Instrumentation for High Energy Physics

Ludwik Dobrzynski
Laboratoire Leprince Ringuet - Ecole polytechnique - CNRS - IN2P3

The British University in Egypt - ESHEP2016

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- *Introduction*
- *Particle ID*
- **Particle momenta measurement**
- *Particle Energy measurement*

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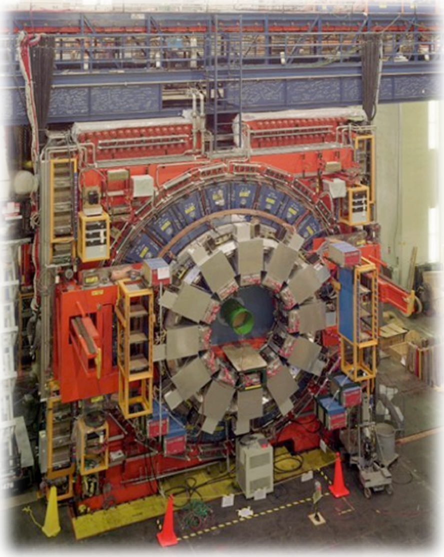
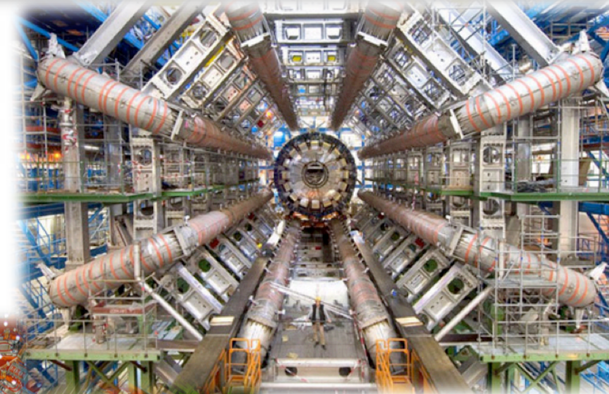
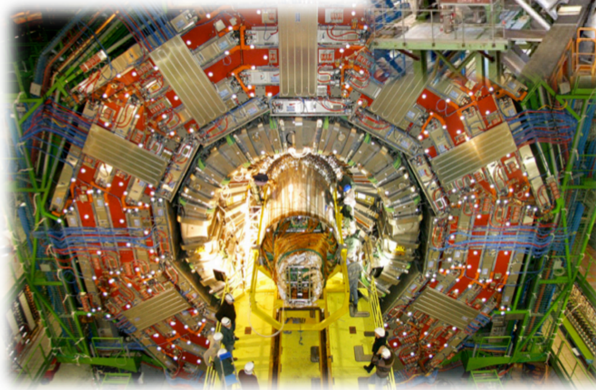
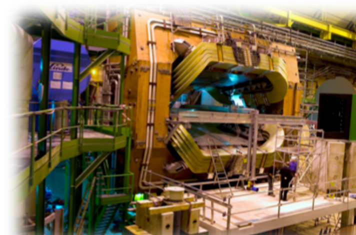
Hadron Colliders: Detectors





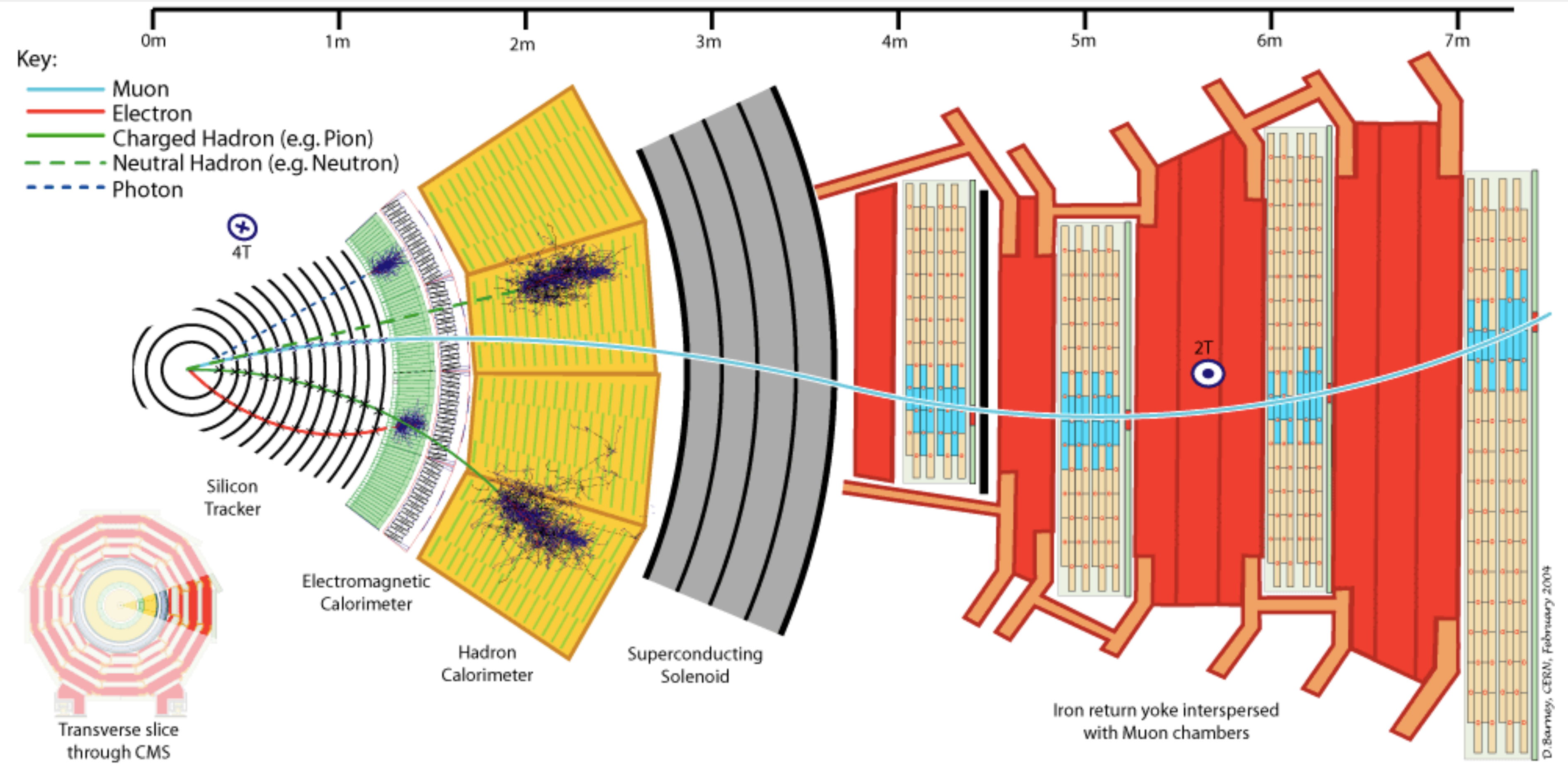


- Multipurpose detectors have similar components :
  - **Inner trackers**
  - **Calorimeters**
  - Outer **muon detectors**



Note: CDF and D0 have ~1 million channels. ATLAS and CMS much larger in magnitude, about 100 million electronic channels !

Objects: Tracking



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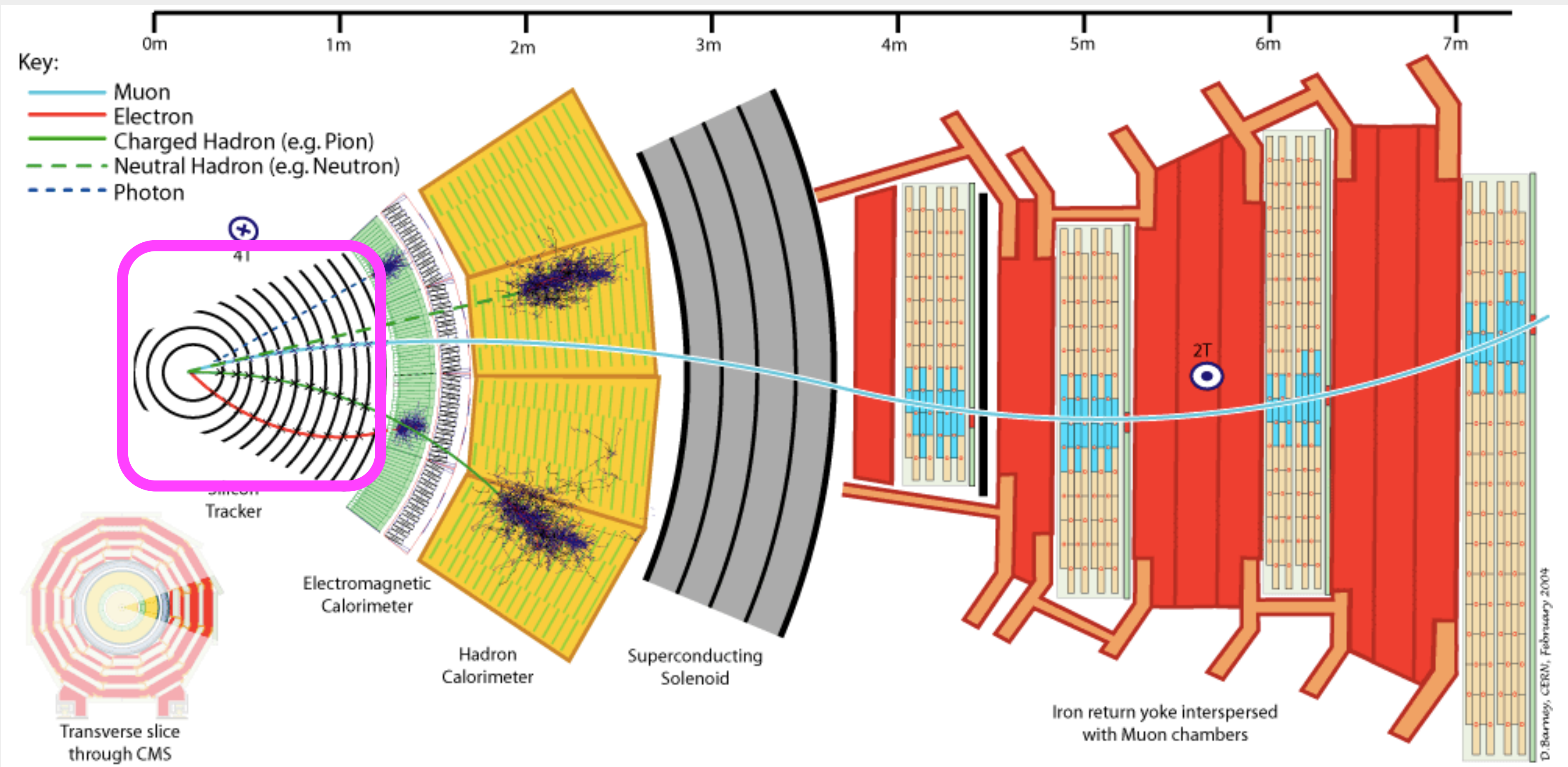

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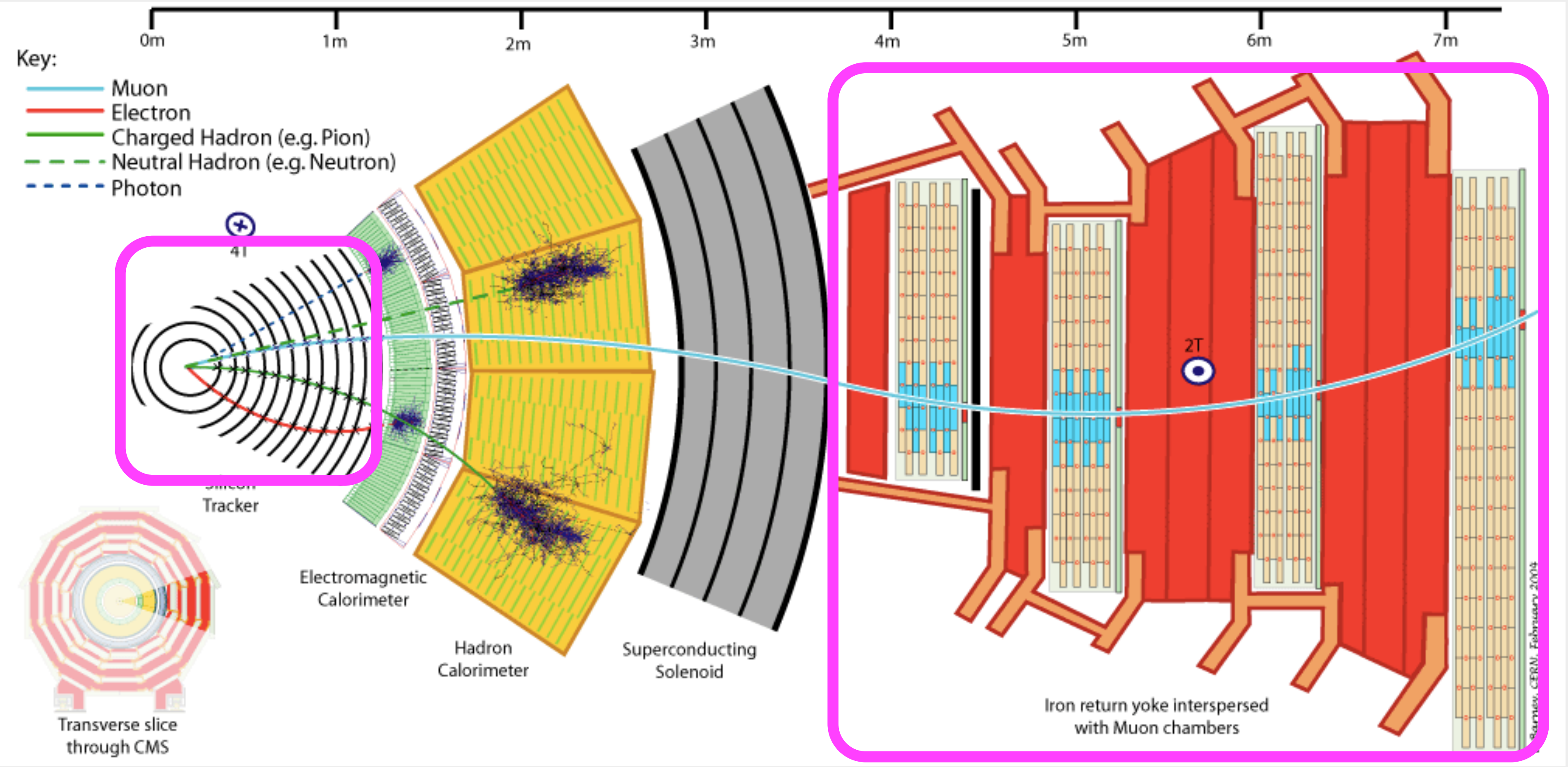

Tracking basic concepts

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- A good tracking performance is critical to allow
  - ***Precise momentum measurement***
  - ***invariant mass determination***
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- Alignment is a prerequisite for tracking

Tracking detectors

Two main classes of detectors :

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- Gaseous detectors : (for more details see)

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- Used for energy measurement (Si, Ge, Ge(Li)) since long time at low energy (nuclear physics).

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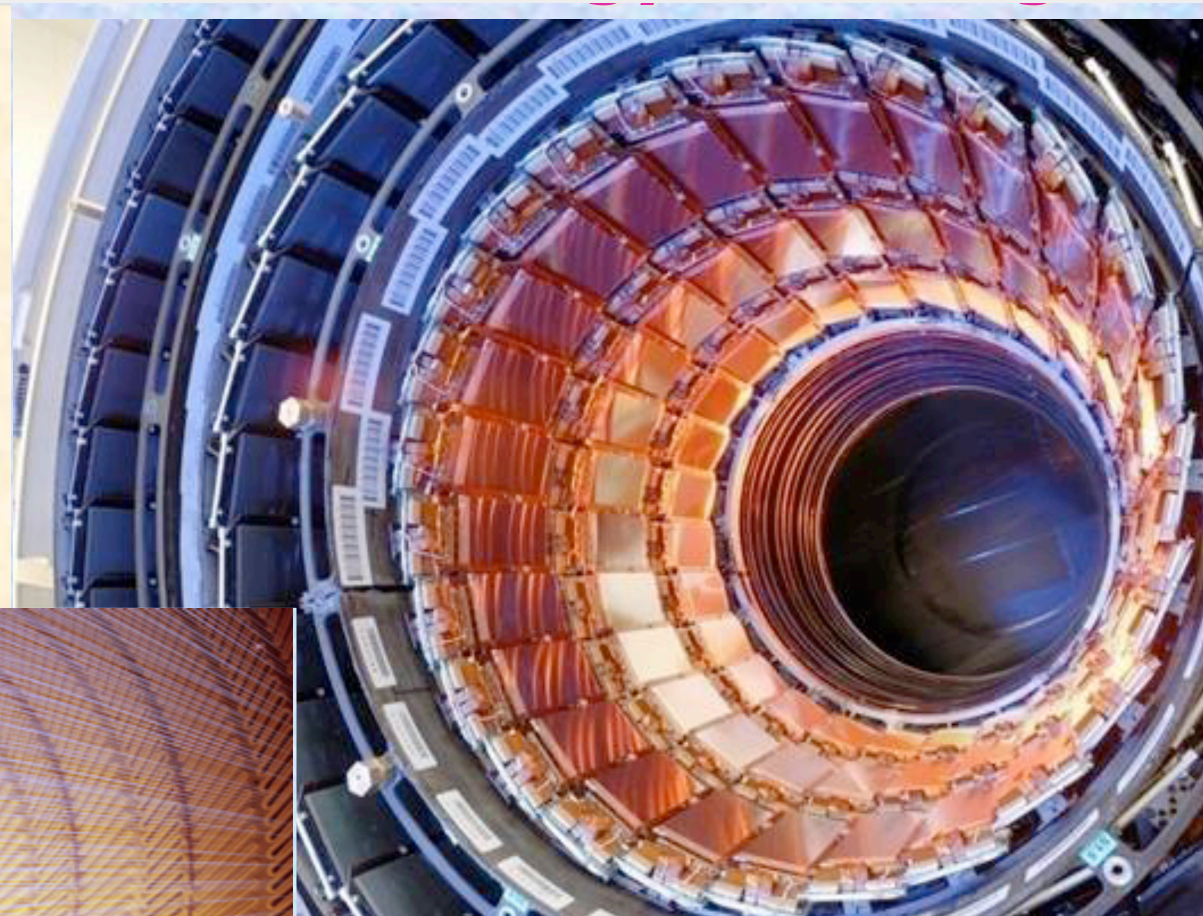
- ***Drawback : no charge multiplication mechanism! and quite dense***

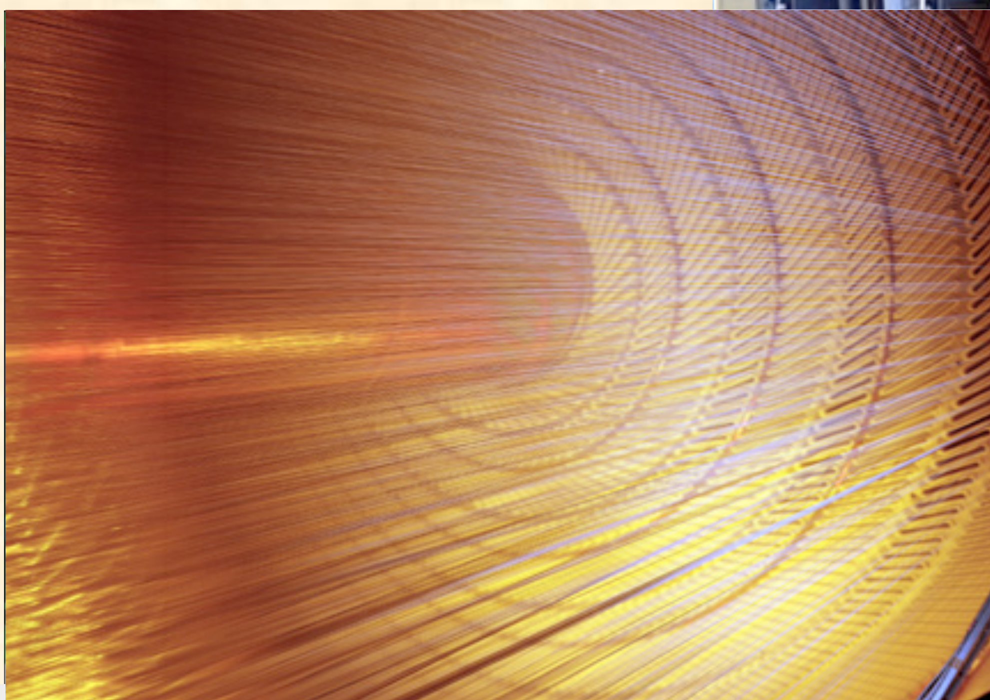
Tracking systems



Gaseous detectors

Measure: hit and/or drift time
➔ Position resolution: ~ 50 µm
➔ Tracks reconstruction
+ Magnetic field
➔ Momentum

Measure also: energy loss dE/dx
➔ Particle ID



Silicon detectors

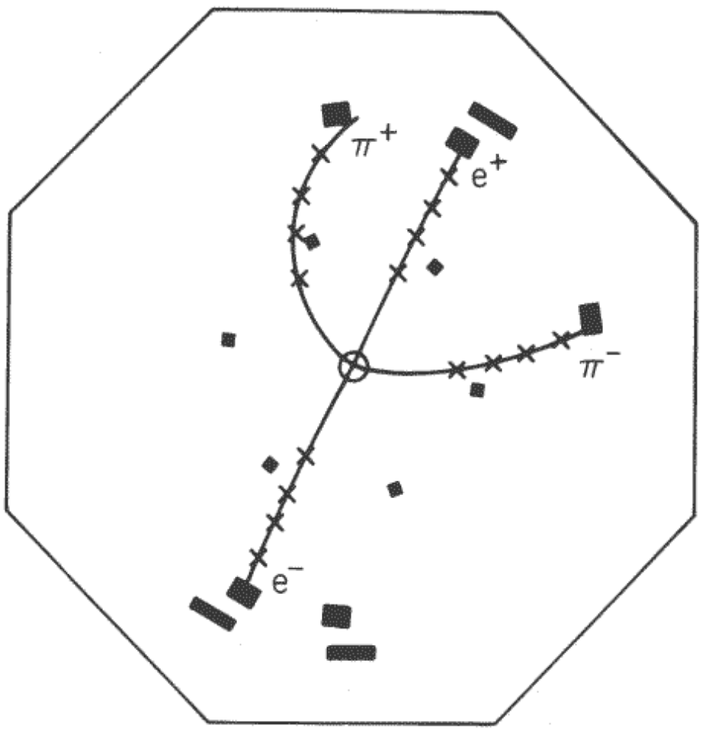
Measure: hits and/or amplitude
➔ Position resolution: ~ 5 µm
➔ Tracks & **Vertices** reconstruction

Increasing challenges

MARK-I detector (SLAC)

e+e- @ 3 GeV

Ψ' (excited state of J/Ψ)



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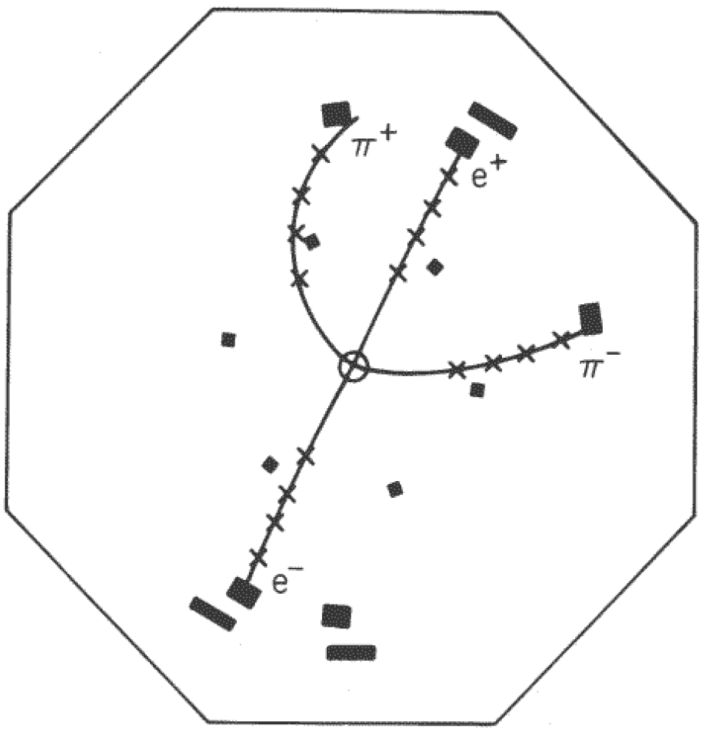
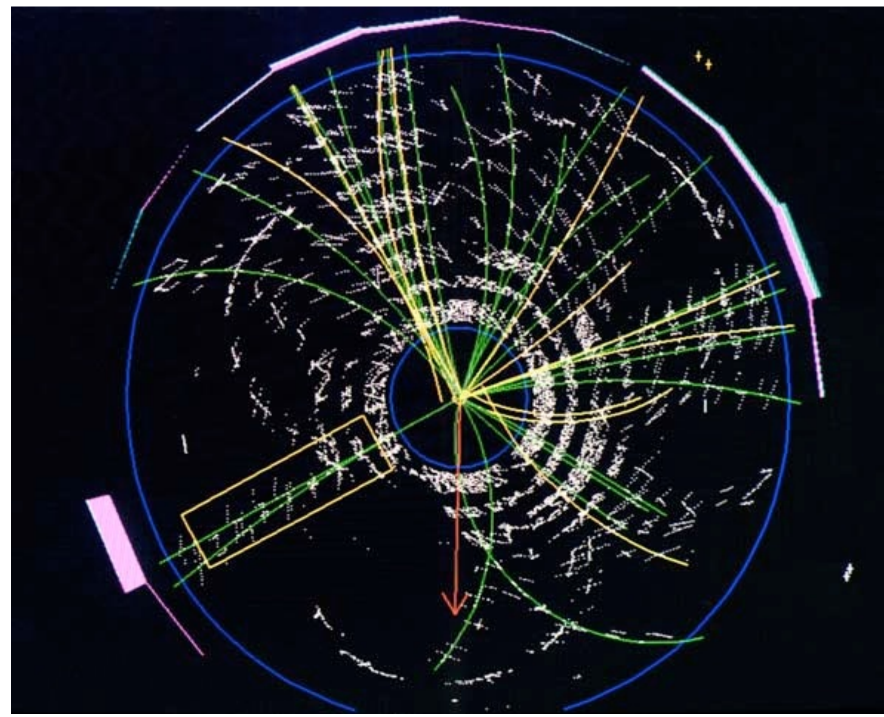


Top quark discovery at CDF and D0
pbarp @ 1,8 TeV



Increasing challenges

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e+
Ψ´ (ex

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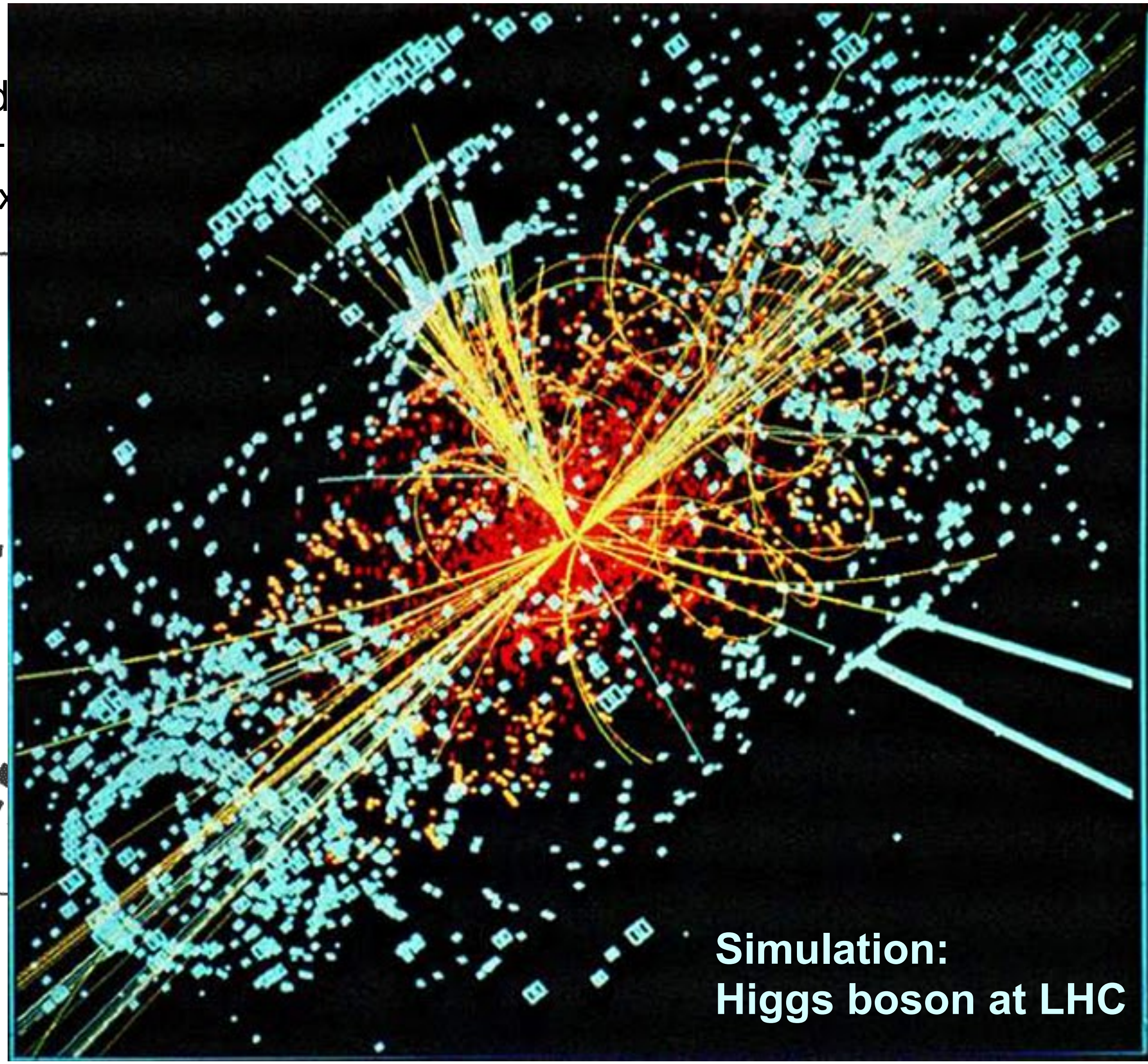

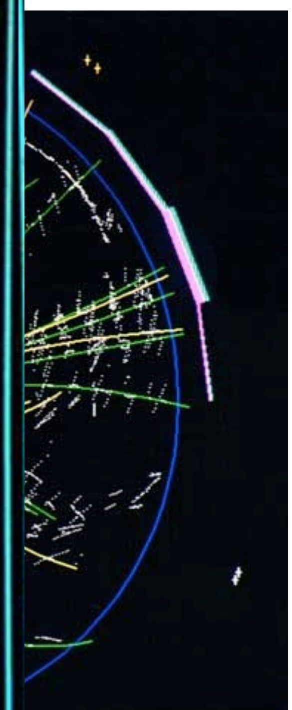

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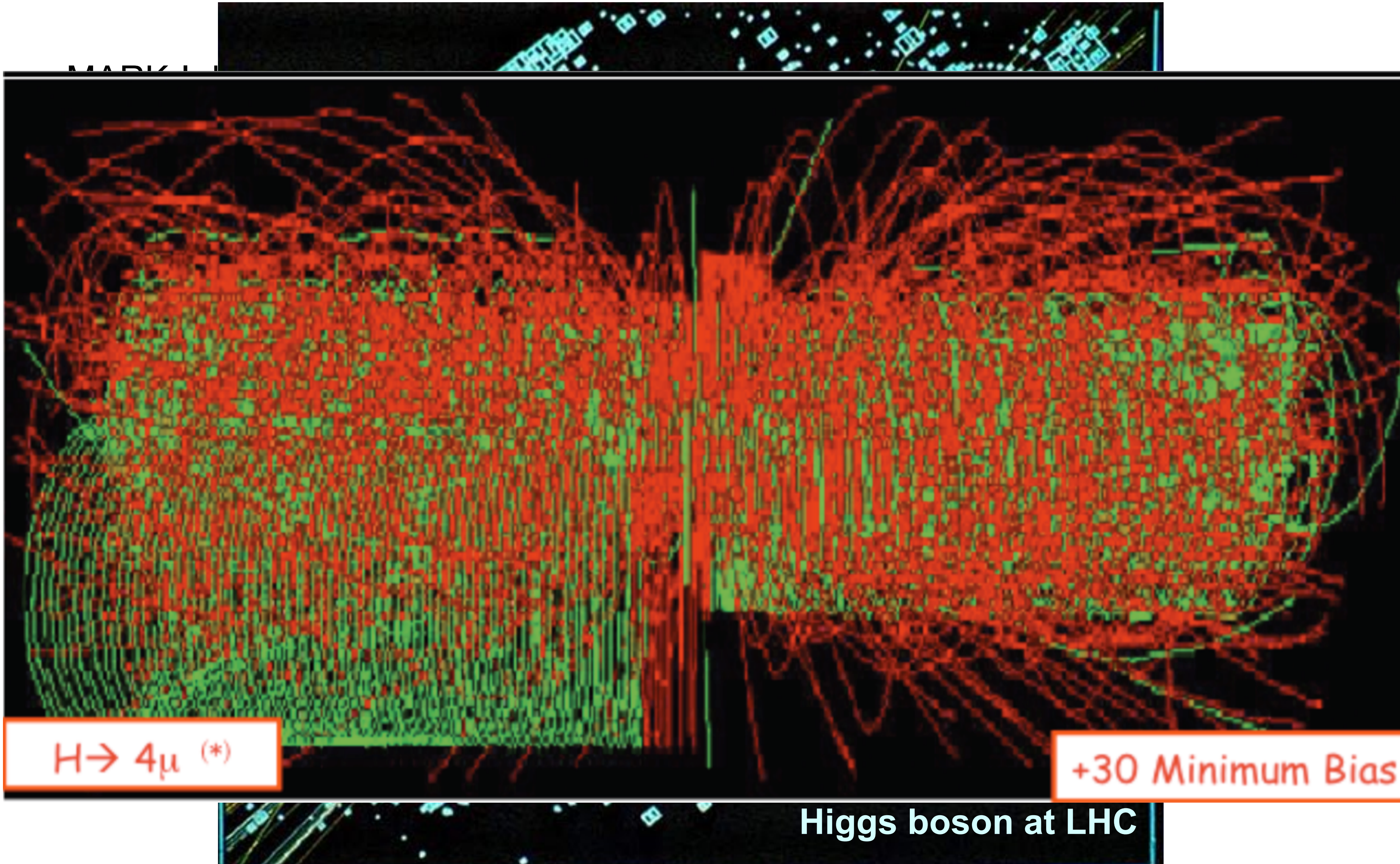

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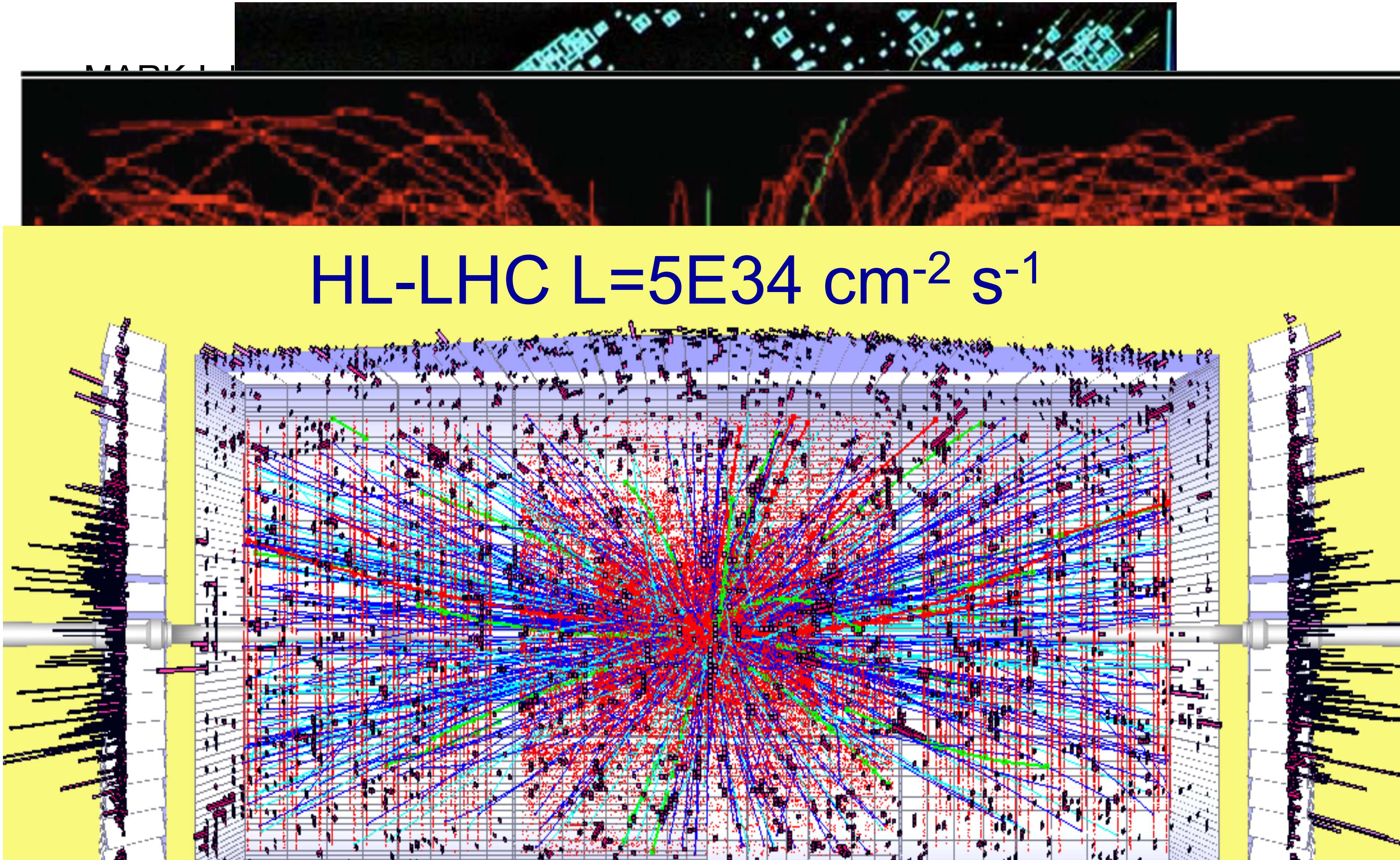
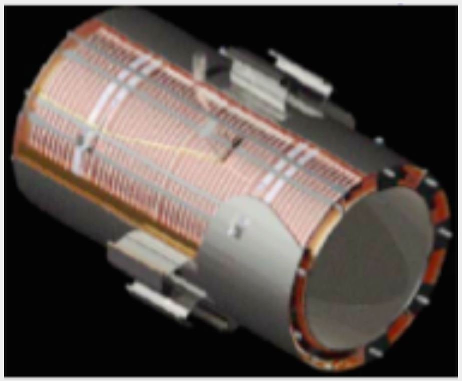
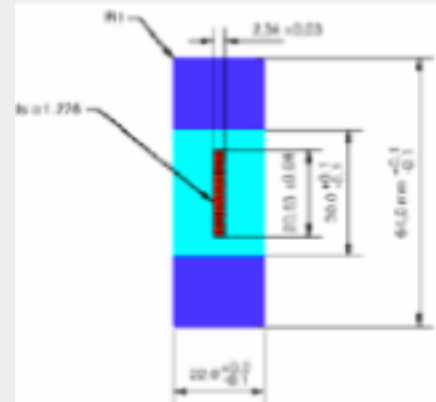


Tracking in HEP : Choice of Magnet

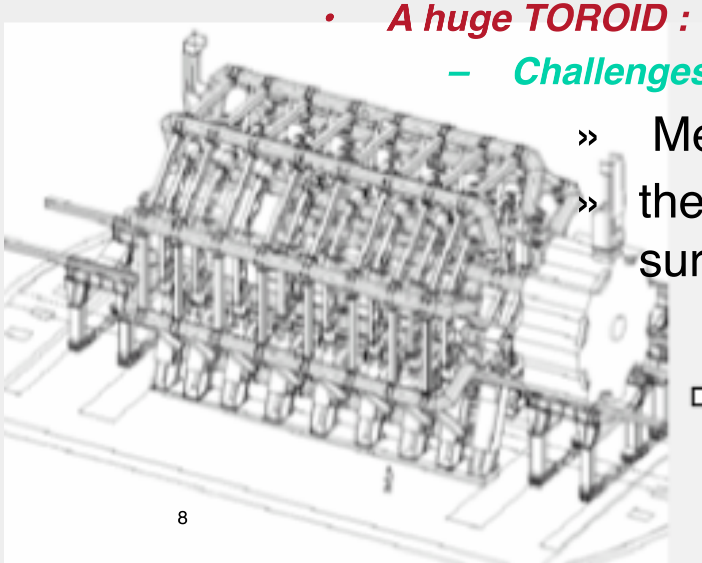
- Basic goal : measure 1 TeV muons with 10% resolution
  - CMS choice B=4T (E=2.7GJ) offer 10-20μm resolution



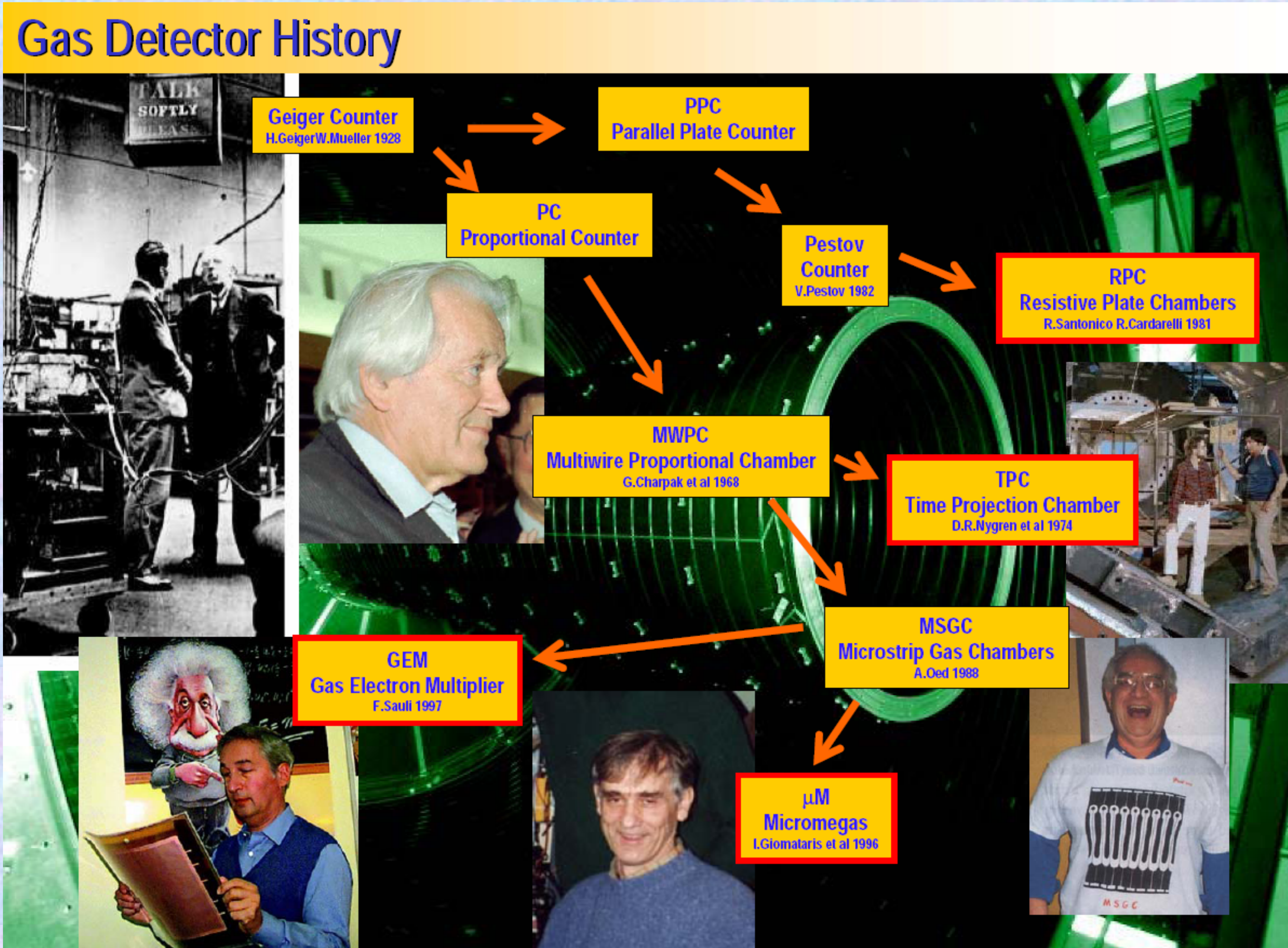
Challenge : 4 turns winding to carry enough courent what imply to have a design to reinforce the superconducting cable



  - ATLAS choice require (50μm resolution):
    - ***A central solenoid***
    - ***A huge TOROID :***
      - ***Challenges :***
        - » Mechanics should resist to a store of 1.5 GJ if quench
        - » the spacial and alignment precision over a large surface area



History of Gaseous Detector Developments

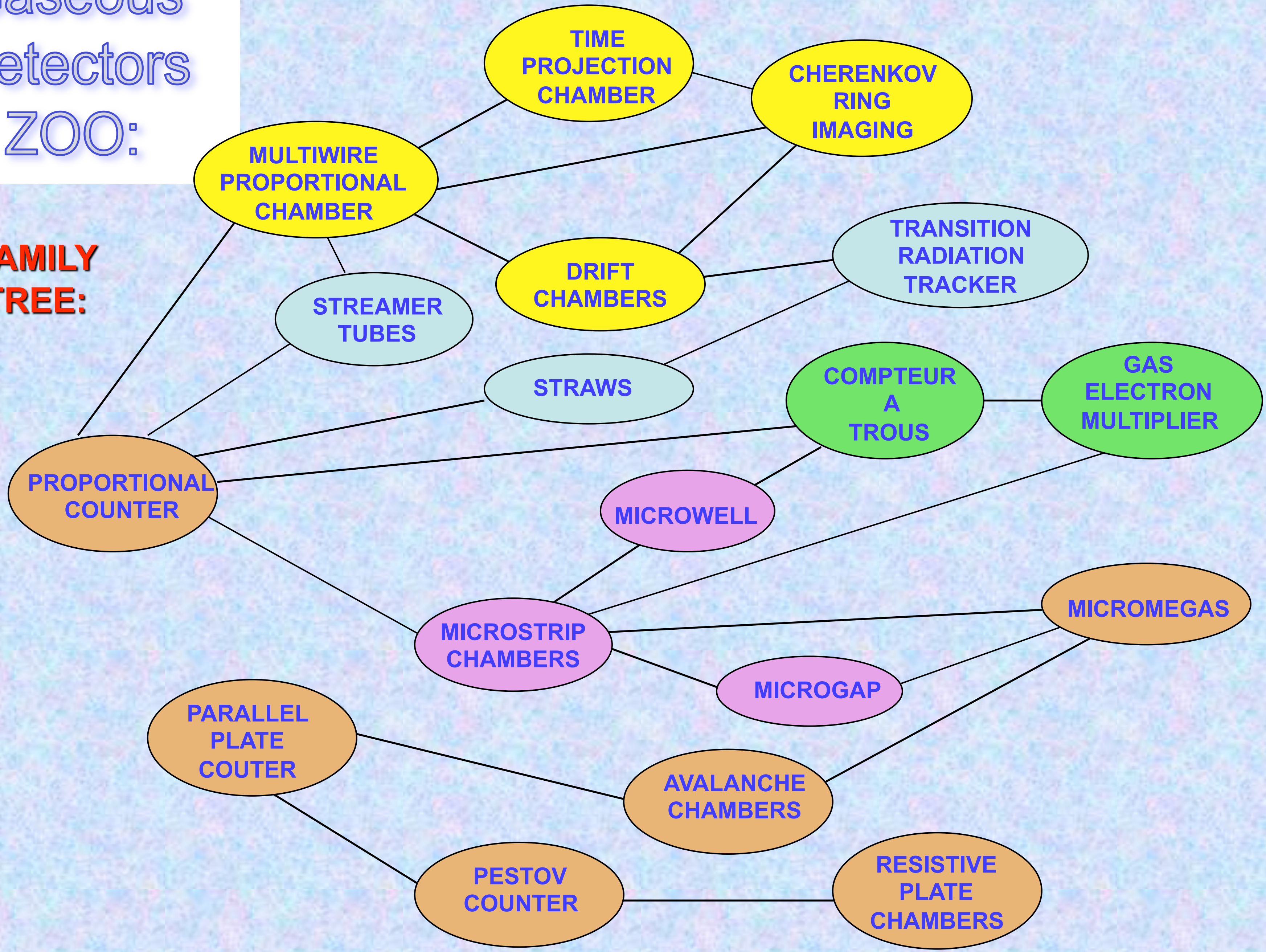


M. Hoch, 2004 Wire Chamber Conference

(for more details see ⟷)

Gaseous Detectors ZOO:

FAMILY TREE:



Tracking

- Particle detection has many aspects:
  - Particle counting
  - Particle Identification = measurement of mass and charge of the particle
  - Tracking

- Charged particles are deflected by B fields:

$$\vec{F} = q\vec{v} \times \vec{B}$$

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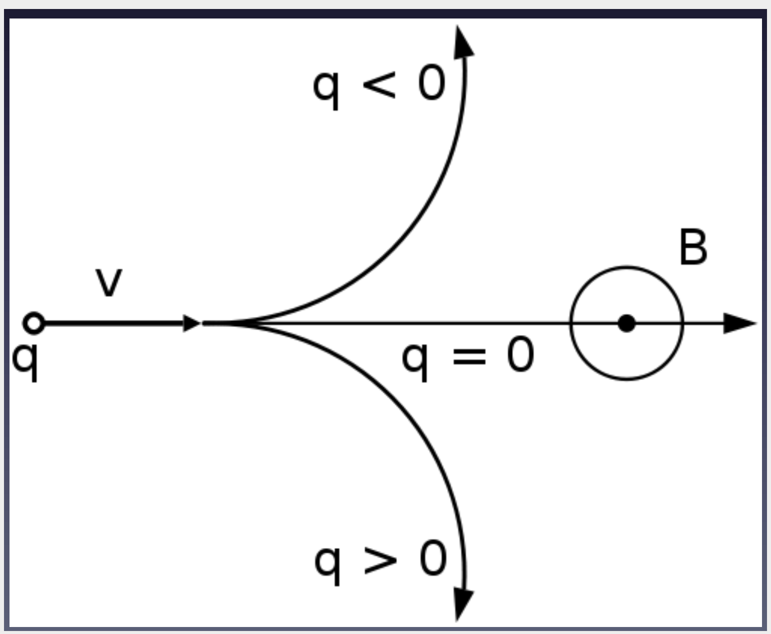

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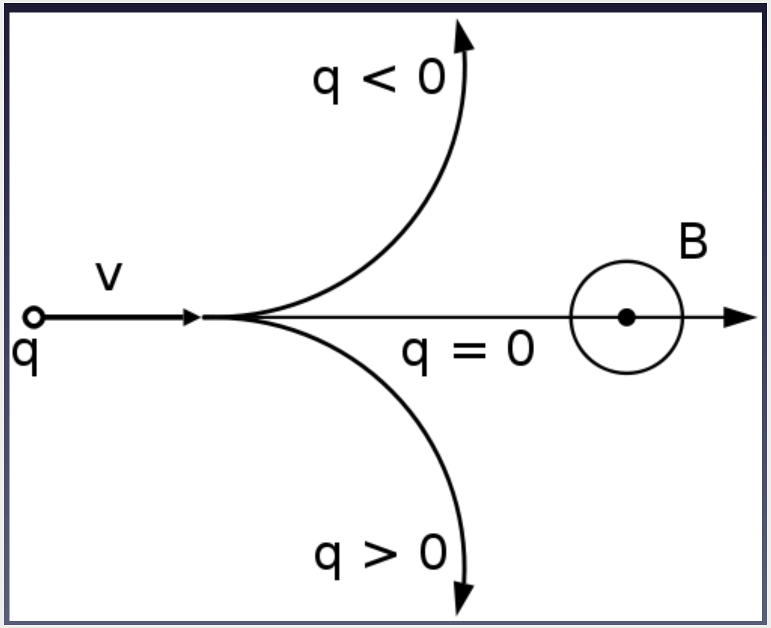
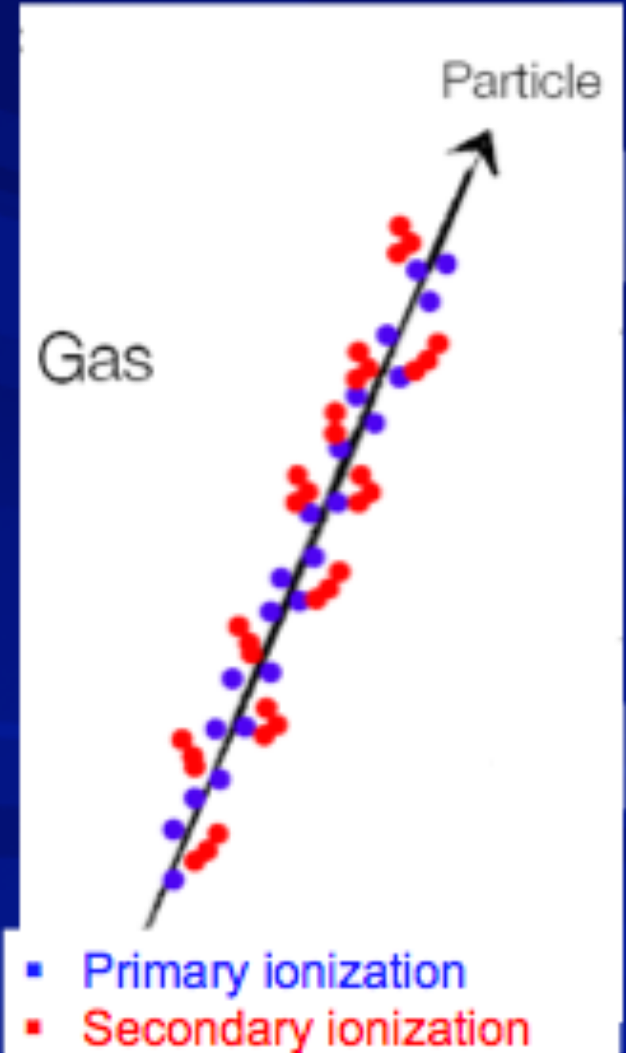


