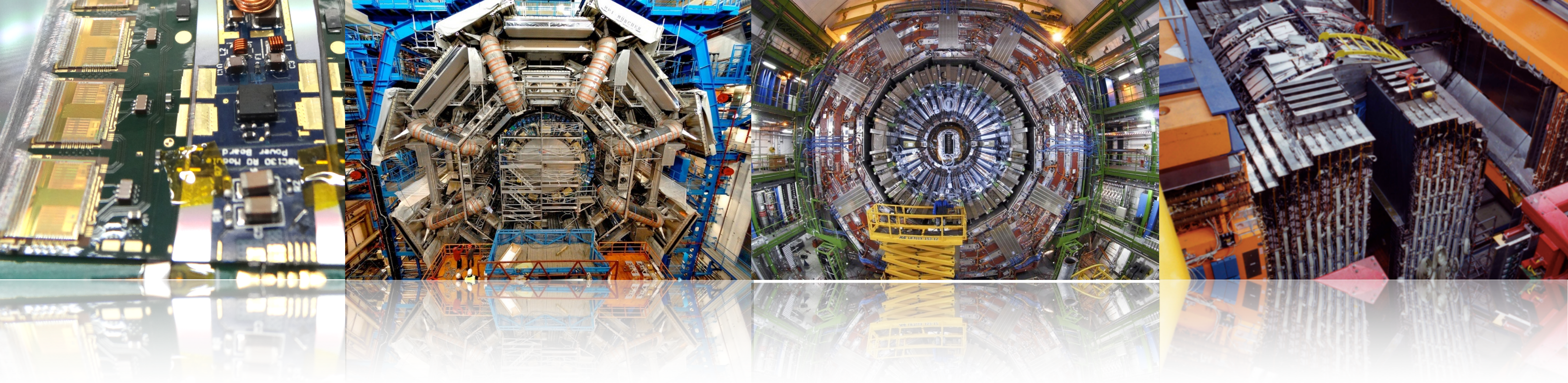


Advanced (Tracking) Detectors

Part 2

Ingrid-Maria Gregor
DESY/Universität Bonn

BND School

Overview

I. **Detectors for Particle Physics**

II. **Interaction with Matter**

Monday

III. **Calorimeter**

Tuesday

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

Wednesday I

V. **Current Pixel and Strip Detector Projects**

Wednesday II

VI. **Examples of what can go wrong**

IV. Tracking Detectors

Tracking

- "tracking" in google image search:









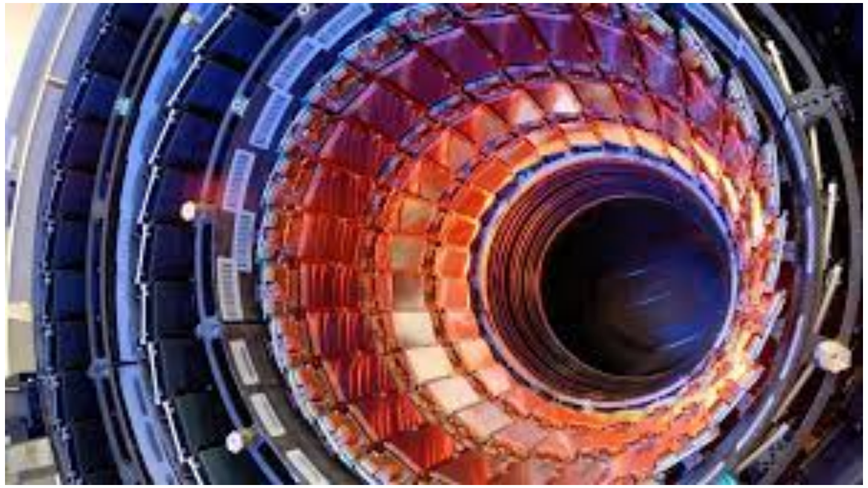


Tracking Detector

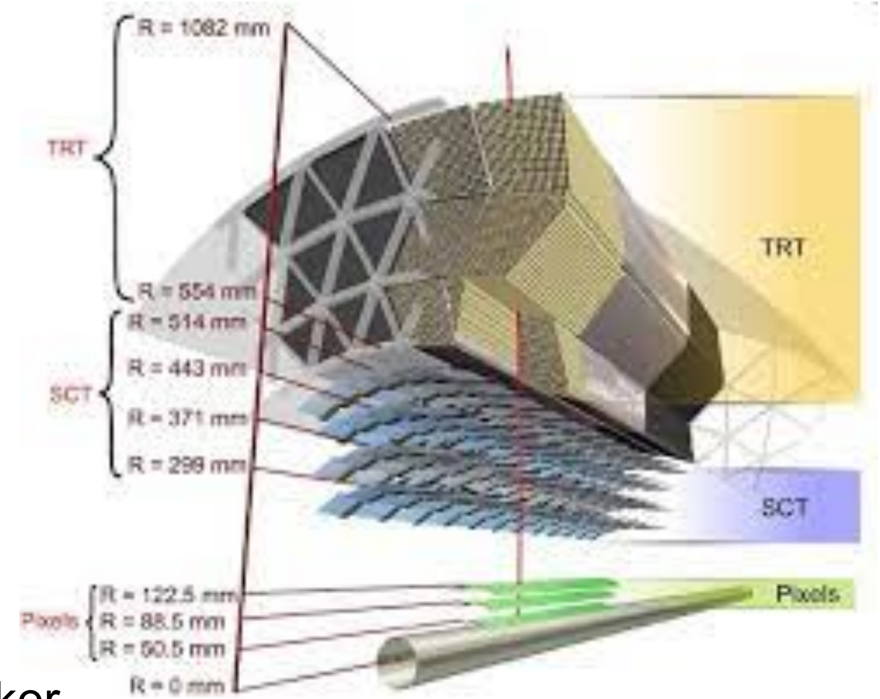
- "tracking detector" in google image search

Bug detector

GPS tracker



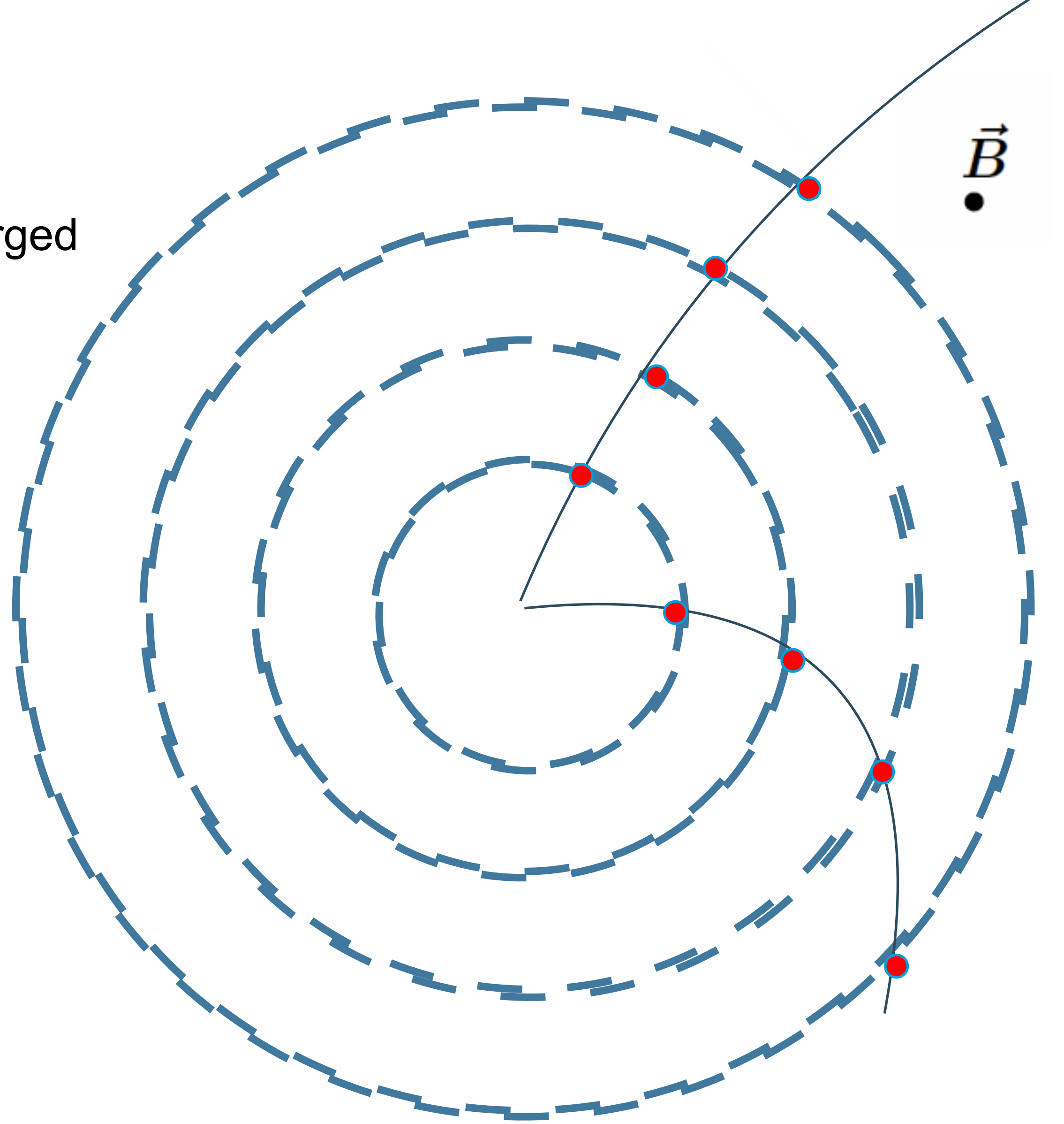
CMS tracker



ATLAS tracker

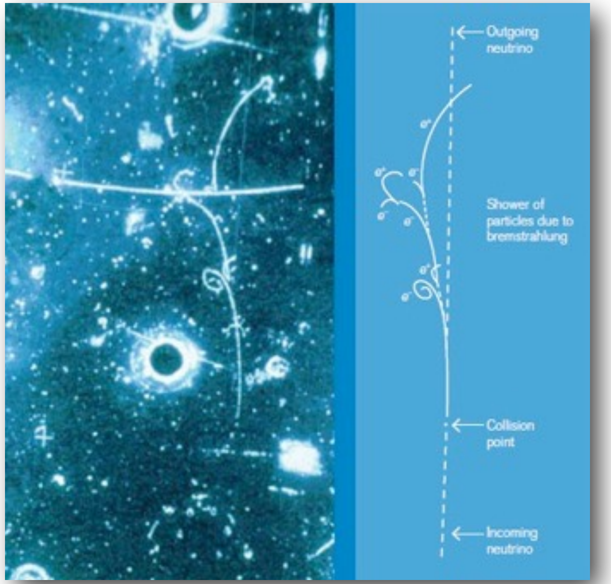
Tracking Detectors

- 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

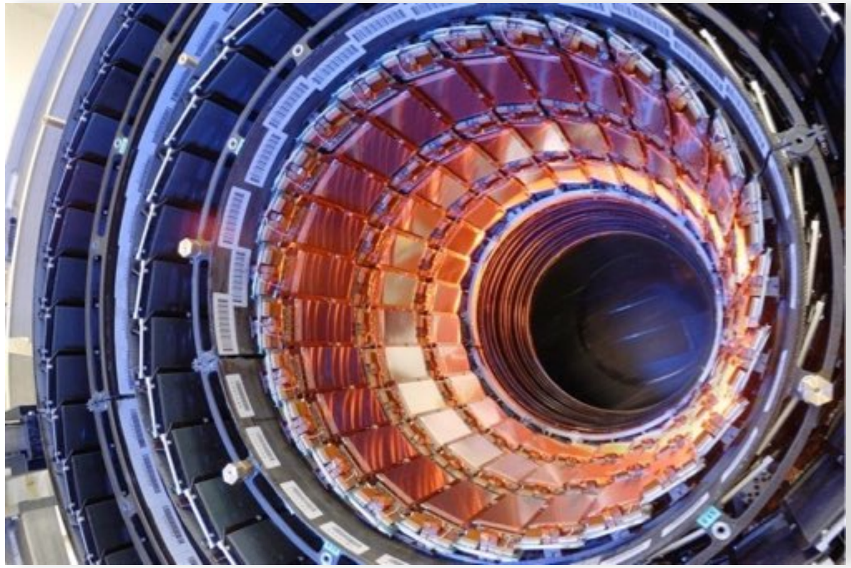


Tracking Detectors - Technologies

- **“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)



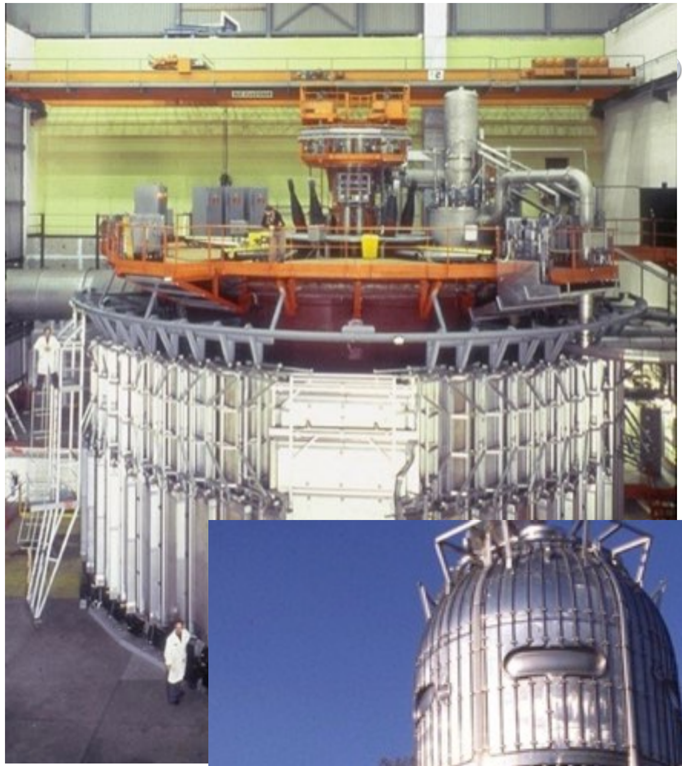
Discovery of neutral currents
Gargamelle, 1972

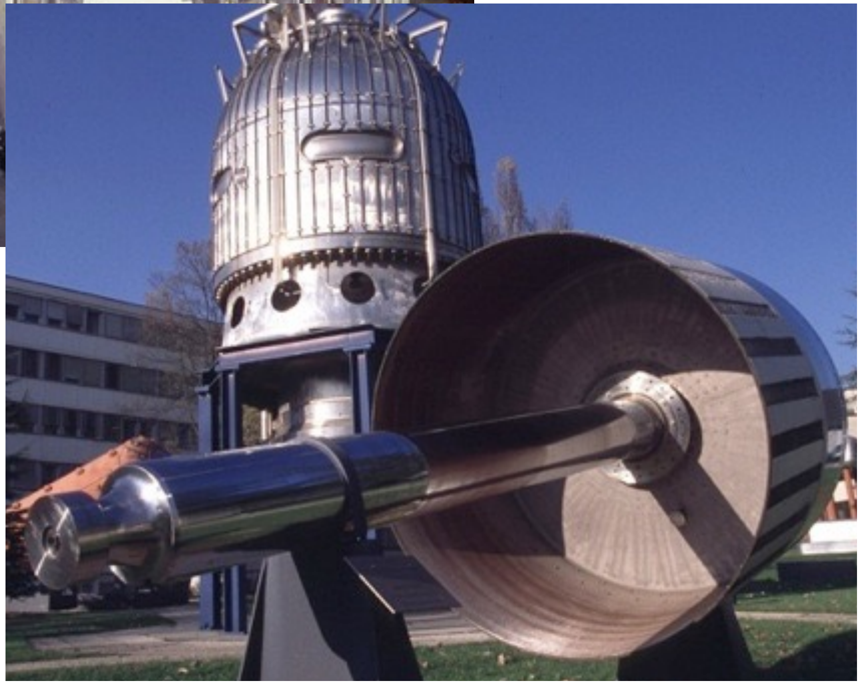


CMS Inner barrel Si Tracker:
Single-Sided Si-Strip

Pictures: CERN

Very "Classic": Bubble Chamber





The biggest: Big European Bubble Chamber

- 3.7 m diameter
- Until 1984 used at CERN for the investigation of neutron hadron interactions

Early report on bubble chamber analysis:

Second United Nations
International Conference
on the Peaceful Uses of
Atomic Energy

A/CONF.15/P/730
U.S.A.
June 1958

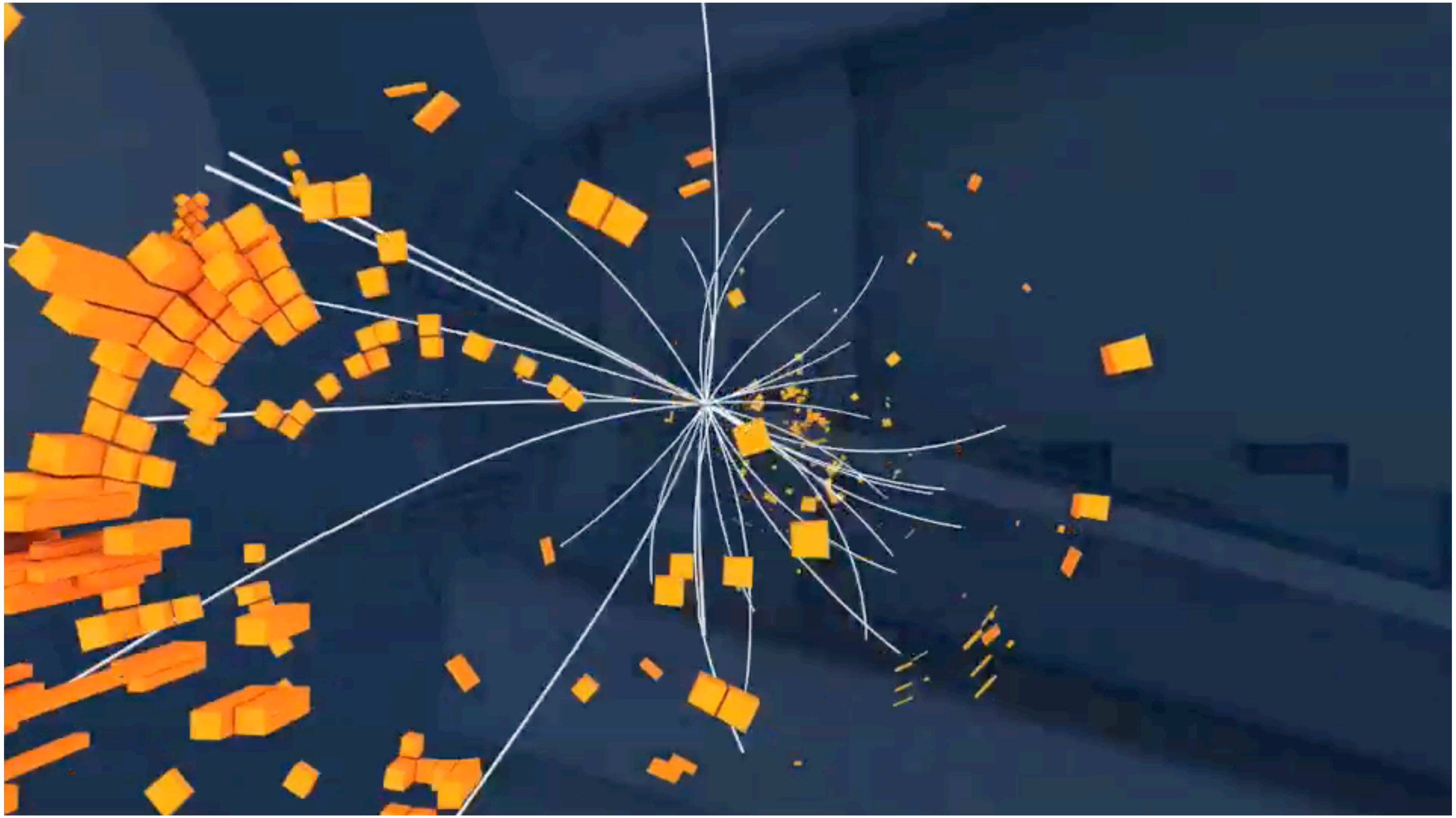
ORIGINAL: ENGLISH

ON THE ANALYSIS OF BUBBLE CHAMBER TRACKS

Hugh Bradner and Frank Solmitz

"… the large number of possible reactions, the variability of appearance of interaction, and the importance of being alert to possible new phenomena make it very important for a **trained physicist** to look at the bubble chamber pictures…."

