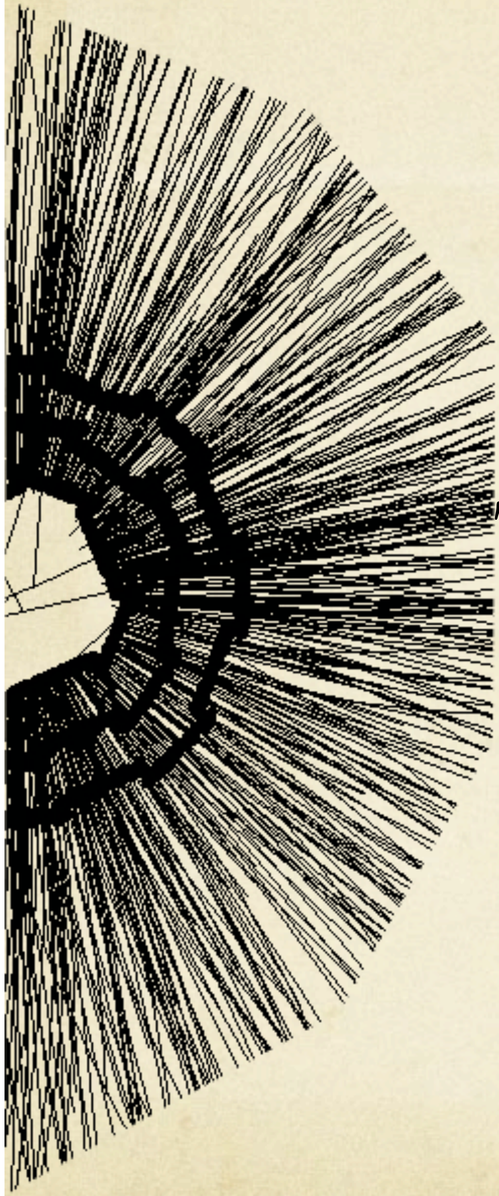
Franco-Asian Particle Physics School
9-21 October 2011, Les Houches



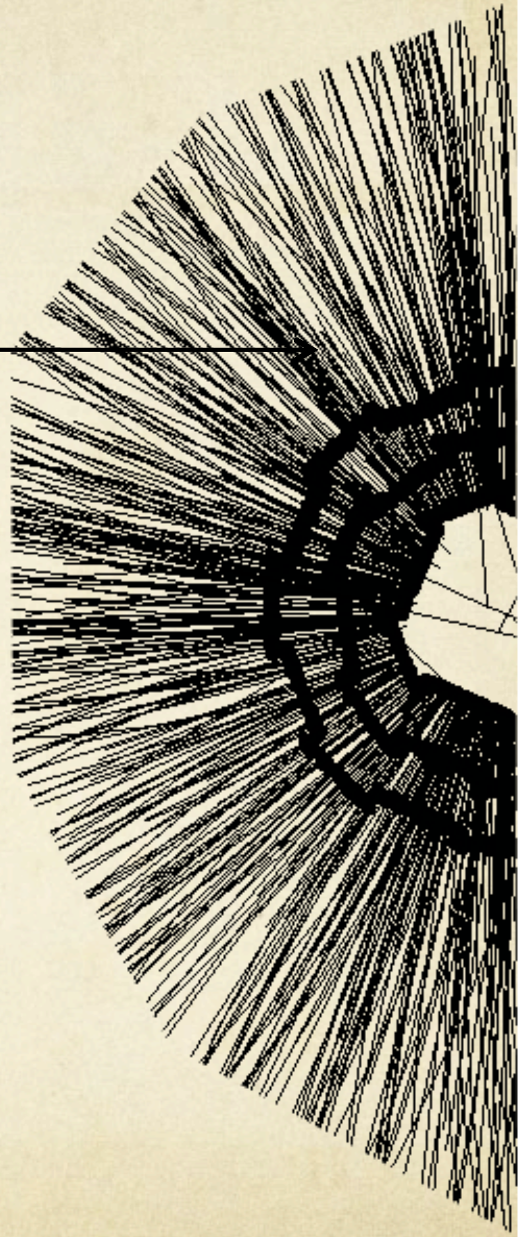
# Tracking and Vertexing in High Energy Physics

Jérôme Baudot (baudot@in2p3.fr)

IPHC
Institut Pluridisciplinaire Hubert CURIEN
STRASBOURG

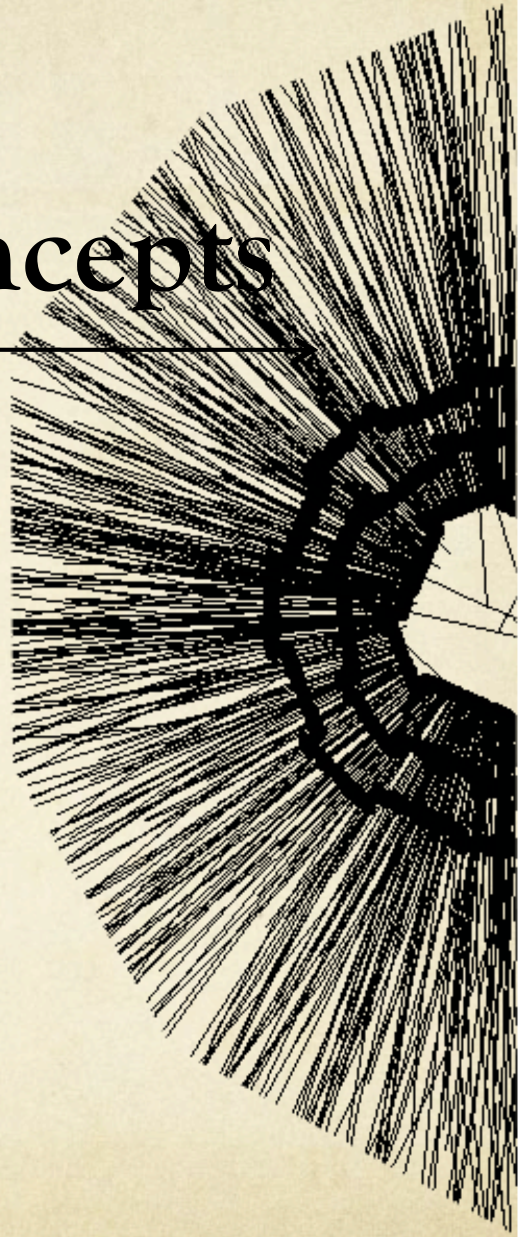
# Lecture outline

1. Motivations & basic concepts
2. Detection technologies
3. Reconstruction algorithms
4. Deconstructing some tracking systems



# 1. Motivations & basic concepts

- Counting tracks
- Identifying through topology
- Figures of merit
- Environmental considerations

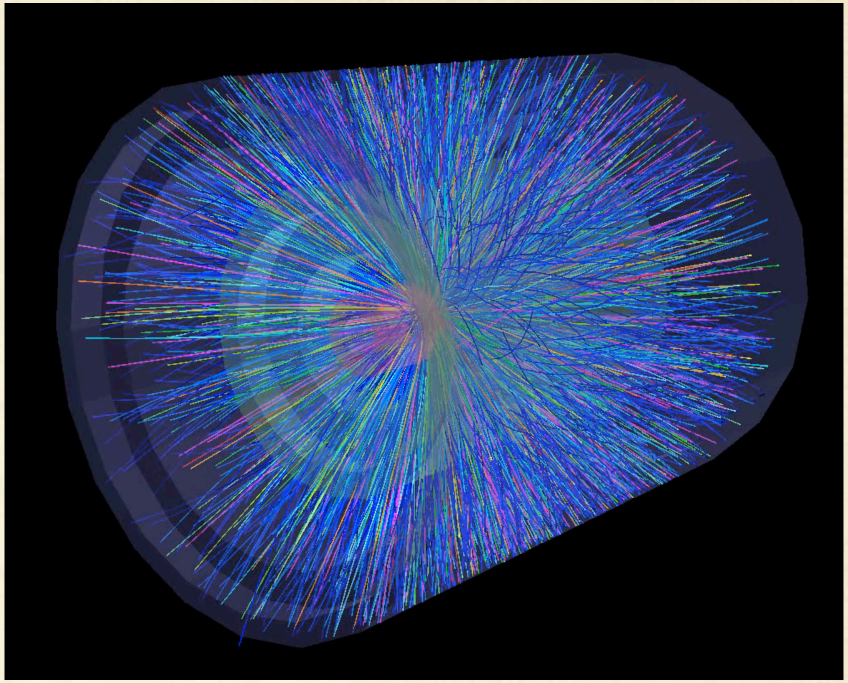


# Tracking

- Understanding an event
  - Materialize & individualize tracks
  - LHC: ~1000 particles per 25 ns "event"
- Measuring the momentum
  - Magnetic field used for curving trajectories

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

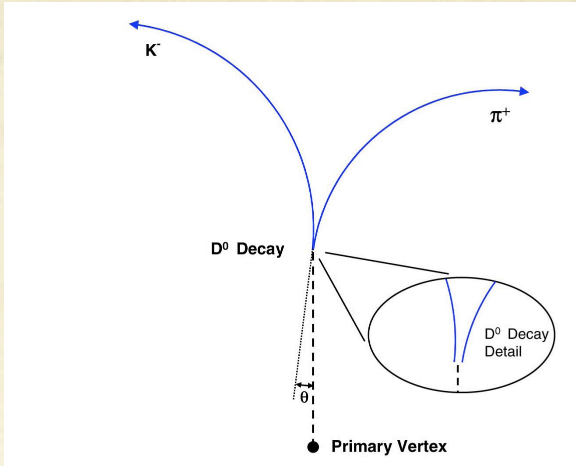
  - In B=4T a 1 GeV/c particle will get a sagitta of 1.5 mm
- Identifying the nature of a (single) track
  - See Marco Zito's lecture

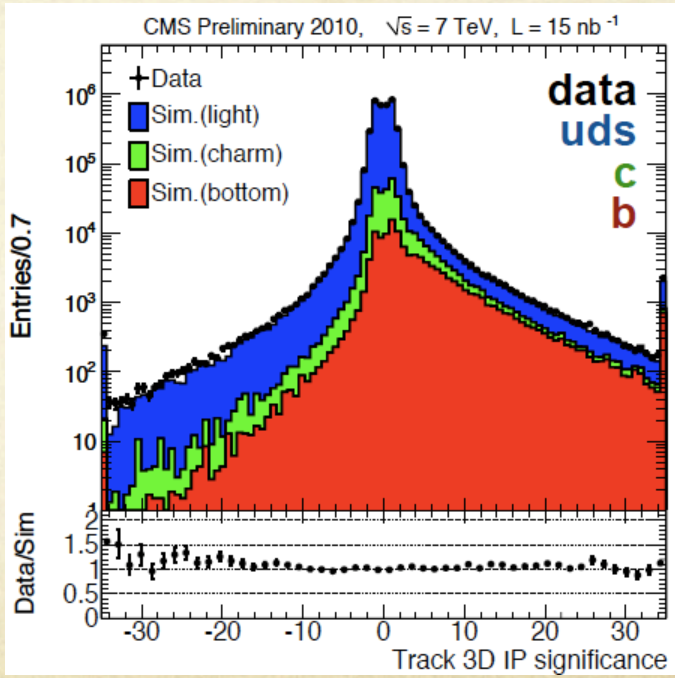


An Pb+Pb event from LHC as recorded by ALICE

# 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
    - $\sigma_{IP}$ ~ 20-100 µm requested

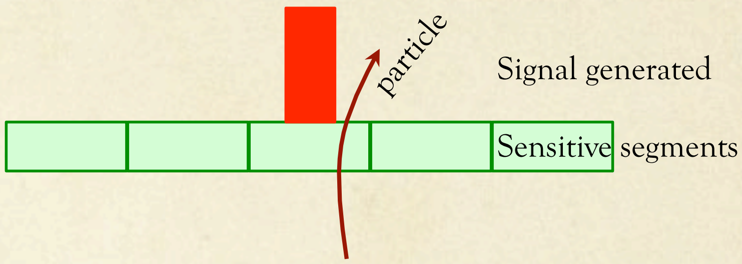


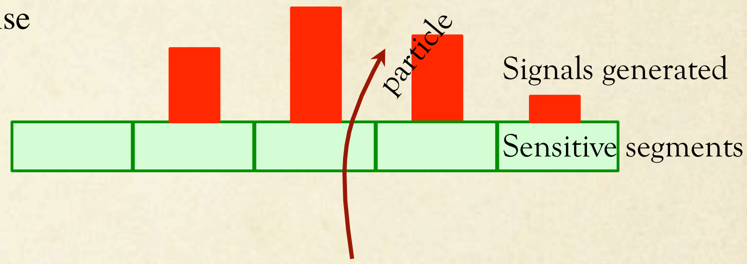




- **Finding the origin**
  - ➛ Where did the collision did occur?
    - Primary vertex (could be multiple)
  - ➛ (life)Time dependent measurements
    - CP-asymmetries @ B factories ($\Delta z$ ~60-120 µm)

# Figures of Merit – 1/2

- **Tracking & Vertexing rely on multiple measurements/track**
  - How to assess performance on a single measurement?
- **Intrinsic spatial resolution**
  - Granularity or segmentation → pitch
    - Digital resolution $\sigma = \frac{\text{pitch}}{\sqrt{12}}$
    - Improved res. through signal sharing (assume signal amplitude measurement) $\sigma \propto \frac{\text{pitch}}{\text{signal/noise}}$
  - Usefull tracking domain $\sigma < 1$mm



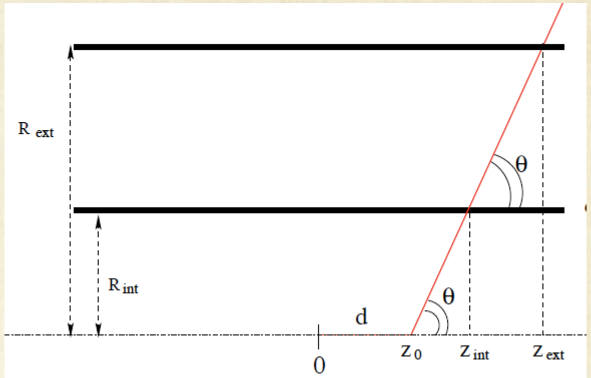




- **Two-track resolution**
  - Ability to distinguish to nearby trajectories
  - Mostly governed by signal spread
- **Efficiency**
  - Driven by Signal/Noise
  - Note: Noise = signal fluctuation ⊕ readout (electronic) noise

# Figures of Merit – 2/2

- Tracking & Vertexing rely on multiple measurements/track
  - Crude estimation of impact parameter (IP) resolution (telescope equation)
    $\sigma_{ext/int}$ = spatial res.

