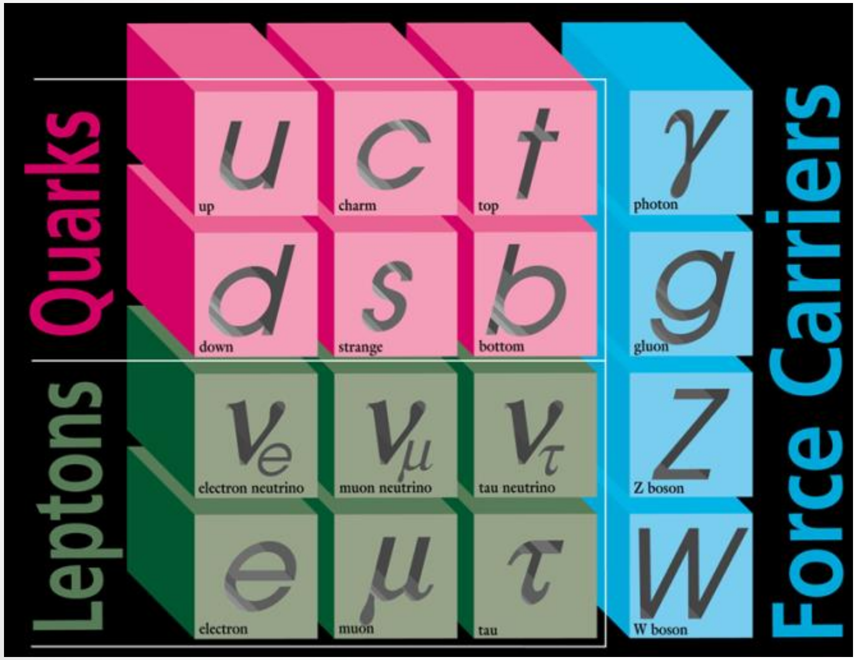
# Detectors

PSI Lab Course 2014

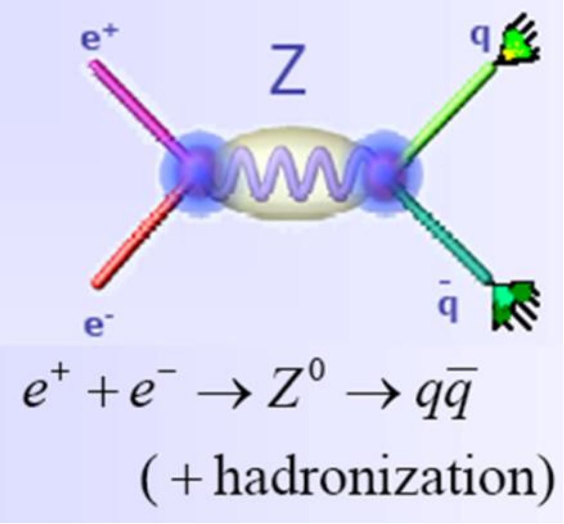
Dirk Wiedner

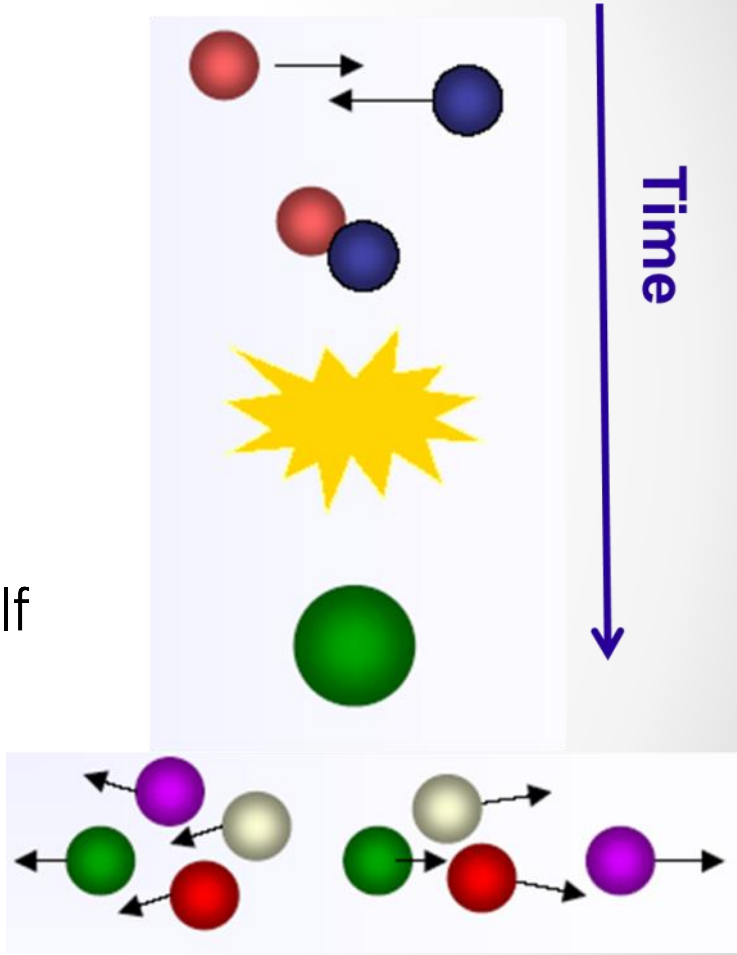
# The Standard Model




- The SM:
  - world is made up of **quarks** and **leptons**
  - interacting by exchanging **bosons**
  - only photons directly visible
- How do we see without seeing?
- What makes Particle Detection possible?

# Particle Reactions

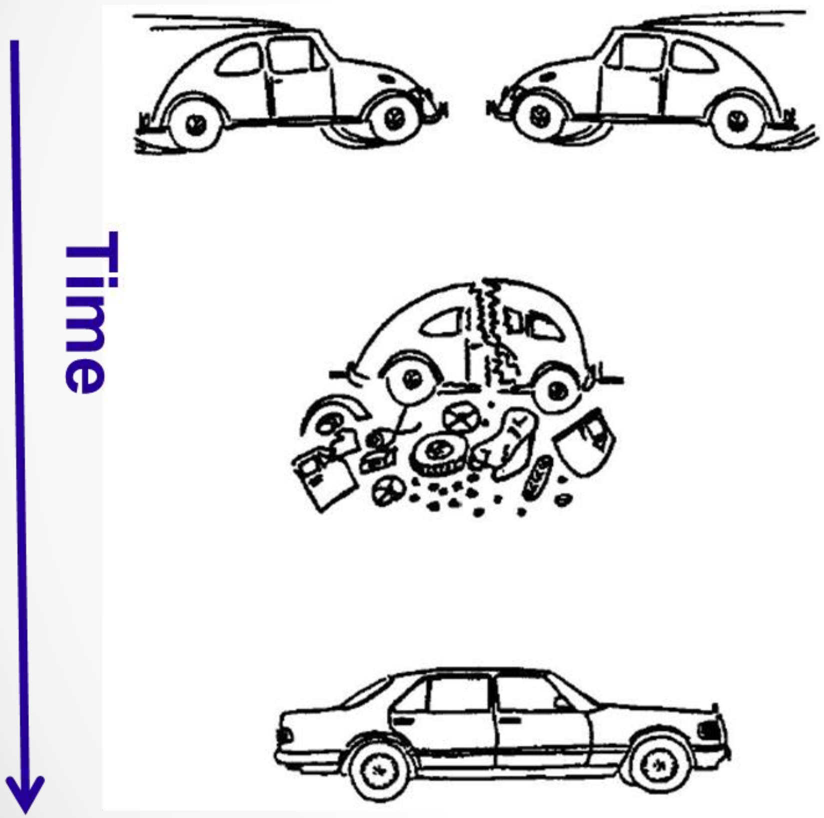



- Idealistic View:
  - Elementary Particle Reaction
- Usually cannot "see" the reaction itself
- To reconstruct the
  - **process** and the
  - **particle properties**

➢ need **maximum information** about **end-products**

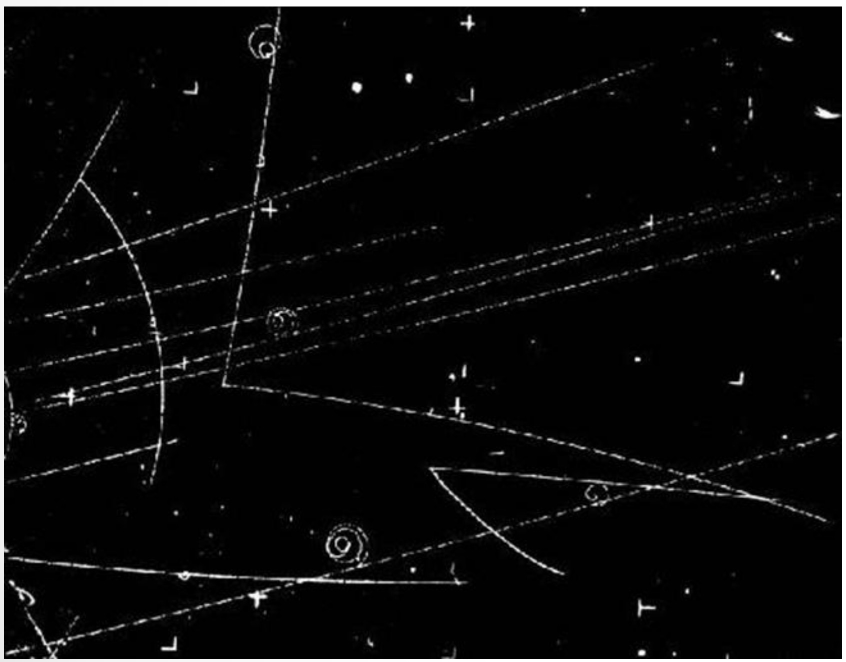
# Principle of an Elementary Particle Measurement



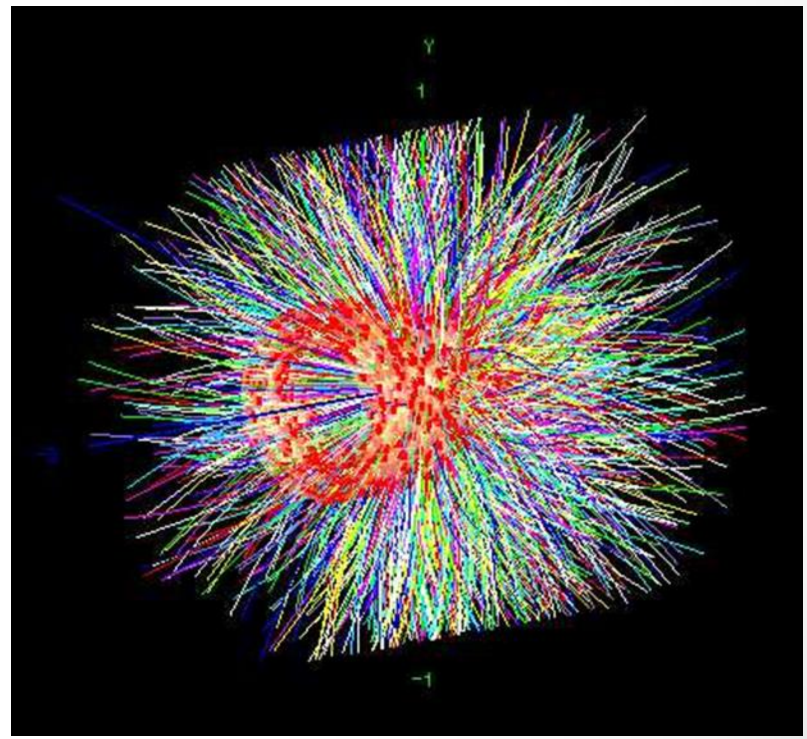

- Need good:
  - Detectors
  - Triggers,
  - Readout
  - ➢ to reconstruct the mess.
- Need good:
  - Analyzers
  - ➢ to put the raw data into a piece of physics.

# Example of two Reactions

Tracks in a Bubble Chamber
(Bubble chambers are not used any more).



Simulated Super LHC event.
(People started to think about a LHC upgrade).



The decay products of elementary particle reactions can look very complicated!

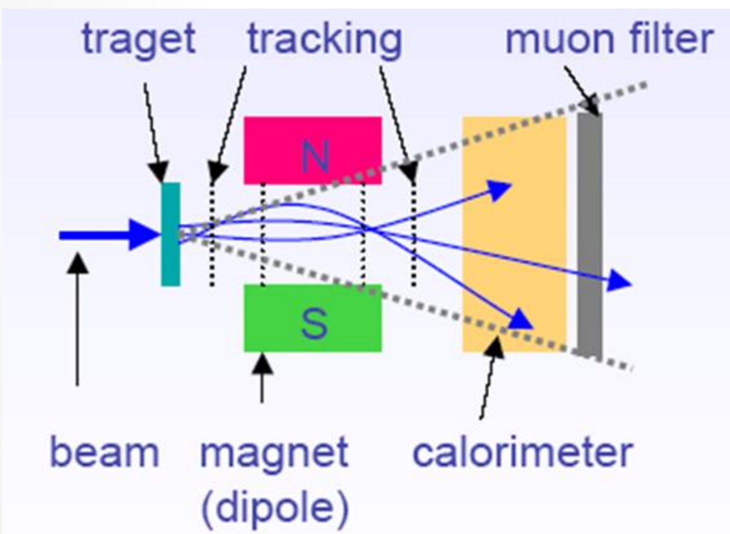
# Global Detector Systems

- Overall design depends on:
  - Number of particles
  - Event topology
  - Momentum/energy
  - Particle identity

- No single detector measures it all…
- ➢ Create detector systems

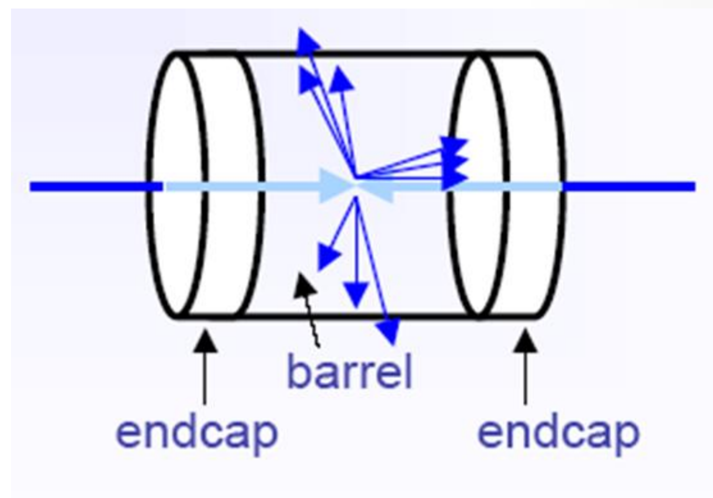
# Global Detector Systems

## Fixed Target Geometry



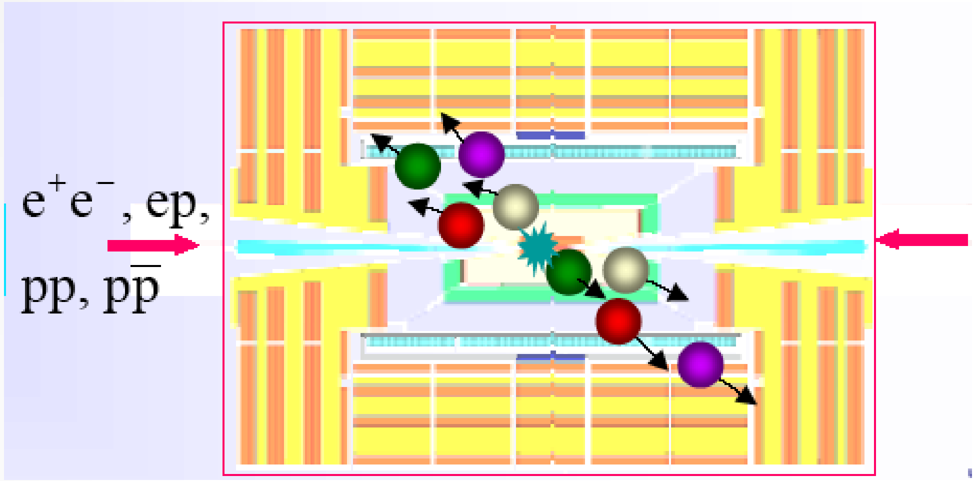

- Limited solid angle dΩ coverage
- Easy access (cables, maintenance)

