Detectors for High-Energy Experiments

High Energy Accelerator Research Organization/J-PARC
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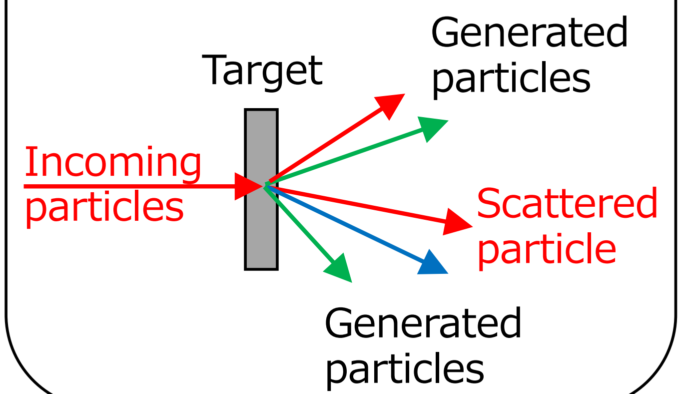
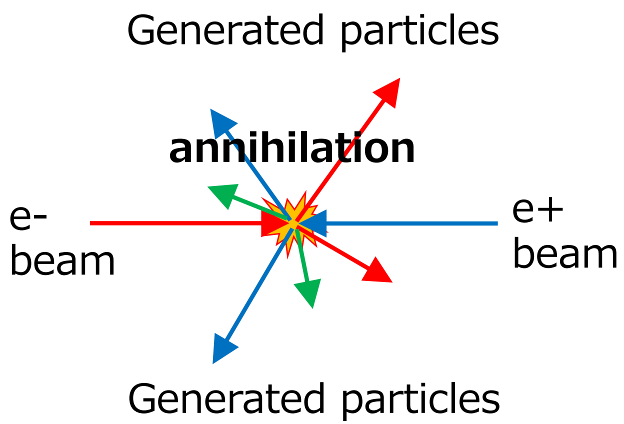
0. Brief Introduction of Colliders

Colliders make head-on collision of beams.

Fixed Target Exp.



e+ e- Colliders



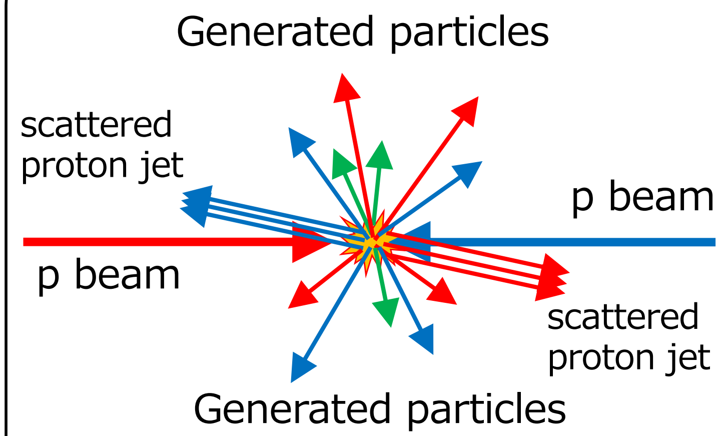
$e+\ e- \rightarrow \gamma \rightarrow$ generated particles

Z^0

etc.

beam :
bunch of billions of particles

Hadron Colliders



Gluons inside of the proton collides, emits a lot of quarks and gluons, and they hadronise into observed baryons.

0. Brief Introduction of Colliders

Colliders can achieve high E_{CM} ;

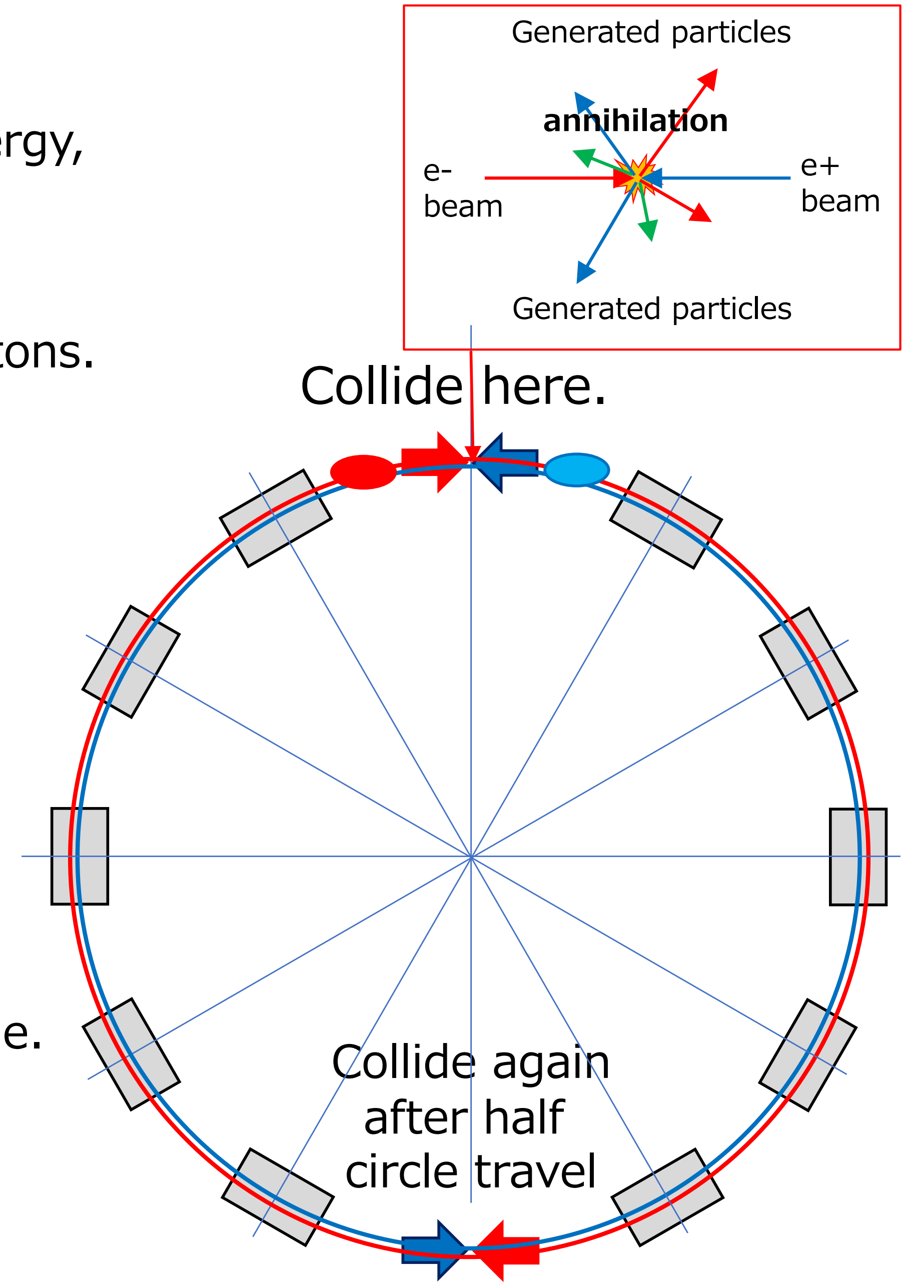
- Particle and anti-particle collision make all their energy, including their rest mass, available for reaction.

$$E_{CM} = Ee- + Ee+$$

- Positrons can be made easily compared to anti-protons.

→ e+e- collider was the first collider (AdA, 1964)

For fixed target experiment, $E_{CM} = \sqrt{2m_T E_{beam}}$



Features

- Circulate beam many times along the circular orbit, and make beams collide many times.
- Particle and anti-particle of the same energy can circulate on the same orbit in opposite direction.
  → Just one set of magnets and vacuum beam pipes.
- Can do experiment at plural locations at the same time.
  - Collision at 12:00 location, and at 6:00 location with one e+ bunch and one e- bunch.
  - More bunches give more collision point.

0. Brief Introduction of Colliders

Luminosity indicates reaction rate.

For the fixed target experiment

cross section ↓

$$N\ [s^{-1}] = N_{beam}\ [/s^{-1}]\ x\ N_{target}\ [/cm^{-2}]\ \ x\ \sigma\ [cm^2]$$

↑ Target is much bigger then beam size。 → beam size does not matter.

Note that above looks a bit different from neutrino case since beam size is bigger than the target in neutrino case.

For colliders, reaction rate N is

cross section ↓

$$N\ [s^{-1}] = \mathcal{L}\ [cm^{-2}s^{-1}]\ x\ \sigma\ [cm^2]$$

↑ **Luminosity** This determines the reaction rate.

$$\mathcal{L} = \frac{N_{e+}\ N_{e-}}{4\pi\ \sigma_x\ \sigma_y}\ f$$

collision frequency ↓ (f)

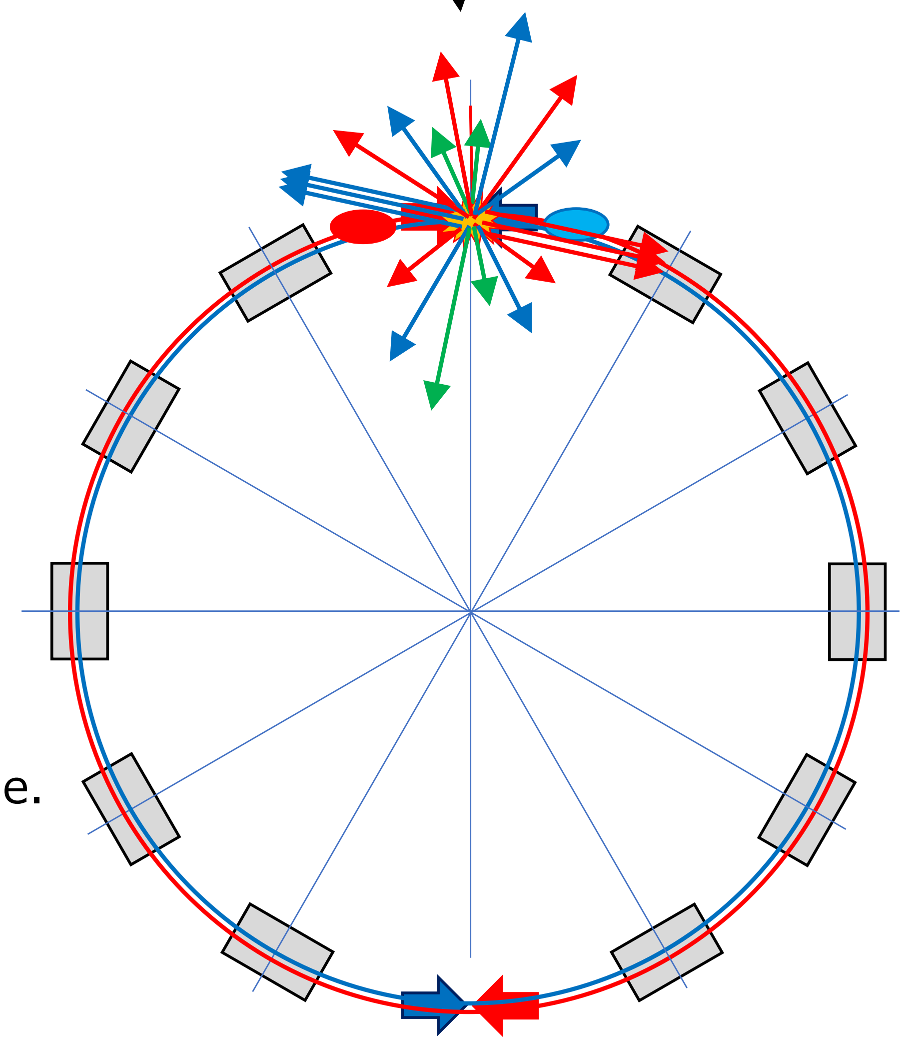
↑ ↑ Beam sizes (σ_x, σ_y)

It is trivial that intense beam gives high reaction rate.

Smaller beam size gives higher density of the beam, and number of "target particle" increases.

0. Brief Introduction of Colliders

Many particles are generated at the collision point,
and fly away to various directions.
We need to detect all those particles
and reconstruct what reaction happened.
→ Make detector surrounding the collision point.



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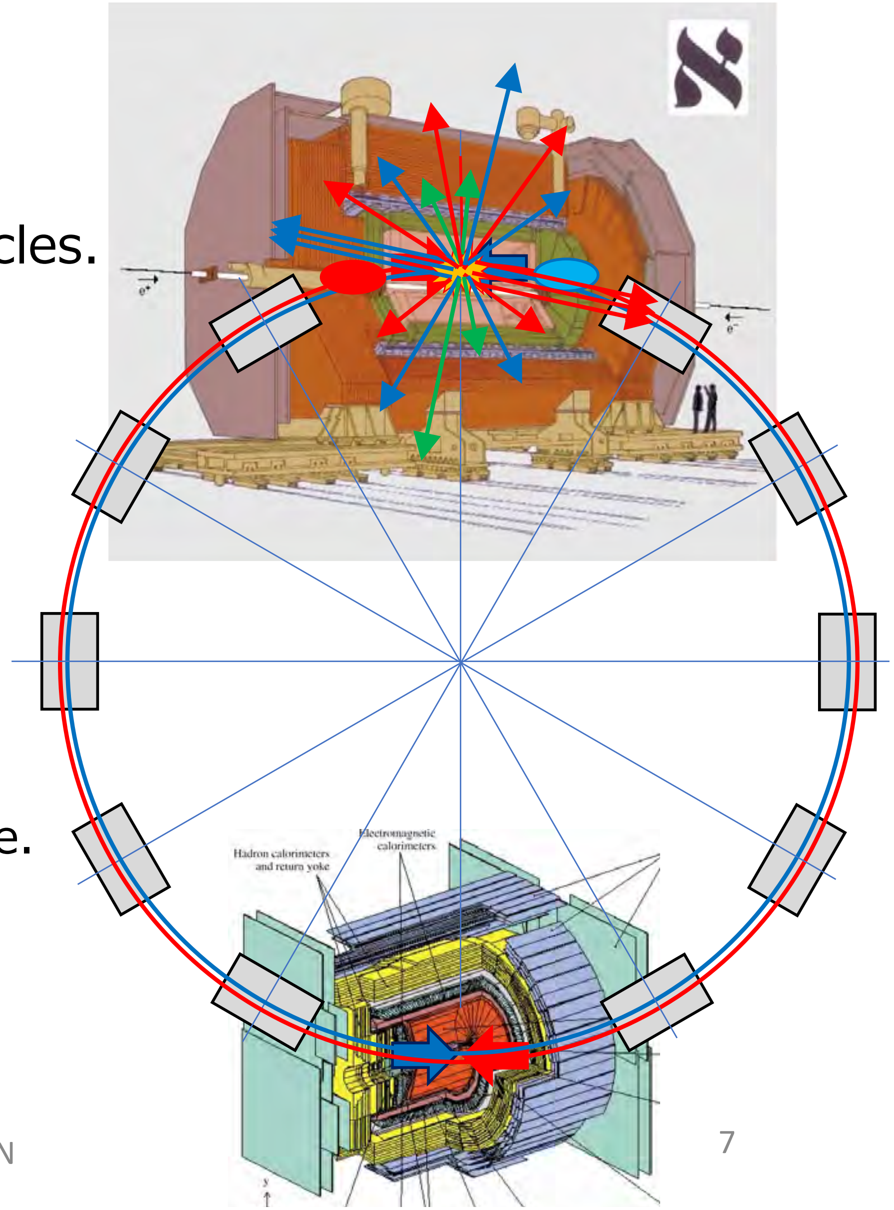
0. Brief Introduction of Colliders

Many particles are generated at the collision point, and fly away to various directions.
We need to detect all those particles and reconstruct what reaction happened.
→ Make detector surrounding the collision point and detect/measure all of the generated particles.

This is the collider detector.



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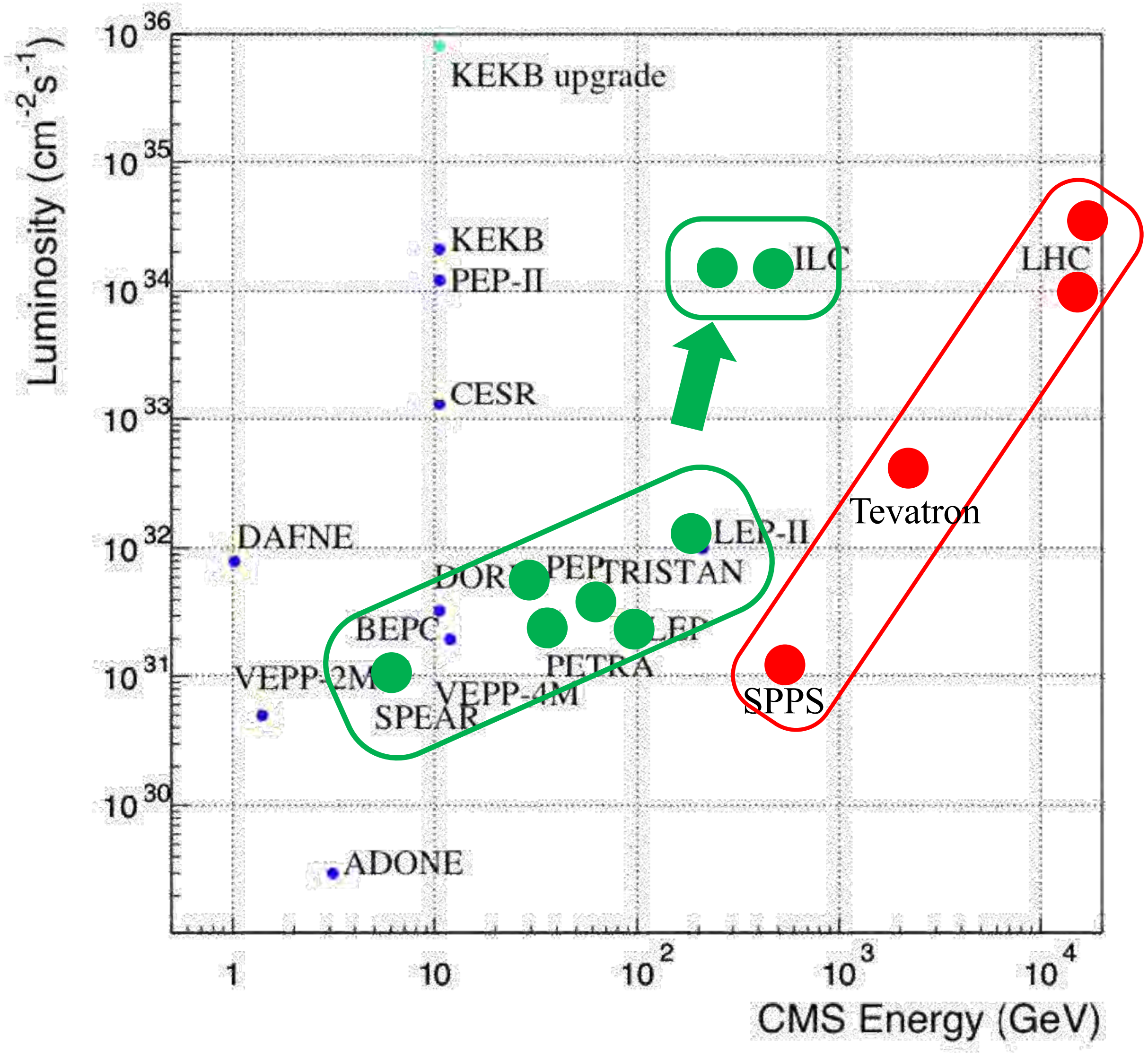
0. Brief Introduction of Colliders

<u>At present highenergy experiments,</u>

Discoveries by *pp* ($p\bar{p}$) collider ●
- Higher energy
- Difficult analysis but do it.

Precision study by e+e- collider ●
- Elementary process suitable for precise analysis

Both colliders were competing to each other before.
After LEP-II, e+e- colliders of higher energy is not realized yet.



大西幸喜氏「KEKB加速器アップグレード計画SuperKEKB」より転載、加筆

1. Overview the various detector configuration

Understand the purpose and configuration

of the detector system

with examples of the actual collider detectors.

1. Overview the various detector configuration

Let's overview various detectors for particle physics,
and get common sense of the integrated detector system.

> The detector system should measure
> what **kind of particles** are emitted, to which **direction**, with what **energy**
> for every particle generated in the reaction.

For this purpose, we measure

- **direction** → Trackers
- **momentum** → Trackers & magnetic field
- **energy** → Calorimeters

Any experiment needs to measure energy / momentum and direction of generated particles.

- **species** → Vertex, Muon, CAL, and dedicated PID detectors

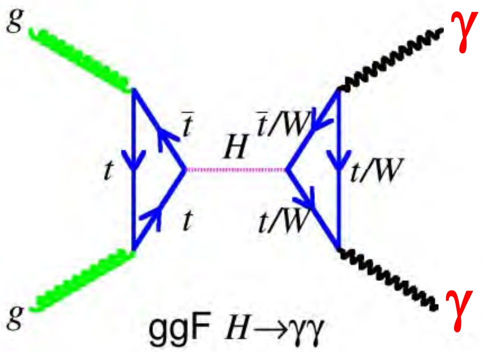
Necessity of particle identification is different experiment by experiment.

for all particles,
being separated from the background particles.

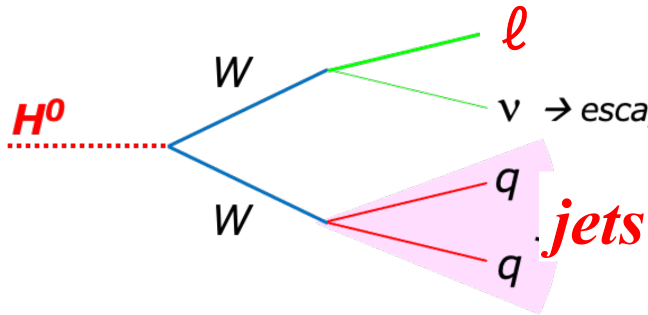
Combinations of various detectors can give you above information.

Common feature of the detector system

- General layout is almost common to many experiments.
- Use characteristics of interaction of particles with matter to measure aimed property.
- We need to measure particles such as ; **e, μ, τ , γ, b, jets, , , and ν as missing P/E.**
- Particle-ID detectors strongly reflect the physics to explore at the experiment.

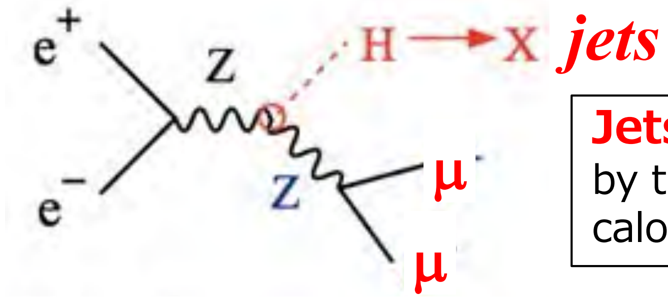


γ measured by EM calorimeters

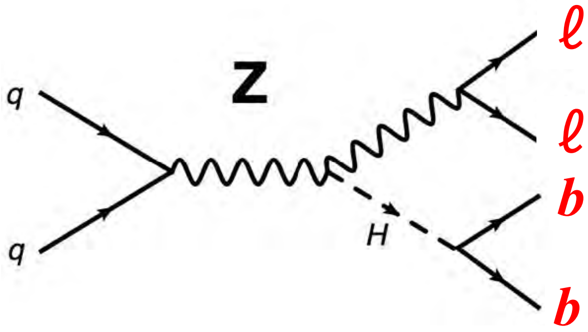


ν as missing P/E

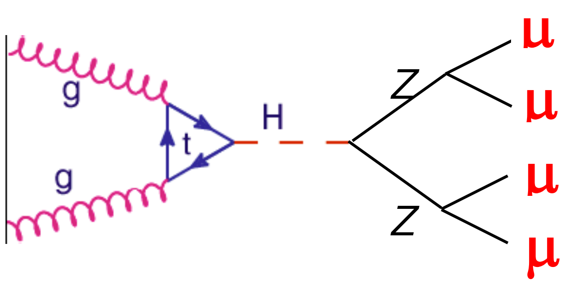
Jets measured by trackers and calorimeters



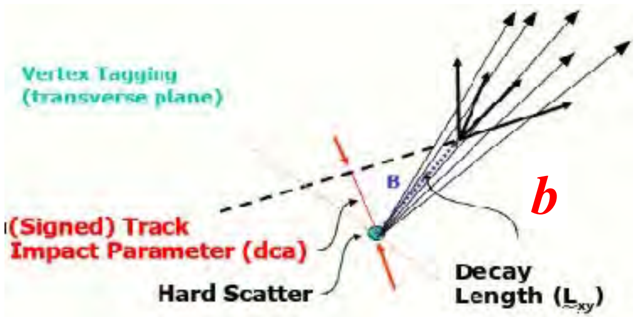
Jets measured by trackers and calorimeters



Leptons measured by trackers, calorimeters, and Muons.



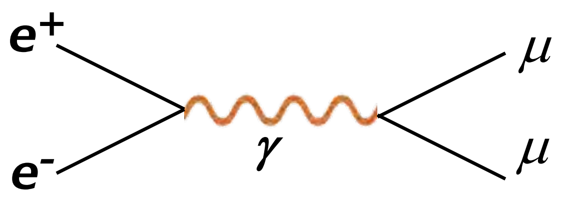
μs measured by muon detectors and trackers



b-quarks identified by vertex detectors.

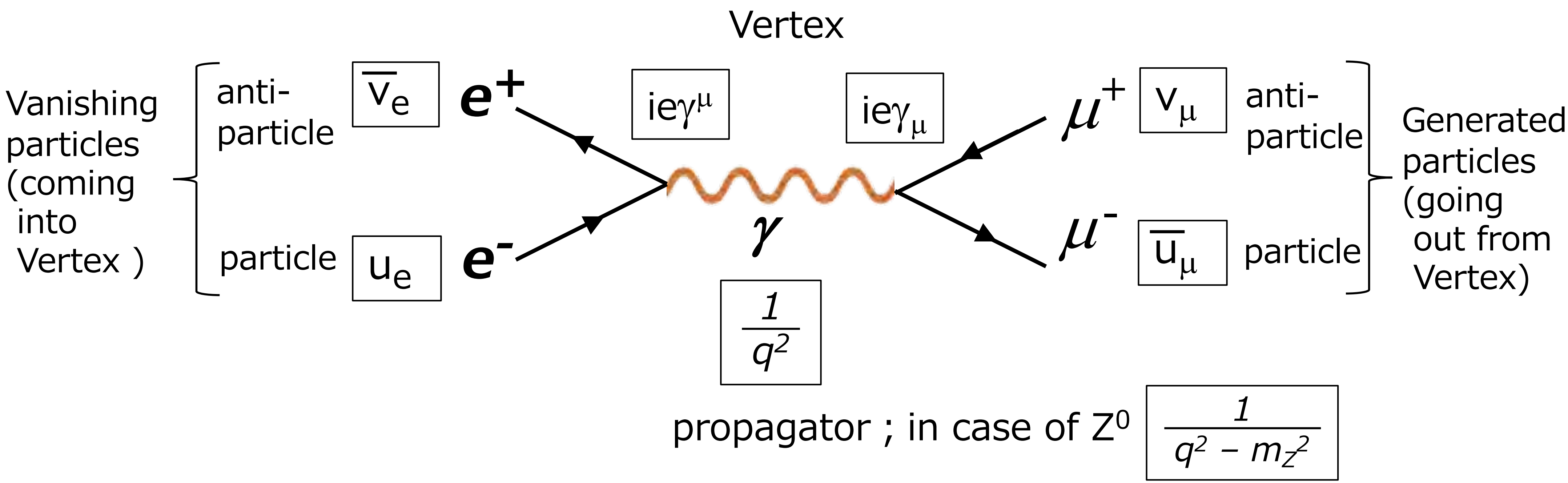
By the way, what is Feynman Diagram ?

