Tracking

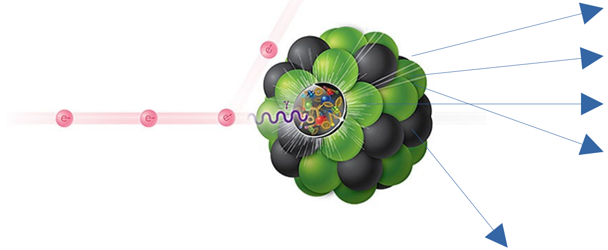
2nd European School on the Physics of the EIC and Related Topics

Benicàssim, July 23rd - 24th 2025

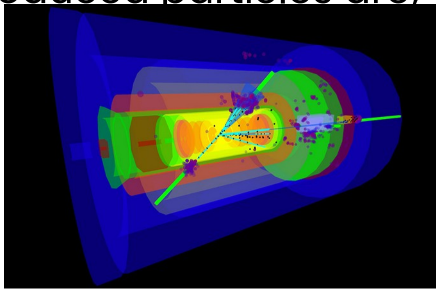
F. Bossù (CEA/Irfu)

From collisions to analysis

We start by colliding electrons against nuclei

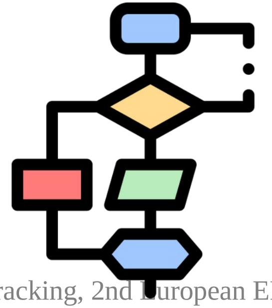


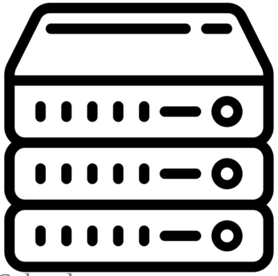
We need detectors to know where and what produced particles are;

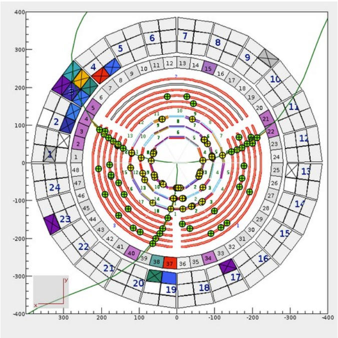


...electronics to read, decode and store signals from sensors;

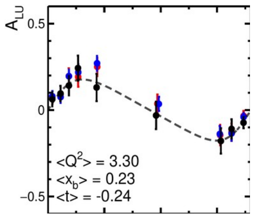
... computing and algorithms to extract features from raw data;







...and person-power to analyze the data and produce physics results



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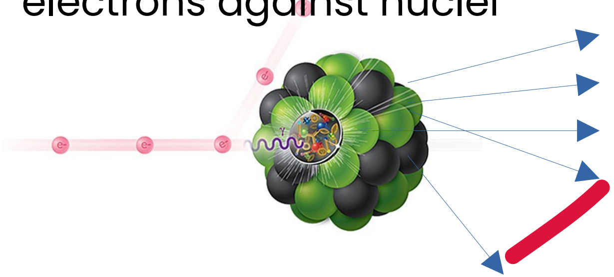

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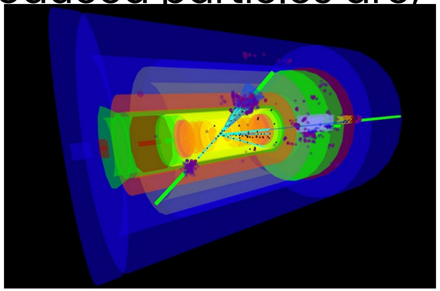

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Tracking

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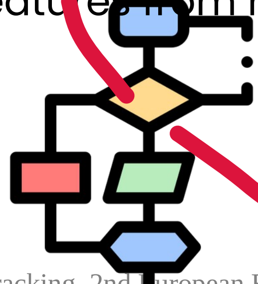

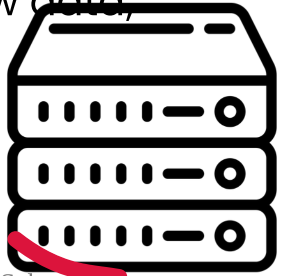

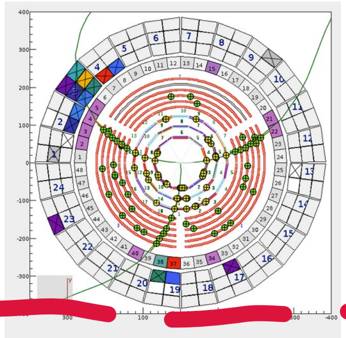

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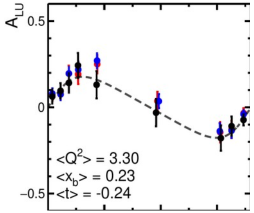
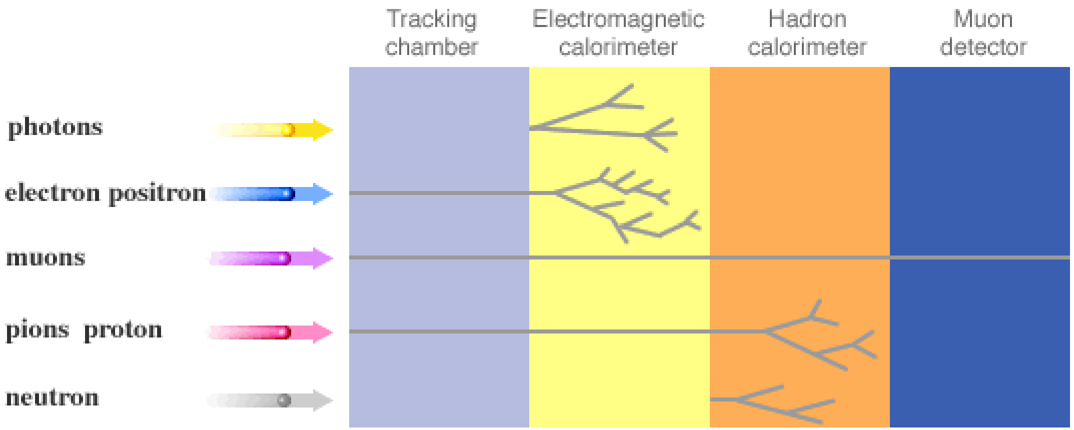


Detecting particles

- Detector designs depend on the desired physics measurements
- Of a particle we might want to know: Origin, Momentum, Charge, Energy, Species.
- Depending on the type of particles and their interaction with matter, we have to use different techniques
- We will need to combine different techniques too



Information of particles

Position sensitive detectors	Direction
Deflection in magnetic field	Momentum and charge
Calorimetry	Total energy
Time of flight and Cherenkov radiation	beta

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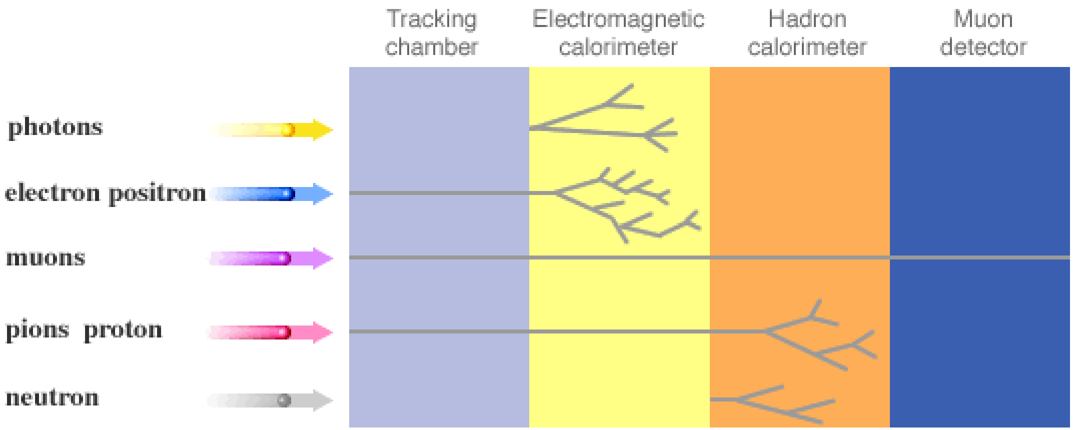
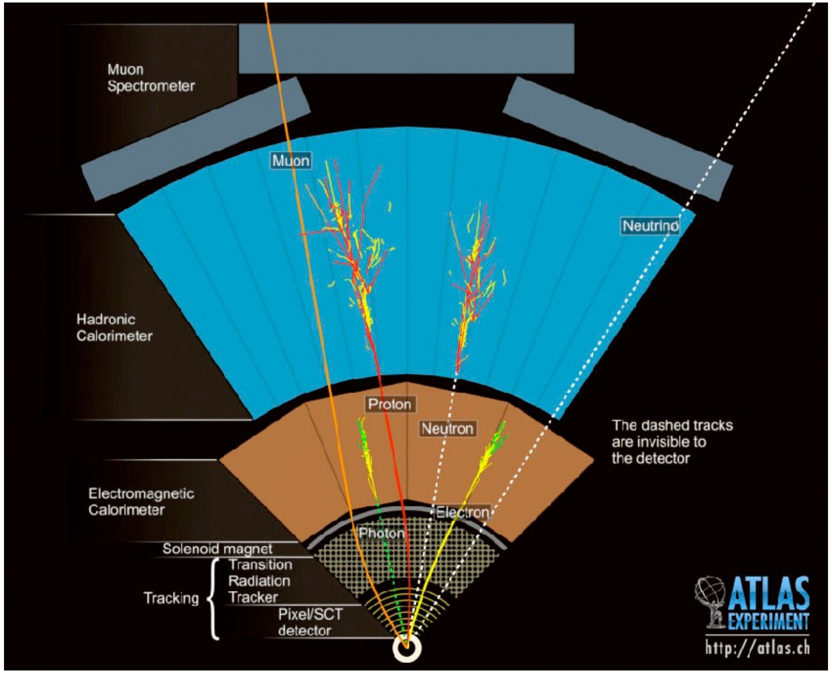


In a collider, we maximize the spectrum of physics measurement with multi-purpose detectors, often in an “onion” concept to maximize acceptance



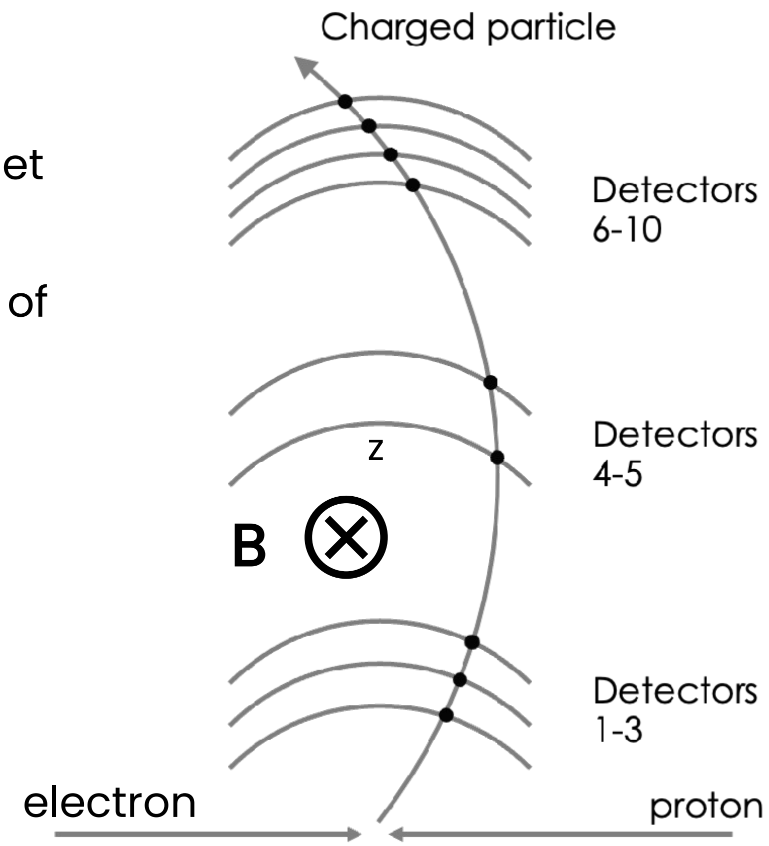
Measuring charged particles

Focus on **charged particles**

We can measure the curvature in a magnetic field to get the **momentum**. The "sign" of the curvature gives the **charge**. Extrapolation of the trajectories give the **vertex** of production.

We need:

- Magnetic field
- Many measurements along the trajectory
- Non-destructive measurements
- Long lever arm



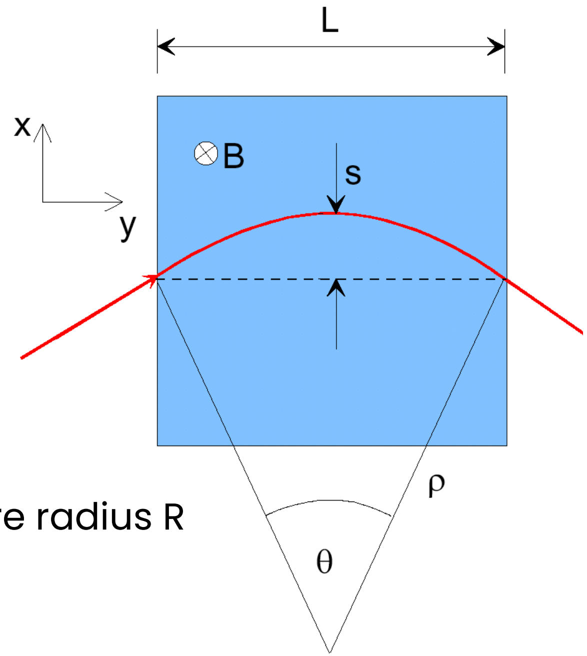
Measuring charged particles

In a magnetic field:

$$\vec{F}_{Lorentz} = \vec{F}_{centrip}$$

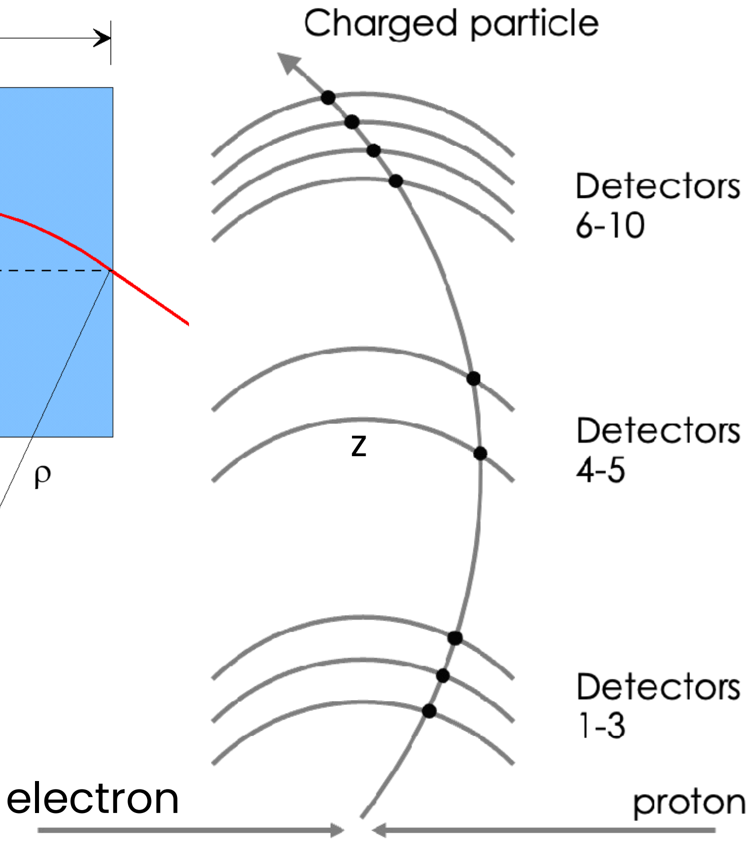
$$qvB = \gamma m \frac{v^2}{R} \Rightarrow qBR = \gamma mv = p$$

$$p\left(\frac{\mathrm{GeV}}{\mathrm{c}}\right) = 0.3B(\mathrm{T})R(\mathrm{m})$$