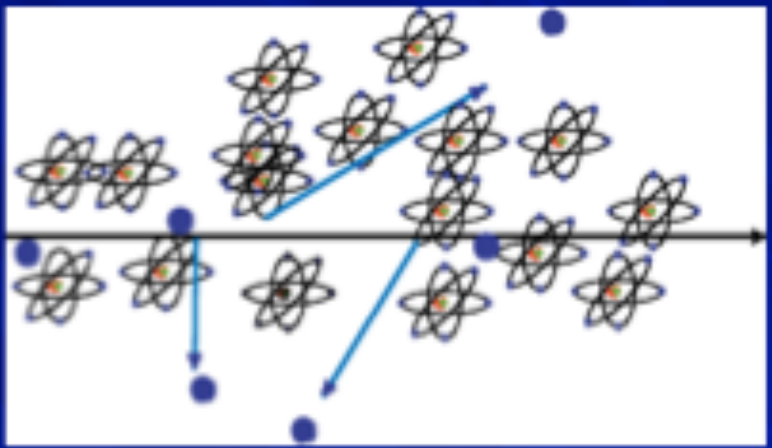
- By measuring the radius of curvature we can determine the momentum of a particle
- If we can measure also β independently we can determine the particle mass.

$$\rho = \frac{p_T}{q|B|} = \frac{\gamma m_0 \beta c}{q|B|}$$

Signal creation

- Charged particle traversing matter leave excited atoms, electron-ion pairs (gases) and electrons-hole pairs (solids)

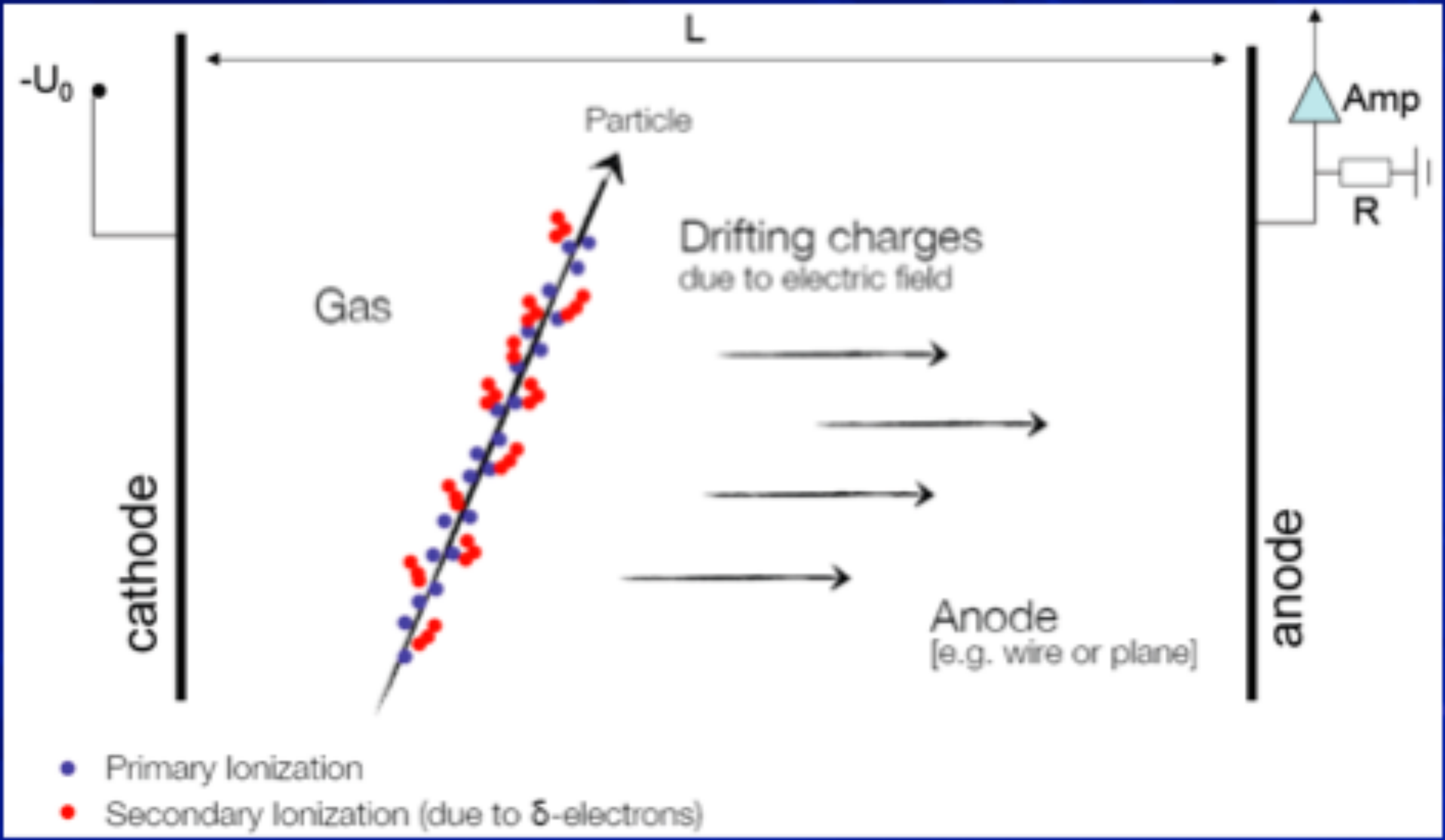




- Excitation: The photons emitted by the excited atoms in transparent materials can be detected with photon detectors

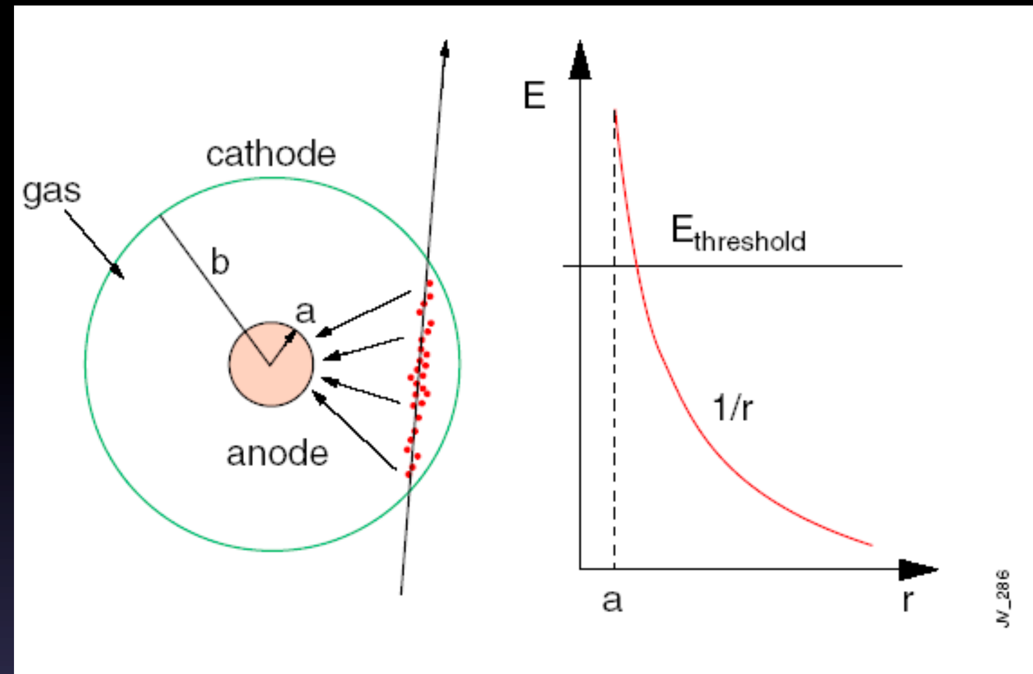
- Ionization: By applying an electric field in the detector volume, the ionization electrons and ions can be collected on electrodes and readout

Gas Detectors: primary



Proportional counter

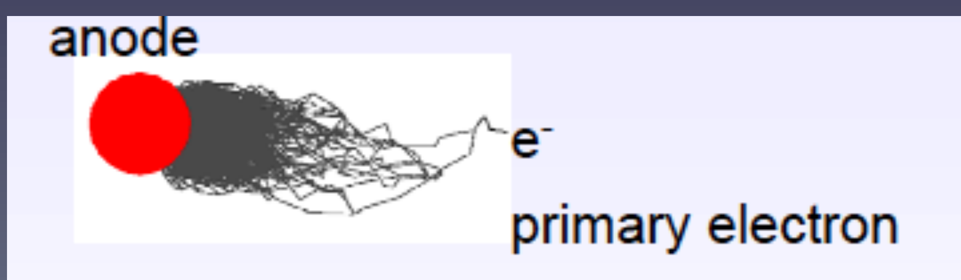
- Cylindrical proportional counter:
  - Single anode wire in a cylindrical cathode
  - e^-/ions drift in the volume



$$E = \frac{V_0}{r \ln(a/b)}$$

- V_0= potential between anode and cathode
- Close to wire (diameter 10 μm) E-field very large (> 10 kV/cm) kinetic energy of the electrons becomes very large → can produce secondary ionization

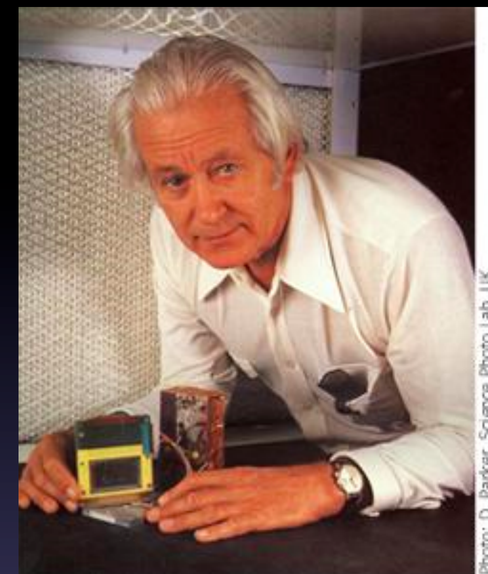
$$\Delta T_{kin} = e\Delta U$$

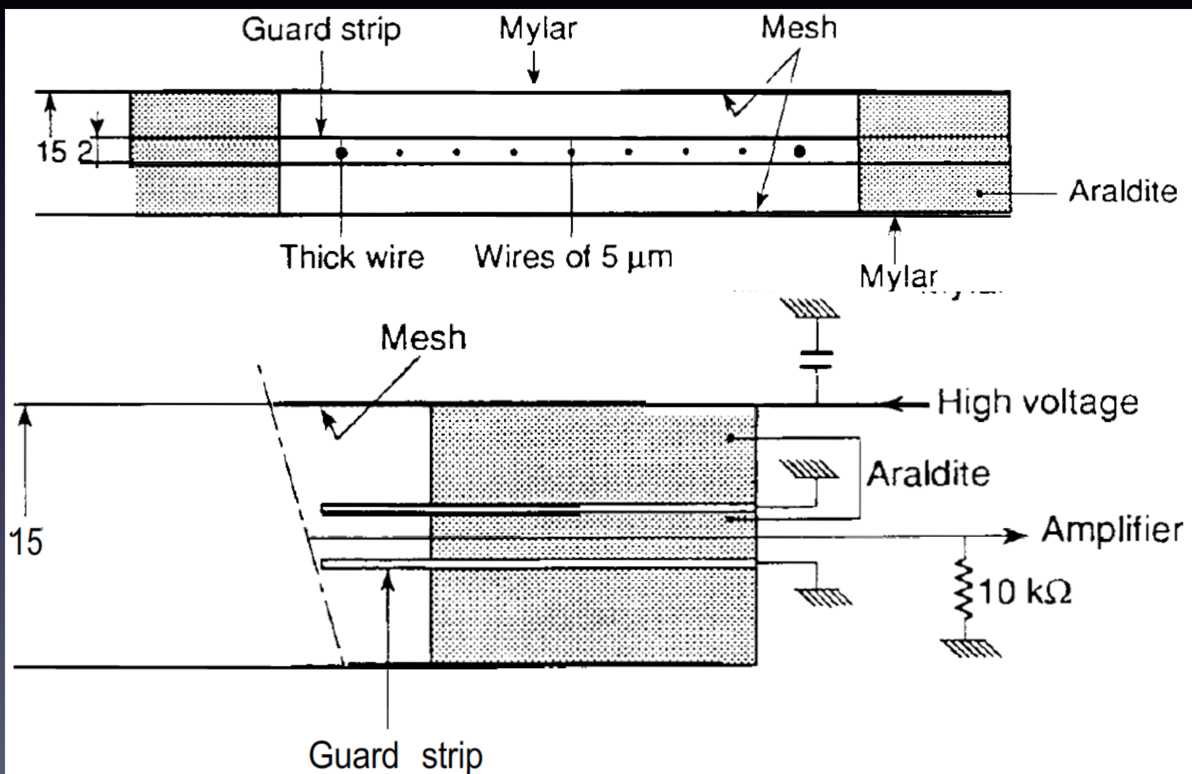


Multiwire proportional chambers

- A proportional counter does not provide the position of the incident particle
- Charpak developed of multi-wire proportional chamber

G. Charpak Nobel price ('92)



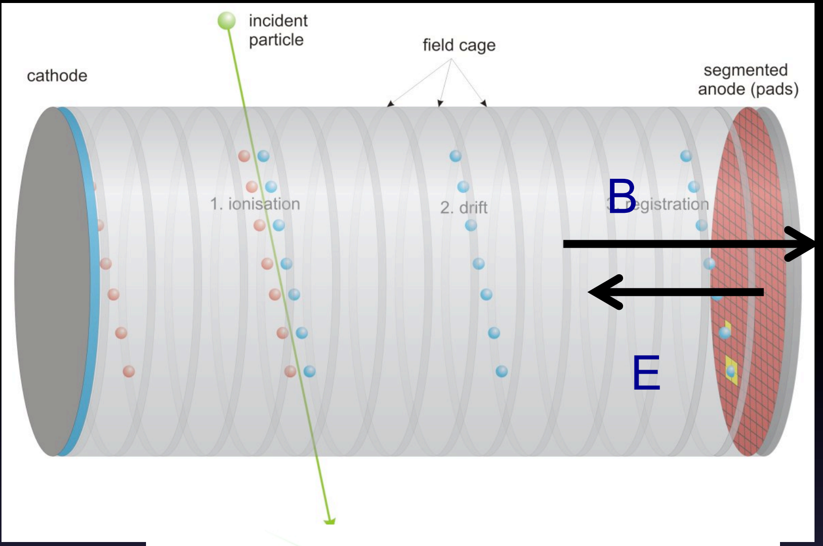


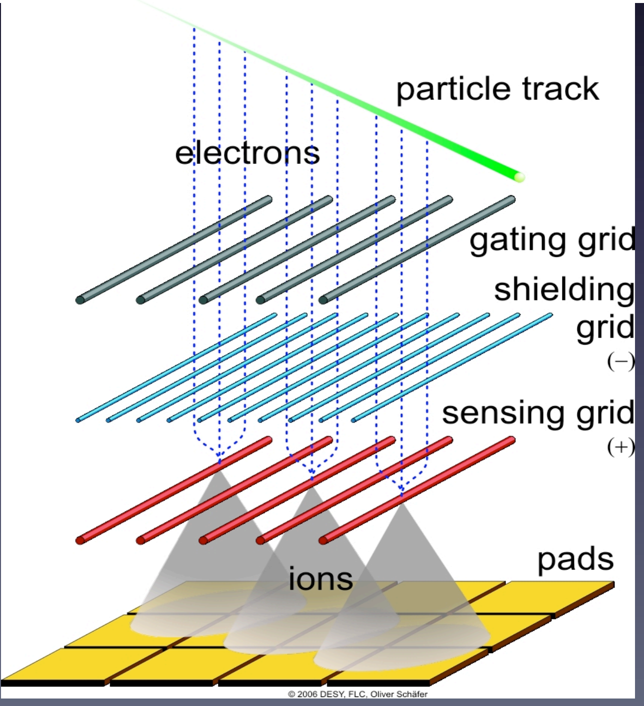
Construction details of the original design of Charpak's multi-wire chambers (from Nobel lecture)

Anode wire =20μ diameter
d=2 mm

Time Projection chamber (TPC)

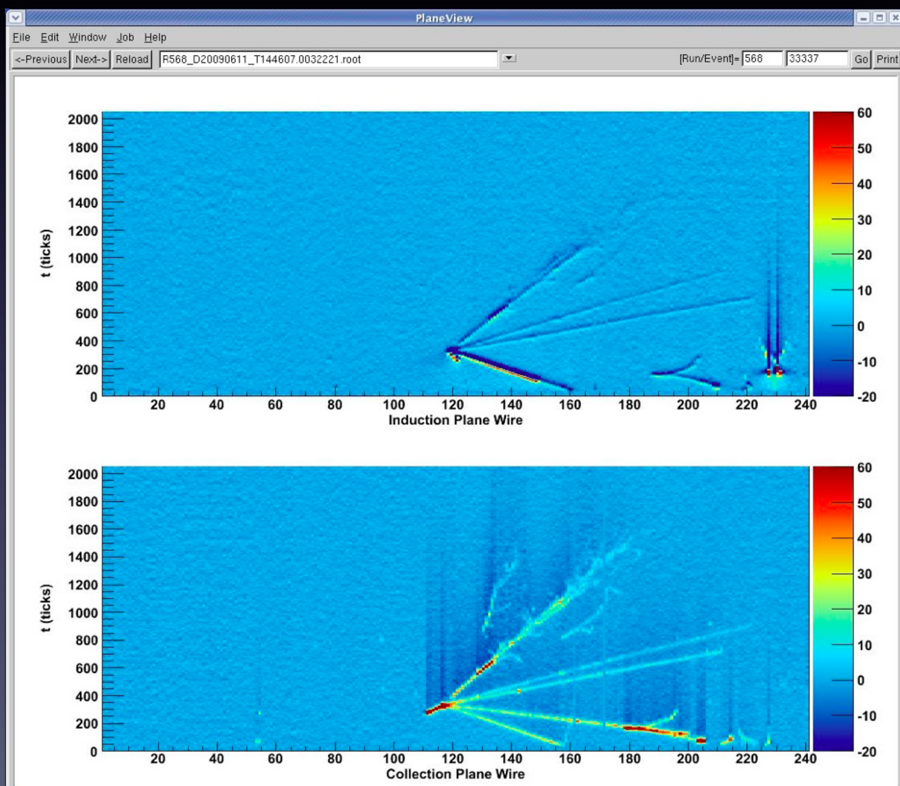
- D.R. Nygren in 1976
- Full 3-D reconstruction
  - XY: MWPC and pads of MWPC at the endcap
  - Z: from drift time measurement (several meters)
    - Field cage for very homogenous electric field
- Typical resolution
  - z and y ≈mm, x=150-300 μm
  - dE/dx ≈5-10%
- Advantages:
  - Complete track information → good momentum resolution
  - Good particle ID by dE/dx
- Challenges
  - Long drift time limited rate
  - Large volume (precision)
  - Large voltages (discharges)
  - Large data volume
  - Difficult operation at high rate





Liquid Argon TPC as a bubble Chamber

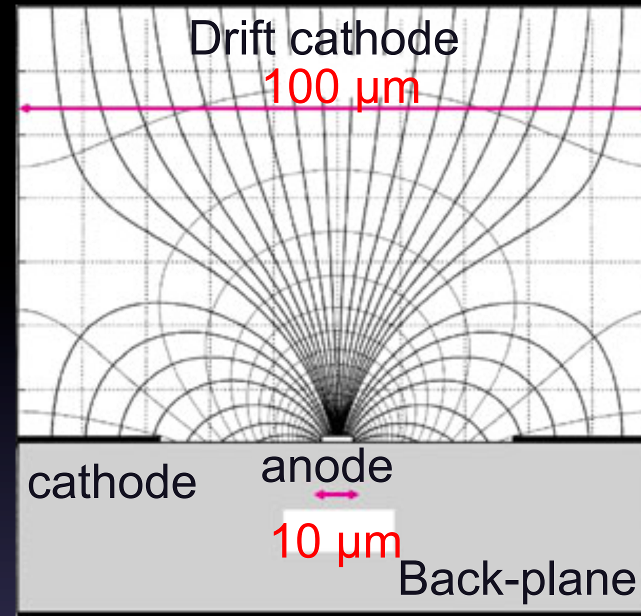
- LAr provides a dense target for neutrinos and for ionization/ Scintillation detection.
- Particle identification comes primarily from dE/dx (energy deposited) along track.
  - Wire spacing ≈ mm and digital sampling provides fine-grained resolution
  - Photons and Electrons can be cleanly separated
- Ideal for neutrino experiments

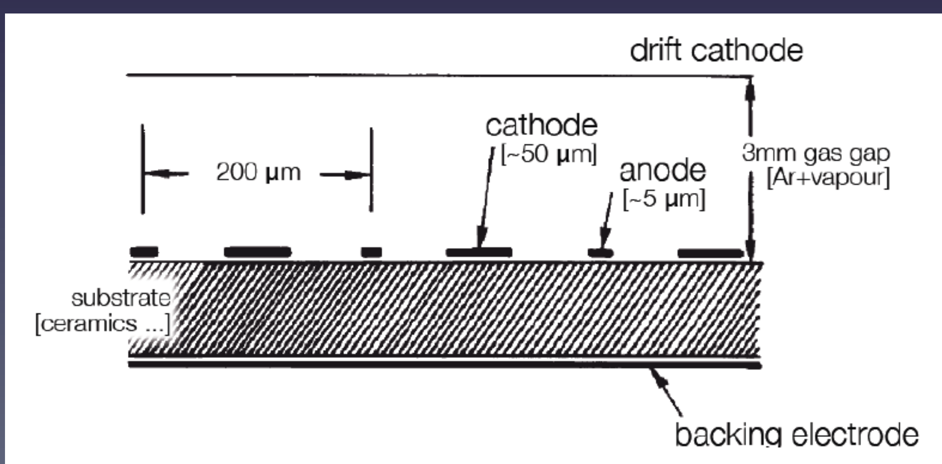


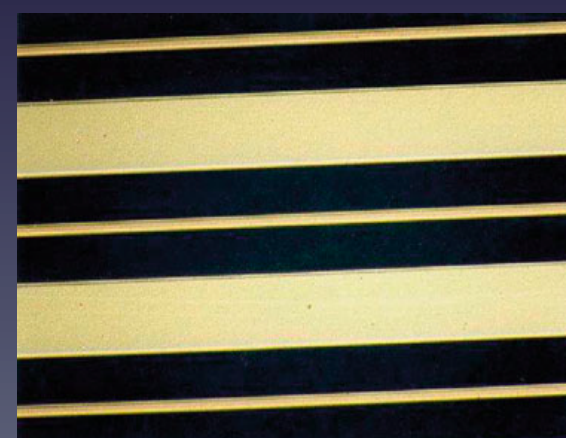
- Microboone and LBNF neutrino experiments

Micro-strip gas chambers (MSGC)

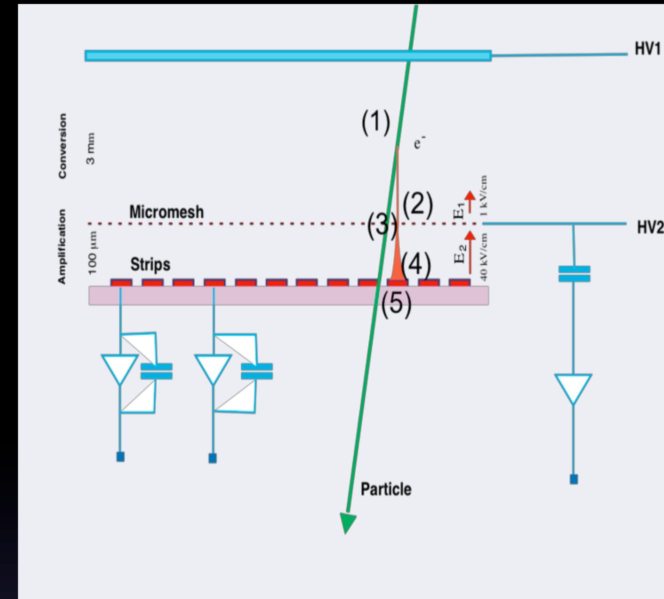
- Replace wires with electrodes on printed circuit board
- Photolithography techniques allow 100 **μ**m pitch
  - Higher granularity over wire chambers
  - High-rate capability **>10^{6}** Hz/mm^{2}
  - Excellent spatial resolution (~30**μ**m)
  - Time resolution in the ns range.
- MSGC were first developed in 1990s
  - Initial problems sparks and anode destruction



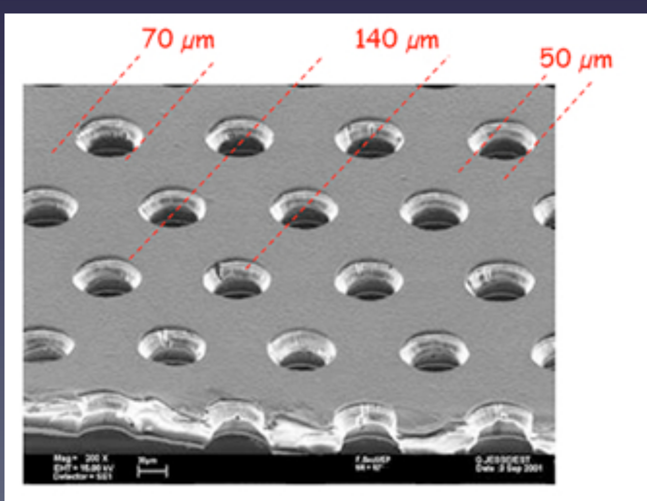


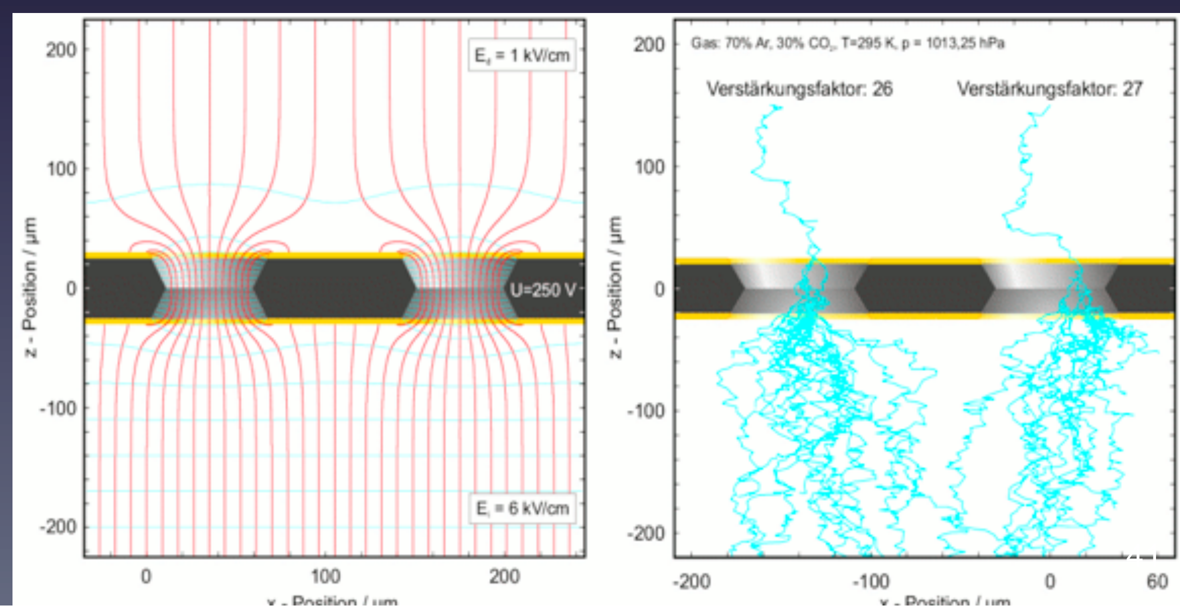


Micromegas and GEM

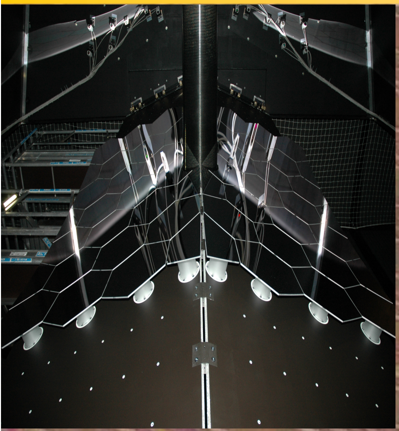


- Micromegas
  - Gas volume divided in two by metallic micro-mesh
  - Gain = 10^4 and a fast signal of 100ns.
- GEM (Gas Electron Multipliers, Sauli 1996)
  - Thin insulating Kapton foil coated with metal film
  - Chemically produced holes pitch ≈100 µm
  - Electrons are guided by high drift field of GEM which generates avalanche
    - Electric field strength is in the order of some 10 kV/cm
    - Avalanche gain of 100 – 1000



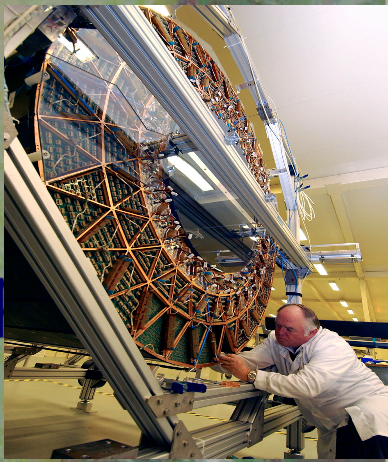


Example: Gaseous Detector in the LHC Experiments



ALICE: TPC (tracker), TRD (transition rad.), TOF (MRPC), HMPID (RICH-pad chamber), Muon tracking (pad chamber), Muon trigger (RPC)

ATLAS: TRD (straw tubes), MDT (muon drift tubes), Muon trigger (RPC, thin ga chambers)

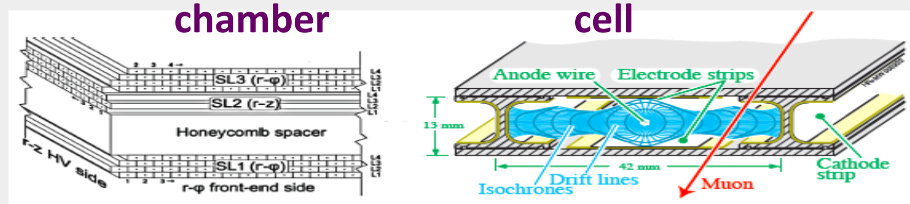


CMS: Muon detector (drift tubes, CSC), RPC (muon trigger)

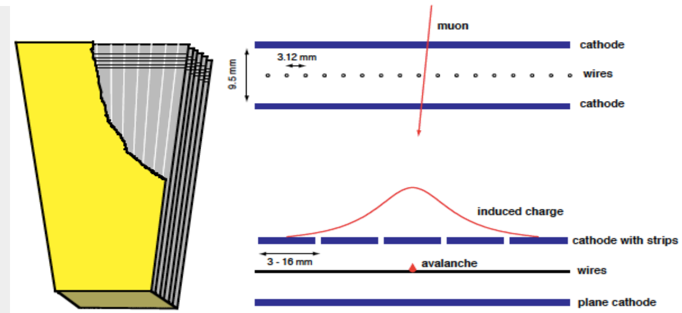
LHCb: Tracker (straw tubes), Muon detector (MWPC, GEM)

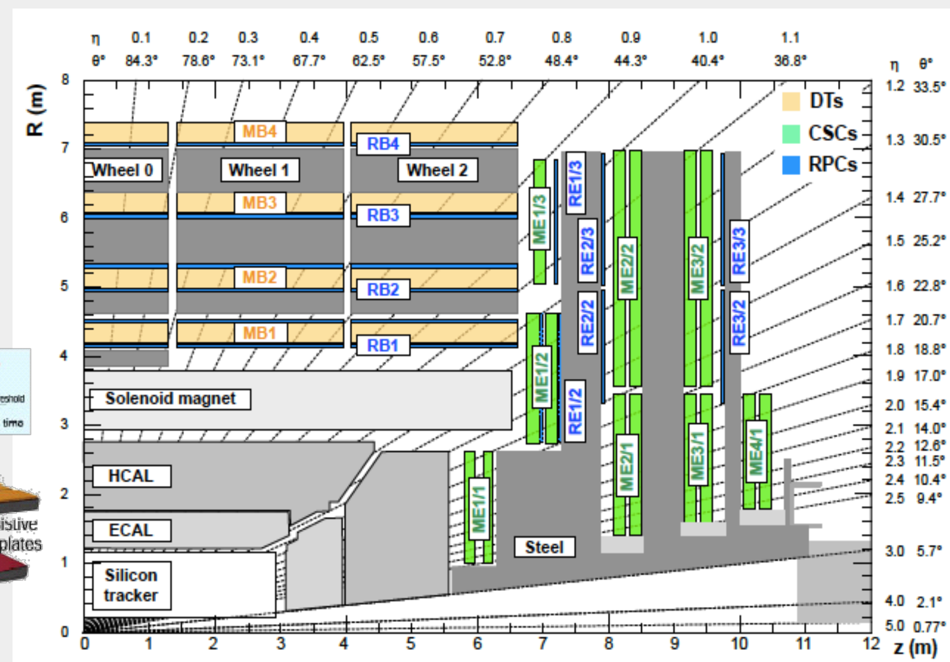
CMS Muon System

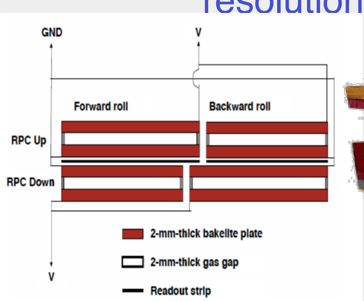
- Drift Tubes (DT) IηI< 1.2
  - 4 stations/wheel
  - cell 42x13 mm^2
  - gas mixture 85% Ar, 15% CO_2
  - drift velocity ~ 55 µm/ns, maximum drift time ~ 400 ns
  - Time resolution <3 ns, spatial ~100 µm
- Cathode Strip Chambers (CSC) 0.9<IηI< 1.2 (MWPC)
  - 1 CSC has 6 layers, strips measure r-ϕ, wires radial
  - gas 50% CO_2, 40% Ar, 10% CF_4
  - 4 stations subdivided in rings
  - Time resolution ~3ns, spatial 50-150 µm
- Resistive Plate Chambers (RPC) IηI< 1.6
  - Double-gap chambers in avalanche mode
  - gas 95.2% Freon, 4.5% isobutane
  - Triggering redundancy, time resolution < 3 ns (spatial ~ 1cm)

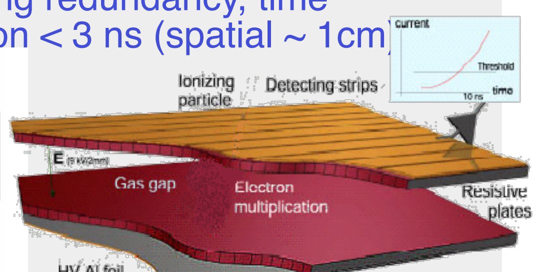


$$x_{hit} = t_{drift} \cdot v_{drift} \equiv (t_{TDC} - t_{ped}) \cdot v_{drift}$$









New dry gas plant

Summary about Gaseous Detectors

- **Gaseous detectors are still the first choice whenever the large area particle detection and medium precision measurements is required**

- **Advances in photolithography and micro-processing techniques in the chip industry during the past decade triggered a major transition in the field of gas detectors from wire structures to micro-pattern devices.**

- **MPGDs became a wide-spread tool for experiments at the ENERGY, INTENSITY and COSMIC FRONTIERs: for high-rate tracking over large sensitive areas, precision reconstruction of charged particles in the TPC, X-ray, UV and visible photon detection and neutron spectroscopy.**

- **Industrial methods of MPGD production allows to extend technology to ~ m^2 unit detectors → many potential MPGD applications within the HEP and beyond**

- **Modern, sensitive & low noise electronics (e.g. Timepix CMOS chip, etc …) will enlarge the range of applications**

MPGD = MultiPaternGAsDetector

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A semiconductor detector is also called a solid state detector.

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Semiconductor detectors are used for:

- ***Nuclear Physics***

Energy measurement of charged particles (MeV range), gamma spectroscopy (precise determination of photon energy)

- ***Particle Physics:*** Tracking or vertex detectors, precise determination of particle tracks and decay vertices

- ***Satellite Experiments***

Tracking detectors

- ***Industrial Applications***

Security, Medicine, Biology,...

Tracking and Vertex Detectors

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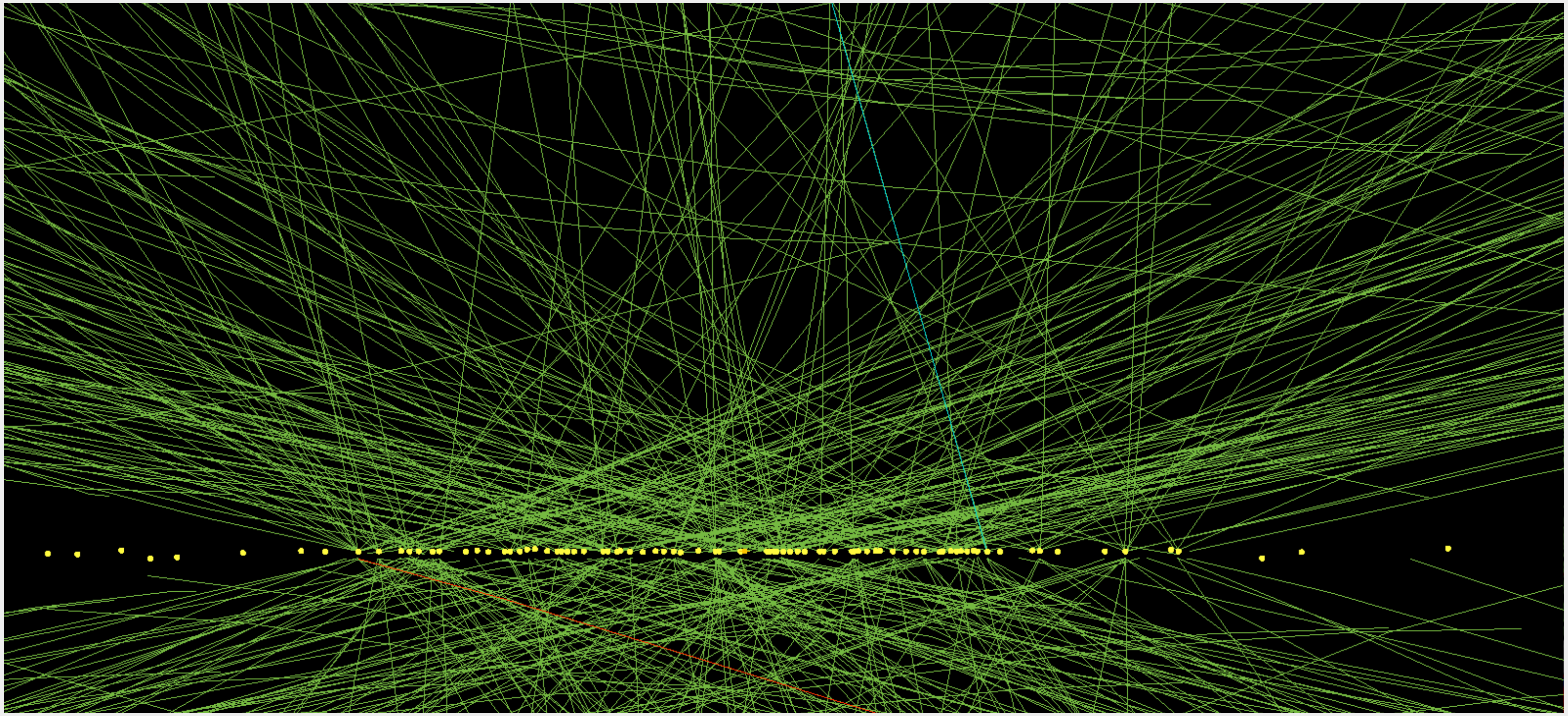

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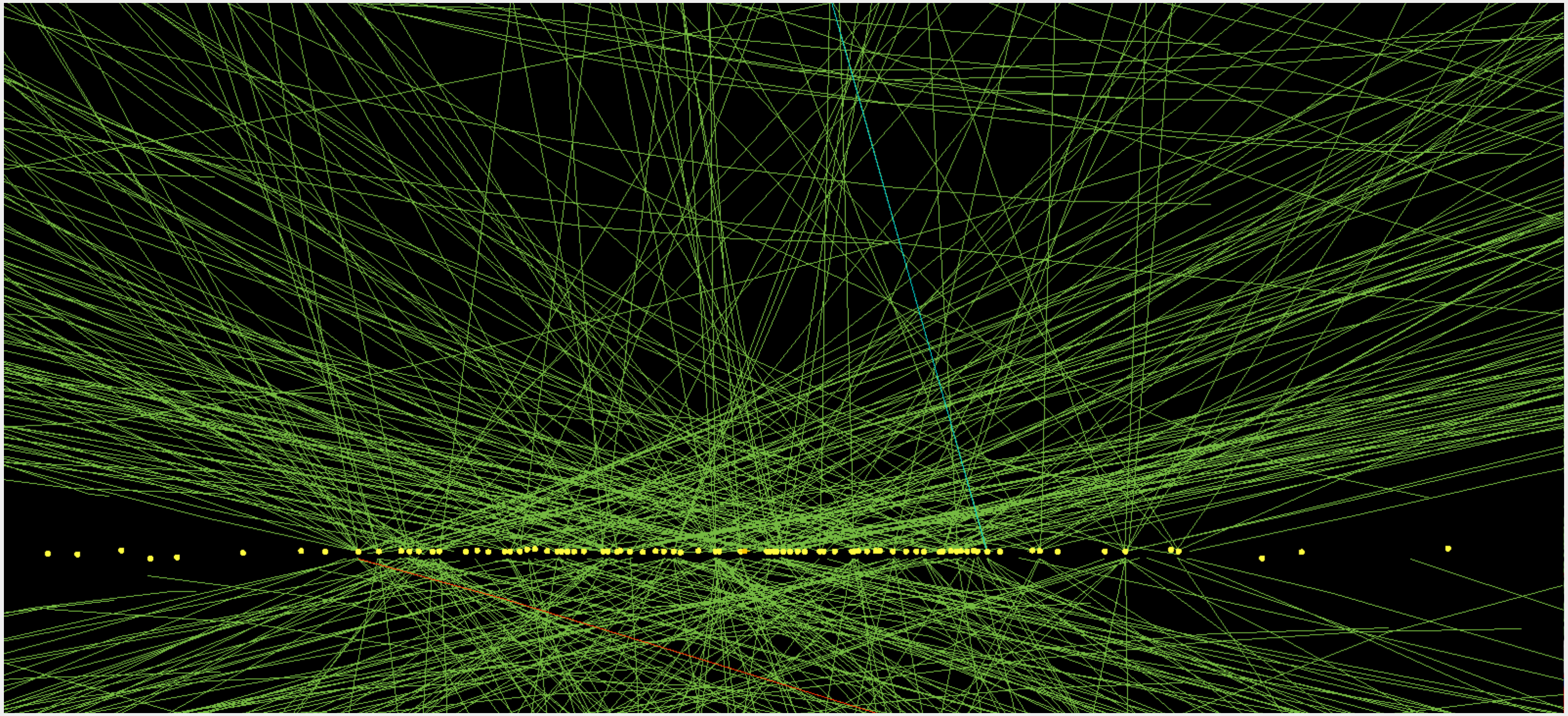

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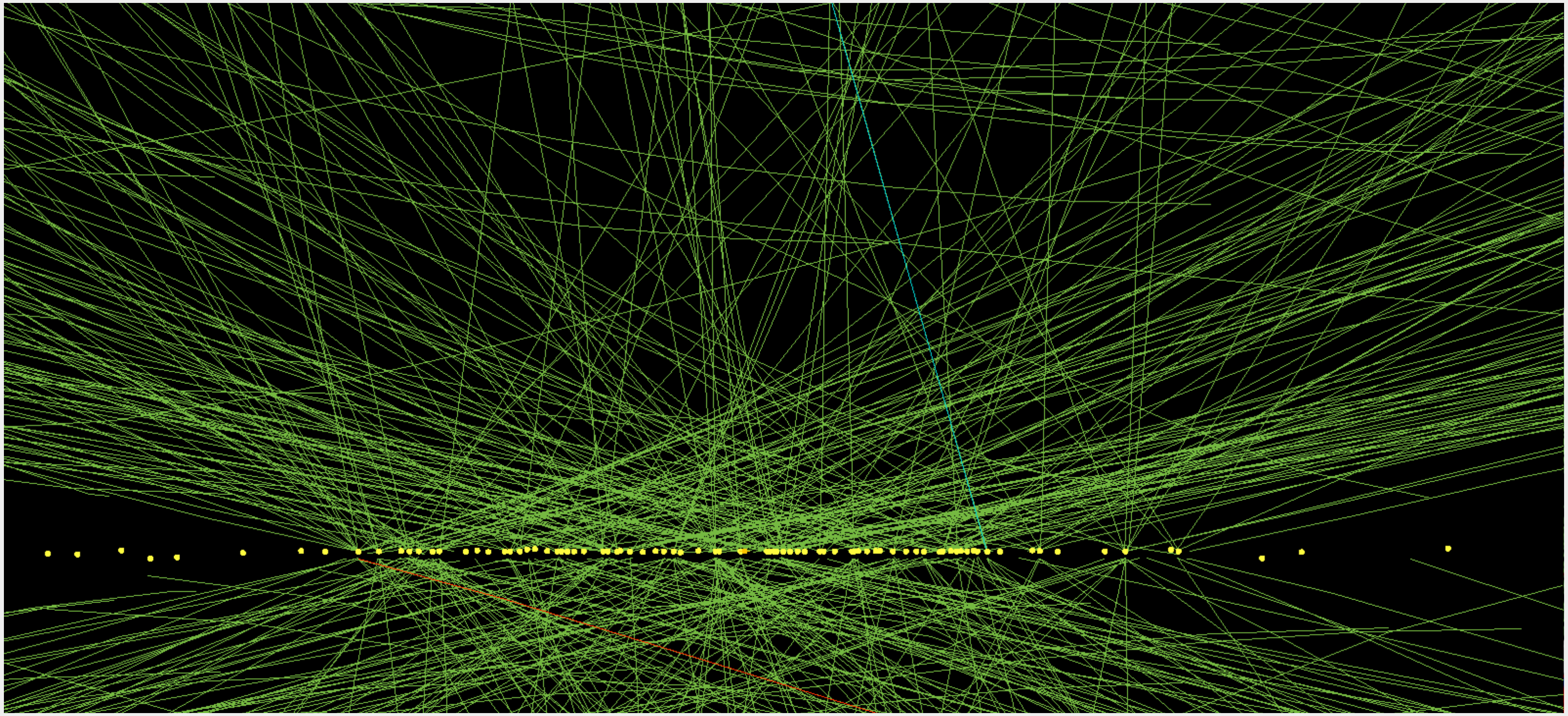

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For More on silicon detector see lectures of V. Manzari

Solid state detectors

Even if new strips ***gas detector*** now stands the high flux, ***alternative is solid state detectors*** :

- Solid state detectors have been intensively used for low energy measurement
- Used as position measurement detectors

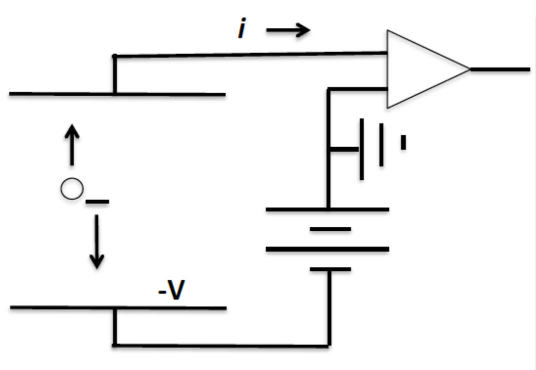
Advantages : (example of Si)

- High radiation hardness
- Can accept very large flux and very small segmentation
- Rigid detectors so self "supporting structures"
- Energy to create e-/hole pair is very low 3.6 eV (1/10 of gas)
- High density 2.33 g/cm2 . dE/dx per track is 390 eV/µm
  - 108 e/h pairs
  - High mobility : 1450 cm2/Vs for electron and 450 for holes
  - small size and fast signal
- ***Very good single point accuracy***

Disadvantages : No charge multiplication , no continuous tracking

- Needs cooling system to operate at low temperature (less radiation effect)
- High density : radiation length before calorimeter
- Cost but less true taken into account the large area produced for LHC

Solid state detectors



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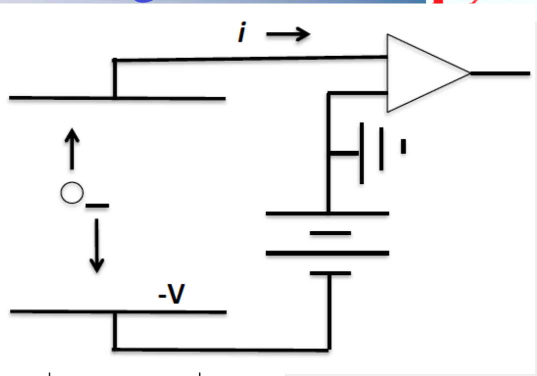

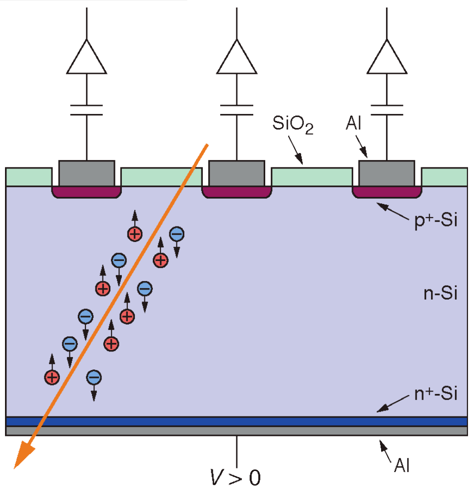

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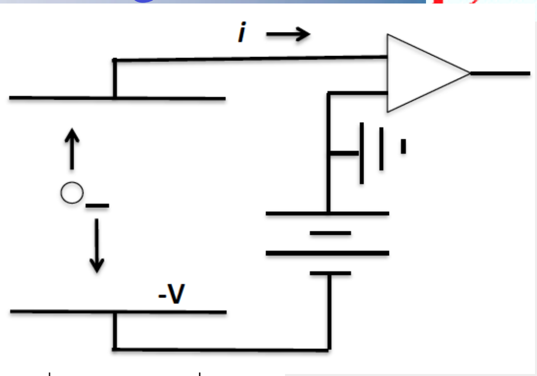

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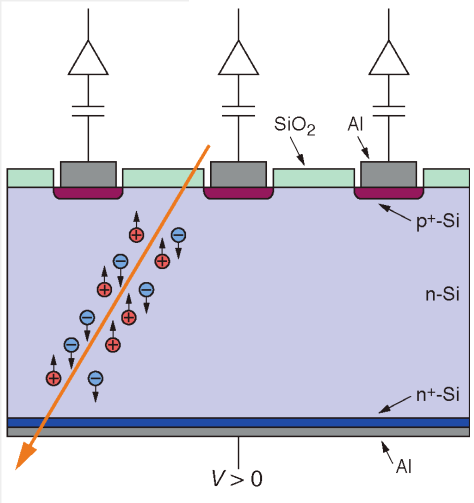
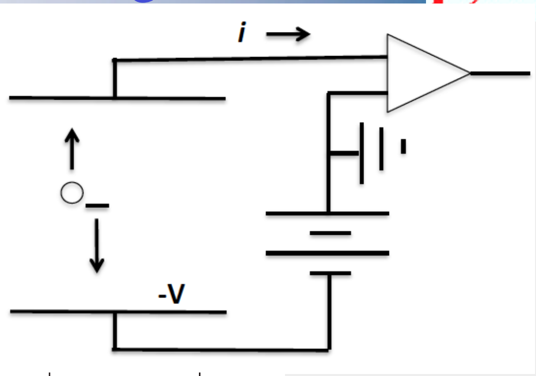


- By segmenting the implant we can reconstruct the position of the traversing particle in one dimension
- Standard parameters :
    - Strips p implants
    - Substrate n doped (~2-10 kOcm) and ~300µm thick
    - Vdep < 200 V
    - Backside Phosphorous implant to establish ohmic contact and to prevent early breakdown

Solid state detectors



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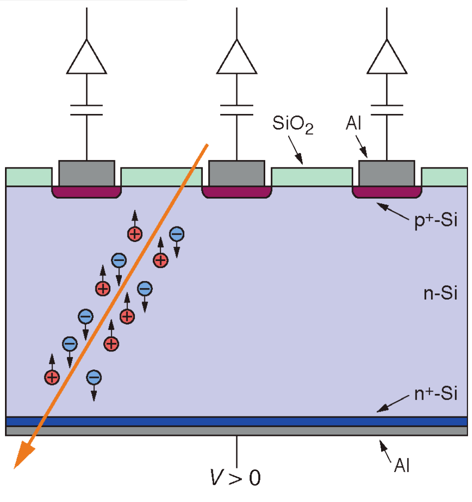

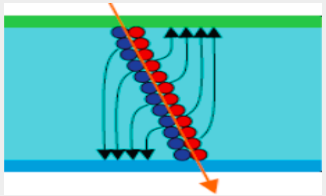

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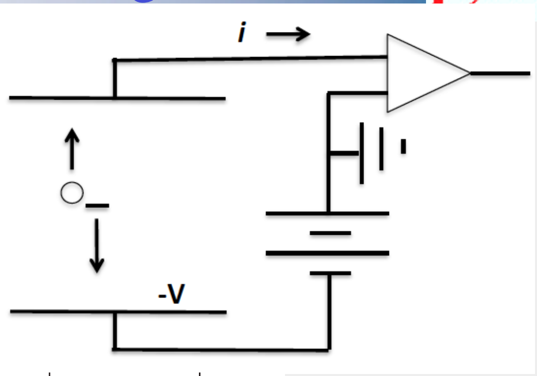

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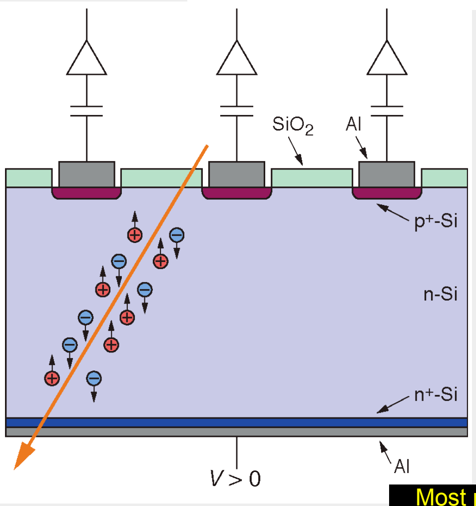

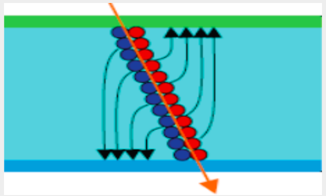

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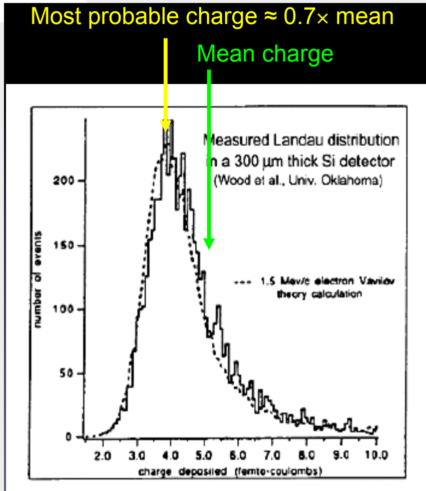

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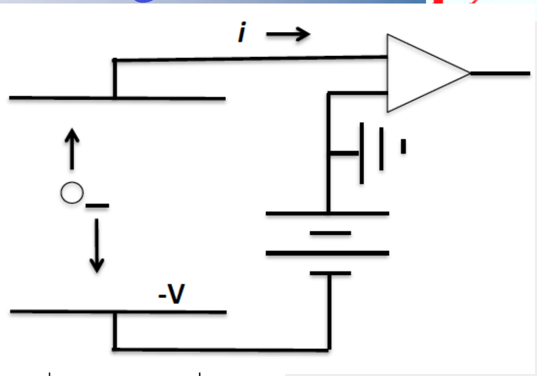

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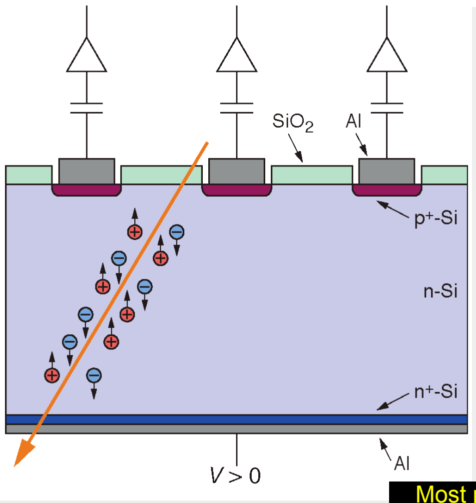
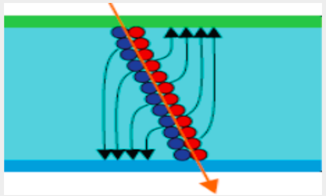
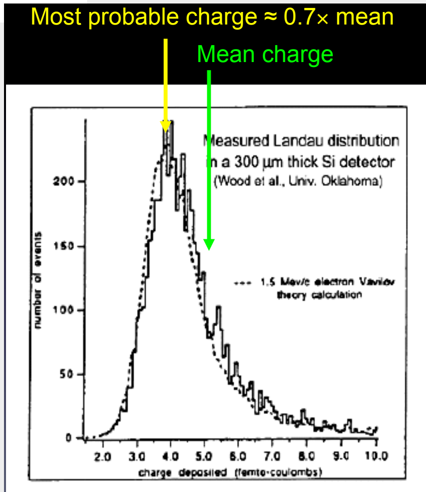




- The signal generated in a silicon detector depends on th thickness of the depletion zone and on the dE/dx of the particule.
  - the distribution is given by a Landau distribution

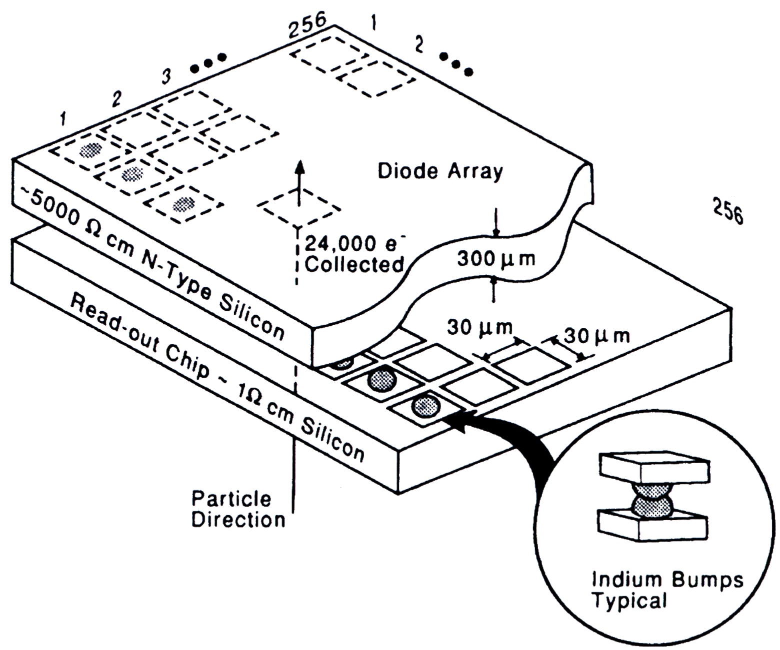


Detail of bump bond connection

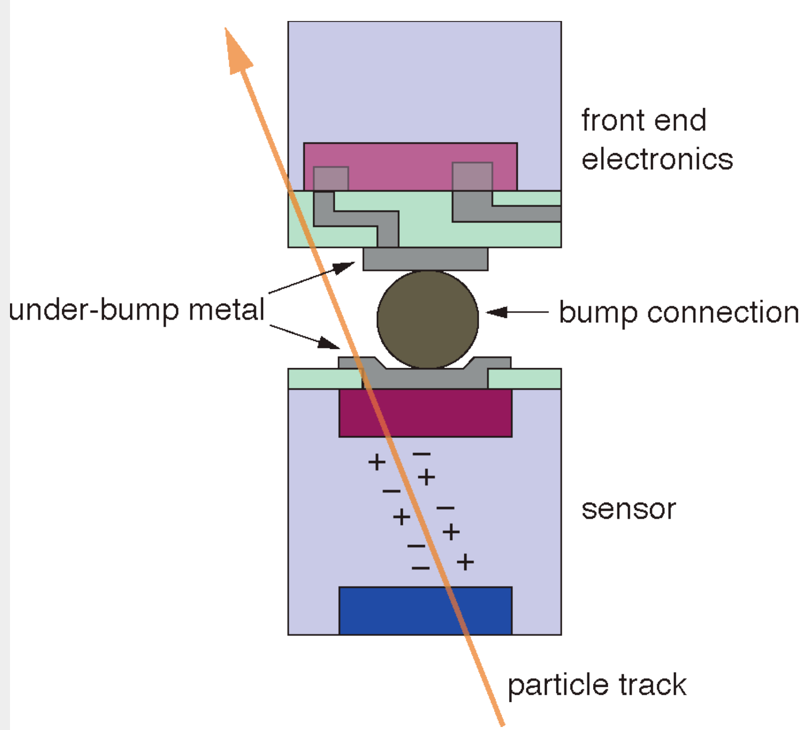
Bottom is the detector, on top the bump bonds make the electrical connection for readout chip:.

