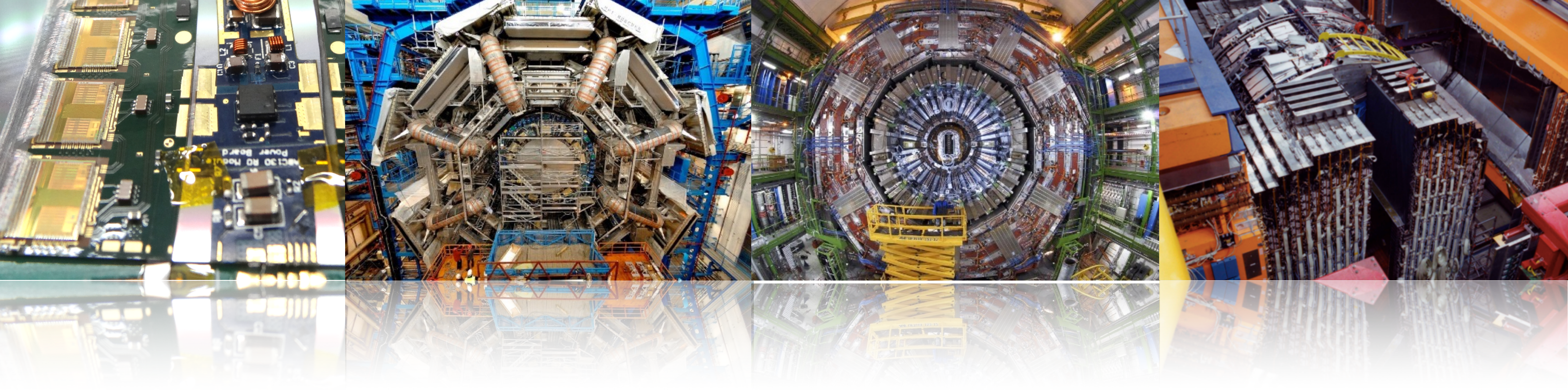


Instrumentation and Detectors

Part 2

Prof. Dr. Ingrid Maria Gregor
DESY/Universität Bonn

BND School

Overview

I. **Introduction Particle Detectors**

II. **Interaction with Matter (short reminder)**

III. **Calorimeter**

IV. **Tracking Detectors Overview**
- Gas detectors
- Semiconductor trackers

V. **Examples where it did not work ….**

} *Part 1*

} *Part 2*

} *Part 3*

Summary Part 1

Ionisation and Excitation:

- Charged particles traversing material are **exciting and ionising** the atoms.
- Average energy loss of the incoming charged particle: good approximation described by the **Bethe Bloch** formula.
- The energy loss fluctuation is well approximated by the Landau distribution.

Multiple Scattering and Bremsstrahlung:

- Incoming particles are **scattering off** the atomic nuclei which are partially shielded by the atomic electrons.
- Measuring the particle momentum by deflection of the particle trajectory in the magnetic field, this scattering imposes a lower limit on the momentum resolution of the spectrometer.
- The deflection of the particle on the nucleus results in an acceleration that causes emission of Bremsstrahlungs-Photons. These photons in turn produced e+e- pairs in the vicinity of the nucleus….

Requirements for calorimetry at future colliders

e^+e^- colliders

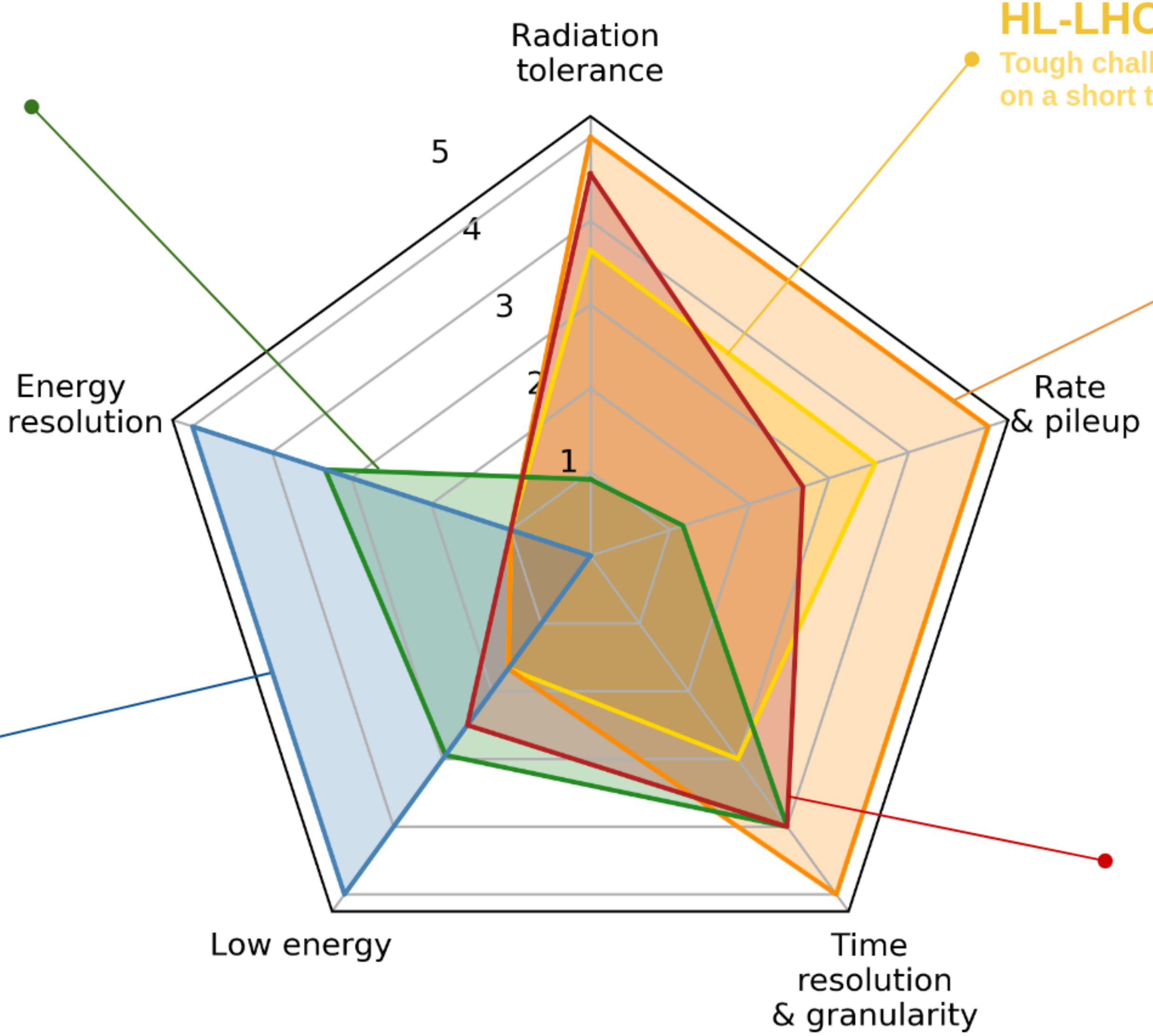
Precision physics benefits from exploiting the best possible energy and time resolution

HL-LHC

Tough challenges on a short timescale

FCC-hh

Setting the toughest challenge on radiation tolerance and pileup conditions



Strong interaction experiments (e.g. EIC)

Requiring the highest energy resolution for low energy photons

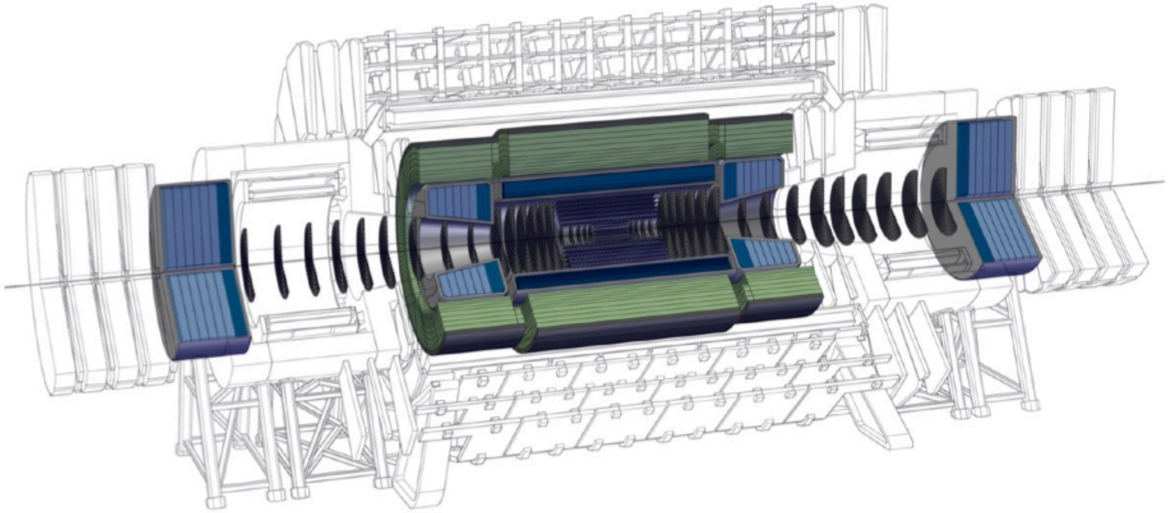
$\mu^+\mu^-$ colliders

High beam induced background and radiation levels, need for ambitious time resolution

Marco T. Lucchini, Milan Bicocca U.

FCC-hh Calorimetry

FCC-hh Calorimetry studies:
https://arxiv.org/abs/1912.09962



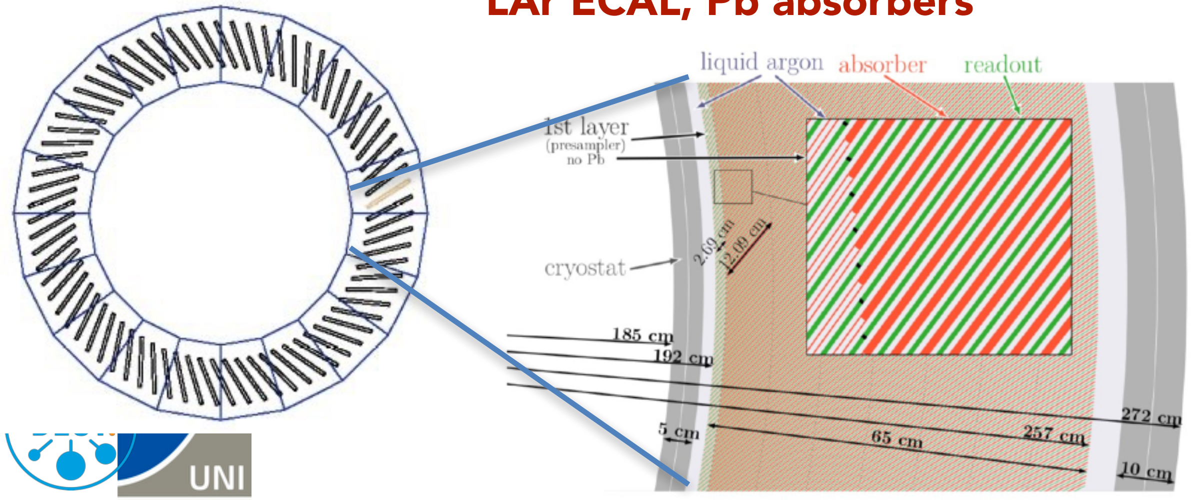
- Good intrinsic energy resolution
- Radiation hardness
- High stability
- Linearity and uniformity
- Easy to calibrate
- High granularity
  - → Pile-up rejection
  - → Particle flow
  - → 3D/4D/5D imaging

$$\frac{\sigma_E}{E} \approx \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Improving resolution with higher energy!

Need to increase radiation tolerance up to 5 10^{18} n_{eq}/cm^2 and 5000MGy (FCAL)

LAr ECAL, Pb absorbers



Barrel HCAL

- **ATLAS type TileCal optimised for particle flow**
  - Scintillator tiles – steel,
  - Read-out via wavelength shifting fibres and SiPMs
- **Higher granularity** than ATLAS
  - 10 instead of 3 longitudinal layers
  - Steel –> stainless Steel absorber (Calorimeters inside magnetic field)
- SiPM readout → faster, less noise, less space

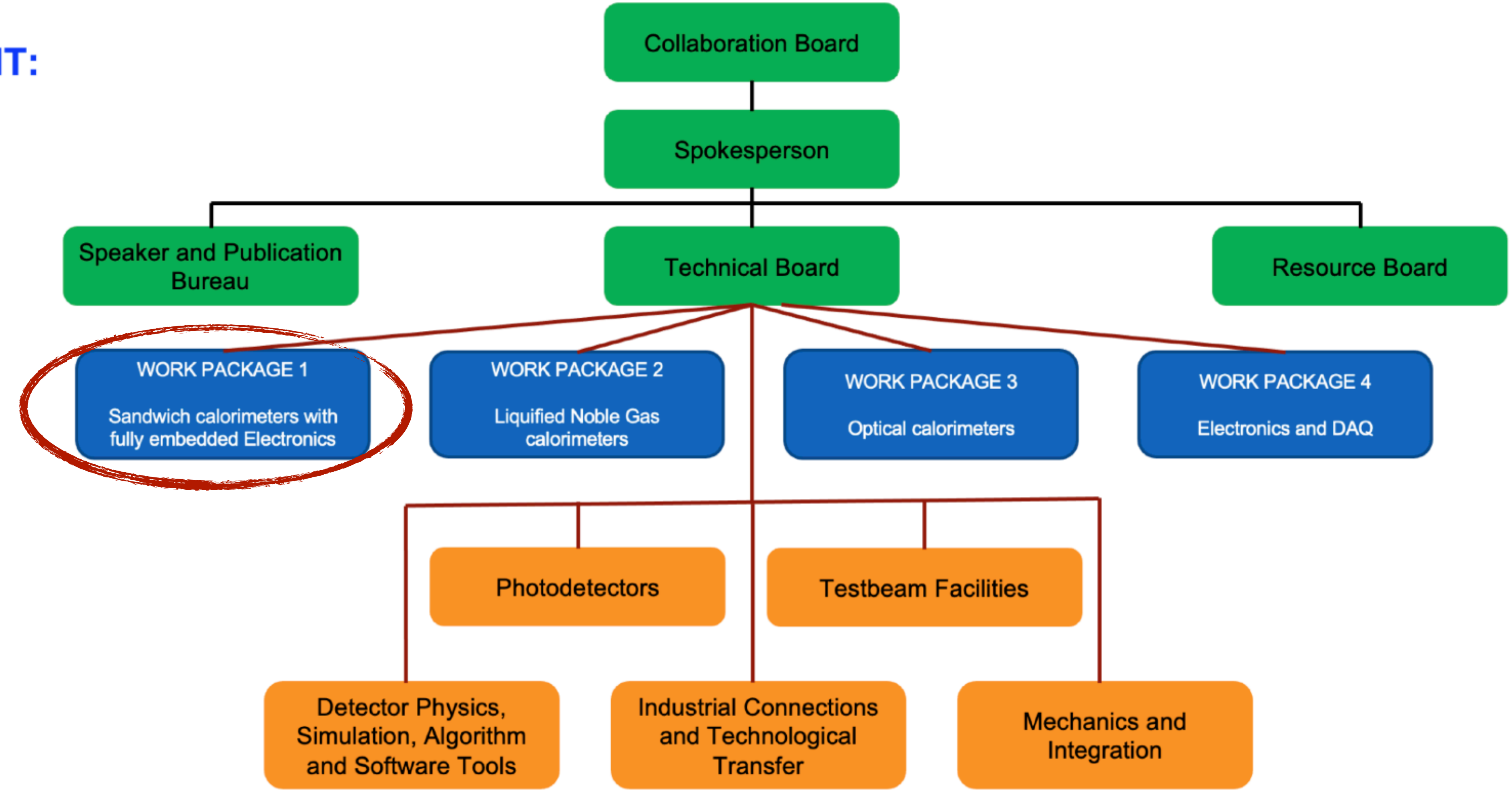
Martin Aleksa, CERN

DRD6 Calorimetry

MANAGEMENT:

WORK PACKAGES:

WORKING GROUPS:



Summary Calorimeters

Calorimeters can be classified into:

Electromagnetic Calorimeters,

- to measure electrons and photons through their EM interactions.