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




  - Second term prevents to benefit from $\sigma_{ext/int} \longrightarrow 0$ (especially at low momentum)

- Material budget
  - multiple scattering from Coulomb interaction with nuclei
  - Distribution of scatter angle: $\sigma_{\theta(ms)} = \frac{13.6\ (\mathrm{MeV/c})}{\beta p} \cdot z \cdot \sqrt{\frac{\mathrm{thickness}}{X_0}} \cdot \left[1 + 0.038\ \ln(\frac{\mathrm{thickness}}{X_0})\right]$

# Environmental conditions – 1/2

- Life in a real collider 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 = radiation
  - Vacuum could be required (space, very low momentum particles)

- Radiation tolerance
  - Two types of radiation
    - Ionizing (generate charges): dose in Gy = 100 Rad
    - Non-ionizing (generate defects): fluence in $n_{eq}$(1MeV)/cm$^2$
  - The inner the detection layer, the harder the radiation (radius$^2$ effect)
  - Examples for the 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

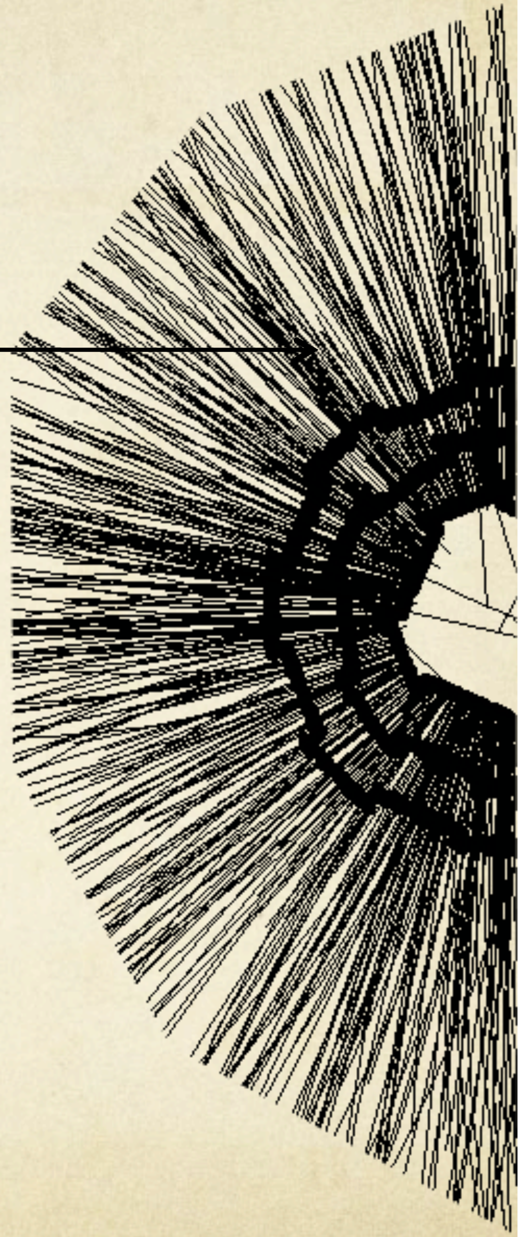
- Timing consideration
  - ➛ Readout speed limits dead time
  - ➛ Time resolution offers time-stamping of tracks
    - Tracks in one "acquisition event" could be associated to their proper collisions event if several have piled-up

- Heat concerns
  - ➛ Spatial resolution ➞ segmentation<br>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

# 2. Detection technologies

- Practical considerations
- Single layer systems
  - Silicon, gas sensors
- Multi-layer systems
  - Drift chamber and TPC
- Tentative comparison
- Leftovers



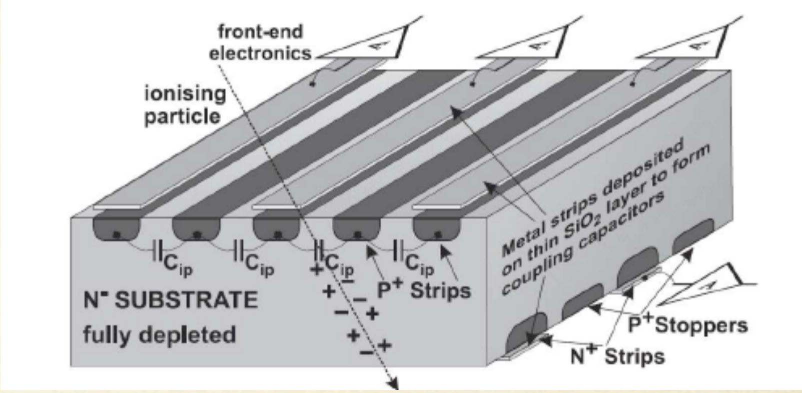
# Practical considerations

- 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 → limited space
    - Material budget is ALWAYS a concern
    - ⇨ trade-offs required

# Silicon sensors: strips

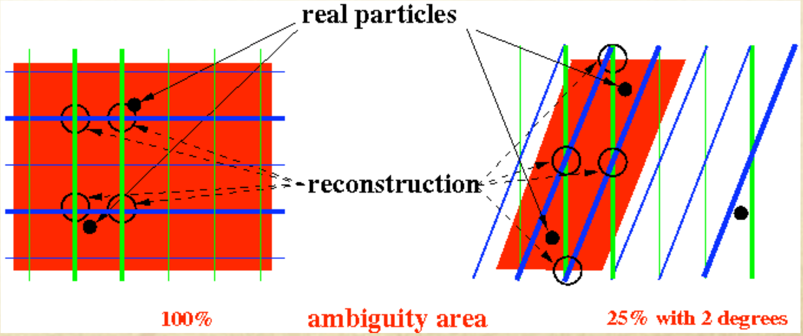
## Basic sensitive element

- 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

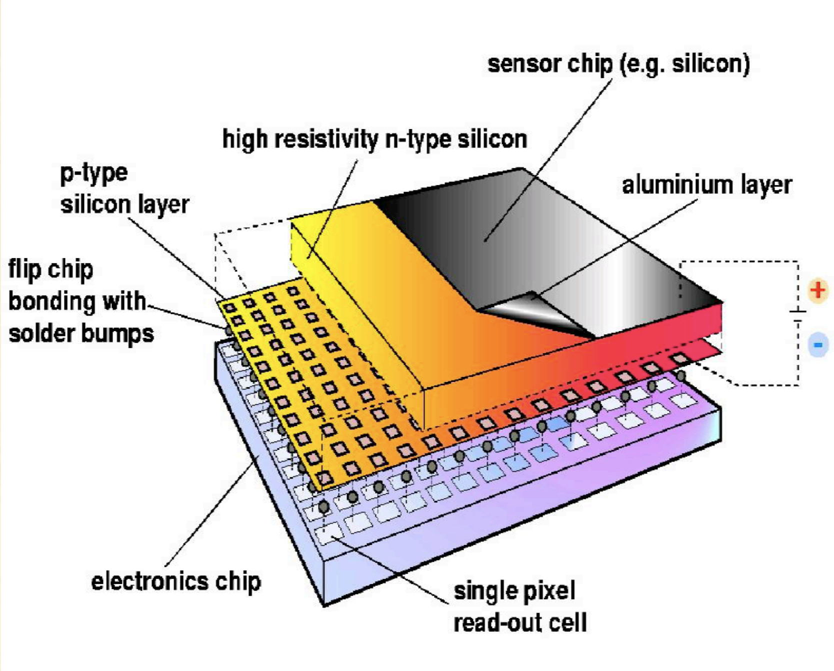
- sensor"easily" manufactured with pitch down to ~25 µm
- 1D if single sided
- Pseudo-2D if double-sided
  - Stereo-angle useful against ambiguities
- Difficult to go below 100 µm thickness

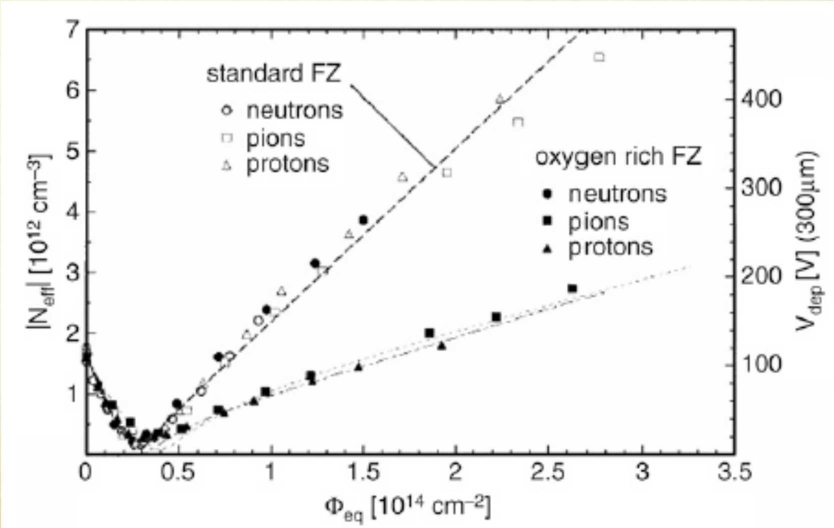


# Silicon sensors: hybrid-pixels

- Concept
  - Strips → pixels on sensor
  - One to one connection from electronic channels to pixels

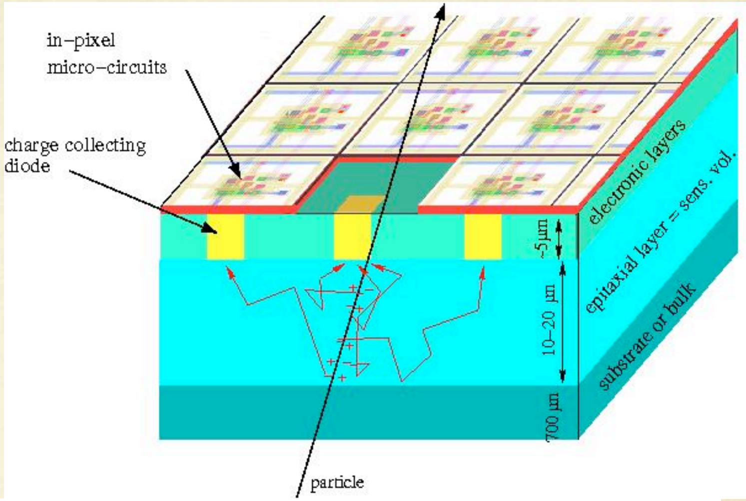
- Performances
  - Real 2D detector & keep performances of strips
    - Can cope with LHC rate (speed & radiation)
  - Pitch size limited by physical connection and #transistors for treatment
    - minimal (today): 50x50 μm$^2$ typical: 100x150/400 μm$^2$
    - spatial resolution about10 μm
  - Material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



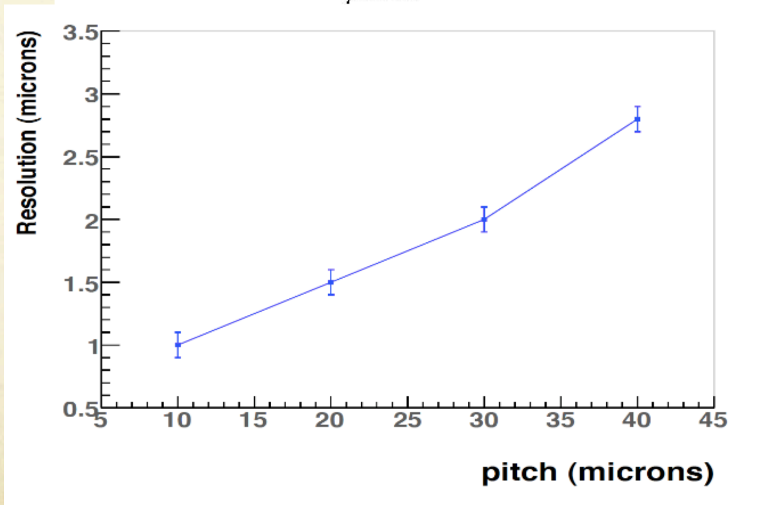



# CMOS Pixel Sensor

- 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: no depletion available
    - Slow (100 ns) thermal drift

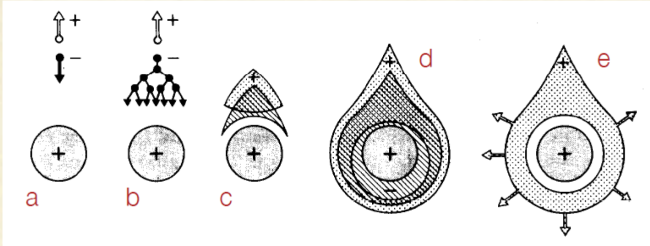



- Performances
  - ➣ Spatial resolution 1-10 μm (in 2 dimensions)
  - ➣ Material budget: ≲ 30 μm
  - ➣ Power budget: 1-5 μW/pixel
  - ➣ Integration time ~ 50-100 μs demonstrated
    - 1 μs in development

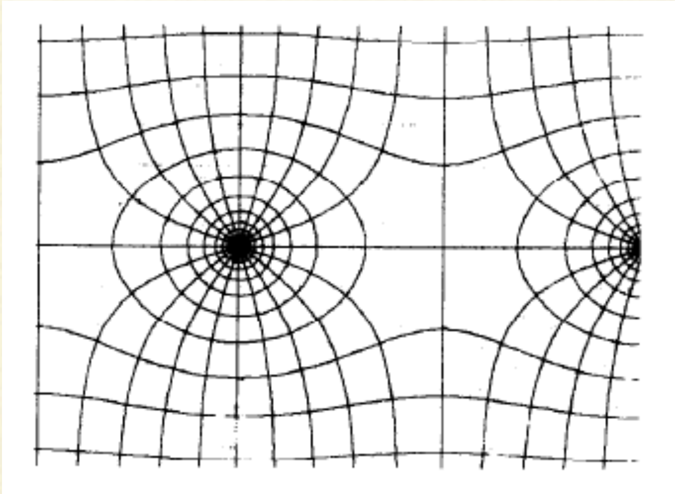


# Wire chambers

- **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



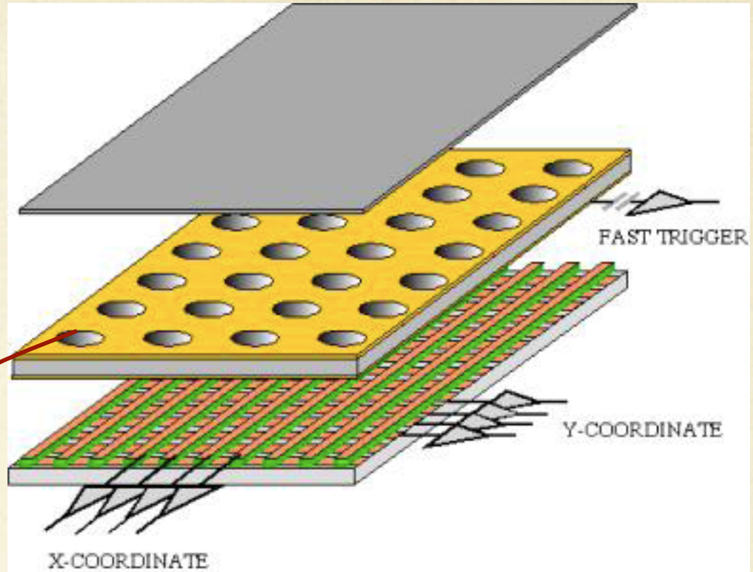

- **Gas proportional counters**
  - Multi-Wire Proportional Chamber
    - Array of wires
    - 1 or 2D positioning depending on readout
    - Wire spacing (pitch) limited to 1-2 mm
  - Straw or drift tube
    - One wire in One tube
    - Extremely fast (compared to Drift Chamber)
    - Handle high rate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

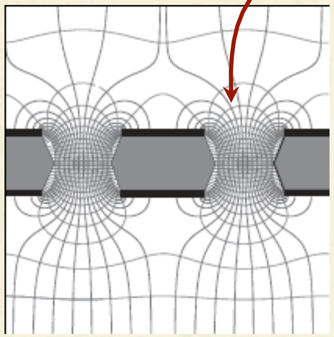


Electric fields line around anode wires

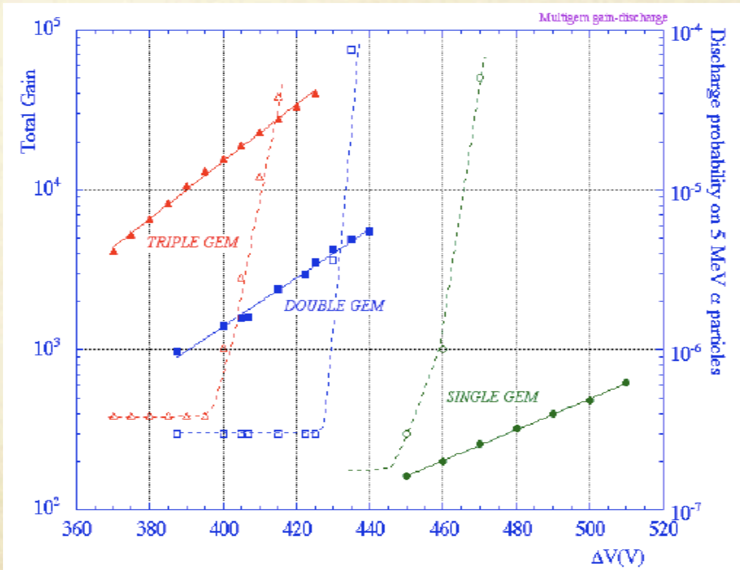
# Wire chambers "advanced"

- 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!