## Collider Geometry




- Full" solid angle dΩ coverage
- Very restricted access

# Ideal Detectors




End products:

- charged particles
- neural particles
- photons

- An “ideal” particle detector would provide…
  - Coverage of **full solid angle**, no cracks, fine segmentation (why?)
  - Measurement of momentum and energy
  - Detection, tracking, and identification of all particles (mass, charge, lifetime)
  - Fast response: no dead time (what is dead time?)
  - Contain no dead material (what is dead material?)
- However, practical limitations:
  - Technology, Space, Budget

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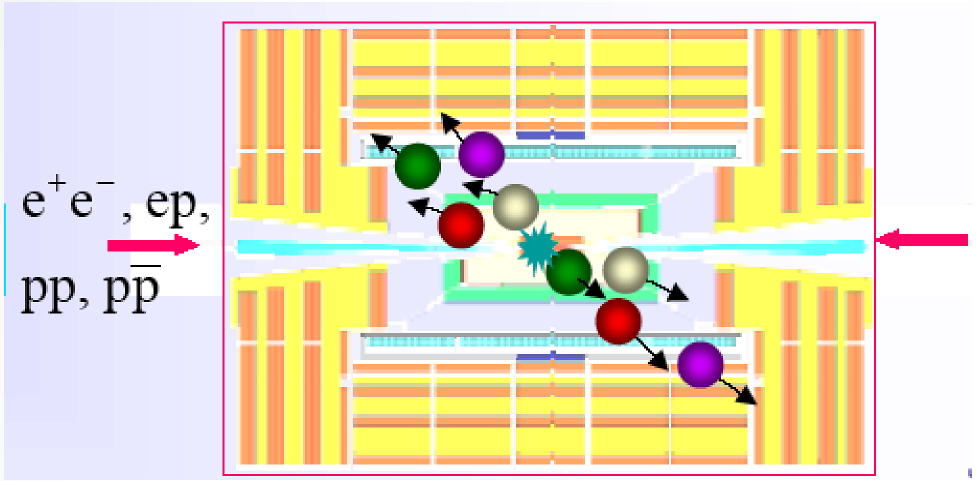


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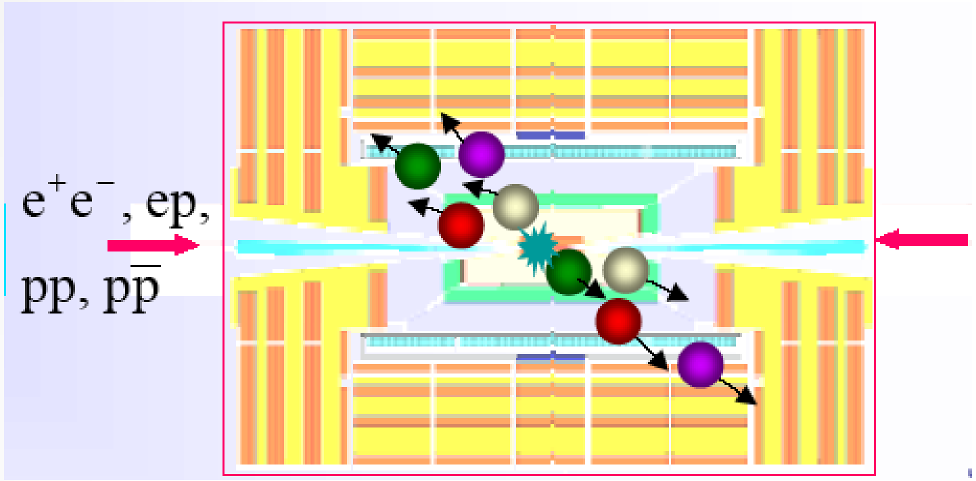


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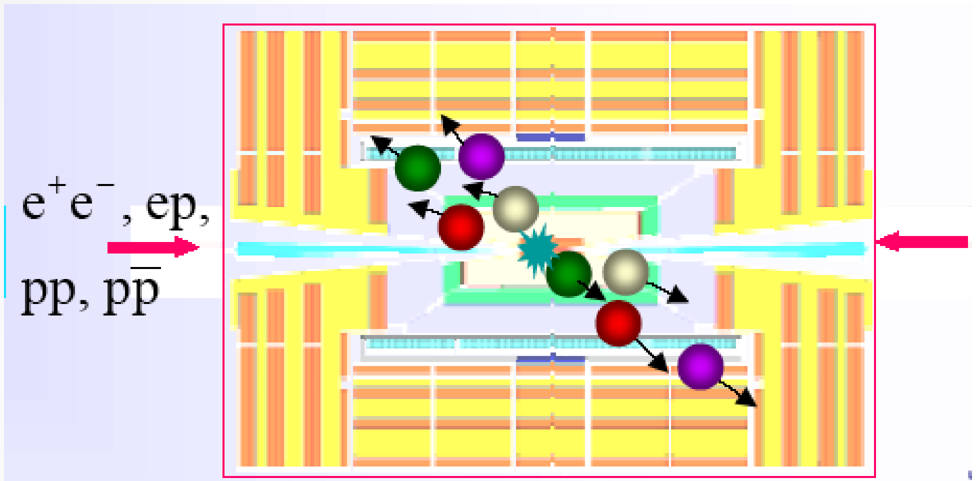


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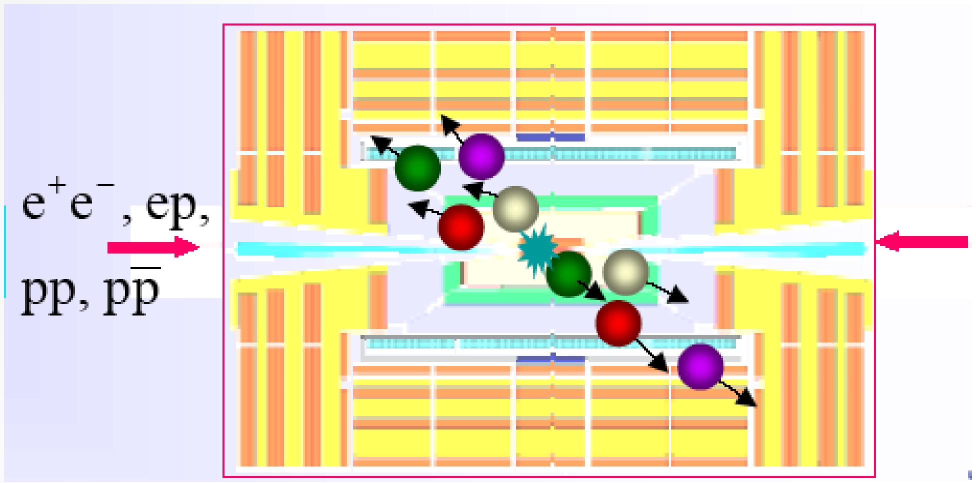


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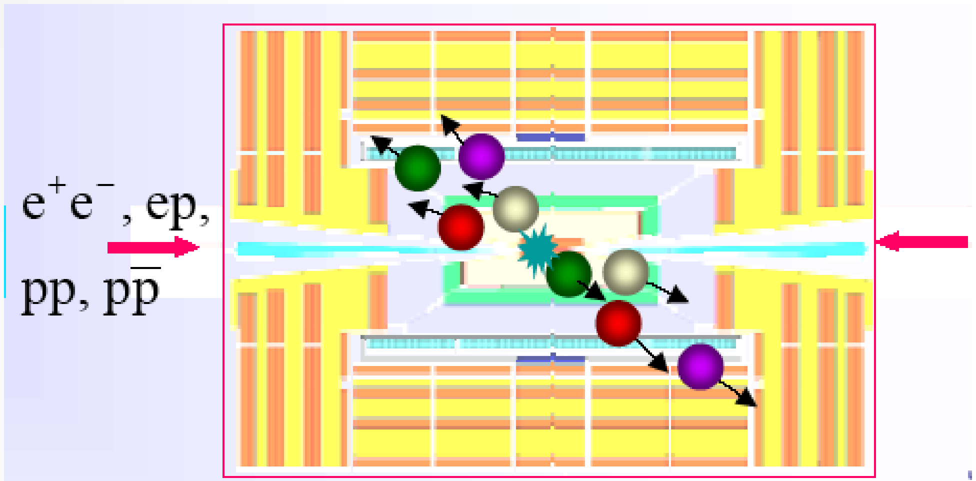


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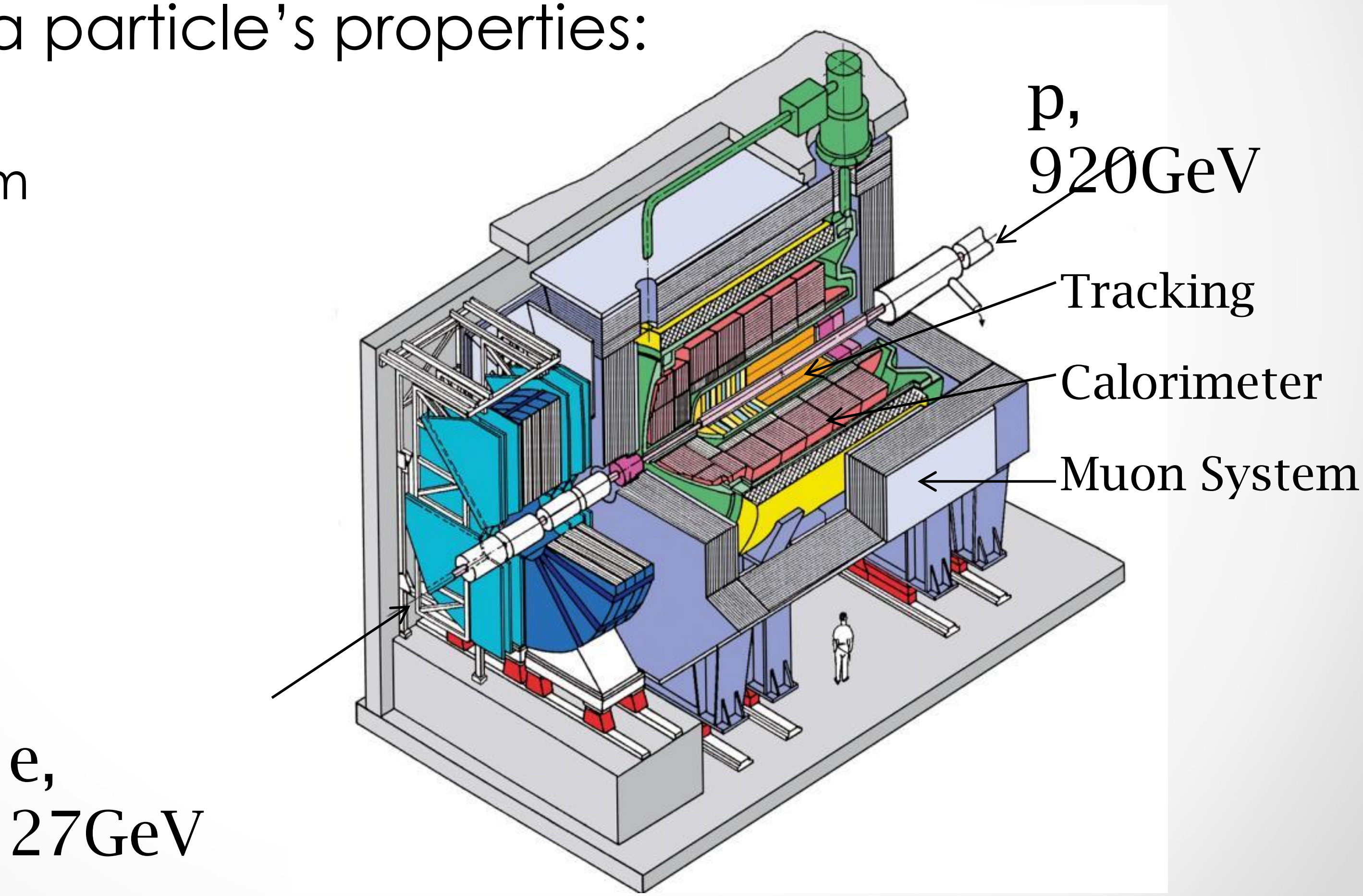
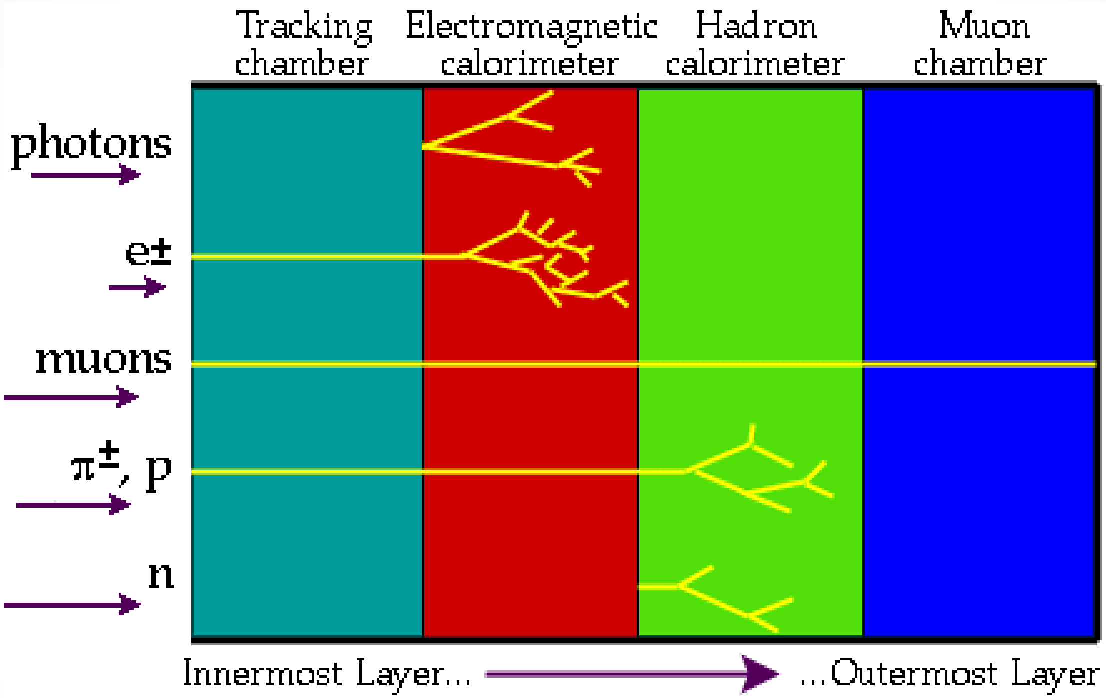
  - **Technology**, **Space**, **Budget**

