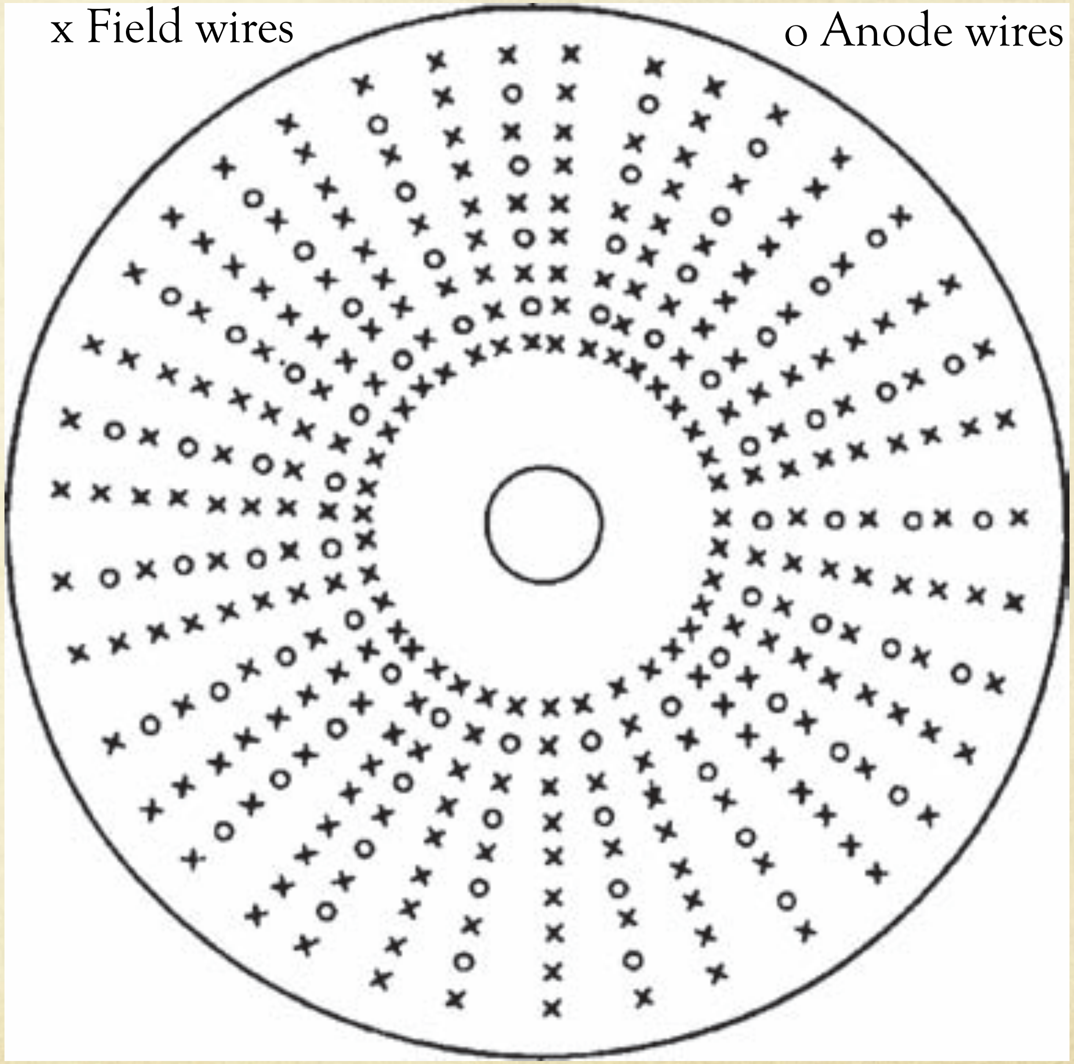
- Related to drift path

$$\sigma \propto \sqrt{\text{drift length}}$$

- Typically 100-200 µm

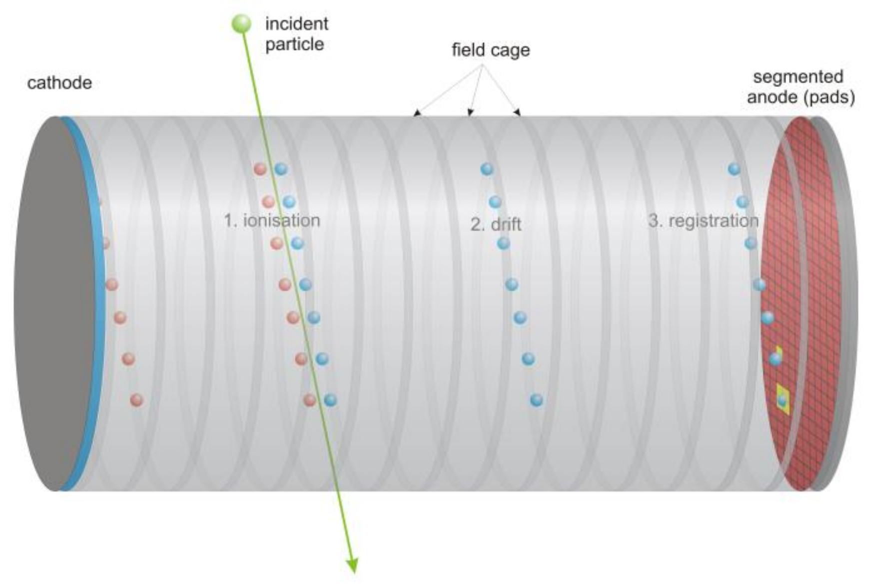
Remarks

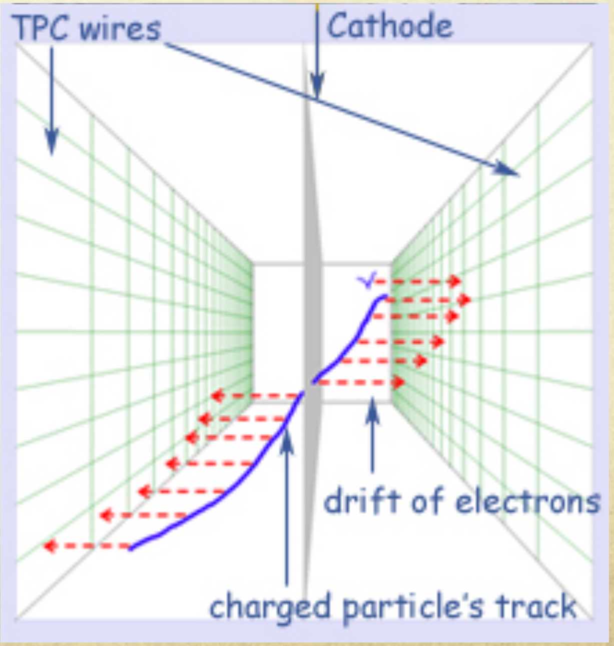
- Could not go to very small radius



Time Projection Chambers 1/2

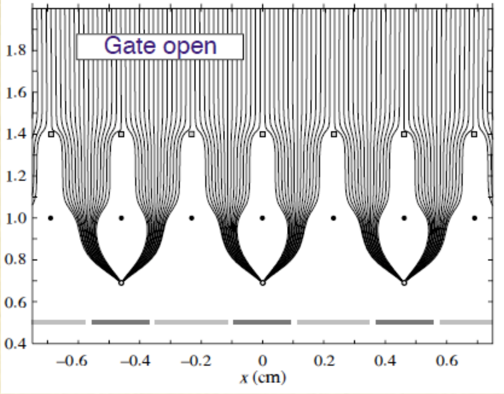
- Benefits
  - Large volume available
  - Multi-task: tracking + Part. Identification
- Basic operation principle
  - Gas ionization → charges
  - Electric field → charge drift along straight
  - End cap readout
    - wire proportional chamber - type
  - Information collected
    - 2D position of charges at end-cap
    - 3rd dimension from drift time
    - Energy deposited from #charges
  - Different shapes:
    - rectangles (ICARUS)
    - Cylinders (colliders)
    - Volumes can be small or very large

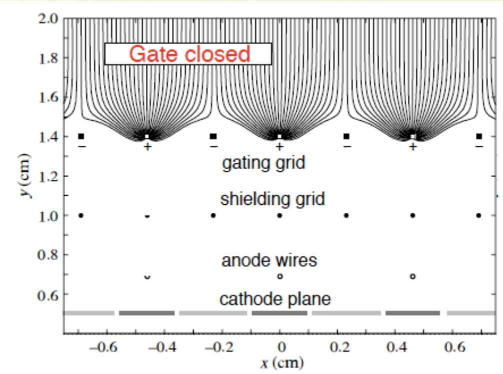




Time Projection Chambers 2/2

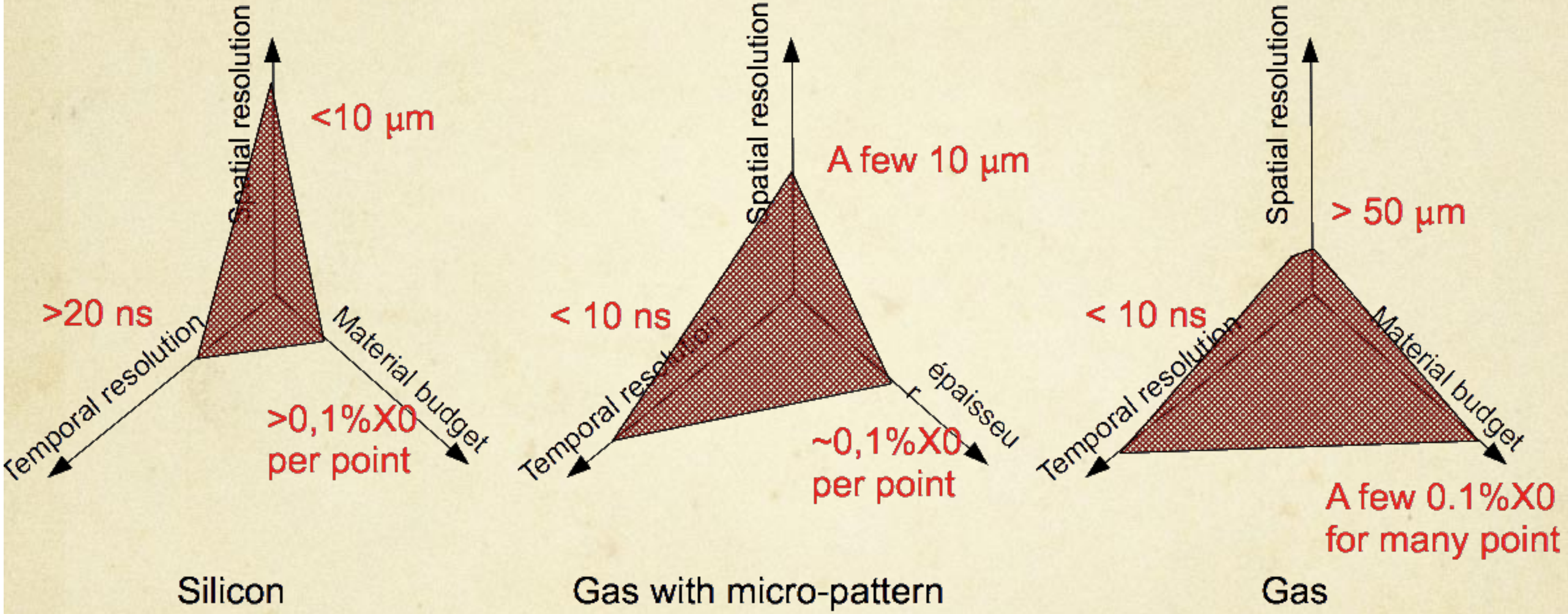
- End cap readout
- Performances
  - Two-track resolution ~ 1cm
  - Transverse spatial resolution ~ 100 - 200 µm
  - Longitudinal spatial resolution ~0.2 - 1 mm
  - Longitudinal drift velocity: 5 to 7 cm/µs
    - ALICE TPC (5m long): 92 µs drift time
    - Limiting usage with respect to collision rate





2. Detector Technologies:

Tentative comparison



2. Detector Technologies:

Magnets

Solenoid

- Field depends on current I, length L, # turns N
  - on the centerline $$B = \frac{\mu_0 N I}{\sqrt{L^2 + 4R^2}}$$
  - Typically: 1 T needs 4 to 8 kA ➛ superconducting metal to limit heat
- Field uniformity needs flux return (iron structure)
  - Mapping is required for fitting (remember B(**x**)?)
  - Usually performed with numerical integration
- Calorimetry outside ➛ limited material ➛ superconducting
- Fringe field calls for compensation

	Field (T)	Radius (m)	Length (m)	Energy (MJ)
ALICE	0.5	6		150
ATLAS	2	2.5	5.3	700
CMS	4	5.9	12.5	2700
ILC	4	3.5	7.5	2000

Supercondiction

- cryo-operation ➛ quenching possible !
- Magnetic field induces energy: $E \propto B^2 R^2 L$
  - Cold mass necessary to dissipate heat in case of quench

