The History of Particle Detectors

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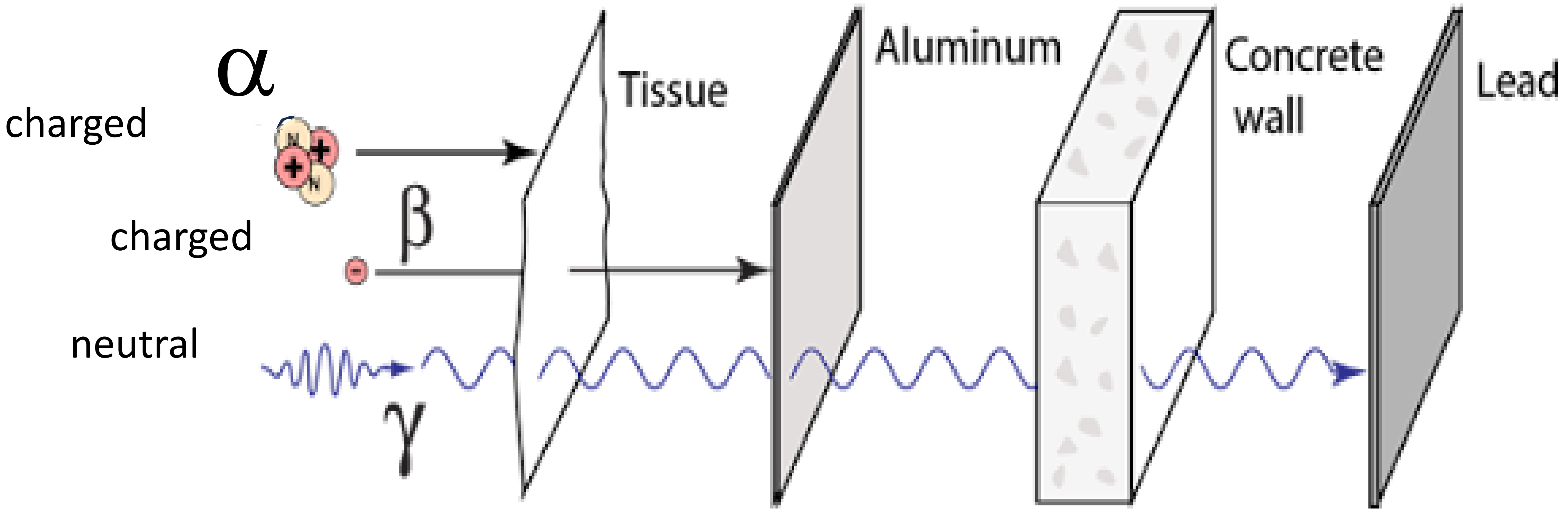
Particle Detectors: Instruments and Methods

- Basic detecting mechanism discovered
- Theoretical understanding – precedes or follows, leads to models
- Fabrication methods and technology
- Analysis techniques and tools
- Particle detectors as systems
- Why discuss the history of particle detectors?
  - It is interesting, and may inspire you to think "outside-the-box" about new ideas or new ways to apply old ideas.
  - It's a good way to win a Nobel Prize

Particle Physics?

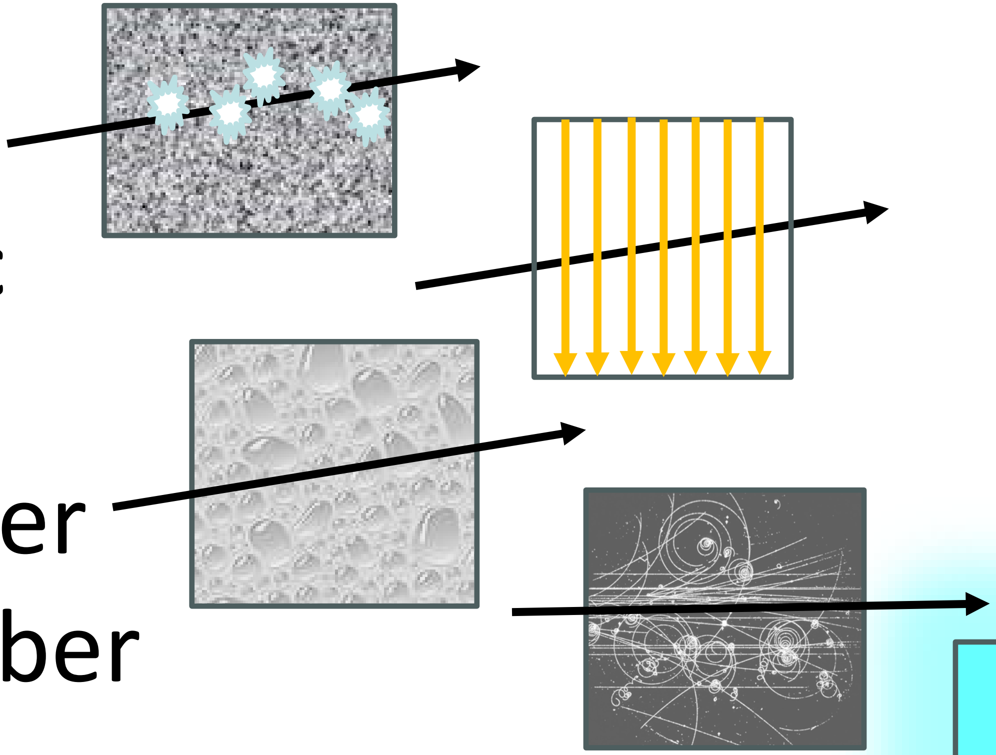
- H. Becquerel (1896): observes that certain elements emit an invisible energy – radioactivity, **which darkens photographic plates**
- Also observe man-made radiations – cathode rays and X-Rays
- These indicate that there is more to natural structure and dynamics than atoms, the Periodic Table, and chemical reactions
- Rutherford cataloged the known forms of radiation according to their penetrating power and response to applied magnetic fields
- Particle physics begins with the attempt to understand radiation

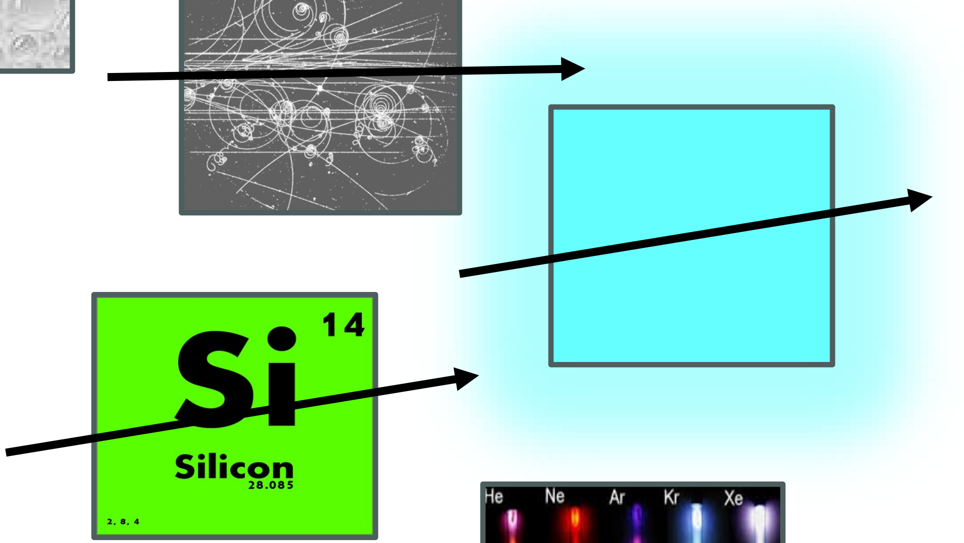


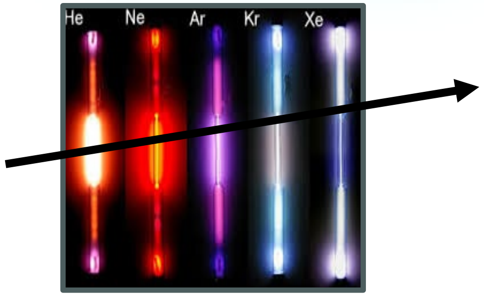
α
charged
β
charged
neutral
γ
Tissue
Aluminum
Concrete
wall
Lead

Quiz question: Which detection method has yielded the most discoveries?

A. Photographic
B. Gas filled
C. Cloud chamber
D. Bubble chamber
E. Light emission
F. Solid state
G. Noble liquids



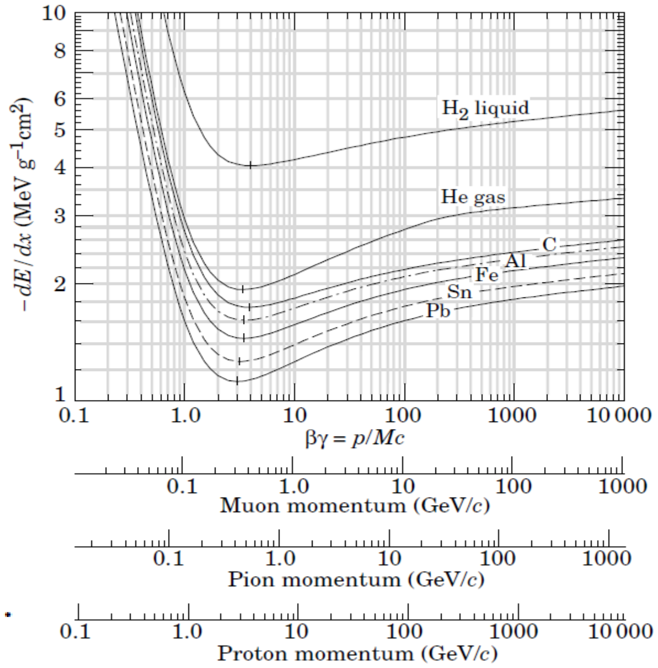


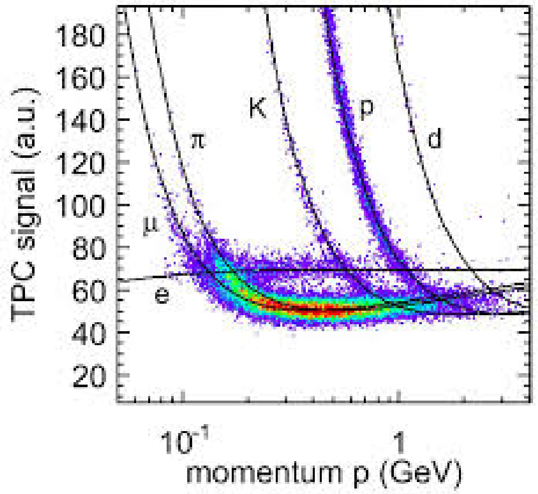


Radiation and Matter

- Much of this worked out in the 1930's-40's
- Heavy charged particles mainly lose energy by collisions with electrons
- Bethe's formula (+Bloch)

$$W_{\max} = \frac{2m_e c^2\,\beta^2\gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}\,.$$





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

m_e = electron mass
$\beta = v/c$,
$\gamma = 1/\sqrt{1-\beta^2}$,
z = charge of incident particle,
I = mean excitation energy,
Z = atomic number, A = atomic mass,
$\delta(\beta\gamma)$ = density effect correction
$K = 4\pi N_A r^2 m_e c^2$
$r_e = e^2/4\pi E_0 m_e c^2$

β rays and heavy high energy particles studied in cosmic rays and accelerators are close to the minimum ionizing value of *dE/dx*. We refer to them as MIPs. $dE/dx \sim 2$ MeV g^{-1} cm^2

Photon interactions in Carbon and Lead

- Photoelectric region
- Compton region
- Pair creation region

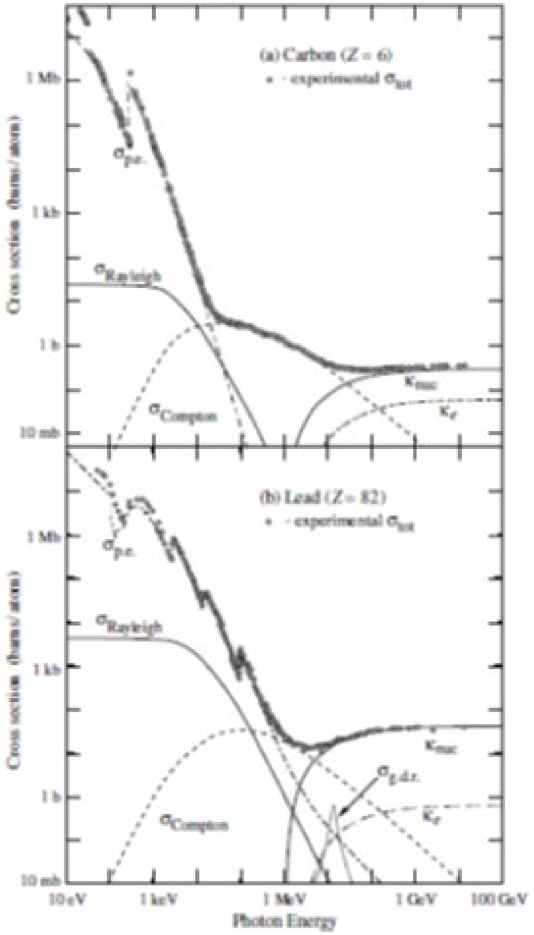
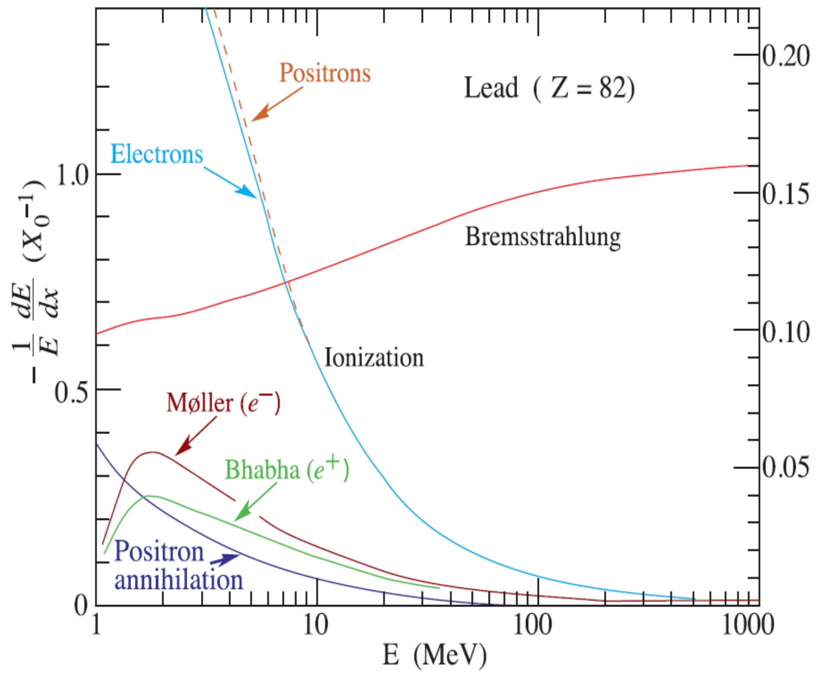


Figure 34.15: Photon total cross sections as a function of energy in carbon and lead, showing the contributions of different processes [50]:

$\sigma_{p.e.}$ = Atomic photoelectric effect (electron ejection, photon absorption)
$\sigma_{Rayleigh}$ = Rayleigh (coherent) scattering–atom neither ionized nor excited
$\sigma_{Compton}$ = Incoherent scattering (Compton scattering off an electron)
κ_{nuc} = Pair production, nuclear field
κ_e = Pair production, electron field
$\sigma_{g.d.r.}$ = Photonuclear interactions, most notably the Giant Dipole Resonance [51]. In these interactions, the target nucleus is usually broken up.



Energy loss by electrons in Lead
Scattering by nuclei cause Bremsstrahlung radiation

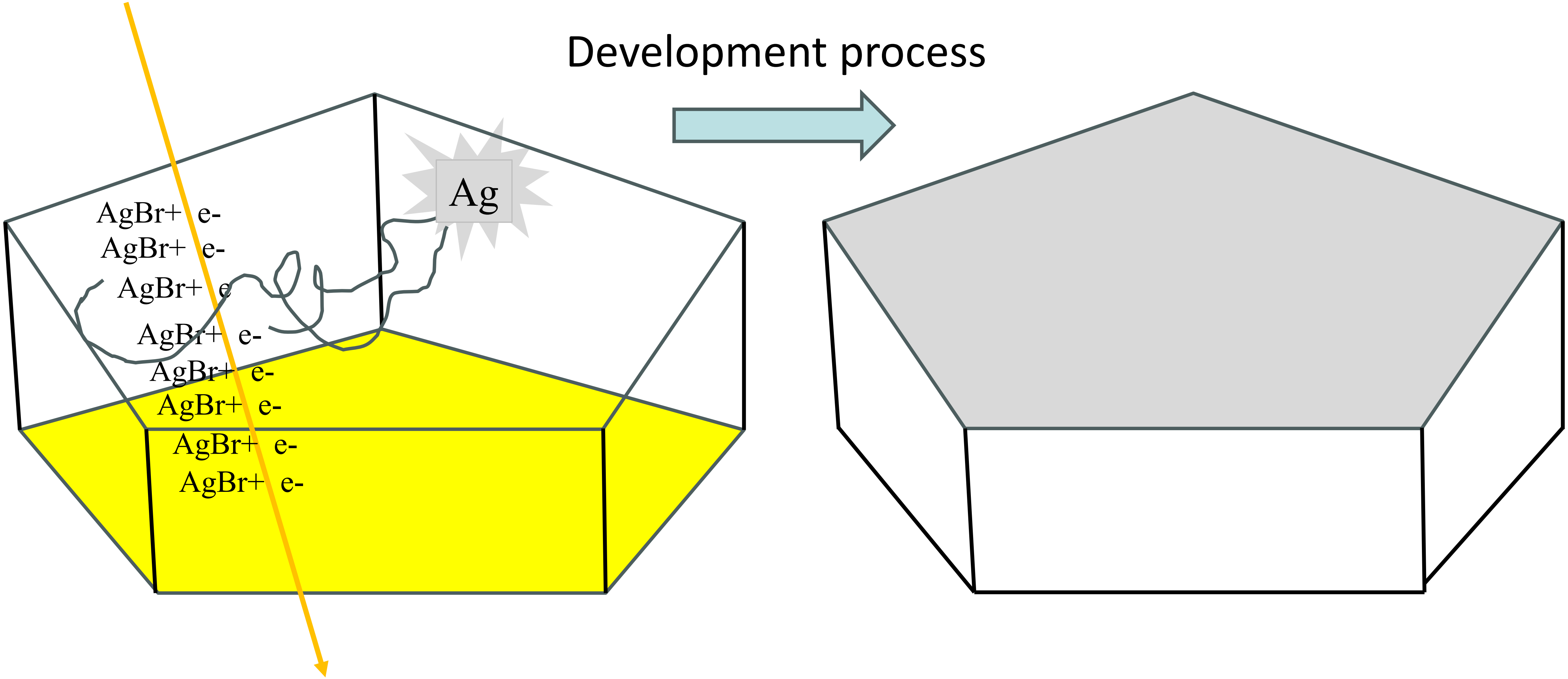
Photographic Materials

- The photosensitivity of certain silver compounds was known since the 18th Century or earlier
- Photography starts in the 1830's with the capture of visible light images on paper
- Becquerel's discovery of radiation is due to the effect on shrouded photographic film
  - So photosensitive materials are also sensitive to radiation
- This remains an empirical observation until the 1930's when the photographic process is first described by Mott and Gurney.

The Latent Image

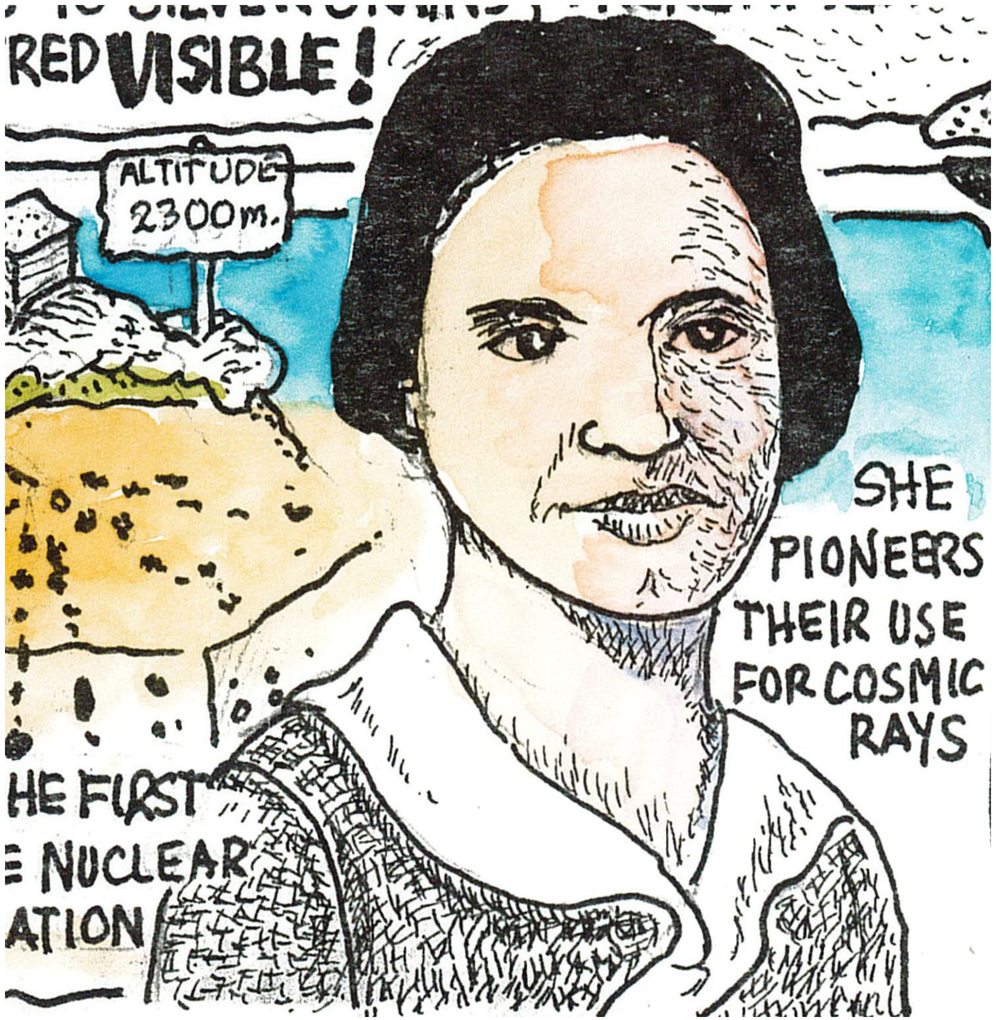
- Photographic film consists of an emulsion in which crystals of silver compounds are suspended. Most common is AgBr of size ~micron scale
- These silver halides are both electronic and ionic conductors/semiconductors
- When exposed to light, or ionizing radiation, electrons enter the conduction band and start to diffuse, positive ions diffuse as well, but more slowly
- The crystal have defects on their surfaces, a particularly effective defect is AgS+
- These defects can capture the electrons and ions
- Due to a sequence of electronic (-) and ionic (+) capture, clusters of a **few** silver atoms are created on the surface
- The chemical development process is catalyzed by these metallic silver clusters leading the conversion of the entire grain to metallic silver. **Gain factor is ~10^9**

Development process

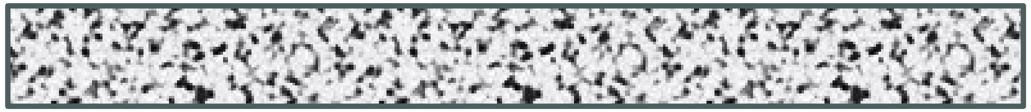


Nuclear Emulsions

- The practical use of the photographic effect, as a particle detector, develops with the work of Marietta Blau (1923-1937)
- Blau tailors the emulsion to meet the needs of particle tracking and applies them to cosmic ray research
- She **works with the Ilford company** to provide the required emulsions
- She develops **systematic optical measurement methods to** interpret emulsion data

