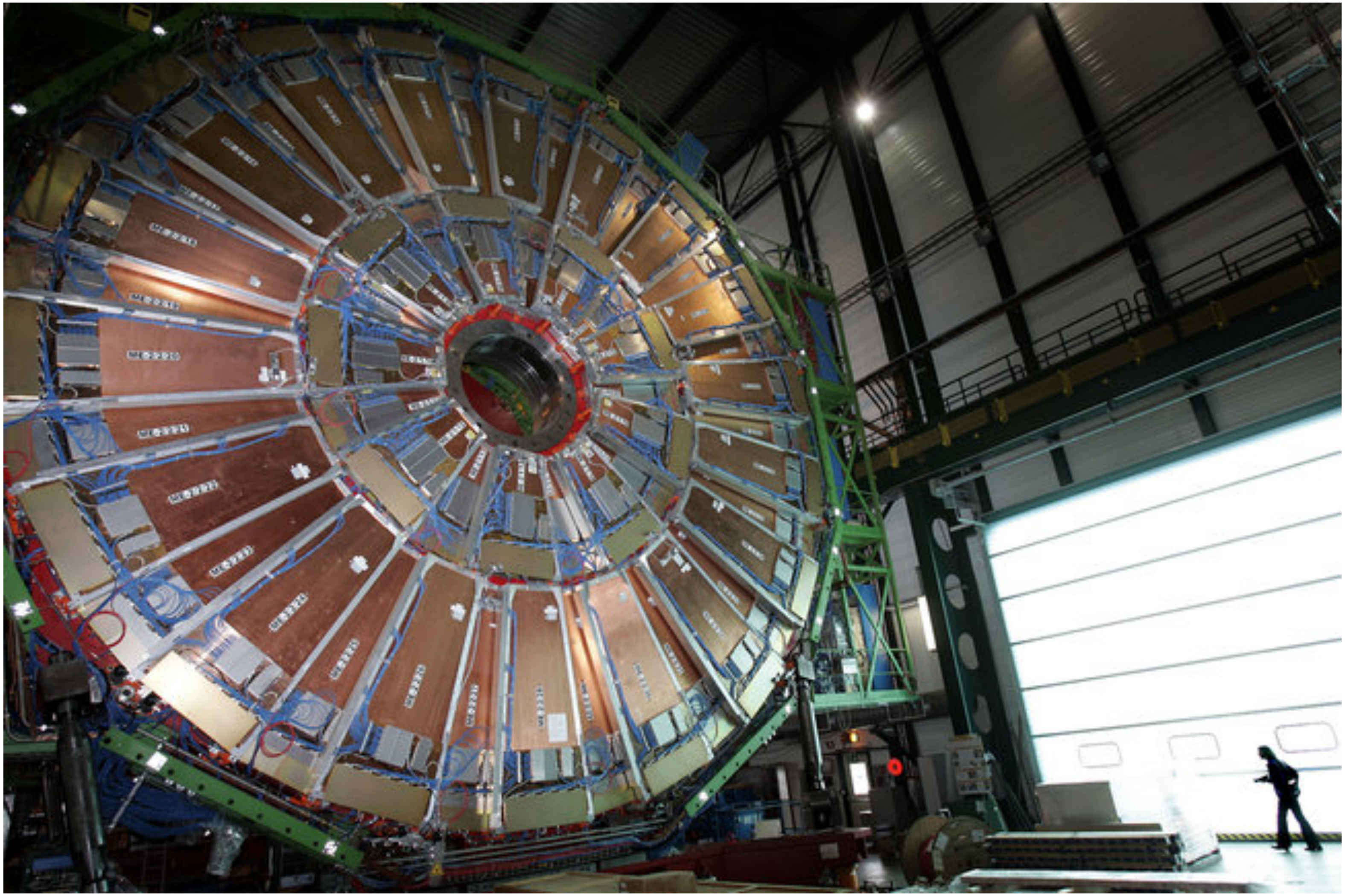
TRACKING DETECTORS



TRACKING DETECTORS

Lecture 1

Basics: propagation of particles in media and measurements

Lecture 2

Main tracking detector concepts and examples of their use

Lecture 3

Overview of muons systems at collider experiments

TRACKING DETECTORS

Lecture 1

Which particles do tracking detectors “track” and what for?

Basics of detection:

- Trail left behind by charged particles in matter
- Transport of ionization to sensors

Basics of measurements:

- overall pattern recognition
- momentum
- direction
- impact parameter
- ancillary: dE/dx, Cherenkov light, transition radiation, …

Historical preamble for next lecture: legacy of the first half of 20th century

What do we "track"?

Merriam-Webster: *track (v) – to follow the tracks or traces of.*

So what do we track?

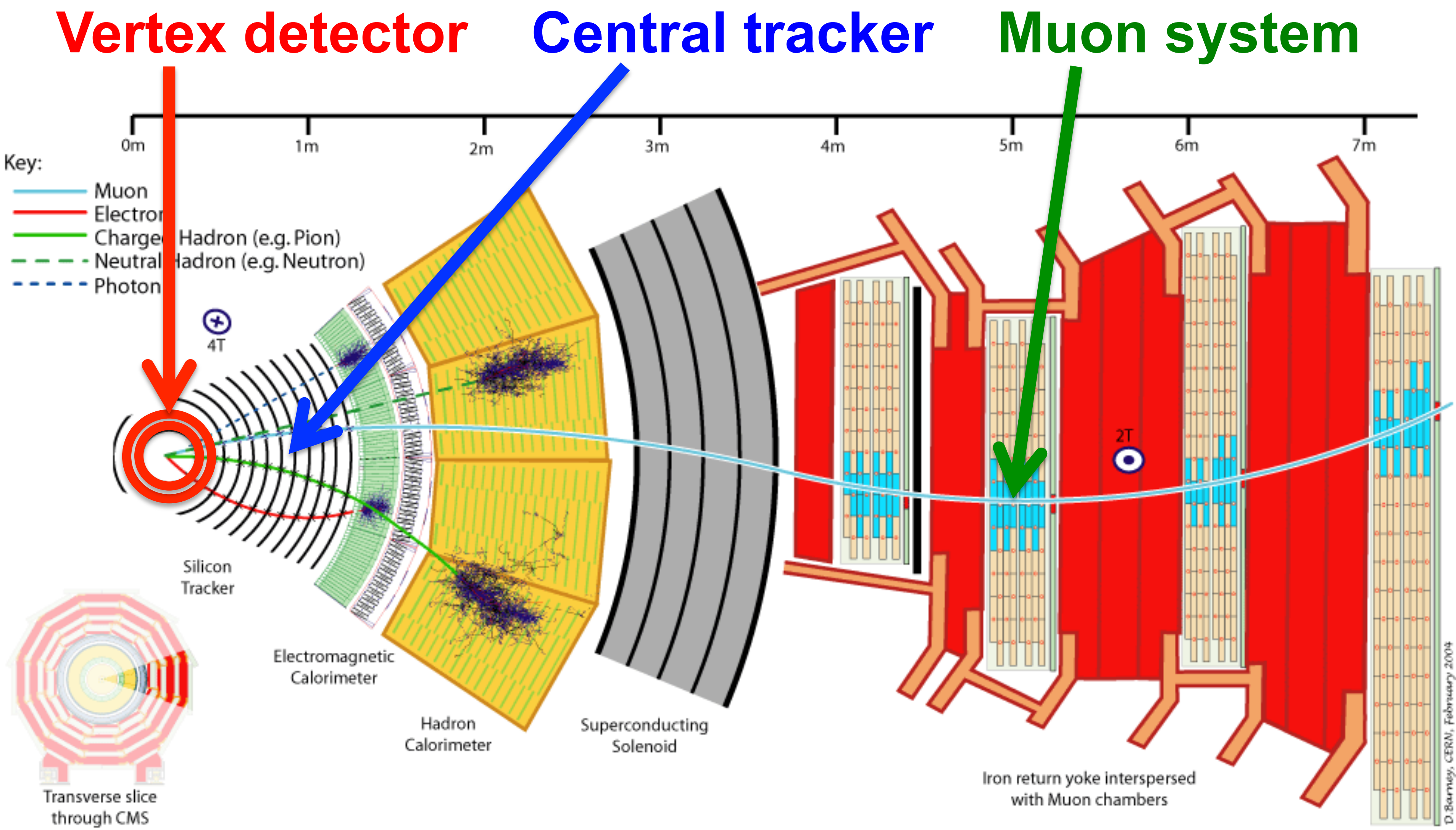
Hard collision gives rise to elementary particles:

- leptons, quarks, gauge bosons
- majority of which quickly decay/hadronize

Only long-lived particles actually enter the detector
(typically, ~cm away from the primary collisions)

- **5 charged (electrons, muons, $\pi^{\pm}$, $K^{\pm}$, p) do leave behind repetitious subtle ionization tracks in the detector volume**
- neutral (photons, n, K^0) interact catastrophically
- neutrinos are not detectable

Tracking in a typical collider experiment



Tracking detector purpose

Resolve multiple charged particles (pattern recognition)

Measure their

- charge and momentum (radius of track's curvature R = p / qB)
- direction
- origin (which helps identify presence of b/c/τ in an event)
- dE/dx (which gives info on velocity and charge: $dE/dx \sim q^2/v^2$)
- sometimes Cherenkov light (β), transition radiation (γ)

Identify, often in concert with other detectors

Basics of detection

Demystifying physics of
charged particle propagation through matter…

Propagation of charged particles through matter

Charged particle leaves behind in matter:

- ionization:
  - average ionization density (dE/dx)
  - fluctuation in ionization density (Landau fluctuations)
- light, when conditions are right:
  - scintillation
  - Cherenkov radiation
  - transition radiation

Charged particle itself is affected by matter too:

- multiple scattering
- bremsstrahlung (catastrophic energy loss)

Average ionization

Bethe-Bloch formula:

$$-\frac{dE}{dx} = 4\pi \frac{z^2\alpha^2}{\beta^2}\frac{Z\rho}{Am_N m_e}\left[\frac{1}{2}\ln\frac{2m_e\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$

m_e, m_N, α—universal constants:
electron and nucleon masses; fine structure constant;