Reaction ; e^+e^- → virtual γ → $\mu^+\mu^-$ is expressed by a Feynman diagram

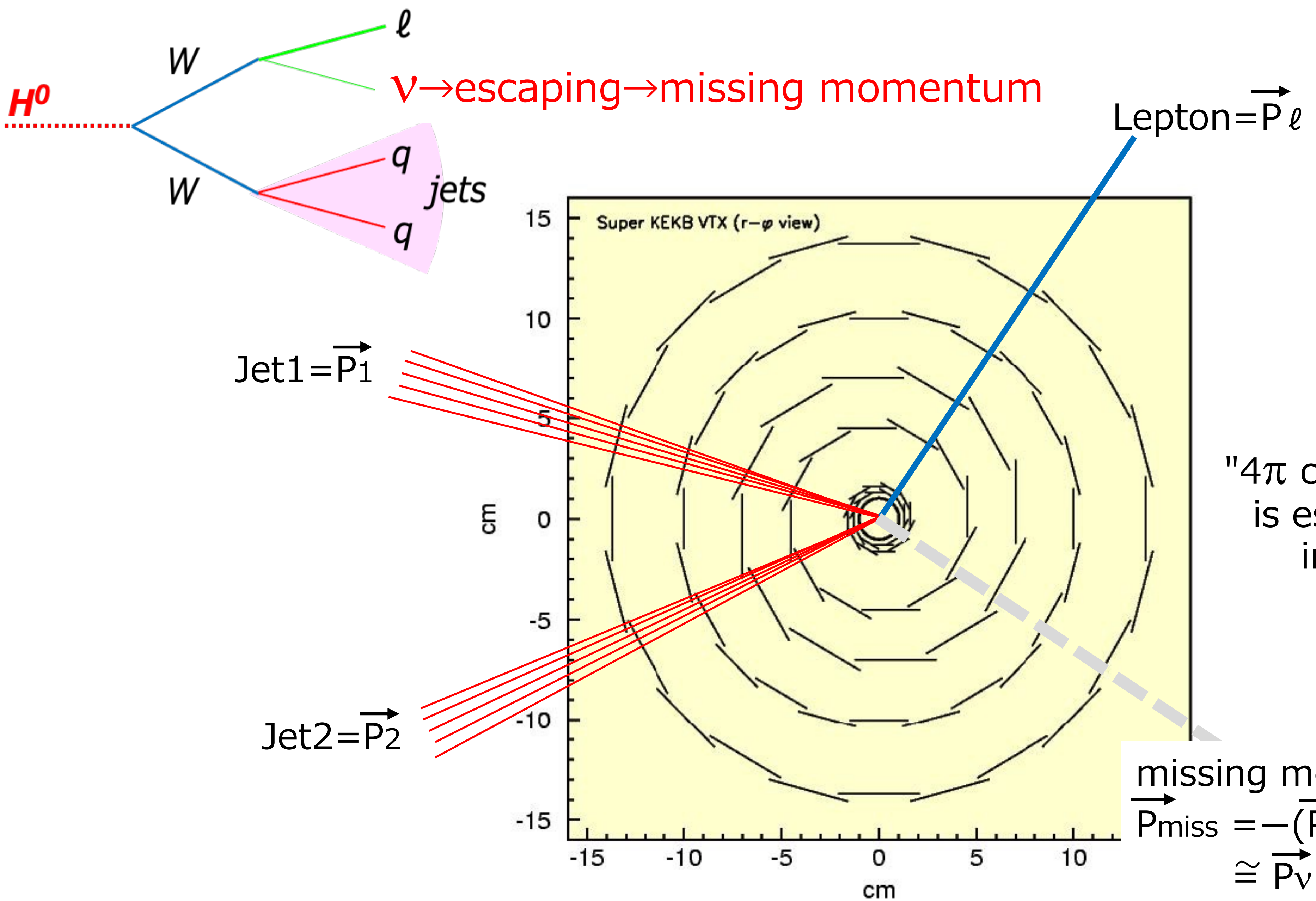


Amplitude $\mathcal{M}$ can be written as

$$\mathcal{M} = -\,(\bar{v}_e\, e\, \gamma^\mu\, u_e)\ \frac{1}{q^2}\ (\bar{u}_\mu\, e\, \gamma_\mu\, v_\mu)$$



By the way, what is missing momentum/energy ?



"4π coverage" is essentially important.

missing momentum

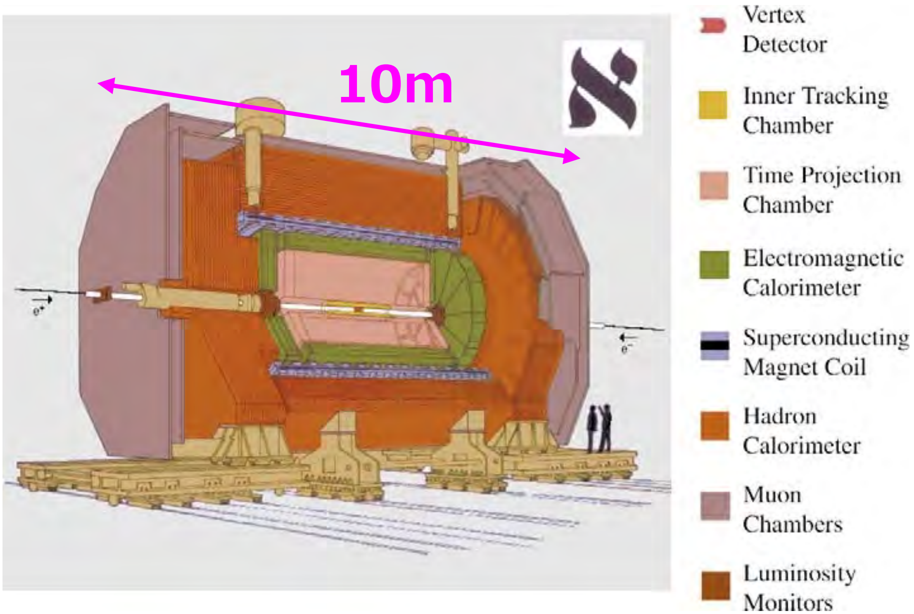
$$\vec{P}_{miss} = -(\vec{P}_1+\vec{P}_2+\vec{P}_\ell) \cong \vec{P}_\nu$$

(if H^0 is generated at rest)

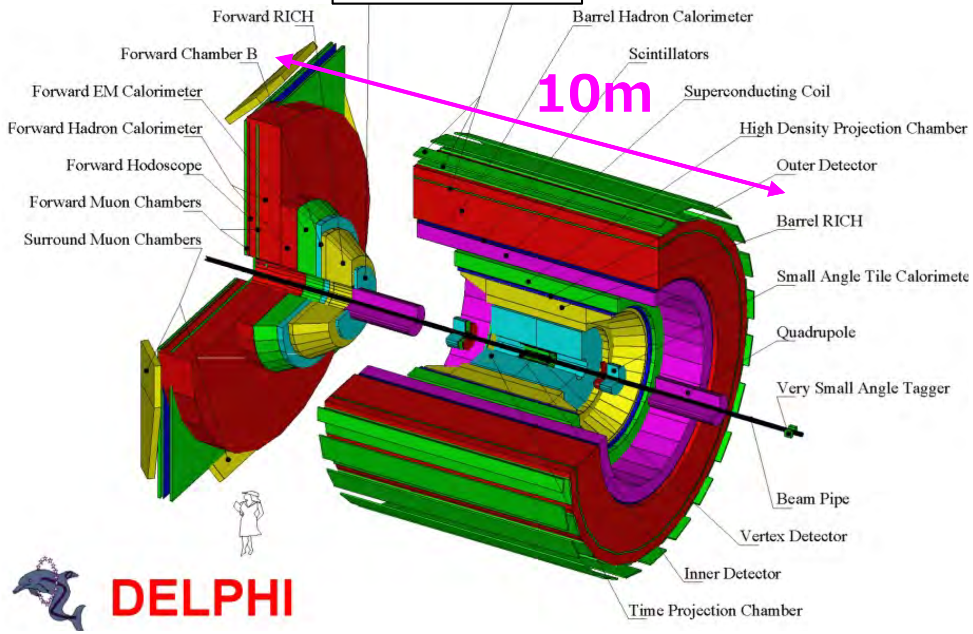
1. Overview the various detector configuration ; LEP

LEP was an e+e- collider at CERN with √S=90-208GeV, operated 1989-2000.

ALEPH



DELPHI



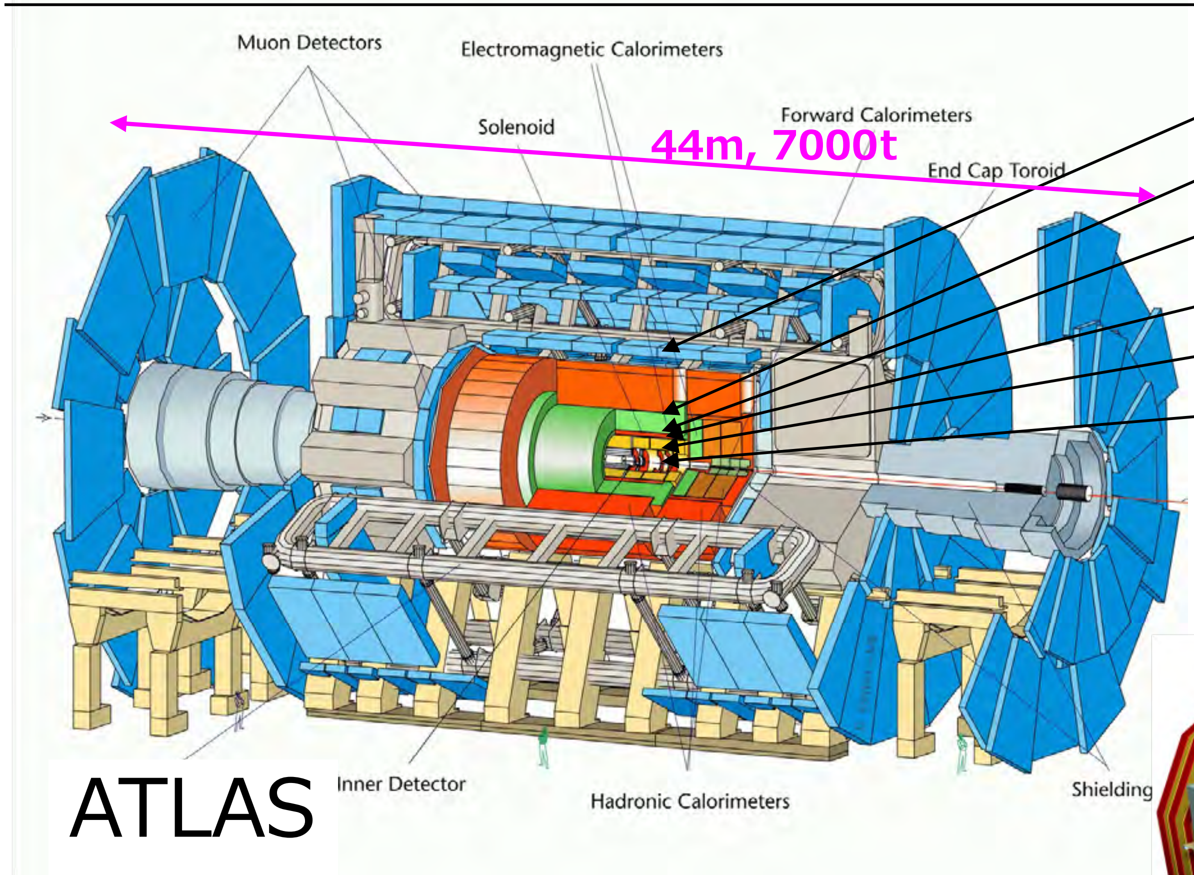
ALEPH:

General-purpose 4π detector
VTX: Si-strip + Drift Chamber
Tracker:TPC
No-dedicated PID
ECAL: High Granularity Pb+Wire Chamber
Solenoid（1.5T）
Hadron Calorimeter
Muon Detector

DELPHI:

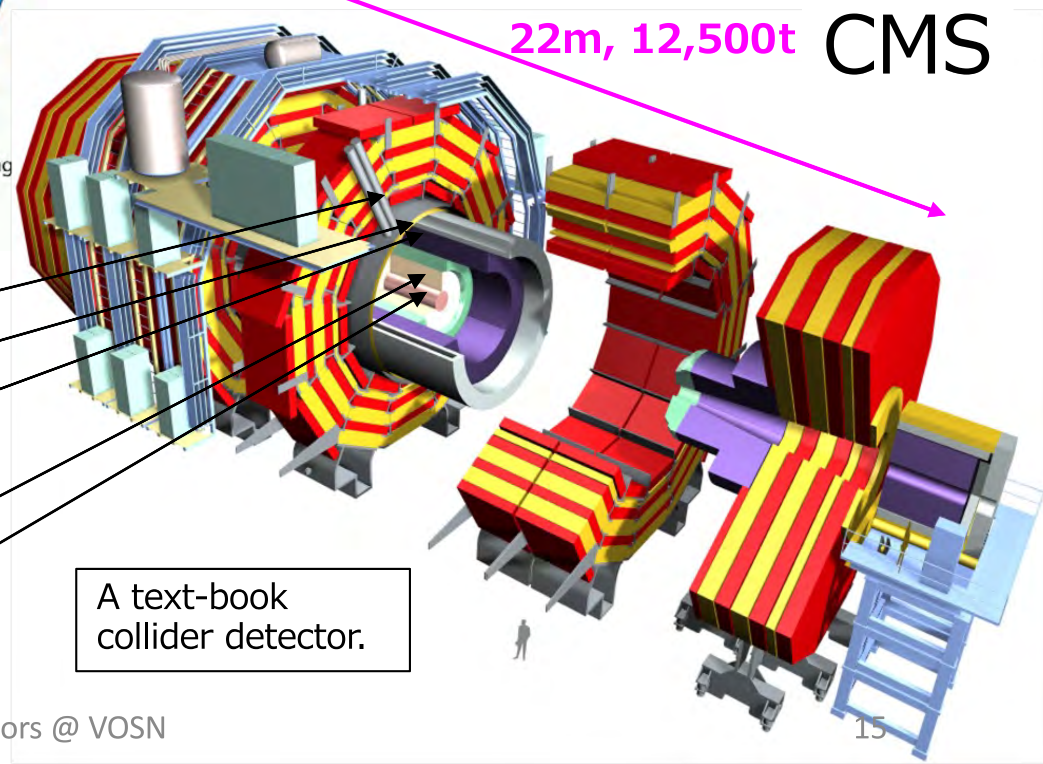
General-purpose 4π detector
VTX: Si-strip
Tracker:TPC
PID : RICH
ECAL: High Granularity Pb+TPC
Solenoid（1.2T）
Hadron Calorimeter
Muon Detector

1. Overview the various detector configuration ; LHC



Muon detector & Troid magnet
Calorimeter ; outside of solenoid
Solenoid（2T）
e-ID
Tracker
Vertex detector

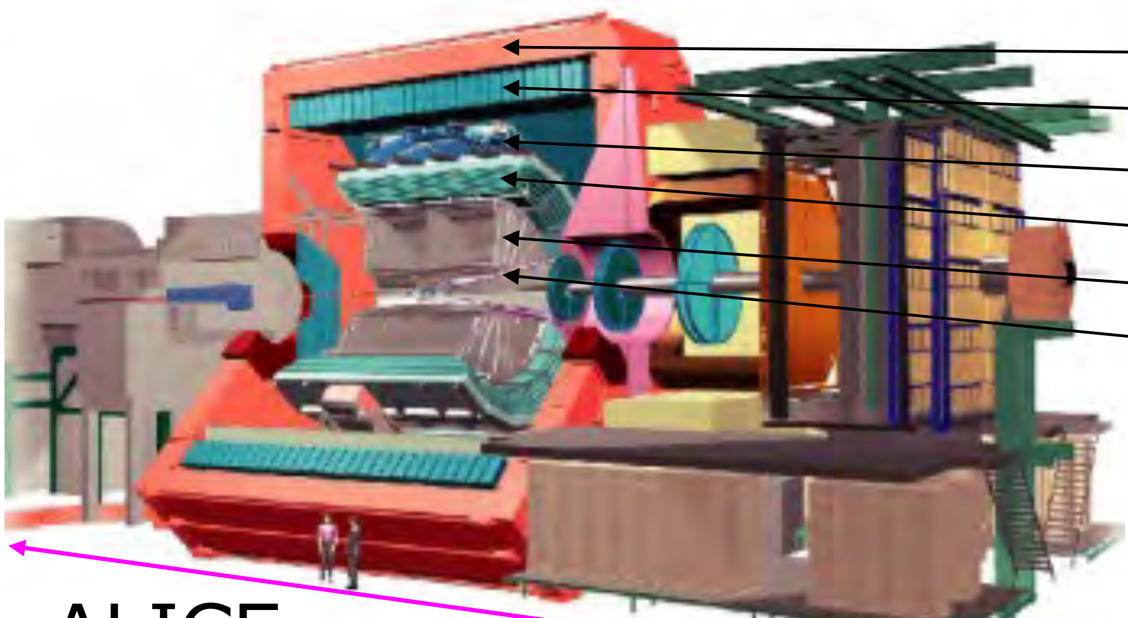
Additional electron identification detector used since thick solenoid is in front of calorimeters.



Muon detector
Solenoid（4T）
Calorimeter
No Dedicated PID
Tracker
Vertex detector

A text-book collider detector.

1. Overview the various detector configuration ; HeavyIon, ILC

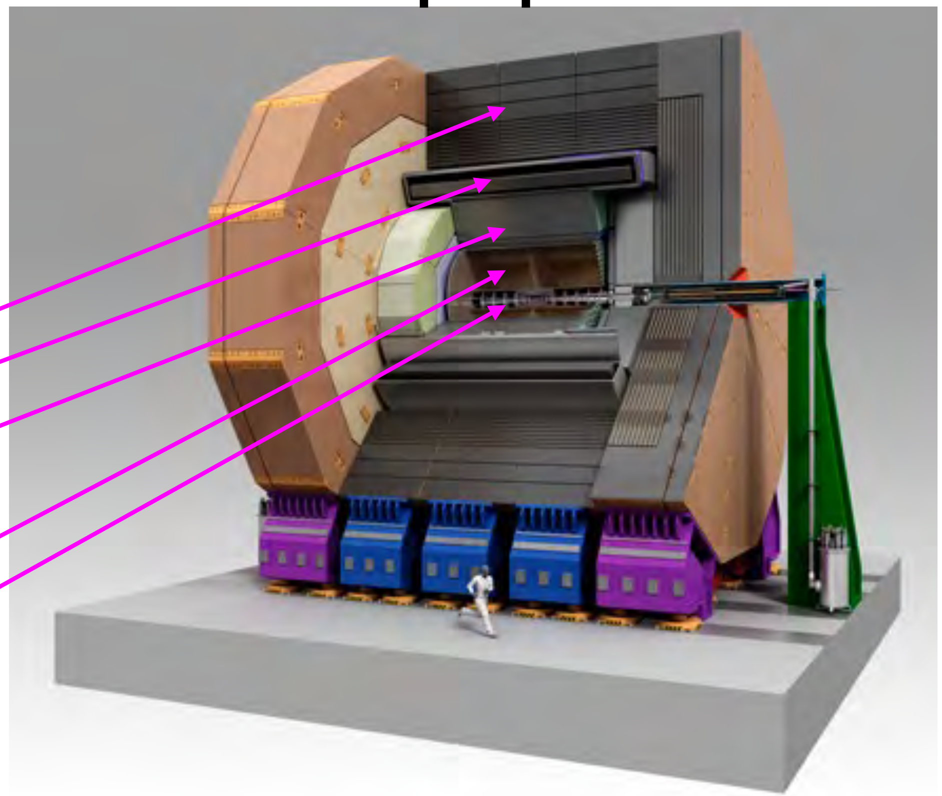


Muon detector
Solenoid（0.5T)
Calorimeter
e-ID
Tracker
Vertex detector

ALICE **26m, 10,000t**

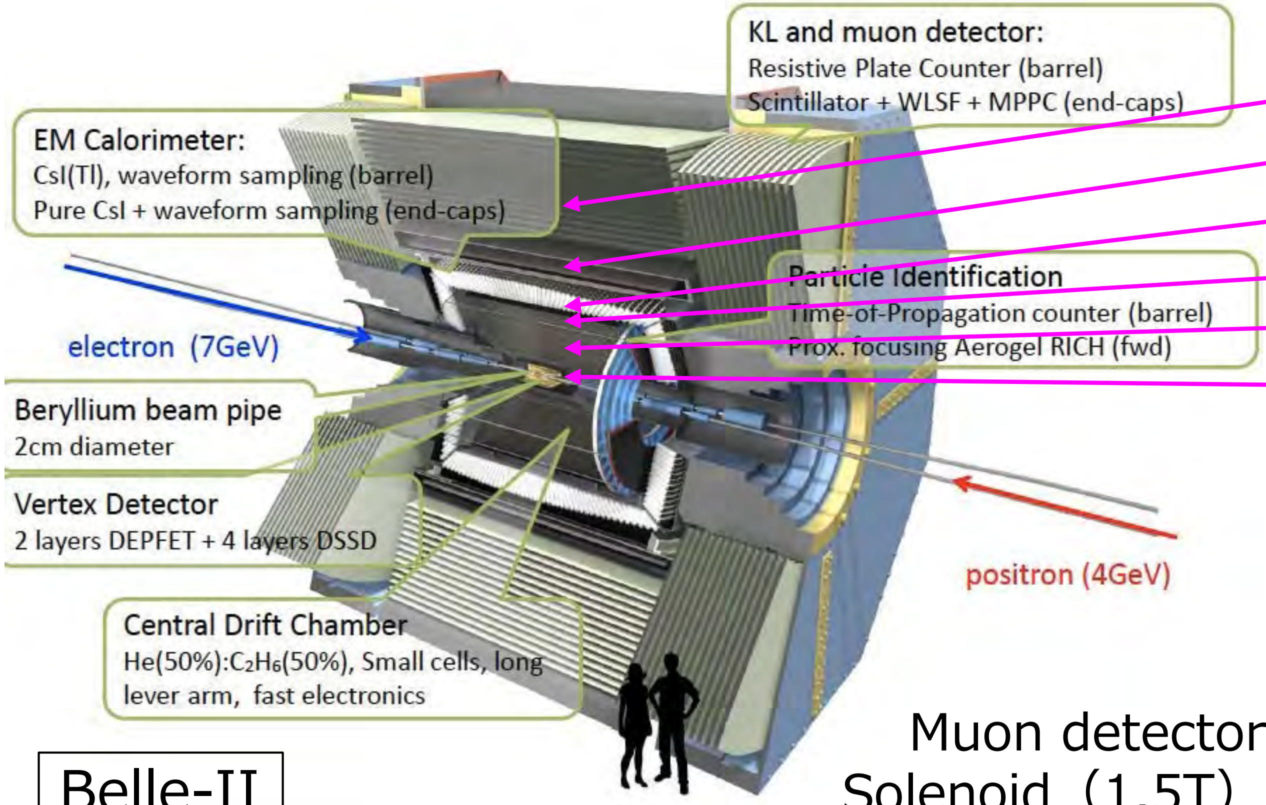
Heavy-ion collision experiment for q-g plasma. The best electron identification needed for their physics target.

General-purpose LCD



Muon detector
Solenoid（3.5T)
Calorimeter
No Dedicated PID
Tracker
Vertex detector

1. Overview the various detector configuration ; B-Factories

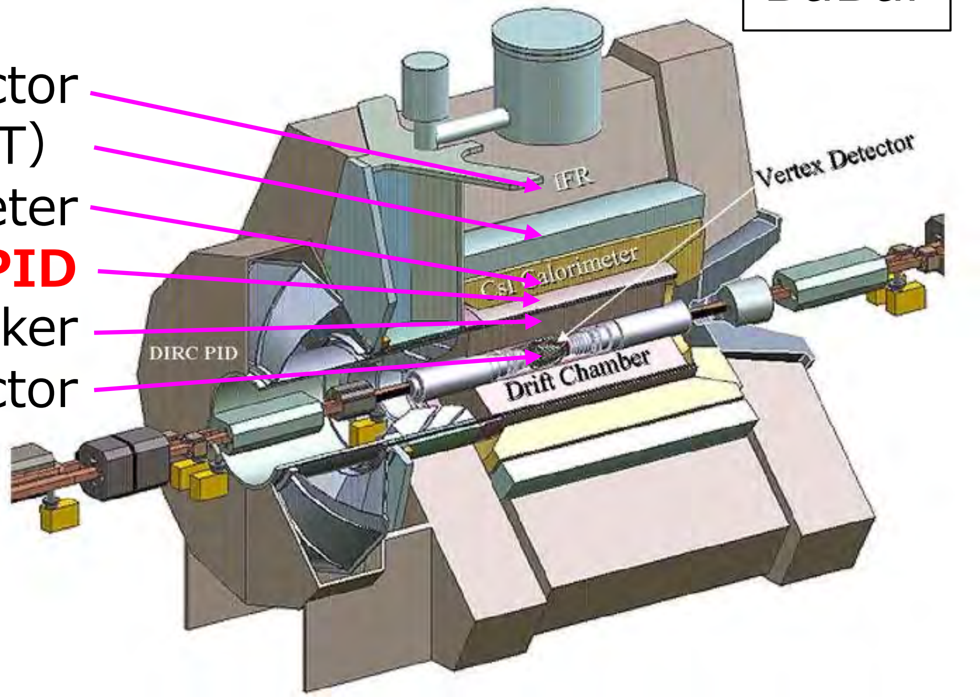


Muon detector
Solenoid（1.5T）
Calorimeter
Ce-PID
Tracker
Vertex detector

Belle-II

BaBar

Muon detector
Solenoid（1.5T）
Calorimeter
Ce-PID
Tracker
Vertex detector

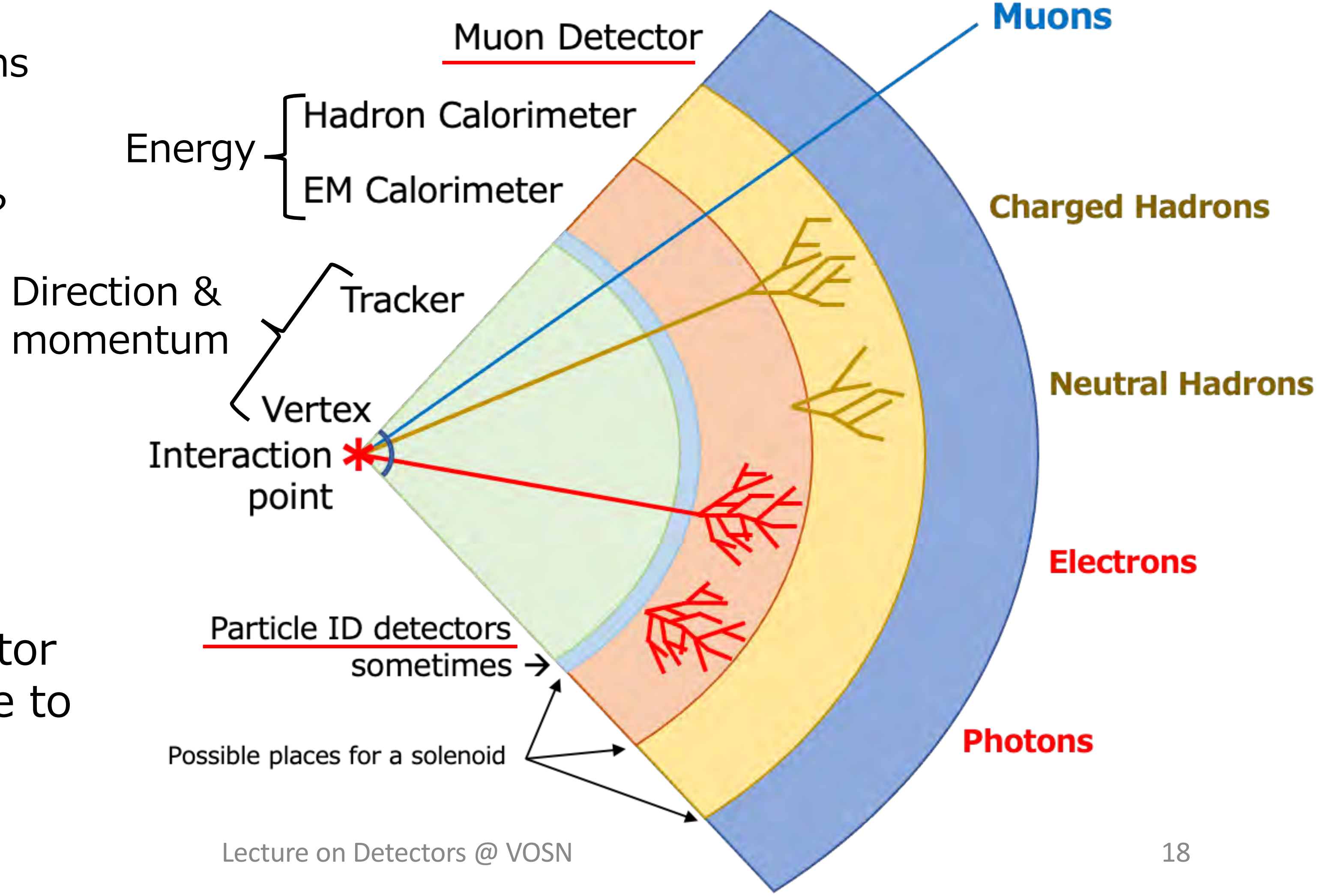


CP violation search →
Precision study of CPV and heavy flavor to explore new (BSM) physics.
Flavor tagging essential.

