Detectors for Measurement of Charged Particles in High Energy/Nuclear Physics

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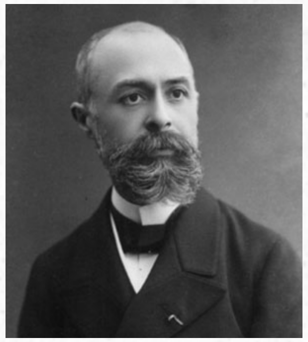
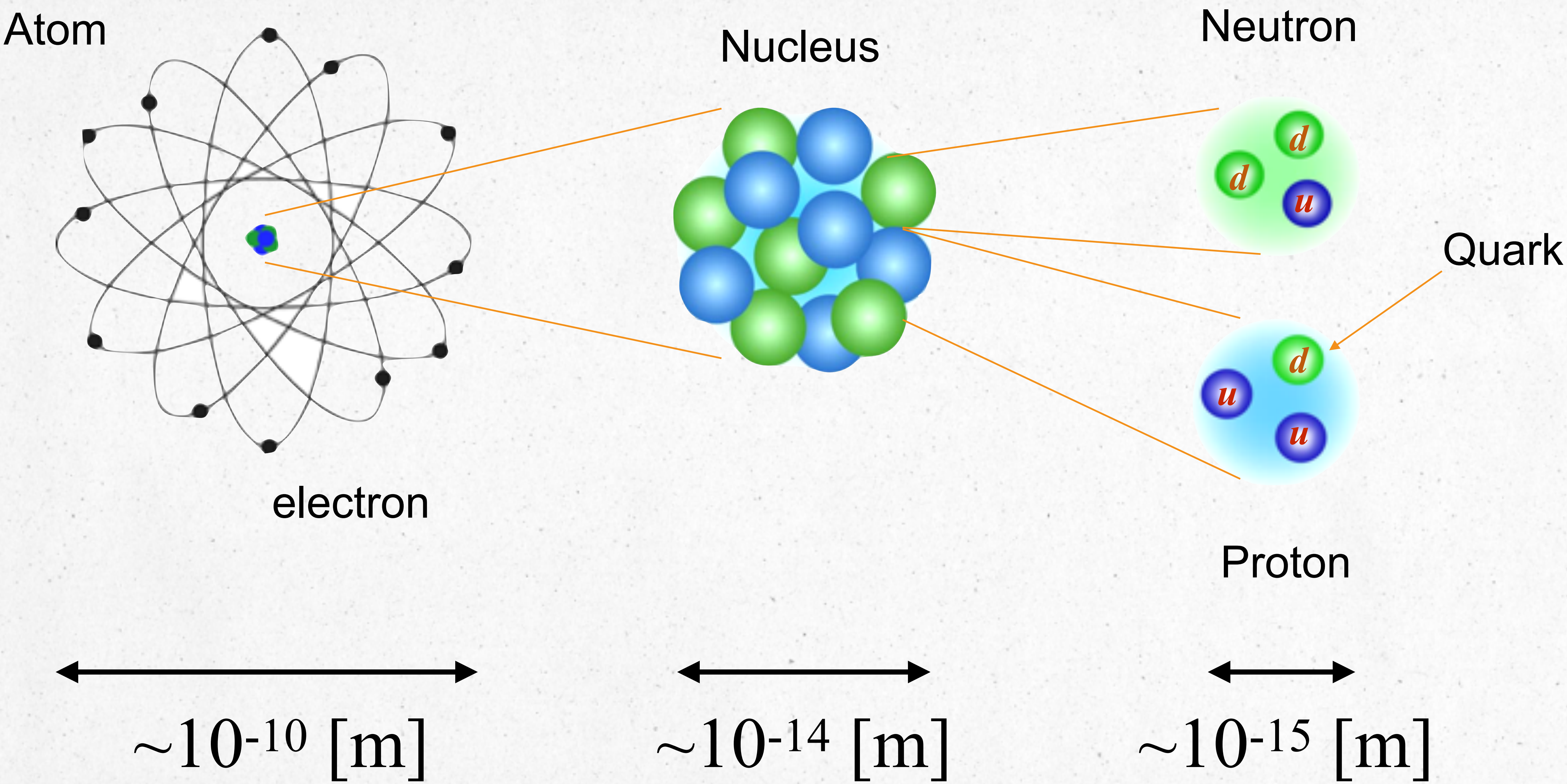
Radiation and Nuclear Physics

- History
  - Discovery of radiation and radioactive material
    - Wilhelm Conrad Röntgen
    - Antoine Henri Becquerel
    - Maria Salomea Skłodowska-Curie (Marie Curie)
    - Pierre Curie
  - Hierarchy of material is recognized
    - Atom
    - Nucleus and electron
      - Stable and unstable nucleus
    - proton and neutron
    - quark and lepton



Photos: wikimedia commons

Atom, Nucleus, Elementally Particle



Radiation

Charged particle

- α-ray
  - ^{4}He nucleus
- β-ray
  - electron and positron (anti-particle of electron)
- X-ray, γ-ray
  - high-energy electromagnetic radiation
    - X-ray: from transition of electron between different orbits
    - γ-ray: from nucleus
- neutron
  - nucleus consists from proton and neutron

Particle Physics

- Elementally particle physics and nuclear physics
  - Physicist wants to know phenomena of nature
  - Physics in small size
    - for example, how to probe inside of atom
    - Discovery of electron (J.J. Thomson)
      - Atom is NOT elementally particle
      - Existence of nucleus (positive charged particle)
      - What is structure of atom?

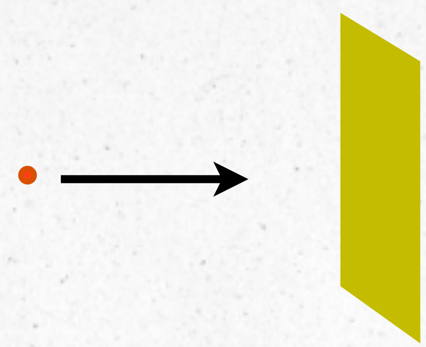
Models of Atom Structure

In 1904, J.J. Thomson's model
Plam pudding model :
+/- particles are distributed evenly

Photo: Wikimedia commons

In 1903, Hantarou Nagaoka
Saturn-like model:
+ particle is solidified in the center
and electrons are turning around

Rutherford scattering

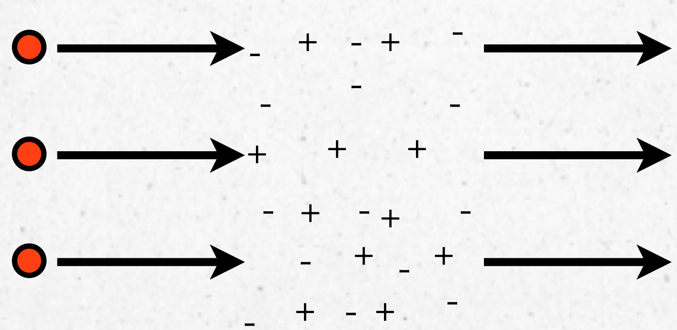


Hits α-ray (^{4}He nucleus) to a thin gold film

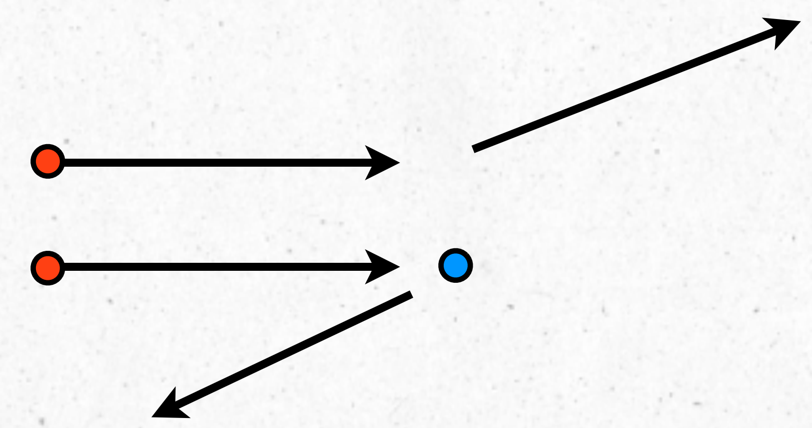
In 1911, Ernest Rutherfod's Lab group
Assistant, Johannes Wilhelm Geiger
Students: Ernest Marsden

Plam Pudding Model

α-ray pass thorough the film



Saturn-like Model



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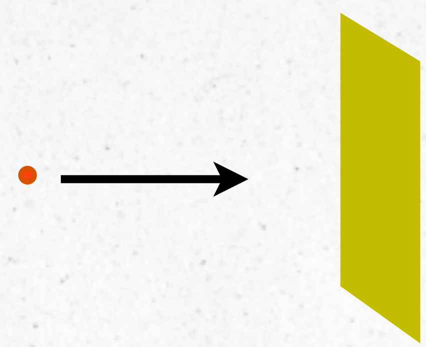

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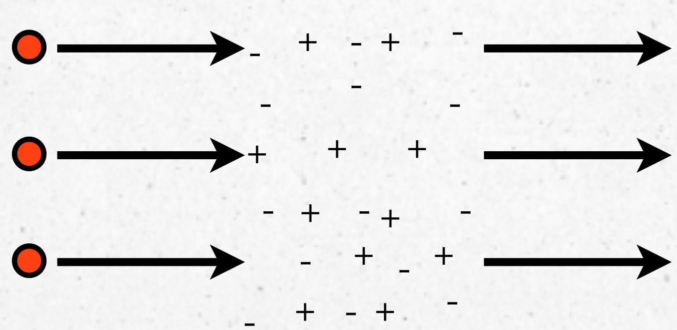
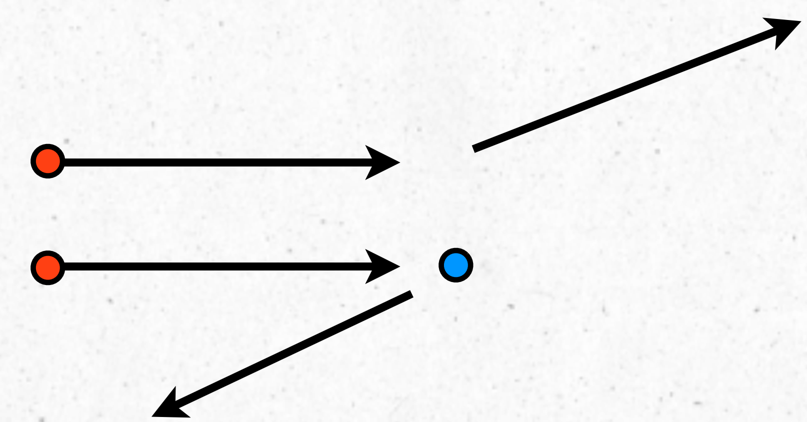


Experiment support this result

Saturn-like Model



To Know Structures in Small World

- Collide elementary particle or nucleus to a target
  - Particle beam and fixed target
  - Collider
- After collision
  - Scattering of particles
  - Emission from inside of target particle
  - Particles newly created
- Detectors to measure and identify
  - Momentum (mass × velocity)
  - Velocity (Time of flight and flight length)
  - Particle species

Units

- In field of elementals particle/Nuclear physics
  - Energy: eV (electron volt)
    - 1 [eV] = 1.6×10^{-19} [J]
  - Length: fm (femto meter)
    - 1 [fm] = 10^{-15} [m] = 10^{-13} [cm]
  - Cross section: b (barn)
    - 1 [barm] = 100 [fm^2] = 10^{-28} [m^2]

- Example
  - Proton
    - mass: 0.938 GeV/c^2, electrical radius ~0.9 fm
      - E= mc^2, c: light velocity
  - Electron
    - mass: 0.511 MeV/c^2 (~ 1/1836 of proton mass)

Measurement Principle of Charged Particles

Passage of Particles Through Matter

- Charged particle
  - Energy loss with electrons in matter
  - Bremsstrahlung radiation
  - Synchrotron radiation
  - Cherenkov radiation
  - Knock-on election (δ-ray)
- X-ray, γ-ray
  - Photoelectric effect
  - Compton scattering
  - Pair production of electron and positron
- Neutron
  - Interaction with nucleus and emission of proton or γ-ray

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Charged Particles

- Nucleus
- Nucleon: component t of nucleus
  - proton (positive charge) and neutron (neutral)
  - Family of Hadrons
- Hadron
  - Particle consisted of quarks
  - Meson (quark and anti-quark)
  - Baryon (three quarks)
- Electron, muon, and tau