To determine p, we need know the curvature radius R

The sagitta: $s \approx \frac{L^2}{8R}$



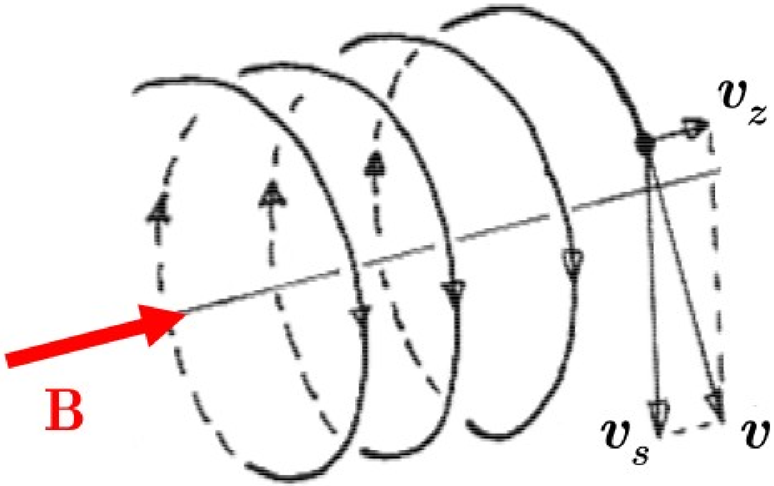
Example: L=1 m, B = 2 T
P_T = 1 GeV → R = 1.67 m → s = 7.4 cm
P_T = 10 GeV → R = 16.7 m → s = 0.74 cm

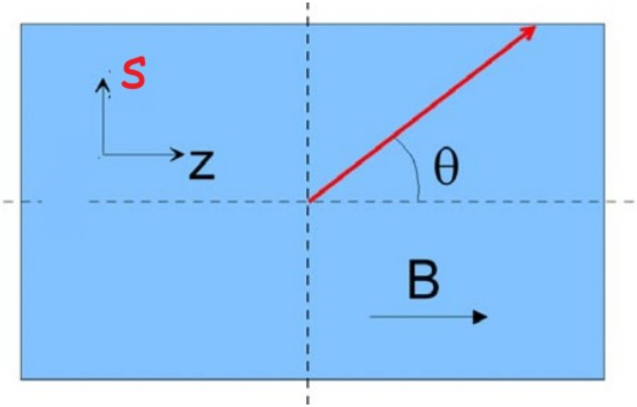
Momentum measurement

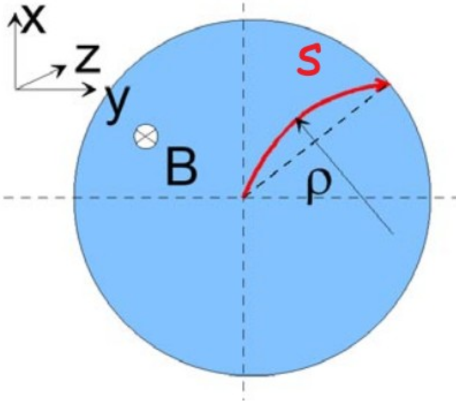
$$\frac{d\vec{p}}{dt} = q\vec{v} \times \vec{B} \qquad \frac{d^2\vec{r}}{ds^2} = \frac{q}{p}\frac{d\vec{r}}{ds} \times \vec{B}$$

A charged particle in a magnetic field follow an helix.

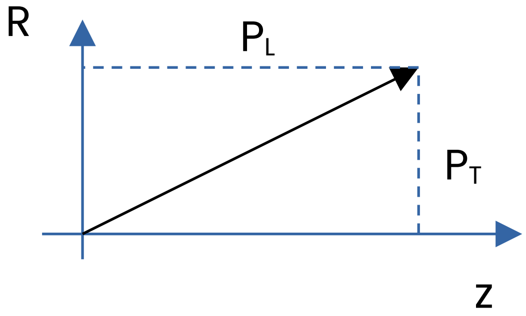
If B not uniform, then a set of differential equation to be solved numerically. Locally, the helix approximation can be used.

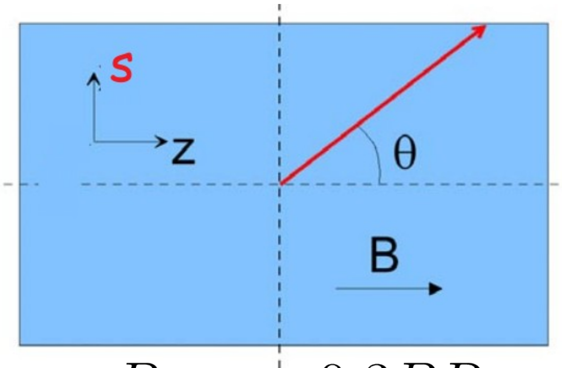


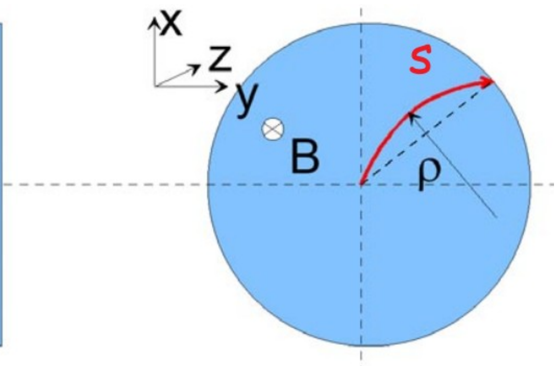




Momentum measurement







$$P = \frac{P_T}{sin(\theta)} = \frac{0.3BR}{sin(\theta)}$$

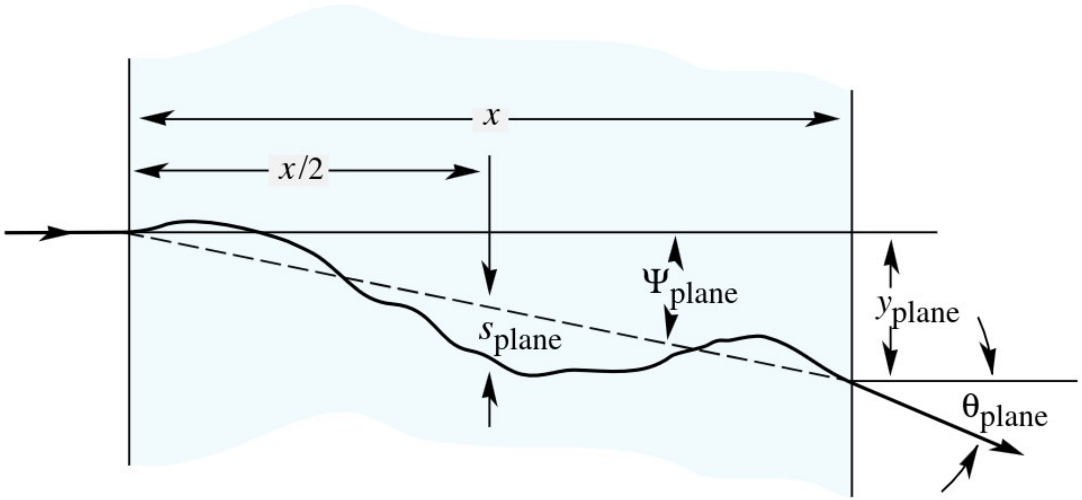
Case for N equidistant measurements with the same uncertainty

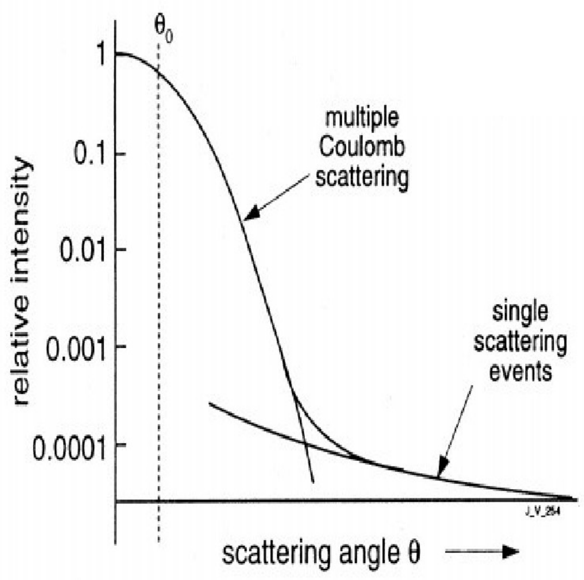
$$\sigma_\theta = \frac{\sigma_z}{L}\sqrt{12\frac{N-1}{N(N+1)}}$$

$$\frac{\sigma_{P_T}}{P_T} = \frac{\sigma_R}{R} = \frac{\sigma_x P_T}{0.3BL^2}\sqrt{\frac{720}{N+4}}$$

$$\left(\frac{\sigma_P}{P}\right)^2 = \left(\frac{\sigma P_T}{P_T}\right)^2 + \cot^2(\theta\sigma(\theta))$$

Multiple scattering





Charged particles scatters multiple times off atomic nuclei.

After many small deflections, the distribution of the exit angle is a Gaussian with with θ_0

Rare “hard” scatters produce large tails

$$\theta_0 = \frac{13.6\text{MeV}}{\beta pc} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 ln \left(\frac{x}{X_0} \right) \right]$$

Depends on x/X_0, i.e. the thinner the layer the smaller the deviation

Momentum measurement uncertainty

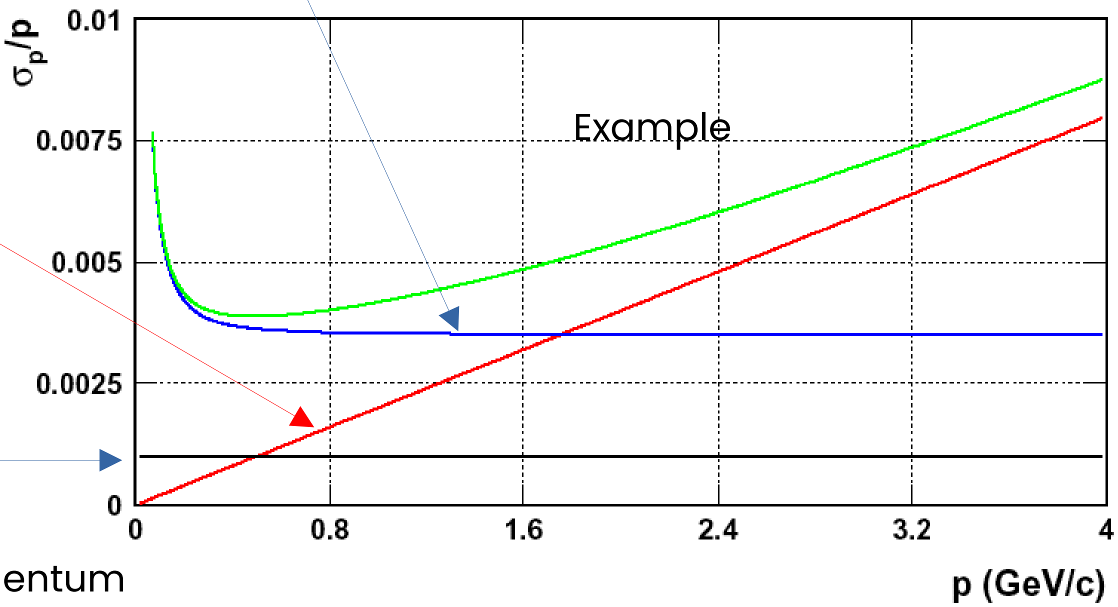
$$\left.\frac{\sigma_{P_T}}{P_T}\right|_{MS} = \frac{\sigma_s^{MS}}{s} = \frac{0.2}{\beta B\sqrt{LX_0 \sin\theta}}$$

For large beta→1, this is momentum independent

$$\frac{\sigma_{P_T}}{P_T} \propto \frac{\sigma_x P_T}{0.3BL^2}$$

Linked to hit resolution

$$\cot(\theta\sigma_\theta)$$



Theta resolution, no dependence with momentum

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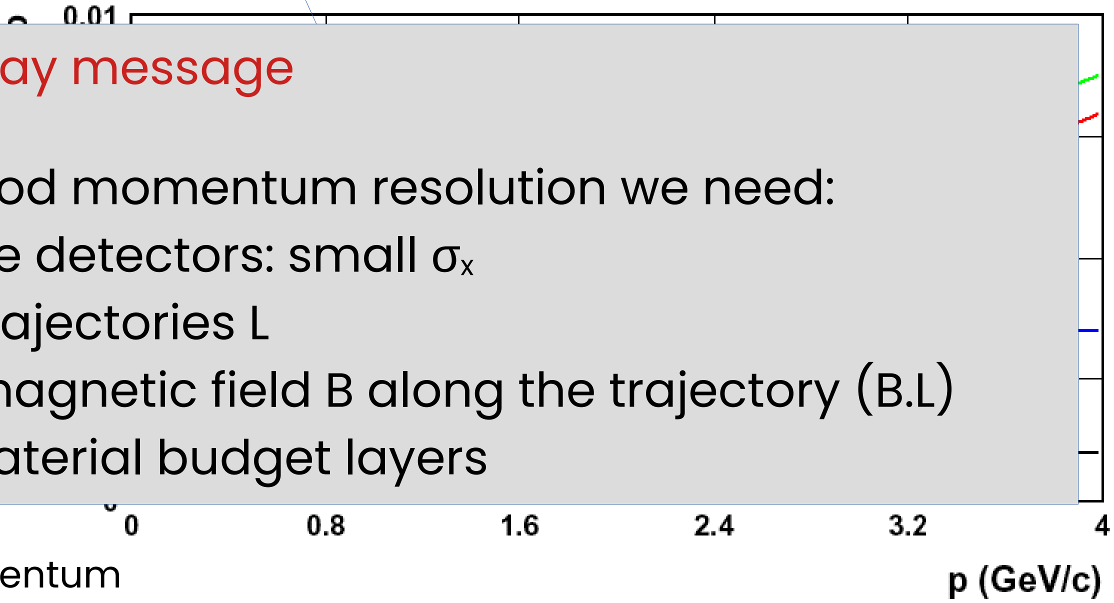