Hadron Calorimeters,

- Used to measure hadrons through their strong and EM interactions.

The construction can be classified into:

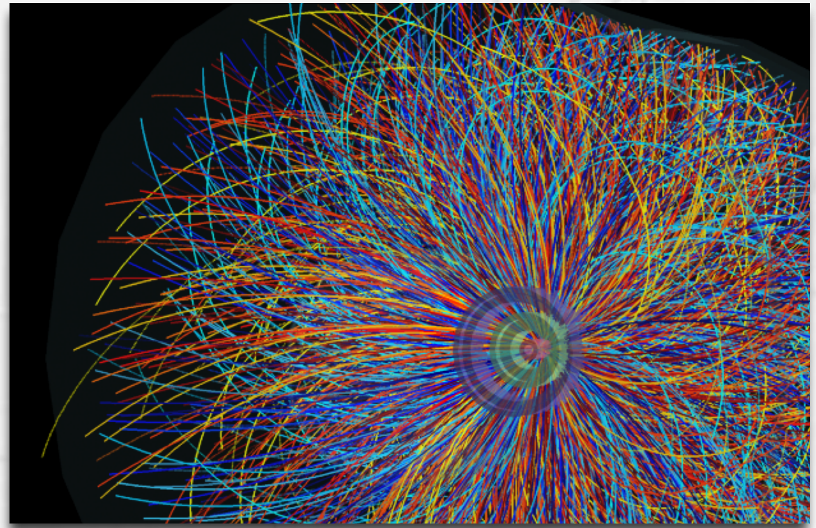
Homogeneous Calorimeters,

- that are built of only one type of material that performs both tasks, energy degradation and signal generation.

Sampling Calorimeters,

- that consist of alternating layers of an absorber, a dense material used to degrade the energy of the incident particle, and an active medium that provides the detectable signal.

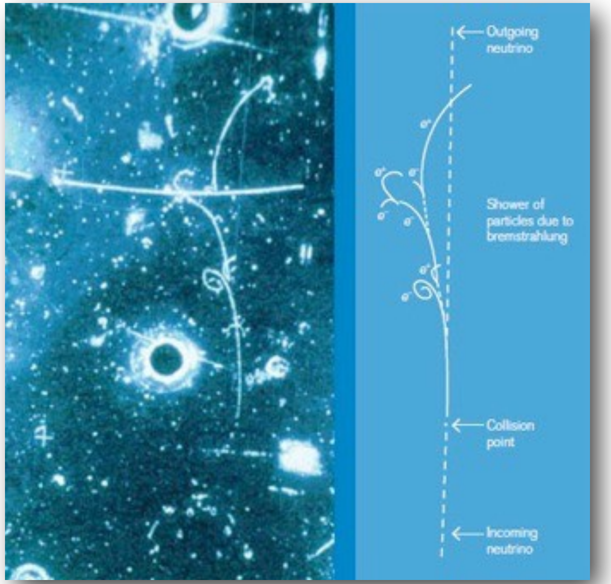
"Tracking" Detectors



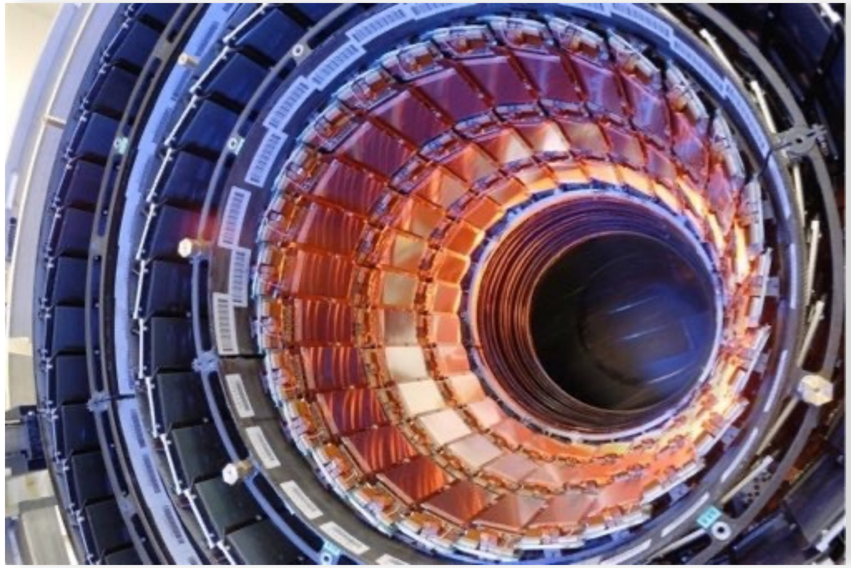
picture: ALICE@CERN

Tracking Detectors - Technologies

- **“Classic”**: Emulsions, cloud, and bubble chambers
  - Continuous media
  - Typically very detailed information but slow to respond and awkward to read out
- **“Modern”:** Electronic detectors, wire chambers, scintillators, solid state detectors
  - Segmented
  - Fast, can be read out digitally, information content is now approaching the “classic” technology
  - Mostly used solid state detector -> Silicon (pixels and strips)



Discovery of neutral currents
Gargamelle, 1972

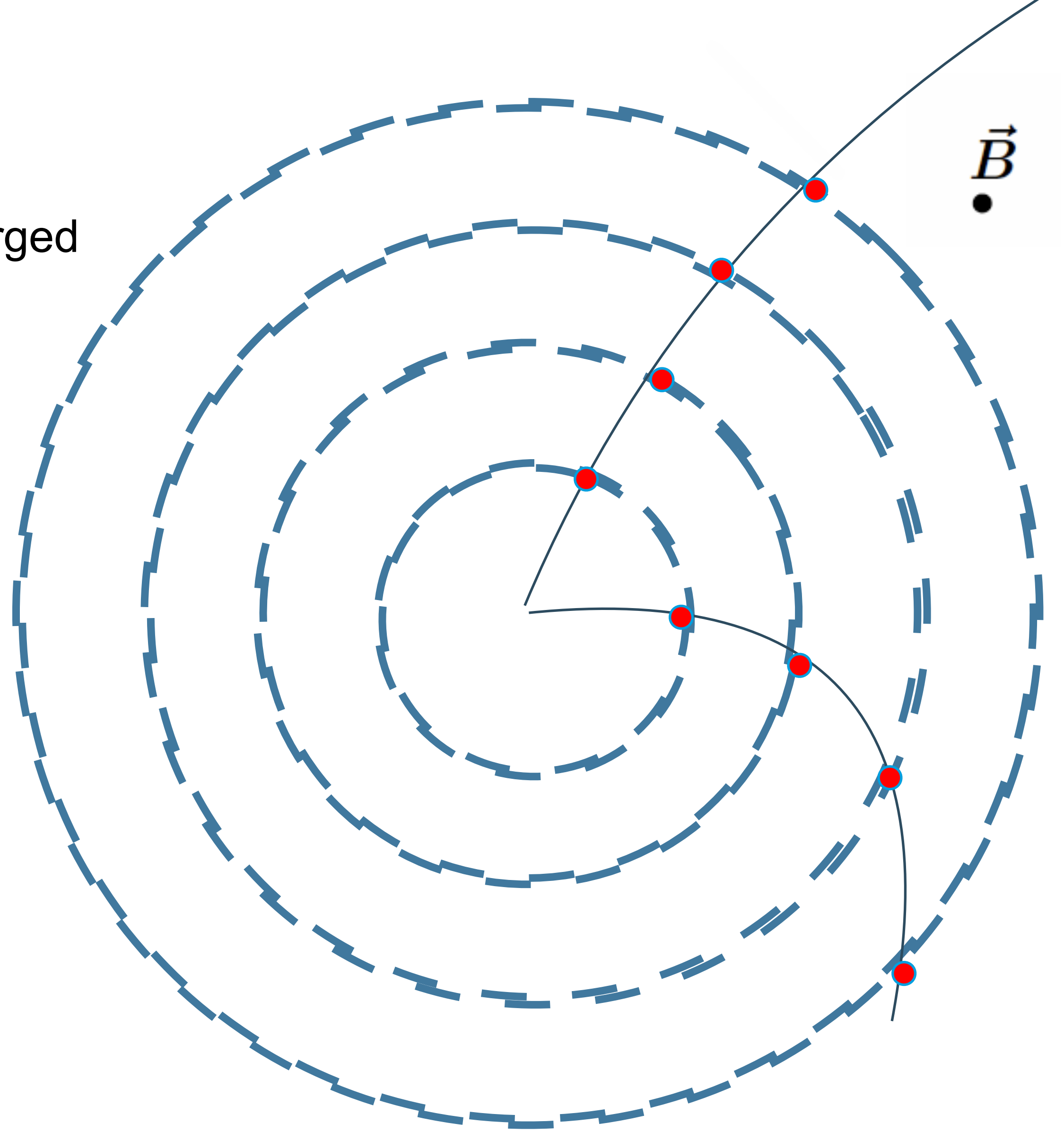


CMS Inner barrel Si Tracker:
Single-Sided Si-Strip

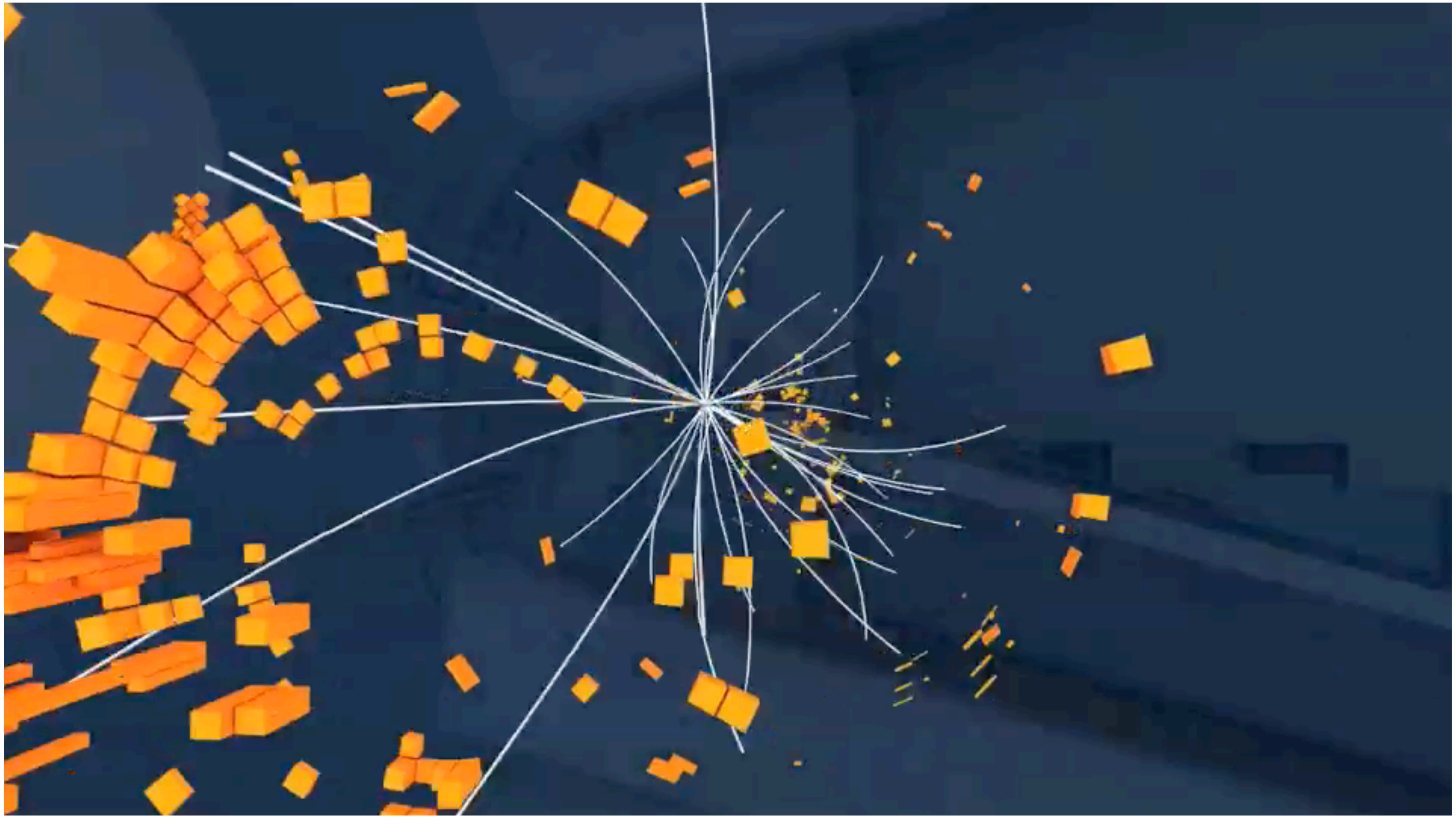
Pictures: CERN

Tracking Detectors

- Precise measurement of track and momentum of charged particles due to magnetic field.
- The trajectory should be minimally disturbed by this process (reduced material)
- Charged particles ionize matter along their path.
  - Tracking is based upon detecting ionisation trails.
  - An "image" of the charged particles in the event



Event Detection and Reconstruction

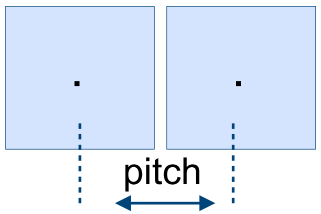


- LHC experiments are giant "cameras" to take "pictures" of p-p collisions
  - taking a picture every 25 nsec (40 MHz) with 100 million channels
- Task of the reconstruction is the interpretation of the picture !
  - answer the question: which particles were produced ?