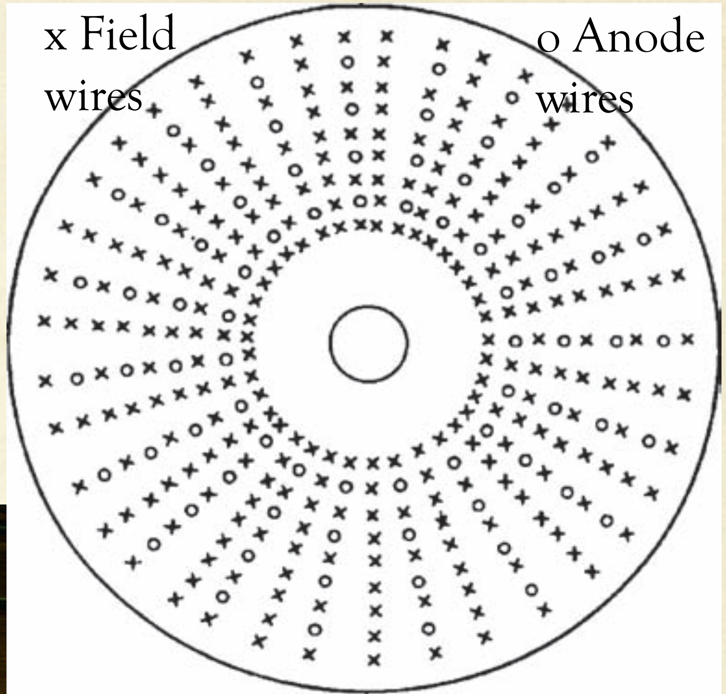


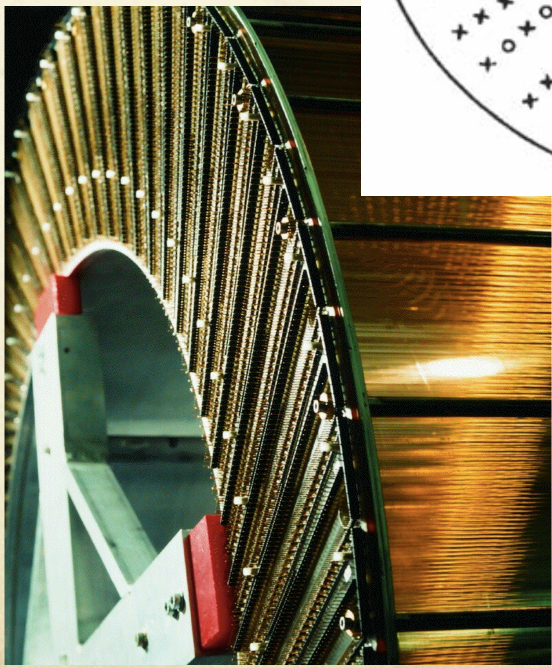
# Drift chambers

- 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

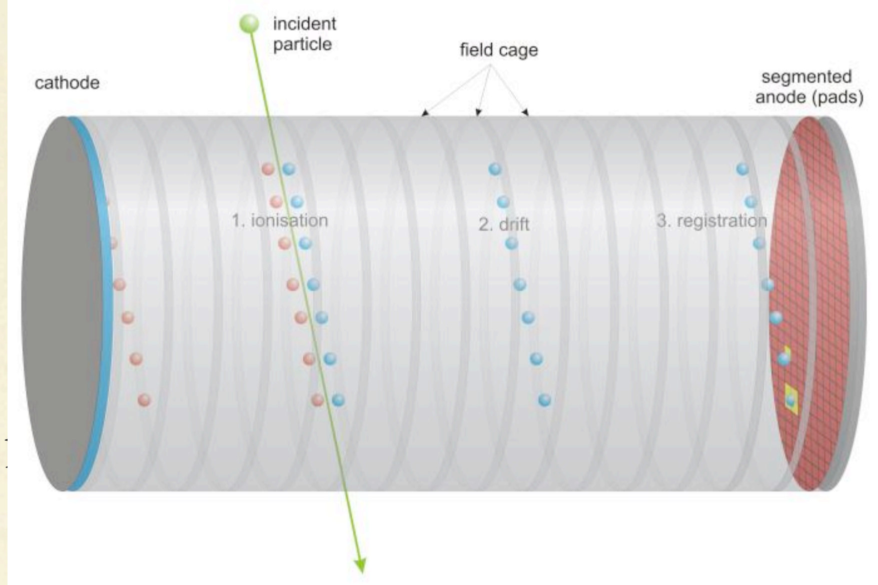


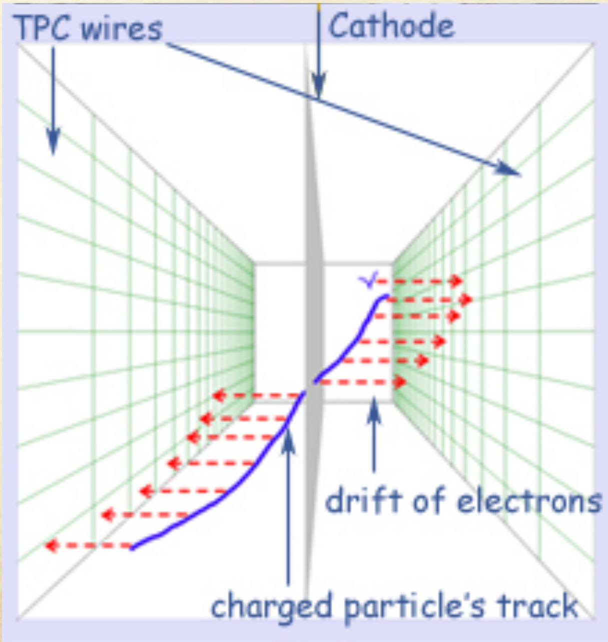



H1 drift chamber

# Time Projection Chambers 1/2

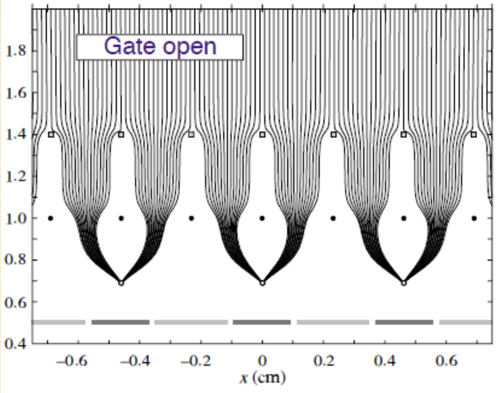
- Benefits
  - Large volume available
  - Multi-task: tracking + Part. Identification
- Basic operation principle
  - Gas ionization → charges
  - Electric field → charge drift along straight p
  - End cap readout
    - wire proportional chamber - type
  - Information collected
    - 2D position of charges 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

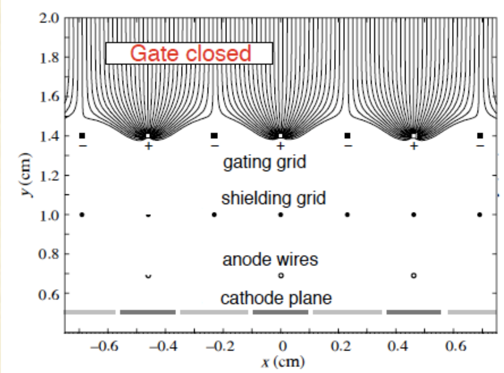


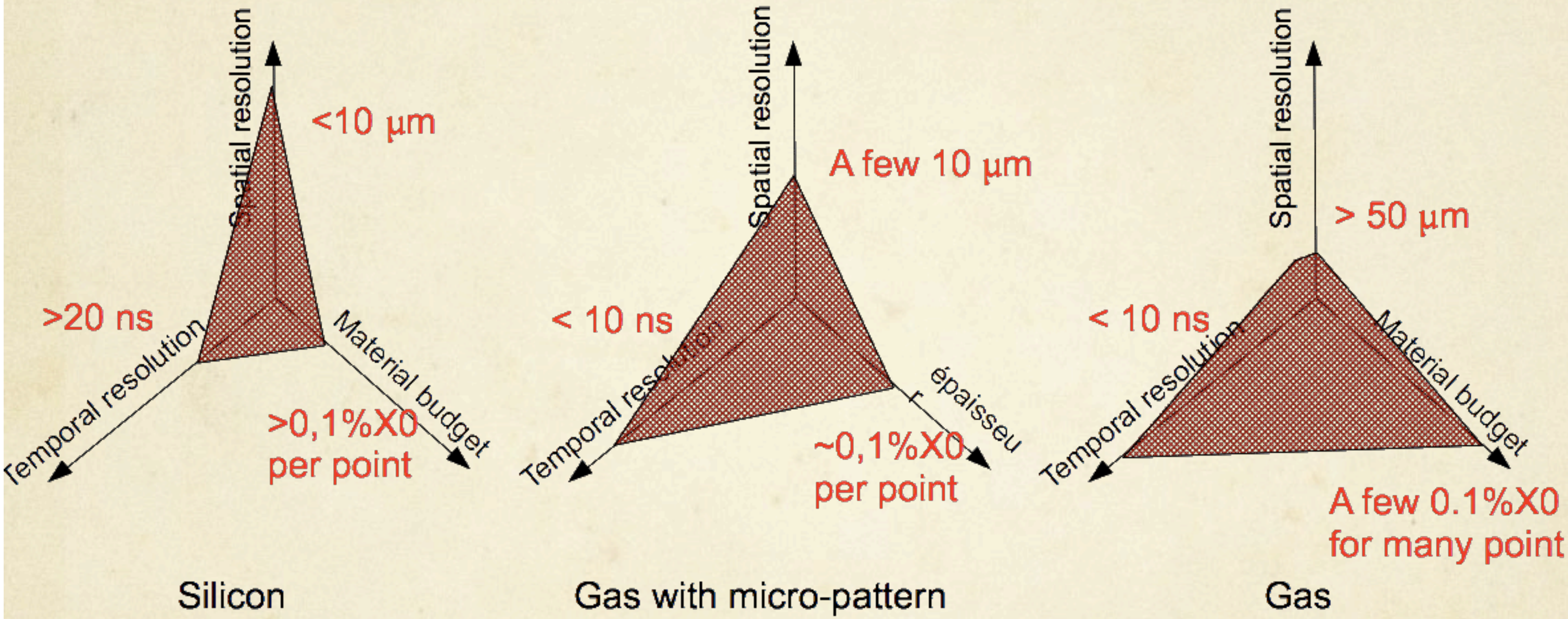
# Time Projection Chambers 2/2

- 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



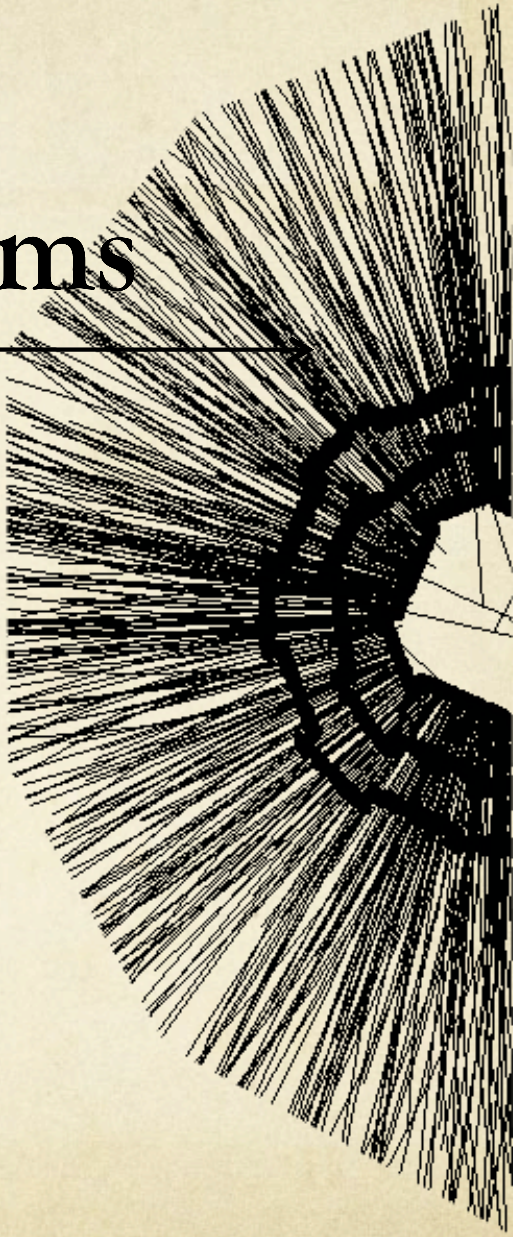
# Tentative comparison



# 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
- 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. Reconstruction algorithms

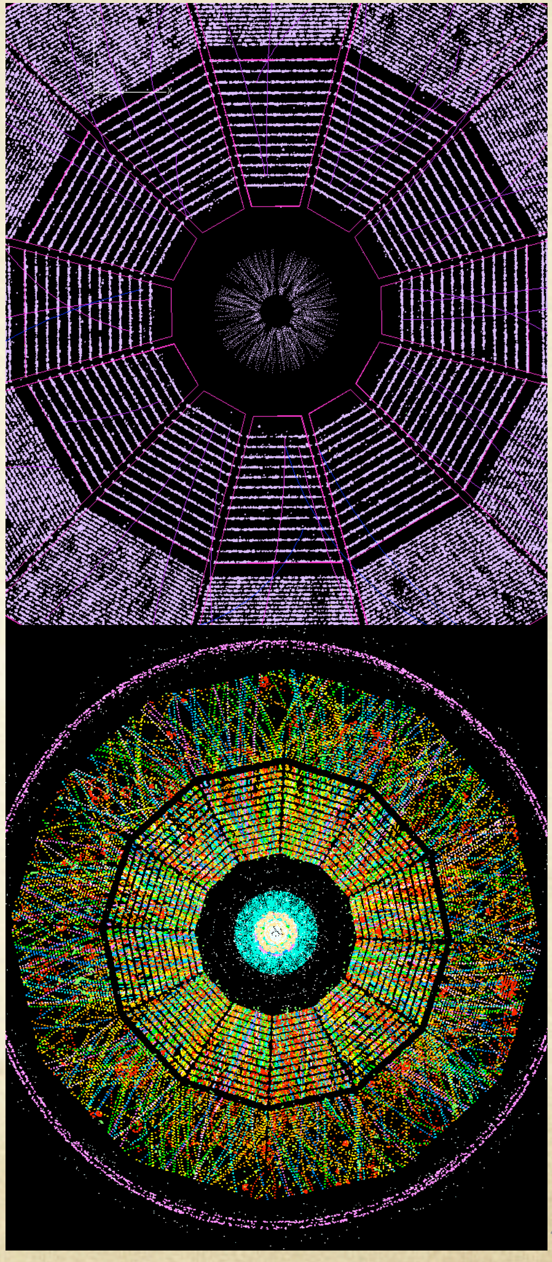


- Finders
- Fitters
- Adaptive methods
- Alignment

# Several tasks

- **Hypothesis**
  - We have sensing layers which provides points
  - We know where those points are located
  - The track model (helix/circle/line) is known

- **A two functions process**
  - Identify hits belonging to the same track (or tracks to the same vertex)
    = pattern recognition or FINDING
  - Adjust the track parameters from the point locations
    (or the vertex parameters from the tracks)
    = FITTING
  - Note: Tracking and Vertexing are conceptually identical