Take away message

For a good momentum resolution we need:

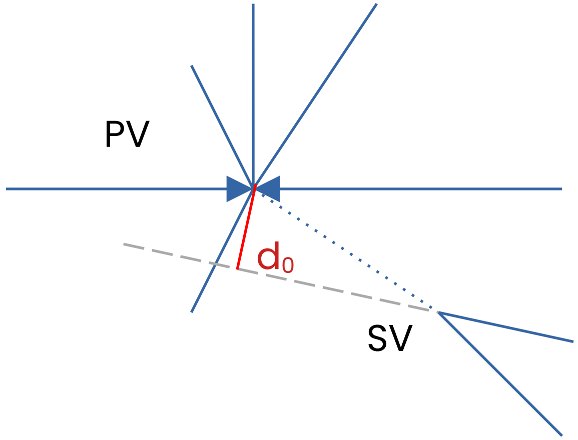
- precise detectors: small σ_x
- long trajectories L
- high magnetic field B along the trajectory (B.L)
- low material budget layers

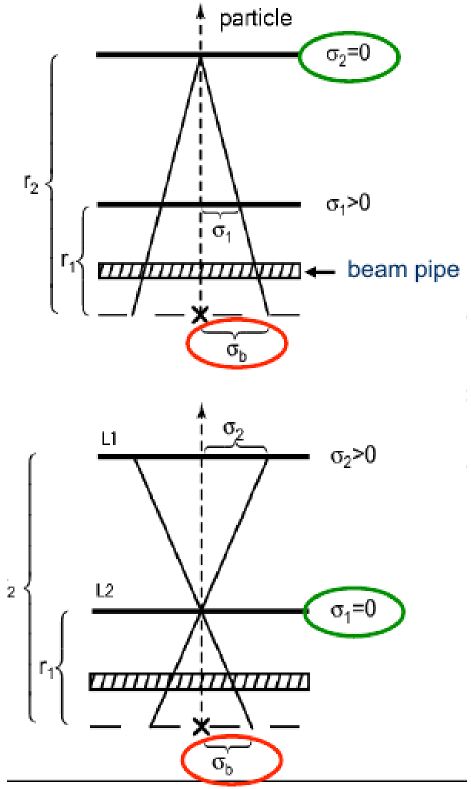
Theta resolution, no dependence with momentum

Vertex reconstruction

Vertex reconstruction is needed for:

- Identify primary collision
- Identify secondary vertices: decays of heavy hadrons
- Separate pile-up events





Simple picture, two detector layers. Let's take two extreme cases

$\sigma_1 > 0$; $\sigma_2 = 0$;

$$\sigma_{d_0} = \sigma_b = \frac{r_2}{r_2 - r_1}\sigma_1$$

$\sigma_1 = 0$; $\sigma_2 > 0$;

$$\sigma_{d_0} = \sigma_b = \frac{r_1}{r_2 - r_1}\sigma_2$$

Multiple scattering $\sigma_{d_0}^{MS} = \theta_0 r_1$

Vertex reconstruction

For two layers, the complete uncertainty is given by

$$\sigma_{d_0} = \sqrt{\left(\frac{r_2}{r_2 - r_1}\sigma_1\right)^2 + \left(\frac{r_1}{r_2 - r_1}\sigma_2\right)^2 + \left(\sigma_{d_0}^{MS}\right)^2}$$

For N layers with the same uncertainties

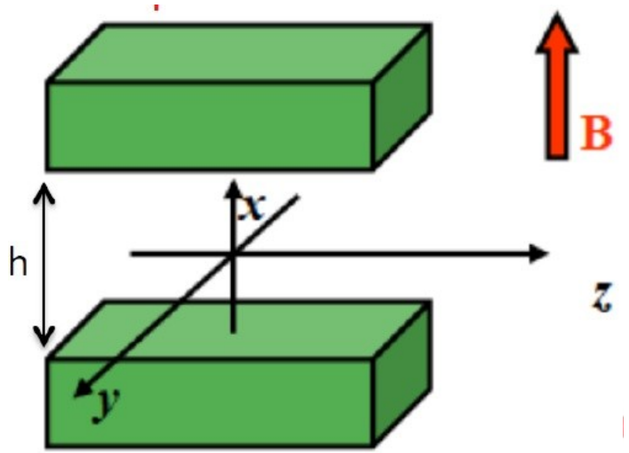
$$\sigma_{d_0} = \sqrt{\sigma_a + x_V^2 \sigma_b^2} = \frac{\sigma_x}{\sqrt{N}}\sqrt{1 + \frac{12(N-1)}{N+1}\left(\frac{x_0}{L}\right)^2} = \frac{\sigma_x}{\sqrt{N}}\sqrt{1 + \frac{12(N-1)}{N+1}\left(\frac{\frac{r_N + r_1}{2}}{r_N - r_1}\right)^2}$$

For best d0 resolutions we need:

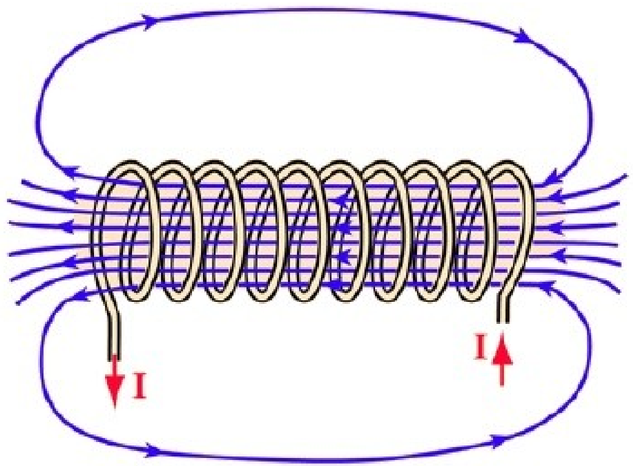
- The first layer to have the best resolution (factor r2/(r2-r1))
- Small material budget
- Long lever arm
- R1 as close as possible to the vertex

Magnets

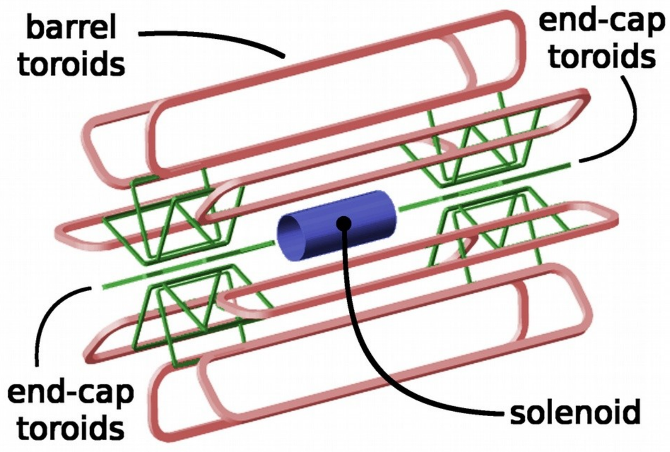
In experiments three field configurations are commonly used:



Dipole



Solenoid



Toroid

Important quantity $$\int B \cdot dl$$

The integral of the magnetic field along the path of the particle. The bigger the better: high field, large field space

Detecting particles

All measurement techniques are based on the same general principle:

"Amplify and read out a signal that is measured from the particle's interaction with some matter"

Generic tracking detector

Particle → Energy deposit → Amplify → Collect signals → Signal processing

Characteristics of a detector

- **Acceptance**: recorded/emitted particles → geometry x efficiency
- **Efficiency**: recorded/impinging particles

Response/resolutions:

- **Spatial resolution:** accuracy of the reconstructed position of where the particle crossed

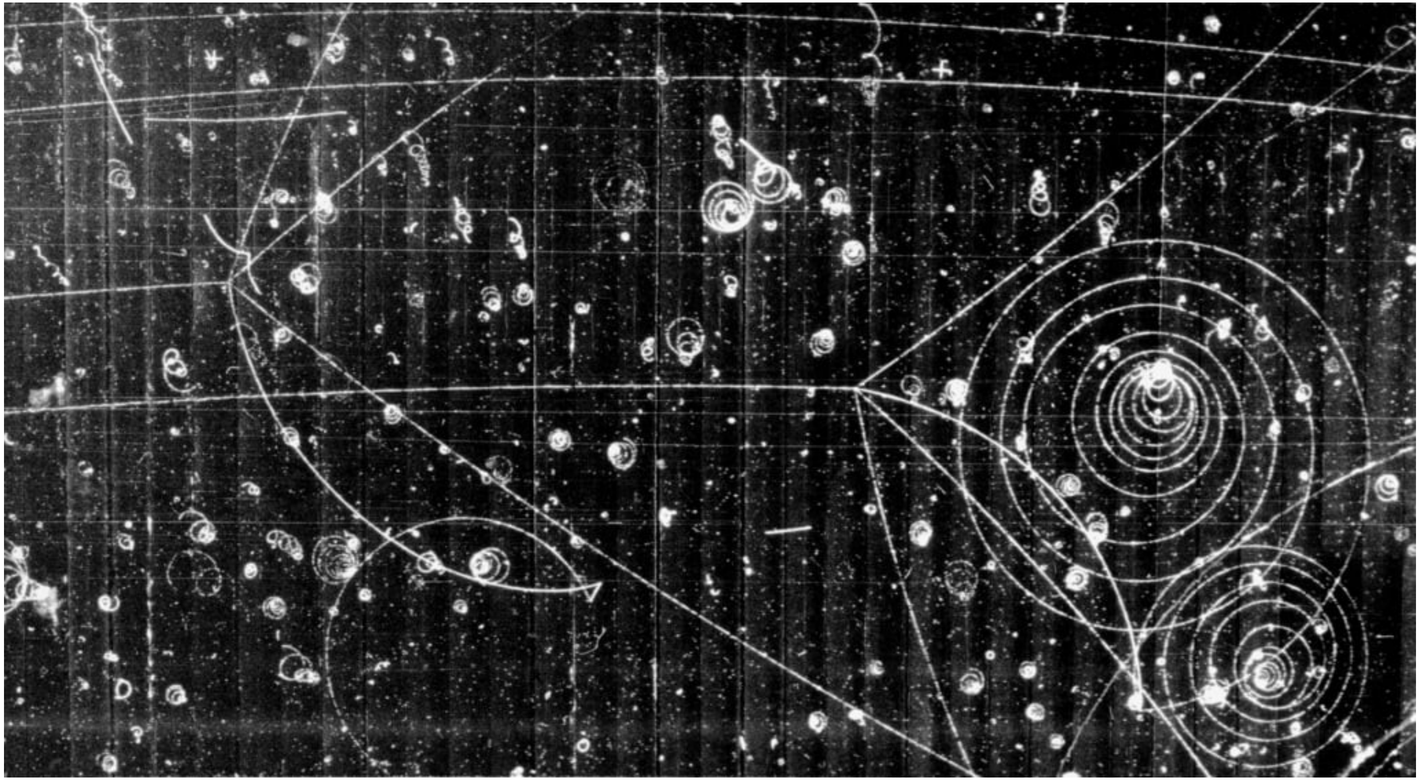
Time response

- Dead time: minimum time interval between events that can be recorded
- **Time resolution**: accuracy of the "event-time"

Detecting particles – Examples

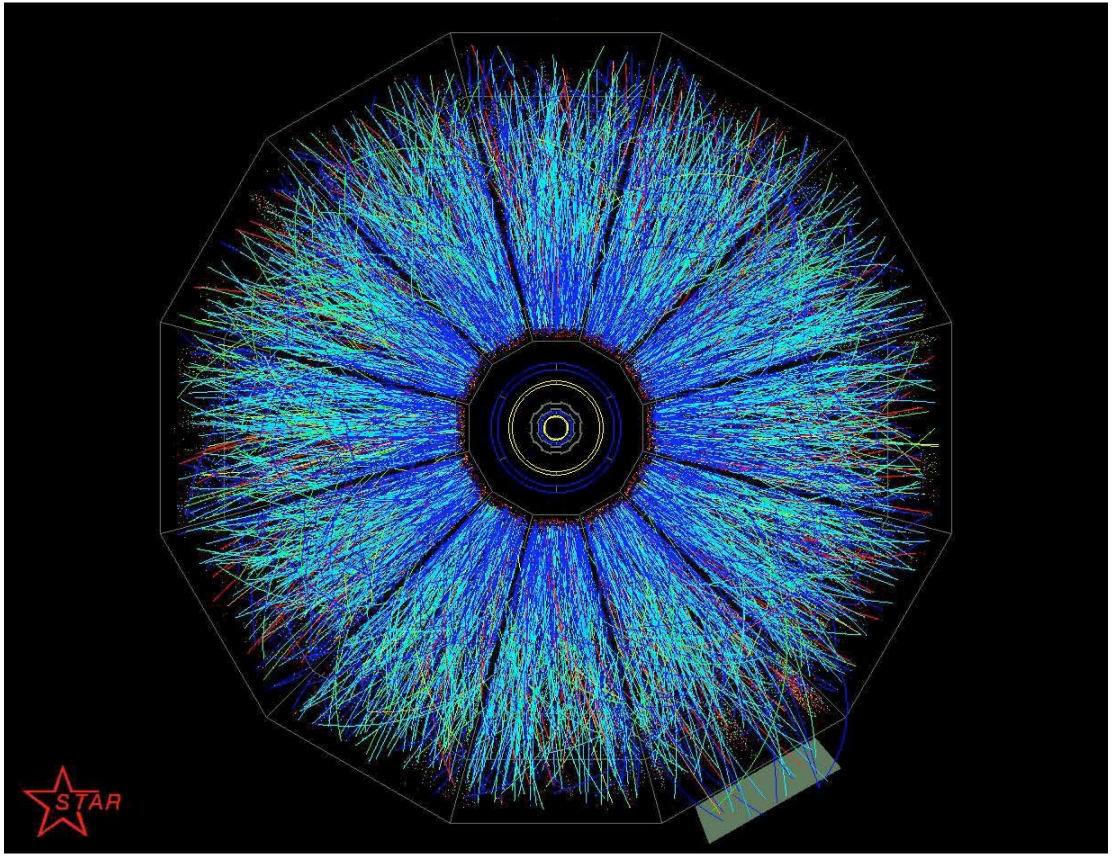
- Bubble chambers

  - Particles heat the liquid (energy deposit)
  - Bubble forms (amplification)
  - Take a picture (collect the signal)
  - Develop the picture (signal processing)
  - Painstakingly look at multiple pictures and measure the traces (“reconstruction algorithms”)



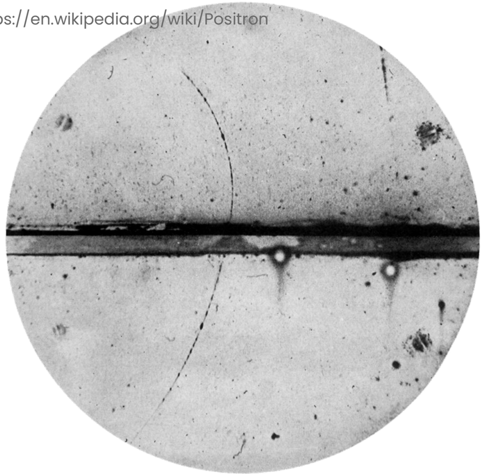
Detecting particles – Examples

- Time projection chambers like in STAR
  - Particles ionize the gas
  - Amplification of primary electrons at anode
  - Read out the electric signals
  - Digitize and store the signals
  - Too many particles per event and too many events for humans, we need computers!