Practical considerations

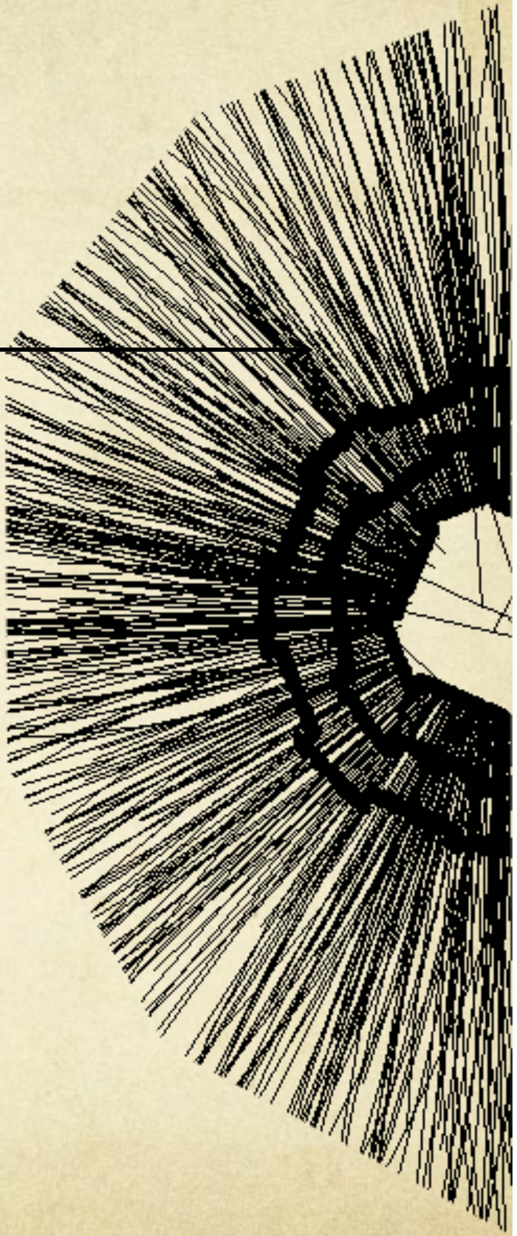
- **From a detection principle to a detector**
  - Build large size or many elements
    - Manufacture infrastructures
    - Characterization capabilities
    - Production monitoring
  - Integration in the experiment
    - Mechanical support
    - Electrical services (powering & data transmission)
    - Cooling (signal treatment dissipates power)
  - Specific to trackers
    - Internal parts of multi-detectors experiment → limited space
    - Material budget is ALWAYS a concern
    - ⇨ trade-offs required

Leftovers

- Silicon drift detectors
  - Real 2D detectors made of strips
  - 1D is given by drift time
- Diamond detectors
  - Could replace silicon for hybrid pixel detectors
  - Very interesting for radiation tolerance
- Plasma sensor panels
  - Derived from flat television screen
  - Still in development
- Charge Coupled Devices (CCD)
  - Fragile/ radiation tolerance
- Signal generation
  ➛ see Ramo's theorem
- DEPFET
  - Depleted Field Effect Transistor detector
  - Real 2D and partly monolithic
- Nuclear emulsions
  - One of the most precise ~ 1μm
  - No timing information → very specific applications
- Scintillators
  - Extremely fast (100 ps)
  - Could be arranged like straw tubes
  - But quite thick (X_0 ~ 2 cm)

3. Standard algorithms

- Finders
- First evaluation of momentum resolution
- Fitters
- Alignment



3. Reconstruction algorithm:

FINDING : 2 strategies

Global methods

- Transform the coordinate space into pattern space
  - "pattern" = parameters used in track model
- Identify the "best" solutions in the new phase space
- Use all points at a time
  - No history effect
- Well adapted to evenly distributed points with same accuracy

Local methods

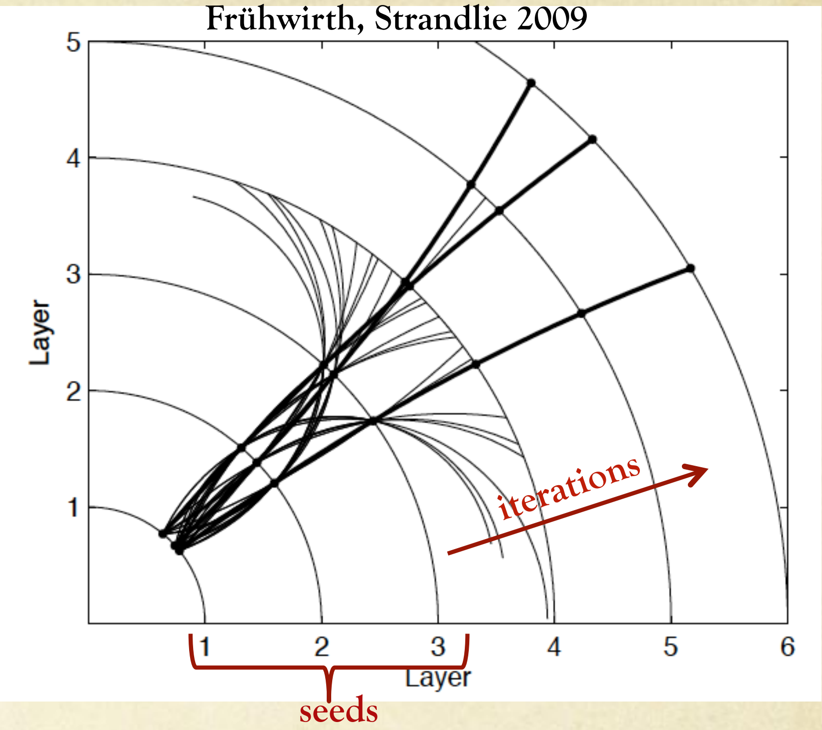
- Start with a track seed = restricted set of points
- Then extrapolate to next layer-point
  - And so on…iterative procedure
- "Wrong" solutions discarded at each iteration
- Possibly sensitive to "starting point"
- Well adapted to redundant information

FINDING drives tracking efficiency

3. Reconstruction algorithm:

Local method

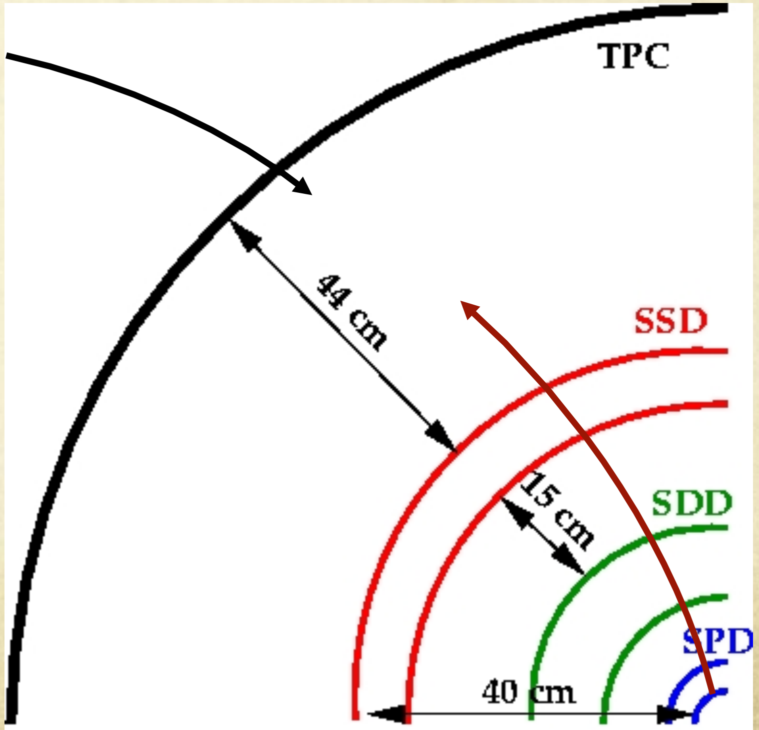
- **Track seed = initial segment**
  - Made of few (2 to 4) points
    - One point could be the expected primary vtx
  - Allows to initialize parameter for track model
  - Farther from primary interaction
    - At lowest density
    - Limit mixing points from different tracks
    - Variant: choose inner layers first to benefit from precision


Frühwirth, Strandlie 2009

- **Extrapolation step**
  - Usually inward (toward primary vtx) onto the next layer
  - Not necessarily very precise, especially **only local model** needed
    - Extrapolation uncertainty ≲ layer point uncertainty
    - Computation speed important
  - Match (associate) nearest point on the new layer
    - Might skip the layer if point missing
    - Might reject a point on 2 basis

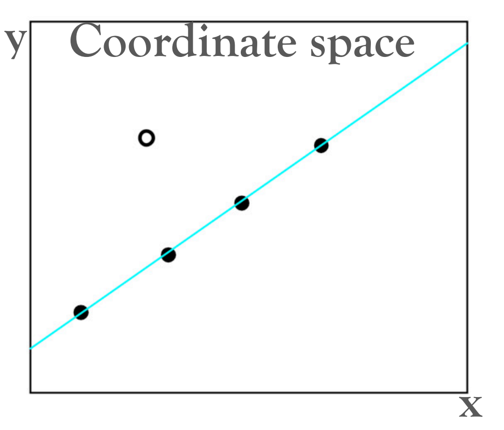
Local method

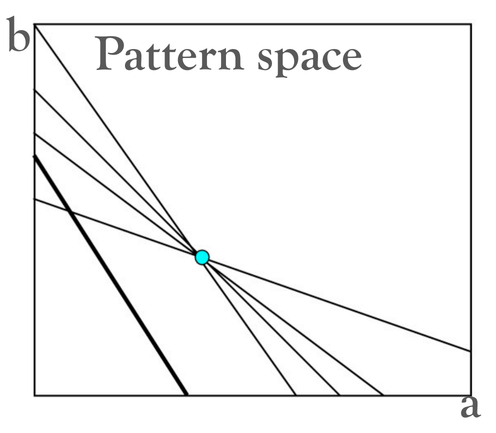
- Variant with track segments
  - First build "tracklets" on natural segments
    - Sub-detectors, or subparts with same resolution
  - Then match segments together
  - Typical application:
    - Segments large tracker (TPC) with vertex detector (Si) ➛ layers dedicated to matching
- Variant with track roads
  - Full track model used from start
- Variant with Kalman filter
  - See later



Global methods

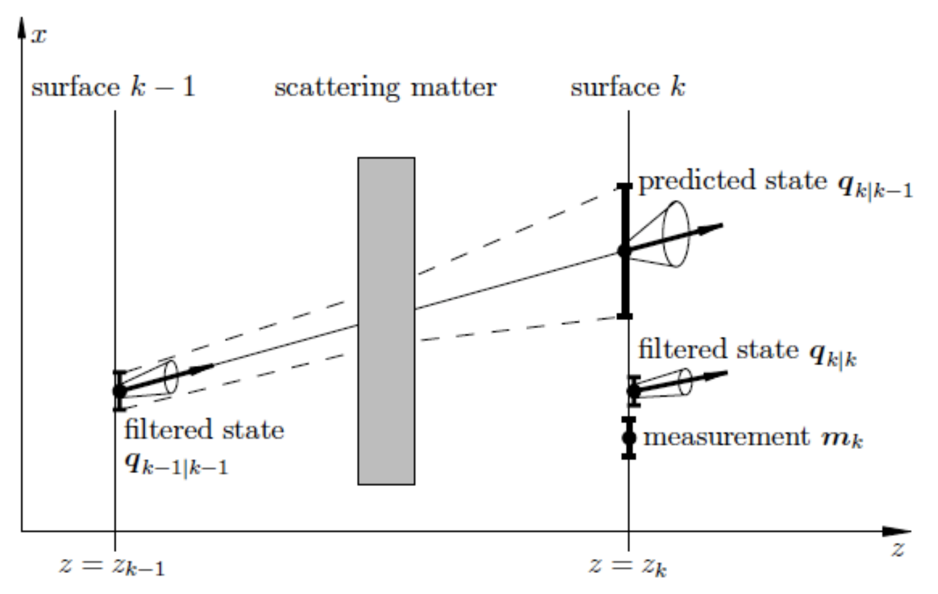
- Brute force = combinatorial way
  - Consider all possible combination of points to make a track
  - Keep only those compatible with model
  - Usually too time consuming…
- Hough transform
  - Example straight track:
    - Coord. space y = a*x + b ⇔ pattern space b = y - x*a
    - Each point (y,x) defines a line in pattern space
    - All lines, from points belonging to same straight-track, cross at same point (a,b)
    - In practice:
      discretize pattern space and search for maximum
  - Applicable to circle finder
    - needs two parameters as well (r, ϕ of center)
      if track is assumed to originate from (0,0)
  - More difficult for more than 2 parameters…





3. Reconstruction algorithm:

FITTING

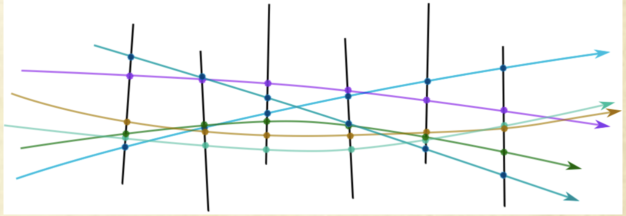


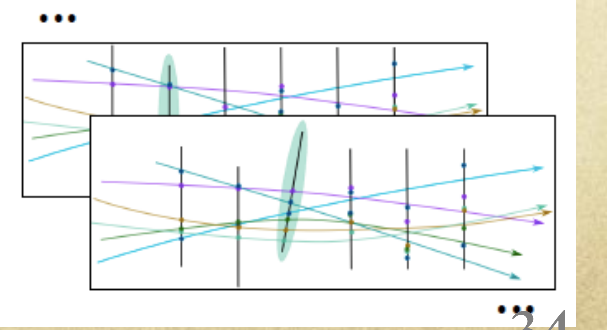
- Why do we need to fit?
  - Measurement error
  - Multiple scattering error
- Recursive method (linear χ^2 and Kalman filter)
  - Start from an initial set of parameters:
  - Propagate to next layer:
    - New parameters
    - AND new covariance matrix
  - Update the covariance matrix with additional uncertainties from
    - Material budget between layers
  - Use new point to update (FIT) parameters and covariance
  - Iterate…
- Notes
  - The method is only matrix computation
  - Can be used for finding as well after propagation step (local finder)
  - Some points can be discarded if considered as outliers in the fit (use χ^2 value)

FITTING drives track extrapolation & momentum res.