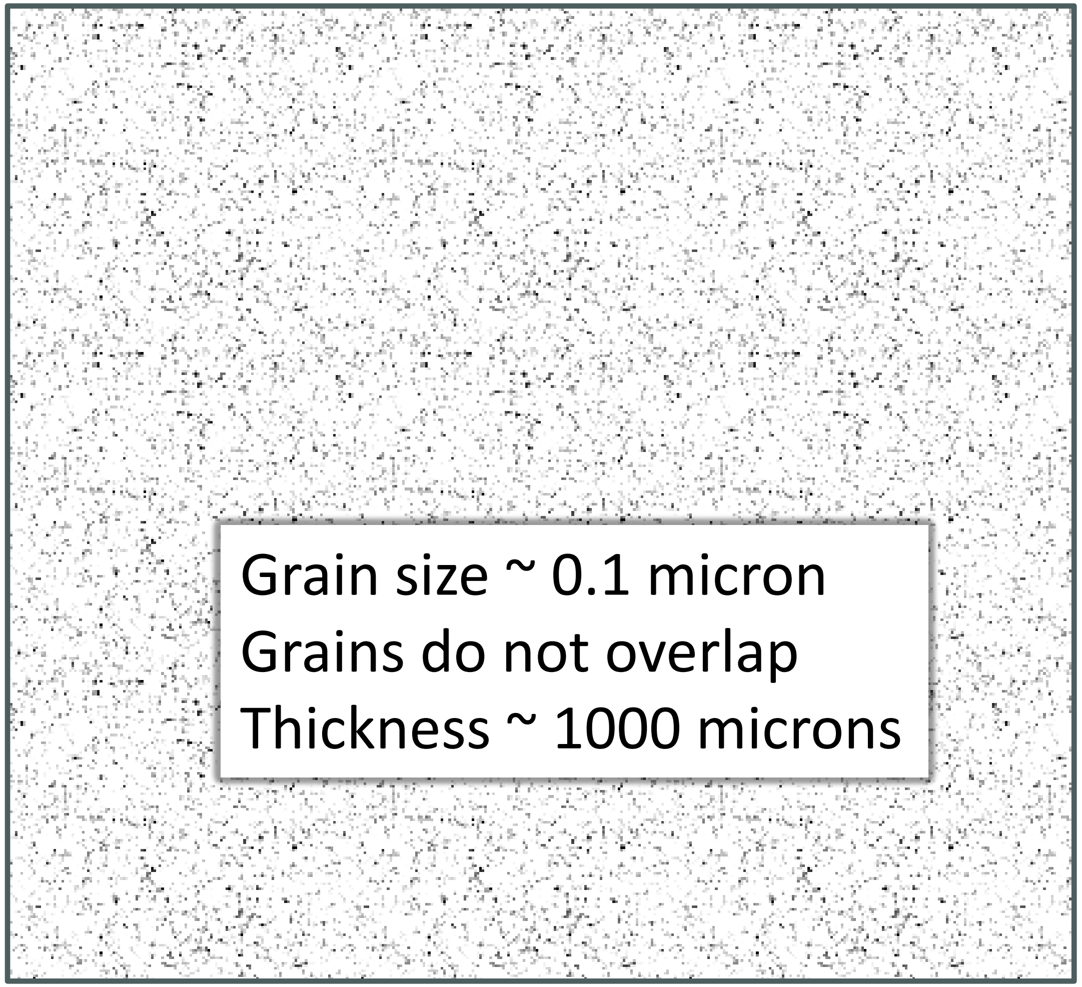


Photographic Film



Grain size ~ 1 micron
Grains overlap
Thickness ~ 100 microns

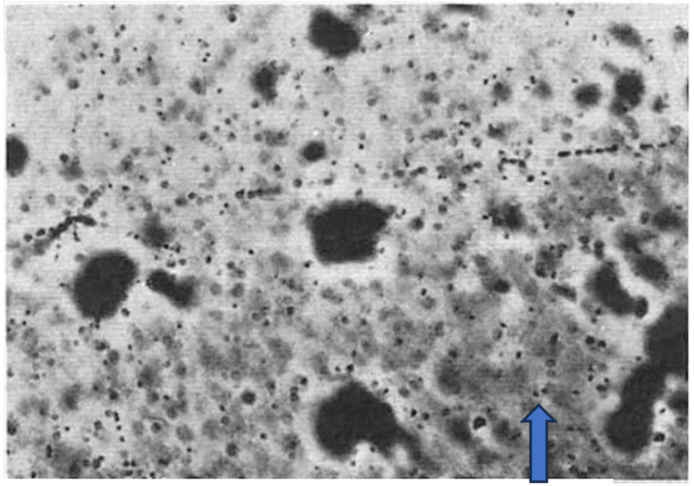
Nuclear Emulsion

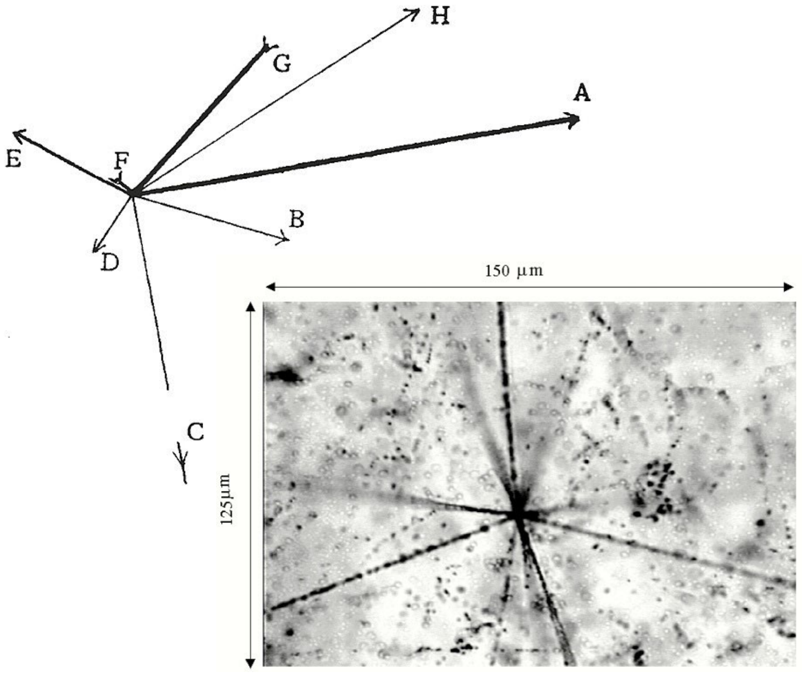


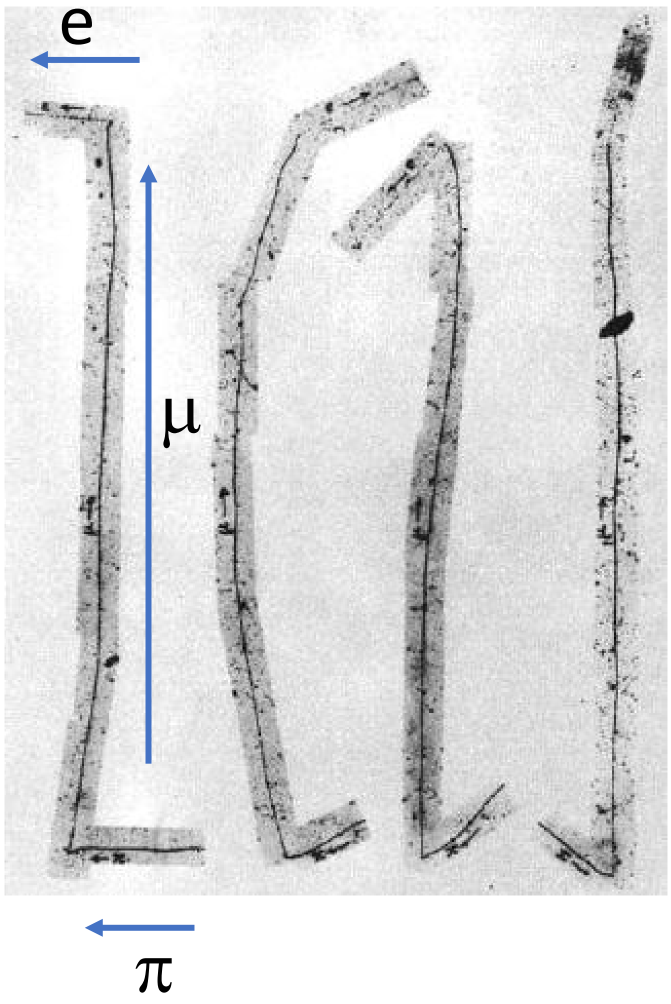
Grain size ~ 0.1 micron
Grains do not overlap
Thickness ~ 1000 microns

Nuclear Emulsions

- Emulsion **stacks** are placed on mountain tops
  - Pic du Midi
  - Jungfrau Joch
  - Chacalaytaya
- Blau first observes nuclear break-up in an emulsion
- In 1947 a group at Bristol observes Yukawa's meson stopping and decaying in emulsions placed on mountain summits







Similar range for μ implies a 2-body decay

τ_{π}~26 ns, τ_{μ}~2.1 μs

The Cloud Chamber

- C.T.R.Wilson studied atmospheric phenomena: Brocken spectra and glories observed from a mountain observatory
- To study these in the lab (1911) he invented a "cloud chamber" which varied the pressure on a supersaturated vapor
- He observed spontaneous **trails** of droplets which he suspected were due to the tracks of ionizing radiation
- An X-ray source nearby confirms this.
- Characterize the radiation by droplet density
- Further improvements included rapid cycling and the diffusion chamber

Droplet Formation in Supersaturated Vapors

- The theoretical understanding of droplets was due to Kelvin (1870) – discussed droplet growth/evaporation in terms of a critical radii
- Small droplets have larger vapor pressure and trend to evaporation
- But droplets need to nucleate – on dust particles or on charges.
- The dynamics differ – **charged** droplets are either stable or growing for fixed saturation

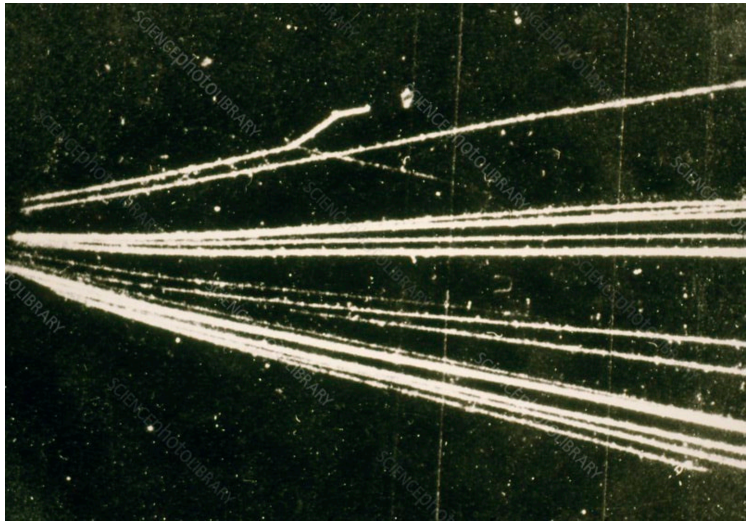
$$\ln \frac{p_r}{p_\infty} = \frac{2M\theta}{RT\rho r}$$

$$\ln \frac{p_r}{p_\infty} = \frac{M}{RT\rho}\left(\frac{2\theta}{r} - \frac{e^2}{8\pi\varepsilon r^4}\right)$$

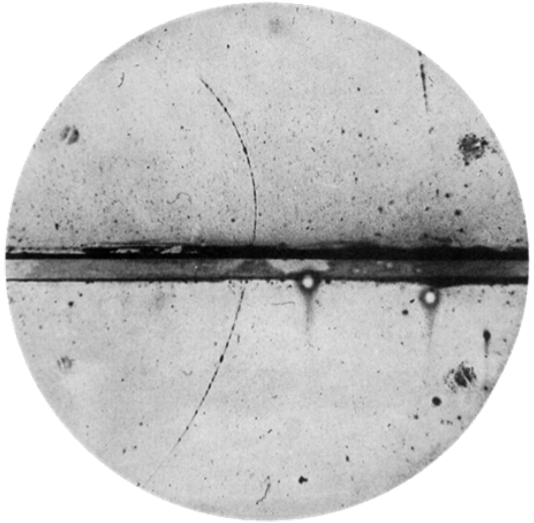
p_r=vapor pressure for droplet of radius r

$\theta =$ surface tension

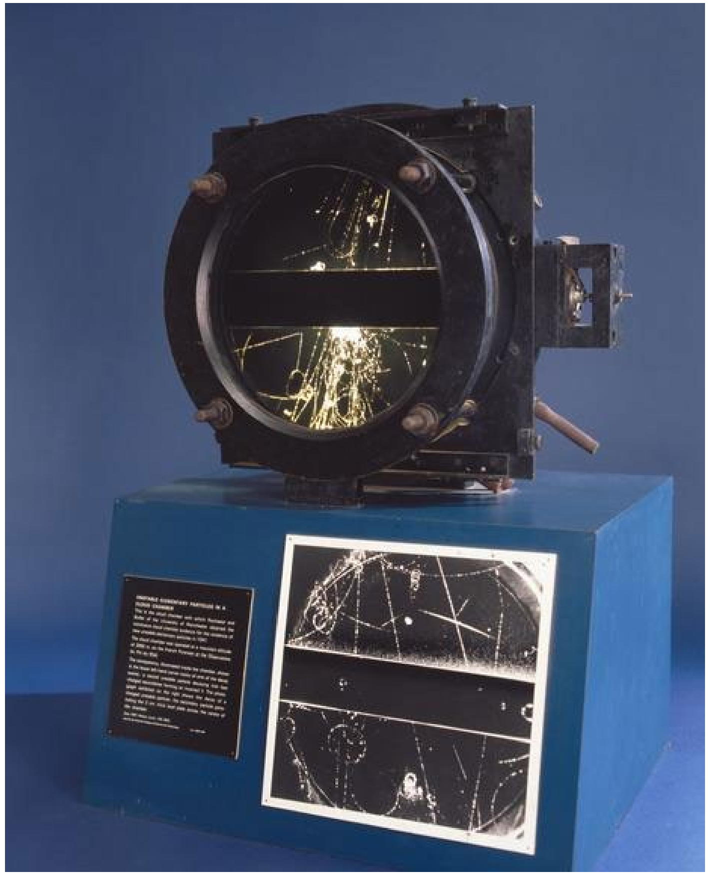
Some Applications of the Cloud Chamber



- Blackett (1925) observes the reaction $\alpha + N \rightarrow O + H^{+}$ in a cloud chamber
- Establishes the proton
- Droplet density depends upon charge



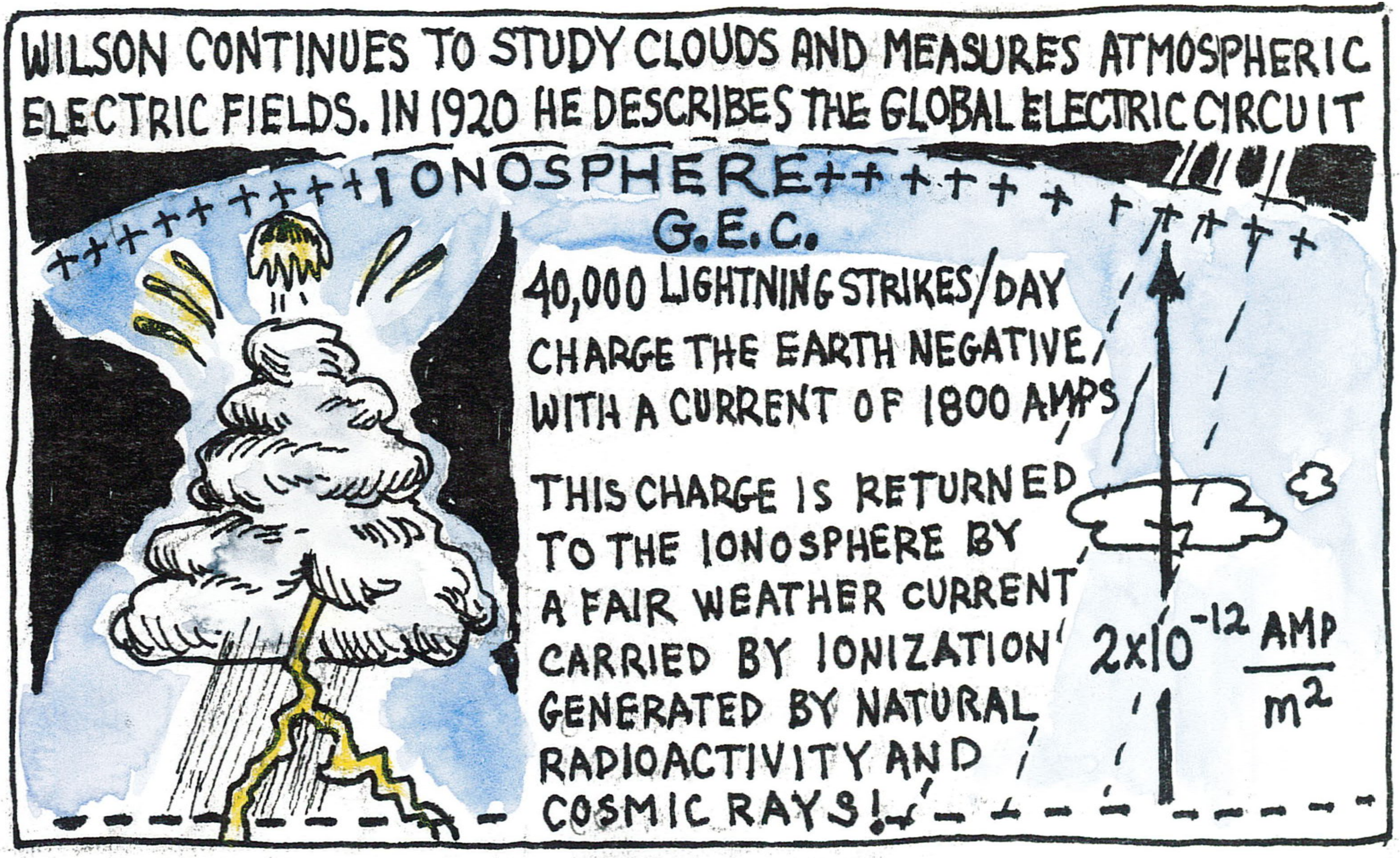
- Anderson (1932) observes the positron
- Confirms Dirac’s prediction of anti-particles



Rochester and Butler (1947) Kaon discovery

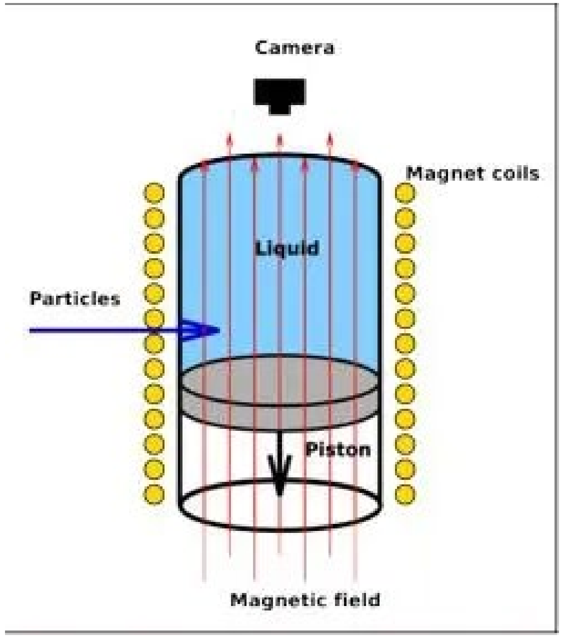
Coda

- Cloud chambers were a workhorse for particle physics using **cosmic rays** until the 1950's when accelerators became the tools of choice
- In 1912 Victor Hess demonstrates the existence of cosmic radiation with **electrometers** in balloon flights – atmospheric ionization rates increasing with altitude
- Wilson continues his interest in atmospheric phenomena and in 1920 he describes the "Global Electric Current"


WILSON CONTINUES TO STUDY CLOUDS AND MEASURES ATMOSPHERIC ELECTRIC FIELDS. IN 1920 HE DESCRIBES THE GLOBAL ELECTRIC CIRCUIT
IONOSPHERE
G.E.C.
40,000 LIGHTNING STRIKES/DAY CHARGE THE EARTH NEGATIVE WITH A CURRENT OF 1800 AMPS
THIS CHARGE IS RETURNED TO THE IONOSPHERE BY A FAIR WEATHER CURRENT CARRIED BY IONIZATION GENERATED BY NATURAL RADIOACTIVITY AND COSMIC RAYS!
2x10^-12 AMP/m^2

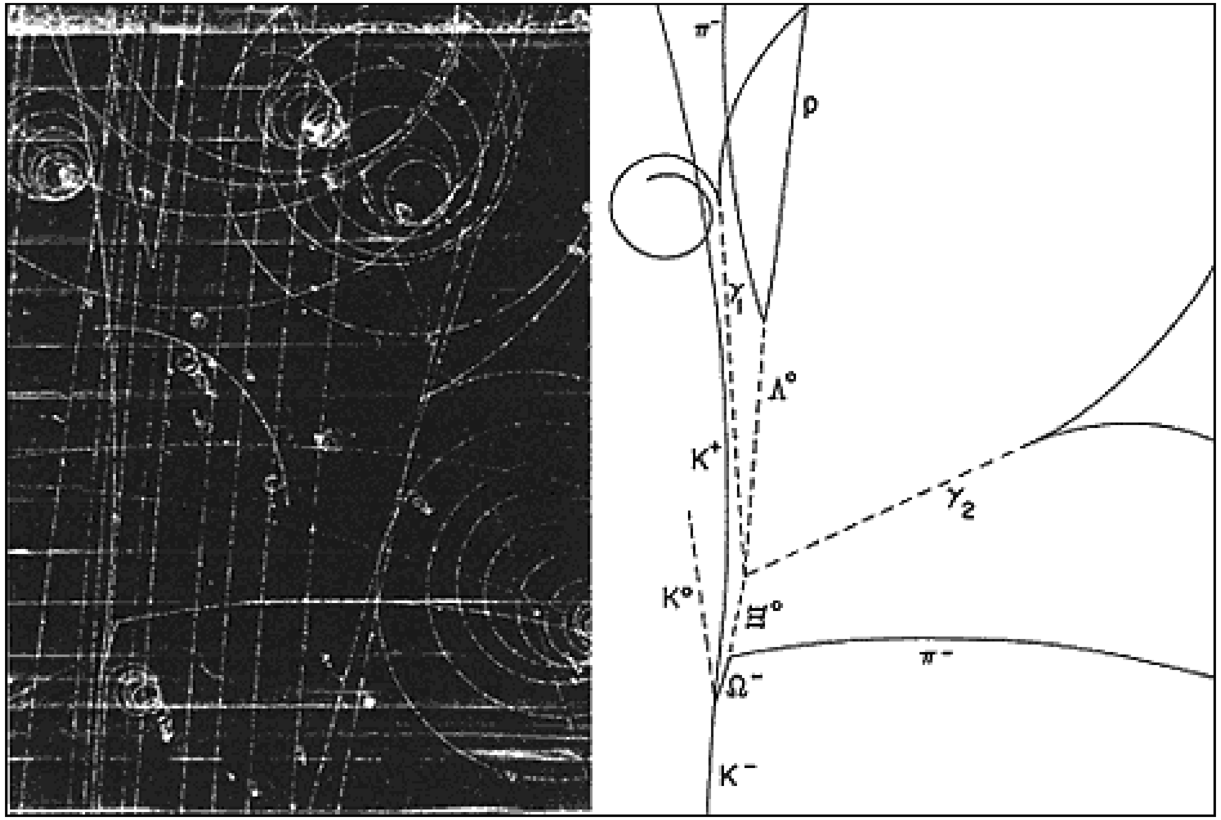
The Bubble Chamber

- The cloud chamber is limited by the low density of the target vapor, Glaser (1953) proposes a superheated liquid target which can be expanded in synchronization with the accelerator cycle – 1st used dimethyl ether at elevated temperature in a glass vessel
- Bubbles form along the tracks of ionizing particles and can be photographed, stereoscopically, while still small, at high resolution

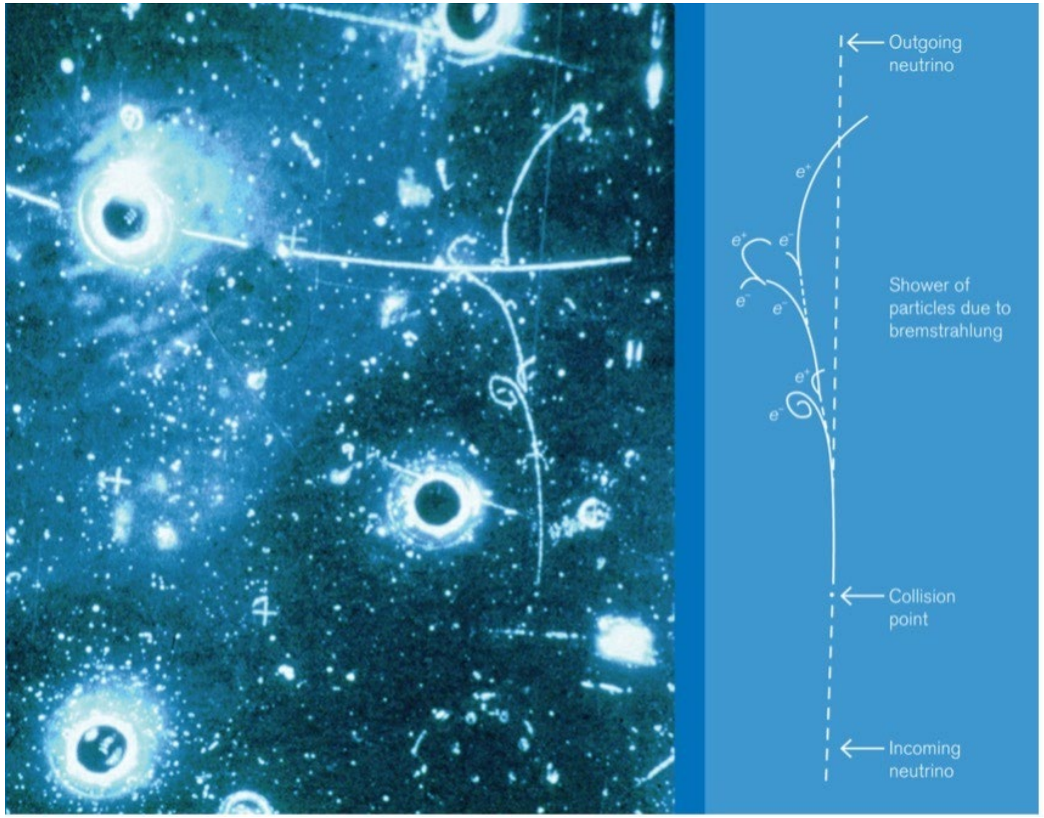


Bubble Formation in Superheated Liquids

- Early versions used ether at elevated temperature
- Cryogenic liquids are found to be a better medium
- Radiation ionizes the liquid – how do bubbles form/grow?
  - Glaser: electrostatic repulsion
  - Seitz: delta ray induced heat spikes
- Neither theory really provides complete consistency
  - The electrostatic theory predicts the operating points
  - But pure Xenon, a scintillator, does not bubble unless it is doped with ethylene, which kills scintillation → supports heat spike model
- In spite of this- many large chambers are operated



An incoming meson interactions with a proton in the liquid to produce a new heavy hadron, Ω^- predicted by the quark model of hadrons (BNL)



An incoming neutrino scatters off an electron in the liquid, continuing unchanged. This is the new neutral weak interaction predicted in the Unified theory (CERN)

Legacy

- Bubble chambers have been surpassed by electronic detector systems
- Bubble chambers were the first tools which really allowed the collection and storage of **large, statistically significant data sets**
- Thousands of photographs had to be systematically scanned and measured – by the 1960's data was digitized and analyzed by computers – **one of the first scientific computing applications**
- The style of computing and data analysis which emerged can still be seen in way we analyze data to this day.