Table of elementary particles

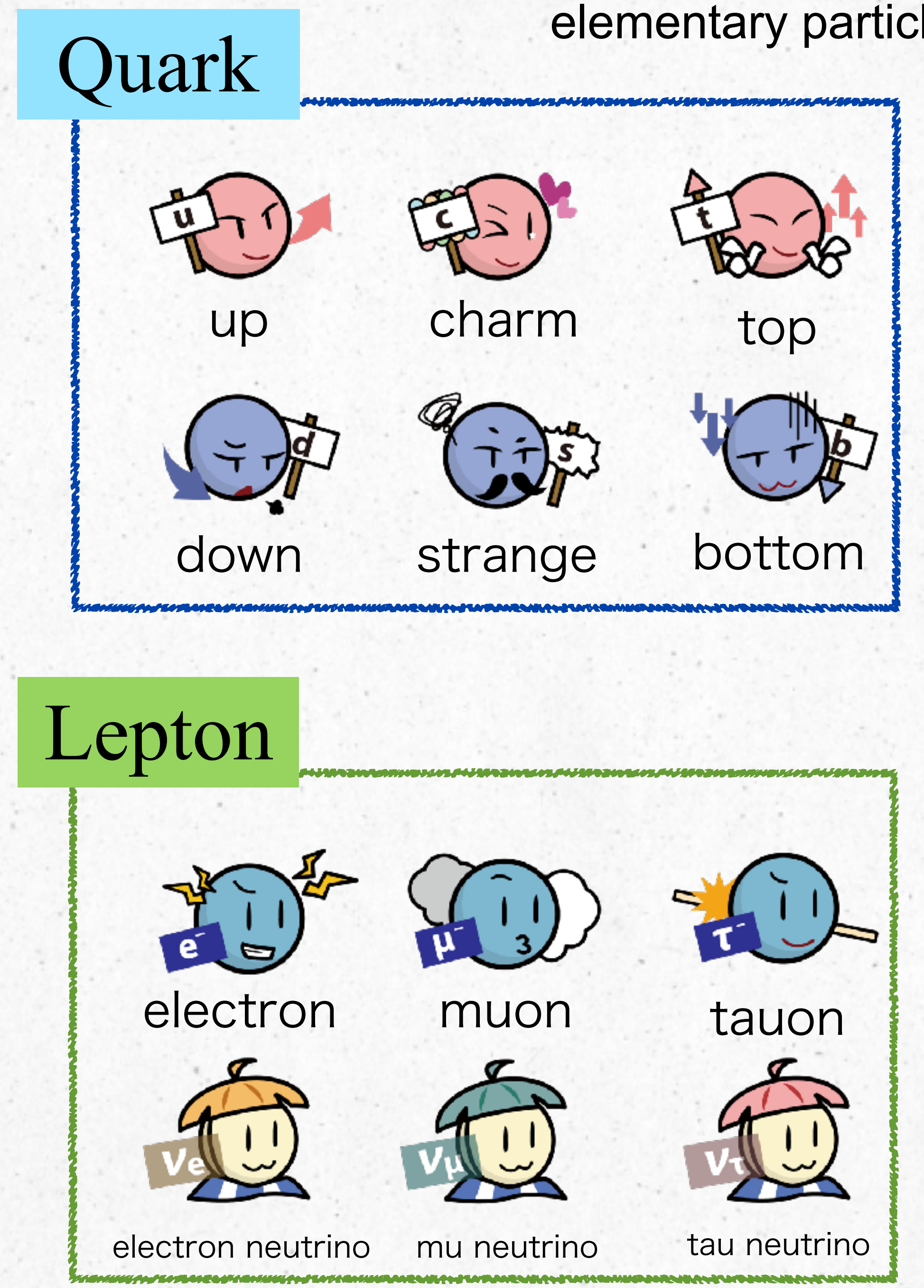

Illustration: Yuki Akimoto, https://higgstan.com/

Interaction of Charged Particle with Matter

- Several processes
  - Energy dependences

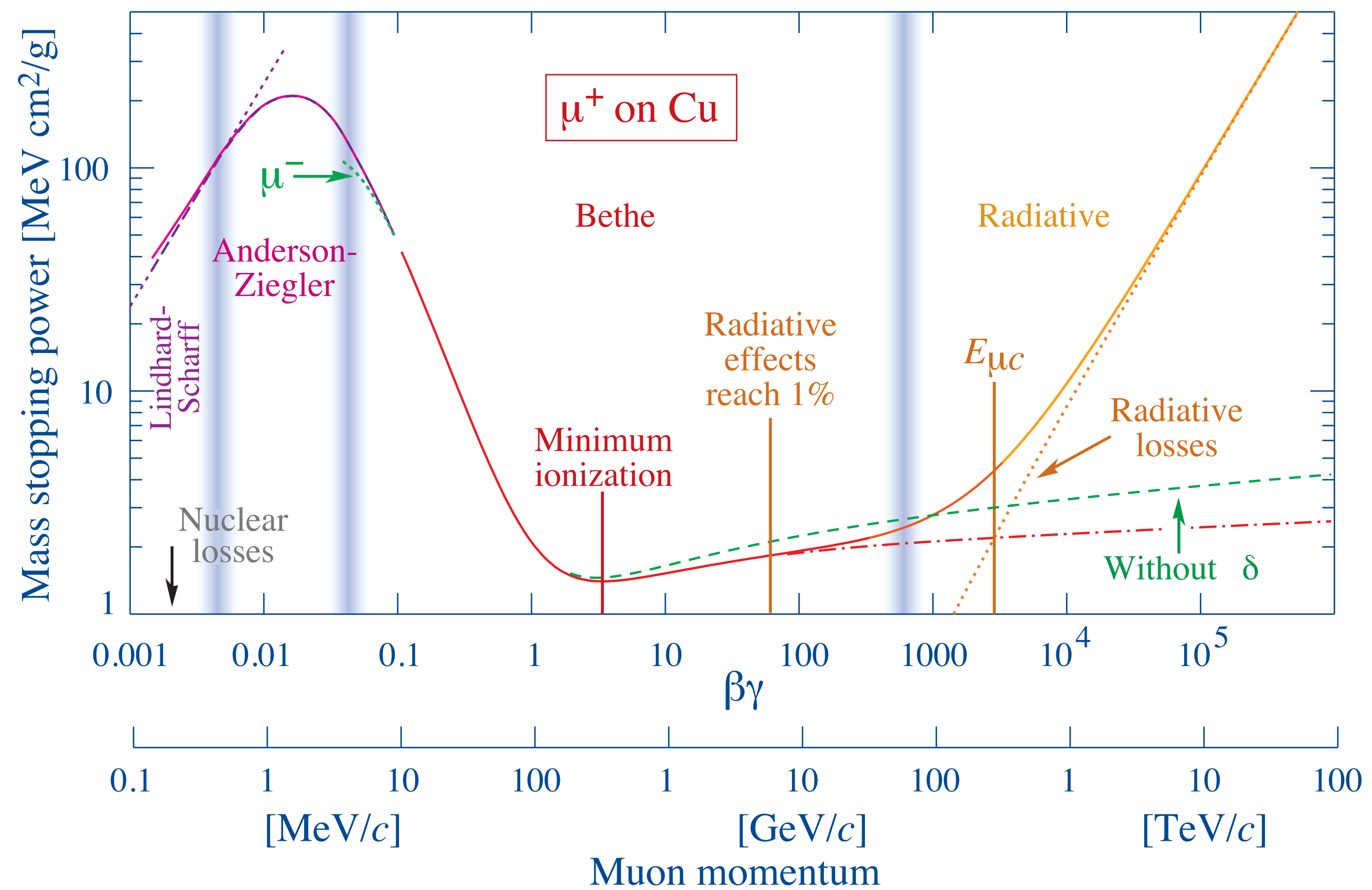

Fig. 33.1: Mass stopping power ($= \langle -dE/dx \rangle$) for positive muons in copper as a function of $\beta\gamma = p/Mc$ over nine orders of magnitude in momentum (12 orders of magnitude in kinetic energy). Solid curves indicate the total stopping power. Data below the break at $\beta\gamma \approx 0.1$ are taken from ICRU 49 [4], and data at higher energies are from Ref. 5. Vertical bands indicate boundaries between different approximations discussed in the text. The short dotted lines labeled "μ^-" illustrate the "Barkas effect," the dependence of stopping power on projectile charge at very low energies [6]. dE/dx in the radiative region is not simply a function of β.

Ref.: M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018).
available on the PDG WWW page (http://pdg.lbl.gov)

Energy Loss

- When the charged particles pass through the matter, its energy loses gradually by ionizing electrons
  - Bethe-Bloch equation

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

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Capital characters: parameters related Matter
lower characters: related incident particle

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Energy Loss

Calculation from the equation

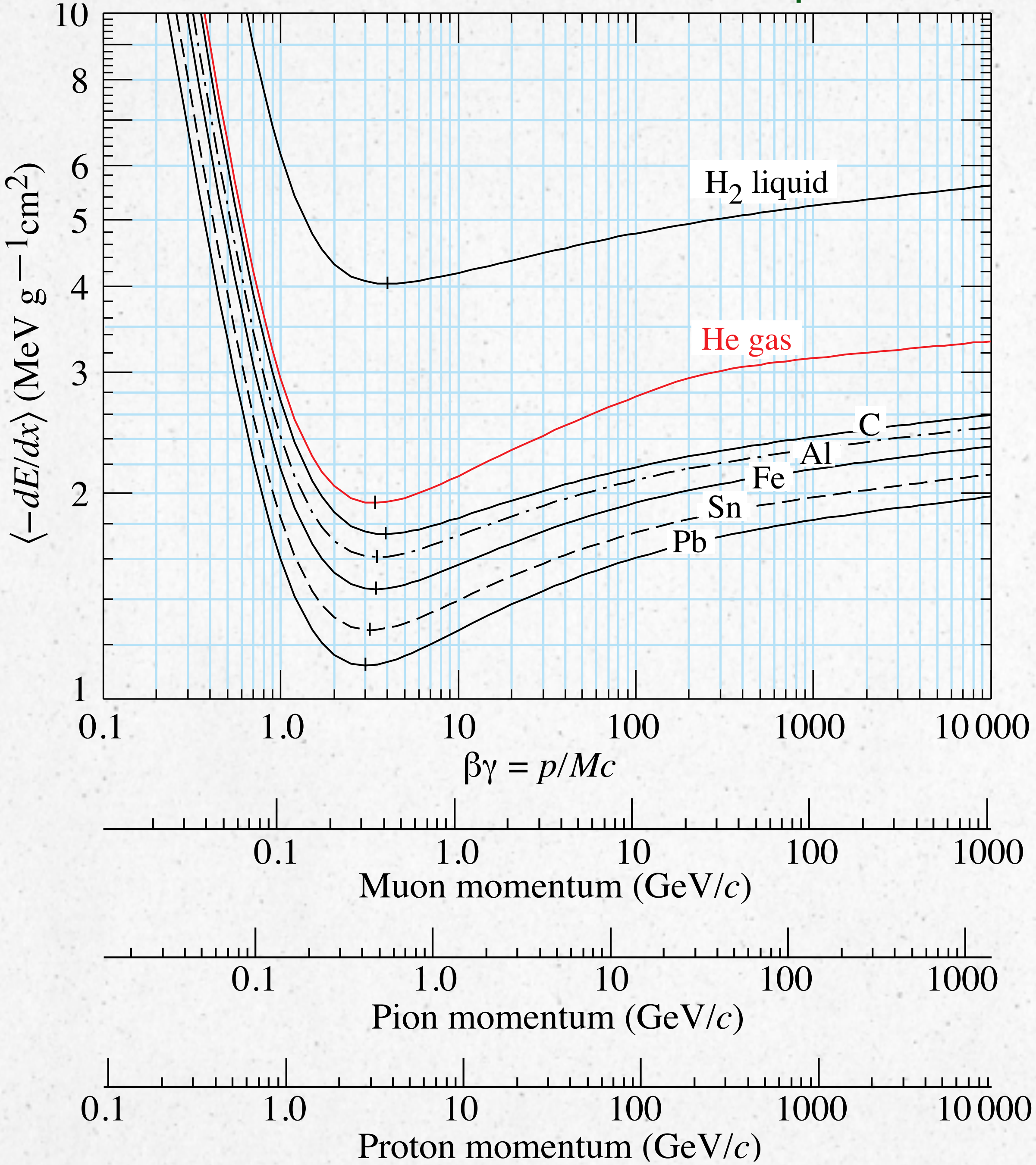

Figure 33.2: Mean energy loss rate in liquid (bubble chamber) hydrogen, gaseous helium, carbon, aluminum, iron, tin, and lead. Radiative effects, relevant for muons and pions, are not included. These become significant for muons in iron for $\beta\gamma \gtrsim 1000$, and at lower momenta for muons in higher-Z absorbers. See Fig. 33.23.

Measurement results of an experiment

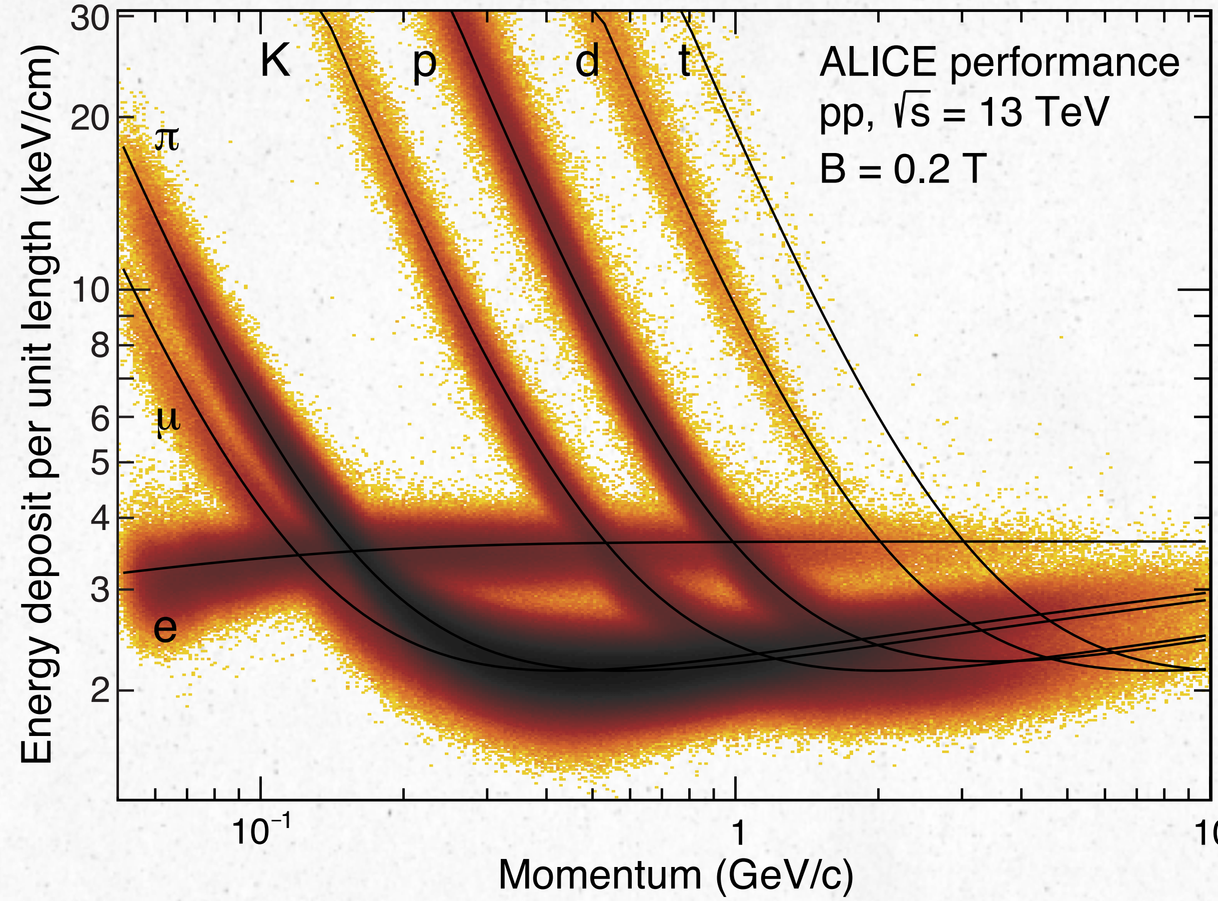

Figure 34.15: Energy deposit versus momentum measured in the ALICE TPC [111].

Ref.: M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018).
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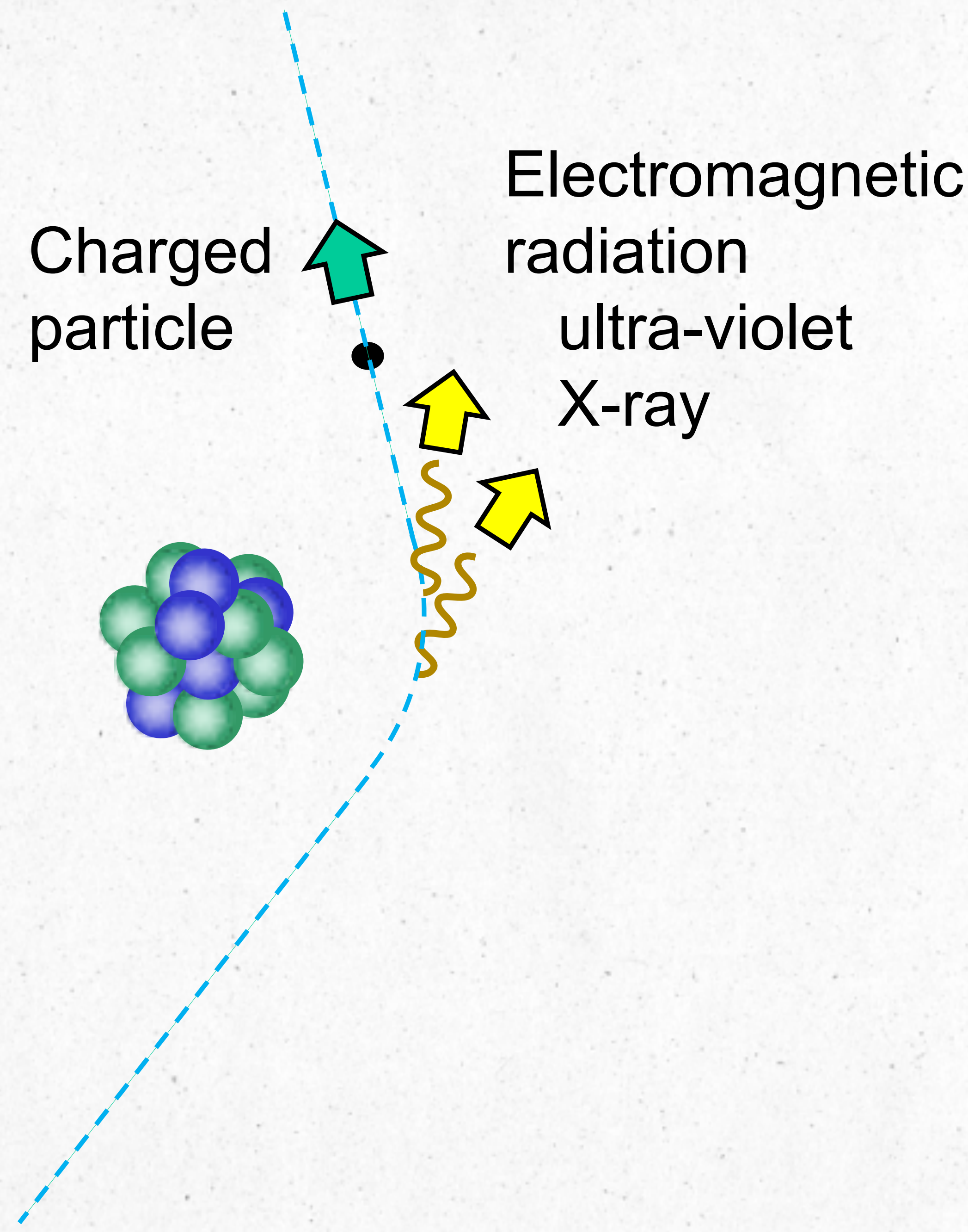
Bremsstrahlung Radiation