1. Overview the various detector configuration

- General layout is common to almost all collider experiments.
- Use characteristics of interaction of particles with matter to measure aimed property.
- Particle identification strongly reflect the physics to explore at the experiment.
  → Have excellent PID or No-dedicated-PID.
  → Variety of Particle-ID detectors used.

- Want to separate kaons from pions ?
- The best electron/γ identification needed ?



General layout of detector components from inside to outside.

2. Interaction of particles with matter

- which determines characteristics of detectors -

2. Interaction of particle with matter

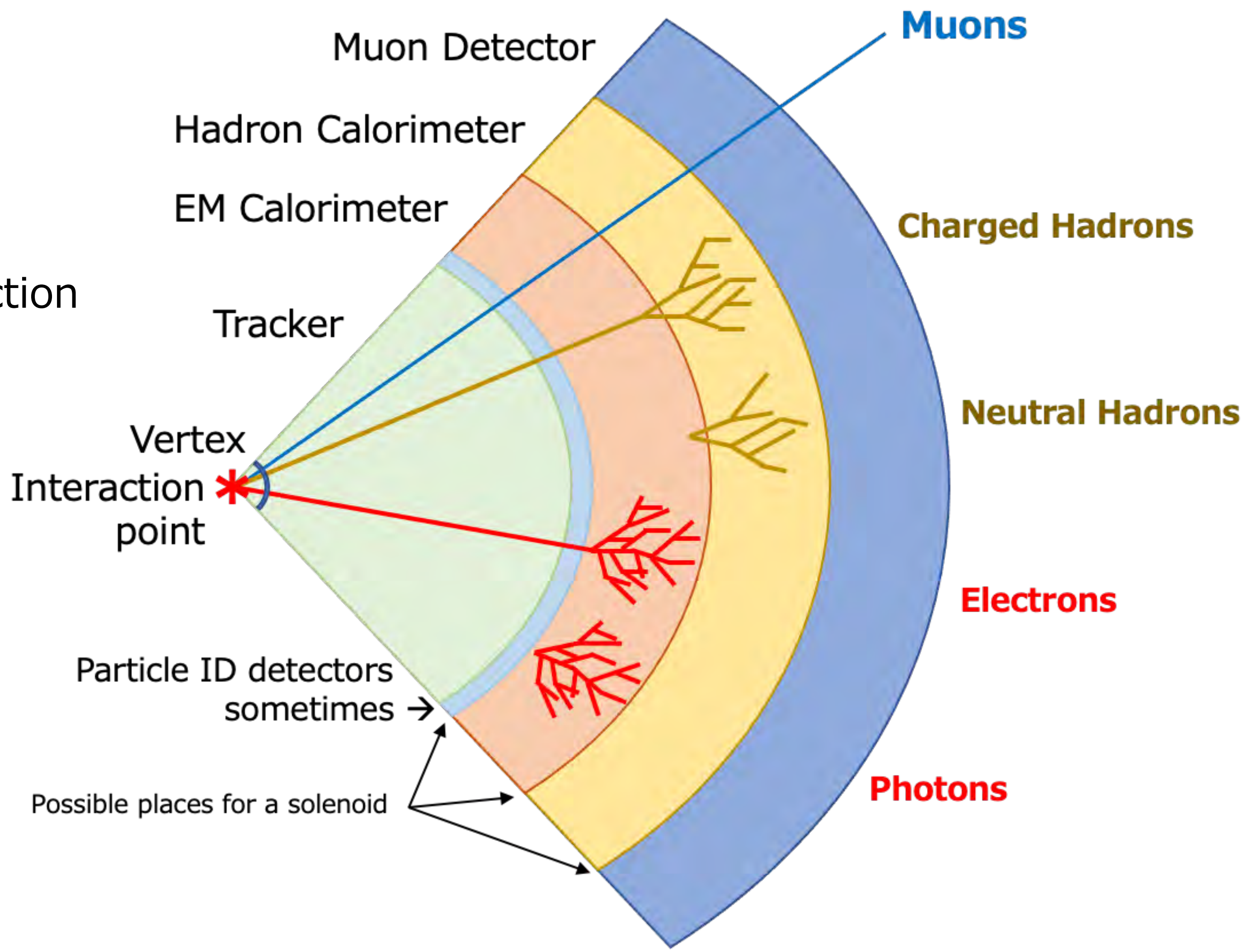
To design a detector for specific particle,
we need to know interaction of particle with matter.

Interaction of **charged particle**

- Ionization
- Electromagnetic Shower
- Hadronic Shower

Interaction of **neutral particle**

- Photon
  - Variety of photon-atom interaction
  - Electromagnetic Shower
- Neutral Hadron
  - Hadronic shower



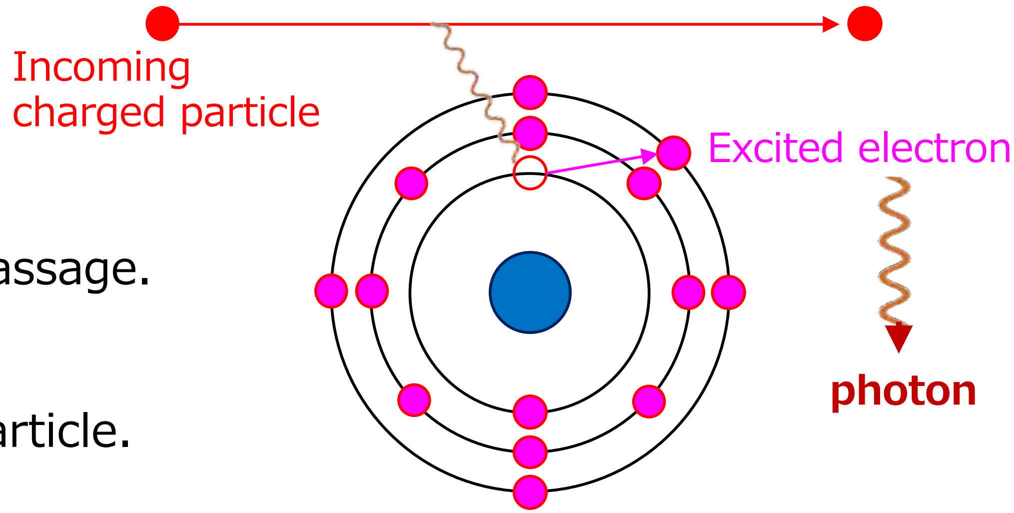
Different interaction mechanisms
are used in combination
for **Particle ID**.

- Ionization
- Cherenkov Radiation
- Transition Radiation
- ToF

2. Interaction of particle with matter ; charged particle

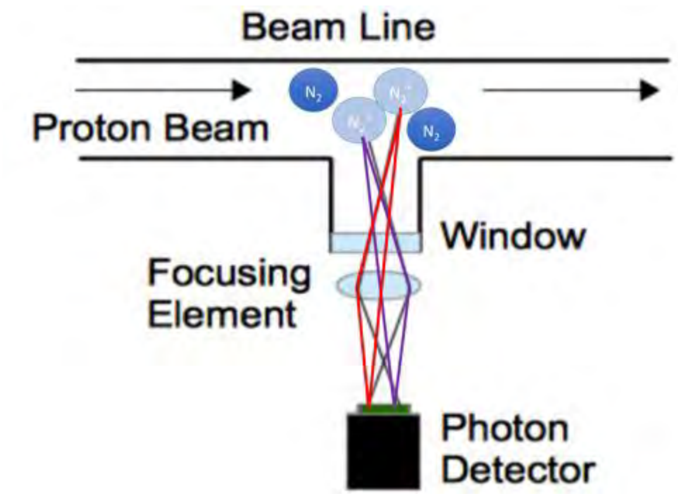
Interaction of charged particle with atom

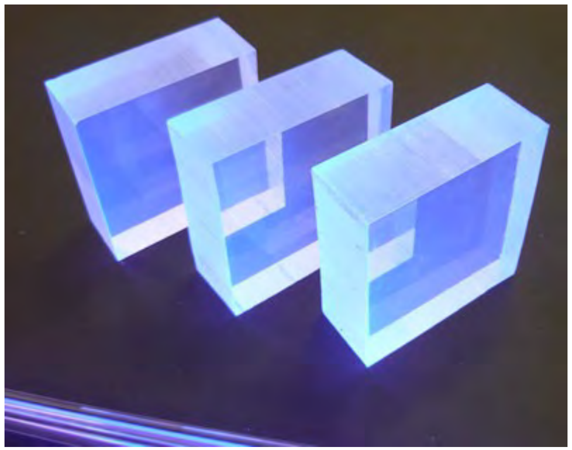
- **Excitation → luminescence/fluorescence**

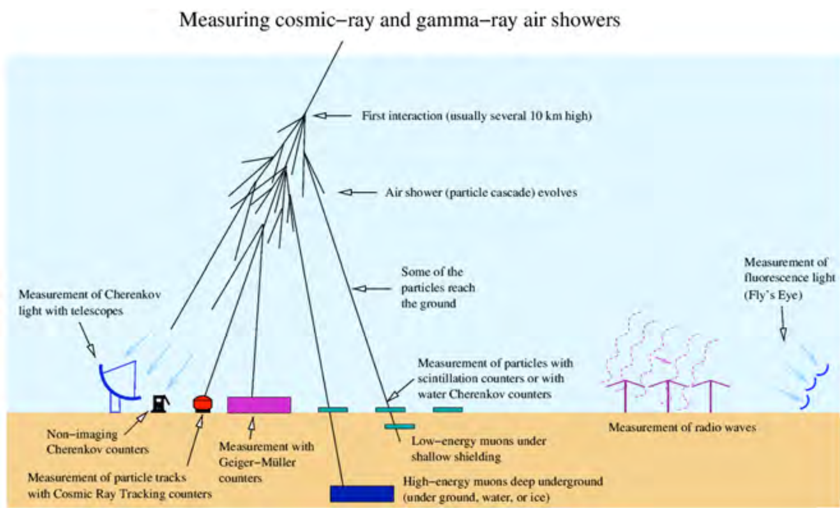


Excited atom emits photon (luminescence) when it returns to the ground state.
→ This photon is used for detection of particle passage.
Scintillators, fluorescent plates, , ,

Also contribute to the energy loss of incoming particle.

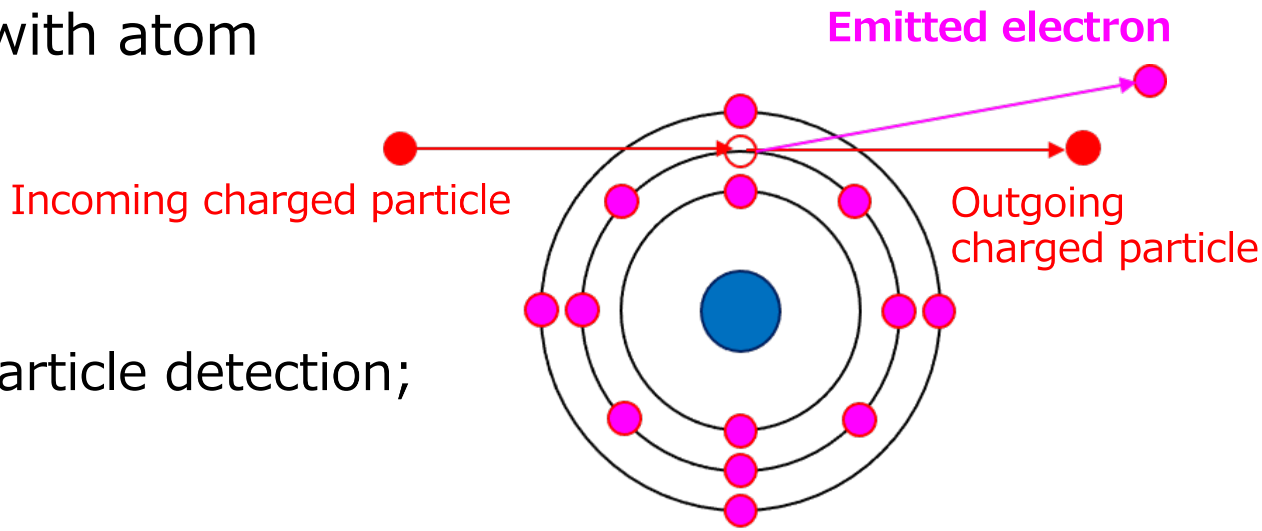






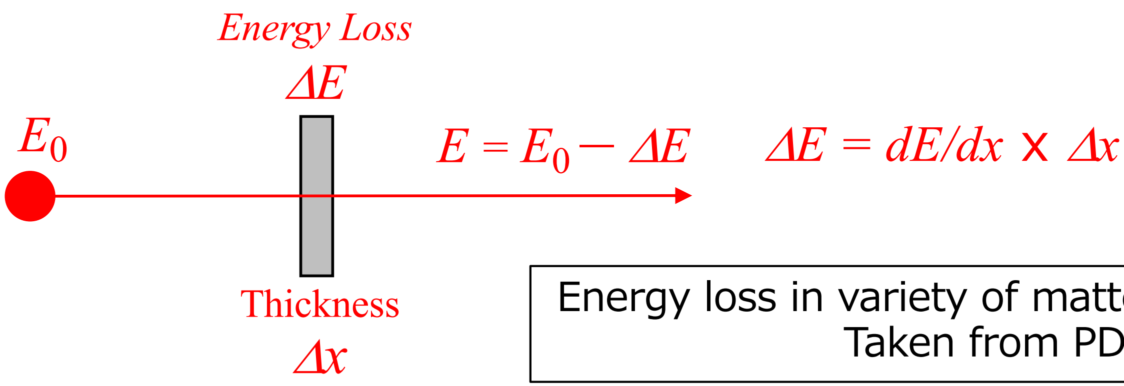
Interaction of charged particle with atom

- **Ionization**

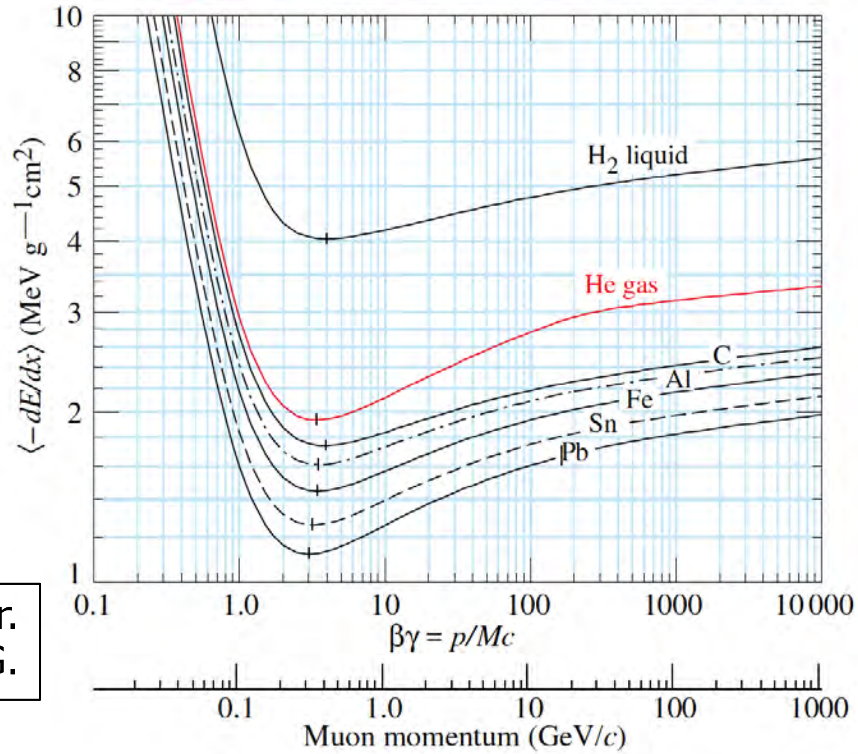


All of thee objects are useful for particle detection;
- ionized atom
- emitted electron
- energy loss of the incoming particle ; d*E*/dx

Energy loss of incoming charged particle, dE/dx, caused by successive ionization with matter atoms is very important mechanism.



Energy loss in variety of matter.
Taken from PDG.



Interaction of charged particle with matter

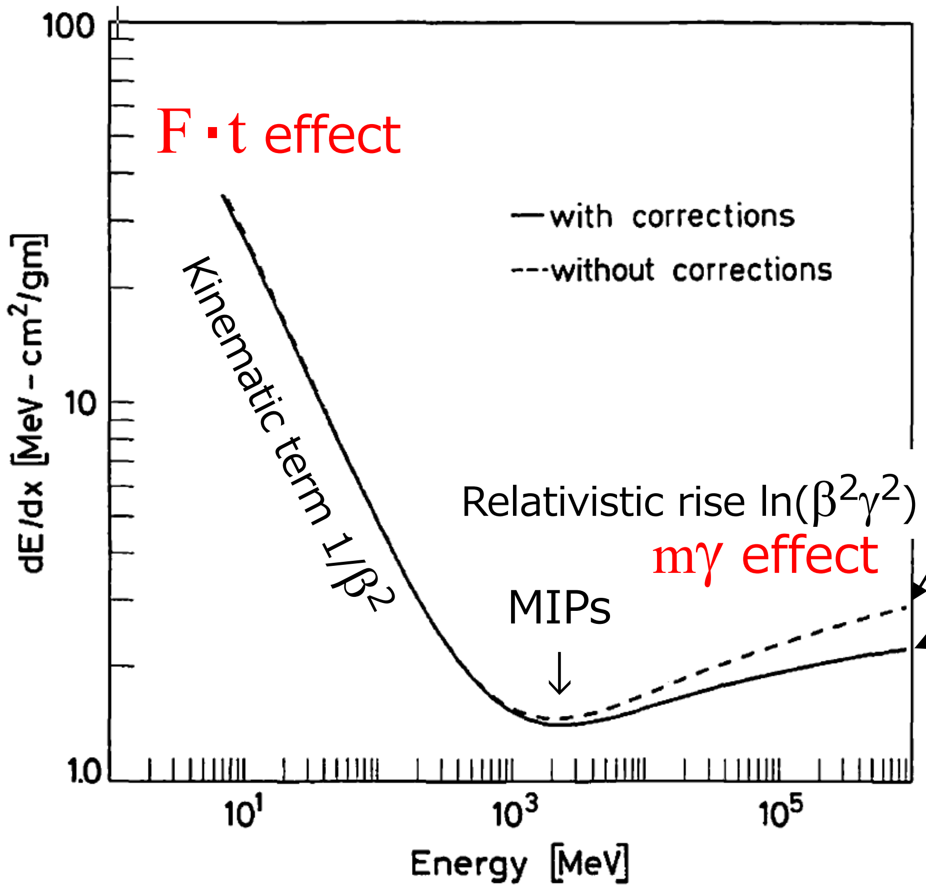
- **Energy Loss dE/dx** (Accumulation of successive microscopic energy loss by ionization)

General behavior is well expressed by this simplified formula;

$$\frac{dE}{dx} \propto \frac{Z^2}{\beta^2} \ln\left(a\beta^2\gamma^2\right)$$

Relativistic rise

↑ Kinematic term



Energy loss in copper for Bohr and BB equations.

Fig. from W.R.Leo.

Bohr's classical calculation

$$-\frac{dE}{dx} = \frac{4\pi N_e z^2 r_e^2 m_e c^2}{\beta^2} \ln\left(\frac{2m_e c^2 \beta^2 \gamma^2}{I}\right)$$

Bethe-Bloch QED calculation

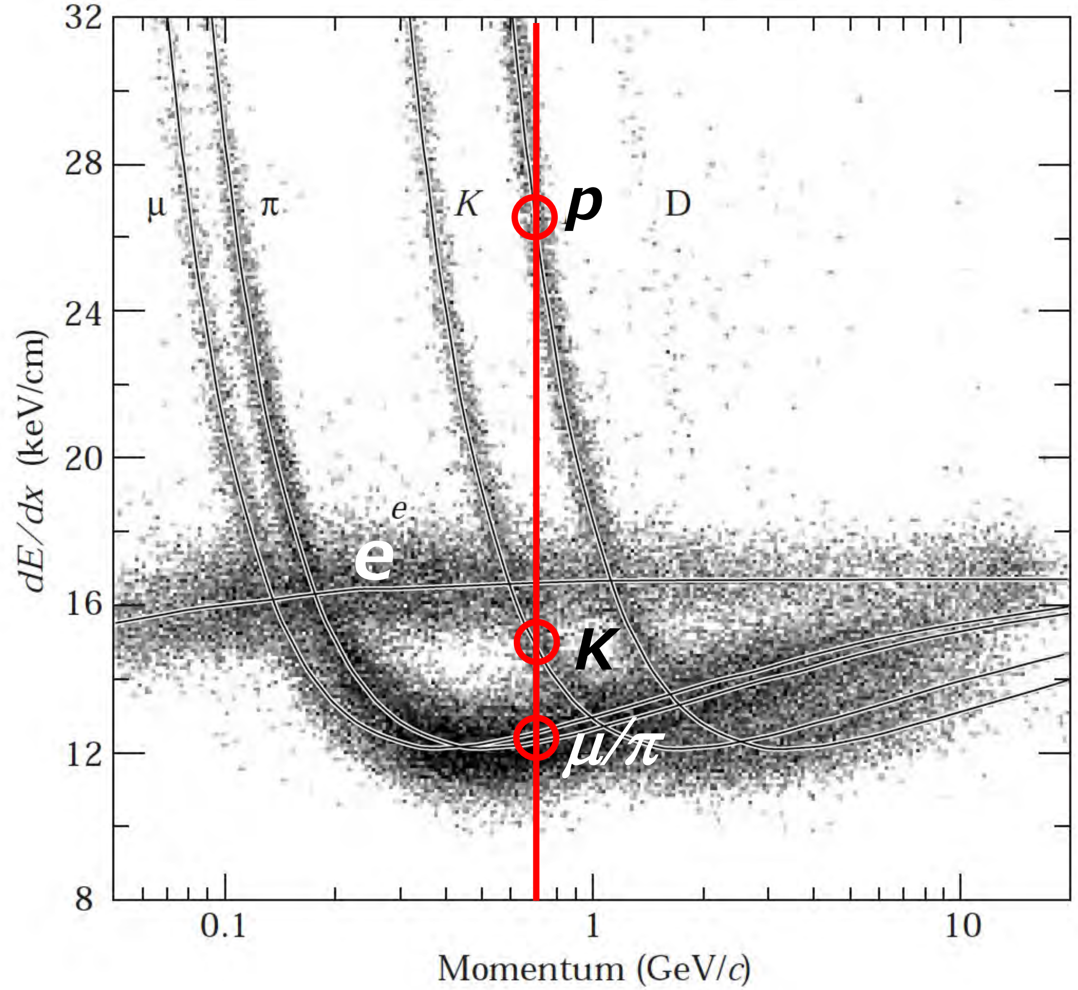
- density effect δ
- shell effect C

$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln\left(\frac{2 m_e \gamma^2 v^2 W_{max}}{I^2}\right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right]$$

Density effect δ:	electric field of incoming particle is shielded by polarized atom.
Shell effect C :	atom electron can not be treated at rest.

Interaction of charged particle with matter

・**Energy Loss dE/dx**



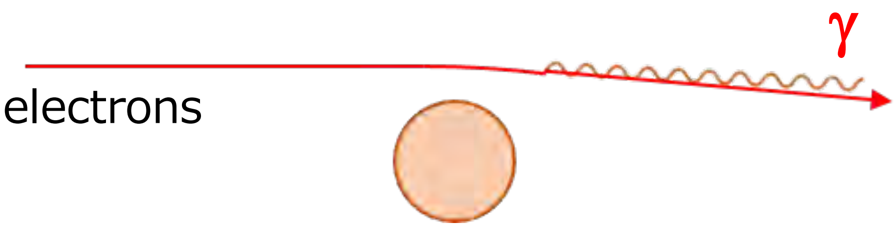
Energy loss for various particles.
Taken from PDG.

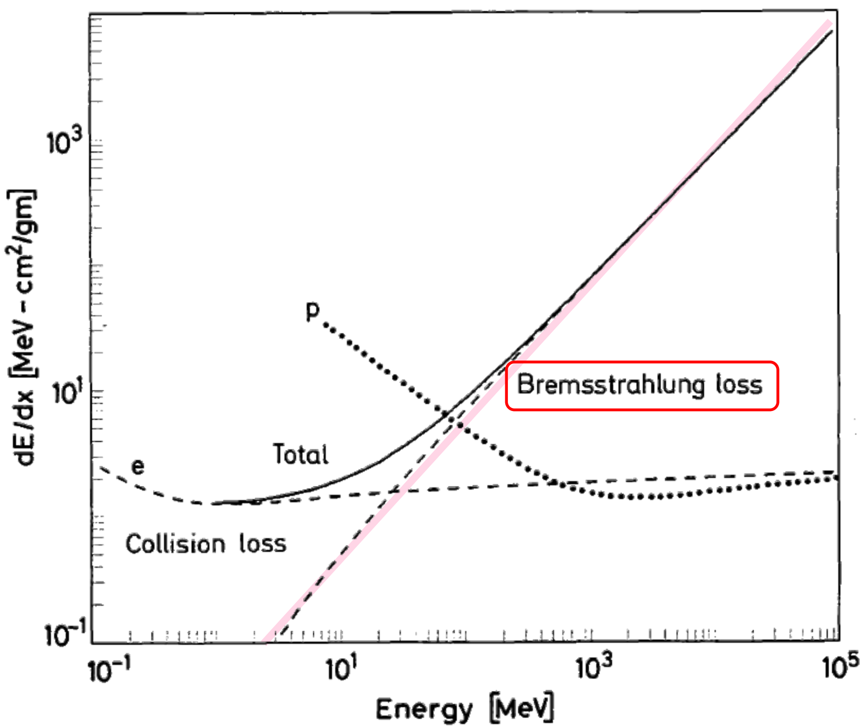
Energy loss depends on β of the particle.
By measuring dE/dx and momentum
of the particle,
one can distinguish particle species
at certain momentum region.