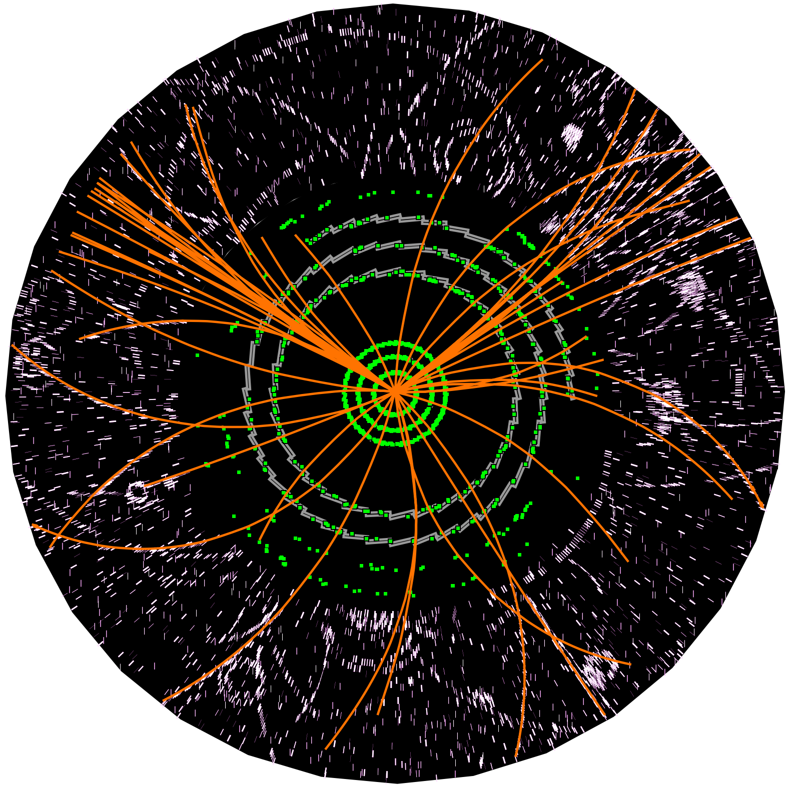
Event Detection and Reconstruction



- 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 ?

The Tracking Problem

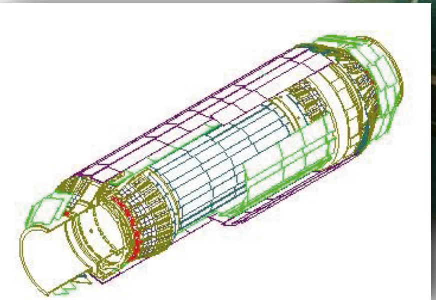
- particles produce in a p-p interaction leave a cloud of hits in the detector

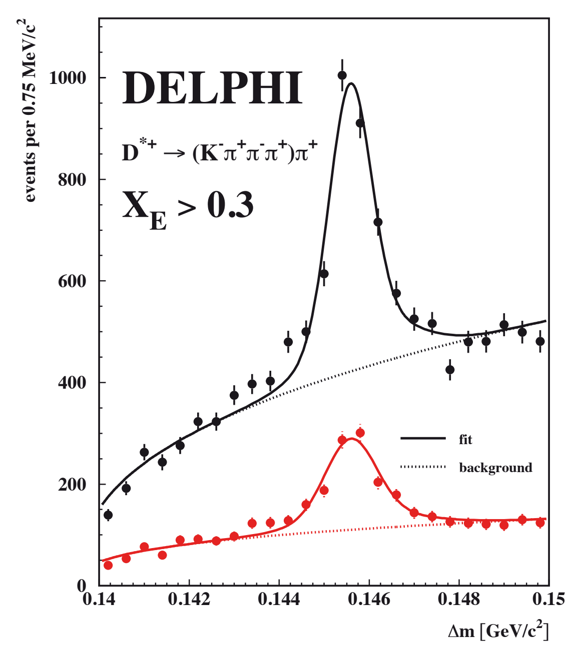


tracking software is used to reconstruct their trajectories

Role of Tracking Software

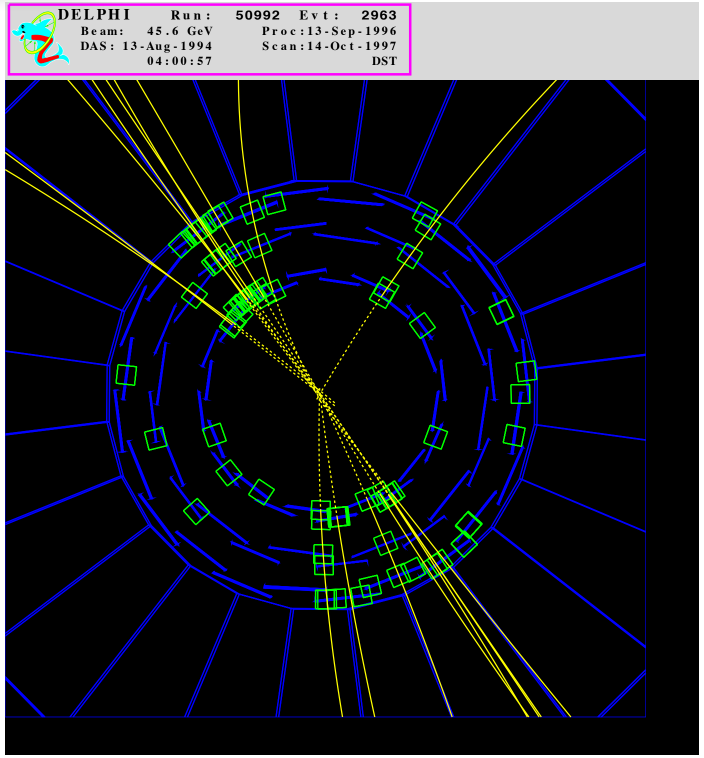
- Optimal tracking software
  - required to fully explore performance of detector
- Example: DELPHI Experiment at LEP
  - silicon vertex detector upgrade
    - initially not used in tracking to resolve dense jets
    - pattern mistakes in jet-chamber limit performance



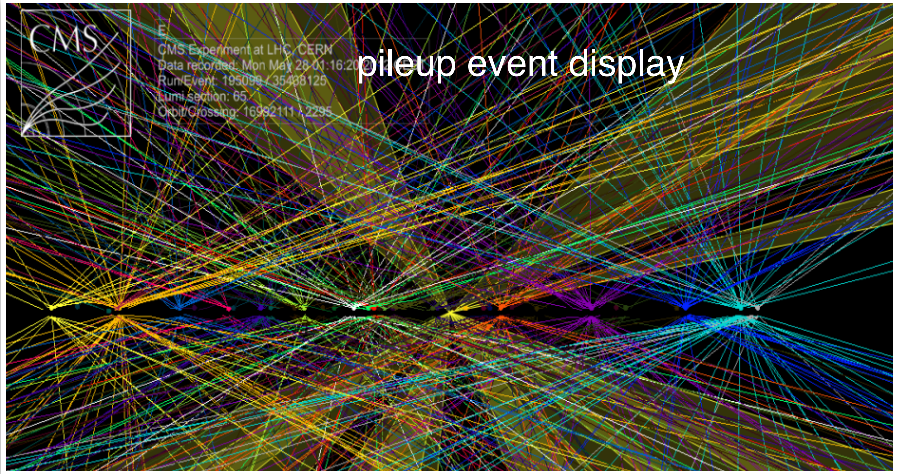


➡ 1994: redesign of tracking software
- start track finding in vertex detector

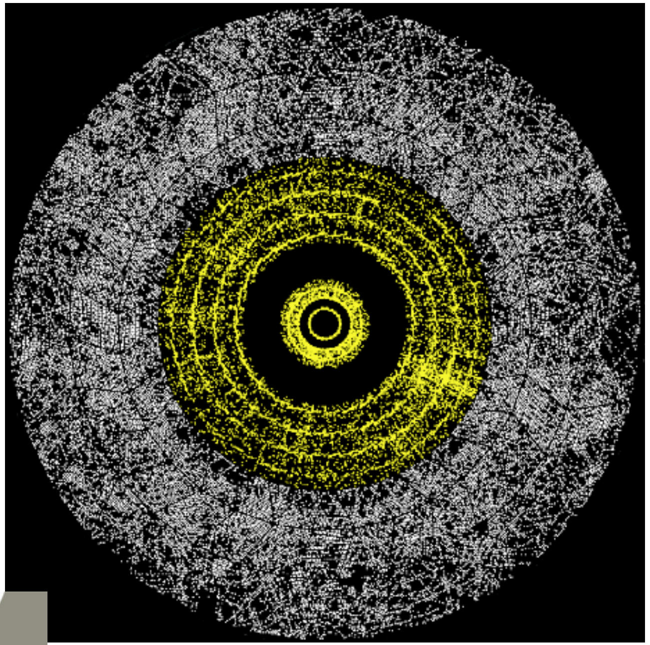
➡ **factor ~ 2.5 more D* signal** after reprocessing



Tracking at the LHC ?

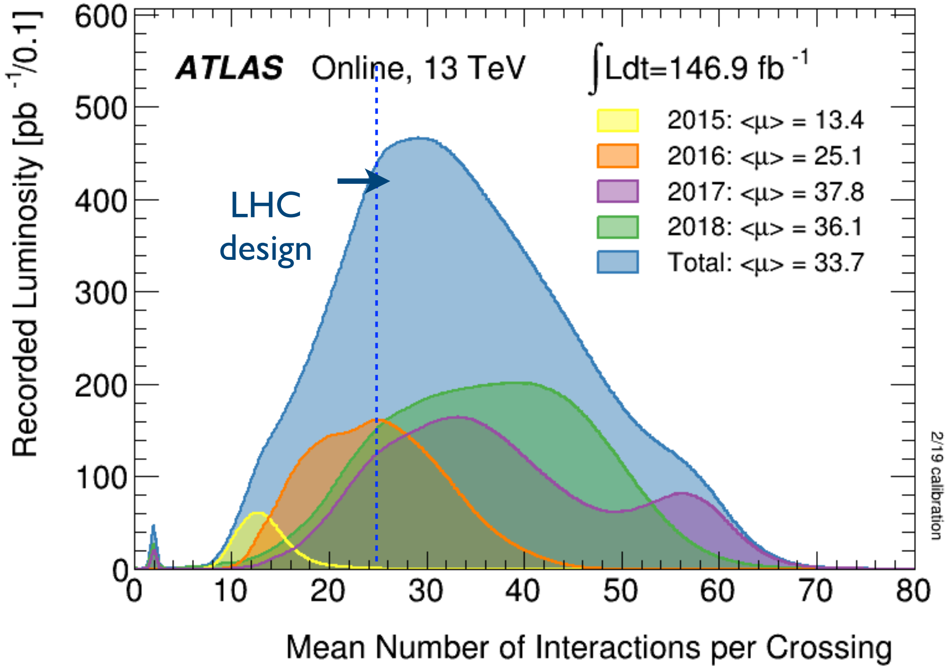


- LHC is a high luminosity machine
  - proton bunches collide every 25 nsec in experiments
  - each time > 20 p-p interactions are observed ! (event pileup)
- Detectors see hits from particles produced by all > 20 p-p interactions
  - ~100 particles per p-p interaction
  - each charged particle leaves ~50 hits



➡ 1 pp collisions looks like

- imagine 50 of them overlapping
- task of tracking software is to resolve the mess …



Some Important Parameters

Tracker: Important Parameter

- **Signal/noise ratio**: signal size for a certain input signal over the intrinsic noise of the detector
  - parameter for analog signals
  - good understanding of **electrical noise charge** needed
  - leakage current (ENC_I)
  - detector capacity (ENC_C)
  - det. parallel resistor (ENC_{Rp})
  - det. series resistor (ENC_{Rs})

$$\mathrm{ENC} = \sqrt{\mathrm{ENC}_C^2 + \mathrm{ENC}_I^2 + \mathrm{ENC}_{R_p}^2 + \mathrm{ENC}_{R_s}^2}$$

example for silicon detector

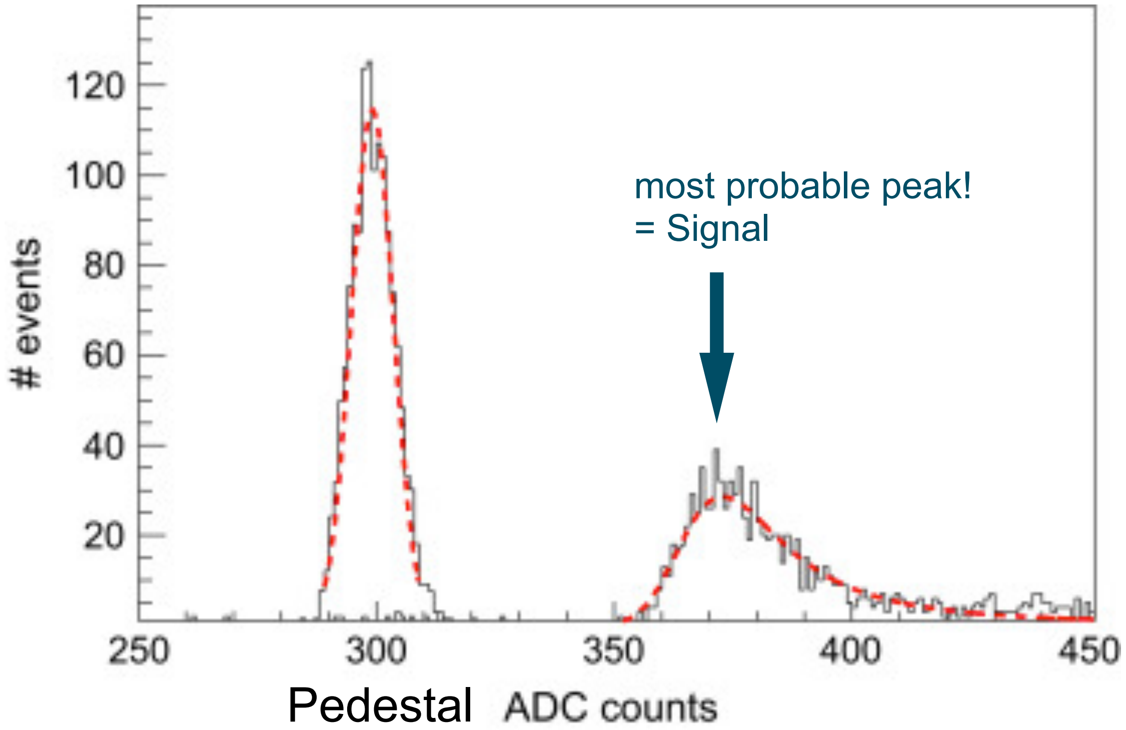
  - signal induced by source or laser (or test beam particles)
  - optimal S/N for a MiP is larger than 20

noise = sigma of pedestal distribution

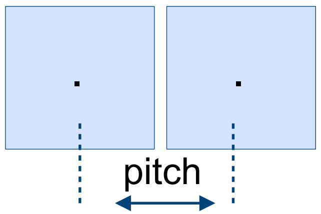
signal = most probable peak - pedestal

With analog readout:

Gaussian distributed "non-signal"
= sigma -> noise

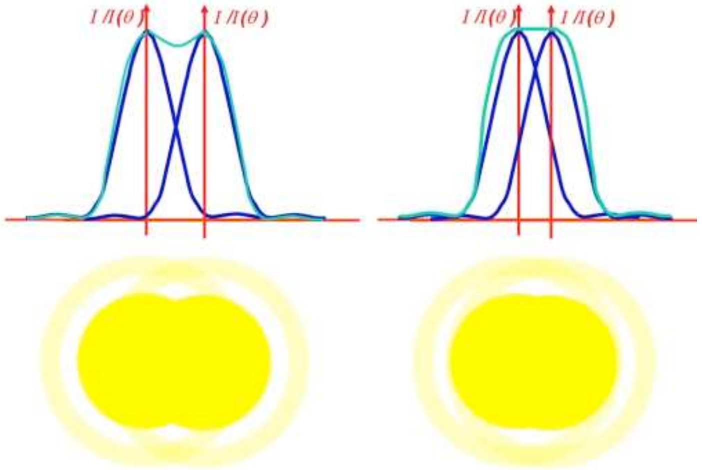


Tracker: Important Parameter



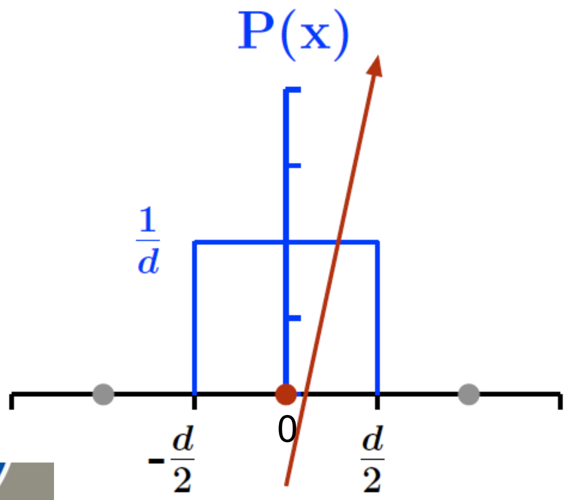
can be tubes, strips, wires, pixels ….

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



- 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):

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

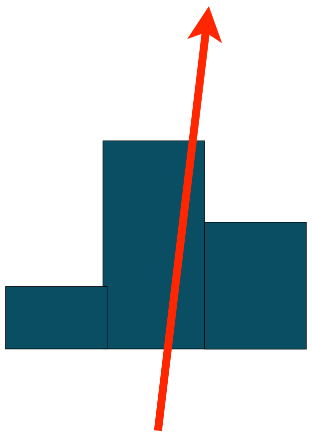
very important !