- Charged particle is bended by acceleration/ deceleration from strong electro-magnetic field by nucleus
- Charged particle emits part of the energy as electromagnetic waves



Bremsstrahlung Radiation

- Dominant process for e^+/e^- (in E> ~ 10 MeV)
- One of processes in Electro-Magnetic shower

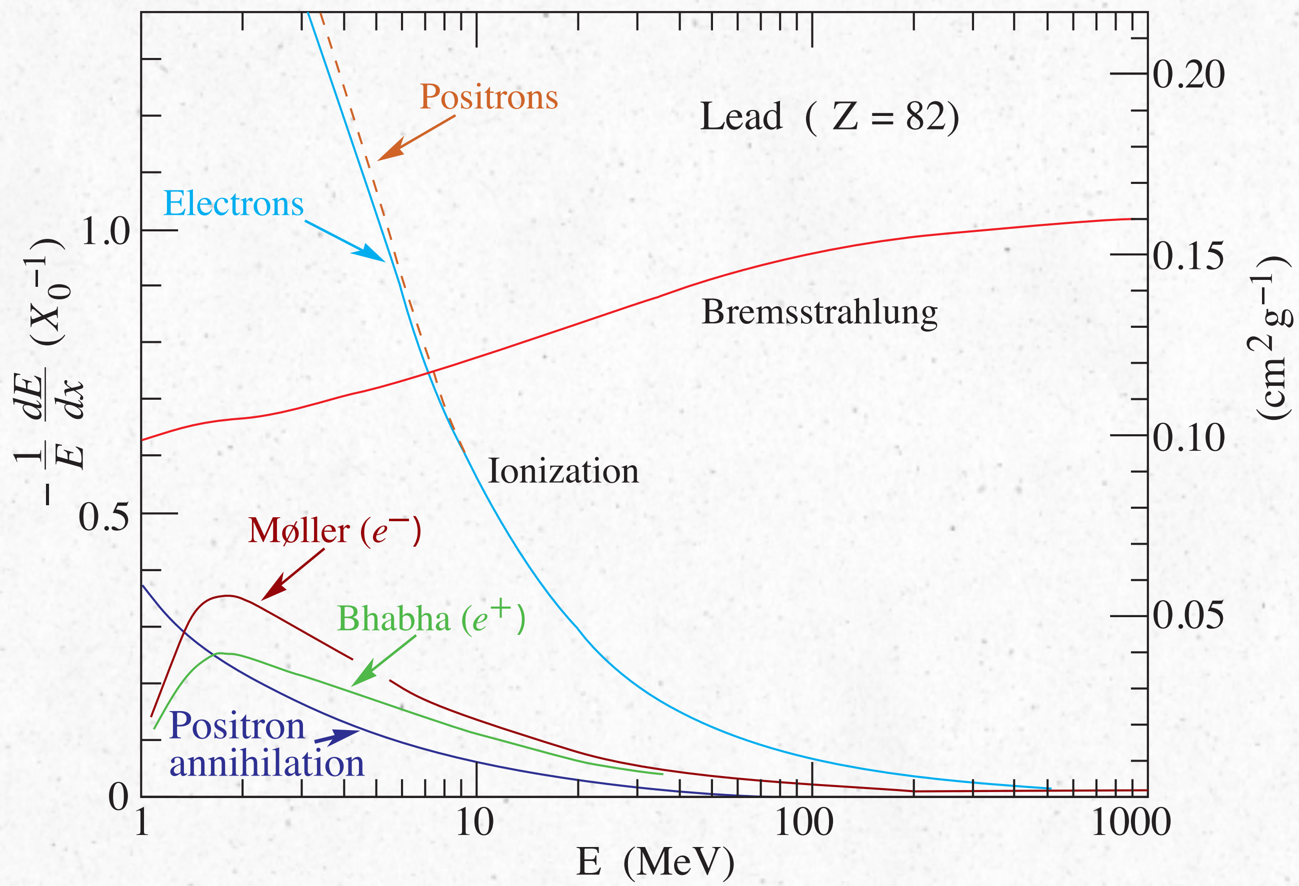


Figure 33.11: Fractional energy loss per radiation length in lead as a function of electron or positron energy. Electron (positron) scattering is considered as ionization when the energy loss per collision is below 0.255 MeV, and as Møller (Bhabha) scattering when it is above. Adapted from Fig. 3.2 from Messel and Crawford, *Electron-Photon Shower Distribution Function Tables for Lead, Copper, and Air Absorbers*, Pergamon Press, 1970. Messel and Crawford use $X_0(\mathrm{Pb}) = 5.82$ g/cm^2, but we have modified the figures to reflect the value given in the Table of Atomic and Nuclear Properties of Materials ($X_0(\mathrm{Pb}) = 6.37$ g/cm^2).

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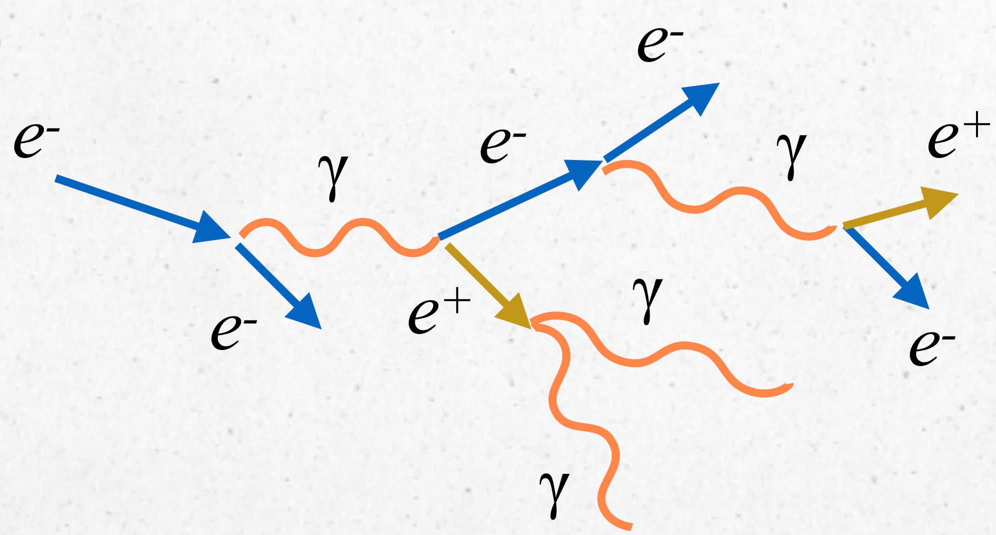

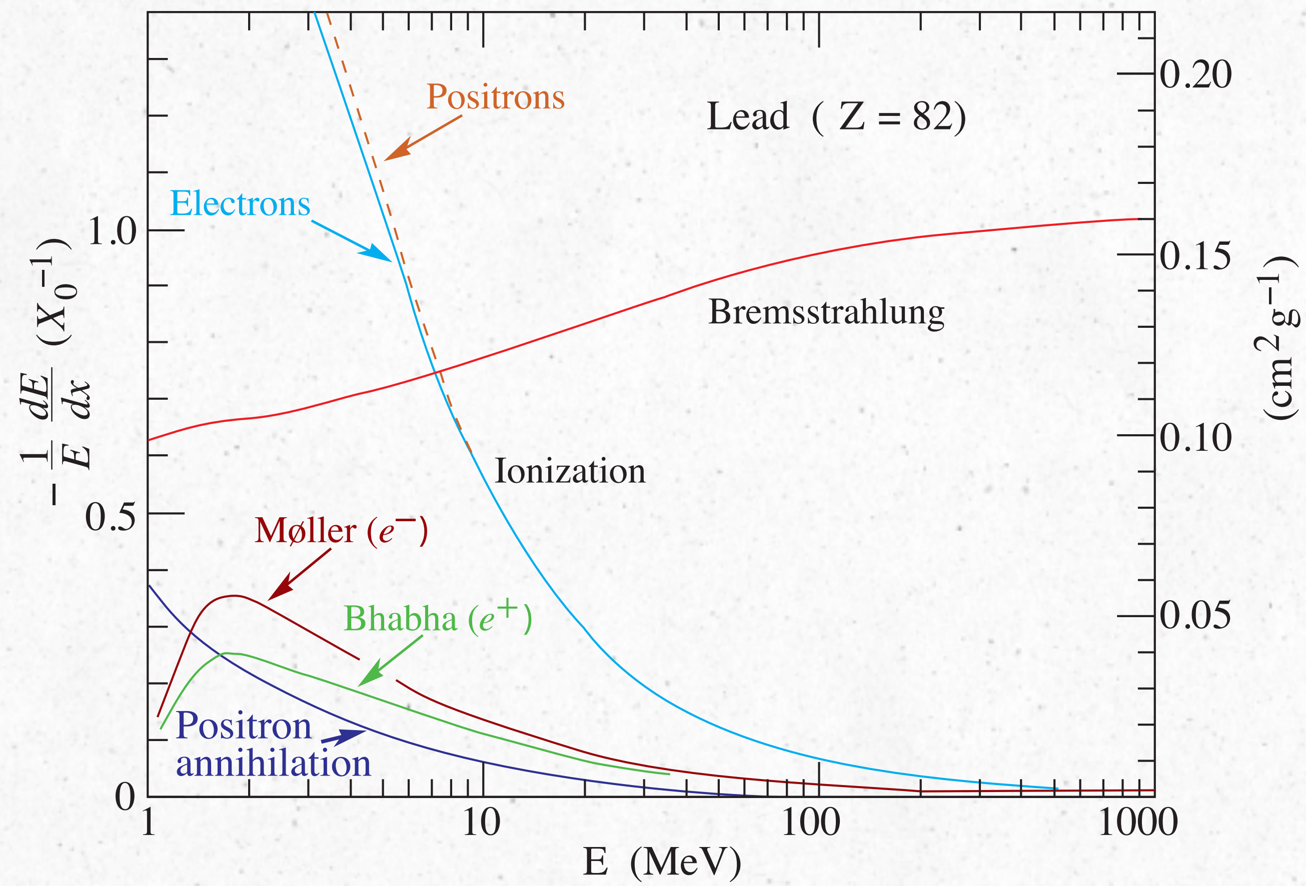

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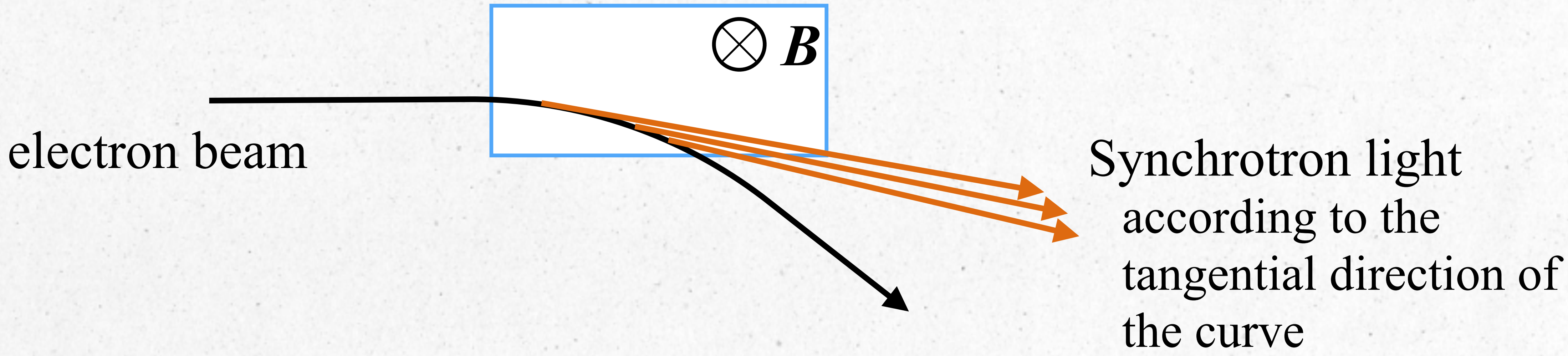
Synchrotron Radiation

- Light was observed from the electron's orbital plane on bending the electron by magnetic field
- As with bremsstrahlung, electromagnetic waves are generated by bending charged particles in a magnetic field
- Infrared light to X-rays
  - Tool to know material structure



Light Source Facilities

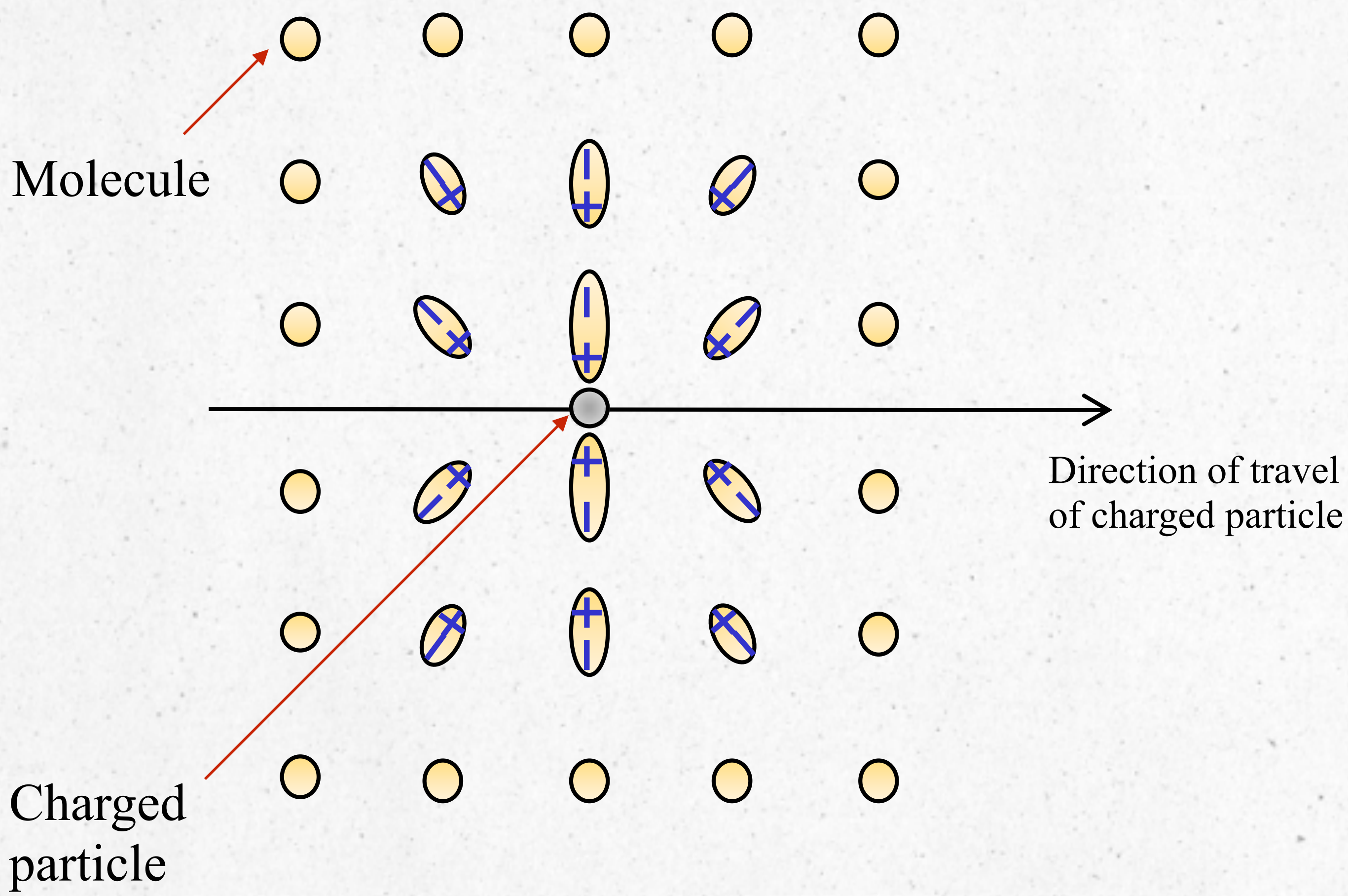
Figure: Journal of Electron Spectroscopy and Related Phenomena 196 (2014) 3–13