Emission of Light Induced by Radiation

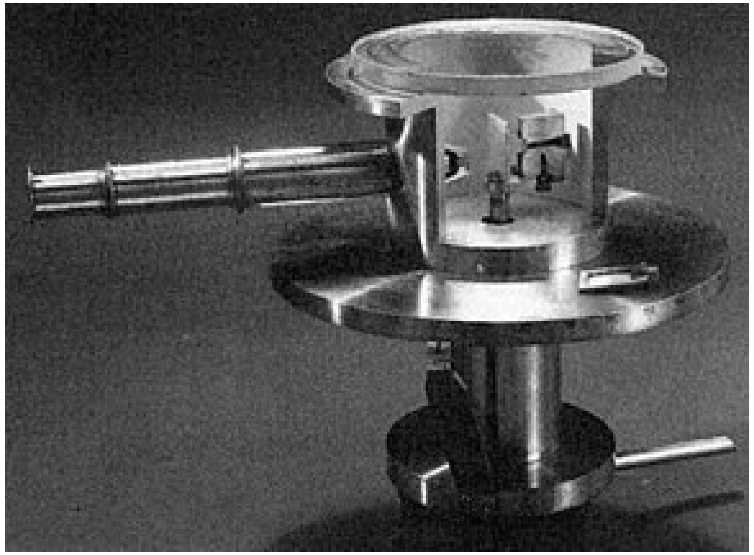
- Radioluminescence: broad category including a variety of process
- Florescence: prompt emission, substance absorbs light and emits at a lower wavelength
- Phosphorescence: delayed emission
- Scintillation: process by which light is emitted after absorption of high energy photons or charged particles
  - Inorganic scintillators: NaI, ZnS, Xe,….
  - Organic scintillators: large variety of solids and liquids
- These processes have been known since the early 20th century
- Cerenkov (1934), Frank and Tamm (1937): a charged particle with $v > c/n$ (in the medium) emits light

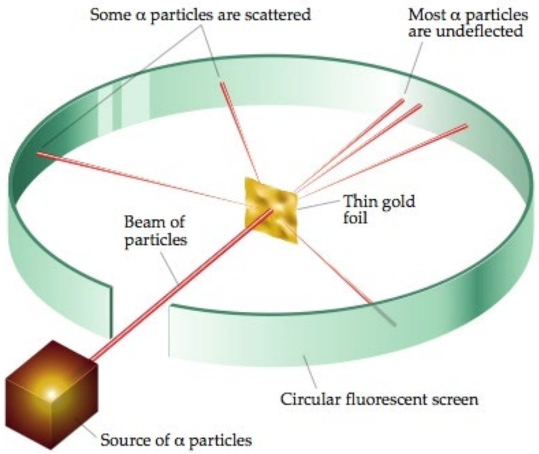
Zinc Sulfide

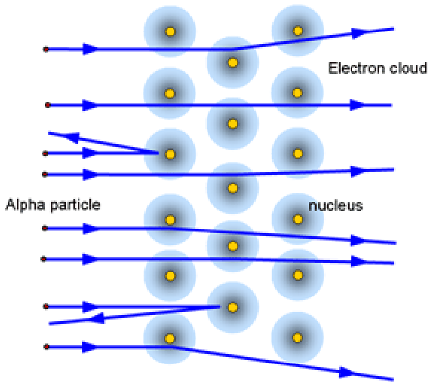
- 1866 Theodore Sidot reports phosphorescence
- 1893 also described by Nicola Tesla
- Enhanced by ppm additions of various activators (Ag…)
- But radiation (other than light) was not yet known (1896)
- By 1906 Rutherford knew that ZnS would fluoresce/scintillate when exposed to alpha particles – uses for the scattering experiment as a detecting surface
- ZnS occurs as a polycrystalline powder, so can only be used in thin layers (ie. screens etc)
- ZnS was, or is, among, the very first inorganic scintillators to be used in particle physics

Rutherford Experiment

- What is the structure of the atom?
- In 1906-13 Rutherford's students, Geiger and Marsden, measure the angular distribution of alpha particles scattered by a thin gold foil
- The technique is to count flashes on a screen coated with ZnS
- While most pass with little deflection they observe occasional (1/8000) at large scattering angles
- Rutherford (1911) interprets this as alpha's scattering from a "point-like" heavy charged nucleus
- Bohr's early model of the atom

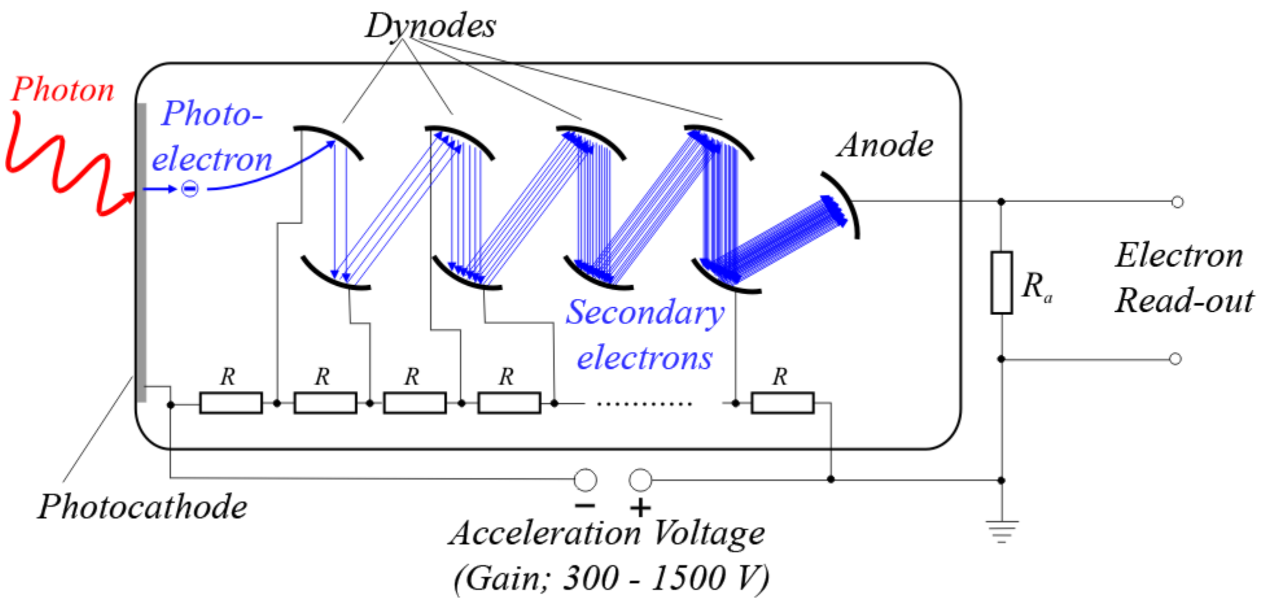






The Photomultiplier Tube

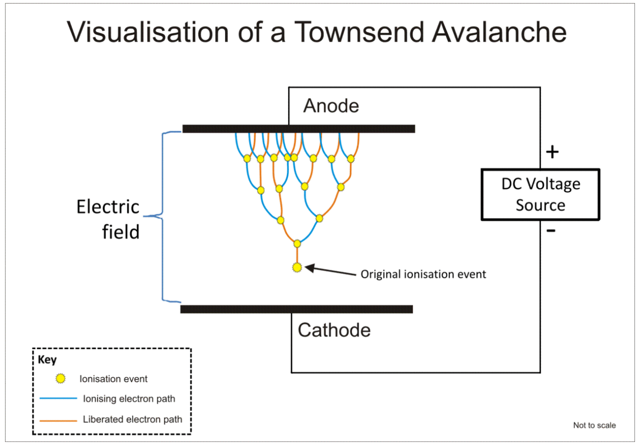
- Geiger and Marsden counted flashes by eye….
- An electronic system for photon detection/amplification is introduced in the 1930’s, matures in the 1940’s
- Photoelectricity and secondary emission
- The phototube signal is very fast ~50 ns transit time, ~1-10 ns risetime
- Coupled with pulse height discriminators and logic this forms the basis of fast nuclear electronics

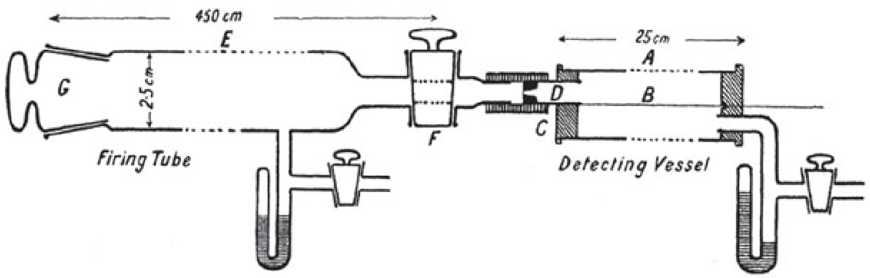


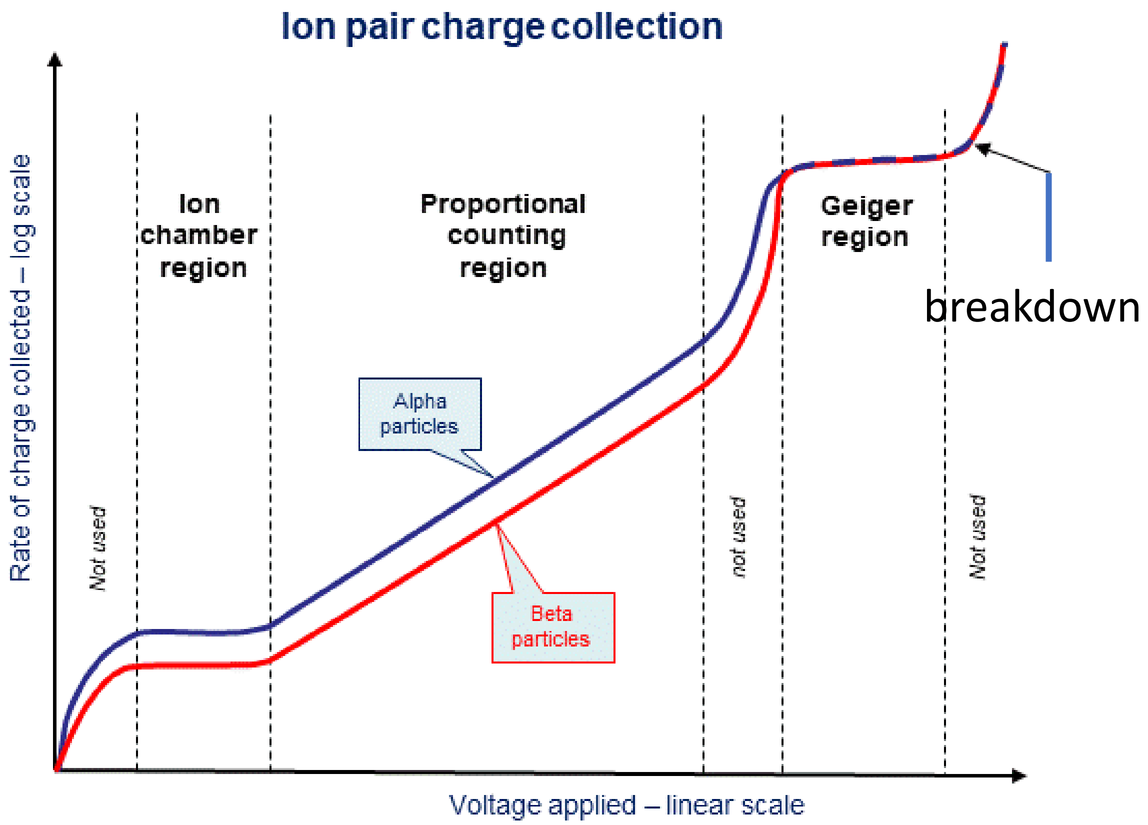
The development and characteristics of PMT’s are deeply linked to industries – RCA and Hamamatsu

Electronic Processes in Gases

- The ionization chamber was known in 1895 (Curie)
- Townsend (1897) studied electrical discharge processes in gases, develops a mathematical description – still the fundamental reference
- Geiger(1908) and Müller(1928) applied this to a gas discharge tube and circuits to quantify radiation and localize it in time (later space)



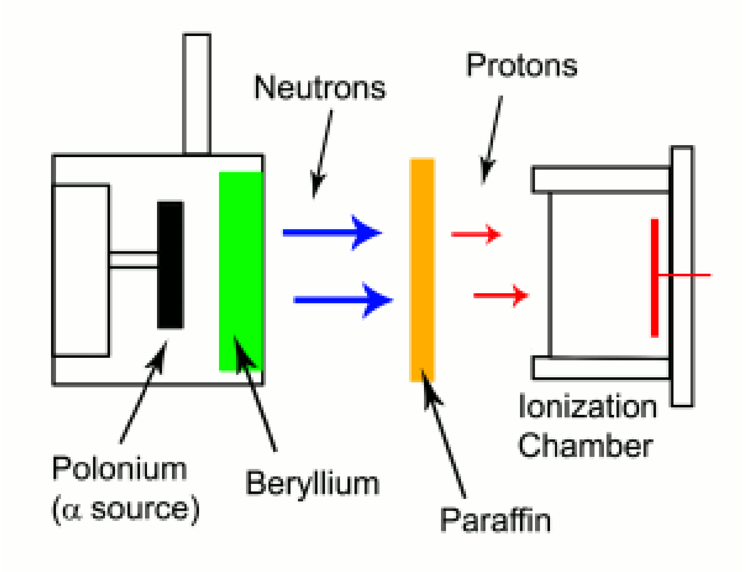


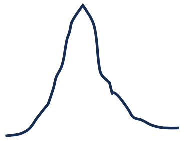


- This is the entry point for a broad technology based upon ionization and gain in gases

The Ion Chamber Region

- Chadwick (1932) the neutron
- Beryllium exposed to alphas was known to emit a very penetrating neutral radiation
- If g rays their energy would be too high
- Placing hydrogen rich paraffin results in the emission of protons, consistent with collisions with neutral particle of similar mass

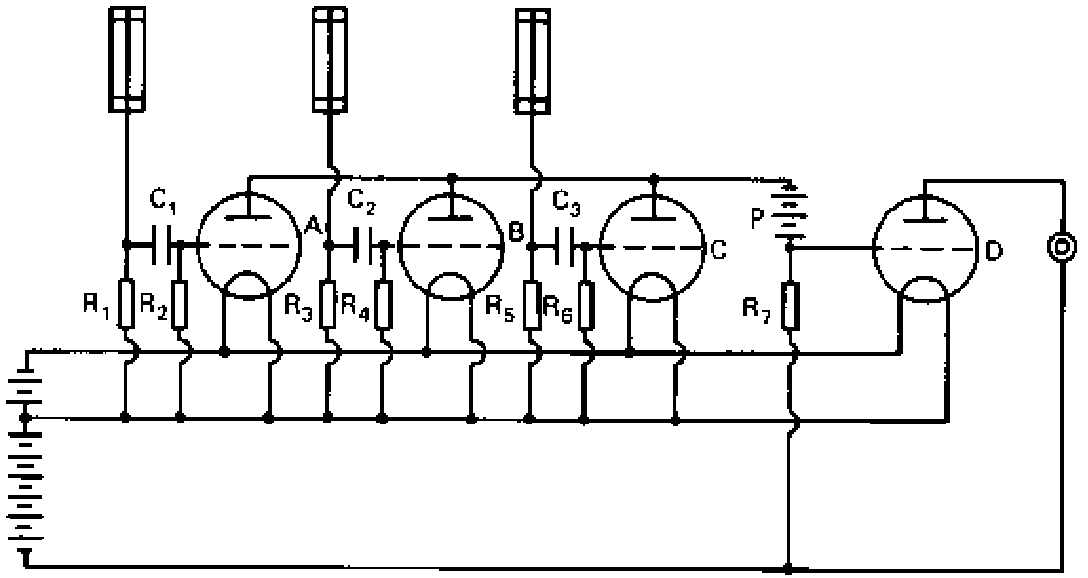


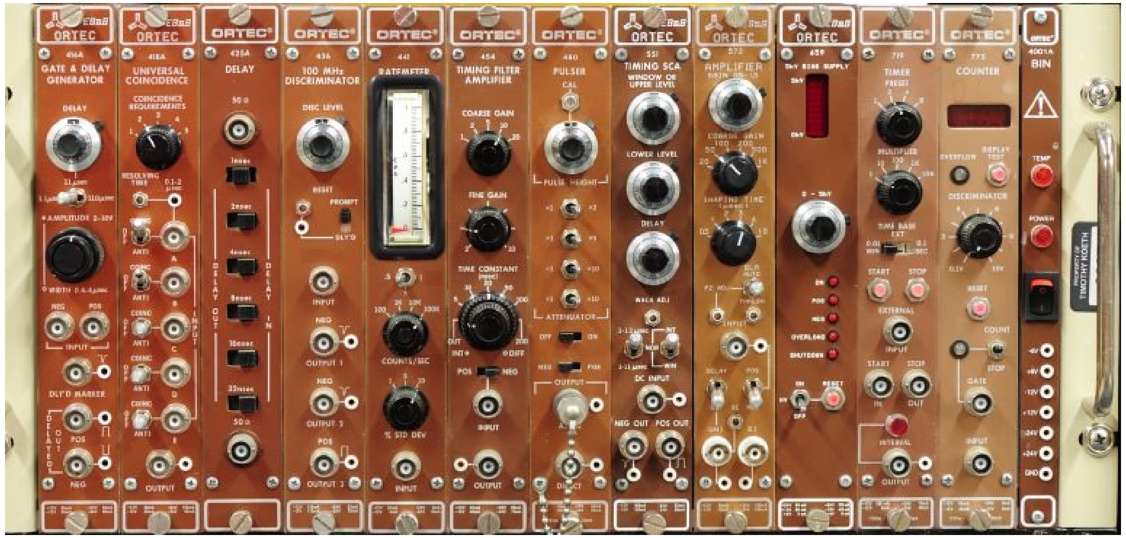


Pulse height

Coincidence Logic

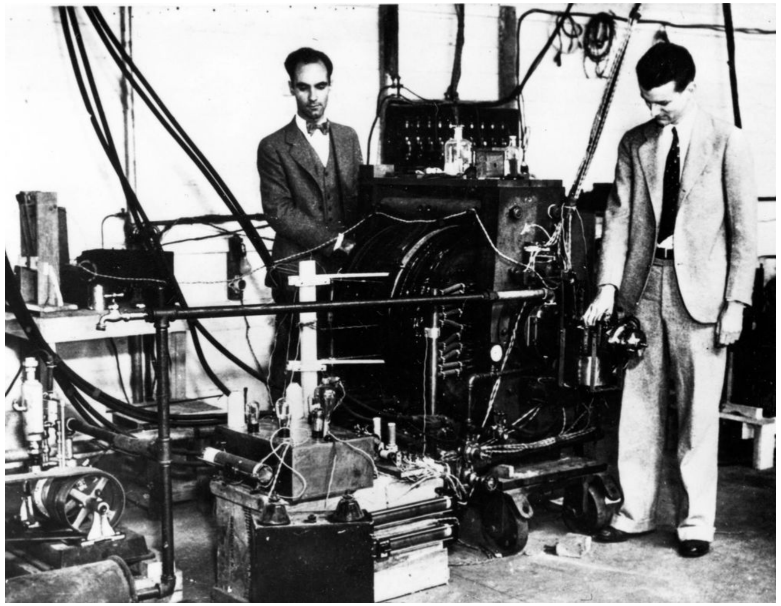
- Beginning in the 1920's it was realized that finding **coincident pulses** in 2 or more gas discharge tubes would be useful
- Track direction, correlations
- Rossi (1930) invents a vacuum tube coincidence circuit with a time resolution of ~100 μsec
- This is the first example of the AND circuit of digital logic
- By the 1960's "Nuclear Instrumentation Modules" (NIM) electronics was standardized and in wide use, to the present time.

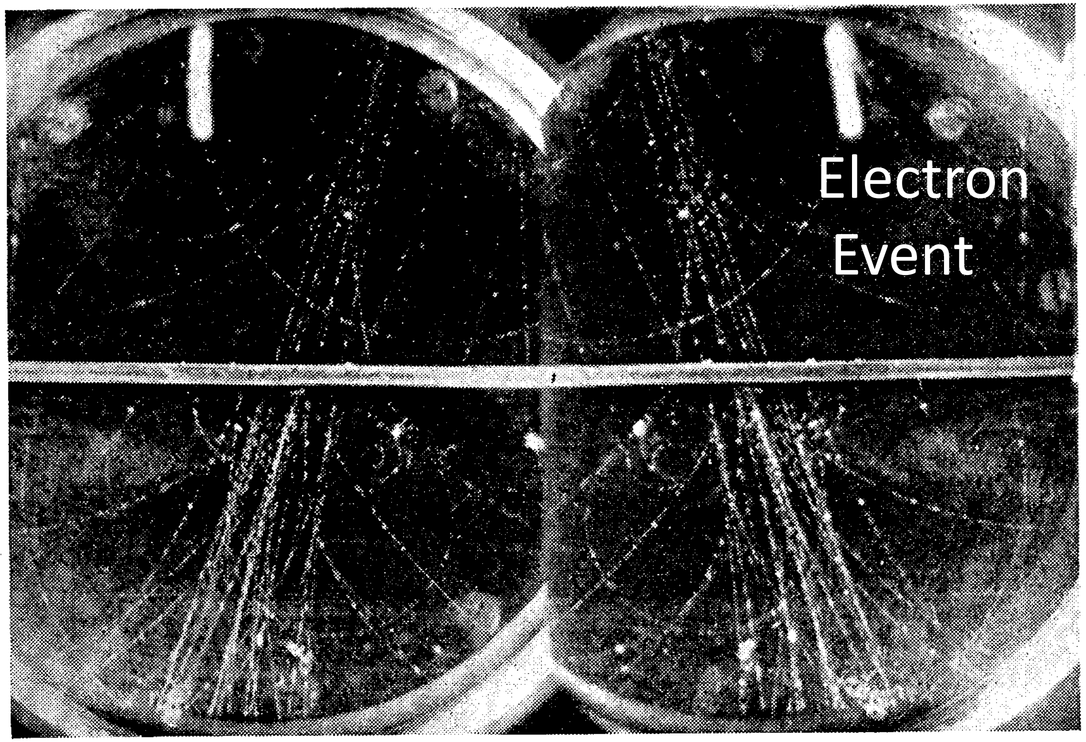




The Geiger Region

- In 1936 Anderson and Neddermeyer operate a **Geiger Counter coincidence** triggered magnetic **cloud chamber** with a **Pt plate across the middle**
- On Pikes Peak (el. 4300 m) they observed a class of particles with distinctly small energy loss relative to electrons
- This was the discovery of the muon

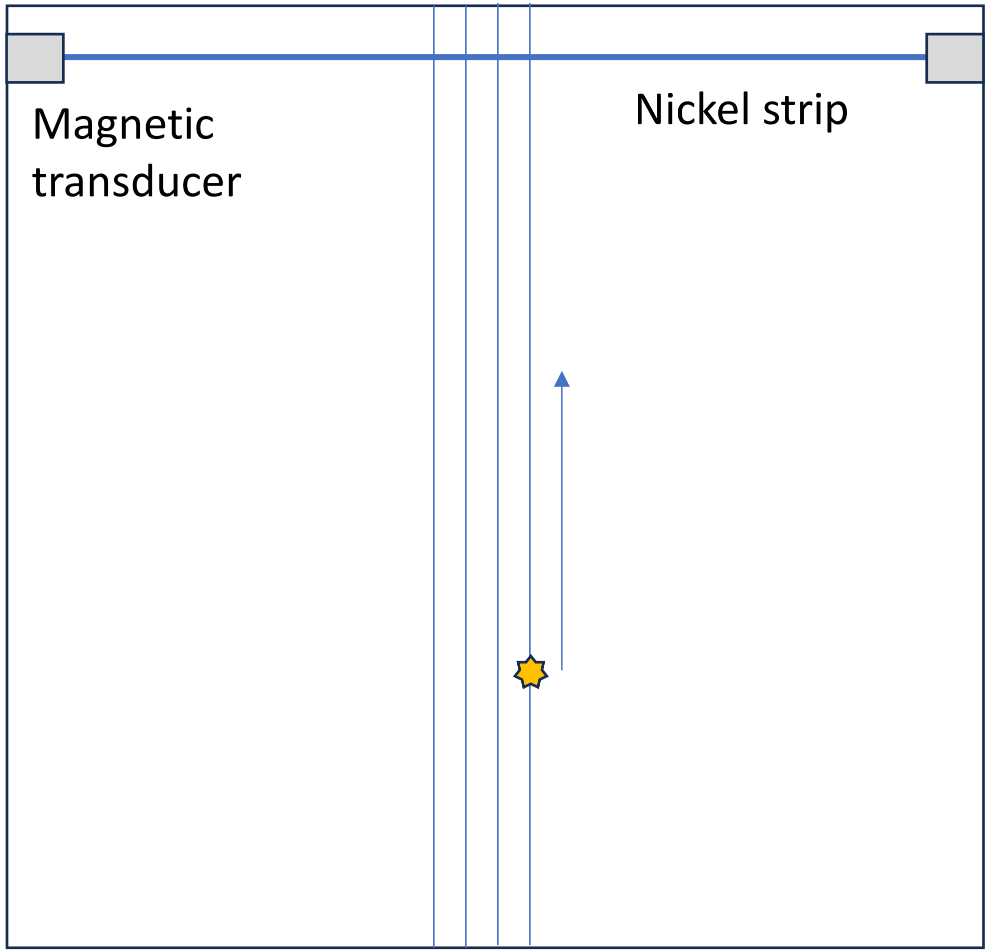




The Breakdown Region

- At very high field ionization leads to conduction through the gas – a spark – with the emission of light and sound
- The earliest devices, studied in the 1940's were referred to as **spark counters** essentially to compare with scintillation counters
- By the 1960's this idea had developed into the **position sensitive spark chamber**
- This device consisted of a thin gap between plates with a pulsed HV, triggered by scintillation counter coincidences
- The spark position was logged by a triggered camera exposure viewing the edges of the gap
- Spark quenches due to collapse of field