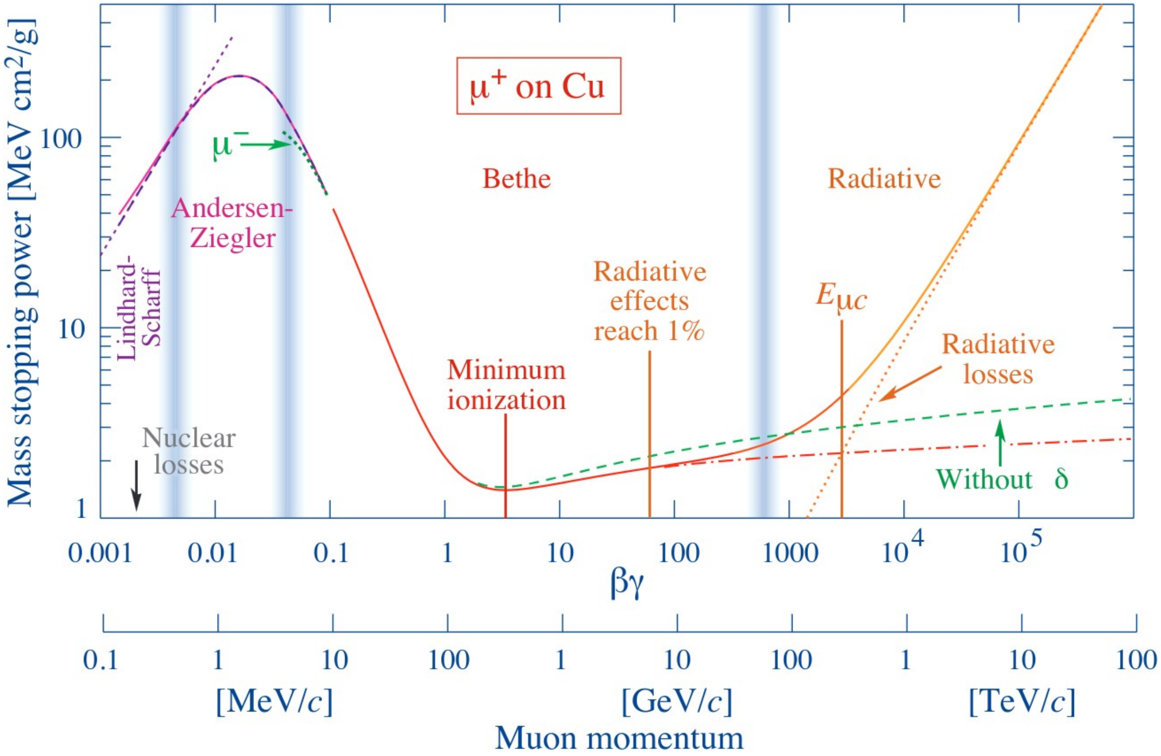


Interaction of charged particles with matter

https://en.wikipedia.org/wiki/Positron



Charged particles lose energy traversing materials. To detect a particle, we need to collect this energy lost.



Two main processes:

- **Energy loss**
- **Multiple scattering**

Other processes

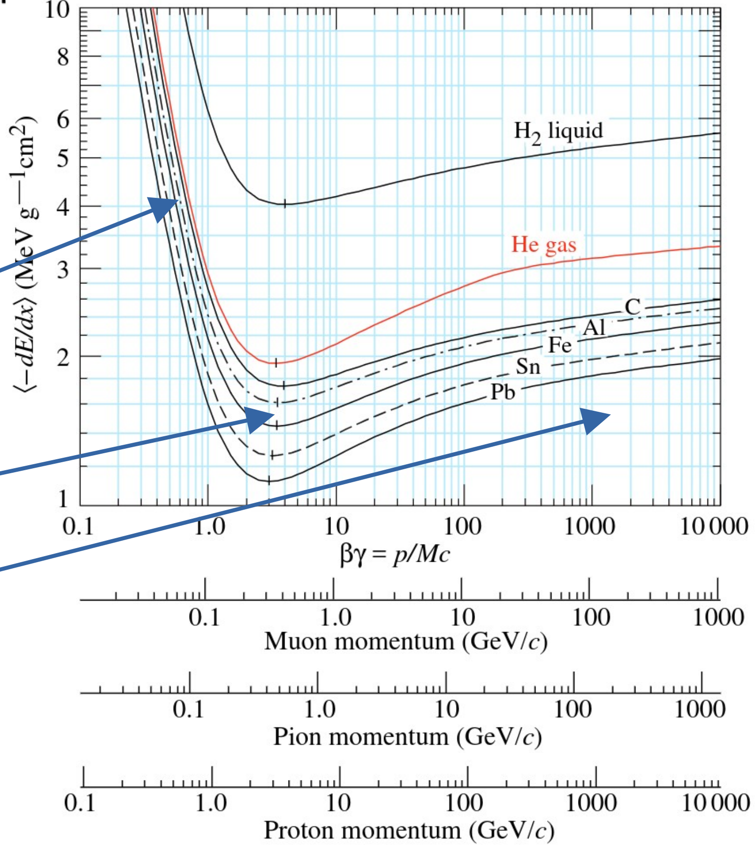
- Bremsstrahlung (mainly e+,e-)
- Nuclear interactions
- Cherenkov radiation
- Transition radiation

Interaction of particles with matter

- Energy loss. **Bethe-Bloch** description

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

- -dE/dx is measured in MeV*cm²/g → ΔE depends on the material density
- Valid in the range $0.1 < \beta\gamma < 1000$, then radiative effects become important
- Three behaviors to keep in mind:
  - ~$1/\beta^2$ for lower momenta
  - Minium ionizing particles (MIP)
  - Logarithmic rise at high momenta



Z/A

Interaction of particles with matter

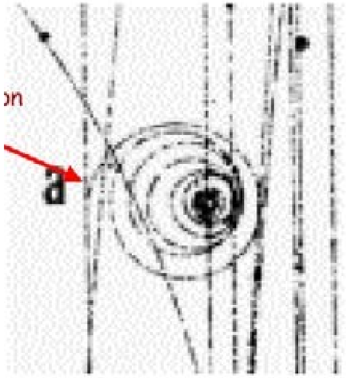
Bethe-Bloch formula gives the average energy loss.

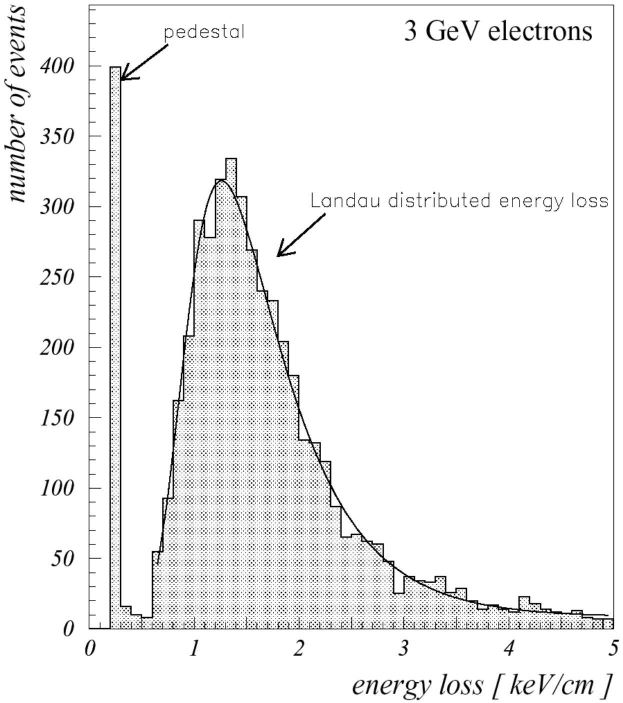
For thick layers, ΔE is approximated by a Gaussian

For thin layers:

- **Rare collisions with ΔE large** (δ rays or knock on electrons)
- Bremsstrahlung

The probability of losing ΔE is described by a Landau distribution





$$P(\Delta E) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}(\lambda + e^{-\lambda})} \qquad \lambda = \frac{\Delta E - \Delta E_{mip}}{\epsilon}$$

Example: 3 GeV electrons in a thin-gap multi wire proportional chamber(ALPEPH)

Interaction of electrons with matter

Electrons and positrons primarily lose energy by bremsstrahlung (E>10MeV)

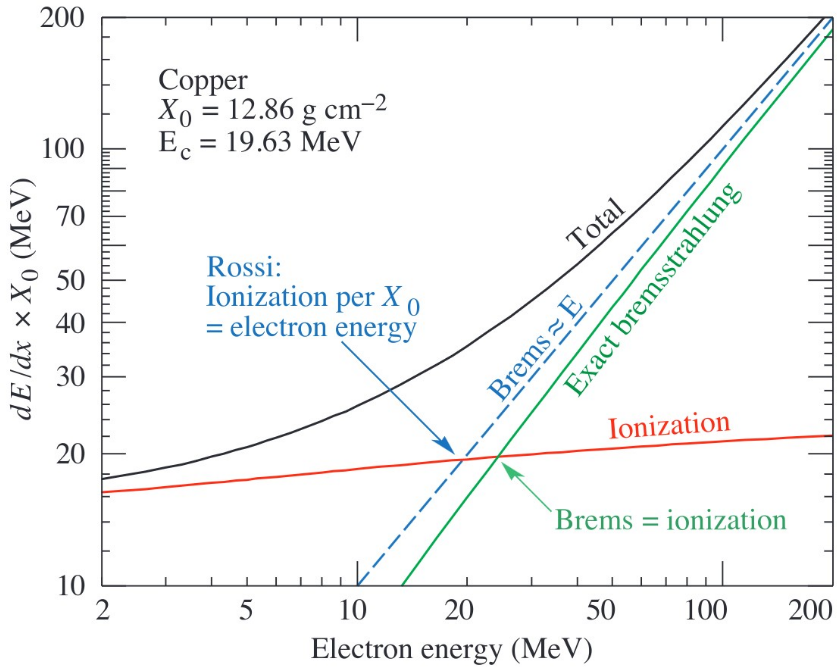
$$-\frac{dE}{dx} \propto Z^2 \frac{E}{m^2}$$

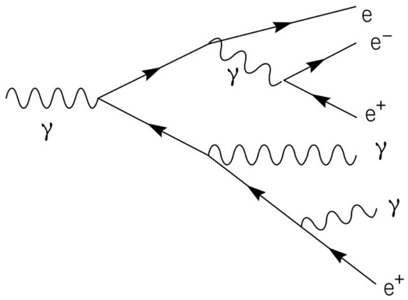
Useful to introduce the **radiation length X_0**

$$E = E_0 e^{-x/X_0}$$

X_0: the average distance a high energy electron loses all but 1/e of its energy

$$X_0 \propto \frac{A}{Z(Z+1)ln(287/\sqrt{Z})}$$





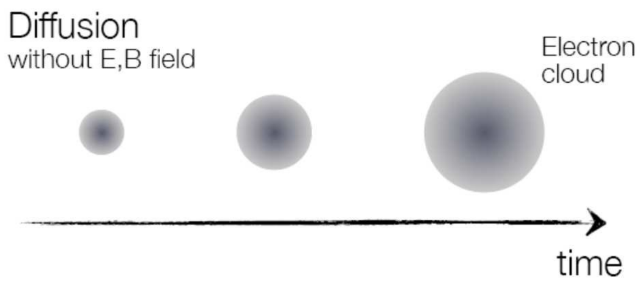
Gaseous detectors

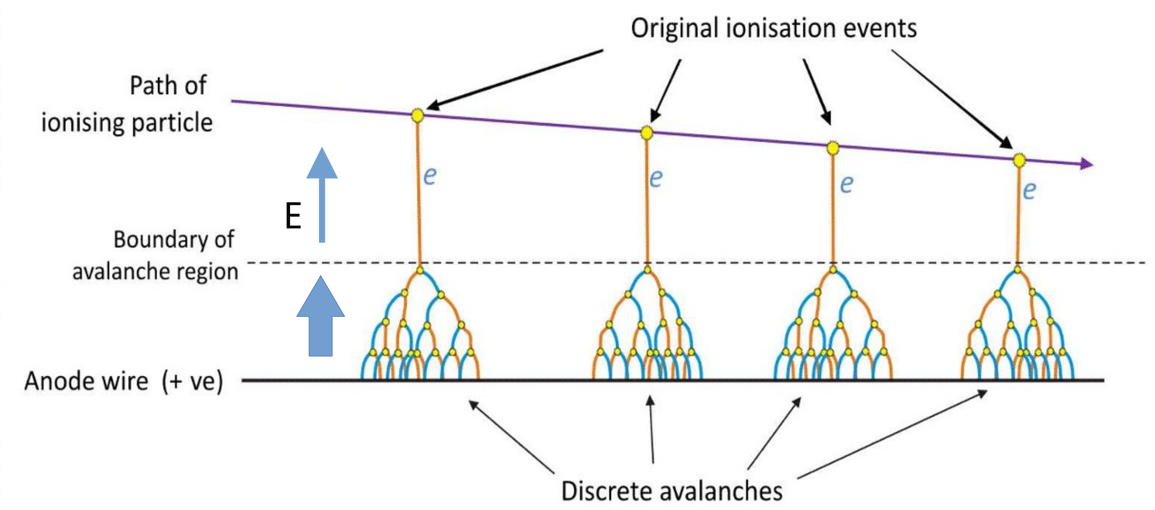
Charge particles ionize the gas.