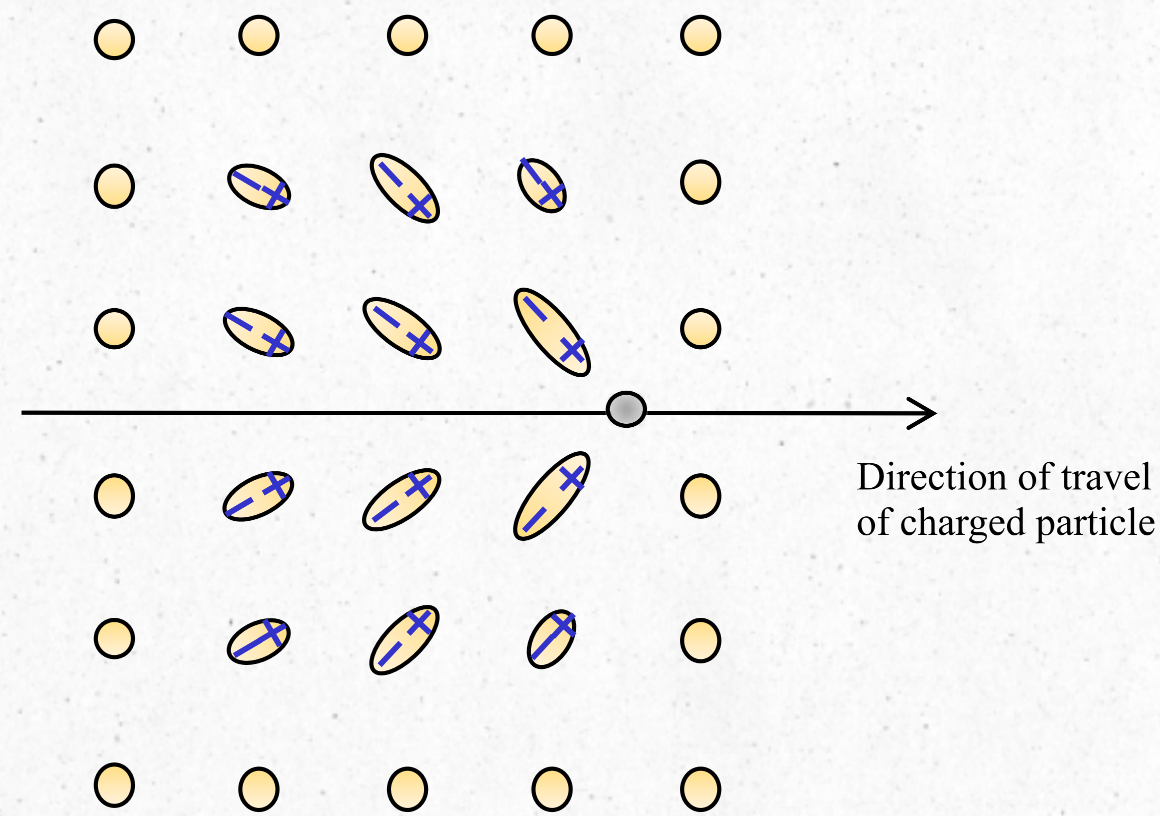
Cherenkov Radiation

- Radiation of particle of which speed is faster than light velocity in a material
  - Velocity of light: c/n
    - c: Speed of light in vacuum
    - n: Refractive index of material
- Discovered by Pavel A. Cherenkov in 1934
  - 1958 Nobel Prize in Physics

Cherenkov Radiation

- Polarization by Coulomb force of charged particle

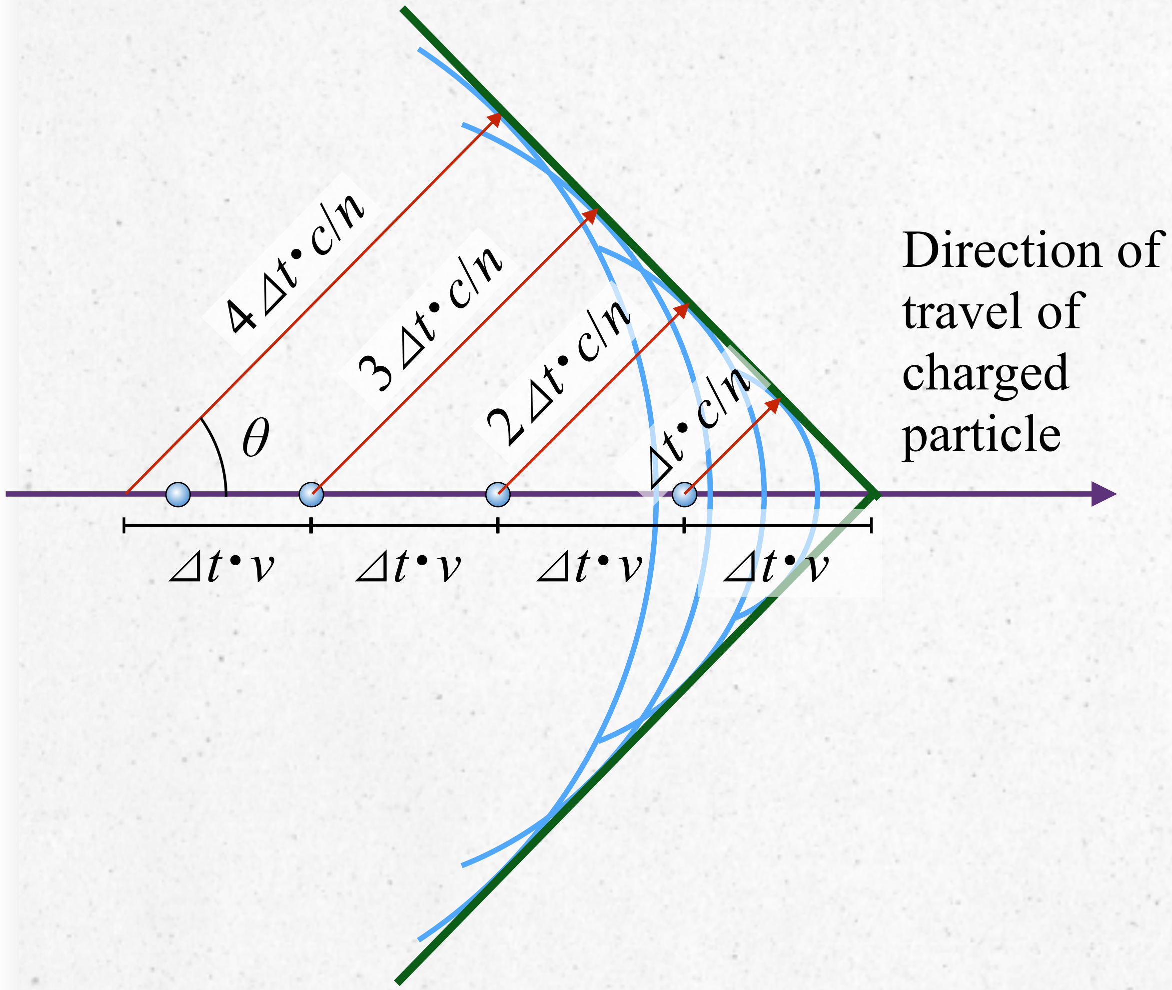




- Symmetric polarization by slow particles
- Even if unpolarized, no emission of electromagnetic wave

- Asymmetric polarization by fast particles
- When the morecules are unpolarized, electromagnetic wave is emitted to the outside.

Cherenkov Radiation



- Spherical electromagnetic wave
  - From each point after unpolarized
- Superimposed wave: Plain
  - Huygens' principle
  - Emitted at an angle of θ with respect to the traveling direction

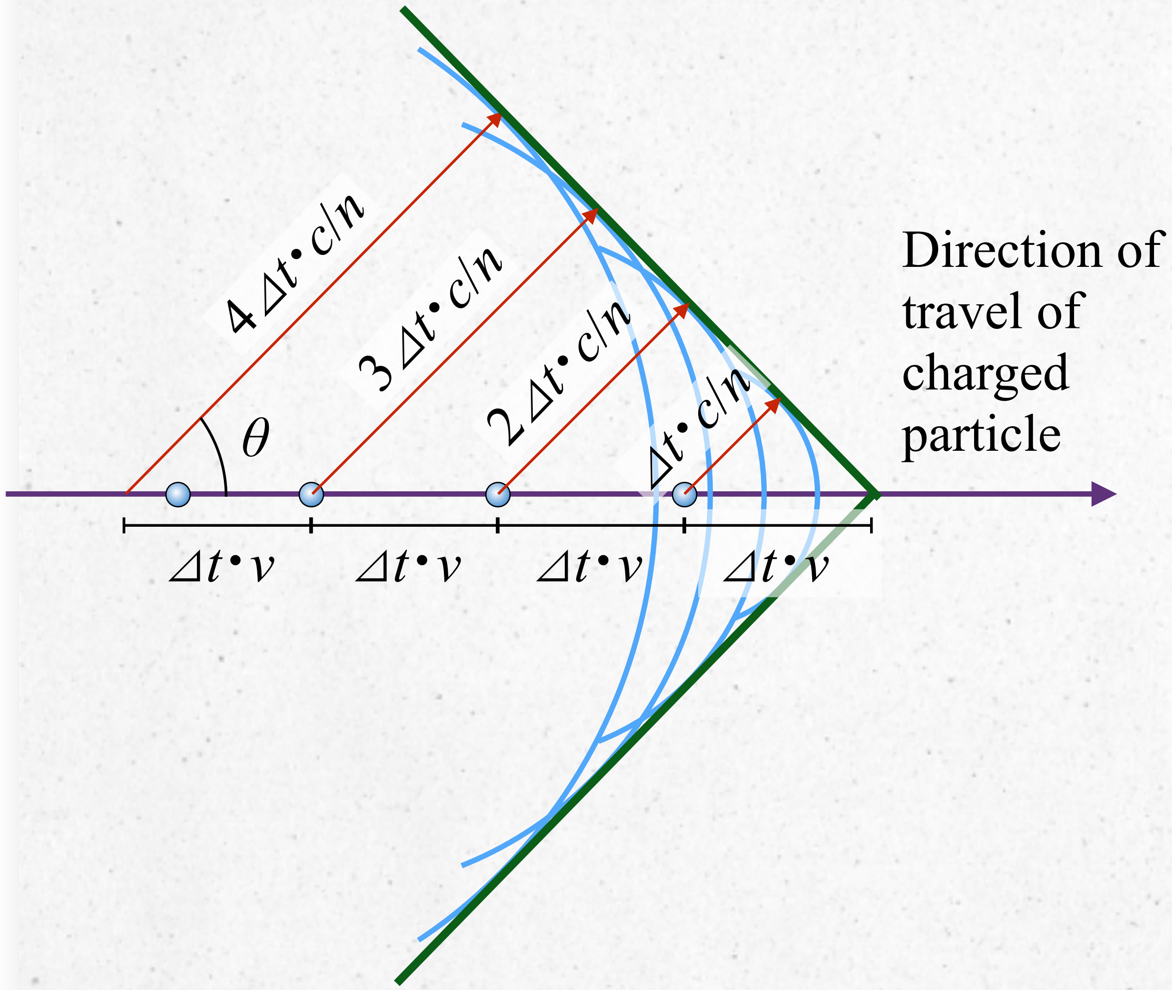
$$\cos\theta = \frac{\Delta t\,(c/n)}{\Delta t\,v} = \frac{1}{nv/c} = \frac{1}{n\beta}$$

- Condition of Cherenkov radiation

$$n\beta \geqq 1 \quad \Rightarrow \quad \beta \geqq 1/n$$

- For same momentum
  - β is differ with mass
  - Cherenkov light is emitted or not emitted
  - angle θ is different from particle mass

Cherenkov Radiation



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Particle identification {
  - Cherenkov light is emitted or not emitted
  - angle θ is different from particle mass

Detectors for Charged Particle Measurement

Signales in Detector

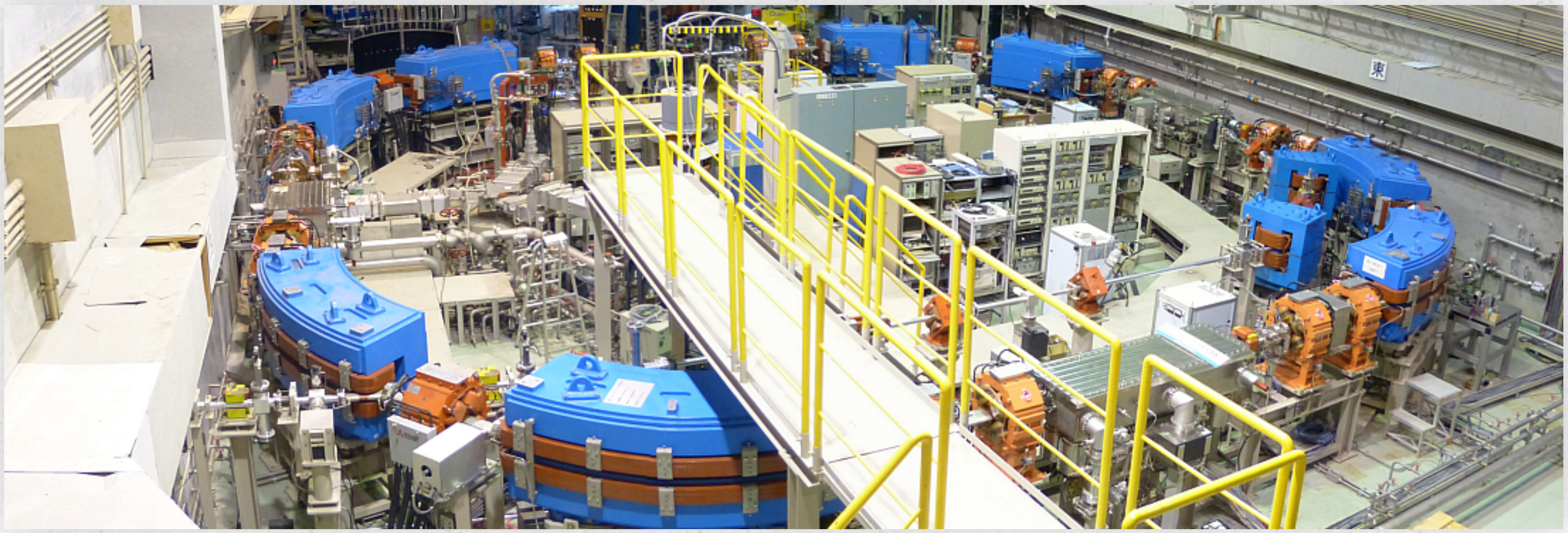
- Charged particle makes a signal by interaction with material
  - Ionization
    - Gas (electron and ion pair)
    - Semiconductor (electron and hole)