Principle

“Flip-Chip” pixel detector: On top the Si detector, below the readout chip,each pixel.



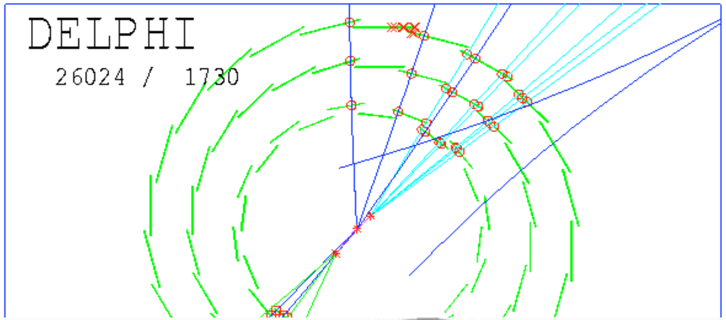
S.L. Shapiro et al., *Si PIN Diode Array Hybrids for Charged Particle Detection*, Nucl. Instr. Meth. A **275**, 580 (1989)

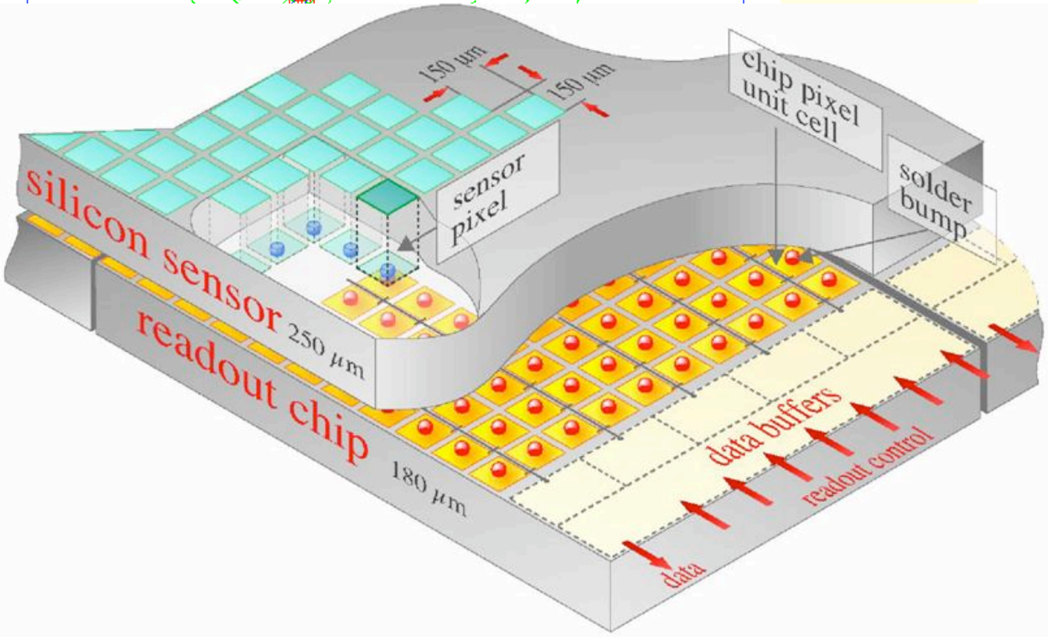


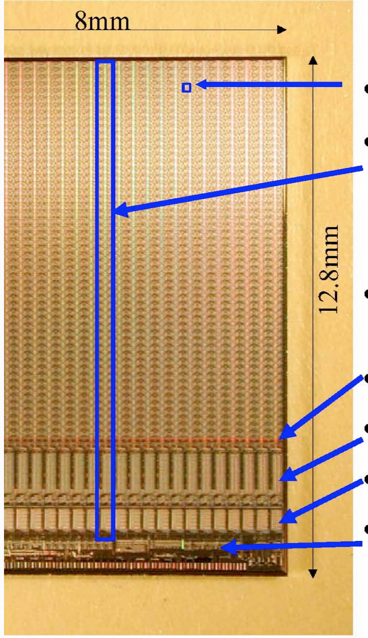
L. Rossi, *Pixel Detectors Hybridisation*, Nucl. Instr. Meth. A **501**, 239 (2003)

Silicon pixel detectors

Silicon sensors and readout electronics with same geometry. First detectors end of 80' (Delphi, H1, Aleph....). Now an unavoidable detectors if one wants to perform b tagging.







PSI43

- 150 µm x 150 µm pixel
- 52x53 pixels in 26 double columns
  345 k transistors

- Periphery:
  78 k transistors
- Pixel−column interface
- Data buffers (4x24 capacitors)
- Timestamp buffers (8x8 bits)
- I2C, DACs, regulators, counters, readout, wirebonds
  6 k transistors

The CMS Silicon Detector

The Concept

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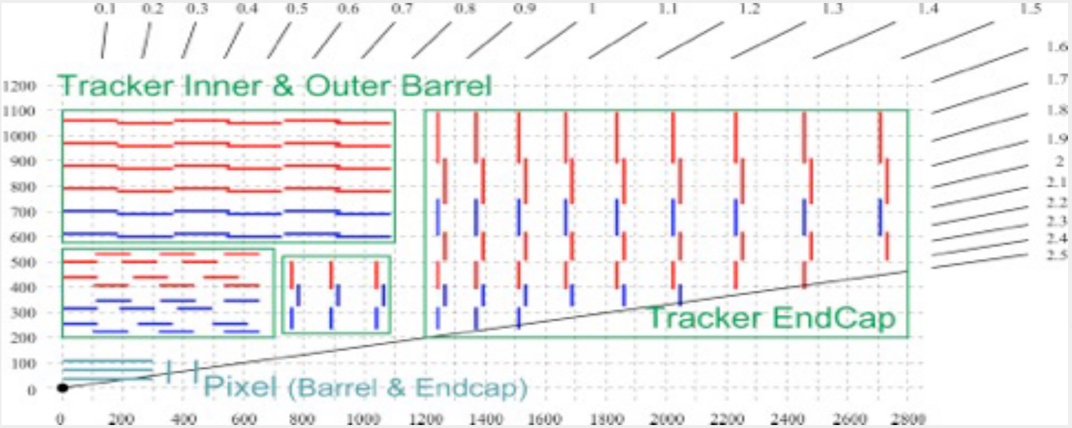
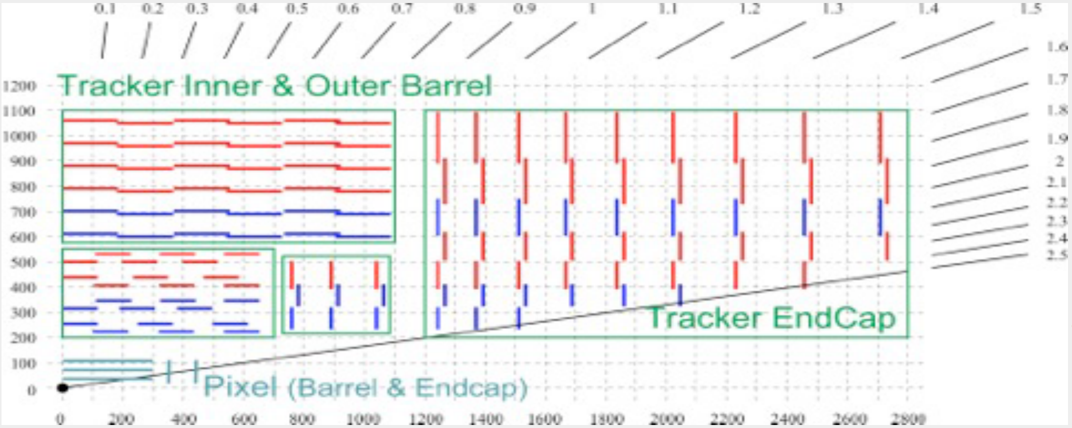


The CMS Silicon Detector

The Concept

Rely on "few" measurements layers, each able to provide robust (clean) and precise coordinate determination



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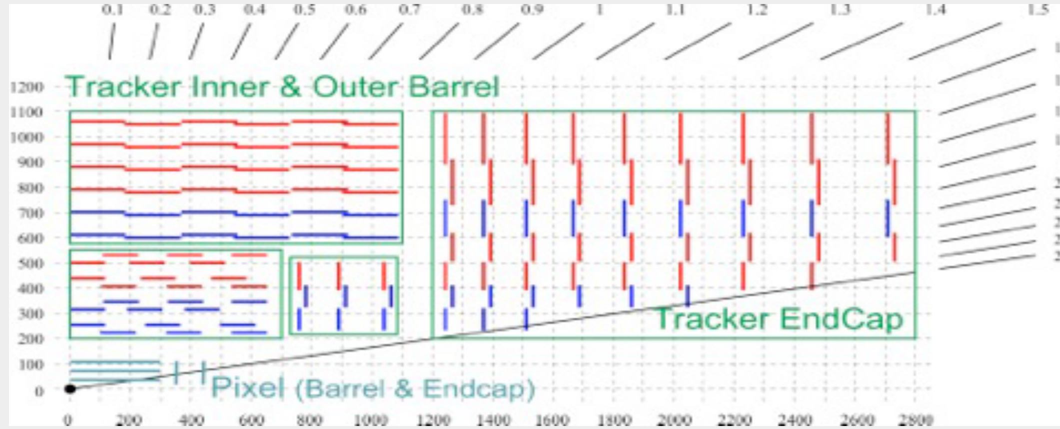

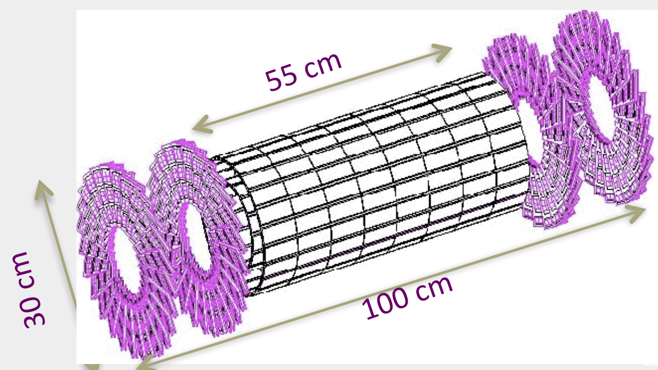

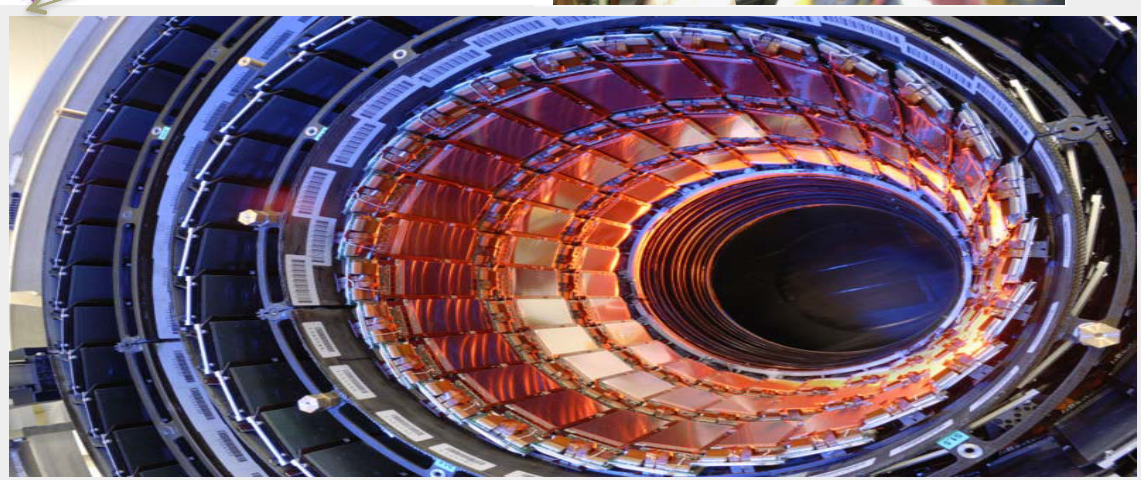

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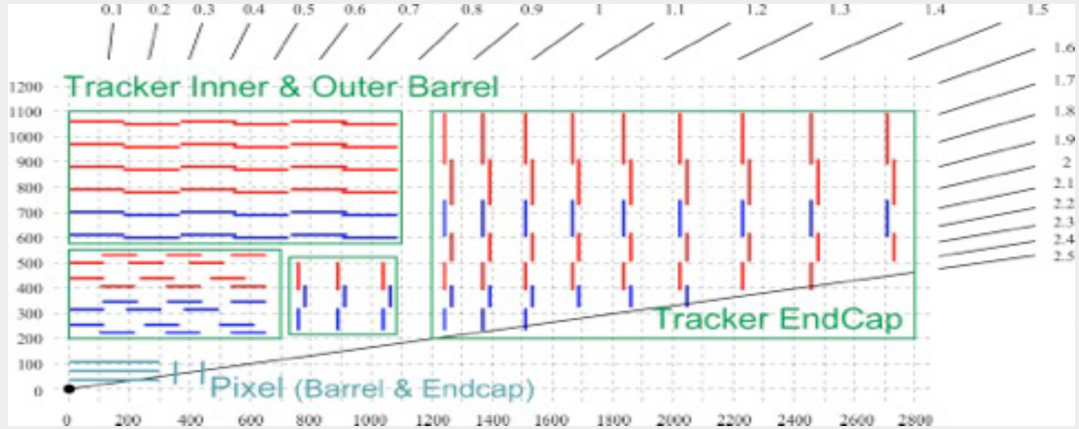
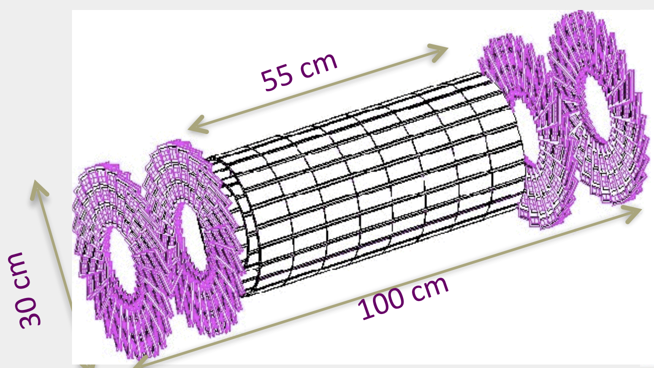
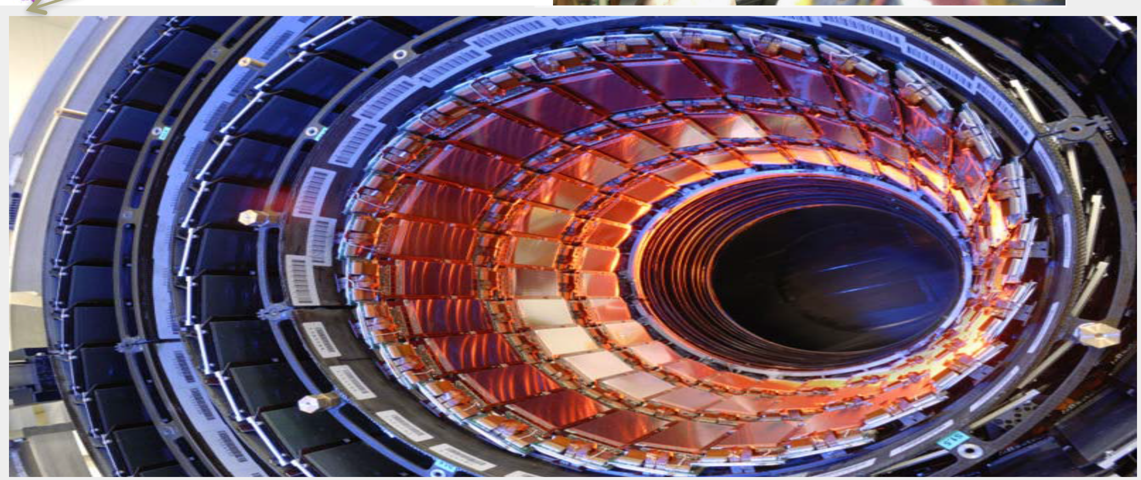


- Largest silicon tracker ever built
  - Radius 110 cm, Length 540 cm
  - Barrel : 13 cylinders (3 pixels)
  - Endcaps : 14 disks (2 pixels) on each side
  - Covers Iηl<2.5





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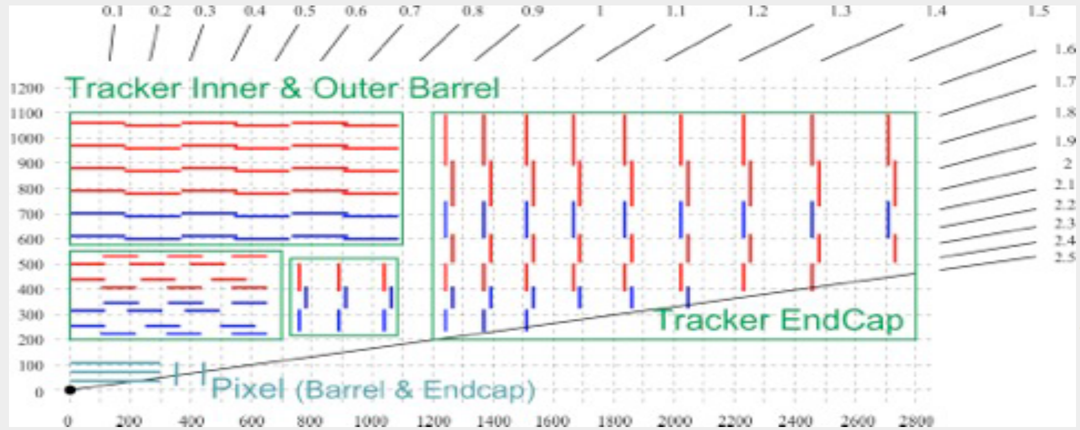

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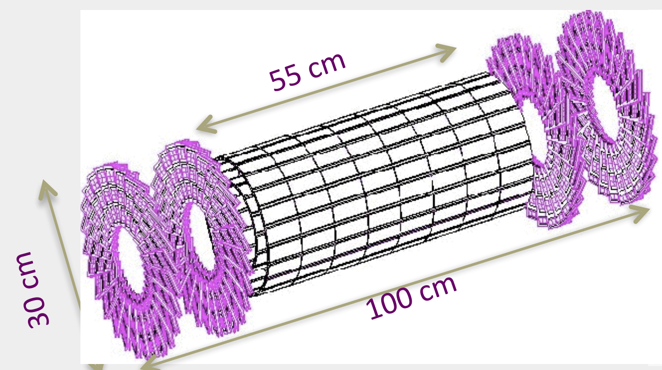
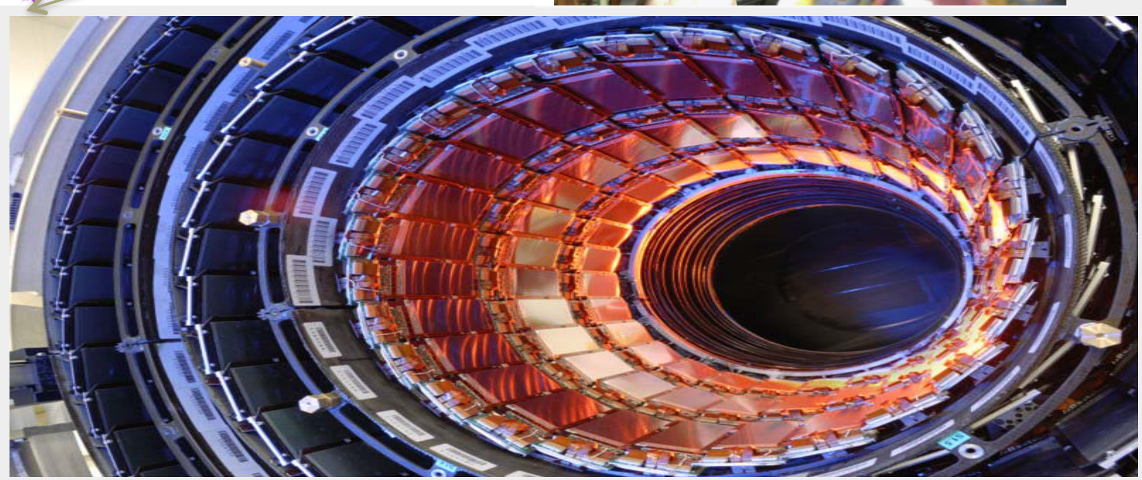


- Pixels: 66M "n+ in n" design
  - 100 x 150 μm² (3D position)
  - 285 μm thick
  - Each Read Out Chip (ROC) reads 80x52 pixels
  - Analog readout:

    improved position resolution from charge sharing



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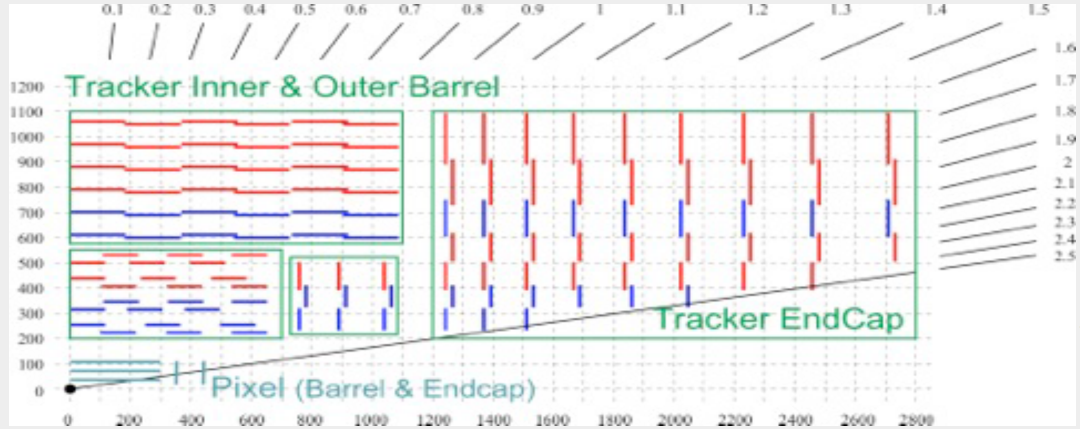
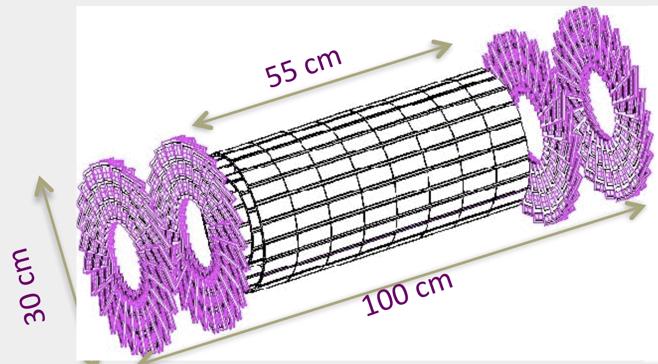
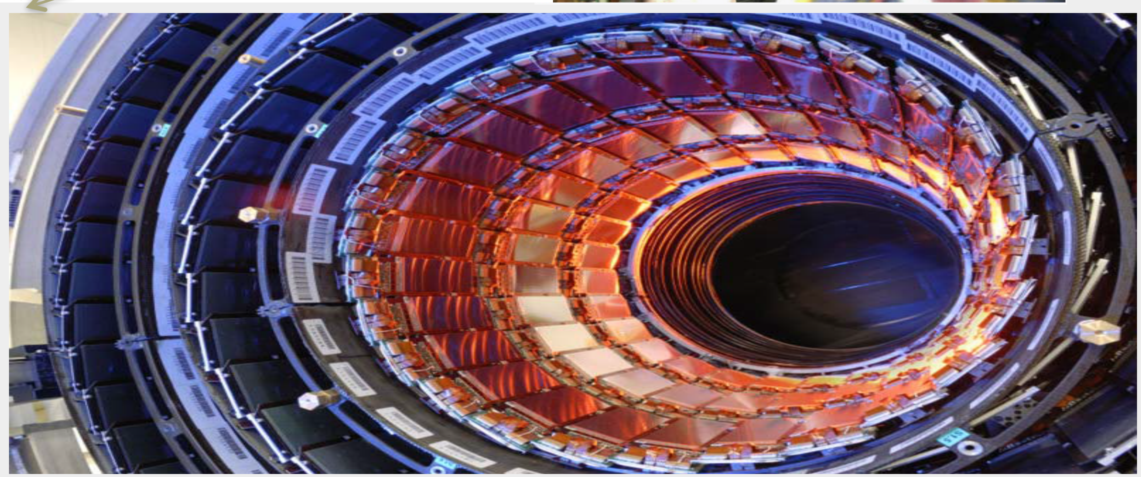


- Largest silicon tracker ever built
  - Radius 110 cm, Length 540 cm
  - Barrel : 13 cylinders (3 pixels)
  - Endcaps : 14 disks (2 pixels) on each side
  - Covers IηI<2.5



- Pixels: 66M "n+ in n" design
  - 100 x 150 µm^2 (3D position)
  - 285 µm thick
  - Each Read Out Chip (ROC) reads 80x52 pixels
  - Analog readout:

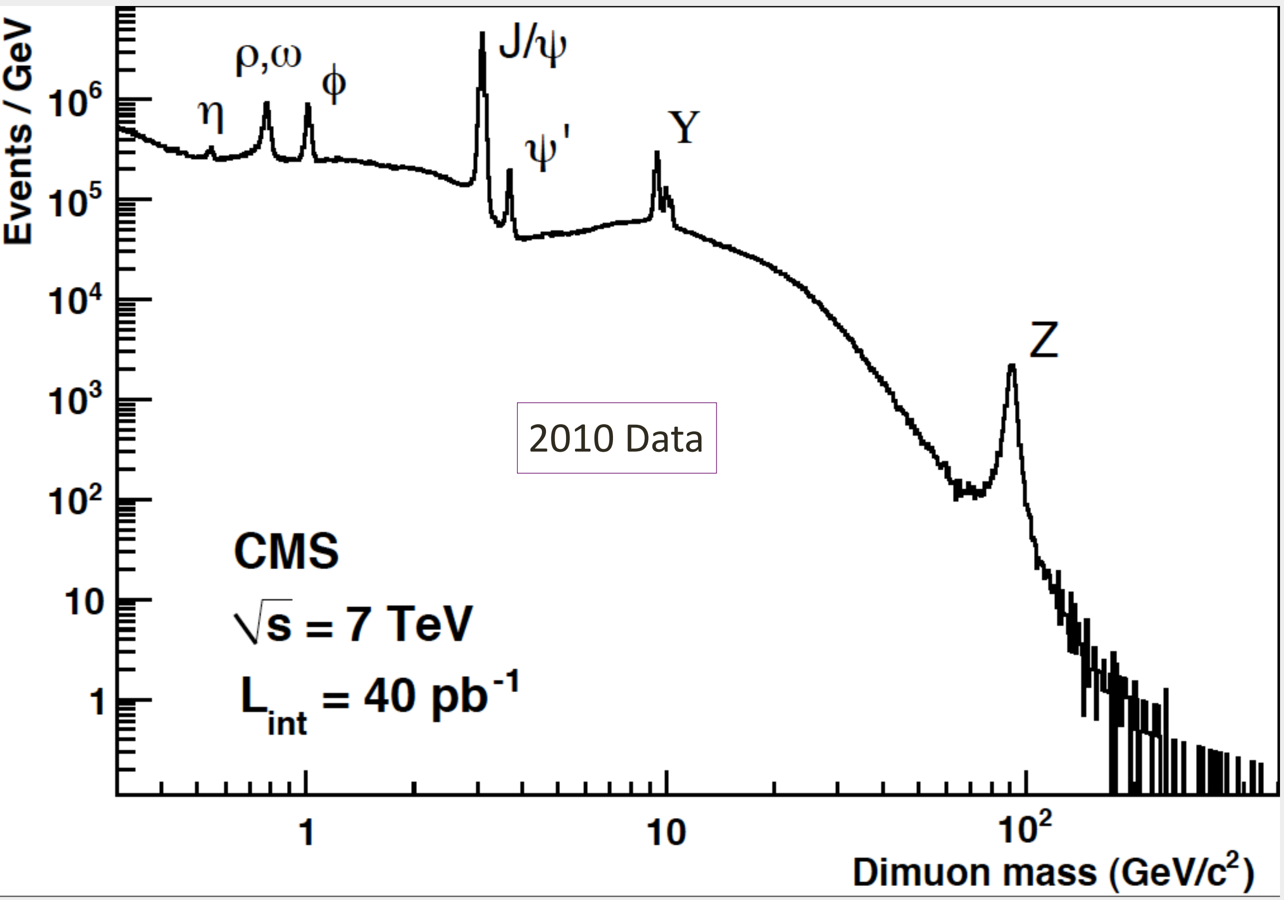
    improved position resolution from charge sharing



- Strips: 9M : "p+ in n" sensors
  - Pitch: 80 to 205 µm (r-ϕ)
  - Thickness: 320 or 500 µm
  - Stereo layers associate back to back 2 microstrip detectors with a relative 100 mrad angle, providing 2D resolution
  - Analog readout

Tracking and Vertex Performance

- Excellent final tracking performance for physics



And excellent muon trigger too!

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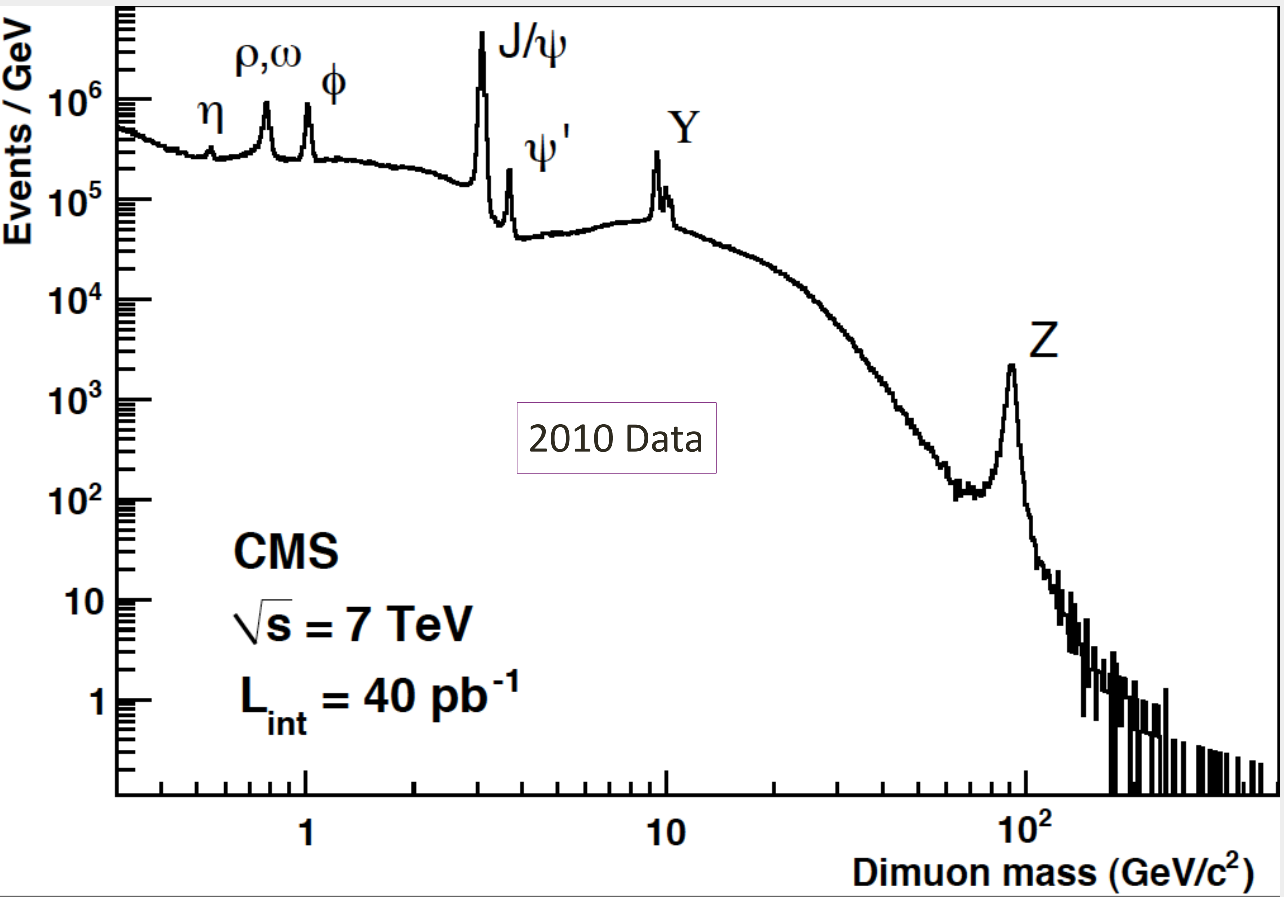
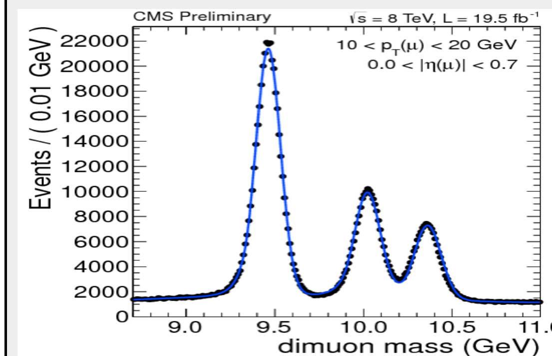


2012 Data



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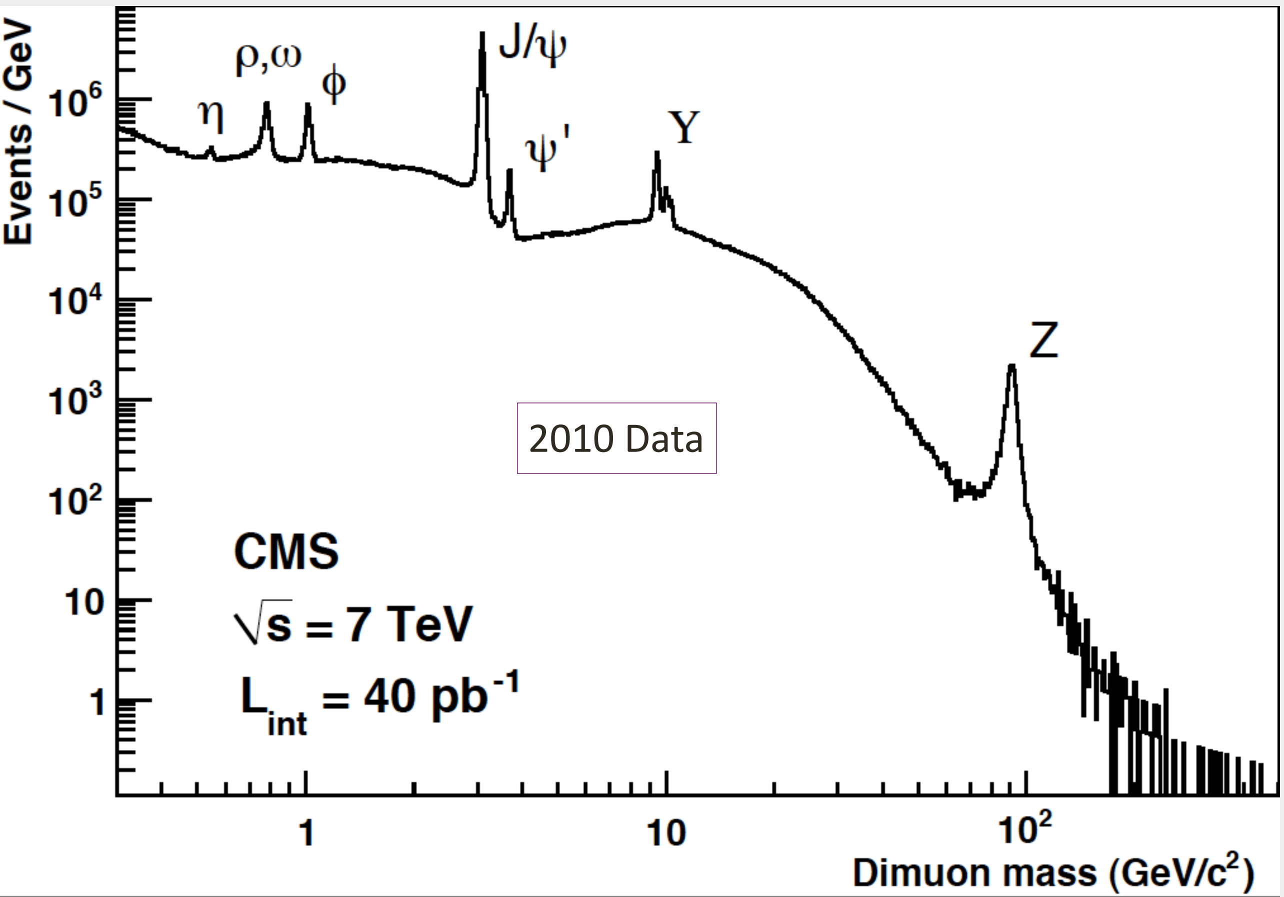

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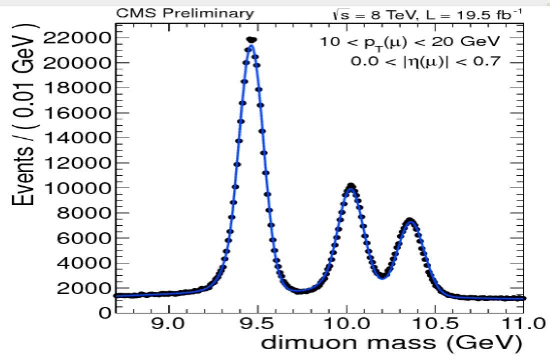
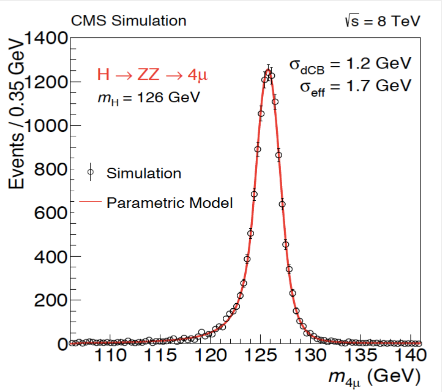


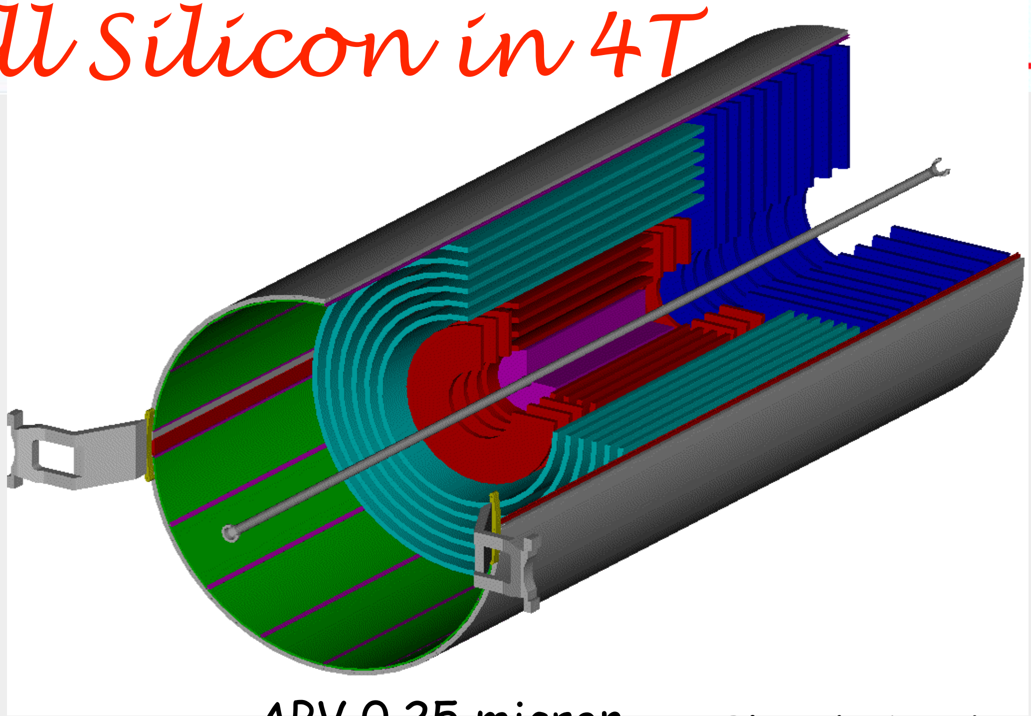
Simulation

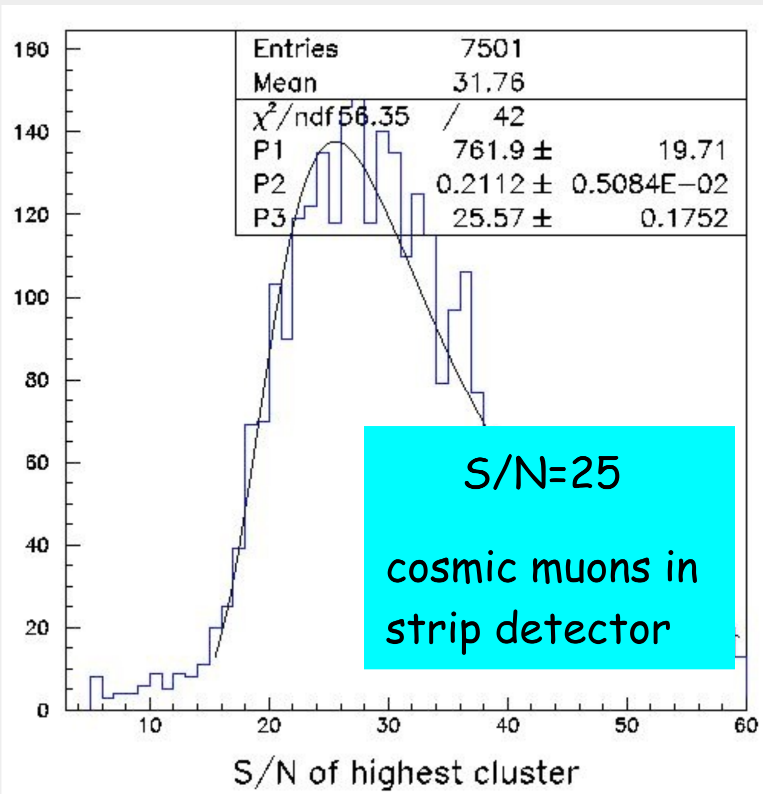


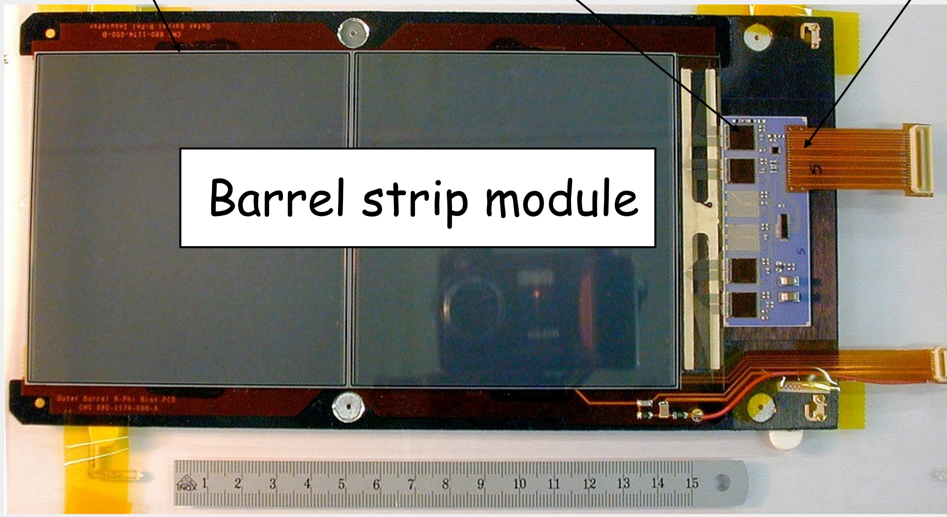
And excellent muon trigger too!