An electric field make the ionization electrons drift towards the anode.

Primary electrons are too few O(100/cm).

A region of high electric field is needed: primary electrons gain enough kinetic energy to trigger additional ionization to amplify the signal exponentially



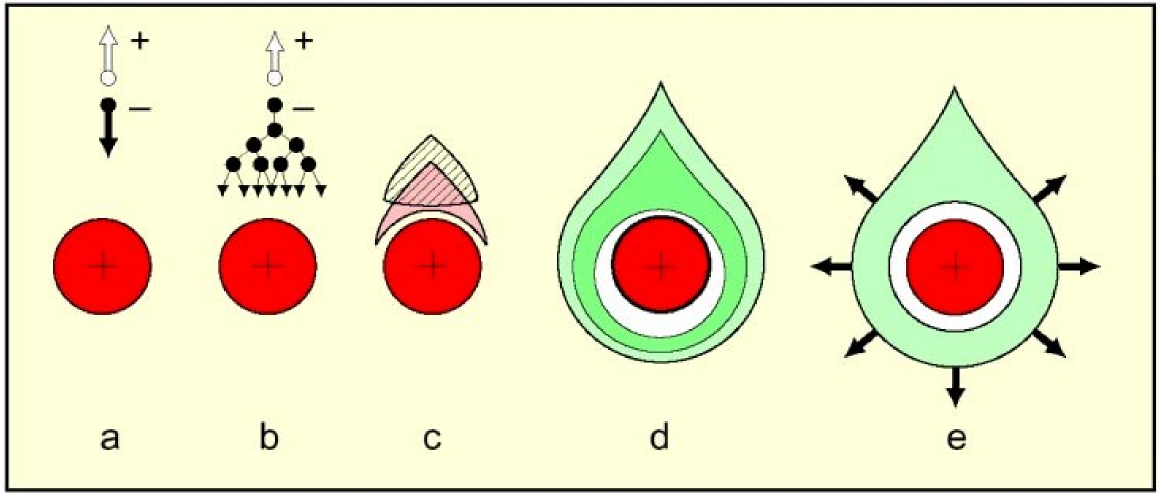


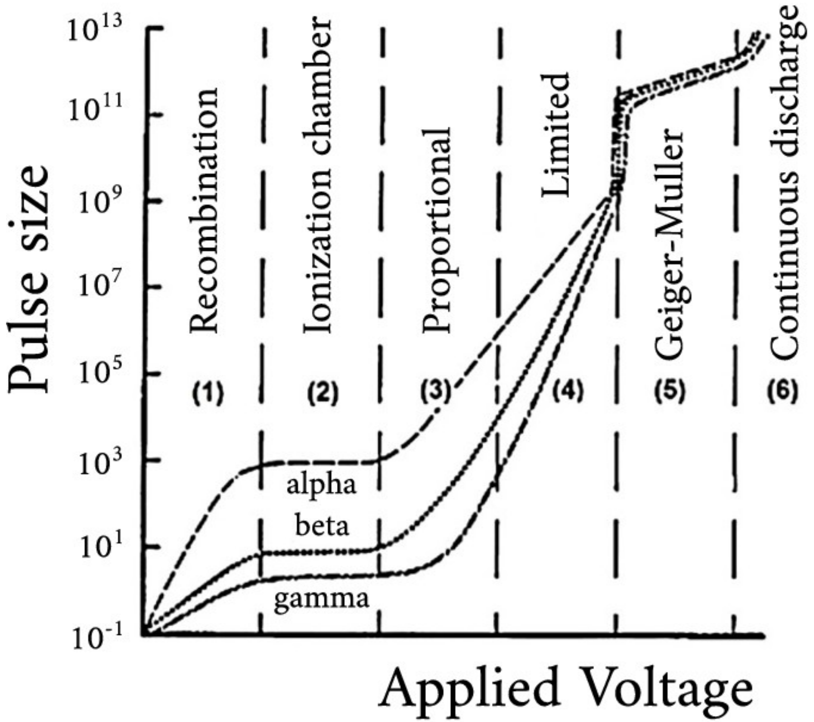
They can cover very large volumes or surfaces

Spatial resolutions O(100μm)

Can be used for dE/dx measurements

Gaseous detectors

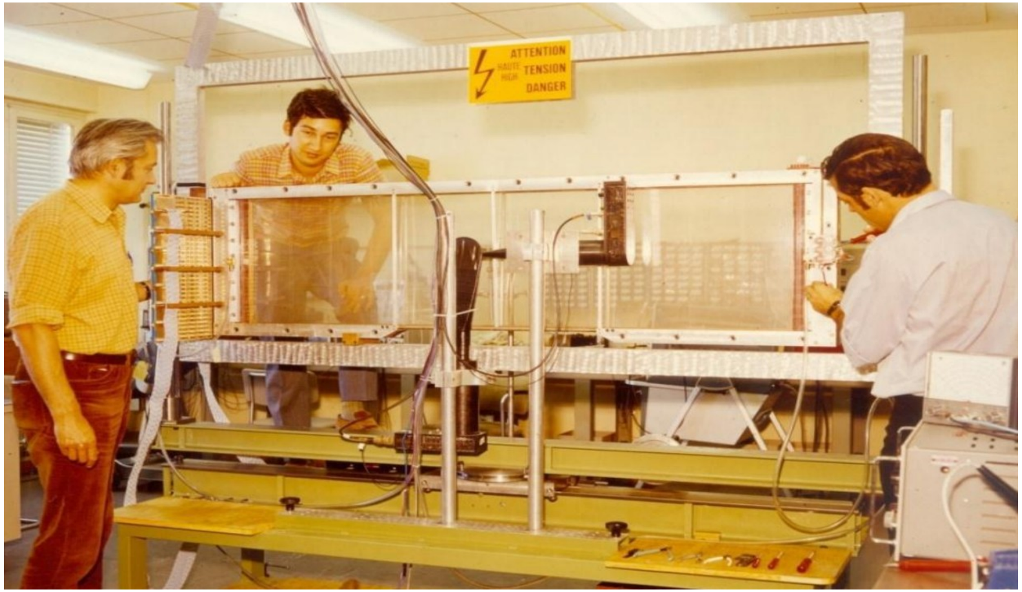


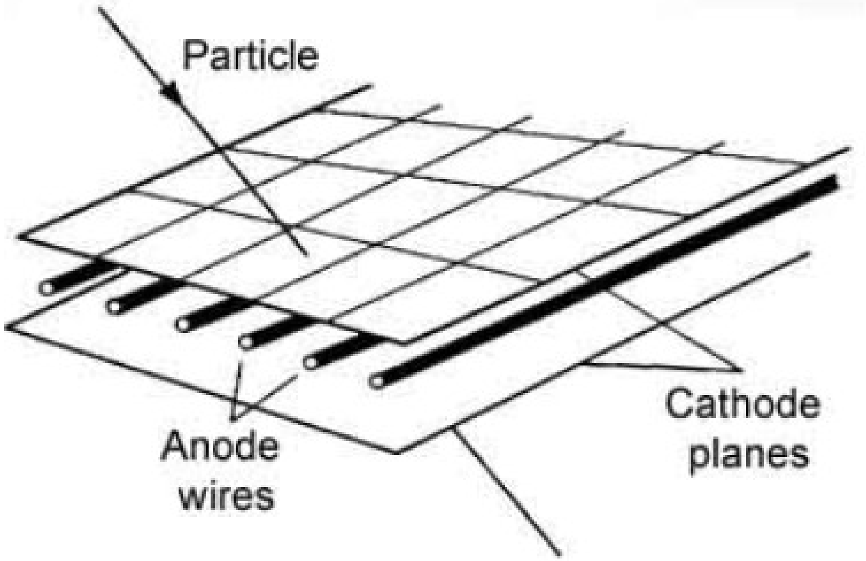


Fast electrons are accelerated by a strong electric field.
Further ionization → avalanche process depend on the applied voltage. Too high and proportionality is lost.
Signals are induced on the electrodes by the movement of the charges. Fast electron signal (<10ns); ions are slower, i.e. longer tail O(100ns).

Gaseous detectors – Wire chambers

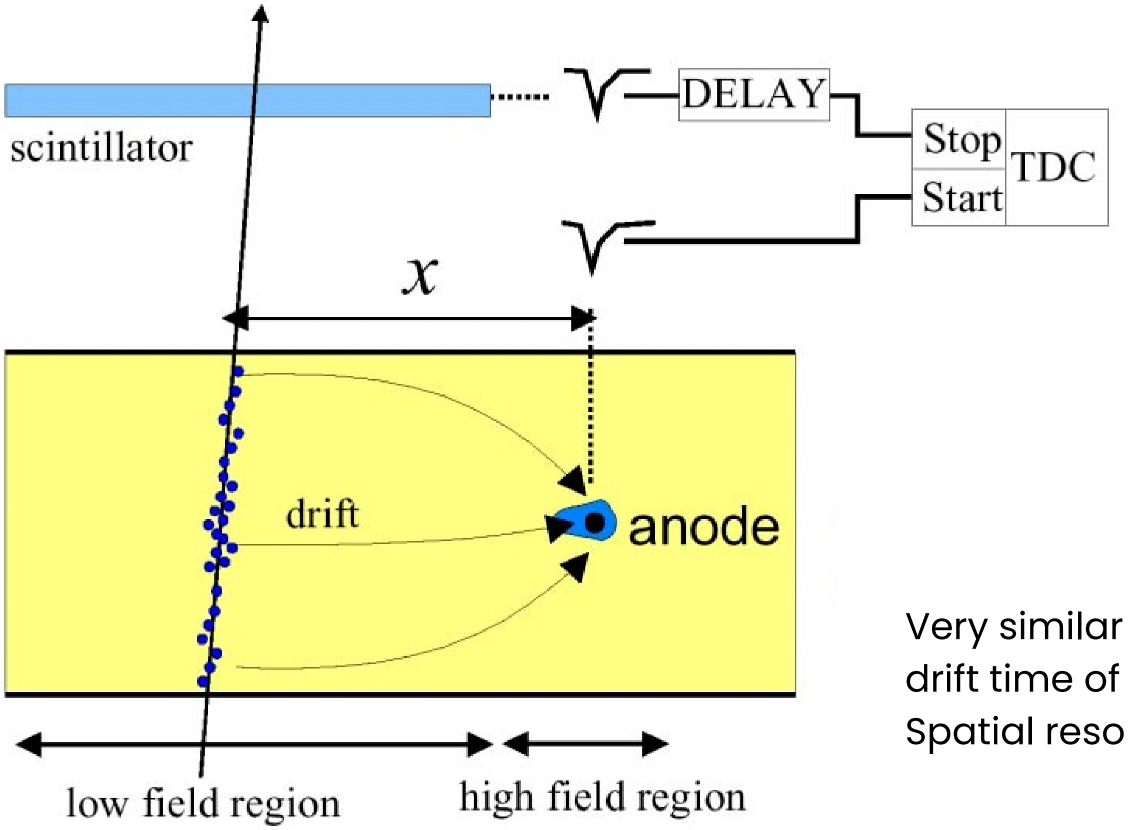
Multi wire proportional chambers (MWPC) revolutionized particle physics experiments.
Invented by George Charpak in 1968.

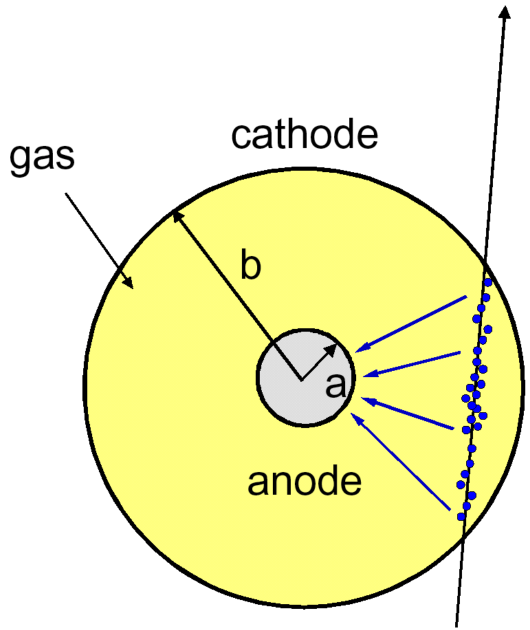




Spatial resolution of MWPC is dominated by the wire spacing.
Closer the wires better the resolution, but more and more wires…

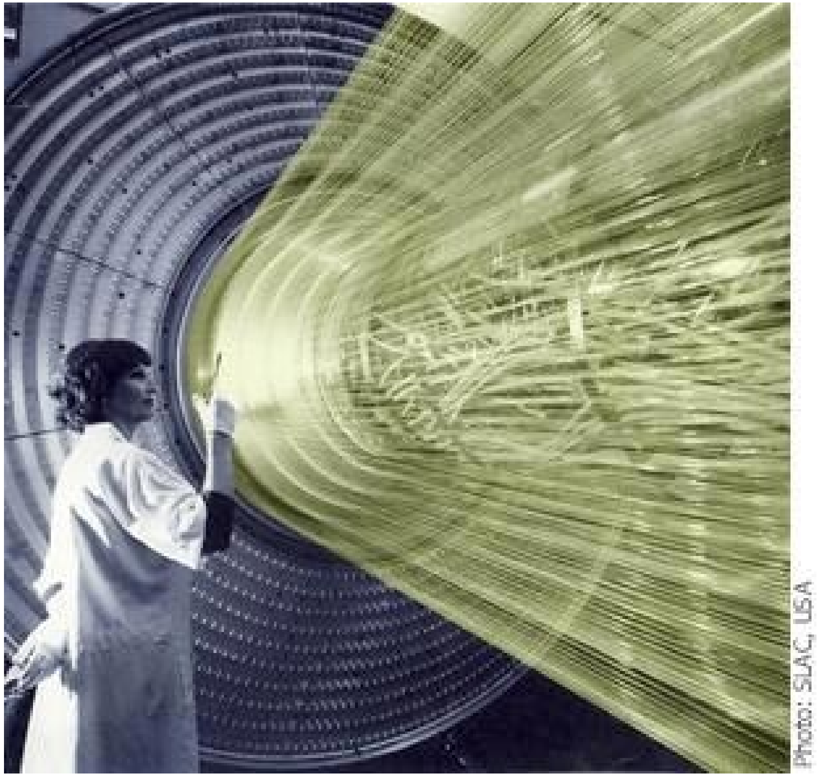
Gaseous detectors – Drift chambers and tubes