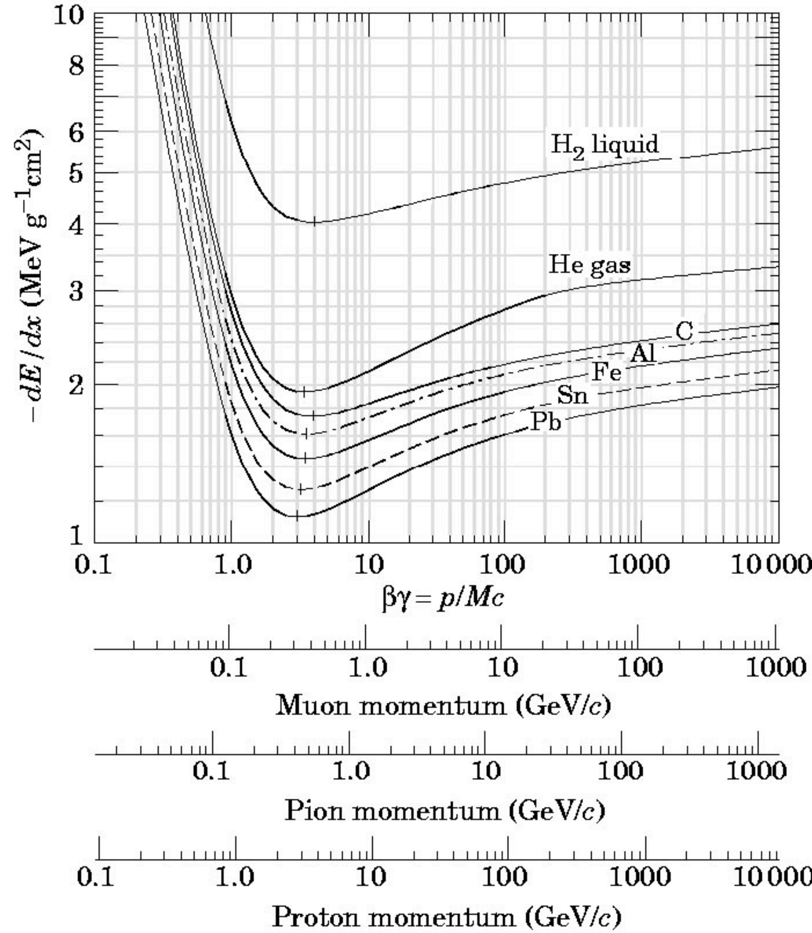
z, β, γ—**incoming particle parameters:**
charge in units of e, velocity β=v/c, gamma factor)

Z, A, ρ, I—**media properties**:
charge and atomic number, density, average ionization potential

T_{max} – maximum energy that can be transferred
from an incoming particle of mass m to an electron

$$T_{\max} = \frac{2m_e\beta^2\gamma^2}{1+2\gamma(m_e/m)+(m_e/m)^2}$$

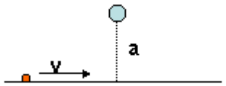
δ—small correction due to media polarization
(for gasses, it is negligibly small)



Deriving the main part of the BB formula

$$-\frac{dE}{dx} = 4\pi \frac{z^2\alpha^2}{\beta^2}\frac{Z\rho}{Am_N m_e}\left[\frac{1}{2}\ln\frac{2m_e\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$

Momentum transfer per electron:



$$dq_z = F_z dt = F_z\frac{dx}{v} = \frac{ze^2}{4\pi(x^2+a^2)}\frac{dx}{v}\frac{a}{\sqrt{x^2+a^2}}$$

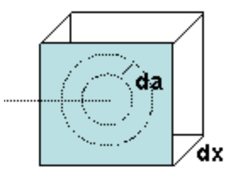
After integration:

$$q = 2\frac{z\alpha}{av}$$

Energy transferred to an electron
(and, hence, lost by incoming particle):

$$T = \frac{q^2}{2m_e} = 2\frac{z^2\alpha^2}{m_e v^2}\frac{1}{a^2}$$

Summing up over all electrons in media



$$dE = \int_{a_{\min}}^{a_{\max}} T\,2\pi a n_e\,da\,dx = 4\pi\frac{z^2\alpha^2}{m_e v^2}n_e\,dx\ln\left(\frac{a_{\max}}{a_{\min}}\right)$$

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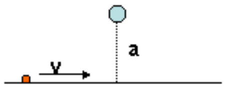

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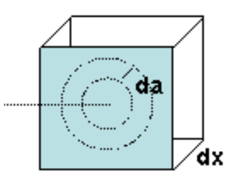

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Cut-off distance $a_{\max}$: T is smaller than ionization potential I (no ionization possible)

$$I = 2\frac{z^2\alpha^2}{m_e v^2}\frac{1}{a_{\max}^2}$$

Effective cut-off distance $a_{\min}$: $T = T_{\max}$

$$T_{\max} = 2\frac{z^2\alpha^2}{m_e v^2}\frac{1}{a_{\min}^2}$$

Density of electrons:

$$n_e = Z\frac{\rho}{Am_N}$$

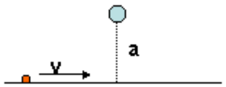
Finally putting all together:

$$-\frac{dE}{dx} = 4\pi \frac{z^2\alpha^2}{\beta^2}\frac{Z\rho}{Am_N m_e}\left[\frac{1}{2}\ln\left(\frac{T_{\max}}{I}\right)\right]$$

Deriving the main part of the BB formula

$$-\frac{dE}{dx}=4\pi\frac{z^2\alpha^2}{\beta^2}\frac{Z\rho}{Am_N m_e}\left[\frac{1}{2}\ln\frac{2m_e\beta^2\gamma^2T_{\max}}{I^2}-\beta^2-\frac{\delta}{2}\right]$$

Momentum transfer per electron:



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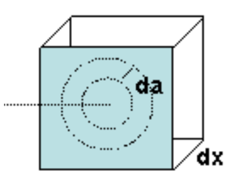
Summing up over all electrons in media



$$dE=\int_{a_{\min}}^{a_{\max}}T2\pi a n_e\,da\,dx=4\pi\frac{z^2\alpha^2}{m_e v^2}n_e\,dx\ln\left(\frac{a_{\max}}{a_{\min}}\right)$$

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$$I=2\frac{z^2\alpha^2}{m_e v^2}\frac{1}{a_{\max}^2}$$

Effective cut-off distance $a_{\min}$: T = $T_{\max}$

$$T_{\max}=2\frac{z^2\alpha^2}{m_e v^2}\frac{1}{a_{\min}^2}$$

Density of electrons:

$$n_e=Z\frac{\rho}{Am_N}$$

Finally putting all together:

$$-\frac{dE}{dx}=4\pi\frac{z^2\alpha^2}{\beta^2}\frac{Z\rho}{Am_N m_e}\left[\frac{1}{2}\ln\left(\frac{T_{\max}}{I}\right)\right]$$

The extra term $2m_e\beta^2\gamma^2/I$ under the log in the BB formula is the relativistic rise:
at relativistic velocities: $a_{\max}$ becomes larger due to squeezing of electric field

Average ionization

Bethe-Bloch formula:

$$-\frac{1}{\rho}\frac{dE}{dx}=\frac{4\pi\alpha^2}{m_N m_e}\frac{z^2}{\beta^2}\frac{Z}{A}\left[\frac{1}{2}\ln\frac{2m_e\beta^2\gamma^2T_{max}}{I^2}-\beta^2-\frac{\delta}{2}\right]$$

Dependence on media is very weak:

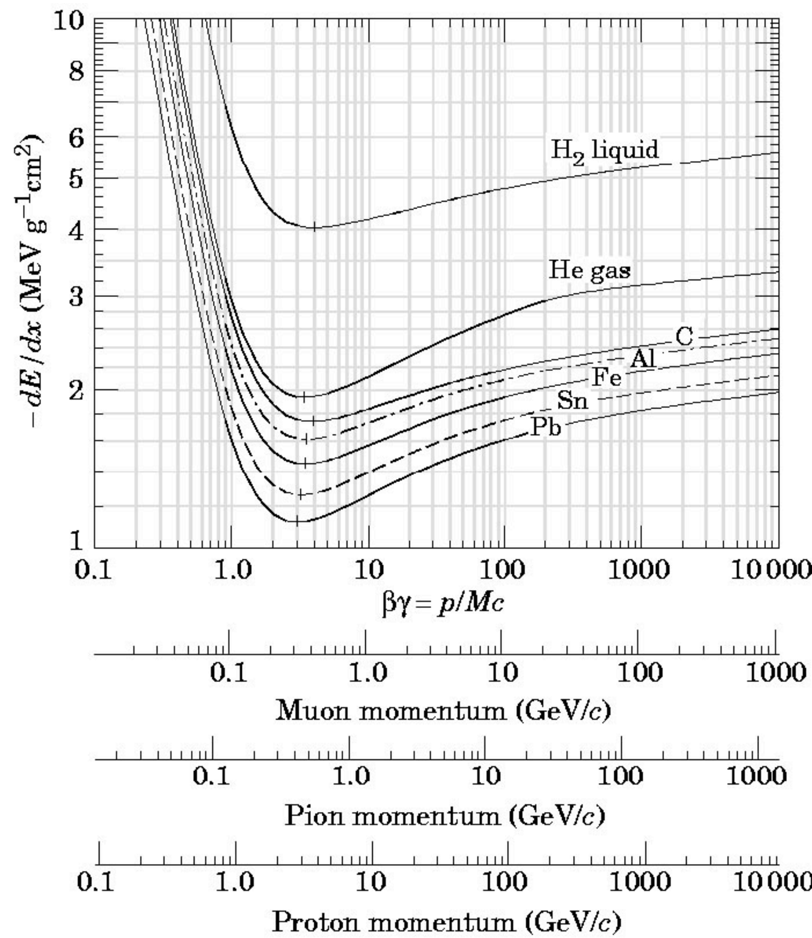
- $Z/A \sim 1/2$, except for hydrogen (=1)
- log of ionization

Main dependence on incoming particle properties via its **charge and velocity: z^2/β^2**

Charged particle with $\beta \sim 1$ is called **minimum ionizing particle (mip)**

all charged relativistic particles look alike!