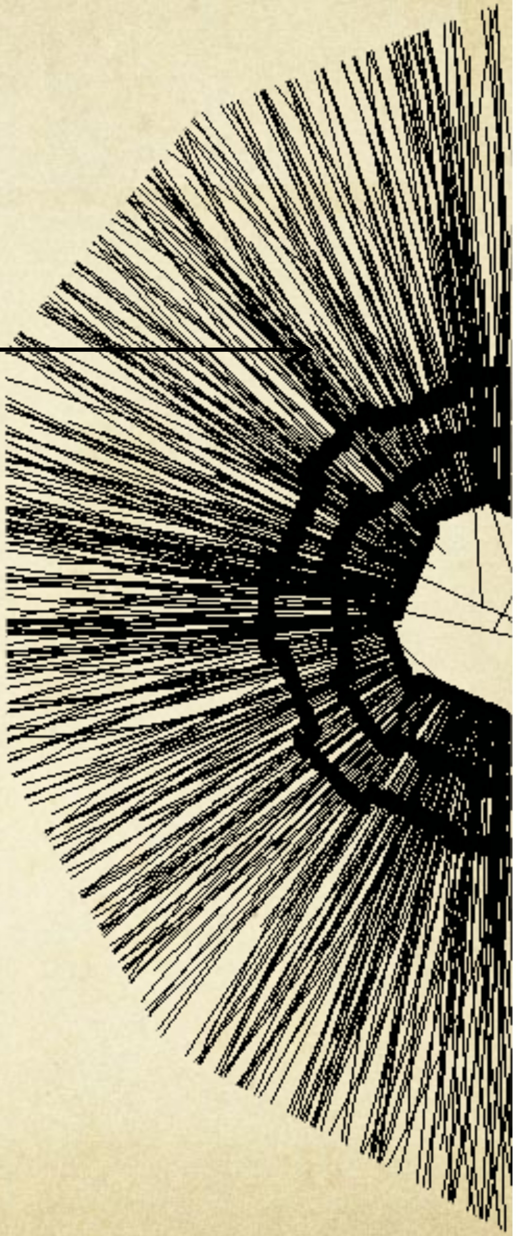
Alignment strategy

- Let’s come back to one hypothesis
  - We know were the point are located
  - True to the extent we know were the detector is!
  - BUT, mechanical instability (magnetic field, temperature, air flow…) and also drift speed variation (temperature, pressure, field inhomogeneity…) limit our knowledge
  - Periodic determination of positions and deformations needed = alignment
- Methods
  - Track model depends on new “free” parameters, i.e. the alignment
  - Global alignment:
    - Fit the new params. to minimize the overall χ^2 of a set of tracks (Millepede algo.)
    - Beware: many parameters could be involved (few 10^3 can easily be reached)
  - Iterative alignment:
    - Use tracks reconstructed with reference detectors and align other detectors by minimizing the “residual” (track-hit distance) width
  - Use a set of well know tracks and tracking-”friendly” environment to avoid bias





4. Advanced methods

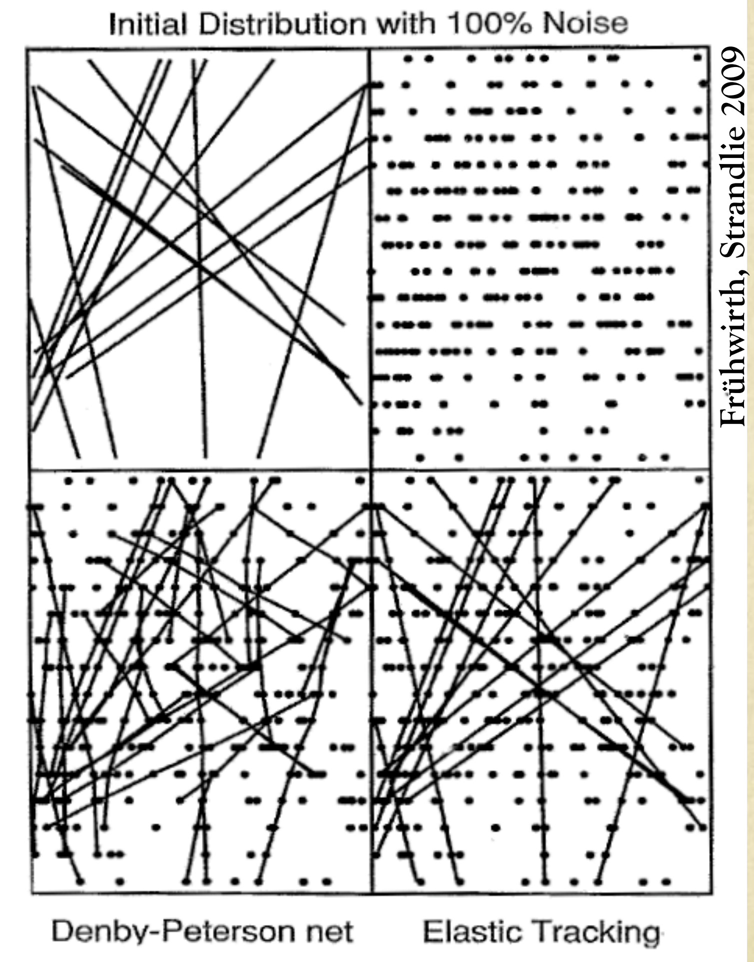


- Neural network
- Cellular automaton

3. Reconstruction algorithm:

Adaptive methods

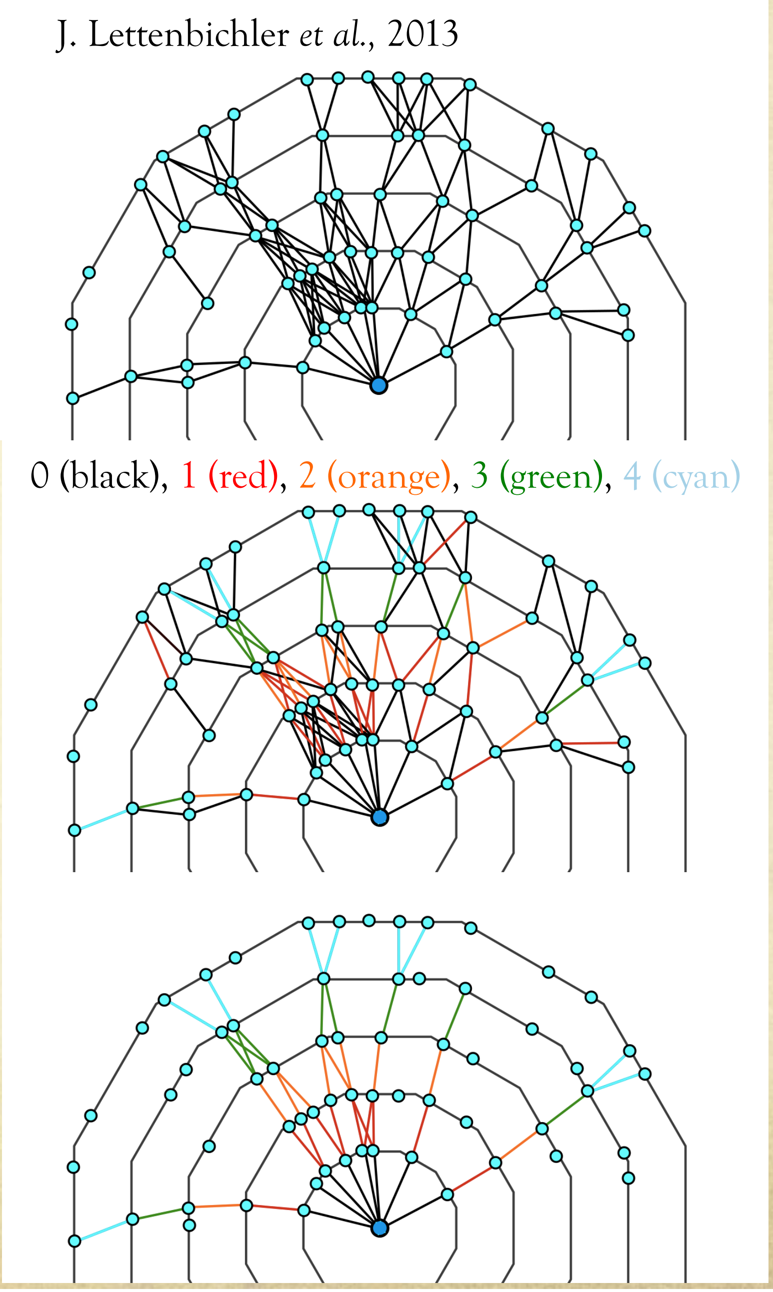
- Shall we do better?
  - Higher track/vertex density, less efficient the classical method
  - Allows for many options and best choice
- Adaptive features
  - Dynamic change of track parameters during finding/fitting
  - Measurements are weighted according to their uncertainty
    - Allows to take into account several "normally excluding" info
  - Many hypothesis are handled simultaneously
    - But their number decrease with iterations (annealing like behavior)
  - Non-linearity
  - Often CPU-time costly (is that still a problem?)
- Examples
  - Neural network, Elastic nets, Gaussian-sum filters, Deterministic annealing



Frühwirth, Strandlie 2009

Cellular automaton

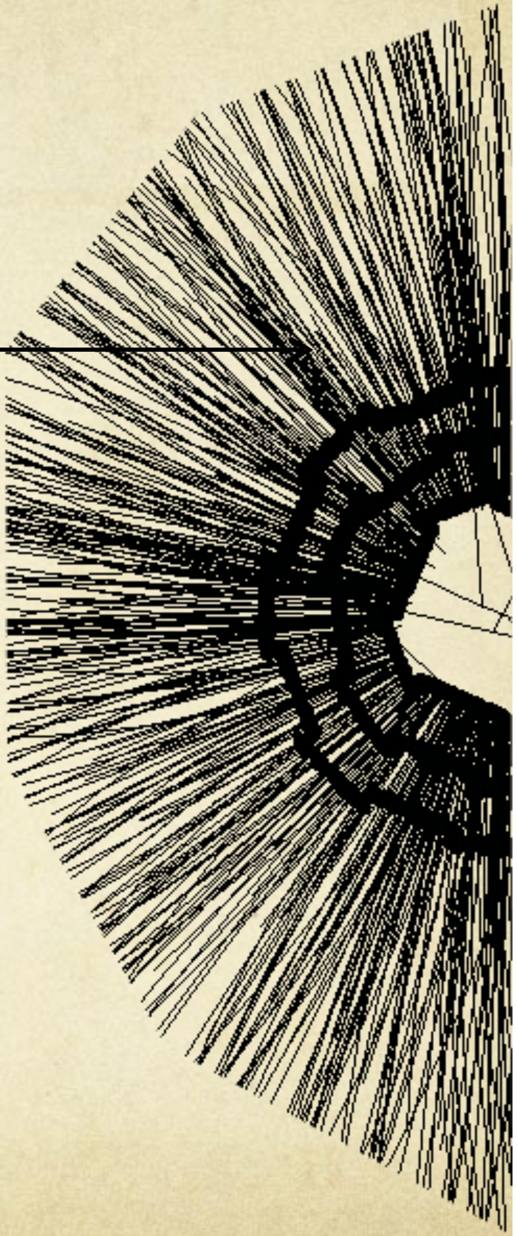
- Initialization
  - built any cell (= segment of 2 points)
- Iterative step
  - associate neighbour cells (more inner)
  - Raise “state” with associated celles
  - Kill lowest state cells


J. Lettenbichler *et al.*, 2013

0 (black), 1 (red), 2 (orange), 3 (green), 4 (cyan)