Interaction of charged particle with atom

- **Bremsstrahlung** When an electron travels close to an atom, it is de-accelerated by the Coulomb field and emits photon.

$$-\left\langle \frac{dE}{dx} \right\rangle_{Brems} \propto \frac{E}{m^2}$$; for mainly electrons



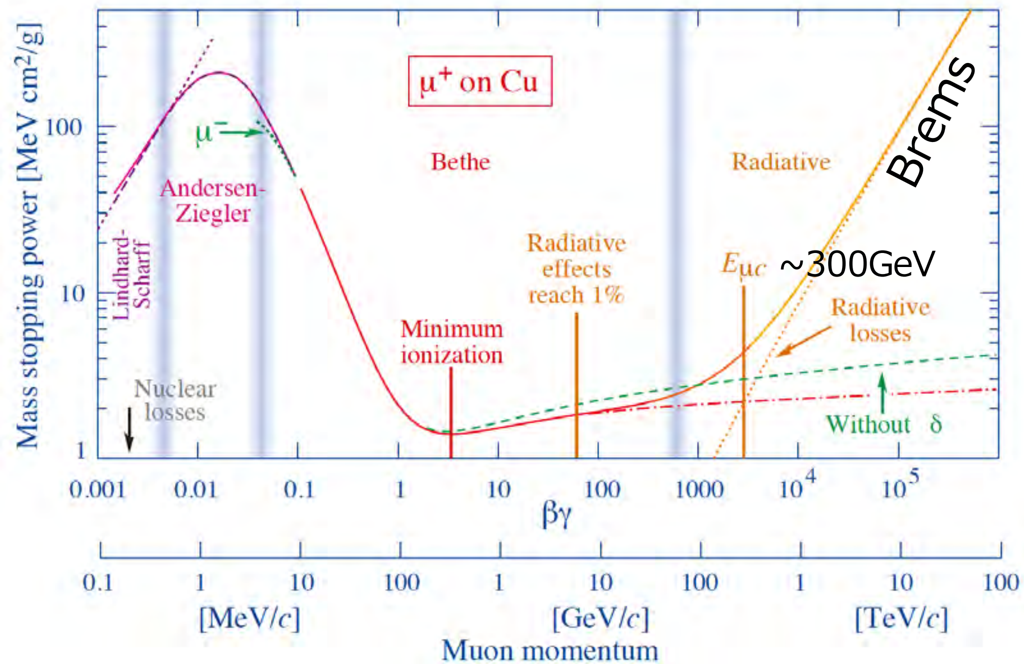


High-energy electrons lose its energy dominantly through bremsstrahlung.

Fig. from W.R.Leo.

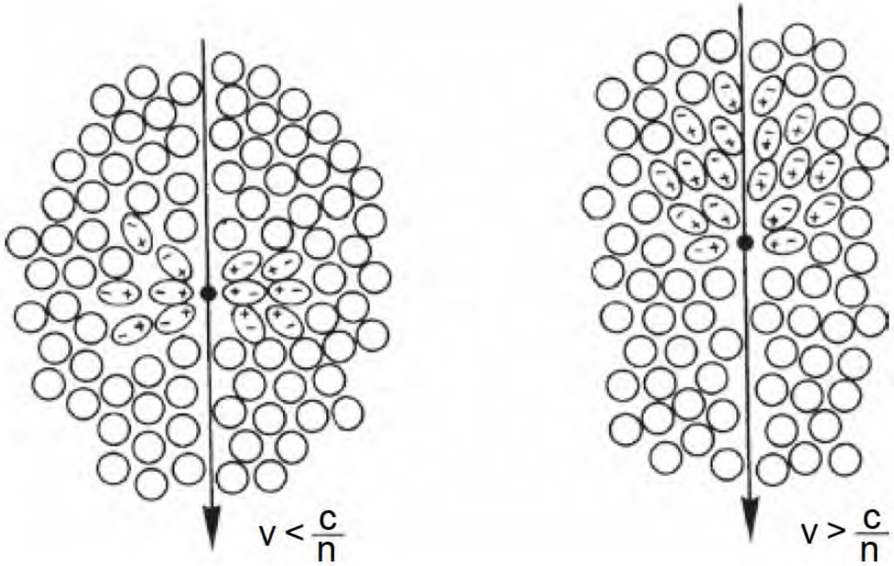
Even muons lose its energy dominantly through bremsstrahlung at very high energy (>TeV).

taken from PDG.



Interaction of charged particle with matter

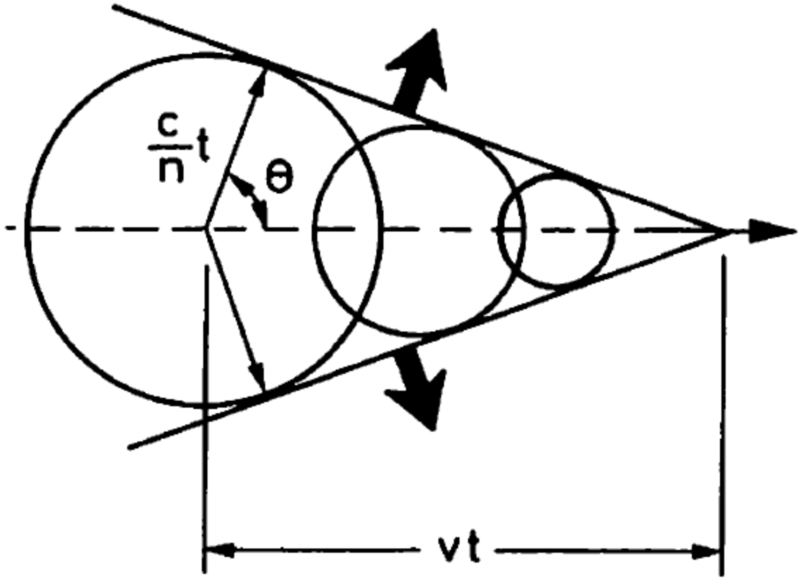
・**Cherenkov Radiation**



Mechanism of Cherenkov radiation generation. If v>c/n, electric field can not be made in front of the particle. Then polarization of material atom behind the particle lines up in the same direction, and dipole radiation becomes coherent.

Fig. from Grupen.

When a charged particle travels in material with speed exceeding that of light in the material, v > c/n Cherenkov radiation is emitted.



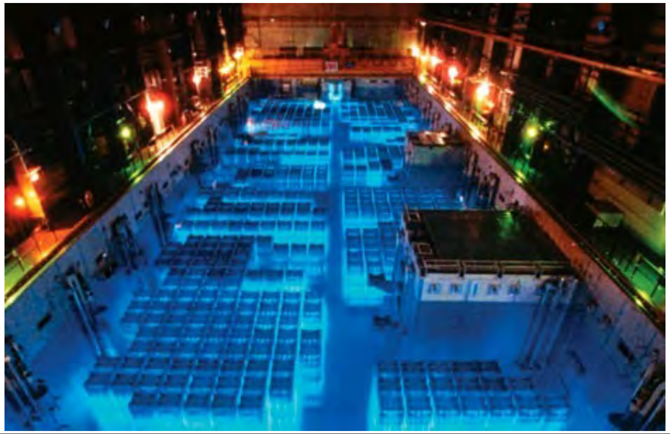
Cherenkov generation condition is $n\beta>1$, and radiation angle θ is $\cos\theta = 1/n\beta$.

Fig. from W.R.Leo.

Interaction of charged particle with matter

・Cherenkov Radiation

Cherenkov generation condition ; $\beta > 1/n$
Radiation angle θ ; $\cos\theta = 1/n\beta$.
→ have sensitivity to β
→ Useful for particle species identification

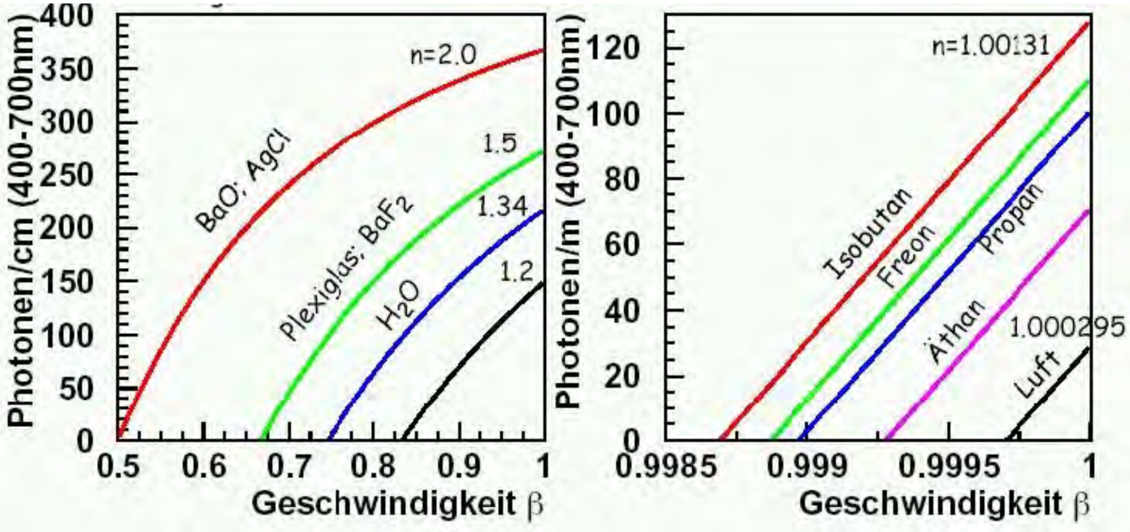


Cherenkov light at a reactor.
from "Cherenkov Radiation" by K.Muller

Number of generated photons are:

$$\frac{d^2N}{d\lambda dx} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) = \frac{2\pi\alpha z^2}{\lambda^2}\sin^2\theta_C$$

Integrate over certain range gives
↓ ↓



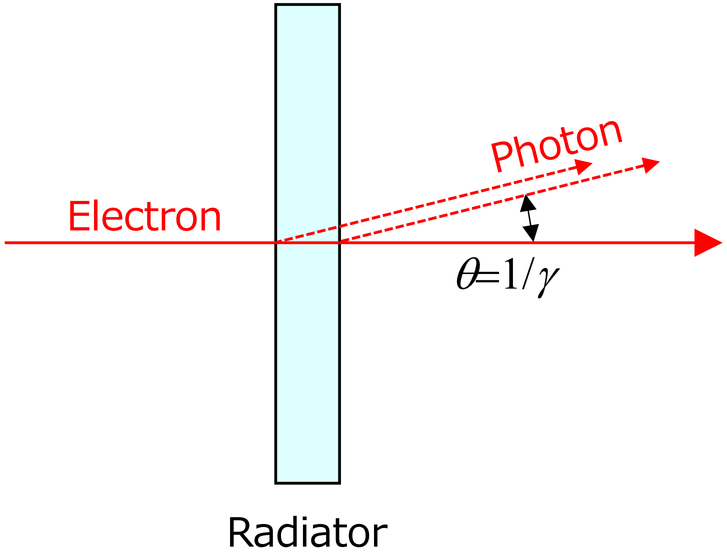
material	n	β threshold	Nphoton
He	1.000 0349	0.99997	0.03/cm
N2	1.000 298	0.9997	0.3/cm
Pentane	1.0017	0.9983	7/cm
Aerogel	1.007-1.13	0.993-0.884	tens/cm
Water	1.33	0.75	210/cm
Polystyrene	1.60	0.63	

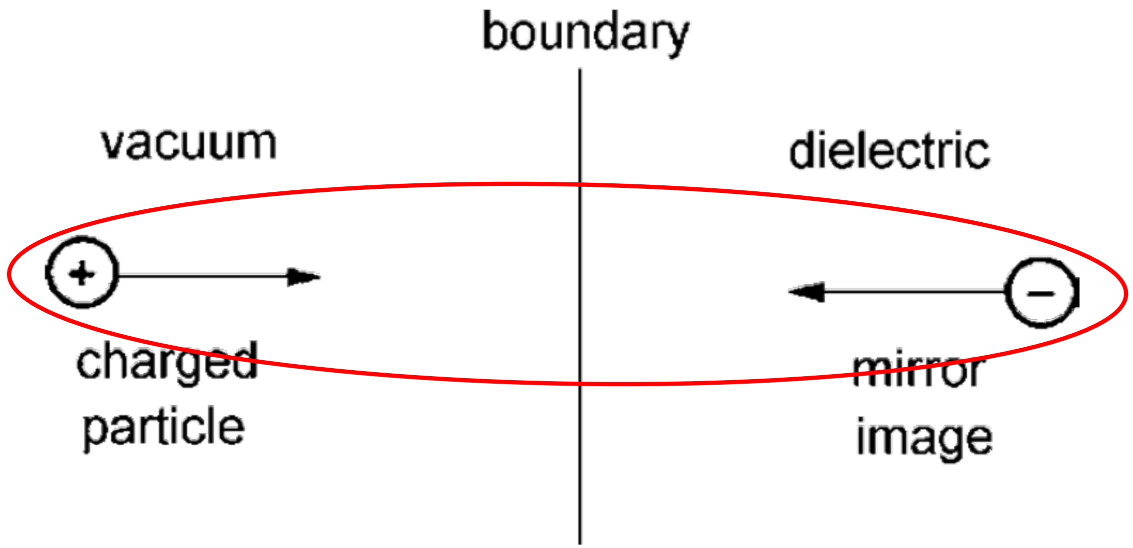
from "Cherenkov Radiation" by K.Muller

Interaction of charged particle with matter

・Transition Radiation

When a charged particle travels crossing boundary of different material, Transition Radiation is emitted.





As the charged particle approaches to the boundary, electric dipole decreases in time and vanishes.
This quick dipole change results in radiation.

Fig. from Grupen.

Interaction of charged particle with matter

- **Transition Radiation**

Emitted energy *S*

$$S = \frac{1}{3}\alpha z^2 \hbar\omega_p \gamma \ , \ \ \hbar\omega_p = \sqrt{4\pi N_e r_e^3} m_e c^2/\alpha$$

Total emitted energy at single boundary is proportional to γ, thus very useful for particle identification
(mostly to identify electrons)

Characteristics ;

- Emitted energy S ~ γ
- Emitted N_{photon} ~ αZ^2 ~**0.01** for electron
  - Photon emission probability is very low.
  - N has almost no γ dependence for hard photon.
- Photon energy $h\nu$ increases as γ increases.
- Emission angle θ ~ $1/\gamma$
  - Coherency of incoming particle field and emitted radiation field requires that emission be in forward cone of $1/\gamma$.

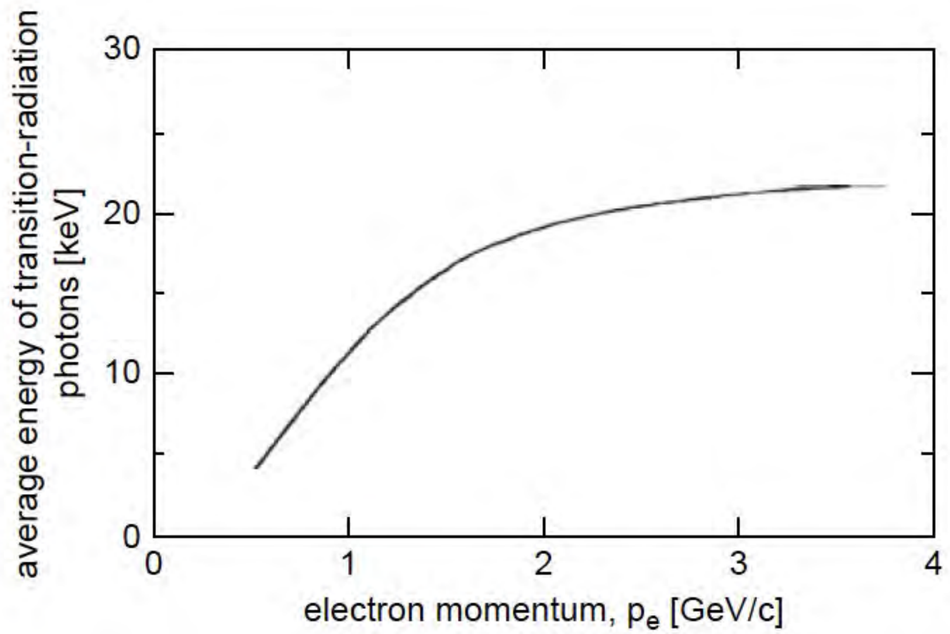


Fig. from Grupen.

Interaction of photon with matter/atom

- Photo-electric effect
- Compton scattering
- Pair creation
- Rayleigh scattering

Plot from PDG.

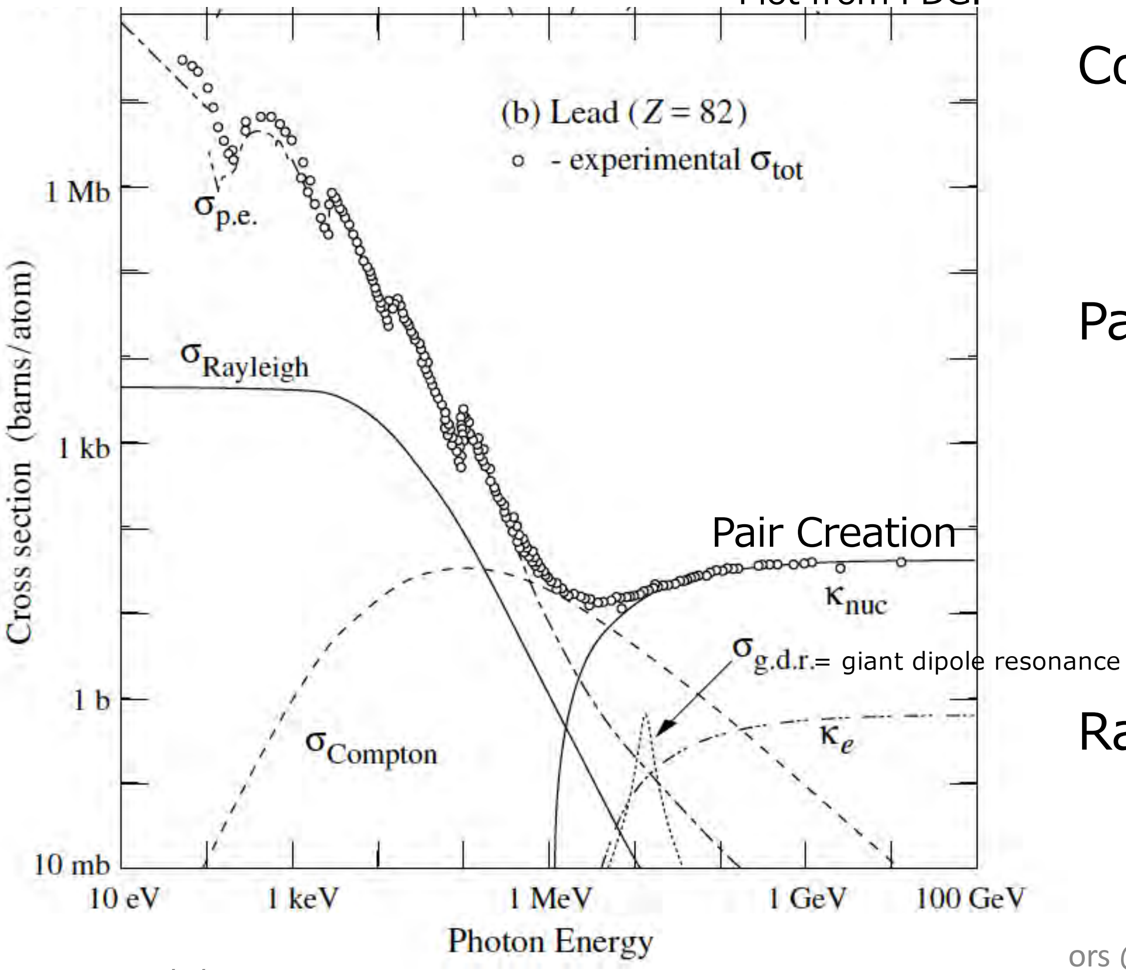
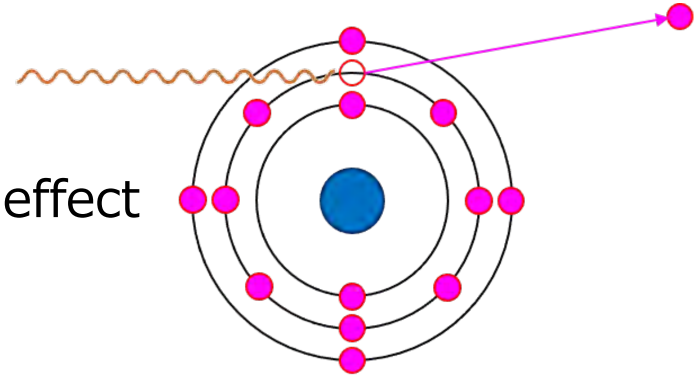
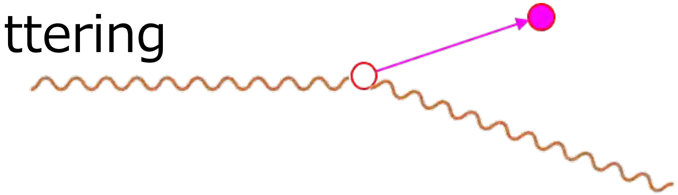


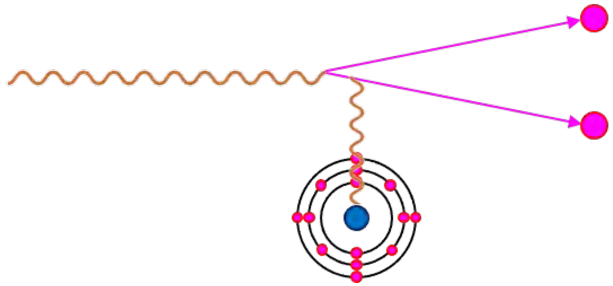
Photo-electric effect



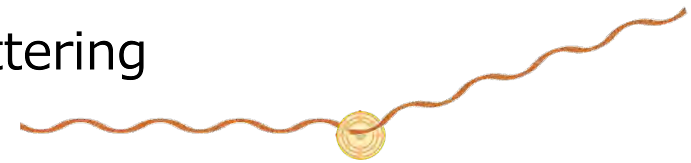
Compton scattering



Pair creation



Rayleigh scattering



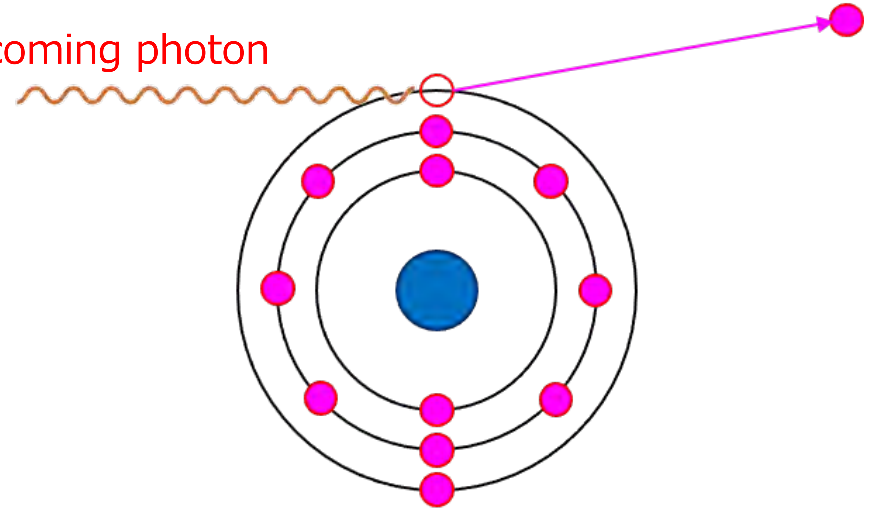
2. Interaction of particle with matter ; photon

Photo-electric effect ; Einstein's Nobel prize in 1921.

$$E_{p.e.} = E_\gamma - I_b$$

I_b = Nuclear binding energy

Has strong Z dependence.



$$\sigma^{K}_{photo} = \left(\frac{32}{\varepsilon^7}\right)^{1/2} \alpha^4 \cdot Z^5 \cdot \sigma^e_{Th}$$

$$\sigma^{K}_{photo} = 4\pi r_e^2 Z^5 \alpha^4 \cdot \frac{1}{\varepsilon}$$

$$\varepsilon = E_\gamma / m_e c^2$$

$$\sigma^e_{Th} = \frac{8}{3} \pi r_e^2$$

Cross section of photoelectric effect
for low-energy photon (upper) and
for high-energy photon ($\varepsilon >> 1$, lower).
σ^e_{Th} is Thomson-scattering cross section.

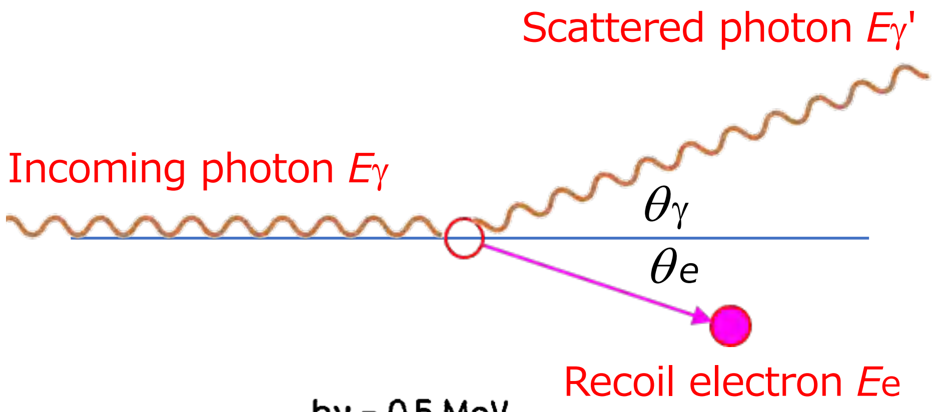
Important process in photo-sensors
- Photo-multipliers
- Image intensifiers

Also used for molecule analysis etc.

Equations from Grupen.

Compton scattering ;

- Photon scattered by quasi-free atomic electrons
- Photon energy >> Binding energy of electrons



Exact probability by Klein-Nishina;

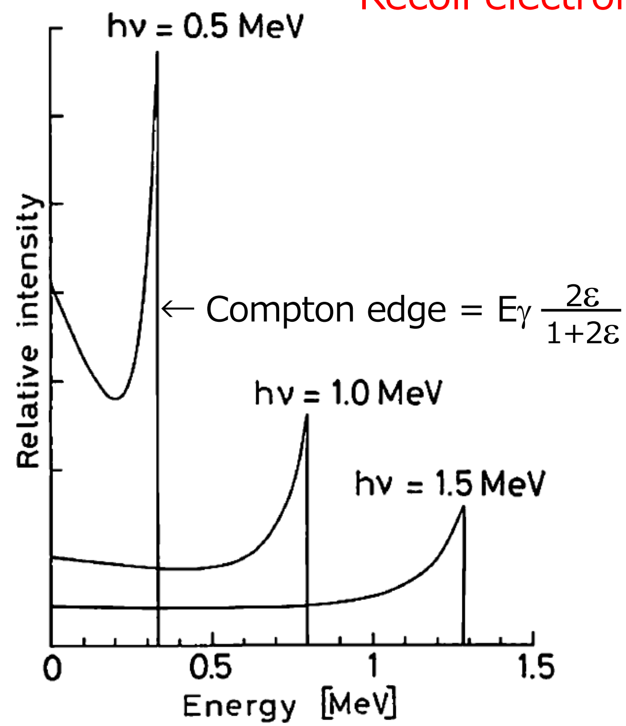
$$\phi_c(E_\gamma, E_\gamma')\,\mathrm{d}E_\gamma' = \pi r_e^2 \frac{N_A Z}{A}\frac{m_e c^2}{E_\gamma}\frac{\mathrm{d}E_\gamma'}{E_\gamma'}\left[1 + \left(\frac{E_\gamma'}{E_\gamma}\right)^2 - \frac{E_\gamma'}{E_\gamma}\sin^2\theta_\gamma\right]$$

And some useful kinematic values;

$$\frac{E_\gamma'}{E_\gamma} = \frac{1}{1+\varepsilon(1-\cos\theta_\gamma)} \qquad \varepsilon = E_\gamma/m_e c^2$$

$$E_{\mathrm{kin}} = E_\gamma - E_\gamma'$$

Formula from Grupen.