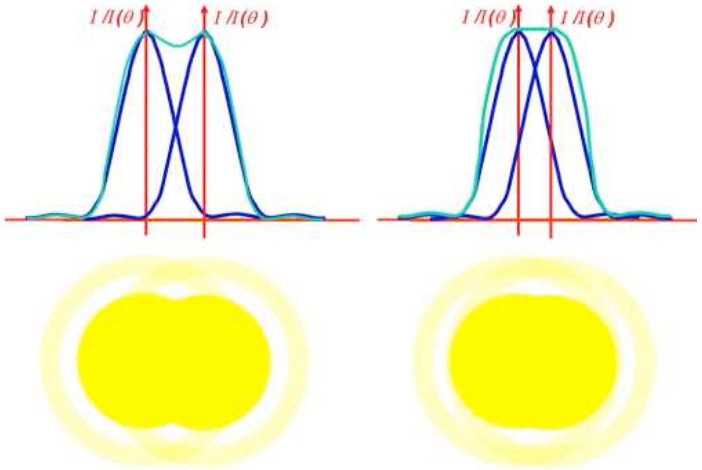
Some Important Parameters

Tracker: Important Parameter

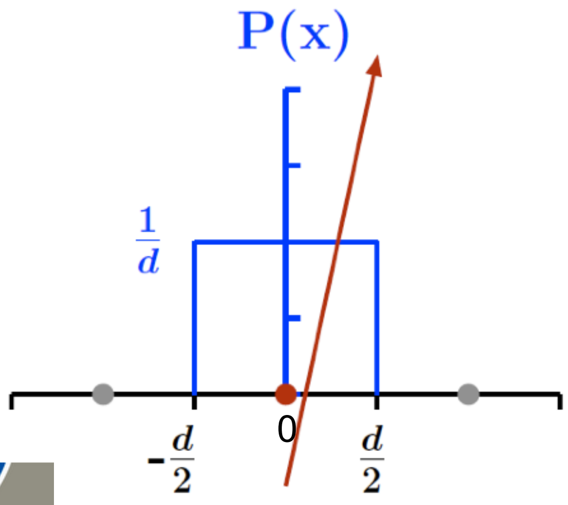
- Important figure of merit: spatial resolution
- Depending on detector geometry and charge collection
  - Pitch (distance between channels)
  - Charge sharing between channels



can be tubes, strips, wires, pixels ….



- Simple case: all charge is collected by one channel
- Traversing particle creates signal in hit channel (binary)
- Flat distribution along pitch; no area is pronounced
  - ➔ Probability distribution for particle passage:



$$P(x) = \frac{1}{d} \qquad \Rightarrow \int_{-d/2}^{d/2} P(x)\,dx = 1$$

The reconstructed point is always the middle of the strip:

$$\langle x \rangle = \int_{-d/2}^{d/2} x\,P(x)\,dx = 0$$

Tracker: Important Parameter

- Calculating the resolution orthogonal to the strip:

$$\sigma_x^2 = \langle (x - \langle x \rangle)^2 \rangle = \int_{-d/2}^{d/2} x^2 \, P(x) \, dx = \frac{d^2}{12}$$

- Resulting in a general term (valid for tracking detectors with a pitch d):

$$\sigma = \frac{d}{\sqrt{12}}$$

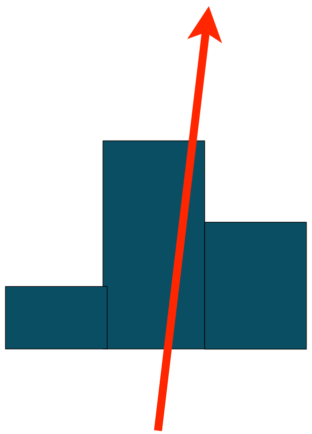
very important !

ATLAS/CMS Pixels

$\sigma_{\mathrm{r}\phi} \approx 10\mu m$

- In case of charge sharing between the strip (signal size decreasing with distance to hit position) and information about signal size
  - resolution improved by additional information of adjacent channels

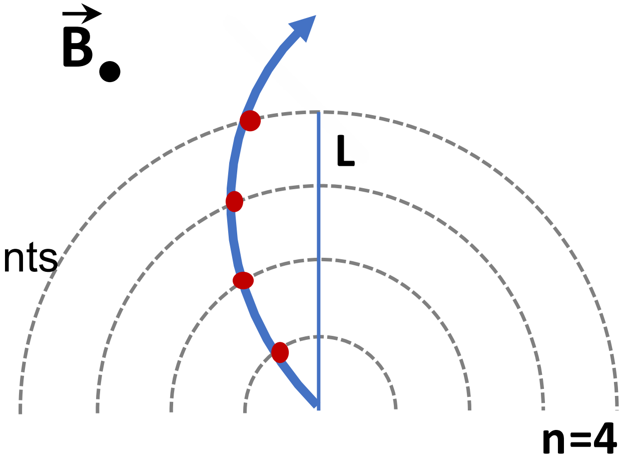
$$\sigma \propto \frac{d}{(S/N)}$$



Momentum Resolution

- Precise measurement of track and momentum of charged particles due to magnetic field.
  - Momentum resolution depending on many factors:

B = magnetic field
σ_y = spatial resolution
n = number of measurement points
L = length (~radius)



Gluckstern formula:

$$\left(\frac{\sigma_{p_T}}{p_T}\right)^2 = \left(\sqrt{\frac{720}{n+4}}\frac{\sigma_y p_T}{0.3BL^2}\right)^2 + \left(\frac{52.3\times 10^{-3}}{\beta B\sqrt{L L_y \sin\theta}}\right)^2$$

Position resolution

The larger the magnetic field **B**, the length **L** and the number of measurement points **n**, and the better the spatial resolution, the better is the momentum resolution

Multiple scattering

For low momentum (β→0), multiple scattering will dominate the momentum resolution. Reduce material!

NIM, 24, P381, 1963

When designing a tracking detector one should well understand what is required for the processes to be observed.

Ideal (non-realistic) tracking detector:
a massless, cheap, infinite granularity, 100% hermetic and efficient, infinite, long lifetime detector

Dream of Super Good Momentum Resolution

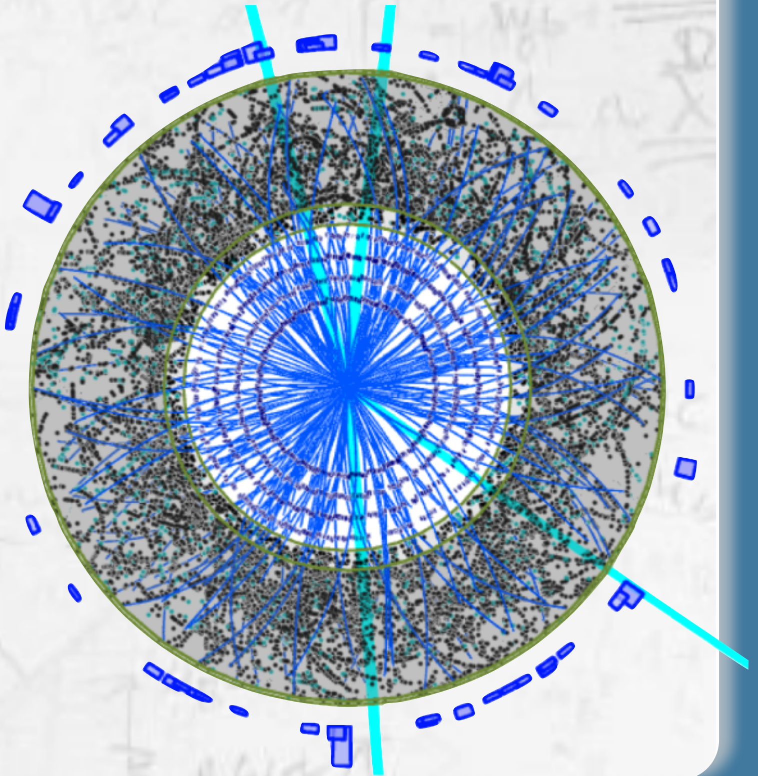
- Momentum resolution crucial for many processes
  - Tracking detector and muon taggers to be optimised
- Comparatively low momenta involved
  - transparency is important (less important for FCC-hh)

$$\frac{\Delta p}{p} \propto \frac{\sigma_{\mathrm{pos}} \cdot p}{BL^2}$$

	BELLE	ILD	SiD	CLD	IDEA	Allegro	LHeC	FCC-hh
Tracking	TPC + MAPS	TPC + silicon	Silicon strips	Silicon strips	Ultra light drift chamber + silicon wrapper	Ultra light drift chamber or Silicon	Macro pixels and strips	Silicon? MAPS?
Muon	Scintillator or RPCs	SiPM on scintillator	SiPM on scintillator (WLS)	???	µRWELL	Drift chambers, RPC, MicroMegas	Thin RPC, sMDTs	MAPS?

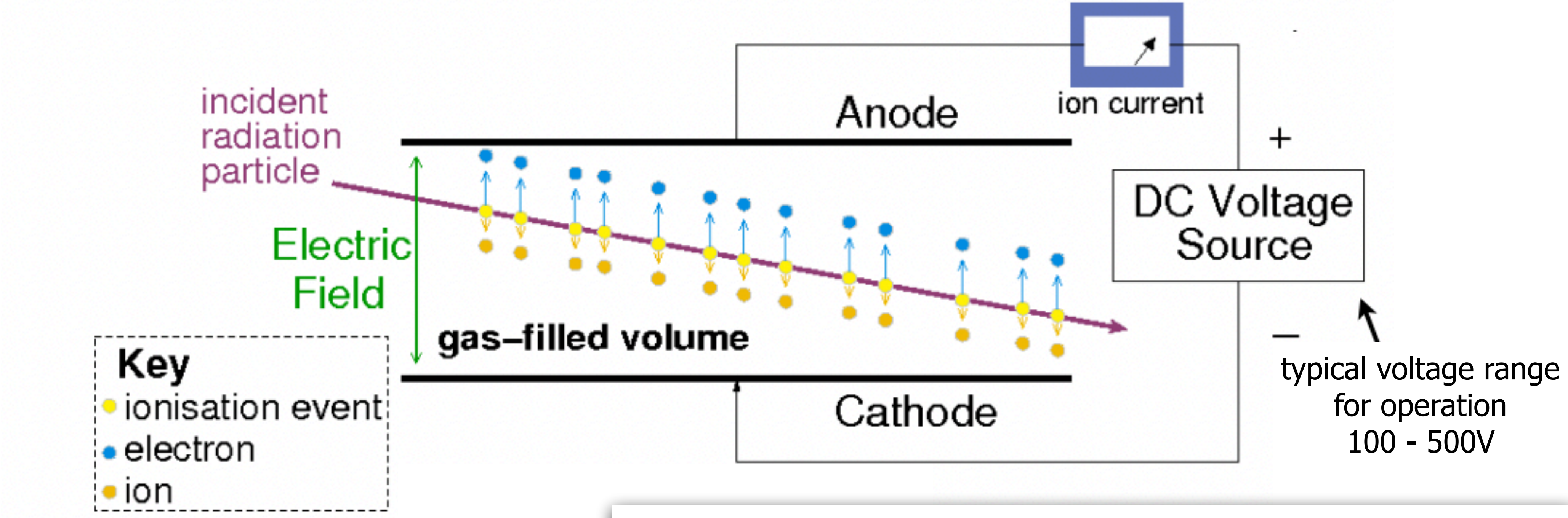
Vertex detector see later

Gas-Detectors



Very Basic Principle

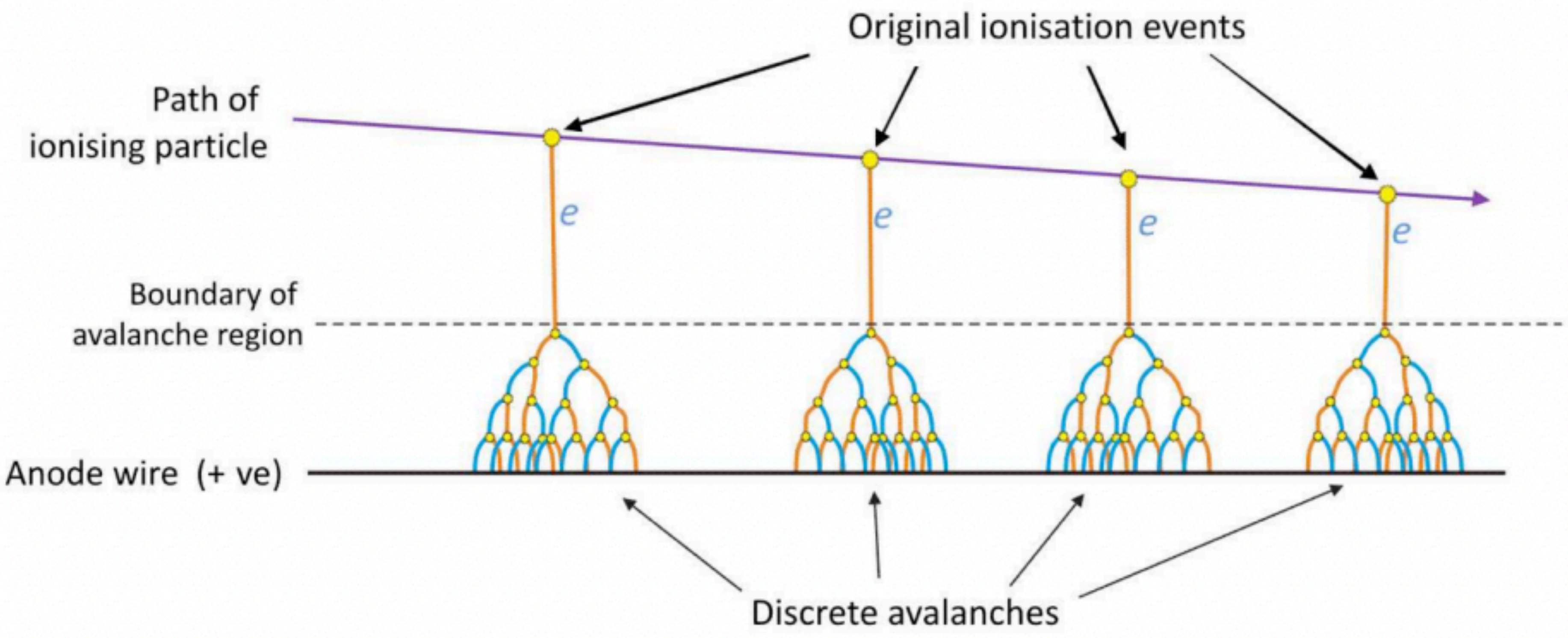
- Make use of ionisation when radiation particle is passing gas