# Individual Detector Types

- Modern detectors consist of many different pieces of equipment to measure different aspects of an event.
- Measuring a particle's properties:
  - Position
  - Momentum
  - Energy
  - Charge
  - Type

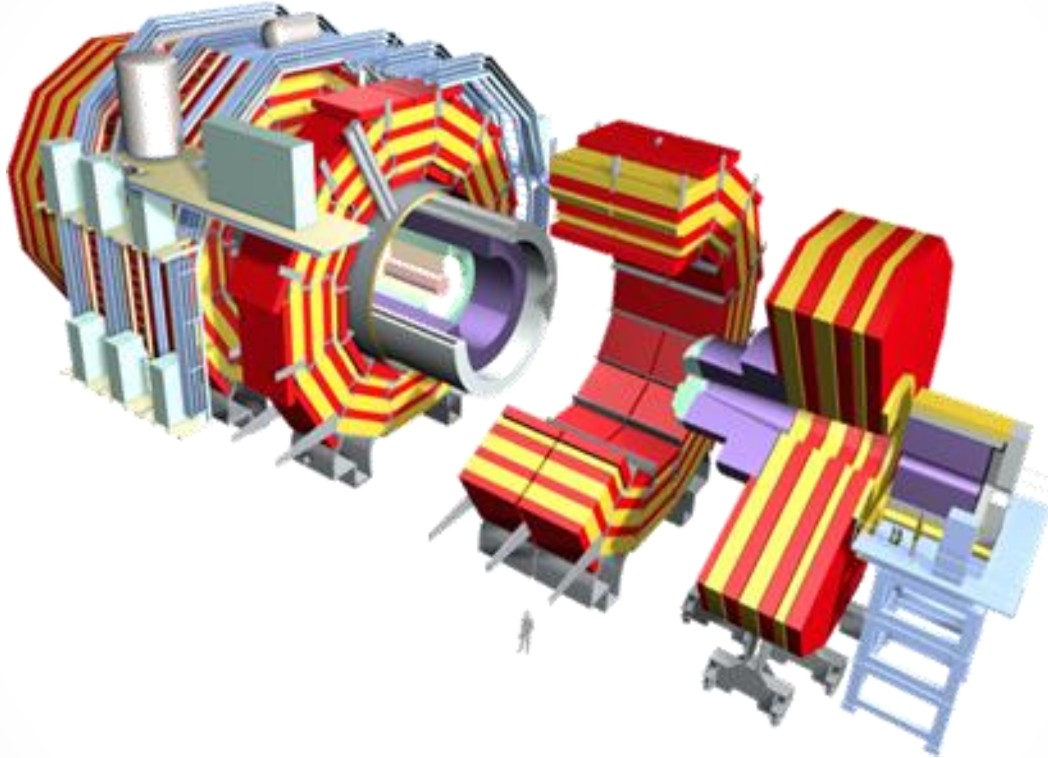


# Particle Decay Signatures




- Particles are detected via their interaction with matter.
- Many types of interactions are involved,
  - mainly electromagnetic.
- In the end, always rely on ionization and excitation of matter.

# Particle Decay Signatures in CMS



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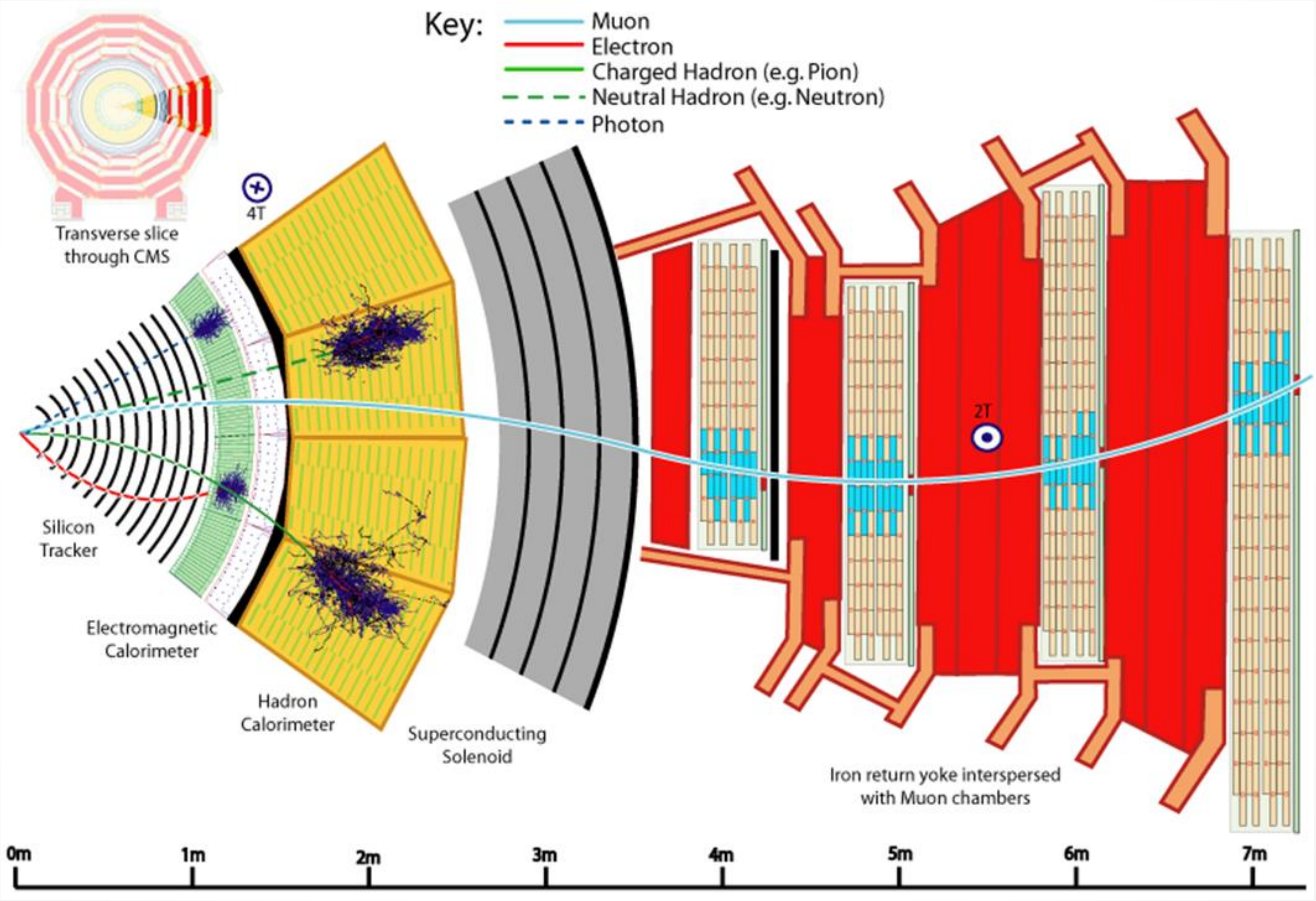
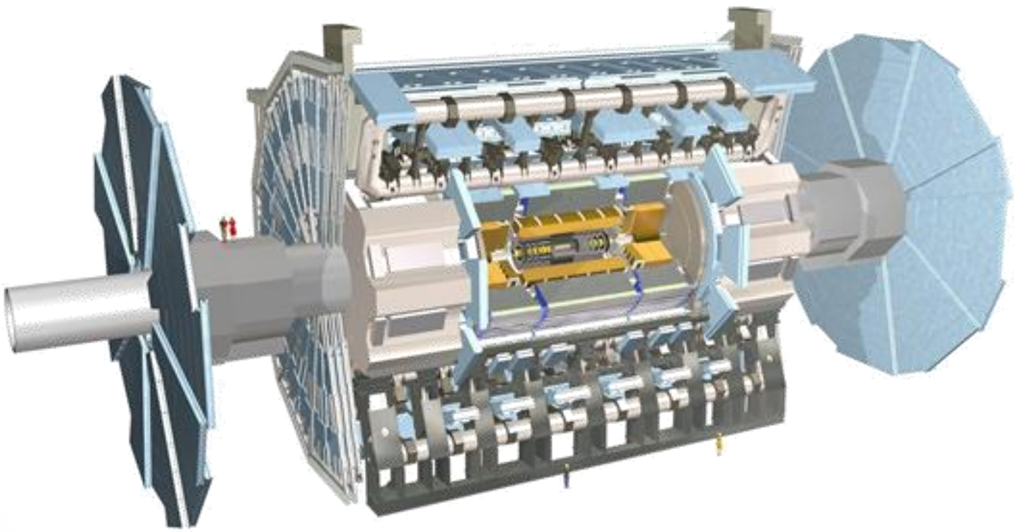


# Particle Decay Signatures in Atlas



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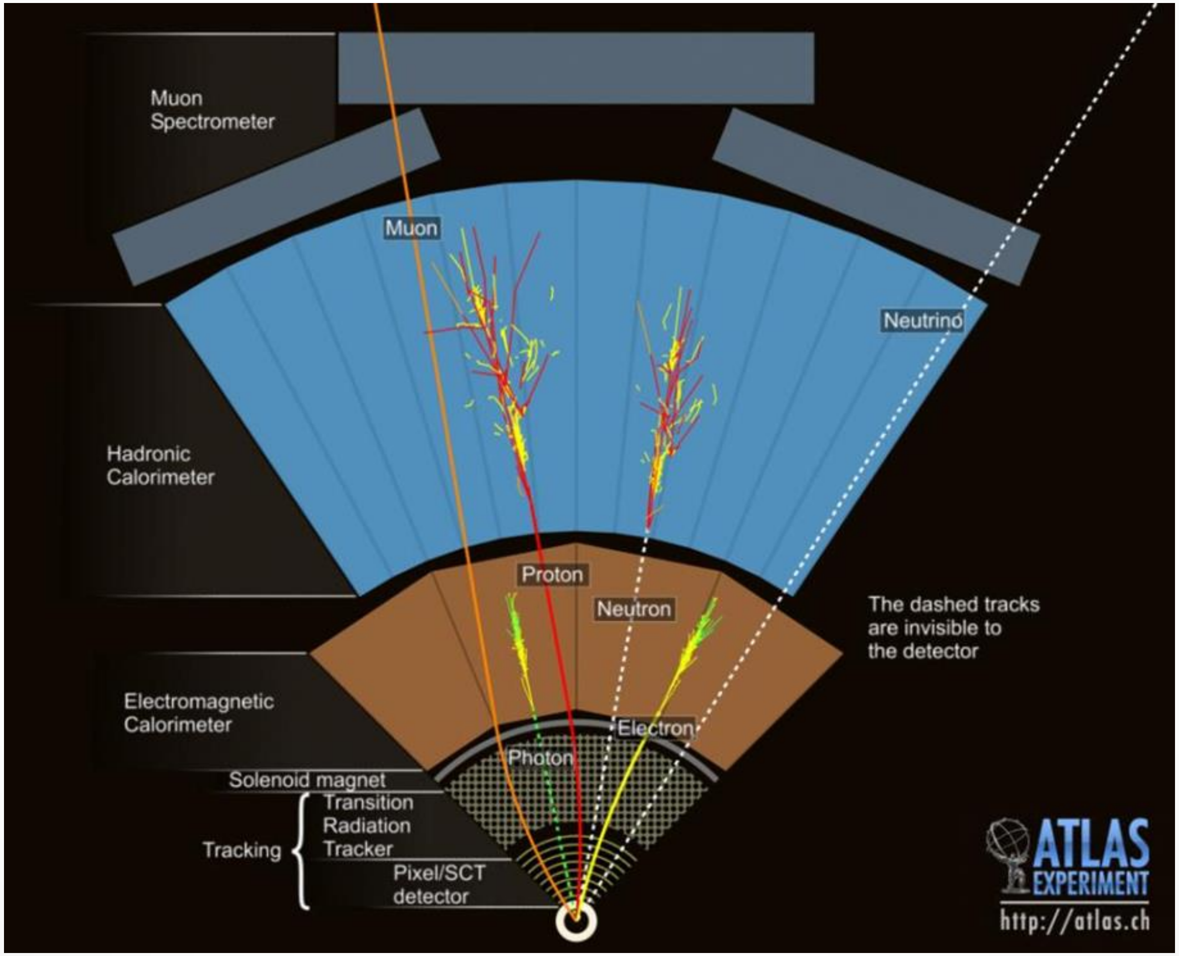
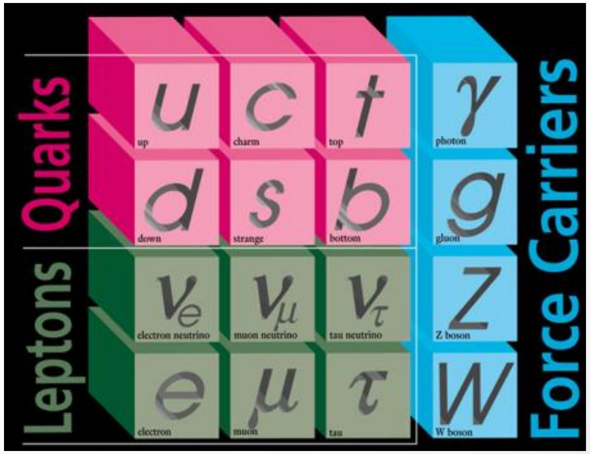


# Particle Identification Methods

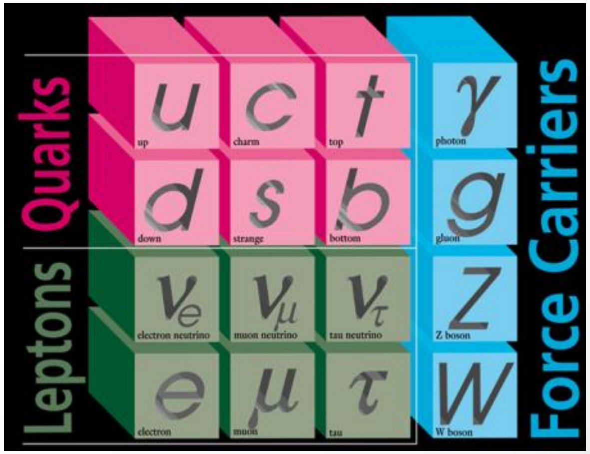
| Constituante | Vertex | Track | PID | Ecal | Hcal | Muon |
|---|---|---|---|---|---|---|
| Electron | Primary | ✓ | ✓ | ✓ | - | - |
| Photon | Primary | - | - | ✓ | - | - |
| u, d, gluon | Primary | ✓ | - | ✓ | ✓ | - |
| Neutrino | - | - | - | - | - | - |
| s | Primary | ✓ | ✓ | ✓ | ✓ | - |
| c, b, tau | Secondary | ✓ | ✓ | ✓ | ✓ | - |
| Muon | Primary | ✓ | - | MIP | MIP | ✓ |