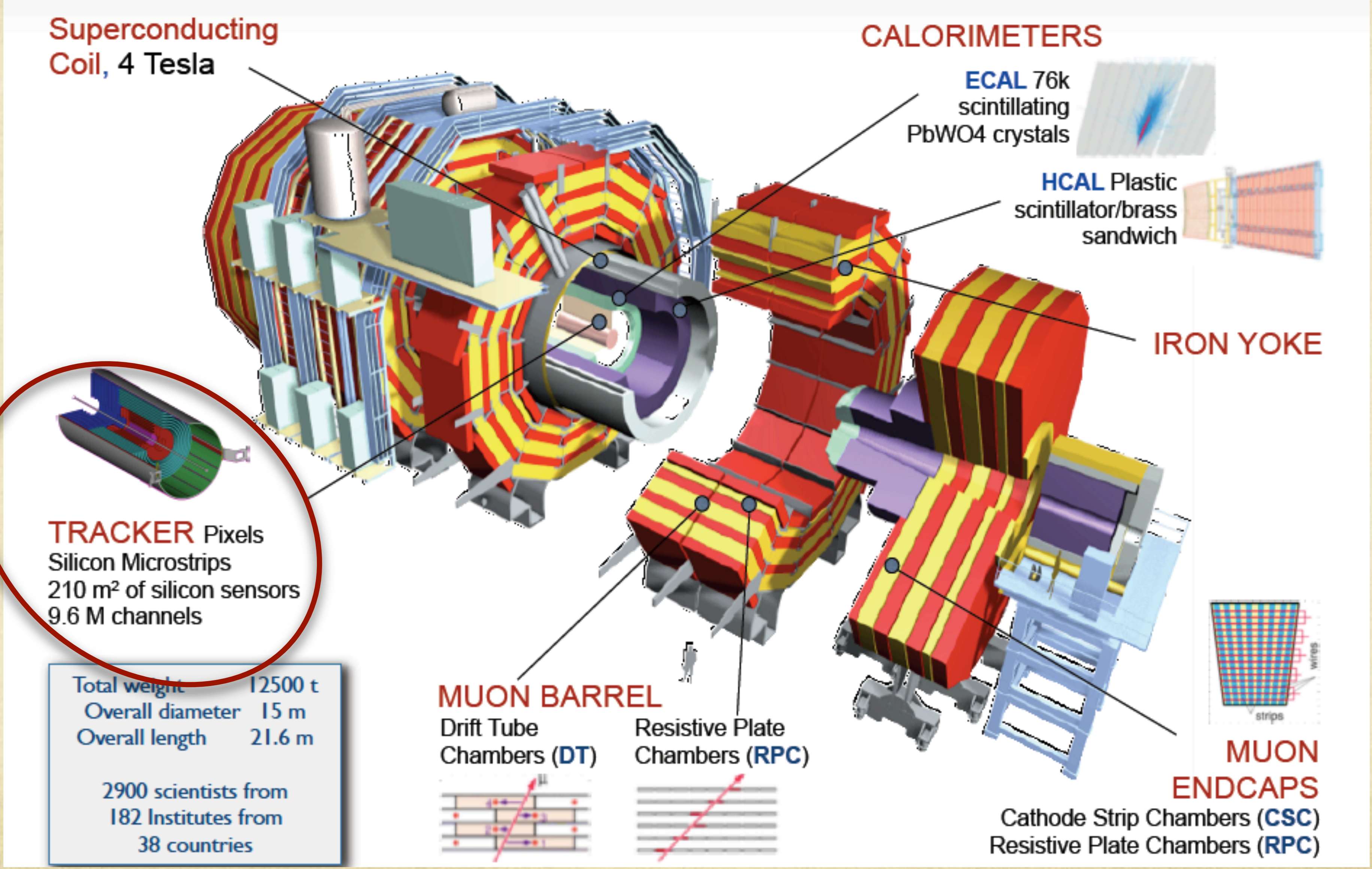
4. Deconstructing some tracking systems

- CMS
- AMS



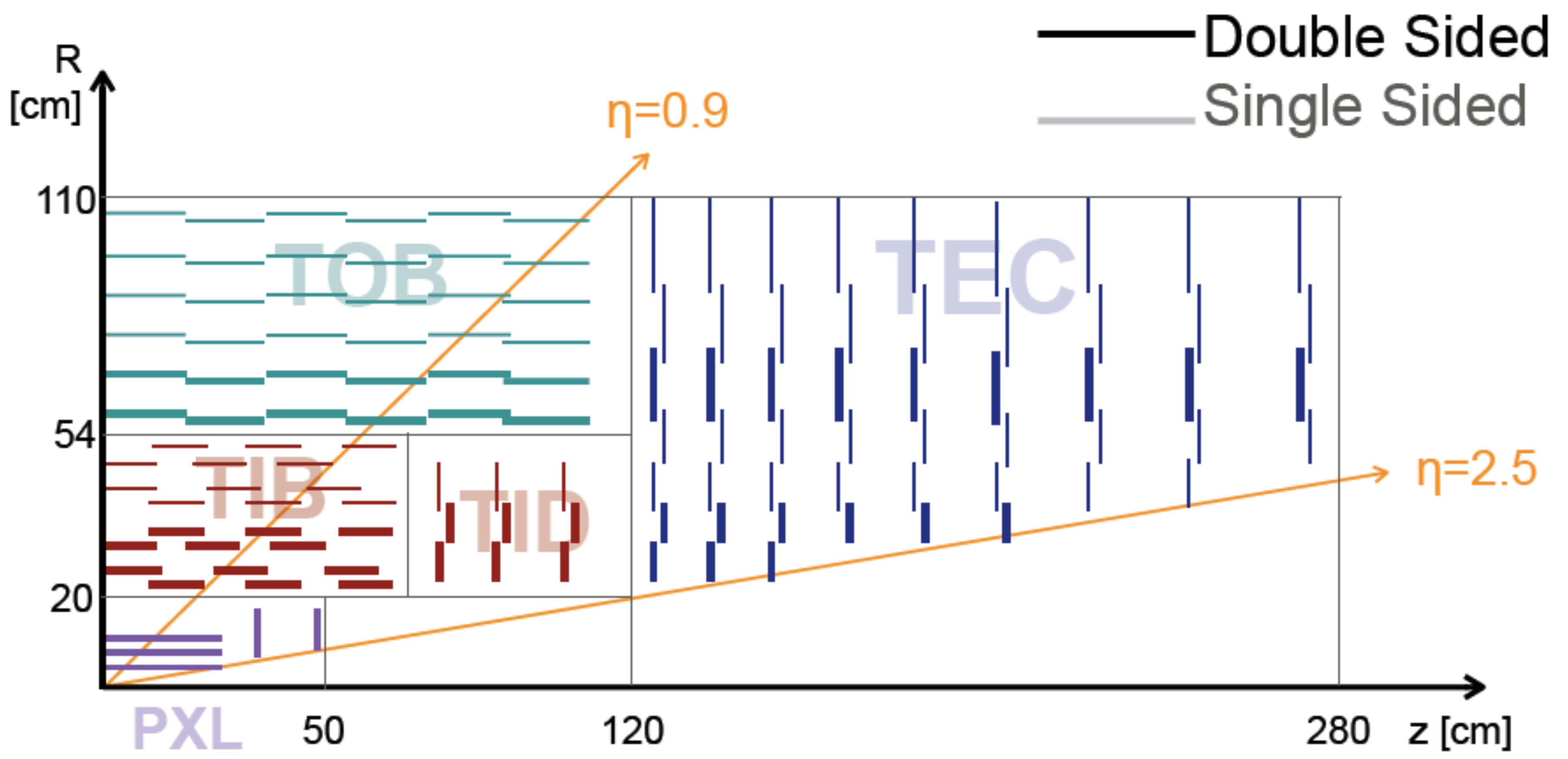
4. Some tracking systems:

CMS



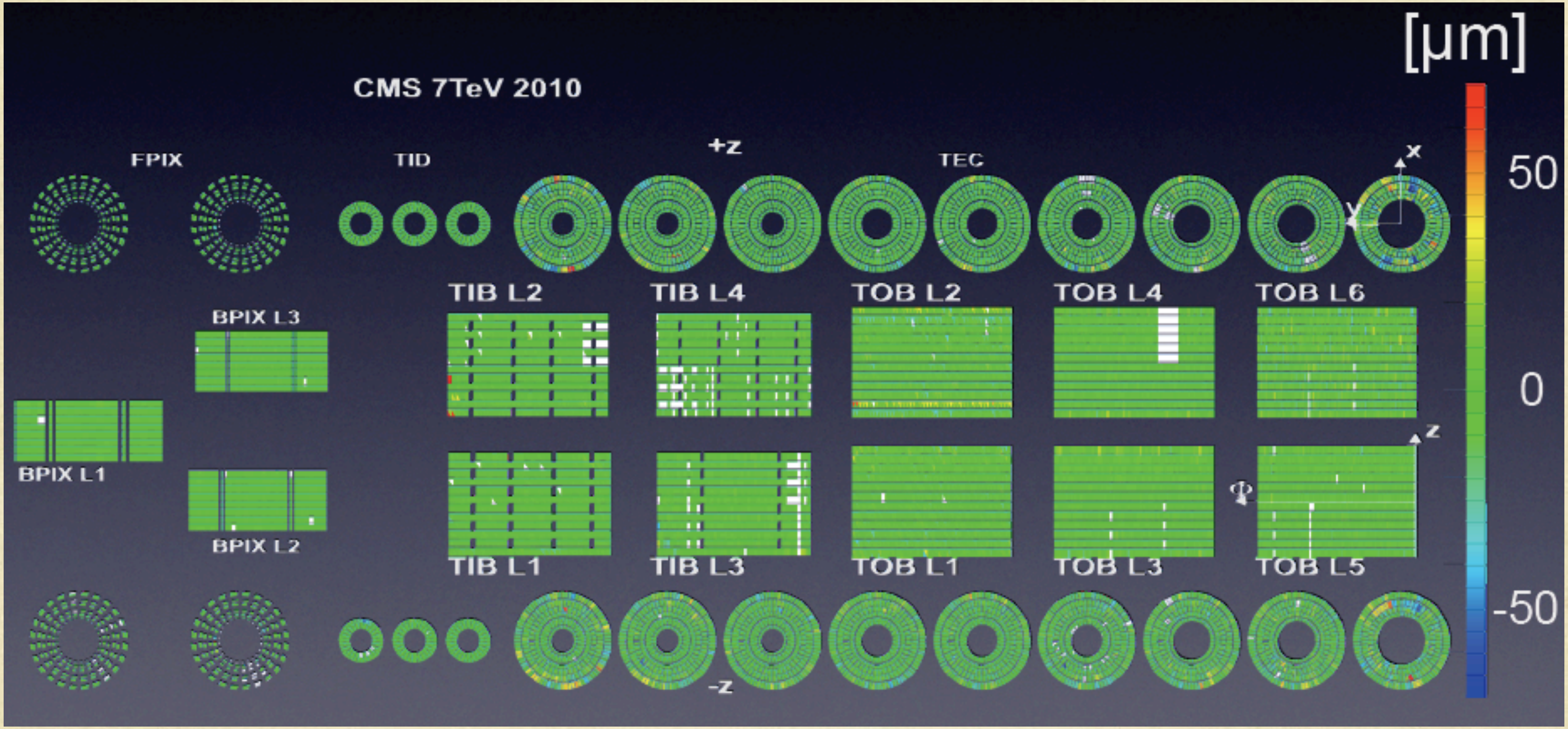
4. Some tracking systems:

CMS



CMS

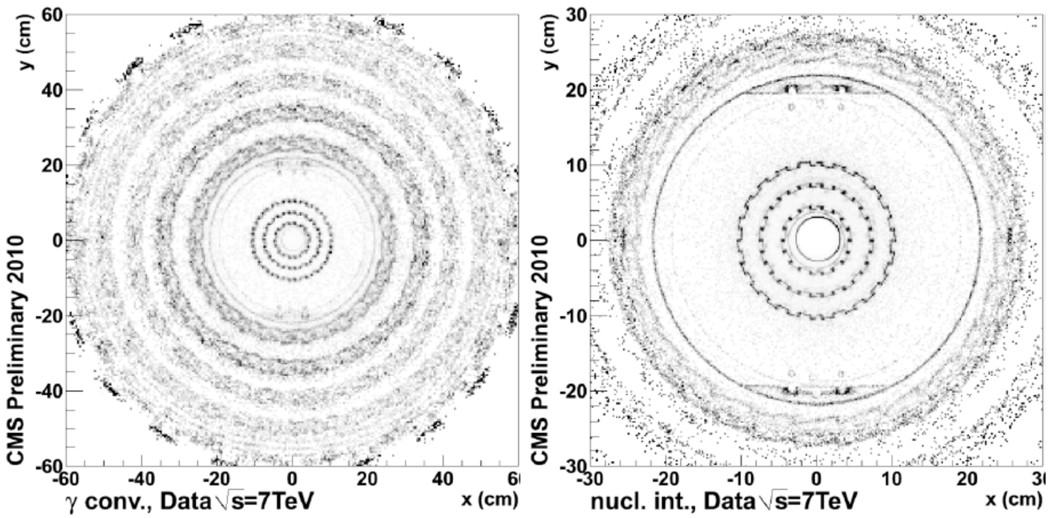
- Alignment residual width



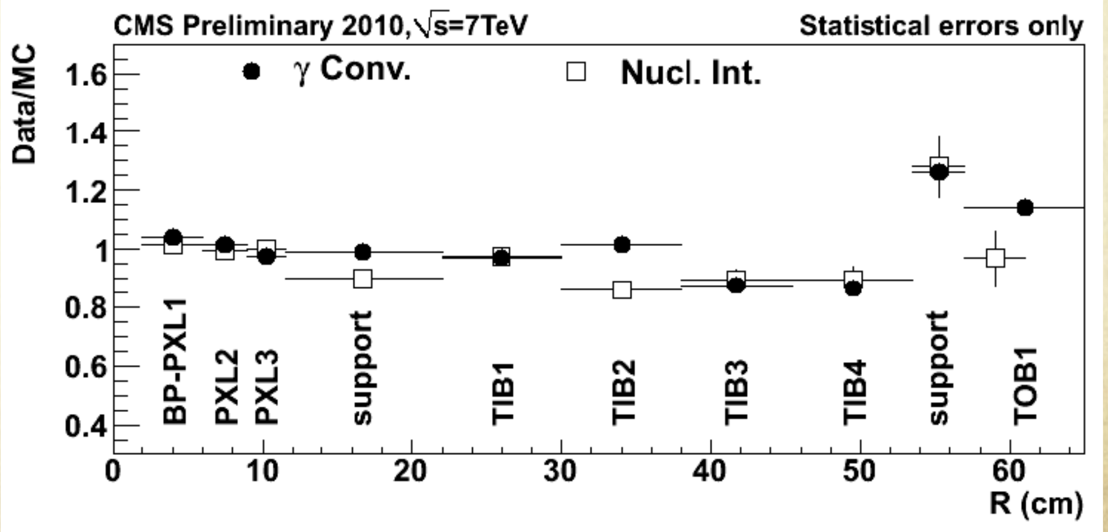
4. Some tracking systems:

CMS

- Taking a picture of the material budget
  - Using secondary vertices from
    photon conversion
    nuclear interaction



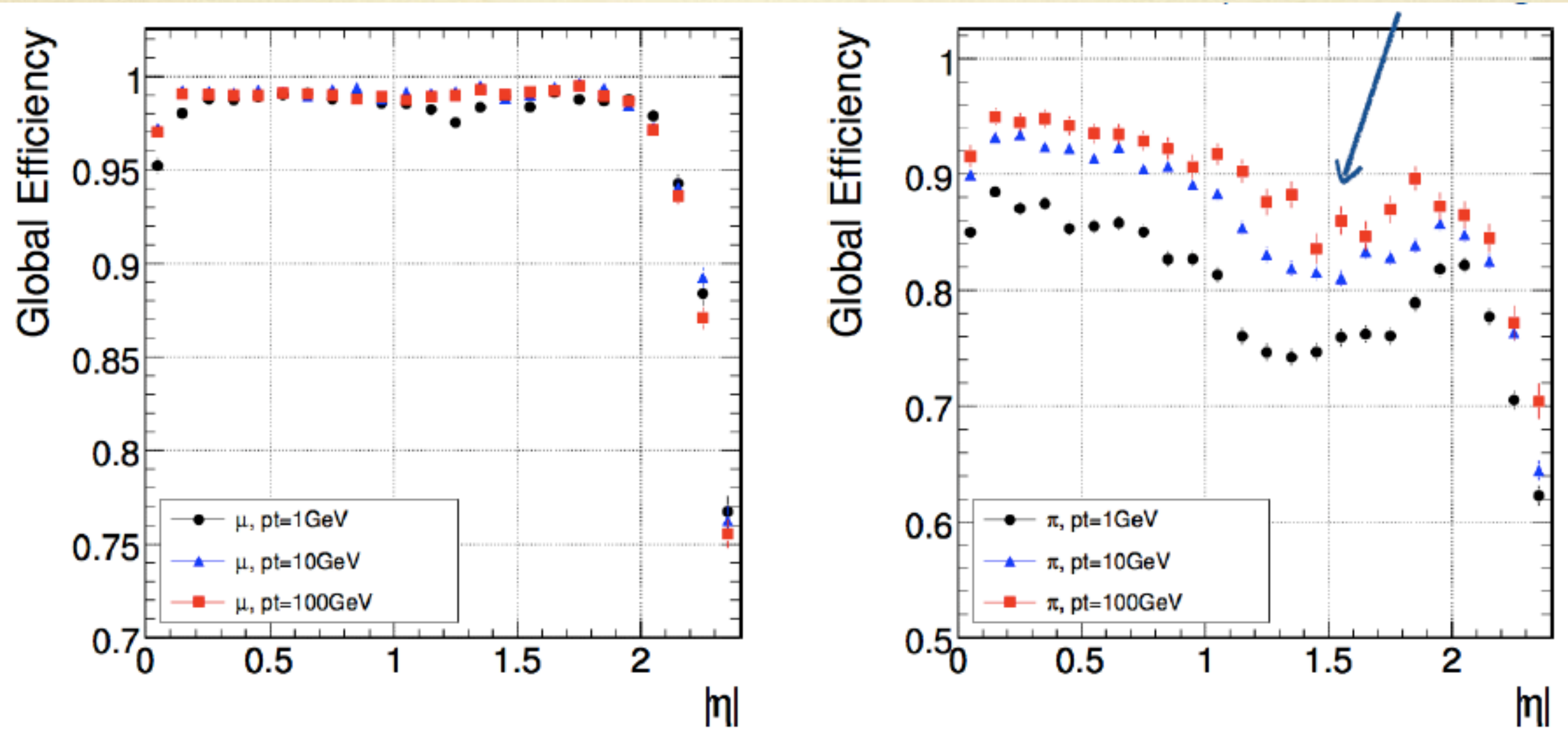
- Measuring it by data/simulation comparison