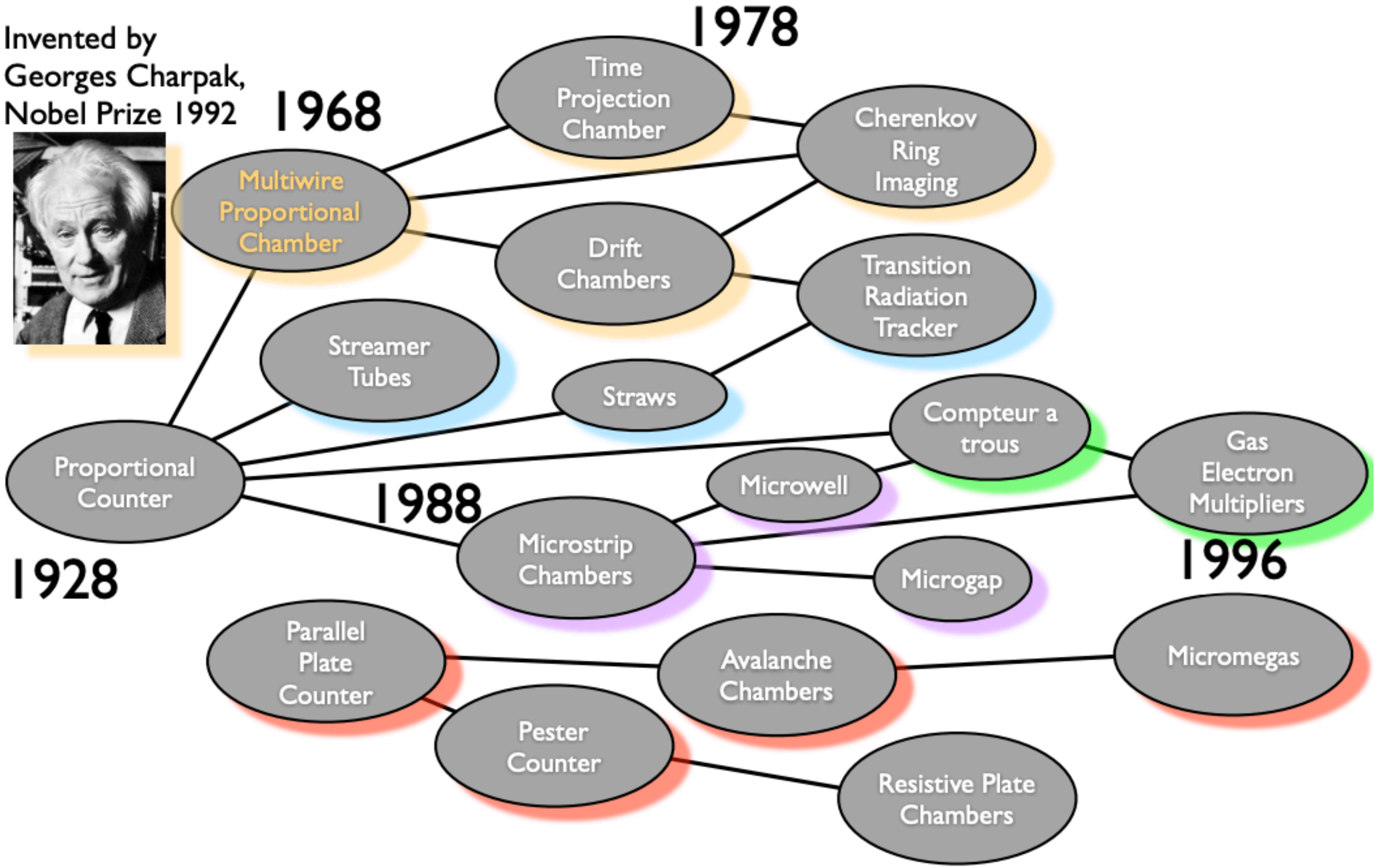
- Passage of particles creates within the gas volume electron-ion pair (ionisation)
- Electrons are accelerated in a strong electric field -> amplification
- The signal is proportional to the original deposited charge or is saturated (depending on the voltage)

Electron avalanches enlarge signal

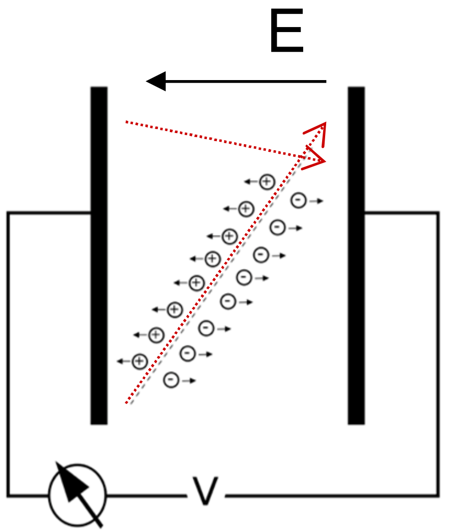
- In ionisation chambers: 100 e-ion pairs (typical number for 1 cm of gas) are hard to detect (typical noise of very modern pixel ASICs is ~ 100e-)
- Need to increase number of e-ion pairs
  ➡ trick: apply higher electrical field



Many different types of Gas Detectors



Proportional Chamber

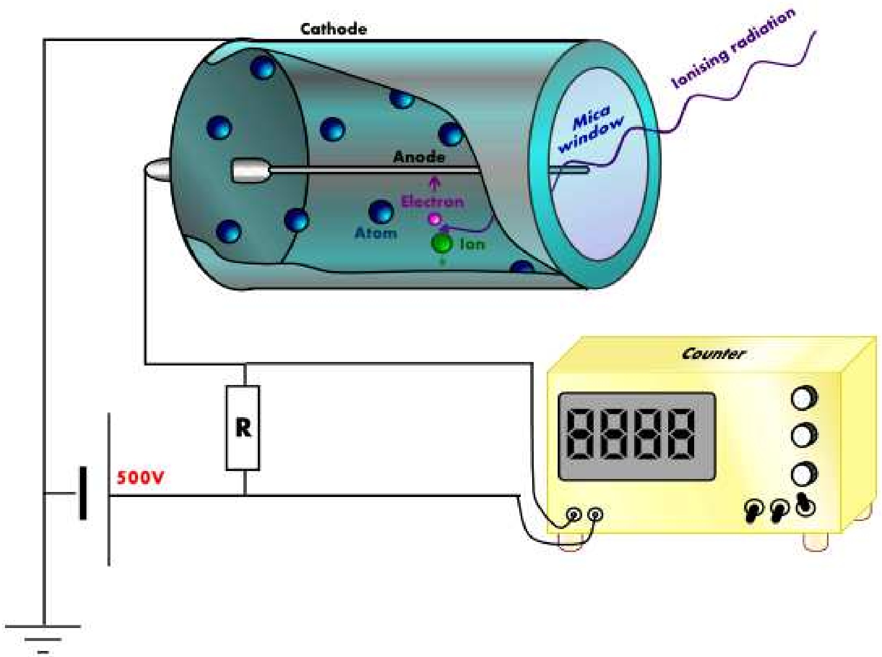


Disadvantage of planar design:

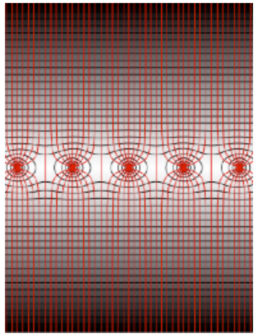
- E uniform and ⊥ to the electrodes:
- amount of ionisation produced proportional to path length and to position where the ionisation occurs
  -> not proportional to energy

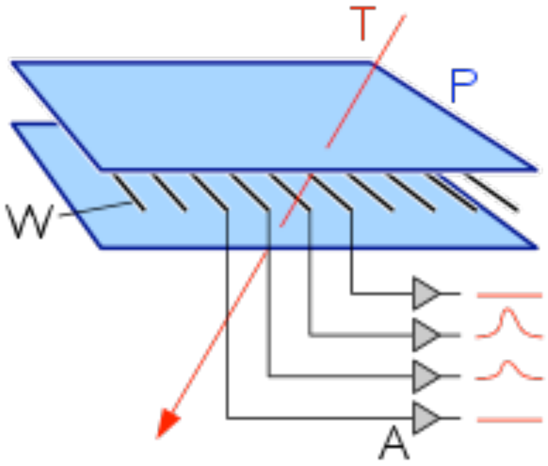
Problem solved using **Cylindrical proportional counter:**

- Single anode wire in a cylindrical cathode
- E~1/r: weak field far from the wire electrons/ions drift in the volume multiplication occurs only near the anode



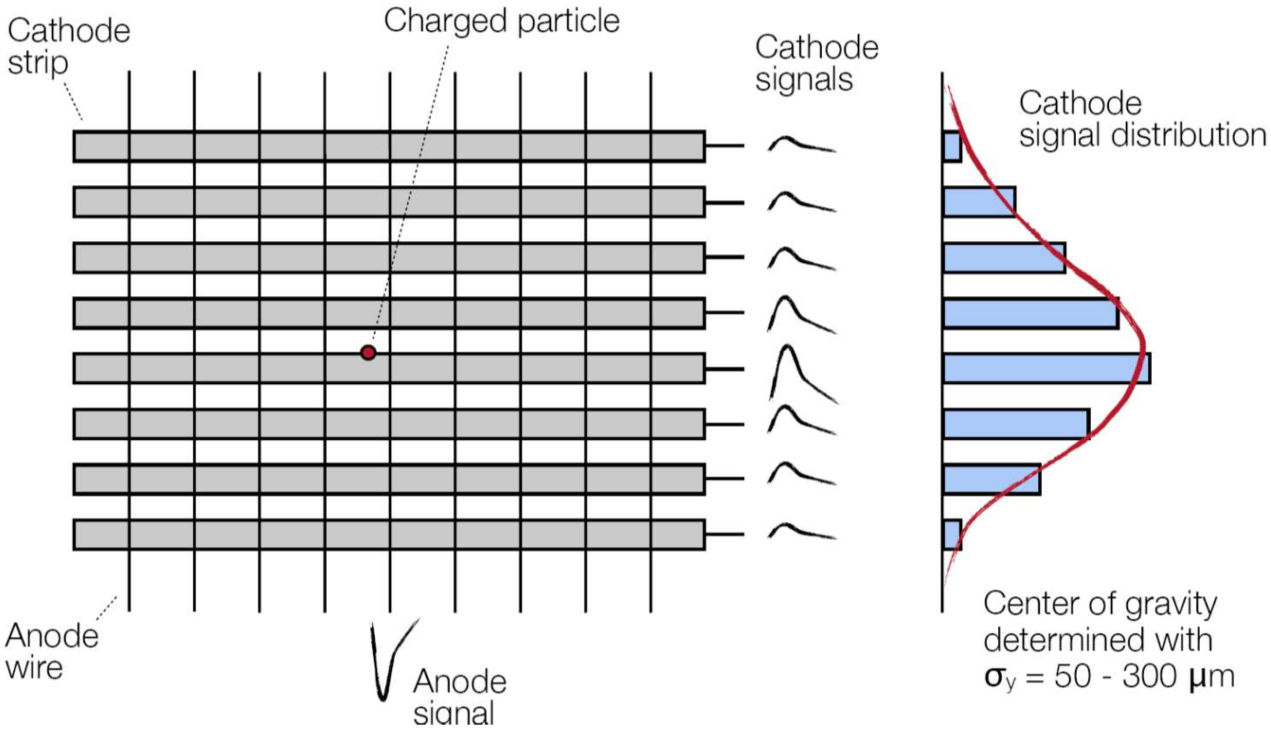
Multi-Wire Proportional Chamber





Signal generation:

- Electrons drift to closest wire
- Gas amplification near wire ➛ avalanche Signal generation due to electrons and mainly slow ions

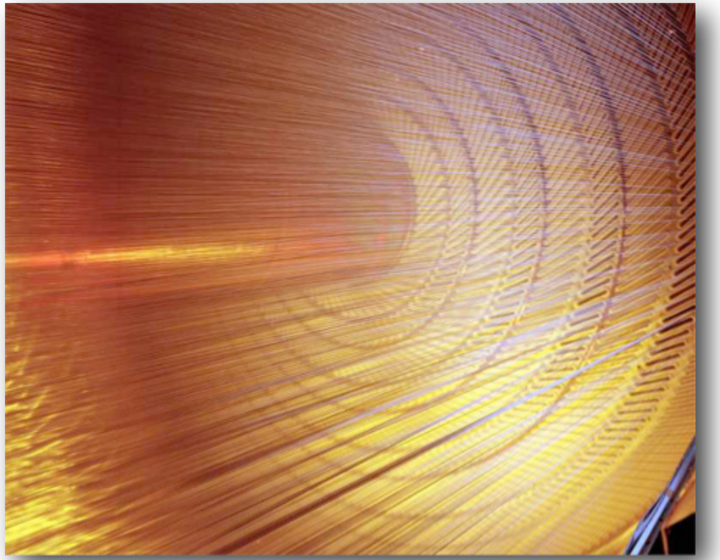


- Only information about closest wire
  ➛ $\sigma_X = d/\sqrt{12}$
  [Only one dimension information]

- **Possible improvements:** - segmented cathode
  - 2-dim.: use 2 MWPCs with different orientation
  - 3-dim.: several layers of such X-Y-MWPC combinations [tracking]

Adding Time: Drift Chamber

- Alternative way to obtain spatial information: measure the electrons drift time:
  - time measurement started by an external (fast) detector, i.e. scintillator counter
  - electrons drift to the anode (sense wire), in the field created by the cathodes with constant velocity
  - the electron arrival at the anode stops the time measurement
  - one-coordinate measurement:

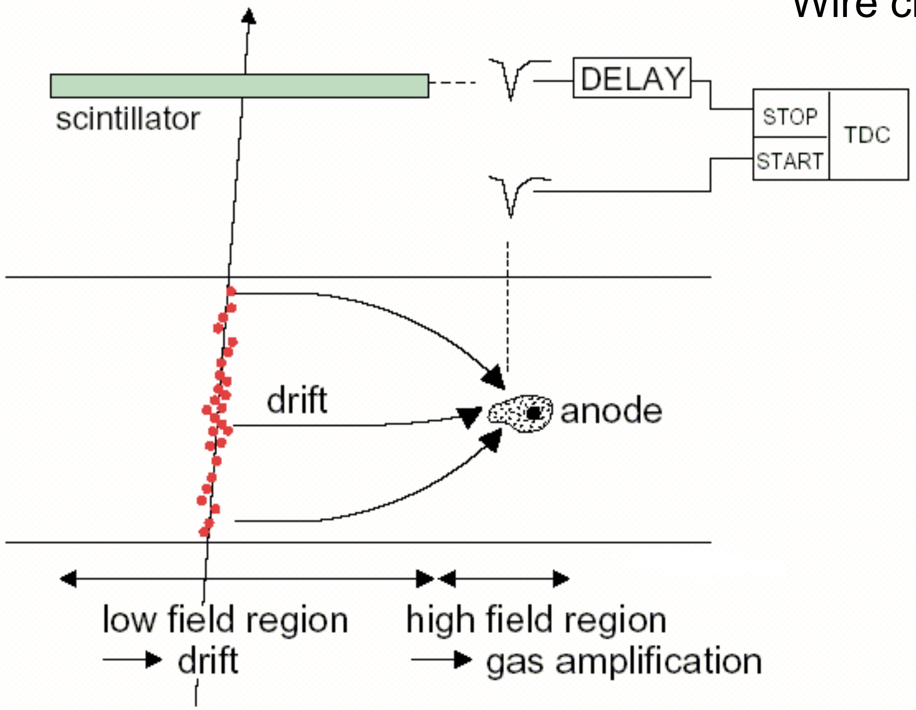


Wire chamber CDF (@Tevatron)

$$x = \int_0^{t_D} v_D dt$$

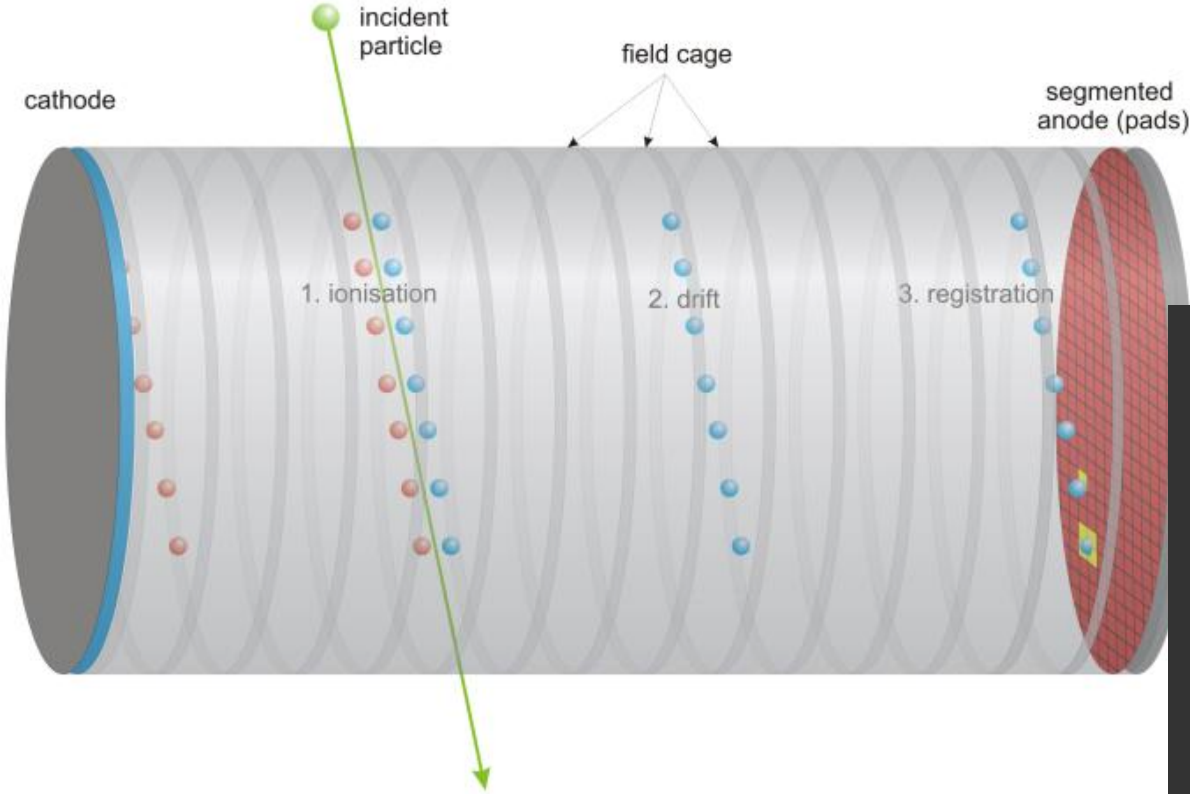
velocity $\vec{v}_D = \mu_{\pm} |\vec{E}|$

μ_+ mobility



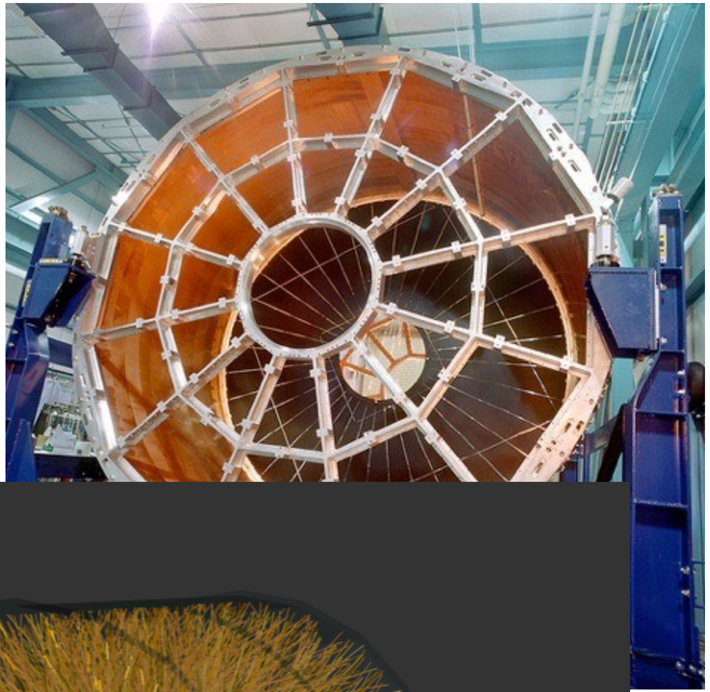
TPC- Time Projection Chamber: 3D

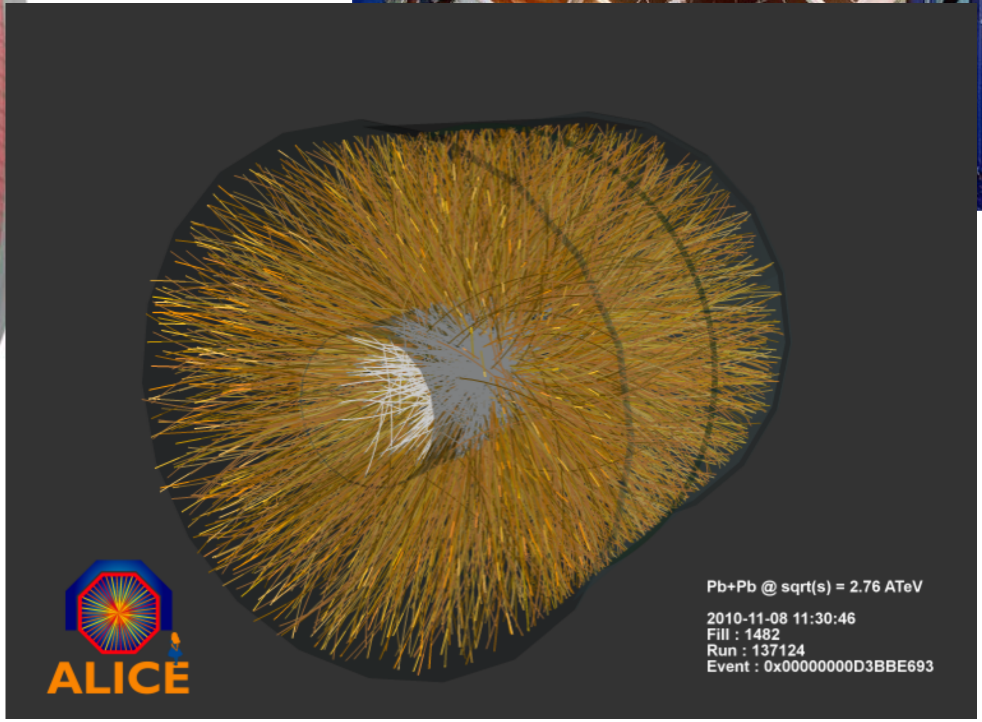
- Combination of the the 2D track information and the time results in a real 3D point



Pic: O. Schäfer

- Readout of the anode usually with multi wire projection chambers
- Nowadays new developments under way.



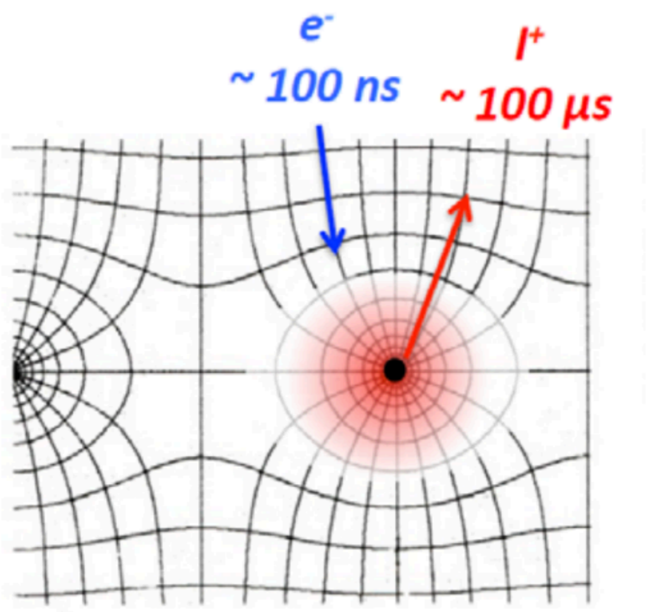


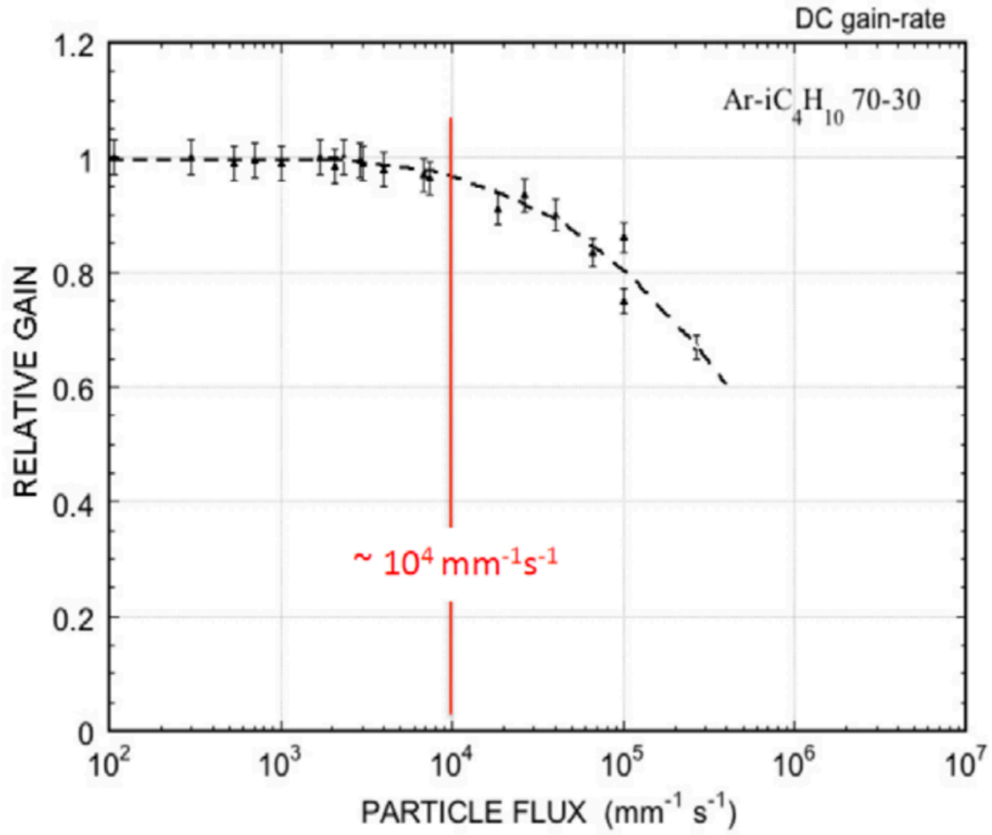
Pic: ALICE Collaboration

Micro-Pattern Gas Detectors

Need for Improvements

- MWPCs have several limitations intrinsic in their conception.
- In multiplication process, creation of large amounts of positive ions, slowly receding towards the cathodes, causes modification of applied electric field
- Drop of gain and efficiency at particle fluxes above ~10^4mm^{-1}s^{-1}.



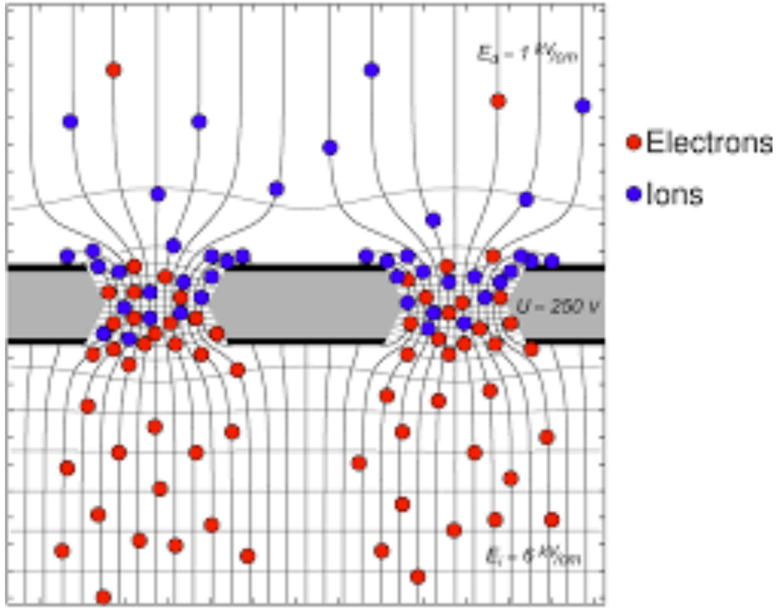


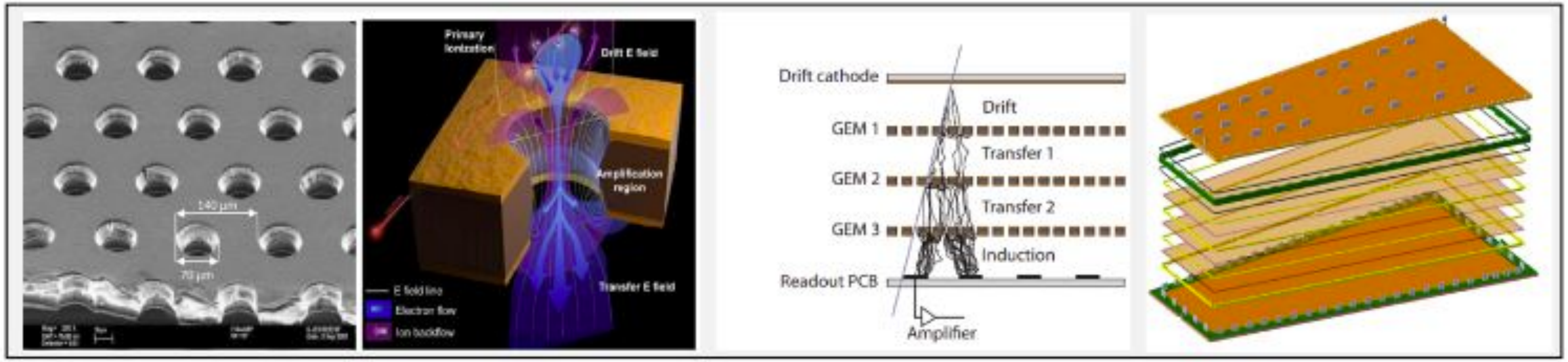
A. Breskin et al, Nucl. Instr. and Meth. 124(1974)189