- PID = Particle ID (TOF, dE/dx)
- MIP = Minimum Ionizing Particle



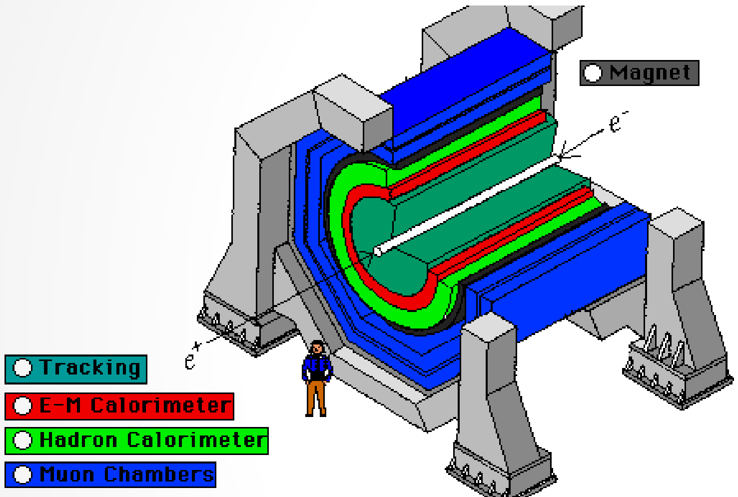
# Particle Detection Methods

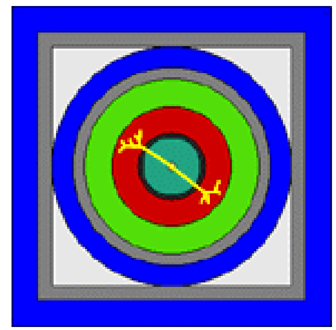
| Signature | Detector Type | Particle |
|---|---|---|
| Jet of hadrons | Calorimeter, Tracking | u, c, t $\rightarrow$ Wb, d, s, b, g |
| Missing energy | Calorimeter | $\nu_e$, $\nu_\mu$, $\nu_\tau$ |
| Electromagnetic shower | EM Calorimeter | e, $\gamma$ |
| Purely ionization interactions, dE/dx | Muon absorber | M, $\tau \rightarrow \mu \nu_\mu \nu_\tau$ |
| Life time, $c\tau \geq 100$ μm | Si-Tracking | b, c, $\tau$ |

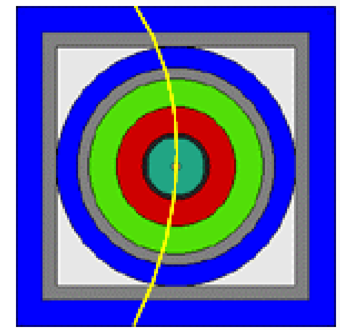


# Quiz: Decays of a Z boson

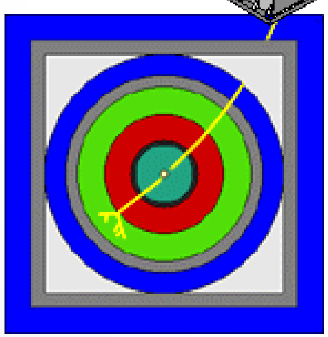
- Z bosons have a very short lifetime, decaying in ~10-27 s, so that:
  - only decay particles are seen in the detector.
  - By looking at these detector signatures, identify the daughters of the Z boson.

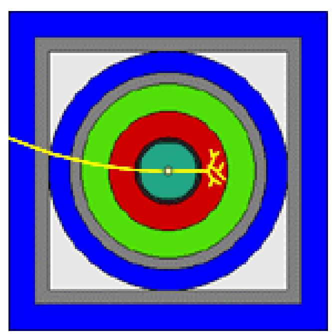


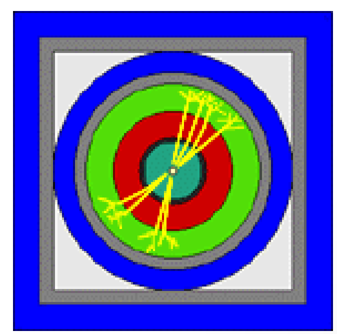



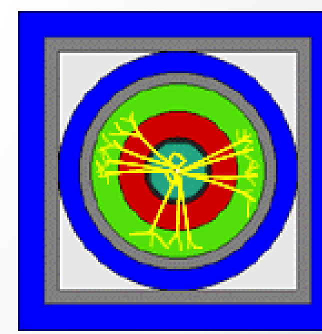


But some daughters can also decay:





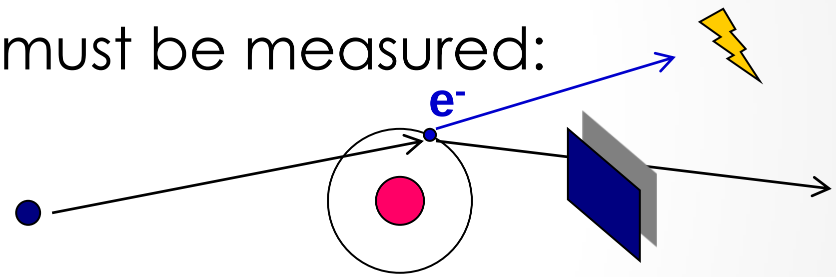




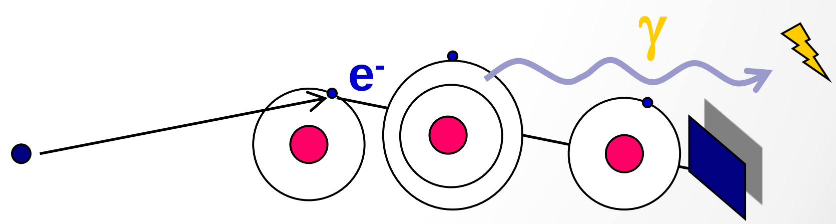
- More fun with Z bosons: http://opal.web.cern.ch/Opal/events/opalpics.html

# Principles of a measurement

- The particle must **interact** with the detector material:
  - **transfer** directly or indirectly **energy** to the medium they are traversing
  - via **ionization** or **excitation** of its constituent atoms.
- An effect of the interaction must be measured:
  - Ionization:




  - Excitation and scintillation:



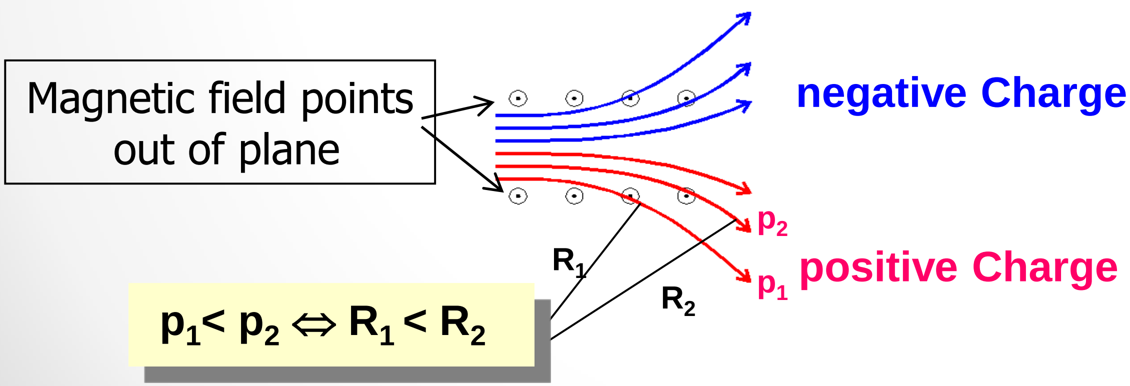

  - Cerenkov radiation
  - Signals from electron-hole pairs (Si-detectors)
- The particle may also be affected by the interaction:
  - energy loss, scattering and absorption

# Measurable Properties of particles

- Production / passage of a particle
- Four-Momentum of particle
- Charge of particle
- Lifetime of particle

# How does one measure the Four-Momentum?

- Energy:
  - with a "calorimeter" (see tomorrow)
- Momentum:
  - with a "magnetic field + track detector"




**Lorentz-Force**

$$q\, v_T\, B = m\, v_T^2/R$$

$$\Downarrow$$

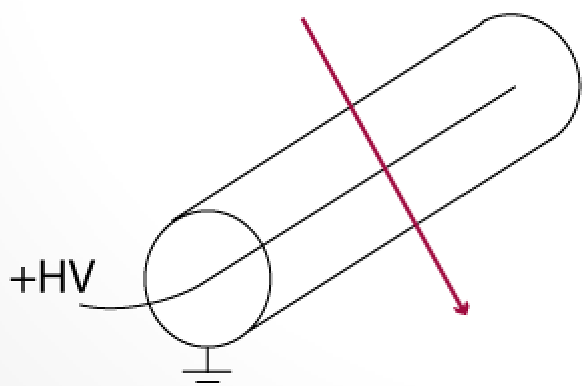
$$q\, B\, R = m\, v_T = \mathbf{p_T}$$

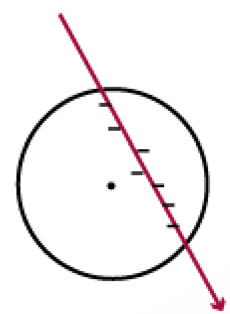
# Tracking:

Proportional Counters
and Drift Chambers

# Charged Particle Tracking

- Two main types:
  - Gas wire chambers
  - Silicon
- Innermost detectors:
  - precise tracking → use Si-Detectors!
- Outer detectors:
  - silicon too expensive!
  - (not true for LHC-detectors also use silicon).
- Basic design: ionization chamber with HV sense wire:

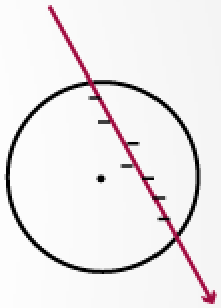


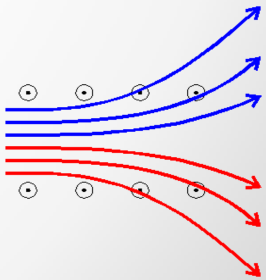



Amplification of $10^3$ - $10^5$ in high field near wire

# Ionization Wire Chambers

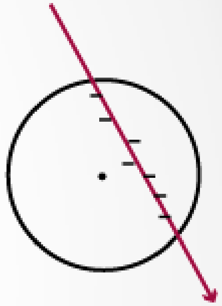
- Wire Chambers:
  - Most commonly used detection devices in high energy physics experiments.
- The Basics of Wire Chambers:
  - Charged particles travels through a gas
  - Gas is ionized by the particle
  - Ionization drifts & diffuses in an electric field toward an electrode
  - Collection and amplification of anode signal charge
  - ➢ detectable signals
  - Measurement of points on trajectory determines p





# Processes in Gases

- When a charged particle passes through gases subject to an E field, it loses energy by:
  - Elastic scattering (small)
  - Excitation: gas atoms/molecules
  - Excite then de-excite by γ emission
  - **Ionization** (most important)

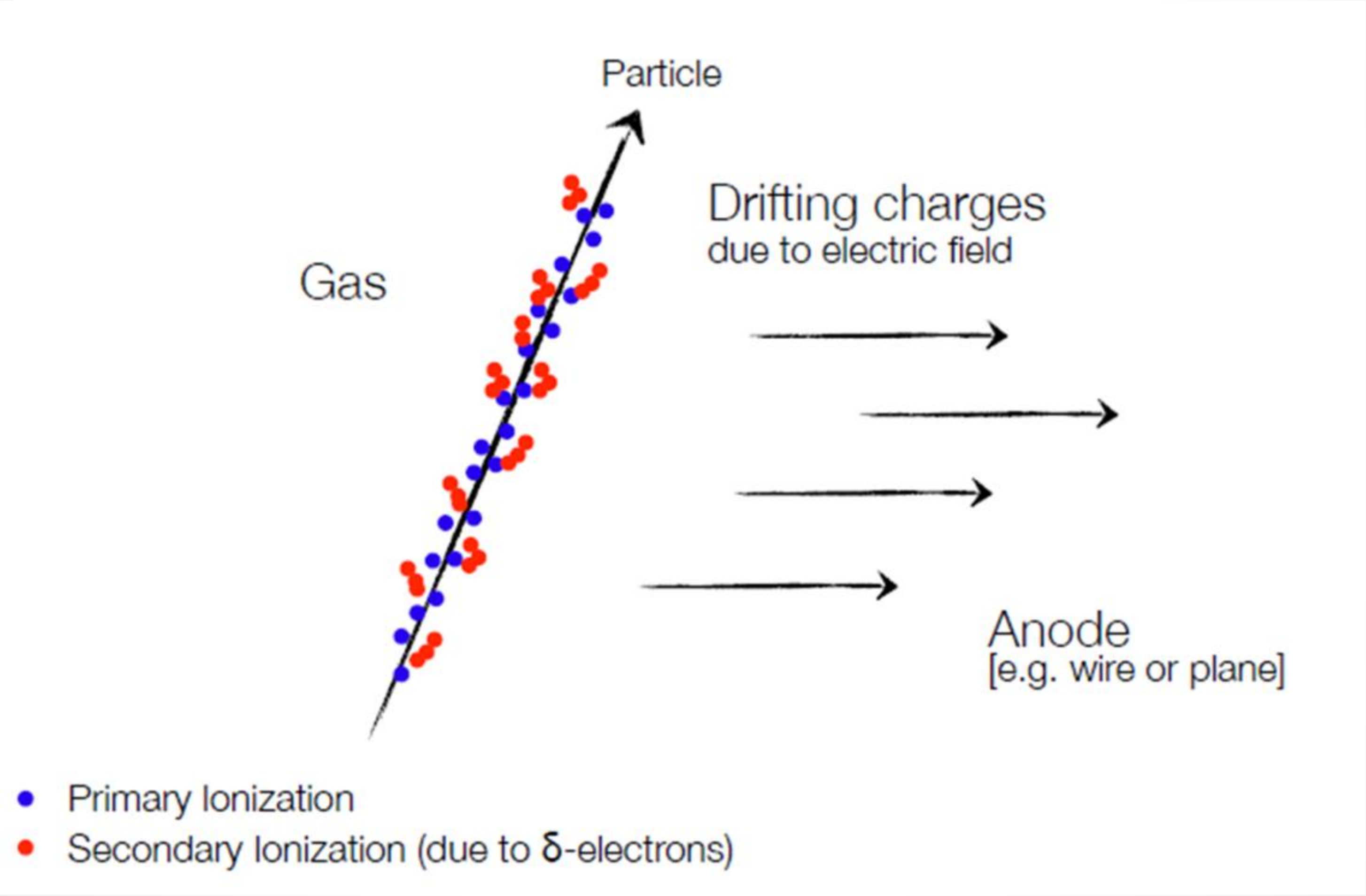


- Ionization:
  - One or more electrons are liberated from atoms of the medium,
  - ➢ leaving positive ions and electrons.
  - Energy imparted to atom exceeds ionization potential of gas.