4. Some tracking systems:

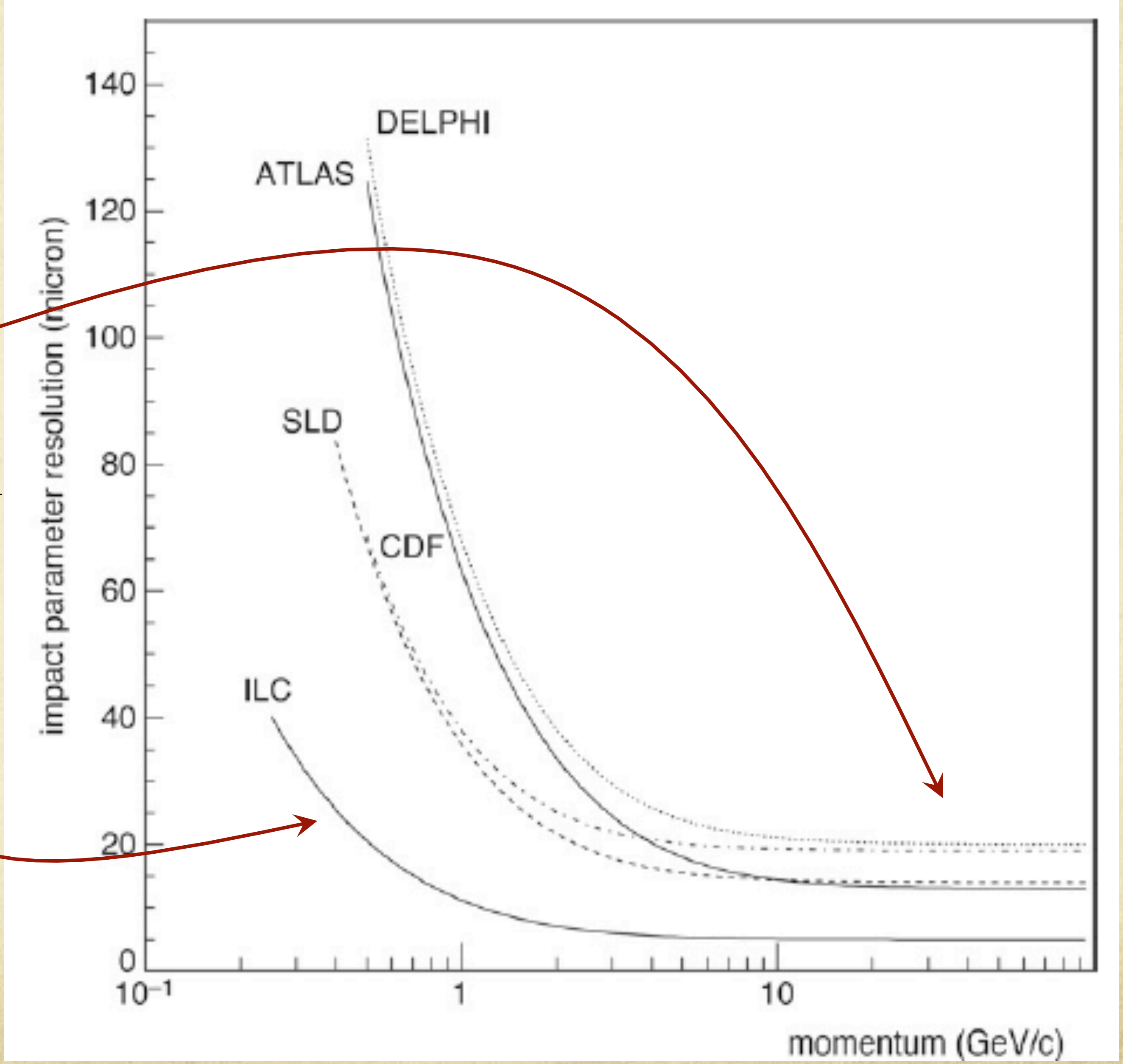
CMS

- Tracking efficiency



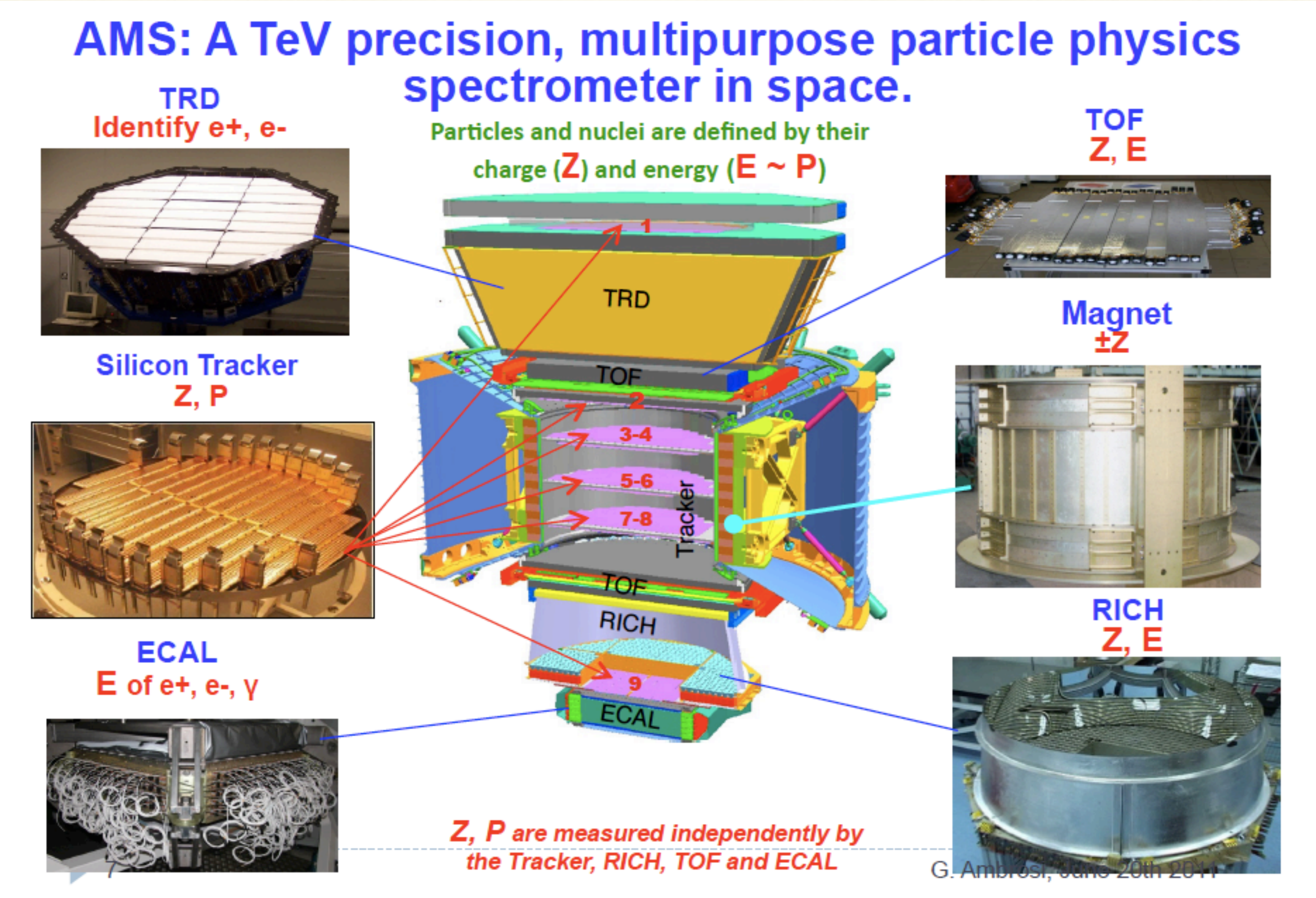
Impact parameter resolution

$$\sigma_{IP} \propto \frac{\sqrt{R_{\text{ext}}^2\sigma_{\text{int}}^2 - R_{\text{int}}^2\sigma_{\text{ext}}^2}}{R_{\text{ext}} - R_{\text{int}}} \oplus \frac{R_{\text{int}}\sigma_{\vartheta(\text{ms})}}{p\sin^{3/2}(\theta)}$$



4. Some tracking systems:

AMS



AMS: A TeV precision, multipurpose particle physics spectrometer in space.

Particles and nuclei are defined by their charge (Z) and energy (E ~ P)