    } Electrical signal
  - Scintillation
    - Electron in material is excited by Coulomb force
    - Visible light / Ultraviolet emission with de-excitation

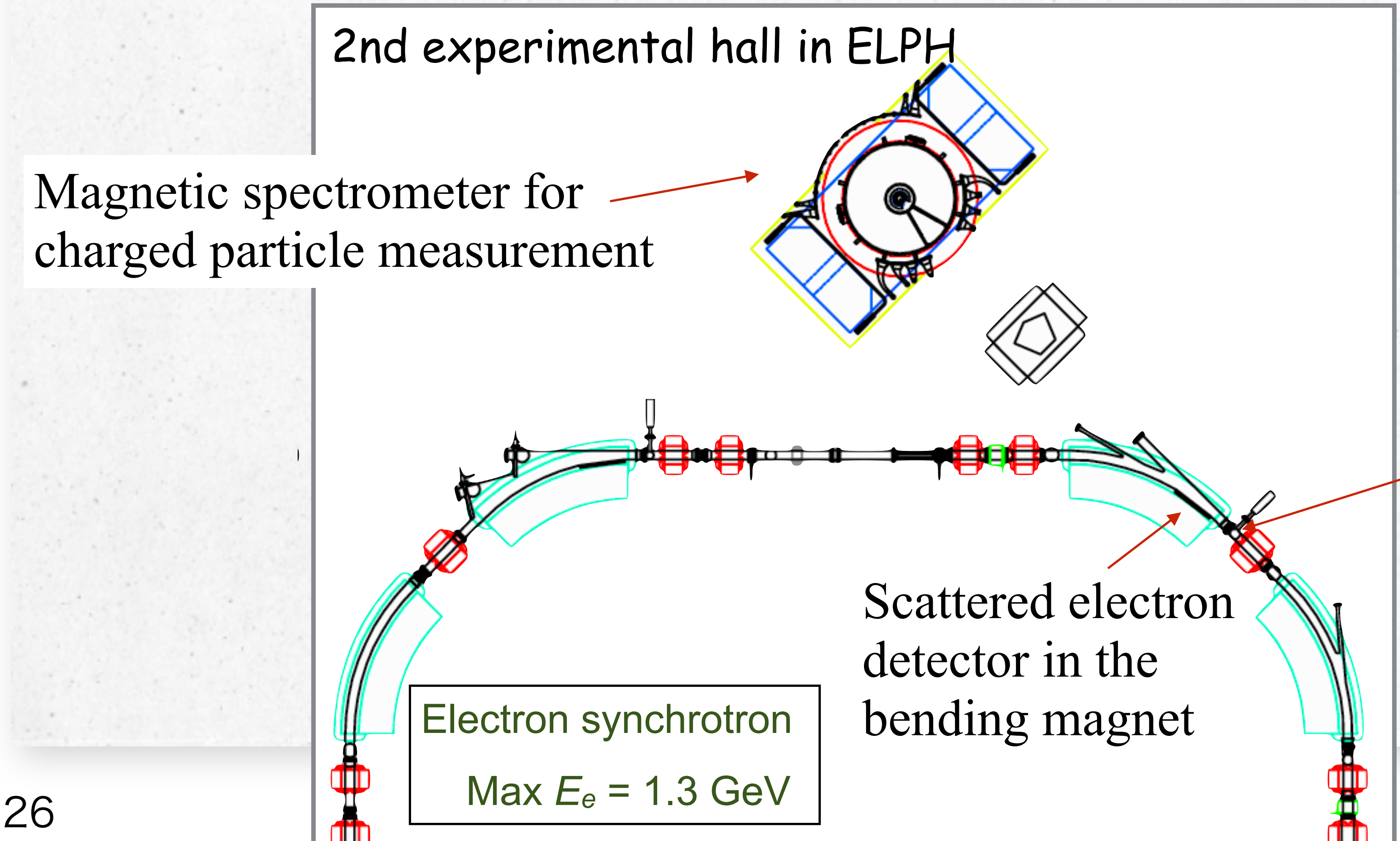
    } Photon
  - Cherenkov light

- Detectors to measure and identify
  - Momentum (mass × velocity)
  - Velocity (Time of flight and flight length)
  - Particle species

Example: NKS2 Experiment at ELPH in Tohoku Univ.

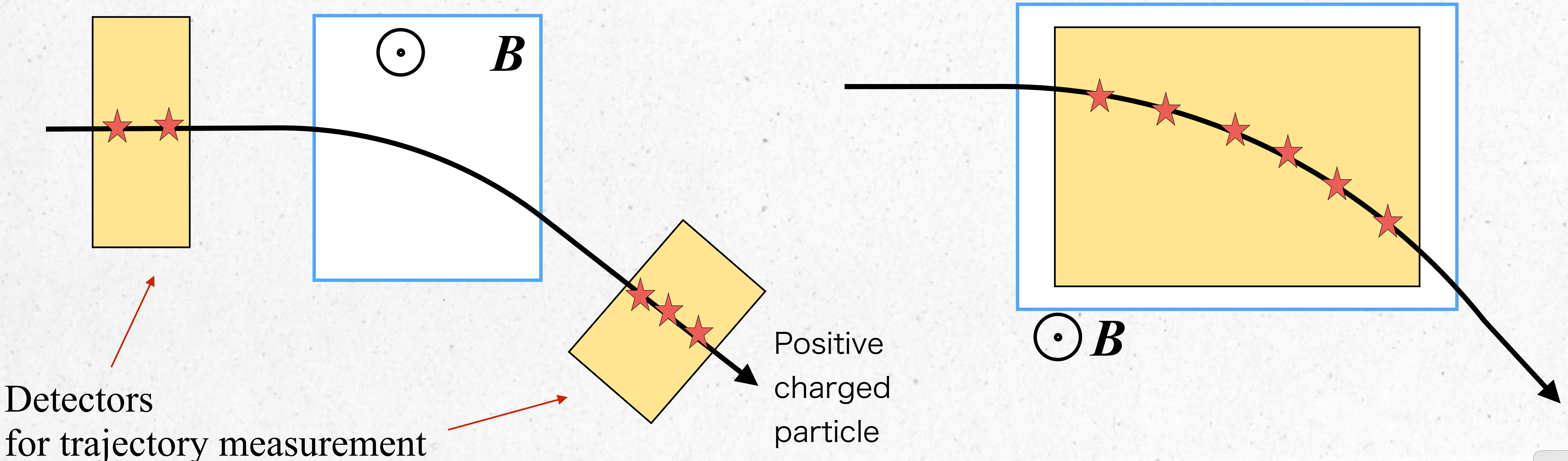


NKS2 experiment:
Measurement of hadron production by γ+p / γ+n reaction

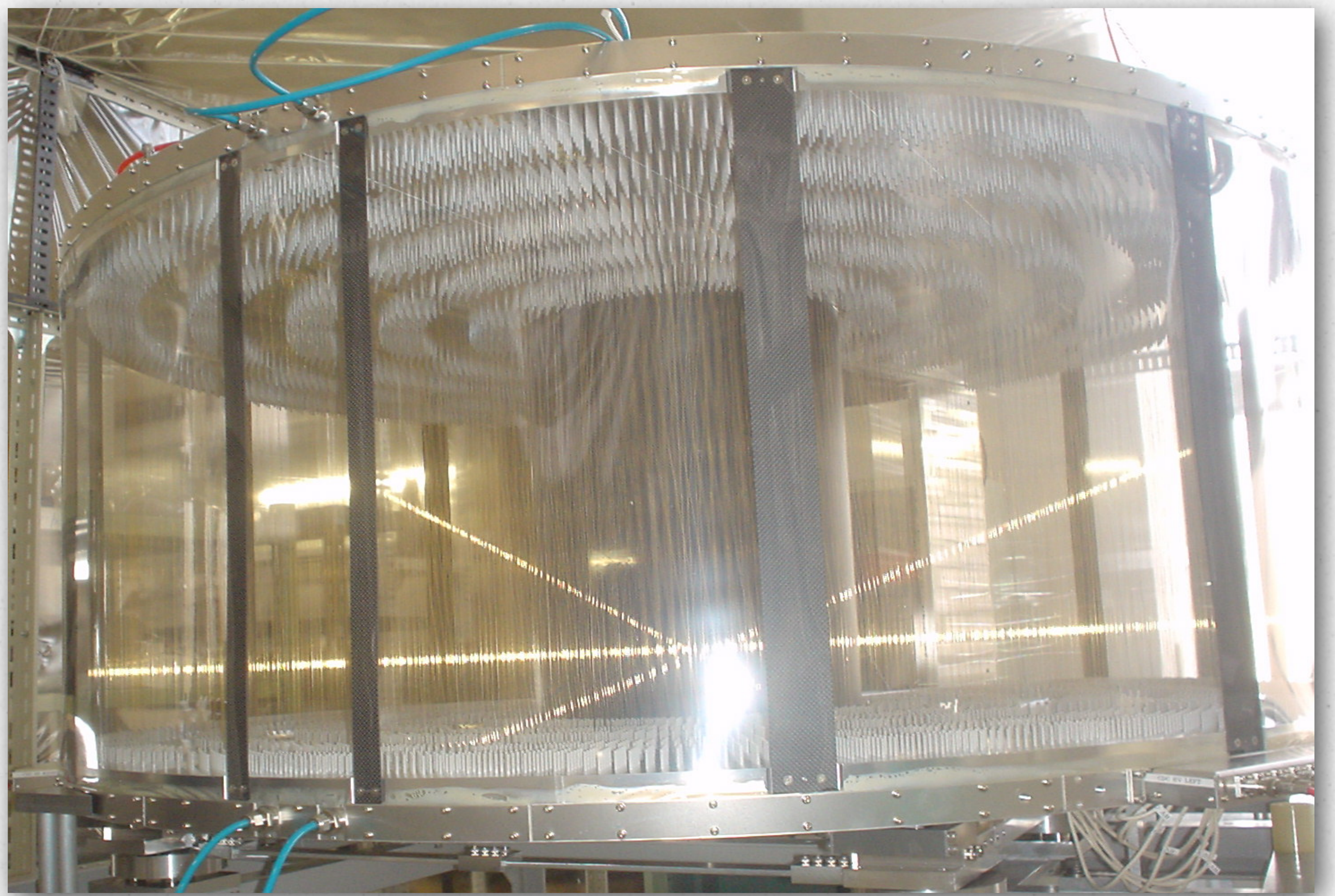


Momentum

- Momentum can be estimated from trajectory in magnetic field
  - Lorentz force: $\boldsymbol{F} = q\boldsymbol{v}\times\boldsymbol{B}$
  - Equation of motion of circle: $\boldsymbol{F} = m\boldsymbol{a} = mv^2/r$
  - $\rho = mv_t/qB = p_t/qB$
    - ρ: radius of bending curve
    - v_t, p_t: transverse component of velocity and momentum
- Trajectory reconstructed from hits in detector(s)
  - Si semiconductor detector, drift chamber, and etc.
  - Typical position resolution: several 10 μm to a few 100 μm