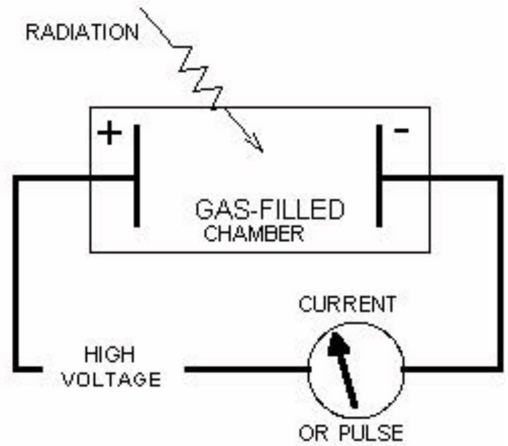
TABLE IX.

| Gas. | Ionization Potential. |
|---|---|
| Argon | 15.6 |
| Nitrogen | 15.8 |
| Carbon Monoxide | 15.0 |
| Hydrogen | 15.1 |
| Helium | 20.5 |
| Mercury vapor | 10.1 |
| Iodine vapor | 8.5 |

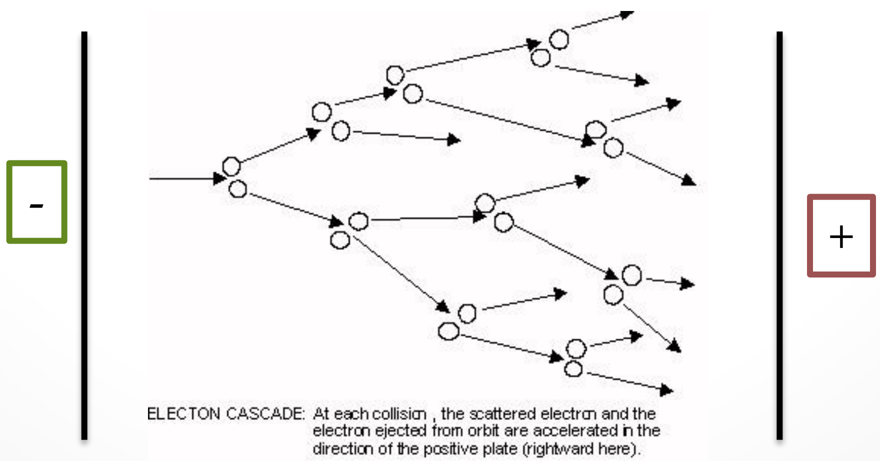
# Principle of Gas Detectors



# Number of Ions v. Voltage

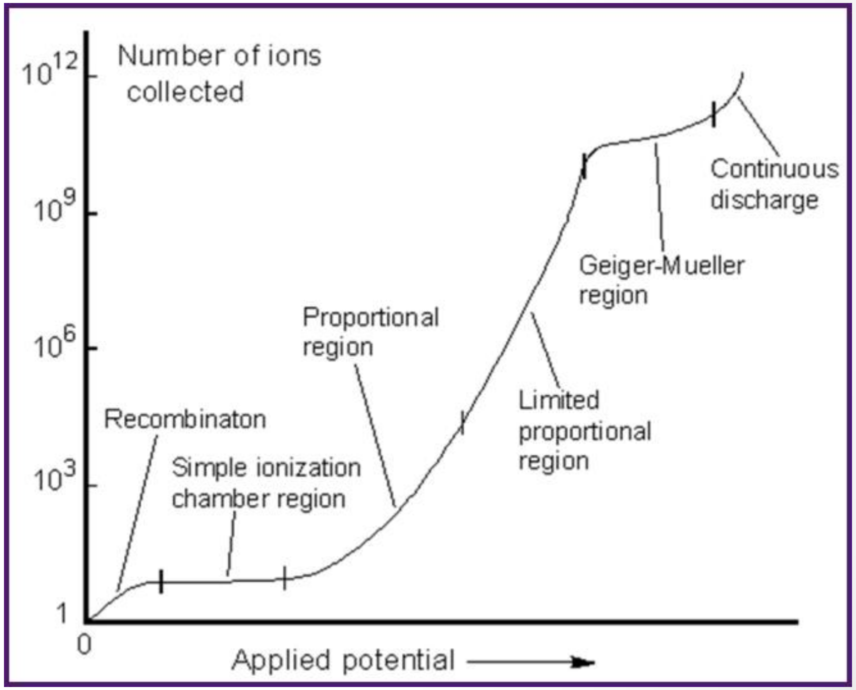



Simplest case: Parallel plate capacitor

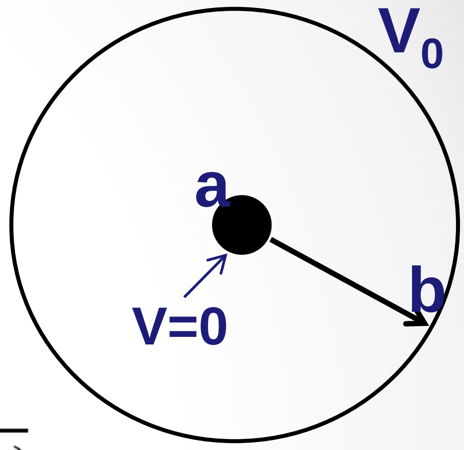


# Number of Ions v. Voltage

- Ionization chamber:
  - Voltage increased such that the charge arriving on plates =
  - charge formed
- Proportional region:
  - Initial electrons accelerated enough to ionize more;
  - avalanche pulse proportional to primary ionization
  - reaches ~$10^8$



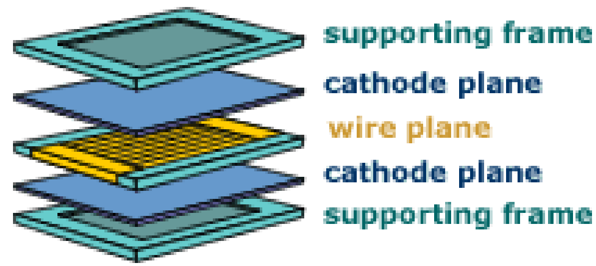
# Proportional Chambers



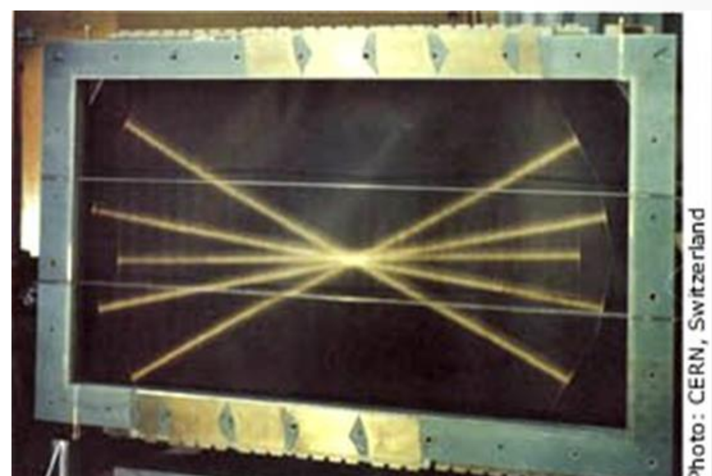

- Cylindrical proportional tube of
  - outer radius *b* at
  - voltage $V_0$ and
  - inner (wire) of radius *a* at voltage zero.
- Electric field inside the chamber:
- $E = \frac{2l}{r}, V_0 = 2l \ln\left(\frac{b}{a}\right), V(r) = V_0 \frac{\ln(r/a)}{\ln(b/a)},\ E(r) = \frac{V_0}{r \ln(b/a)}$
- Charged particle ->
  - Ionization.
  - $e^-$ move toward anode
  - High fields near wire
  - Multiplication of $e^-$s by collisions:
  - at small r the energy gain can exceed ionization potential.
  - Runaway process, like avalanche in PMTs.
- Typical Gas gain~$10^5$ - $10^8$, Geiger region!

# Multi-wire Proportional Chambers

- MWPC invented by Charpak at CERN
  - Principle of proportional counter is extended to large areas:
  - Stack several wire planes up in different direction to get position location.