CMS tracker: full Silicon in 4T

- 5.4 m long, barrel and disks
- 210 m² Si sensors
- Full volume (24 m3) at -10°C
- 10M strips
- 67M pixels (100 x 150 μm)

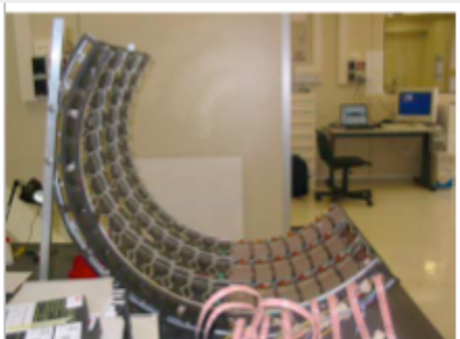


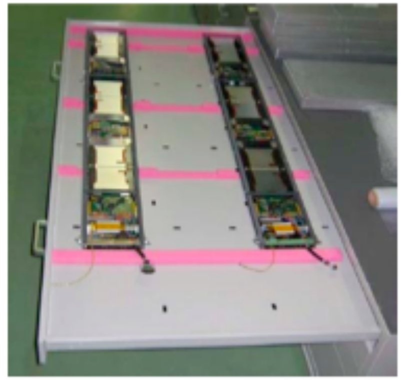


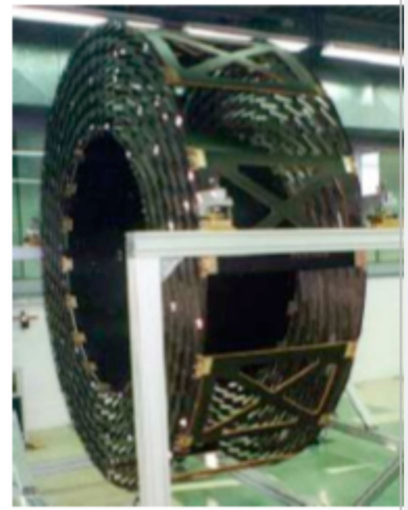


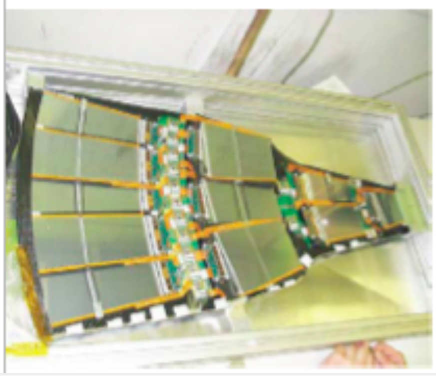
CMS Silicon detector

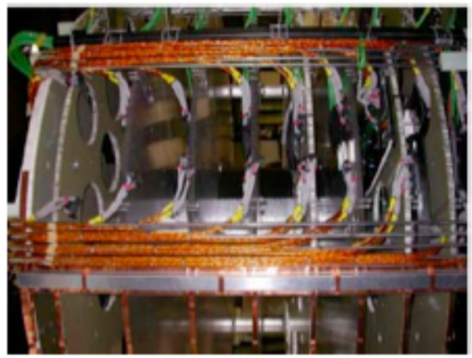
Shells. Rods and petals

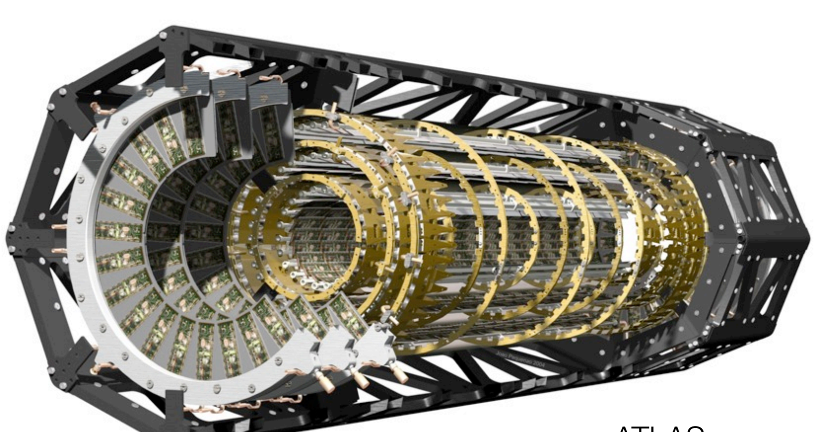




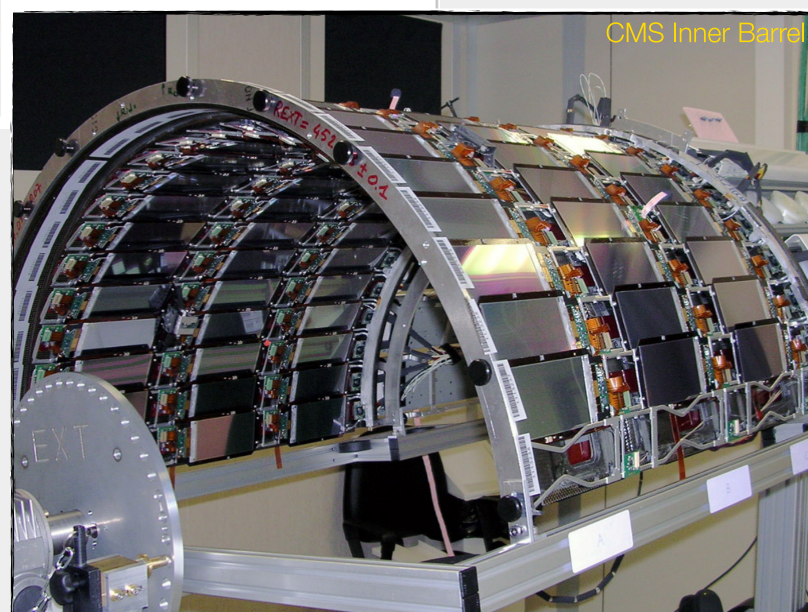




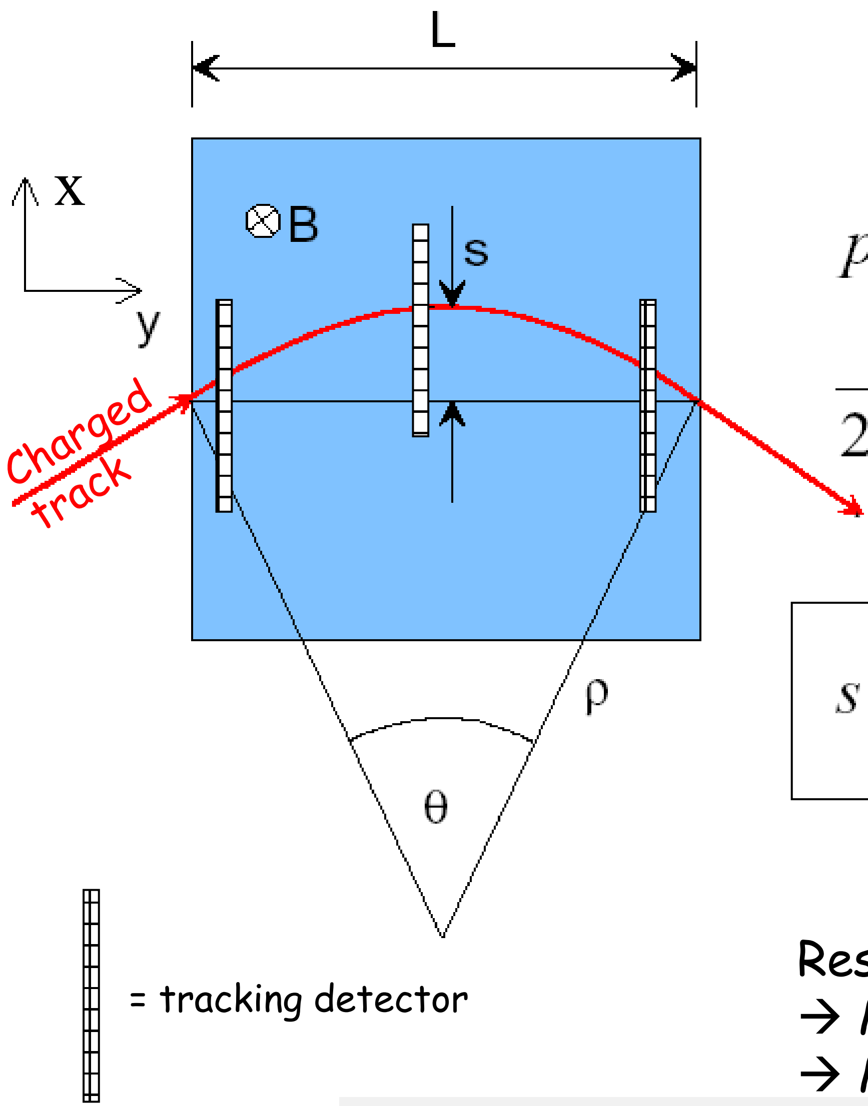




ATLAS
Pixel Detector



Momenta measurement



$$p_T\ (\mathrm{GeV/c}) = 0.3B\rho \quad (\mathrm{T \cdot m})$$

$$\frac{L}{2\rho} = \sin\theta/2 \approx \theta/2 \quad \rightarrow \quad \theta \approx \frac{0.3L \cdot B}{p_T}$$

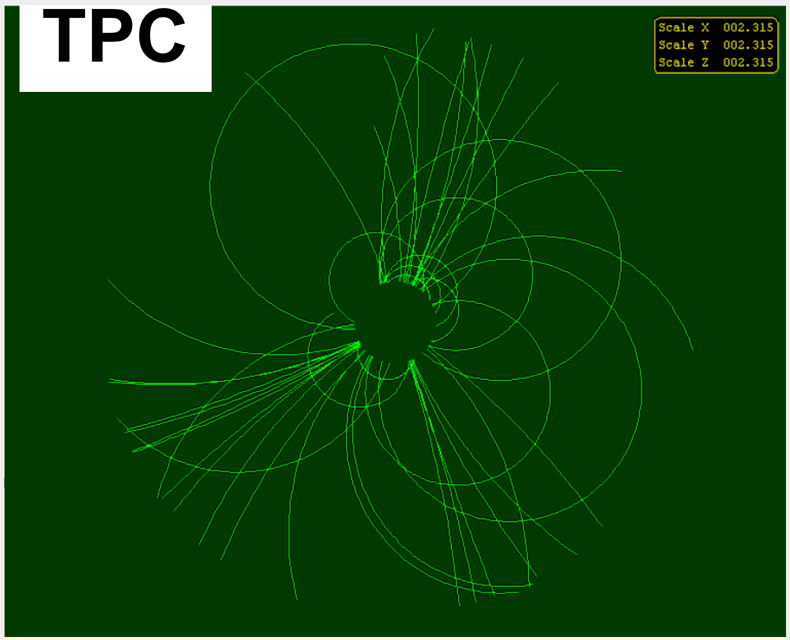
$$s = \rho(1-\cos\theta/2) \approx \rho\frac{\theta^2}{8} \approx \frac{0.3}{8}\frac{L^2 B}{p_T}$$

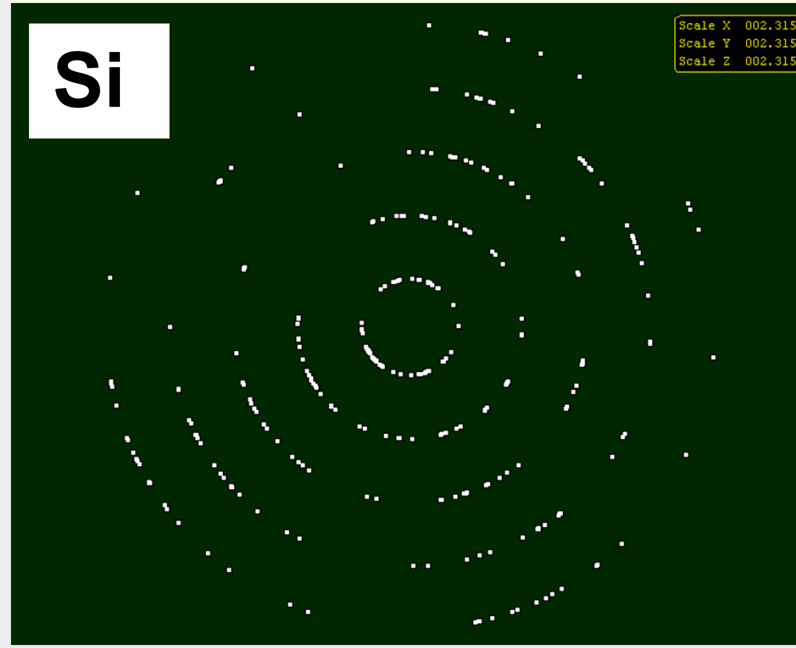
Resolution degrades because of
→ Multiple scattering (material in the detector)
→ Misalignment

- **In more realistic detector with N points (equally spaced):**

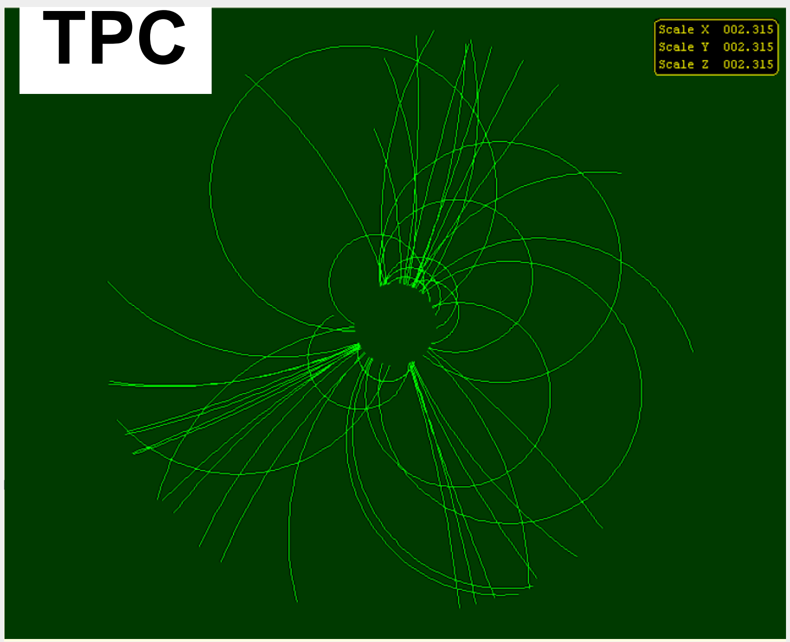
$$\frac{\sigma(P_T)}{P_T} \approx \sqrt{\frac{720}{N+4}}\sigma_x \frac{p_T}{0.3BL^2}$$

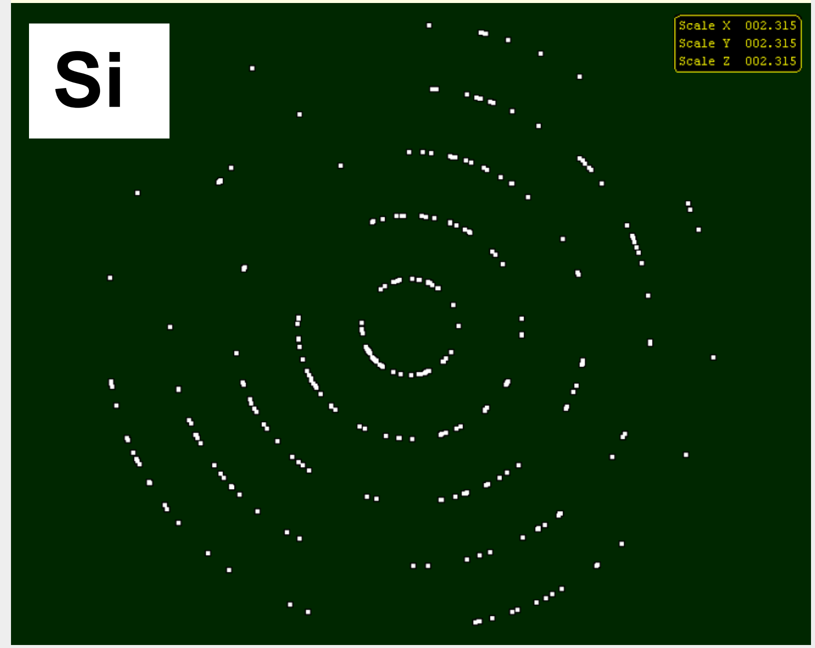
Summary


TPC
Scale X 002.315
Scale Y 002.315
Scale Z 002.315


Si
Scale X 002.315
Scale Y 002.315
Scale Z 002.315

Summary





- Charged track detectors have taken full benefit of progress in magnets (supra) (high field, large dimensions and electronics developments). ***Whatever technologies B field knowledge*** + ***alignment of detectors is very important***.

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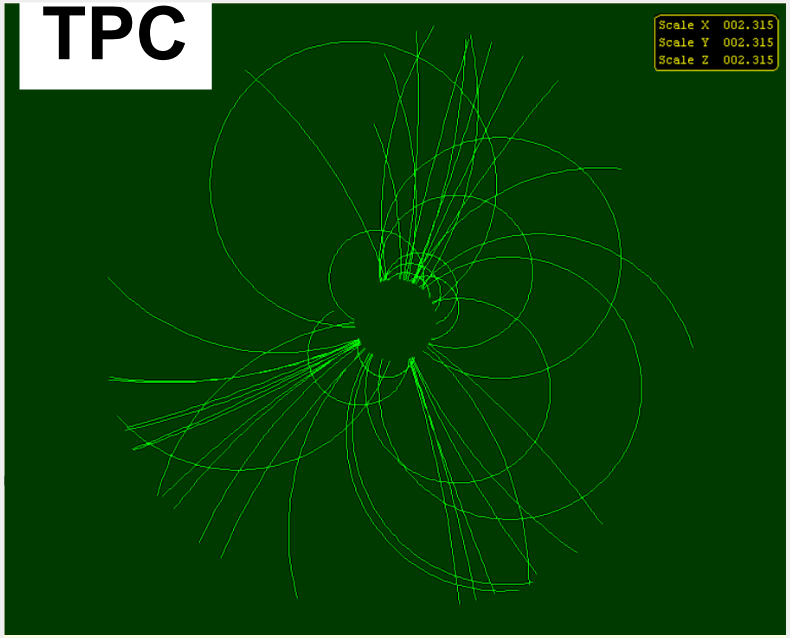

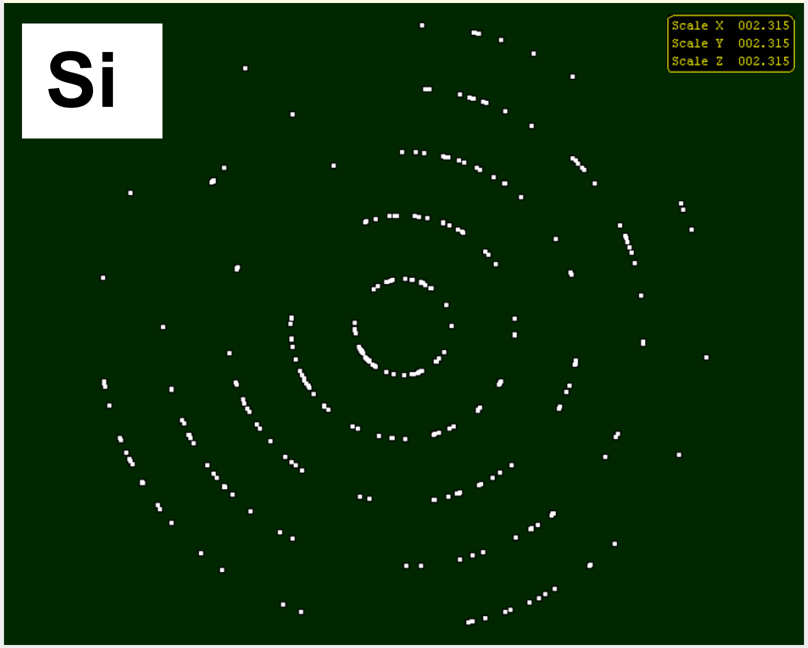

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- ***Gaseous*** are used since 60' but have really a new revival with the micro strips gas chambers (high flux is no more a problem). Good resolution can be really performant with pixel readout ***Many applications, not only in HEP.***

  ===> New TPC will probably use these readout devices in ILC experiments project

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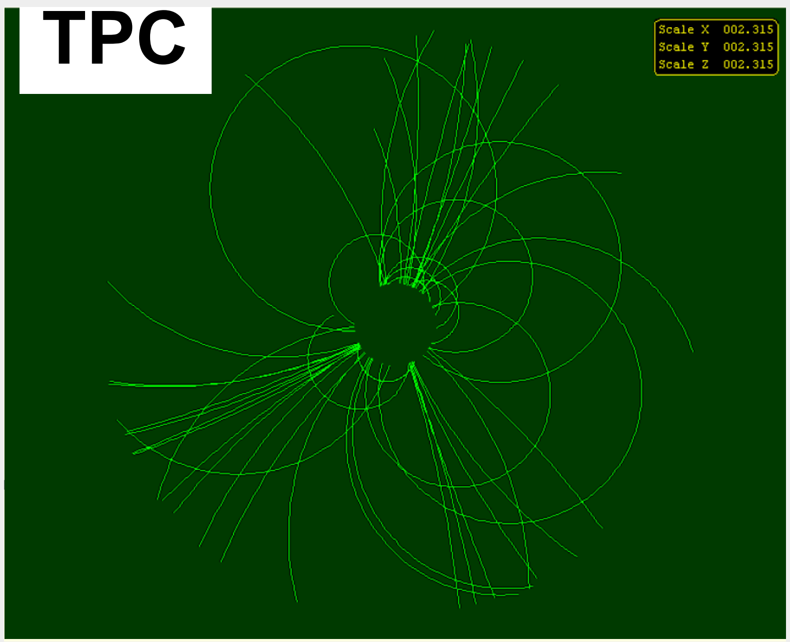

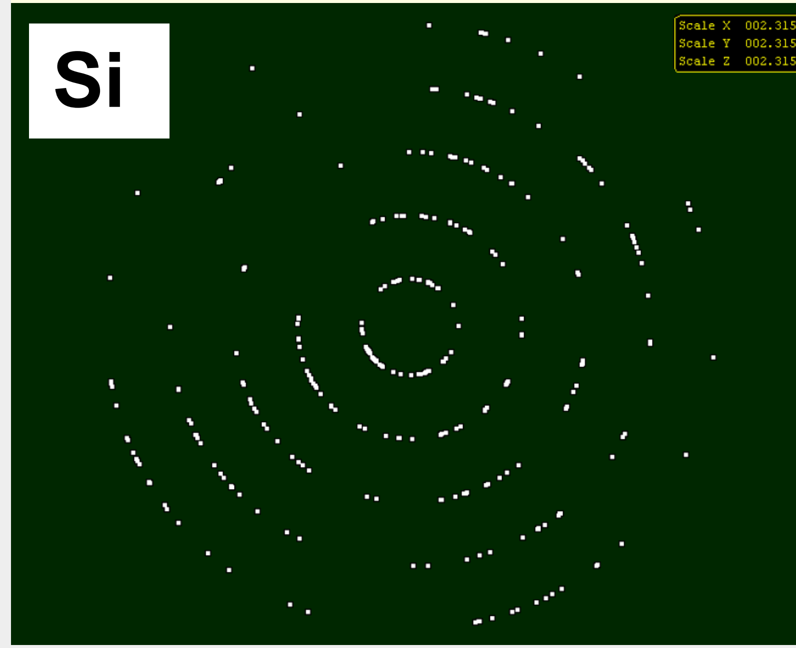

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  ===> New TPC will probably use these readout devices in ILC experiments project
- ***Solid state detectors*** : considerable progress in parallel with electronics readout. Their size rises by one order of magnitude in LHC experiment (200 m^2 in CMS detector of Si) Many R&D to improve radiation hardness, readout speed, material budget.....

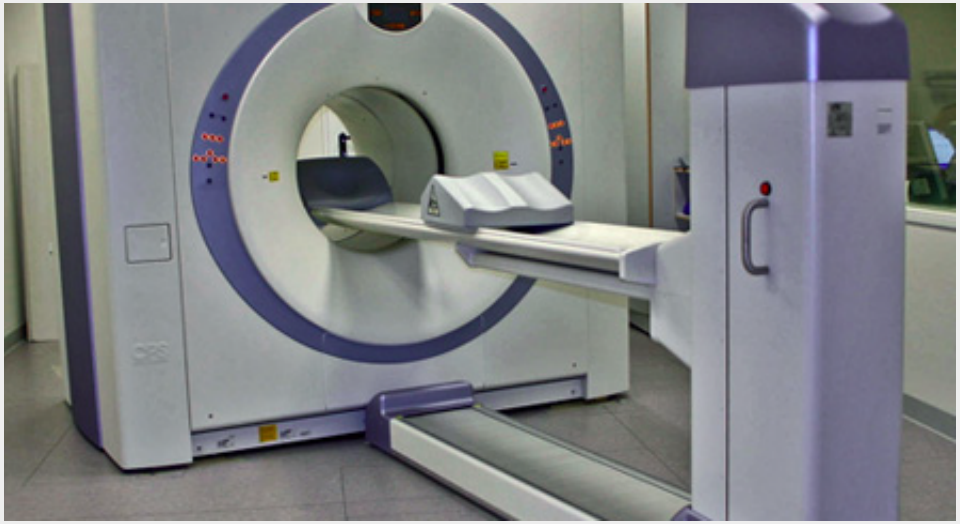
Comparisons of performances

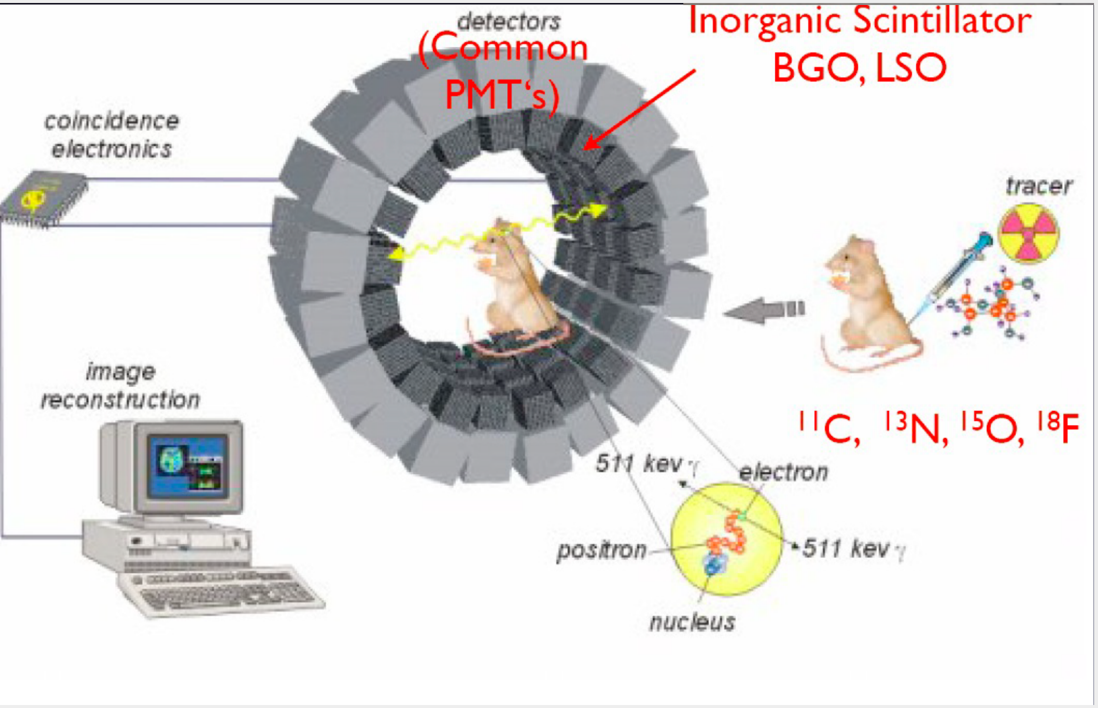
Table 28.1: Typical spatial and temporal resolutions of common detectors. Revised September 2003 by R. Kadel (LBNL).

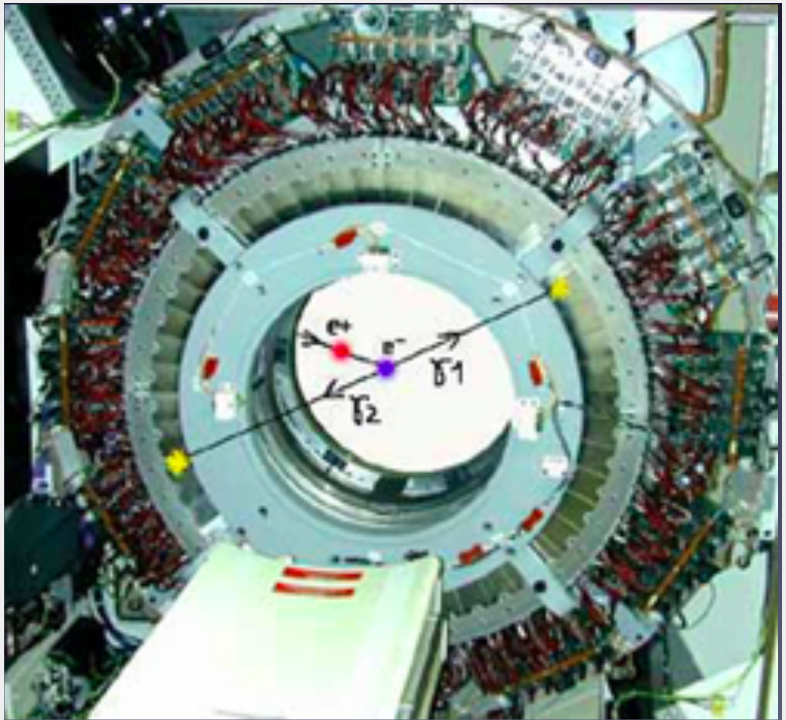
Detector Type	Accuracy (rms)	Resolution Time	Dead Time
Bubble chamber	10–150 μm	1 ms	50 ms[a]
Streamer chamber	300 μm	2 μs	100 ms
Proportional chamber	50–300 μm[b,c,d]	2 ns	200 ns
Drift chamber	50–300 μm	2 ns[e]	100 ns
Scintillator	—	100 ps/n[f]	10 ns
Emulsion	1 μm	—	—
Liquid Argon Drift [Ref. 6]	∼175–450 μm	∼ 200 ns	∼ 2 μs
Gas Micro Strip [Ref. 7]	30–40 μm	$<$ 10 ns	—
Resistive Plate chamber [Ref. 8]	$\lesssim$ 10 μm	1–2 ns	—
Silicon strip	pitch/(3 to 7)[g]	h	h
Silicon pixel	2 μm[i]	h	h

h : limitation is given by the readout electronics but intrinsically can be very small

Application of HEP Detectors: PET







Detector Output

Layer-based position measurements
- Pixel
- Silicon Strip
- Muon chambers (Drift, Cathode Strip, etc..)

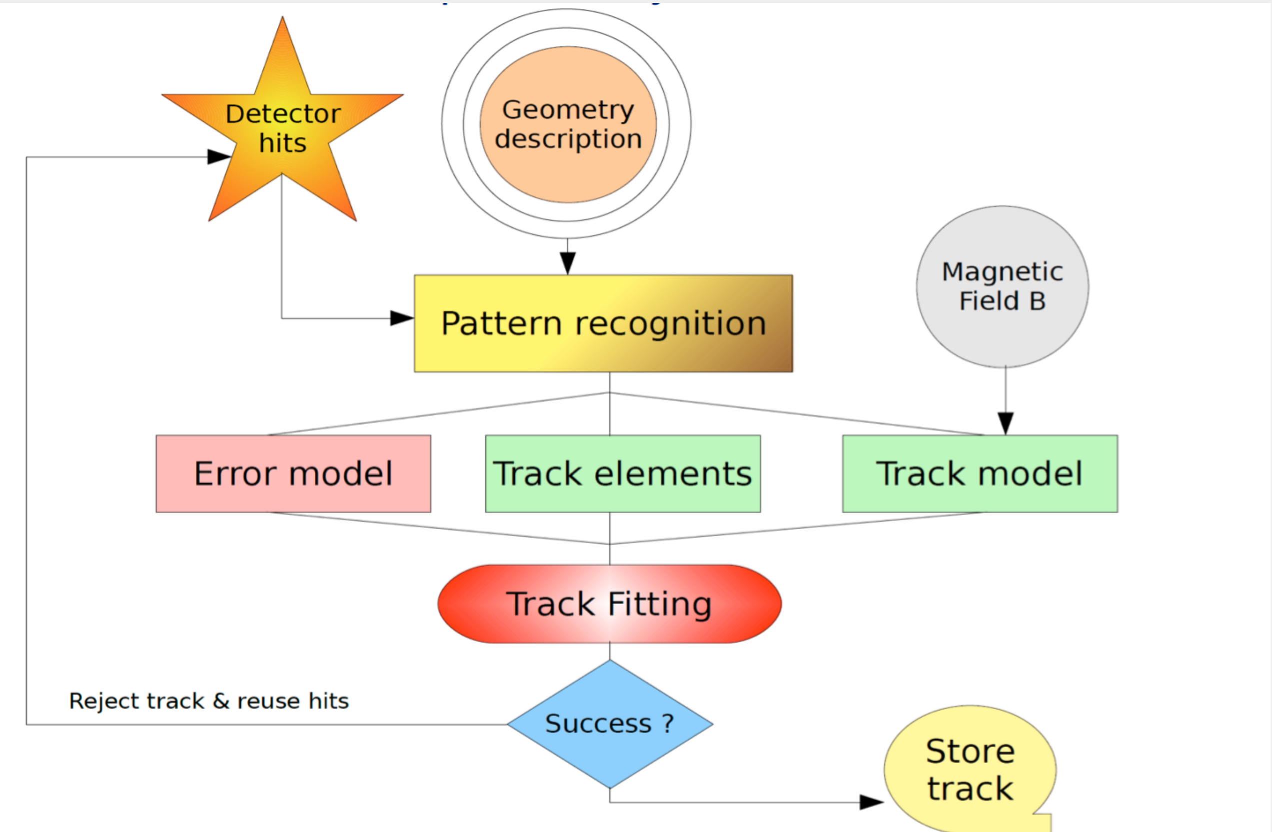
Continuous position measurements: TPC, TRD, etc..

Tracking Steps

Detector Output

Layer-based position measurements
- Pixel
- Silicon Strip
- Muon chambers (Drift, Cathode Strip, etc..)

Continuous position measurements: TPC, TRD, etc..



Tracking Steps

Detector Output → **Analysis input**

Layer-based position measurements
- Pixel
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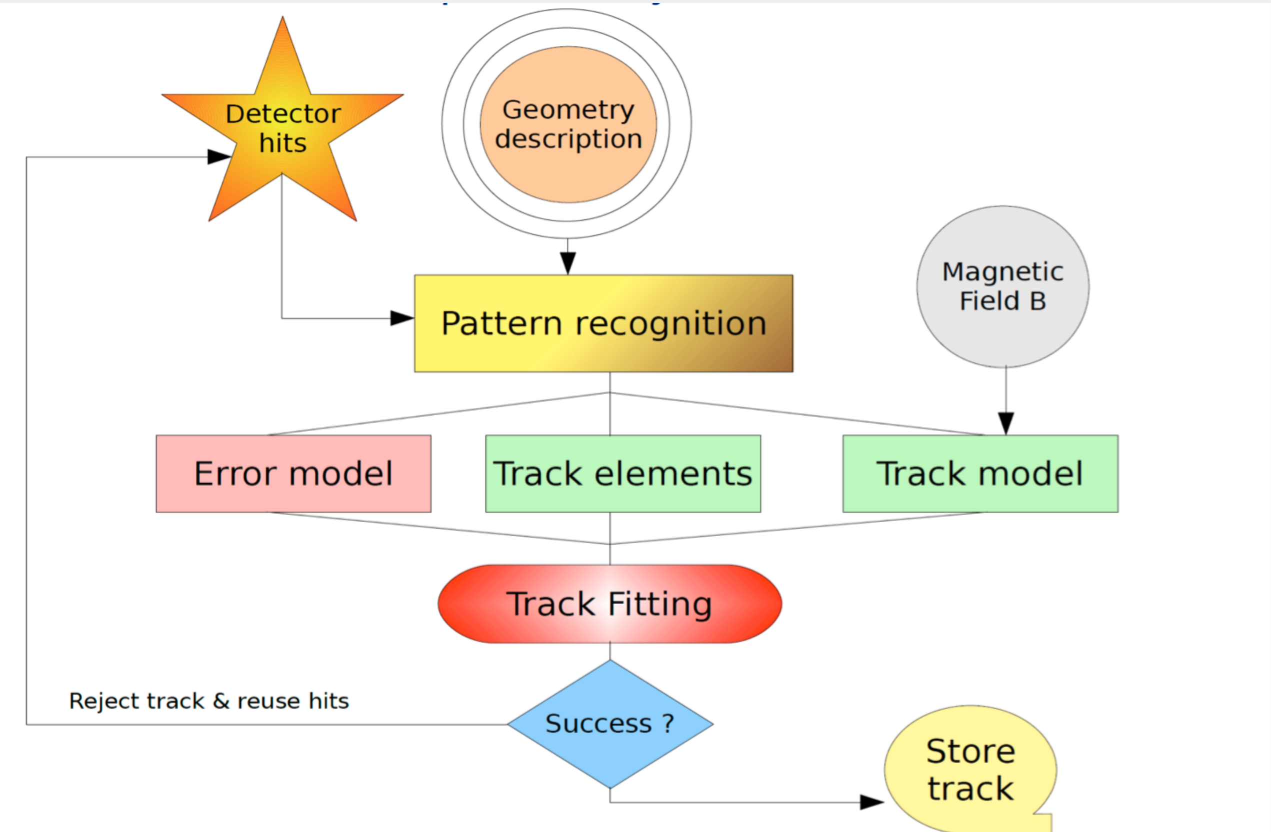
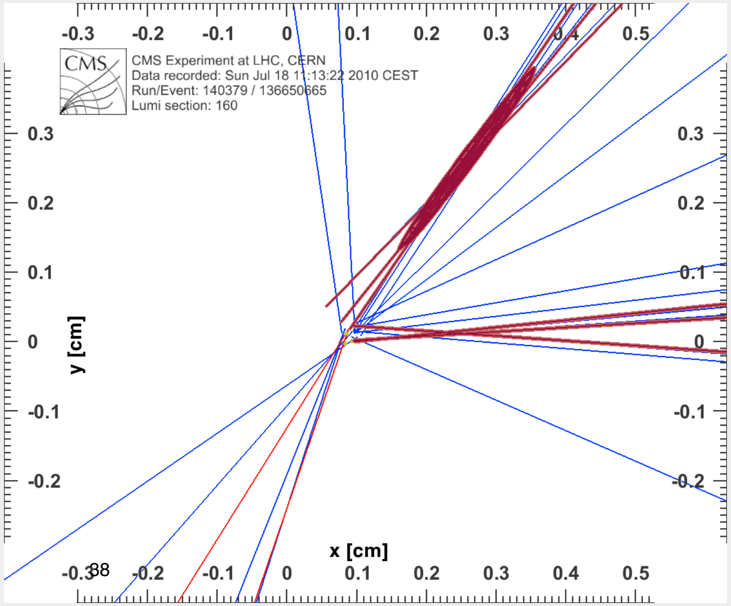


Track reconstruction:
Four momentum of charged particles
Charge sign
ID tags of particles

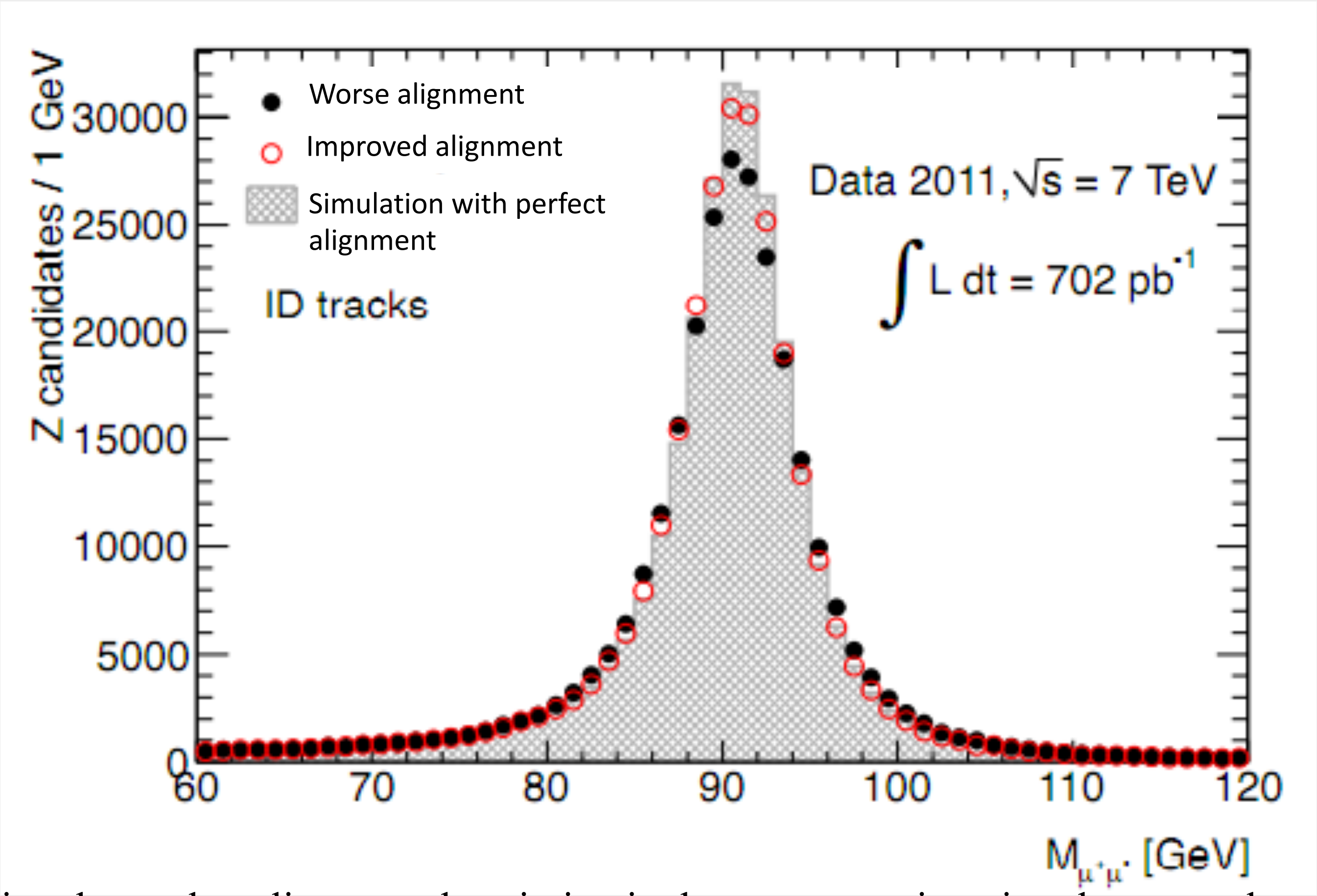
Event reconstruction:
Collision vertex
Track impact parameter
Secondary vertex

- Track finding is very important for analysis
- Tracks are used directly in the reconstruction of
  - Electrons
  - Muons
  - And to a lesser extent in Tau, Jet and photon reconstruction
- For reconstructed tracks, we know
  - Momentum
    - straighter the track the higher momentum it is
  - Charge
  - Point of closest approach to the interaction point (secondary vertex)



(important to identify particles such as b-quarks which have a long lifetime and so travel a measurable distance before they decay)

Tracker Alignment



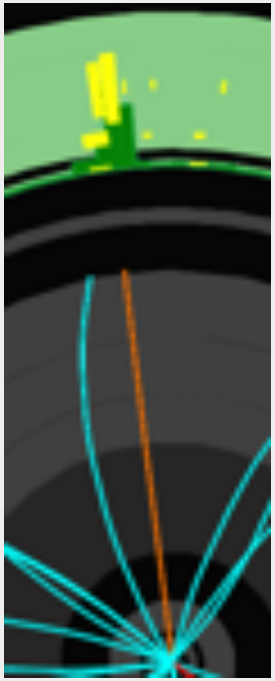
- Improving the tracker alignment description in the reconstruction gives better track momentum resolution which leads to better mass resolution.

- Can see the reconstructed Z width gets narrower if we use better alignment constants. Very important for physics analysis to have good alignment.

- Alignment of detector elements can change with time for example when the detector is opened for repair, or when the magnetic field is turned on and off.

Object reconstruction :

Electron/Photon Identification



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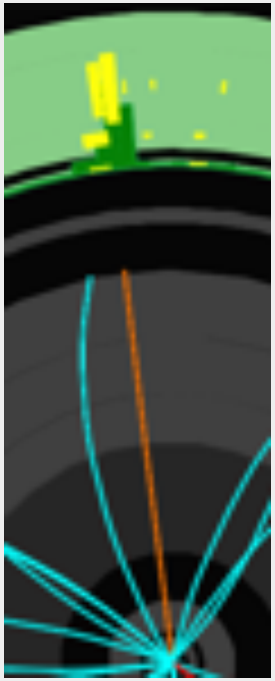
- ***Electron/Photon*** reconstruction takes as input the ***tracks and calorimeter clusters*** already produced



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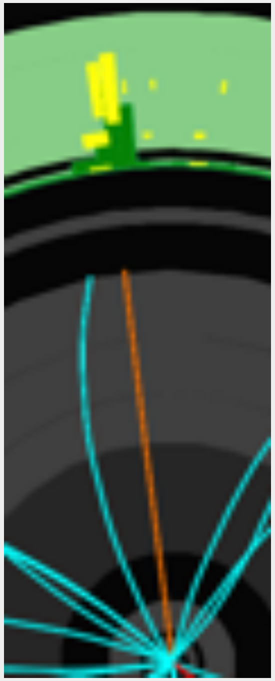

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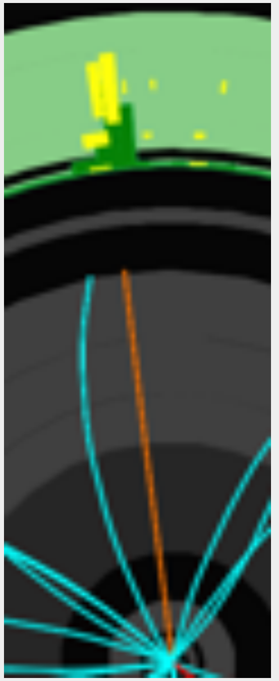

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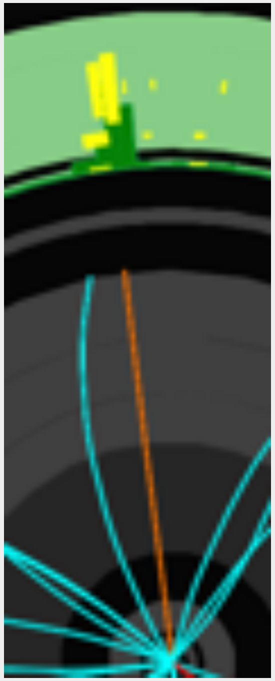

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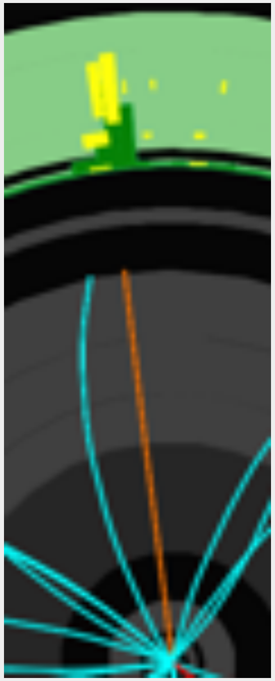

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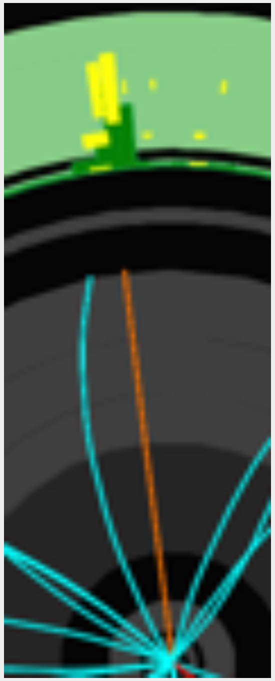

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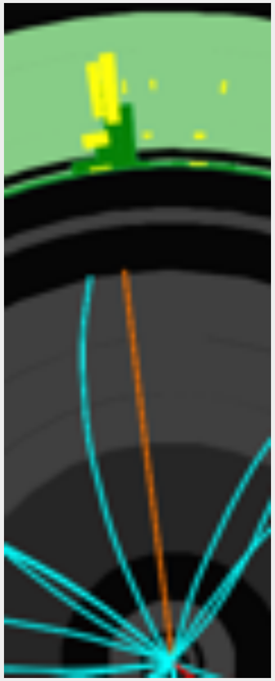

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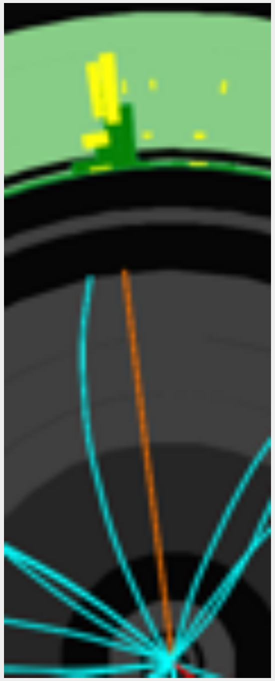

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Jets and Electron/Photon Backgrounds

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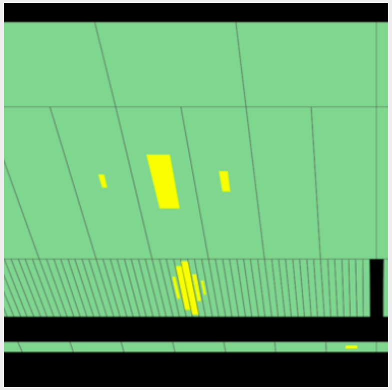

Example of an electron energy deposit in the electromagnetic calorimeter in ATLAS.
Use shower shape variables based on size of cluster in the radial and longitudinal directions to distinguish from hadronic showers

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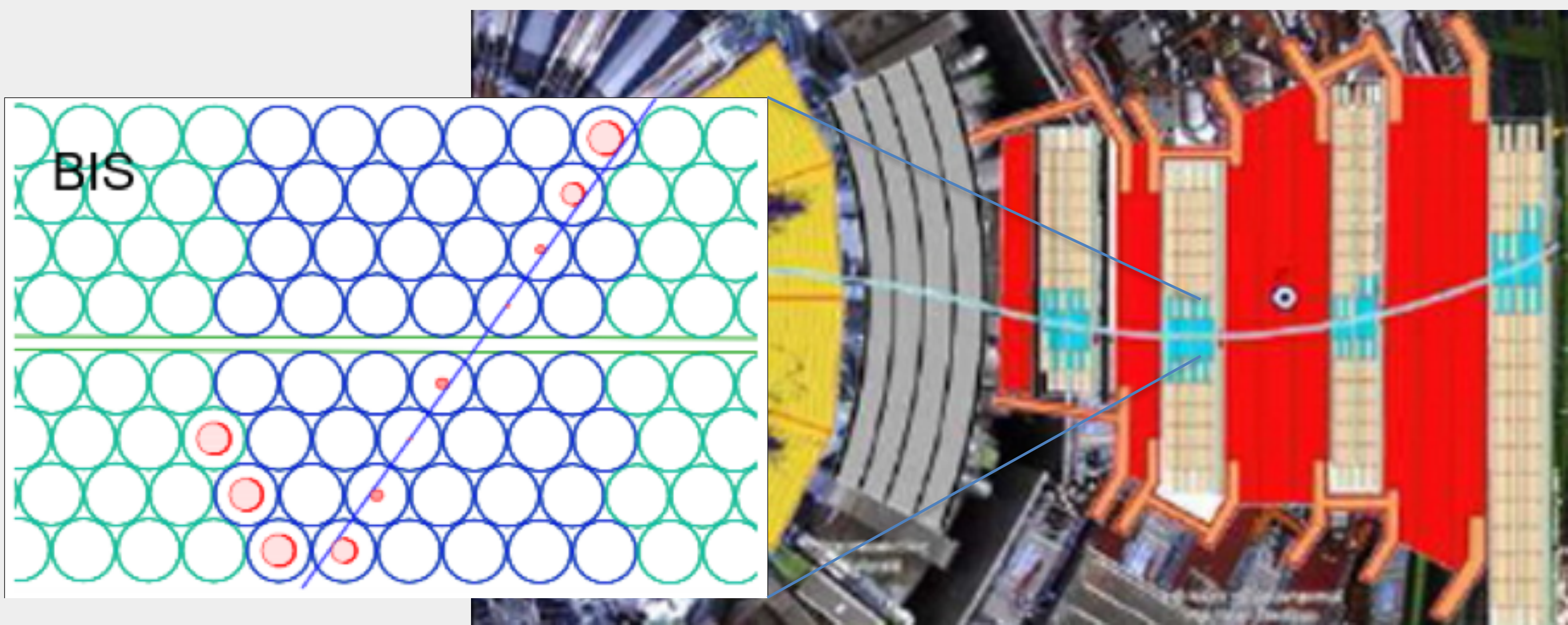
    - Alignment of the muon detectors also very important to get best momentum resolution

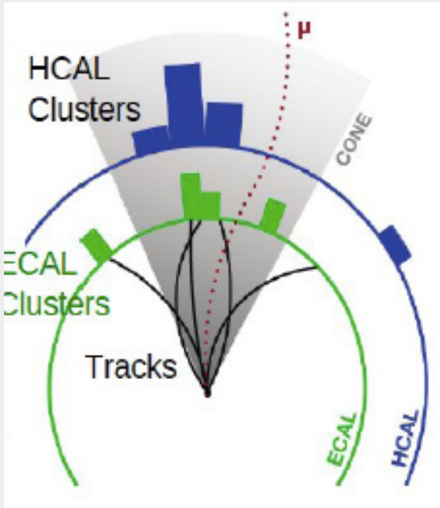
Muon segment in drift tubes



Particle Flow and Missing E_T

- ***Particle Flow*** : from all sub-detector reconstruct stable particles (e, μ, photons, charged and neutral hadrons) and so optimize particles types, direction and energies.

Particle Flow and Missing E_T



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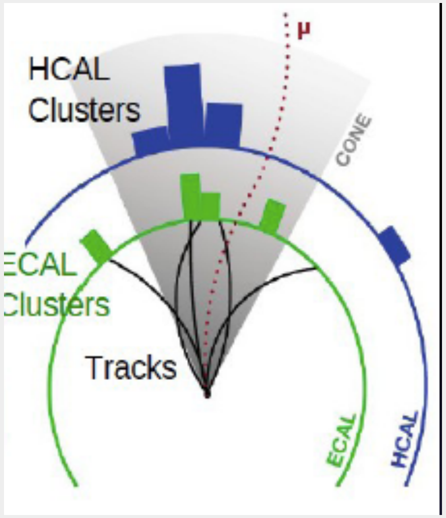

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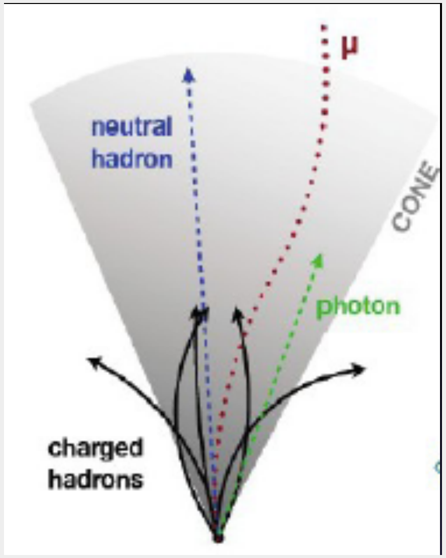

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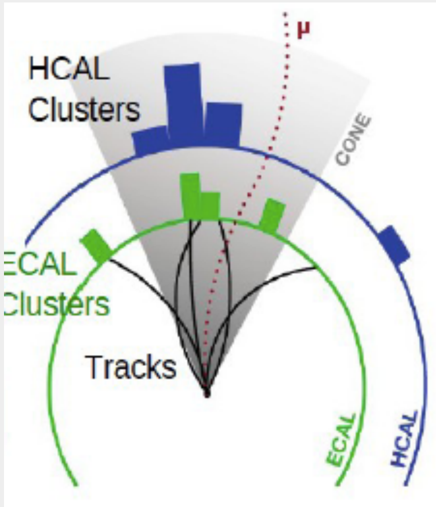

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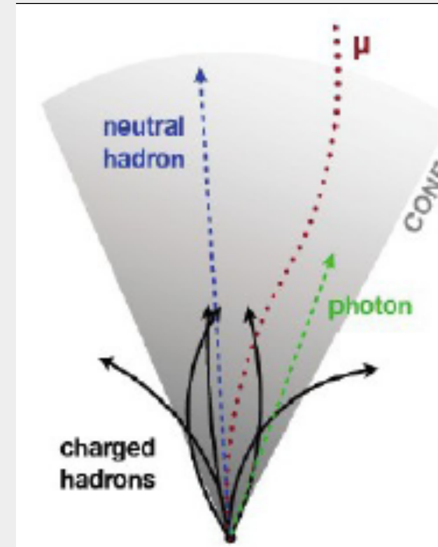

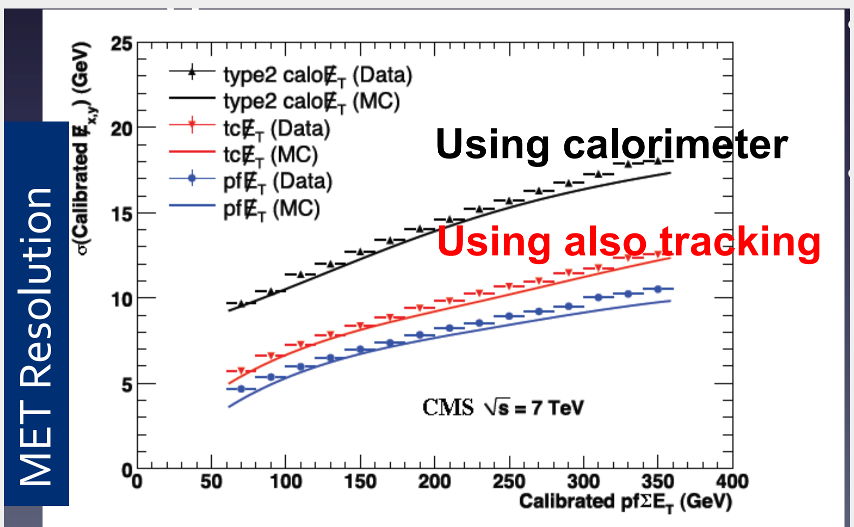

$$E_T^{\text{miss}} = -\sum_i p_T(i)$$

- At the LHC an unknown proportion of the energy of the colliding protons escapes down the beam-pipe.
- If invisible particles (neutrinos, neutralinos ?) are created their momentum can be constrained in the plane transverse to the beam direction

Summary

- As particles travel through matter they interact (through the EM force) and transfer part of their energy to the detector.
- At the energies of interest ionization is the dominating mechanism.
- Gaseous detectors measure the ionization of gas to identify the path followed by particles.
- Silicon detectors use the ionization of silicon. They permit a much better accuracy but are more expensive.
- Accurate tracking is important for example to detect displaced vertices (long lived particles such as states with b and c quarks).
- This played an important role in the discovery of the top quark and in the study of CP violation.