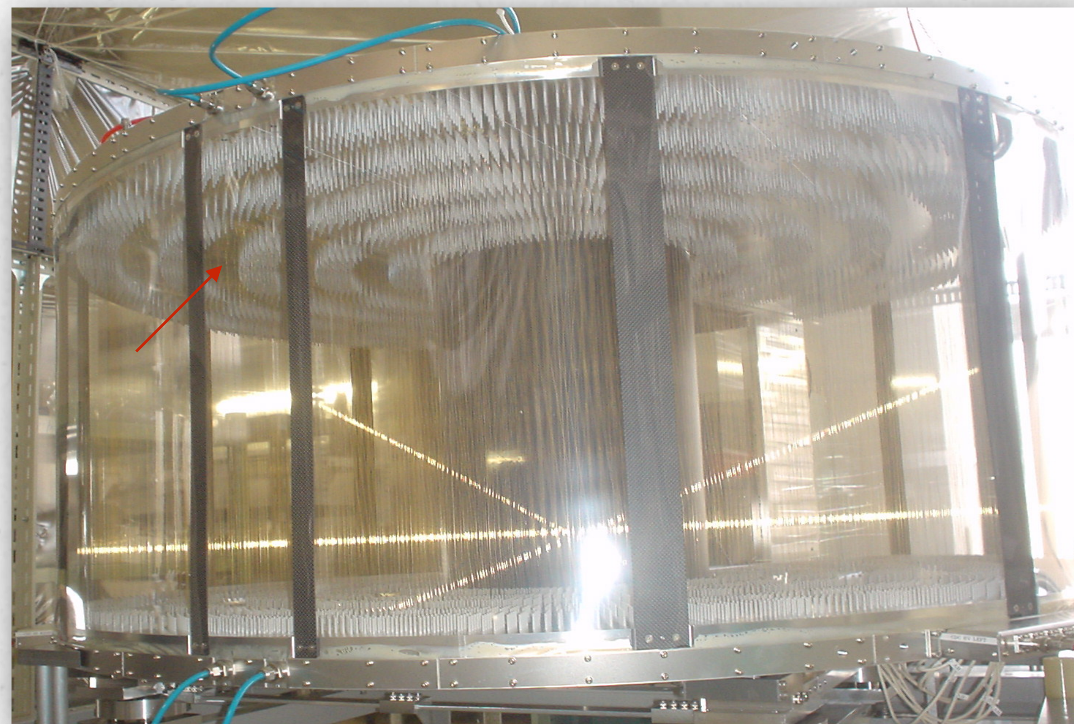
Drift Chamber of NKS2

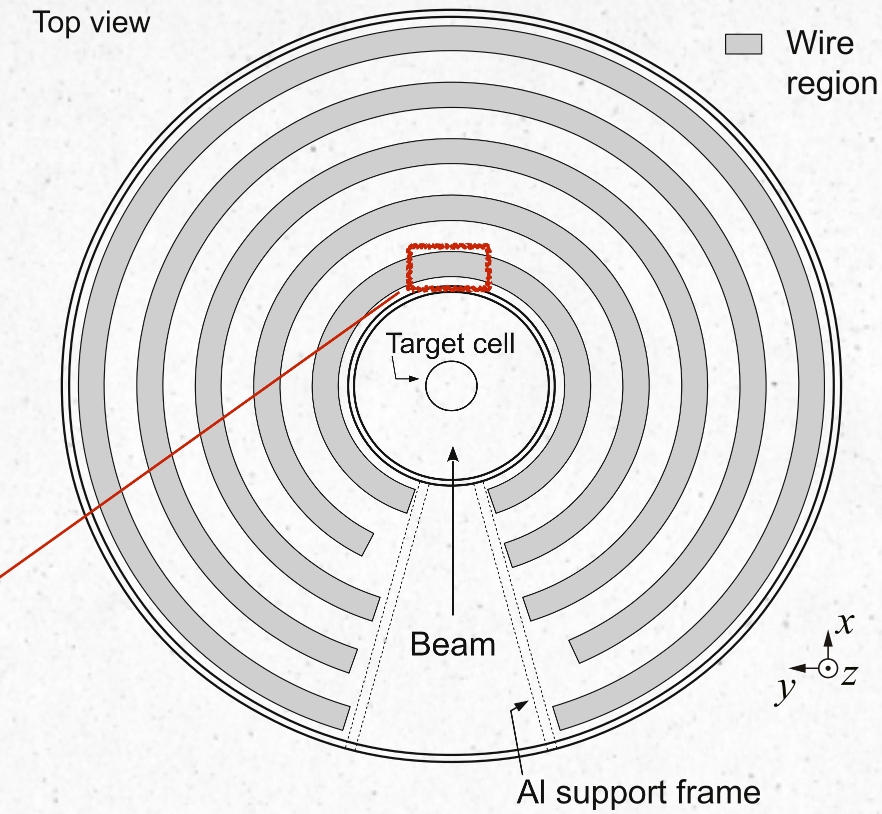


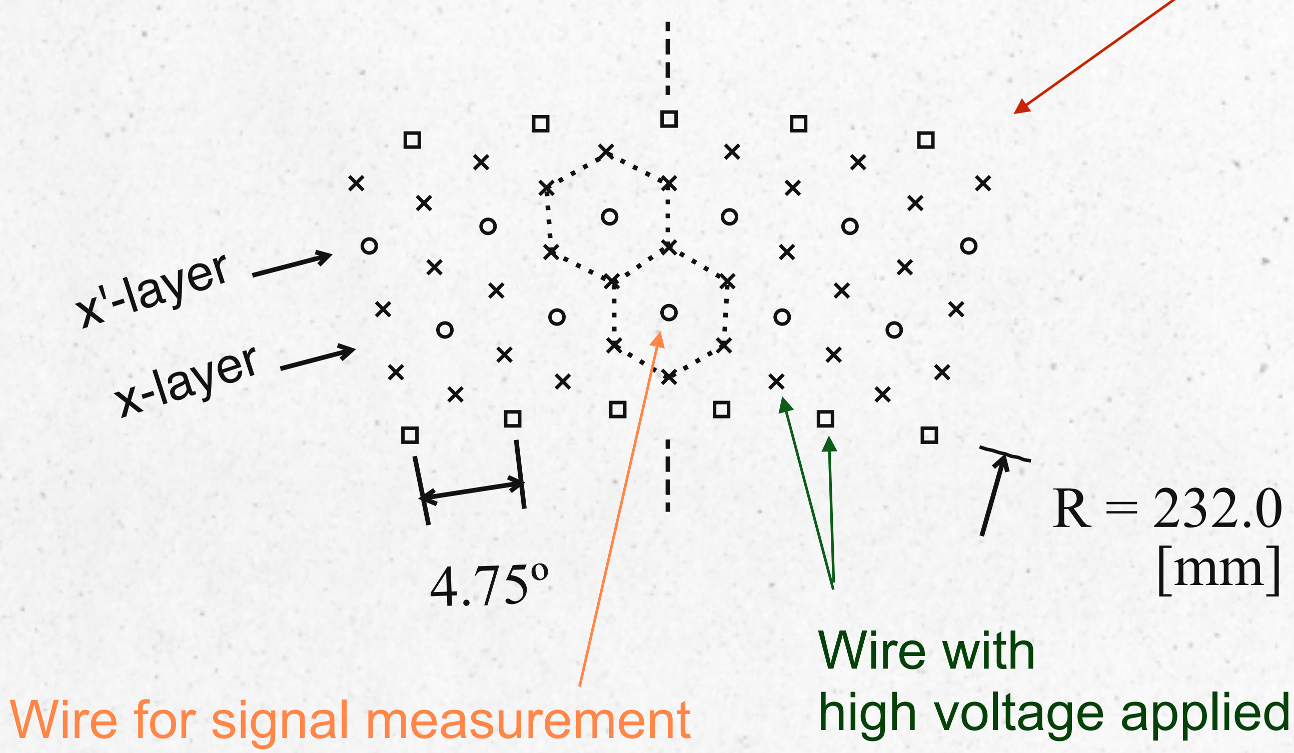
Many wires in gas volume

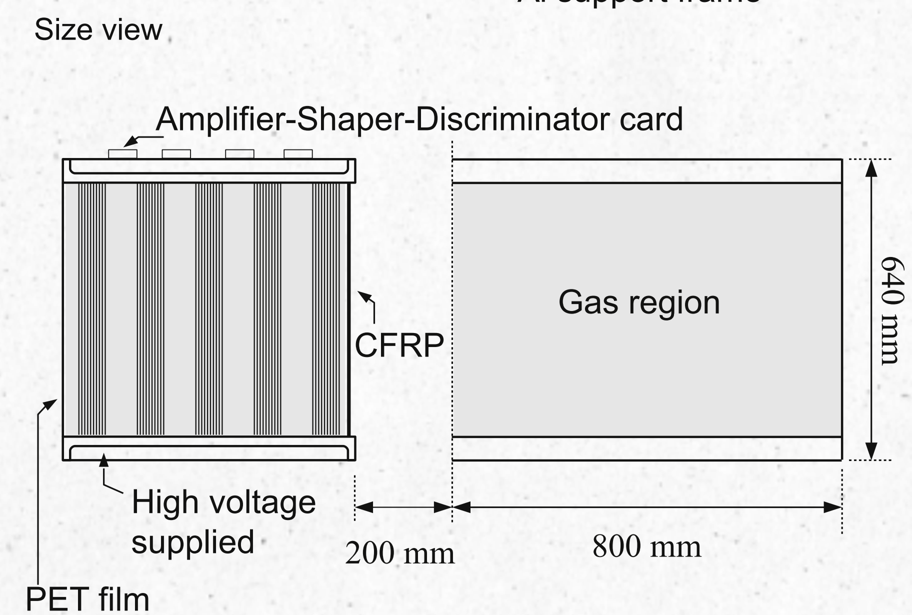
Wire: make electrical field and detection of signal

Drift Chamber of NKS2



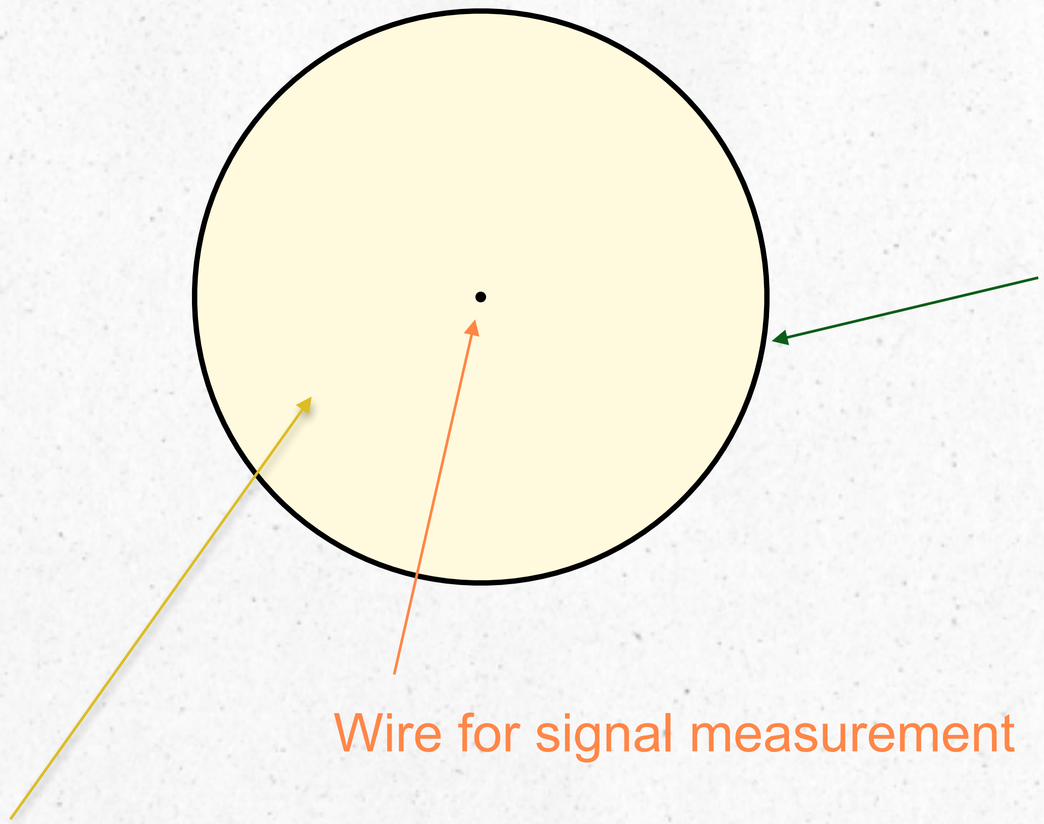






Figures: Nucl. Instrum. Methods A886 (2018) 88-103

Principle of Drift Chamber



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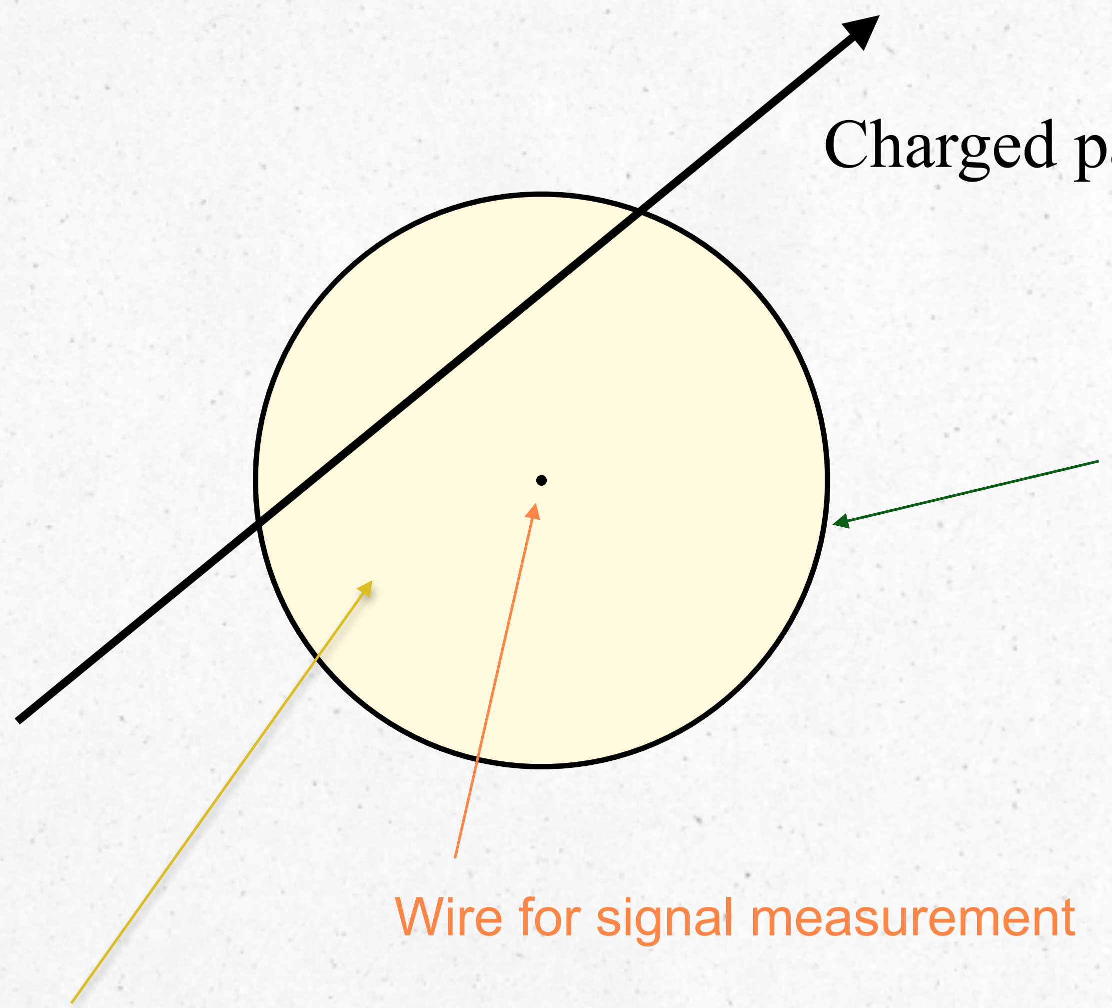

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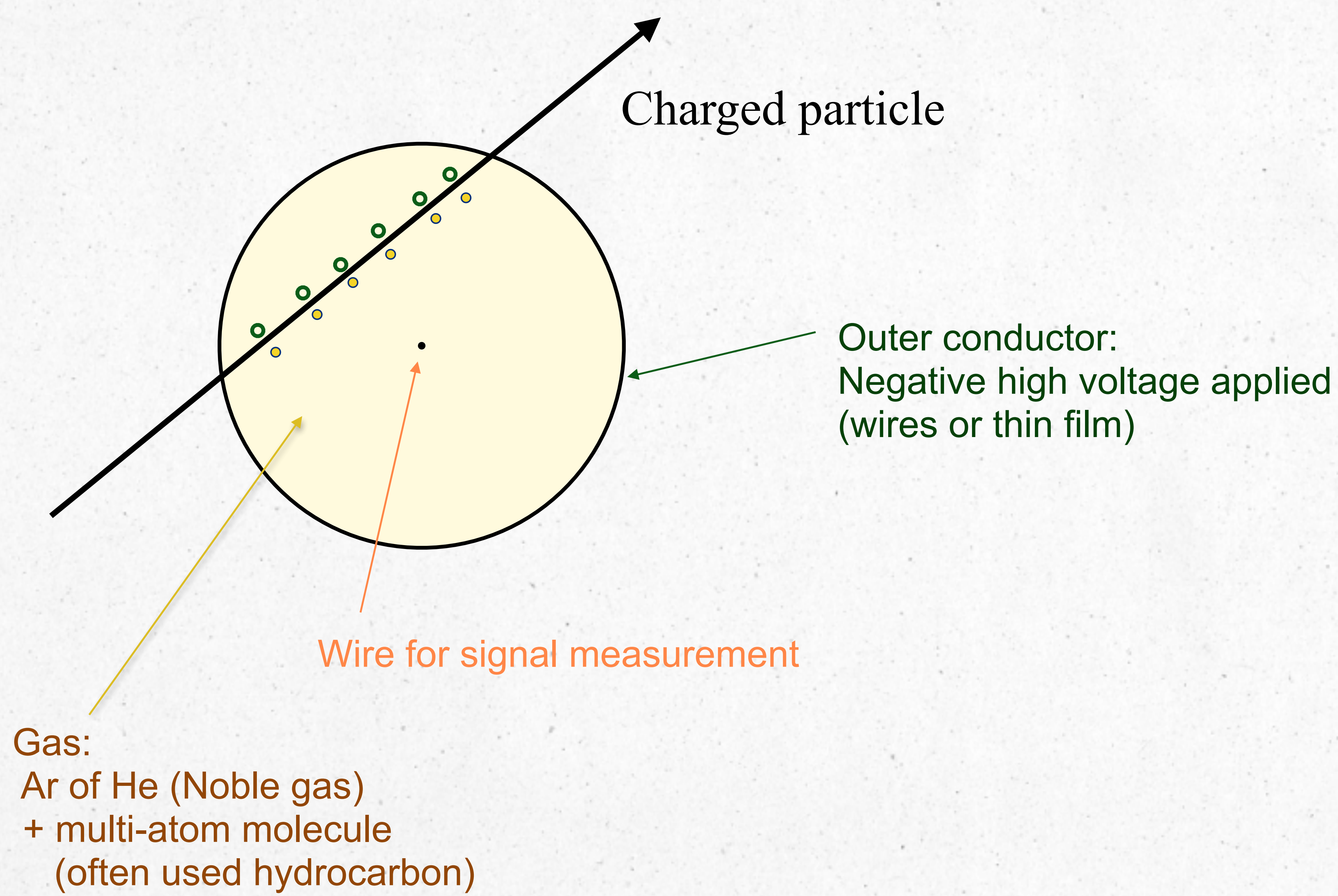