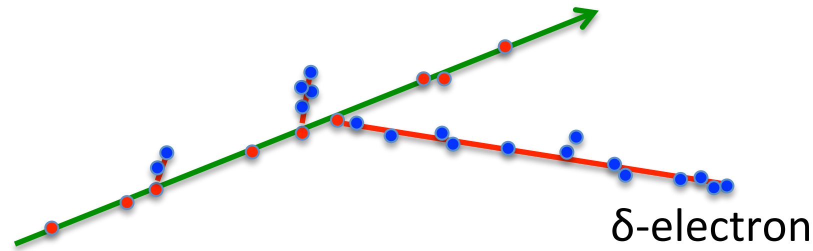
Rule of thumb: ΔE = (2 MeV)×ρ[g/cm^3] per cm



dE/dx fluctuations

Charged particle leaves behind

electrons of the primary ionization,
which can produce their own mini-tracks…
(particularly energetic primary electrons are called δ-electrons)

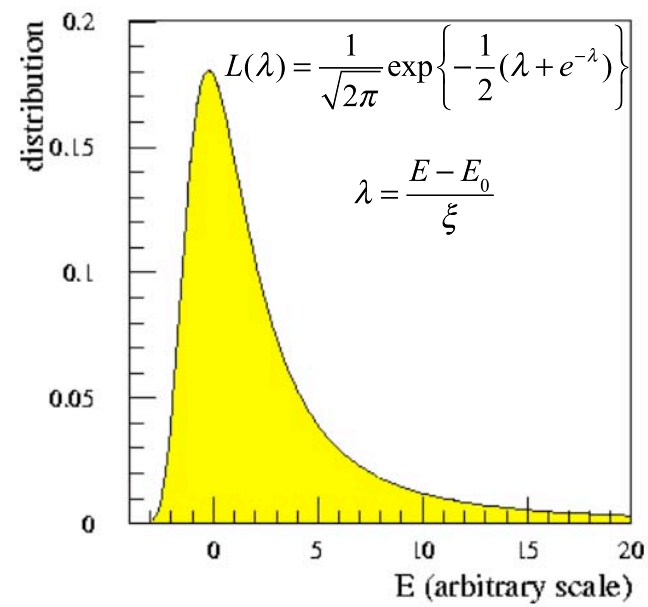


… resulting in the final total ionization.

Clusters of primary ionization are spaced according to Poisson distribution with $n_{primary}$

Total energy loss distribution in thin layers of media have long tails due to δ-electrons.

In thick layers, the distribution becomes Gaussian according to the central limit theorem.



	eV/pair	$n_{primary}$	n_{total}
CO_2	33	34 per 1 cm	91 per 1 cm
Si	3.6	30,000 / 300 μm	←

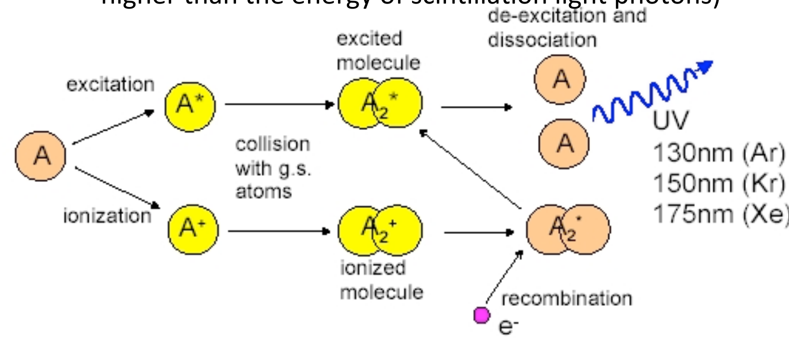
typical electronic noise >1000 e
(gaseous detectors need additional amplification somewhere)

Scintillation

Charged particle leaves a wake of excited molecules

Certain type of media can release some of this excitation energy in a form of low energy photons (visible light, UV) for which media can be fairly transparent

Scintillation in noble gases
(note original excitation/ionization energy is much higher than the energy of scintillation light photons)



Energy carried away by scintillation is small

- <1% × (dE/dx)
- up to 10^4 photons per MeV of dE/dx

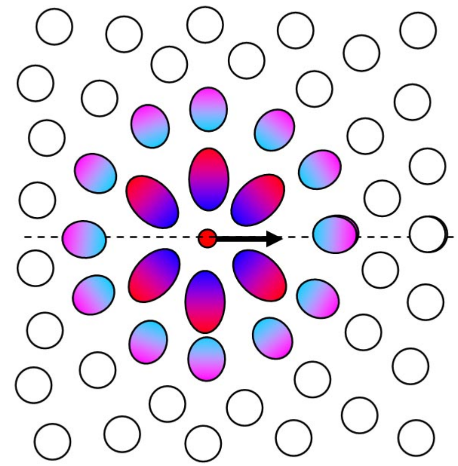
many; can be used instead of ionization

Light emission decay time:

- ~10 μs in noble gases
- 10 – 1000 ns in inorganic materials (10 ns in $PbWO_4$)
- ~ 2 ns in fast organic scintillators

fast

Cherenkov radiation



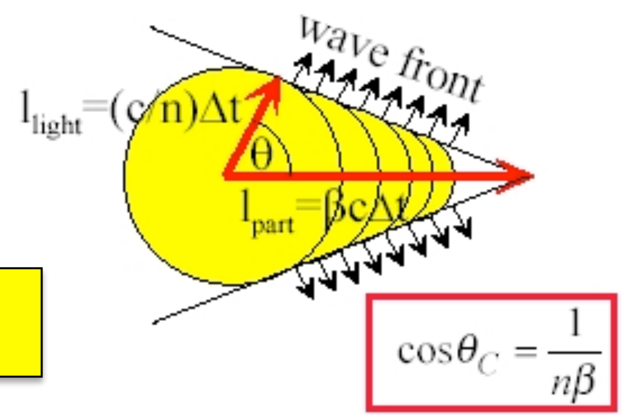
Charged particle leaves a wake of polarized media

As molecules/atoms depolarize, they emit radiation in all directions

If particle travels with speed greater than speed of light in media, the depolarization radiation interferes constructively and builds up a shock wave emitted at the "classic" shock wave angle:

$$\cos\theta_C = \frac{v_{light}}{v_{particle}} = \frac{1}{n\beta}$$

⇐ can be used to measure β

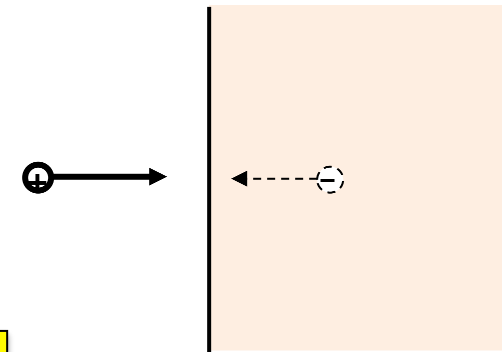


Energy carried away by Cherenkov radiation is tiny

- ~10^{-4} × (dE/dx)
- about 100 vis. light photons per MeV of dE/dx ⇐ few

Transition radiation

Boundary between two media
with different dielectric constants



Classical EM point of view:

- Static point charge:
  - induces dipole-like electric field
- Moving charged particle:
  - changing dipole field
  - this must give rise to radiation

Probability of emitting a photon
per one boundary transition: $p = \alpha = \frac{1}{137}$

very few

Typical energy of a photon: $E = \frac{1}{4}\omega_p \gamma$

where $\omega_p = \sqrt{(N_e e^2)/(\varepsilon_0 m_e)}$ (≈ 20 eV for plastics)

Very boosted charged particles can produce distinct localized clusters of large ionization induced by X-ray photons, e.g.:

- 20-GeV electrons → 200 keV
- while 20-GeV pions → 1 keV

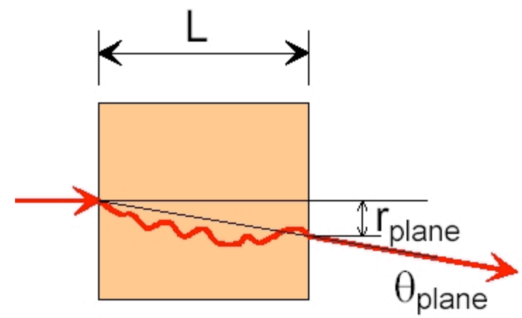
can be used to help identify electrons

Multiple Coulomb scattering

Rutherford scattering formula:

- projectile: q=ze, p, β
- target: Q=Ze

$$\frac{d\sigma}{d\Omega} = \frac{1}{4}\left(\frac{zZ\alpha}{\beta p}\right)^2 \frac{1}{\sin^4(\theta/2)}$$

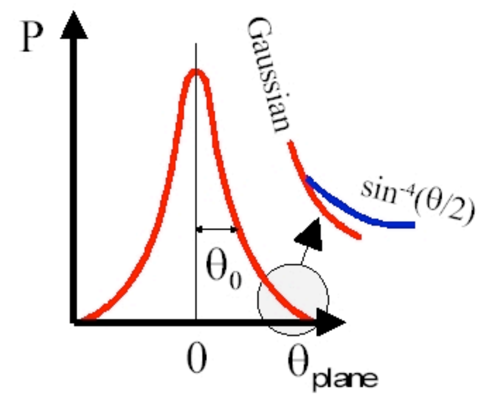


Displacement in a random walk (N steps of size d) has a Gaussian distribution of width D

$$D \sim \sqrt{d \cdot N}$$

After many scatterings, expect the following dependence for deflection angle:

$$\theta_{rms} \sim \frac{zZ}{\beta p}\sqrt{L \cdot n_A}$$



Actual formulae:

$$\theta_{rms} = (14 MeV)\frac{z}{\beta p}\sqrt{L / X_0}$$

$$r_{rms} = \frac{1}{\sqrt{3}} L\theta_{rms}$$

where radiation length X_0 is a characteristic of media

$$\frac{1}{X_0} \approx Z(Z+1)\cdot\frac{\rho}{A}\cdot\frac{\ln(287 / Z^{0.5})}{\left(716\ g/cm^2\right)}$$

Bremsstrahlung (“breaking”) radiation

Charged particle undergoing a Coulomb scattering experience acceleration and must radiate

Once in a while radiation can be very catastrophic taking away a large fraction of particle’s energy

Average energy losses are proportional to particle’s energy (unlike ionization energy losses)

For electrons: $-\frac{dE}{dx} = \frac{E}{X_0}$

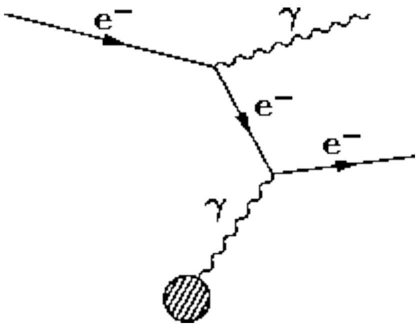
Contemporary trackers are fairly dense
(e.g. ATLAS and CMS tracker ~ 1 X_0 thick):

electrons require dedicated track reconstruction taking into account substantial progressive losses of energy

Critical energy:

bremsstrahlung dE/dx = ionization dE/dx

For electrons: 20 MeV in iron (7 MeV in lead)



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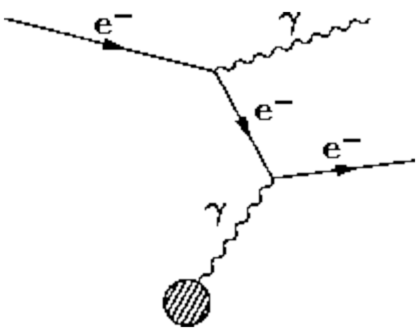


How about muons?