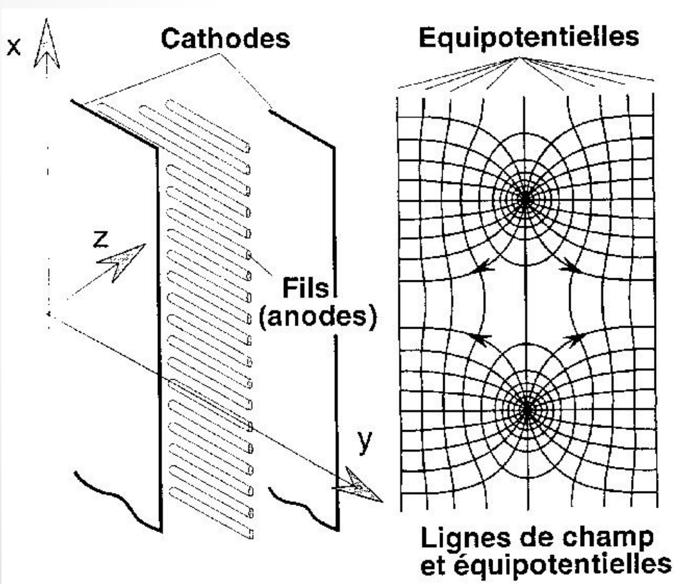


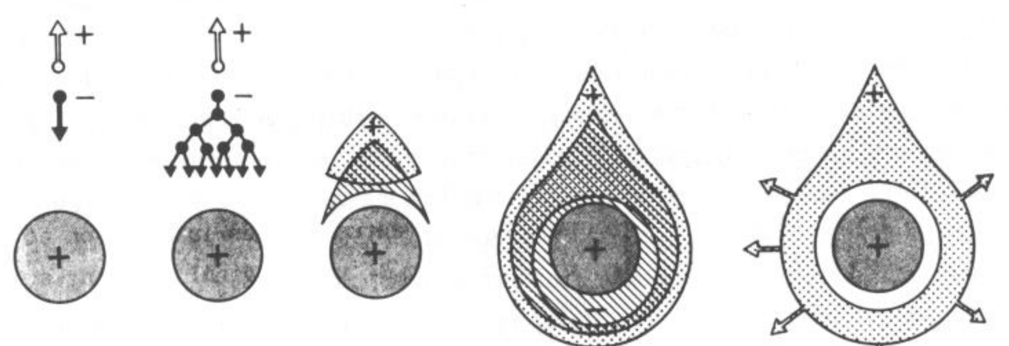




# Multi-wire Proportional Chambers

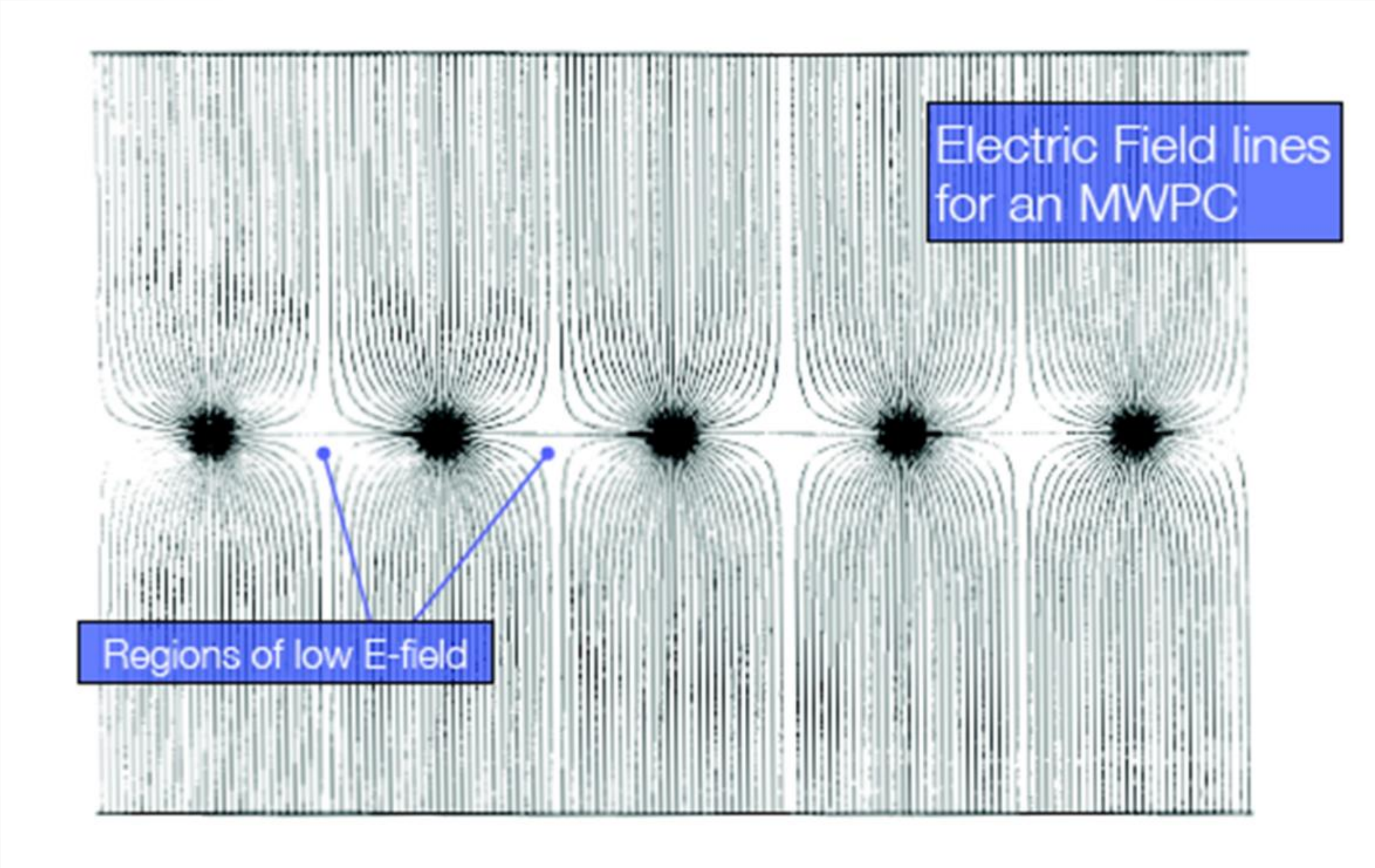
G. Charpak
Nobel Prize 1992



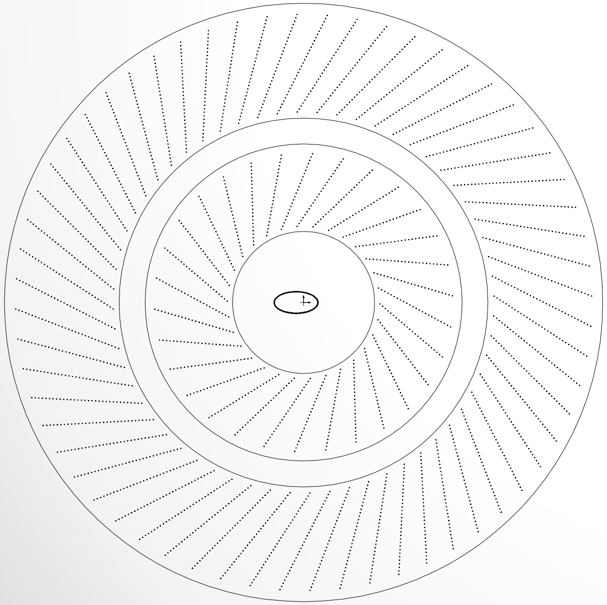
Avalanche developing

# Drift Chambers - Field Formation

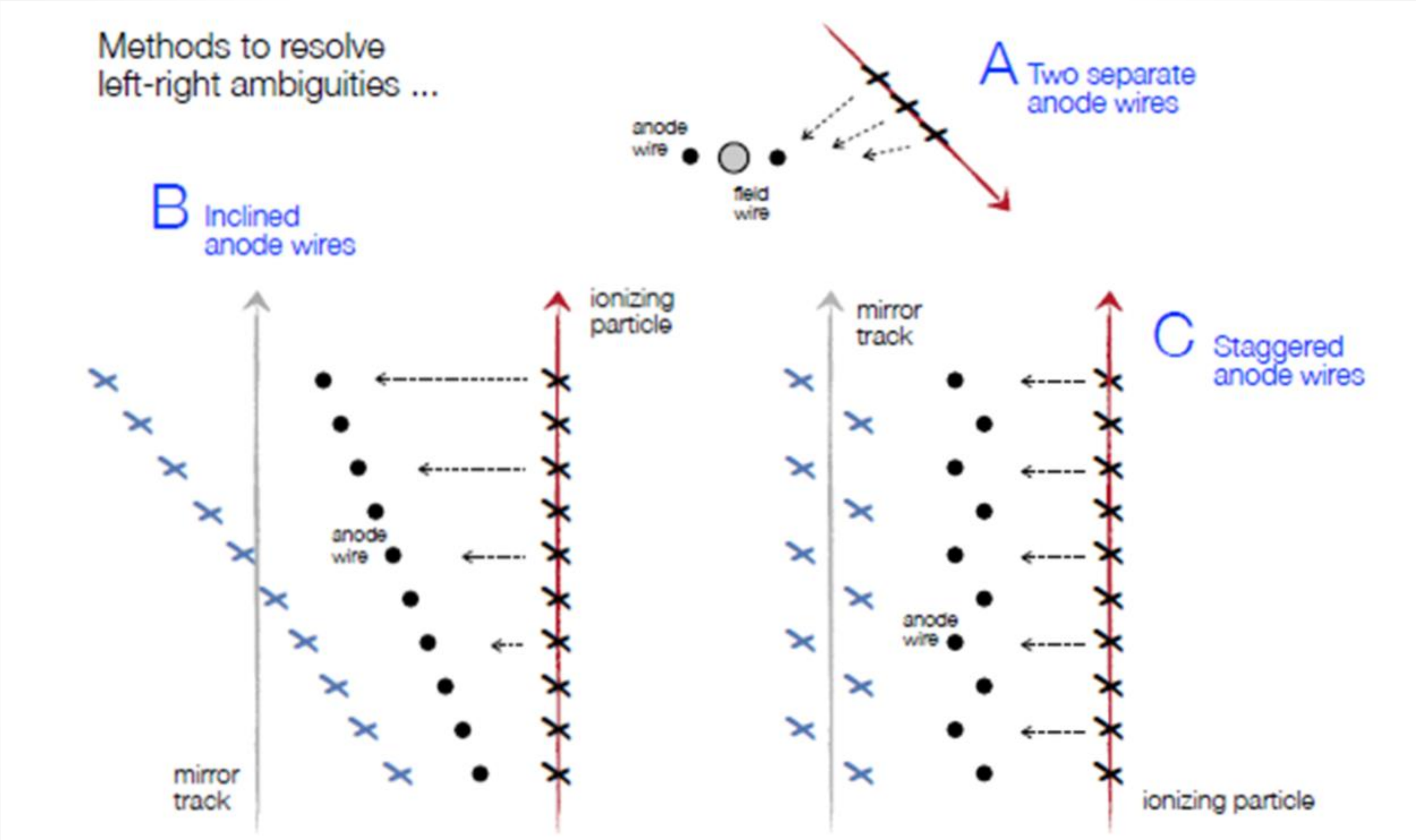


# Large Area Drift Chambers

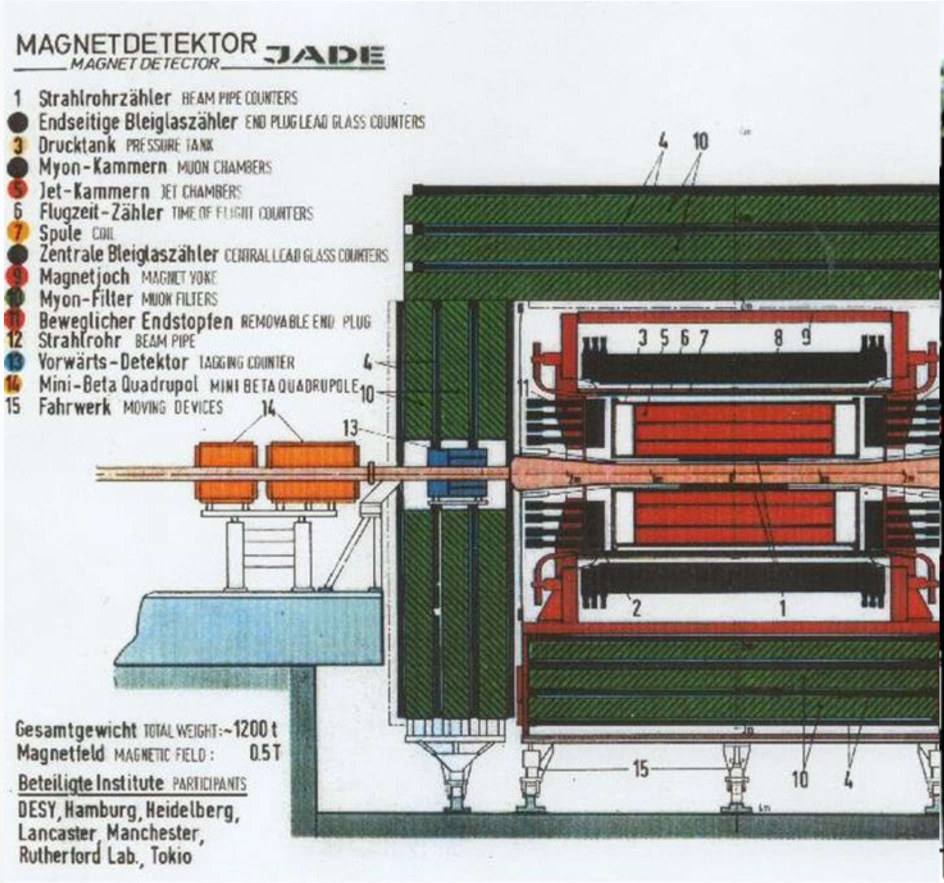
- The “open cell” drift chamber uses
  - field and sense wires:
  - field wires create shape of electric field,
  - sense wires detect time of arrival of pulse.
- Position of particle: $x = x_{wire} + v_{drift}\, t_{drift}$