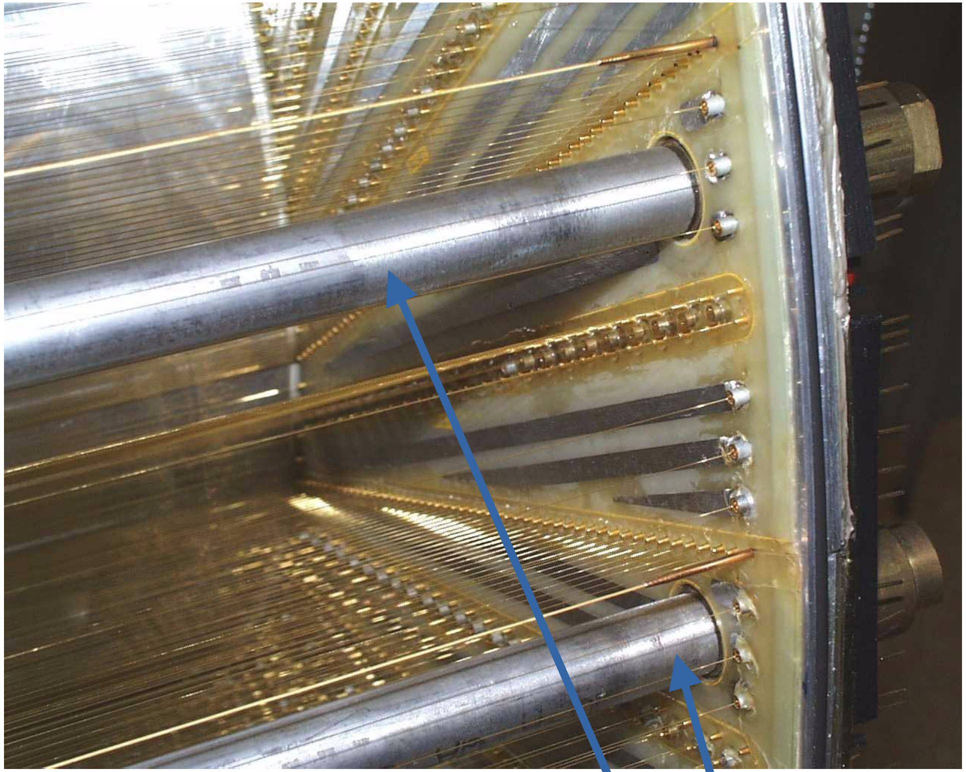




Very similar to MWPC, but with a measurement of the drift time of primary electrons.
Spatial resolution improved.

Gaseous detectors – Drift chambers





H1 Drfit Chamber: ~15000 wires, 6 tons of force

Supporting rods

Gaseous detectors – MPGDs

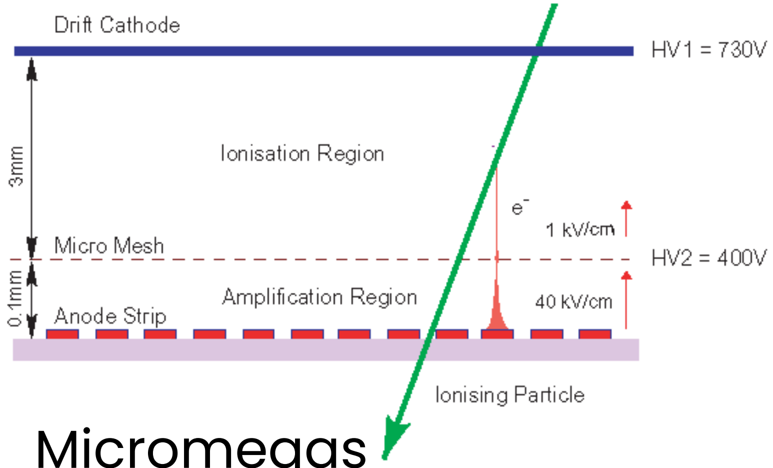
Micro-Pattern Gaseous Detectors:

Use industrial techniques for printed circuit boards (PCBs) and photolithography.

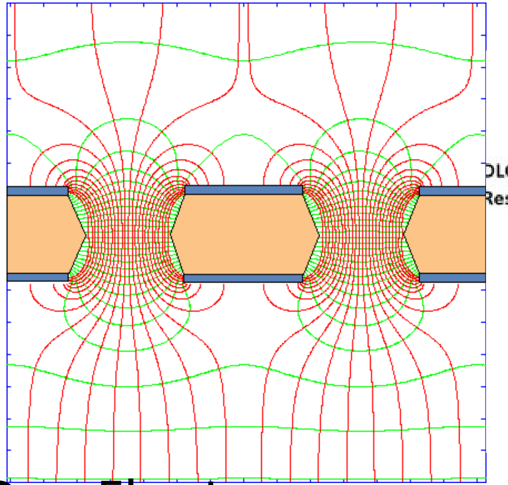
Allow for easier production than wire chambers.

Many technologies, but they share similar traits: an ionization (drift) region, a micro-metric structure for high electric fields, readout channels part of a PCB.

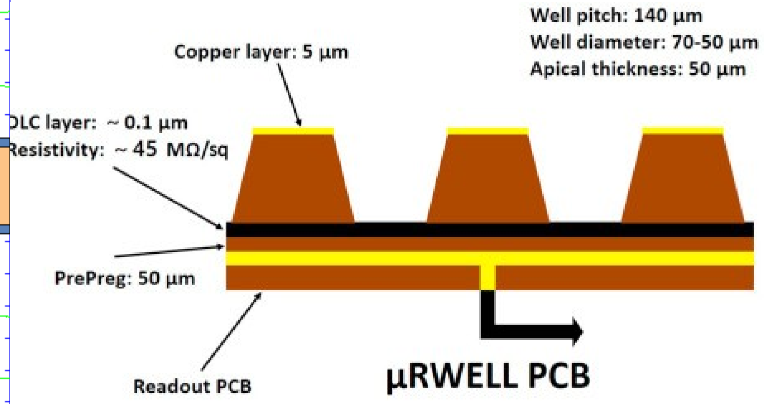
Spatial resolutions (<100μm). Time resolutions (~10ns). High rates O(100kHz/cm2).



Micromegas



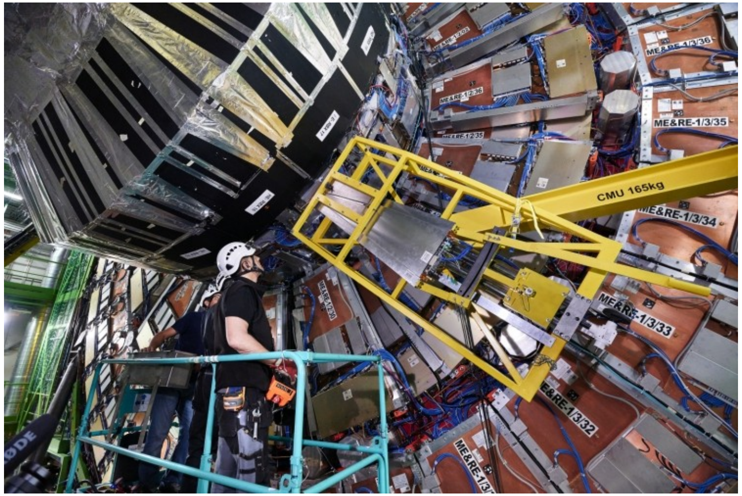
Gas Electron Multiplier: GEM

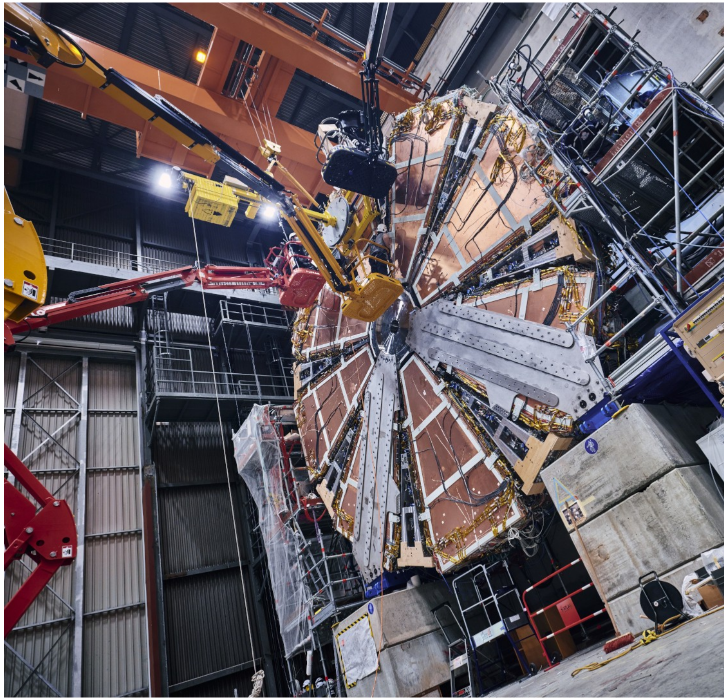


MRWell

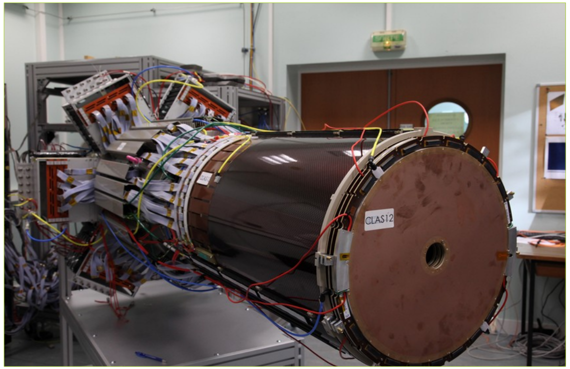
Gaseous detectors – MPGDs

GEMs in CMS



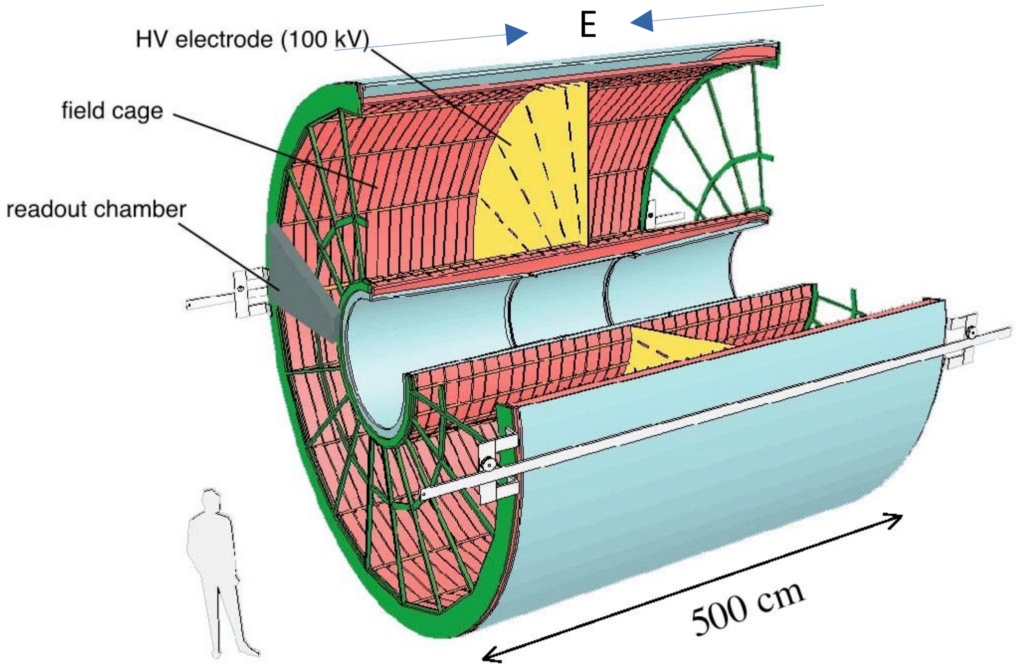


ATLAS New Small Wheels
Micromegas and small thin gap chambers

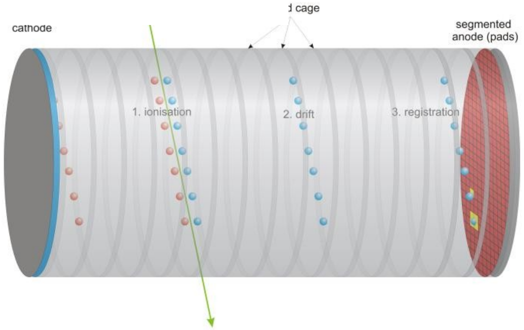


Cylindrical Micromegas
for CLAS12

Gaseous detectors – TPC



Schema of the ALICE TPC



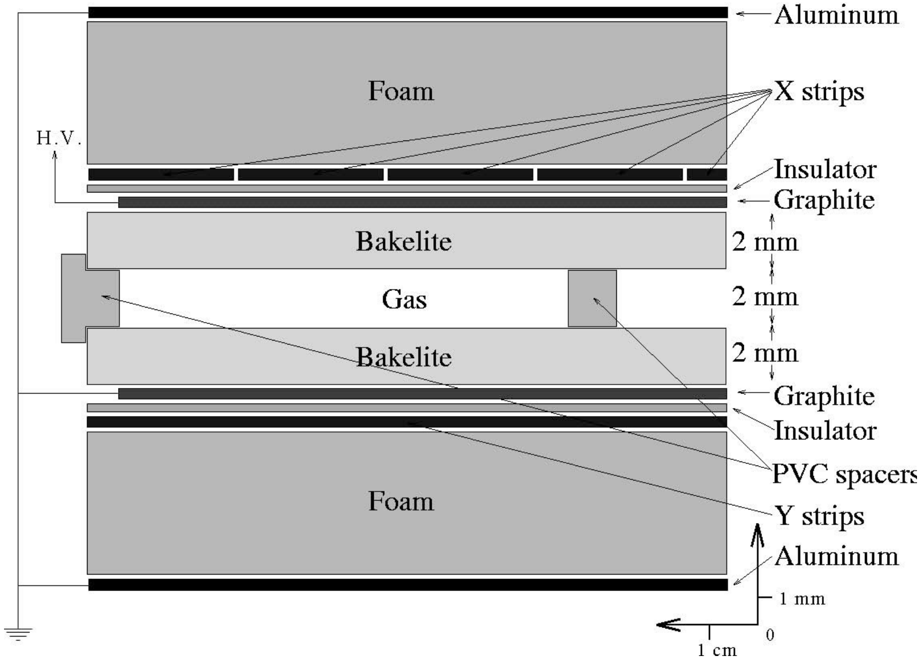
Time Projection Chamber

- Large gas volume
- Minimal amount of material
- Electrons drifts to the readout chambers (MWPCs or MPGDs)
- 3D measurement of the particle trajectory
- Long drift times O(10μs) limit the event rate
- Careful calibration of the drift velocity, controlling temperature, pressure and gas purity