Scattering depends on particle's momentum (Rutherford formula) and does NOT depend on its mass: **electrons and muons experience the same kicks in momentum**

Radiation is proportional to acceleration squared; acceleration ~ 1/m. Hence:
muons will radiate $(m_e/m_\mu)^2$ ~ 1:40,000 less intensely

Critical energy for muons: ~1 TeV in iron

Transport of ionization to sensors

Drift in electric field

Drift in electric and magnetic fields

Diffusion

Losses

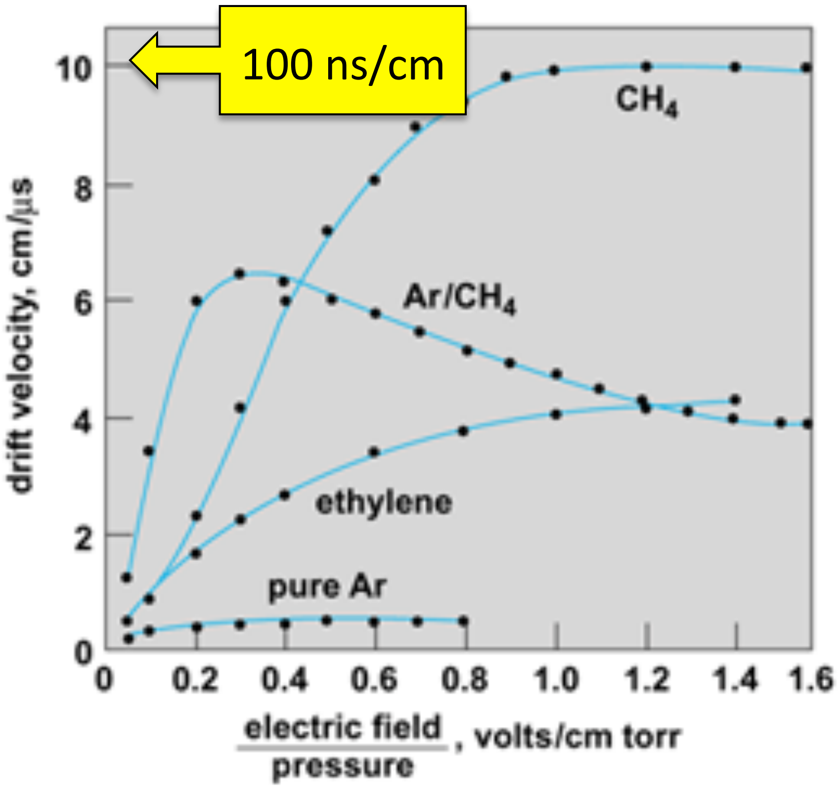
Transport: drift in E

Both electrons and ions left behind in media after passing of a charged particle will drift in presence of E-field

Drift velocity: $\vec{v}_{drift} = \mu \cdot \vec{E}$

mobility μ

- depends on electric field strength: proportional to E for small fields, but often saturates at 1-10 cm/μs for high field
- in gasses, depends on E/p (p=pressure)
- 1000 times smaller for ions



Transport: drift in E and B

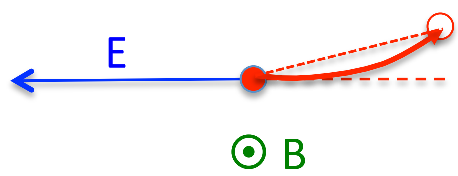
Between collisions, motion of electrons in electric and magnetic fields is driven by the Coulomb (qE) and Lorentz (qvB) forces.

Electrons drift in a direction not parallel to E: **Lorentz angle**

Simplified back-of-envelope considerations:

$$F_x = eE$$

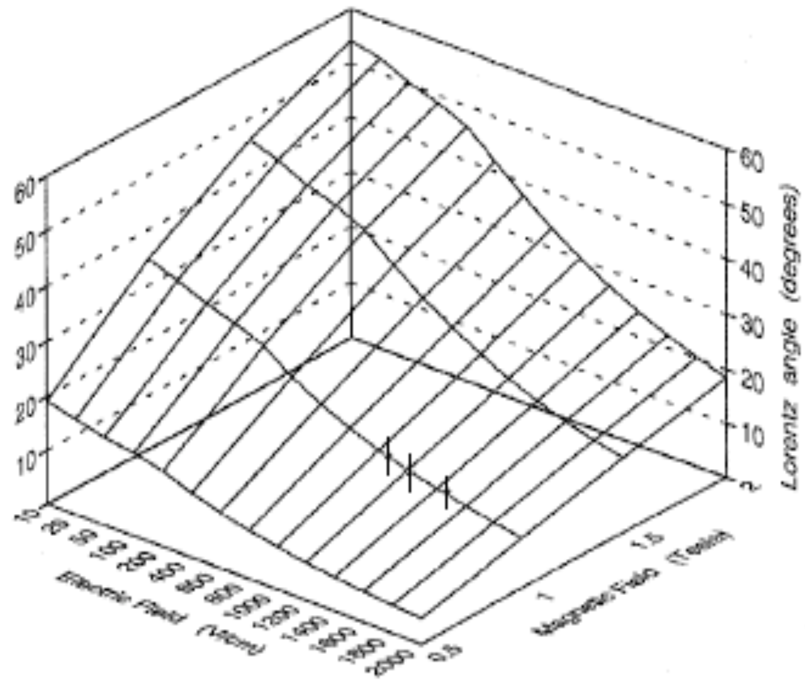
$$d_x = \frac{1}{2} a_x \tau^2 = \frac{1}{2} \frac{eE}{m} \tau^2 = d_0$$



$$\langle F_y \rangle = e \langle v_x \rangle B = \left(\frac{1}{2} \frac{eE}{m} \tau \right) \cdot eB$$

$$d_y \sim \langle a_y \rangle t^2 = \left(\frac{1}{2} \frac{eE}{m^2} \tau \cdot eB \right) \cdot \tau^2$$

$$\tan \alpha = \frac{d_y}{d_x} \sim \frac{e}{m} B \cdot \tau \sim B \cdot \sqrt{\frac{d_0}{E}}$$



Expect: Lorenz angle ~ B and 1/sqrt(E)

Transport: diffusion

Both electrons and ions diffuse in space as they drift in the field

Diffusion: random walk driven by:

- thermal motion
- and re-scattering on media molecules/atoms

Diffusion: $\sigma_x = \sqrt{2Dt} = \sqrt{2D\frac{x}{v_{drift}}}$

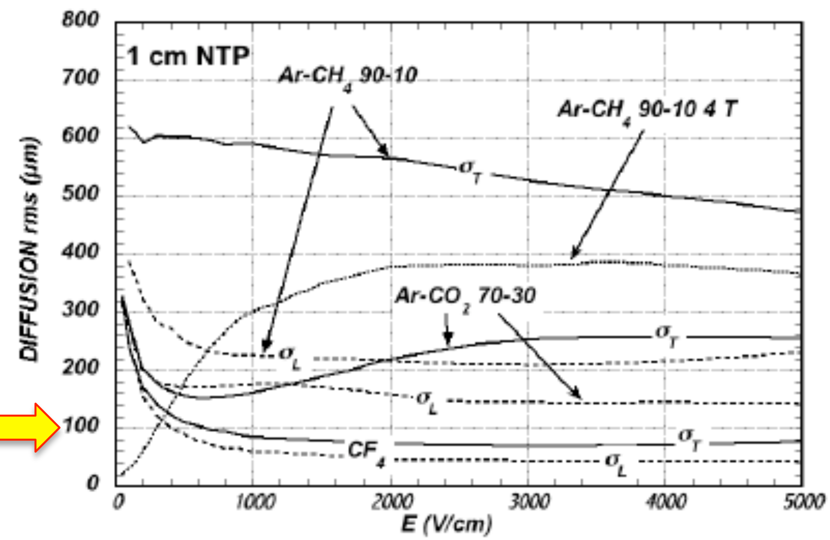
100 µm in 1 cm

Diffusion coefficient D

depends on re-scattering cross section

density of media

diffusion after 1 cm drift



Basics of measurements

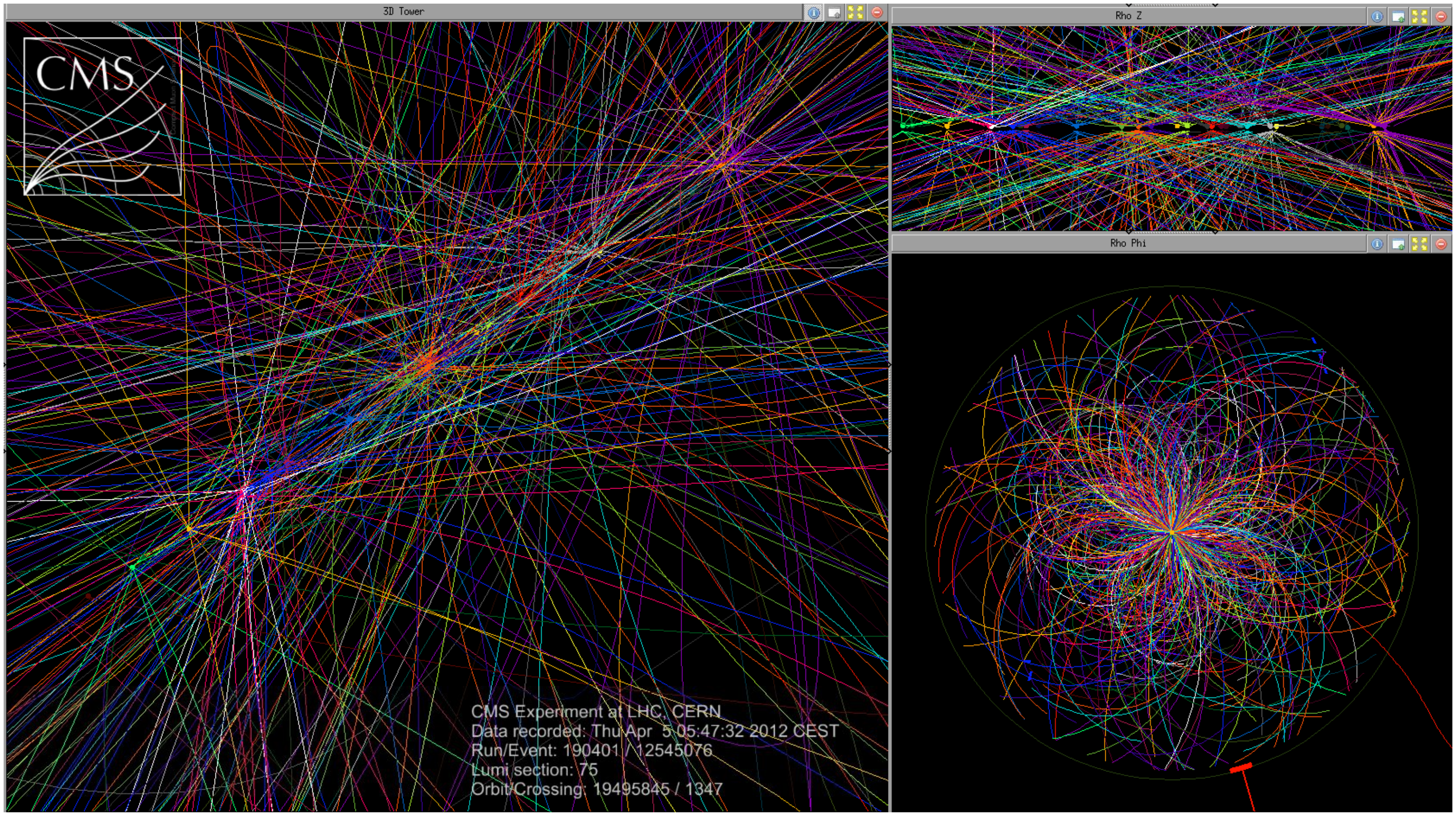
Overall pattern of charged particles in an event