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To extend your knowledge

Text books (a selection)

– C. Grupen, B. Shwartz, Particle Detectors, 2nd ed., Cambridge University Press, 2008
– G. Knoll, Radiation Detection and Measurement, 3rd ed. Wiley, 2000
– W. R. Leo, Techniques for Nuclear and Particle Physics Experiments, Springer, 1994
– R.S. Gilmore, Single particle detection and measurement, Taylor&Francis, 1992
– K. Kleinknecht, Detectors for particle radiation , 2nd edition, Cambridge Univ. Press, 1998
– W. Blum, W. Reigler, L. Rolandi, Particle Detection with Drift Chambers, Springer, 2008
– R. Wigmans, Calorimetry, Oxford Science Publications, 2000
– G. Lutz, Semiconductor Radiation Detectors, Springer, 1999

Review Articles

– Experimental techniques in high energy physics, T. Ferbel (editor), World Scientific, 1991.
– Instrumentation in High Energy Physics, F. Sauli (editor), World Scientific, 1992.
– Many excellent articles can be found in Ann. Rev. Nucl. Part. Sci.

Other sources

– Particle Data Book Phys. Lett. B592, 1 (2008) http://pdg.lbl.gov/pdg.html
– R. Bock, A. Vasilescu, Particle Data Briefbook http://www.cern.ch/Physics/ParticleDetector/BriefBook/
- ICFA schools lectures : http://www.ifm.umich.mx/school/ICFA-2002/
- O. Ullaland http://lhcb-doc.web.cern.ch/lhcbdoc/presentations/lectures/Default.htm
– Proceedings of detector conferences (Vienna VCI, Elba, IEEE, Como)
– Journals: Nucl. Instr. Meth. A, Journal of Instrumentation

Trigger and DAQ

- R. Fernow : Introduction to experimental particle physics (C.U.P. 1986)
- R. Frühwirth, M. Regler, R.K. Bock, H. Grote and D. Notz ; Data Analysis Techniques for High-Energy Physics (2nd ed.) (C.U.P. 2000)
- CERN-Latin American Schools of Physics : Usually an article on trigger and DAQ

References

- Sze, Physics of semiconductor devices
- Helmuth Speiler lecture notes (www-physics.kbl.gov/~spieler)
- G. Lutz, Semiconductor radiation detectors : Device Physics, Springer (2007)
- Doris Eckstein (DESY lectures)
- Gino Bolla UTEV seminar: http://www.fnal.gov/orgs/utev/past_speakers.html
- R. Lipton Academic lectures: http://www-ppd.fnal.gov/eppoffice-w/Academic_Lectures/Past_Lectures.htm
- Steve Worm notes on Radiation Damage
- Silicon Microstrip Detectors , A. Peisert, in " Instrumentation in High Energy Physics ", F .Sauli (ed), World Scientific, (1992).
- Pixel Detectors, Rossi, Fisher, Rohe, Wermes, Springer
- M. Moll thesis on Radiation Damage

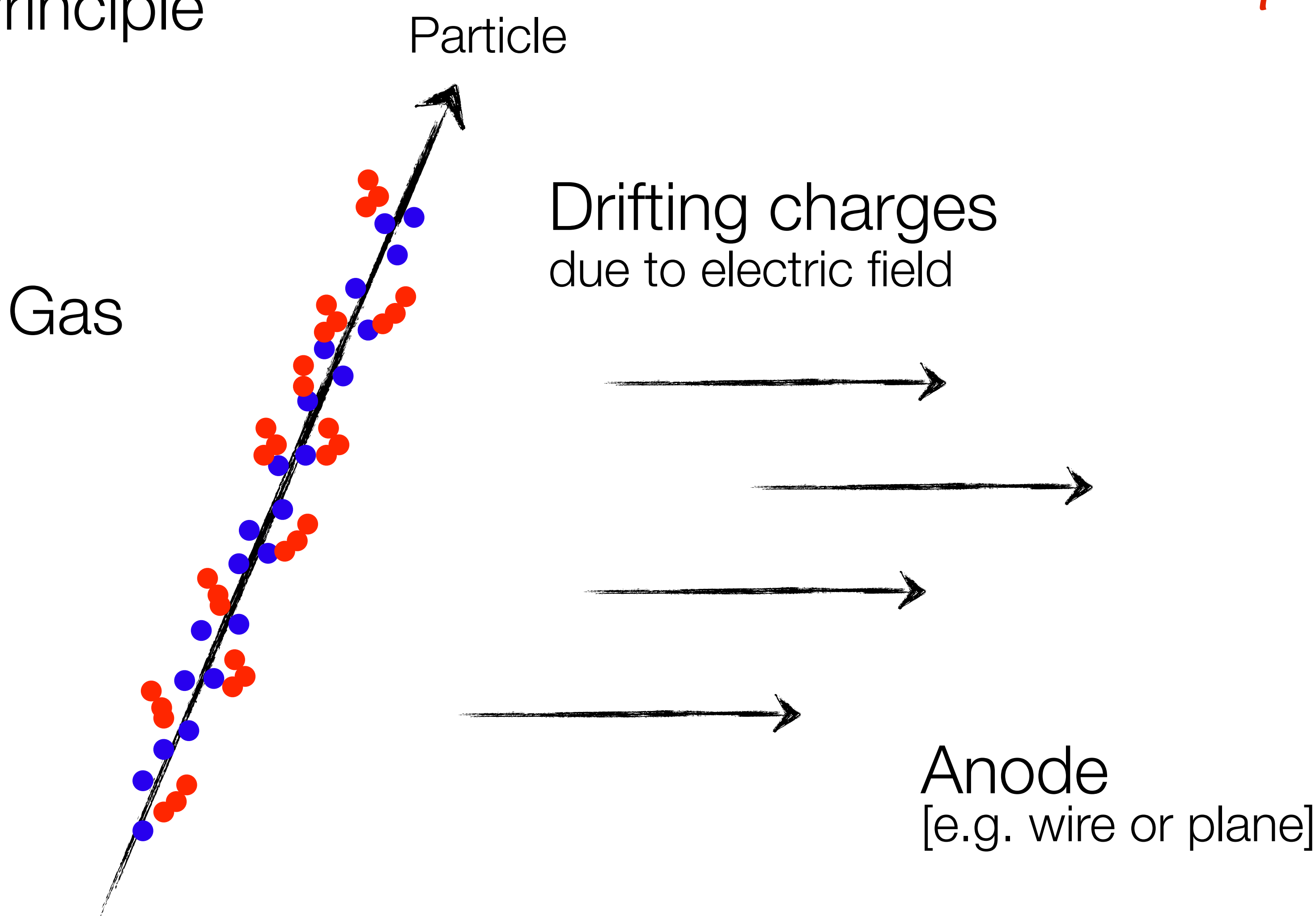
BACKUP

- Gaseous Detectors — for details see
- Large volume Particle Tracking — for details see
- Exemple of Gaseous detectors — for details see
- The Silicon Sensors — for details see
- Silicon detectors — for details see
- Overview of readout electronics — for details see
- Why do we need Trigger — for details see

To Backup

Schematic Principle

of gas detectors

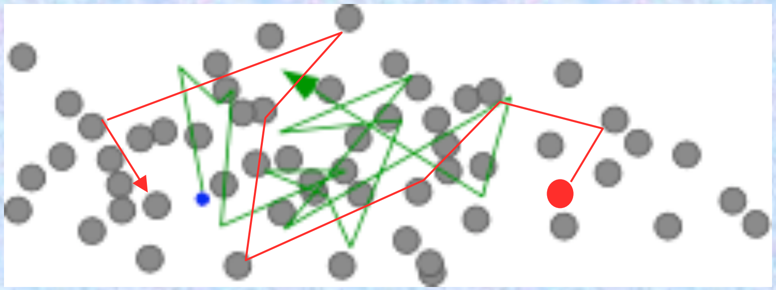


- Primary Ionization
- Secondary Ionization (due to δ-electrons)

Back

Drift and Diffusion of Charges in Gases

ELECTRIC FIELD E = 0: THERMAL DIFFUSION

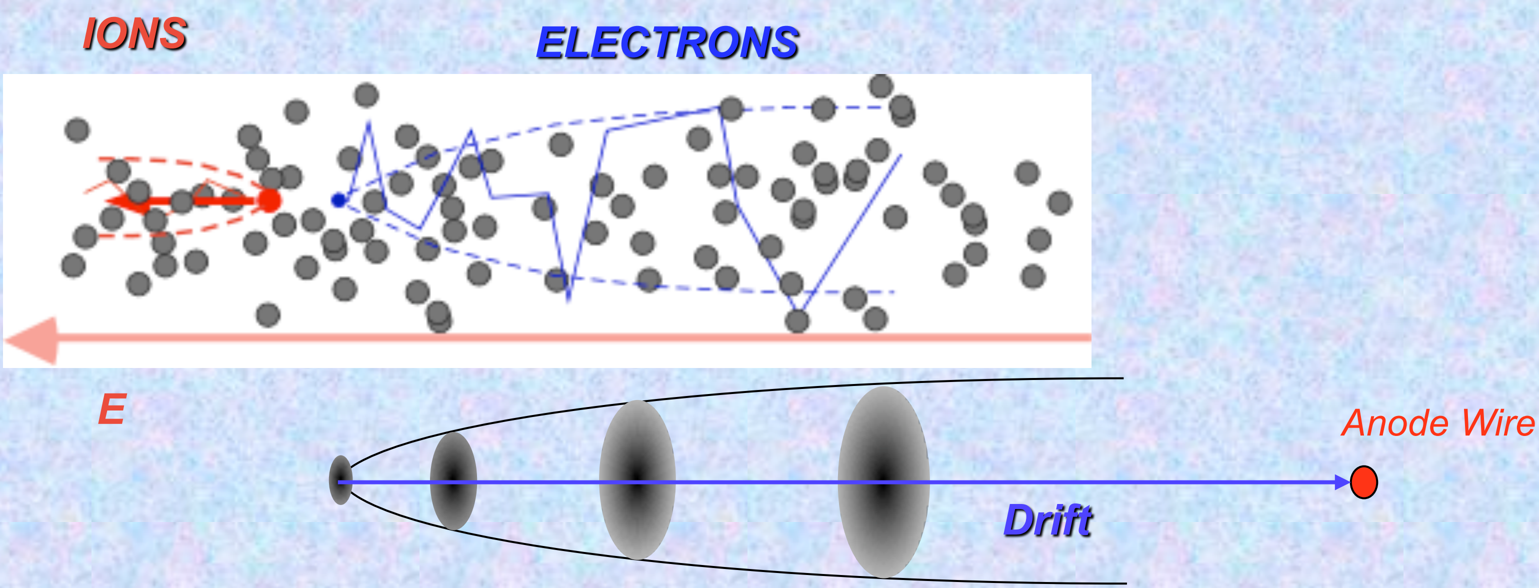


Maxwell energy distribution:

$$F(\boldsymbol{\varepsilon}) = C\sqrt{\boldsymbol{\varepsilon}}\, e^{-\frac{\varepsilon}{KT}}; \quad \langle\varepsilon\rangle \sim kT \sim 0.025 \text{ eV}$$

RMS of charge diffusion: $\sigma_x = \sqrt{2Dt}$

ELECTRIC FIELD E > 0: CHARGE TRANSPORT AND DIFFUSION



Diffusion in gases (no E-field)

* In absence of other effects, at thermal energies, the mean speed of the charges (given by the Maxwell distribution of the energies) is:

$$v = \sqrt{\frac{8kT}{\pi m}}$$

where k is Boltzmann's constant, T the temperature and m the mass of the particle

* The charges diffuse by multiple collisions, and a local distribution follows a Gaussian law:

$$\frac{dN}{dx} = \frac{N_0}{\sqrt{4\pi Dt}} \exp\left(-\frac{x^2}{4Dt}\right)$$

where N_0 is the total number of charges, x the distance from the point of creation and D the diffusion coefficient

* Then the linear and volume r.m.s. of the spread are:

$$\sigma_x = \sqrt{2Dt}$$

$$\sigma_V = \sqrt{6Dt}$$

For instance, the radial spread of ions in air in normal conditions is about 1 mm after 1 second

Drift and mobility in gas

- In the presence of an electric field, electrons and ions will drift in the gas. The drift velocity for electrons can be much higher w.r.t. ions since they are much lighter.

- $\mu = v/E$ is the mobility of a charge where v is the drift velocity and E the electric field.

- Ions :
  - Mean velocity v^+ is proportional to E/P
  - Mobility μ^+ is constant (average energy of ions almost unmodified up to very high electric fields)

- Electrons:
  - Drift velocity $v^- = (e/2m).E.\tau$ where τ is the mean time between collision
  - Typical value around 5 cm/µs are obtained (ions thousand times slower)

Charge multiplication

- $\alpha = 1/\lambda$ is the probability of ionization per unit length with λ the mean free path of the electron for a secondary ionizing collision
- For n electrons, there will be $dn = n\alpha dx$ new electrons created in a path dx
- Then $n = n_0 e^{\alpha x}$ with α: first Townsend coefficient
- And we can define a multiplication factor M:

$$M = \frac{n}{n_0} = \exp\left[\int_{r_1}^{r_2} \alpha(x)\,dx\right]$$

α is a function of x (non uniform electric fields)

- Limitation of M: above 10^8, sparks occur (Raether limit)
- Calculating α (or gas gain) for different gases (model by Rose and Korff):

$$\frac{\alpha}{p} = A\exp\left(\frac{-Bp}{E}\right)$$

where A and B depend on the gas

Gaseous Detectors

Ionization statistics:

Mean free path λ:
[typical values]

He	0.25 cm
Air	0.052 cm
Xe	0.023 cm

[➛ σ_I(He) ≈ 100

Mean distance between two ionizations: $\lambda = 1/(n_e \sigma_I)$

Mean number of ionizations: $\langle n_p \rangle = L/\lambda$

σ_I : Ionization x-Section
n_e : Electron density
L : Thickness

n_p Poissonian distributed:

$$P(n_p, \langle n_p \rangle) = \frac{\langle n_p \rangle^{n_p} e^{-\langle n_p \rangle}}{n_p!}$$

P(0) = exp(-L/λ) yields λ, σ_I
using (in)efficiency of gas-detectors

Also important:

Mobility of charges:
Influences the timing behavior of gas detectors ...

Diffusion:
Influences the spatial resolution ...

Avalanche process via impact ionization:
Important for the gain factor of the gas detector ...

Recombination and electron attachment:
Admixture of electronegative gases (O_2, F, Cl ...) influences detection efficiency ...

Ion mobility:

With external electric field: ions obtain velocity v_D in addition to thermal motion; on average ions move along field lines of electric field E ...

Kinetic energy:

Temperature sorry ...

$$\langle T_{\rm ion}(\mathrm{E} \neq 0)\rangle = \langle T_{\rm ion}(\mathrm{Therm.})\rangle = \frac{3}{2}kT$$

approximately equal to thermal energy, as the (heavy) ions loose typically half their energy when colliding with the non-ionized gas atoms.

Drift velocity v_D develops only from one interaction to another ...
Assuming $v_D(t=0) = 0$ and collision time τ yields:

$$\vec{v} = \vec{a} \cdot \tau = \frac{e\vec{E}}{M} \cdot \tau \qquad \tau = \lambda(T_{\rm kin})/v_{\rm therm.} = \mathrm{const.}$$

since T_{kin} essentially thermal, and $v_{therm.}$ thus constant ...

$$\vec{v}_D = \langle \vec{v} \rangle = \frac{1}{2}\vec{v} = \frac{e|\vec{E}|}{2M} \cdot \tau = \mu_+|\vec{E}|$$

Drift velocity v_D for ions proportional to E !

μ_+ : ion mobility   e.g. $\mu_+ = 0.61\ \mathrm{cm^2/Vs}$ for C_4H_{10}

[E = 1 kV/cm; typical drift distances = few cm ➛ typical ion drift time = few ms]

Electron mobility:

Equation of motion:
[in E,B field]

$$m\ddot{\vec{x}} = e\vec{E} + e(\vec{v} \times \vec{B}) + m\vec{A}(t)$$

$\vec{v} = \dot{\vec{x}}$ instantaneous electron velocity

$m\vec{A}(t)$ time-dependent stochastic force
[describes collisions with gas atoms]

Assume:

- E and B field constant between collisions
- Time averaged stochastic term can be represented by friction term
- Time between collisions small with respect to considered time interval: Δt » τ
- Drift velocity at fixed E constant, i.e. average acceleration vanishes, $\langle \ddot{x} \rangle = 0$

$$\vec{v}_D = \langle \vec{v} \rangle$$

$$\langle m\ddot{\vec{x}} \rangle = e\vec{E} + e(\vec{v}_D \times \vec{B}) - \frac{m}{\tau}\vec{v}_D = 0$$

with $\mu = \mu_- = \frac{e\tau}{m}$

$\omega = \frac{eB}{m}$

B = 0:

$$\vec{v}_D = \frac{e\tau}{m}\vec{E} = \mu_- \vec{E}$$

Remark:
μ_+ « μ_- as M » m ...

B ≠ 0:

$$\vec{v}_D = \mu \cdot \vec{E} + \omega\tau \cdot \vec{v}_D \times \hat{\vec{B}}$$

$$\rightarrow \vec{v}_D = \frac{\mu|\vec{E}|}{1+\omega^2\tau^2}\left[\hat{\vec{E}} + \omega\tau\hat{\vec{E}} \times \hat{\vec{B}} + \omega^2\tau^2(\hat{\vec{E}} \cdot \hat{\vec{B}})\hat{\vec{B}}\right]$$

Component ⊥ to E,B

Component in direction of B

Electron mobility: $\vec{v}_D = \mu \vec{E}$
[B = 0]

Compare:
Electrons: v_D of order cm/μs
Ions: v_D of order cm/ms

Consider two situations:

$T_{kin,e} \gg kT$ — gas atoms have only a few low-lying energy levels such that electrons can lose little energy in collisions [hot gases]

$$\lambda(T_e) \sim \lambda(E) \text{ and } \mu \sim \tau \sim 1/\sigma(E)$$

μ not constant!
[If $\lambda \sim 1/E$; v_D = const]

Electrons accelerated in E-field until sufficient energy is reached ...
Higher E-field yields smaller mean free path ➛ constant v_D possible ...
[Example: v_D = 3 – 5 cm/μs for 90% Ar/10% CH_4]

$T_{kin,e} \approx kT$ — gas atoms have many low-lying energy levels such that electrons loose all energy they gain between collisions [cold gases]

$$\mu \approx \text{const.} \quad \text{and} \quad v_D \propto E$$

Similar to situation with ions ...
[Example: $\mu = 7 \cdot 10^{-3}$ cm^2/μs V for 90% Ne/10% CO_2; v_D = 2 cm/μs @ 300 V/cm]

Avalanche Multiplication

Large electric field yields
large kinetic energy of electrons ...

➛ Avalanche formation

Larger mobility of electrons results in liquid
drop like avalanche with electrons near head ...

Mean free path: λ_{ion}
[for a secondary ionization]

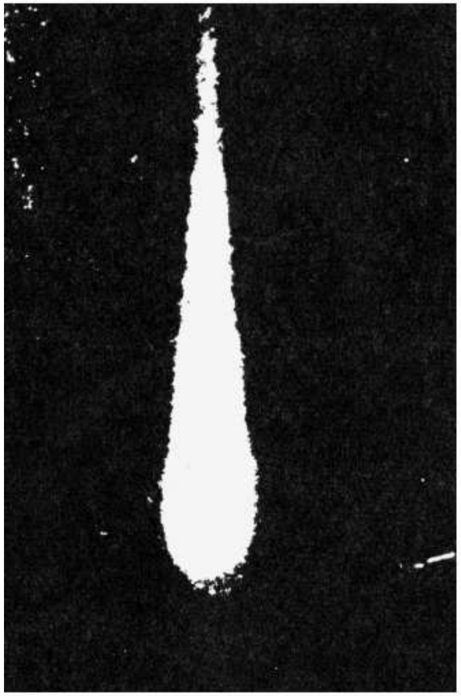
Probability of an ionization per
unit path length: $\alpha = 1/\lambda_{ion}$ [1st Townsend coefficient]

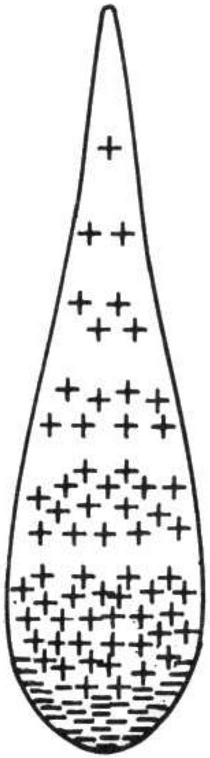
$$dn = n \cdot \alpha \, dx$$

$$n = n_0 e^{\alpha x}$$

n(x) = electrons at location x

Townsend avalanche





Drop-like shape of an avalanche

Left: cloud champer picture
Right: schematic view

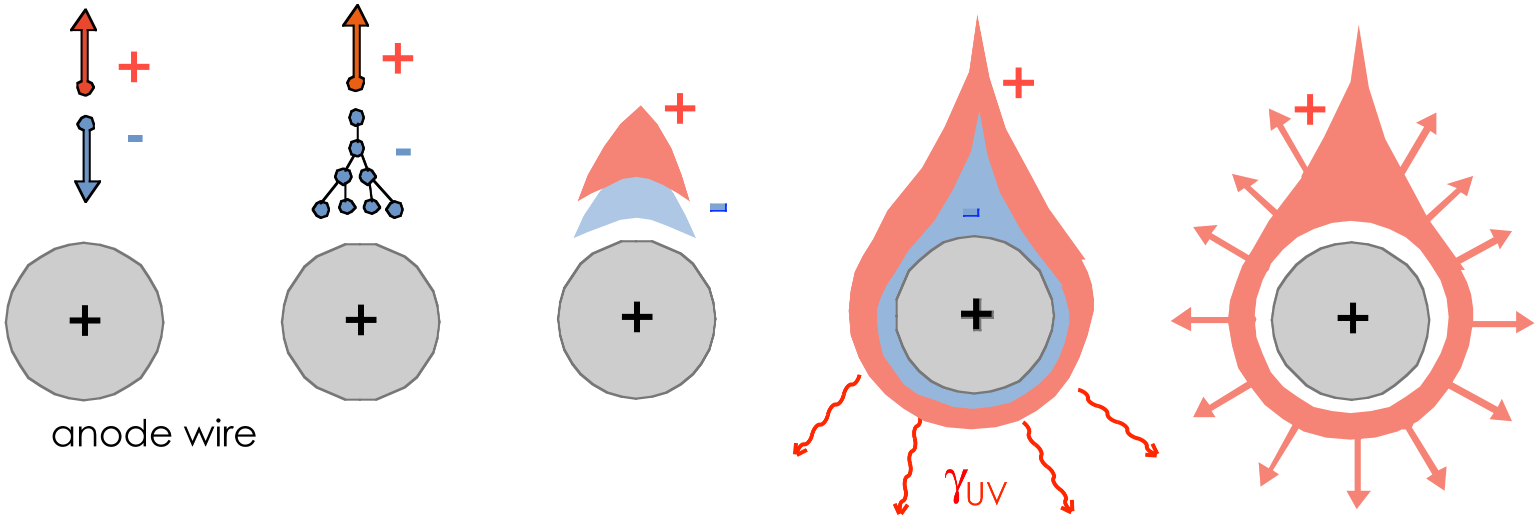
Gain:

$$G = \frac{n}{n_0} = e^{\alpha x}$$

and more general for $\alpha = \alpha(x)$: $$G = \frac{n}{n_0} = \exp\left[\int_{x_1}^{x_2} \alpha(x) dx\right]$$

[Raether limit: $G \approx 10^8$; $\alpha x = 20$; then sparking sets in ...]

Avalanche phenomenon



* One electron drifts towards the anode wire:
  - Electric field is increasing
  - Ionizing collisions → pair multiplication

* Due to lateral diffusion and difference of velocity of electrons-ions, a drop-like avalanche develops near the wire

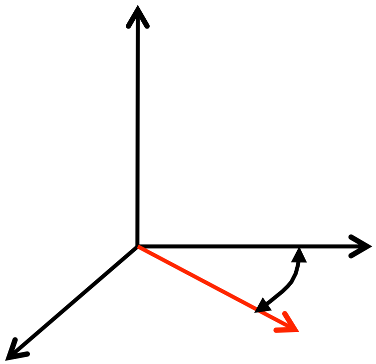
* UV photons are emitted → risk of uncontrolled amplification (spark)

* Electrons are collected in a very short time (few ns) and ions drift slowly towards the cathode

Magnetic field

The drifting electrons cloud is rotated by an angle θ_B in the plane perpendicular to E and B.

$\vec{E} \perp \vec{B}$



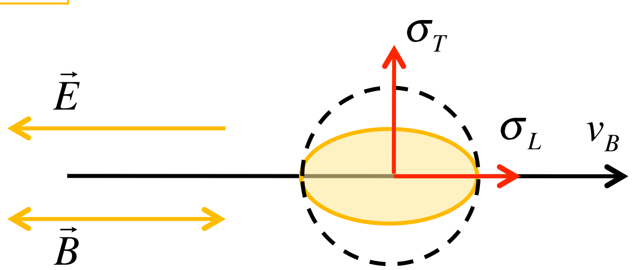
$$\tan\theta_B = \omega\tau$$

τ : mean collision time

$$v_B = \frac{E}{B}\frac{\omega\tau}{\sqrt{1+\omega^2\tau^2}}$$

$\omega = eB/m$ → Larmor frequency

$\vec{E} \parallel \vec{B}$



$$v_B = v_0$$

$$\sigma_L = \sigma_0$$

Drift velocity unchanged

$$\sigma_T = \frac{\sigma_0}{\sqrt{1+\omega^2\tau^2}}$$

Transverse diffusion is reduced

Back

To Backup

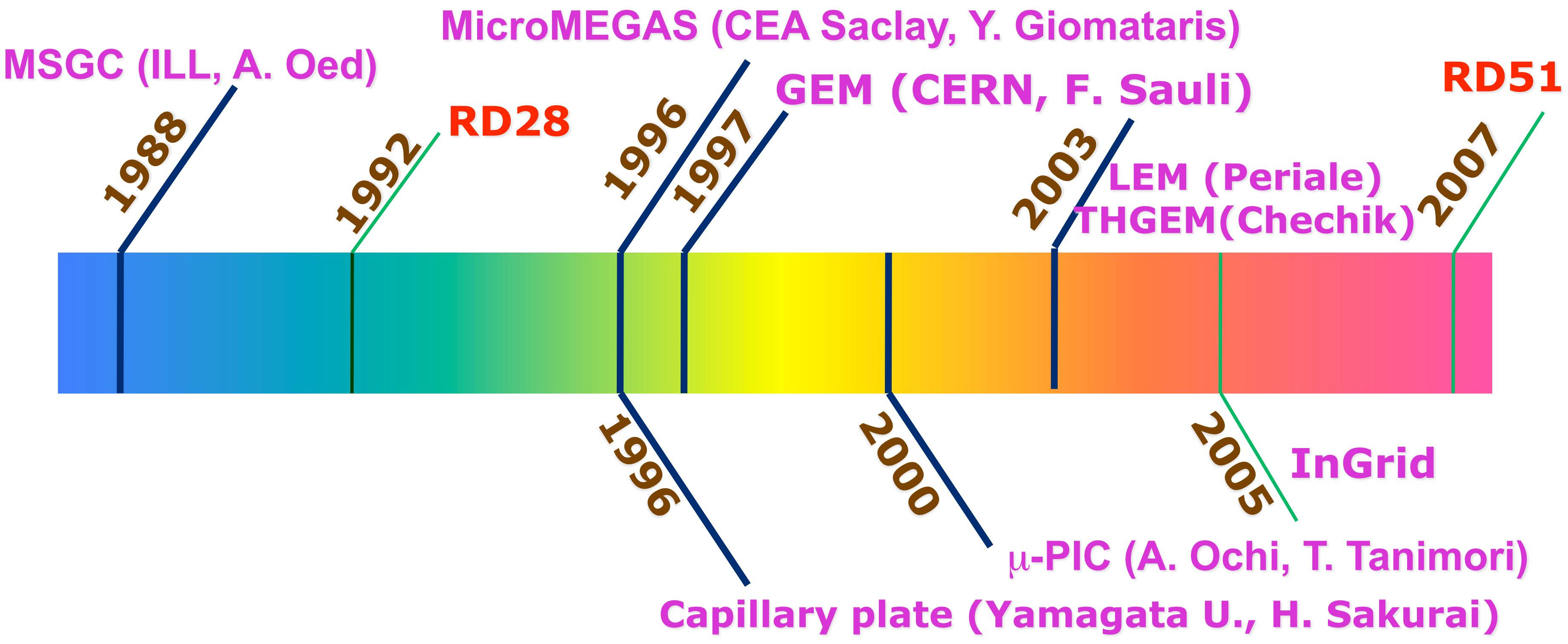
Gas Detectors

Large Volume Particle Tracking

Back

MPGD Developments: Historical Roadmap*

(*Many more micro-pattern structures were developed; shown only those presented in this talk)



From A.Ochi ADA2012@Kolkata (updated)

EXAMPLE OF GASEOUS DETECTORS

To Backup

Single Wire Proportional Counter

Relations:

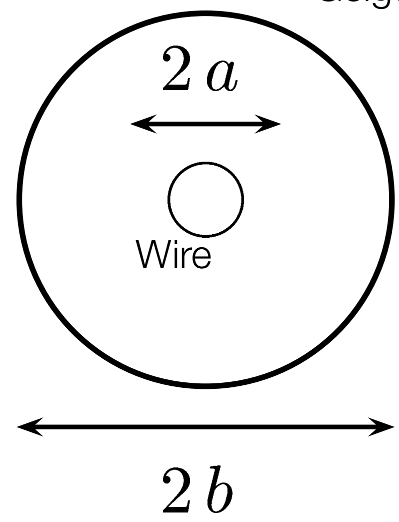
E-field: $|\vec{E}| = \frac{\lambda}{2\pi\epsilon_0}\frac{1}{r}$

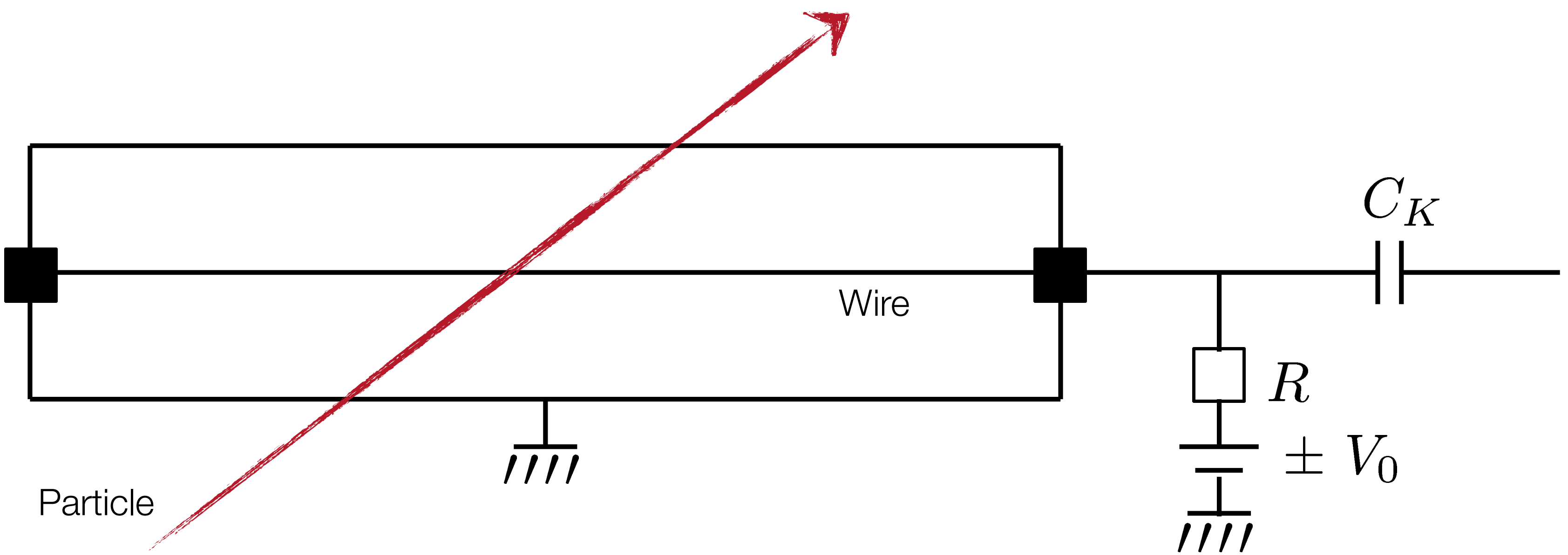
with:
$\lambda = Q/L$
[linear charge density]

Voltage: $V_0 = \frac{\lambda}{2\pi\epsilon_0}\ln\frac{b}{a} = \frac{\lambda}{C}$

Capacity: $C = \frac{2\pi\epsilon_0}{\ln\frac{b}{a}}$ [F/m]
[per unit length]

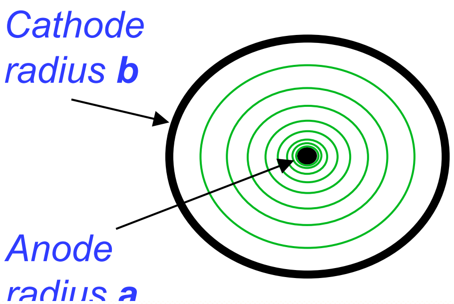
Geiger Counter





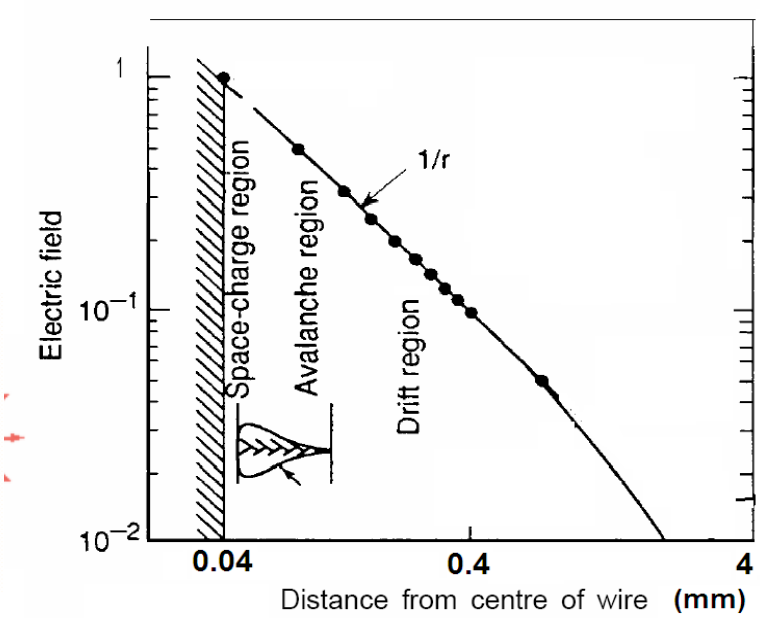
Single Wire Proportional Counter

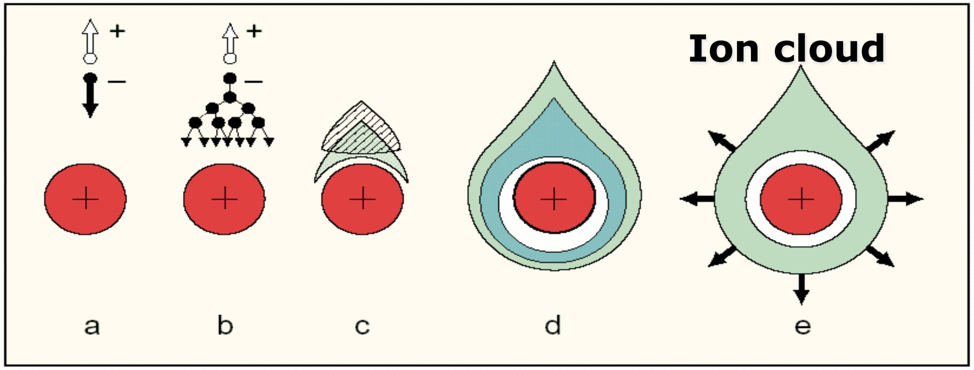
Thin anode wire (~20–50μm) coaxial with cathode:



$$E(r) = \frac{CV_0}{2\pi\varepsilon_0}\frac{1}{r}$$

Avalanche development in the high electric field (~ 250 kV/cm) around a thin wire (multiplication region ~ 100 μm):





Time development of an avalanche in a proportional counter

A single primary electron proceeds towards anode in regions of increasingly high fields, experiencing ionizing collisions; due to the lateral diffusion, a drop-like avalanche, surrounding the wire develops.

Moving charges create signal on nearby electrodes – the electron induced signal is almost negligible !!!

Single Wire Proportional Counter

Ionization mode:

full charge collection
no multiplication; gain ≈ 1

Proportional mode:

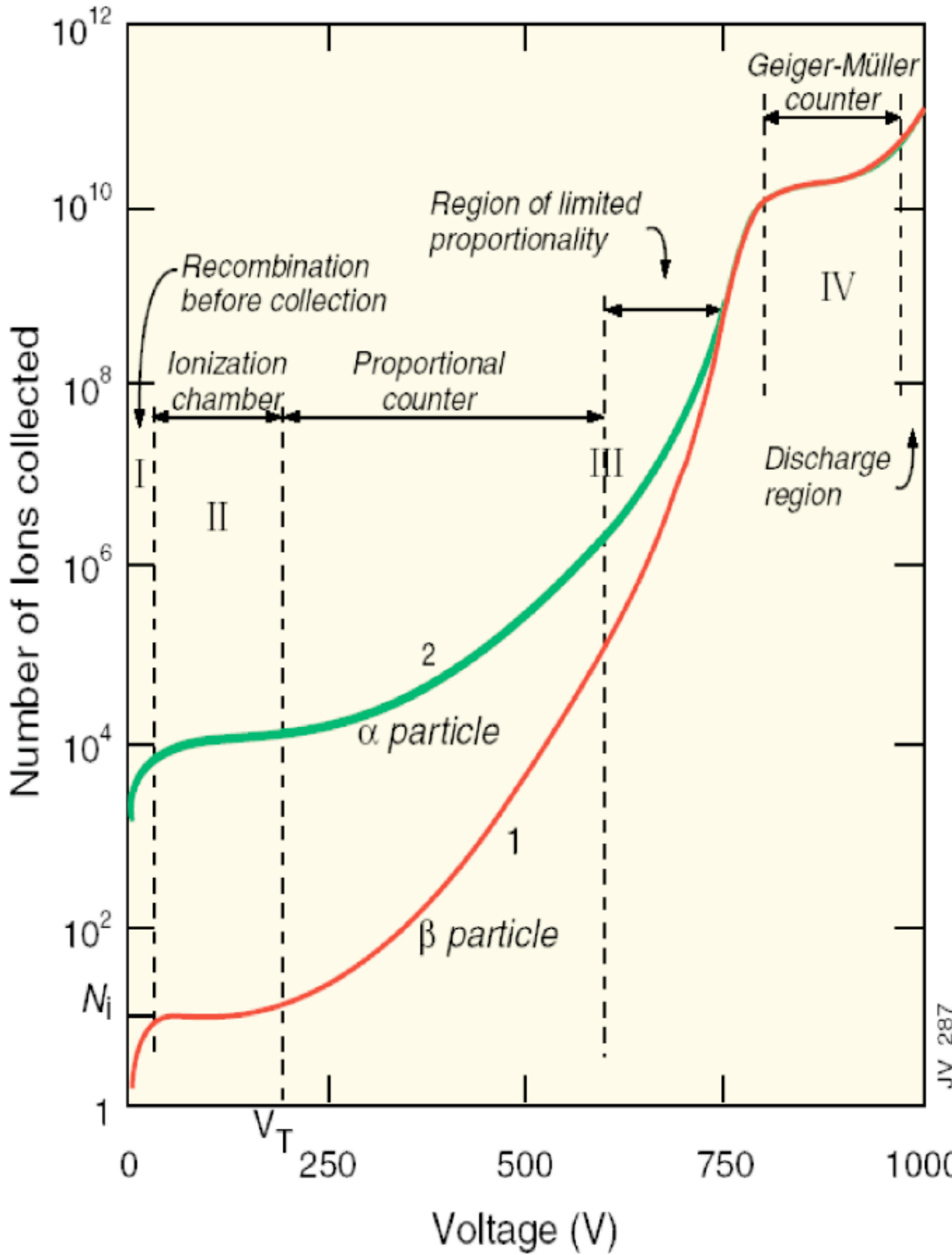
multiplication of ionization
signal proportional to ionization
measurement of dE/dx
secondary avalanches need quenching;
gain ≈ $10^4 - 10^5$

Limited proportional mode:
[saturated, streamer]

strong photoemission
requires strong quenchers or pulsed HV;
gain ≈ 10^{10}

Geiger mode:

massive photoemission;
full length of the anode wire affected;
discharge stopped by HV cut



Drift Chambers - Principle

Measure drift time t_D
[need to know t_0; fast scintillator, beam timing]

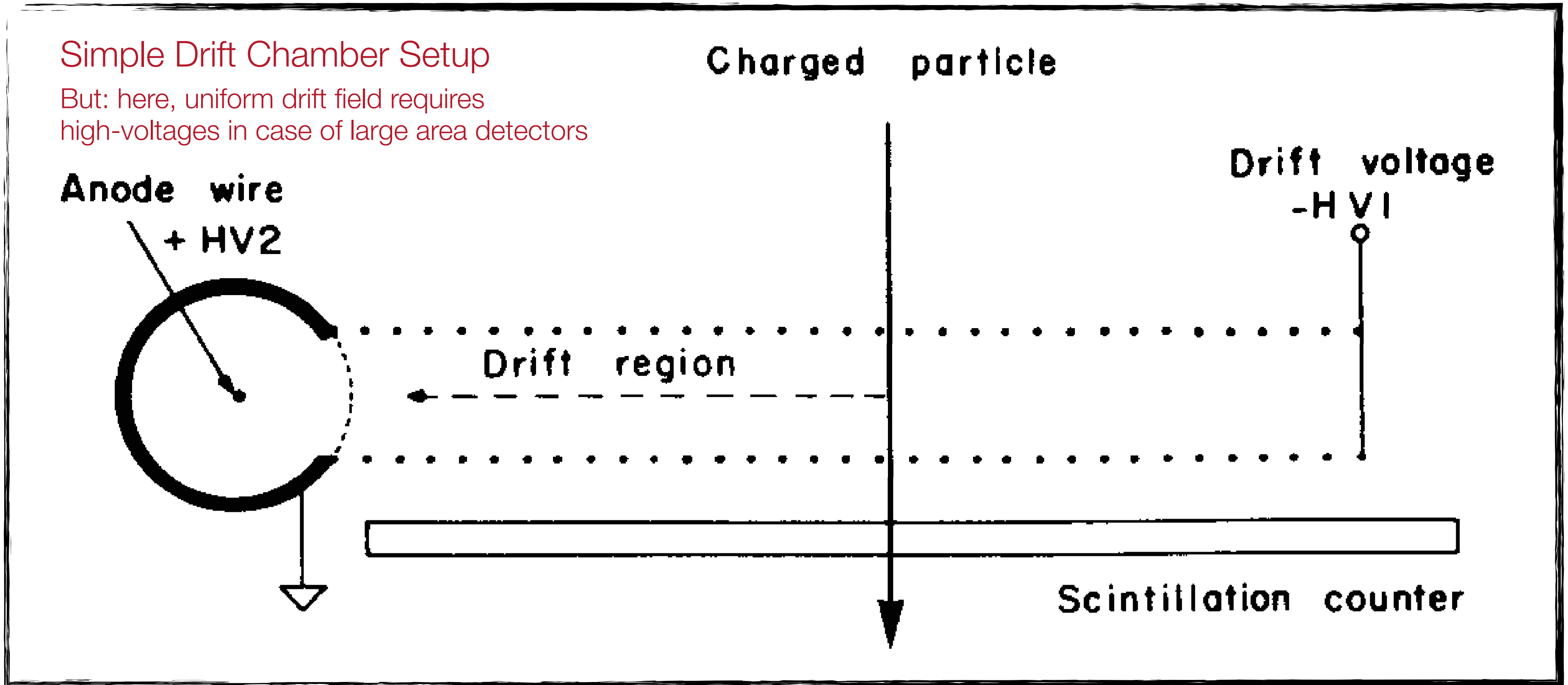
Determine location of original ionization:

$$x = x_0 \pm v_D \cdot t_D$$
$$y = y_0 \pm v_D \cdot t_D$$

If drift velocity changes along path:

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

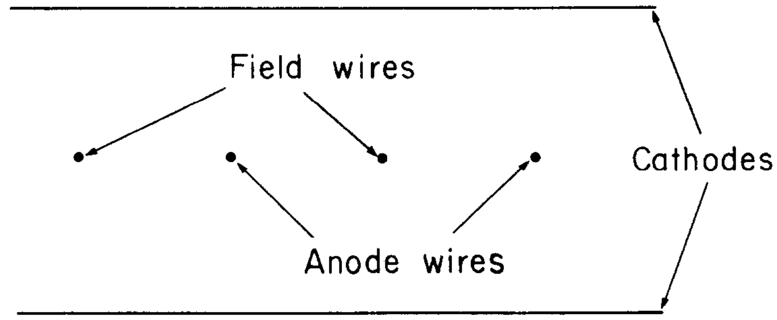
In any case:
Need well-defined drift field ...



Drift Chambers - Field Formation

Modified MWPC ...

Introduce field wires to avoid
low field regions, i.e. long drift-times



Field wires are
at negative potential ...

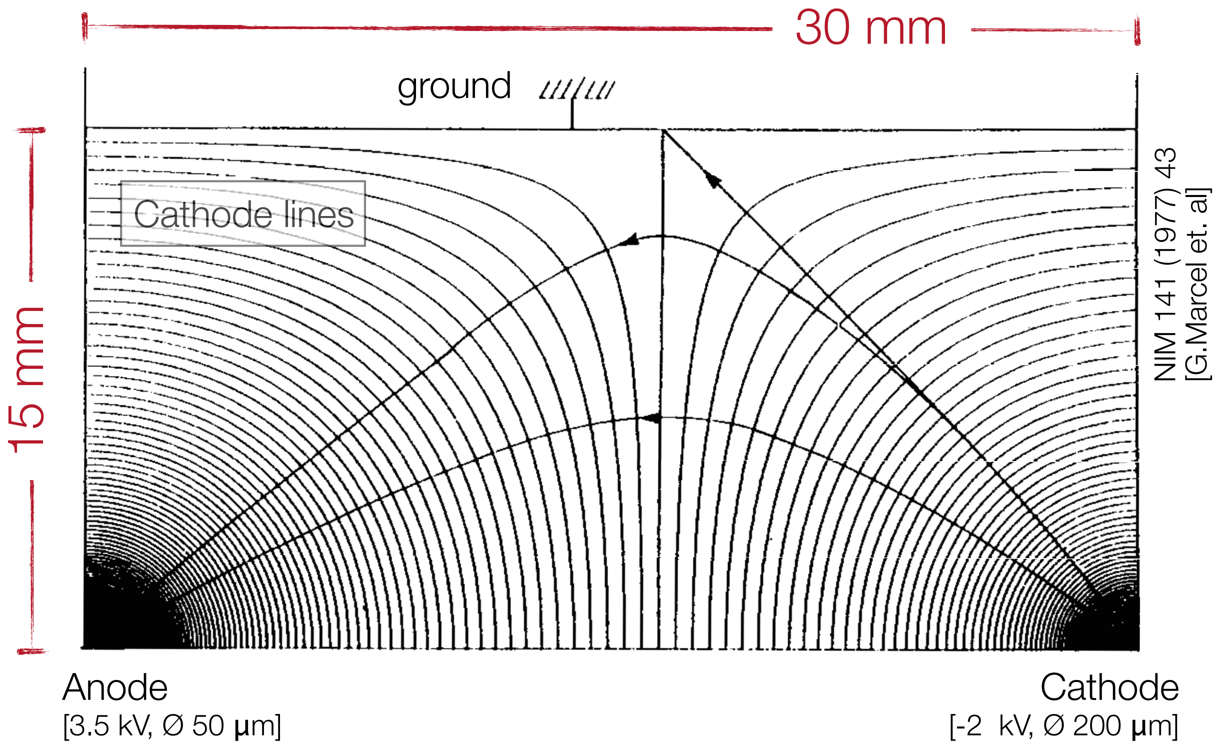
Anode wires are
at positive potential ...

Cathode planes are
at zero potential ...

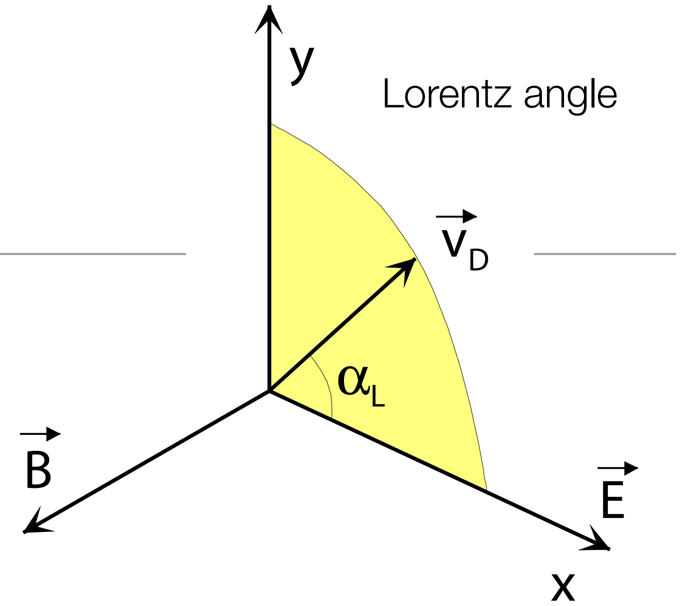
But:

Uniform drift field requires:
Gap length/wire spacing ≈ 1

i.e. for typical convenient wire spacing
one needs thick chambers ...



Drift Chambers – Lorentz Angle



Require B field for momentum measurement ...

In general drift field E ⊥ to B field ...

➛ Lorentz angle: $\alpha_L = \measuredangle(\vec{v}_D, \vec{E})$ ...

Reminder:

$$\vec{v}_D = \frac{\mu|\vec{E}|}{1+\omega^2\tau^2}\left[\hat{\vec{E}} + \underbrace{\omega\tau\hat{\vec{E}} \times \hat{\vec{B}}}_{\text{Component } \perp \text{ to E,B}} + \underbrace{\omega^2\tau^2(\hat{\vec{E}}\cdot\hat{\vec{B}})\hat{\vec{B}}}_{\text{Component in direction of B}}\right]$$

Using:

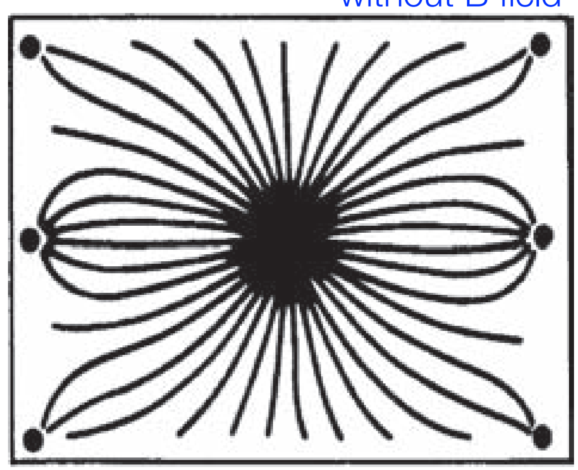
$$v_{D,x} = \frac{\mu E}{1+\omega^2\tau^2}$$

$$v_{D,y} = \frac{\mu E}{1+\omega^2\tau^2}\cdot\omega\tau$$

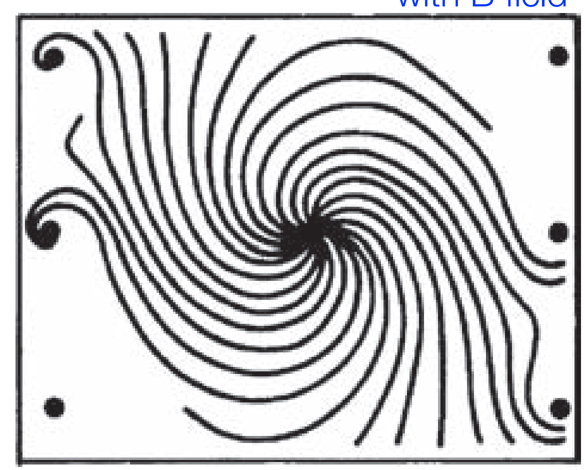
➛ $$\tan\alpha_L = \omega\tau = v_D\frac{B}{E}$$

[with $\omega = \frac{eB}{m}$ and $\tau = \frac{mv_D}{eE}$]

without B field



with B field



Resolution determined by
accuracy of drift time measurement ...

Influenced by:

Diffusion [$\sigma_{Diff.} \sim \sqrt{x}$]

see above: $\sigma^2 \sim 2Dt = 2Dx/v_D \sim x$ ...

δ-electrons [σ_δ = const.]