TRD
Identify e+, e-

Silicon Tracker
Z, P

ECAL
E of e+, e-, γ

TOF
Z, E

Magnet
±Z

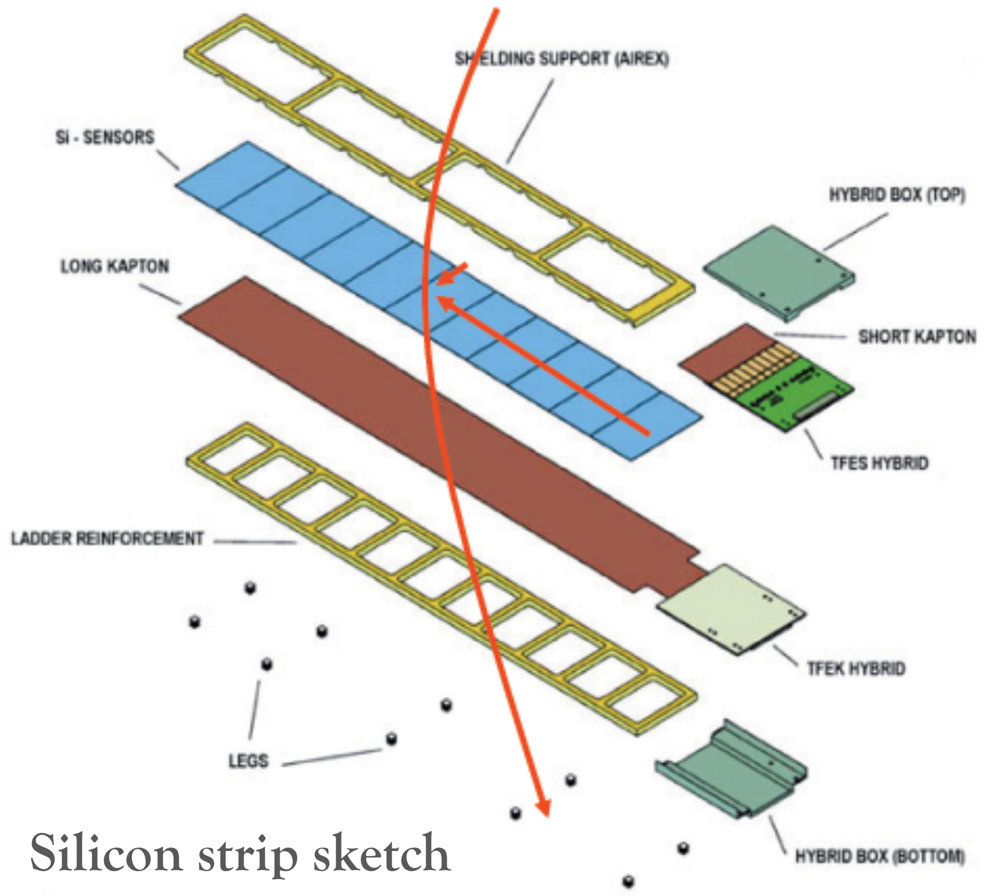
RICH
Z, E

Z, P are measured independently by the Tracker, RICH, TOF and ECAL

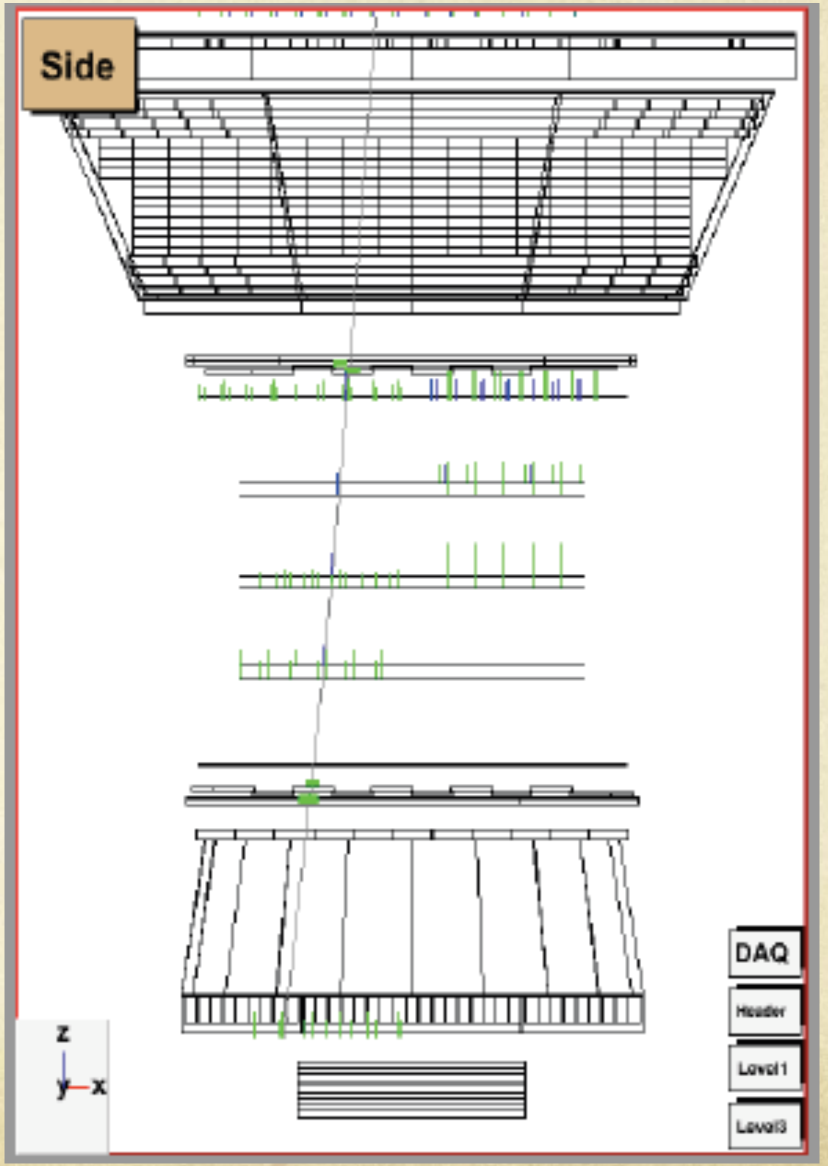
G. Ambrosi, June 20th 2011

4. Some tracking systems:

AMS



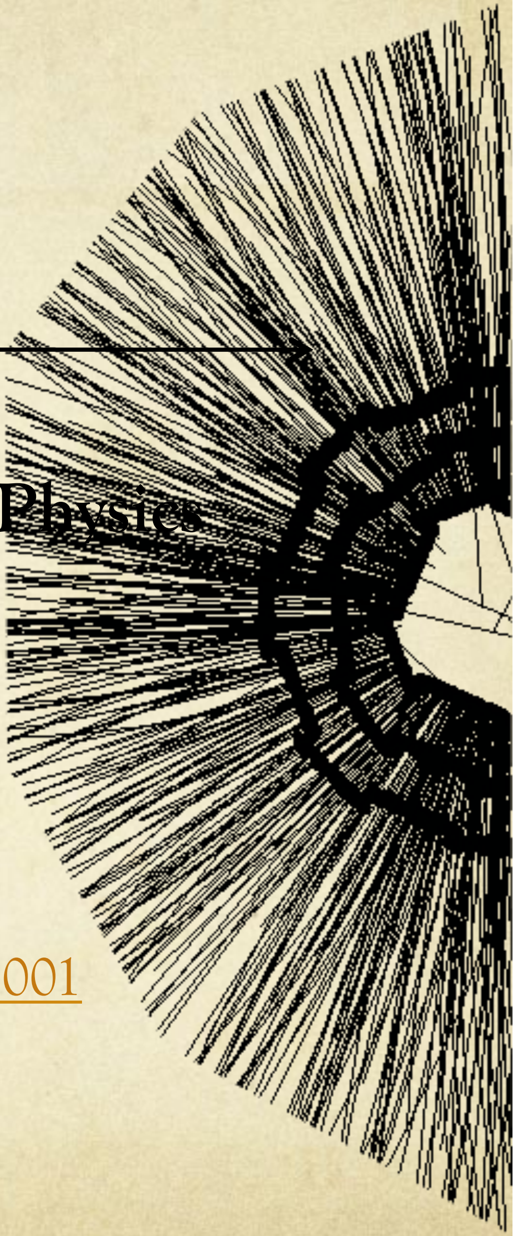
Silicon strip sketch



Summary

- Fundamental characteristics of any tracking & vertexing device:
  - (efficiency), granularity, material budget, power dissipation, “timing”, radiation tolerance
  - All those figures are intricated: each technology has its own limits
- Many technologies available
  - None is adapted to all projects (physics + environment choose, in principle)
  - Developments are ongoing for upgrades & future experiments
    - Goal is to extent limits of each techno. → convergence to a single one?
- Reconstruction algorithms
  - Enormous boost (variety and performances) in the last 10 years
  - Each tracking system has its optimal algorithm
- Development trend
  - Always higher hit rates call for more data reduction
  - Tracking info in trigger → high quality online tracking/vertexing
- Link with:
  - PID: obvious with TPC, TRD, topological reco.
  - Calorimetry: Particle flow algorithm, granular calo. using position sensors

References



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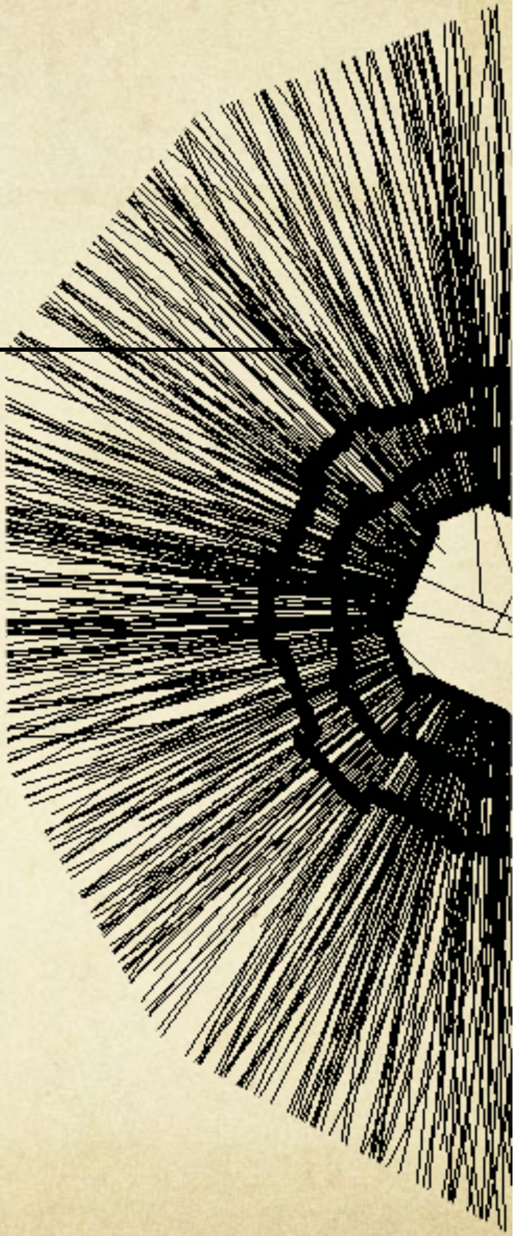
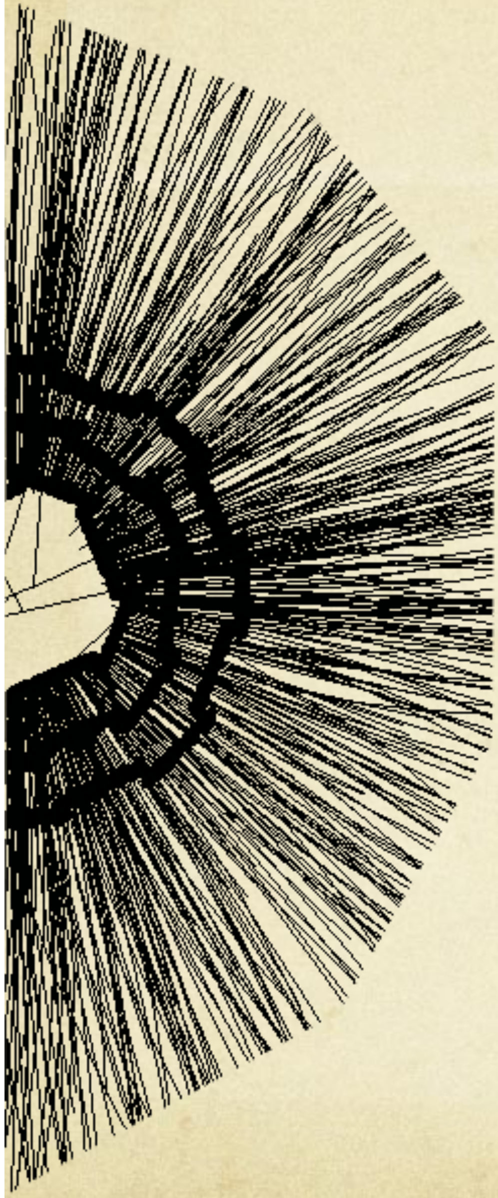
Was not discussed



- Particle interaction with matter
- The readout electronics
- Cooling systems
- The magnets to produce the mandatory magnetic field for momentum measurement