GEMS

F. Sauli, GEM: A new concept for electron amplification in gas detectors, NIM A386(1997) 531

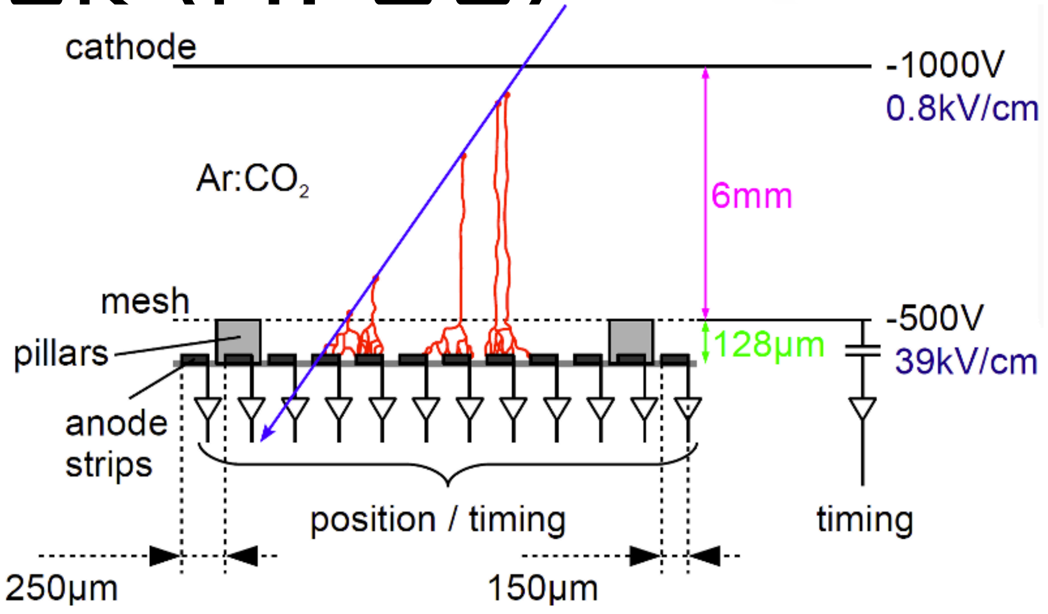
- Electrons are collected on patterned readout board.
- A fast signal can be detected on the lower GEM electrode for triggering or energy discrimination.
- All readout electrodes are at ground potential.
- Positive ions partially collected on the GEM electrode

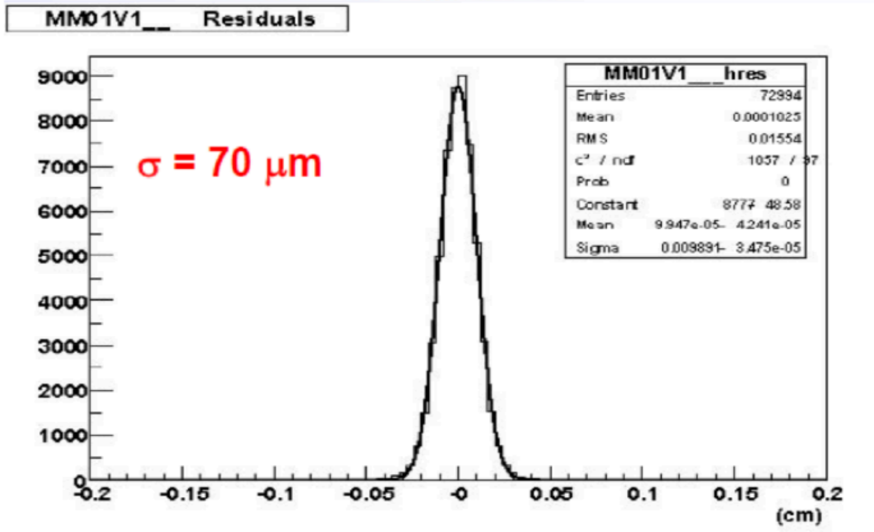




MicroPatter Gas Detector (MPGS)

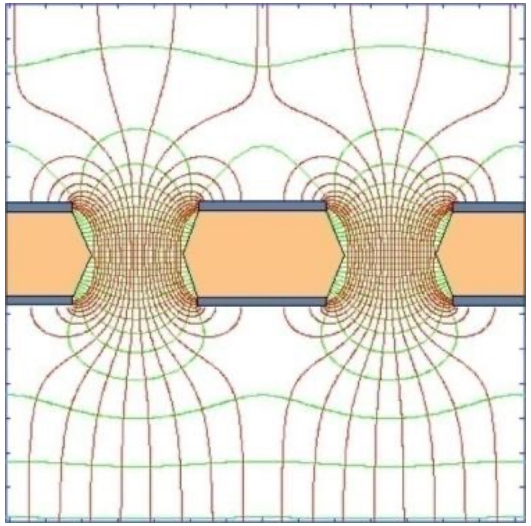
- Micromegas (Micro Mesh Gas Detectors)
  - high position resolution with readout strip pitch of 250 to 500 micrometers.
  - Charged particles ionize the detector gas
  - Electrons from ionization amplified in avalanche between a fine micro mesh and readout strips.
  - High rate capability

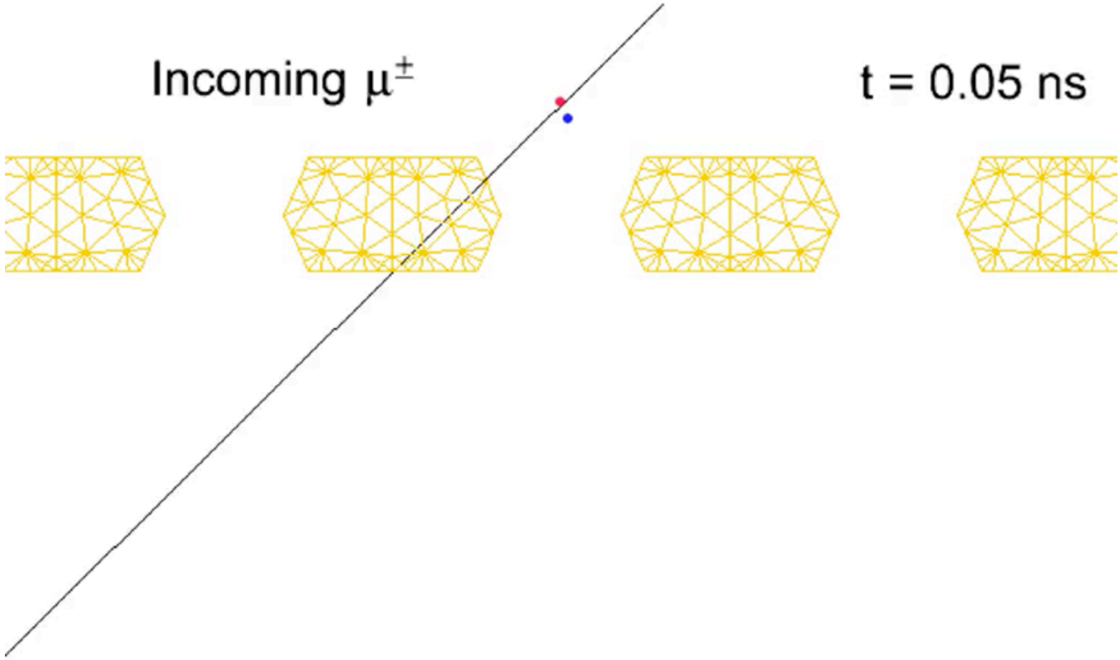




Space resolution

Ion Backflow





- Animation of the avalanche process
  - monitor in ns-time electron/ion drifting and multiplic
  - electrons are blue,
  - ions are red,
  - the GEM mesh is yellow

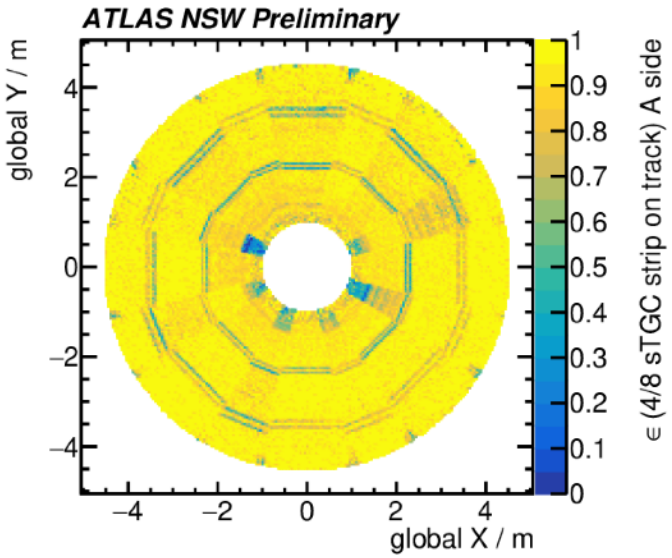
- Simulation: Garfield++
  (Particle Detector Simulation Toolkit)

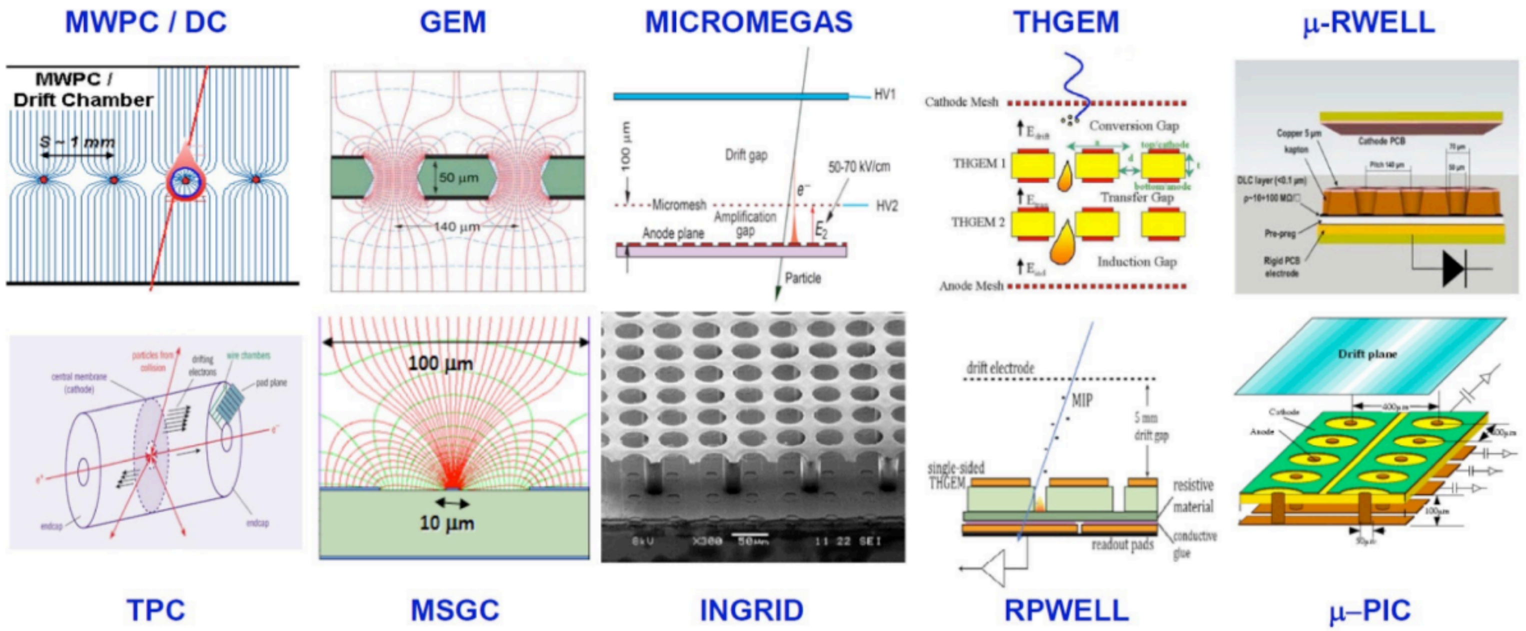
http://cern.ch/garfieldpp/examples/gemgain The RD51 collaboration

Gas Detectors ongoing R&D

alive and kicking

- Micro-pattern gas detectors were game changer
- Primary choice for large-area coverage with low material budget & dE/dx measurement & ToF functionality
- Large Areas:
  - LHC developments led to unprecedented large systems, mostly based on MPGDs



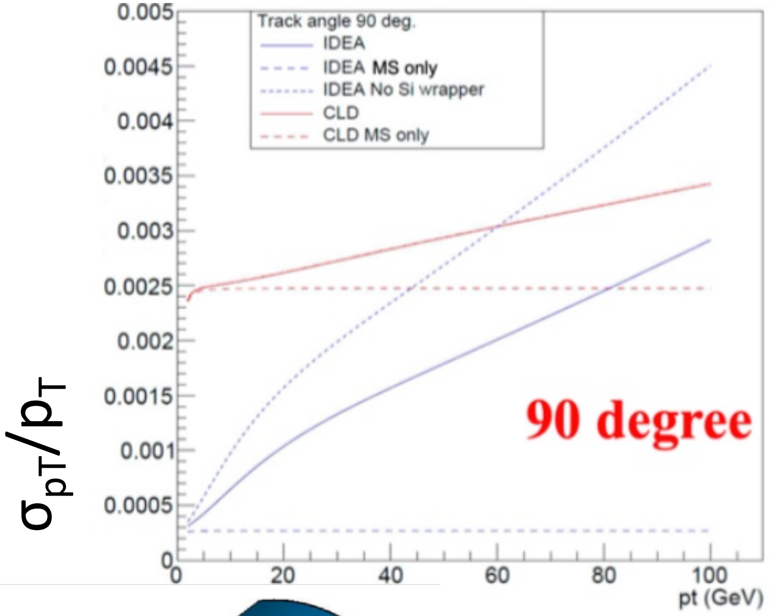


- Fast Timing:
  - Fast timing with Multi-Gap RPCs: achieved ~60ps time resolution
  - Micromegas with timing (PICOSEC concept): 25ps
- Eco-friendly gas mixtures
  - 92% of emissions at CERN are related to LHC experiments