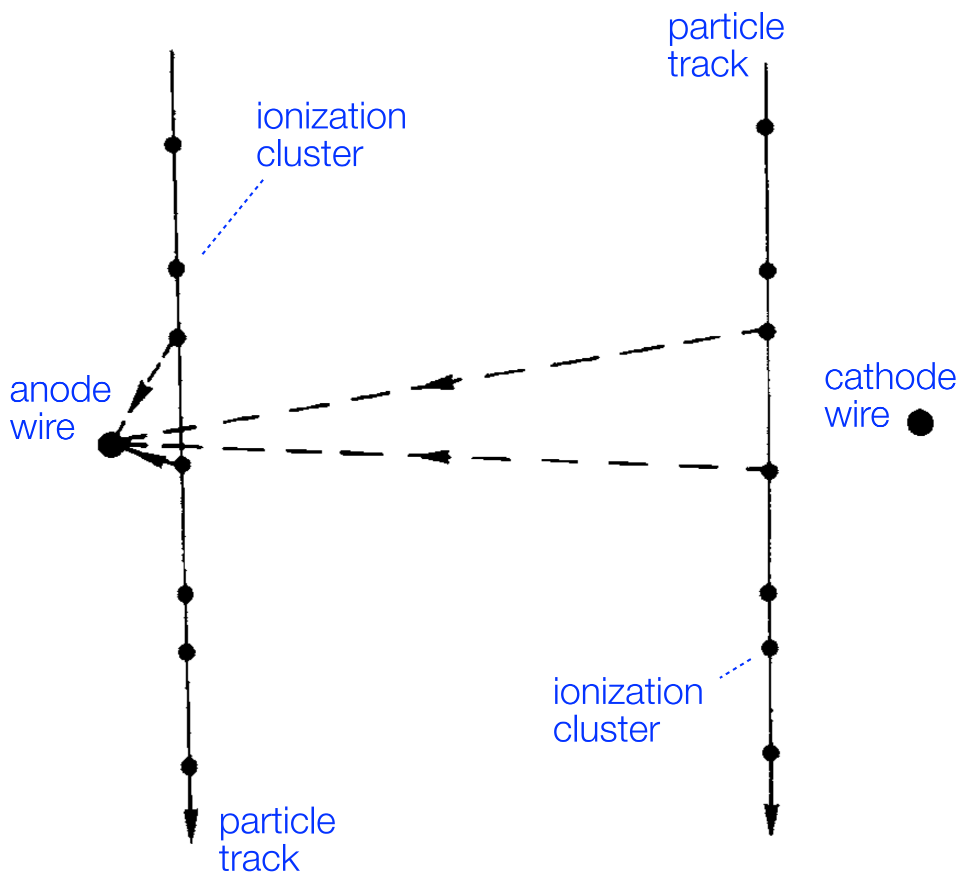
independent of drift length; yields constant term in spatial resolution ...

Electronics [$\sigma_{electronics}$ = const.]

contribution also independent of drift length ...

Primary ionization statistics [$\sigma_{prim} = 1/x$]

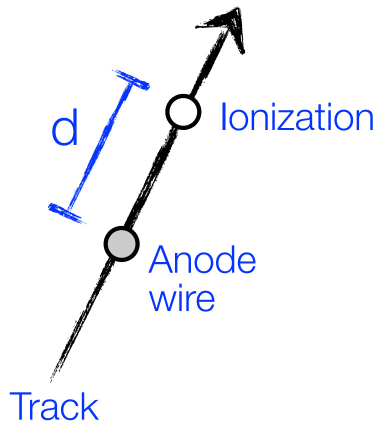
Spatial fluctuations of charge-carrier production result in large drift-path differences for particle trajectories close to the anode ...
[minor influence for tracks far away from anode]



Drift Chamber - Spatial Resolution

Primary ionization statistics:

Step 1: Consider a track passing through an anode wire ...

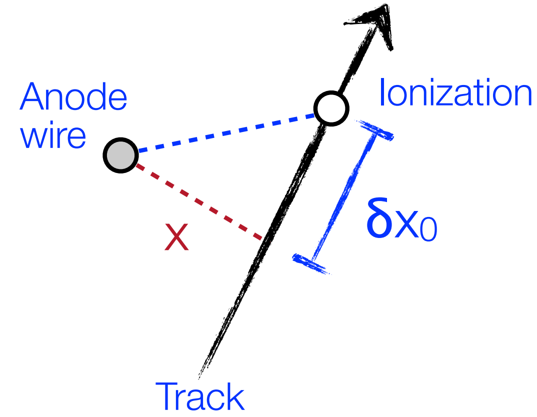


Probability of no ionization within distance d:

$$P_0(d) = e^{-2Nd}$$

with
N: number of ionizations per unit length

Average minimum distance of closest ionization cluster:



Normalization

$$\delta x_0 = \langle d_{\min} \rangle = \int_0^\infty x e^{-2Nx}\, 2N\, dx = \frac{1}{2N}$$

$$\sigma^2_{\langle d_{\min} \rangle} = \int_0^\infty (x - \frac{1}{2N})^2 e^{-2Nx}\, 2N\, dx = \frac{1}{4N^2}$$

Step 2: Track at distance x ...

$$\delta x = \sqrt{x^2 + (\delta x_0)^2} - x = x \left(\sqrt{1 + \left(\frac{\delta x_0}{x}\right)^2} - 1 \right) \approx \frac{x}{2} \left(\frac{\delta x_0}{x}\right)^2 \propto \frac{1}{x}$$

Drift Chamber - Spatial Resolution

$$\sigma_x^2 = \left(\frac{1}{64N^2}\right)\cdot\frac{1}{x^2} + \frac{2D}{v_d}\cdot x + \sigma_{\mathrm{const}}^2$$

1st ionization statistics — diffusion — electronics, δ-electrons

Possible improvements:

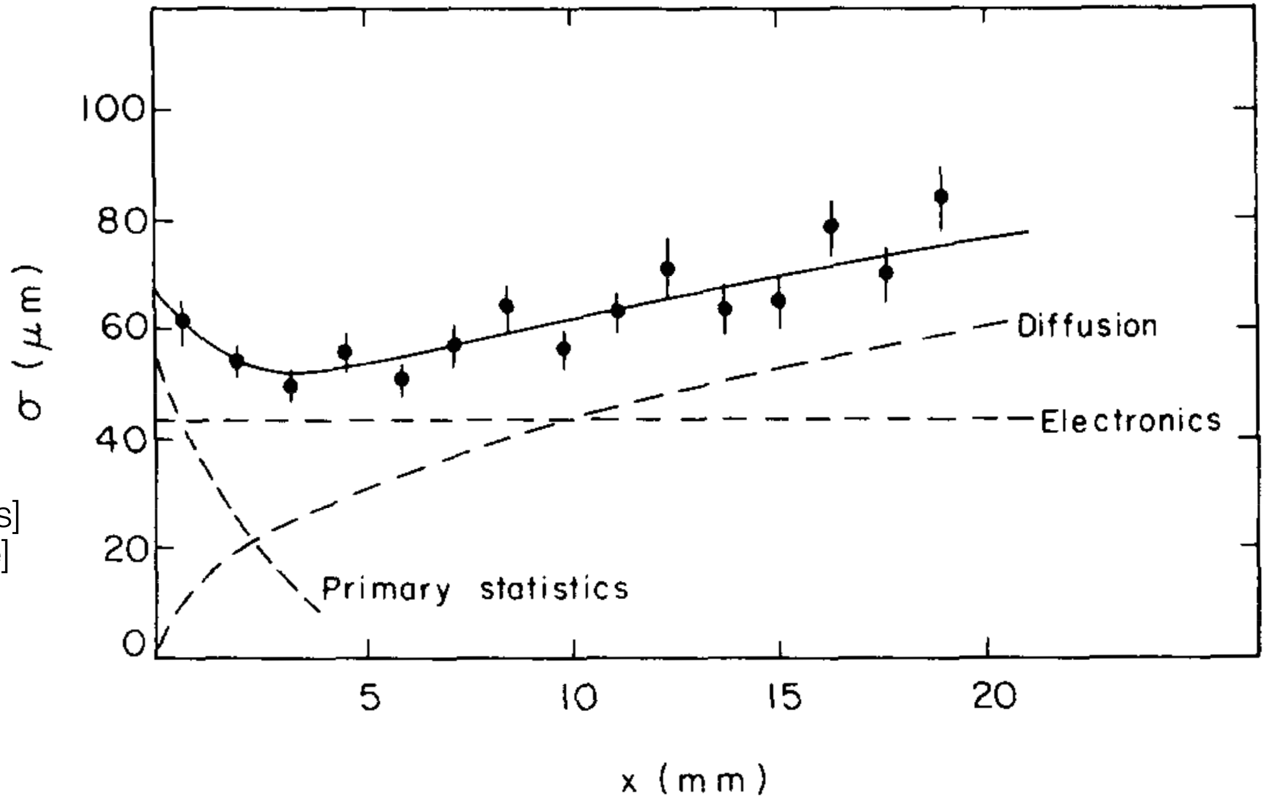
Increase N by increasing pressure ...

Decrease D by increasing pressure ...

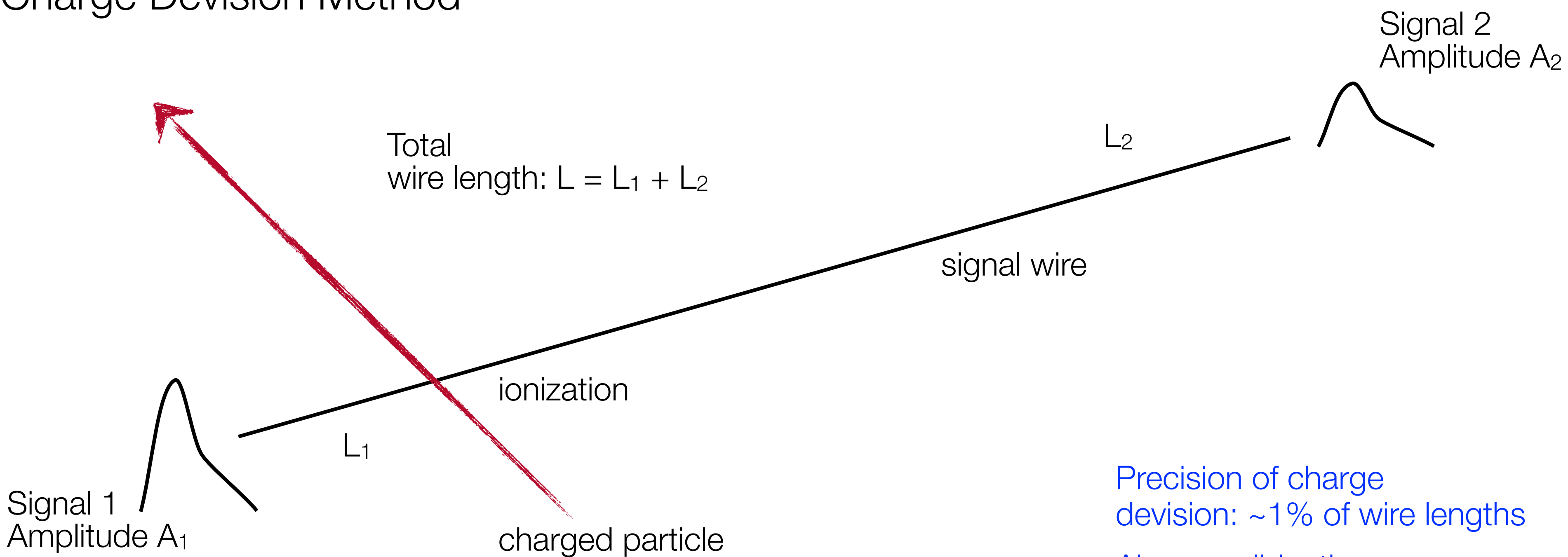
$$D \sim \frac{\lambda_0^2}{\tau} \sim \frac{1/n^2}{1/n} \sim \frac{1}{n}$$

[n: particle density in gas]
[increases with pressure]

i.e.: increase pressure ...
[up to 4 atm possible]



Principle of
Charge Devision Method



Precision of charge devision: ~1% of wire lengths

Also possible: time measurement on both ends

Determination of L_1, L_2:

$$L_2 = \frac{A_1}{A_1 + A_2} \cdot L \qquad L_1 = \frac{A_2}{A_1 + A_2} \cdot L$$

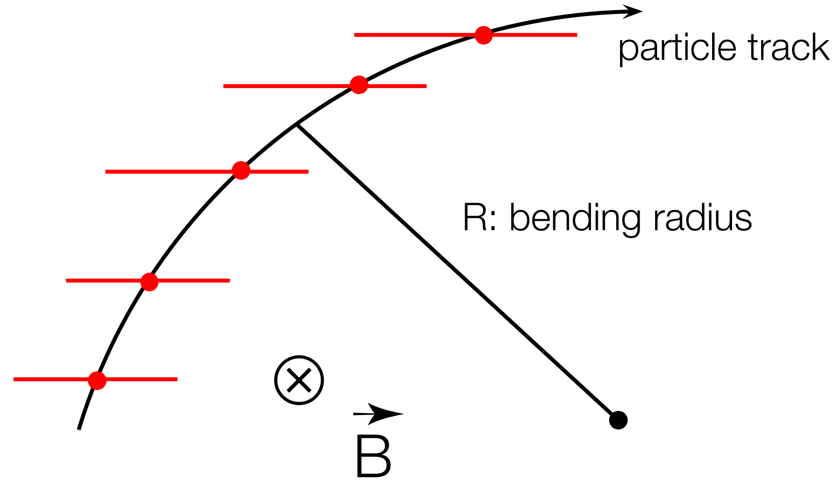
Magnetic Spectrometer Resolution

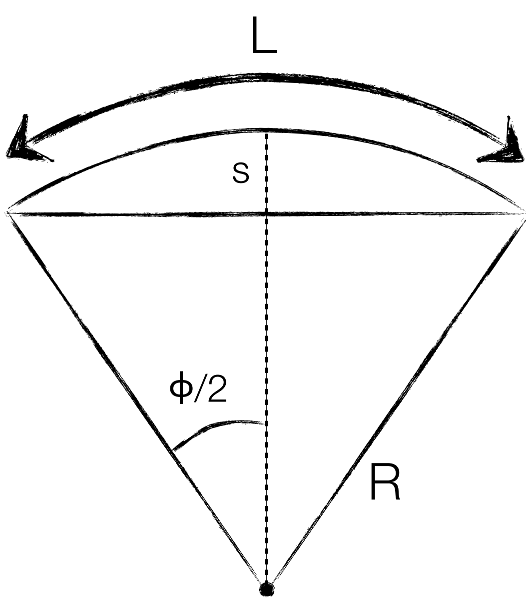
Momentum determination

in a cylindrical drift chamber ...

$$\frac{mv^2}{R} = evB \quad \rightarrow \quad p = eB \cdot R$$

$$\boxed{p \left[\frac{\text{GeV}}{c}\right] = 0.3 B\,[\text{m}] \cdot R\,[\text{T}]}$$





For Sagitta s:

$$s = R - R\cos\frac{\phi}{2} \approx R\,\frac{\phi^2}{8} \qquad \text{with } \phi = \frac{L}{R}$$

$$s = R\frac{L^2}{8R^2} = \frac{L^2}{8R} \quad \text{and} \quad R = \frac{L^2}{8s}$$

$$\rightarrow \quad \frac{\Delta p}{p} = \frac{\Delta R}{R} = \frac{L^2}{8Rs} \cdot \frac{\Delta s}{s}$$

Magnetic Spectrometer Resolution

Momentum measurement uncertainty:

$$\frac{\sigma_p}{p} = \frac{L^2}{8Rs}\cdot\frac{\sigma_s}{s} = \frac{L^2}{8R}\cdot\frac{\sigma_s}{L^4/64R^2} = \frac{\sigma_s}{L^2}\cdot 8R = \frac{\sigma_s}{L^2}\cdot\frac{8p}{eB} \sim p\cdot\frac{\sigma_s}{BL^2}$$

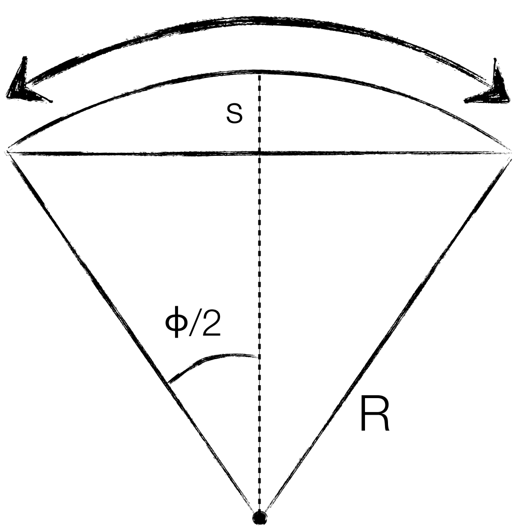
Uncertainty σ_s depends on number and spacing of track point measurements; for equal spacing and large N:

$$\sigma_s = \frac{\sigma_{r\phi}}{8}\sqrt{\frac{720}{N+5}}$$

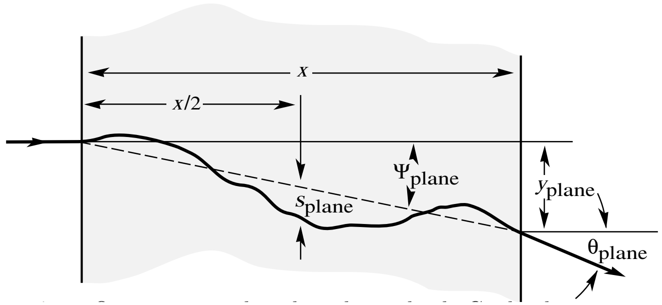
see: Glückstern, NIM 24 (1963) 381 or
Blum & Rolandi, Particle Detection ...

Good momentum resolution:

- large path length L
- large magnetic field B
- good Sagitta measurement



Multiple scattering contribution:



Reminder:

$$\sigma_\phi = \frac{13.6\mathrm{MeV}}{\beta c p} z\sqrt{x/X_0}\,[1+0.038\ln(x/X_0)]$$

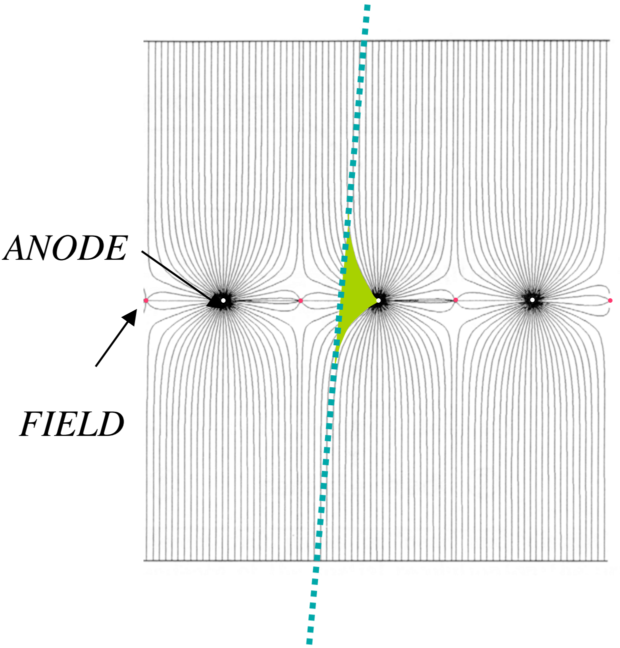
$$\sigma_\phi \approx \frac{14\ \mathrm{MeV}/c}{p}\sqrt{\frac{L}{X_0}}$$ and $$\frac{\sigma_p}{p} = \frac{\sigma_R}{R} = \frac{\sigma_\phi}{\phi}$$

as $R = \frac{L}{\phi}$

Drift Chambers

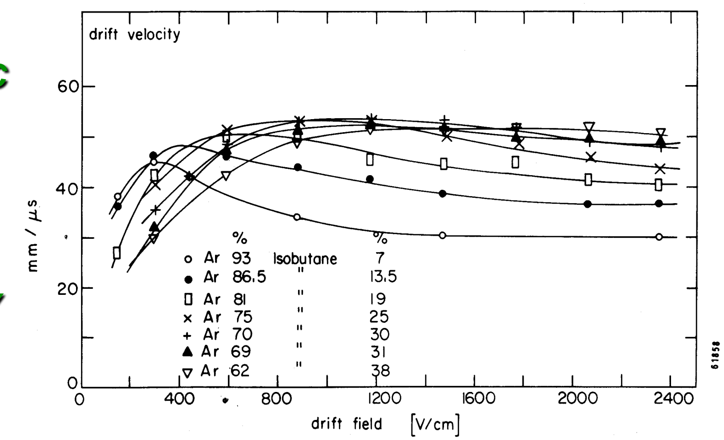
FIRST DRIFT CHAMBER OPERATION (H. WALENTA ~ 1971)
HIGH ACCURACY DRIFT CHAMBERS (Charpak-Breskin-Sauli ~ 1973-75)

THE ELECTRONS DRIFT TIME PROVIDES THE DISTANCE OF THE TRACK FROM THE ANODE:



HIGH AND UNIFORM ELECTRIC FIELD IN MOST OF THE VOLUME

Preferetially GAS MIXTURE WITH SATURATED DRIFT VELOCITY (linear space-time relation)



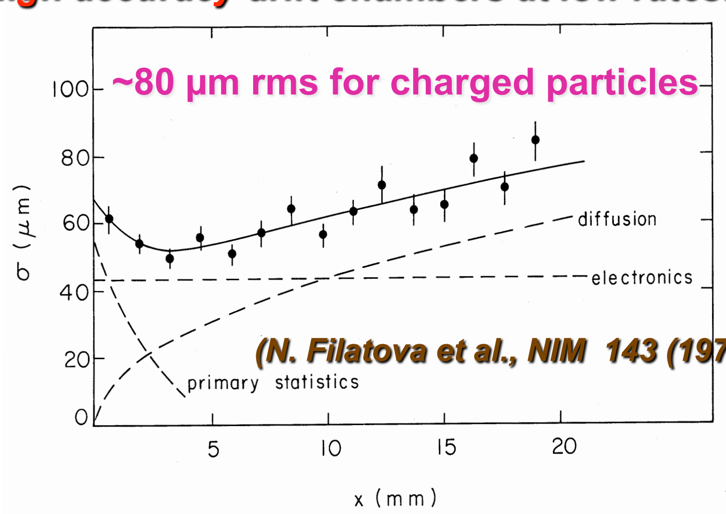
The spatial resolution is not limited to the cell size

Space resolution determined by:

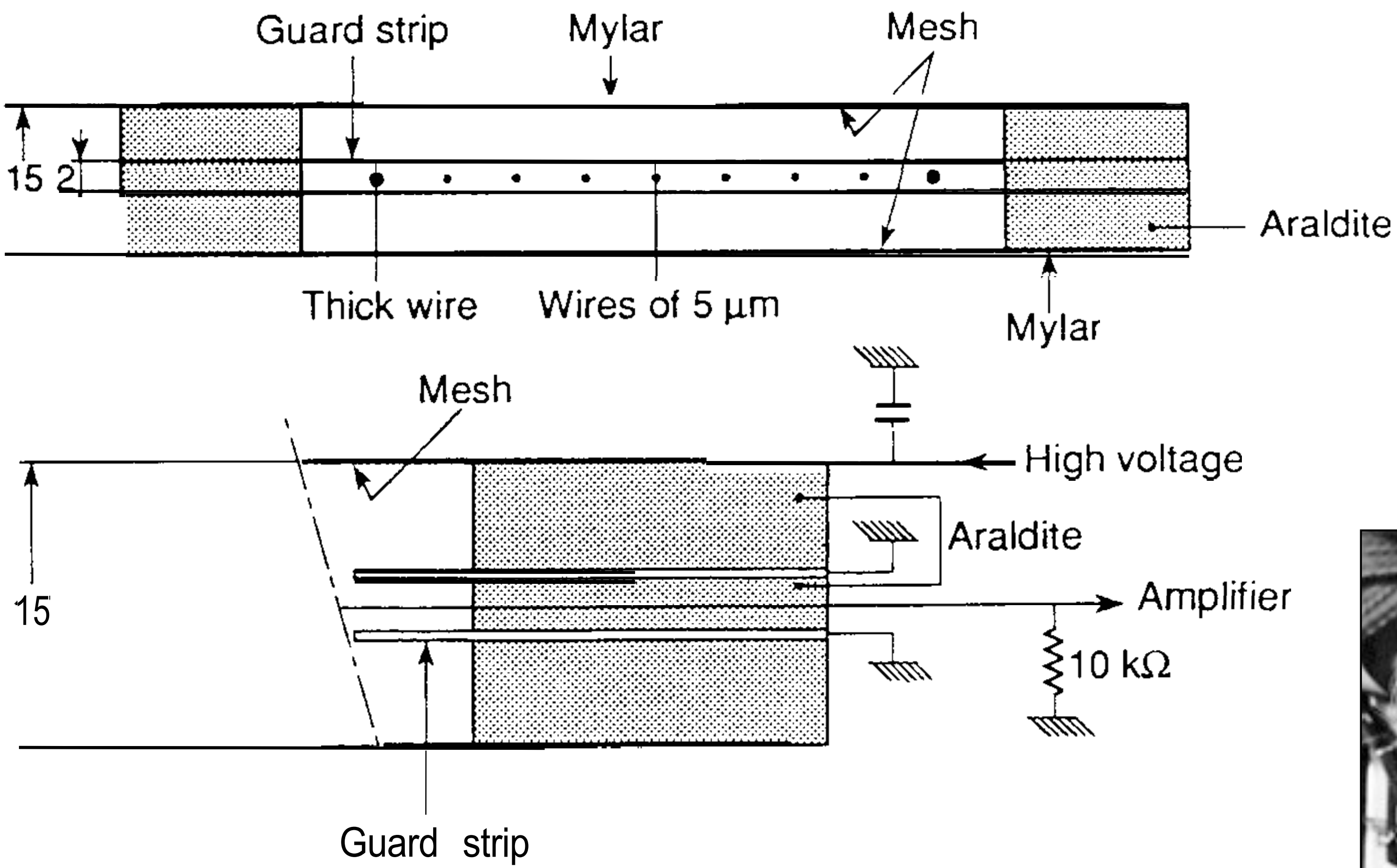
- *Distribution of primary ionization*
- *Diffusion*
- *Readout electronics*
- *Electric field (gas amplification)*
- *Range of 'delta electrons'*

A. Breskin et al, Nucl. Instr. and Meth. 124(1975)189

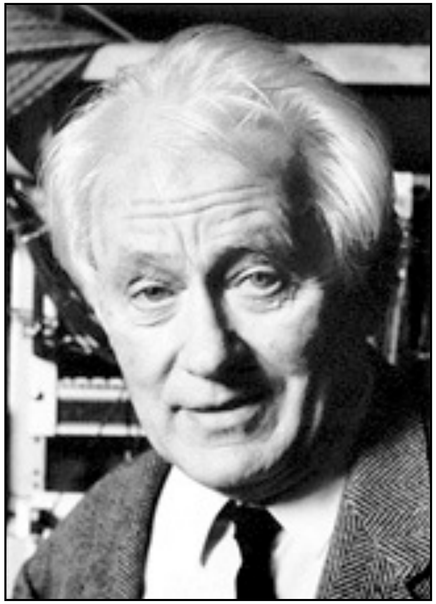
High accuracy drift chambers at low rates:



(N. Filatova et al., NIM 143 (1977) 17)



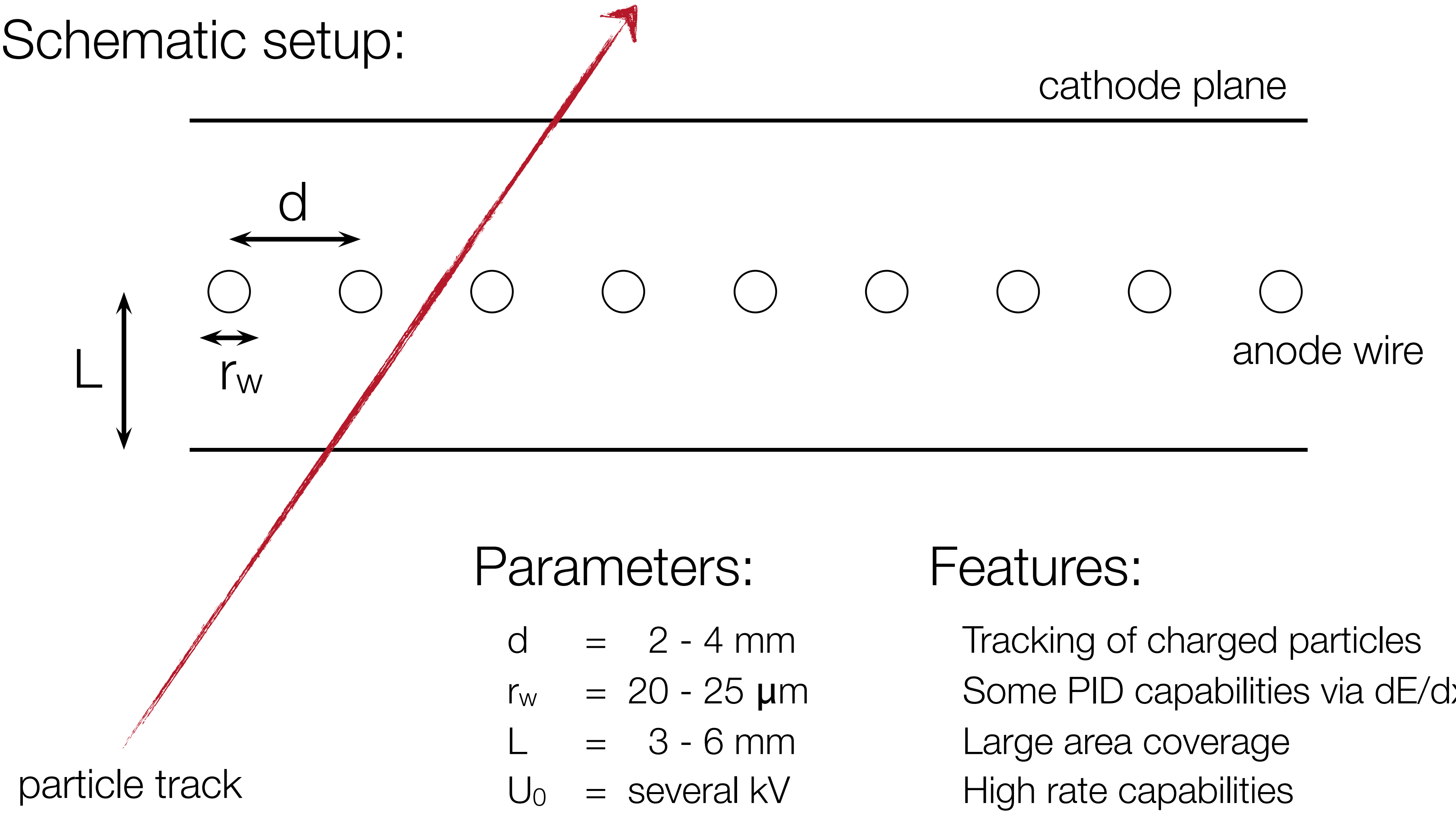
G. Charpak
Nobel Prize 1992



MWPC construction details
from Charpak's nobel lecture [1967 design]

Sense wires [∅ = 20 µm] separated by 2 mm; wires lie between two cathode meshes; edges of the planes are potted in Araldite ...

Schematic setup:



Parameters:

- $d = 2 - 4$ mm
- $r_W = 20 - 25$ μm
- $L = 3 - 6$ mm
- U_0 = several kV

Total area: $O(m^2)$

Features:

- Tracking of charged particles
- Some PID capabilities via dE/dx
- Large area coverage
- High rate capabilities

Multi-Wire Proportional Chamber (MWPC)

Signal generation:

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

main contribution

Timing resolution:

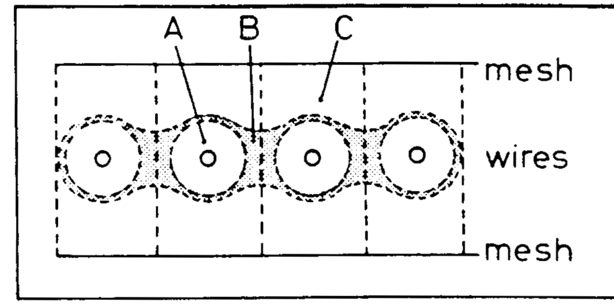
Depends on location of penetration
For fast response: OR of all channels ...
[Typical: σ_t = 10 ns]

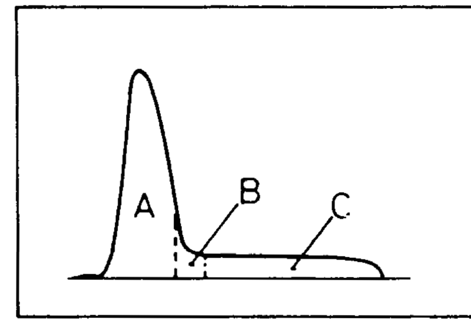
Space point resolution:

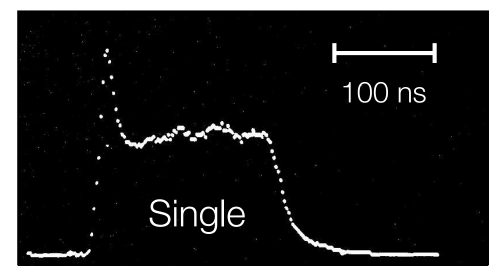
Only information about closest wire ➛ $\sigma_x = d/\sqrt{12}$
[Not very precise and only one for one dimension ...]

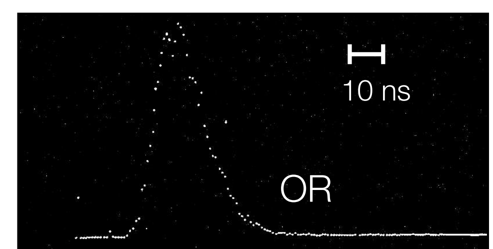
2-dim.: use 2 MWPCs with different orientation ...
3-dim.: several layers of such X-Y-MWPC combinations.

Possible improvement: segmented cathode ...

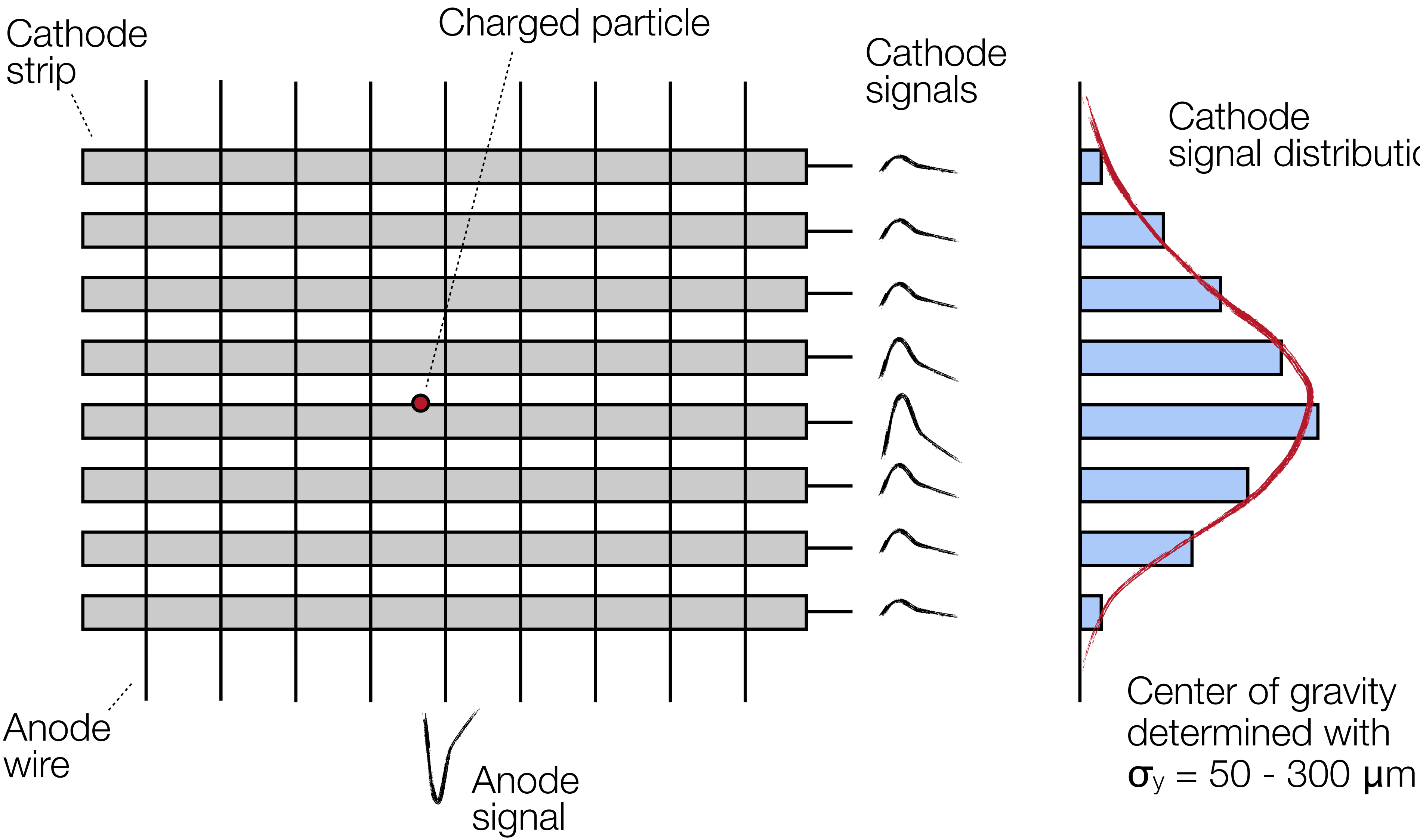






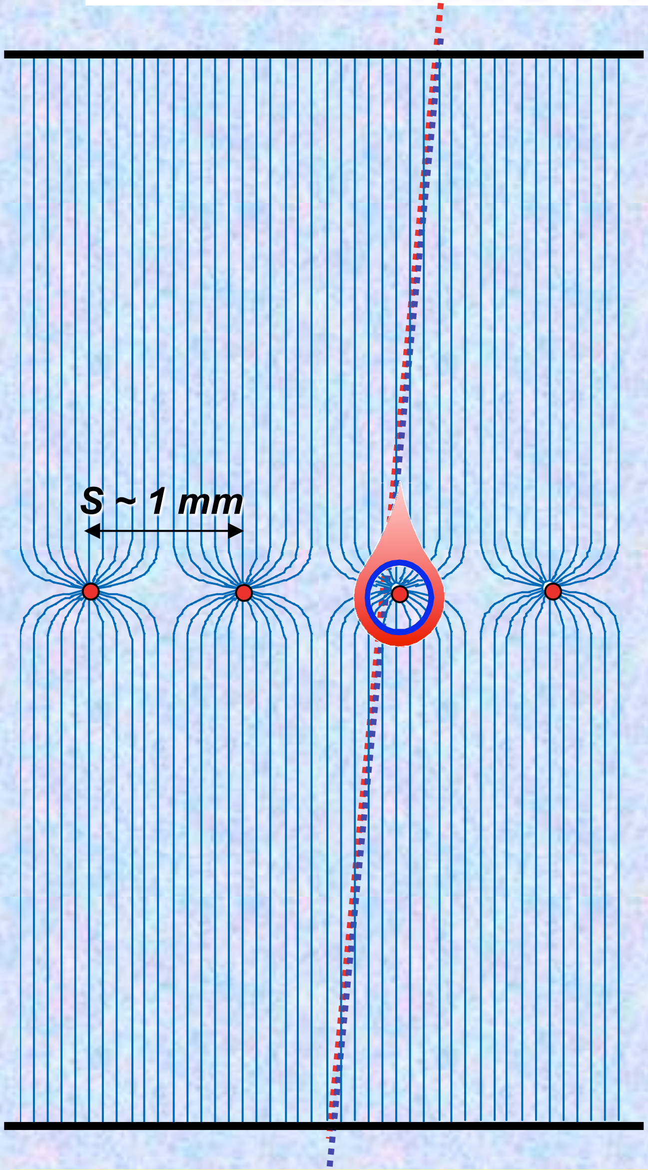


Multi-Wire Proportional Chamber (MWPC)



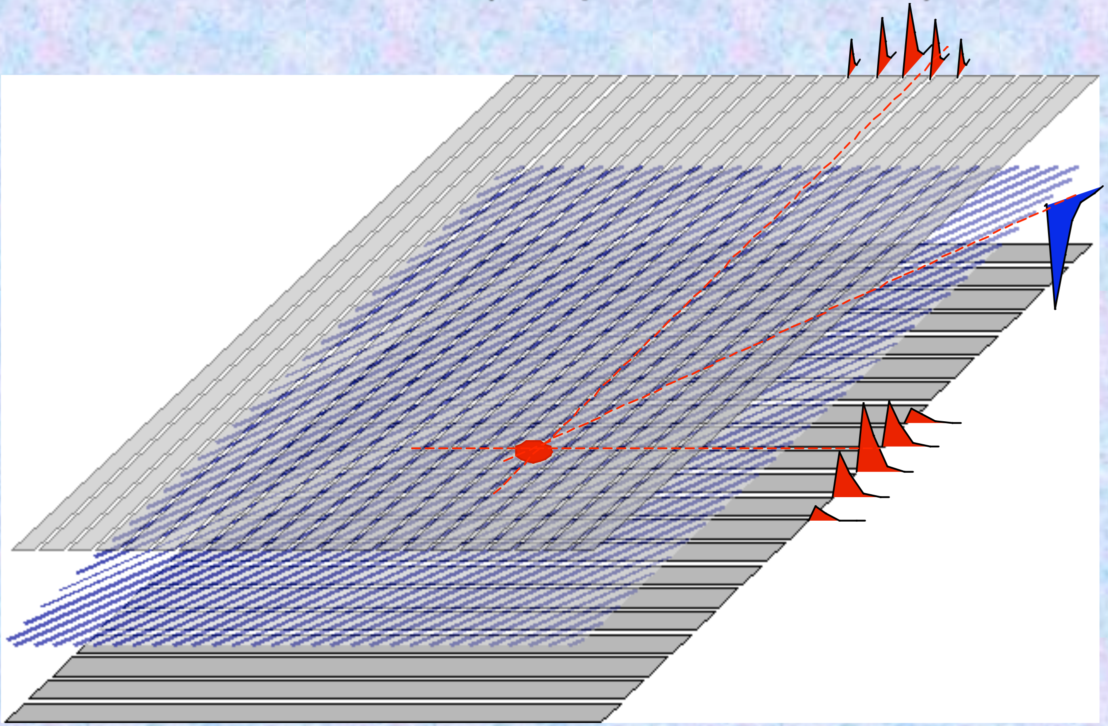
Center of gravity determined with σ_y = 50 - 300 μm

Multi-Wire Proportional Chamber (MWPC)



High-rate MWPC with digital readout:
Spatial resolution is limited to $s_x \sim s/\mathrm{sqrt}(12) \sim 300\ \mu m$

TWO-DIMENSIONAL MWPC READOUT CATHODE INDUCED CHARGE (Charpak and Sauli, 1973)



Spatial resolution determined by: Signal / Noise Ratio
Typical (i.e. 'very good') values: S ~ 20000 e: noise ~ 1000e
Space resolution < 100 μm

Resolution of MWPCs limited by wire spacing
better resolution → shorter wire spacing → more (and more) wires…

Time Projection Chambers

Electronic 'bubble chamber'
Full 3D reconstruction ...

xy : from wires and pads of MWPC ...
z : from drift time measurement

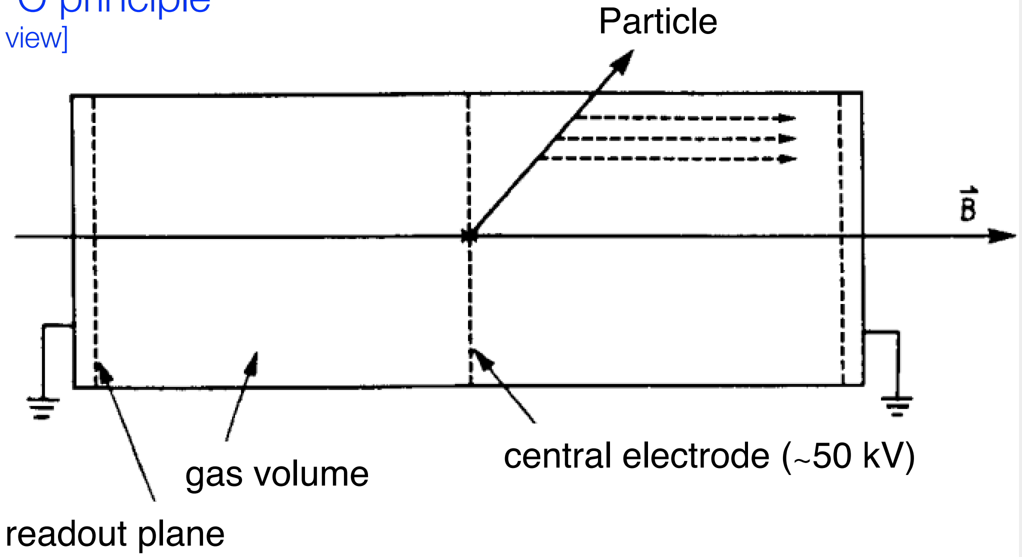
Momentum measurement ...

space point measurement
plus B field ...

Energy measurement ...

via dE/dx ...

TPC principle
[rz view]



TPC setup:

(mostly) cylindrical detector

central HV cathode
MWPCs at end-caps of cylinder

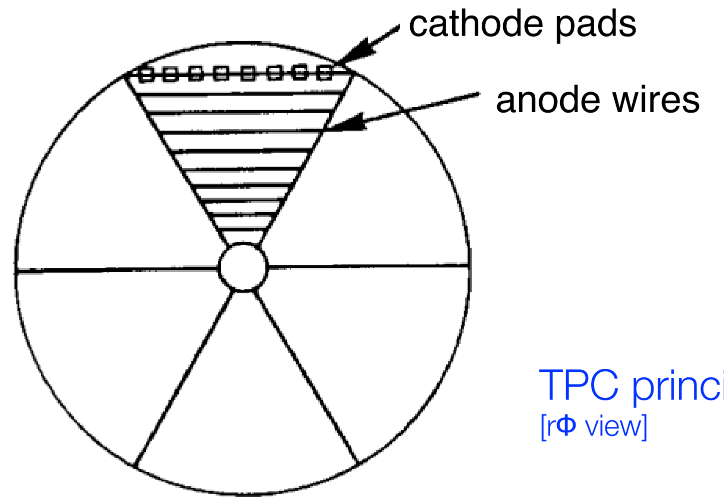
B || to E ➛ Lorentz angle = 0

Charge transport :

Electrons drift to end-caps

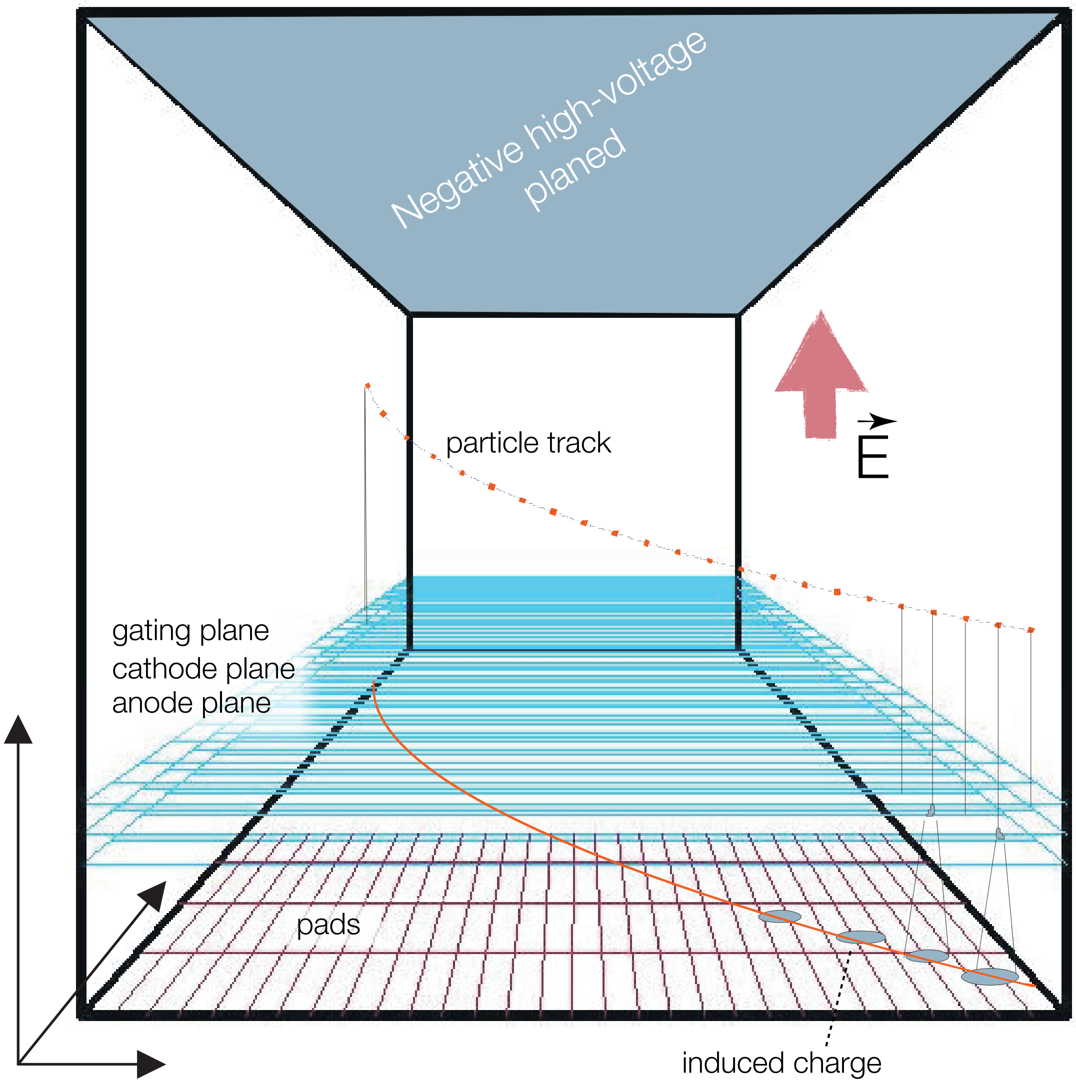
Drift distance several meters

Continuous sampling of induced charges in MWPC



TPC principle
[rΦ view]

Time Projection Chambers



Advantages:

Complete track within one detector yields good momentum resolution

Relative few, short wires (MWPC only)

Good particle ID via dE/dx

Drift parallel to B suppresses transverse diffusion by factors 10 to 100

Challenges:

Long drift time; limited rate capability [attachment, diffusion ...]

Large volume [precision]

Large voltages [discharges]

Large data volume ...

Extreme load at high luminosity; gating grid opened for triggered events only ...

Typical resolution:

z: mm; x: 150 - 300 μm; y: mm
dE/dx: 5 - 10%

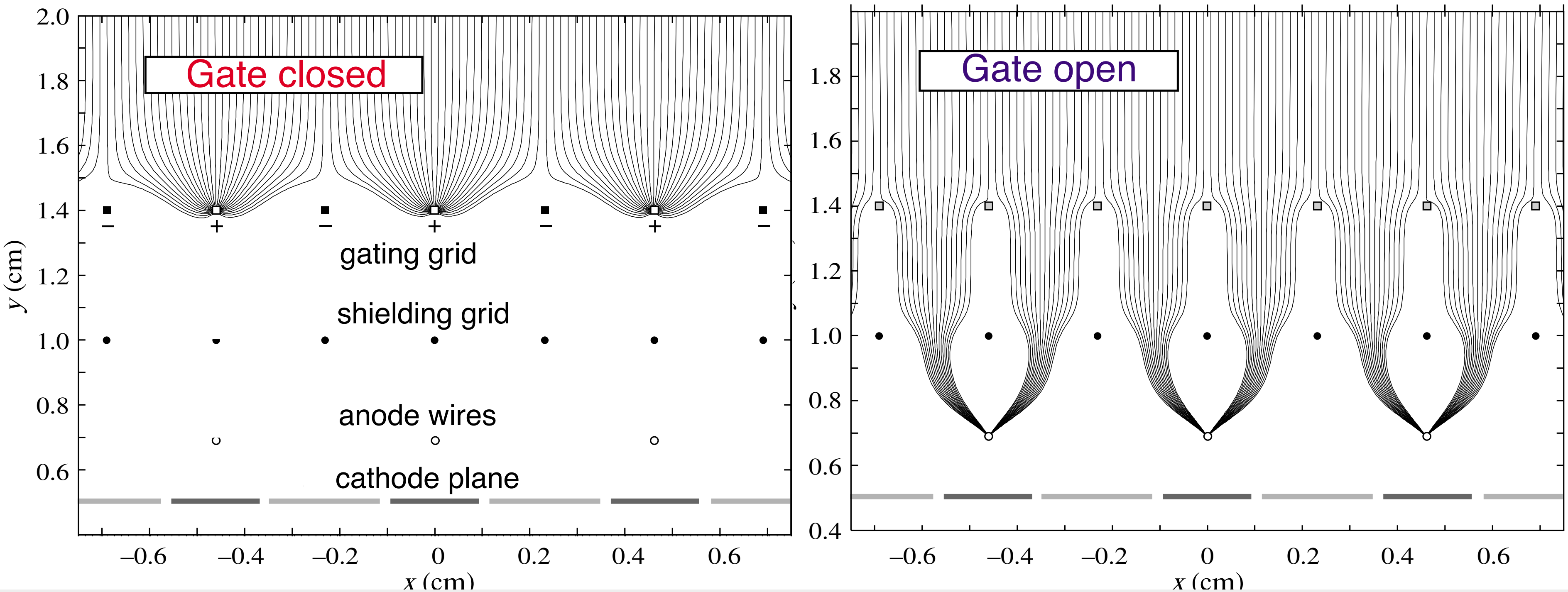
Difficulty: space charge effects due to slow moving ions change effective E-field in drift region ....

Important: most ions come from amplification region

Solution: Invention of gating grid; ions drift towards grid ...