Energy spectra of recoil electrons.
Fig. from W.R.Leo.

Inverse Compton scattering is widely used to generate high-energy γ's by colliding Laser and high-energy electrons.

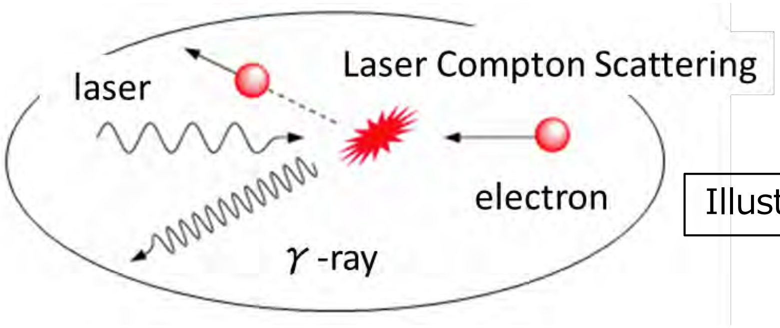
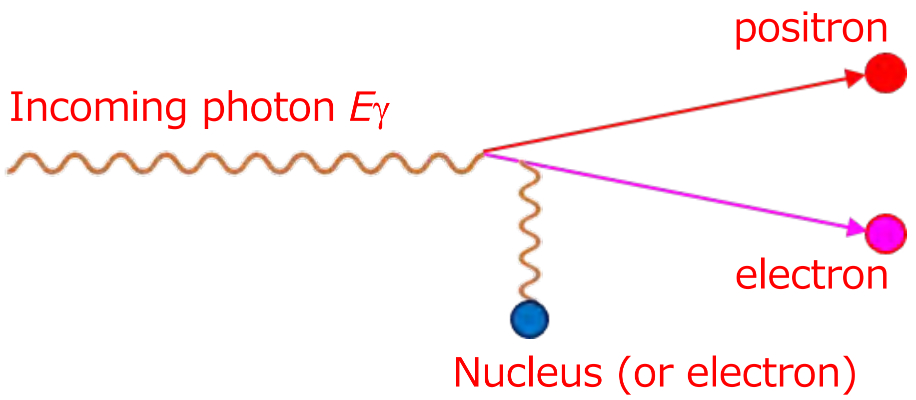


Illustration from QST-web.

Pair creation

- High-energy γ creates electron-positron pair under strong coulomb field of nucleus.
  $E\gamma > 2m_e$ + nucleus recoil energy



Production cross sections are ;

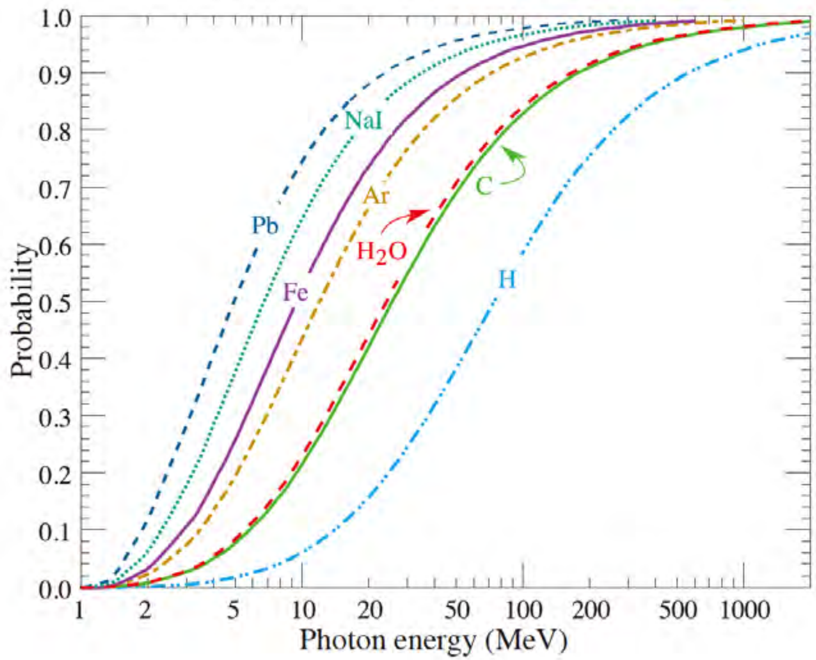
$$\sigma_{\text{pair}} = 4\alpha r_e^2 Z^2 \left(\frac{7}{9}\ln 2\varepsilon - \frac{109}{54}\right)$$ at low energy

$$\sigma_{\text{pair}} = 4\alpha r_e^2 Z^2 \left(\frac{7}{9}\ln \frac{183}{Z^{1/3}} - \frac{1}{54}\right)$$ at high energy

At very high energy, it asymptotically approaches to

$$\sigma_{\text{pair}} \approx \frac{7}{9} \cdot \frac{A}{N_A} \cdot \frac{1}{X_0} \qquad X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln(183\, Z^{-1/3})}$$

Formula from Grupen.



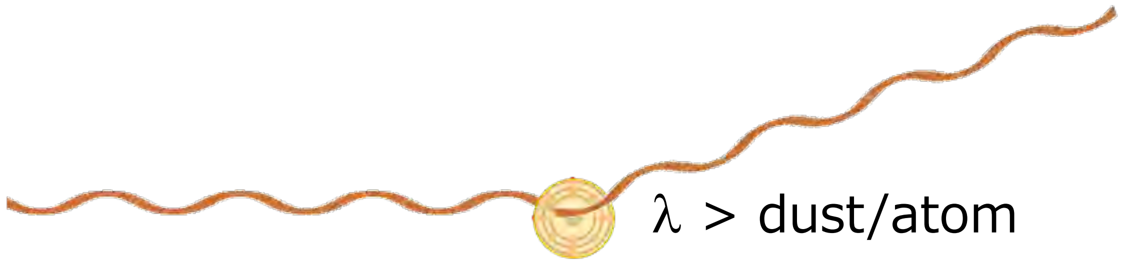
Plot from PDG.

Dominant process for $E\gamma$ >10~20MeV, and causes 'electromagnetic shower', important for energy measurement by calorimeters.

Rayleigh scattering

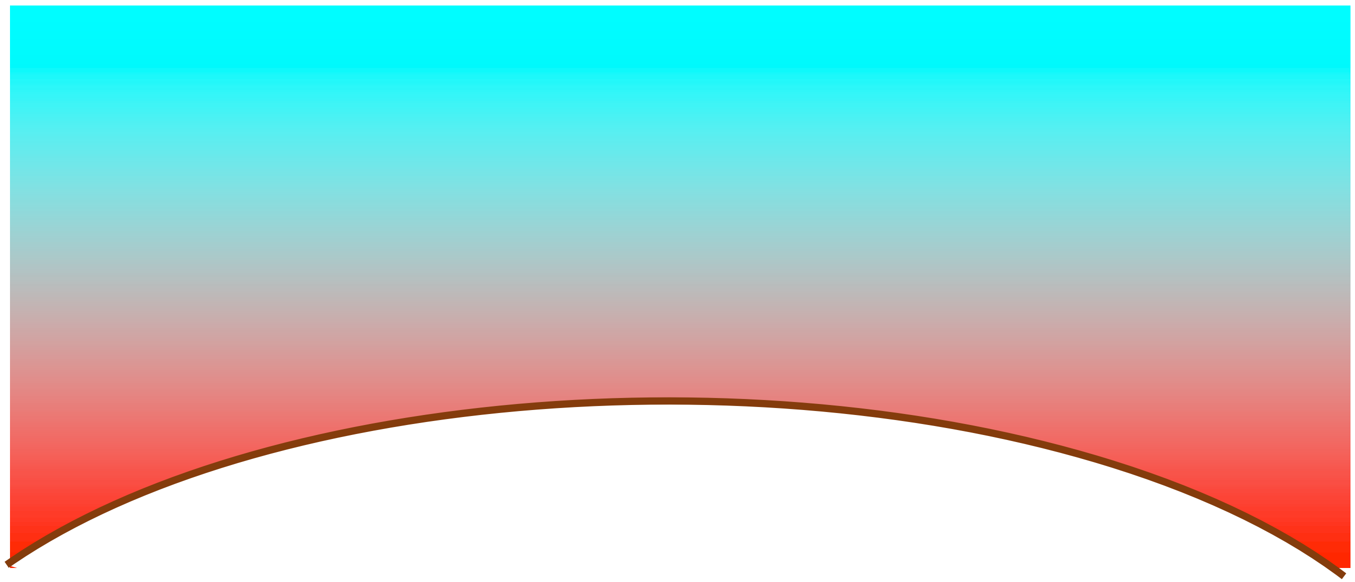
Take place at low energy.

Photon wave length λ > scatterer size.
Collective scattering as whole scatterer,
and no excitation takes place.



The over-head blue sky daytime and red sky sunset glow are
due to the Rayleigh scattering of blue light by dust particles in air.

Has no application in
high-energy detectors.



Electromagnetic Shower

- High-energy electron emits γ,
  emitted γ creates electron-positron pair,
  pair-created electron/positron again emits γ, , , ,

→ electromagnetic cascade = shower

As shower growth, number of particles increases, and energy of each particle decreases. Eventually their energy become too low to generate particles any more, and cascade ceases.

Shower is used to measure energy of electron and γ. Electron momentum is also measured by trackers. These are complementary.

Shower cascades (schematiclly)

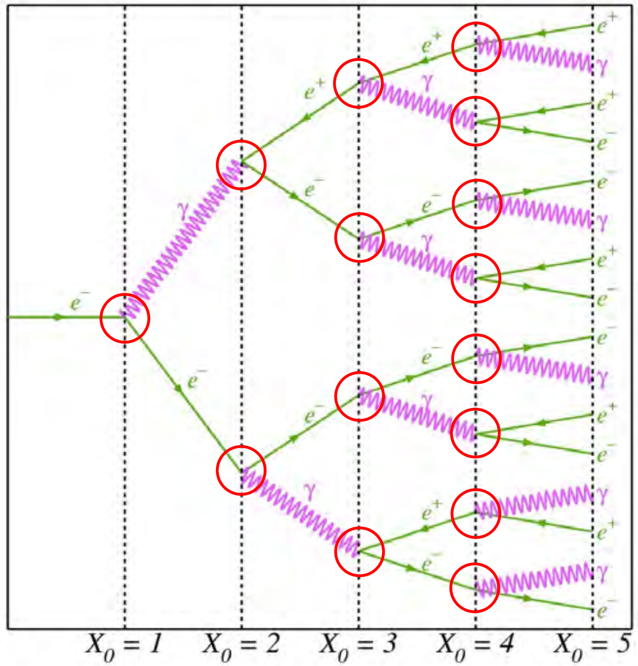
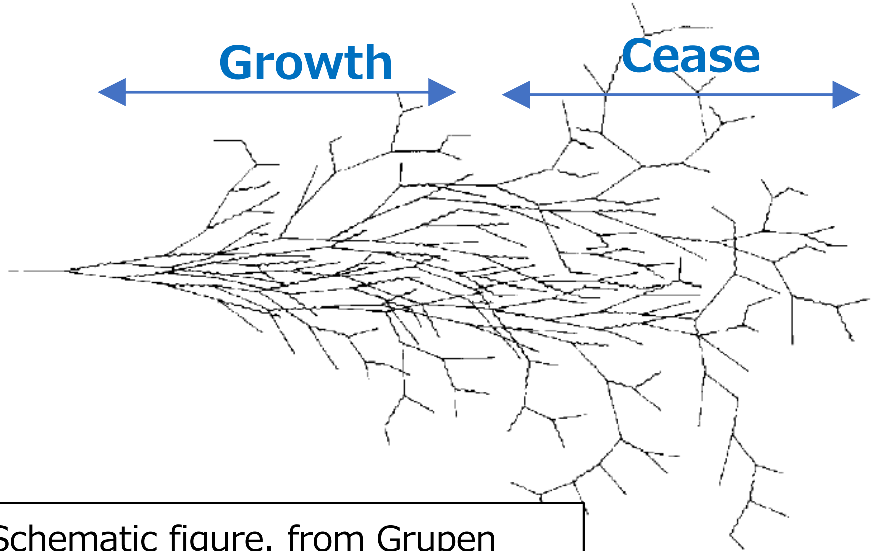
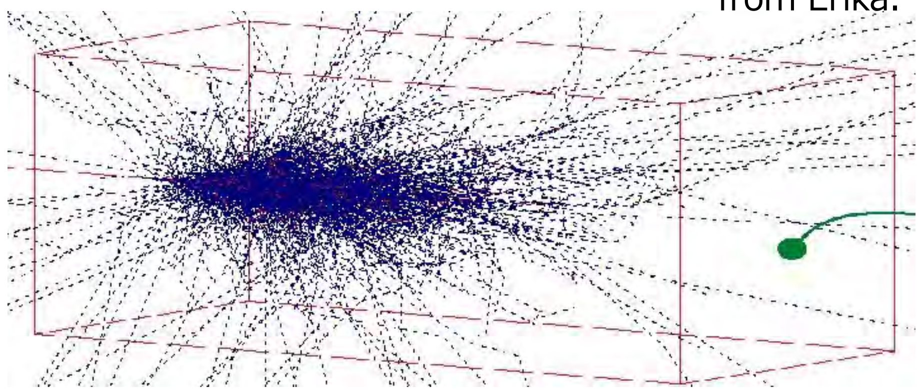


Figure from K.Lang.



Schematic figure. from Grupen

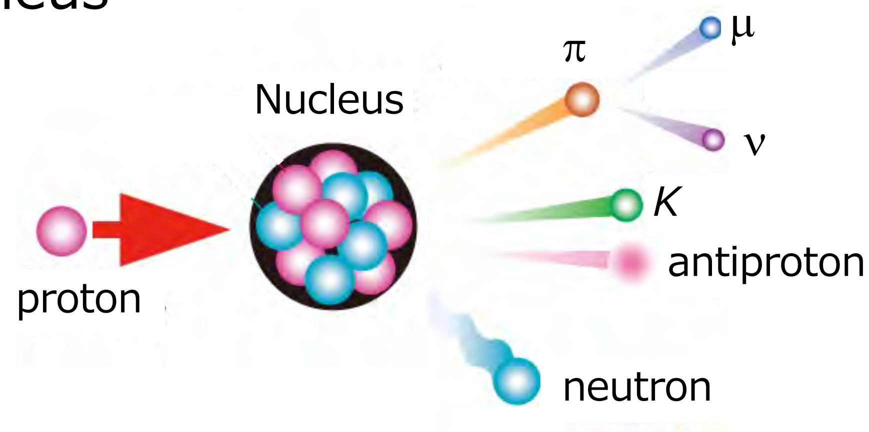
GEANT simulation EM shower. Quite dense and crowded.
from Erika.

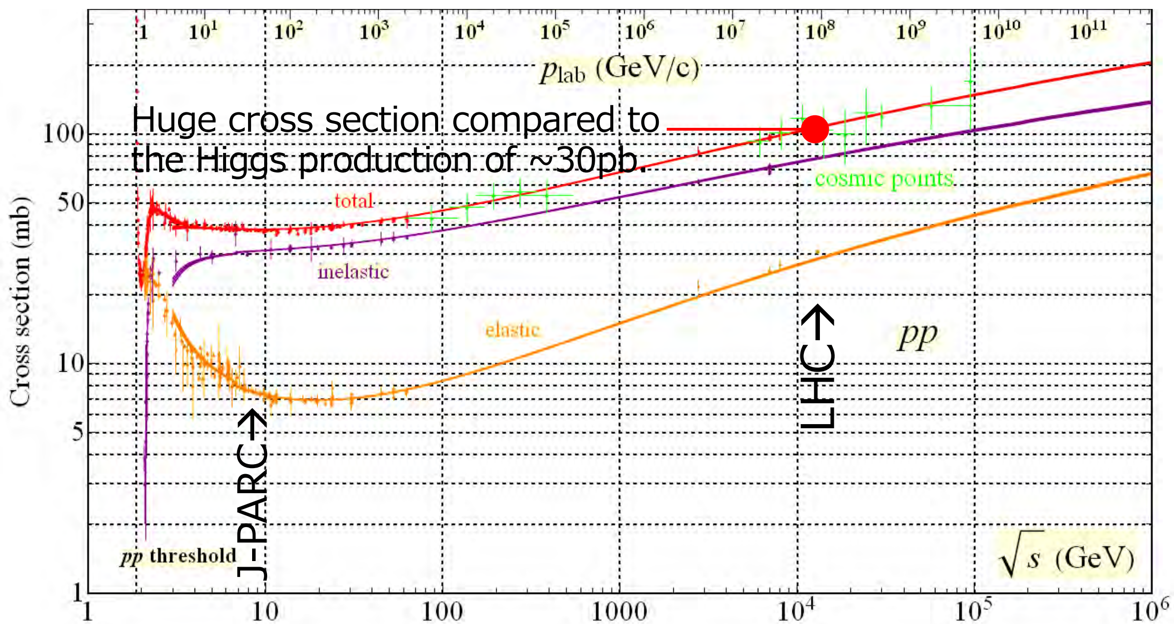


Interaction of Hadron with matter/atom/nucleus

- **Nuclear reaction**

High-energy hadrons do hadronic interaction with nucleus, and generates variety of secondary particles ; π, K, η, ρ, p, n, Λ, γ, e, μ, , ,





Plot from PDG.

Some fundamental formula:

$\sigma_{tot} = \sigma_{el} + \sigma_{inel}$

Since strong interaction is short-range, roughly,

$\sigma_{tot}(pA) = \sigma_{tot}(pp) \cdot A^{2/3}$

Hadronic interaction length λ can be expressed

$\lambda = 1/n \cdot \sigma_{tot}(pA) = A/(\sigma_{tot}(pp) \cdot A^{2/3} \cdot N_A \cdot \rho)$

$\sim A^{1/3}$

And flux attenuation after x-passage becomes

$N(x) = N_0 \cdot \exp(-x/\lambda)$

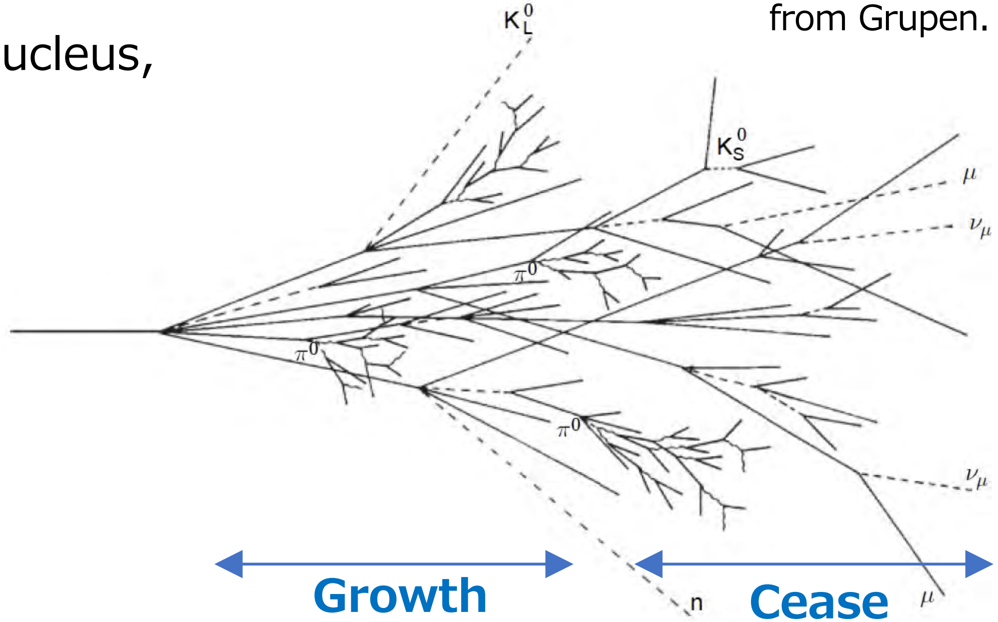
Hadronic shower

High-energy hadrons do hadronic interaction with nucleus, and generates variety of secondary particles.
In matter, the secondaries interact with nucleus and generates tertiaries ･･･
→ hadron shower cascade

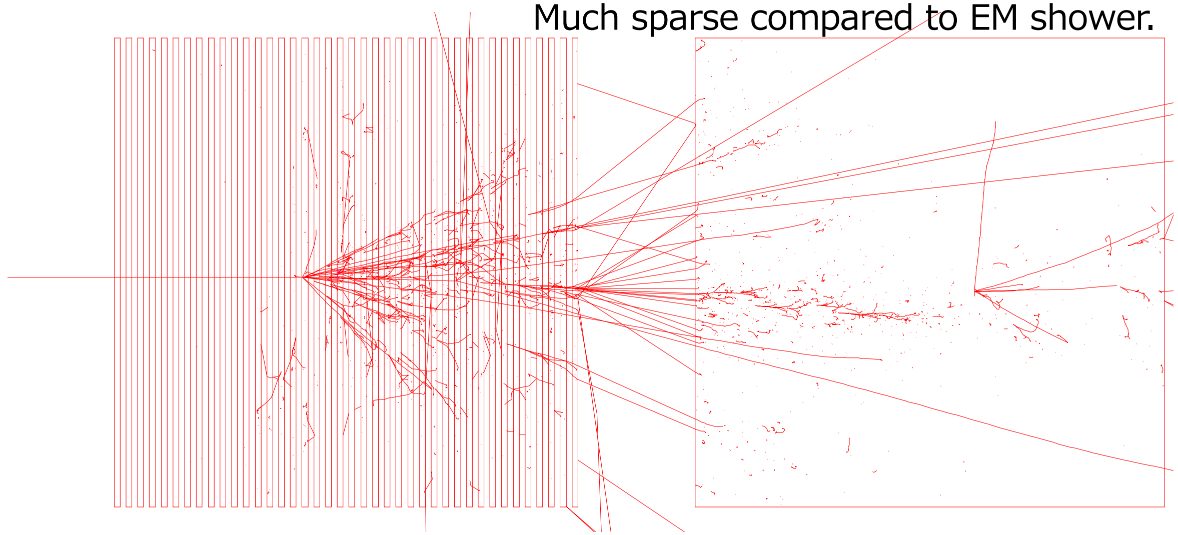
As shower growth, number of particles increases, and energy of each particle decreases.
Eventually their energy become too low to generate particles any more, and cascade ceases.

This process is used to measure energy of neutral hadrons.
(Charged hadron energy is better measured by measuring momentum by trackers.)

Growth of hadron shower in matter. from Grupen.



GEANT simulation of 40GeV proton on Iron. Much sparse compared to EM shower.



2. Interaction of particle with matter ; summary

Interaction of **charged particle** with matter/atom

- Excitation
- Ionization
- Cherenkov Radiation
- Transition Radiation
- Bremsstrahlung
- Nuclear reaction
- Electromagnetic/Hadronic Shower

Interaction of **Photon** with matter/atom

- Photo-electric effect
- Compton scattering
- Pair creation

and Electromagnetic Shower

Interaction of **Hadron** with matter/atom

- Nuclear reaction

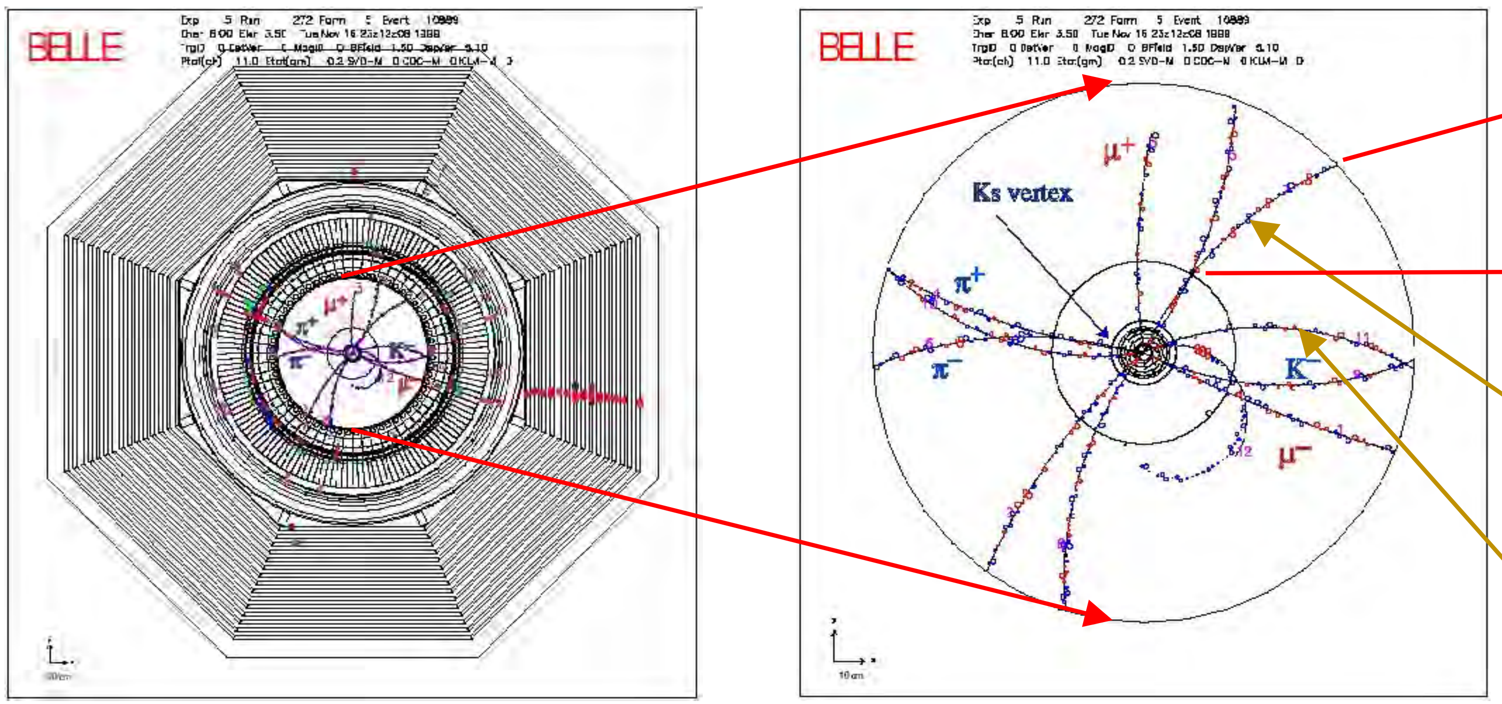
and Hadronic shower

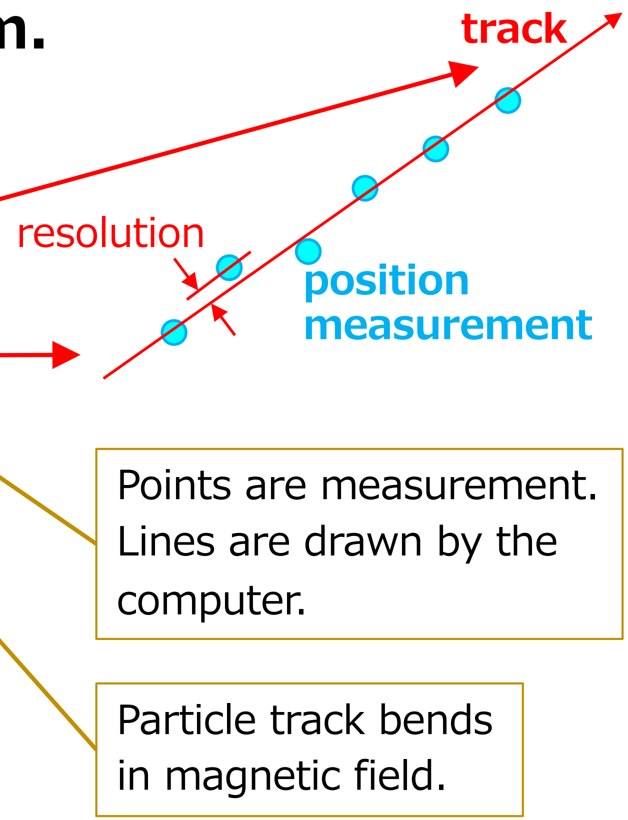
Operation of Detectors

3. Tracker & Vertex Detector

Measure the position of the particle along its path
and reconstruct the particle track.
Calculate momentum together with B-field.
Do not disturb particle's travel,
and do not affect the measurement of following particle-ID.