ATLAS/CMS Pixels

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

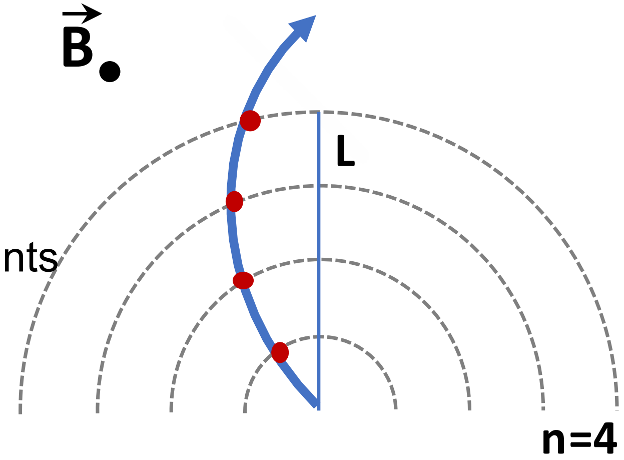
- In case of charge sharing between the strip (signal size decreasing with distance to hit position) and information about signal size
  - resolution improved by additional information of adjacent channels

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



Momentum Resolution

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



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

Gluckstern formula:

$$\left(\frac{\sigma_{p_T}}{p_T}\right)^2 = \left(\sqrt{\frac{720}{n+4}}\frac{\sigma_y p_T}{0.3BL^2}\right)^2 + \left(\frac{52.3\times10^{-3}}{\beta B\sqrt{LL_y \sin\theta}}\right)^2$$

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

Tracker: Important Parameter

- **Detector efficiency** ϵ: probability to detect a transversing particle
  - should be as close to 100% as possible
  - i.e. 12 layer silicon detector with 98% efficiency per layer -> overall tracking efficiency is only 78%
  - needs to be measured in test beam

$$\epsilon = \frac{N_{\text{meas}}}{N_{\text{exp}}}$$

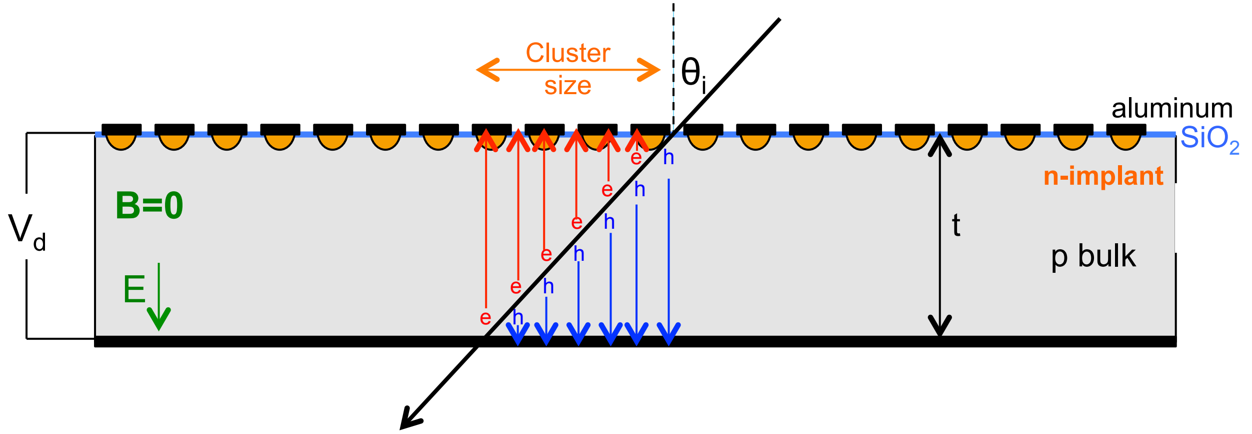
ATLAS

$\epsilon_{\text{Pix}} > 97\%$	$\epsilon_{\text{Strips}} > 99\%$
$\epsilon = 0.99$	$\epsilon = 0.98$
$\epsilon^7 = 0.93$	$\epsilon^7 = 0.87$

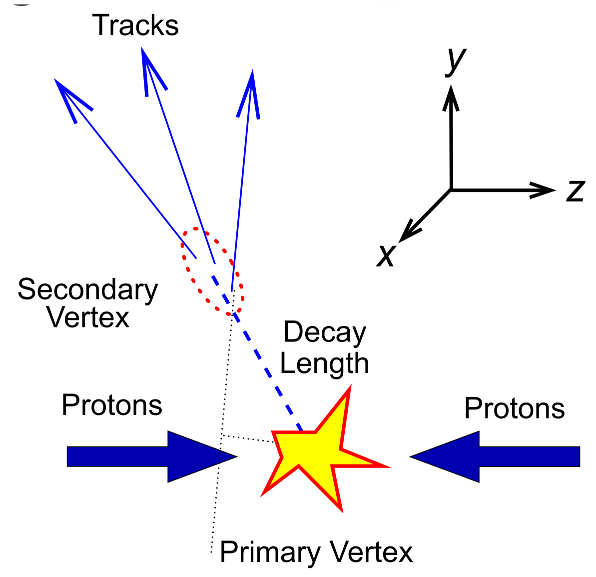
- **Track reconstruction efficiency:** how well a full track is reconstructed

$$\epsilon_{track} = \frac{N_{\text{inner}}}{N_{\text{muon}}} \qquad \epsilon_{\text{track}} > 95\%$$

- **Cluster size** : number of hit pixels/strips belonging to one track
  - usually given in unit of strips or pixels
  - depending on angle of incidence



Impact Parameter Resolution



- Impact parameter resolution = shortest distance between the reconstructed track and the associated primary vertex

polar angle

$$\sigma^2_{r\phi} = \sigma^2_{rz} = a^2 + b^2 \cdot \frac{1}{(p \cdot sin^{\frac{3}{2}}\theta)^2}$$

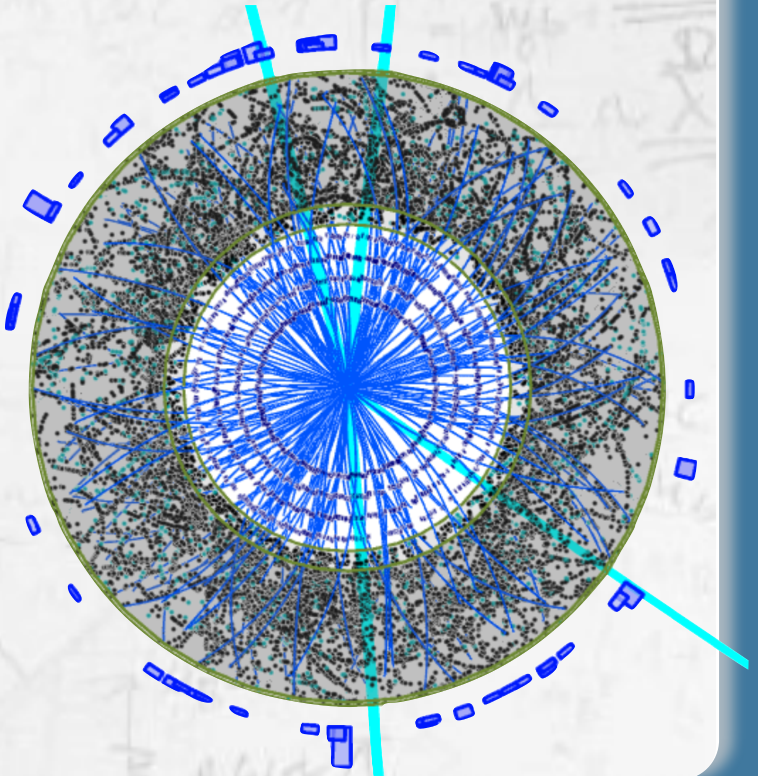
intrinsic resolution of the tracking system (no multiple scattering)

influence of multiple scattering (geometry)

Accelerator	a (µm)	b (µm)
LEP	25	70
SLD	8	33
LHC	12	70
RHIC-II	13	19
ILC/CLIC	<5	<15

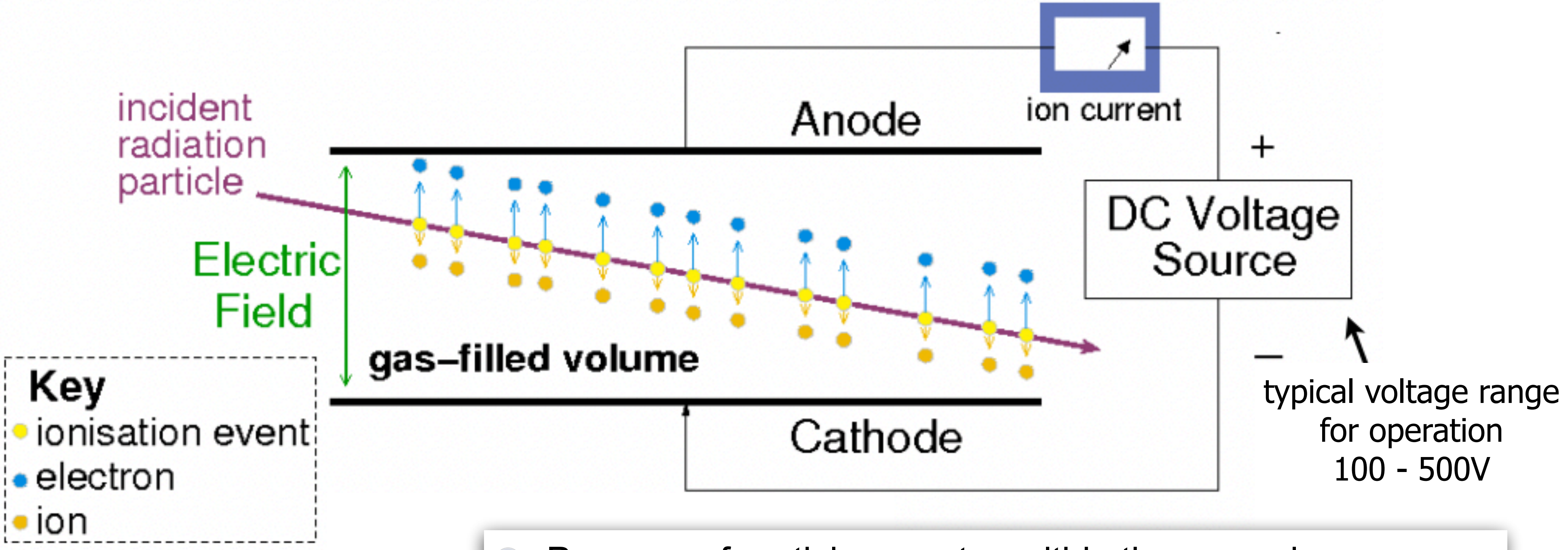
ATLAS $\sigma_{\mathrm{IP}} > 10\mu m$ for 100GeV track

IV.a Gas-Detectors



Very Basic Principle

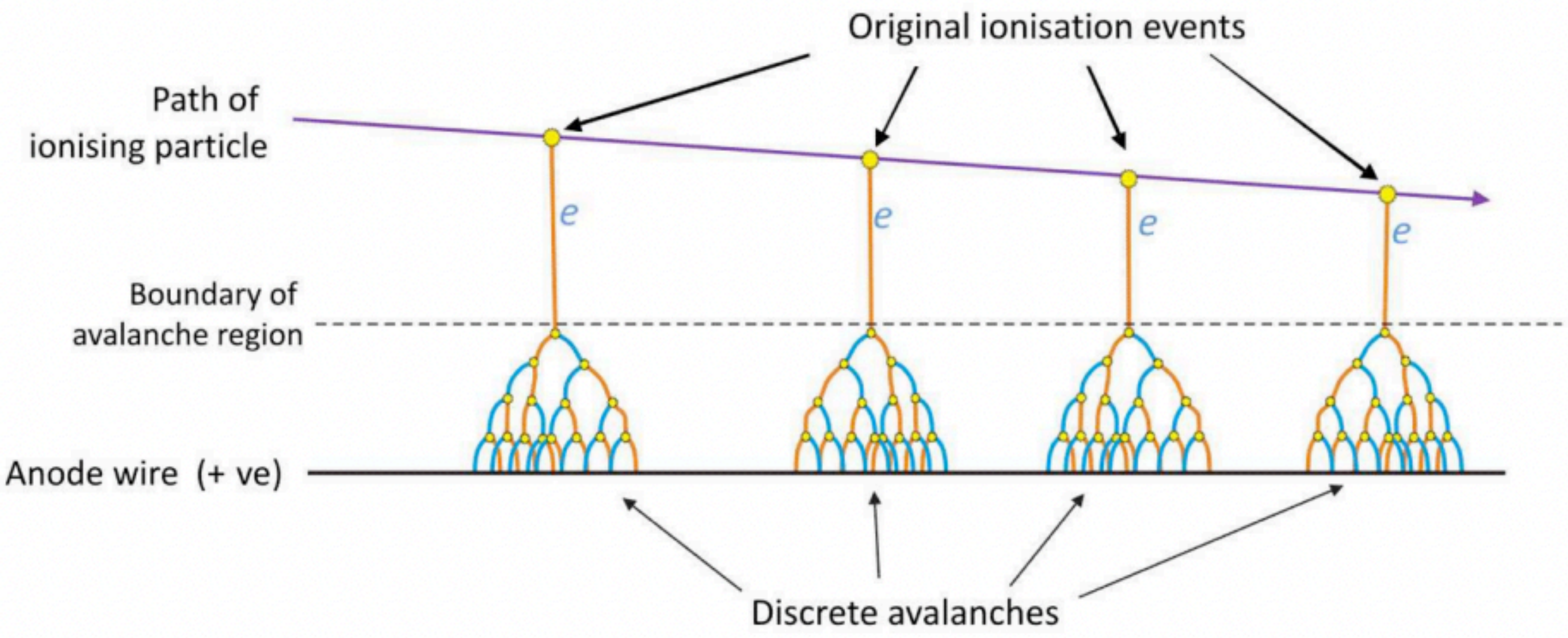
- Make use of ionisation when radiation particle is passing gas



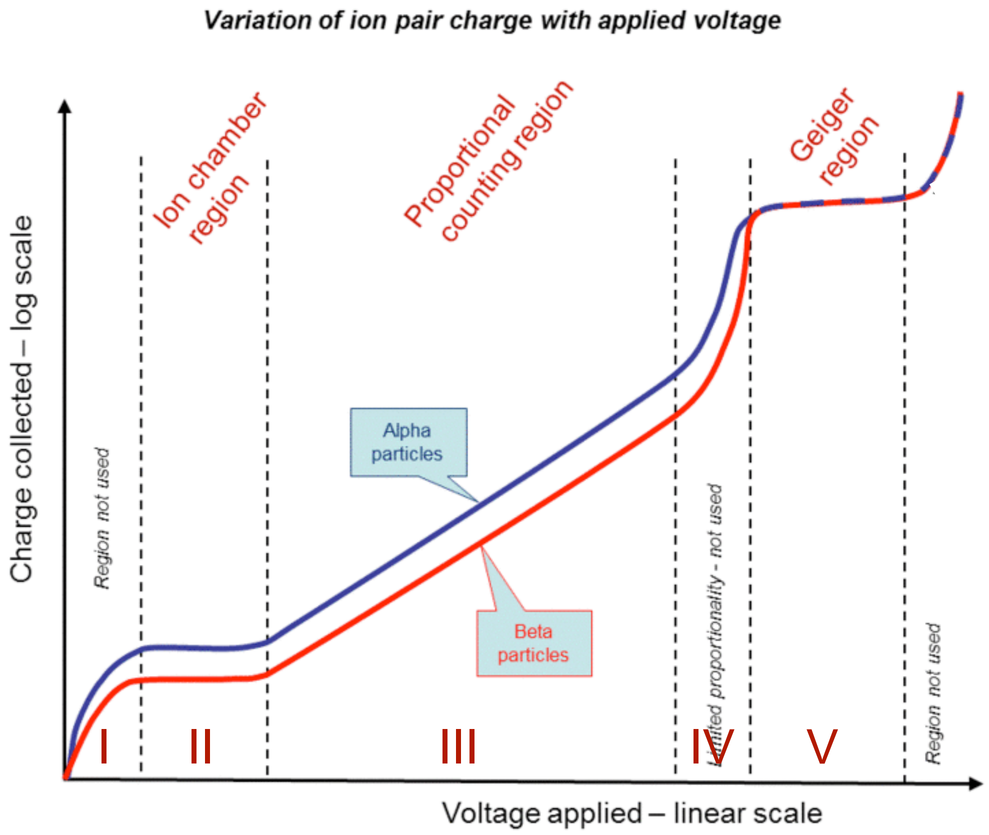
- Passage of particles creates within the gas volume electron-ion pair (ionisation)
- Electrons are accelerated in a strong electric field -> amplification
- The signal is proportional to the original deposited charge or is saturated (depending on the voltage)

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



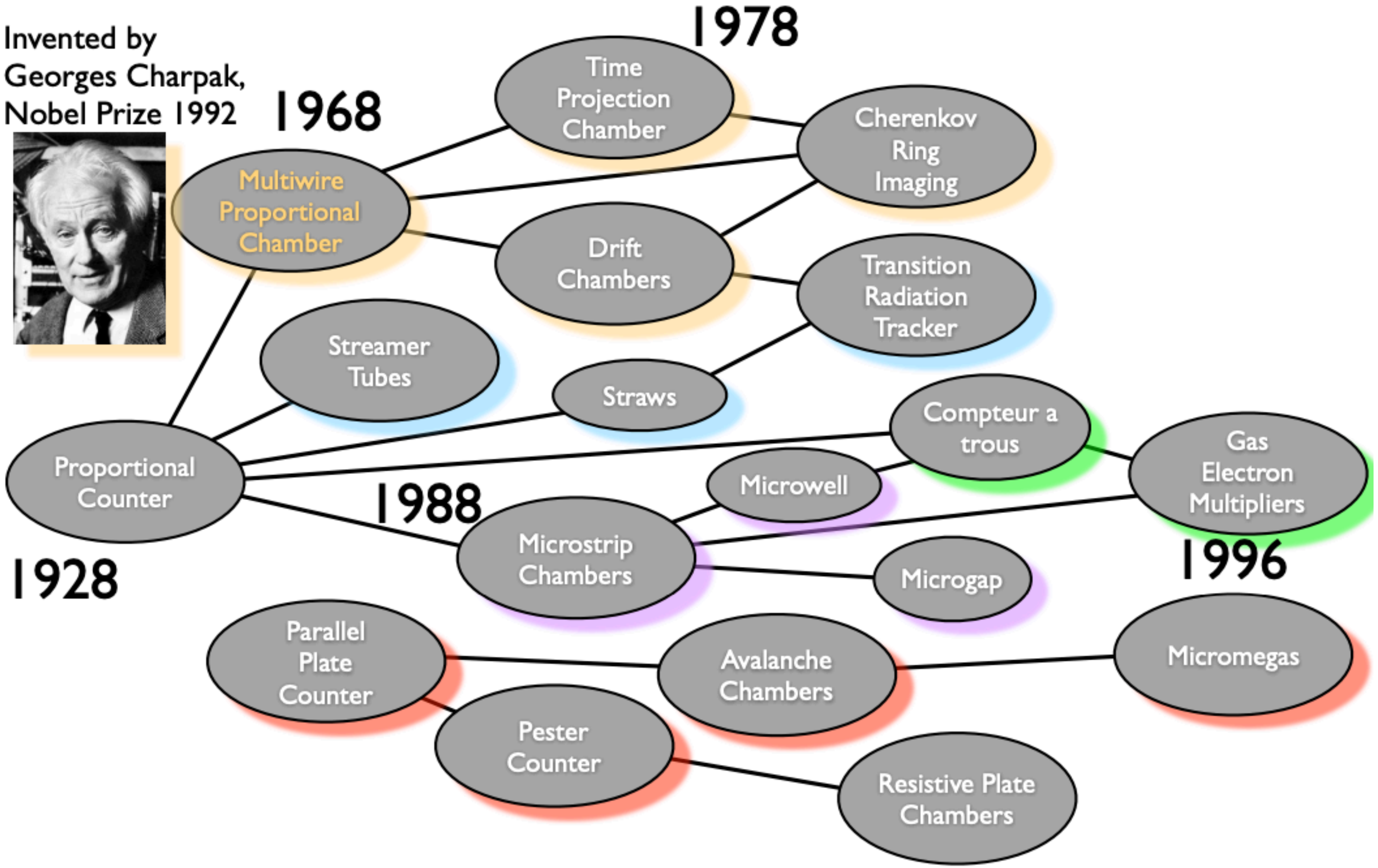
Modes of Operation



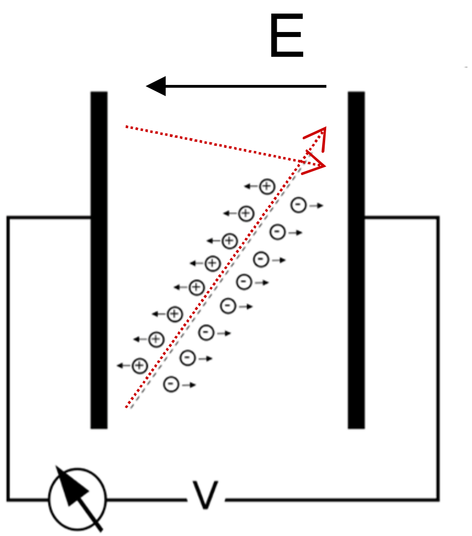
- **Region I:**
  At very low voltage charge begins to be collected but **recombination** dominates
- **Region II:**
  All electron-ion pairs are collected before recombination (plateau)
- **Region III:**
  Above the threshold voltage V_T the field is strong enough to allow **multiplication** and in the proportional mode; gains $>10^4$ can be achieved with the detected charge **proportional to the original energ deposition.**
- **Region IV:**
  Eventually the proportionality begins to be lost due to space charge build-up around the anode which distorts the E field.