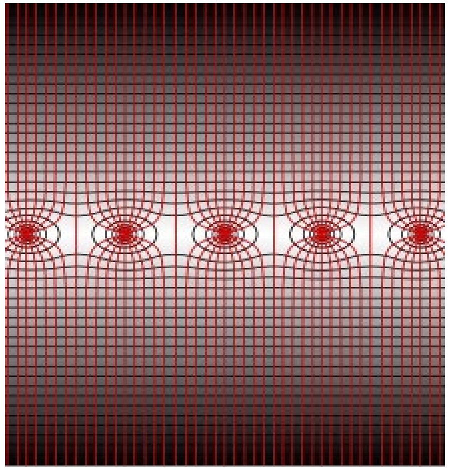
Filmless Readout of Spark Chambers

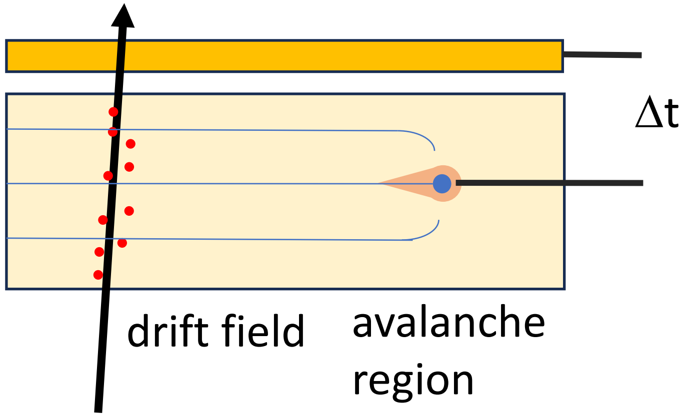


- First utilized in the early 1960's
- Magnetostriction
- Electric current → magnetic field→ mechanical deformation which propagates down the strip at speed of sound →sensed in magnetic pickups at one or both ends
- Pulses are shaped and timed by electrics and logged to (paper) tape
- Early example of a full electronic sensor + front end + DAQ chain
- In use well into the 1980's for large neutrino detectors

The Proportional Region

- For moderate voltage the Townsend process is local and is proportional to the energy deposited in the gas
- Implies a high spatial resolution
- Charpak (1967) invents the multiwire proportional chamber (MWPC)offering position sensitivity over large areas
- He (1969) and Walenta (1971) invent the drift chamber which uses drift time as well as wire spacing to improve localization and reduce channel count



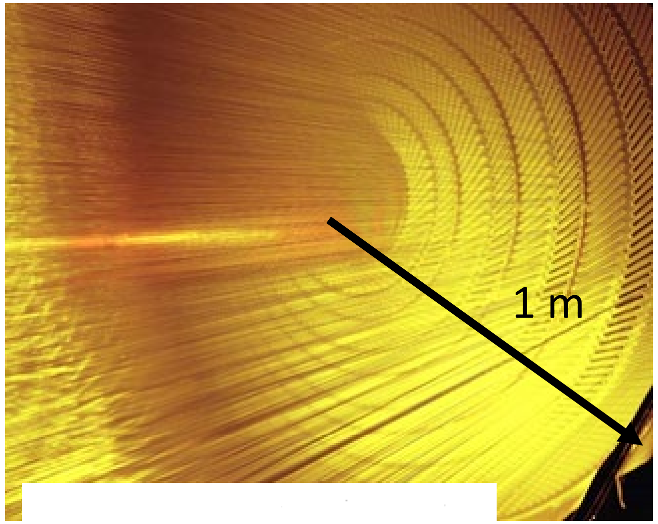


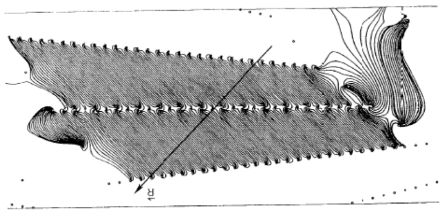
Resolution determined by

1) Wire spacing $\sigma = \frac{p}{\sqrt{12}}$
2) Charge sharing

Large number wires and electronics

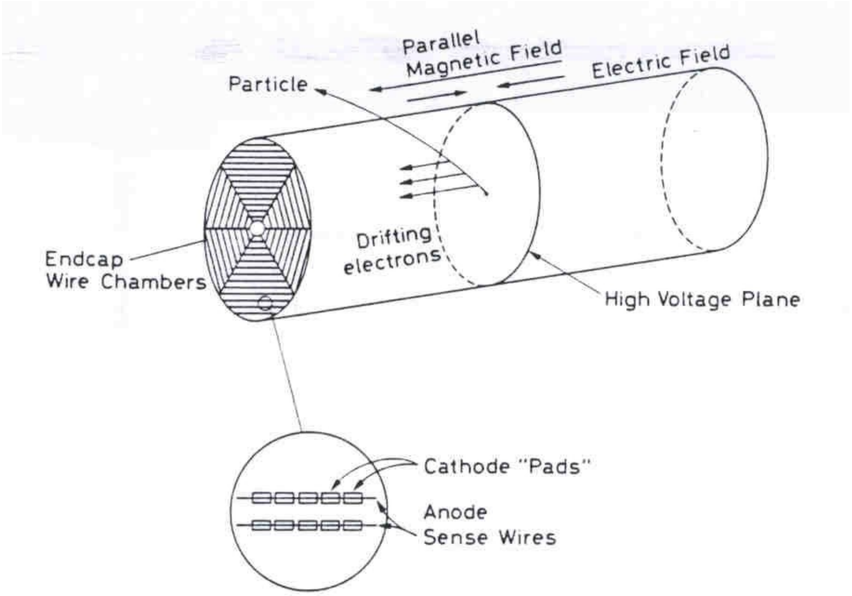
A large cylindrical drift chamber

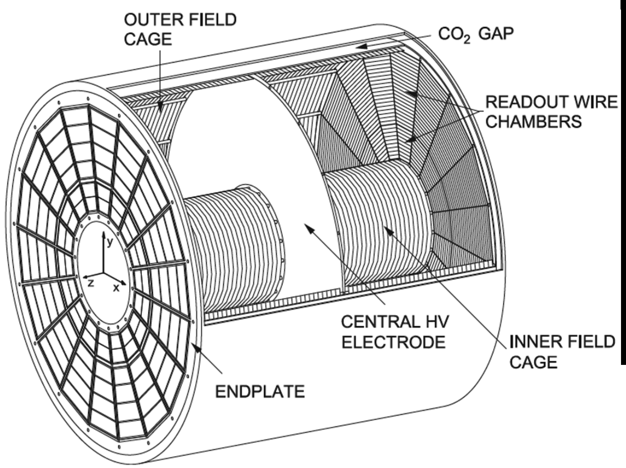


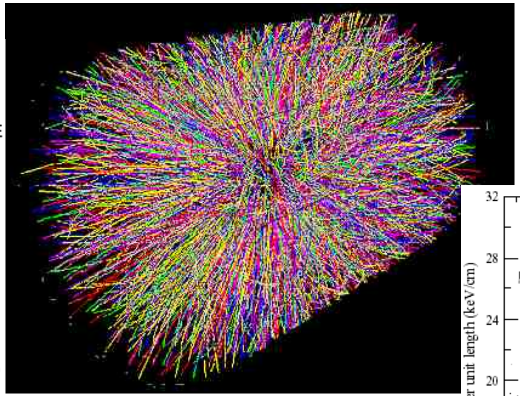


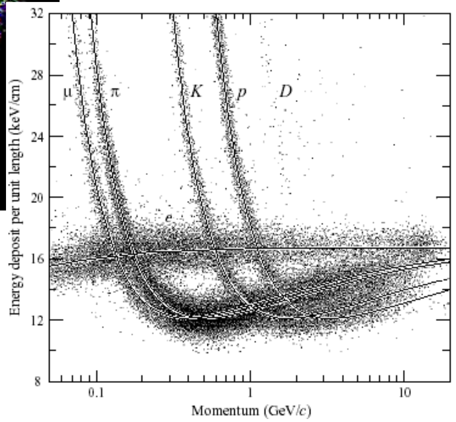

ATTENTION
TENSION
DANGER

Time Projection Chamber: 3D tracking





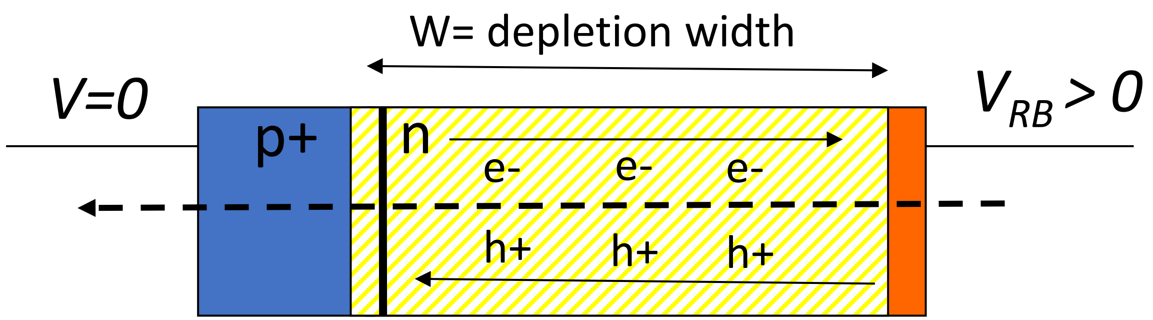




- Nygren (1974): Diffusion of drifting charge degrades resolution (Berkeley)
- For B II E transverse diffusion is suppressed by $\frac{1}{\sqrt{1+\omega^2\tau^2}}$ where $\omega = \frac{eB}{m}$ and $\tau =$ mean collision time
- End faces are instrumented with 2D readout – wires and pads, 3rd dimension is drift time
- Large number of ionization measurements → dE/dx → velocity, with momentum give mass
- Can also be filled with cryogenic noble liquids (LAr, LXe), imaging neutrino detector, dark matter

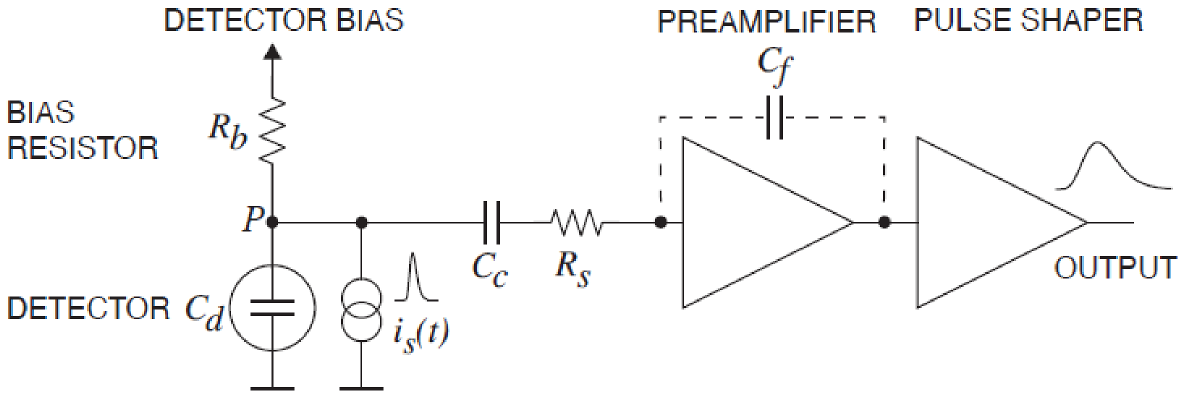
Solid State Detectors and Electronics

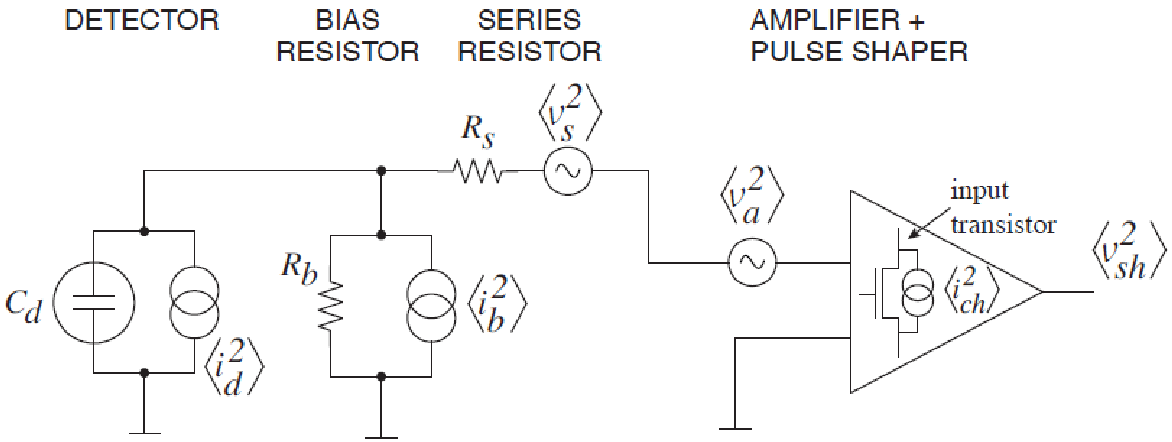
- The Crystal Counters: the possibility of a solid ionization chamber was appreciated already in the late 1940's
- Early studies used compound semiconductors such as AgCl
- By the 1950's it was understood that silicon and germanium were ideal materials – provide dramatic improved energy resolution, as compared to scintillators or gas, due to the small energy required to create ionization
- Require high resistivity, low leakage current: materials development
- But focus was on nuclear spectroscopy not particle physics
- Thick reverse biased asymmetric pn junction

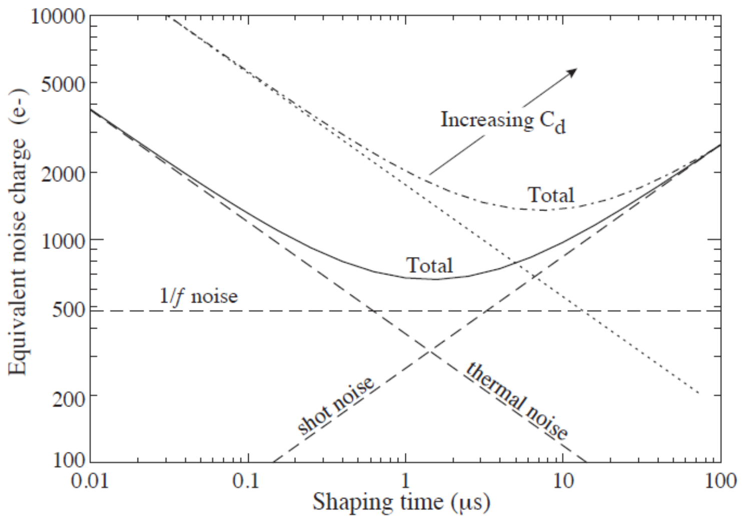


Nuclear Electronics

- In the 1960's, with the proliferation of electronic detectors and the emergence of field effect transistors, major advances begin in electronics to **process signals** from detectors
- Signals are generally current pulses – want to measure the magnitude and/or the time of the pulse, often in the presence of noise – charge sensitivity vs current sensitivity
- What are the noise sources? How to optimize Signal/Noise?
- Key ideas are due to the work of Radeka, Goulding, Gatti, Spielder, among others



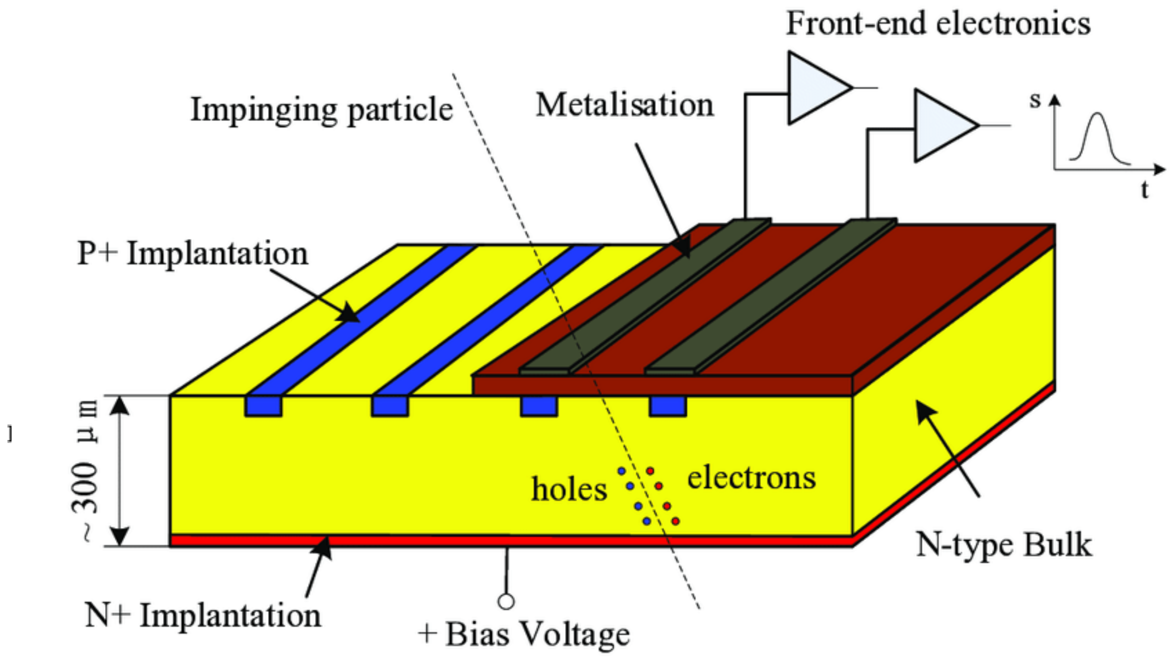


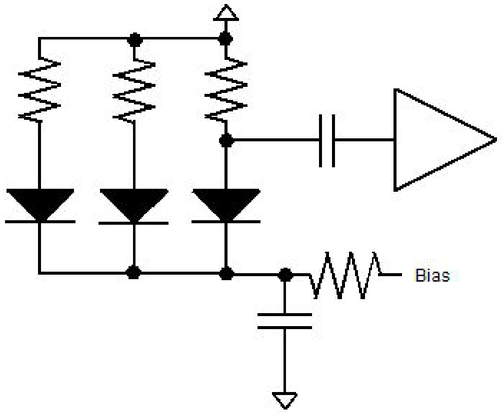


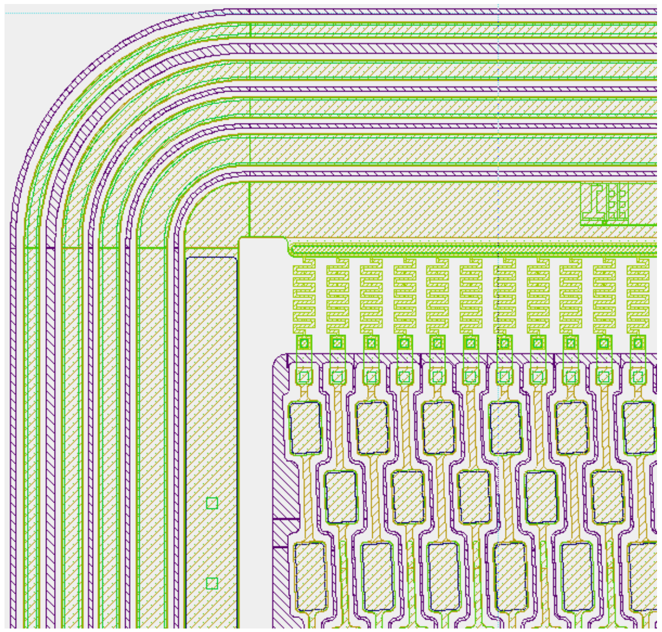
The development of detailed noise models (1960's-1970's) – for both time invariant and variant shaping, coupled with numerical circuit simulation tools (SPICE) (1980's) provide the basis for design and optimization of low noise systems to read out particle detectors

Silicon Microstrip Detector (Kemmer 1980)

- Leverage microlithography and growing wafer scale to fabricate large position sensitive arrays → improved resolution on the **μm scale,** measure decay vertices
- Asymmetric diode junction, reverse bias, high resistivity bulk, low V_{dep}, low leakage
- Signal ∝ width of depletion zone. Drift time ~7 ns to cross 300 microns





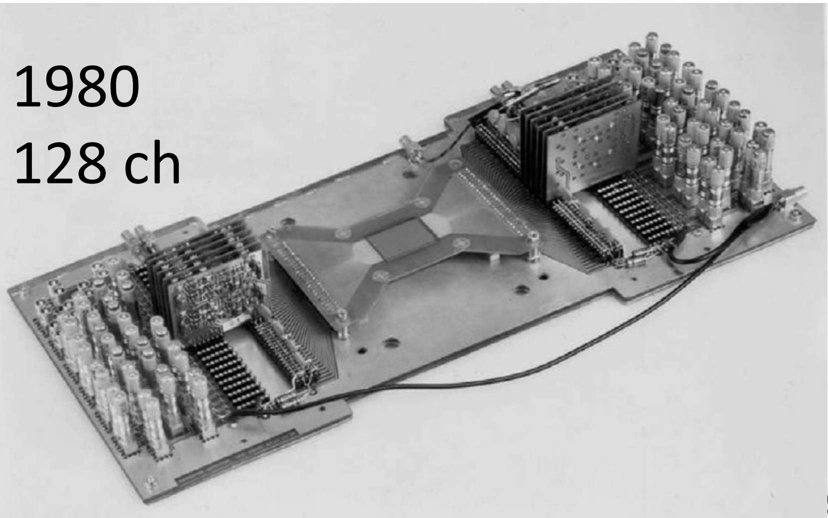


Strip pitch 50-100 μm

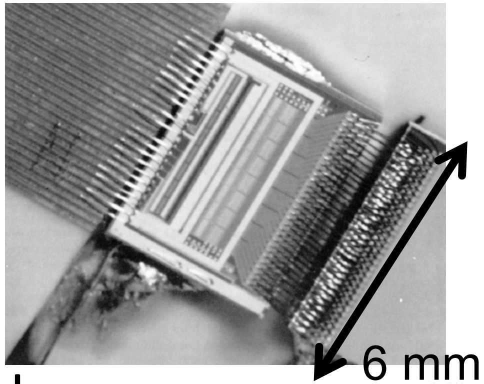
Leverage low noise techniques with microelectronics for high density readout

Microplex: Hyams, Parker, Walker (1984)

1980
128 ch



1984
128 ch



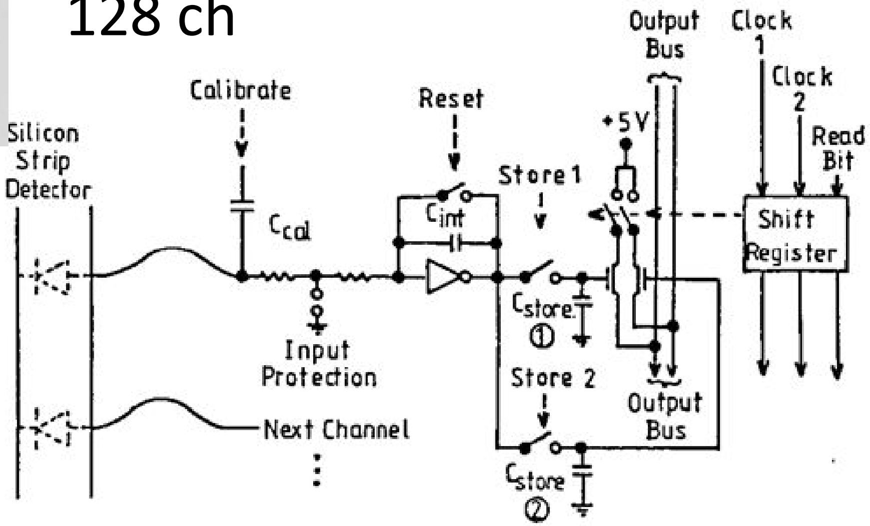
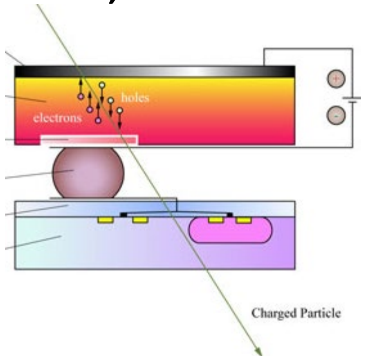
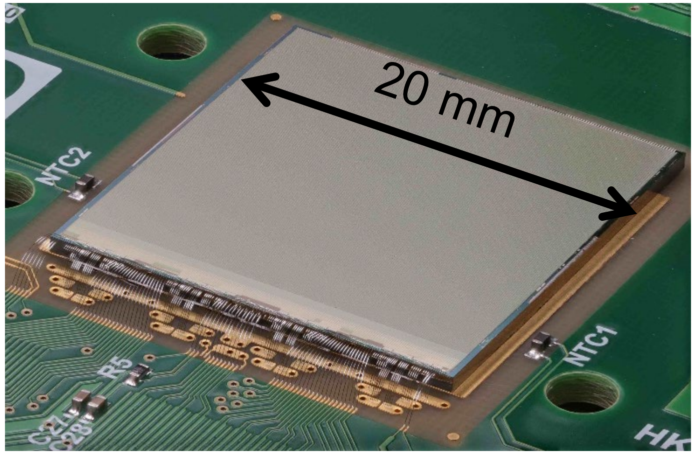