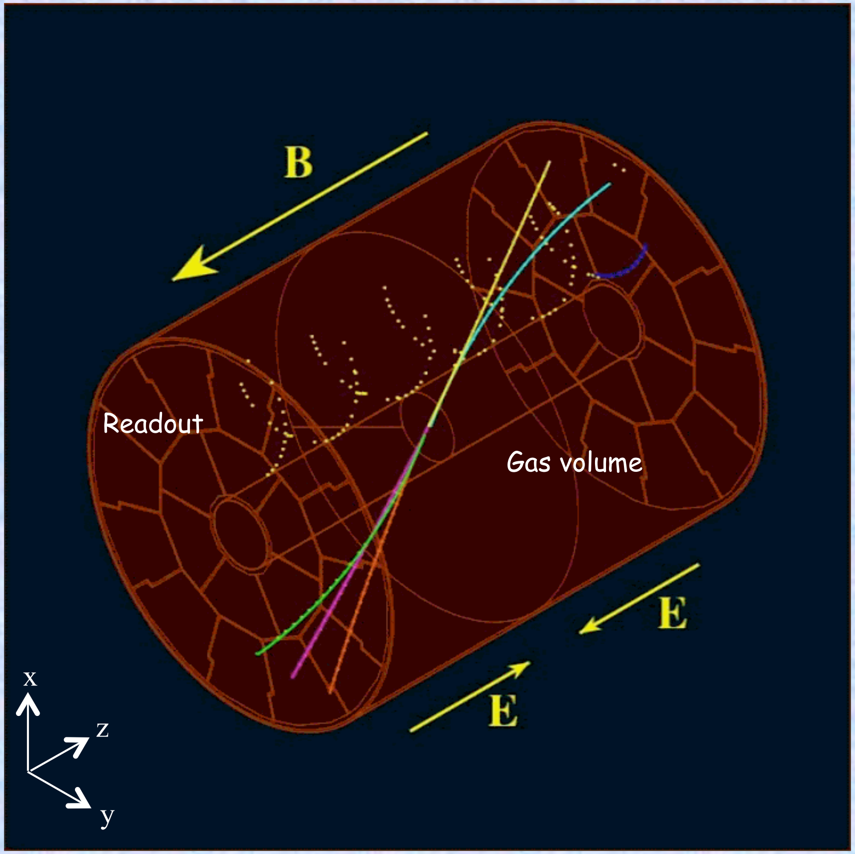
[Also: shielding grid to avoid sense wire disturbance when switching]

Requires external trigger to switch gating grid ...



Time Projection Chamber (TPC)

The TPC is a gas-filled cylindrical chamber with one or two endplates (D. Nygren, 1974)



1976: proposal for PEP4 at LBL
Proven technology: DELPHI, ALEPH (LEP), Ceres, NA49, STAR (heavy-ion experiments)
Future experiments: ALICE (LHC), ILC

	STAR	ALICE	ILC
Inner radius (cm)	50	85	32
Outer radius (cm)	200	250	170
Length (cm)	2 * 210	2 * 250	2 * 250
Charge collection	wire	wire	MPGD
Pad size (mm)	2.8 * 11.5 6.2 * 19.5	4 * 7.5 6*10(15)	2 * 6
Total # pads	140000	560000	1200000
Magnetic field [T]	0.5	0.5	4
Gas Mixture	Ar/CH4 (90:10)	Ne/CO2 (90:10)	Ar/CH4/CO2 (93:5:2)
Drift Field [V/cm]	135	400	230
Total drift time (μs)	38	88	50
Diffusion $\sigma_T(\mu m/\sqrt{cm})$	230	220	70
Diffusion $\sigma_L(\mu m/\sqrt{cm})$	360	220	300
Resolution in $r\varphi (\mu m)$	500-2000	300-2000	70-150
Resolution in $r z (\mu m)$	1000-3000	600-2000	500-800
dE/dx resolution [%]	7	7	< 5
Tracking efficiency[%]	80	95	98

Ingredients:

- Field cage for the E field
- Magnet for the B field
- Amplification system at the endplates
- Gating grid to suppress the ion feedback
- Laser calibration

ALICE TPC:

Length: 5 meter
Radius: 2.5 meter
Gas volume: 88 m^3

Total drift time: 92 μs
High voltage: 100 kV

End-cap detectors: 32 m^2
Readout pads: 557568

159 samples radially
1000 samples in time

Gas: $Ne/CO_2/N_2$ (90-10-5)
Low diffusion (cold gas)

Gain: > 10^4

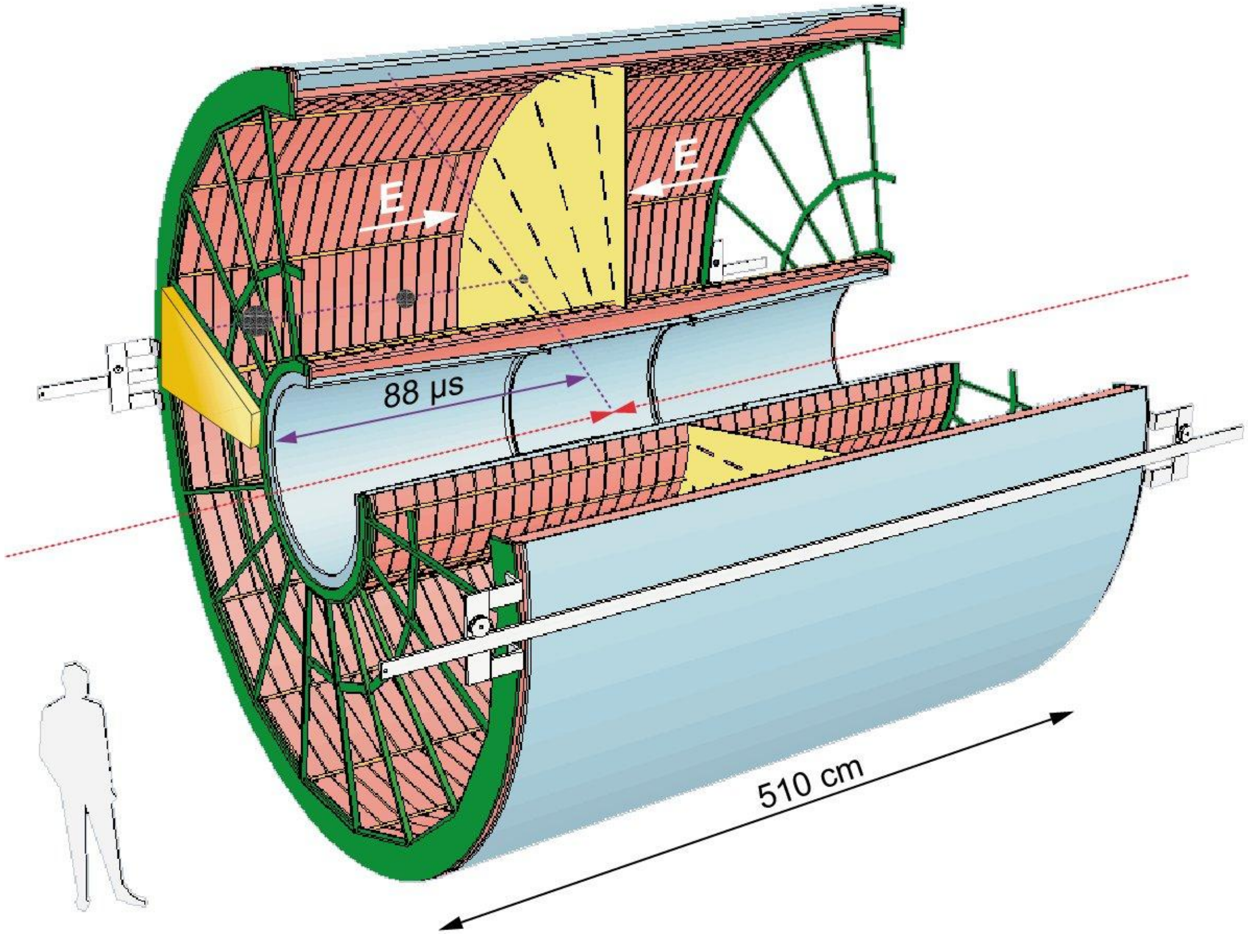
Diffusion: σ_t = 250 μm
Resolution: $\sigma \approx$ 0.2 mm

σ_p/p ~ 1% p; ε ~ 97%
$\sigma_{dE/dx}/(dE/dx)$ ~ 6%

Magnetic field: 0.5 T

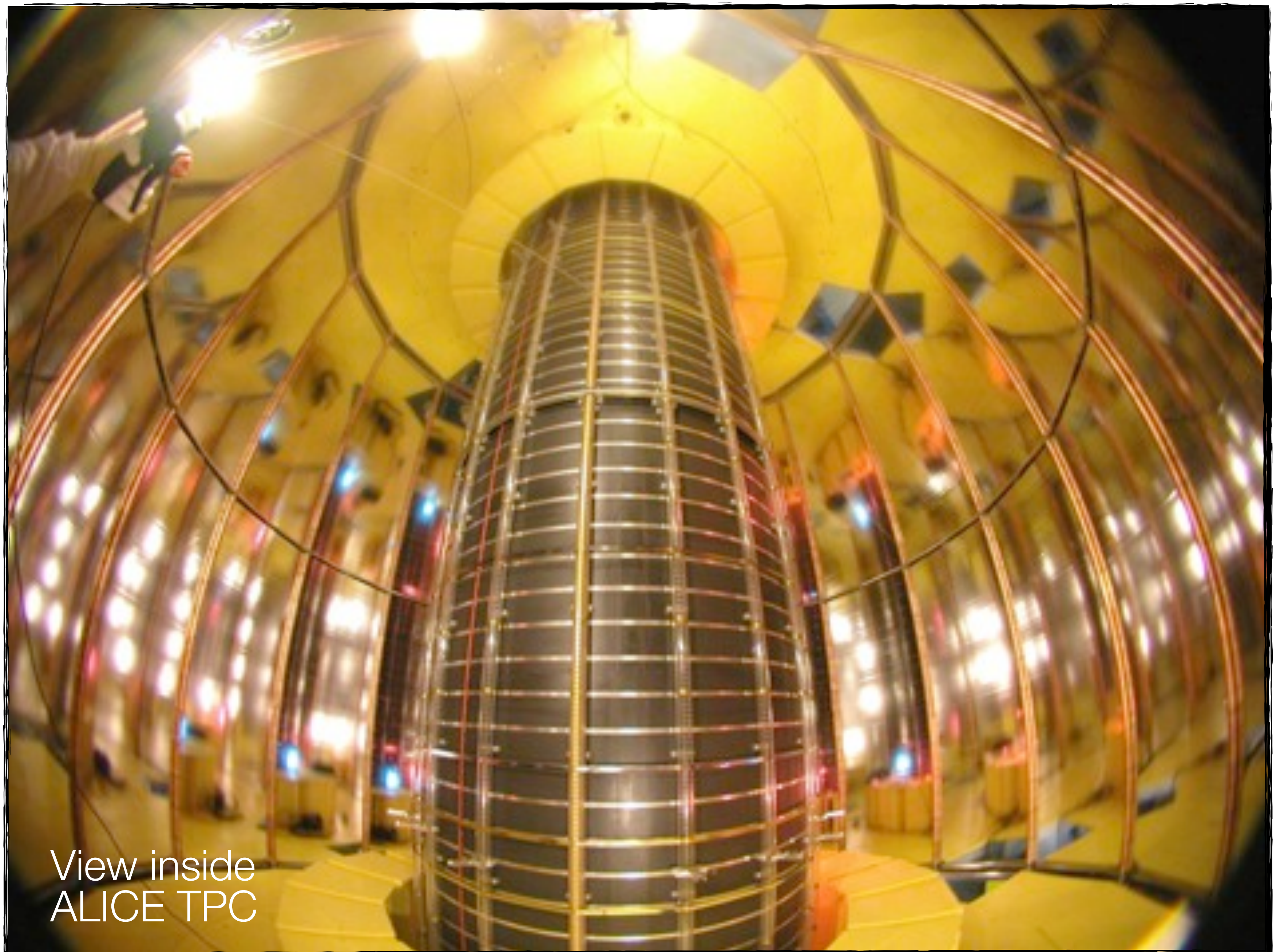
Pad size: 5x7.5 mm^2 (inner)
6x15 mm^2 (outer)

Temperature control: 0.1 K
[also resistors ...]



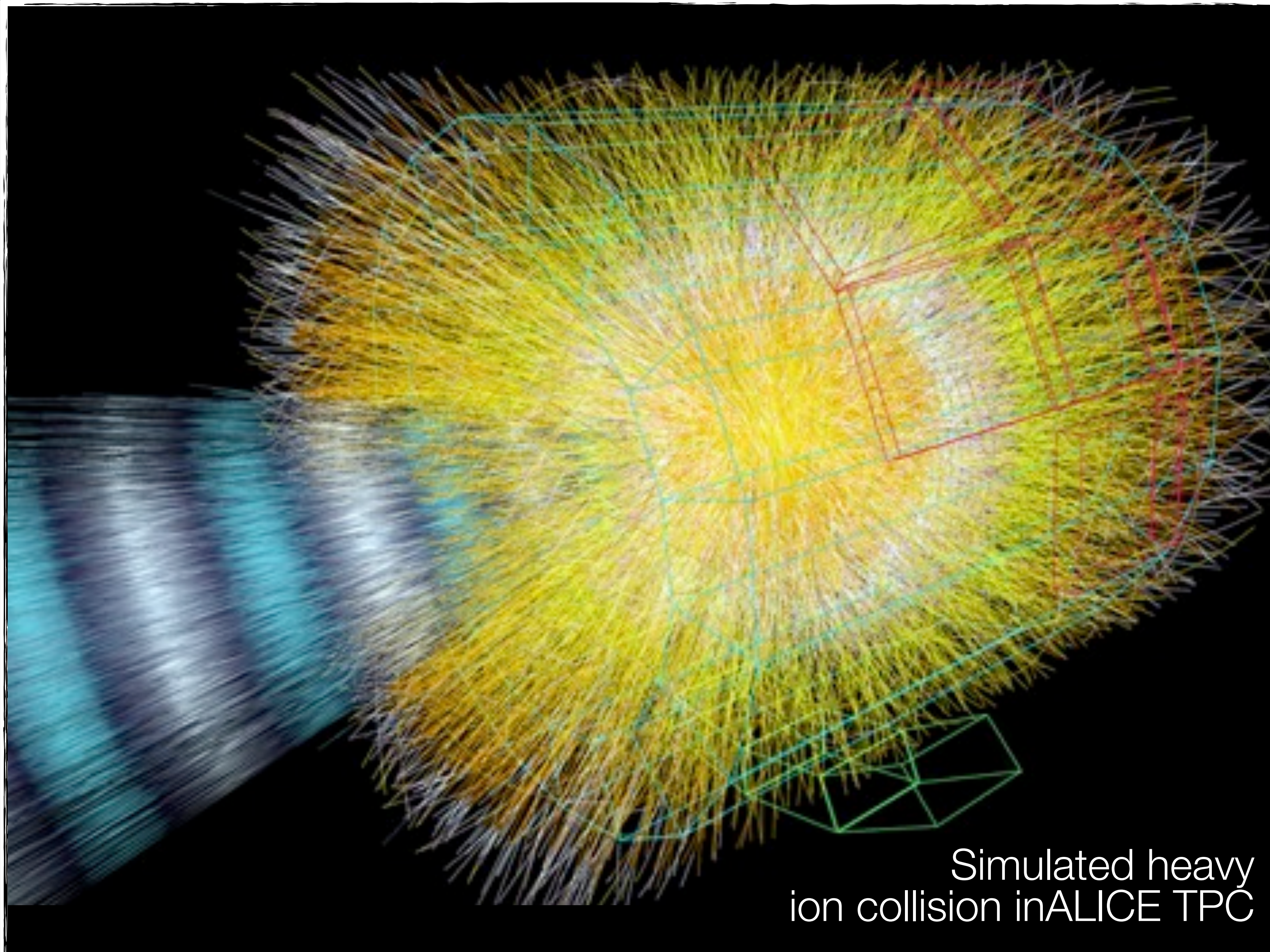
Material: Cylinder build from composite material of airline industry (X_0= ~ 3%)

Time Projection Chambers

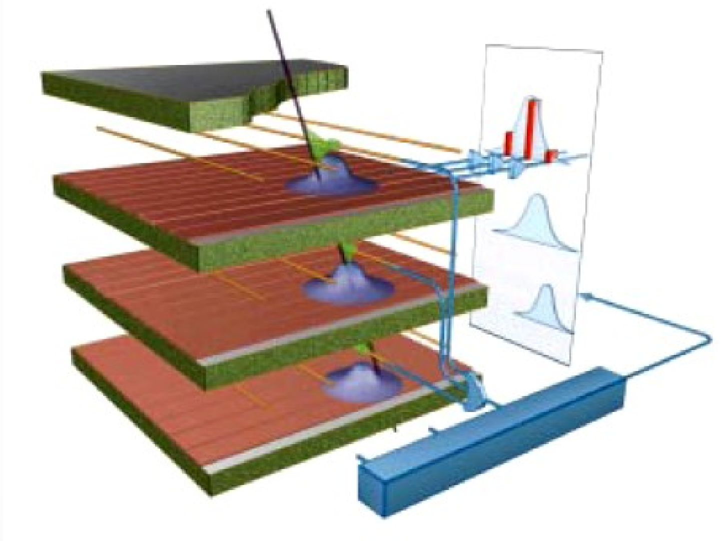


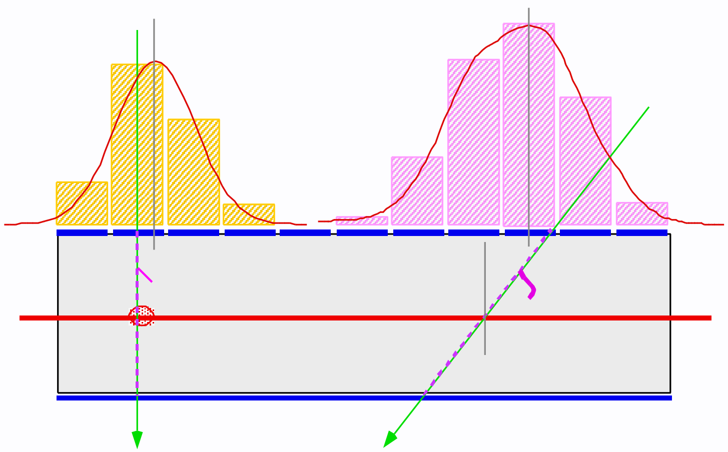
View inside
ALICE TPC

Time Projection Chambers

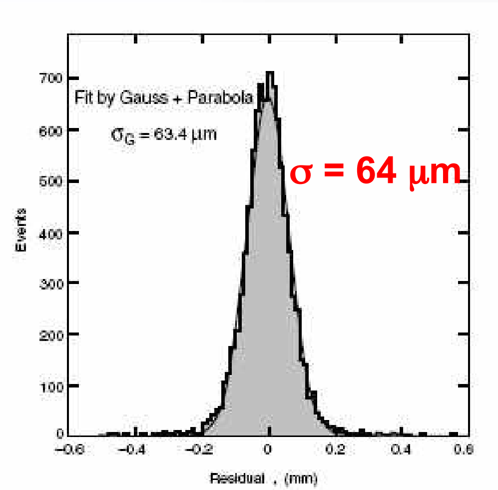


Precise measurement of the second coordinate by interpolation of the signal induced on pads.
Closely spaced wires makes CSC fast detector.

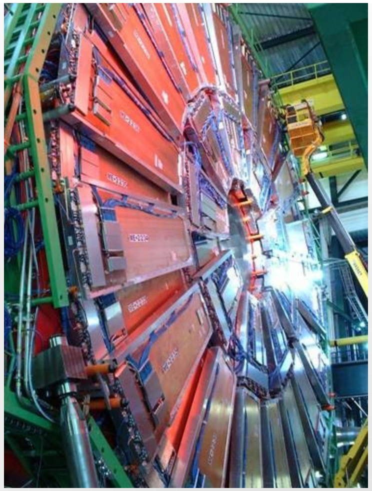




Center of gravity of induced signal method.



Space resolution



CMS

Resistive Plate Chambers

Basic idea:

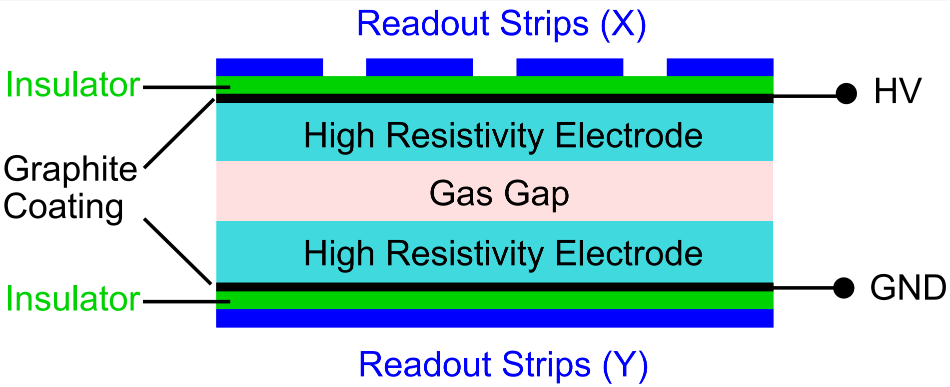
Use parallel plate chamber with high field ...

Electrons of ionization clusters start to produce an avalanche immediately ...

Induced signal = sum of all simultaneously produced avalanches ...

Signal: immediate ...

in contrast to e.g. wire chambers where avalanche only generated in vicinity of wire ...



Schematic image of typical RPC geometry

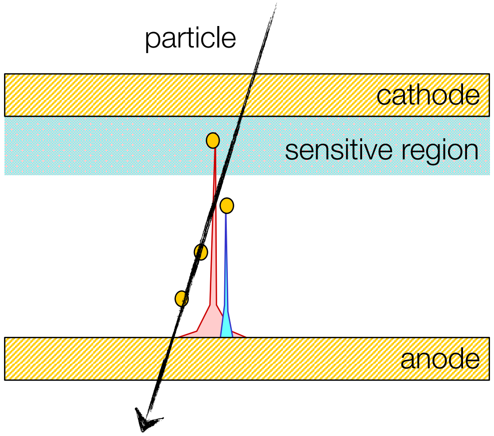
But:

Electron avalanche develops according to Townsend [see above]:

$$n = n_0 e^{\alpha x}$$

$$G = \frac{n}{n_0} = e^{\alpha x}$$

α : Townsend coefficient
x : traversed path length
G : amplification (gain)



Schematic view of avalanche process

Gap size matters!
[the smaller the better]

Raether limit: G ≈ 10^8; $\alpha x = 20$; then sparking sets in ...

Thus: only avalanches traversing full gas gap produce detectable signal, i.e. limited signal region close to cathode ...

As maximum gain < 10^8; sensitive region limited to 25% of gap ...
Time jitter: ~ time to cross sensitive region ...

Pestov chamber [1970]

[First example of resistive plate chamber]

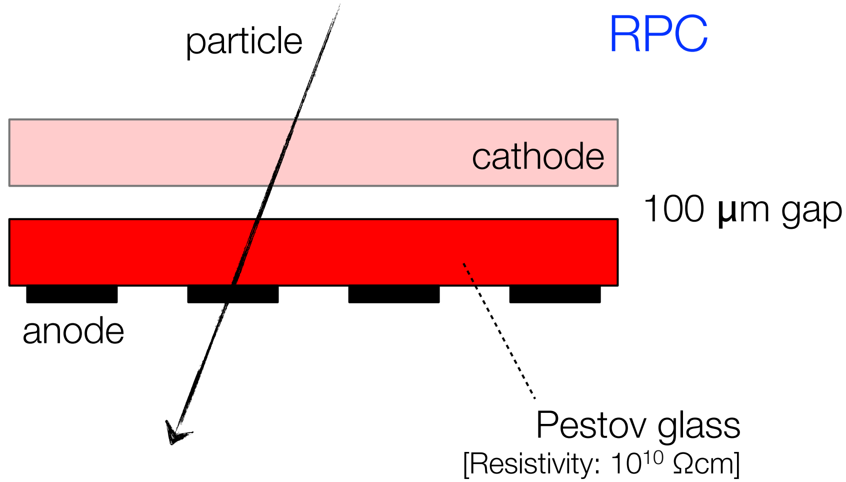
Glass electrode (Pestov glass) + metal electrode

Operated at very high gas pressure: 12 atm
[For large density of primary ionization i.e. good detection efficiency]

Gas gap of 100 μm; time resolution: 50 ps

Disadvantages:

- Mechanical constraints high pressure
- Non-commercial glass (high resistivity)
- Limited sensitive volume
- Long tails of late events

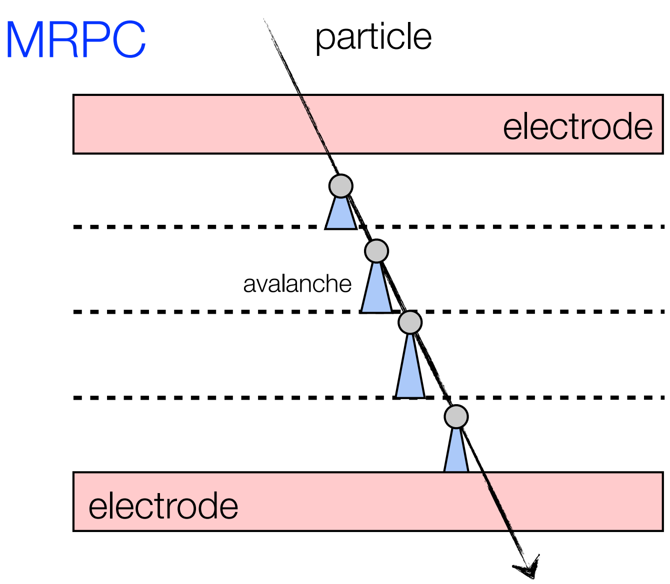


Multi-gap RPC

[Developed for ALICE particle ID]

Idea: very high gas gain for immediate avalanche production, but mechanism to stop avalanche growth before sparking

Solution: add boundary layers invisible to fast induced signal; external electrodes sensitive to any of the initiated avalanches



Resistive Plate Chambers

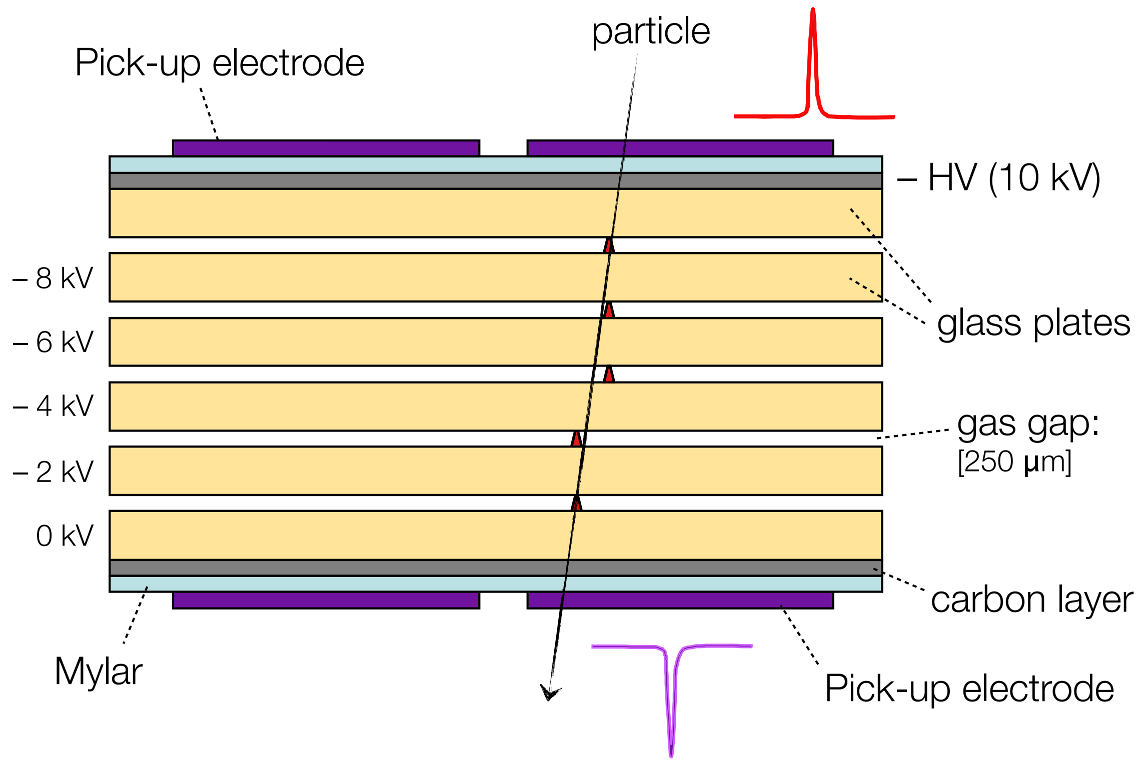
Multi-gap Resistive Plate Chamber

Stack of equally spaced resistive plates with voltage applied to external surfaces ...

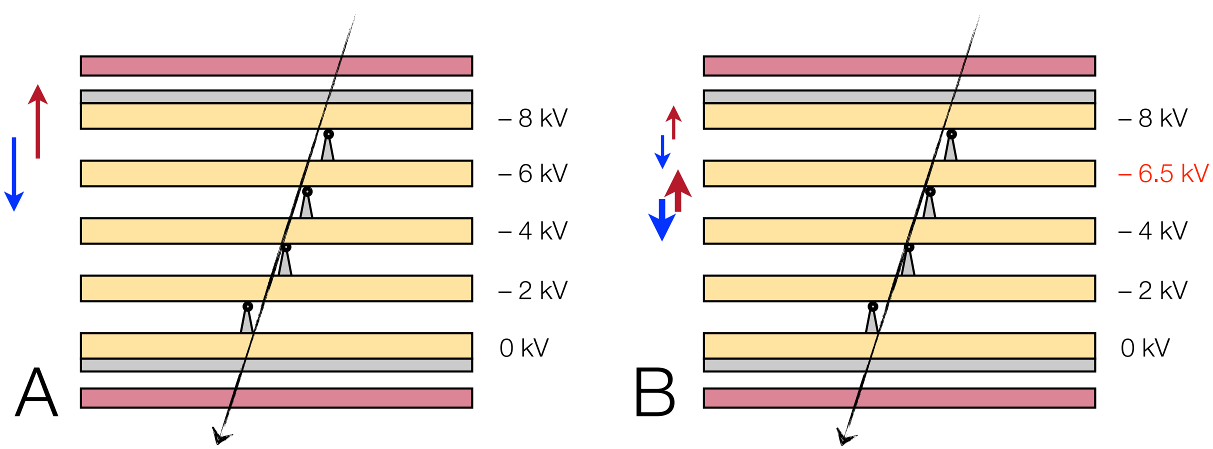
Internal plates electrically floating ...

Electrodes on external surfaces ...
[Resistive plates transparent to induced signal]

Internal plates take correct voltage ...
[Feedback due to electron/ion flow]



Feedback principle:



Flow of electrons
Flow of positive ions

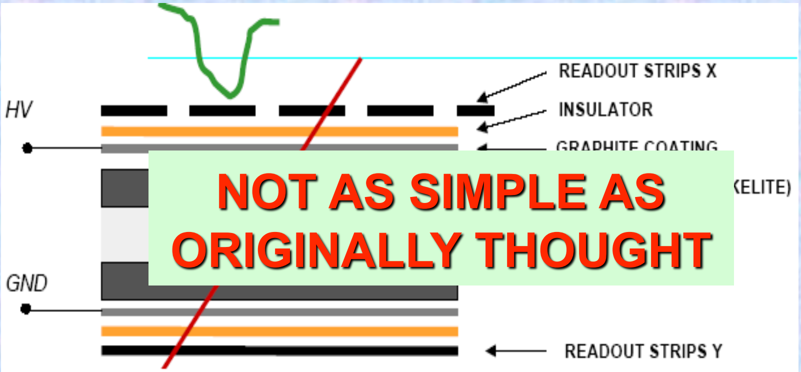
A: Same 2 kV across each gap; same gain, i.e. same charge flow ...

B: Flow to layer with 6.5 kV not symmetric; flow decreased for electrons and increased for ions ...

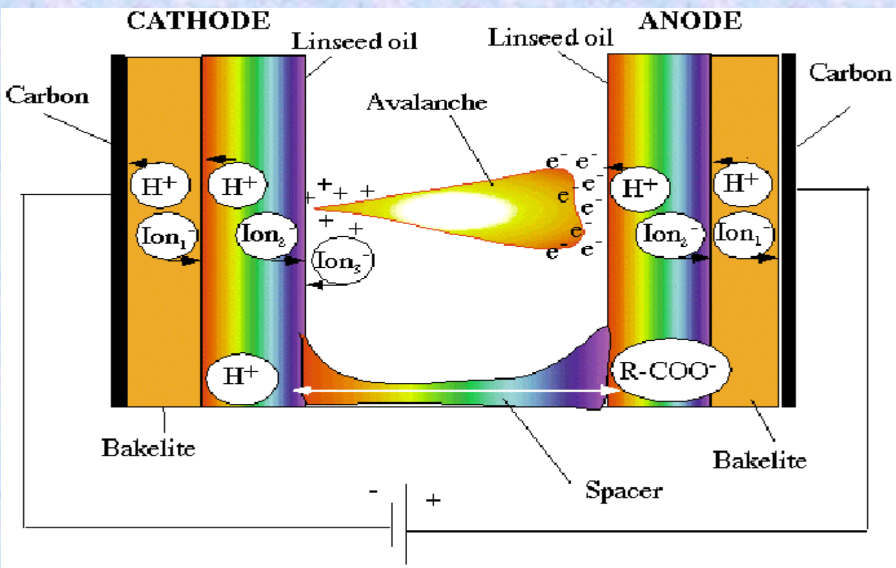
→ System will go back to symmetric state with 2kV for all gaps ...

Conceptual View of a Resistive Plate Chamber (RPC)

RPC: Resistive Plate Chamber
Parallel-Plate capacitor: E> 100kV/cm



- ***Resistive plate: Oiled bakelite or ionic-conductive glass***
- ***High electrode resistivity (10^9-10^{12} Ω cm) limits energy contained in charge avalanche***
- ***Resistivity limits the rate capability***
- ***Major advantages:***
  good time resolution (~1 ns),
  With multi-gap RPC (~ 50 ps)
  large area coverage at affordable cost



Ionic conduction model of RPC:

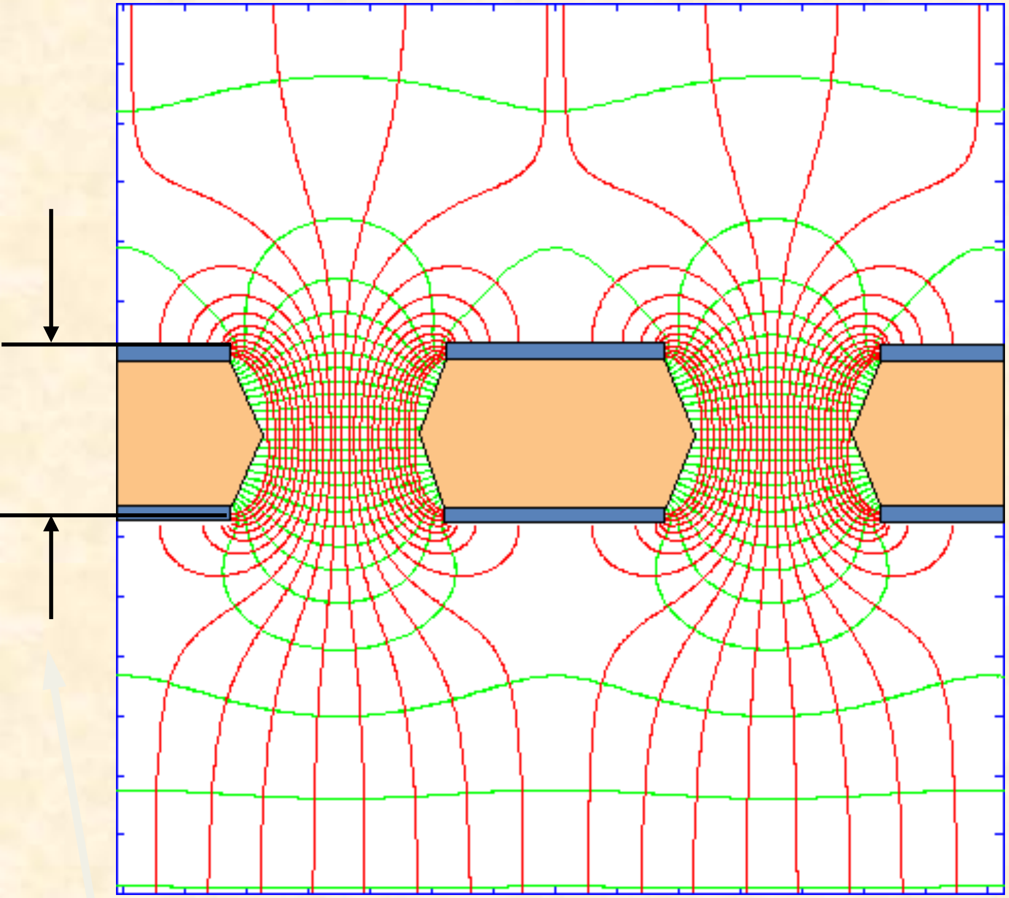
There are several ions involved in the current flow.

The charge exchange has to work well to prevent charging effects at various boundaries: gas, the linseed oil, the Bakelite and the graphite.

If a resistivity buildup occurs at some boundary, there may be a charging effect → subsequent 'RPC death'

R. Santonico, Nucl. Instr. and Meth. A 187(1981)377
R. Santonico, Nucl. Instr. and Meth.A 263(1988)20
J. Va'vra, Nucl. Instrum. Methods A515(2003)1

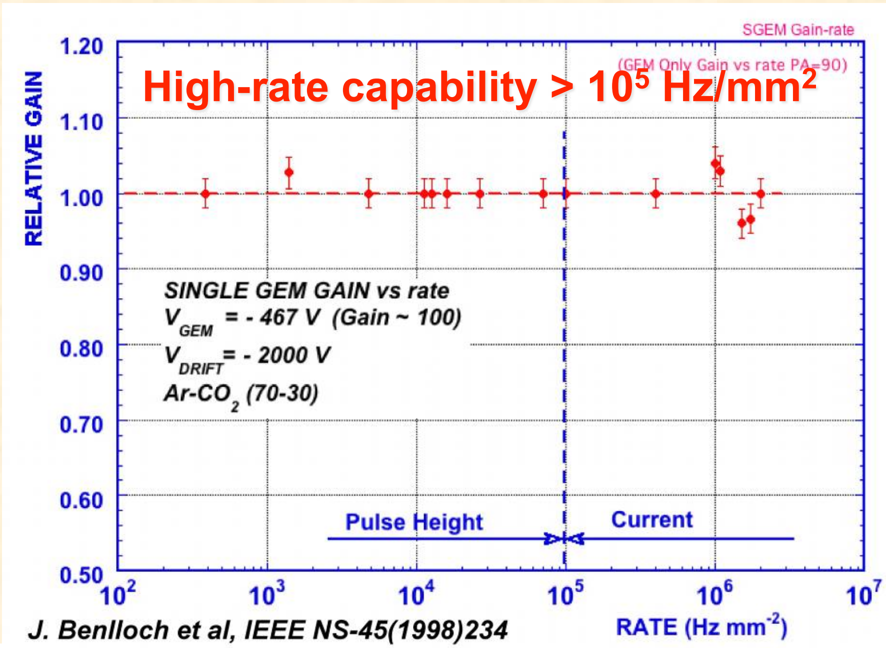
Gas Electron Multiplier (GEM)



Thin metal-coated polymer foil chemically pierced by a high density of holes.

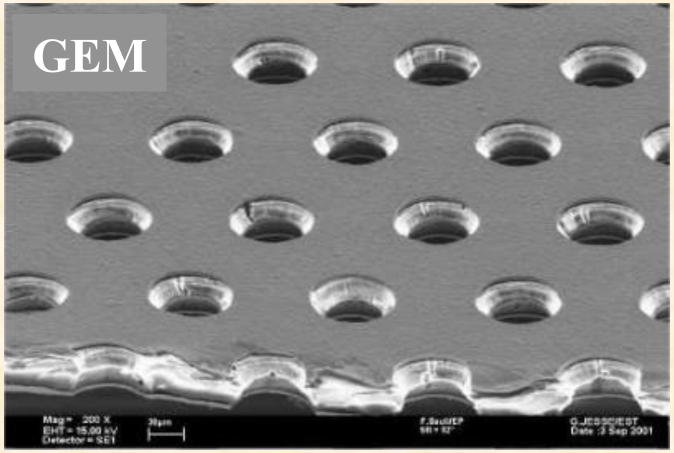
Upon applying a voltage gradient, electrons released on top side, drift into the hole, multiply in avalanche and transfer the other side.

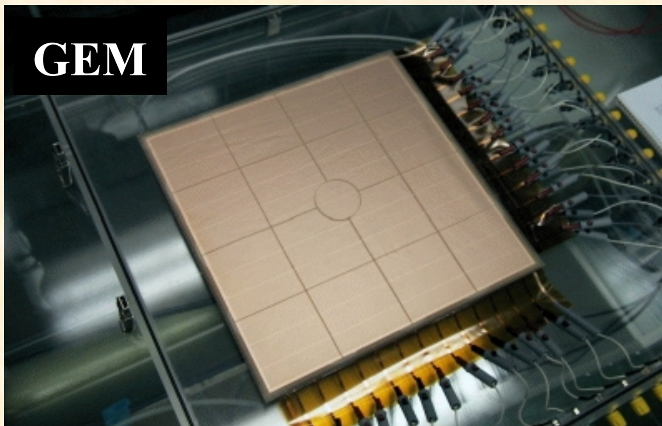
Proportional gains $>10^3$ obtained in most common gases.



Thickness: ~ 50 mum
ΔV: 400 - 600 V
Hole Diameter: ~ 70 mum
Pitch: ~140 mum

F. Sauli, Nucl. Instrum. Methods A386(1997)531
http://gdd.web.cern.ch/GDD/

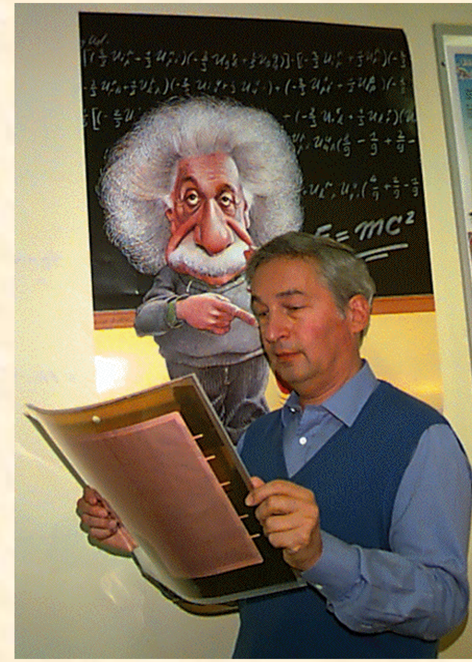


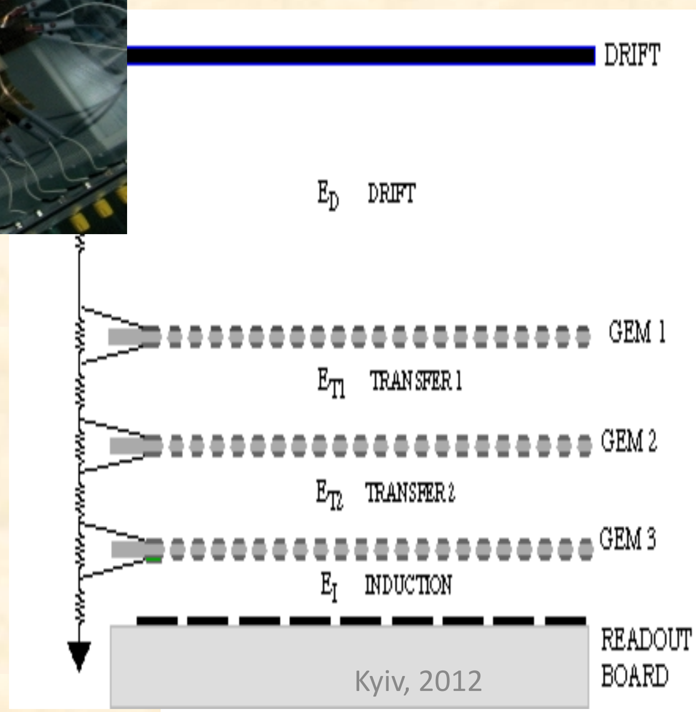


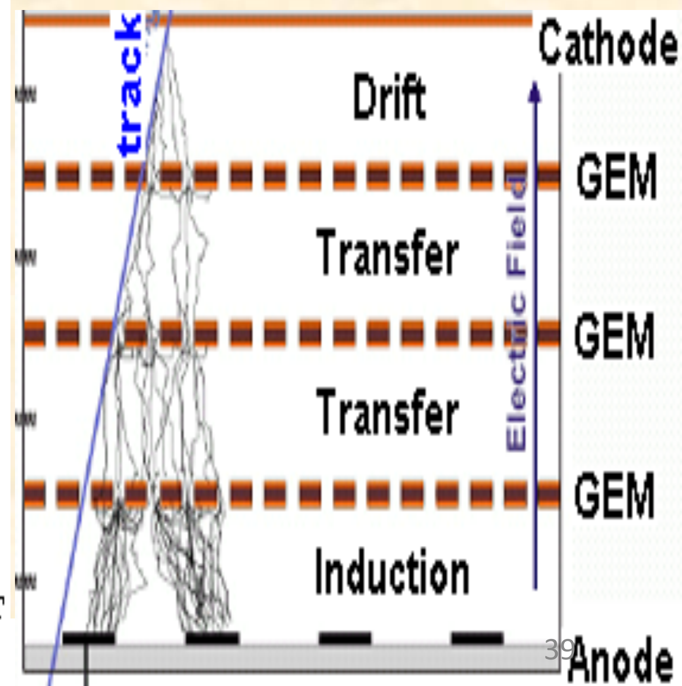
Gas Electron Multiplier (GEM):

F. Sauli, NIM A386(1997) 531;
F. Sauli, http://www.cern.ch/GDD

Separation of amplification stage (GEM) and readout stage (PCB, anode)







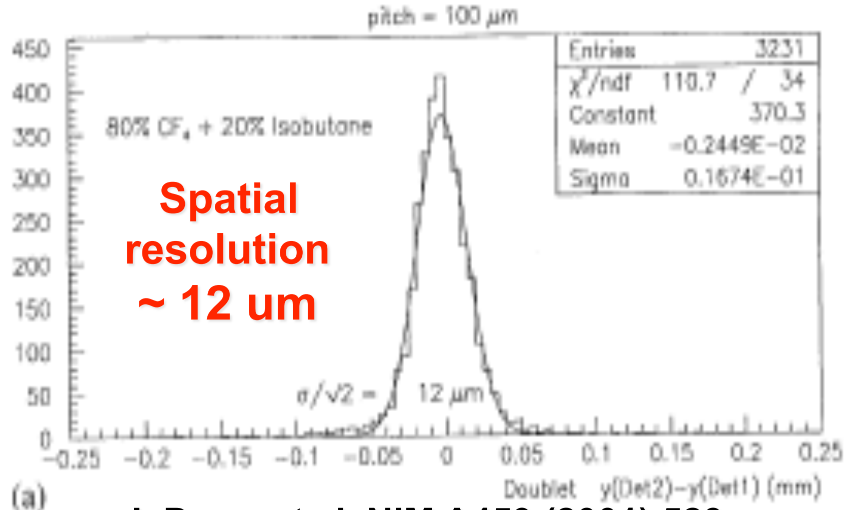
Back

MICROMEsh GASeous chamber (MICROMEGAS)

Parallel plate multiplication in thin gaps between a fine mesh and anode plate

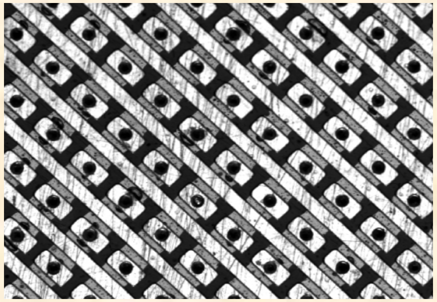
Y. Giomataris, NIM A376(1996) 29

Small gap→ good energy resolution

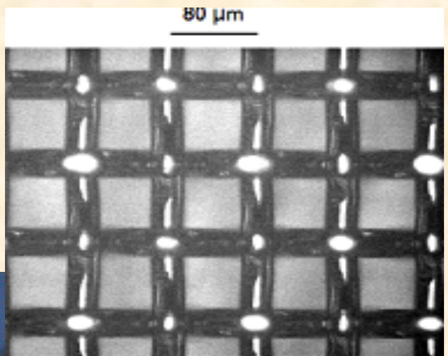


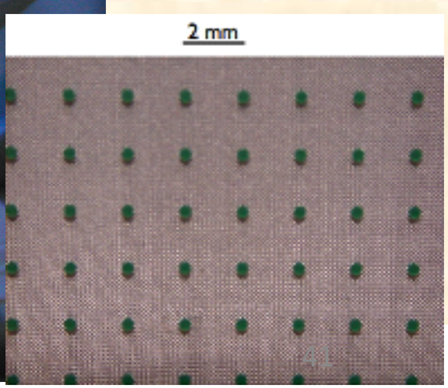
J. Derre et al, NIM A459 (2001) 523

CAST readout:



"Bulk" Micromegas:





The Silicon Sensors

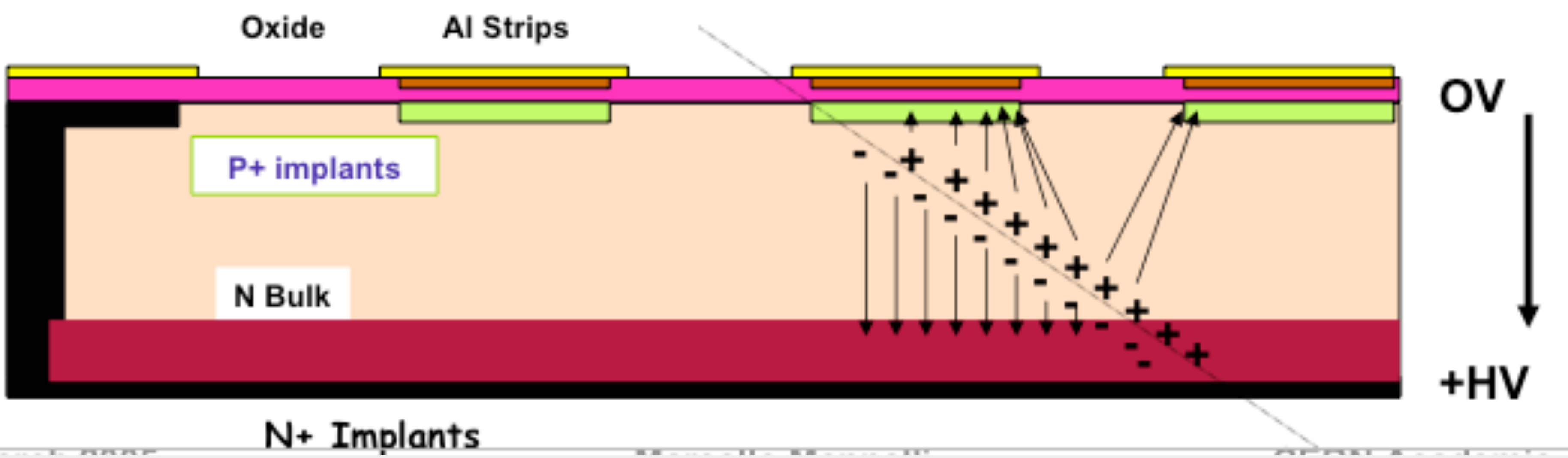
The reverse biased p-on-n diode

Bulk depletes from P+ implants, “front-side“ to N+ implant, “back-side”

Electron-hole pairs generated in the depleted region drift to the N+ and P+ electrodes respectively and generate a signal ~ to the depleted sensor thickness

Electron-hole pairs generated in the (conductive) un-depleted region recombine locally, and generate no signal

Even in a partially depleted sensor, the signal on the “front-side” is localized



To Backup

The Silicon Sensors
Electrical characteristics of strip detectors

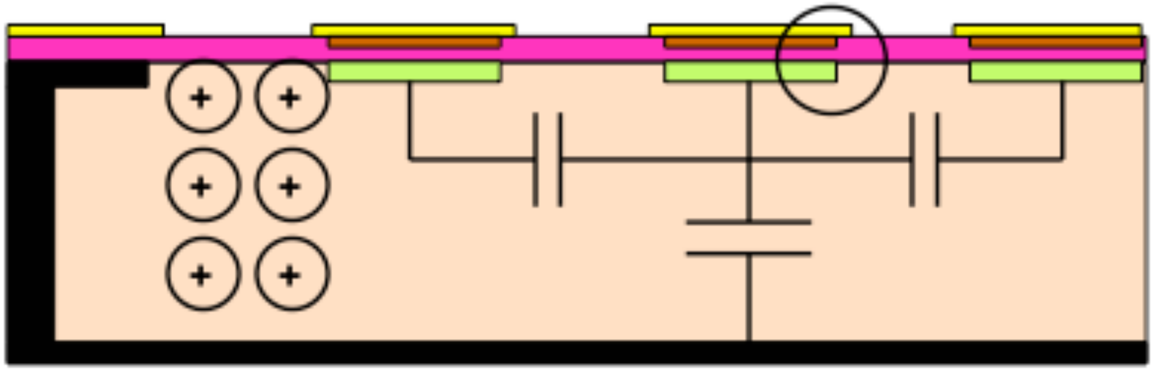
Sensor thickness & bulk resistivity: determines depletion voltage ($V_{depletion}$ ~ Neff * Thickness^2)

Strip Pitch / Width ratio: determines strip capacitive couplings & electronic noise

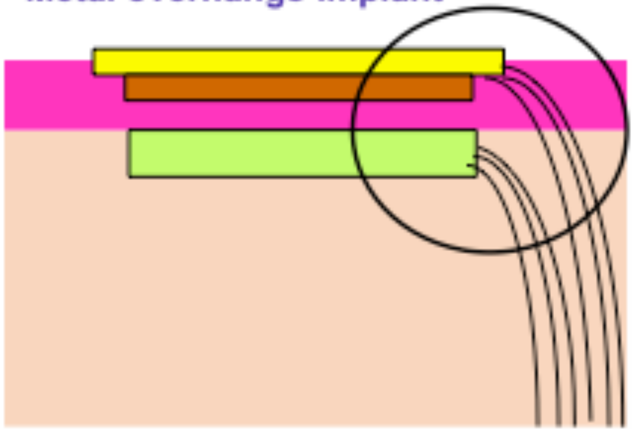
Strip Pitch & Width; Width of metal vs. implant: determine Electric field geometry, in particular high field region at strip edges & sensor breakdown characteristics

Nb. Breakdown voltage in Silicon Oxide ~ 30 * breakdown voltage in Silicon bulk

Single-Sided Lithographic Processing (AC, Poly-Si biasing)



Metal overhangs implant



Radiation damage eventually results in "type inversion"

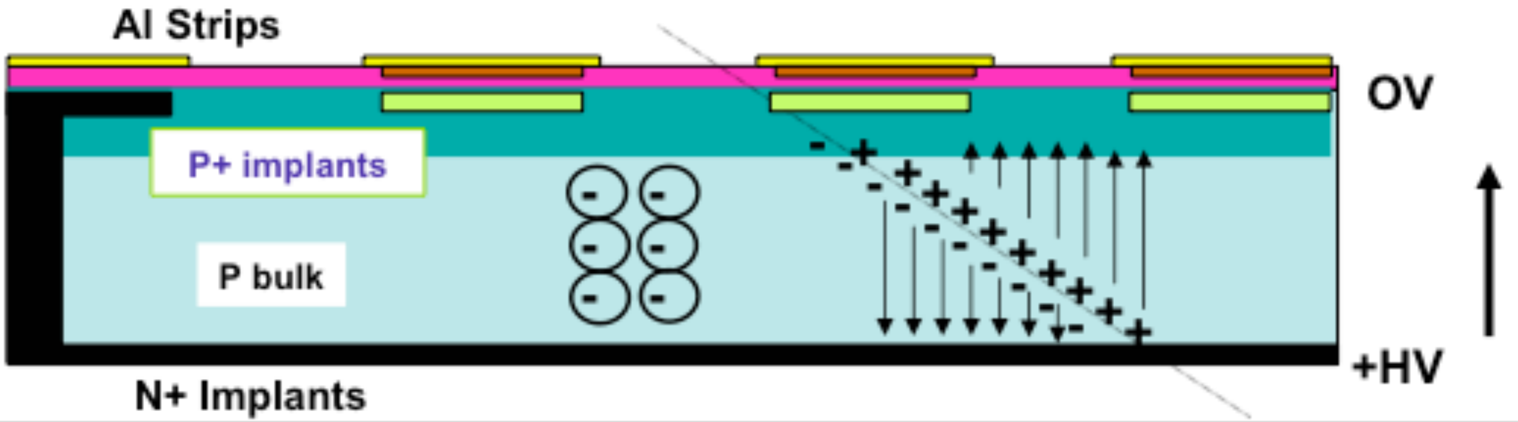
- The initially N bulk undergoes "type inversion" and becomes P
- The depletion voltage decreases and then increases again with higher fluence
- The effectively P bulk depletes from N+ implants, "back-side", to P+ implant, "front-side"

Electron-hole pairs generated in the depleted region drift to the N+ and P+ electrodes respectively and generate a signal ~ to the depleted sensor thickness

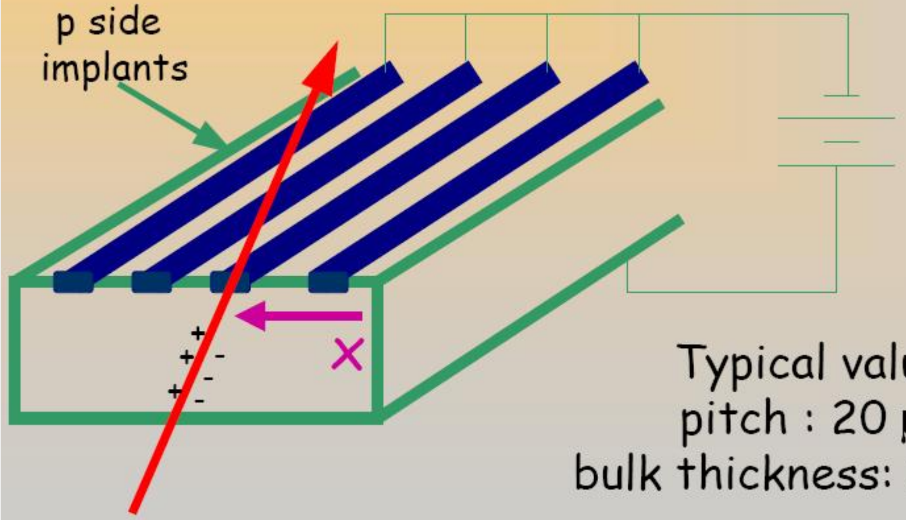
Radiation induced defects trap charge, leading to a loss of signal unless high fields

In the partially depleted sensor, the signal on the "front-side" is no longer localized

Sensor leakage current increases linearly with fluence (by ~ 3 orders of magnitude)

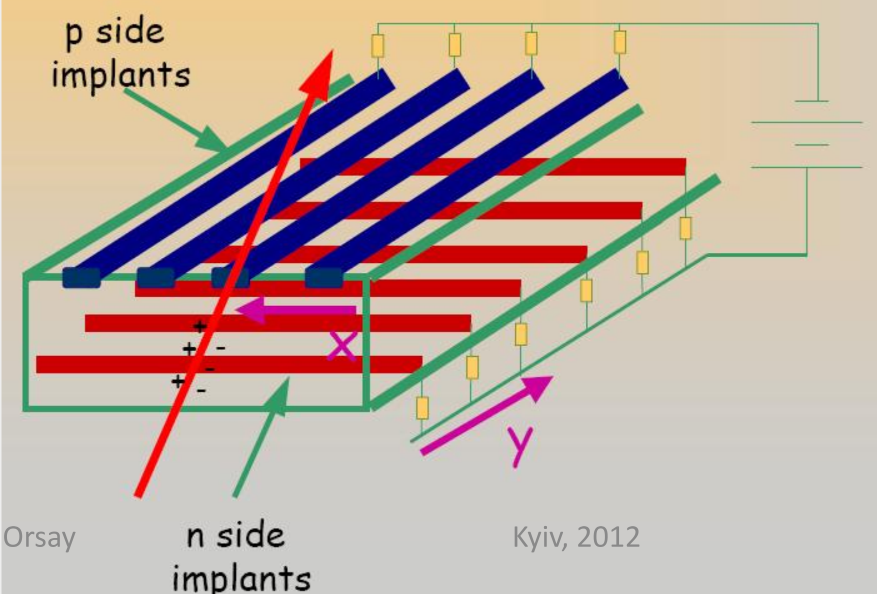


Measure coordinate → strips



Typical values used are
pitch : 20 µm - 150 µm
bulk thickness: 150 µm - 500 µm

Strips on both sides → 3D measurement

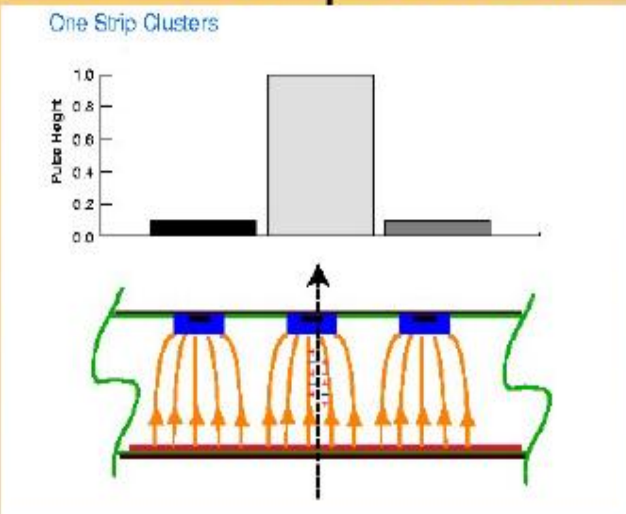


But!