For each track:

- momentum
- direction
- displacement w.r.t. the primary collision
- dE/dx (velocity, charge)
- Cherenkov light, transition radiation

Two-particle invariant mass (derived from above – for discussion section)

Basics of measurements: pattern recognition



Need good multi-track resolution (high segmentation)

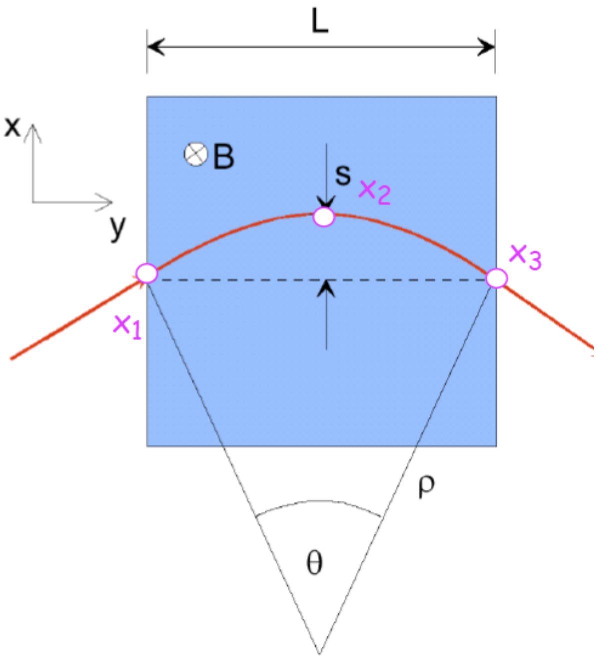
Basics of measurements: momentum

Momentum can be derived from measuring sagitta:

$$\rho = \frac{p_T}{qB}$$

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

$$p_T = \frac{1}{8}\frac{qBL^2}{s}$$



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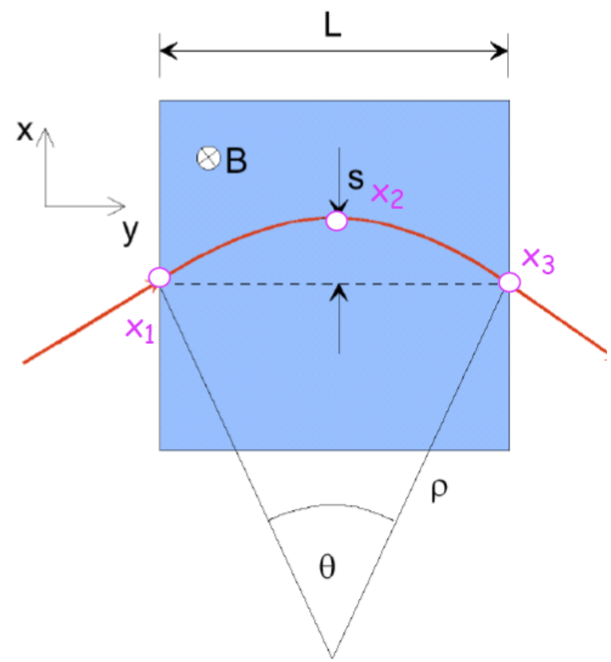
$$p_T = \frac{1}{8}\frac{qBL^2}{s}$$



Error in measuring sagitta → error in measuring p_T

$$\frac{\delta p_T}{p_T} = -\frac{\delta s}{s}$$

$$\frac{\sigma_{p_T}}{p_T} = \frac{\sigma_s}{s}$$

Basics of measurements: momentum

Assume three measurements only: x_1, x_2, x_3

Instrumental errors in measuring x:

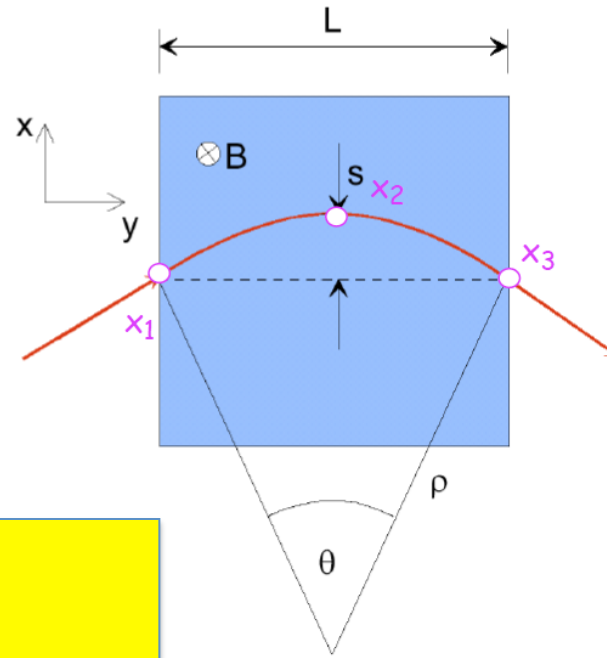
$$s = x_2 - \frac{x_1 + x_3}{2}$$

$$\delta s = \delta x_2 - \frac{1}{2}\delta x_1 - \frac{1}{2}\delta x_3$$

$$\sigma_s = \sqrt{\frac{3}{2}}\sigma_x$$

$$\frac{\sigma_{p_T}}{p_T} = \sqrt{\frac{3}{2}}\frac{\sigma_x}{s} = \sqrt{96}\,\frac{\sigma_x}{qBL^2}\cdot p_T$$

errors grow with p_T
large field helps as 1/B
large volume helps as $1/L^2$



$$s = \frac{1}{8}\frac{qBL^2}{p_T}$$

Basics of measurements: momentum

Assume three measurements only: x_1, x_2, x_3

Instrumental errors in measuring x:

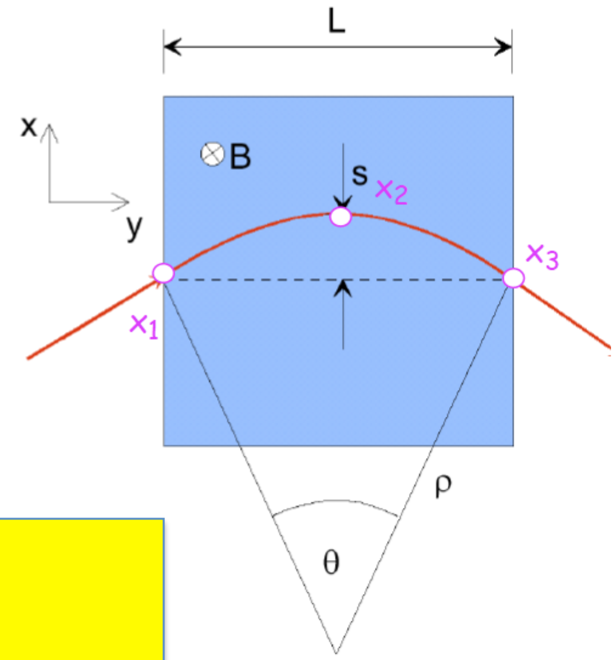
$$s = x_2 - \frac{x_1 + x_3}{2}$$

$$\delta s = \delta x_2 - \frac{1}{2}\delta x_1 - \frac{1}{2}\delta x_3$$

$$\sigma_s = \sqrt{\frac{3}{2}}\sigma_x$$

$$\frac{\sigma_{p_T}}{p_T} = \sqrt{\frac{3}{2}}\frac{\sigma_x}{s} = \sqrt{96}\,\frac{\sigma_x}{qBL^2}\cdot p_T$$

errors grow with p_T
large field helps as 1/B
large volume helps as $1/L^2$



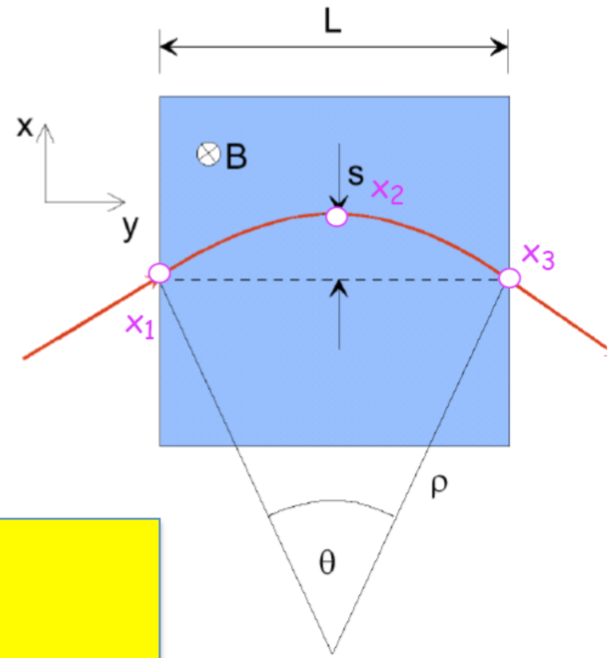
$$s = \frac{1}{8}\frac{qBL^2}{p_T}$$

For a large number N of measurements along the track:

$$\frac{\sigma_{p_T}}{p_T} == \sqrt{\frac{720}{N+4}}\,\frac{\sigma_x}{qBL^2}\cdot p_T$$