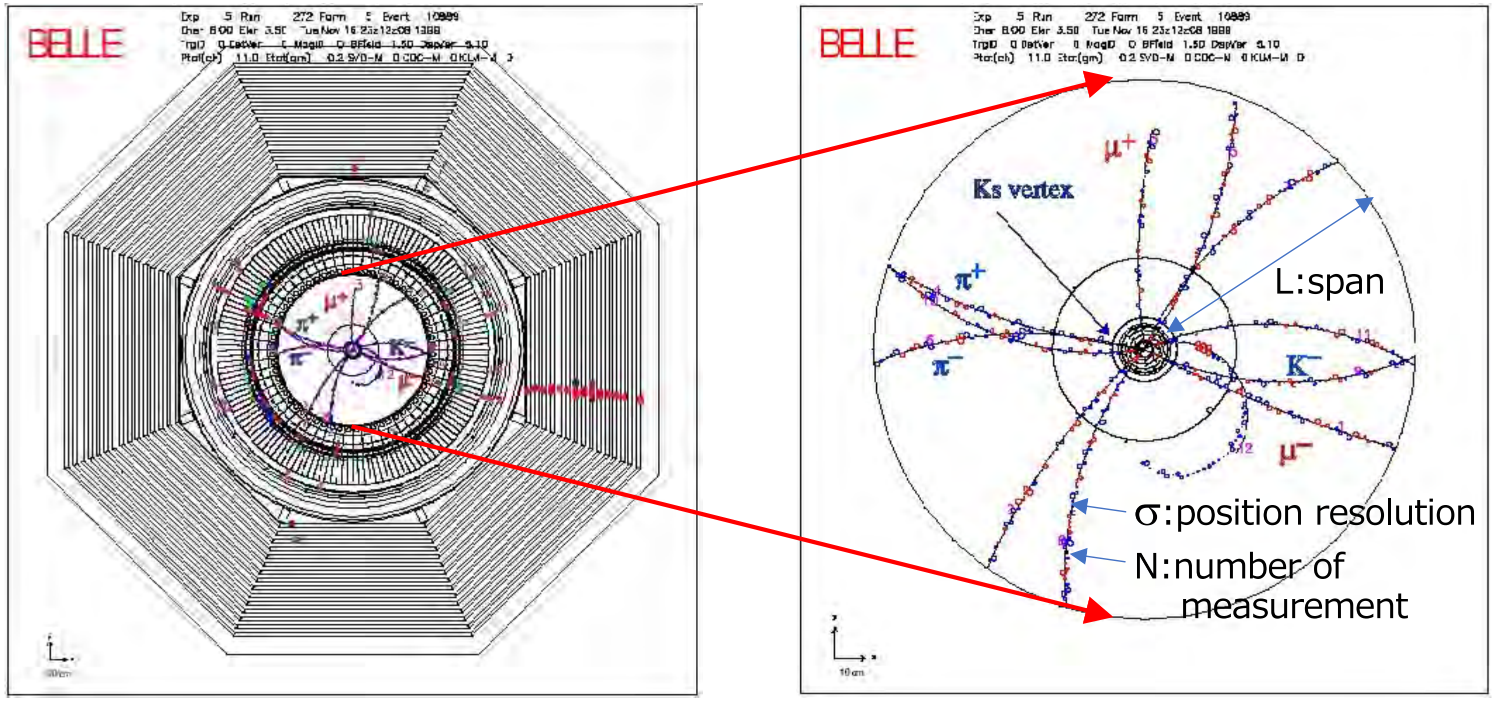
Trackers measure particle direction and momentum.





- Measure space points of charged particle along its passage.
- Connect space points, do fitting, reconstruct the track, and obtain radius of the track.
- With magnetic field B and track radius ρ, momentum P can be calculated. (~P=0.3Bρ)
- Various Trackers for different cases (multiplicity, jet collimation, , ,)
  - Multiwire drift chambers → Belle-II, BaBar,,,
  - Jet Chambers → OPAL, H1, ZEUS,,,
  - Time Projection Chambers → ILD, ALICE, ALEPH, DELPHI,,,
  - Silicon Tracker → ATLAS, CMS, SiD,,,

Trackers measure particle direction and momentum.



Approximately

P [GeV]=0.3$B\rho$ [T・m]

Resolution, in general

$\sigma P_T/P_T = a \cdot P_T \oplus b$

$a \propto \sigma/(BL^2\sqrt{N})$

Large radius, strong B, good position resolution, many measurement points.

ATLAS (achieved)

$\sigma P_T/P_T = 0.05\% \cdot P_T \oplus 1\%$

ILC (design criteria)

$\sigma P_T/P_T = 0.01\% \cdot P_T \oplus 0.2\%$

- Charged particle momentum be measured by trackers, while neutral particle energy be measured by calorimeters.
- Energy loss measurement by trackers is valuable for particle-ID.
- Low mass needed to avoid scattering/kink in the tracker and avoid disturbing following PID.

In case of jets:

- Many tracks close to each other.
  → Need excellent two-track separation, fine pitch to reduce occupancy.
- Need to avoid double counting of track and cluster → precise track-cluster matching needed.
  → P&E resolution, precise track extrapolation, two-track separation, and fine granularity.

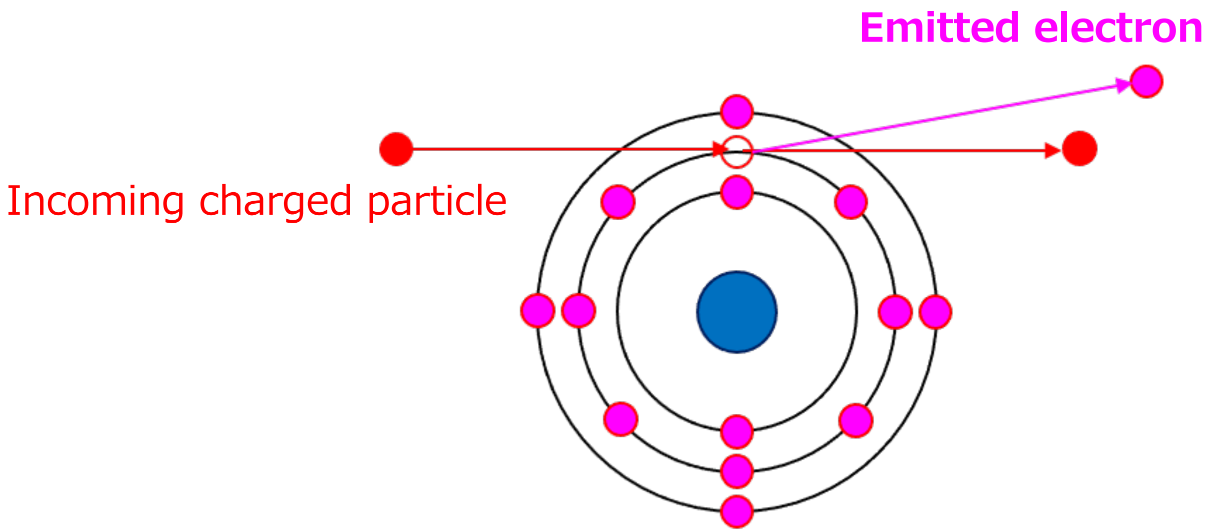
How do trackers measure space points ?

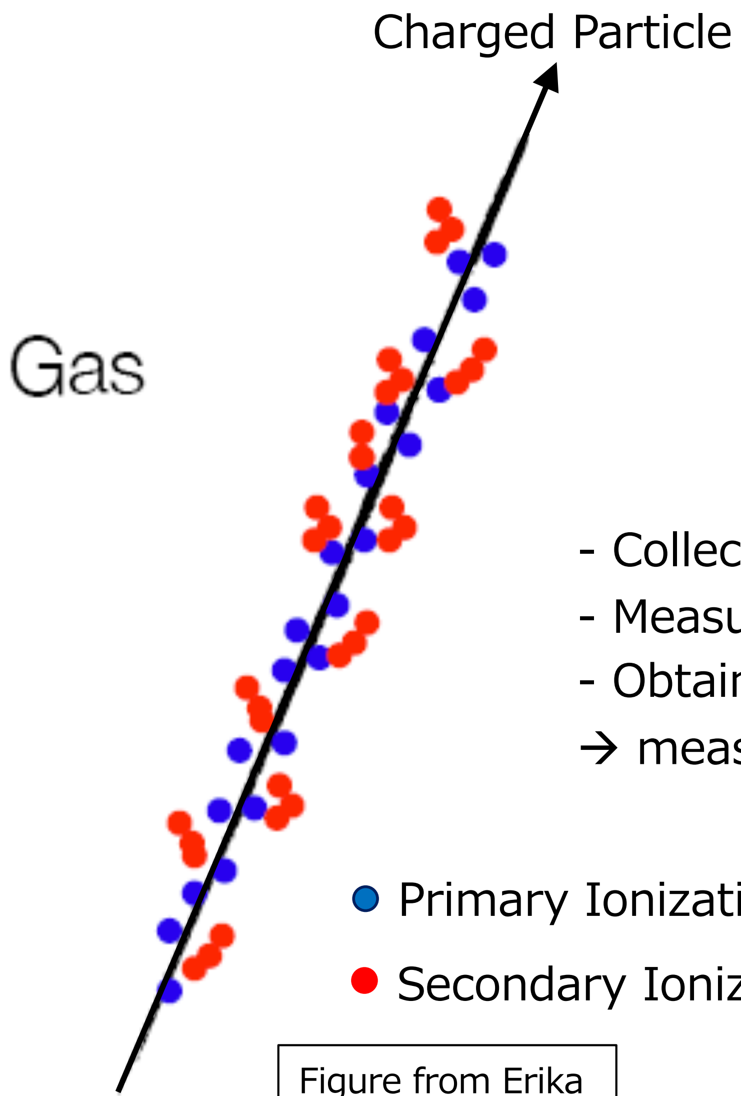
Interaction with matter : ionization

- Gas trackers
  - Principle of gas chambers
  - wire chambers
  - drift chamber
  - jet chambers
  - TPC
  - Various chambers
- Silicon trackers
  - Principle of silicon detector
  - Strip
  - Pixel
  - VTX detectors

3. Operation of detectors ; Trackers ; Gas Chambers

A charged particle passes through material → Ionization
This is the starting point of various detectors.





- Collect the charge generated by ionization (somehow)
- Measure the collected charge (somehow)
- Obtain the space coordinate of the ionization point (somehow)

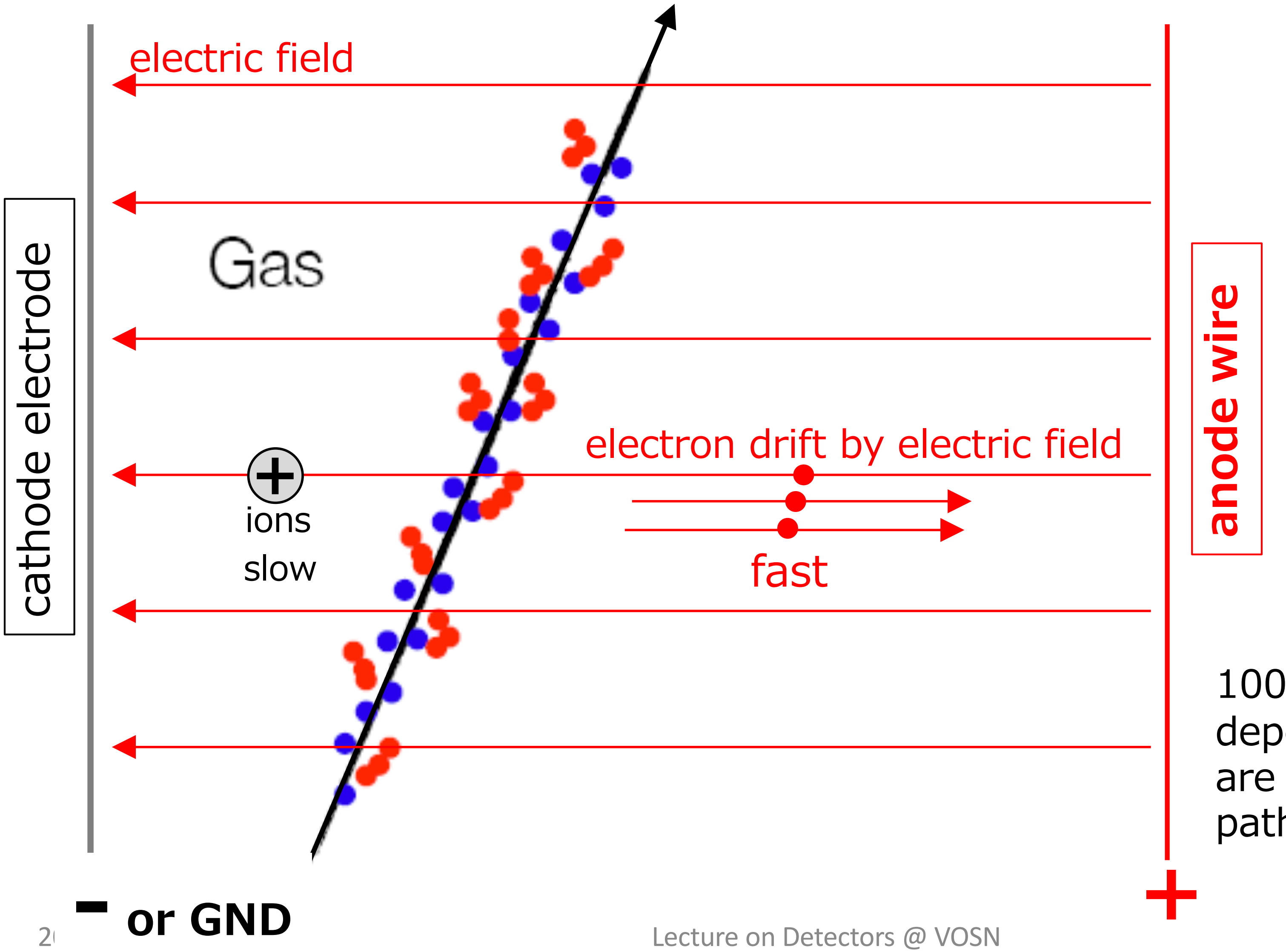
→ measure the space-points of the particle

- Primary Ionization (ions and electrons)
- Secondary Ionization (δ-ray ; ionization by primary electrons)

Figure from Erika

Operation principle of gas chambers

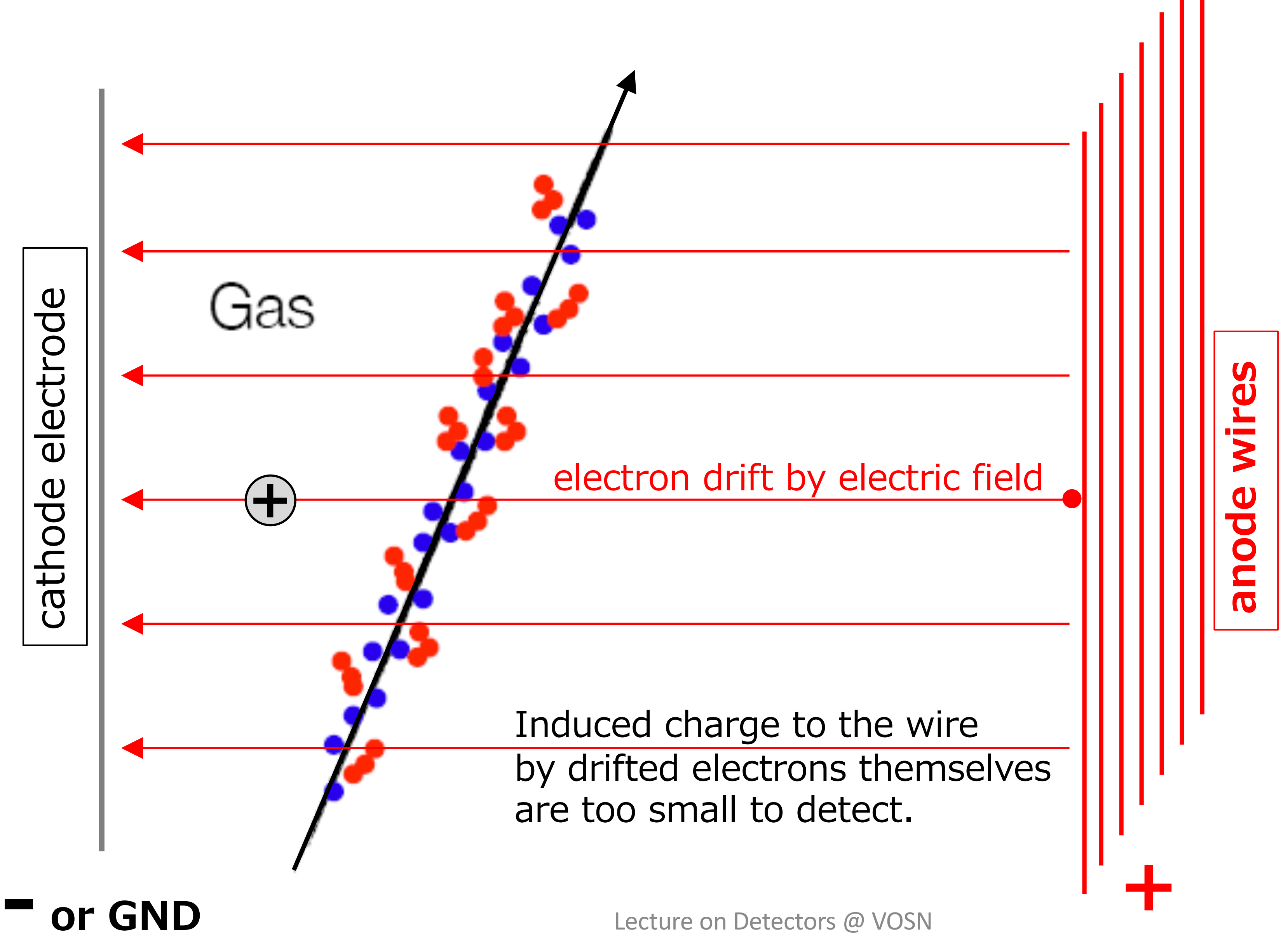
wire chamber ; drift of emitted electrons and avalanche multiplication



100-200 electron-ion pairs, depending on the gas type, are generated for 1cm path in the gas.

Operation principle of gas chambers

wire chamber ; drift of emitted electrons and avalanche multiplication



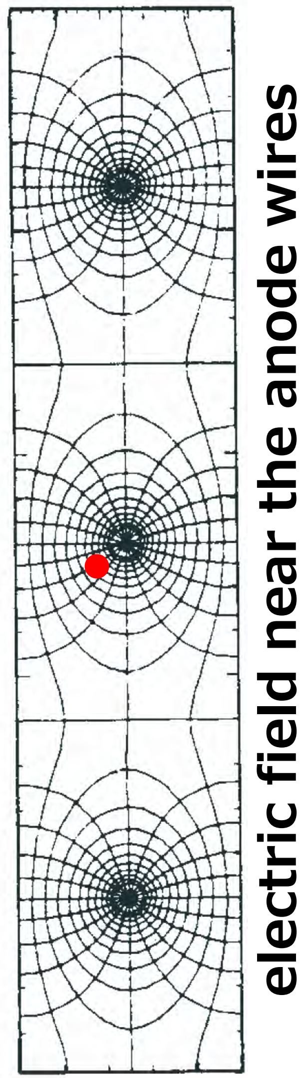
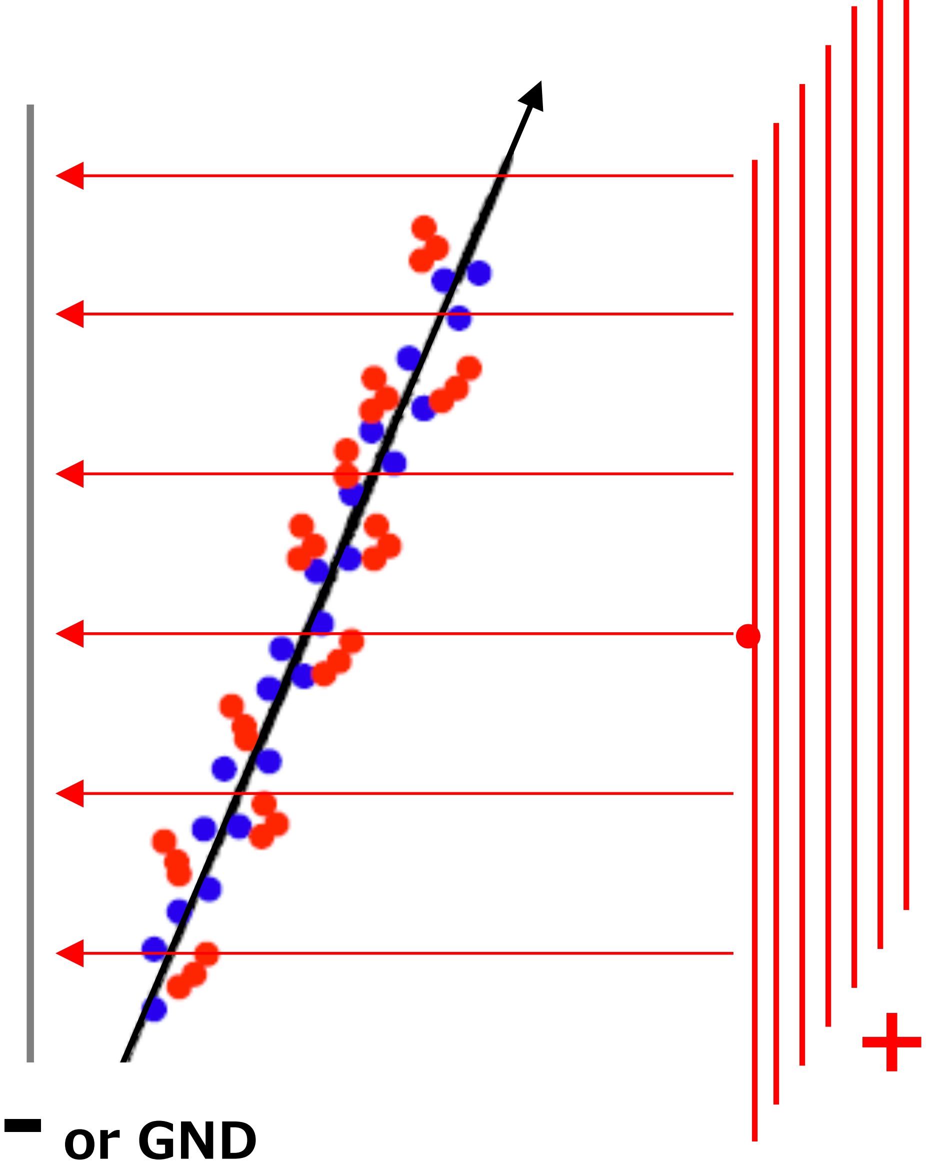


Figure from Joram

Operation principle of gas chambers

wire chamber ; drift of emitted electrons and avalanche multiplication



Strong electric field near the wire.

⇩

Drift electrons are accelerated.

⇩

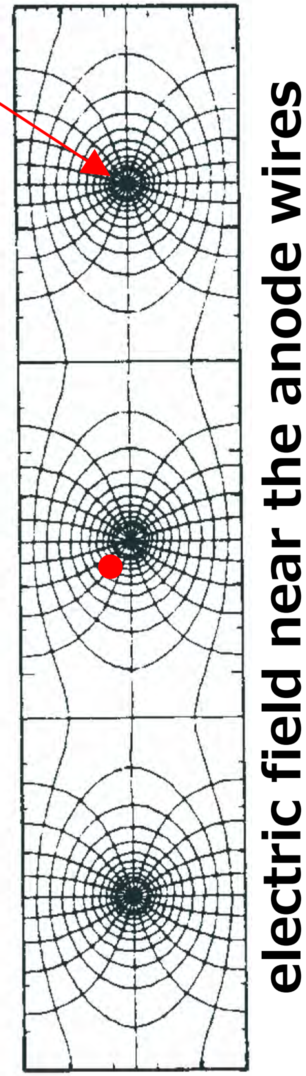
Drift electrons ionize gas atoms.

⇩

Ionized electrons are also accelerated and further ionize.

⇩

A lot of ionization generated
→ **avalanche multiplication**
Gain depends on gas type, wire radius, applied voltage,,, and typically $10^4 \sim 10^5$.



Avalanche multiplication of electrons

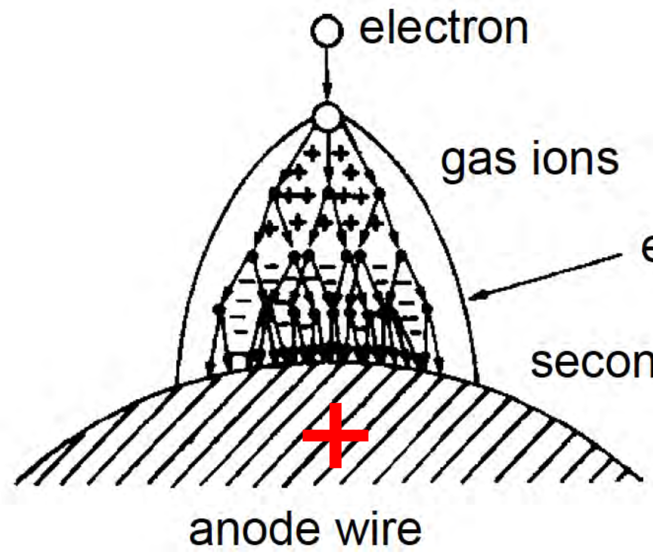
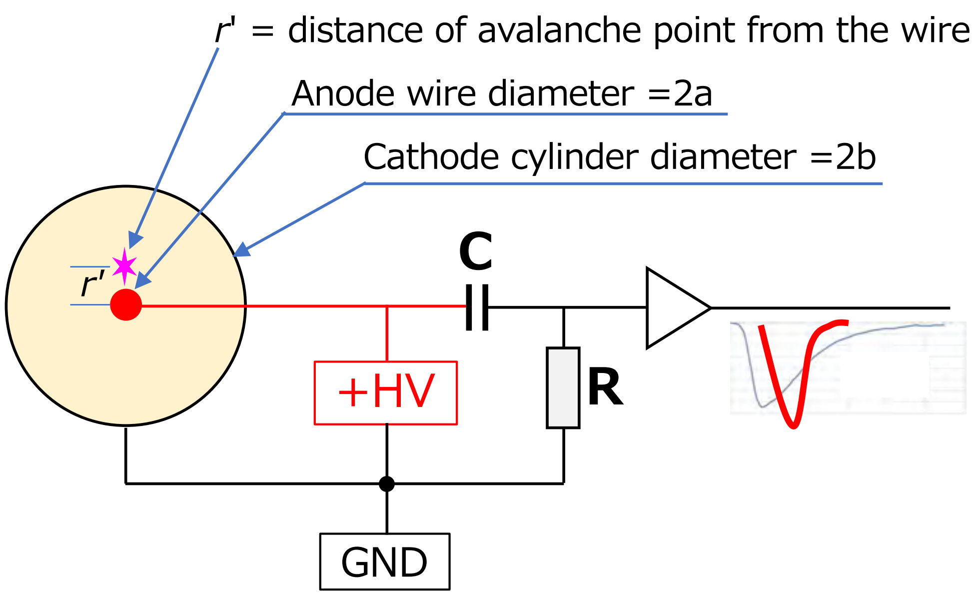


Figure from Grupen



Signal generation at the wire

- Electrons move to the wire and induce charge.
  Electrons are very quickly absorbed by the wire.
- Ions move away and induce charges on the wire.
  Their movement is rather slow.
- Wire picks up induced charges by the movements.
- Calculate induced voltage ; $V_{\mathrm{ion}} >> V_{\mathrm{electron}}$
- Ion is slow, thus signal continues long.
  → Readout circuit clips it.