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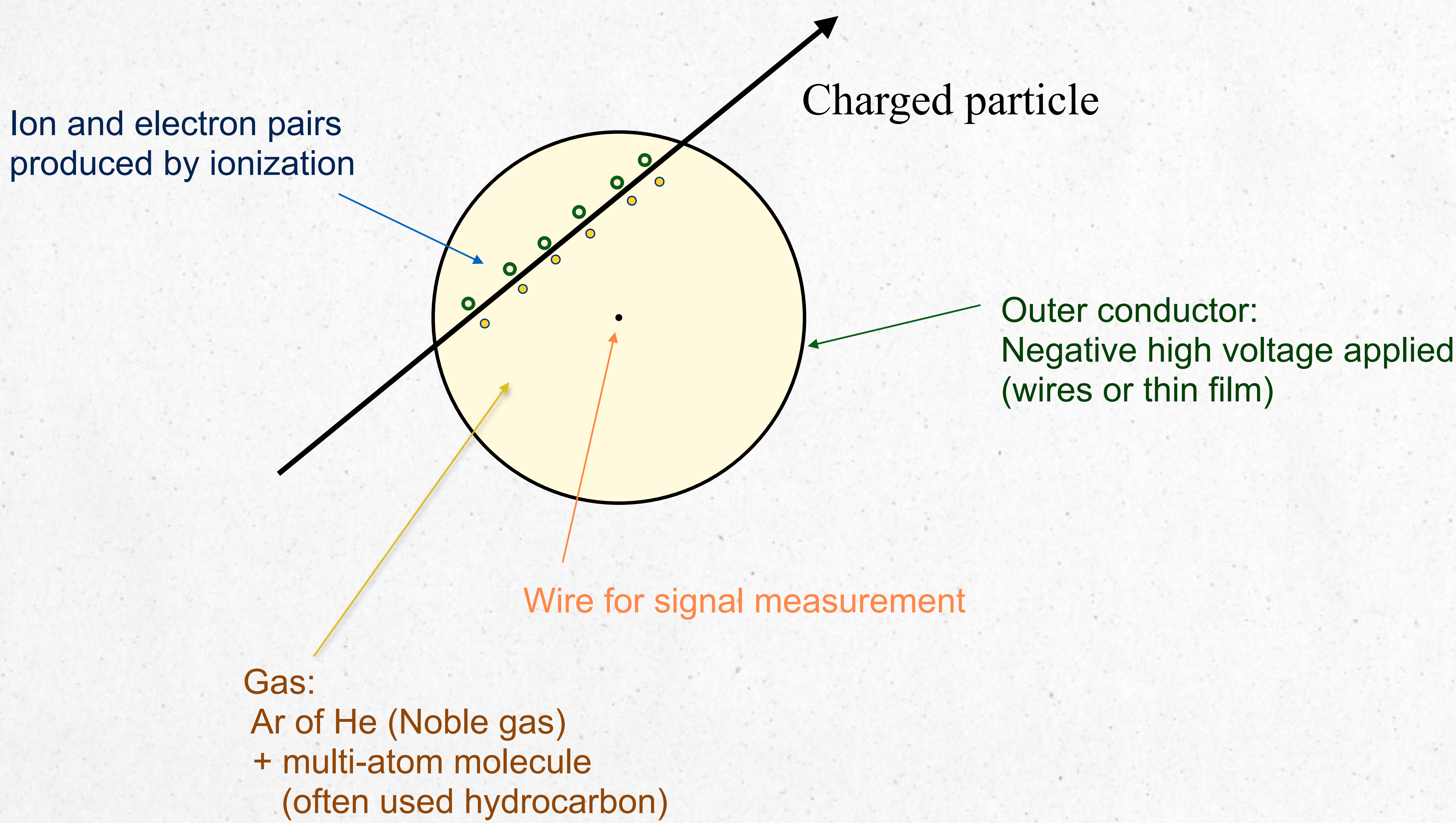
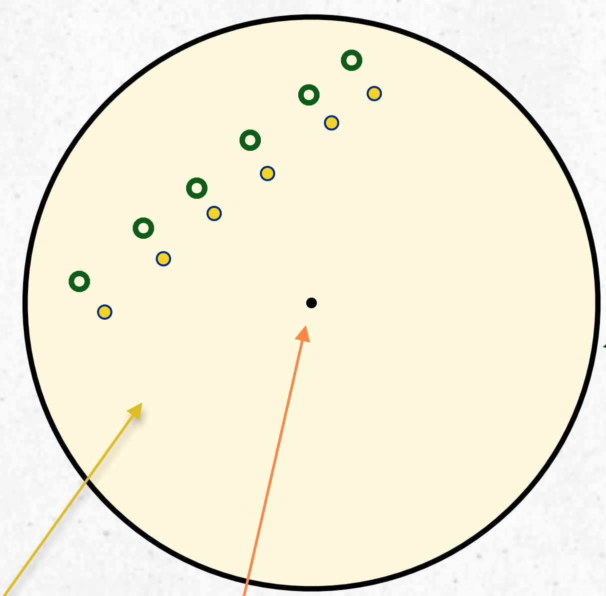


Principle of Drift Chamber

Ions
Moved to outer conductor
Slower than electron

Electrons
Moved to signal wire



Outer conductor:
Negative high voltage applied
(wires or thin film)

Wire for signal measurement

Gas:
Ar of He (Noble gas)
+ multi-atom molecule
(often used hydrocarbon)

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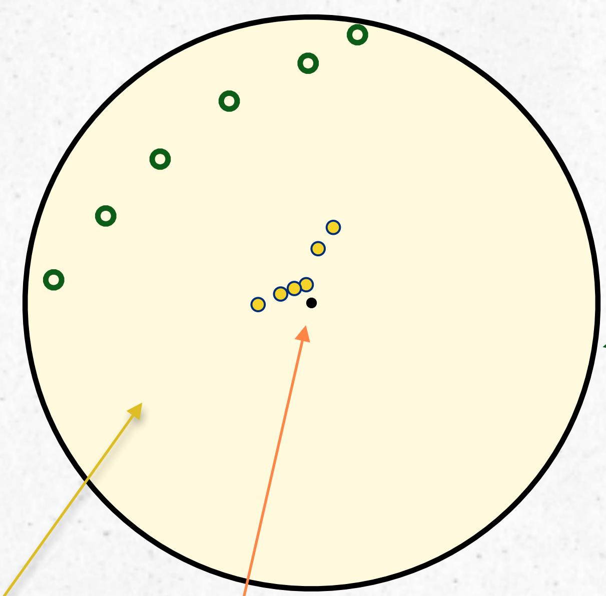

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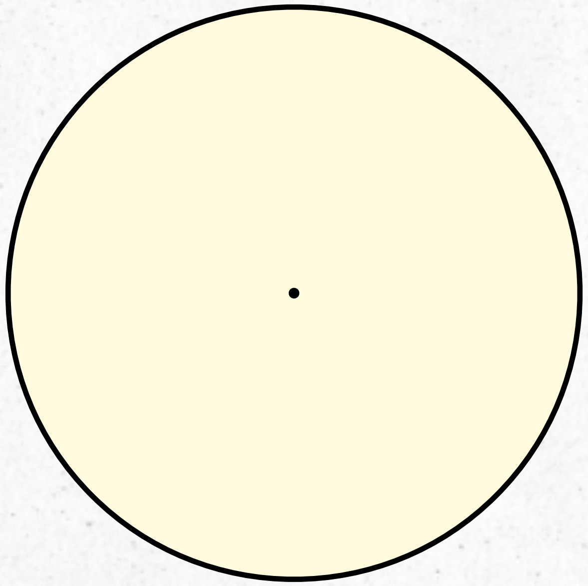

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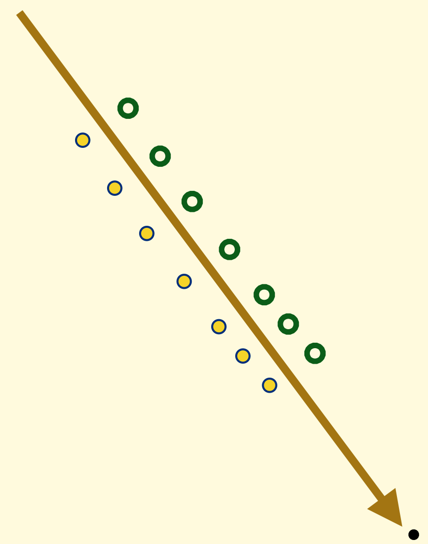
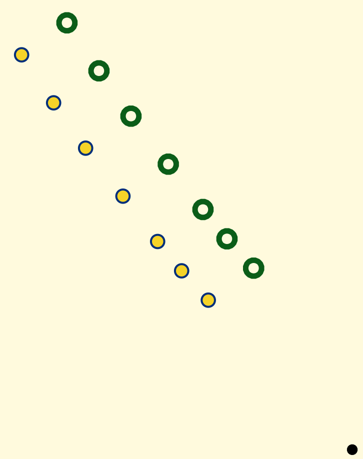


Electron
accelerated at close to wire
due to strong electric field and
makes electron-ion pairs

Electrons produced makes the other pairs

Repeat the processed
→ Avalanche amplification: $\sim 10^5$ - 10^6

Principle of Drift Chamber



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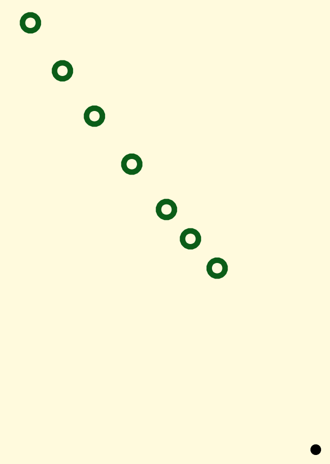

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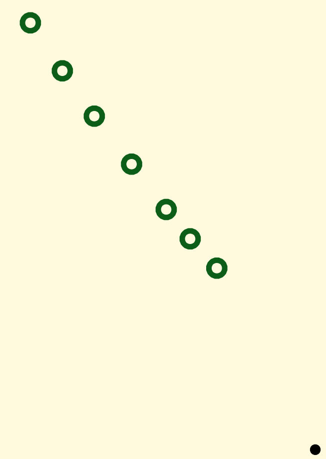
→ Avalanche amplification: $\sim 10^5$ - 10^6

Principle of Drift Chamber

Ions
Still remained around wire after electrons were absorbed into the wire

→ Ions induce charge on wire

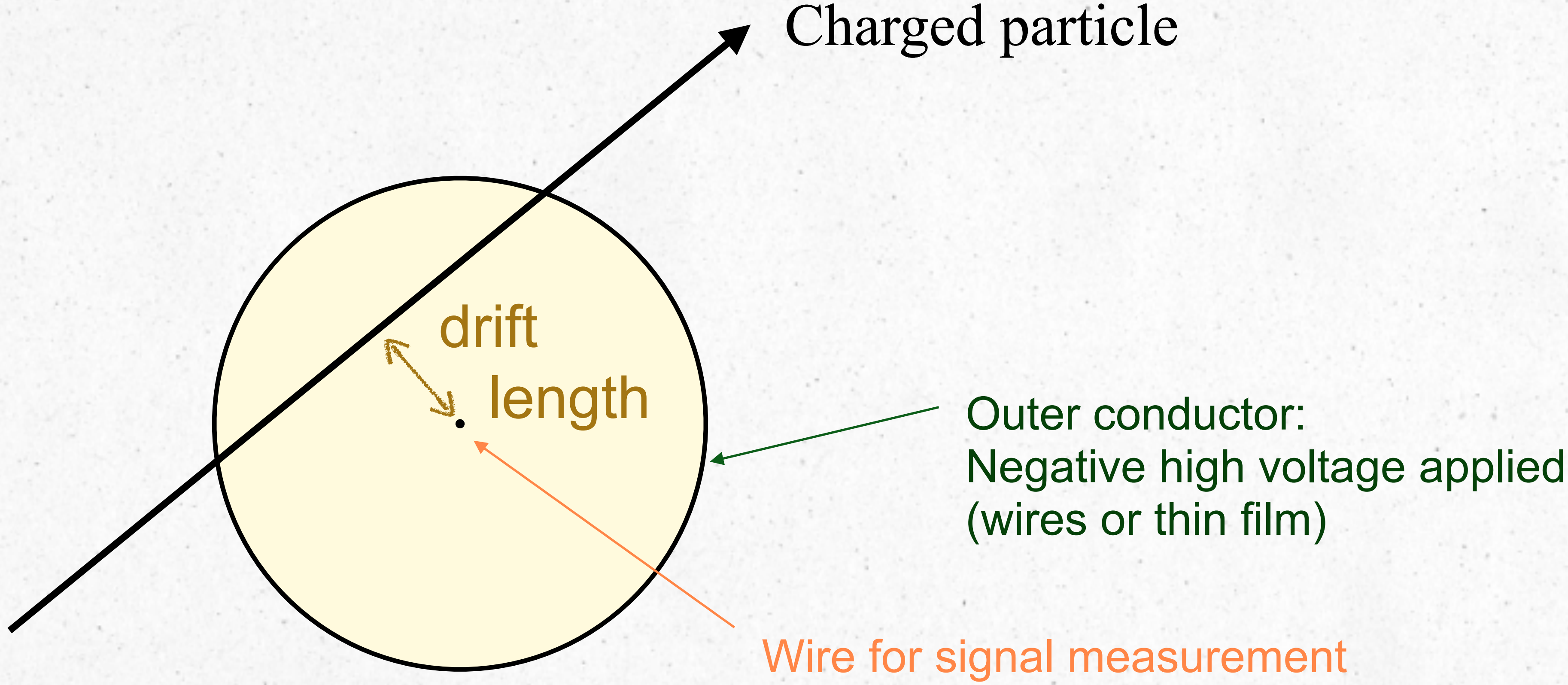


Electron
accelerated at close to wire due to strong electric field and makes electron-ion pairs

Electrons produced makes the other pairs

Repeat the processed
→ Avalanche amplification: $\sim 10^5$ - 10^6

Principle of Drift Chamber

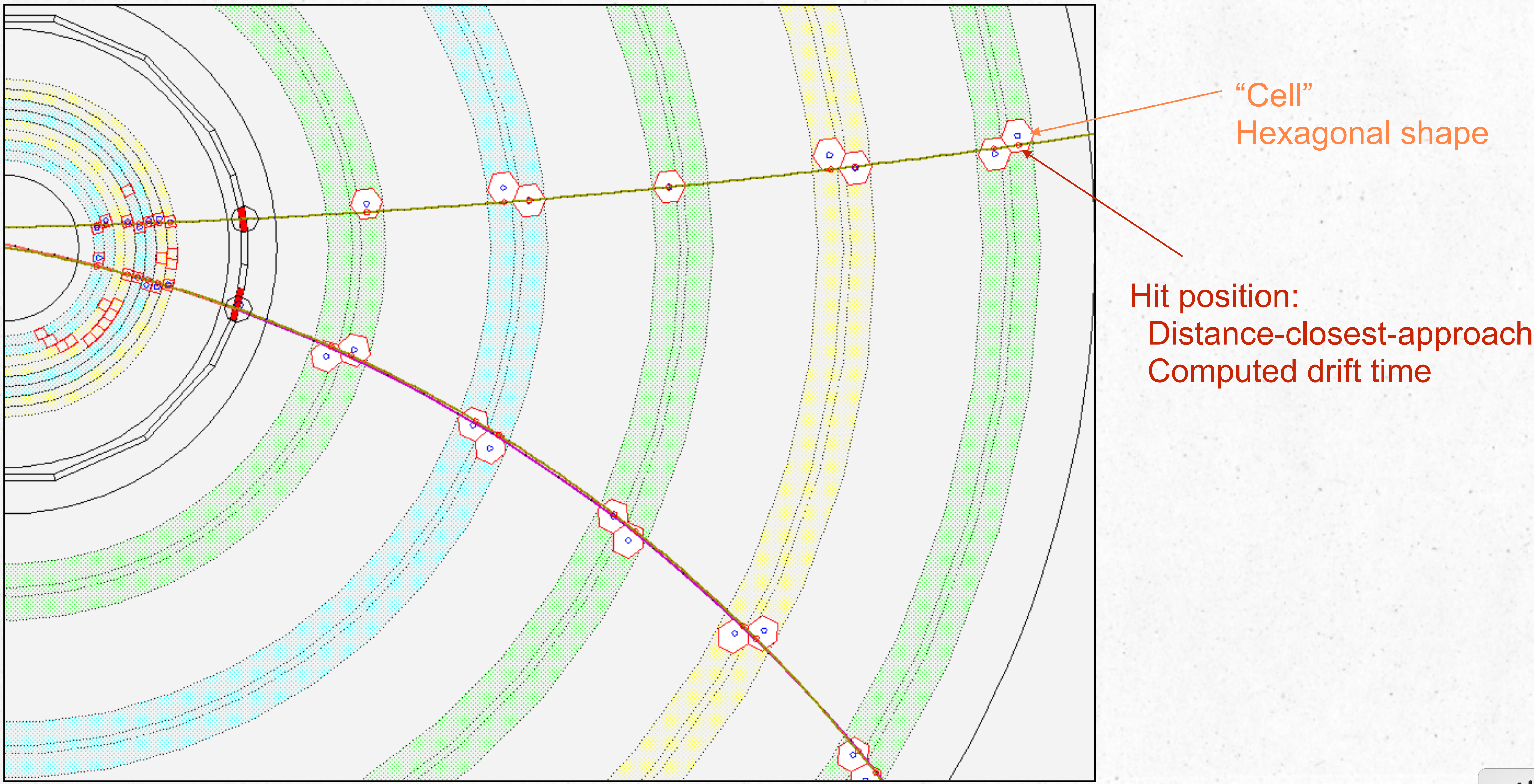


Speed of electron in gas: ~ 5 cm/μs
  Slower than charged particle we want to measure the trajectory
    (~ close to c: 30 cm/ns = 30000 cm/μs)