Example: Drift Chamber

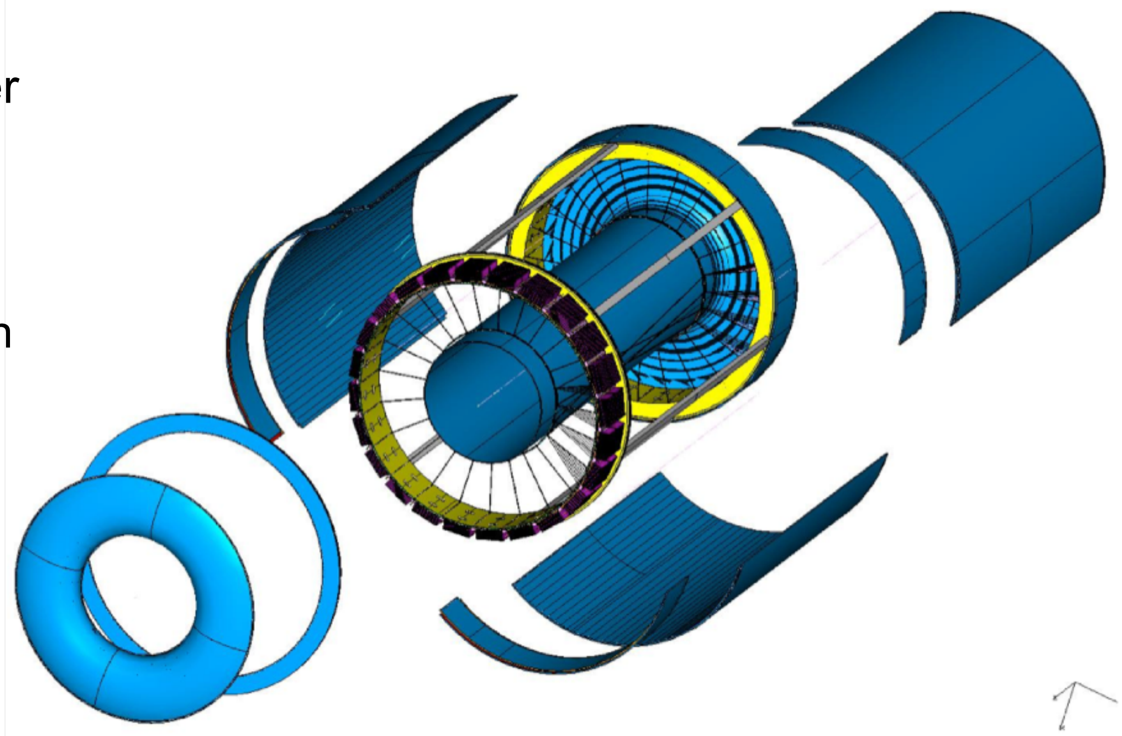
IDEA detector

- **Advantages**
  - Extremely transparent: minimal multiple scattering and secondary interactions
  - Continuous tracking: reconstruction of far-detached vertices
  - Particle separation via dE/dx or cluster counting (dN/dx)



IDEA: Extremely transparent Drift Chamber

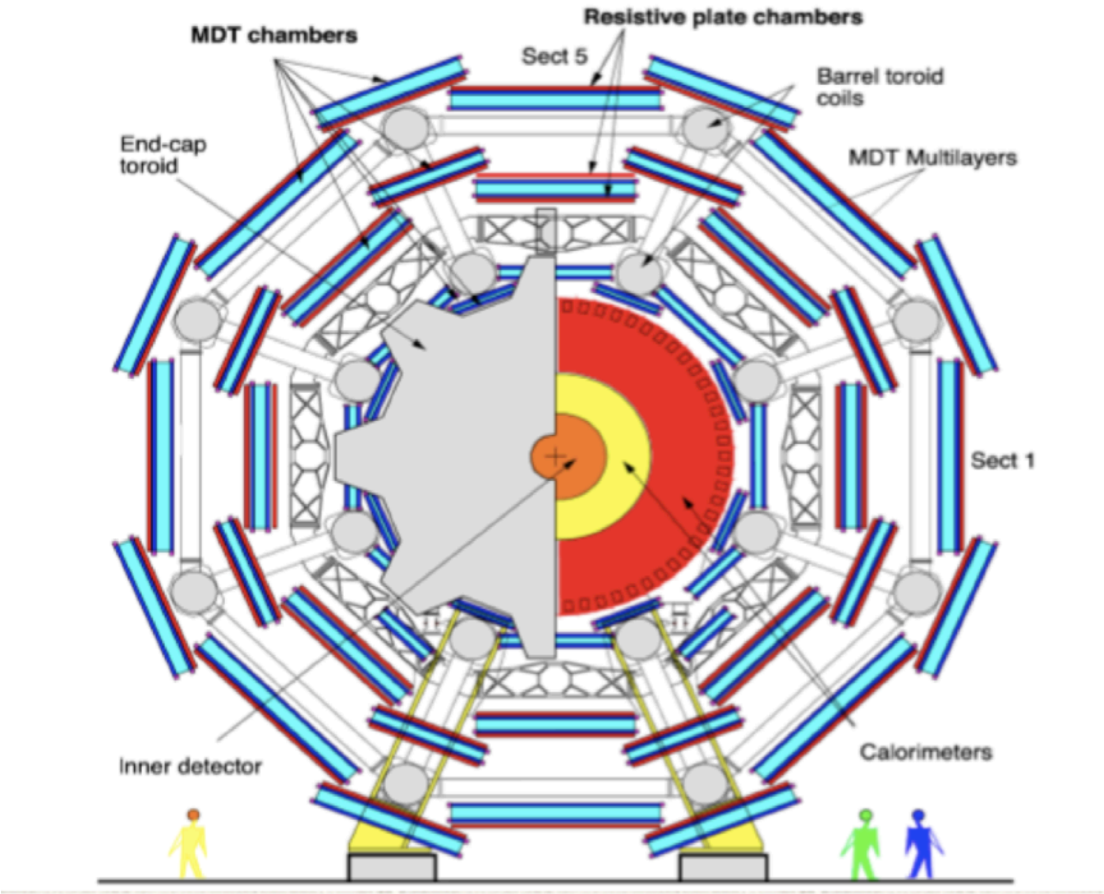
- Gas: 90% He – 10% iC_4H_{10}
- Radius 0.35 – 2.00m
- Total thickness: 1.6% of X_0 at 90^o
  - Tungsten wires dominant contribution
- 112 layers for each 15^o azimuthal sector
- max drift time: 350 ns



Muon-Detectors

Also Gas Detectors: Muon Detectors

- Identification and precise momentum measurement of muons outside of the magnet
- Benchmark design for muon detectors: momentum measurement better than 10% up to 1 TeV.
  - $\Delta pT/pT \approx 1/BL^2$



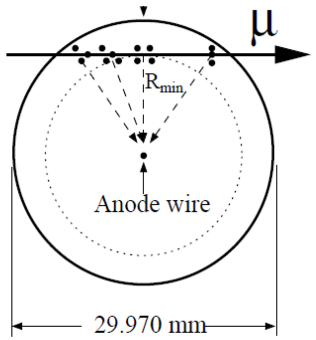
- A muon tracks can be:
  - “standalone” purely based on muon system
  - “combined” btw muon system and inner detector

Example: ATLAS

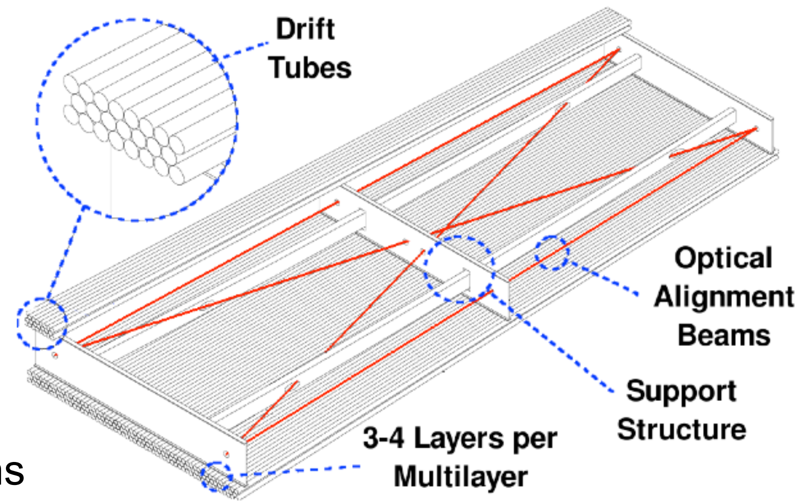
- independent muon system -> excellent stand capabilities

Precision Chambers

1) Monitored Drift Tubes (MDT)



Drift Tube

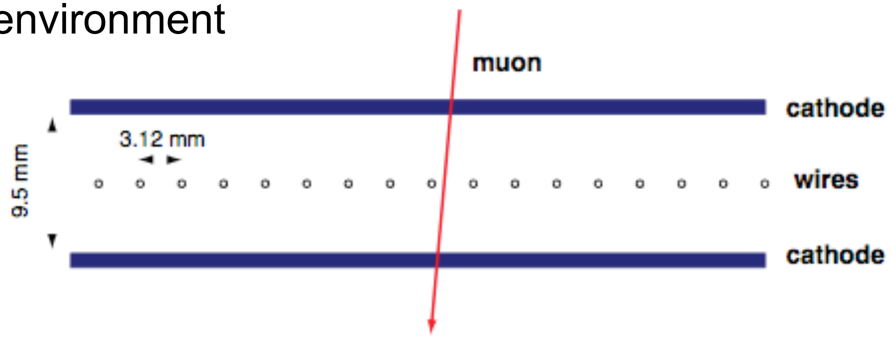


High-pressure drift tubes
$\sigma(R)\approx 100\mu m$, $T_{drift}\approx 700ns$

- Gas-filled drift tubes with central wire
- Signal read out on both ends
- Spatial resolution increased by recording drift time.

2) Cathode Strip Chambers

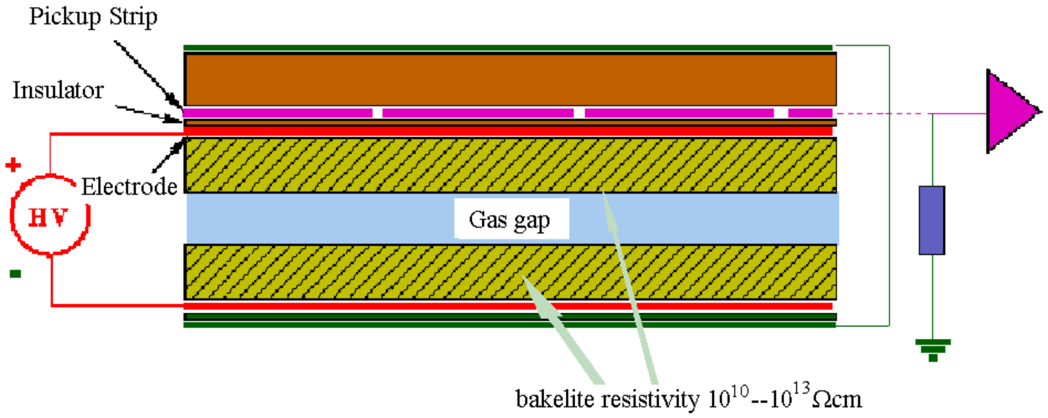
Operation in high rate environment
$\sigma(R)\approx 60\mu m T_{drift}\approx 20ns$



- Array of anode wires crossed with copper cathode strips within gas volume.
- Short drift distances.
- Suited for high eta (“forward”)

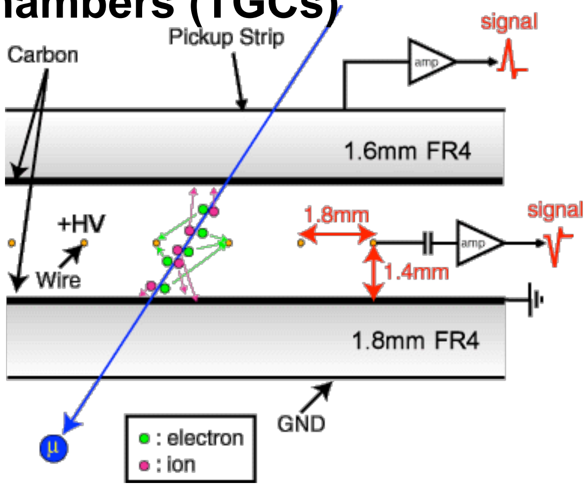
Trigger Chambers

1) Resistive Plate Chambers (RPCs)



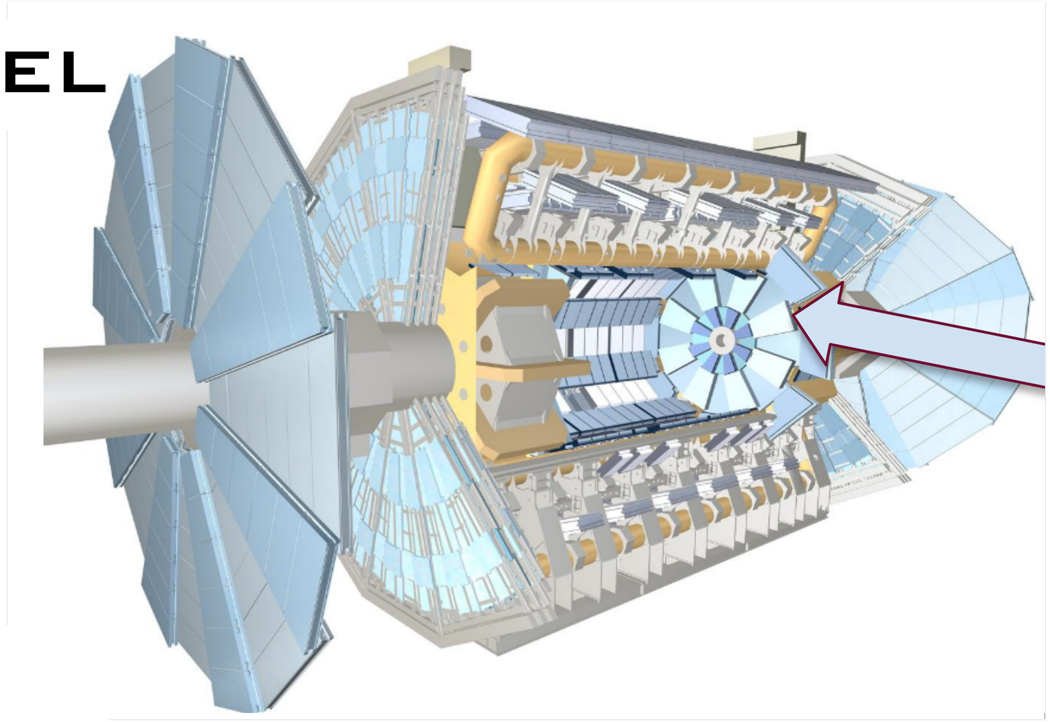
- Robust detector with up to 5ns time resolution
- Charge carriers drift towards anode and get multiplied by electric field (avalanche).
- Applied high voltage at parallel plate electrodes leads to uniform electric field in the gas gap.
- The propagation of the growing number of charges induces a signal on a read out electrode.