Basics of measurements: momentum

Assume three measurements only: x_1, x_2, x_3



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$$\frac{\sigma_{p_T}}{p_T} = \sqrt{\frac{3}{2}}\frac{\sigma_x}{s} = \sqrt{96}\,\frac{\sigma_x}{qBL^2}\cdot p_T$$

errors grow with p_T
large field helps as 1/B
large volume helps as $1/L^2$

Multiple scattering:

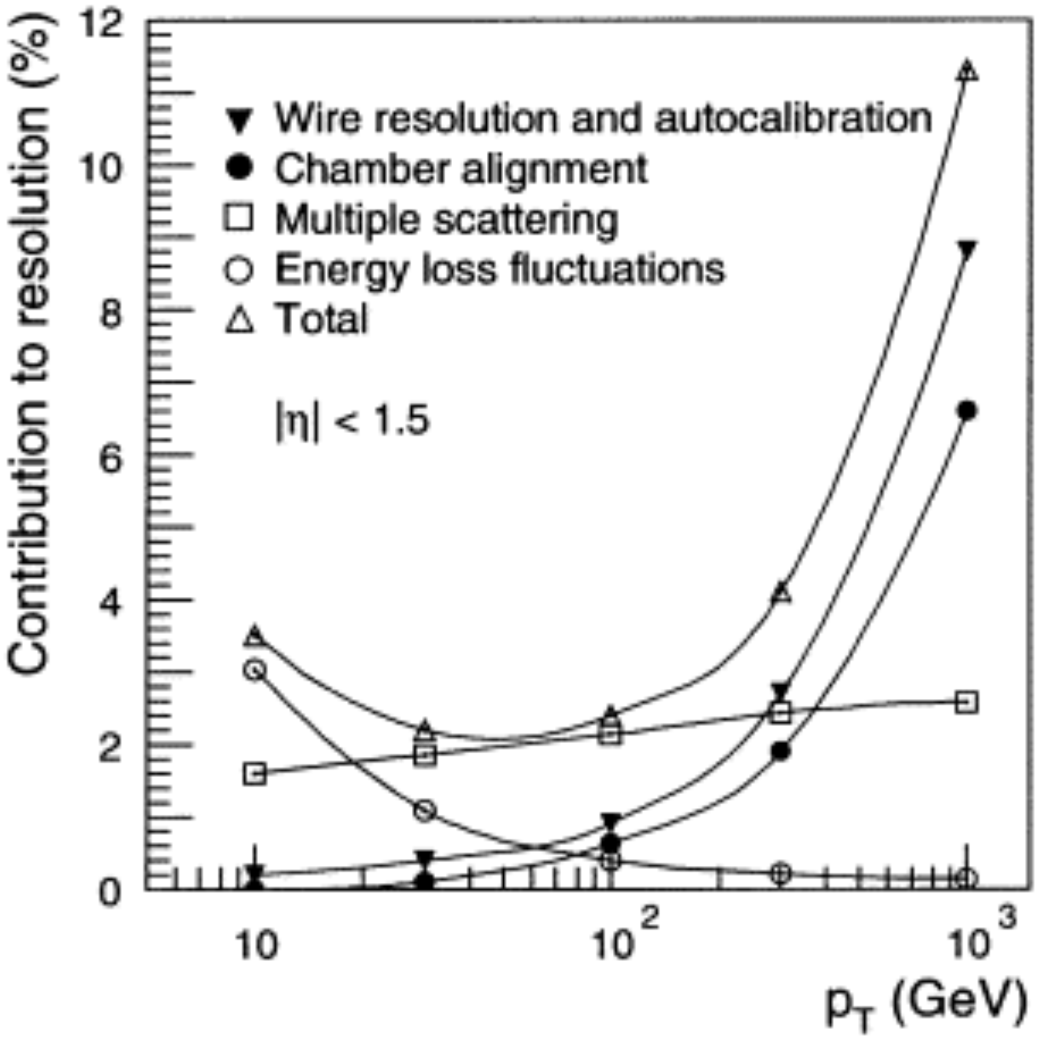
$$\sigma_s \sim \frac{q}{\beta p_T}\sqrt{\frac{L}{X_0}}\cdot L$$

$$\frac{\sigma_{p_T}}{p_T} = \frac{\sigma_s}{s} \sim \frac{1}{\beta BL}\sqrt{\frac{L}{X_0}}$$

errors are p_T independent
large field helps as 1/B
large volume helps as 1/L (for a fixed L/X_0)

$$s = \frac{1}{8}\frac{qBL^2}{p_T}$$

Basics of measurements: momentum



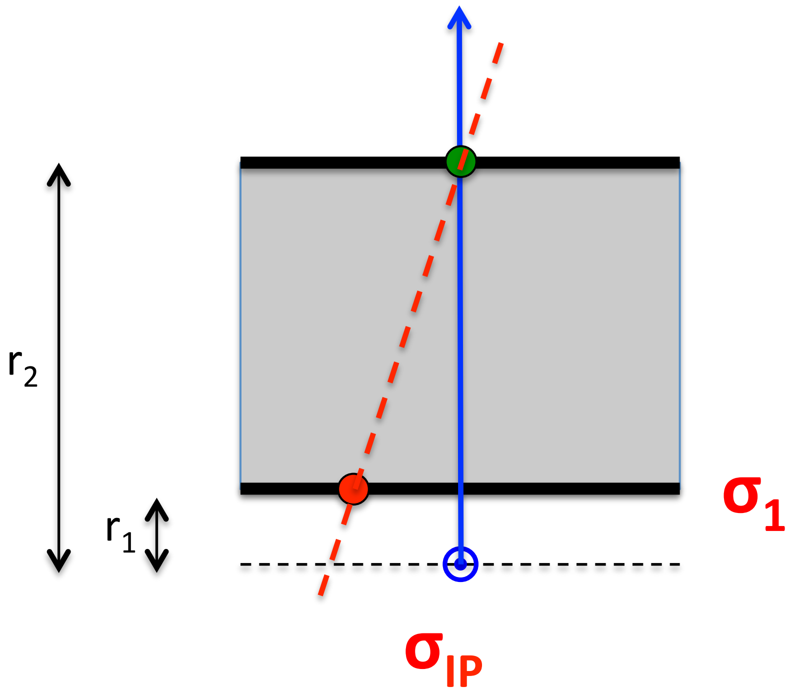
Basics of measurements: invariant mass

Measurement of invariant mass of two particles depends on measurements of

- their momenta
- and their directions (opening angle)

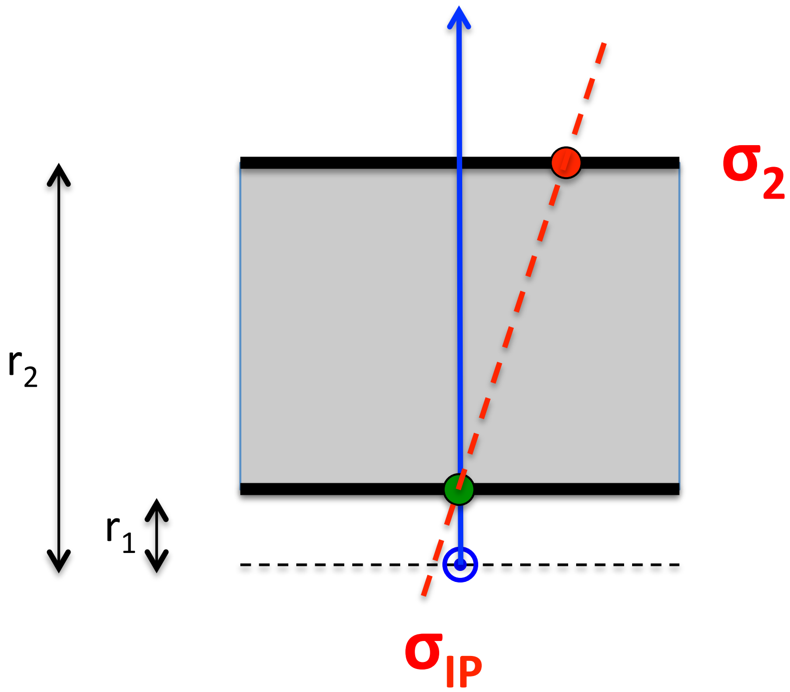
Topic for the discussion session today:
What is driving the two-particle mass resolution?

Basics of measurements: impact parameter (inner layer meas. errors)



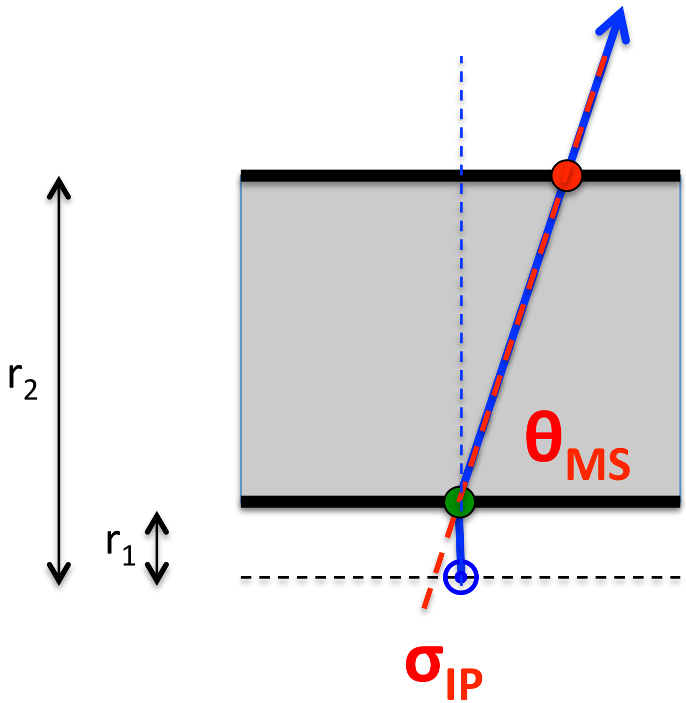
$$\sigma_{IP} = \frac{r_2}{r_2 - r_1} \cdot \sigma_1$$

Basics of measurements: impact parameter (outer layer meas. errors)