Drift time of electron
  Time delay of signal respect to charged particle passage
  Distance from wire to charged particle trajectory

Example of Tracking in NKS2

- Reconstruction of trajectory from hit information
  - Resolving equation of motion in magnetic field



Time-of-Flight: TOF

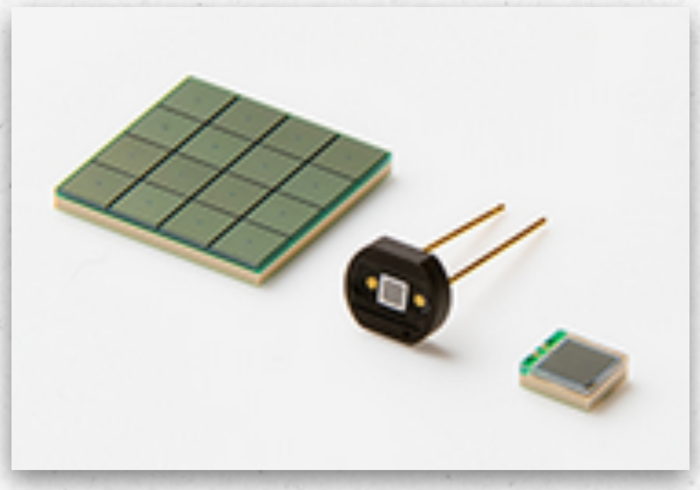
- Timing measurement of passage of charged particle
  - For velocity calculation
  - Typical timing resolution: several 10 ps to several 100 ps
- Two set of TOF detector
  - Absolute time measurement is difficult
    - Recording time is vary with condition
    - Relative time among detector is not changed

TOF Detectors

- Plastic scintillator + photon sensor
  - Photon sensor
    - Photo-Multiplier Tube (PMT)

Plastic scintillator is surrounded by a black sheet
to avoid large current flow in PMT due to external light

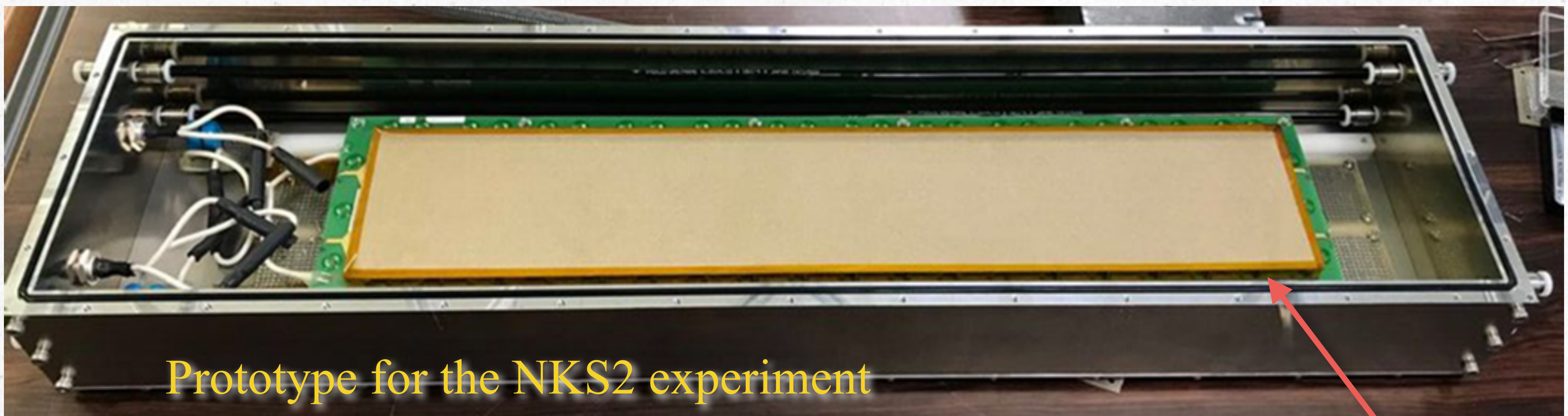
    - Silicon Photo-Multipier (SiPM)
      - Avalanche photo-diode operating Geiger mode
      - Work in magnetic field
      - Small size



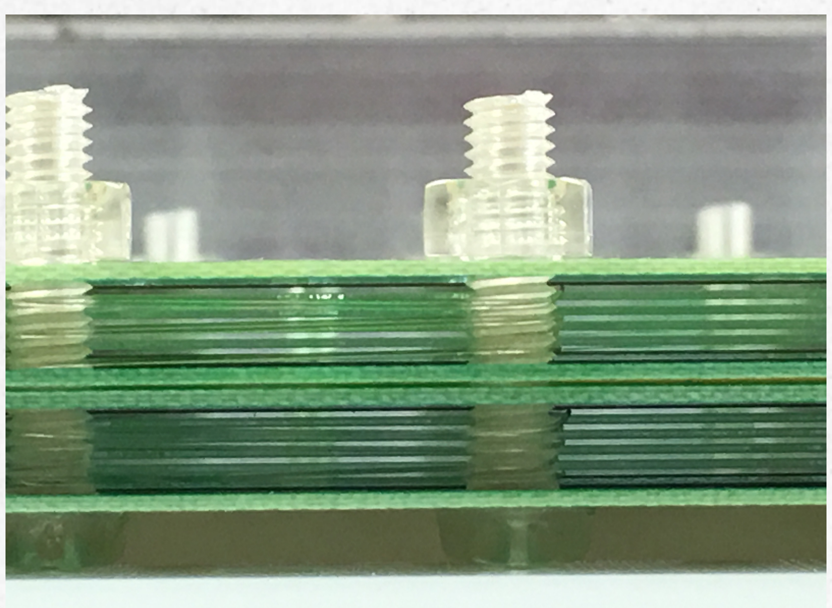
MPPC by HAMAMATSU

TOF Detectors

- Multi-gap Resistive Plate Chamber
  - Gas multiplier with Geiger mode



47 cm × 3.5 cm strip
Readout from both ends



Gas:
R-134a+SF_6 (90:10)

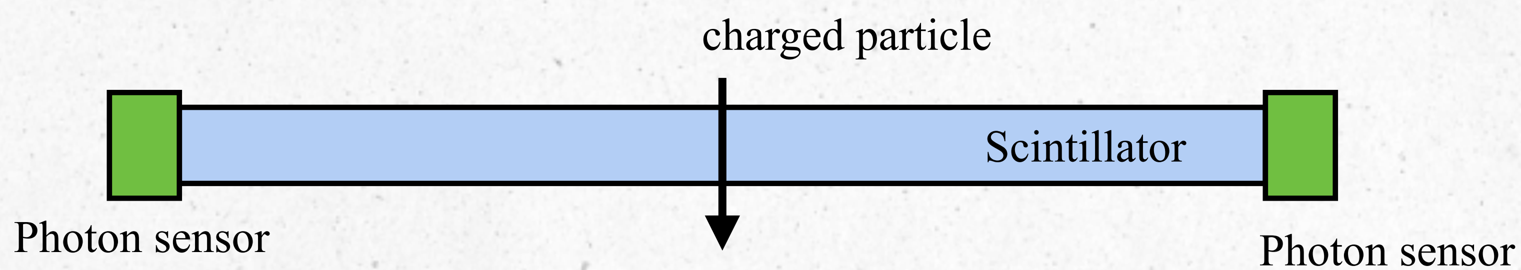
0.4^{th} mm soda-lime glass
#2 fish line (∅ 0.23mm)
5-gap and double-stack

Intrinsic resolution
~120 ps

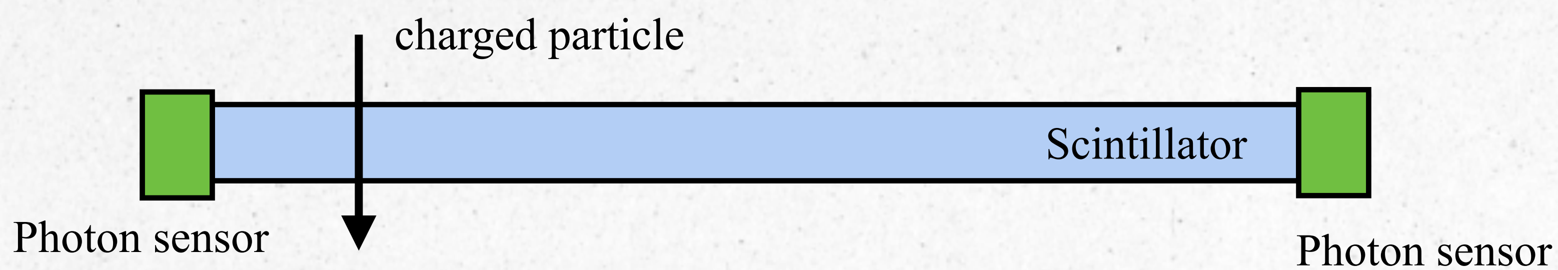
TOF Detector as Hodoscope

- Hodos: Way or path in Greek
  - Hodoscope: Position detector
  - Array of plastic scintillation counters
- Two side read-out of signal
  - Time difference of hit signal at both edge
  - → distance from hit position to both edge

Example 1:
Charged particle pass through center of scintillator



Example 2:
Charged particle pass through close to edge of scintillator



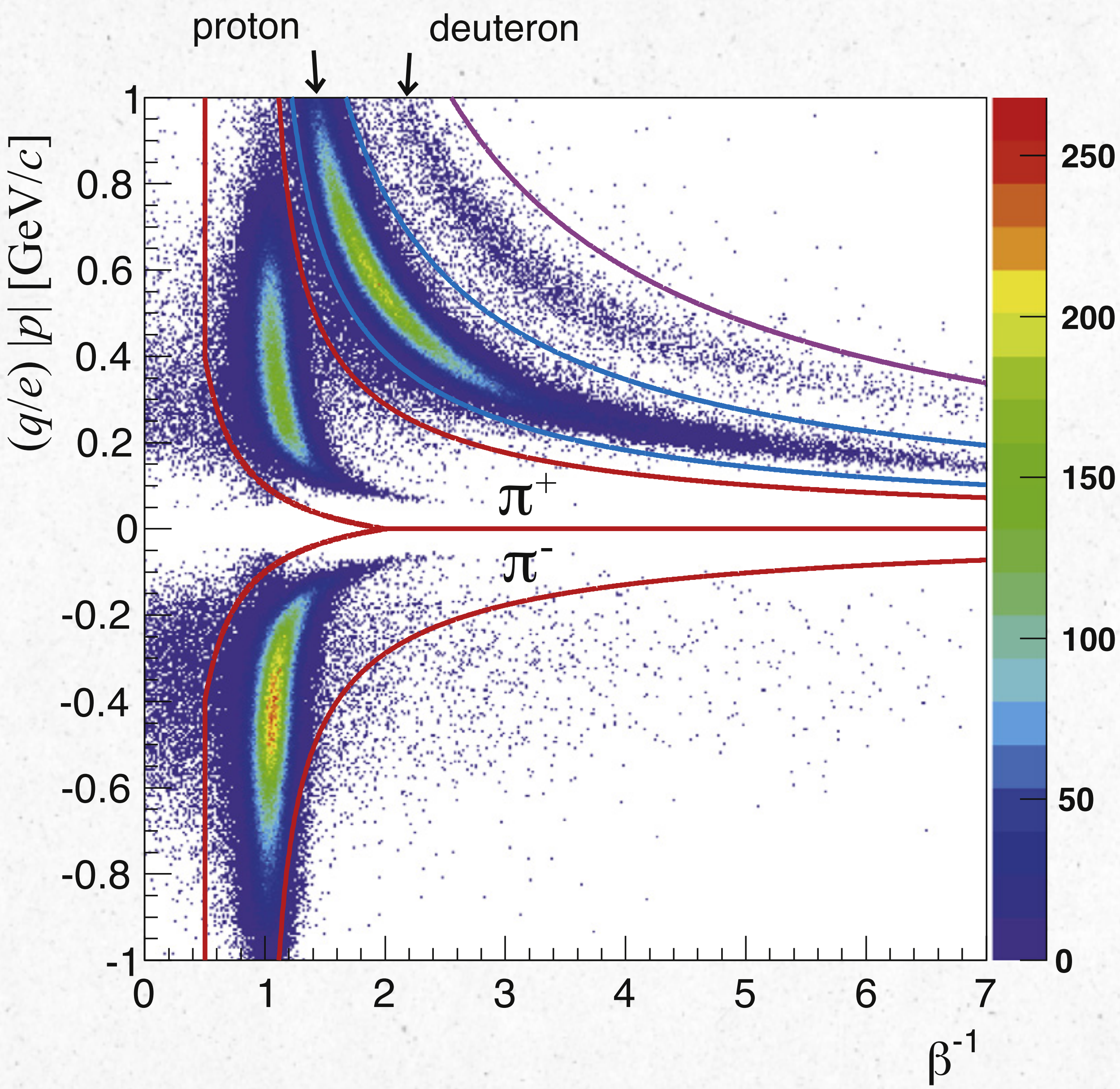
Particle Identification

- Characteristics of particle
  - Charge sign
    - Bending direction in magnetic field
  - Mass
    - Momentum and velocity (Flight-path / TOF)

$$E^2 = (mc^2)^2 + (pc)^2$$

$$p^2 = \frac{v^2E^2}{c^4} = \beta^2\frac{E^2}{c^2}, \text{where } \beta = \frac{v}{c}$$

$$(mc^2)^2 = p^2c^2\left(\frac{1}{\beta^2} - 1\right)$$



Figures: Nucl. Instrum. Methods A886 (2018) 88-103

Summary

- Topics
  - Radiation and nuclear physics
  - Charged particle measurement
    - Principle
    - Detectors
      - Example from NKS2 experiment at ELPH, Tohoku Univ.
- The technique in elementary particle/nuclear physics
  - Many applications in medical
    - Using radiation, radioactive material, and accelerator