2) Thin Gap Chambers (TGCs)



- Derivative of MWPCs
- Operation in saturated mode. Signal amplitude limited by by the resistivity of the graphite layer

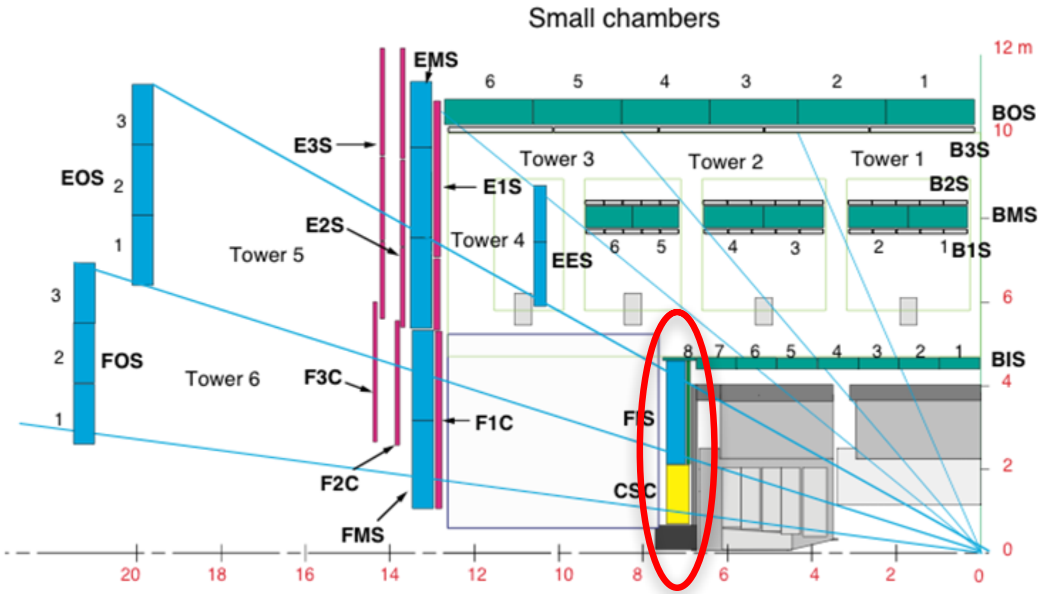
Phase-1: New Small Wheel



- Consequences of luminosity rising beyond design values for forward muon wheels
  - Degradation of the tracking performance (efficiency / resolution)
  - L1 muon trigger available bandwidth exceeded unless thresholds are raised

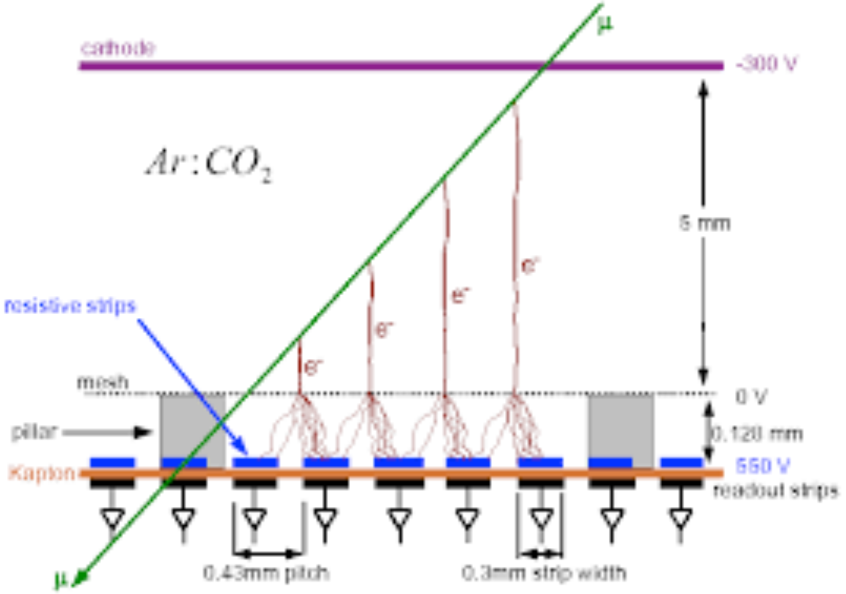
- Replace Muon Small Wheels with New Muon Small Wheels (NSW)
  - Improved tracking and trigger capabilities meets Phase-2 requirements
    - compatible with <μ>=200, up to L~7x10^{34} cm^{-2}s^{-1}

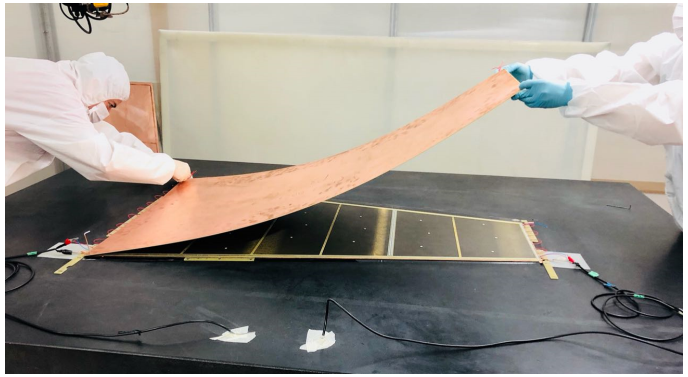
Coverage:
Tracking up to η = 2.7
Triggering up to η = 2.4

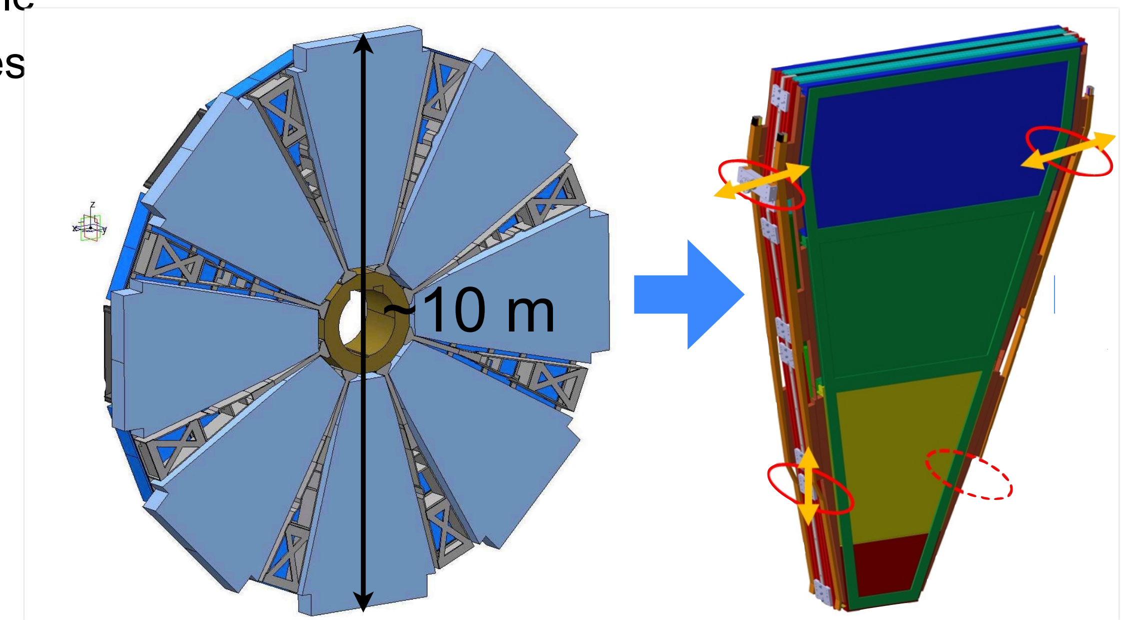


Phase-1: New Small Wheel

- Precision: MicroMegas
  - Space resolution < 100 μm independent of incidence angle
  - High granularity -> good track separation
  - High rate capability due to small gas amplification region and small space charge effect
- Timing: Small strip Thin Gap Chambers (sTGC)
  - Space resolution < 100 μm independent of incidence angle
  - Space resolution < 100 μm independent of incidence angle
  - Bunch ID with good timing resolution to suppress fakes
    Track vectors with < 1 mrad angular resolution



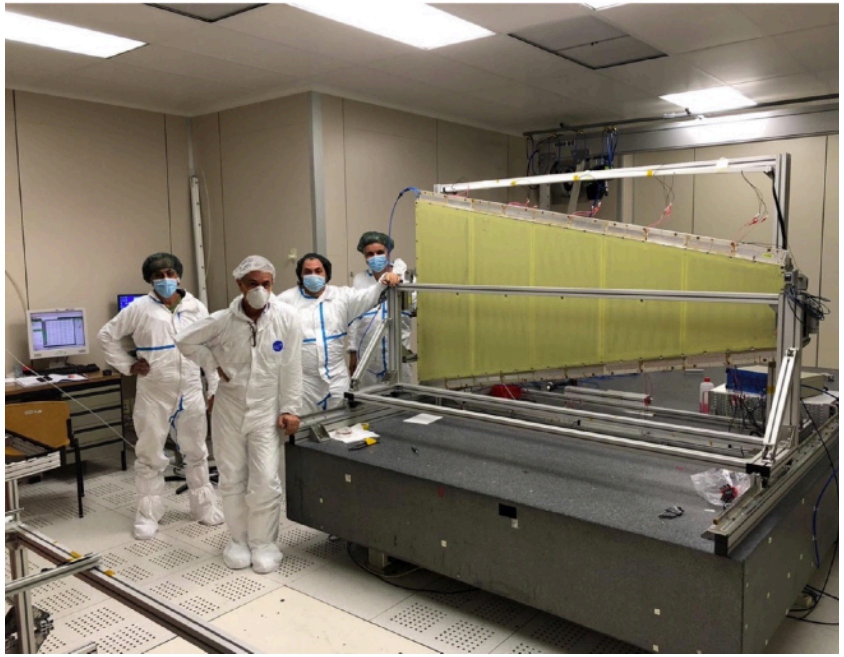


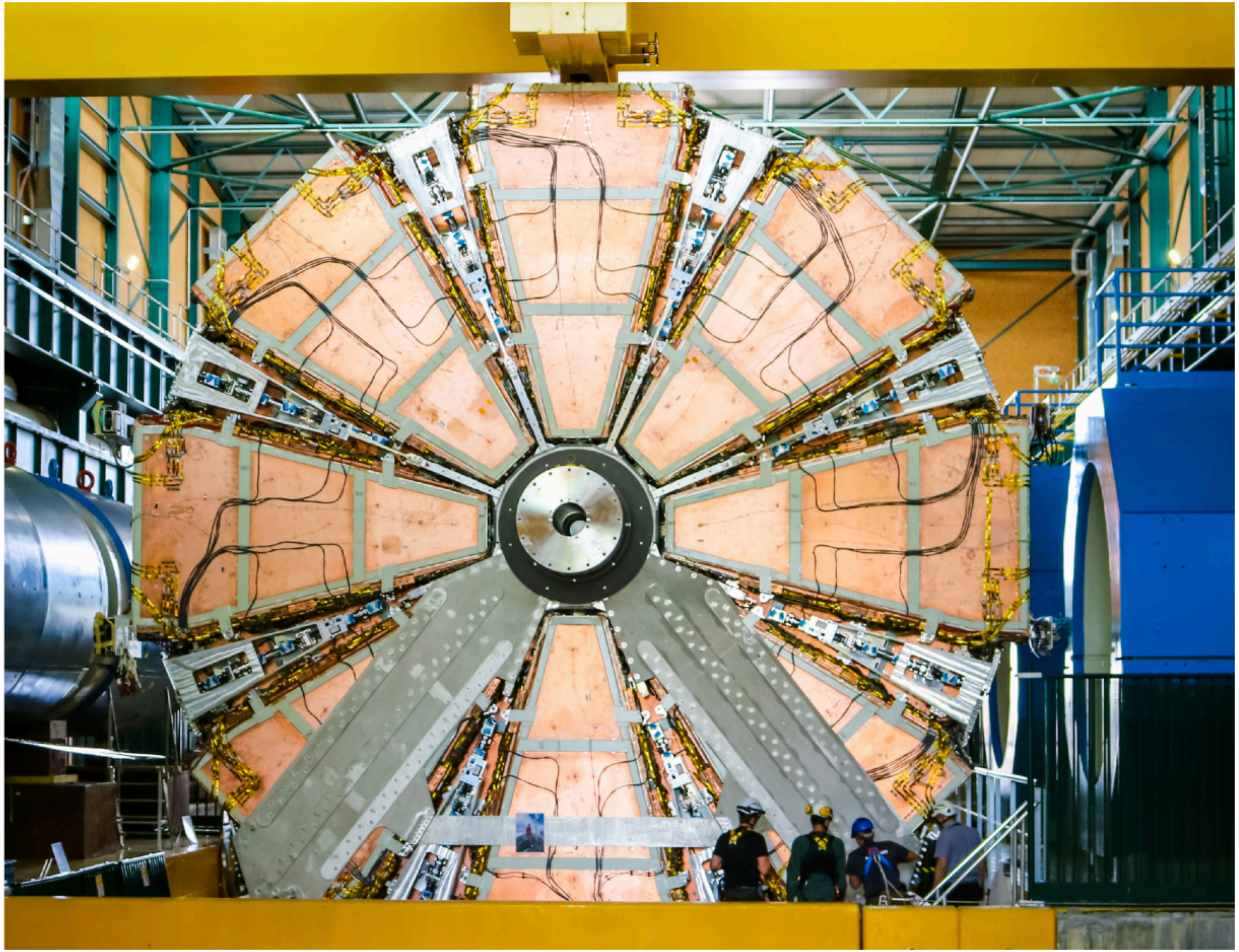


Total area of 1200 m^2

On the way to the Cavern

- After 10 years of work

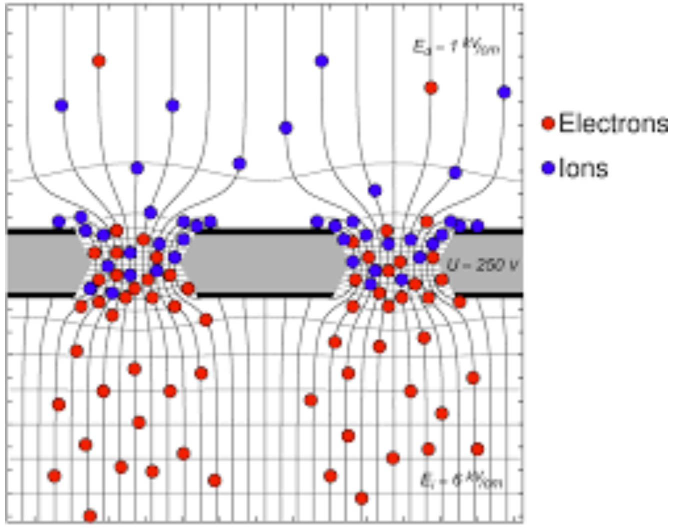




Summary Part 2

Tracking Detectors

- Precise measurement of track and momentum of charged particles due to magnetic field.
- Mostly based on ionisation



Gas Detectors

- Many different flavours being used
- Very light detectors

Muon Detectors

- “Outer tracking detectors” also used for triggering
- Mostly gas detectors

Next part!!

Semiconductor Detectors

- In particle physics based on silicon
- Pixel and strip detectors for innermost regions of experiments