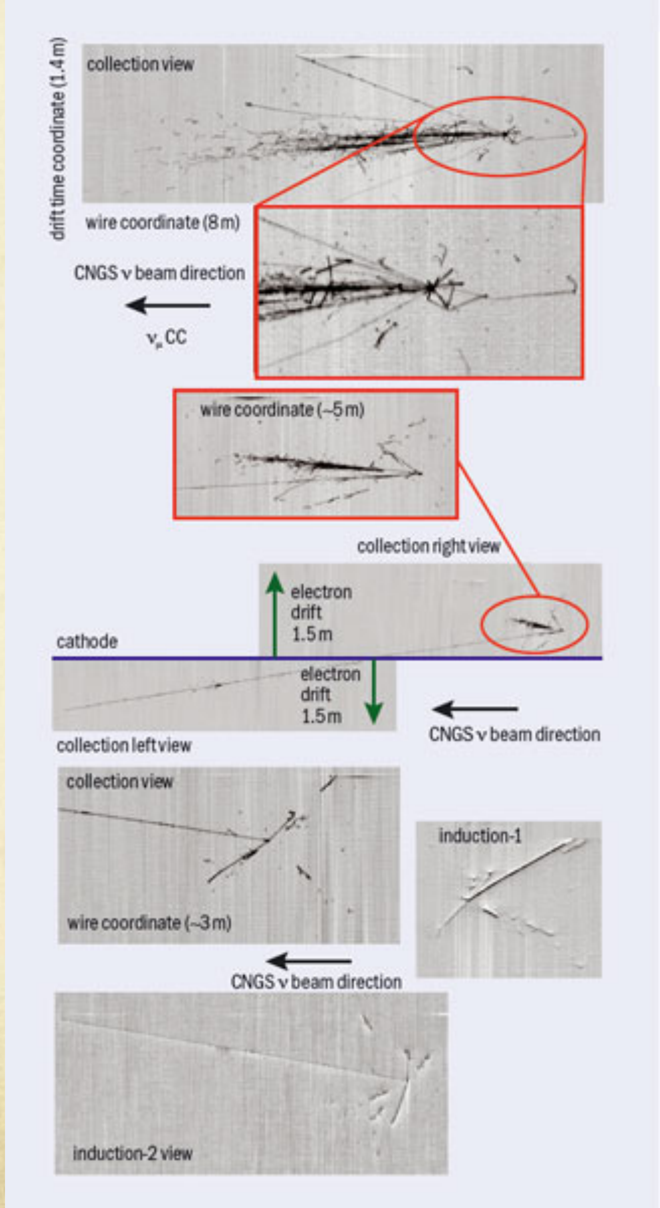
Backups

OPAL drift chamber

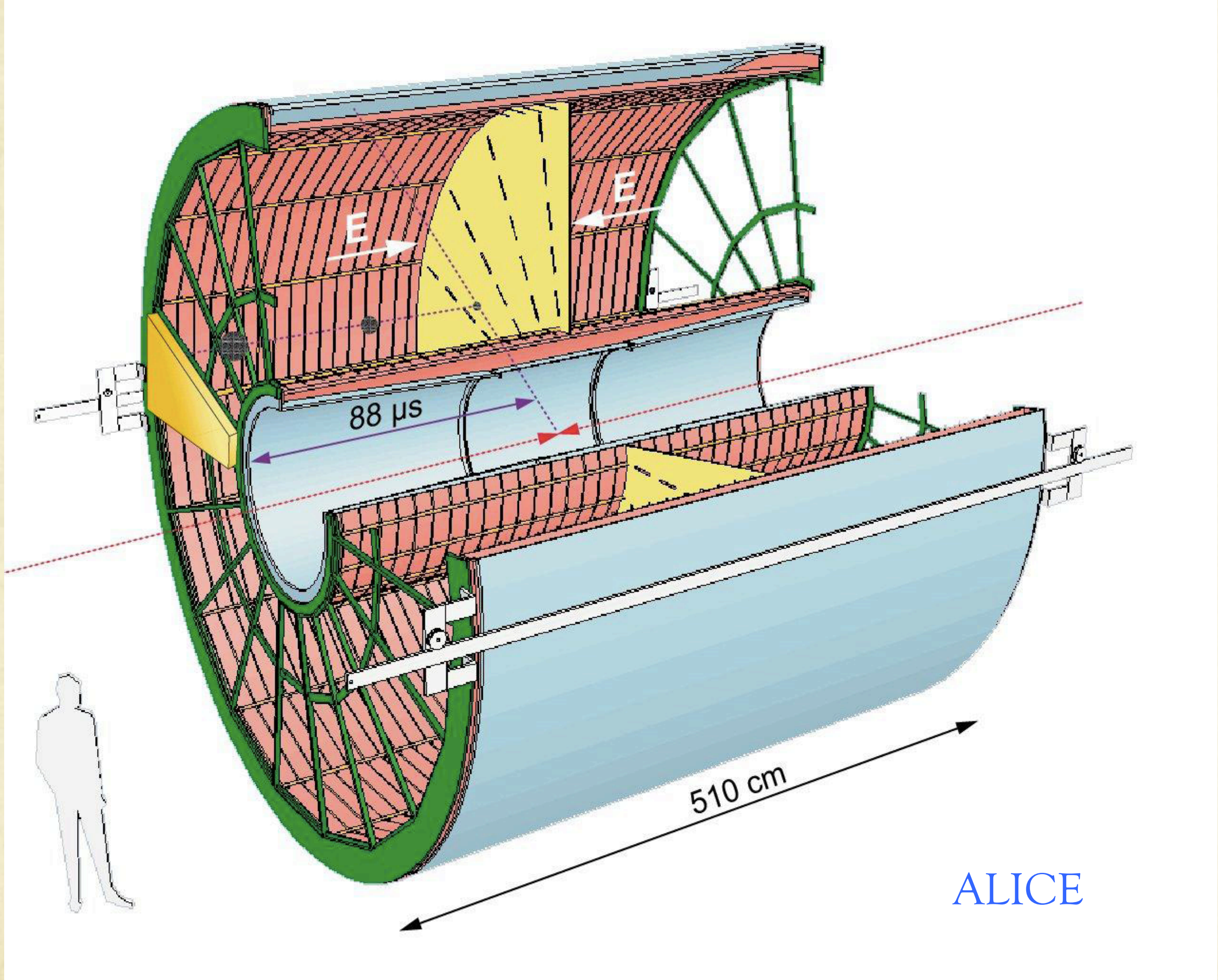
○

ICARUS - event

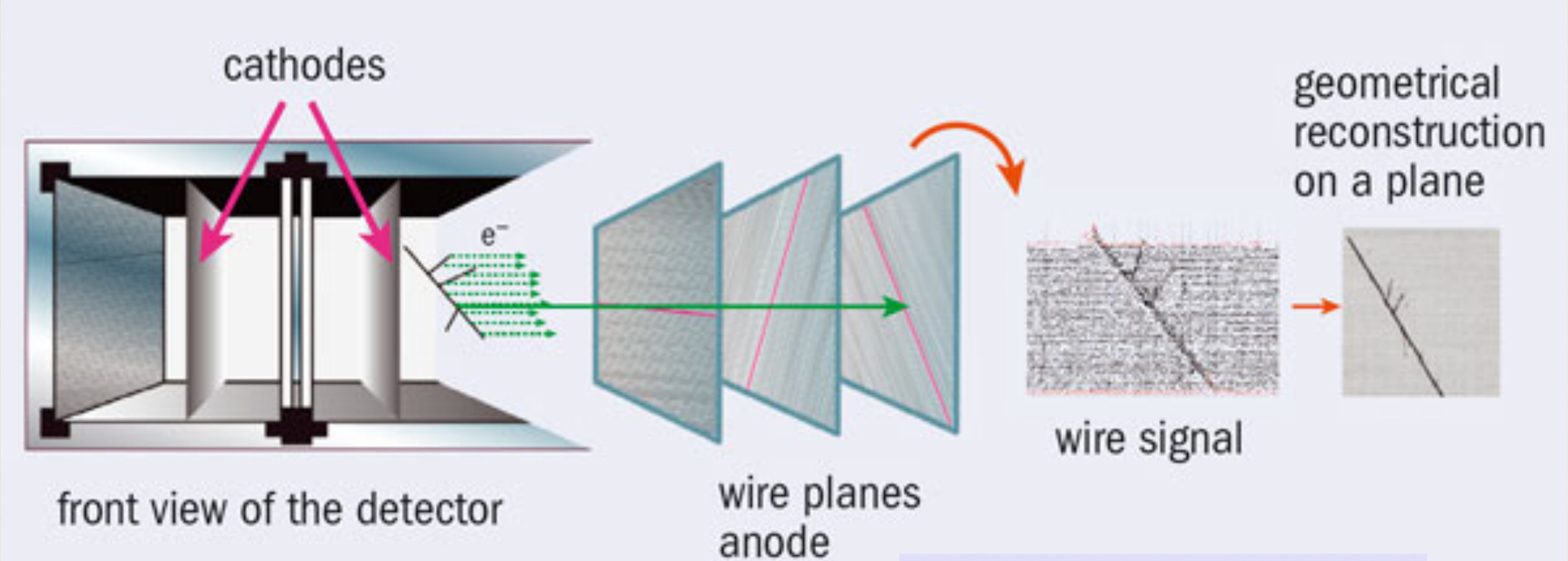
-

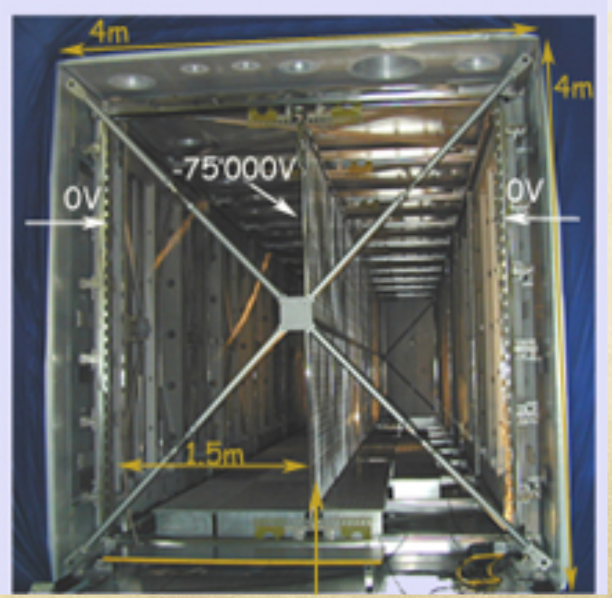


ALICE - TPC



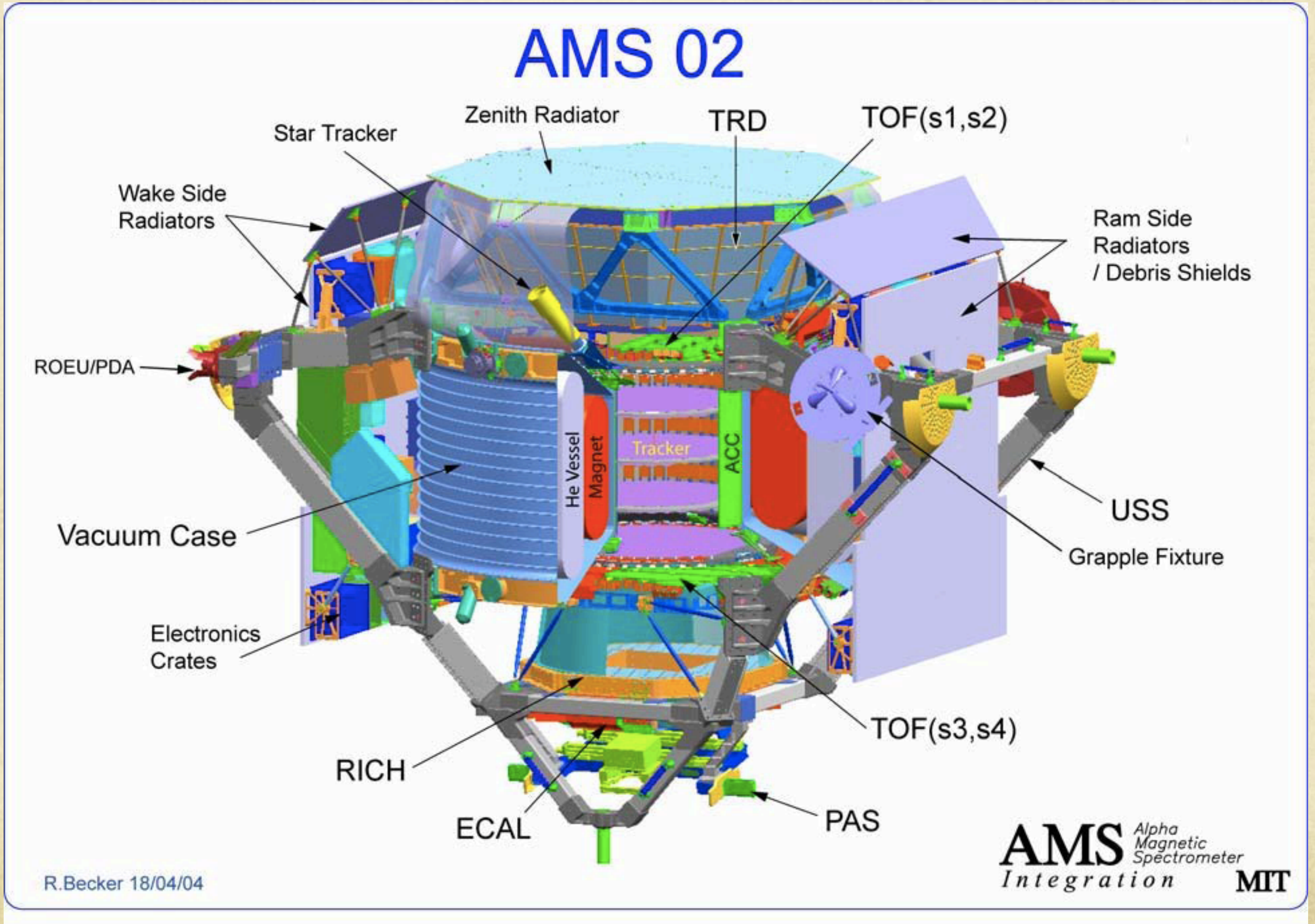
ICARUS - TPC


cathodes
e⁻
front view of the detector
wire planes
anode
wire signal
geometrical reconstruction on a plane

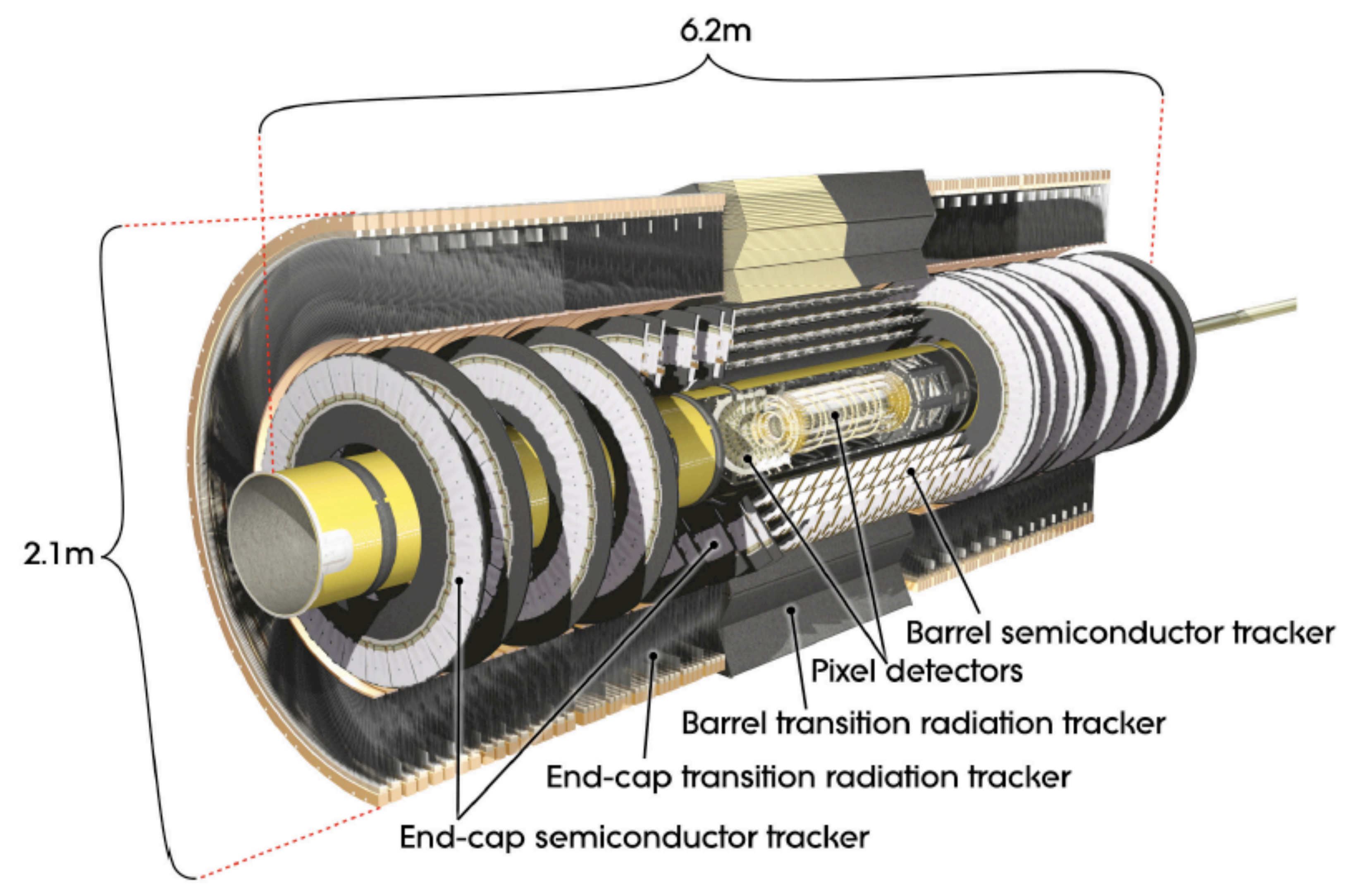

4m
4m
-75000V
0V
0V
1.5m

Backups:

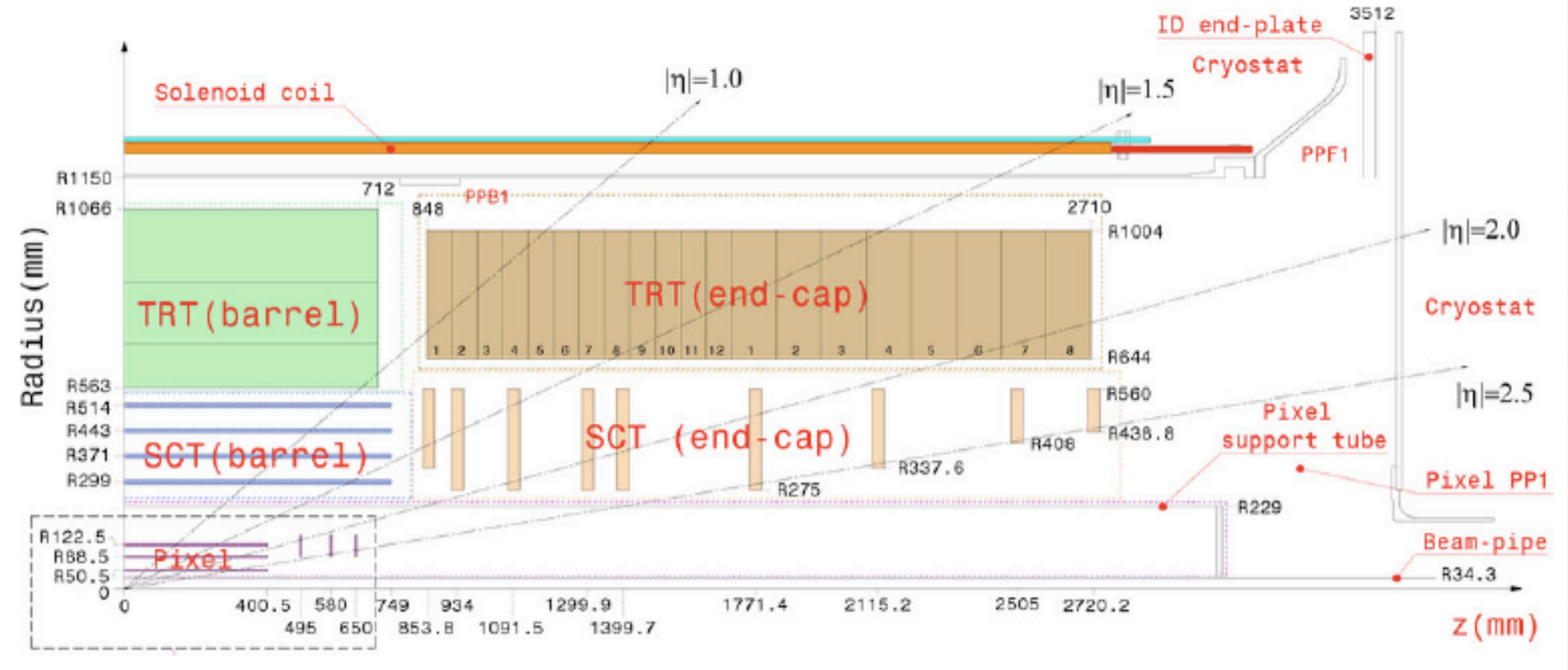
-


AMS 02
Zenith Radiator
TRD
TOF(s1,s2)
Star Tracker
Wake Side Radiators
Ram Side Radiators / Debris Shields
ROEU/PDA
He Vessel
Magnet
Tracker
ACC
Vacuum Case
USS
Grapple Fixture
Electronics Crates
TOF(s3,s4)
RICH
ECAL
PAS
AMS Alpha Magnetic Spectrometer Integration
MIT
R.Becker 18/04/04

ATLAS tracking setup



ATLAS tracking setup



Backups:

CMS

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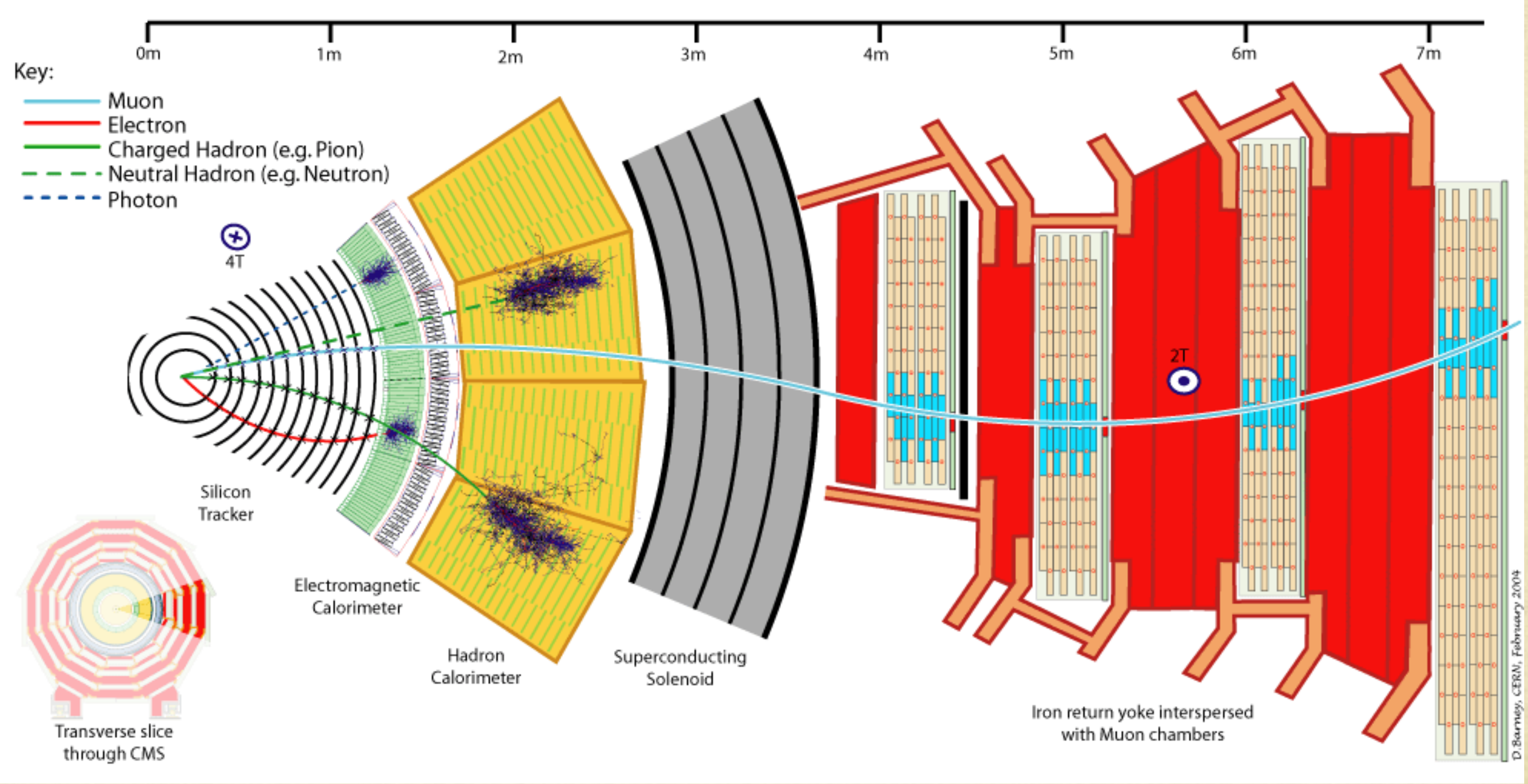
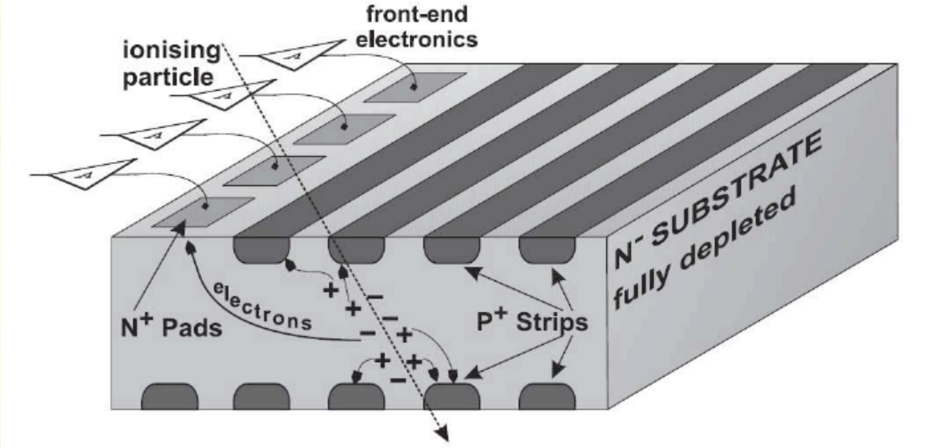

0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

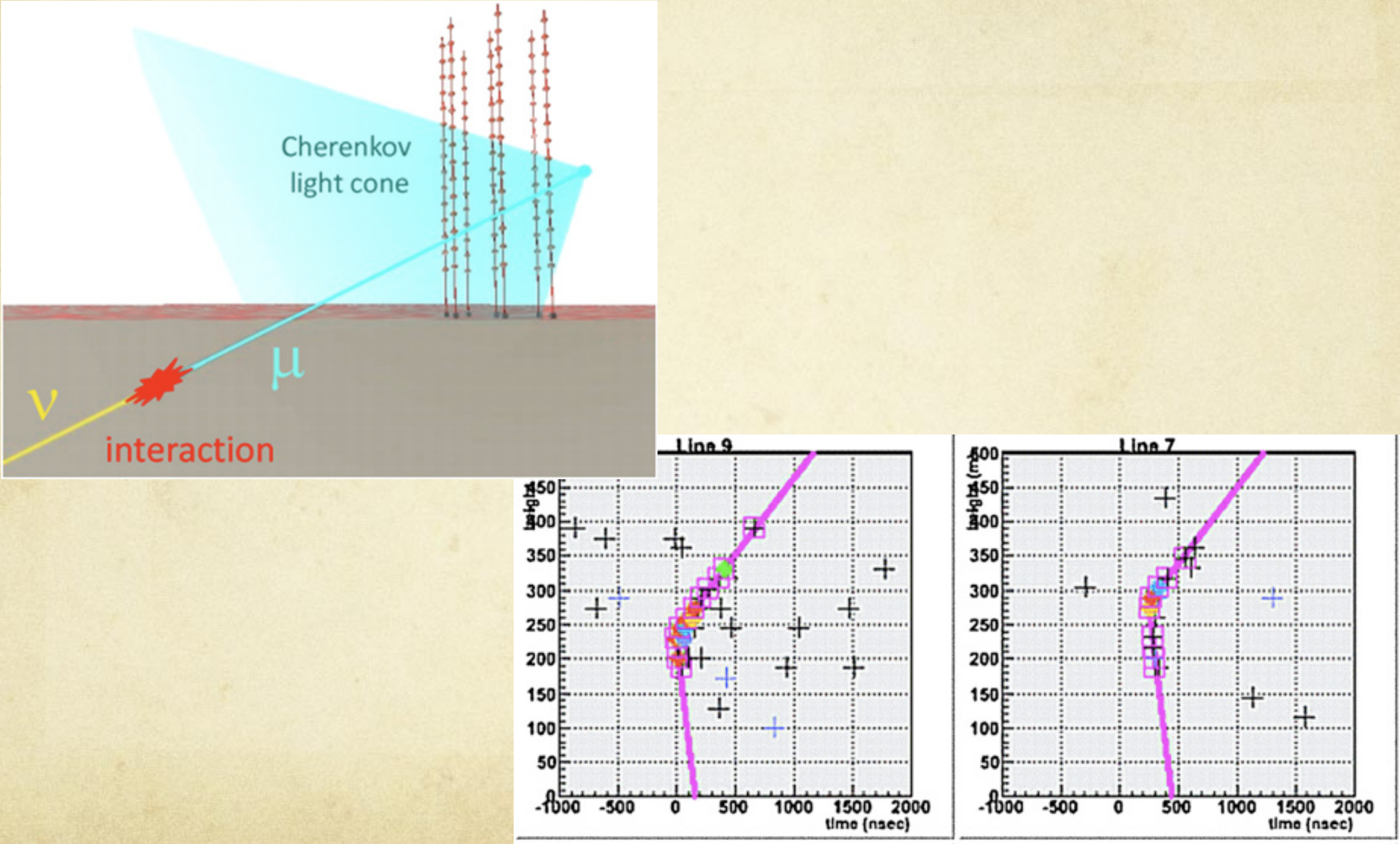
Silicon sensors: drift

○

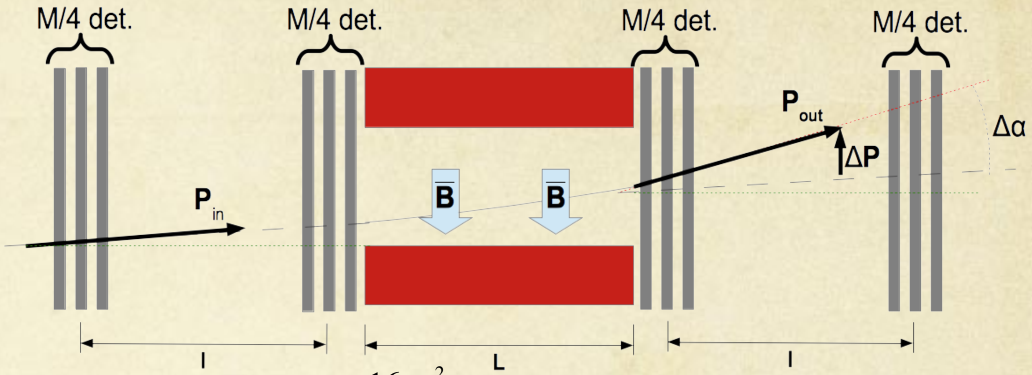


Backups:

ANTARES



Resolution on P: fixed target



- Hypothesis
  - ➛ M detectors,
    each with σ single point accuracy
  - ➛ Uniform field over L from dipole
    - Trajectory: $\Delta p = p\,\Delta\alpha$ $\quad \Delta\alpha = \left|\frac{0.3qBL}{p}\right|$
    - Bending:
  - ➛ Geometrical arrangement optimized for resolution
    - Angular determination on input and output angle: $\sigma_\alpha^2 = \frac{16\,\sigma^2}{M\,l^2}$
- Without multiple scattering $\quad \Delta\alpha = \left|\frac{0.3qBL}{p}\right|$
  - ➛ Uncertainty on momentum