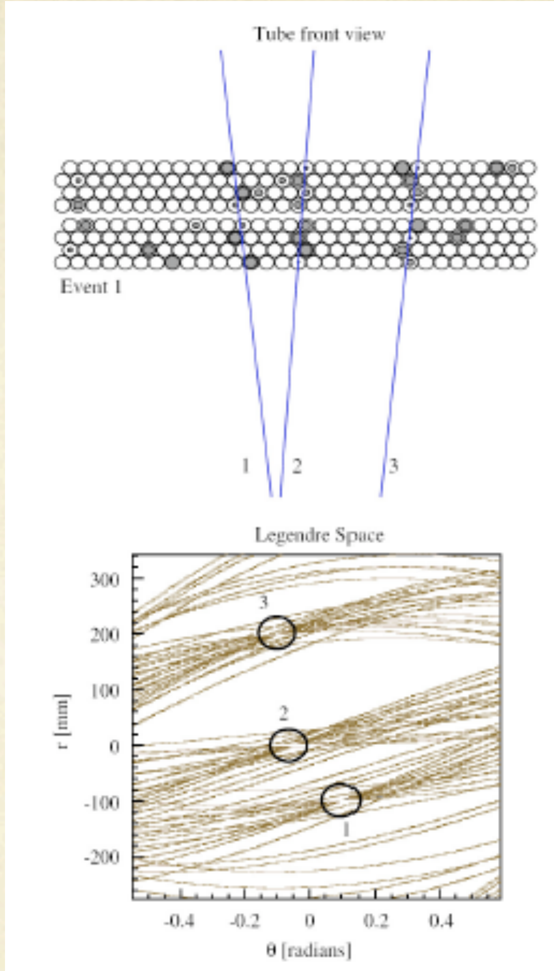
An event Au+Au @ 200 GeV by STAR

hits only

tracking done

# FINDING

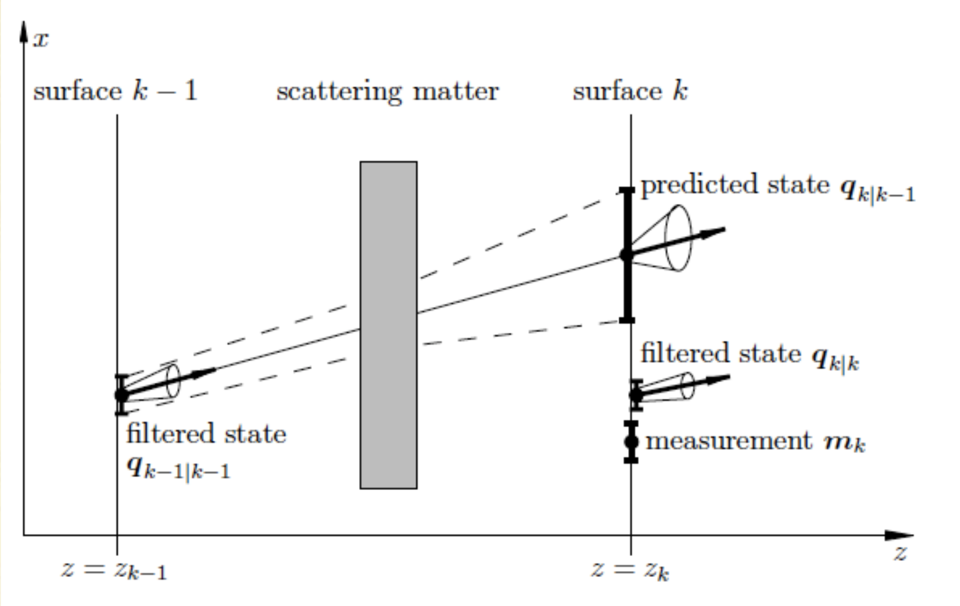
- Global methods
  - Use all points at a time
  - Transform the phase space
    - Circles  lines
    - Lines points
  - Identify the best solutions in the new phase space
  - Well adapted to evenly distributed points with same accuracy




- Local methods
  - Start with a seed = group of restricted #hits most probably belonging to the same track
    - Initiate the track parameter
  - project to next layer
  - Find the "best" point
    - Use $\chi^2$ approach to define "best" $\frac{(\mathrm{pos}_{\mathrm{hit}} - \mathrm{pos}_{\mathrm{track}})^2}{\text{spatial res.}^2}$
  - Recompute track param & iterate to next layer

**FINDING drives tracking efficiency**

# FITTING

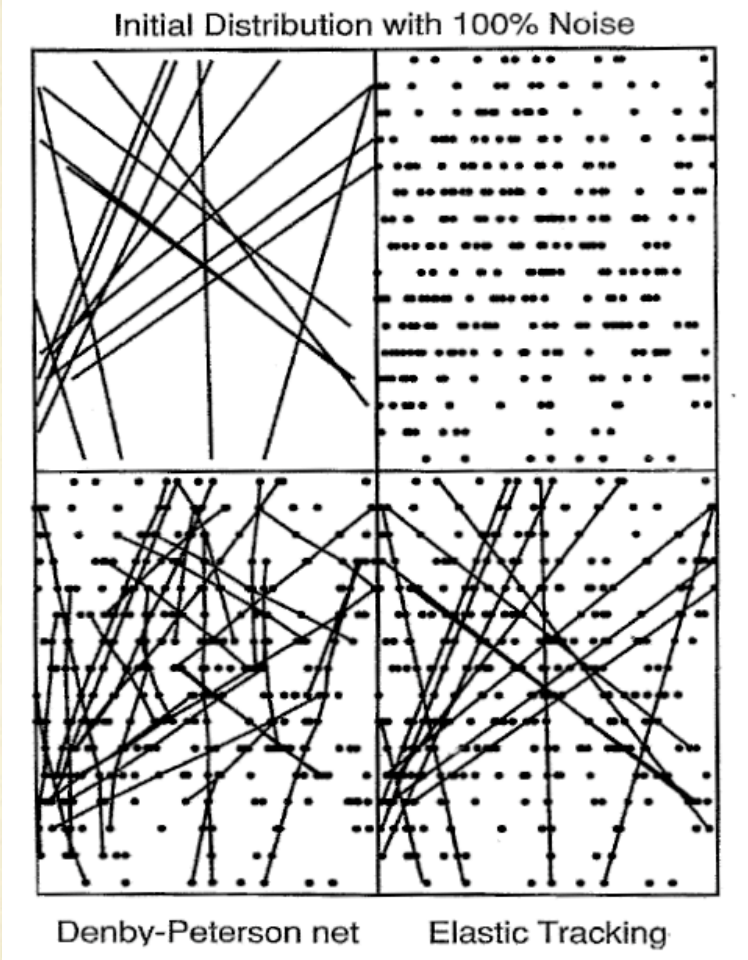



- **Why do we need to fit?**
  - Measurement error
  - Multiple scattering error
- **Recursive method (linear $\chi^2$ and Kalman filter)**
  - Start from an initial set of parameters:
  - Propagate to next layer:
    - New parameters
    - AND new covariance matrix (see F.Le Diberder's lecture)
  - 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 $\chi^2$ value)

FITTING drives track extrapolation & momentum res.

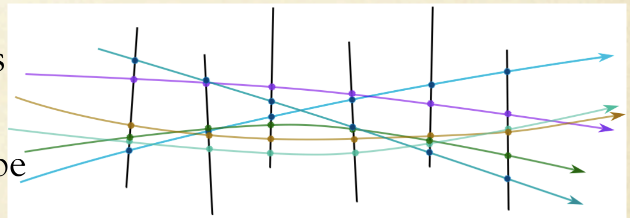
# Adaptive methods

- 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

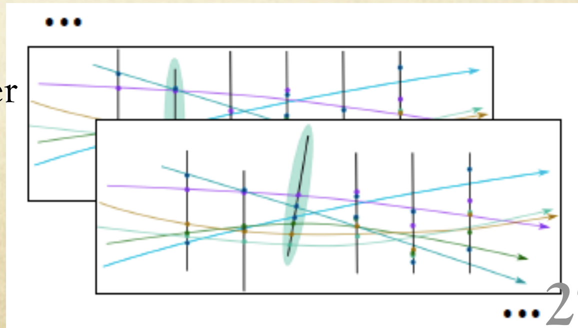


# Alignment strategy

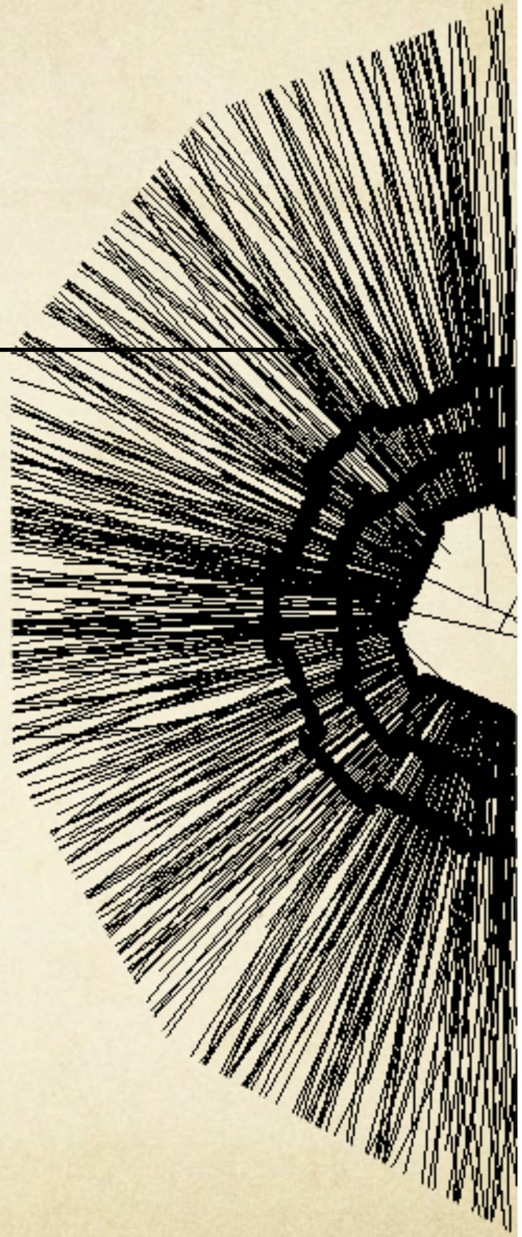
- Let's come back to one hypothesis
  - We know were the point are located
  - True to the extent we know were the detector is!
  - BUT, mechanical instability (magnetic field, temperature, air flow…) and also drift speed variation (temperature, pressure, field inhomogeneity…) limit our knowledge
  - 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 $\chi^2$ 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