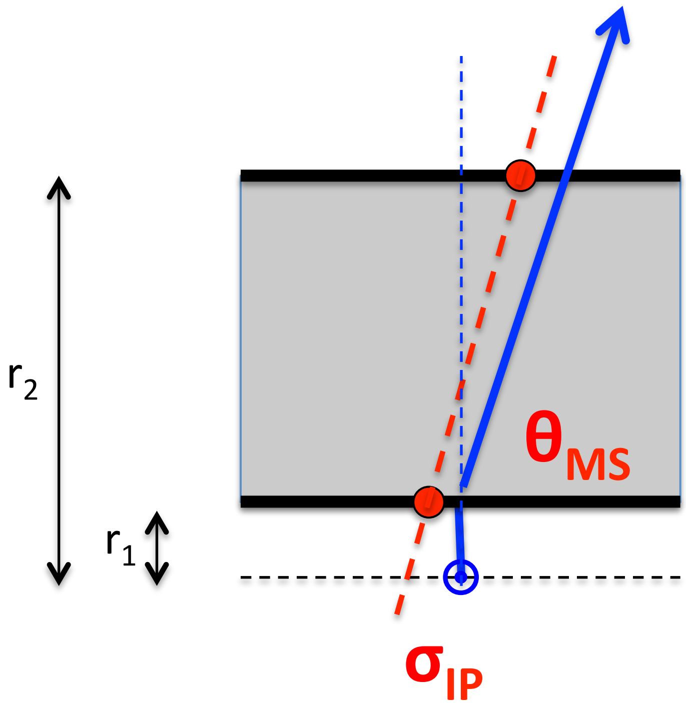
$$\sigma_{IP} = \frac{r_1}{r_2 - r_1} \cdot \sigma_2$$

Basics of measurements: impact parameter (multiple scattering)



$$\sigma_{IP} = r_1 \cdot \theta_{MS} = r_1 \cdot \frac{14\ \text{MeV}}{p}\sqrt{\frac{L}{X_0}}$$

Basics of measurements: impact parameter (putting all together)



$$\sigma_{IP} = \frac{r_2}{r_2 - r_1} \cdot \sigma_1 \oplus \frac{r_1}{r_2 - r_1} \cdot \sigma_2 \oplus r_1 \cdot \frac{14\ \mathrm{MeV}}{p} \sqrt{\frac{L}{X_0}}$$

Desired detector properties

- σ_1 small
- r_1 close
- multiple scattering low (improves as 1/p)

Historic preamble

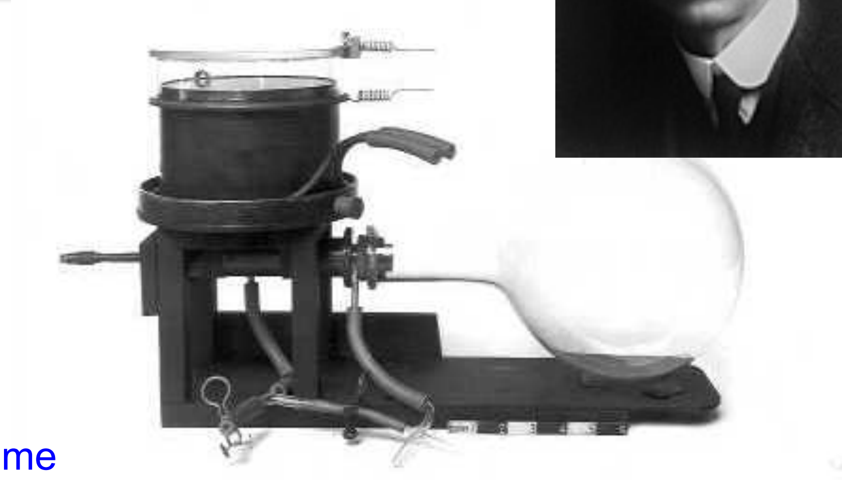
The age of photographing events:

- Cloud chamber
- Emulsion
- Bubble chamber

Cloud chamber

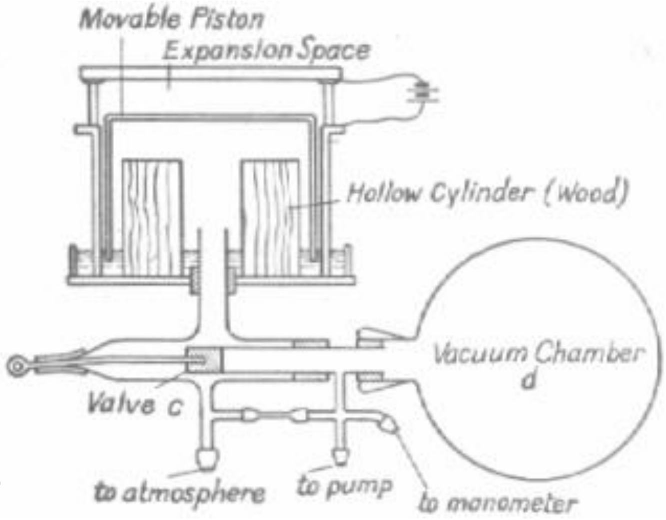
Invented by Charles Wilson in 1899. Nobel prize in 1927
"*for his method of charged particles detection*"

Used through mid-1950s



Principle:

- chamber with oversaturated vapor
- oversaturation is set by fast expansion of the volume
- ionization clusters left behind by a charged particle become centers of condensation
- droplets can be photographed



Basic performance parameters:

- moderate spatial resolution (mm)
- small/moderate volume (up to ~1 m)
- slow (a few pictures per min)
- measure
  - p from curvature of track in magnetic field: $R \sim 1/p$
  - v from ionization density: $dE/dx \sim 1/v^2$

Cloud chamber

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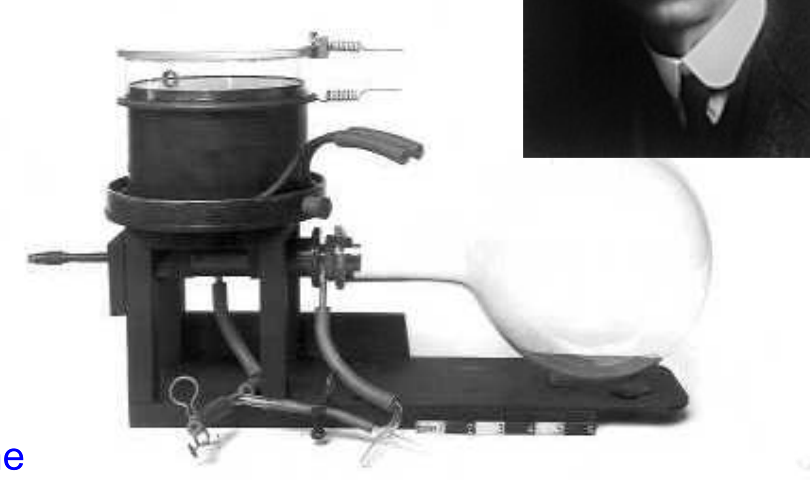

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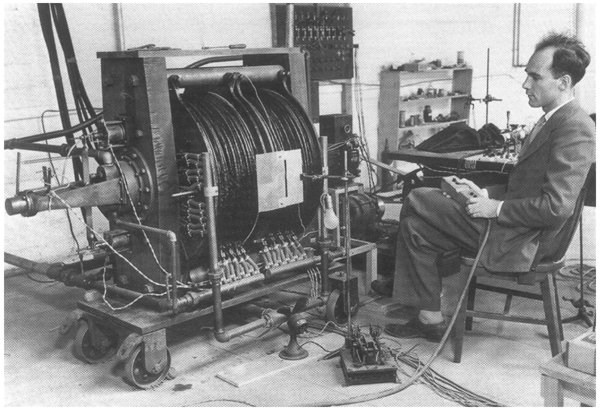
Discovery of positron in cloud chamber

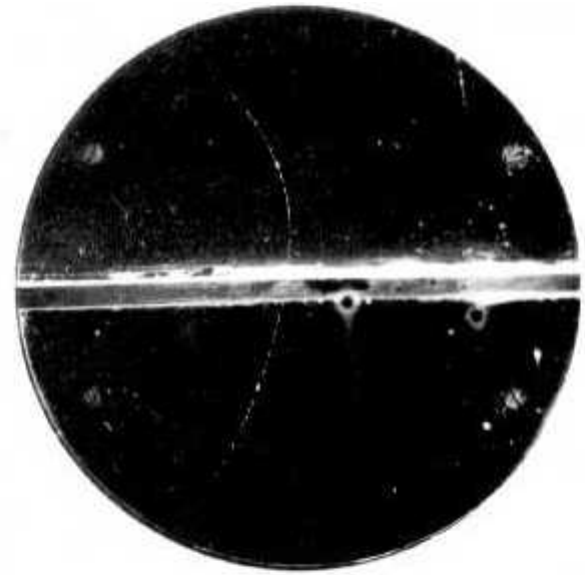
Carl Anderson discovered positron in 1932.

Nobel prize in 1936 "*for his discovery of antimatter when he observed positrons in a cloud chamber*"



Photograph shows:

- a single track crosses the lead plate in the middle
- the track is bent by a magnetic field pointing into the picture
- curvature of the track is higher in the upper portion, which means momentum is smaller there
- hence, particles goes upward and its **charge is positive**
- proton, the only known positively charged particle at that time, with the measured momentum would
    - have very low velocity
    - produce much higher ionization density along the track ($1/v^2$)
    - lose much more energy in the lead plate
- the only possible explanation: **particle's mass must be much smaller than proton's and comparable to electron's mass**



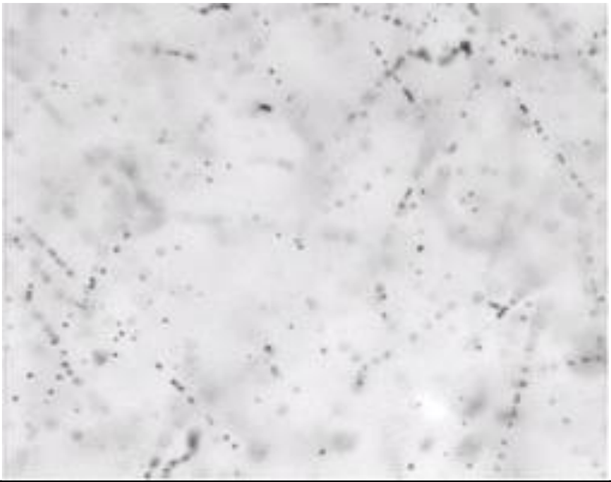
Emulsion

Developed by C. F. Powell in mid-1940. Nobel prize in 1950 “for his development of the photographic method of studying nuclear processes and his discoveries regarding mesons made with this method ”

Still used in some very specialized experiments

Principle:

- a few mm thick emulsion with AgBr molecules
- ionization breaks up these molecules
- in process of developing, released silver is locked in the emulsion, while the remainder is washed out
- silver grains, half-a-micron in size, can be seen in microscope and photographed



Basic performance parameters:

- unsurpassed spatial resolution (0.2 μm)
- very small volume
- continuously records everything passing through
- painstaking analysis of the record
- measure
  - p from multiple scattering: $d\theta \sim 1/p$
  - v from ionization density: $dE/dx \sim 1/v^2$