For electrons

$$V^- = -\frac{q}{lCV_0}\int_{a+r'}^{a}\frac{d\phi(r)}{dr}dr = -\frac{q}{2\pi\epsilon_0 l}\ln\left(\frac{a+r'}{a}\right)$$

For ions

$$V^+ = \frac{q}{lCV_0}\int_{a+r'}^{b}\frac{d\phi(r)}{dr}dr = -\frac{q}{2\pi\epsilon_0 l}\ln\left(\frac{b}{a+r'}\right)$$

$$V^-/V^+ = \frac{\ln(a+r'/a)}{\ln(b/a+r')}$$ ~ 1/100 typically.

Equations from Erika

3. Operation of detectors ; Trackers ; Gas Chambers

Expected performance depends on various chamber configurations;

- Multi-wire proportional chambers or Drift chambers or Jet chambers or Time projection chambers or , , , ,
- wire readout or pad readout or micro-pattern gas detectors or , , , ,
- on/off or pulse-height or timing
- single-hit or multi-hit or FADC

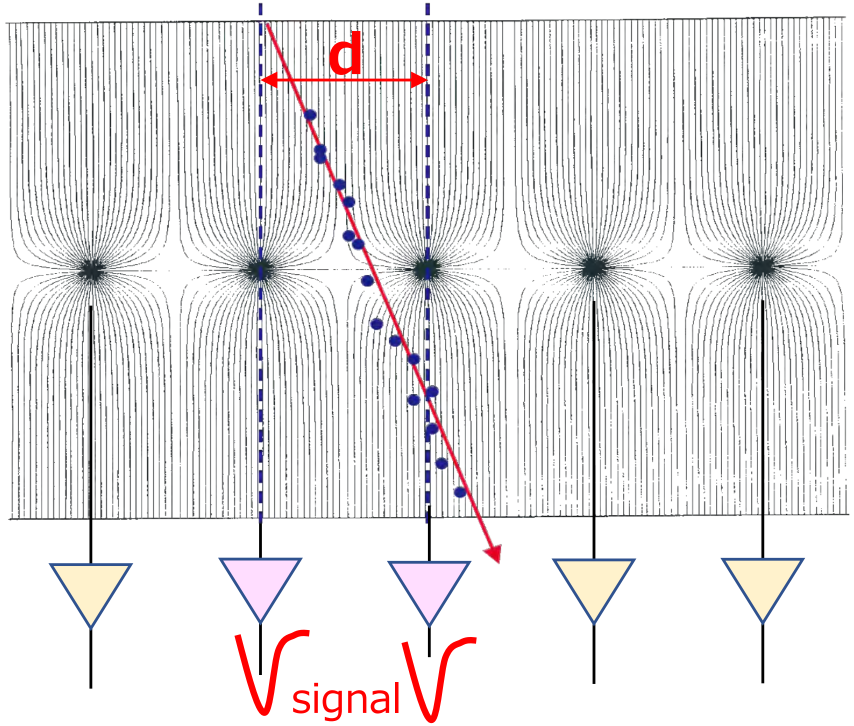
Related Performances are;

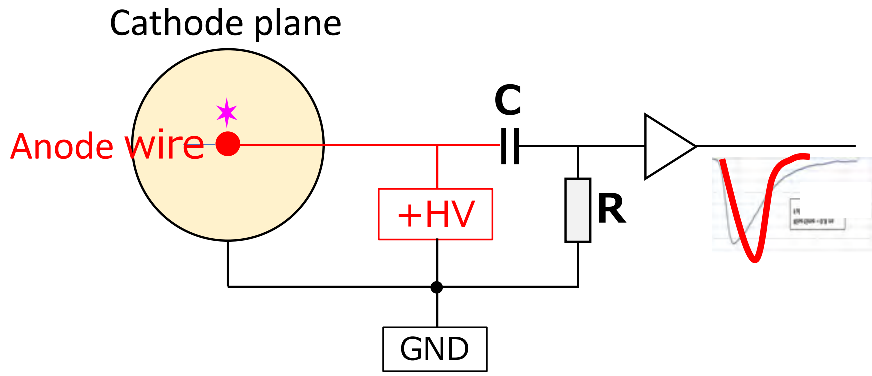
- timing resolution
- position resolution
- energy-deposit measurement
- occupancy
- two-track (hit point) separation
- material thickness
- available size
- cost

and so on...

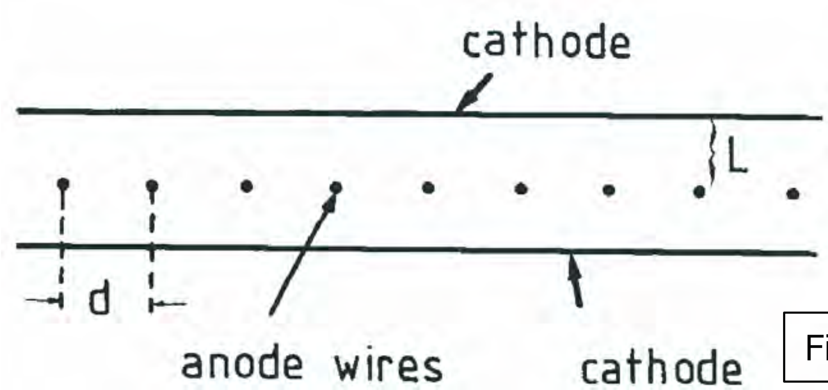
Multi-wire Proportional chamber (MWPC)

Array of many wires and measure the position





Signals from wires are read-out.



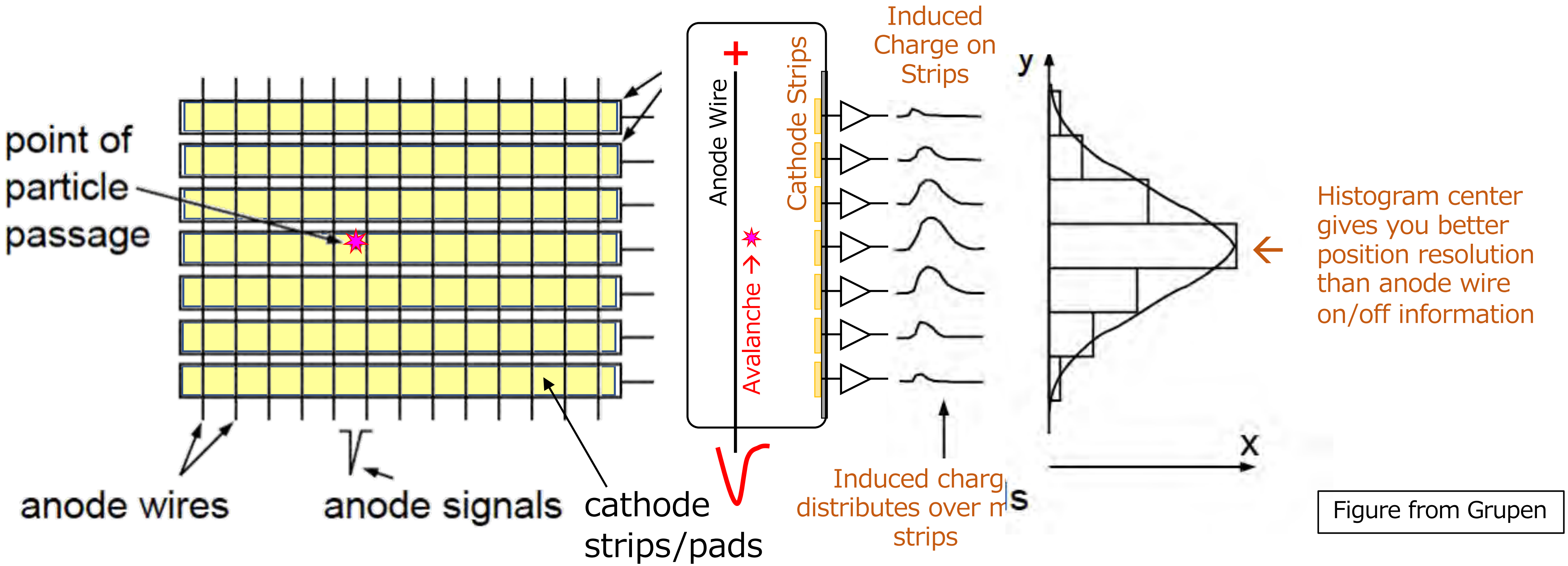
Figures from Joram

Expected performance

- position resolution = d/√12 ~0.6mm for d=2mm ; usually on/off readout
- timing measurement ~10ns
- large size possible (but not extremely large ; wires become unstable)
- multi-hit measurement capability ; none. usually 1hit for 1wire.
  Not suitable for jet measurement. For low-multiplicity event measurement.
- cost [/m^2] ; inexpensive

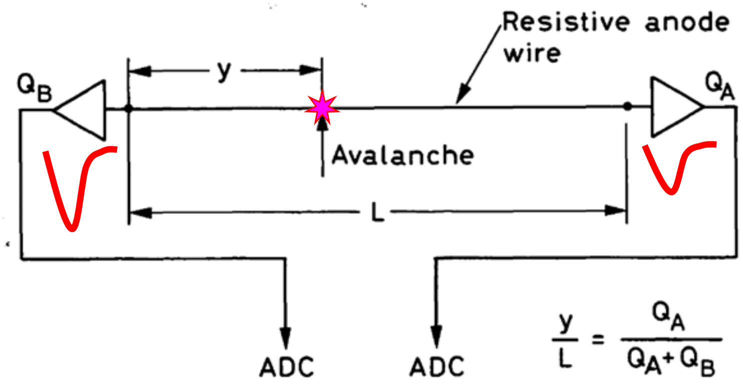
Multi-wire Proportional chamber (MWPC)

Pad/Strip Analog Read-out (instead of wire-read-out)



Pad/strip analog read-out ;
Measure induced charge over the pads/strips.
Center of the charge distribution gives better resolution (ex. 0.1mm)
than on/off discrete anode wire readout (ex. 0.6mm).

Multi-wire Proportional chamber : Two-dimensional Read-out

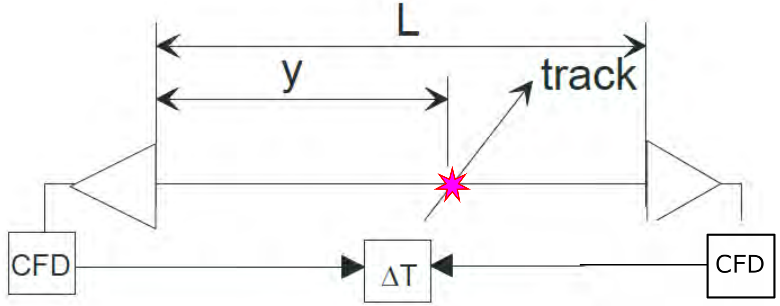


Charge division

Read out signal charge from both ends of the wire.
Pulse-height ratio gives hit position along the wire.

$\sigma_{y/L}$~0.5% → σ_y~1cm

from W.R.Leo

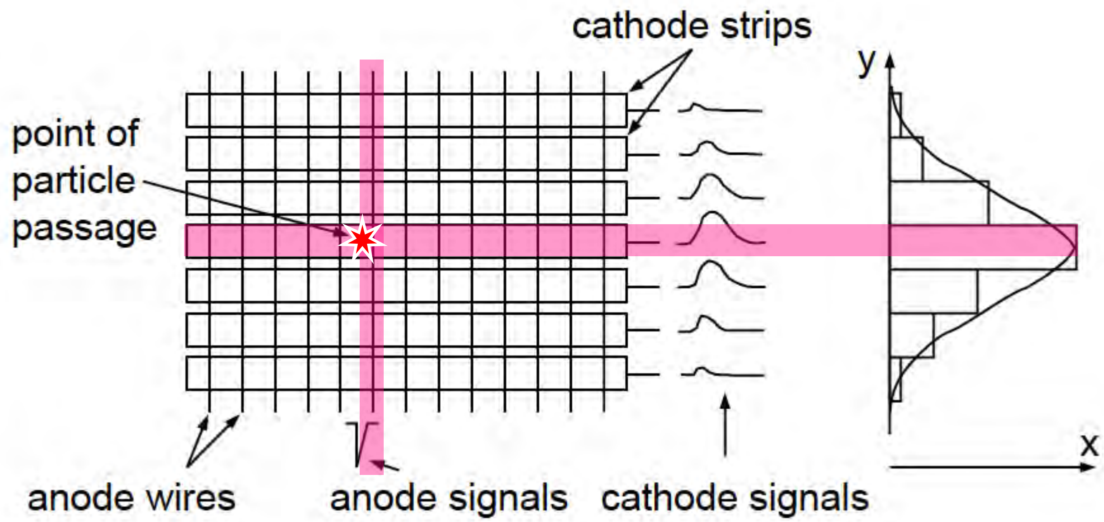


Time difference

Read out signal timing from both ends of the wire.
Time difference gives hit position along the wire.

σ_t~100ps → σ_y~4cm

from Joram



Read out both anode wires and cathode pads/strips.

Drift chamber

- Uniform drift electric field is made by field shaping wires with appropriate voltage gradient.
- Ionized electrons drift along the electric field toward the sense wire, and measure the timing of signal w.r.t. particle passage (=external trigger)

→ position information (=time x velocity of electron in the gas)

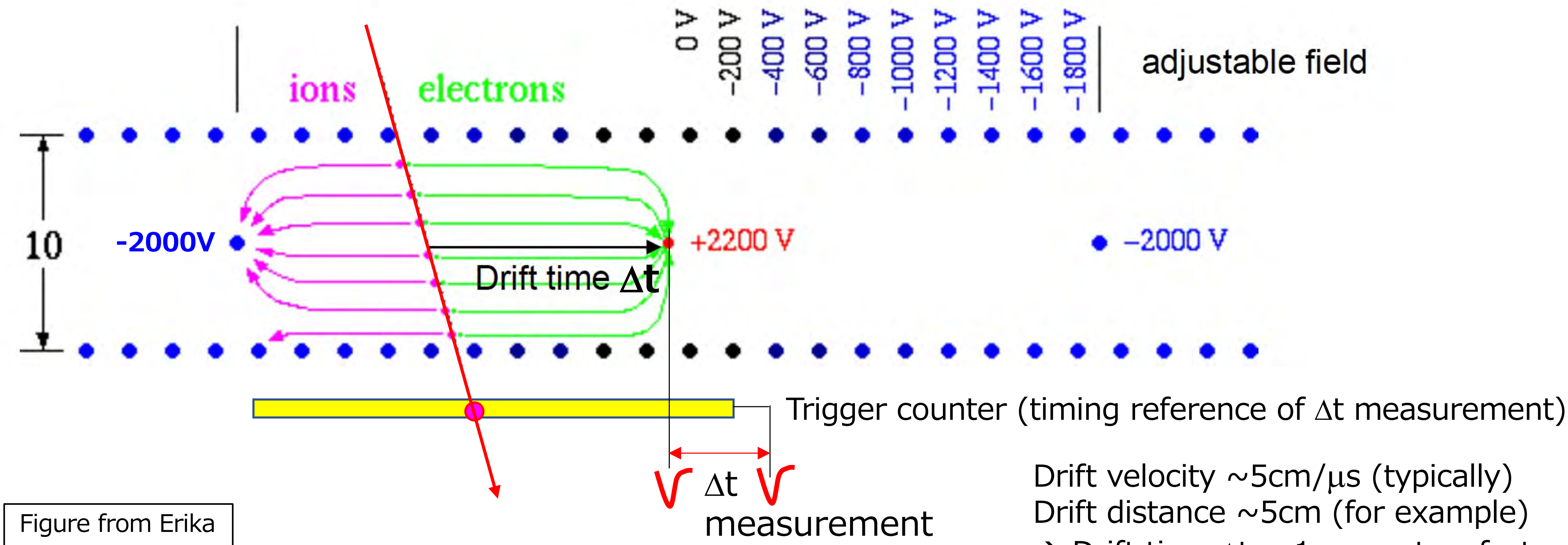
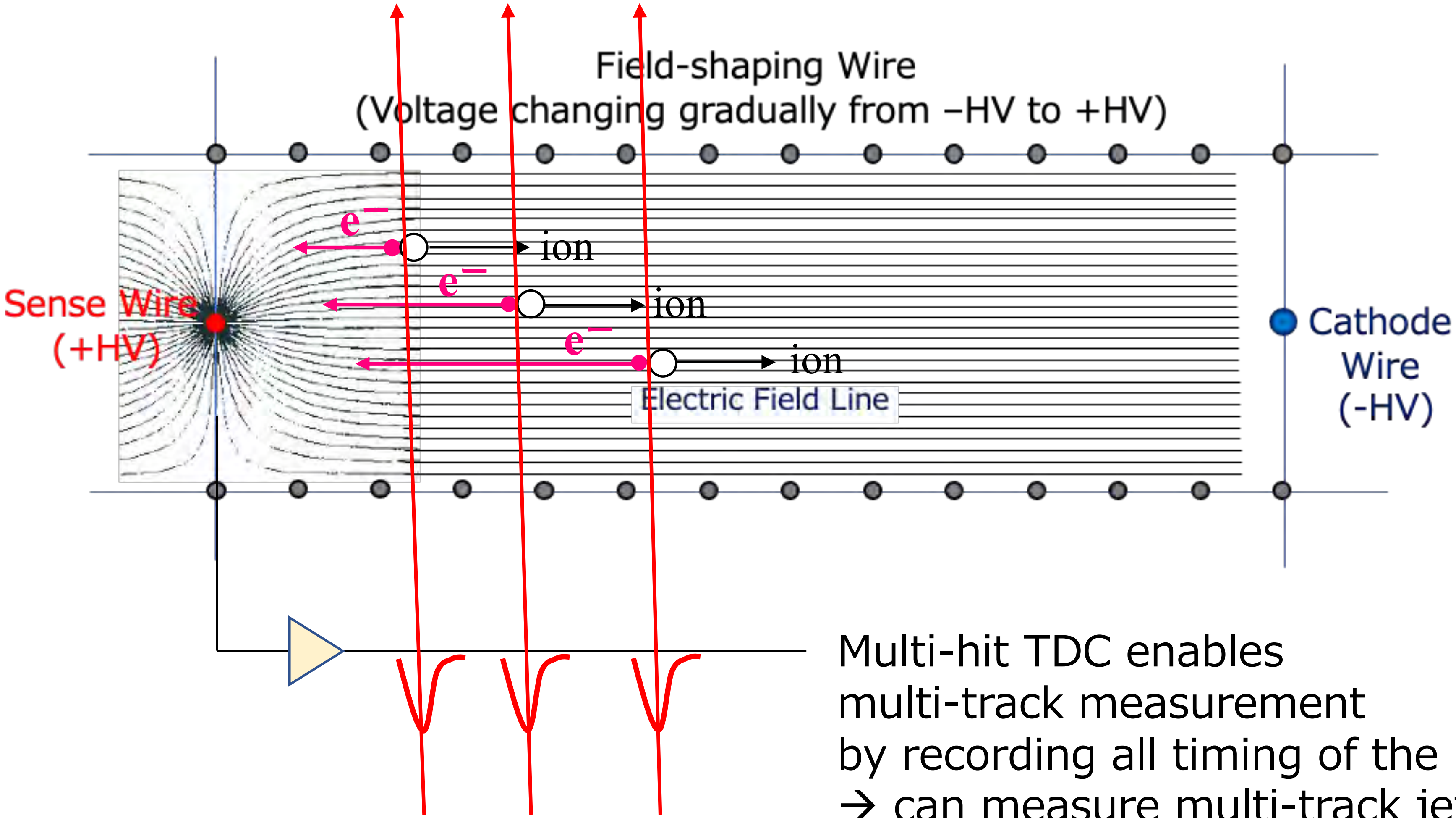


Figure from Erika

Drift velocity ~5cm/μs (typically)
Drift distance ~5cm (for example)
→ Drift time Δt ~ 1μs ; not so fast.

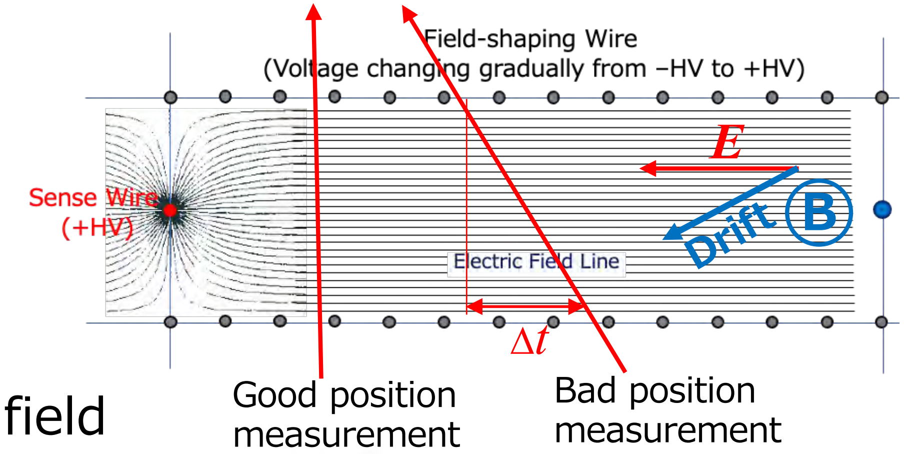
Drift chamber



Multi-hit TDC enables
multi-track measurement
by recording all timing of the pulse train.
→ can measure multi-track jet.

Drift chamber

Many factors affect the position resolution;
- diffusion of drifting electrons
- non-uniform electric field
- track incident angle to the field line
- Lorentz angle of drift line due to magnetic field



Left-Right ambiguity
→ multi-layer configuration

Drift chambers give you
only distance from the wire.
→ Two hit position candidates.
→ One is true, the other is a ghost.
True hit positions coincide, but ghost positions apart.

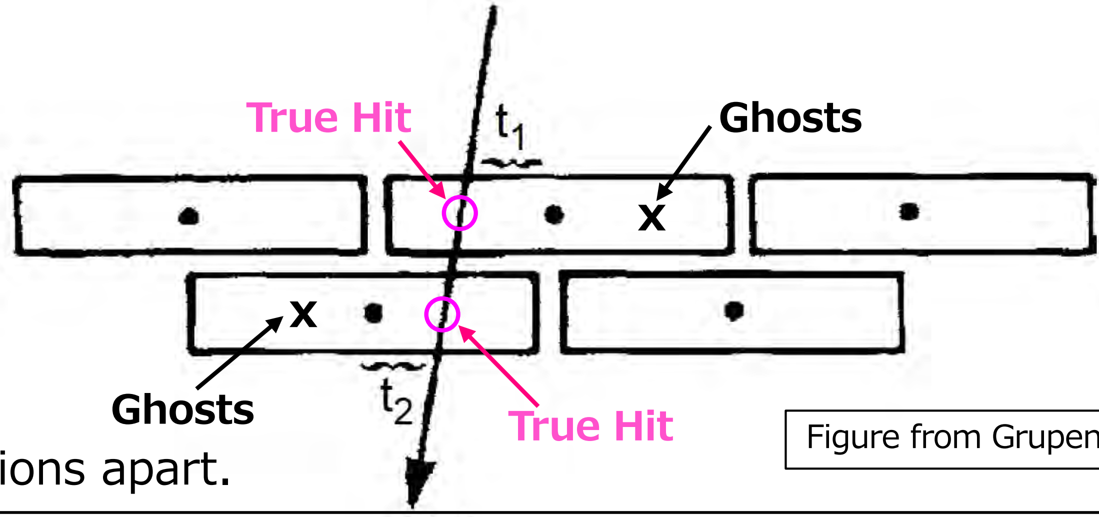


Figure from Grupen

Expected performance
- good position resolution 50~100μm (depends on drift length, track angle, ***B*** etc.)
- no timing measurement (external timing needed)
- large size possible (occupancy matters)
- multi-hit measurement capability with multi-hit TDC → jet chamber
- less cost ; less wires, less readout channels

Tracking by chamber planes

Stack many layers of chamber planes
→ many position measurements
→ Track reconstruction

Simple stack of MWPC layers in case of fixed-target experiments.