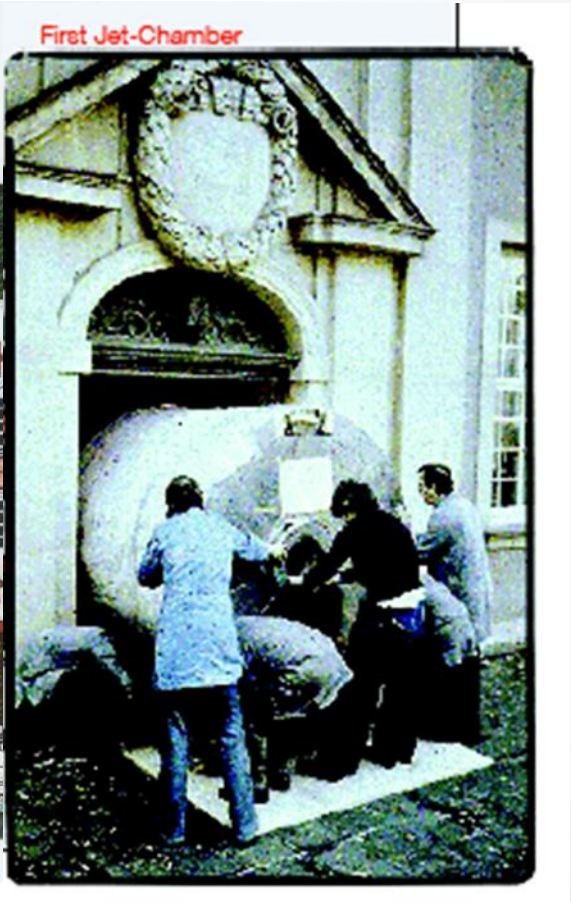


# Drift Chamber - Ambiguities

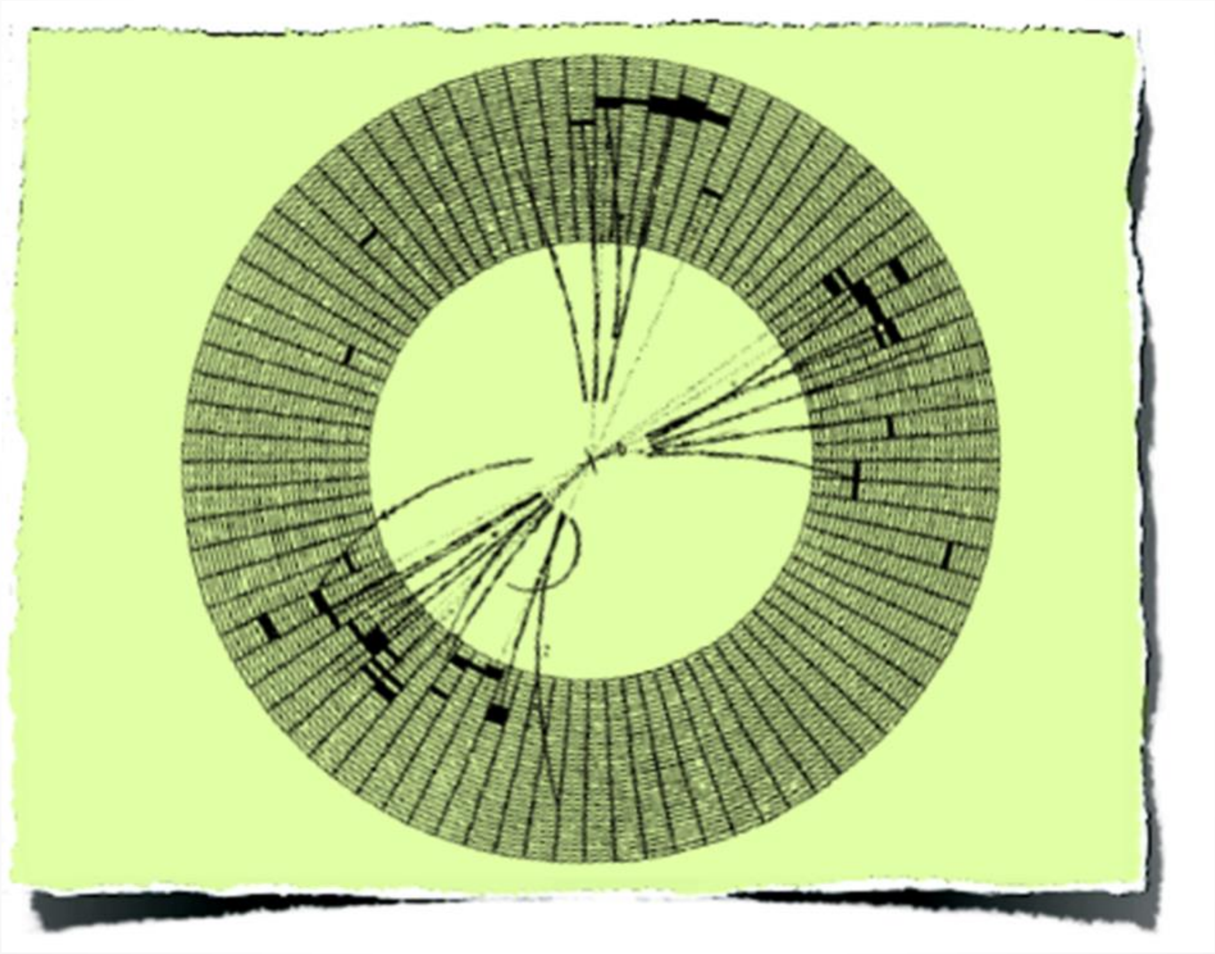


# Drift Chamber - Jade

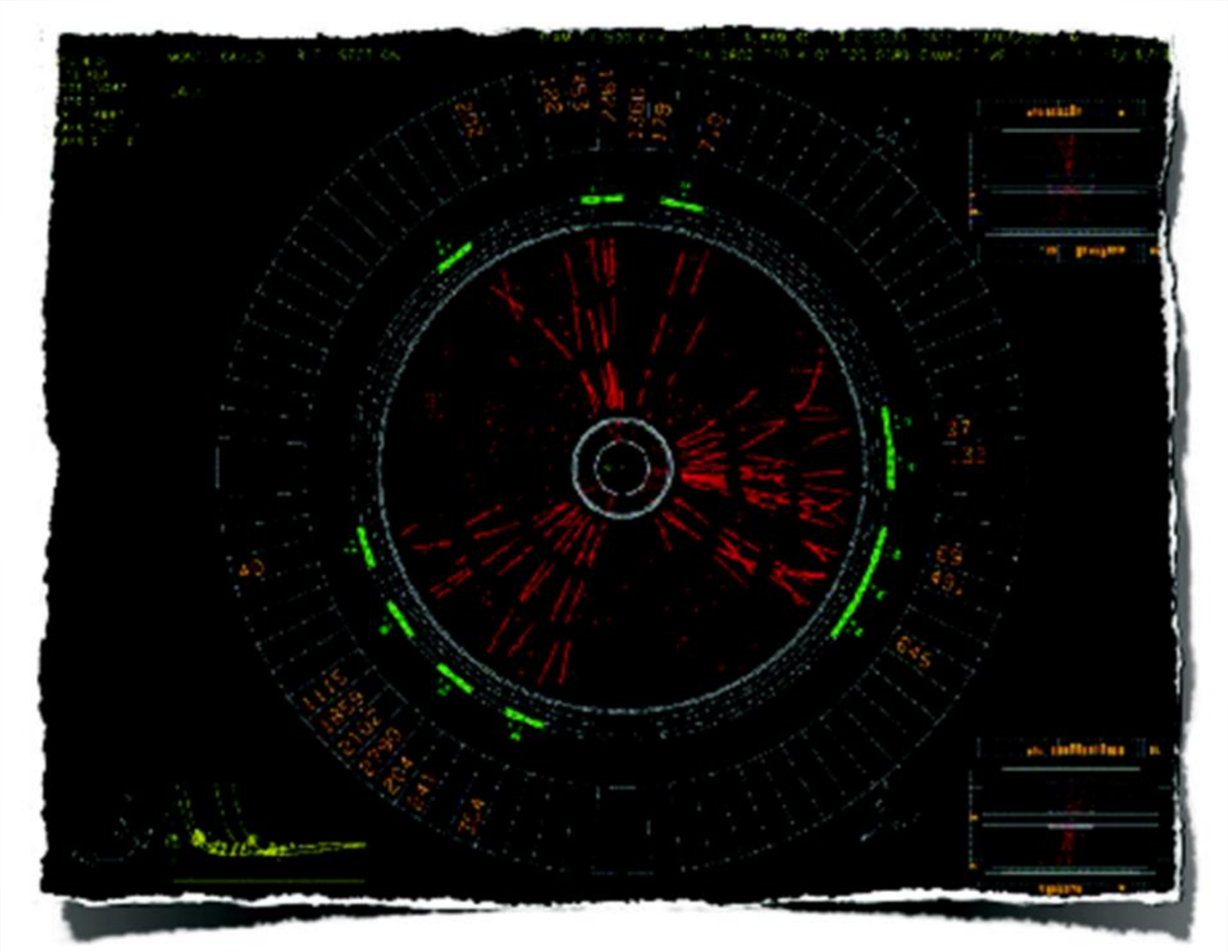


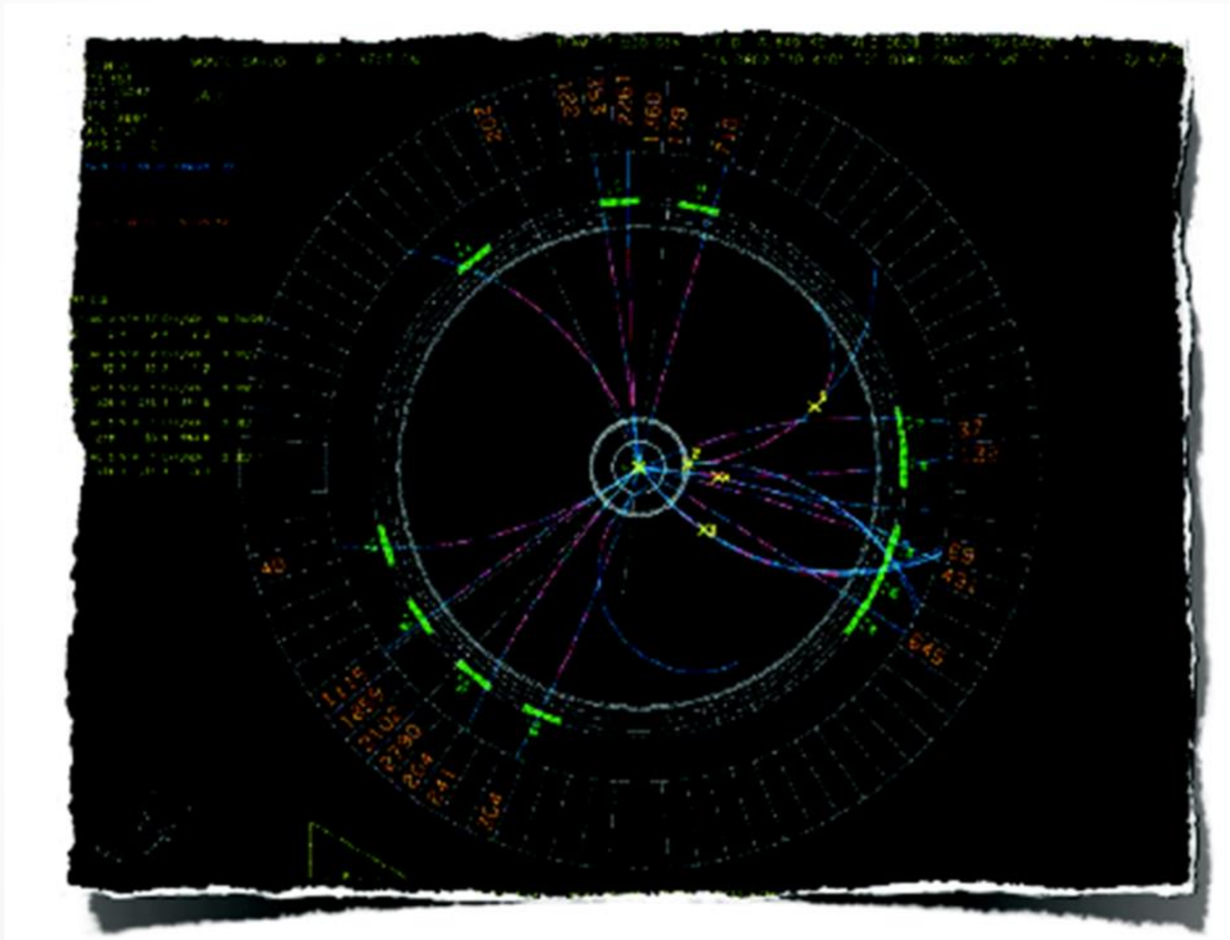
# Drift Chamber - Jade



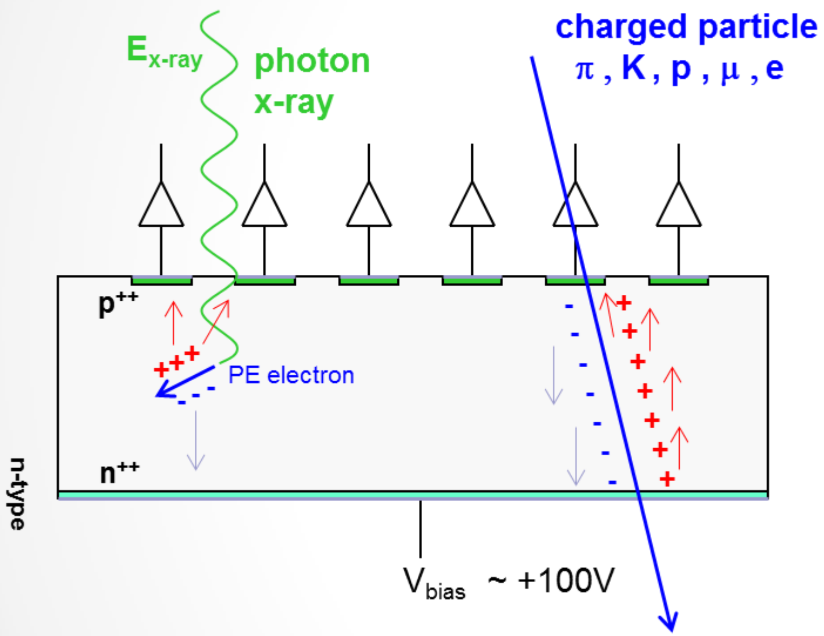
# Drift Chamber - Jade



# Drift Chamber - Jade

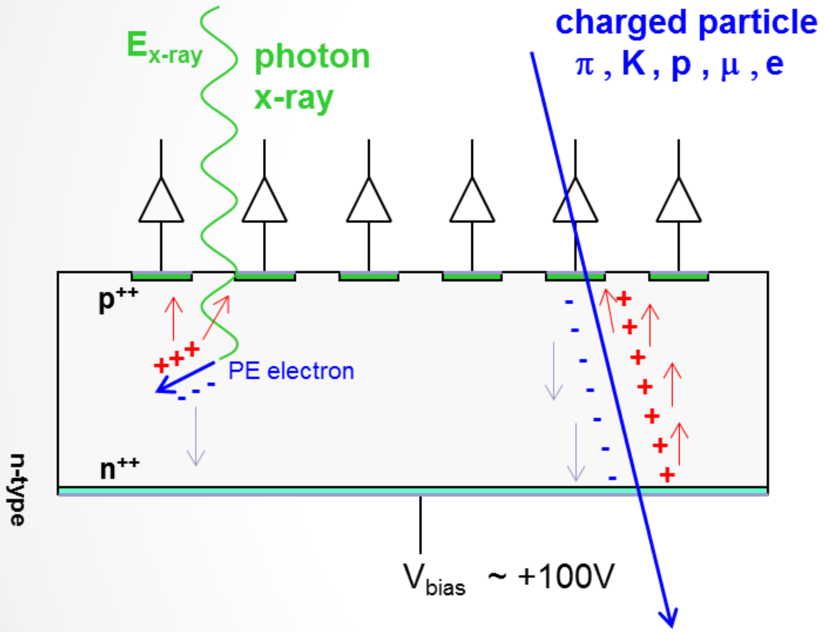


# Segmented Silicon Diode Sensors for Particle Detection



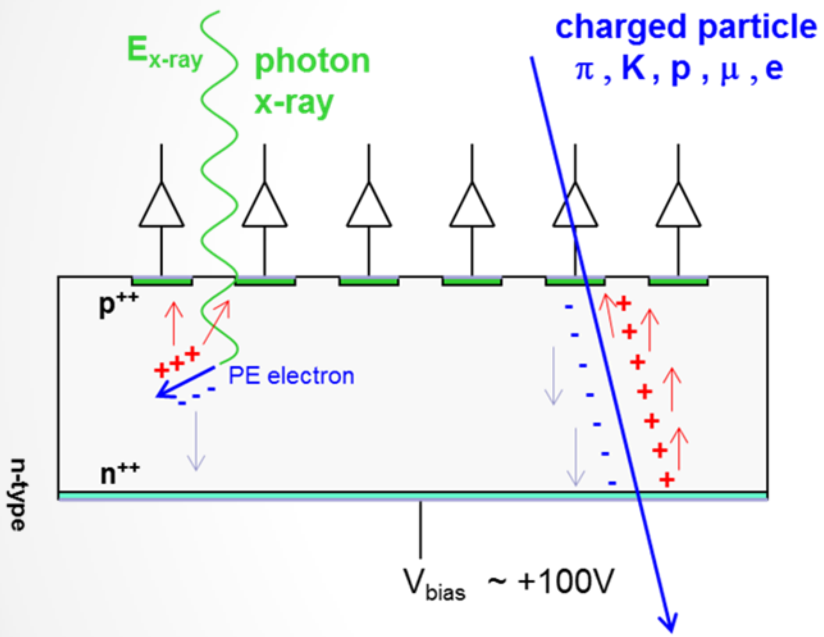

- For charged tracks resolution depend on:
  - segmentation pitch (strips, pixels)
  - charge sharing (angle, B-field, diffusion)
  - S/N performance of readout electronics
  - δ-rays

# Segmented Silicon Diode Sensors for Particle Detection




- Shared Charge collection on segmented electrodes due to:
  - Diffusion during drift time
  - Lorentz angle due to presence of B-field
  - Tilted tracks
- Individual readout of charge signal on electrodes allows position interpolation that is better than pitch of segmentation.

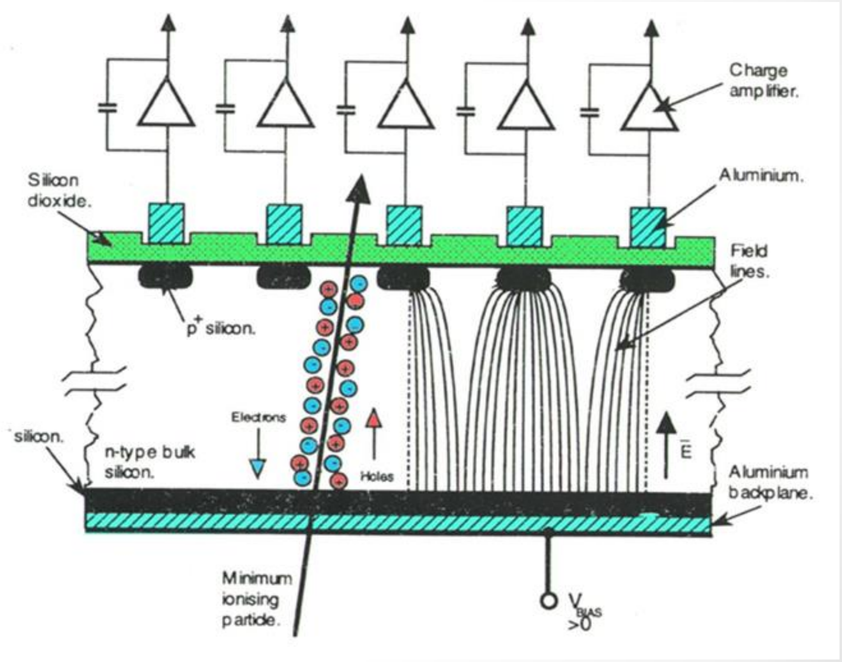
# Segmented Silicon Diode Sensors for Particle Detection




- Silicon microsrip detectors in HEP:
- Strip pitch = 50μm
- Position resolution ~1.5μm achieved

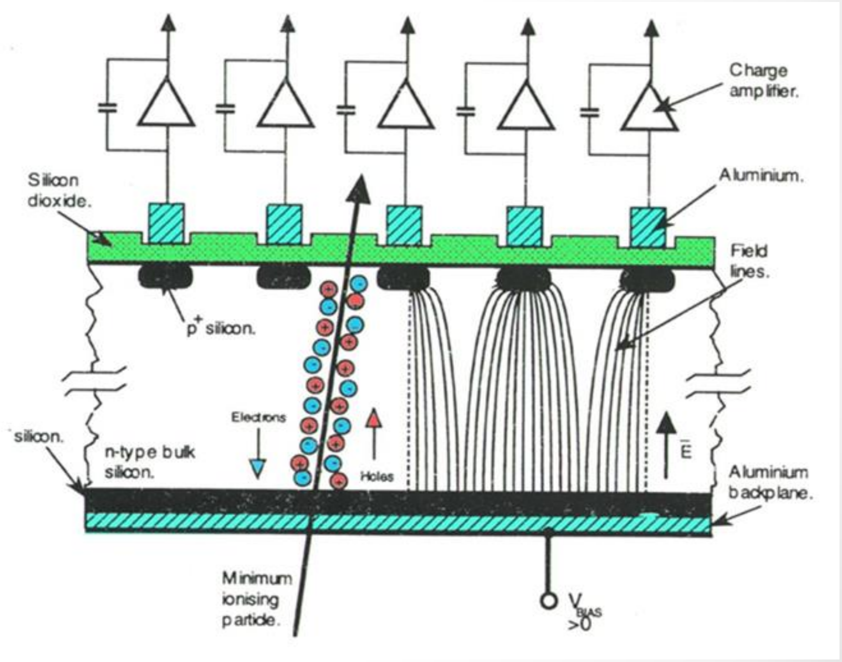
# Charge collection

- Electrons and holes
  - separated in the electric field and
  - collected on the implanted strips:
  - Electrons drift 10 ns
  - Holes drift 25 ns
  - Need high-purity silicon to avoid trapping.



# Charge collection

- Position resolution:
  - 5-30 μm
  - for strip pitch of 50-100 μm
  - better with pulse-height interpolation
- Silicon detectors are
  - fast and have
  - high resolution
- Further readout electronics required to amplify the charge
  - Need many channels to cover large areas.

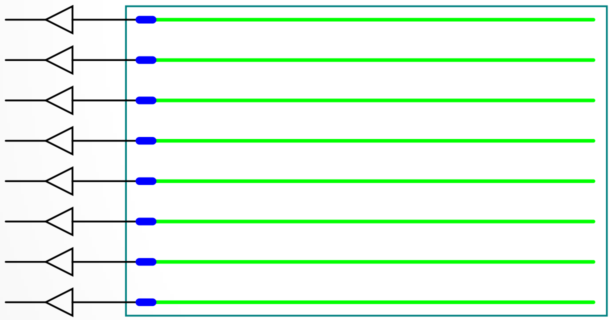


# From Strips to Pixels

- very high rate & high multiplicity
  - requires 2 D – segmentation of silicon sensors.
- connection to readout electronic chips !!