Figure 1. Block diagram of the Microplex circuit

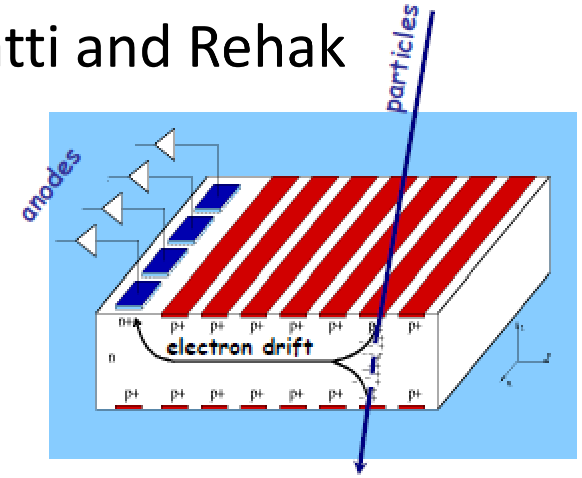
2020
153,600 ch



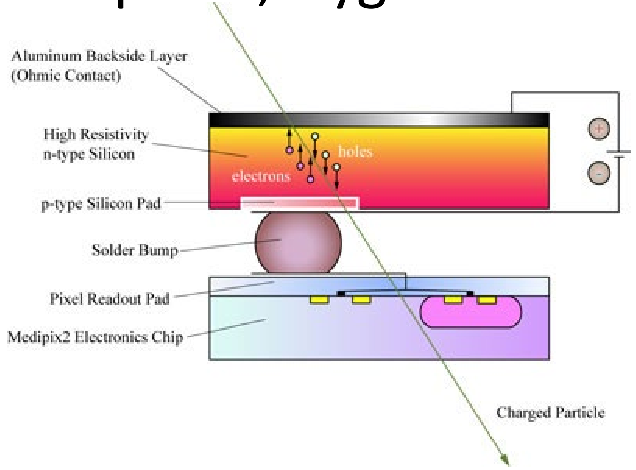


Variations on the PiN Strip

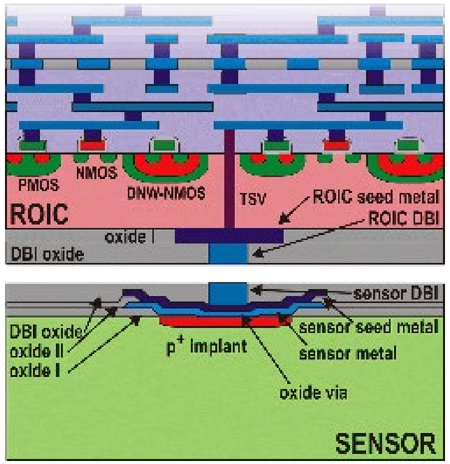
Drift
Gatti and Rehak

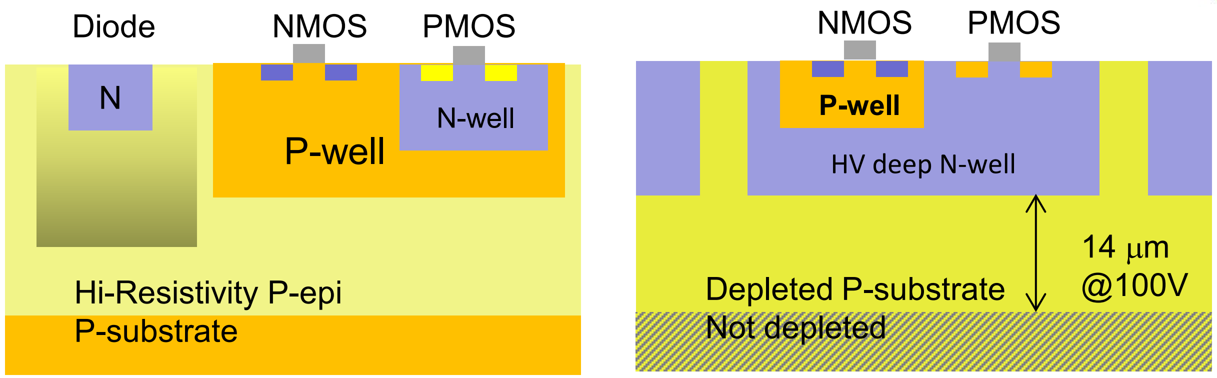


Hybrid
Spieler, Nygren et al

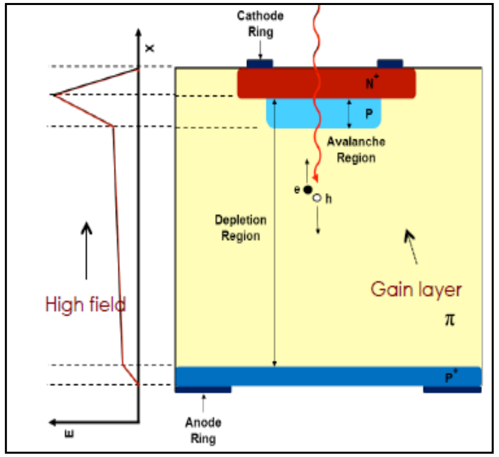


Vertical





LGAD: Sadrozinski



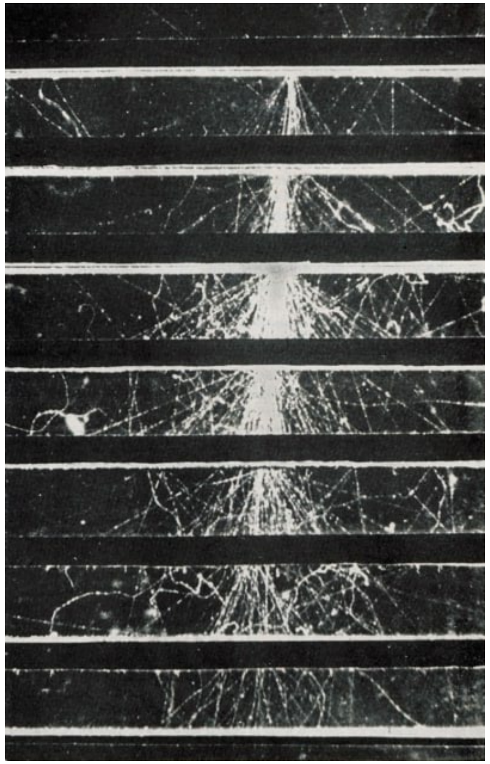
Monolithic Active Pixels (MAPs) Hi-Resistivity and HV

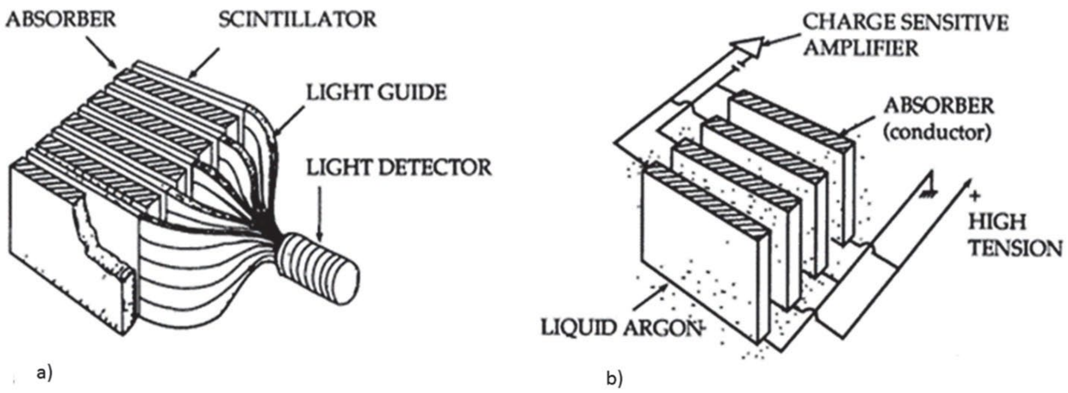
Particle Detectors as Systems

- Cosmic Rays: Anderson’s counter triggered cloud chamber
- Fixed target
  - Scattering experiments – the structure of nucleons
  - Spectrometers – search for new particles, measurements
- Colliding beams
  - Lepton colliders
  - Hadron colliders
- Non-accelerator

Calorimeters

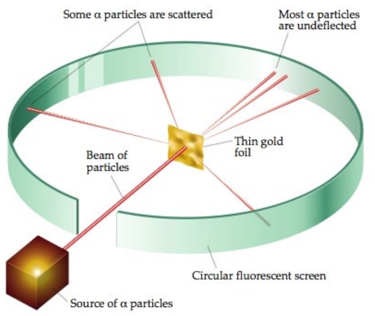
- Unlike a tracker, which strives have as little mass as possible, calorimeters absorb all the energy and transform it into a proportional signal through the process of a particle shower
  - EM calorimeter optimized for EM shower: #X_o
  - Hadron calorimeter for nuclear cascade: #λ
- Ionization in a gas, liquid, or solid leading to charge collection or scintillation
- Total absorption: liquids, crystals
- Sampling: alternating plates of lead (EM), steel, or Uranium (hadronic), with planes of scintillator, gas ionization detectors, noble or exotic liquids
- Signals are proportional to # MIPs crossing
- Typically give fast signals which can be used to trigger a full readout of the entire detector

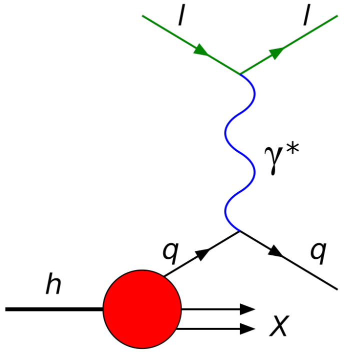


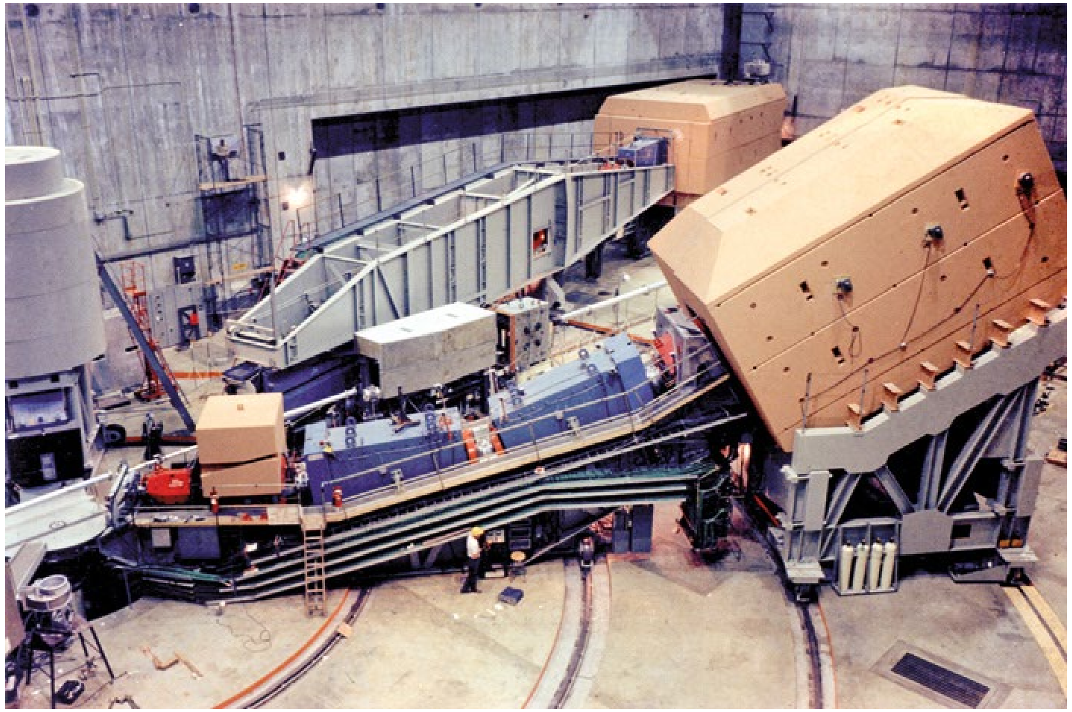


The SLAC-MIT Experiment

- Are quarks real?
- By the late 1960’s the idea that protons (and all hadrons) were composed of quarks was taken seriously, but do they play a role in dynamics?
- At Stanford, **a repeat of Rutherford’s experiment** using high energy electrons as the beam and protons as the target
- Observe clear evidence for hard scattering from point like constituents with fractional charge
- Scattered electrons are selected magnetically and measured with arrays of **scintillation counters**
- Later repeated elsewhere with neutrinos or muons





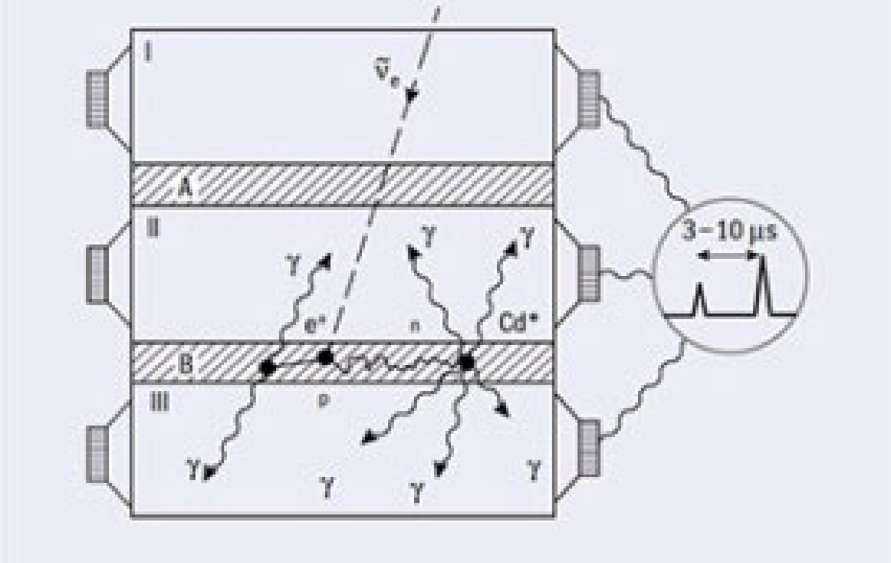


Neutrino Detectors

- Do neutrinos exist?
- What is their nature?
- Neutrinos as probes
- Astrophysics

The Neutrino Exists

- Pauli proposed the neutrino in 1930 to explain the continuous β decay spectrum
- A nuclear reactor should be a copious source of (anti)neutrinos: 5 x 10^{13} $\bar{\nu}_e$ cm^{-2} s^{-1}
- In 1954 Reines and Cowen placed a 200 liter Cd doped water target near a reactor
- Sandwiched between layers of **scintillators/PMT's**



$n \rightarrow p + e^- + \bar{\nu}_e$ β decay in reactor

$\bar{\nu}_e + p \rightarrow n + \mathrm{e}^+$ Inverse β decay in water

$\mathrm{e}^+ + \mathrm{e}^- \rightarrow \gamma\gamma$ Annihilation to 2 gamma which yield prompt light in scintillator

$n + {}^{108}Cd \rightarrow {}^{109}Cd + \gamma$ Slow n is captured in Cd
Second light pulse a few ms later

- Observe ~3 **delayed coincidence** events/hour when the **reactor was on**

The Two Neutrino Experiment

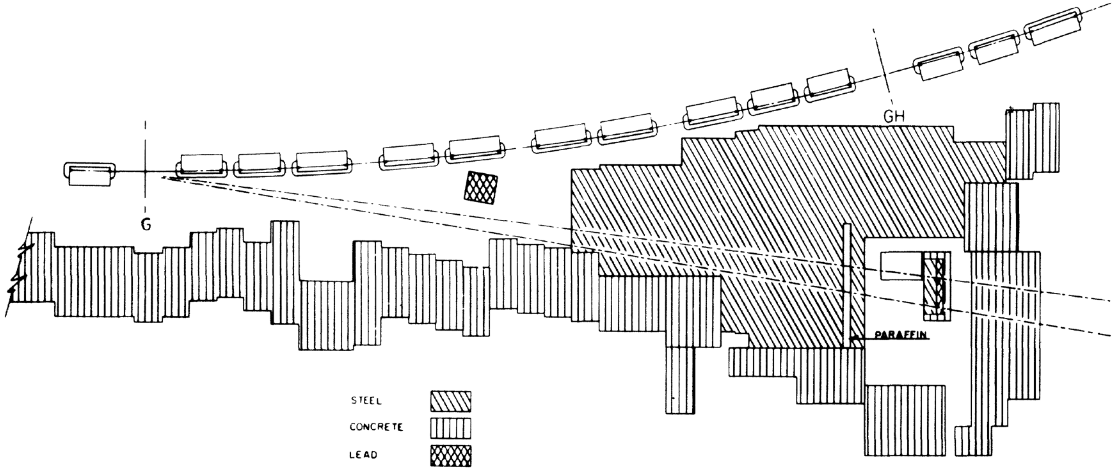


FIG. 1. Plan view of AGS neutrino experiment.

- Are the neutrinos from
π decay and β decay the same?
- Spark chambers
- Anti-coincidence
scintillation counters
- Data collected photographically

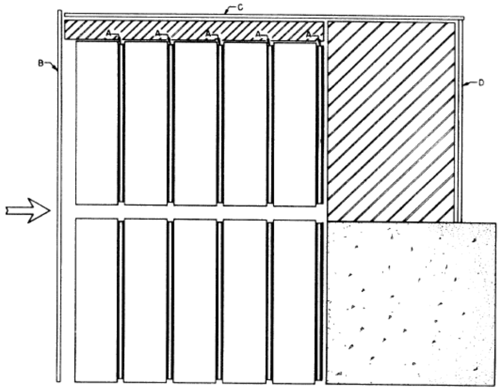
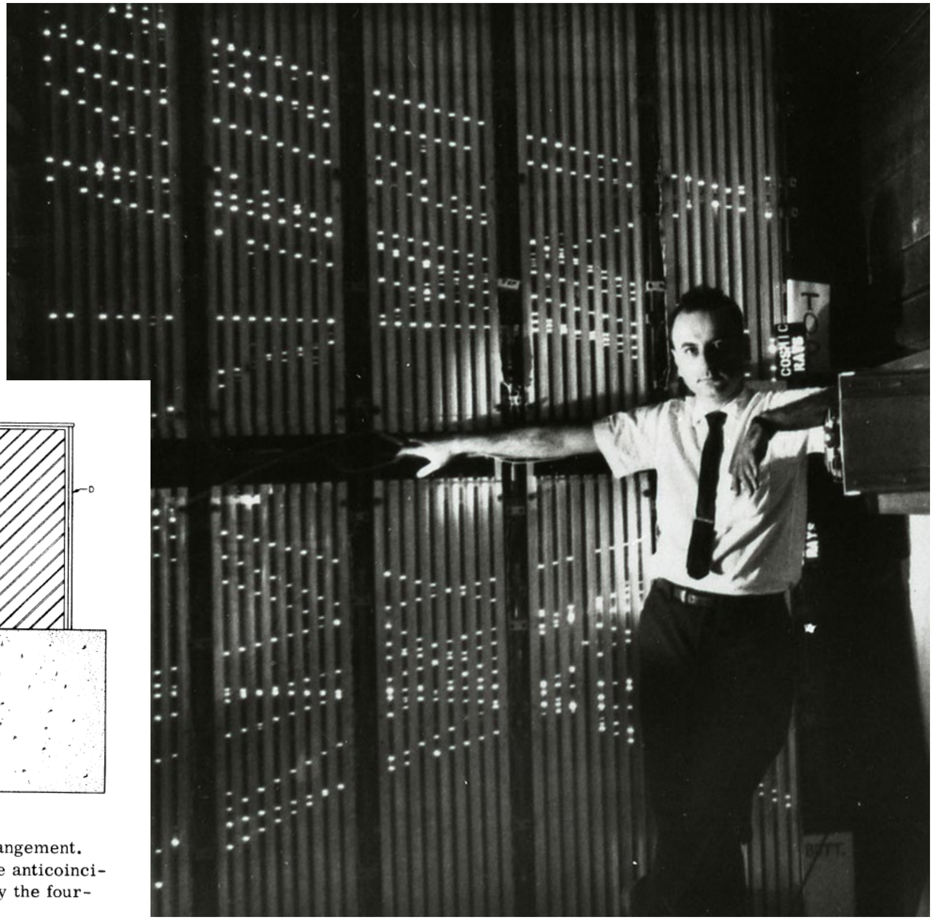
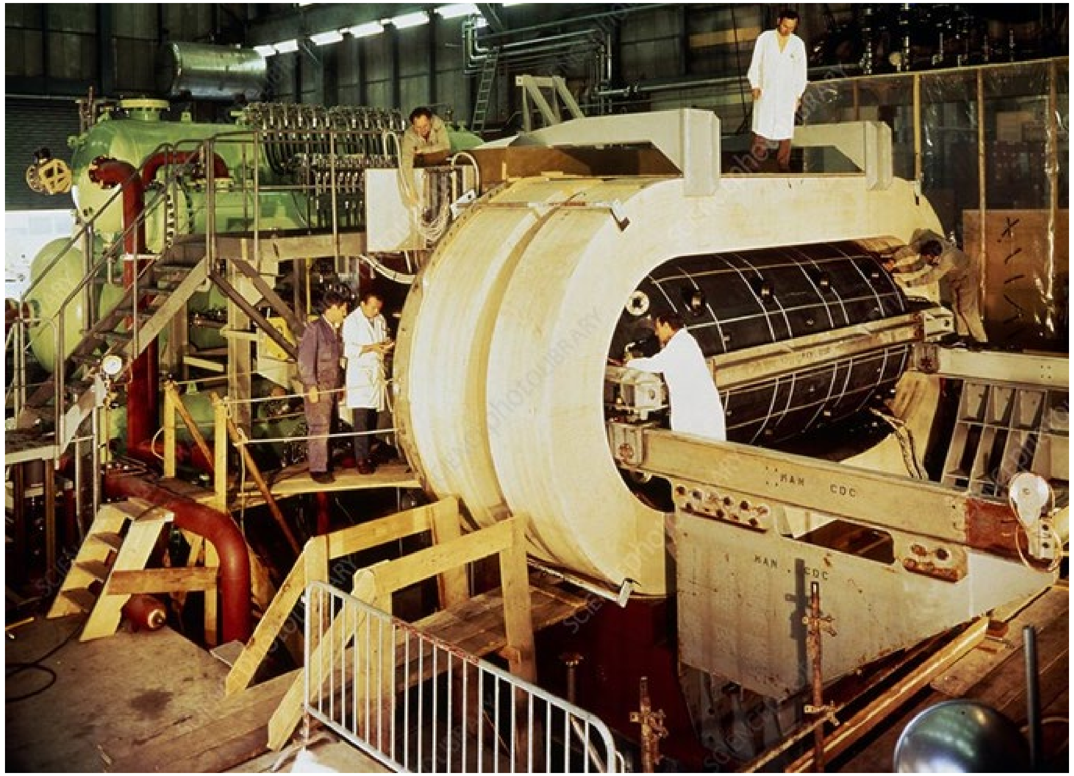


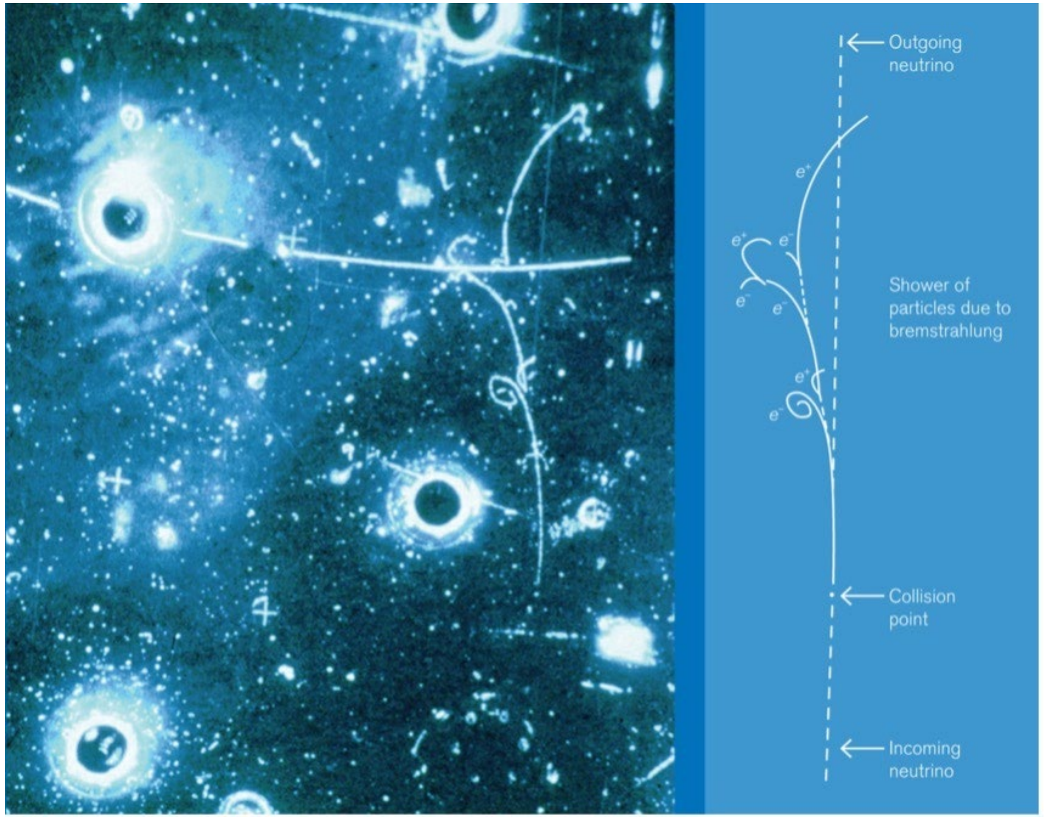
FIG. 3. Spark chamber and counter arrangement. *A* are the triggering slabs; *B*, *C*, and *D* are anticoincidence slabs. This is the front view seen by the four-camera stereo system.