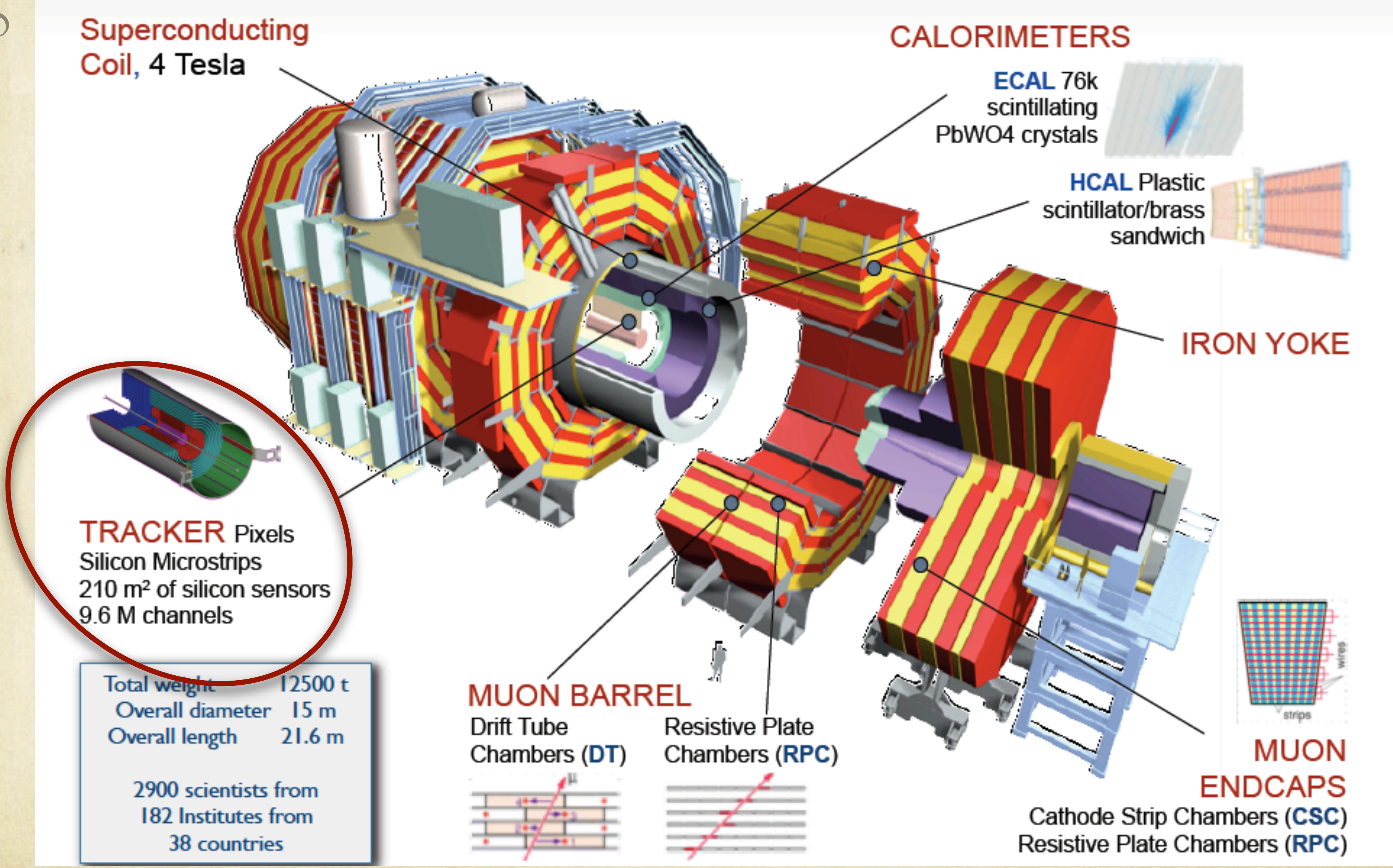


# 4. Deconstructing some tracking systems

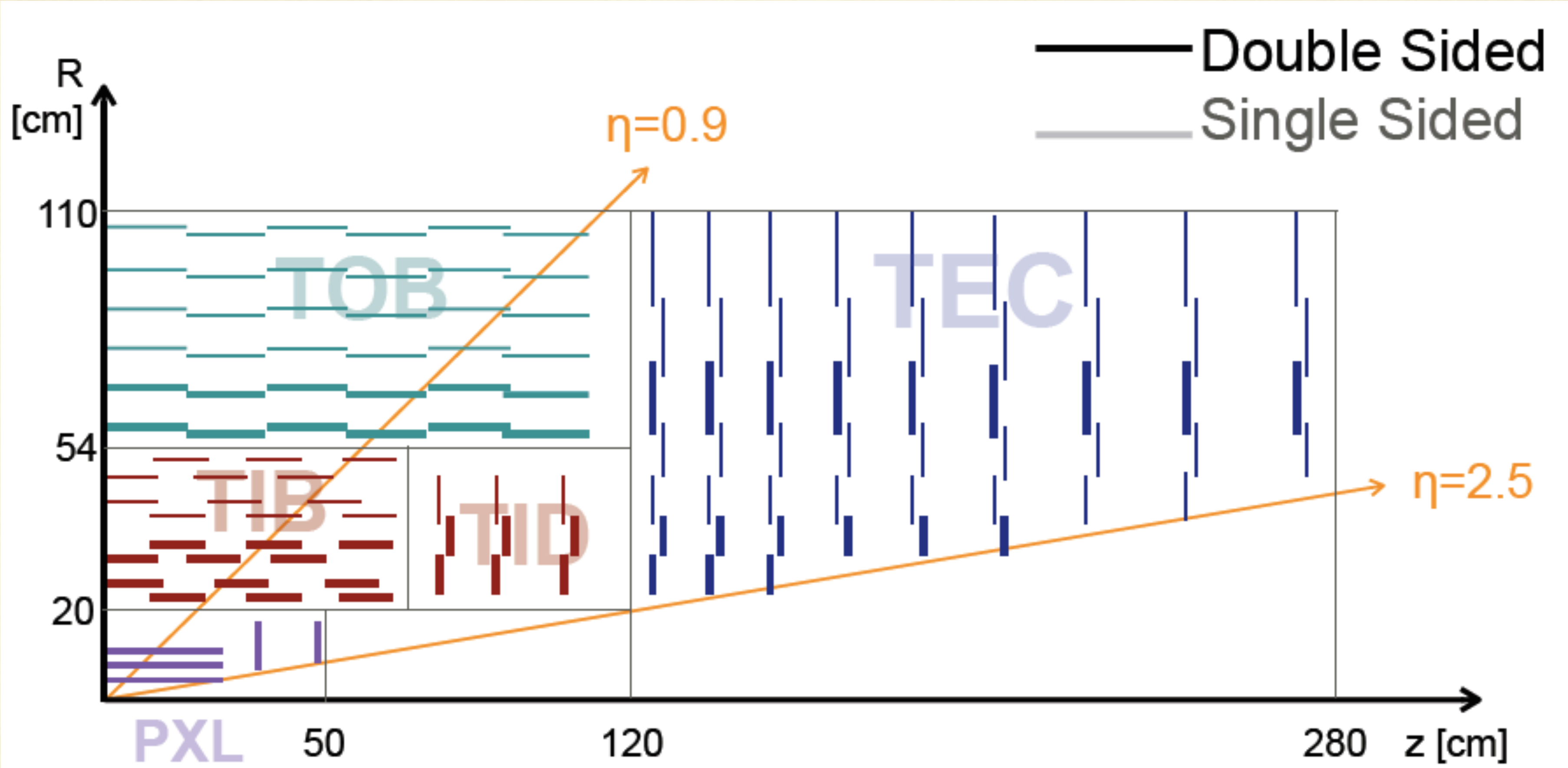


# 4. Some tracking systems:

CMS

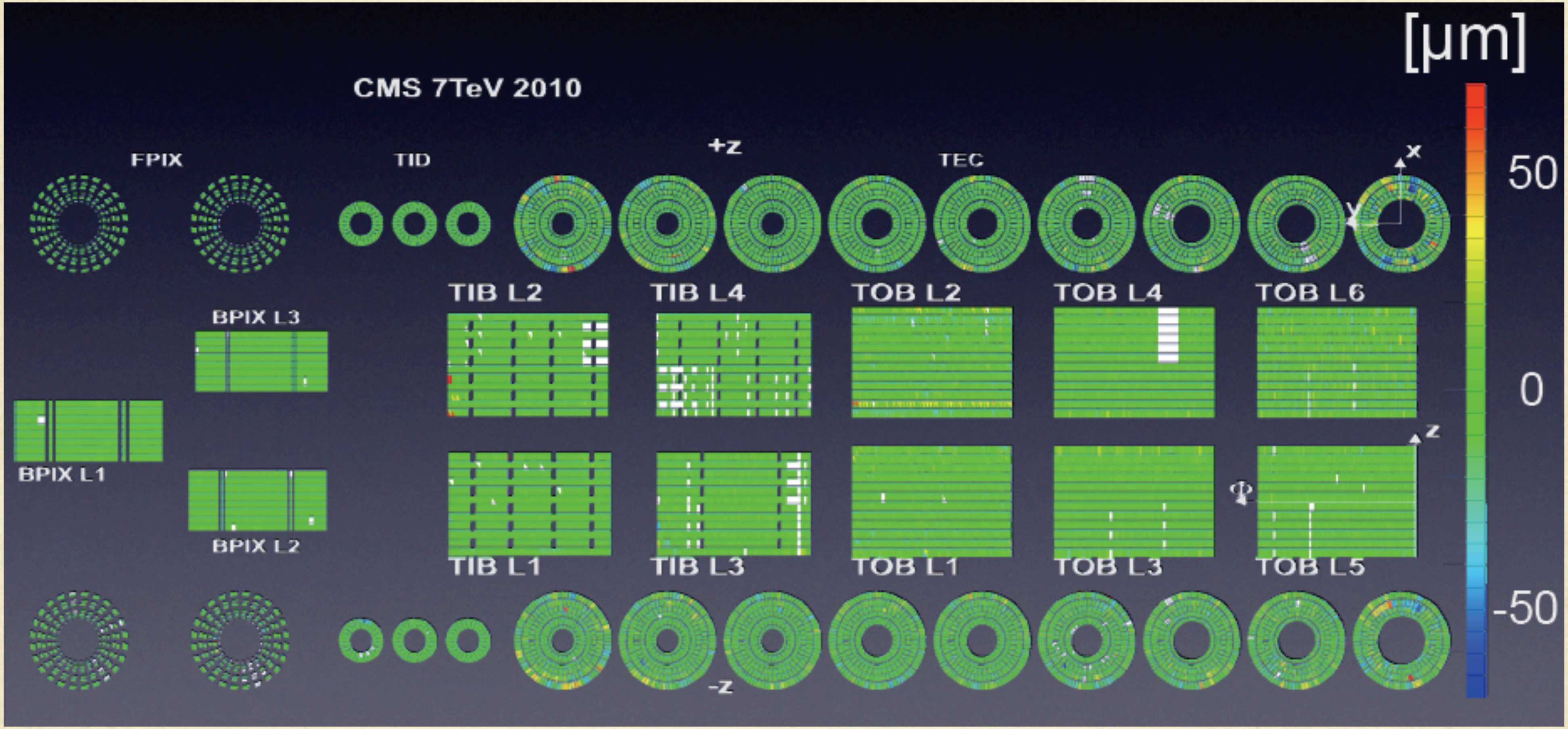


CMS


Double Sided
Single Sided
R [cm]
η=0.9
η=2.5
110
54
20
TOB
TEC
TIB
TID
PXL
50
120
280
z [cm]

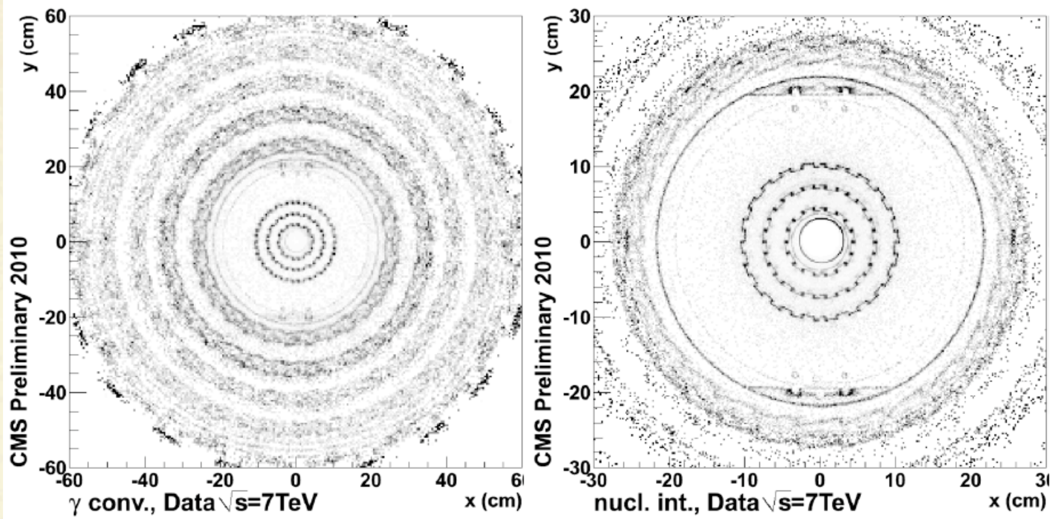
CMS

- Alignment residual width

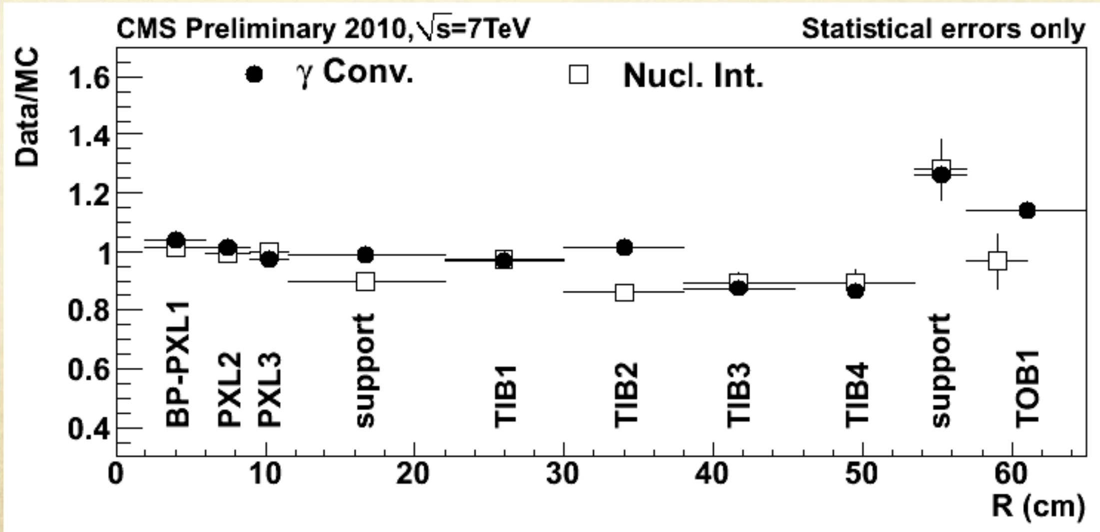


# CMS

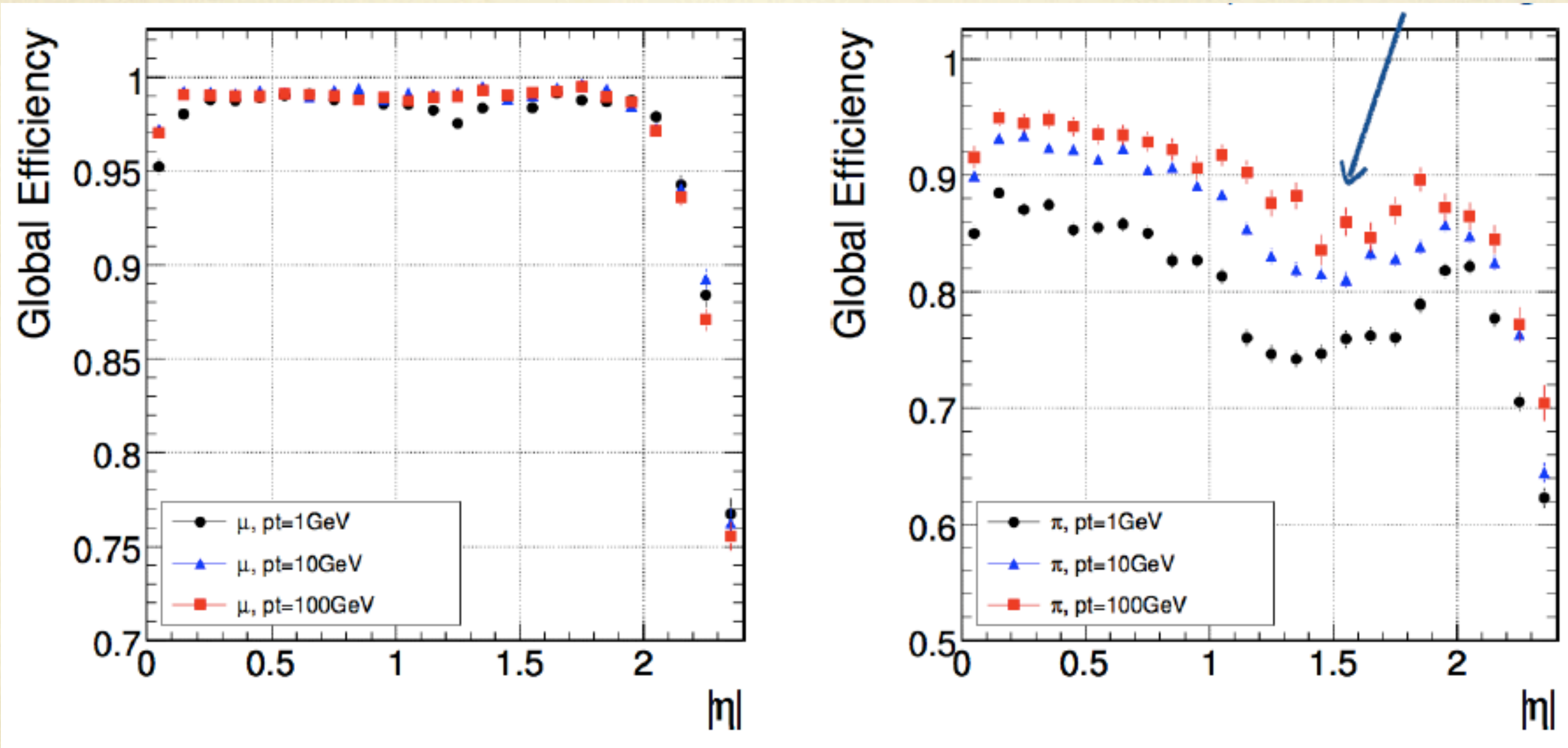
- Taking a picture of the material budget
  - Using secondary vertices from
    photon conversion
    nuclear interaction