- **Region V:** In the **Geiger-Muller mode** photons emitted from the de-exciting molecules spread to other parts of the counter triggering a chain reaction with many avalanches along the length of the anode
  - Size of the induced signal in independent of the original energy deposition

Many different types of Gas Detectors



Proportional Chamber

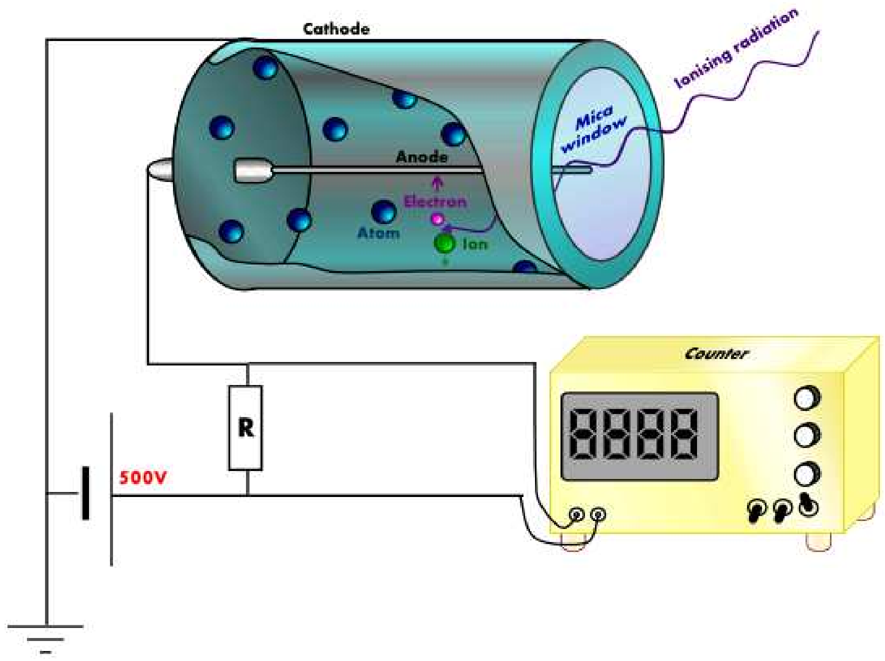


Disadvantage of planar design:

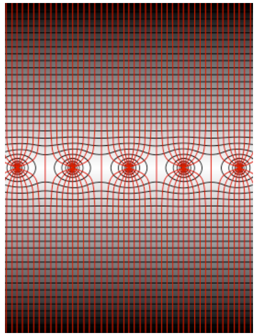
- E uniform and $\perp$ to the electrodes:
- amount of ionisation produced proportional to path length and to position where the ionisation occurs
  -> not proportional to energy

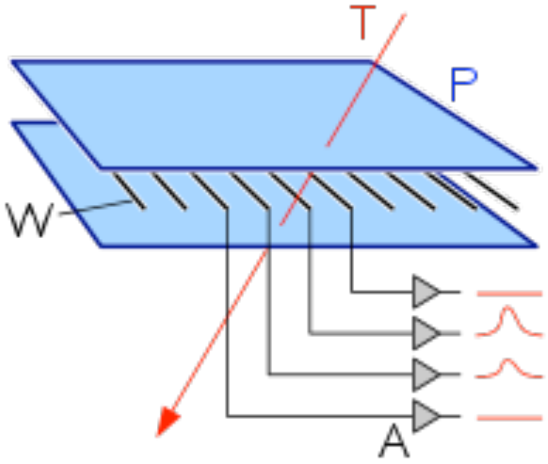
Problem solved using **Cylindrical proportional counter:**

- 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



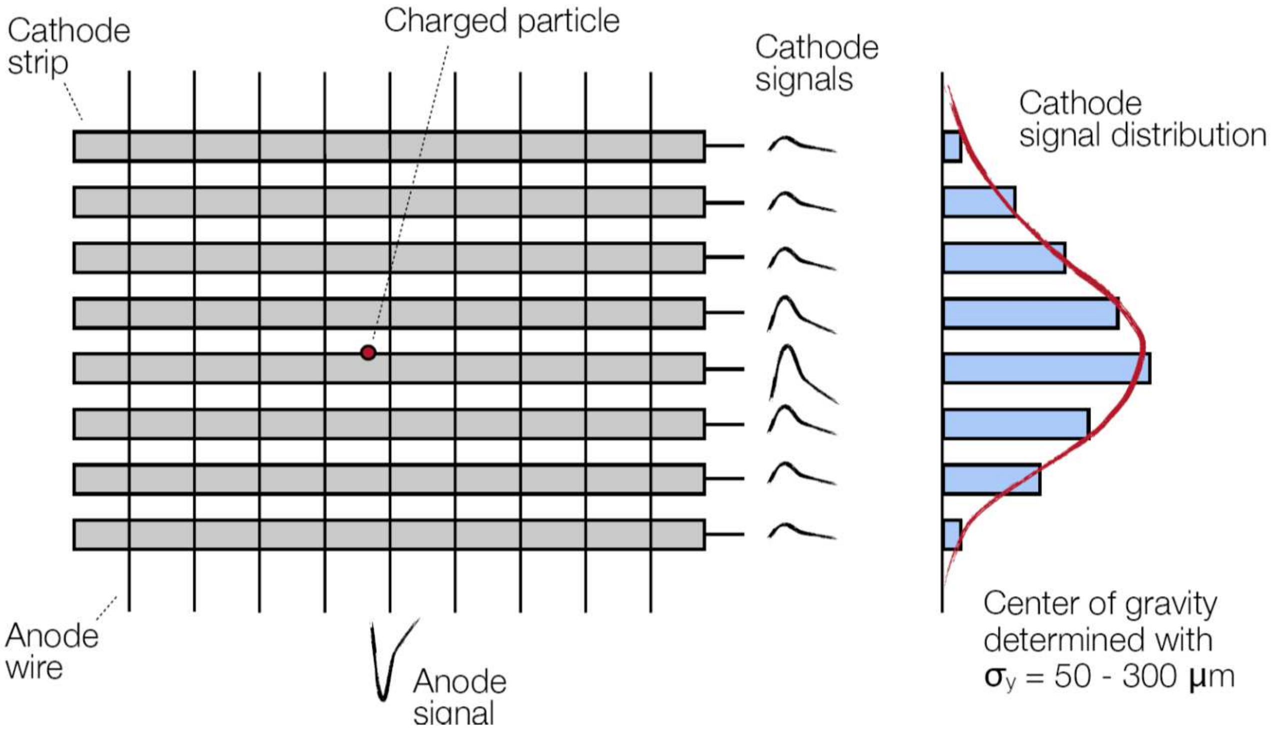
Multi-Wire Proportional Chamber





Signal generation:

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

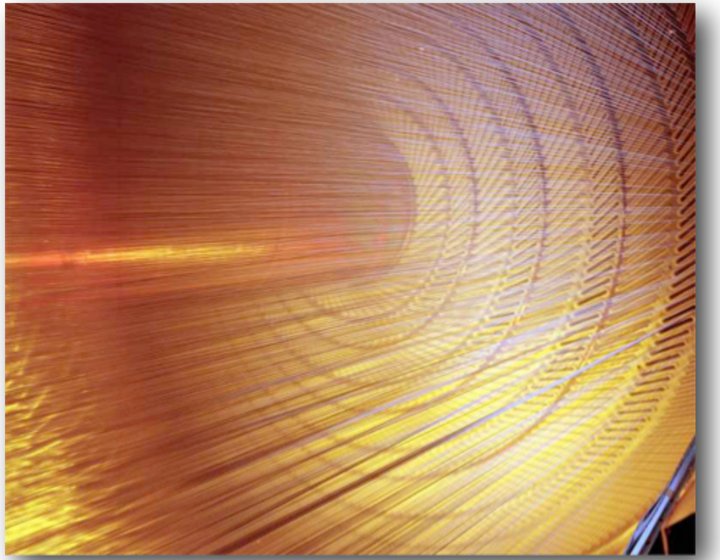


- Only information about closest wire ➛ $\sigma_x = d/\sqrt{12}$
  [Only one dimension information]

- **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:

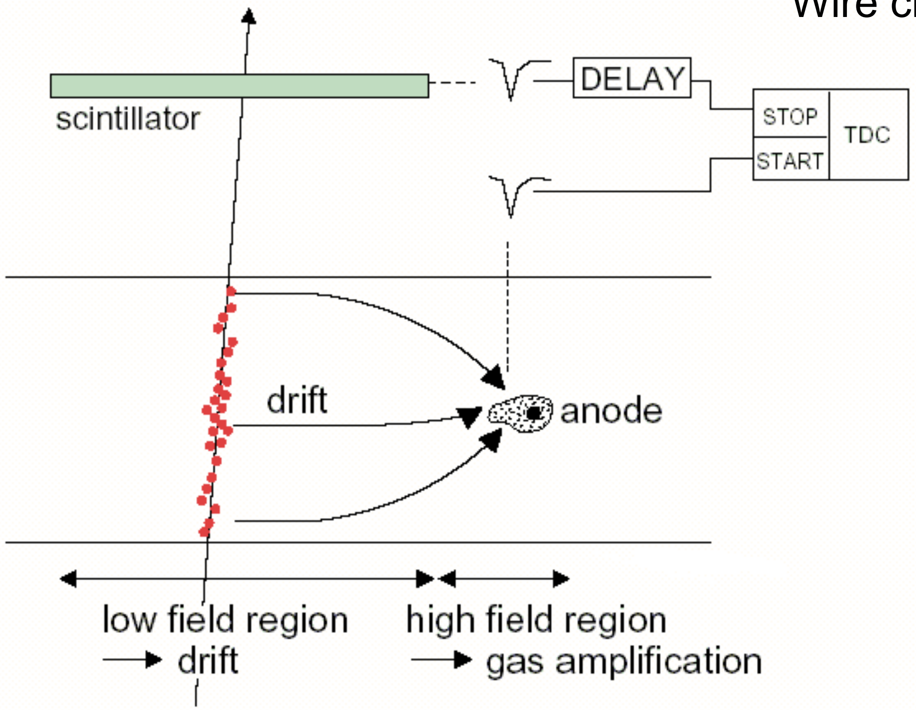


Wire chamber CDF (@Tevatron)