Discovery of pion

In 1947 using emulsions, Powell's team observes a new π-meson that

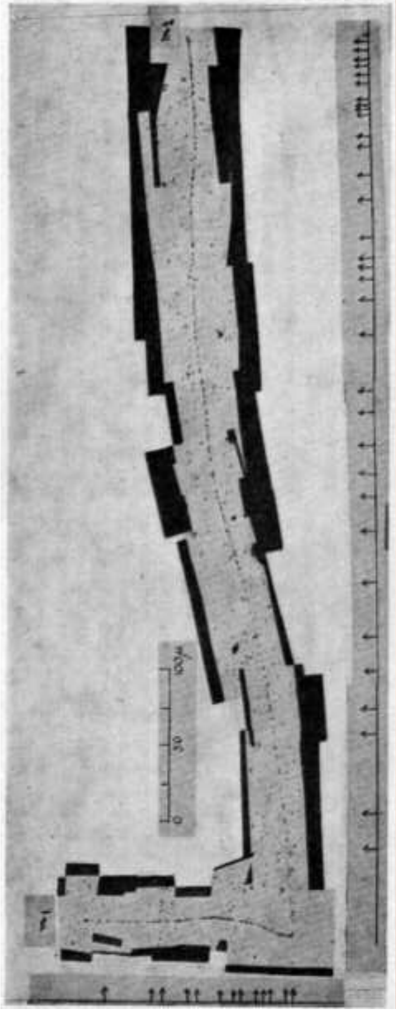
- decays to μ-meson (discovered by Anderson in 1937 using a cloud chamber): π ➔μ + neutral
- can be born in nuclear disintegration and can lead to nuclear disintegration

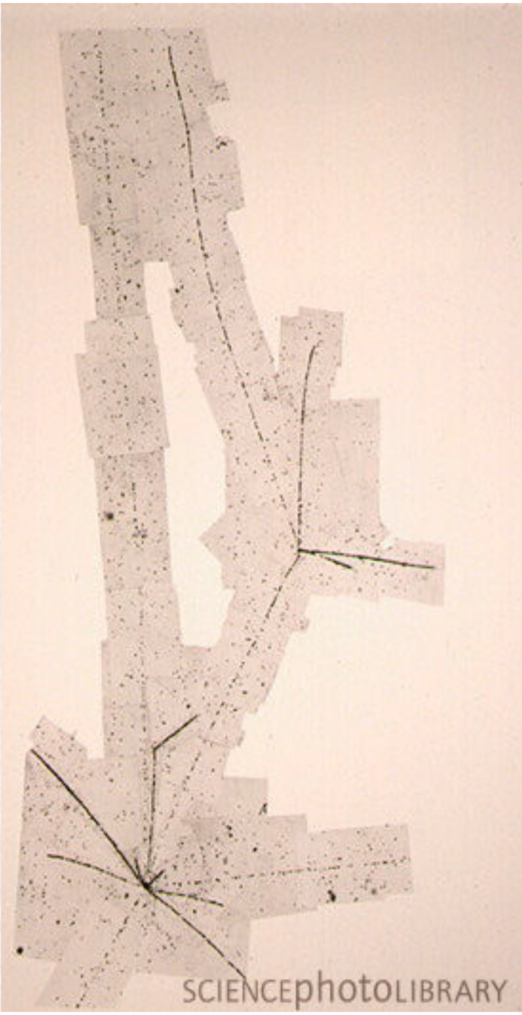
Left photograph shows:

- Meson π enters from left, slows down (grain count: $1/v^2$; multiple scattering: $1/p$), and stops
- at the stop point, a new fast meson μ appears (grain count; multiple scattering) travels upward, slows down, and exits emulsion just before stopping

Right photograph shows:

- Meson enters from above (left), slows down, disintegrates nucleus
- a few high velocity mesons emerge
- one of them moves up-right, slows down, stops, and disintegrates another nucleus
- yet another high velocity meson appears and moves upward, slows down, and exits emulsion

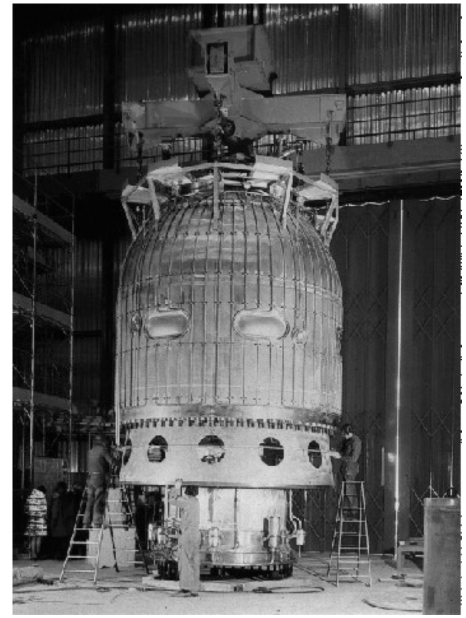


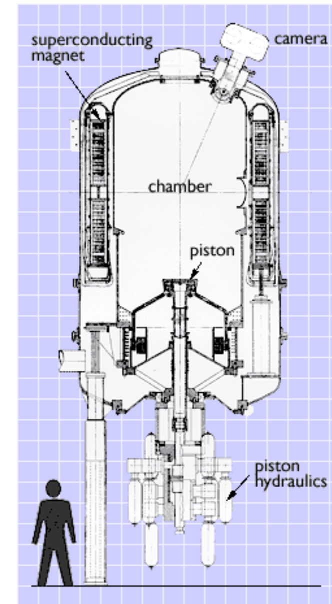


Bubble chambers

Invented by Donald Glaser in 1952. Nobel prize in 1960
“for the invention of the bubble chamber ”

Used till 1980s,
still used in very specialized experiments (e.g. COUPP)





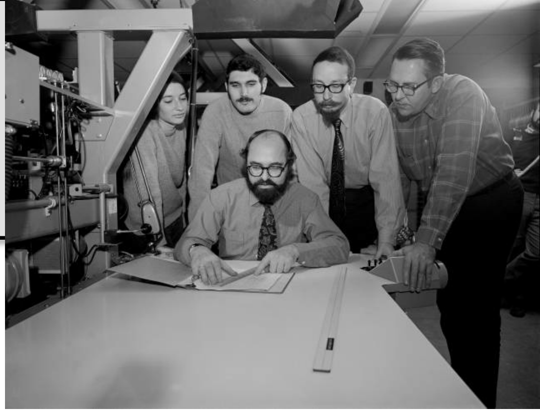
Principle:

- pressurized liquid (e.g. liquid hydrogen at 5 atm) just below the boiling point
- overheated state is set by a fast drop of pressure
- ionization clusters left behind by a charged particle become centers of bubble formation (boiling)
- bubbles are photographed
- pressure is applied to prevent real boiling

Basic performance parameters:

- good spatial resolution (100 μm)
- moderate/large volume (up to a few m^3)
- slow (tens of pictures per second)
- measure
  - p from curvature of track in magnetic field
  - v from ionization density

Discovery of Ω^-



In 1962, Gell-Mann and Ne'eman predict Ω^- (last particle in the J=3/2 decuplet of baryons) with well specified properties:

- mass ~ 1680 MeV
- spin = 3/2
- isospin = 0
- strangeness = -3
- lifetime ~ 10^{-10} s
- main decay modes: $\Xi^0\ \pi^-$ and $\Xi^-\ \pi^0$

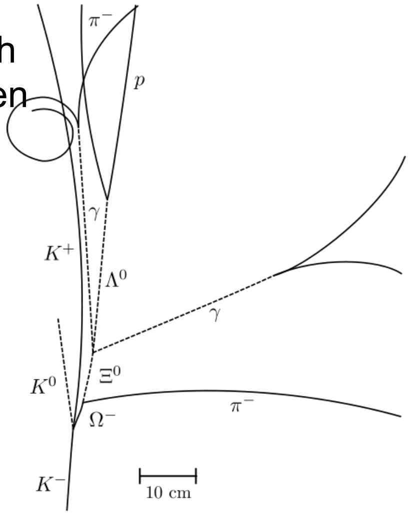
In 1964, Ω^- is discovered in a bubble chamber photograph of a Kp interaction event at AGS accelerator in Brookhaven

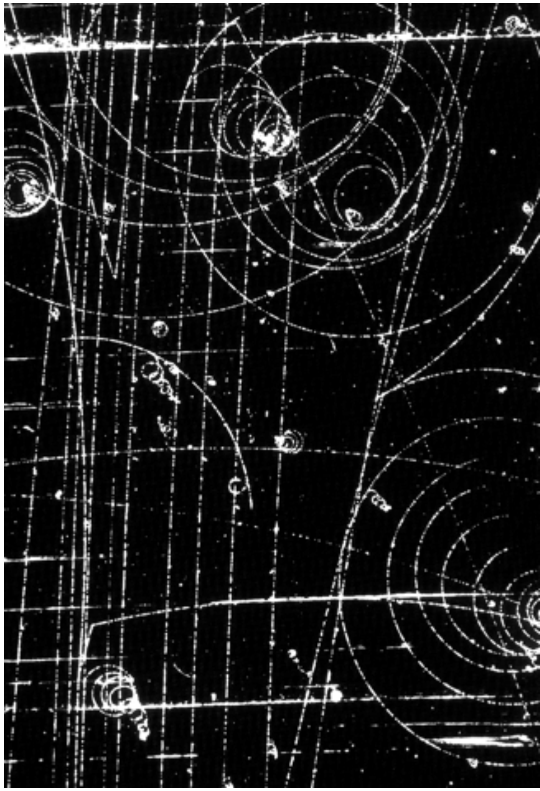
$$\underset{\bar{u}s}{K^-} + \underset{uud}{p} \rightarrow \underset{sss}{\Omega^-} + \underset{u\bar{s}}{K^+} + \underset{d\bar{s}}{K^0}$$

$$\underset{sss}{\Omega^-} \rightarrow \underset{uss}{\Xi^0} + \underset{\bar{u}d}{\pi^-}$$

$$\underset{uss}{\Xi^0} \rightarrow \underset{uds}{\Lambda^0} + \pi^0$$

$$\underset{uds}{\Lambda^0} \rightarrow \underset{uud}{p} + \underset{\bar{u}d}{\pi^-}$$





Summary

We track 5 charged particles: e, μ, π, K, p

Tracking is made possible thanks to: ionization trail (sometimes we also use light)

The ionization trail itself: all high energy particles look alike! (mip)

We reconstruct (with errors!):

- overall pattern of charged particles in an event
- momentum of particles
- origin of particles (looking for displaced tracks – telltale signs of b/c/τ)
- sometimes subtle signs helping to distinguish e/μ/π/K/p: dE/dx, extra photons