- Measuring it by data/simulation comparison

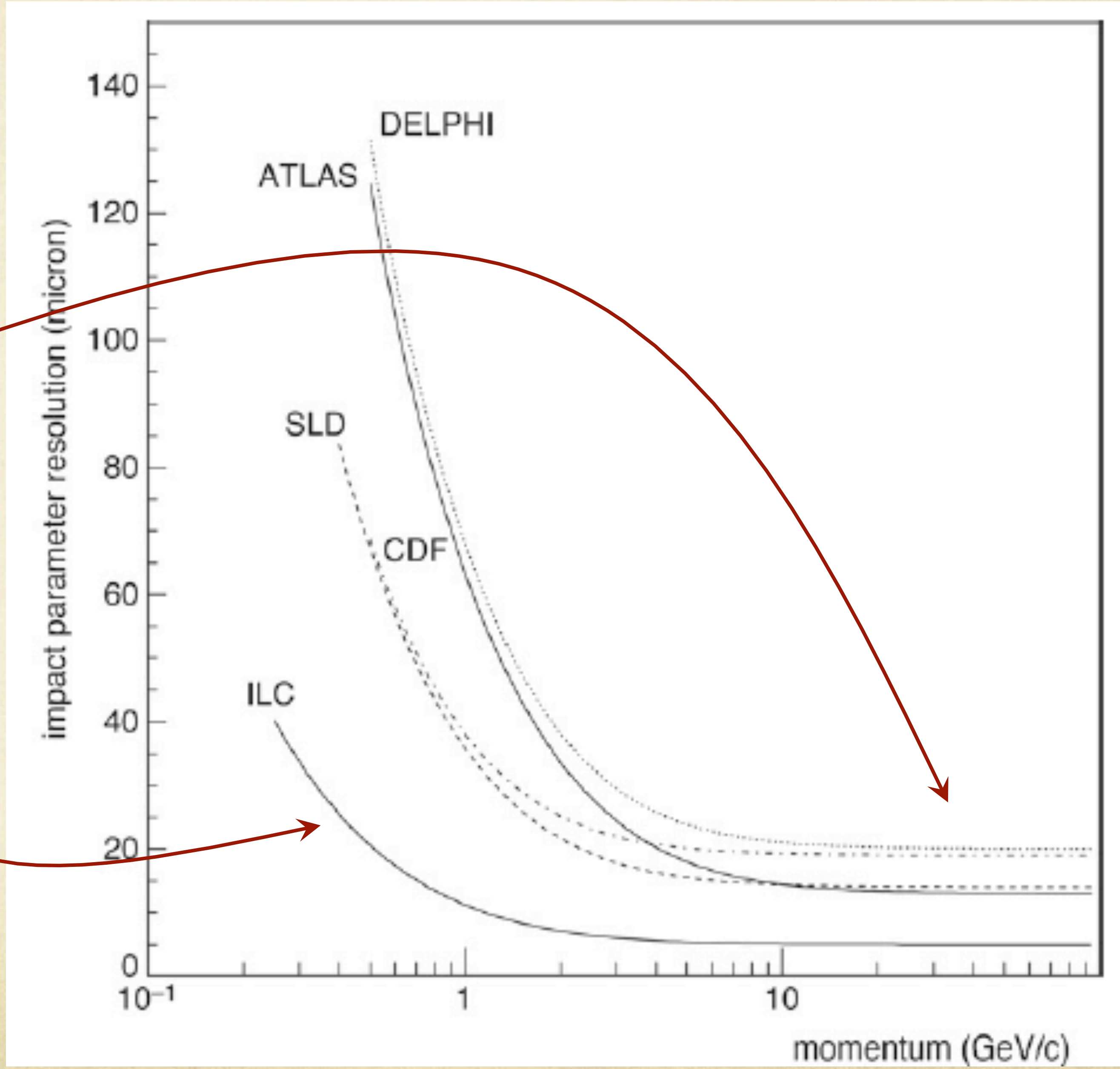


- Tracking efficiency

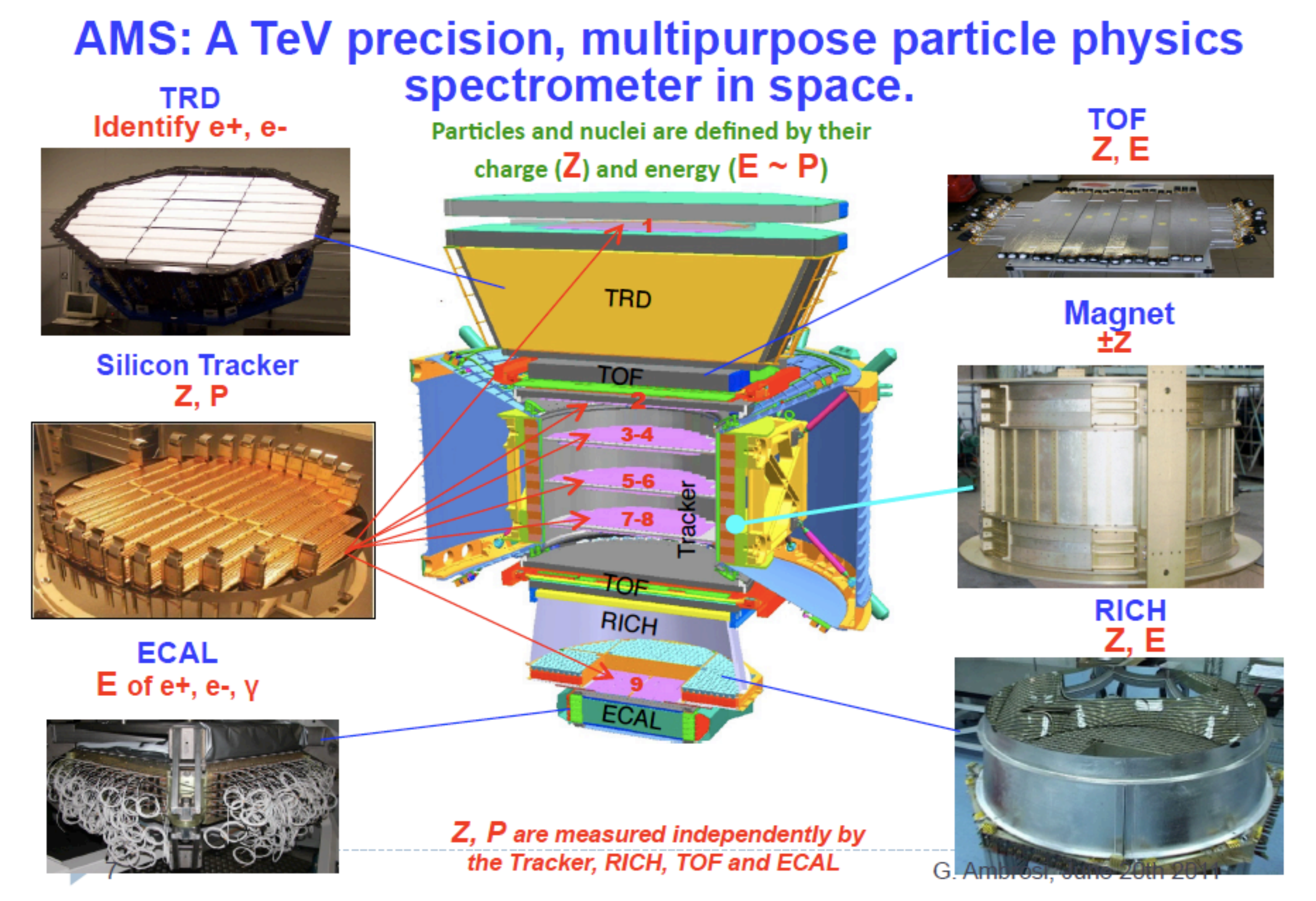


# Impact parameter resolution

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

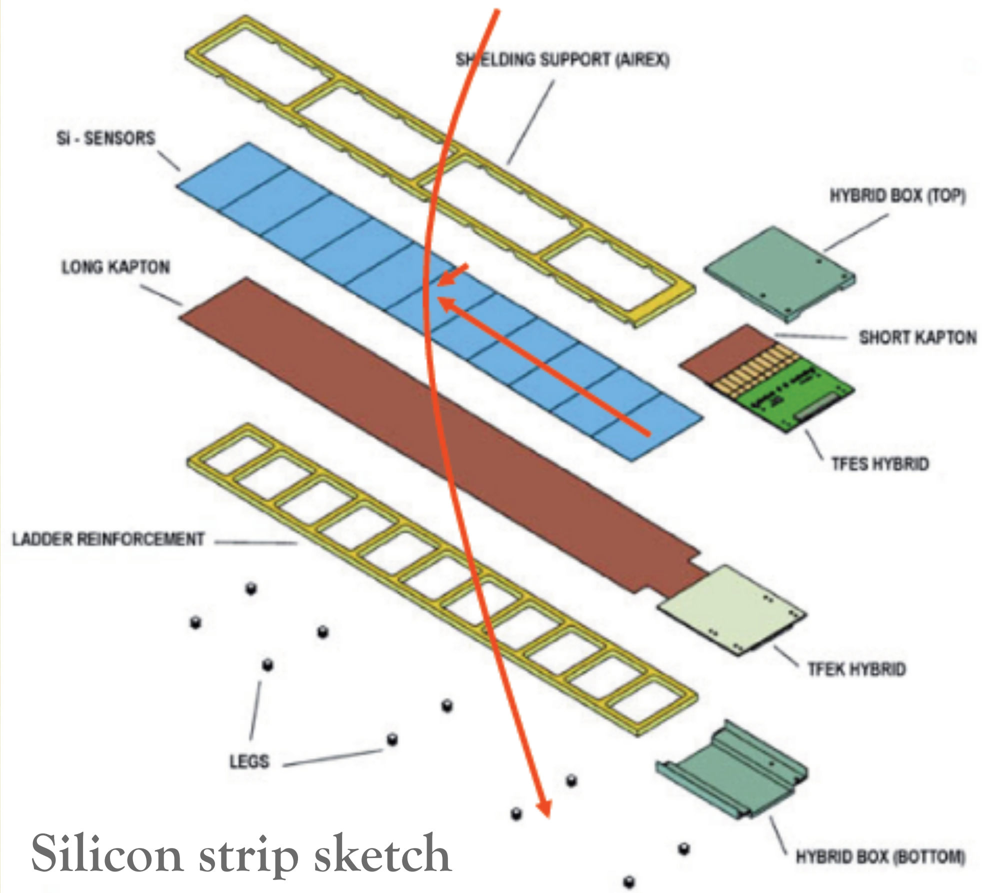


# AMS

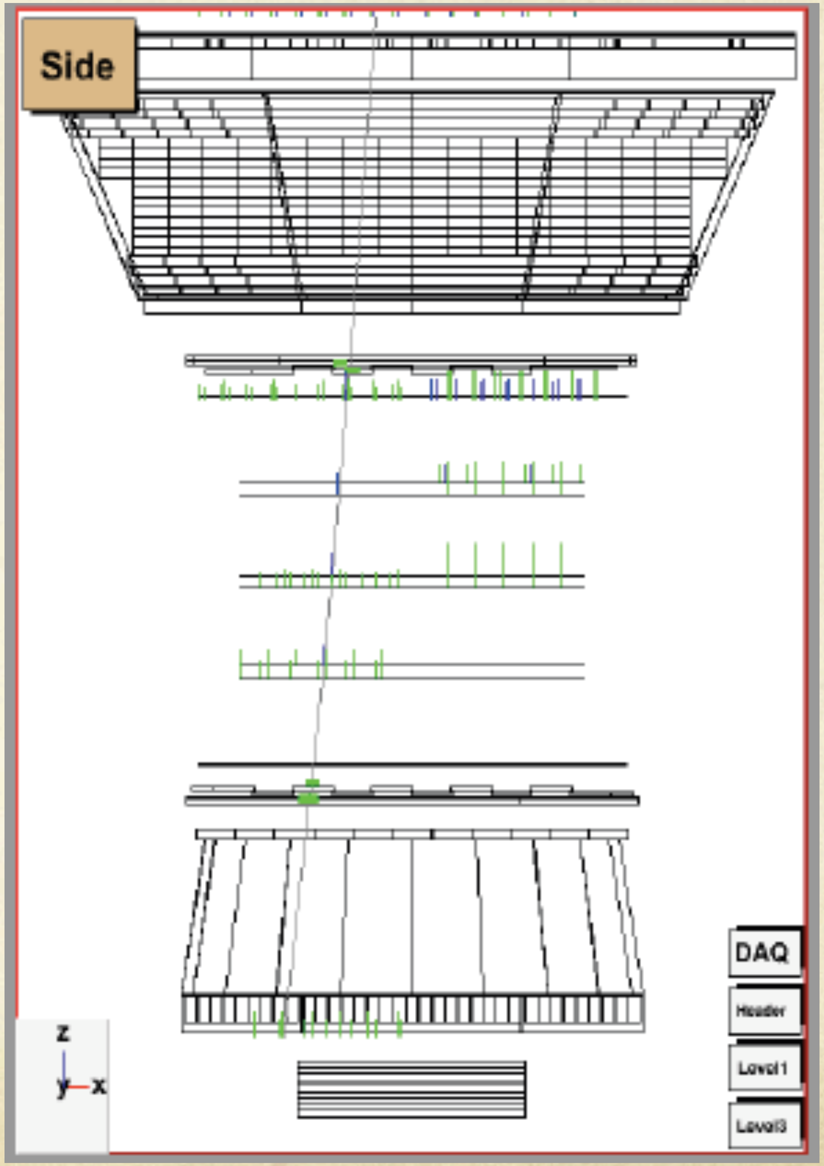

AMS: A TeV precision, multipurpose particle physics spectrometer in space.
Particles and nuclei are defined by their charge (Z) and energy (E ~ P)
TRD
Identify e+, e-
Silicon Tracker
Z, P
ECAL
E of e+, e-, γ
TOF
Z, E
Magnet
±Z
RICH
Z, E
TRD
TOF
1
2
3-4
5-6
7-8
Tracker
TOF
RICH
9
ECAL
Z, P are measured independently by the Tracker, RICH, TOF and ECAL
G. Ambrosi, June 20th 2011

# 4. Some tracking systems:

AMS




Silicon strip sketch



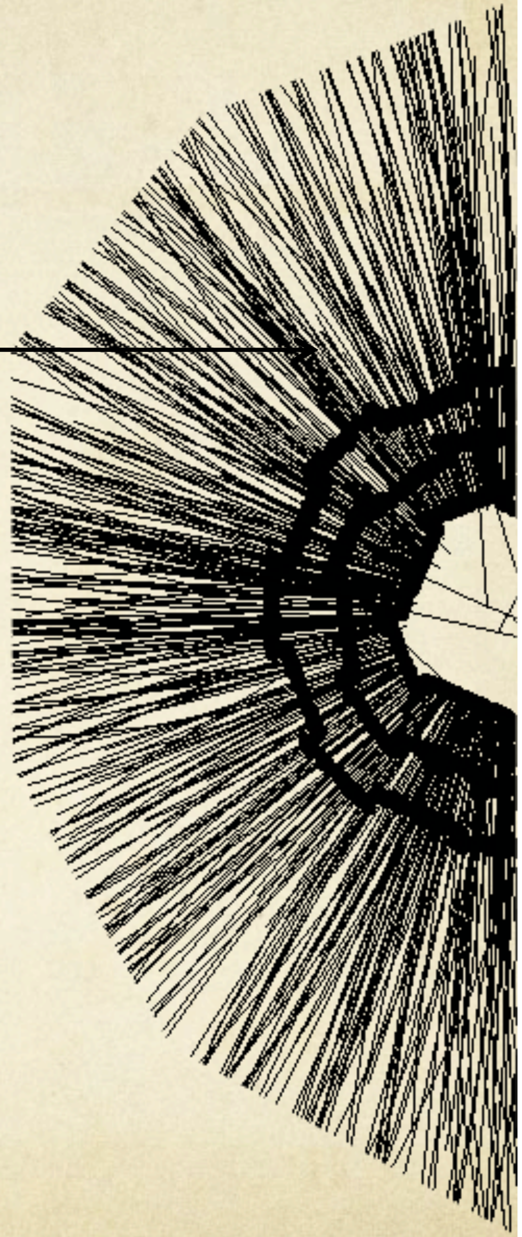
# Summary

- **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

What is this?