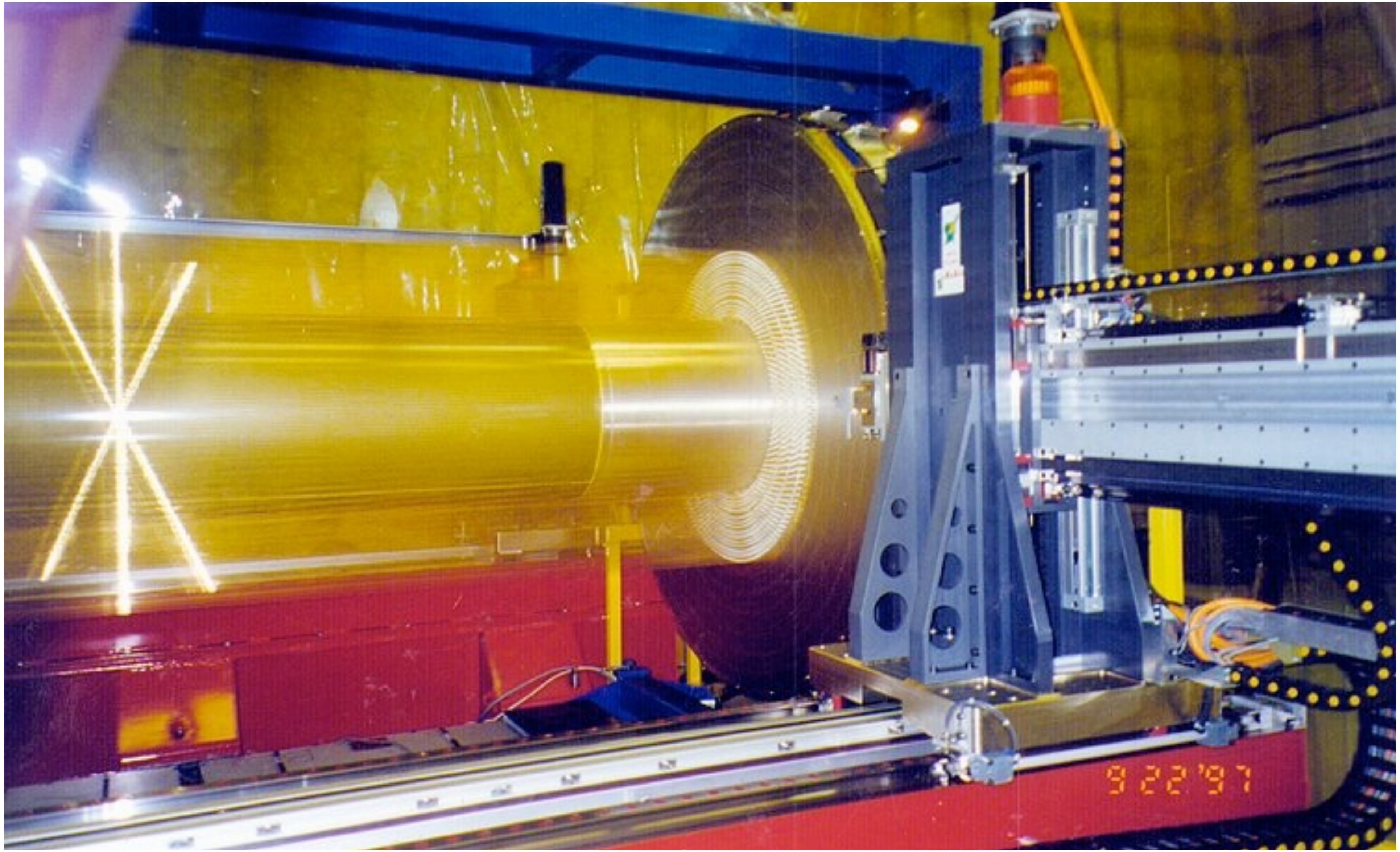
$$x = \int_0^{t_D} v_D dt$$

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

μ_+ mobility

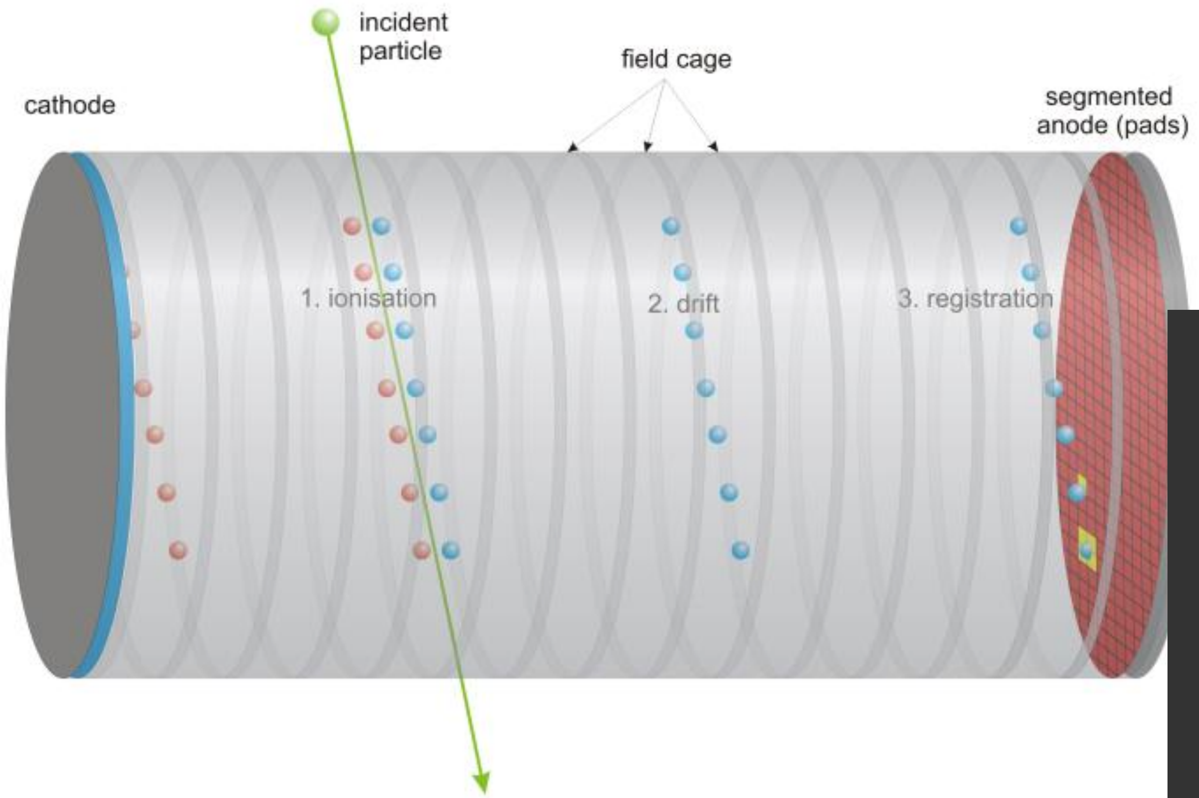


Wire Stringing In Progress

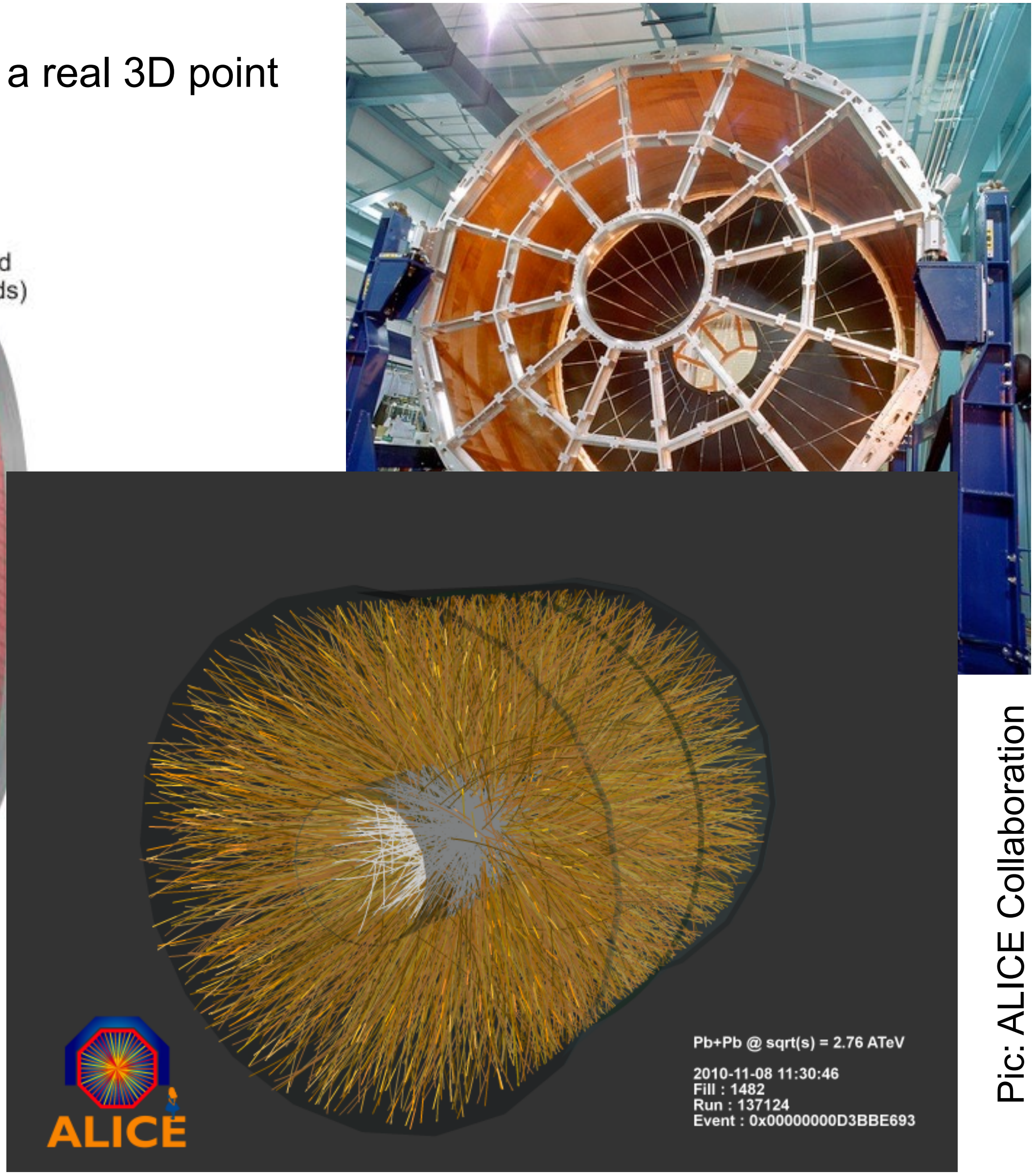


TPC- Time Projection Chamber: 3D

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



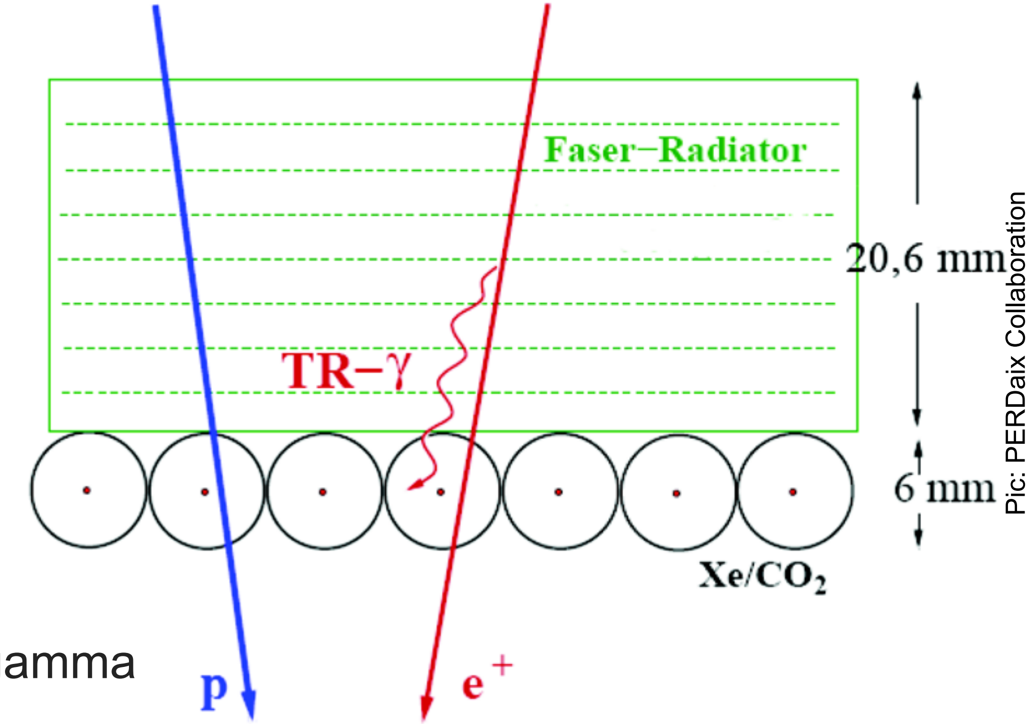
Pic: O. Schäfer



Pic: ALICE Collaboration

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

Transition Radiation



Transition Radiation

- Produced by relativistic charged particles when they cross the interface of two media of different refraction indices
- Can be explained by re-arrangement of electric field

- Energy loss at a boundary is proportional to the relativistic gamma factor.
- A significant amount of transition radiation is produced for a gamma greater than 1000.
- Gamma factor of protons is, up to a momentum of 5GeV, still in the order of 10.
- Positron's gamma is greater than 1000 starting at 0.5GeV momentum.

$$I \propto m\gamma = \frac{1}{\sqrt{(1-\beta^2)}}$$

=> particle identification

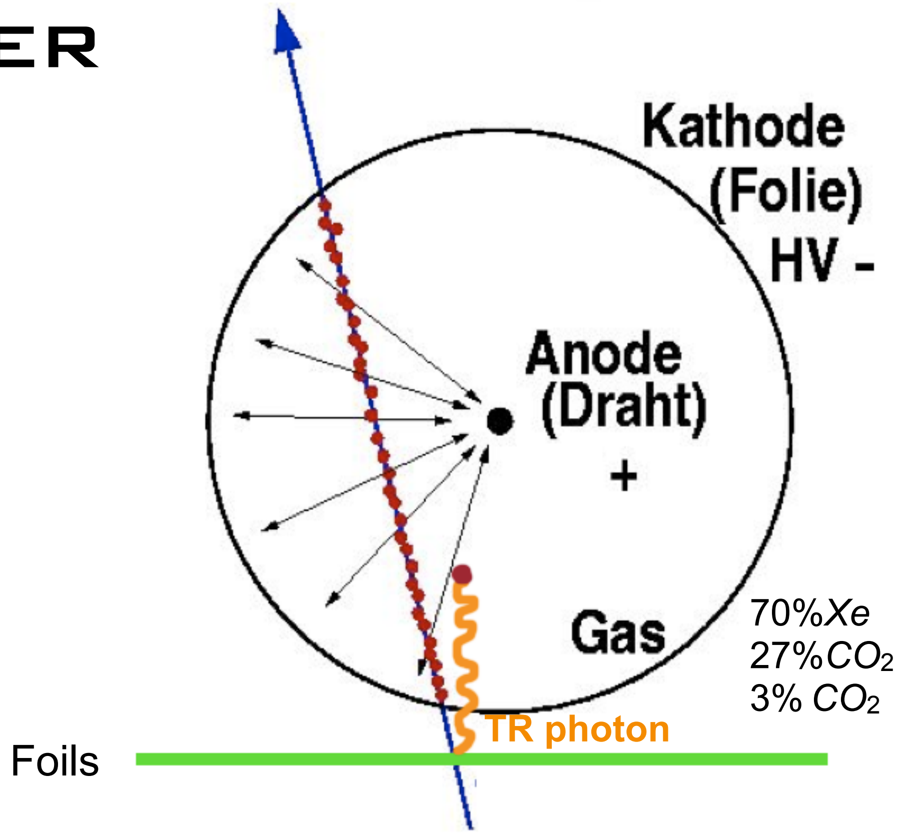
Transition radiation tracker

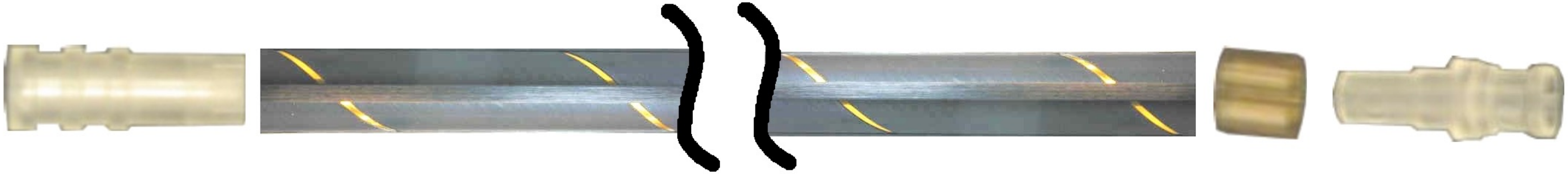
Signal formation

- charged particles ionize the gas
- electrons drift towards the wire
- gas amplification avalanche
- first arrival determines drift time

Signal readout

- signal gets amplified
- sampled in 24 time bins of 3.12 ns
- each time bin compared against threshold (≈ 300 eV): 24-bit pattern
- buffered in 6-μs readout pipeline
- passed on to central ATLAS DAQ



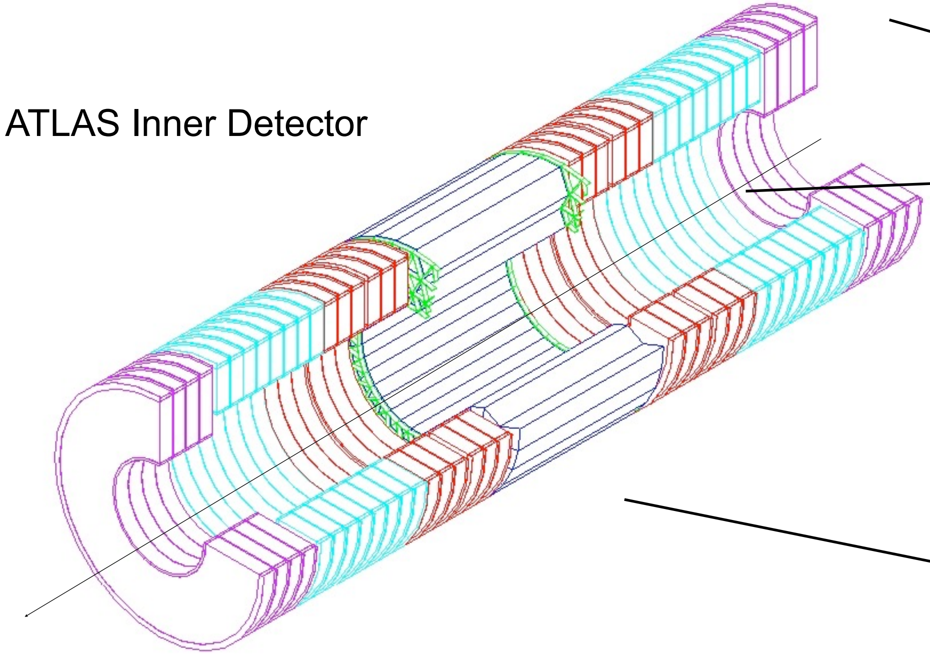


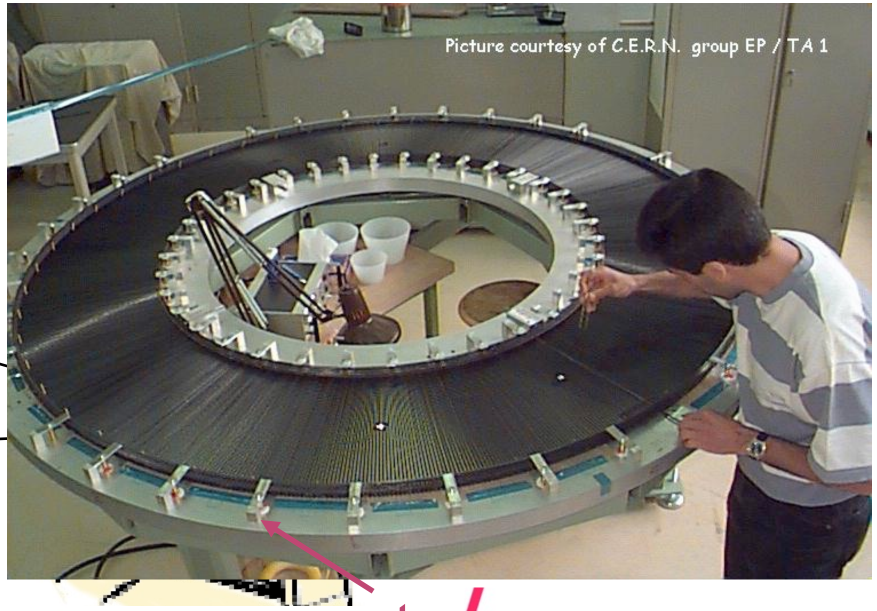
allows self supporting structures

A Stack of Straws

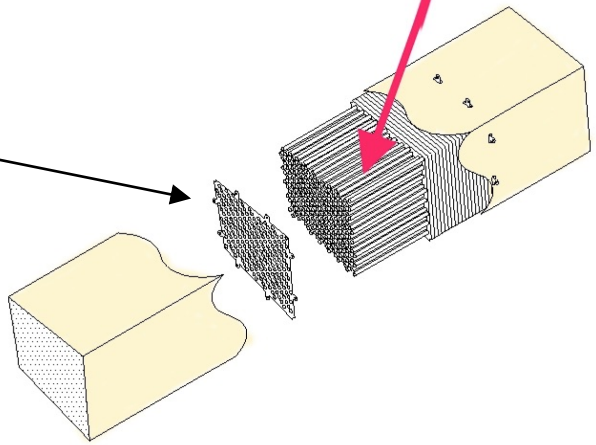
Endcap (~32000 straws)
radial from beam axis

ATLAS Inner Detector



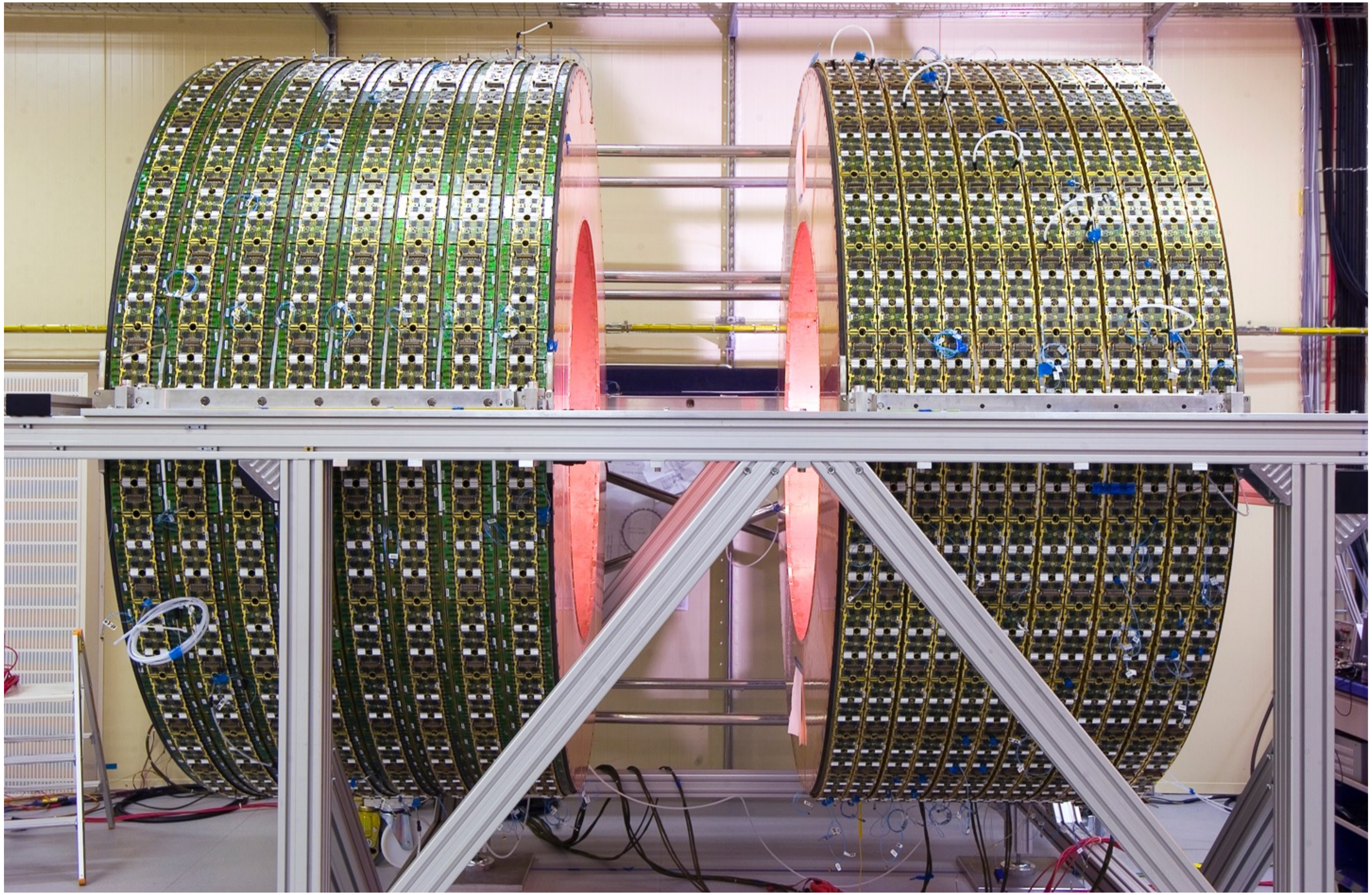


straws



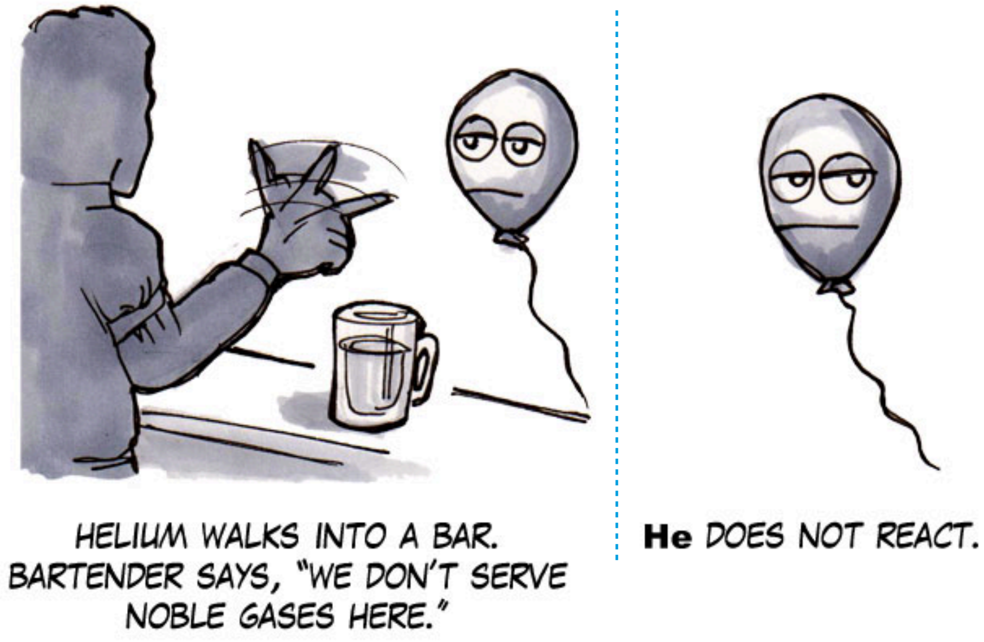
Barrel (~10000 straws)
parallel to beam axis

The First ATLAS TRT End-Cap (3 Aug 2005)



Choice of Fill Gas

- Avalanche multiplication occurs in all gases but there are specific properties required from a “magic” gas mixture
  - Low working voltage (low ionisation potential)
  - Stable operation at high gain
  - High rate capability (fast recovery)
  - Good proportionality
- **Noble gases** are usually the principal components of a useful gas
  - No molecules to absorb energy in inelastic collisions

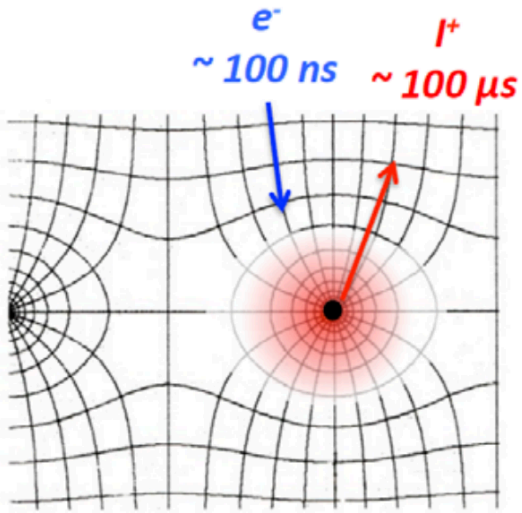


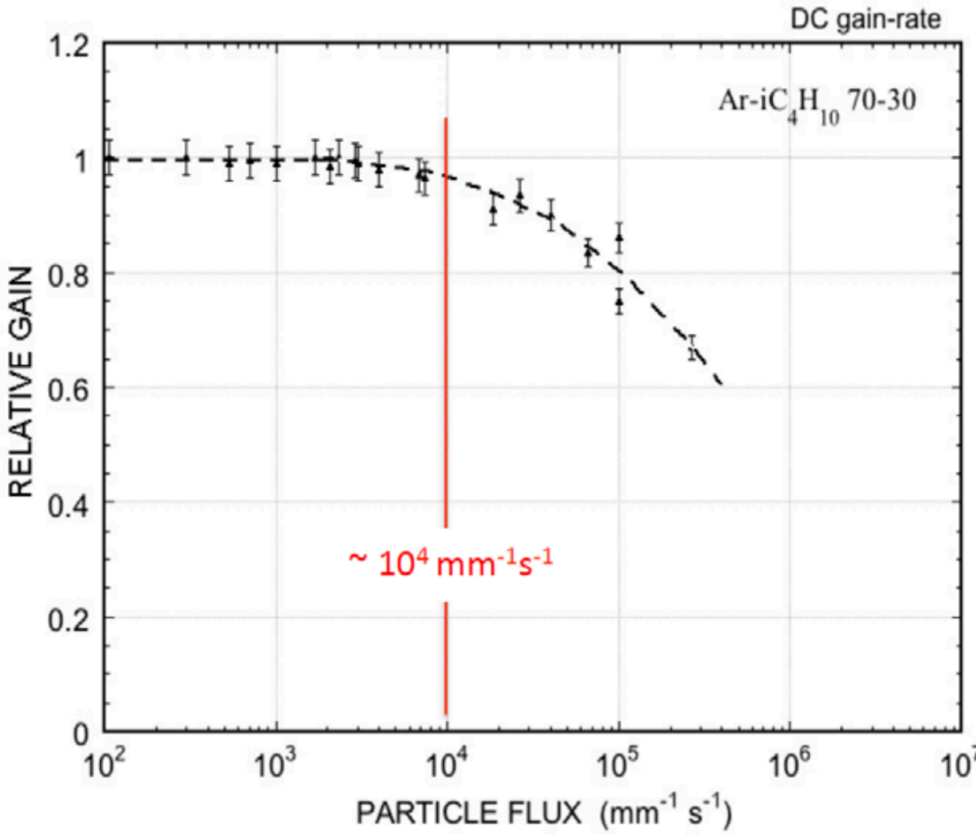
- **Argon** gives more primary ionisation than Helium or Neon
  - Kr and Xe are better and have been used but they are expensive
- However: chamber full of argon does not produce stable operation and suffers breakdown at low gain:
  - High excitation energy for noble gases (11.6eV for Ar) means that UV photons emitted from atoms excited in the avalanche process have enough energy to eject photoelectrons from the cathode material
  - Photoelectrons initiate further avalanches.
  - Process becomes self-sustaining ® continuous discharge.