Neutral Currents

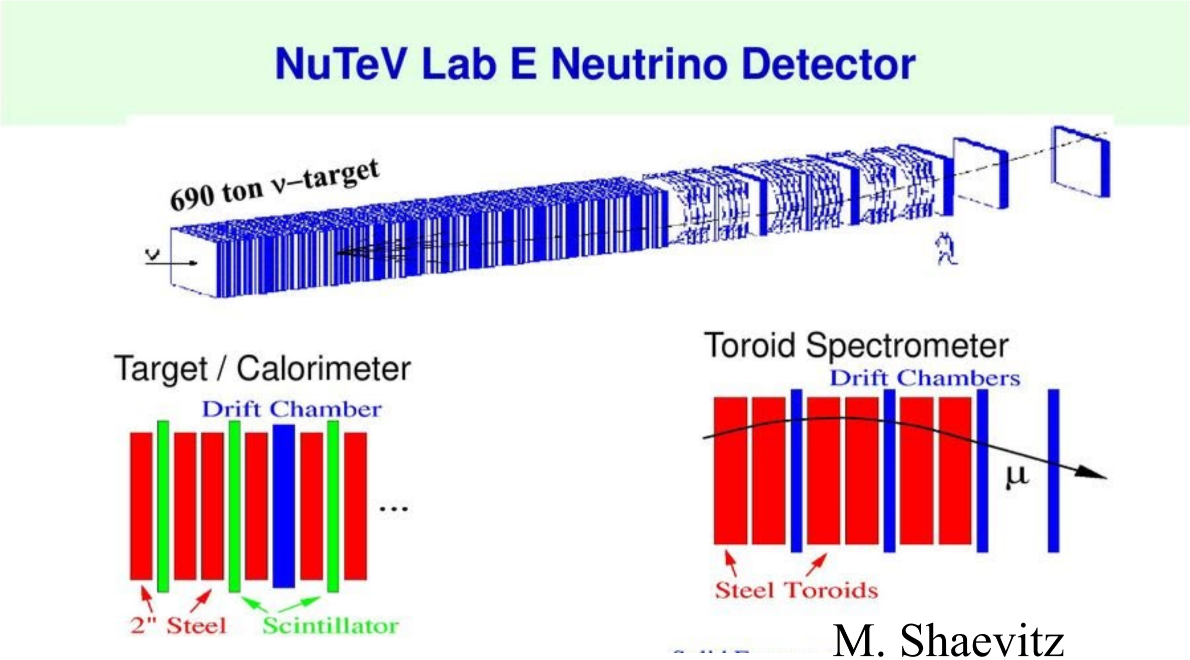


Gargamelle Bubble Chamber
CERN



An incoming neutrino scatters off an electron in the liquid, continuing unchanged. This is the new neutral weak interaction predicted by the EWK Standard model

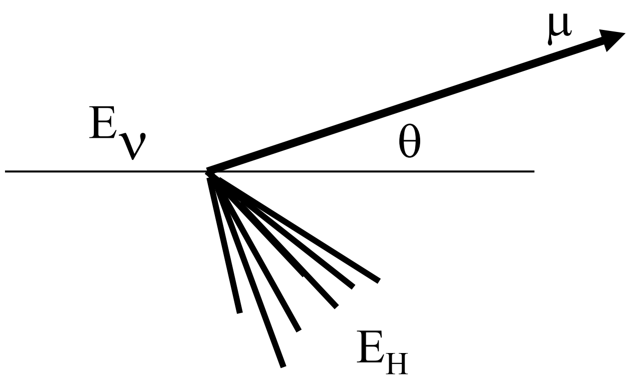
Large Electronic Detectors: Nucleon Structure and $\sin^2\theta_w$



M. Shaevitz

14

- Iron target
- Liquid Scintillation Counters
- Drift chambers
- Magnetic toroids



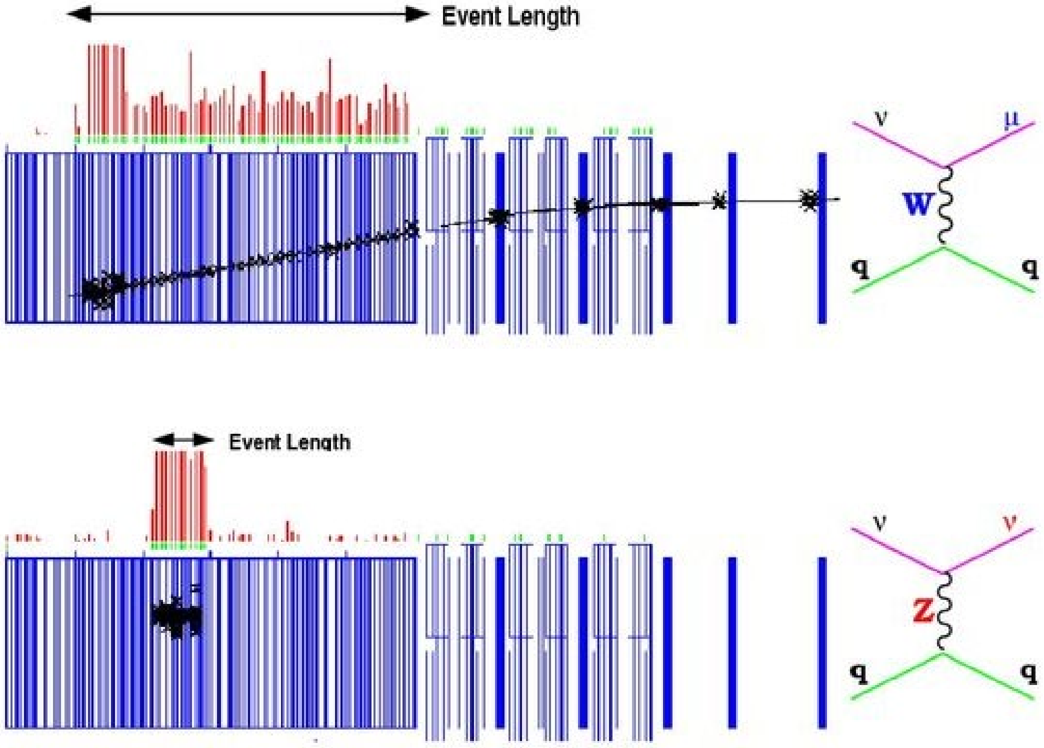
$$Q^2 = 4E_\mu E_\nu \sin^2\frac{\theta}{2} \qquad y = \frac{E_H}{E_\nu}$$

$$\nu = E_\nu - E_H \qquad x = \frac{Q^2}{2M\nu}$$

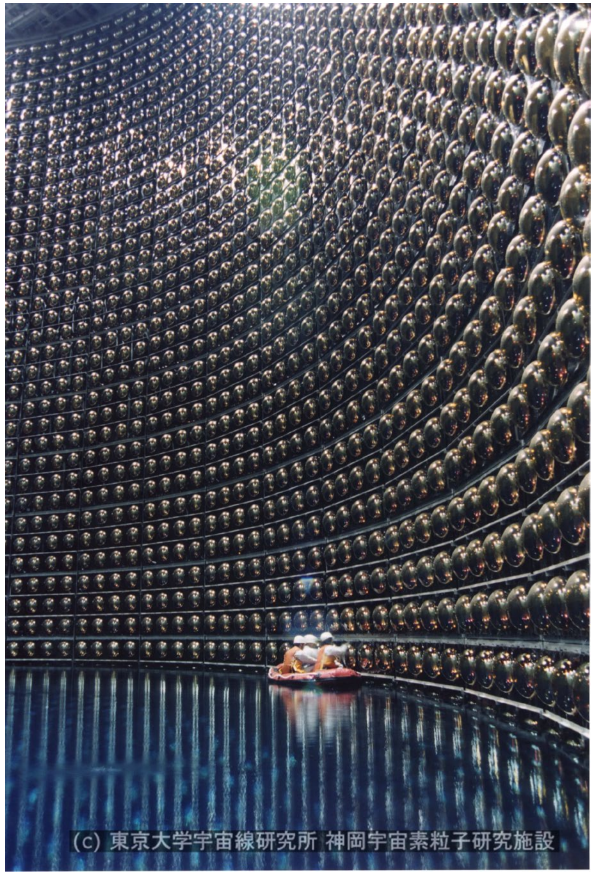
Nucleon substructure and the fundamental interaction between ν's and quarks are studied by event distributions in the x, y, and Q^2 variables

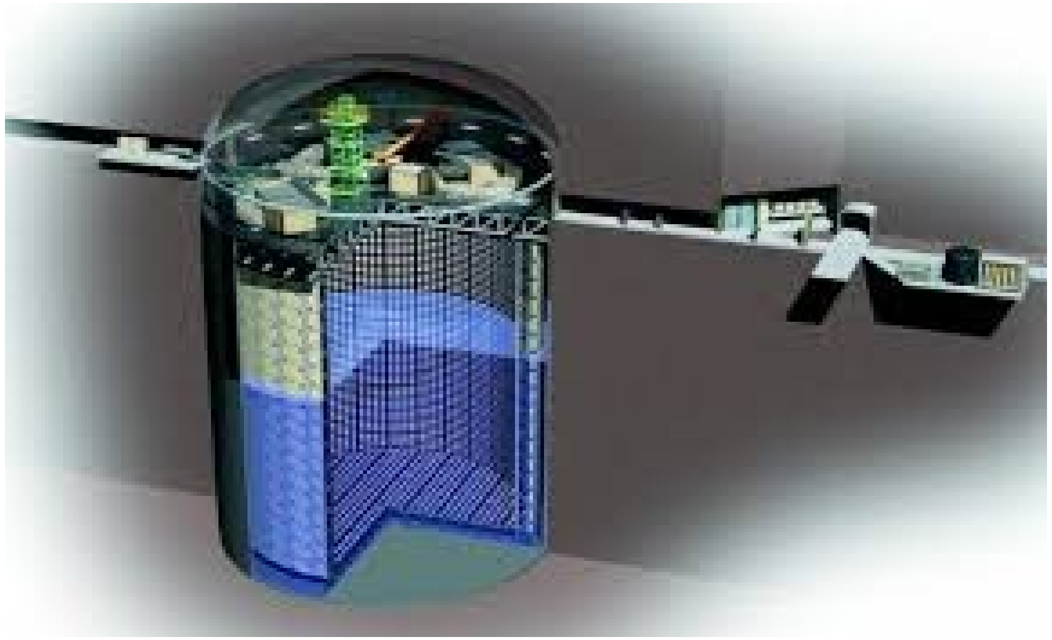
Neutral Current / Charged Current Event Separation

Separate NC and CC events statistically based on the "event length" defined in terms of # counters traversed

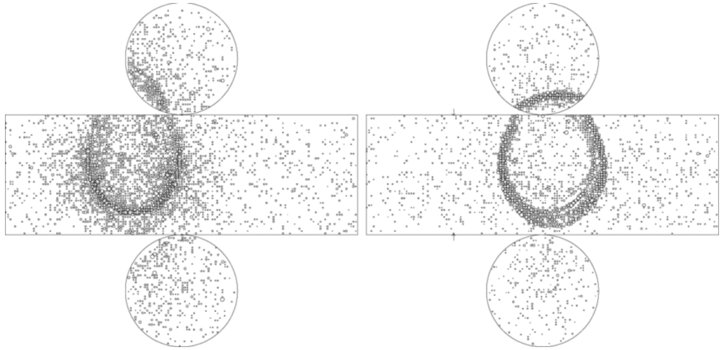


Neutrino Oscillations





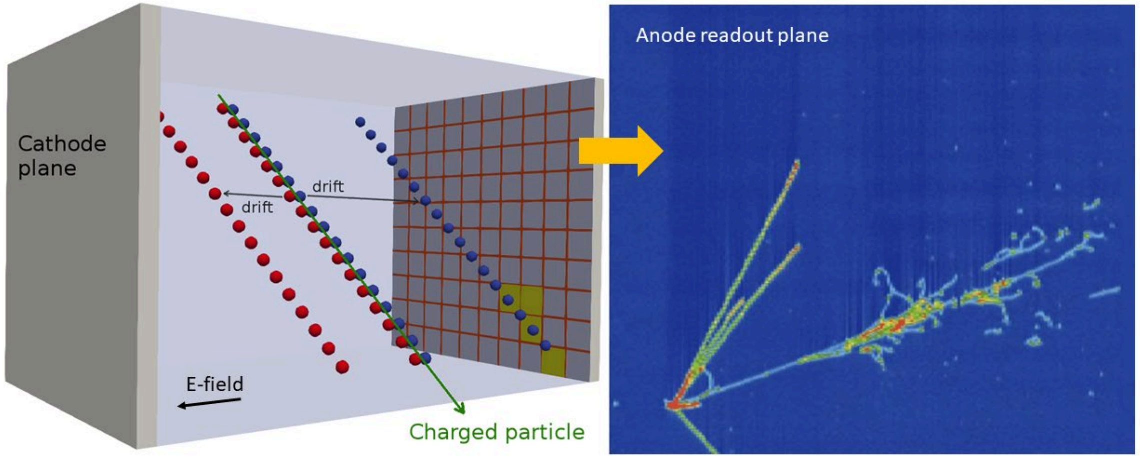
SNO detector
Tank of D_2O, 9600 PMT
Sensitive to both ν_e through CC
and ν_e, ν_μ, ν_τ through NC

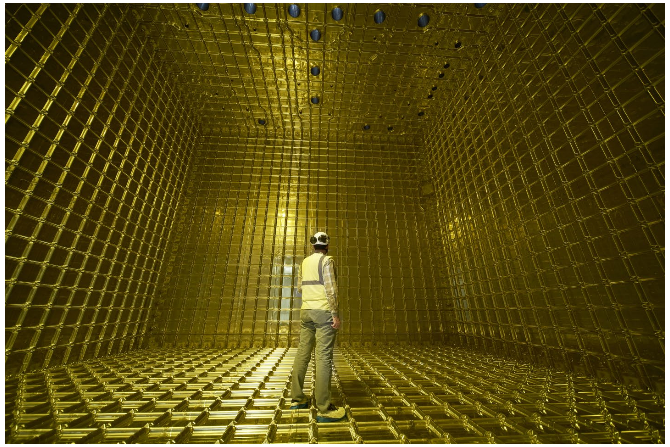


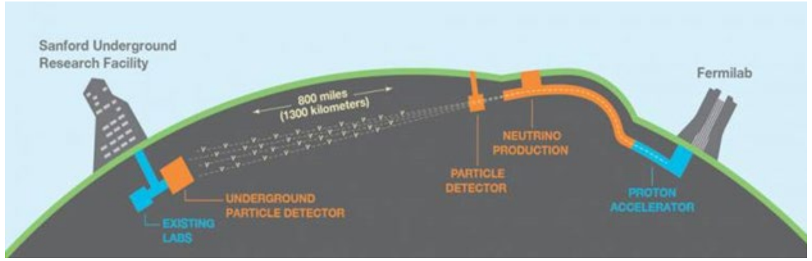
Super-K detector
Water Cerenkov, ~11,000 PMT's
Measure rates of up/down
going atmospheric ν

Large LAr TPC: integrated calorimeter/tracker

- For a new generation of neutrino oscillation experiments a long baseline measurement will occur between FNAL and South Dakota
- Here the TPC concept is applied to a large volume of liquid argon which acts simultaneously as a neutrino target, tracker, and calorimeter



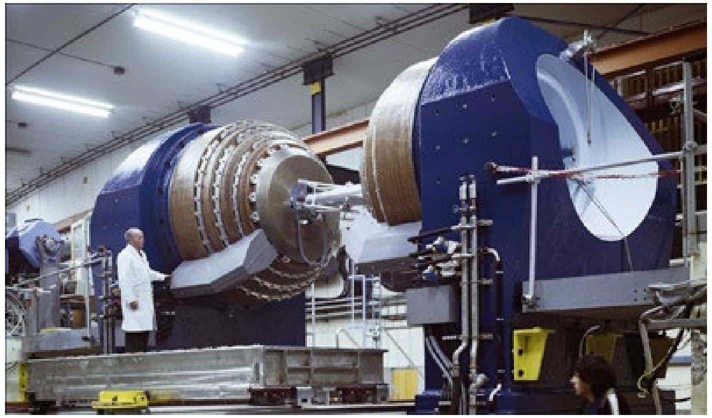




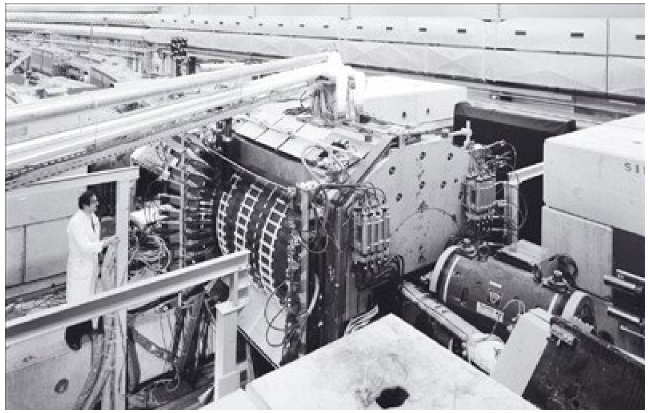
Collider Detectors: The Intersecting Storage Ring (ISR)

- The ISR at CERN ran from 1971-1984 at a p-p collision energy of 62 GeV, luminosity up to 2x 10^{33}
- A variety of experiments pioneered influential detector technologies and configurations (Willis)
- **However, the ISR was ahead of its time.**
- Notions of QCD motivated hard scattering, and heavy quark production were not yet appreciated at the outset – prejudiced the initial program towards forward scattering
- The ISR discovered the rising pp cross section and saw early signs of what was to be dijets but it missed the charm and bottom particles which were instead found at SLAC, BNL, and FNAL
- By 1980 hadron collider physics was dominated by the CERN proton-antiproton collider at a collision energy of 540 GeV

- New detector technologies
- MWPC's
- LAr calorimetry
- Compensated hadron calorimetry
- Fast readout/trigger



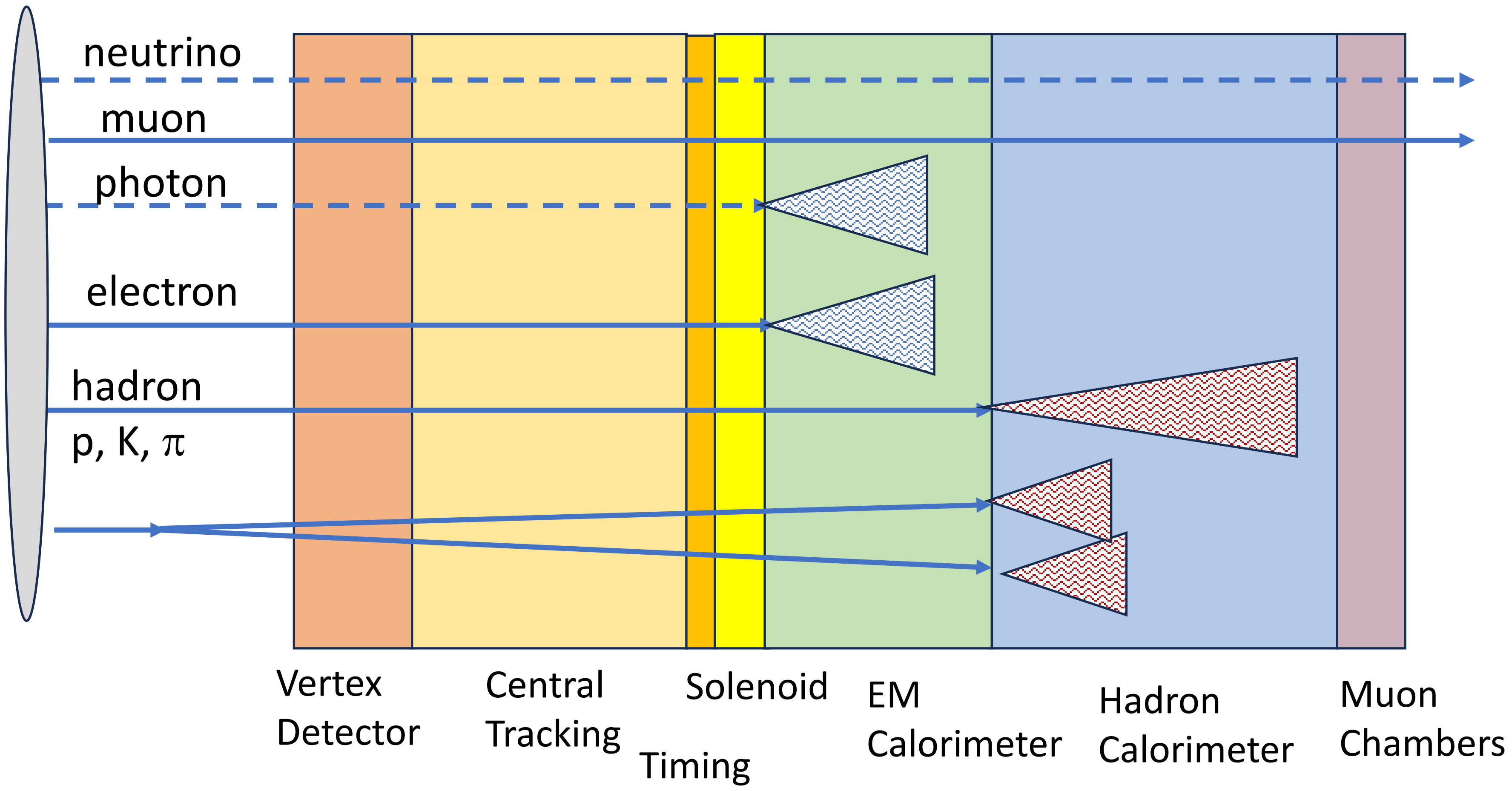
~1980 AFS – later high pT detector



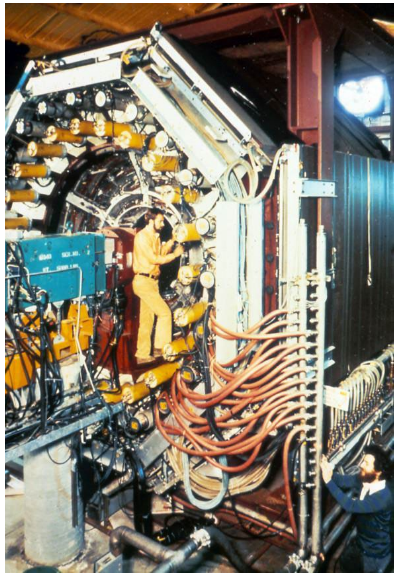
CCOR thin superconducting Solenoid, cylindrical drift

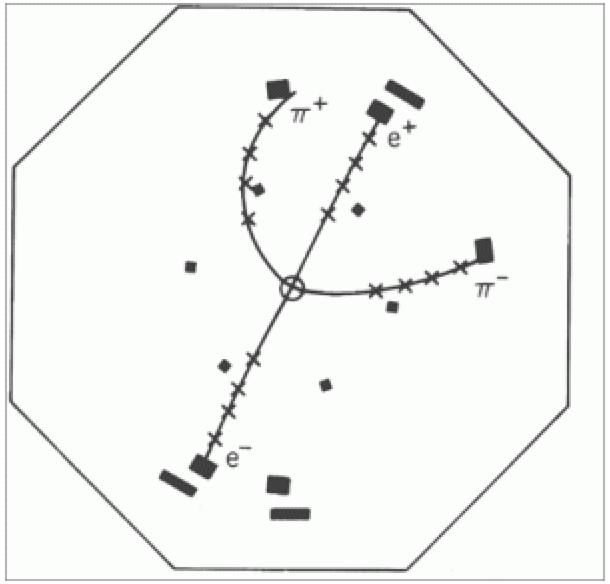
Elements of a Collider Detector

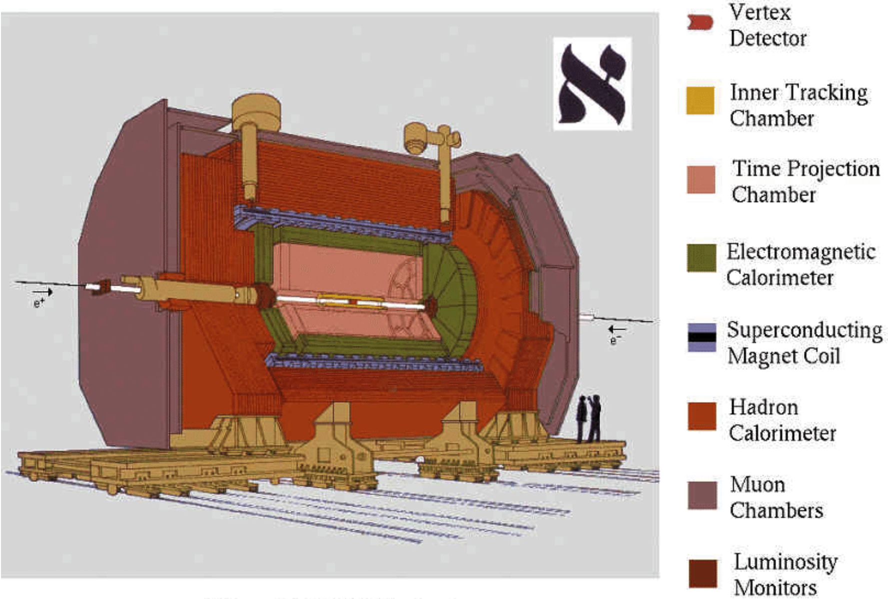
Solid lines leave minimum ionization signals in detector and bend in the magnetic field
Dashed lines leave no ionization