- complex ($$$)
- strip isolation (see next slide)
- readout (see slide after)

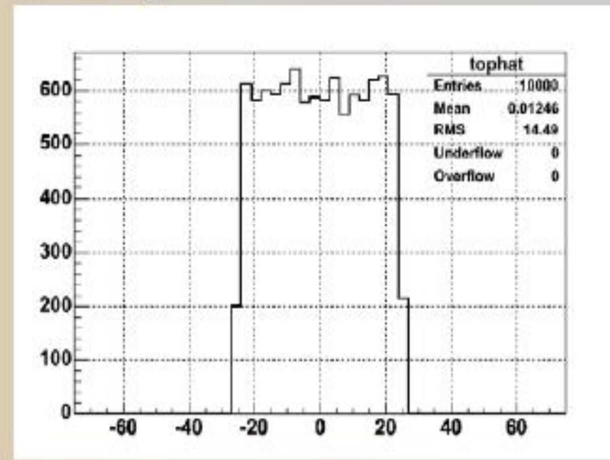
Resolution is the spread of the reconstructed position minus the true position

For one strip clusters

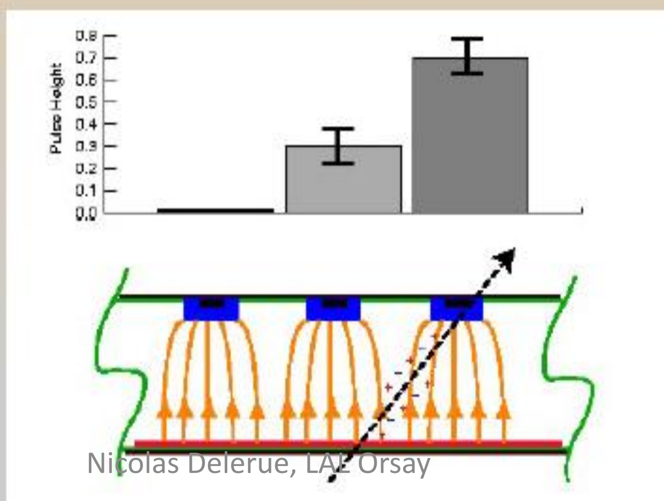


$$\sigma = \frac{\text{pitch}}{\sqrt{12}}$$

"top hat" residuals

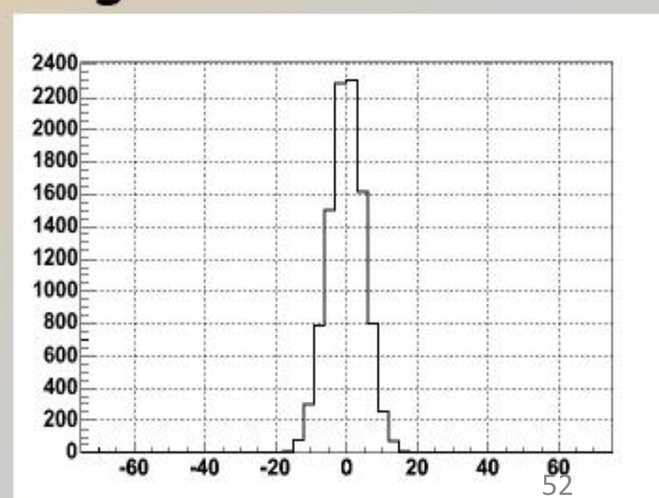


For two strip clusters



$$\sigma \approx \frac{\text{pitch}}{1.5 * (S/N)}$$

"gaussian" residuals



To Backup

SILICON DETECTORS

Back

Elemental semiconductors

★ Germanium:

Used in nuclear physics, due to small band gap (0.66 eV) needs cooling (usually done with liquid nitrogen at 77 K)

★ Silicon:

Standard material for vertex and tracking detectors in high energy physics, can be operated at room temperature, synergies with micro electronics industry.

★ Diamond (CVD or single crystal):

Large band gap, requires no depletion zone, very radiation hard, drawback is a low signal and high cost!

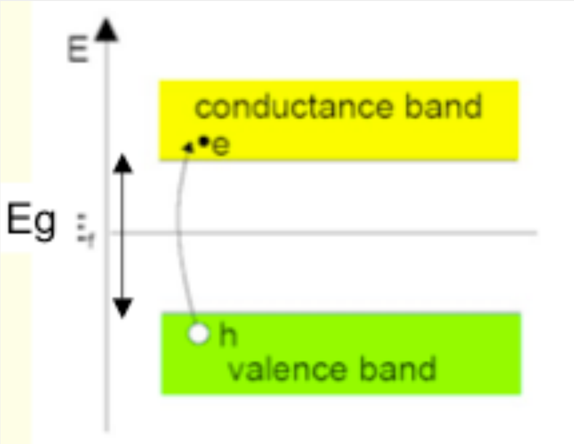
Compound semiconductors

Compound semiconductors consist of two (binary semiconductors) or more atomic element.

- GaAs: Faster and probably more radiation resistant than Si.
- CdTe: High atomic numbers (48+52) hence very efficient to detection

The ideal semiconductor detector

One of the most important parameter of a detector is the signal to noise ratio (SNR). A good detector should have a large SNR. However this leads to two contradictory requirements:



- ✘ Large signal
  - ➔ low ionisation energy ➔ small band gap
- ✘ Low noise
  - ➔ very few intrinsic charge carriers
  - ➔ large band gap

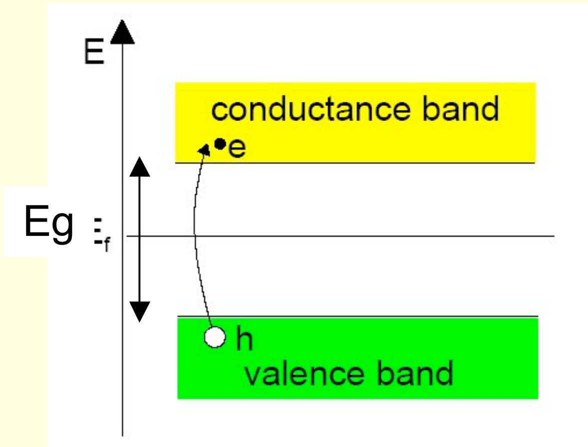
An optimal material should have $Eg \approx 6$ eV.

In this case the conduction band is almost empty at room temperature and the band gap is small enough to create a large number of e-h+ pairs through ionisation.

Such a material exist, ==> Diamond.

However even artificial diamonds (e.g. CVD diamonds) are too expensive for large area detectors.

Solid state detectors



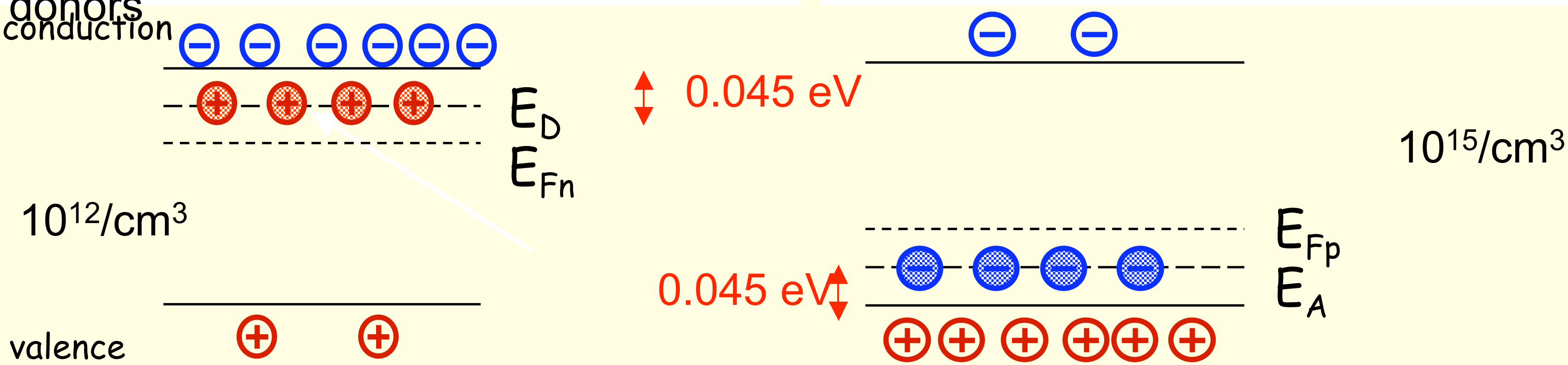
At T=0 Semi Conductor is an insulator but when T ↗
electron density (n) = Hole density (p) = n_i
$1.45.10^{10}/cm^3$ for silicon (given by exp(-Eg/kT))

In a 1cm x 1cm x 300μm detector already $4.5.10^8$ free charges against $3.2.10^4$ e/h produced for a mip particle

→ S/√N =1 no chance to see signal
→ Should reduce the number of free charge carriers
→ Depletion of detector using doping

Doping type N with As,P acts as donors

Doping type P with B ,Ga, AL, In as acceptors



Electrons are the majority carriers

holes majority carriers

DC coupled strip detector

- Through going charged particles create e-h+ pairs in the depletion zone (about 30.000 pairs in standard detector thickness).
- These charges drift to the electrodes.
- The drift (current) creates the signal which is amplified by an amplifier connected to each strip.
- From the signals on the individual strips the position of the through going particle is deduced.

A typical n-type Si strip detector:

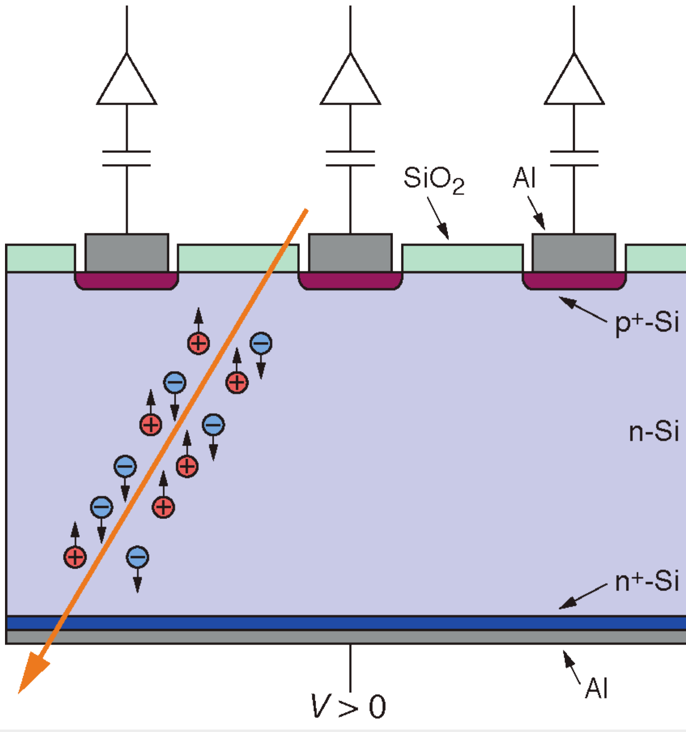
★ n-type bulk: ρ > 2 kΩcm

➔ thickness 300 µm

★ Operating voltage < 200 V.

★ n+ layer on backplane to improve ohmic contact

★ Aluminum metallization

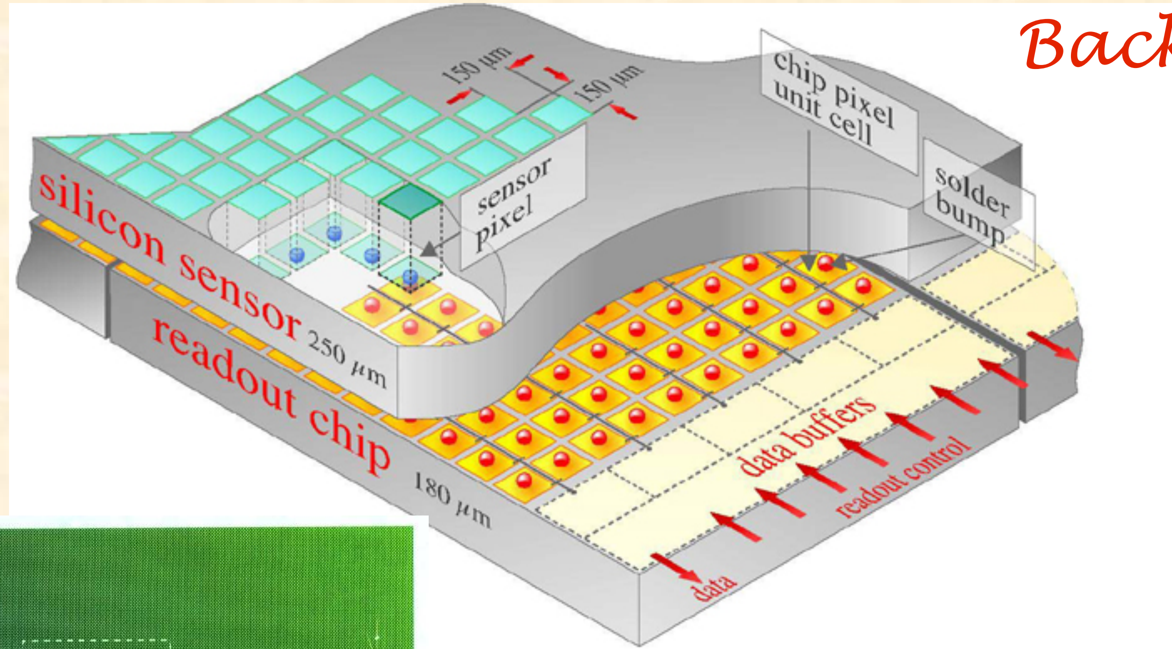


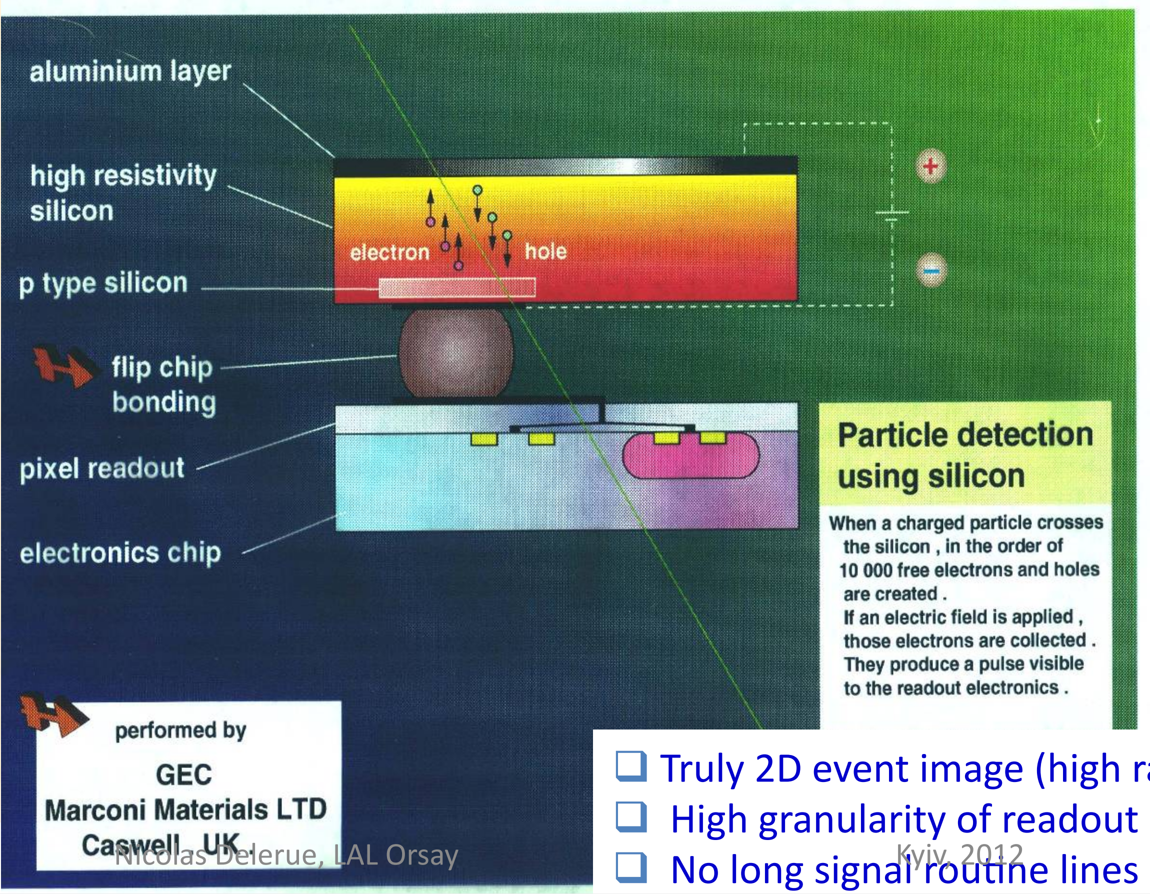
From strips to pixels

Back

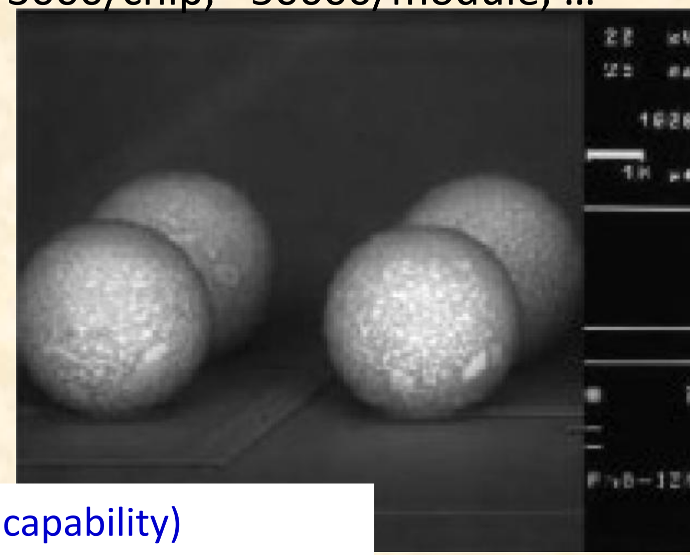
Flip-chip assembly

Pixel detector bump bonded to a read-out chip





PbSn or In, 6-20 µm
~3000/chip, ~50000/module, …

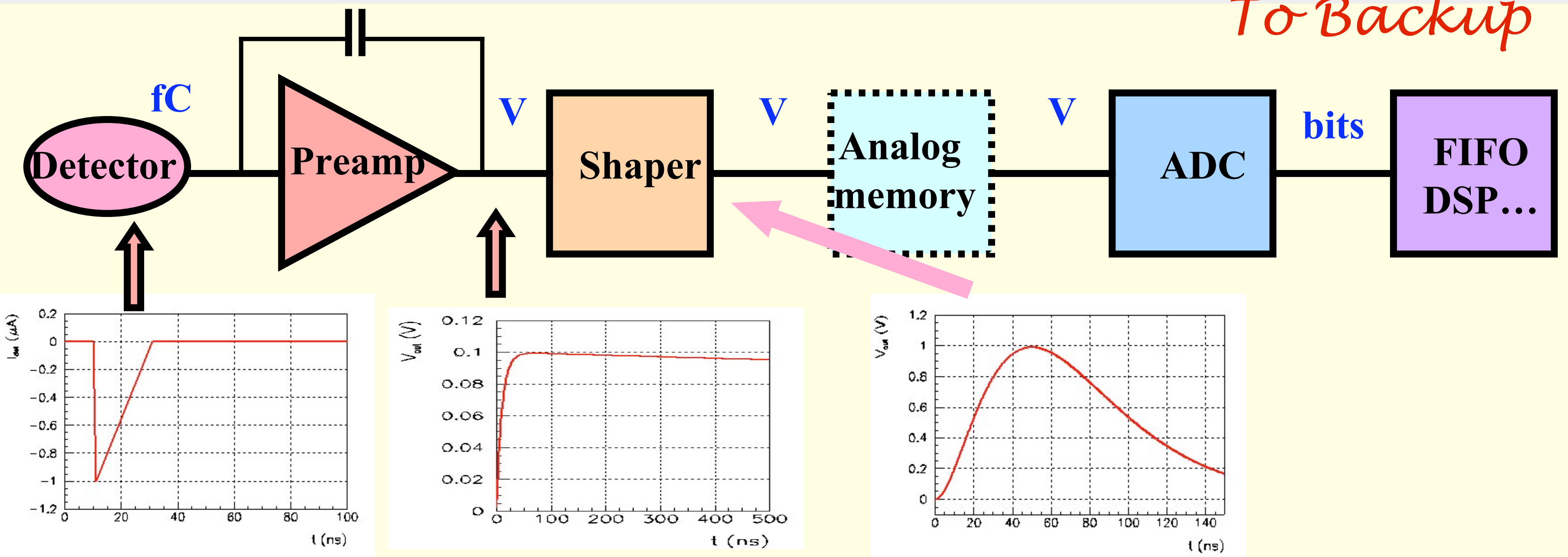


op, 23-24 October 2002

- ❑ Truly 2D event image (high rate capability)
- ❑ High granularity of readout plane (~50 mum)
- ❑ No long signal routine lines (low noise)

Overview of readout electronics

To Backup



Most front-ends follow a similar architecture :

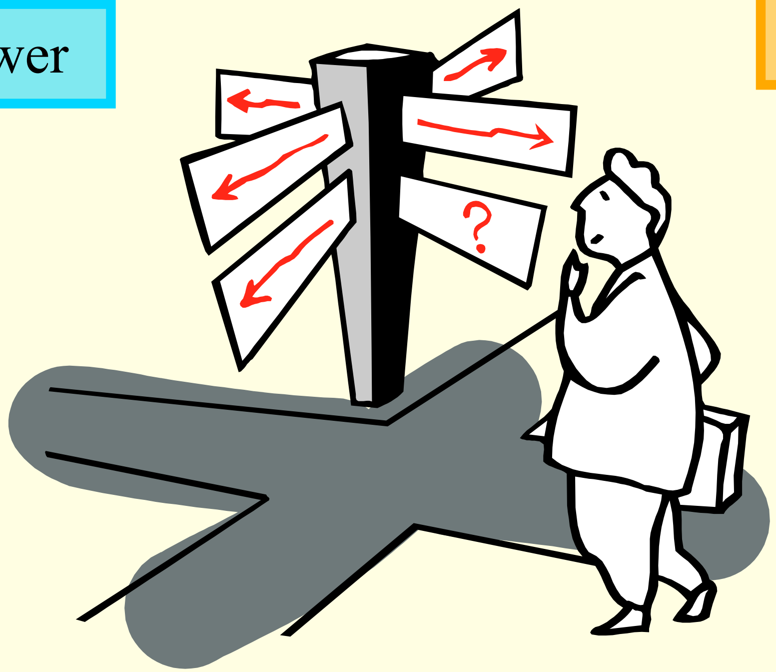
- Very small signals (fC) -> need amplification and optimisation of S/N (filter)
- Measurement of amplitude and/or time (ADCs, discris, TDCs)
- Several thousands to millions of channels
- Needs time to decide to keep or not the event : memory

Constraints as seen by a Electronics engineer (From C. de La Taille / LAL)

Low noise

Low power

High speed



Large dynamic range

High reliability

Radiation hardness

<u>Low cost !</u>

<u>(and even less)</u>

Low material

Why do we Need a Trigger

To Backup

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- Experiments in High Energy Physics are different from those in many other areas :

the reactions are measured collision by collision

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- As these functions crucially affect what is analysed ***(what is not triggered is LOST)***
  - account needs to be taken of what is kept, and under what conditions,
  - by recording a summary of the selection decision per event,
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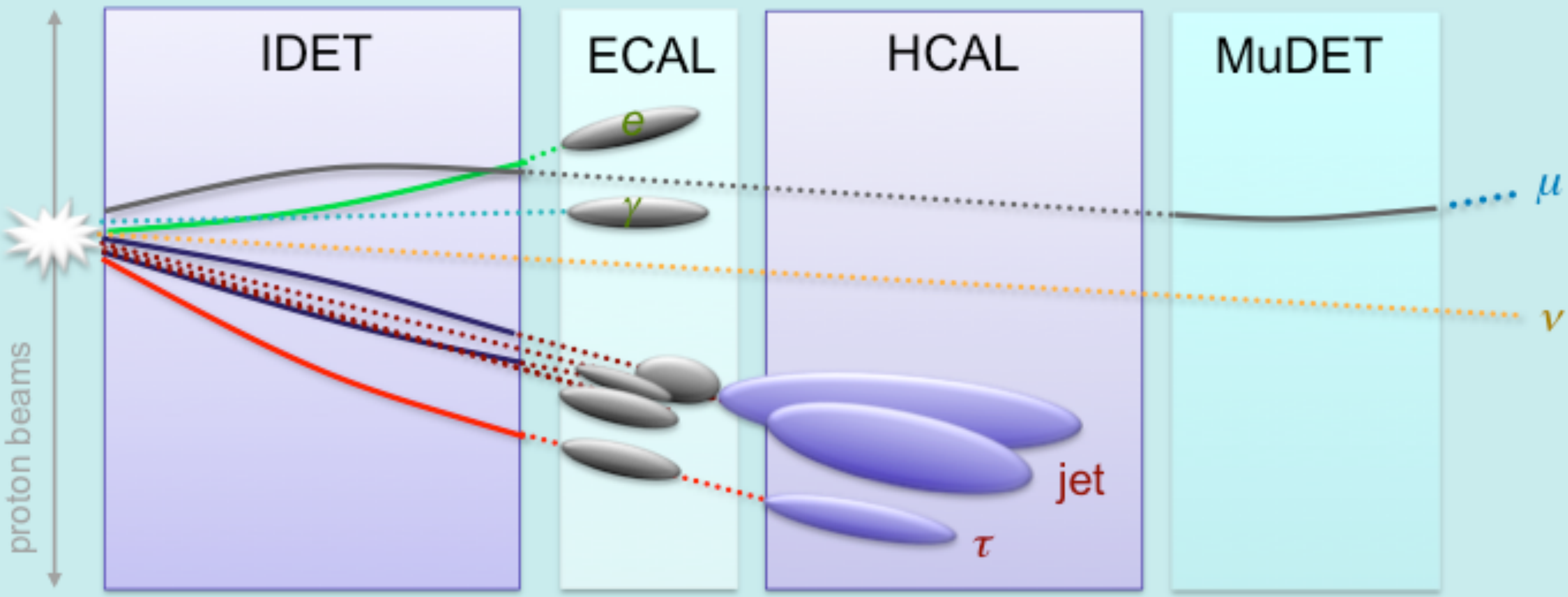
- ***The trigger system controls these functions***

To Backup

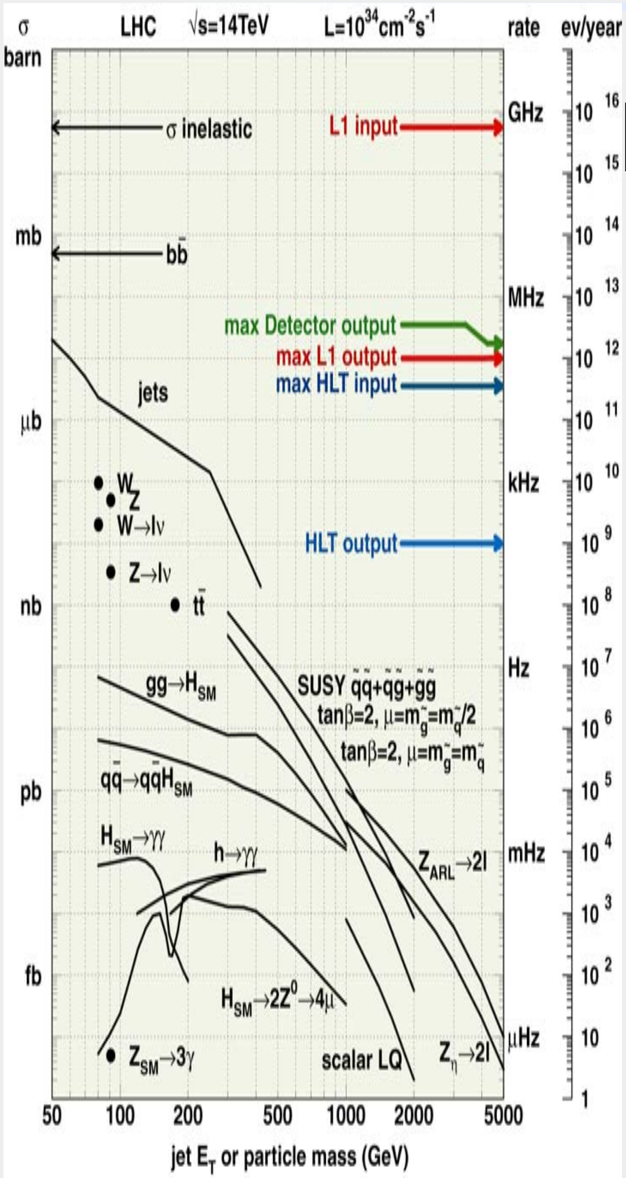
Trigger Signatures

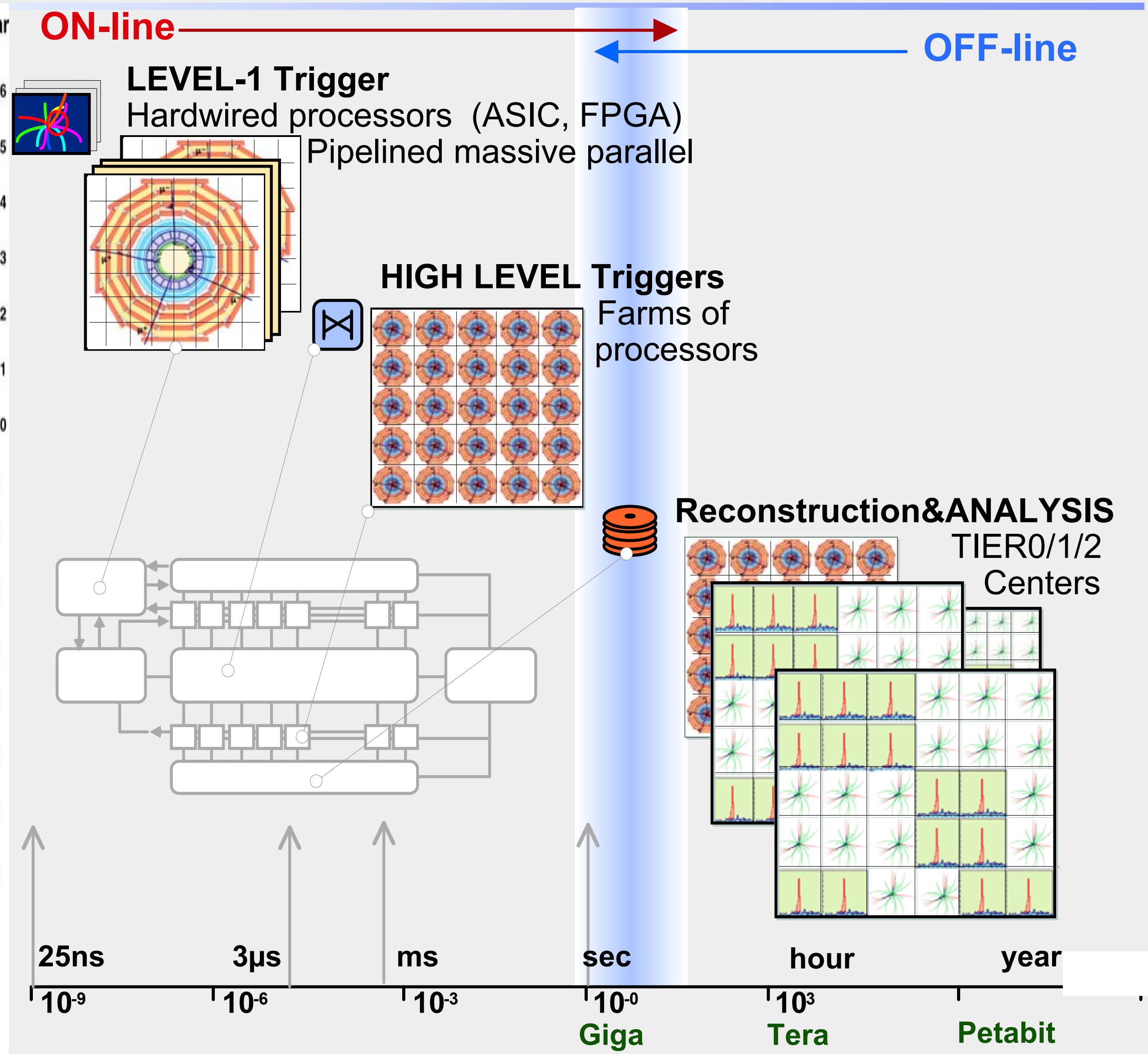


Features distinguishing new physics from the bulk of the SM cross-section

- Presence of high-p_T objects from decays of heavy particles (min. bias <p_T> ~ 0.6 GeV)
- More specifically, the presence of isolated high-p_T leptons or photons
- The presence of known heavy particles (W, Z)
- Missing transverse energy (either from high-p_T neutrinos, or from new invisible particles)

Physics selection at the LHC





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- ***The time between 2 BC's (50ns) is far too short to allow a trigger to be processed***
- ***Solution is to break the algorithm into tasks that can be processed in one BC, and arrange that data from each successive BC are stored.***

Pipelining

- ***Most experiences (except Alice) have up to 30 interactions per Bunch Crossing (BC), and must be able to process each BC.***
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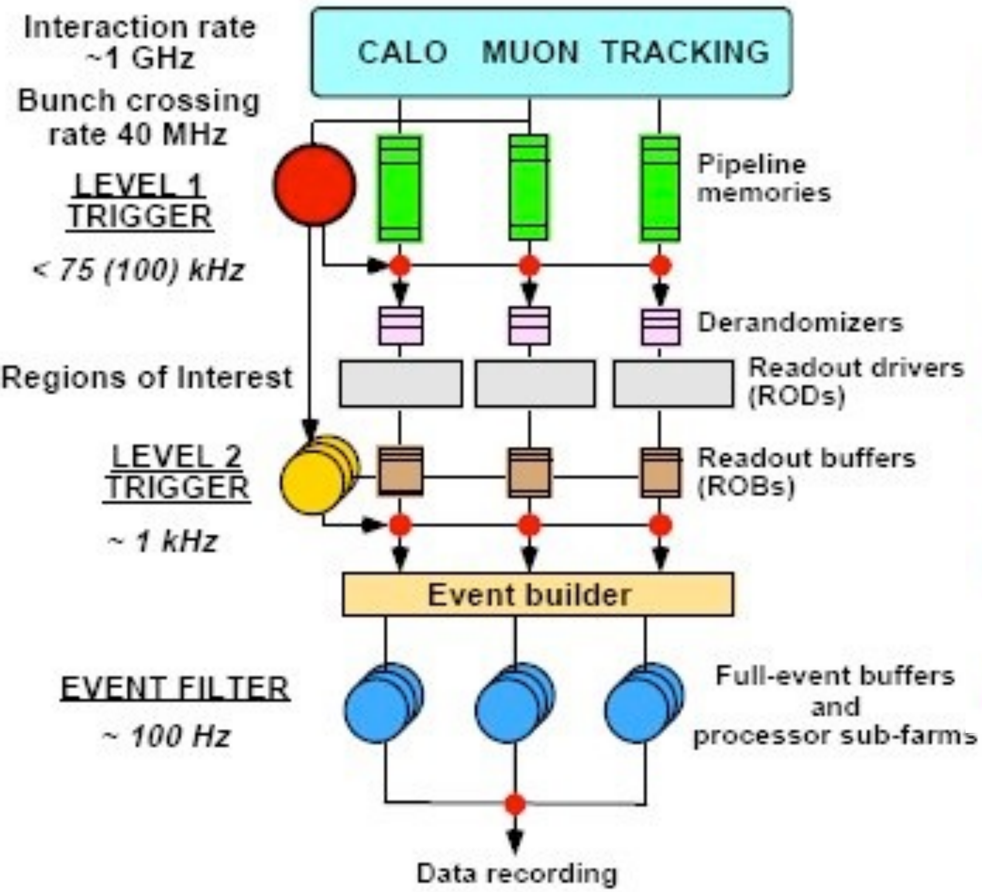
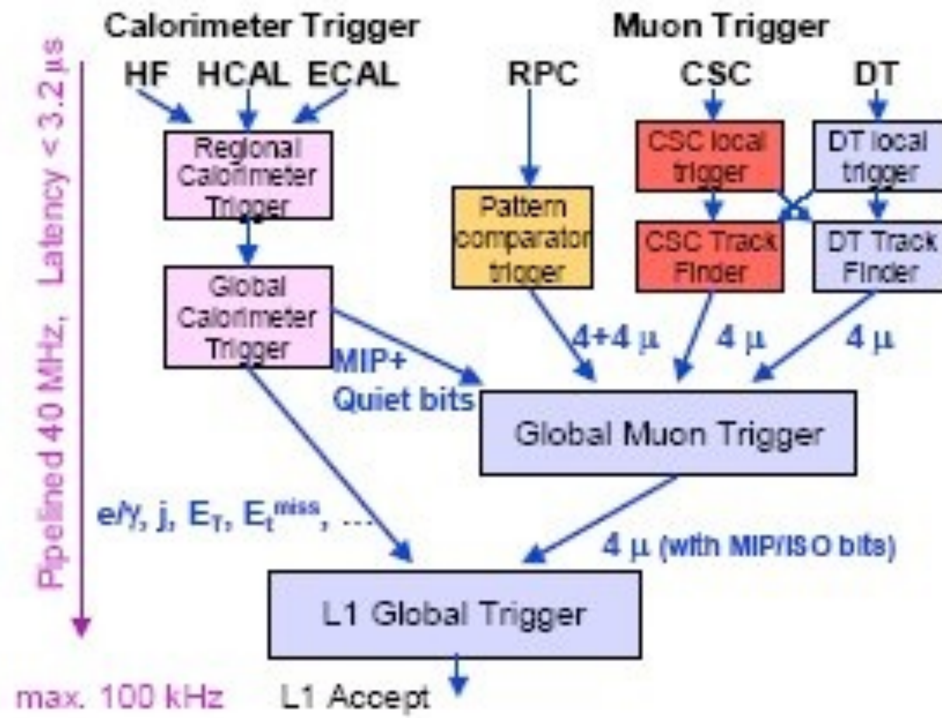
- *Data from non triggering detectors are also stored in shift registers, advancing one position per BC. If when the trigger decision is made, it turns out the no needed which are discarded data.*

Pipelined-multilevel-triggers



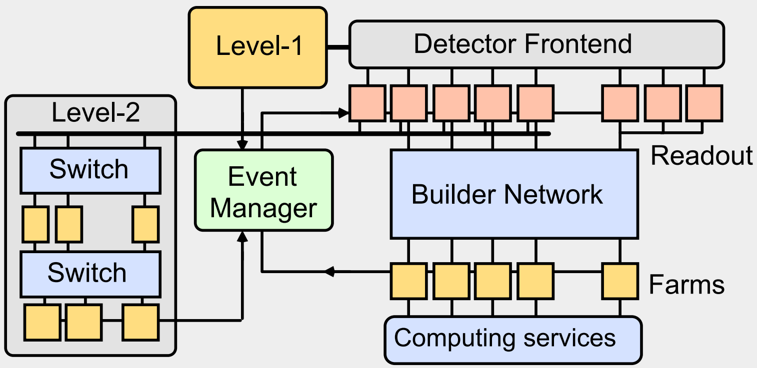


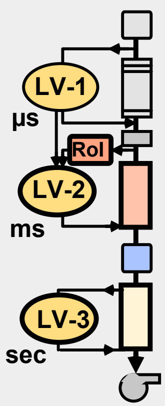
40 MHz —LVL1→ 100 kHz —(LVL2+LVL3)→ 100Hz

synchronous 3 μs — asynchronous

Three Physical entities (Atlas)

- **Additional processing in LV-2: reduce network bandwidth requirements**





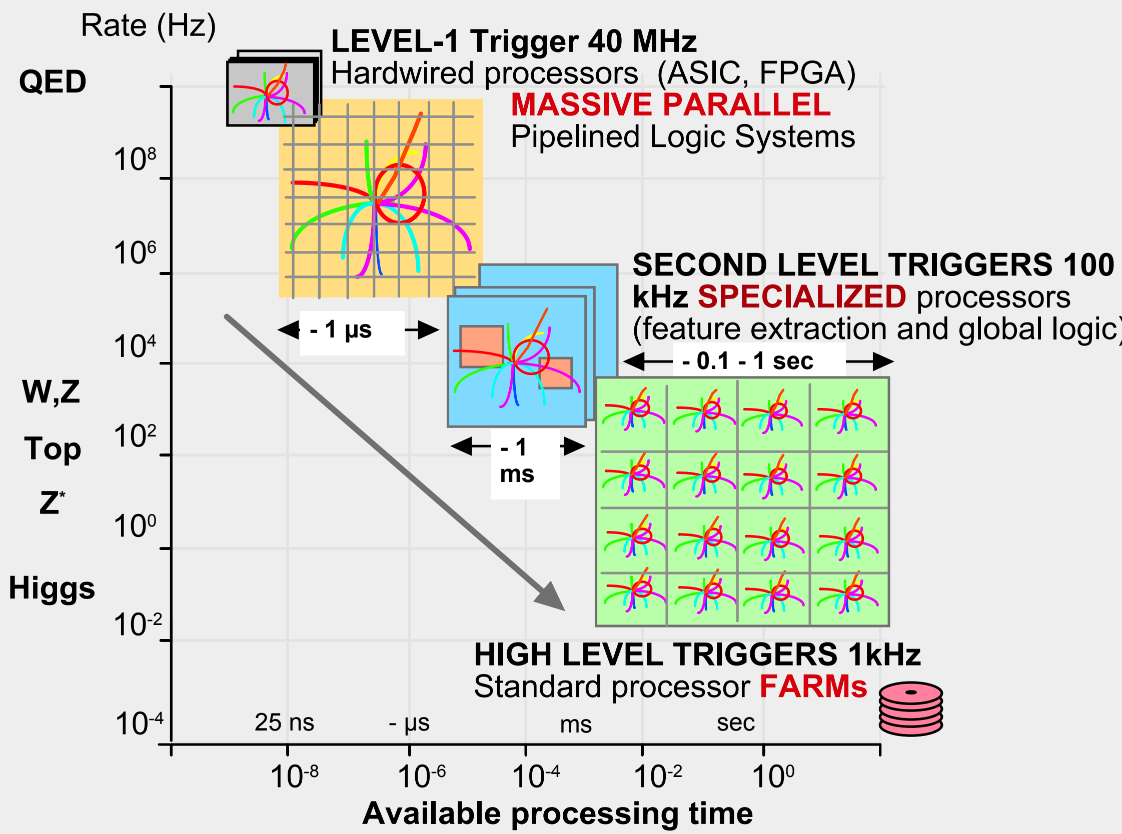
40 MHz

10^5 Hz

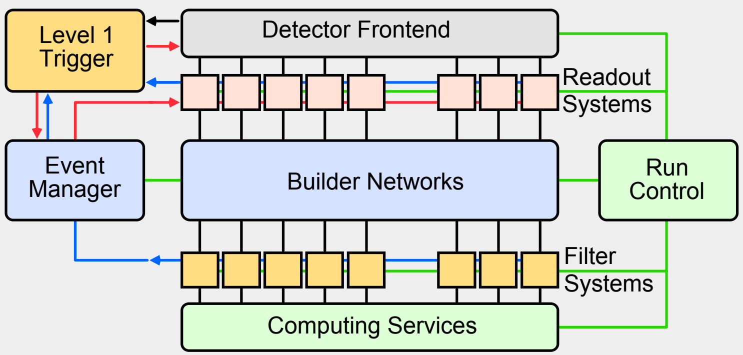
10^3 Hz

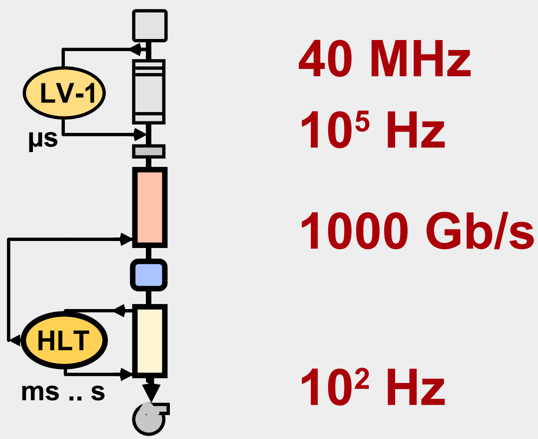
10 Gb/s

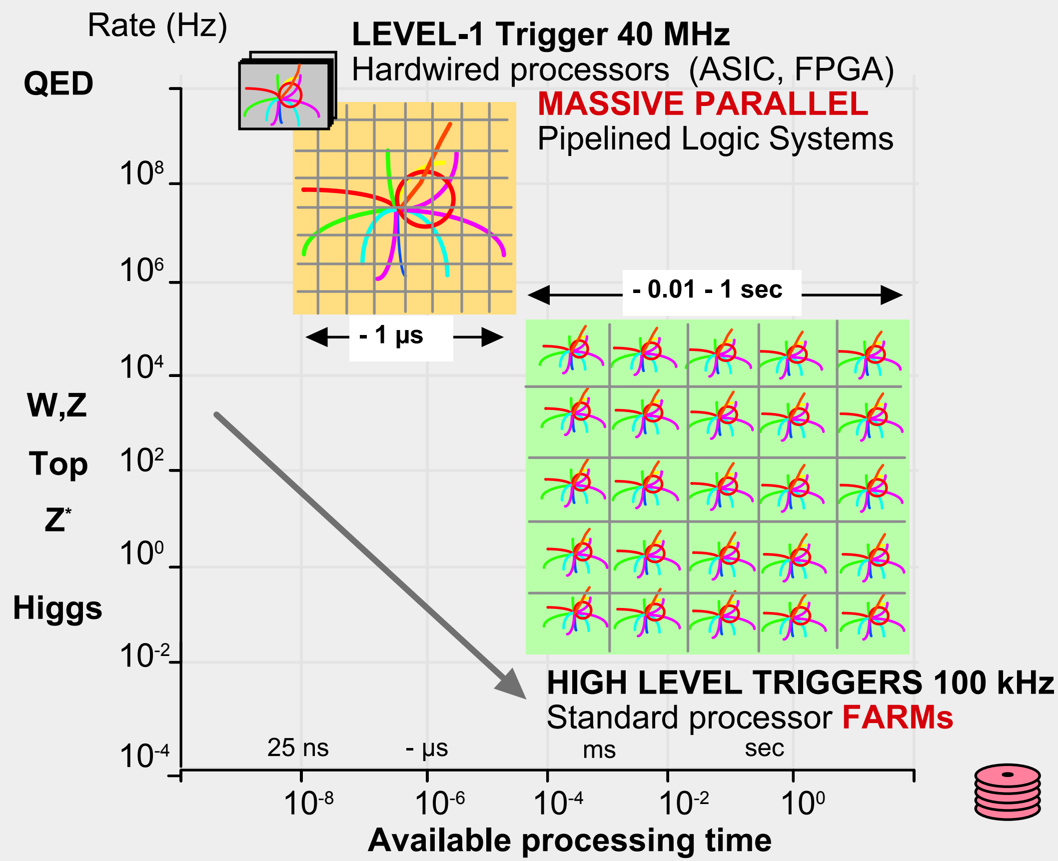
10^2 Hz



Two physical entities (CMS)







- Reduce number of building blocks
- Rely on commercial components (especially processing and communications)

Challenges for Future Detectors: Experimental Opportunities

The Energy Frontier
- Rad hard, low mass vertex sensors
- Triggering at luminosities > $10^{35}/cm^2/s$
- 4 μm point tracking resolution
- Hadronic jet energy resolutions of 30%/sqrt(E)

The Intensity Frontier
- Low-cost efficient photo-detectors
- Large volume, long drift LAr TPC with maintained purity and robust readout
- Psec level time-of-flight for rare decays

The Cosmic Frontier
- Background rates in dark matter detectors down to a level of 1 nuclear recoil per ton per year
- Depth of observation of galaxy clusters
- Probe the Planck scale of space-time