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 ~$10^4 mm^{-1}s^{-1}$.

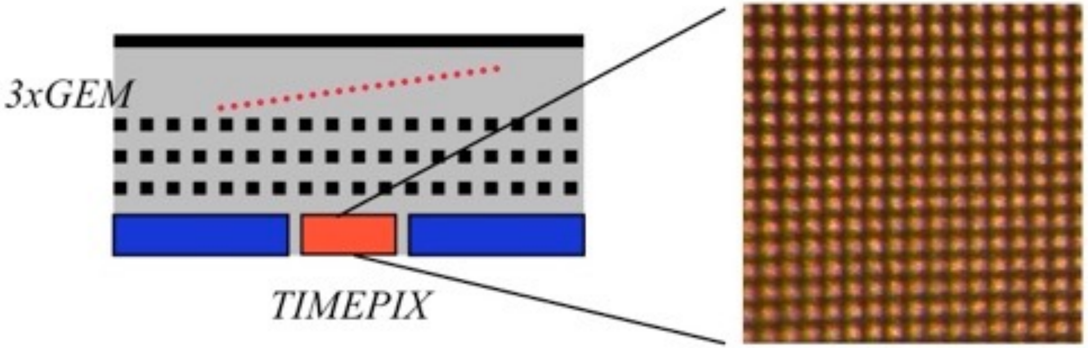


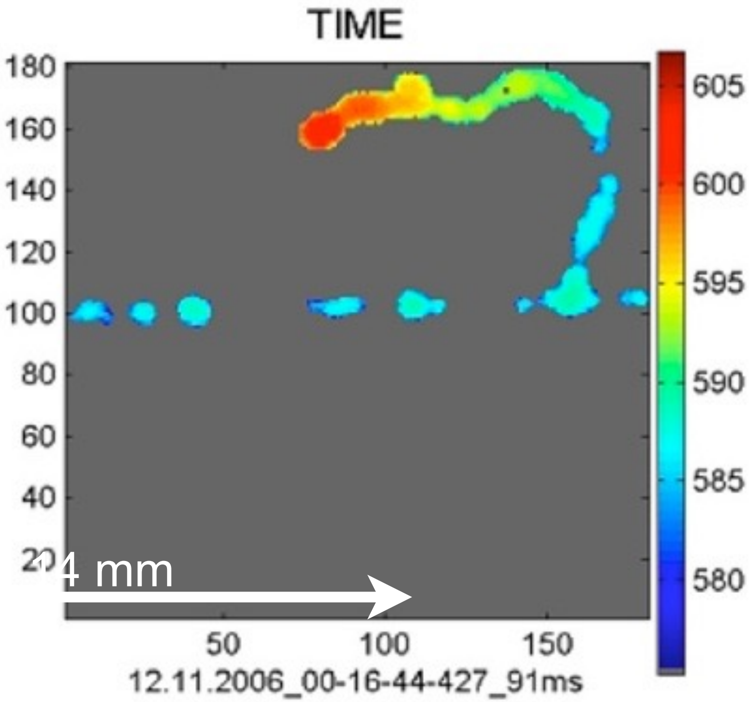


A. Breskin et al, Nucl. Instr. and Meth. 124(1974)189

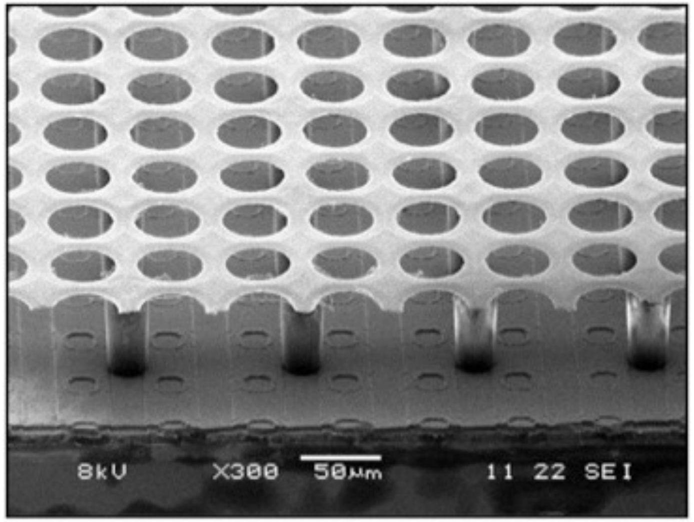
MPGDs as next generation detector

- Combination of gas detectors and Silicon
  - Integration of MPGDs with pixel read out chips





- Amplification and read out made of silicon

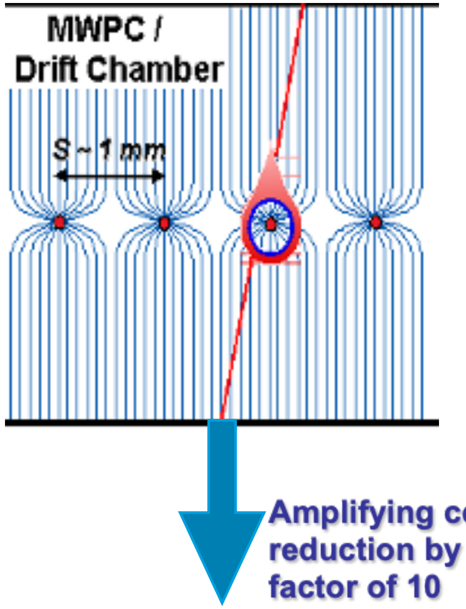


Advantages of gas detectors:
- Low radiation length
- Gas can be replaced regularly: Reduction of radiation damages!

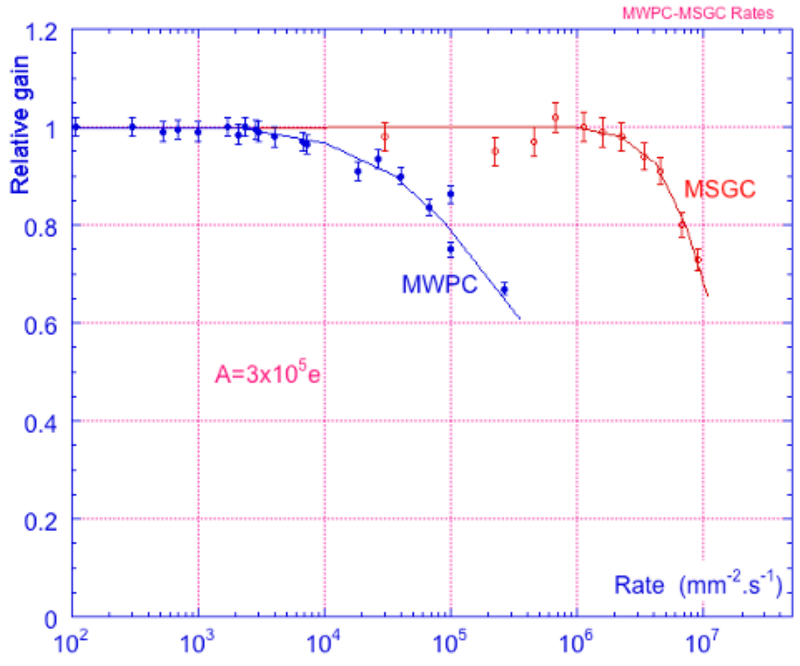
Microstrip Gas Chambers (MSGSs)

- MSGSs rely on micro-electronics technology, using precision (1-2mm) lithographic techniques, to overcome two major limitations of MWPCs:
  - Spatial resolution orthogonal to the wire is limited by the wire spacing (>1mm)
  - Rate capability is limited by the long ion collection time (tens of μs)

- Alternating narrow anode strips and wider cathode strips deposited on an insulator by photolithography
- MSGCs are rather prone to discharge, particularly in difficult environments.

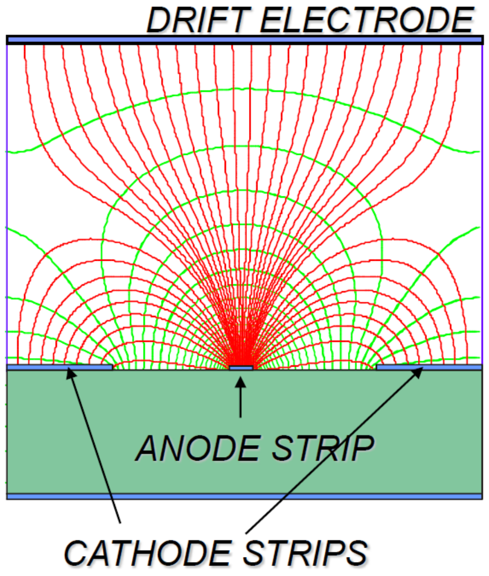


Amplifying cell reduction by factor of 10



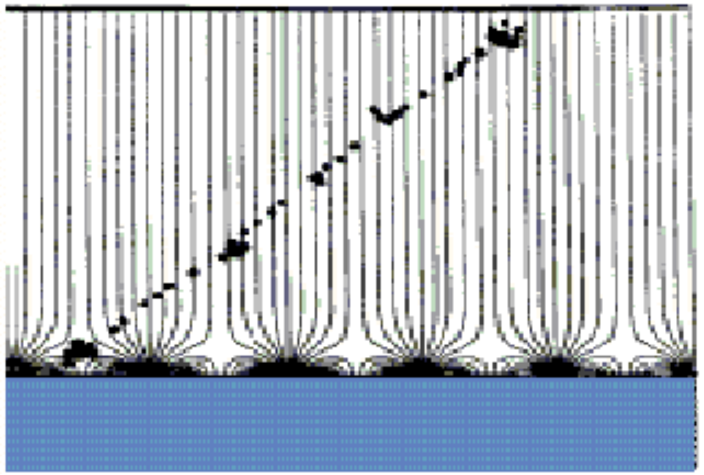
Rate capability limit due to space charge overcome by increased amplifying cell granularity

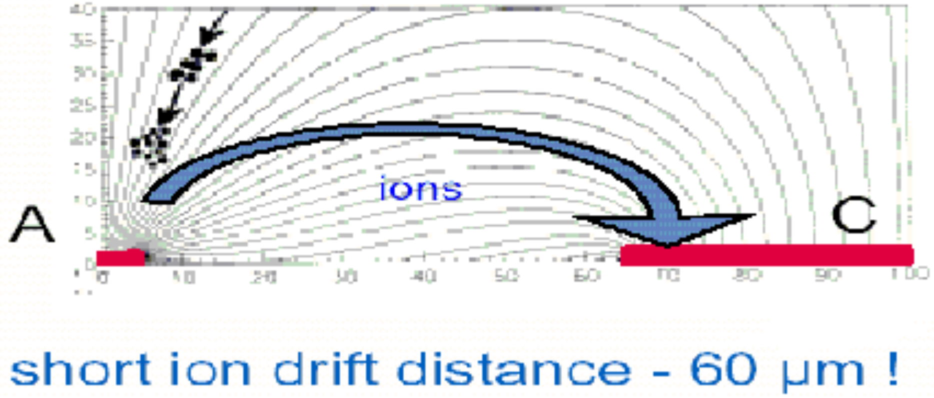
R. Bouclier et al, Nucl. Instr. and Meth. 367(1996)328



MSGCs (contd)

- Cathode strips are arranged between the anode strips for an improved field quality and to improve the rate by **fast removal of positive ions**
  - Reduced dead time between signals

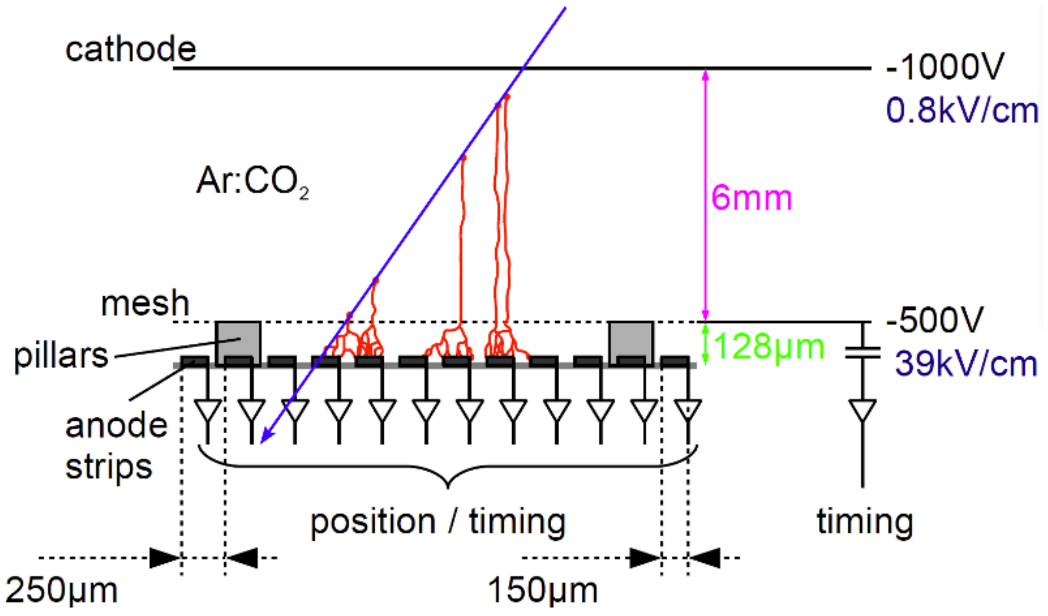


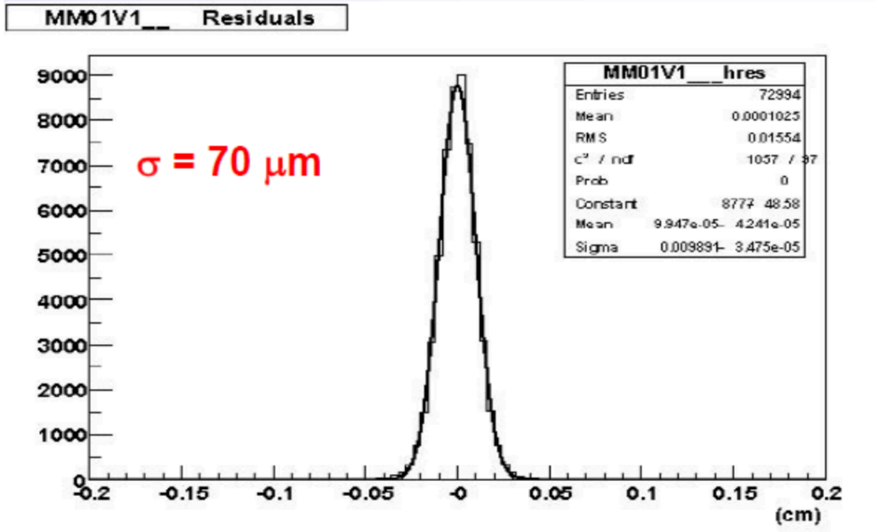


- Rate and spatial resolution improved w.r.t. MWPCs by more than an order of magnitude
  - Spatial resolution can be a few tens of microns
- Segmentation of the cathodes also possible to allow 2-dimensional readout

Micromegas

- 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



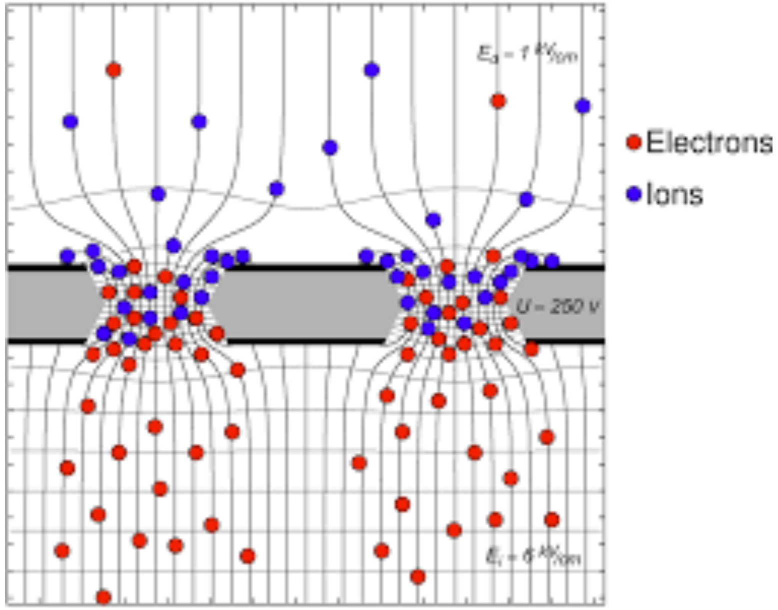


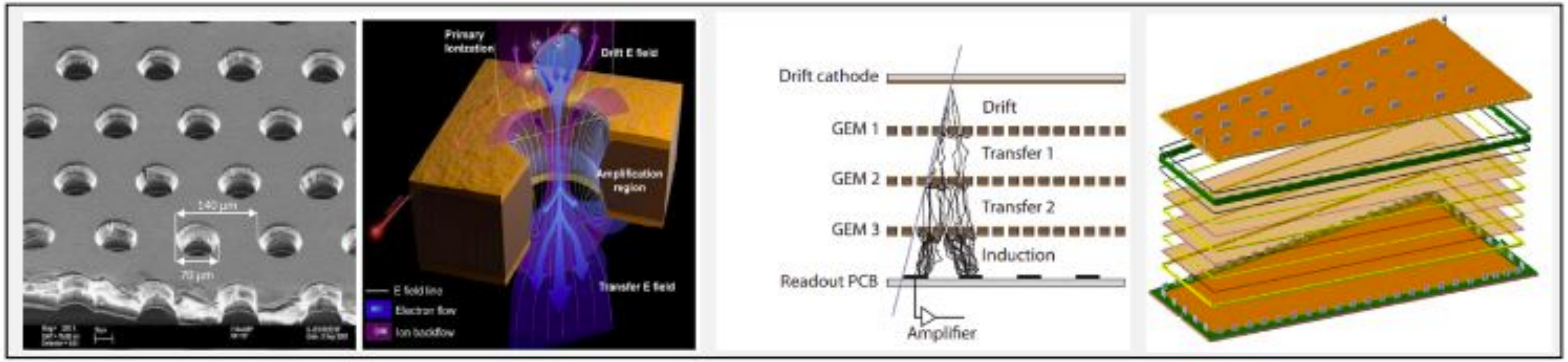
Space resolution

GEMS

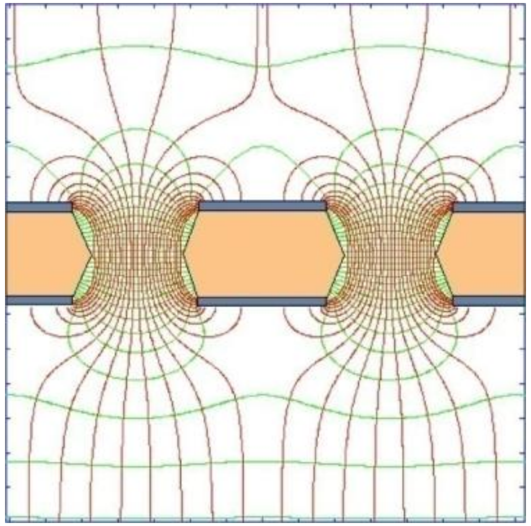
F. Sauli, GEM: A new concept for electron amplification in gas detectors, NIM A386(1997) 531