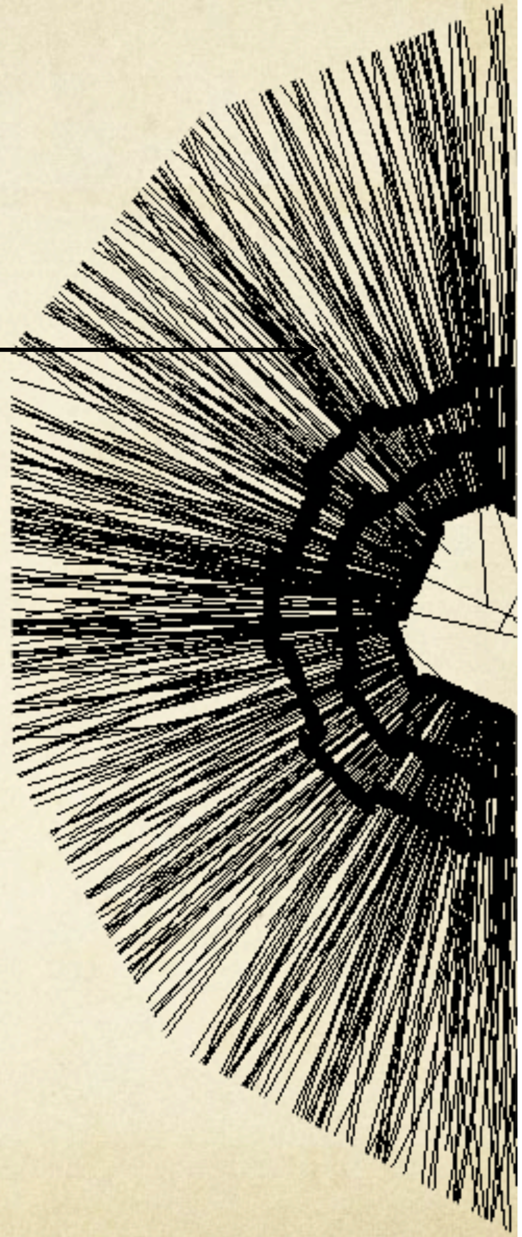
# References

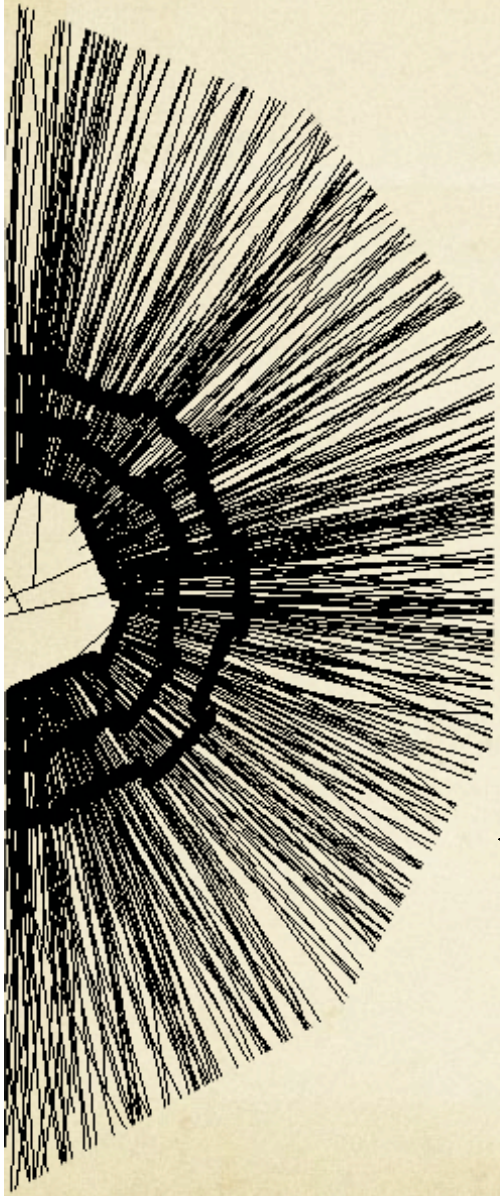
- …



# Was not discussed

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

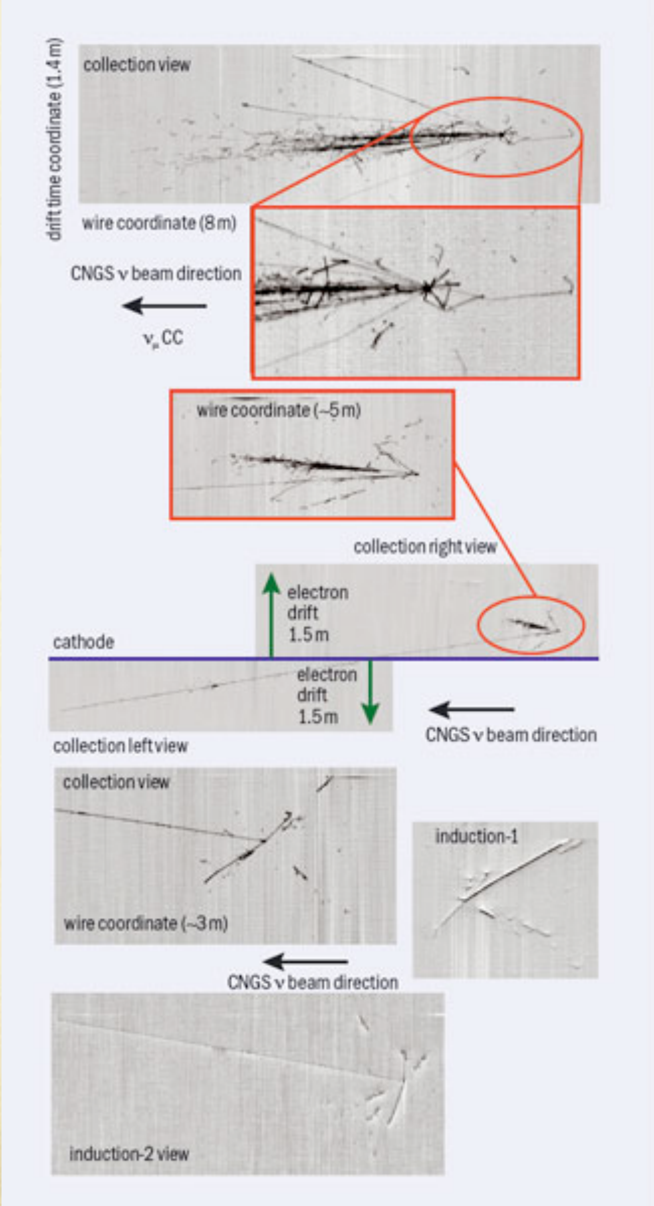




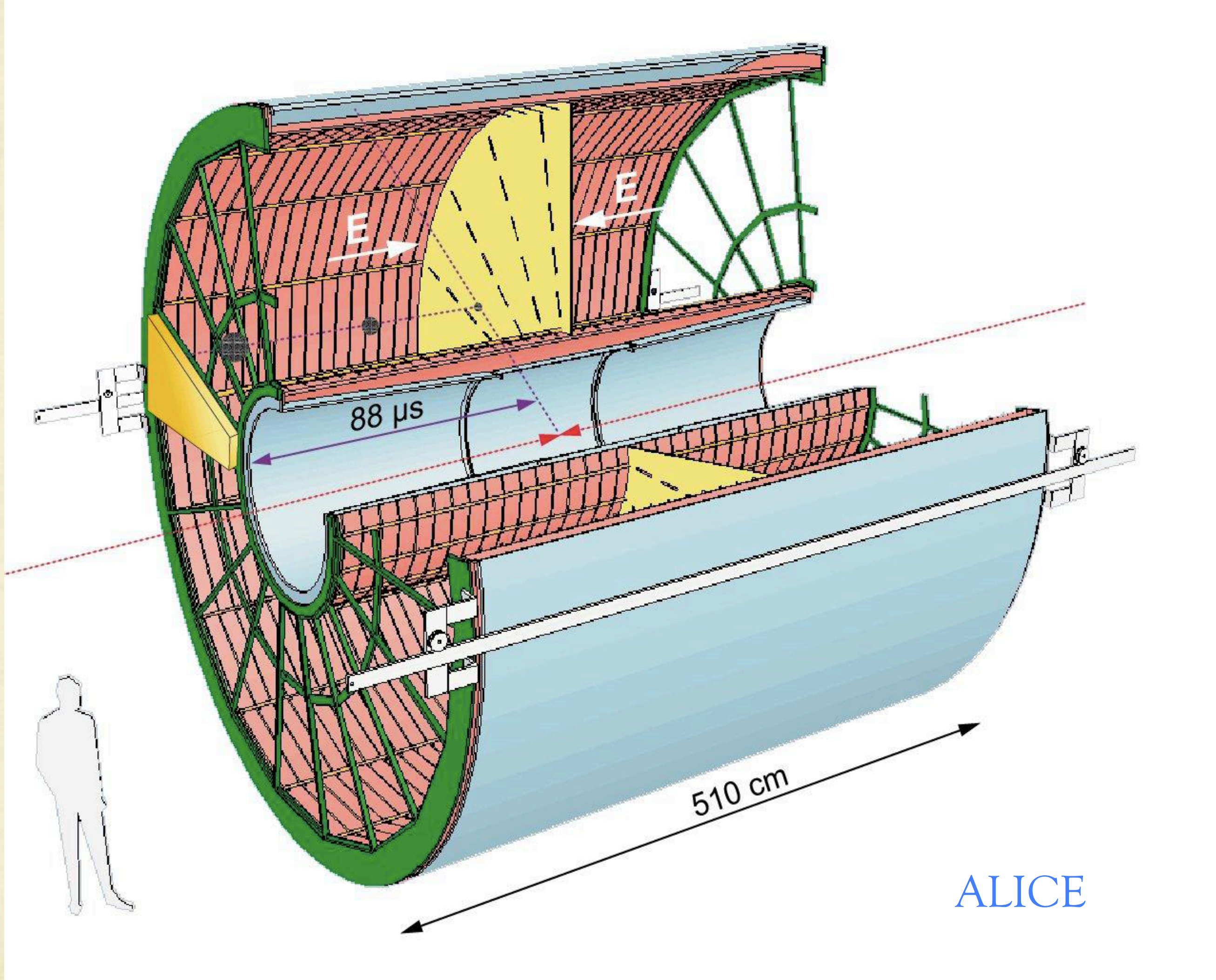
# Backups

# OPAL drift chamber

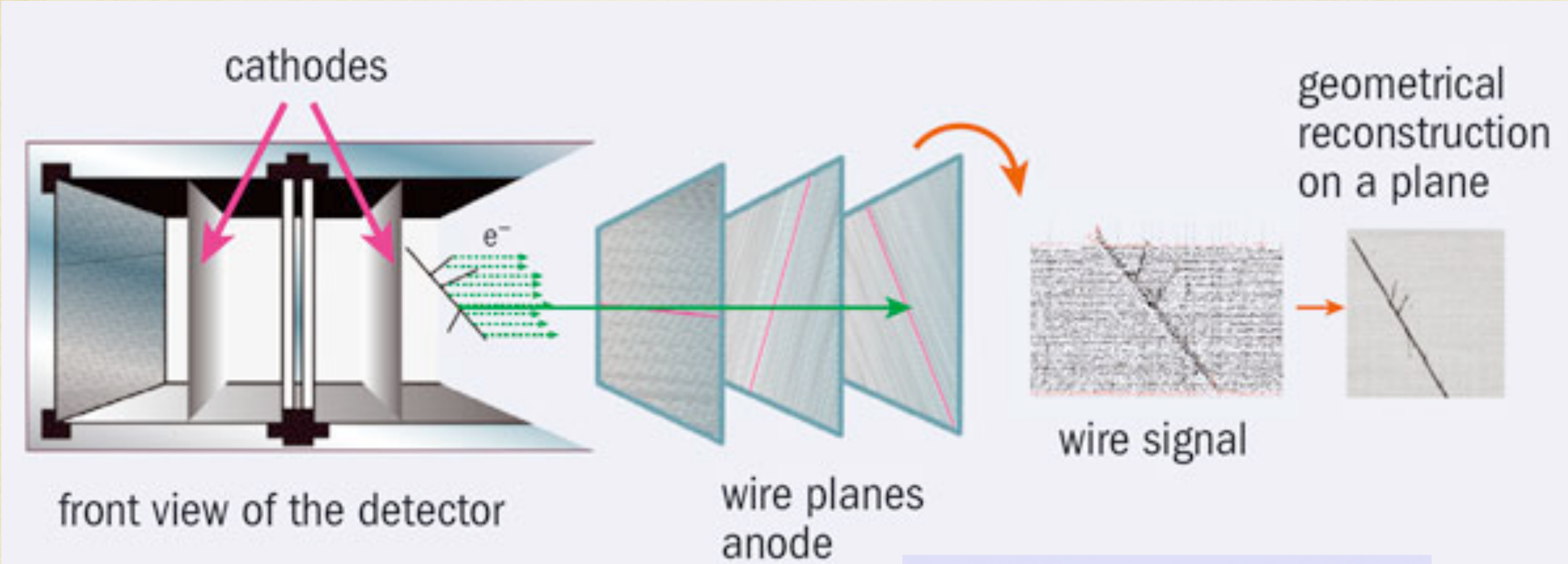
# ICARUS - event

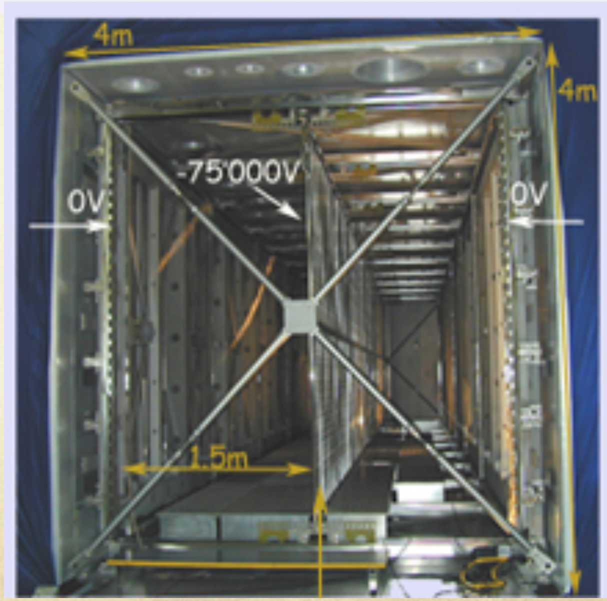


# ALICE - TPC

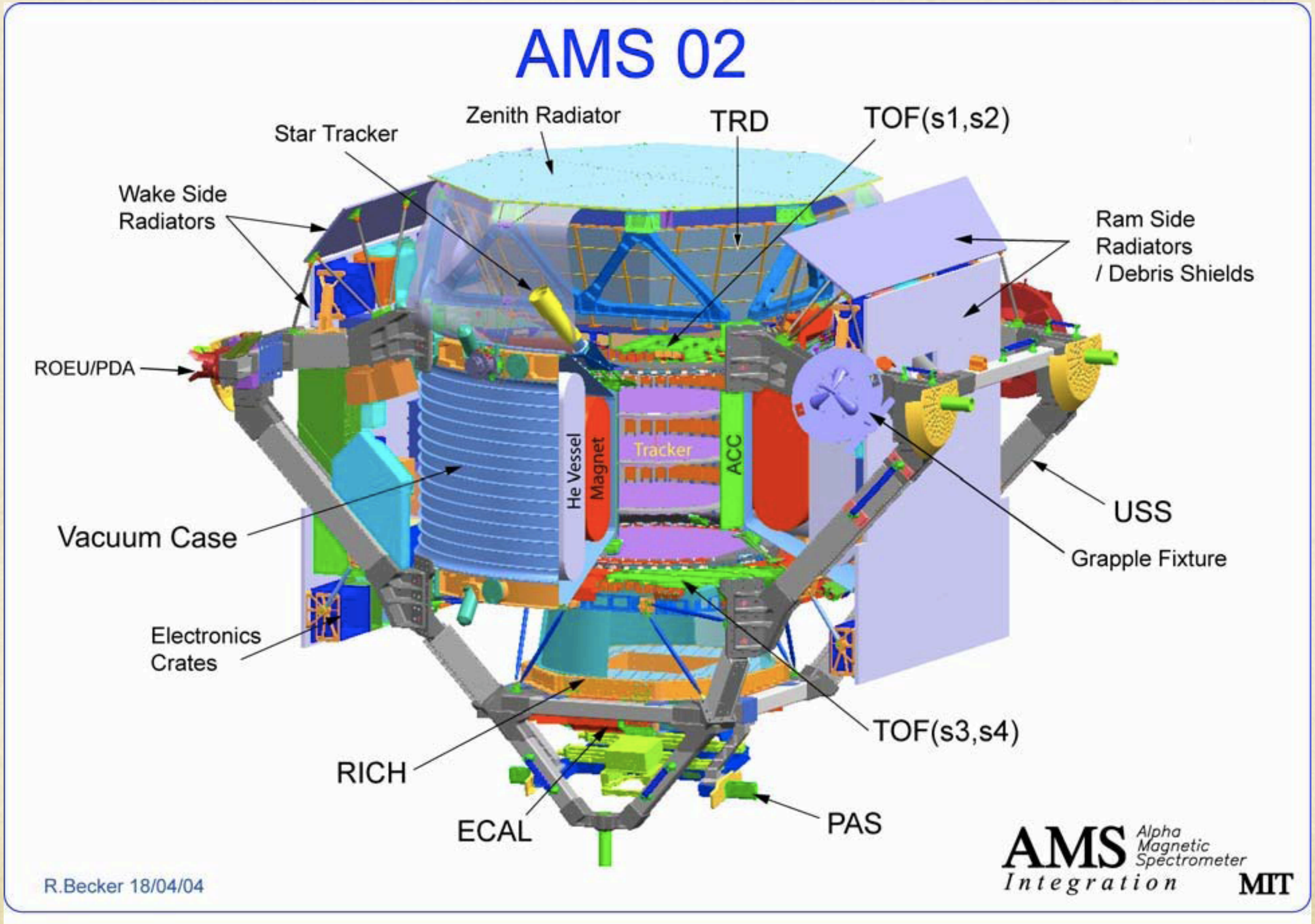


# ICARUS - TPC

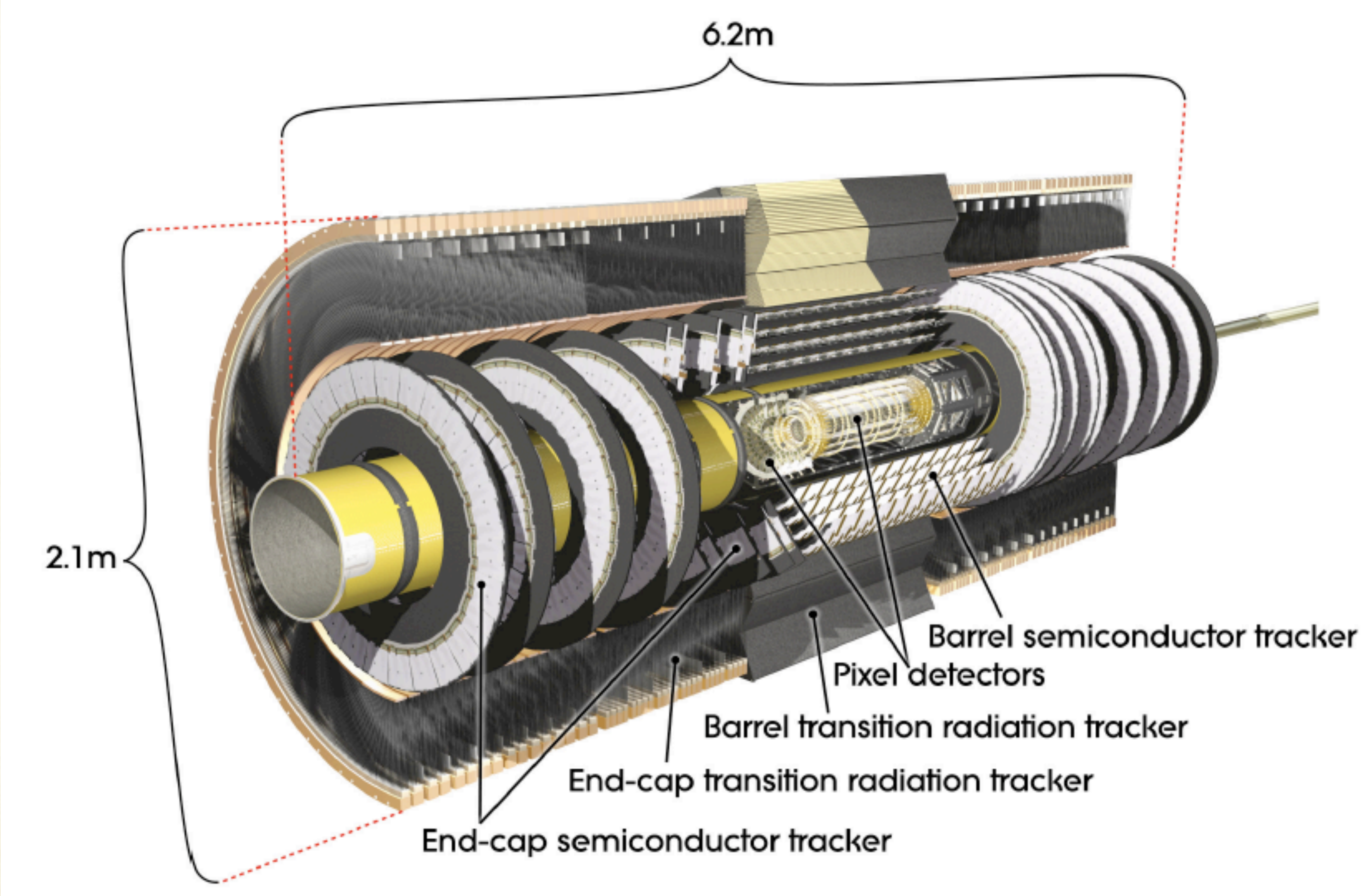

cathodes
e⁻
geometrical reconstruction on a plane
wire signal
front view of the detector
wire planes anode