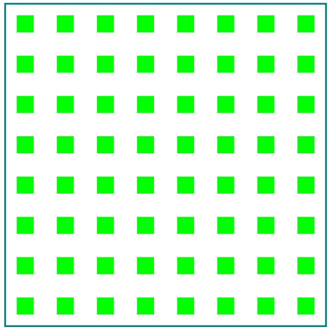
Micro strip Detectors → Pixel Detectors

**LEP, HERA, Tevatron** $10^5$ increase **LHC**



**1 D – connection**

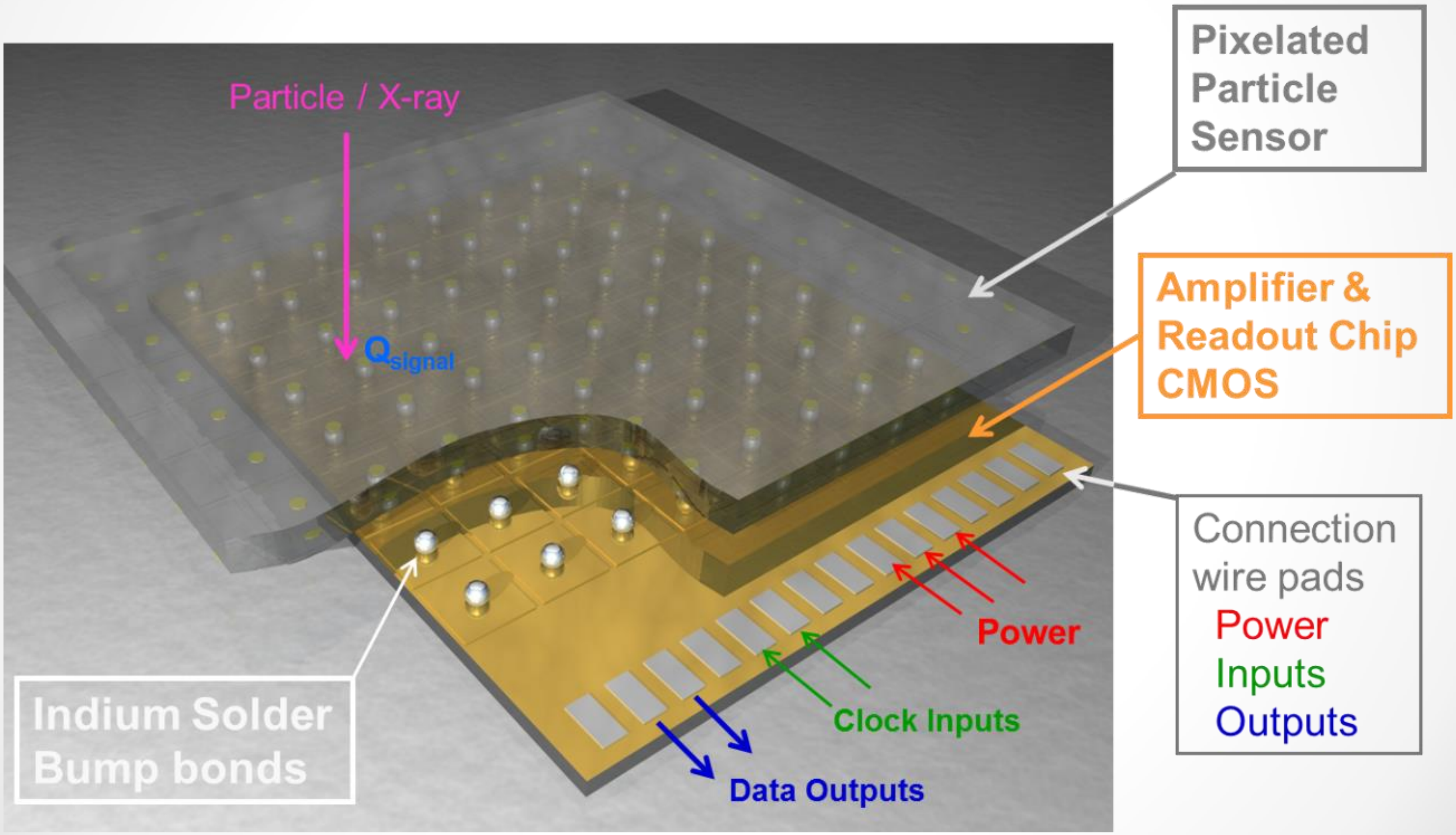
**wire-bonding**



**2 D – connection**

**- bump-bonding**
**- wafer bonding**
**- 3D integration**

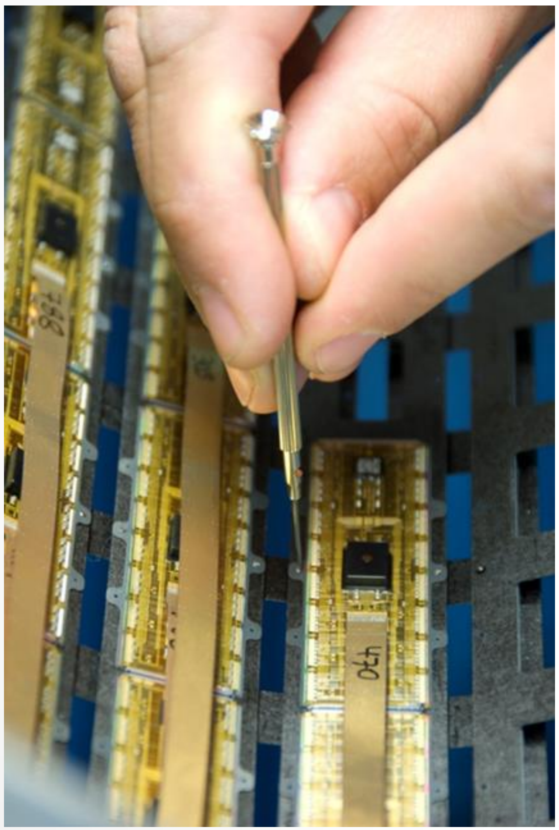
# Hybrid Pixel Detectors




Particle / X-ray → Signal Charge → Electr. Amplifier → Readout → Digital Data

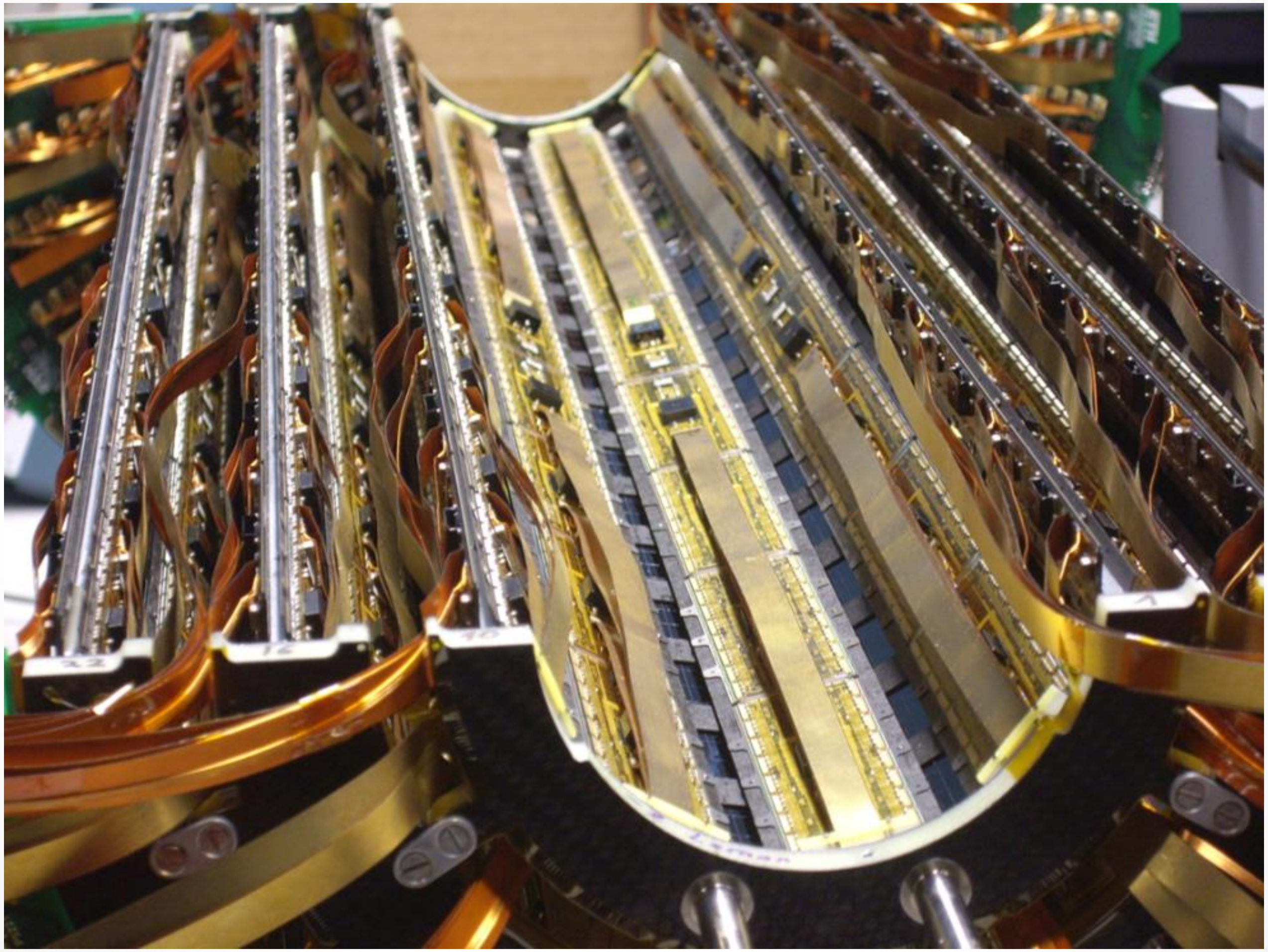
# CMS Pixel Detector

for the Large Hadron Collider



768 pixel modules
~0.75 $m^2$

# 48Mega Pixel Detector with 40 MHz Frame Rate



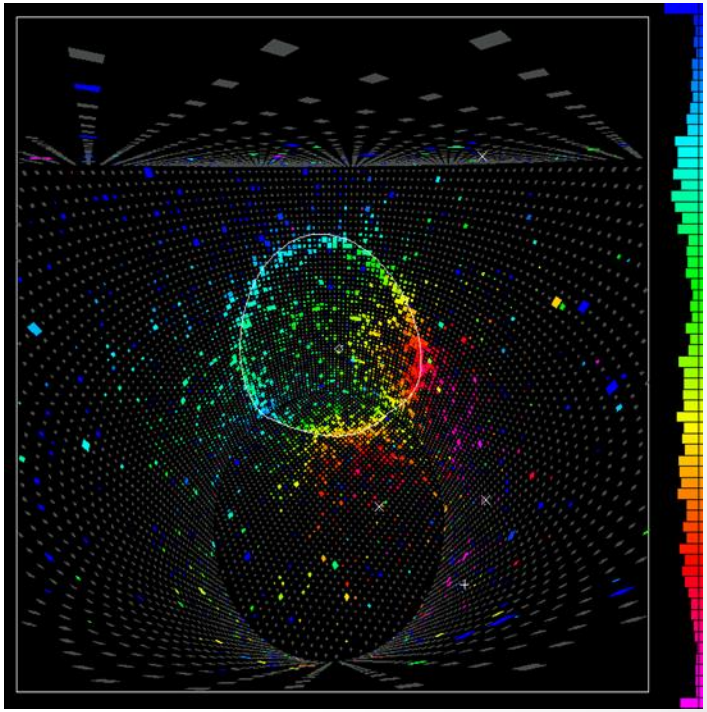
# Cherenkov Radiation


P. Cherenkov: 1935
Nobelpreis 1958

A light cone, so called Cherenkov radiation is emitted

- whenever charged particles pass through matter
- with a velocity v exceeding the velocity of light in the medium.
- Measure angle of light cone -> v of particle; Particle ID possible

airplane passing the sonic wall

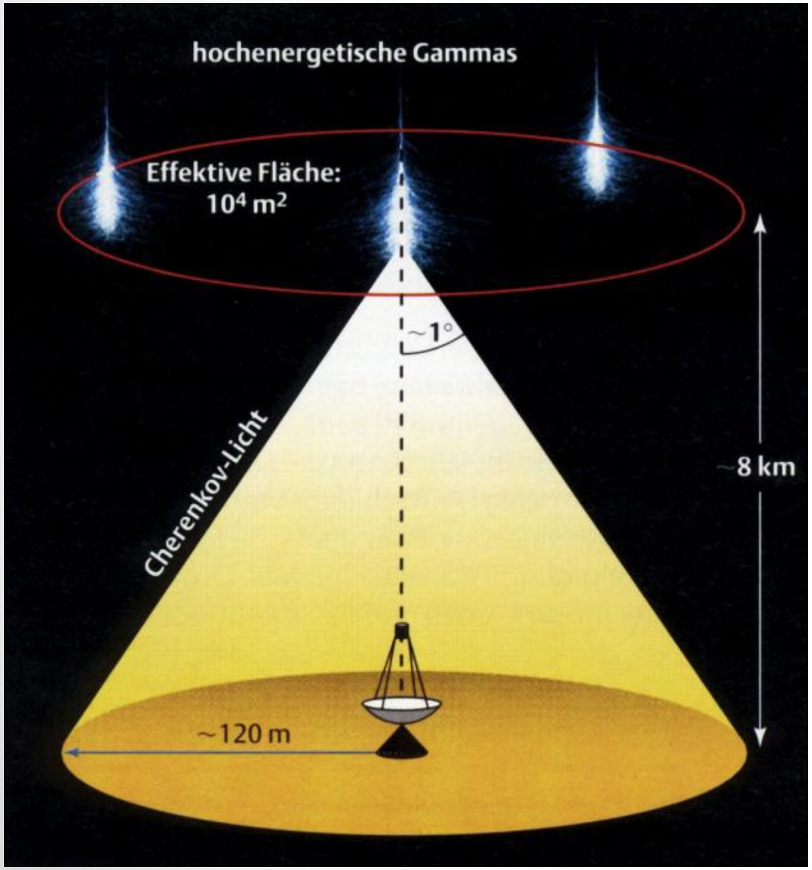


Event of Super Kamiokande

**See** http://webphysics.davidson.edu/applets/applets.html for a nice illustration

# Application in Astroparticle Physics

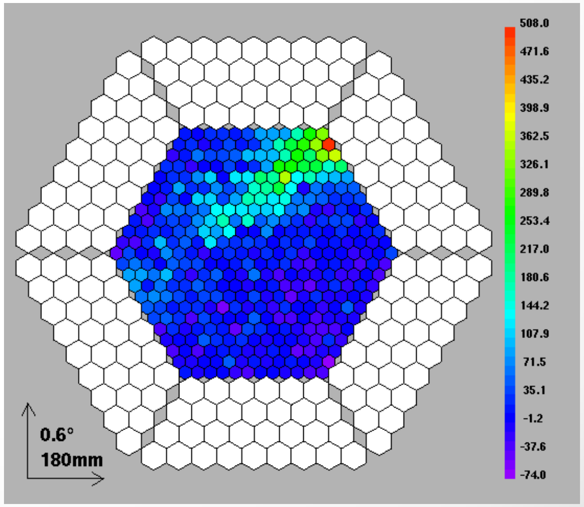
- Detection of high energetic $\gamma$'s via Cherenkov light in the atmosphere




Hess telescope

Magic telescope

Event Display Magic



# Some Literature

- **Web**:
  - The Particle Detector BriefBook: http://rkb.home.cern.ch/rkb/PH14pp/node1.html
  - (there is also a Data Analysis BriefBook)
  - http://pdg.lbl.gov/ --> Summary and Reviews
- **Lectures:**
  - http://wwwhephy.oeaw.ac.at/p3w/halbleiter/VOTeilchendetektoren.html
  - http://www.kip.uni-heidelberg.de/~coulon/Lectures/Detectors/
  - http://www.desy.de/~blist/vl-detektor-ws07/
  - www.physics.ucdavis.edu/Classes/Physics252b/Lectures/252b_lectureXX.ppt XX = 1,2,3,4
- **Script:**
  - http://www.physik.tu-dortmund.de/E5/E5-alt-alt/index.php?content=25&lang=de

# More Literature

- **Text books:**
- C.Grupen: Particle Detectors, Cambridge UP 22008, 680p
- D.Green: The physics of particle Detectors, Cambridge UP 2000
- K.Kleinknecht: Detectors for particle radiation, Cambridge UP, 21998
- W.R. Leo: Techniques for Nuclear and Particle Physics Experiments, Springer 1994
- G.F.Knoll: Radiation Detection and Measurement, Wiley, 32000
- W.Blum, L.Rolandi: Particle Detection with Driftchambers, Springer, 1994
- G.Lutz: Semiconductor radiation detectors, Springer, 1999
- R. Wigmans: Calorimetry, Oxford Science Publications, 2000
- **Review articles:**
- T.Ferbel (ed): Experimental Techniques in High Energy Physics, Addison-Wesley 1987
- **Web:**
- Particle Data Group: Review of Particle Properties: pdg.lbl.gov