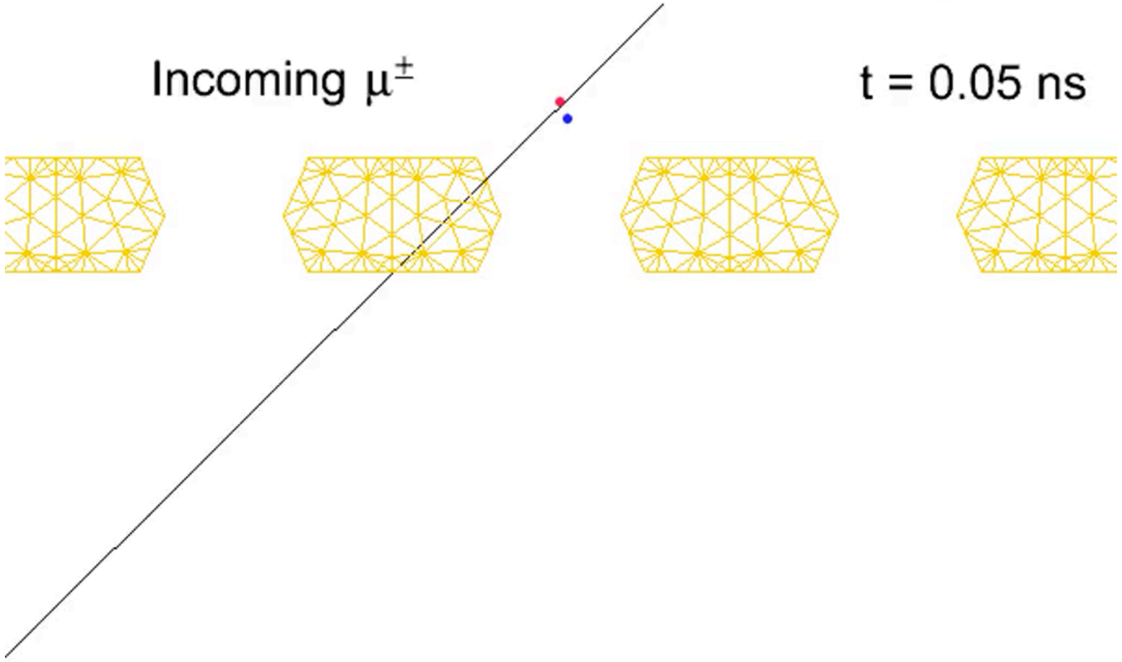
- Electrons are collected on patterned readout board.
- A fast signal can be detected on the lower GEM electrode for triggering or energy discrimination.
- All readout electrodes are at ground potential.
- Positive ions partially collected on the GEM electrode





GEM – Gas Electron Multiplier





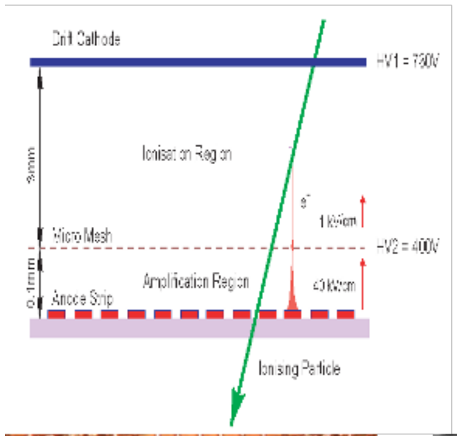
- Animation of the avalanche process
  - monitor in ns-time electron/ion drifting and multiplic
  - electrons are blue,
  - ions are red,
  - the GEM mesh is orange

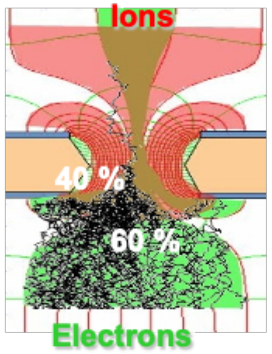
- Simulation: Garfield++
  (Particle Detector Simulation Toolkit)

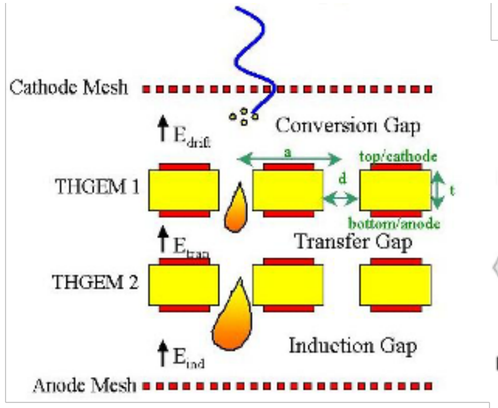
http://cern.ch/garfieldpp/examples/gemgain The RD51 collaboration

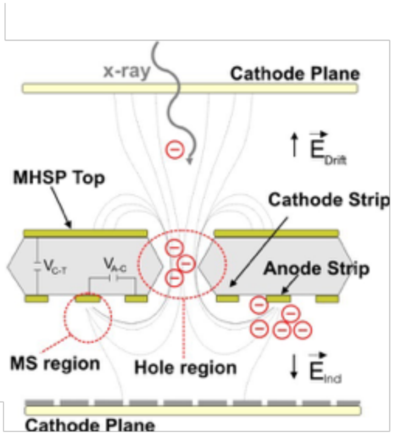
Current Trents in Gas Detectors

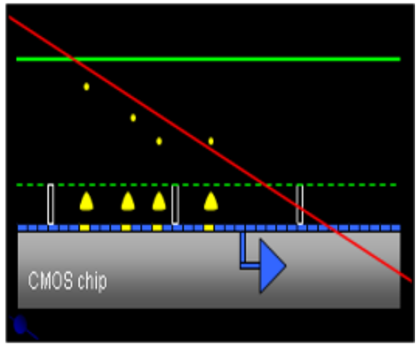
- Current Trends in Micropattern Gaseous Detectors
  - Manufacturing Technologies
  - Micromegas
  - GEM
  - ThickGEM/RETGEM
  - MPDG with CMOS pixel ASICs
  - Ingrid Technology

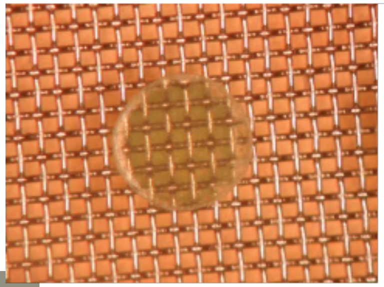




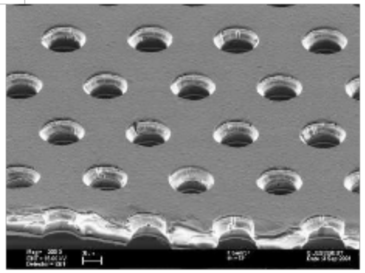




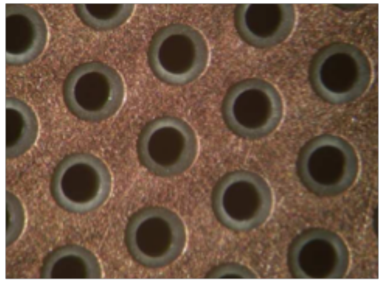




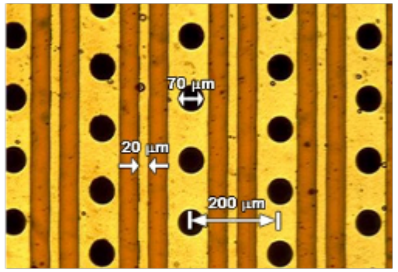
Micromegas



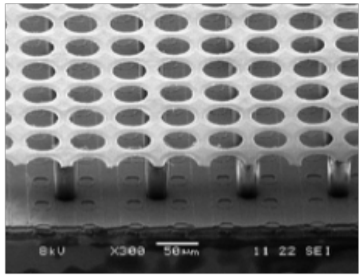
GEM



THGEM



MHSP



Ingrid

Current Trents in Gas Detectors

- Current Trends in Micropattern Gaseous Detectors
  - Manufacturing Technologies
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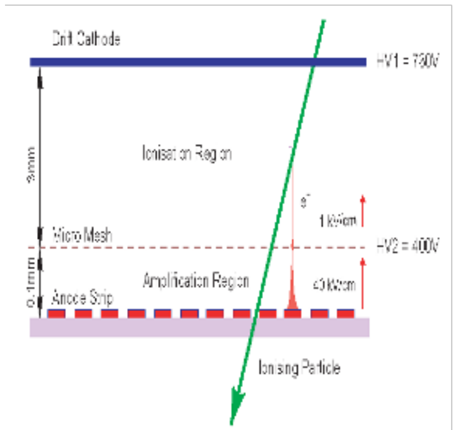
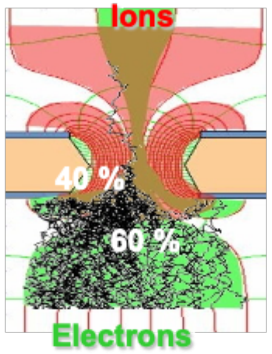
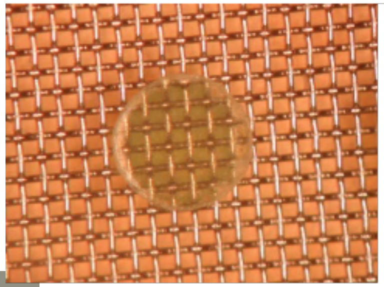
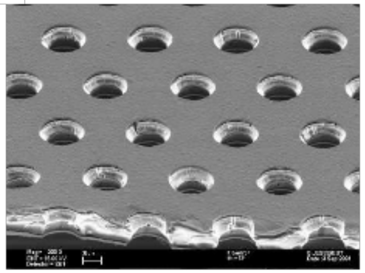
  - GEM
  - ThickGEM/RETGEM
  - MPDG with CMOS pixel ASICs
  - Ingrid Technology







Micromegas



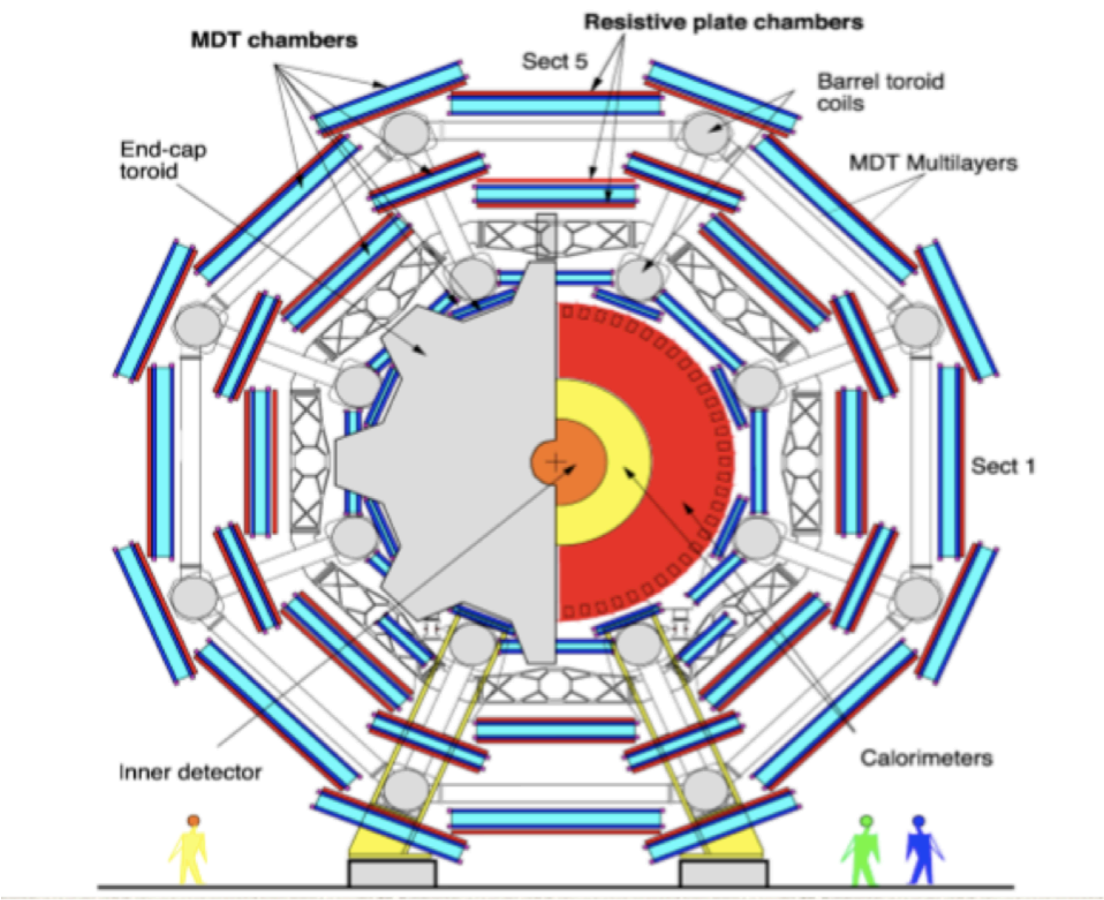
GEM

- Applications (HEP, Astrophysics, Nuclear Physics, Industrial and Medical)
  - Charged Particles Tracking
  - Triggering
  - TPC Readout
  - Calorimetry, Muon Detectors
  - Photon Detectors (UV and Visible Light Detection)
  - X-Ray Astronomy
  - Soft X-Ray Imaging
  - Neutron Detection
  - Cryogenic Detectors C

IV.B 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.
  - $\Delta pT/pT \approx 1/BL^2$



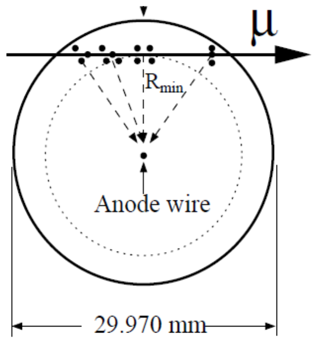
- A muon tracks can be:
  - “standalone” purely based on muon system
  - “combined” btw muon system and inner detector

Example: ATLAS

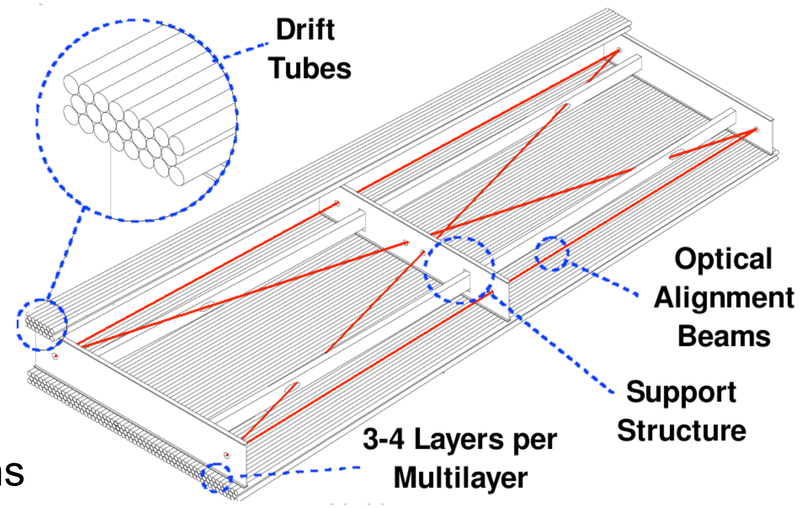
- independent muon system -> excellent stand capabilities

Precision Chambers

1) Monitored Drift Tubes (MDT)



Drift Tube

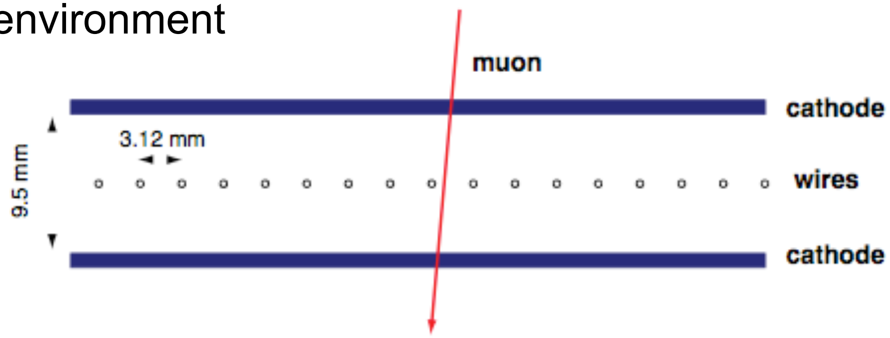


High-pressure drift tubes
$\sigma(R) \approx 100\mu m$, $T_{drift} \approx 700ns$

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

2) Cathode Strip Chambers

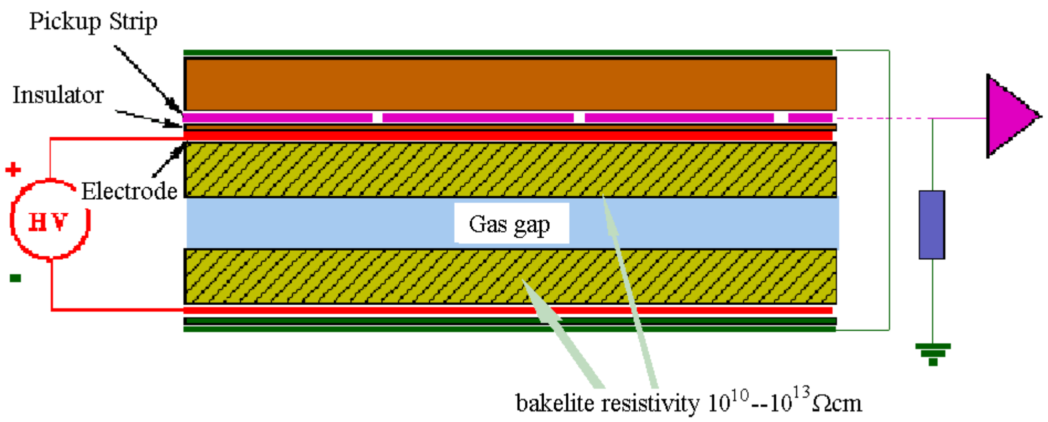
Operation in high rate environment
$\sigma(R) \approx 60\mu m T_{drift} \approx 20ns$



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

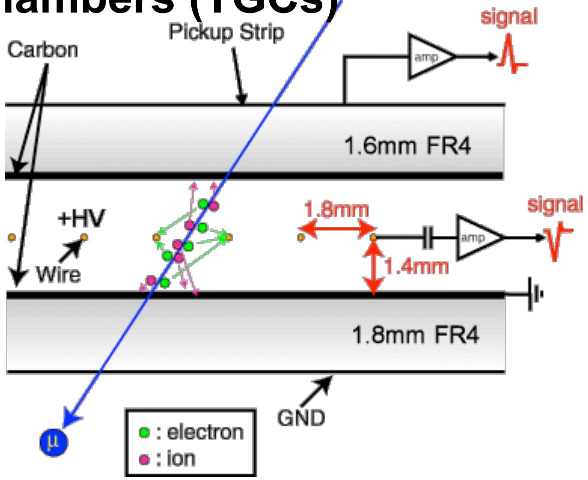
Trigger Chambers

1) Resistive Plate Chambers (RPCs)