4m
4m
-75 000V
0V
0V
1.5m

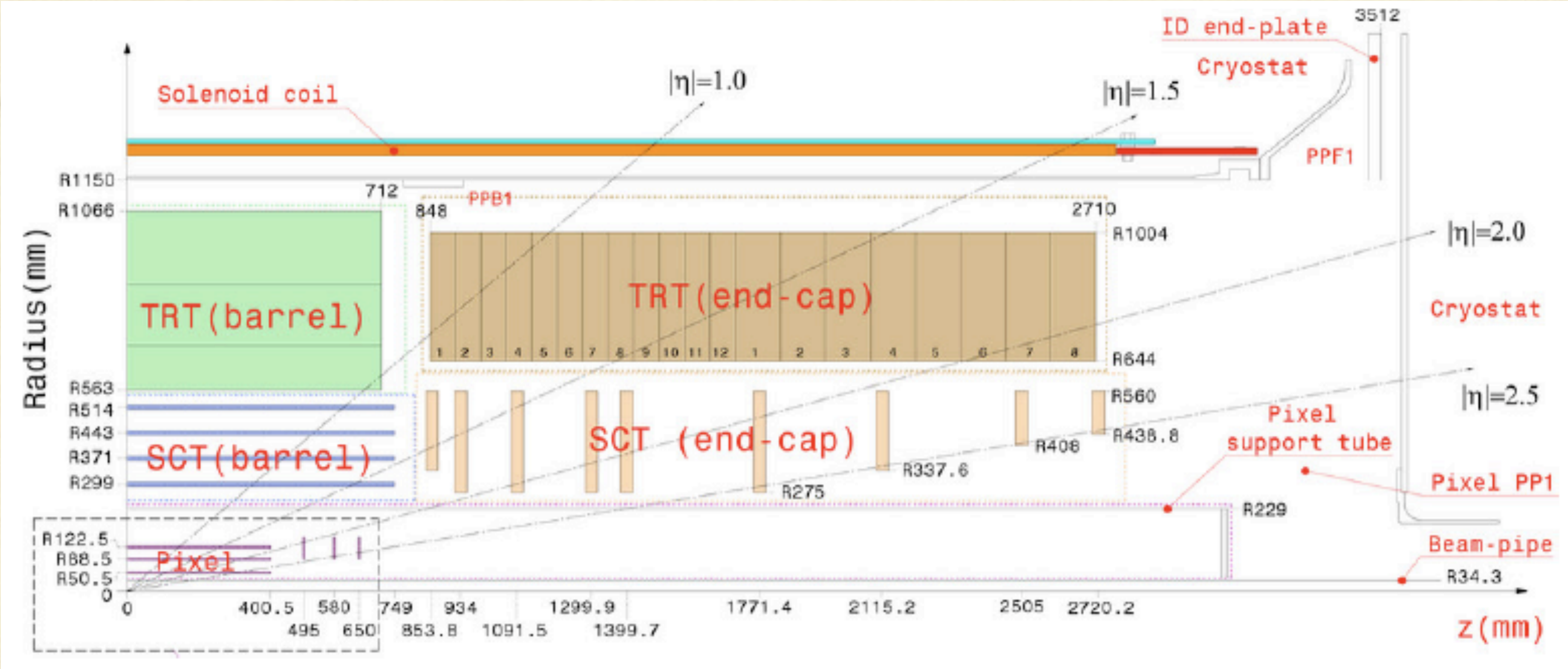
# Backups:


AMS 02
Zenith Radiator
Star Tracker
TRD
TOF(s1,s2)
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
R.Becker 18/04/04
AMS Alpha Magnetic Spectrometer
Integration
MIT

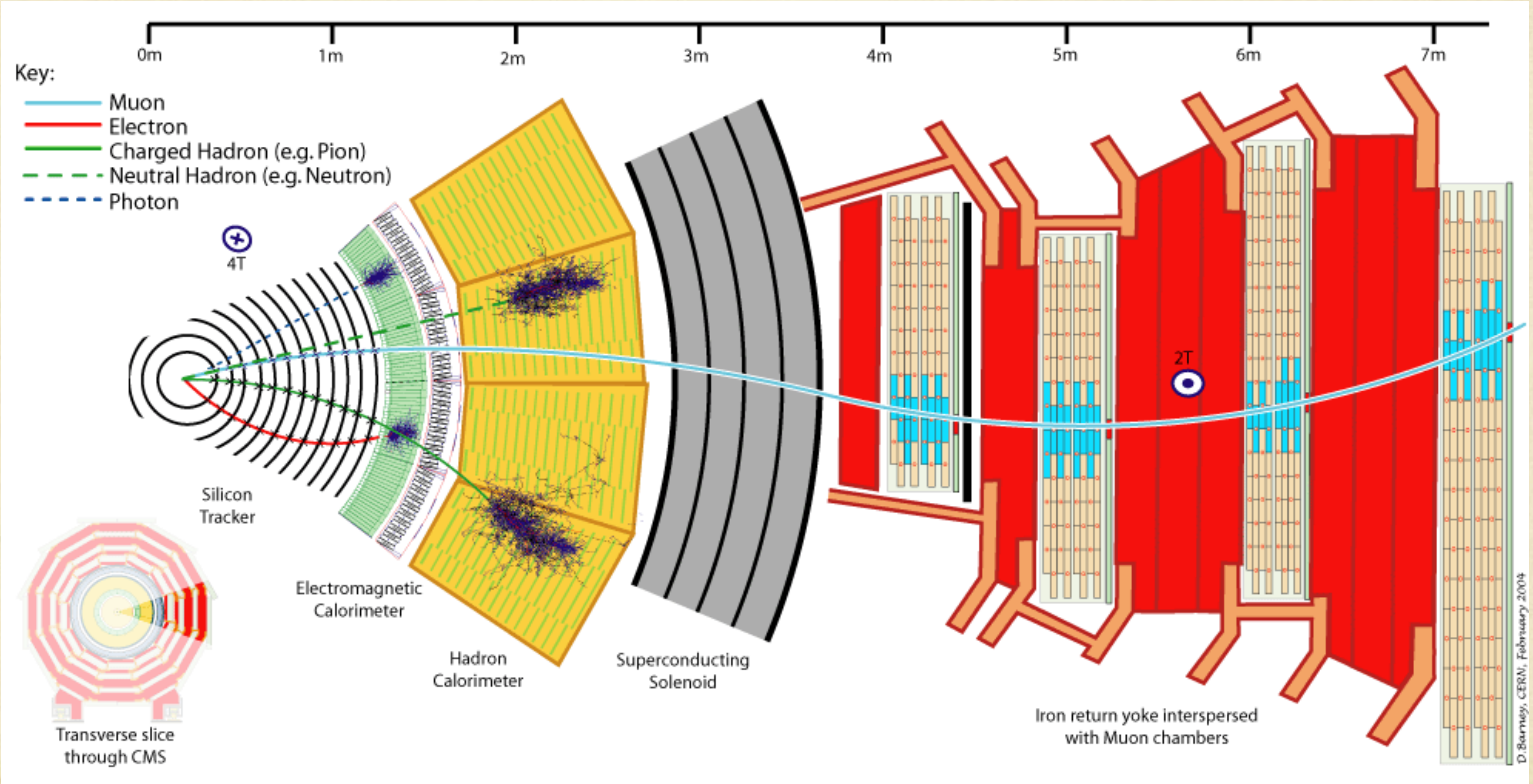
# ATLAS tracking setup



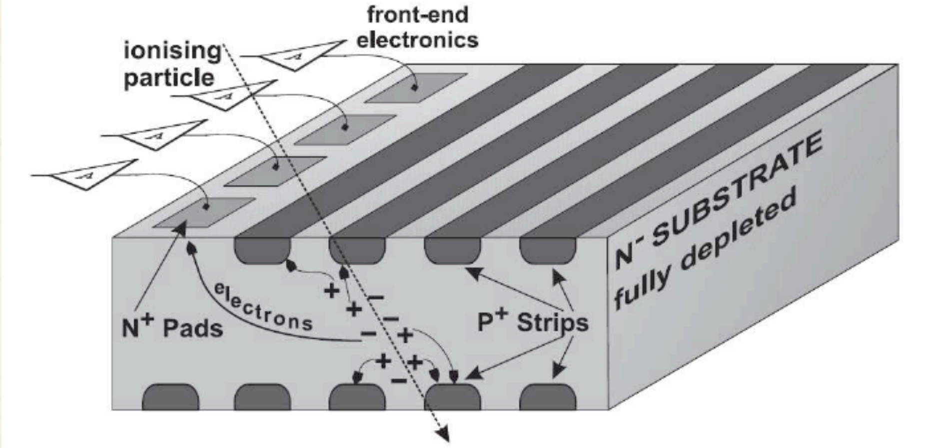
# ATLAS tracking setup



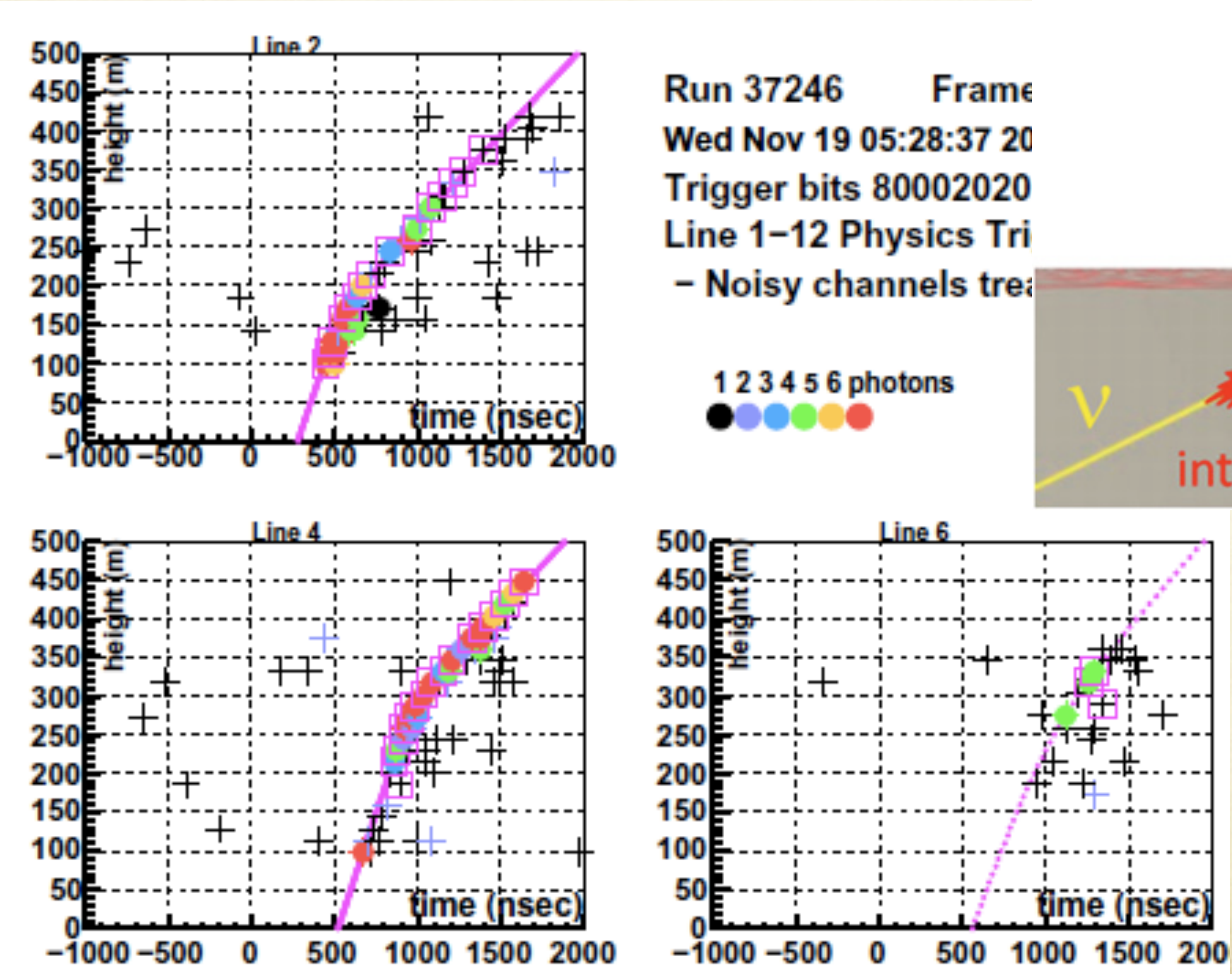
# CMS

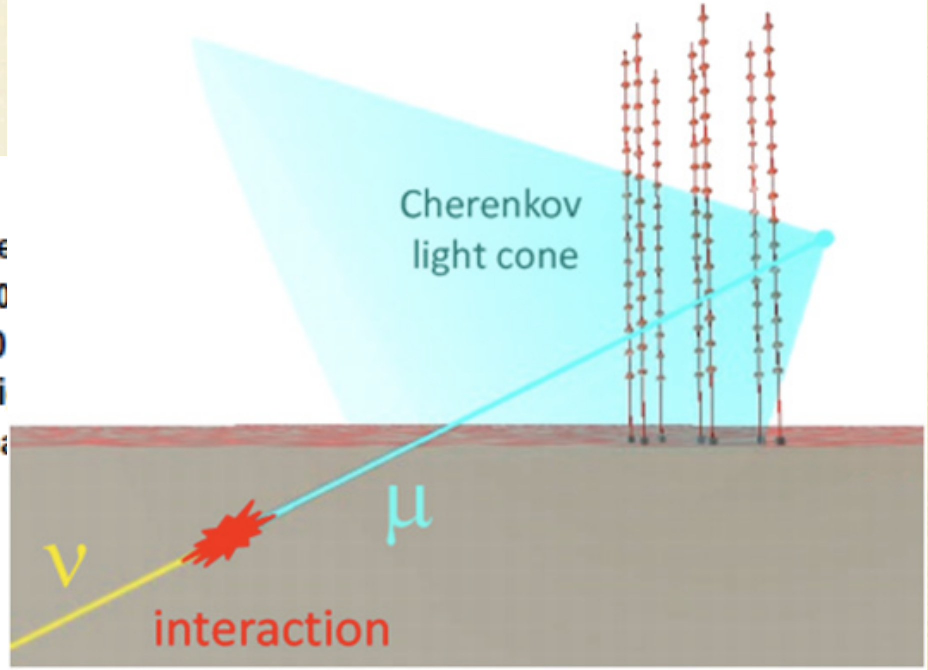

0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February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

# Silicon sensors: drift



# ANTARES


Line 2
Line 4
Line 6
height (m)
time (nsec)
Run 37246 Frame
Wed Nov 19 05:28:37 20
Trigger bits 80002020
Line 1−12 Physics Tri
− Noisy channels trea
1 2 3 4 5 6 photons


Cherenkov
light cone
μ
ν
interaction