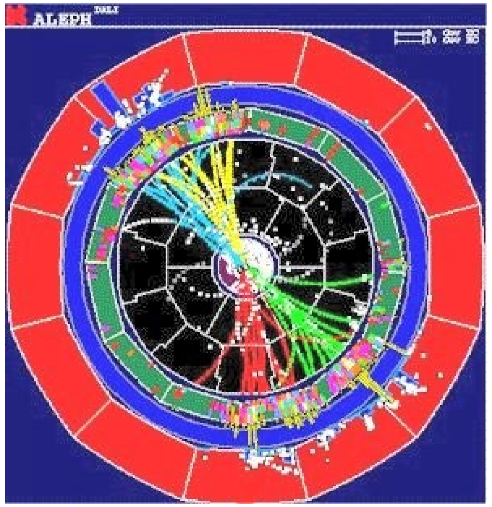


Lepton Collider Detectors





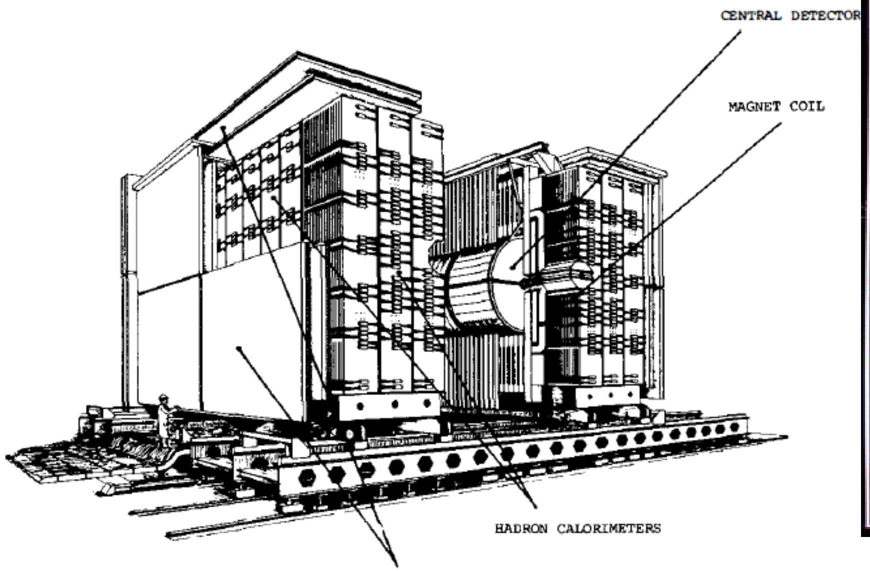


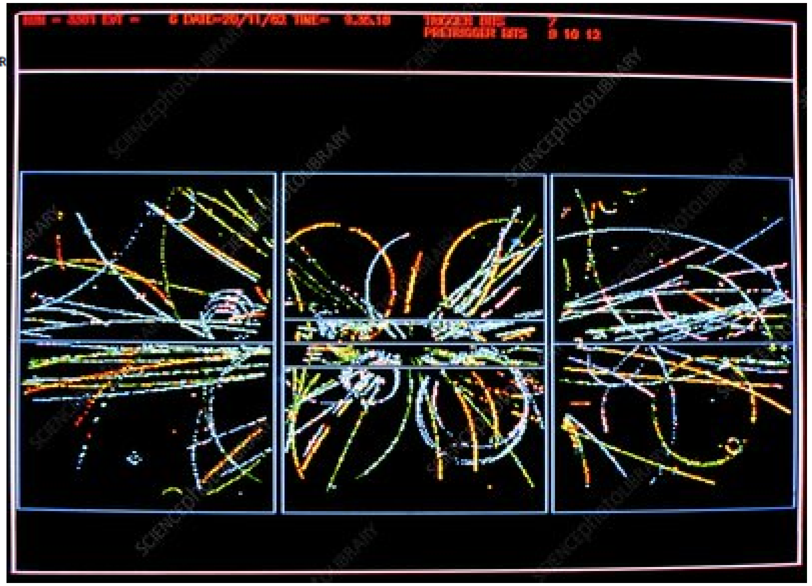


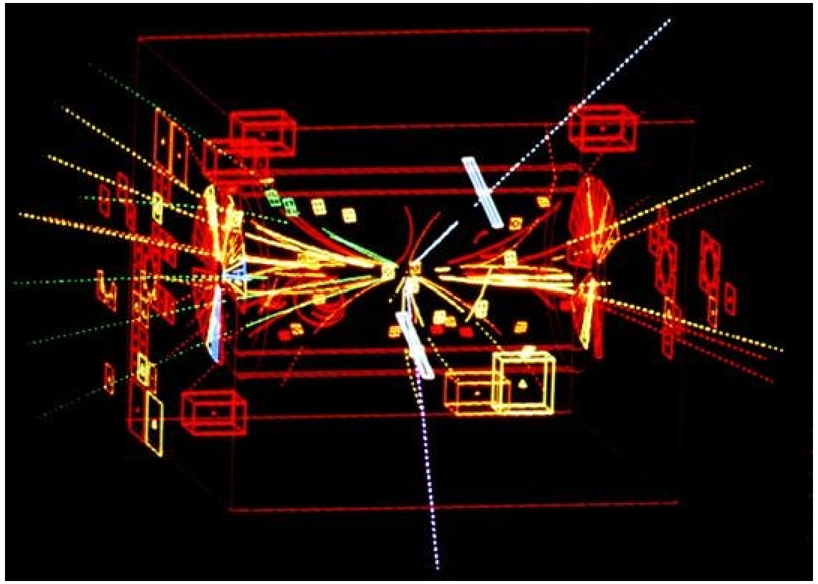
- Early 1970's SPEAR (SLAC) – spark chambers, solenoid, EM calorimeter
- 1990's LEP (CERN) physics at the Z pole and W pair energies – higher resolution tracking and vertex detectors, add hadron calorimeters and muon detection systems

The UA1 Experiment (1979): $p + \bar{p} \rightarrow anything$

- Search for the W and Z particles: $W \rightarrow e\nu$: electron + missing energy
- Precision tracking: drift chamber = electronic bubble chamber
- **Hermetic** calorimeters: capture everything else
- Rate W/Rate All ~ 2 x 10^{-7} Require fast DAQ and triggering





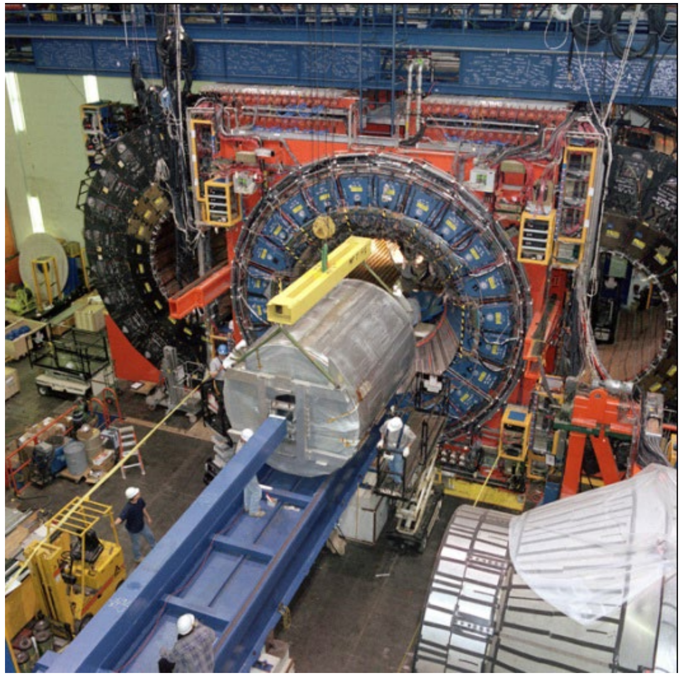


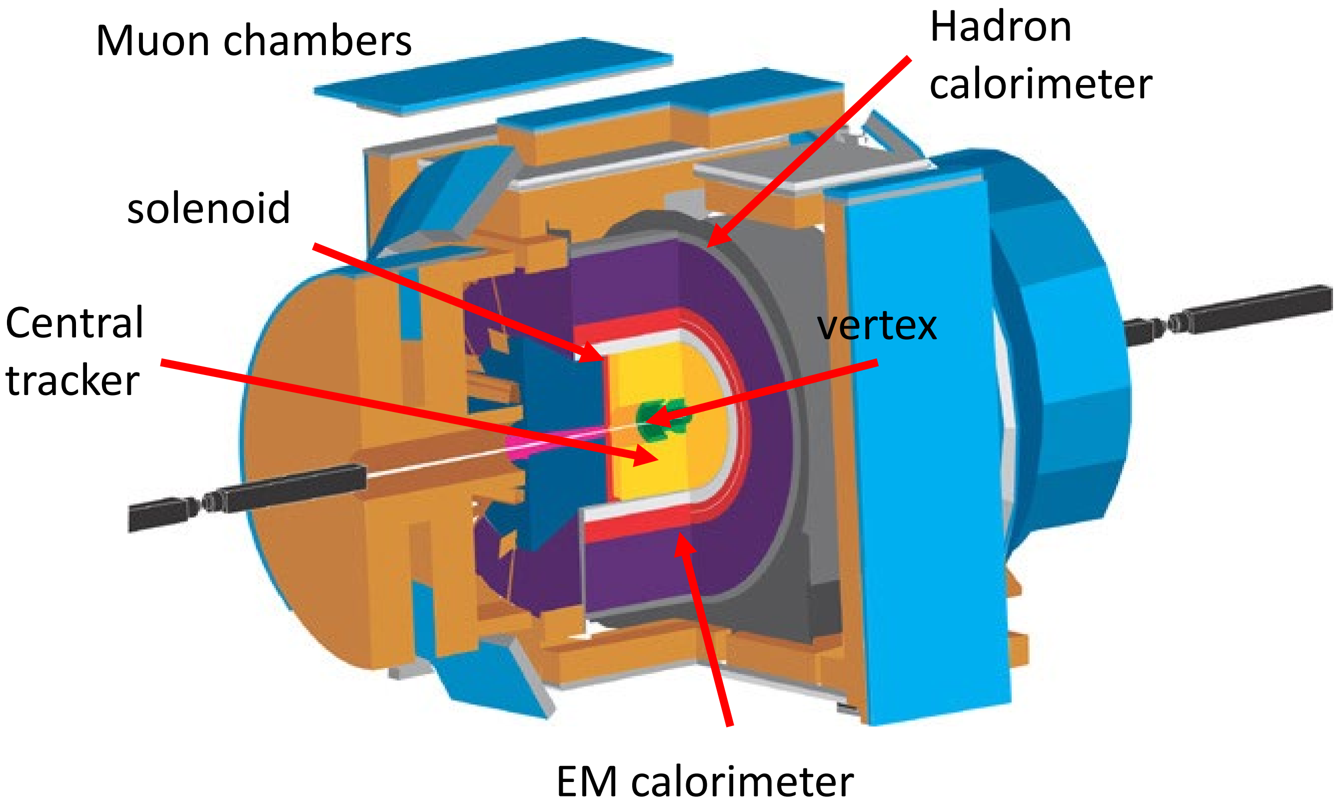
The Standard Model and Beyond(?)

- Following the discovery of the W and Z the focus turned to completing the Standard Model at higher energy hadron colliders
- Find additional quarks
- Find the Higgs Particle
- Is there anything beyond?
- The approach was similar to that of the W and Z but required faster, and higher resolution detectors, larger data sets, and an improved projective geometry
- A key feature of these searches are relatively long lived unstable particles $\tau \sim 10^{-12}$ seconds ($c\tau \sim 100$'s of μm) – "vertex detectors"

The Collider Detector at Fermilab 1985-2011

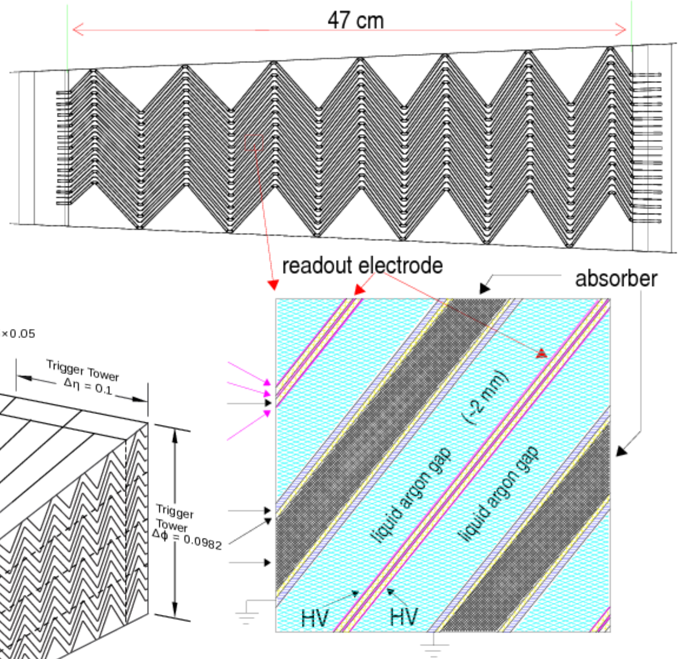
Mature realization of a hadron collider detector with **a projective hermetic** geometry, **precision vertex and central tracking**, and multiple layers of online trigger processing. The later LHC detectors retain these features enhanced by **faster read out,** improved resolution and **radiation resistance**

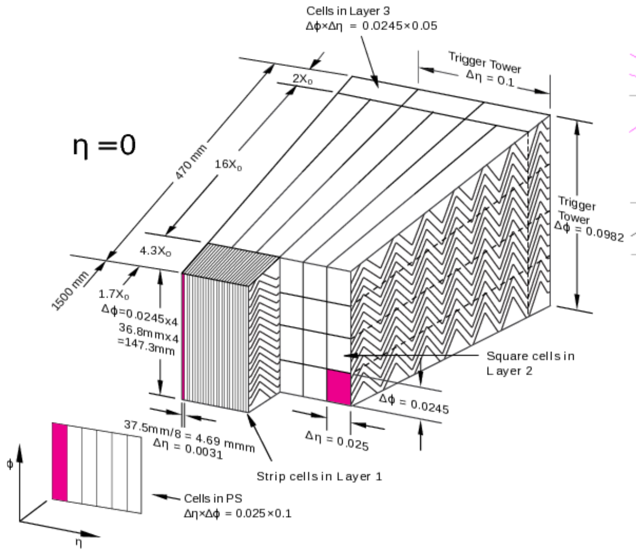




Projective
Lead/Scintillator = electrons/γ
Iron/Scintillator = hadrons

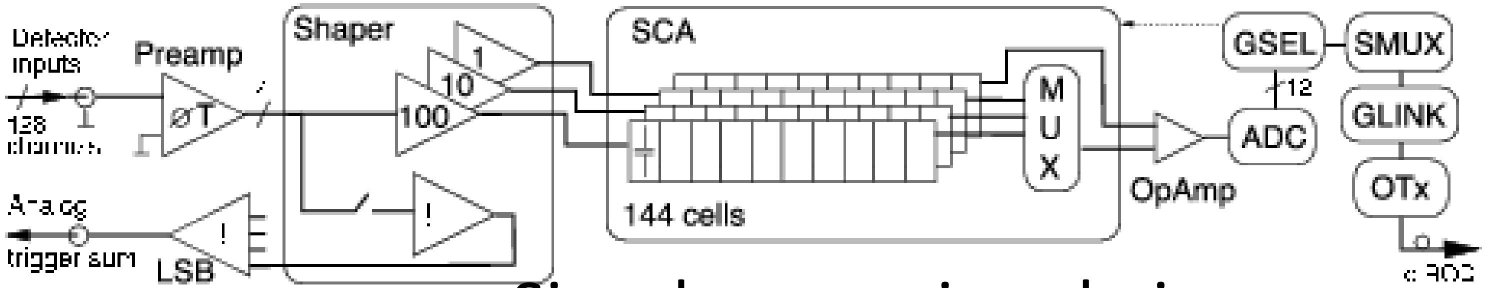
Projective
Copper
Liquid Argon





ATLAS

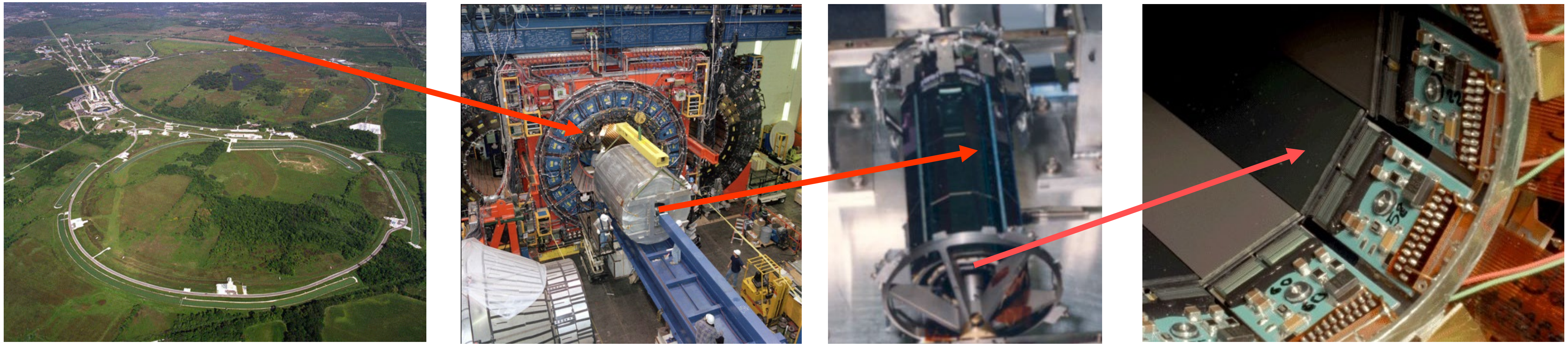
Analog pipeline clocked at collision frequency



Fast trigger output

Signal processing chain

Finding top (the 6th quark) at the Fermilab~1995…..

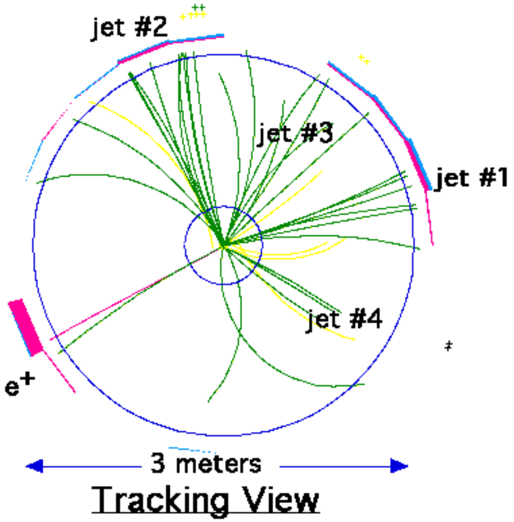


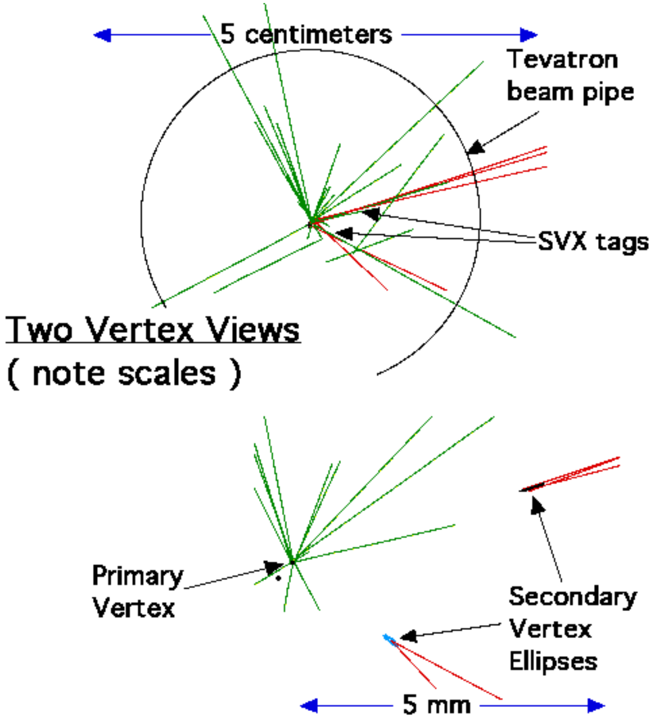
1.9 TeV

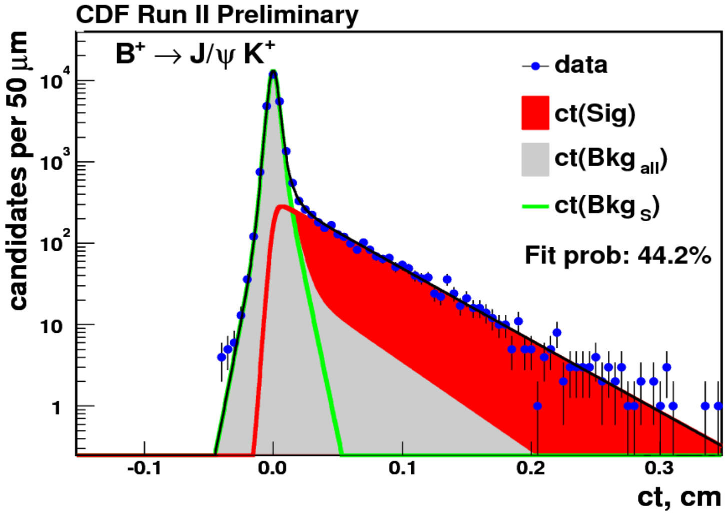
$p + \bar{p} \rightarrow t + \bar{t}$+X

$t \rightarrow b + X$

$\tau_b \sim 10^{-12}$seconds

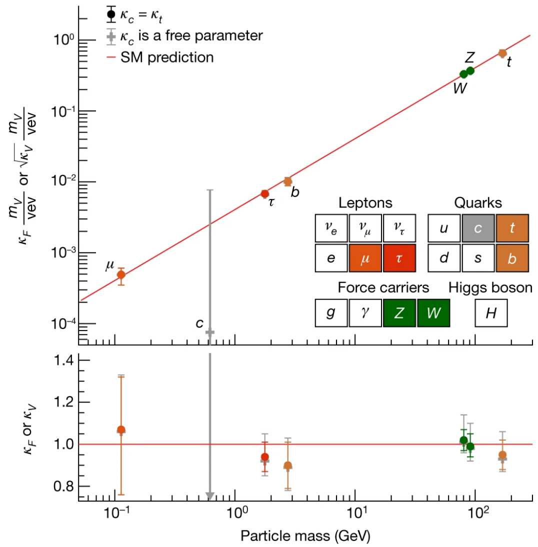


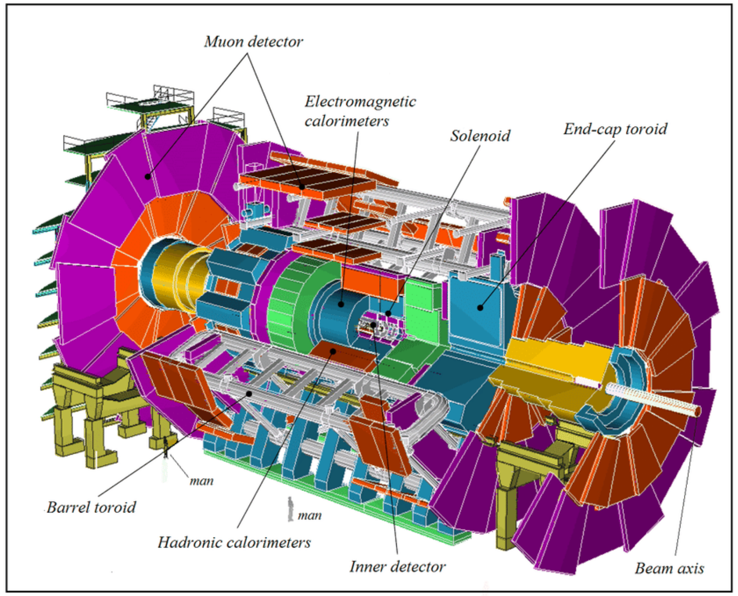


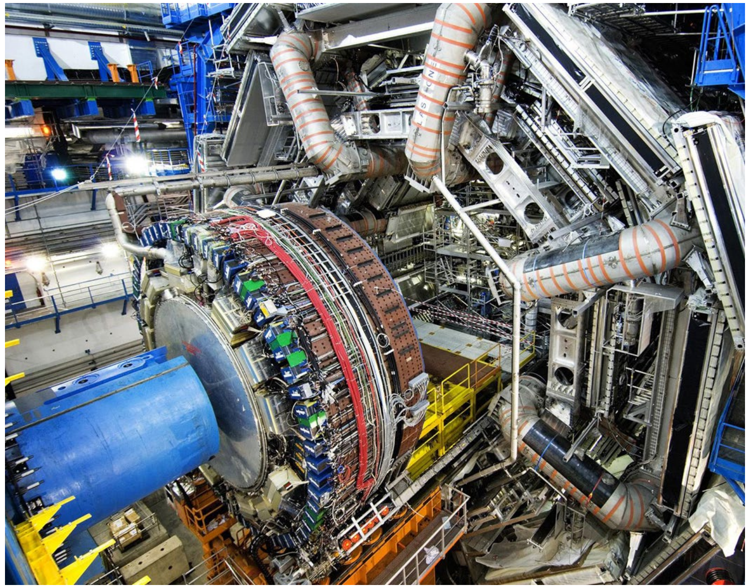


This decade

- The Large Hadron Collider at CERN
- 14 TeV pp collisions@ 40 MHz
- Two large general purpose detectors: ATLAS and CMS designed for the Higgs search
- Higgs discovery (2012)
- Upgrade for x10 data
- Increased radiation, data rates, overlap