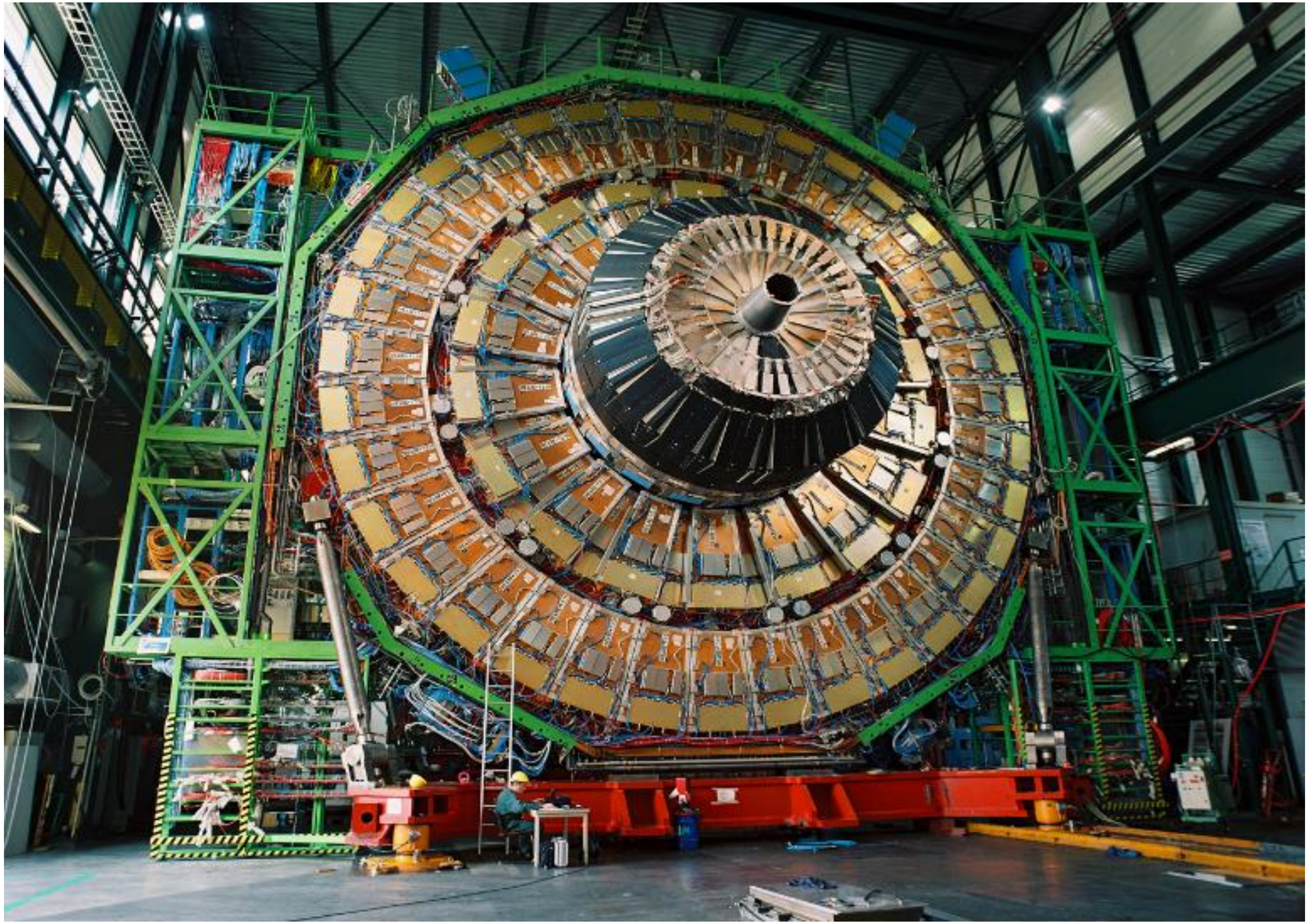
- Robust detector with up to 5ns time resolution
- Charge carriers drift towards anode and get multiplied by electric field (avalanche).
- Applied high voltage at parallel plate electrodes leads to uniform electric field in the gas gap.
- The propagation of the growing number of charges induces a signal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

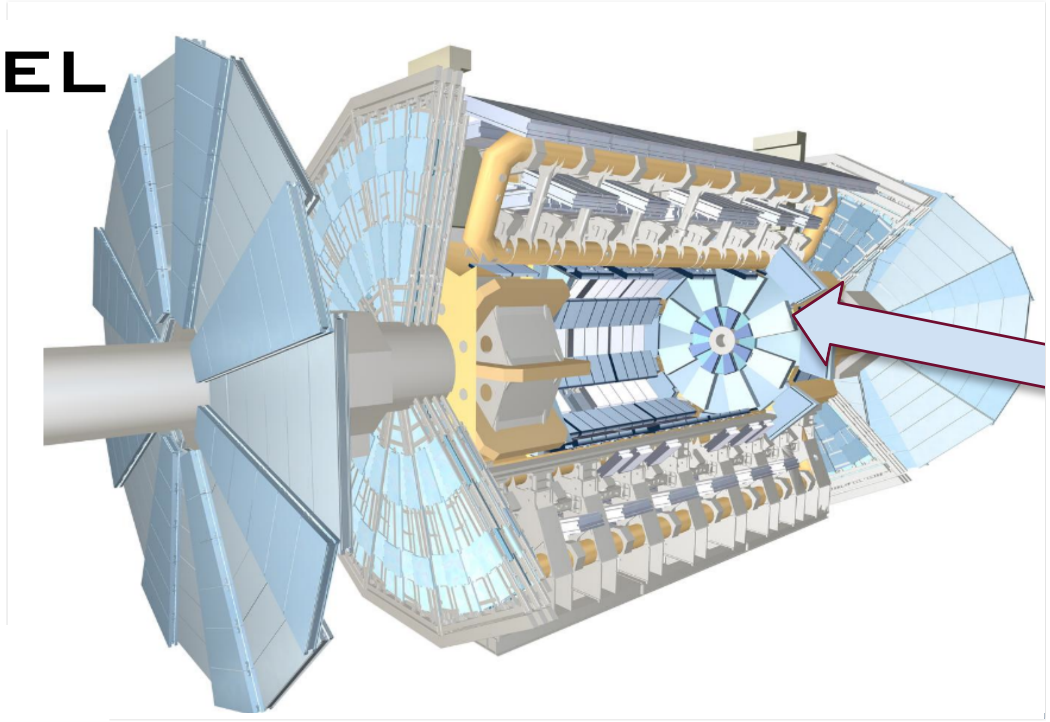
RPC detectors at CMS

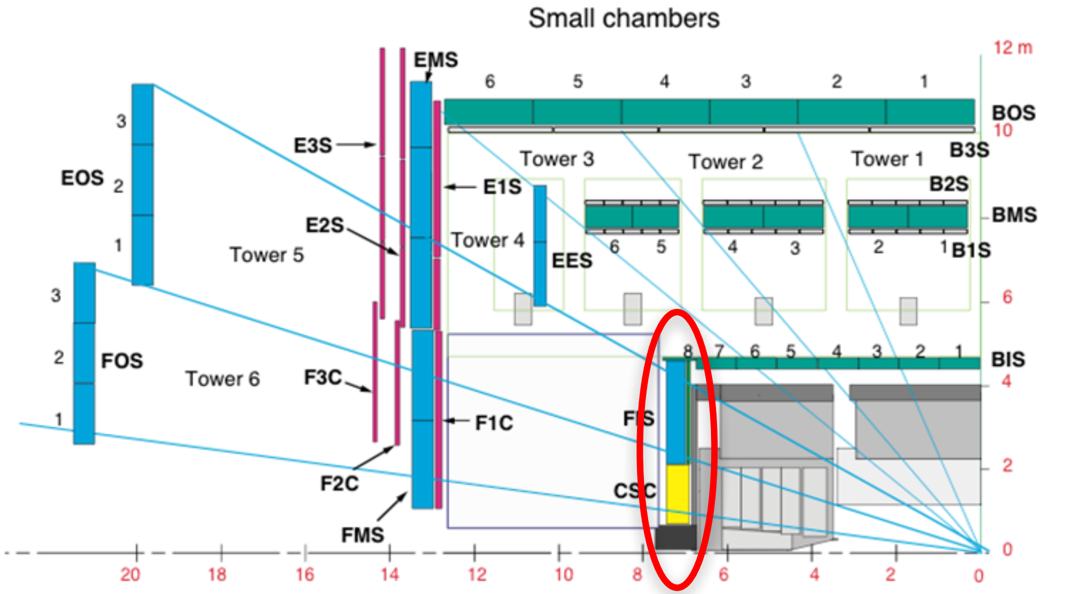


Phase-1: New Small Wheel

- 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}

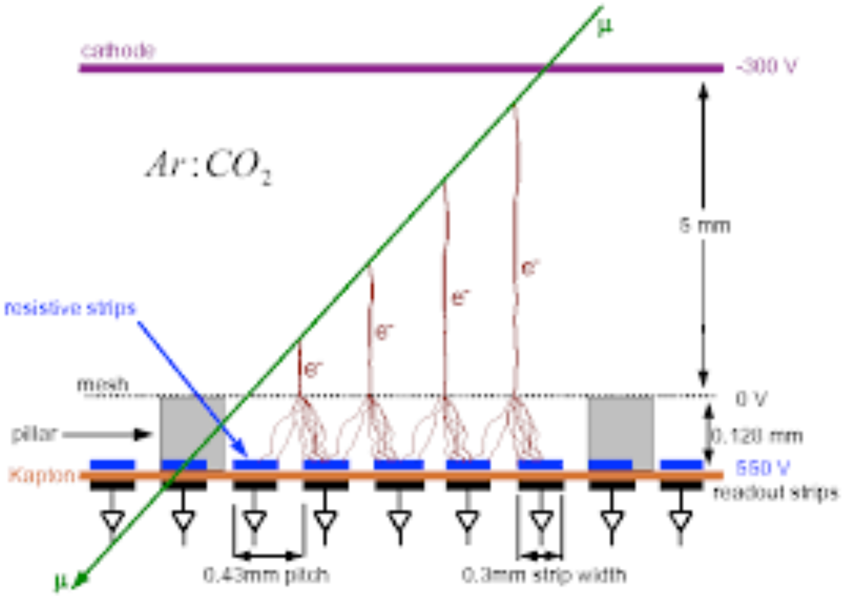


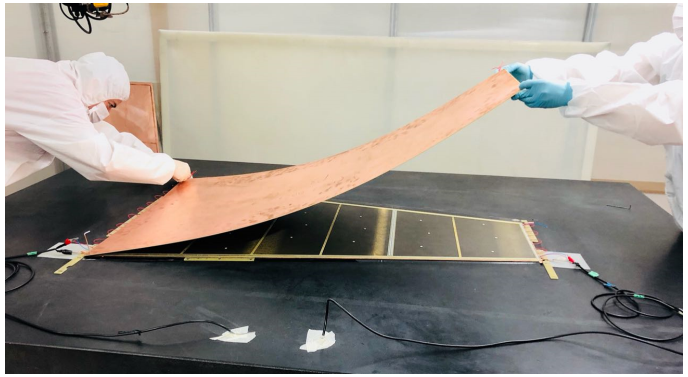


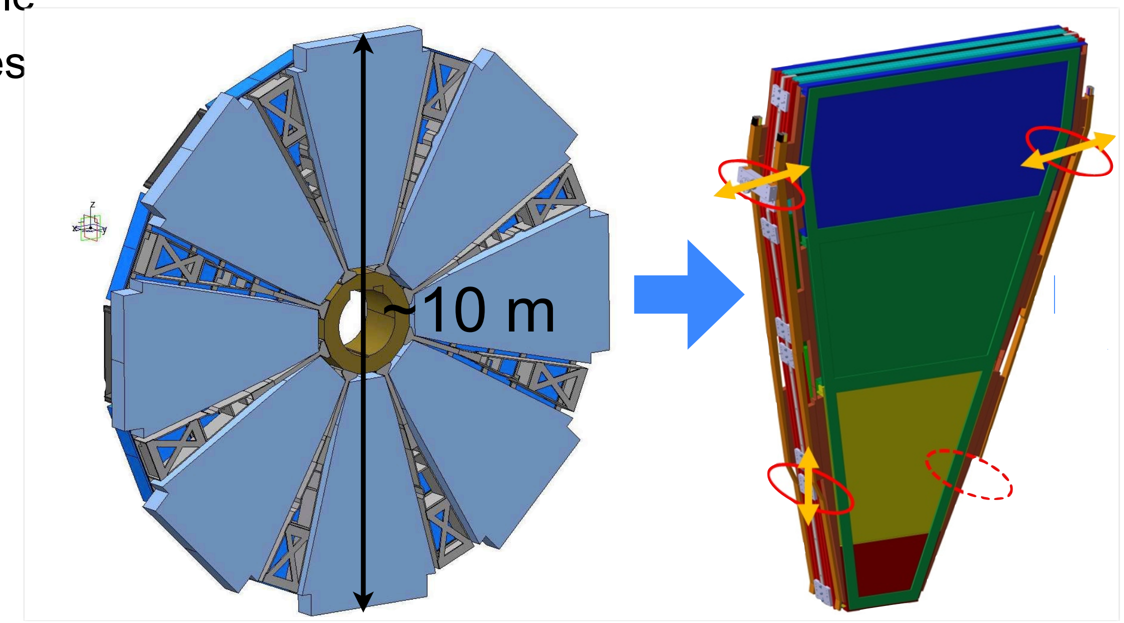
Coverage:
Tracking up to η = 2.7
Triggering up to η = 2.4

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



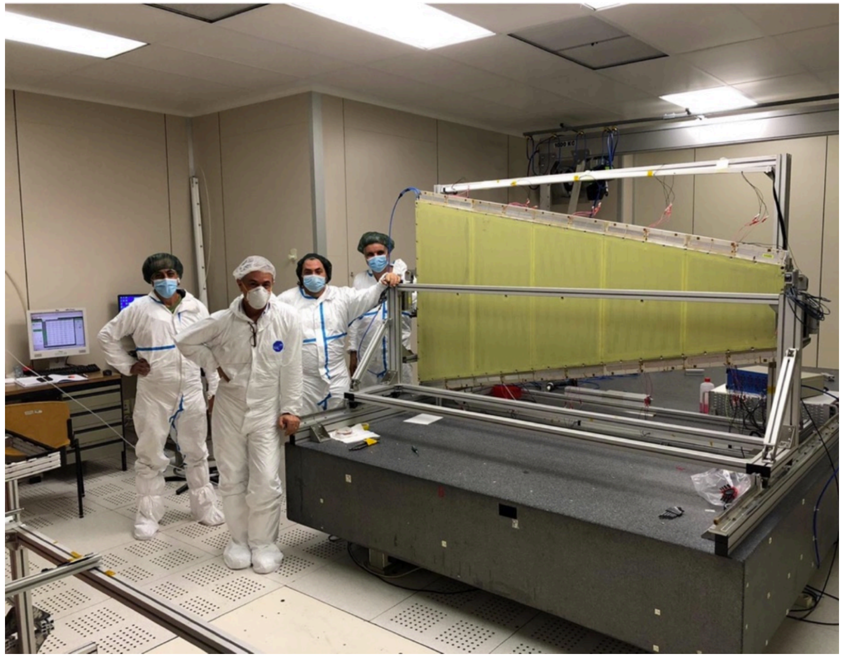


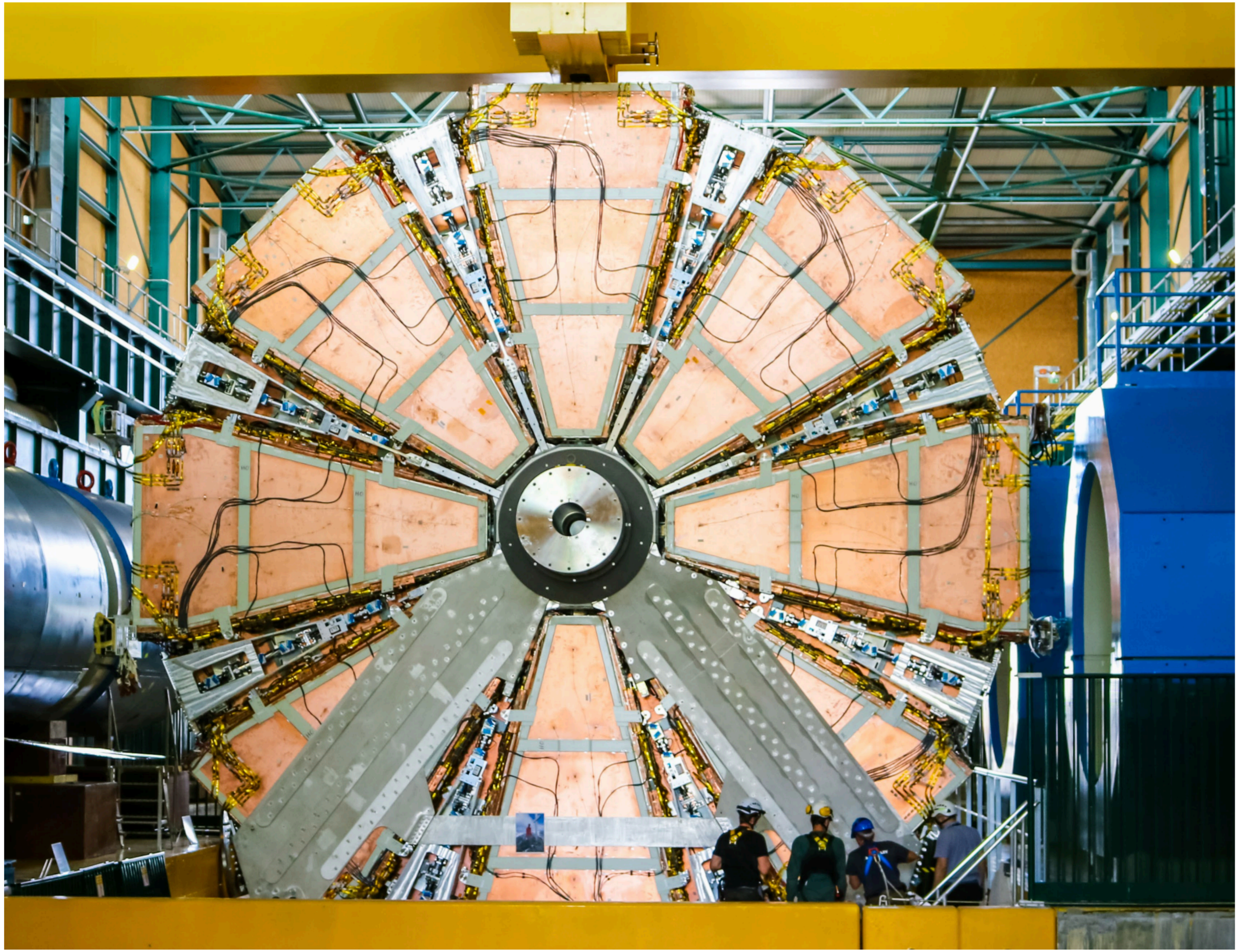


Total area of 1200 m 2

On the way to the Cavern

- After 10 years of work

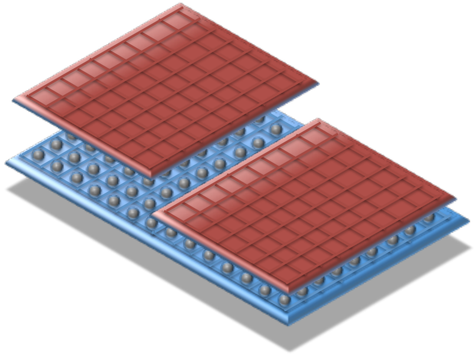




Summary Part 2

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

Tomorrow !!

Semiconductor Detectors

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