Gaseous detectors – RPCs

Resistive Plate Counters

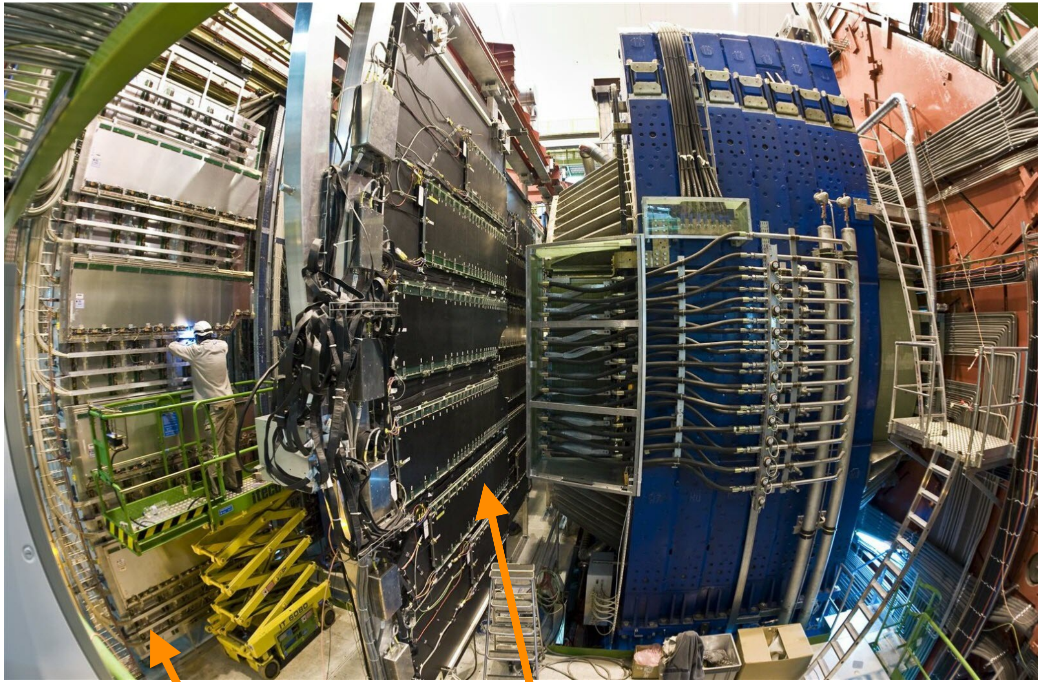
- Very high resistivity electrodes
- Gas mixtures with high photon absorption
- Relatively simple to build and relatively cheap
  - Ideal for large area muon systems
- Fast signals (<5ns): ideal for trigger systems
- Signals readout by capacitive induction on both sides, 2D information



Gaseous detectors – RPCs

Ideal for muons systems

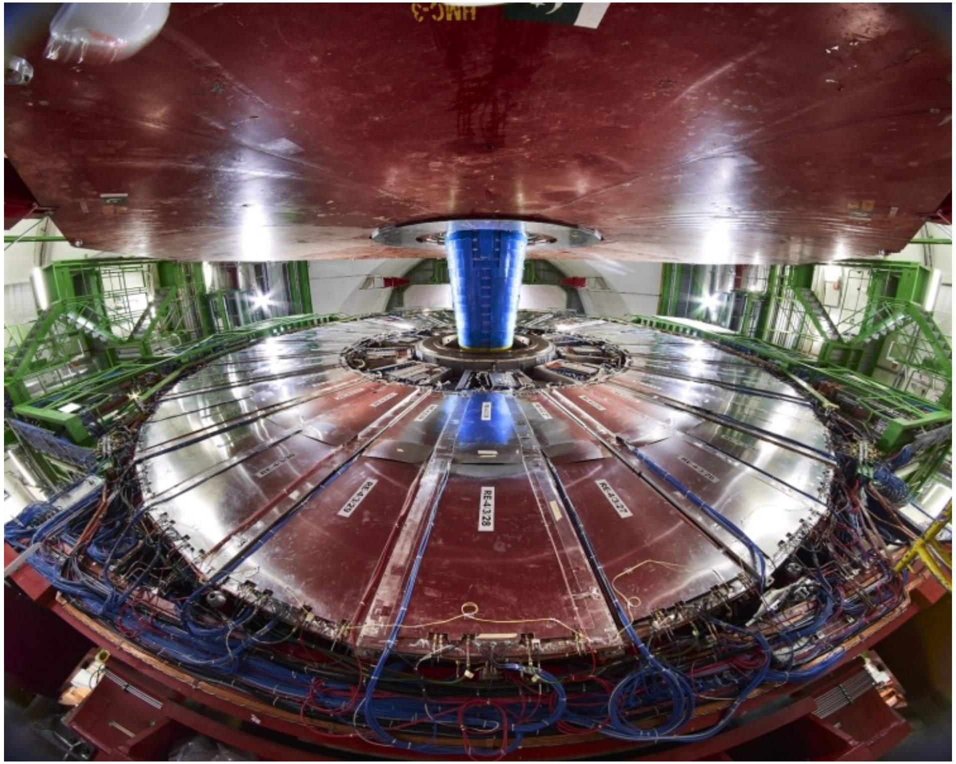
ALICE



RPCs

Wire chambers

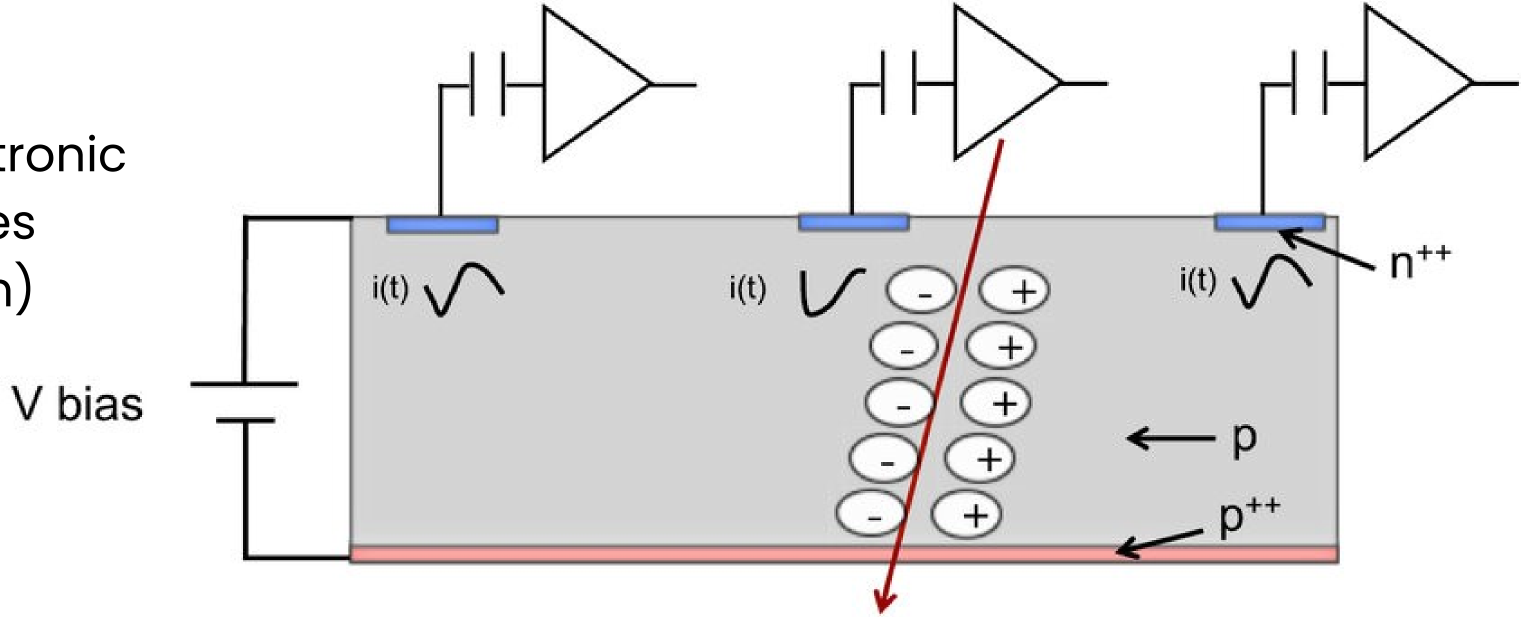
CMS



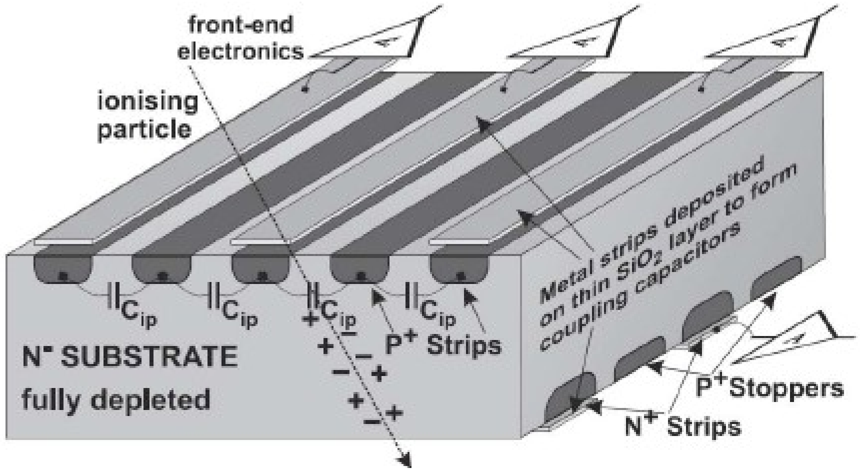
Silicon detectors

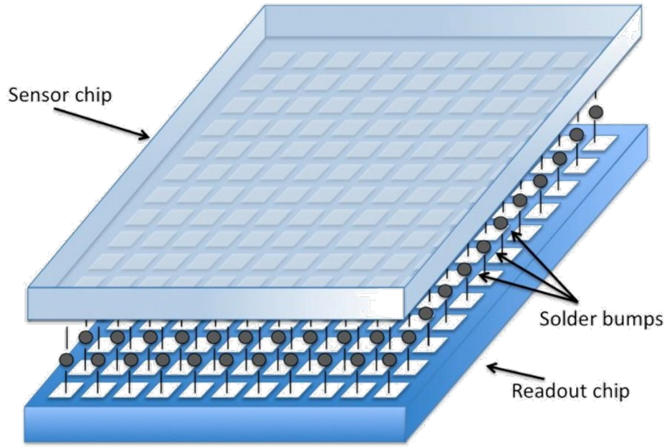
Based on the p-n junction, i.e. a diode.
A reverse bias makes the depletion region larger.
A charged particle creates electron-hole pairs. A MIP ~22k paris in 300μm Si.

- Leveraging the electronic industry technologies
- Can provide O(10μm) spatial resolutions
-



Silicon detectors – Strips and Pixels





Strip detectors
- Pitch O(25μm)
- For 2D information, double sided detectors needed with stereo angle
- Collection time ~15ps/μm
- Proven radiation hardness

Pixel detectors
- Spatial resolution O(10μm)
- The readout chip bump bonded on top → material budget limitation
- Same radiation hardness as strip, but a real 2D detector
- Many channels to readout…

Silicon detectors – Strips and Pixels

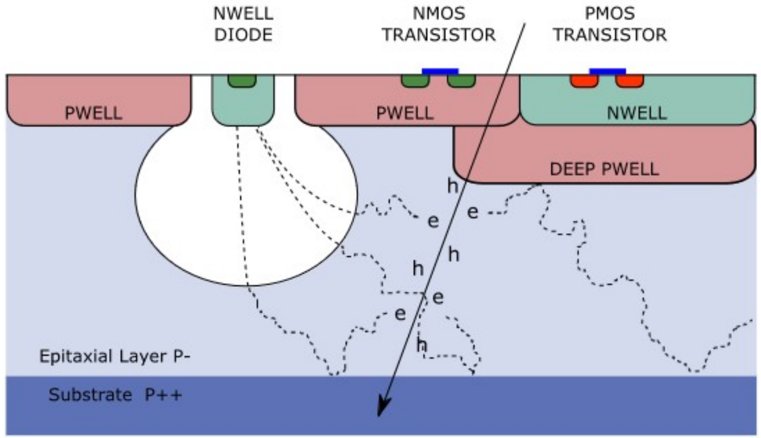
CMS Tracker

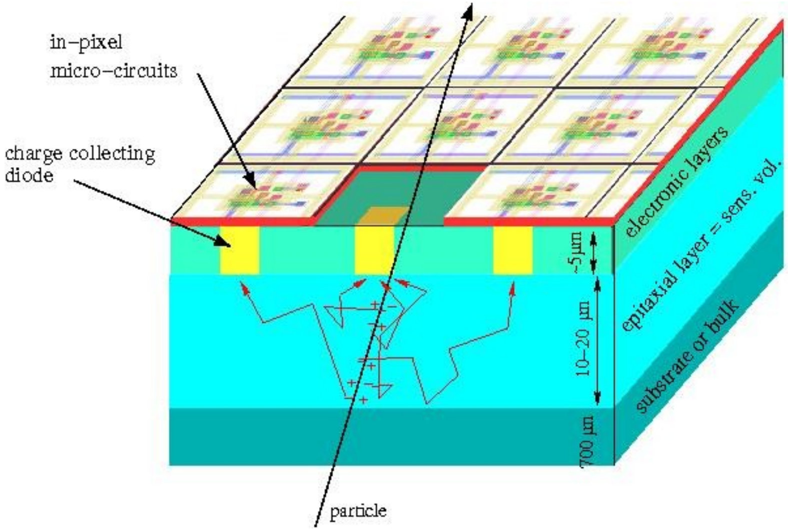
66M pixels, 100x150μm^2

10.7M strip channels,
210m^2 of silicon

Silicon detectors – CMOS

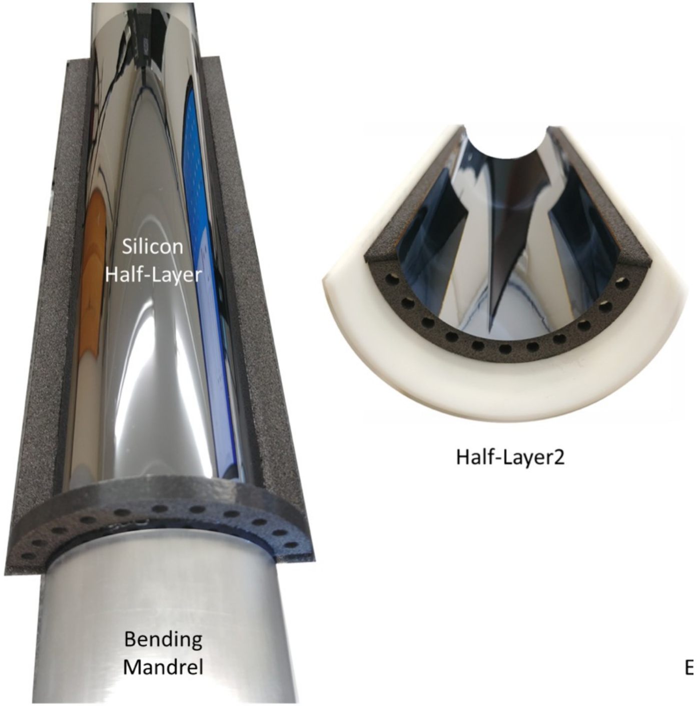
- CMOS industrial technology can be used for particle detectors
- Implement an array of sensing diodes
- Amplify the signals with transistors in the pixel, near the diode
- Full depletion not systematically reached
  - Slow thermal drift
  - Limited non-ionizing radiation tolerance
- Good 2D spatial resolution (<10μm)
- Low material budget (~50μm)
- Long integration time O(10μs)