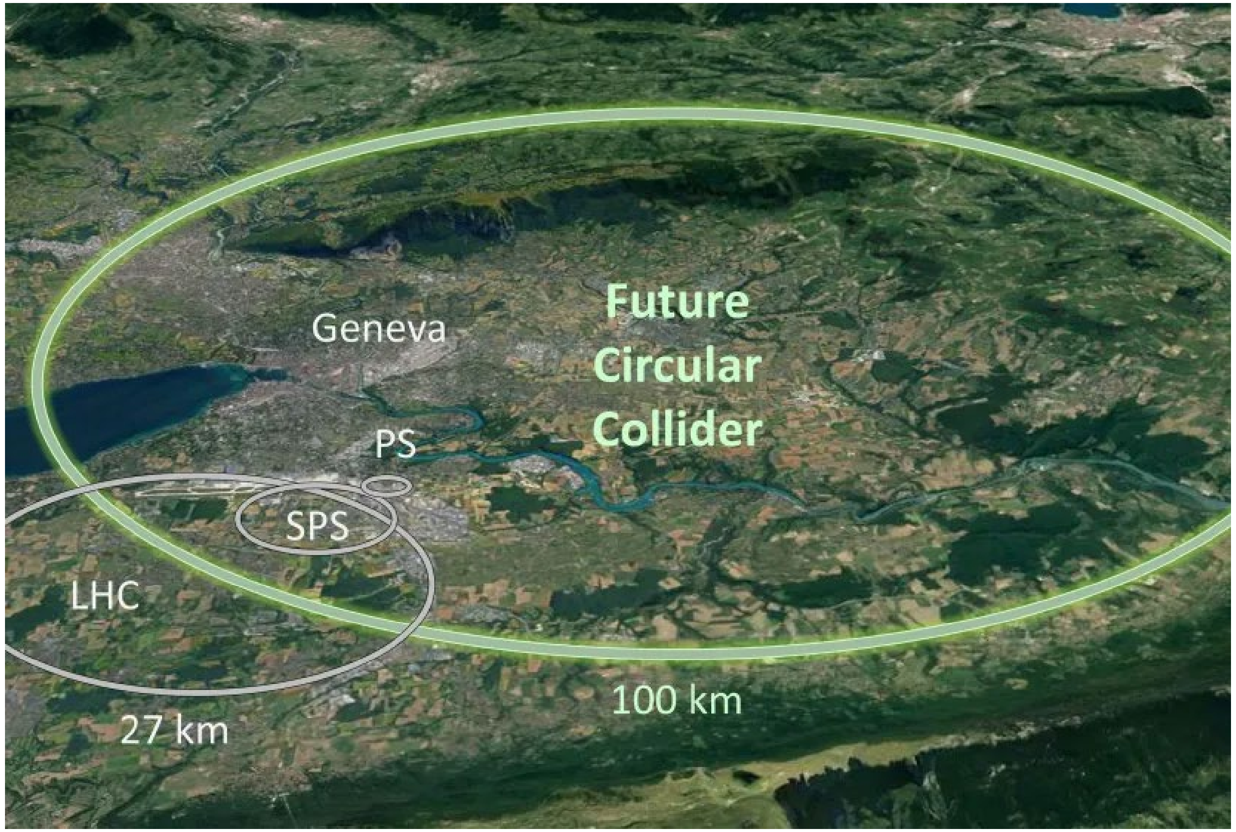


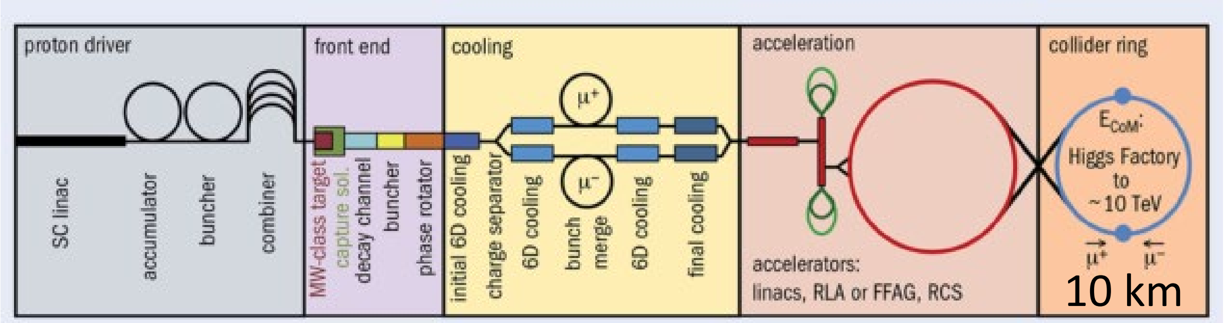
The Future

- The field envisions a long range (~25-75 year) program which will require new instruments and methods
- Future colliders to a) test the standard model with a precision of 10^{-5}, and then b) achieve a factor of 10 in collision energy
  - The Higgs Factory = an electron/positron collider to directly produce 10^6 Higgs
  - A new high energy proton collider or a muon collider
- Dark matter detectors with significantly lower mass detection threshold
  - Instead of nuclear targets, exploit coherent excitations in matter at low temperature
- Large survey instruments and focal planes to study Dark Energy

Future Colliders

- Large international effort to evaluate science, detectors, accelerators
- CERN: 1st stage decision in ~2 years
- FCCee ~2045: collide e^+e^- at 4 energies in order to perform precision tests of the SM = indirect search for new physics
- FCChh ~2070's: after developing high field superconducting magnets (~20T) collide protons at ~100 TeV (10 TeV parton CMS) to directly search for physics BSM
- Alternatives: a μ collider, a linear e^+e^- collider, and FCC in China
- All future colliders present interesting instrumentation challenges for sensors, electronics, and system aspects





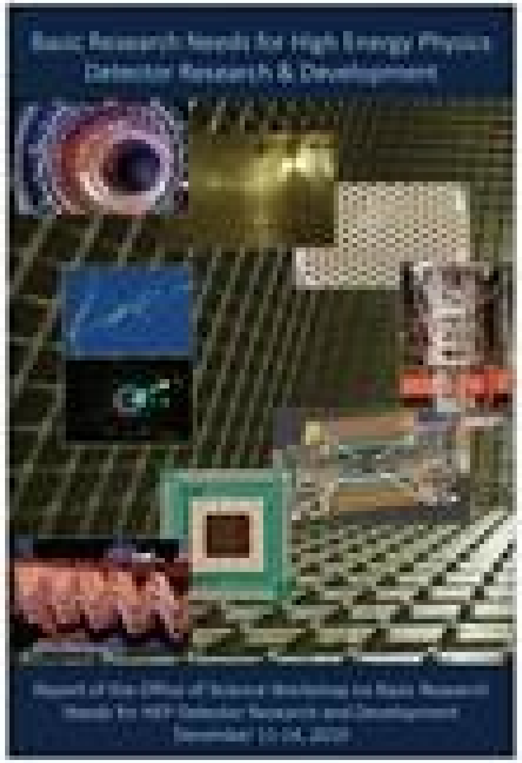
Not to scale

Future Detector and Electronics Challenges

- Extremely low mass to enable high precision measurements
  - Ultra thin (~50 microns) sensors and electronics
  - Data transmission: low mass, high speed links
  - Power management: high efficiency to reduce material and losses, innovative cooling schemes
  - Possibility to operate at high temperature
- Precise knowledge of detector performance – acceptance, efficiency to control systematics
- Local intelligence: capable of compressing data in real time to reduce BW
- Granularity/Timing: fine grained pixelated sensors ~50 μm^2, fast timing with 10-100 ps resolution, covering several m^2 - ~100 m^2 (albeit with less granularity)
- Radiation hardness: relates to the future of the LHC and FCChh, requiring sensors which can sustain up to 10^{17} 1 MeV n_{eq}, and electronics which can absorb up to 10 GRad.
- Integrate new technologies – advanced node, WBG, thin films, nano, Si photonics
- Integrate new tools and components/capabilities

The Future of Particle Detectors

- In 2019-20 the Dept of Energy Office of High Energy Physics requested a community study of needs for transformational instrumentation R&D for future HEP experiments. Report released Aug 2020
- https://science.osti.gov/hep/Community-Resources/Reports
- See also ECFA Detector R&D Roadmap: https://cds.cern.ch/record/2784893



Basic Research Needs for High Energy Physics Detector Research and Development

Led by

Ian Shipsey and Bonnie Fleming

Our colleague Ian Shipsey passed away on October 7, 2024. These lectures are dedicated to him.

Conclusions

- Particle physics began in the attempt to understand radiation – 1896 Becquerel
- Seek sensors/electronics to measure position, time, and energy
- 2^7 years of scientific progress built upon instrumentation, technology, and theory
- Coordinating Panel on Advanced Detectors: CPAD Conference Nov 18-22, Knoxville Tn., 2025 in Philadelphia
- References from the Particle Data Group
- https://pdg.lbl.gov/2024/web/viewer.html?file=../reviews/rpp2024-rev-passage-particles-matter.pdf
- https://pdg.lbl.gov/2024/web/viewer.html?file=../reviews/rpp2024-rev-particle-detectors-accel.pdf
- https://pdg.lbl.gov/2024/web/viewer.html?file=../reviews/rpp2024-rev-particle-detectors-non-accel.pdf

Backup/Extras

Key Papers

- Geiger: E. Rutherford and H. Geiger (1908) "An electrical method of counting the number of α particles from radioactive substances," Proceedings of the Royal Society (London), Series A, vol. 81, no. 546, pages 141–161.
- Geiger and Muller: H. Geiger and W. Müller (1928), "Elektronenzählrohr zur Messung schwächster Aktivitäten" (Electron counting tube for the measurement of the weakest radioactivities), Die Naturwissenschaften (The Sciences), vol. 16, no. 31, pages 617–618
- Wilson: Malcolm Longair, C.T.R. Wilson and the cloud chamber, Astroparticle Physics, Volume 53, 2014, Pages 55-60, ISSN 0927-6505, https://doi.org/10.1016/j.astropartphys.2013.01.010.
- Sime, R.L., Marietta Blau: Pioneer of Photographic Nuclear Emulsions and Particle Physics. Phys. Perspect. 15, 3–32 (2013). https://doi.org/10.1007/s00016-012-0097-6
- B. Rossi, "Method of registering multiple simultaneous impulses of several Geiger counters," Nature 125 (3156), 636–636 (1930).
- Photomultiplier Tube: J. Slepian, Westinghouse Electric, "Hot Cathode Tube" U.S. patent 1,450,265, Issued April 3, 1923 (Filed 1919)
- Donald A. Glaser (1952). "Some Effects of Ionizing Radiation on the Formation of Bubbles in Liquids". Physical Review. 87 (4): 665. Bibcode:1952PhRv...87..665G. doi:10.1103/PhysRev.87.665.

Continued

- Charpak
- Walenta
- F. S. Goulding and D. A. Landis, "Signal Processing for Semiconductor Detectors," in IEEE Transactions on Nuclear Science, vol. 29, no. 3, pp. 1125-1141, June 1982, doi: 10.1109/TNS.1982.4336332
- Nygren: D.R.,The Time Projection Chamber: A New 4 pi Detector for Charged Particles, 1974, 21 pages, Part of 1974 PEP summer study, Published in: eConf C740805 (1974) 58, Contribution to: 1974 PEP Summer Study, Report number: PEP-0144
- Kemmer J. ,Fabrication of low noise silicon radiation detectors by the planar process (1980) Nuclear Instruments and Methods, 169 (3), pp. 499 - 502, Cited 208 times.DOI: 10.1016/0029-554X(80)90948-9
- Radeka
- Willis: Willis, W.J.; Radeka, V. (14 May 1974). "Liquid-Argon Ionization Chambers as Total-Absorption Detectors". Nuclear Instruments and Methods. 120 (2): 221–236. Bibcode:1974NucIM.120..221W. doi:10.1016/0029-554X(74)90039-1.
- Gatti and Rehak

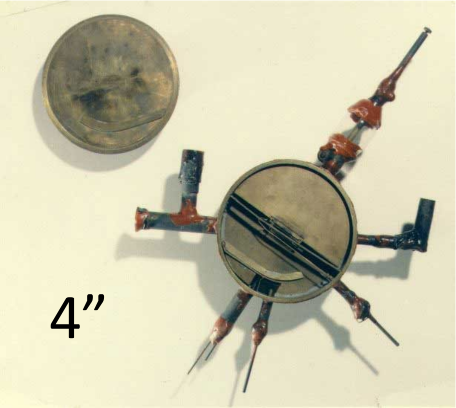
Fundamentals

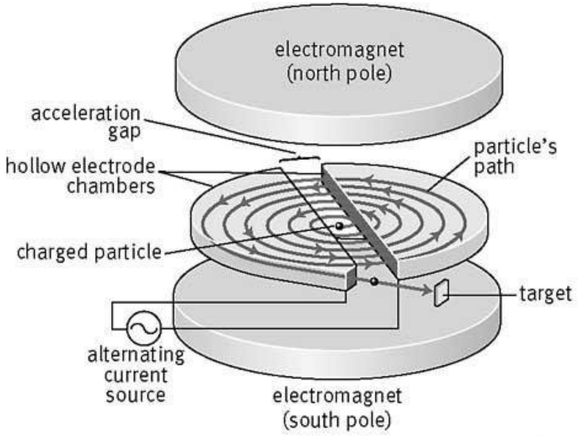
- Electrical Processed in Gas: John S. Townsend (1901) "The conductivity produced in gases by the motion of negatively charged ions," Philosophical Magazine, series 6, 1 (2) : 198-227.
- Photoelectricity: Hertz, H. (1887), Ueber einen Einfluss des ultravioletten Lichtes auf die electrische Entladung. Ann. Phys., 267: 983-1000. https://doi.org/10.1002/andp.18872670827
- Gurnsey and Mott:
- Cerenkov
- Semiconductors: Shockley, W.
- Grove

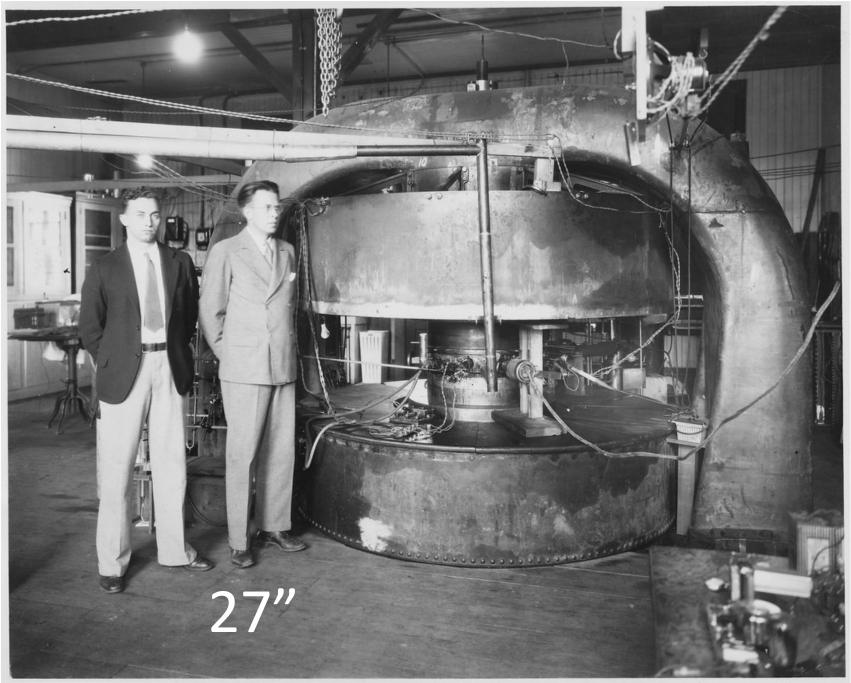
Rossi's coincidence circuit, the first fast electronic coincidence circuit of the parallel type, became essential in cosmic-ray research. It allowed the simultaneous registration of electrical pulses from any number of Geiger-Müller counters and had a resolving time of 10^{-3} second, an order of magnitude faster than Walther Bothe's coincidence circuit. The plates of the three triodes A, B, and C are connected together and to the positive terminal of a battery P whose negative terminal is grounded through the resistance R_7. The grids of the three triodes are coupled electrostatically to the central wires of the three Geiger-Muller counters. The grids of the three triodes in a normal state are grounded, so a current then flows in them and in their common plate resistor R_7, and the potential drop through it holds the grid of the triode D at a negative potential, thus inhibiting the plate current. If a charged particle enters one of the Geiger-Müller counters and causes it to discharge, then the corresponding grid will experience a negative potential and the plate current will stop. If this happens in one or two of the triodes, then the current in the third one will still experience a potential drop in the ground resistor R_7, and the current in the triode D will still be inhibited. Only when all three Geiger-Müller counters discharge simultaneously will the current in the resistor R_7 stop, bringing the grid of the triode D to ground potential and starting a current flow in it. Source: Rossi, "Method of Registering" (ref. 10), p. 636.

A tool to reach higher energies...

- E.O. Lawrence (1935) invents the cyclotron.
- An electro-magnetic system to accelerate charged particles to “arbitrarily” high energy, limited by the practical size of the device
- A magnet traps a particle in a spiraling orbit
- Alternating electrostatic fields accelerate the particles
- Initially used to study nuclear reactions
- After WWII becomes the dominant source of high energy beams for particle physics

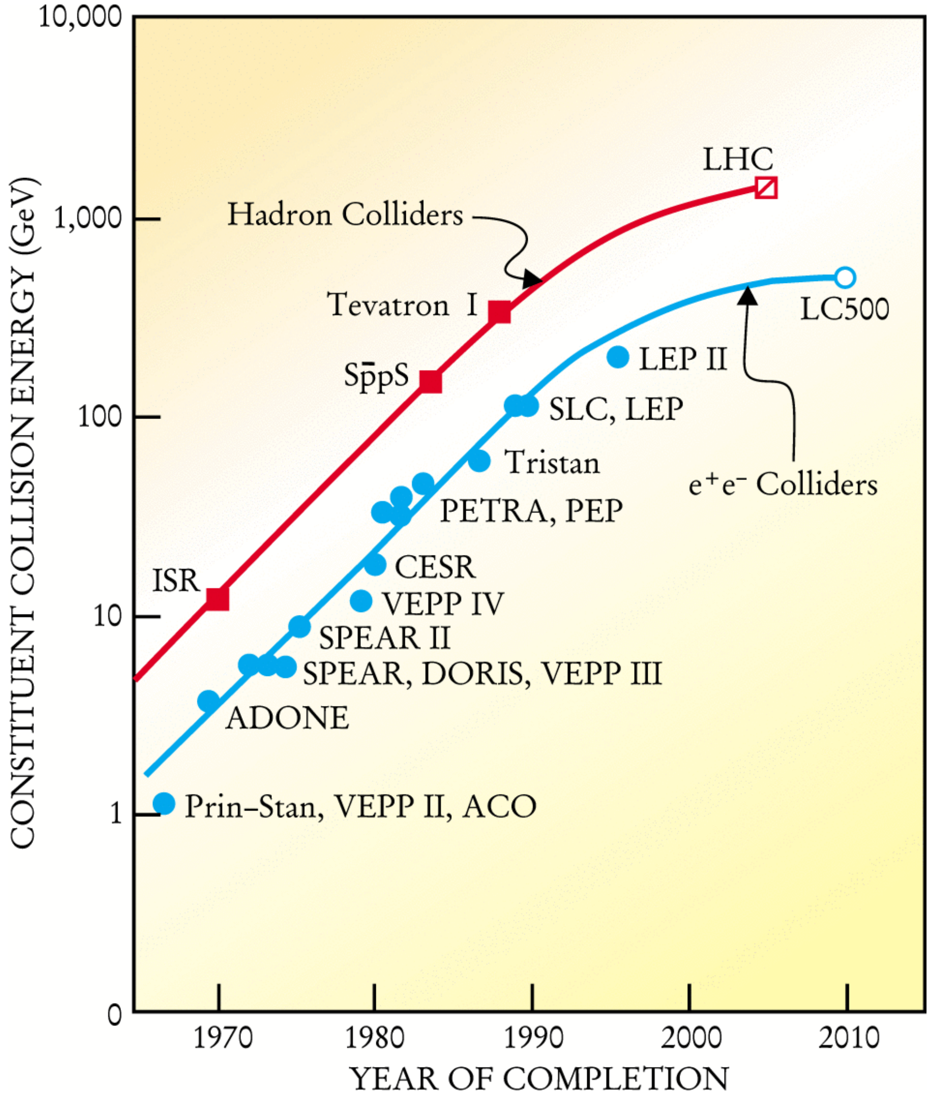


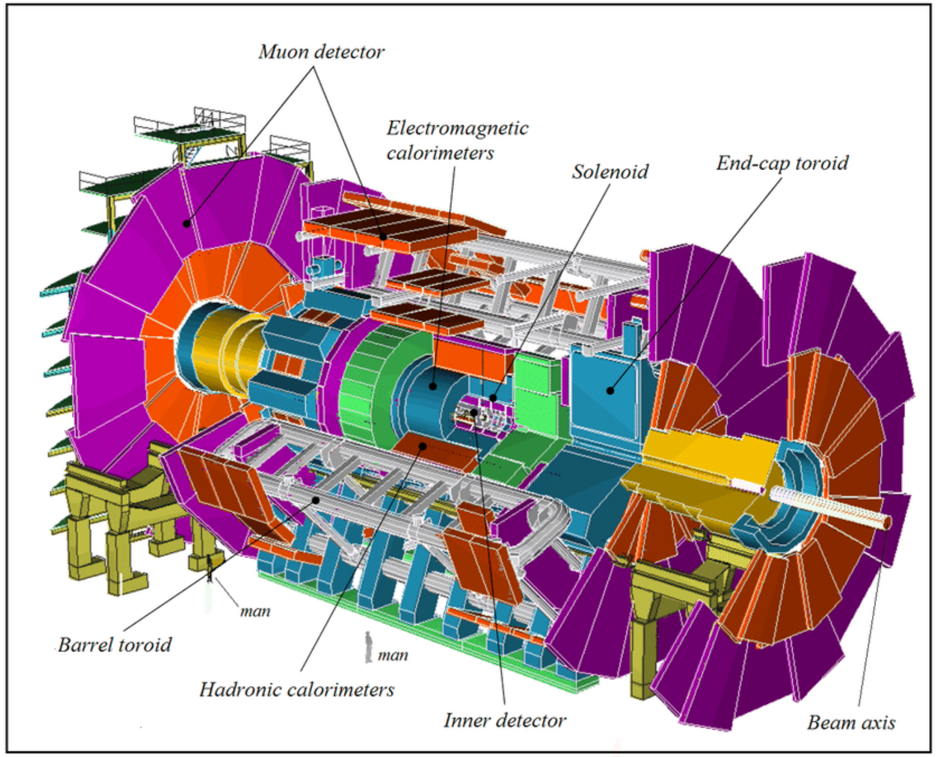


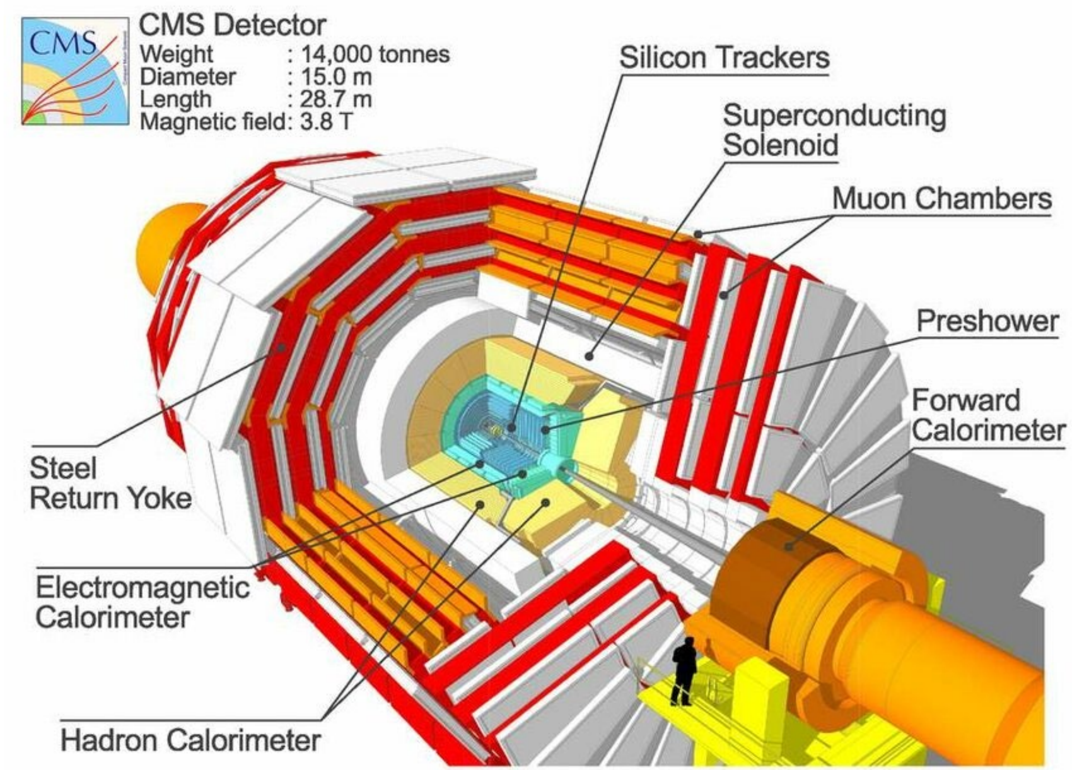


Accelerators

- 1950: Cosmotron 1 GeV
- 1955: Bevatron 6 GeV
- 1959-60: AGS/PS 33/28 GeV
- 1967: SLAC Linac 18 GeV
- 1972: Fermilab/SPS 400 GeV
- 1974: SPEAR 3-4 GeV
- 1979: PEP/PETRA 15 GeV
- 1980: SppS 540 GeV
- 1985: Tevatron 1.8 TeV
- 1989 LEP (90, 160 GeV)
- 2008: LHC 14 TeV
- 2029: HL-LHC same
- 2045: ILC/FCCee 90-240 GeV
- 2070: FCChh/μCollider 10 TeV







- ATLAS(left): Optimized for higher mass Higgs: precision silicon tracking, solenoid, LAr EM calorimeter, Fe/Scintillator hadron calorimeter, air core superconducting toroidal muon spectrometer
- CMS (right): Optimized for lower mass Higgs: precision silicon tracking, crystal EM calorimeter, hadron calorimeter, all inside the solenoid, muon tracked in iron return yoke