Silicon detectors – CMOS

CMOS in ALICE

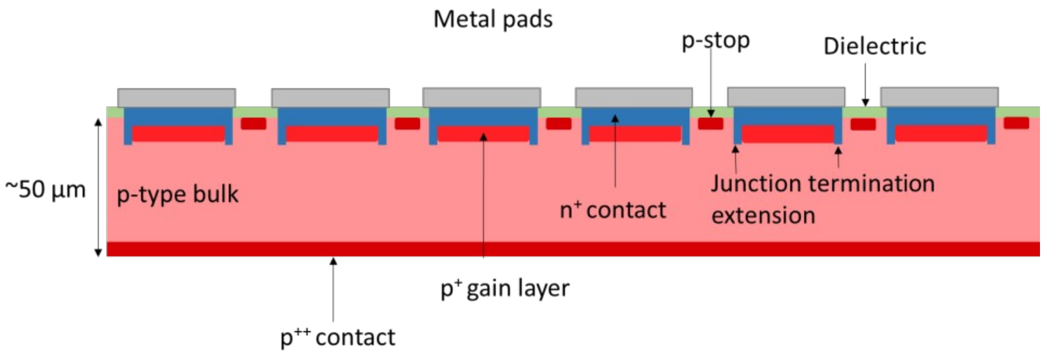


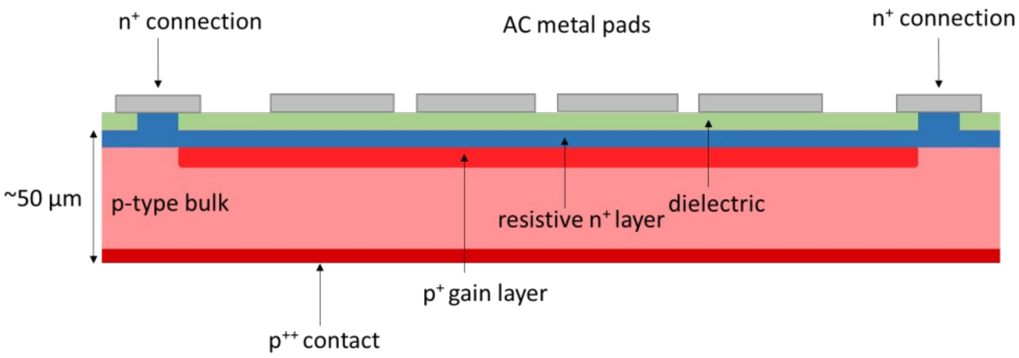
Mock-up of ALICE ITS3,
with bent silicon sensors

Silicon detectors – (AC)-LGAD

Silicon low-gain avalanche diode (LGAD)

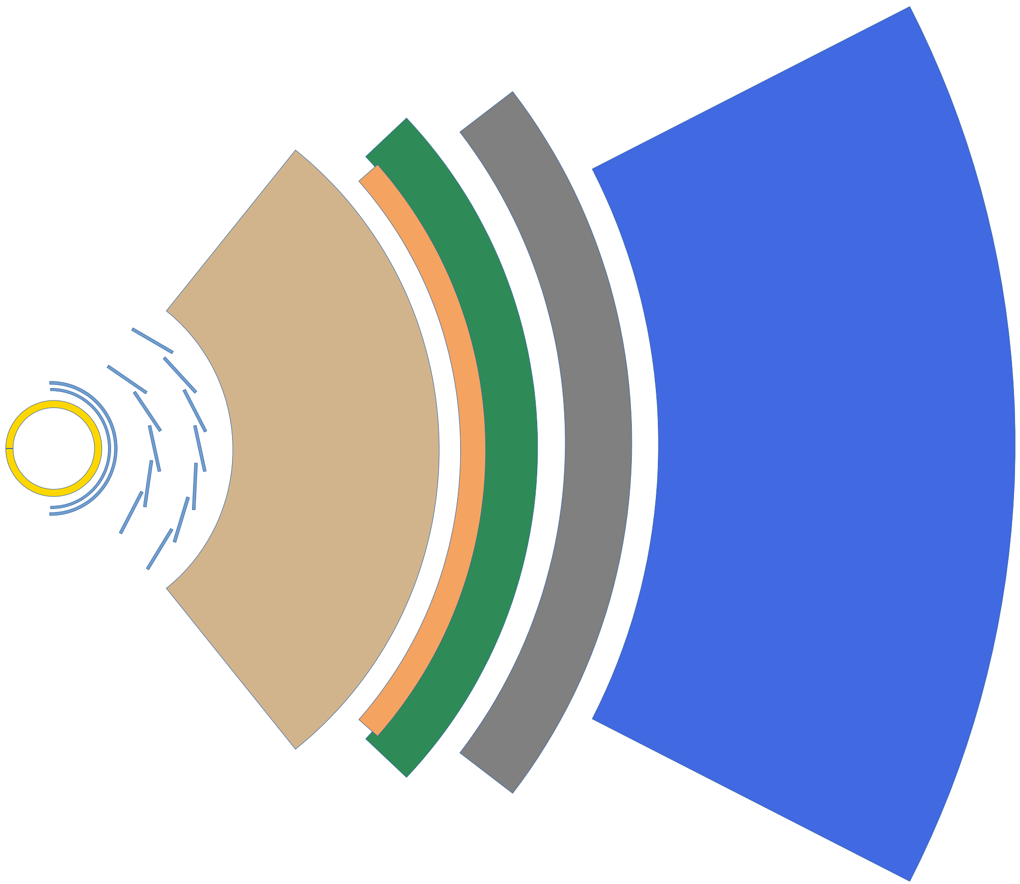
- Thin sensors (~50µm)
- Gain rage 5-50, provided by the multiplication in the p+ multiplication layer
- Very good timing resolution 20-30ps
- Good radiation hardness





AC-LGAD:
Charges are spread in the resistive n+ layer
Signal pick-up in metal pads
Allow for better position resolution

Build a tracking system in a collider



Beam pipe: must be small and light

Vertex layers: very close to the beam pipe, low material for minimal MS, very good spatial resolution. **Silicon pixels.**

First tracking layers. Good precision. **Silicon pixels or strips.**

At large radii, too expensive to use silicon. This is the place for gaseous trackers:TPC, drift chambers, MPGDs. (They might also participate to PID)

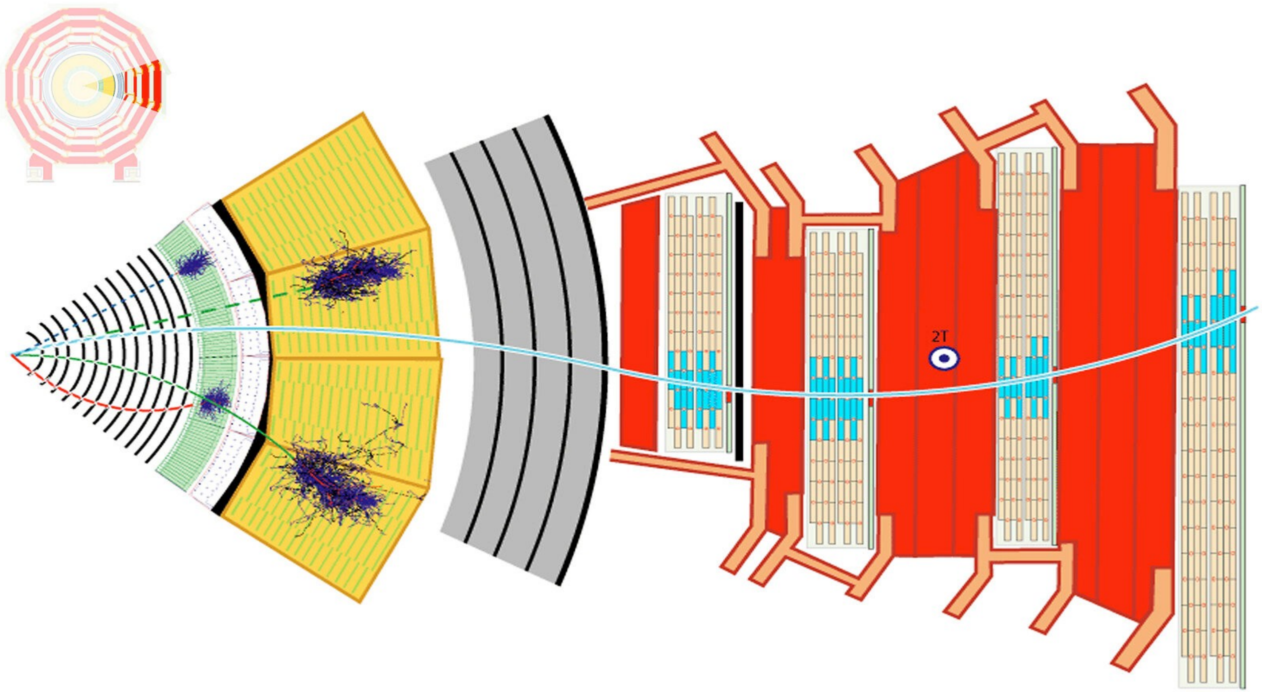
Time of flight (might also be part of tracking). Calorimetry, destructive measurement

We need a magnet!

Here, only muons survive. Large surfaces are ideal for gaseous detectors (MPGDs and RPCs)

Build a tracking system in a collider

Example: CMS Experiment

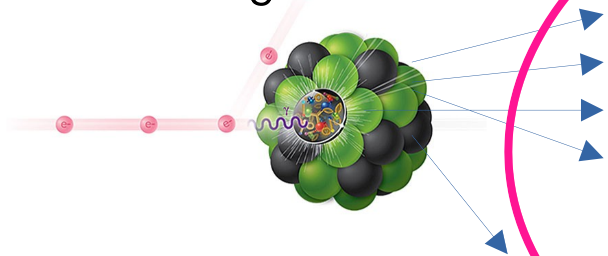


Of course, this design should be adapted at the physics and at the environment.

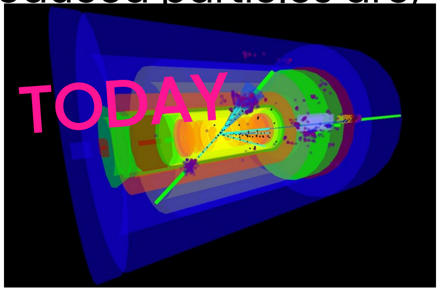
- Priorities (electrons vs muons vs hadrons…)
- Energies: CoM 140GeV vs 13 TeV is not the same
- Rates, backgrounds, radiation
- Space available
- Budget

Summary

We start by colliding electrons against nuclei

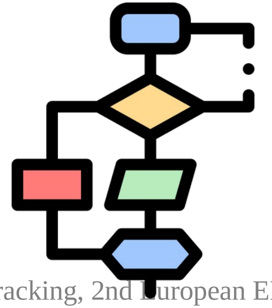


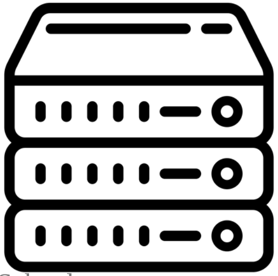
We need detectors to know where and what produced particles are;

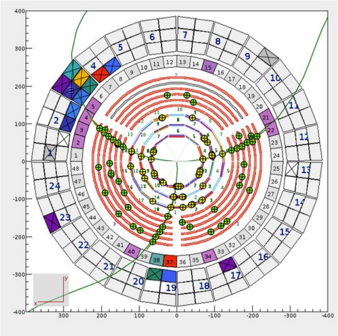


...electronics to read, decode and store signals from sensors;

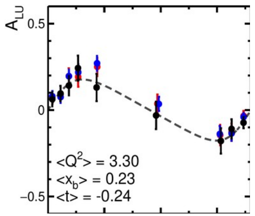
... computing and algorithms to extract features from raw data;







...and person-power to analyze the data and produce physics results



Summary

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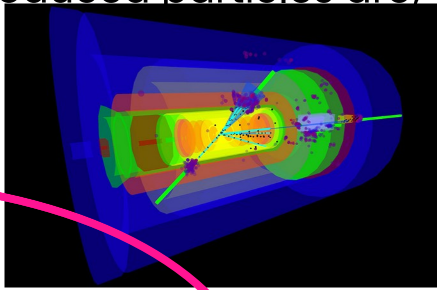
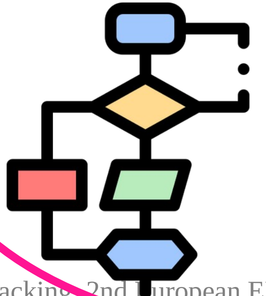
We need detectors to know where and what produced particles are;

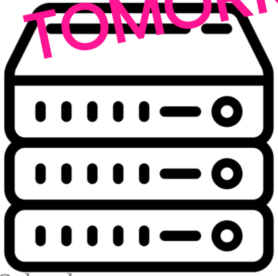


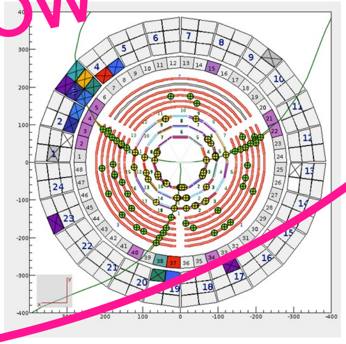
…electronics to read, decode and store signals from sensors;

… computing and algorithms to extract features from raw data;

TOMORROW







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