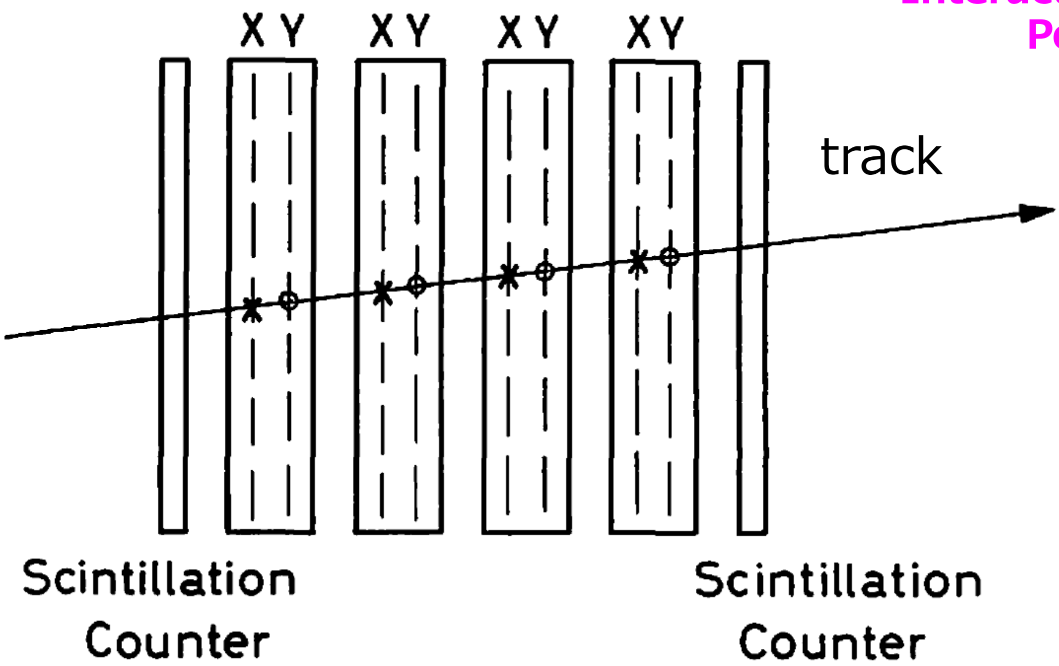


Figure from W.R.Leo

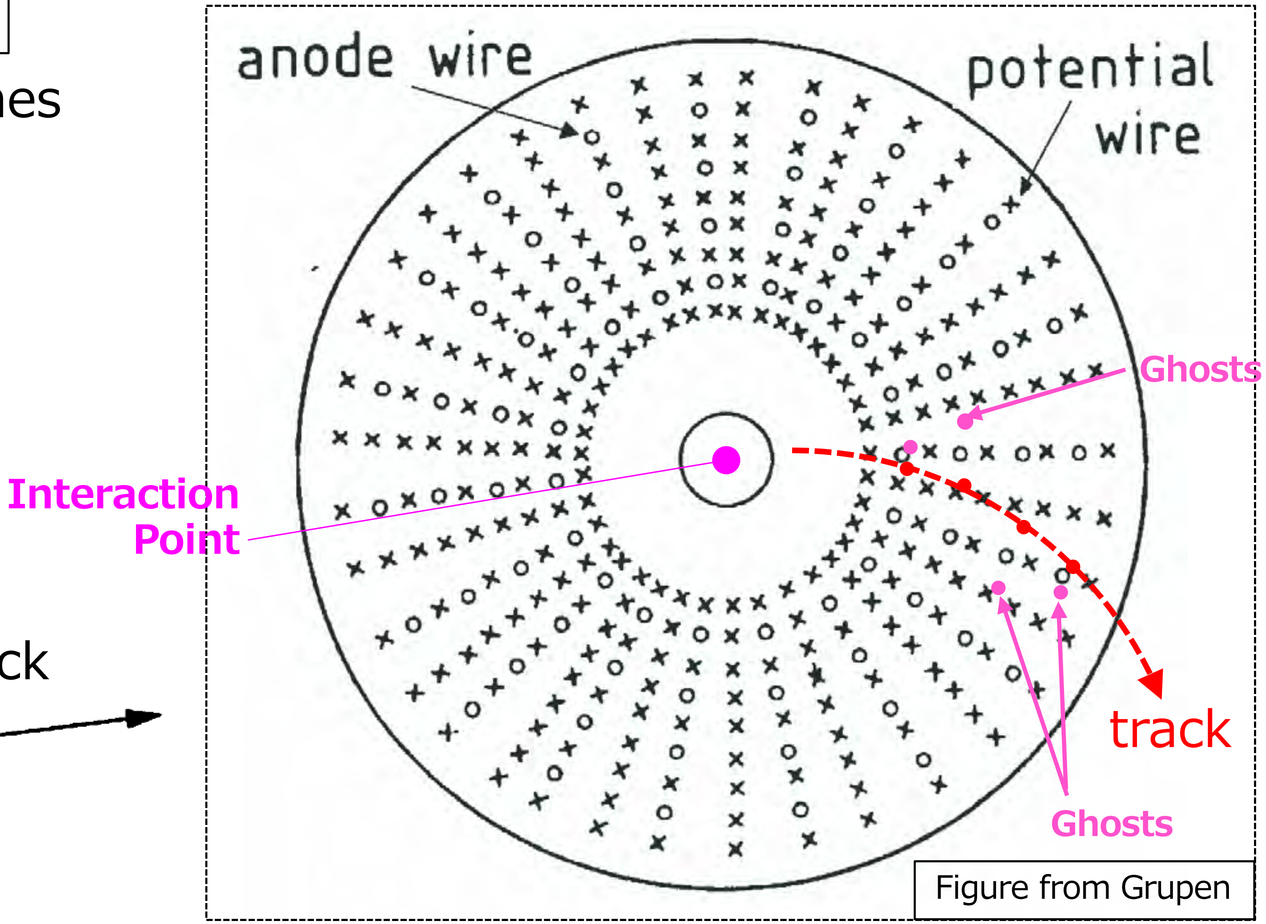
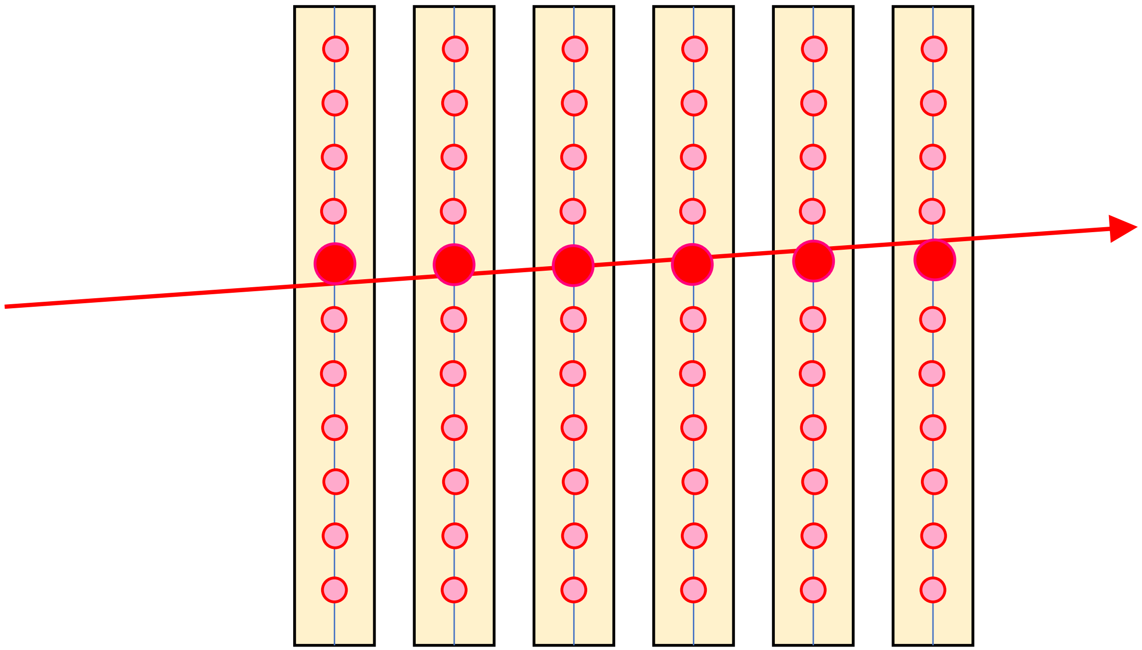


Figure from Grupen

"Cylindrical Drift Chamber" in colliders. Cylindrically multi-layered drift chambers are surrounding the interaction point.

Occupancy

If number of tracks are small compared to the number of wires, track reconstruction is simple and successful.

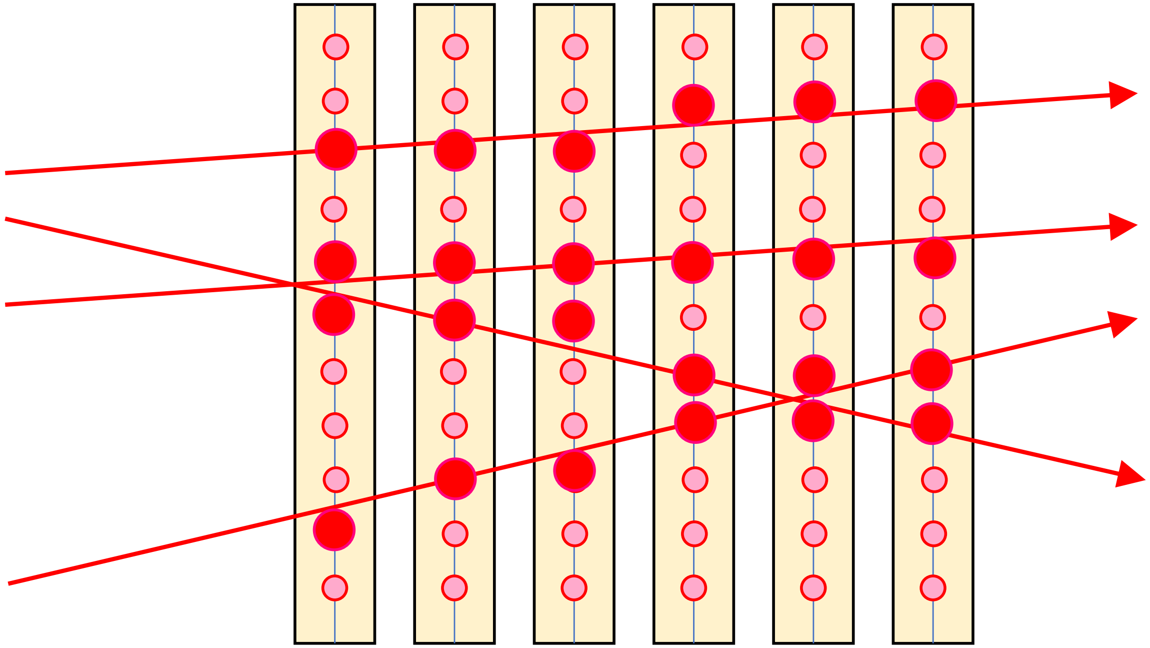


If just one particle passed through the chamber planes, reconstruction of the track is simple without any ambiguity.

Occupancy is fraction of hit channels to the total channels. This is different from resolution.

Occupancy

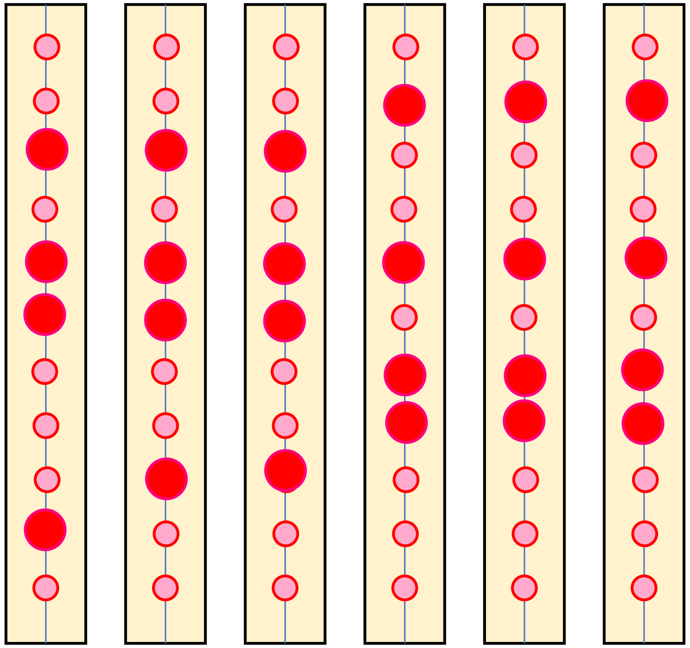
If number of tracks are too many compared to the number of wires, track reconstruction screws up.



If number of particles passing through the chamber planes is large, reconstruction of the track has ambiguity.

Occupancy

If number of tracks are too many compared to the number of wires, track reconstruction screws up.

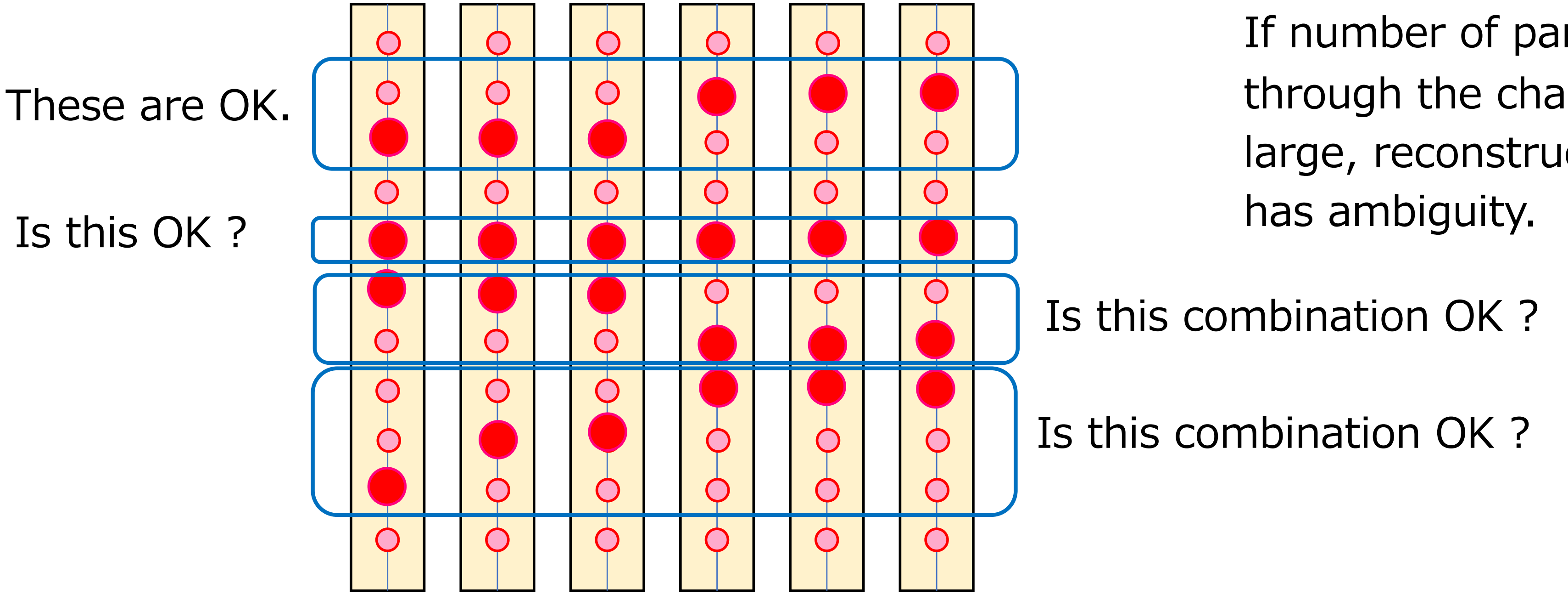


If number of particles passing through the chamber planes is large, reconstruction of the track has ambiguity.

Can we find out correct combination of hit points ?

Occupancy

If number of tracks are too many compared to the number of wires, track reconstruction screws up.



If number of particles passing through the chamber planes is large, reconstruction of the track has ambiguity.

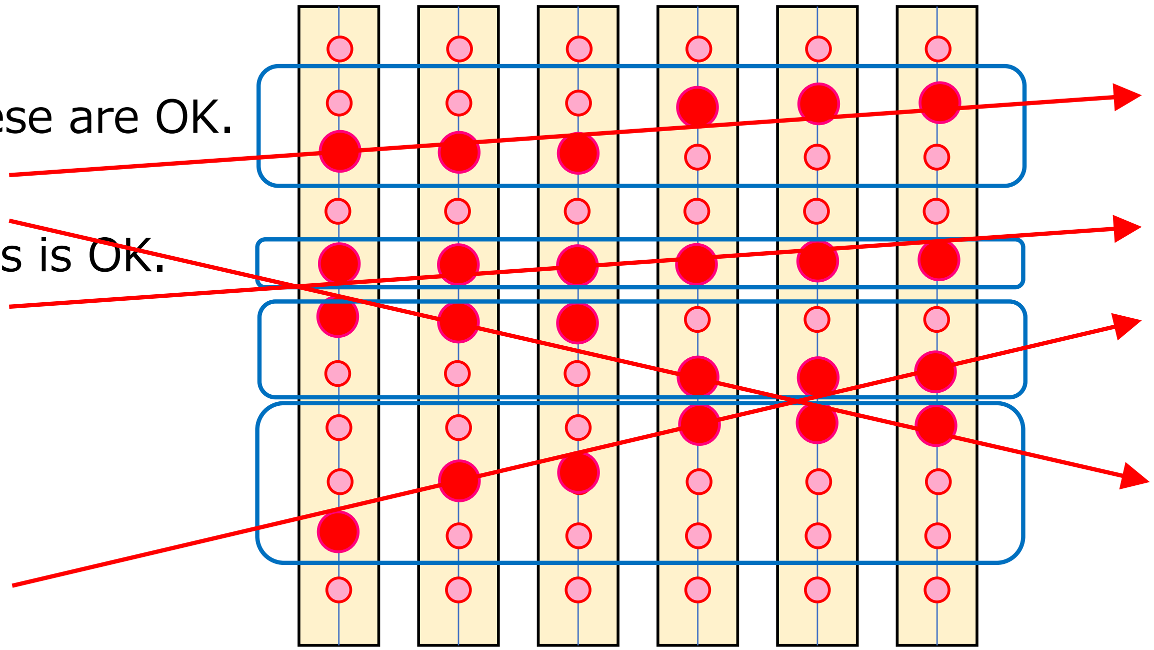
Occupancy

If number of tracks are too many compared to the number of wires, track reconstruction screws up.

If number of particles passing through the chamber planes is large, reconstruction of the track has ambiguity.
Better position resolution does not help.

These are OK.

This is OK.

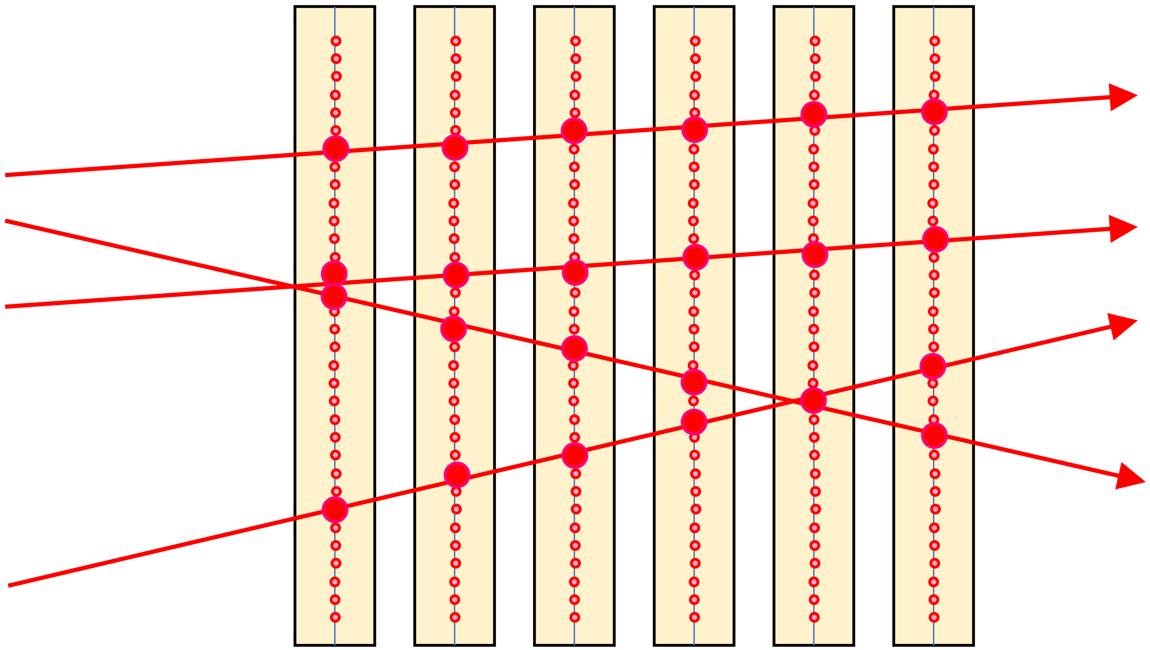


This combination is wrong.

This combination is wrong.

Occupancy

If number of tracks are too many compared to the number of wires, track reconstruction screws up.

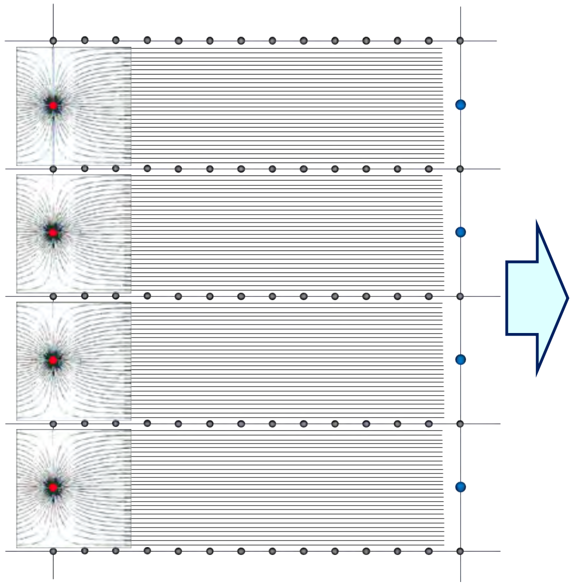


Finer readout pitch with larger readout channels removes ambiguity of reconstruction of the tracks.

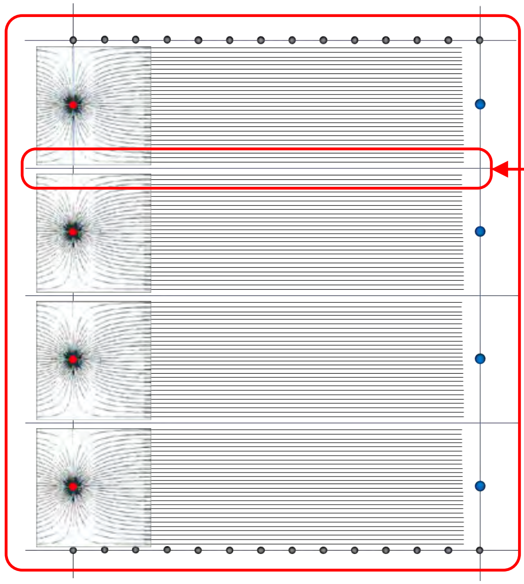
Keeping occupancy small enough is crucially important for jetty event measurement.

Jet chamber

Drift chamber with many wires in a "cell" and measure "Track Segment"

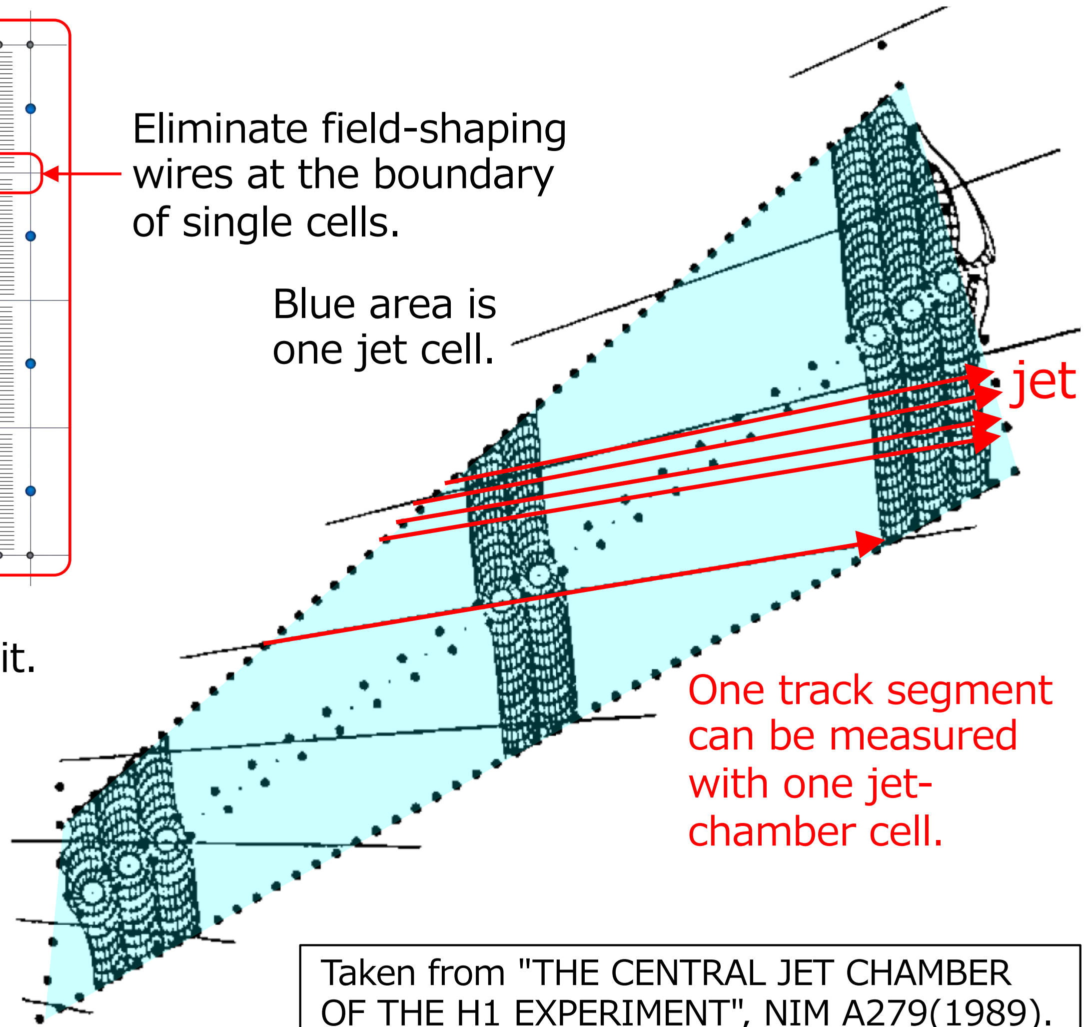


Stack many layers of single-cell drift chamber.



Large Jet-Cell with many sense wires in it.

Eliminate field-shaping wires at the boundary of single cells.



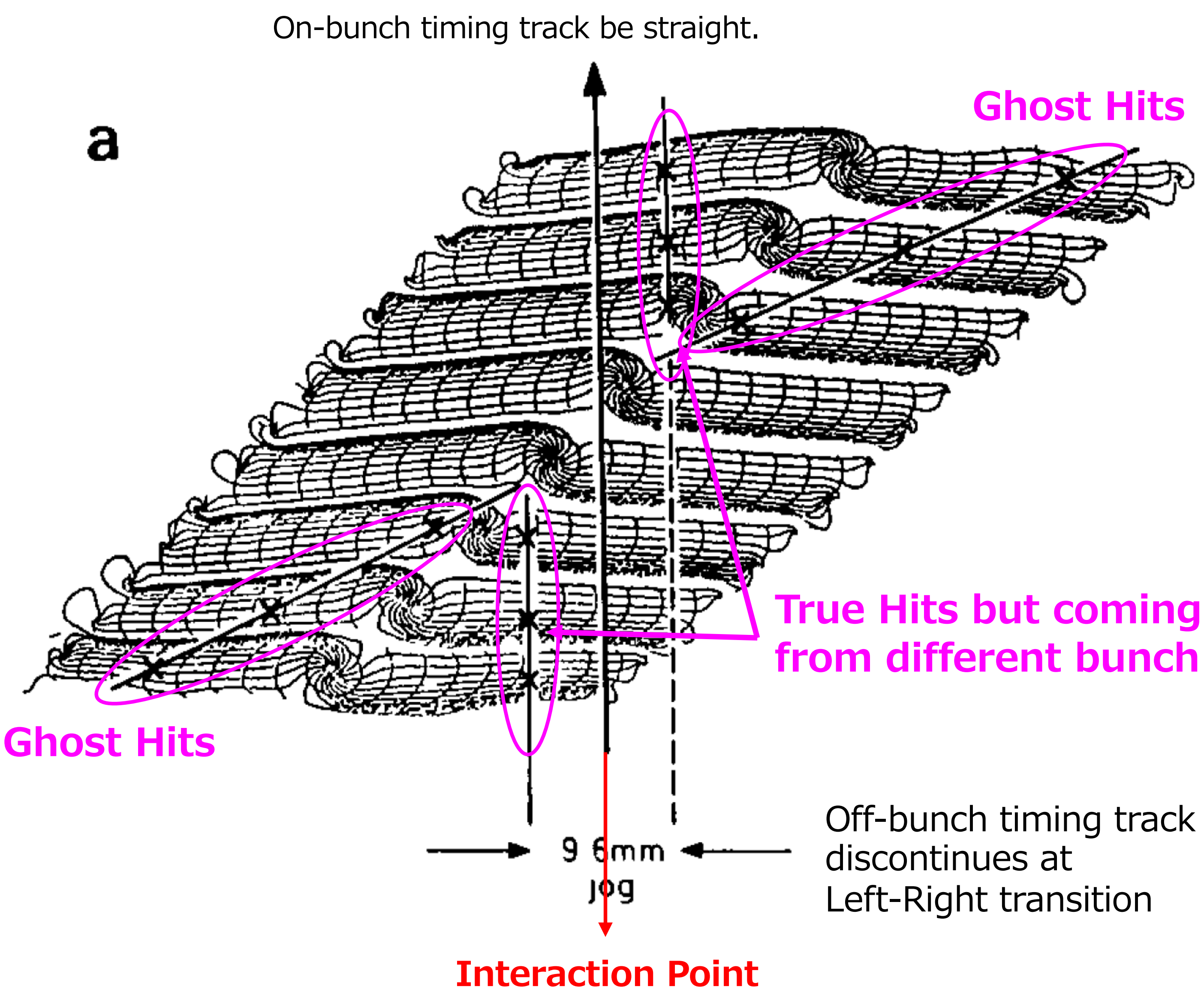
One cell of H1 jet chamber. Straight lines are pointing interaction point. Drift field is designed to be perpendicular to the I.P. pointing lines under 30^{o} Lorentz angle.

Taken from "THE CENTRAL JET CHAMBER OF THE H1 EXPERIMENT", NIM A279(1989).

3. Operation of detectors ; Trackers ; Gas Chambers

Jet chamber

DESY-HERA-ZEUS Jet Chamber



Deformed electric field by magnetic field, with a track of off-timing bunch crossing, and ghost hits.

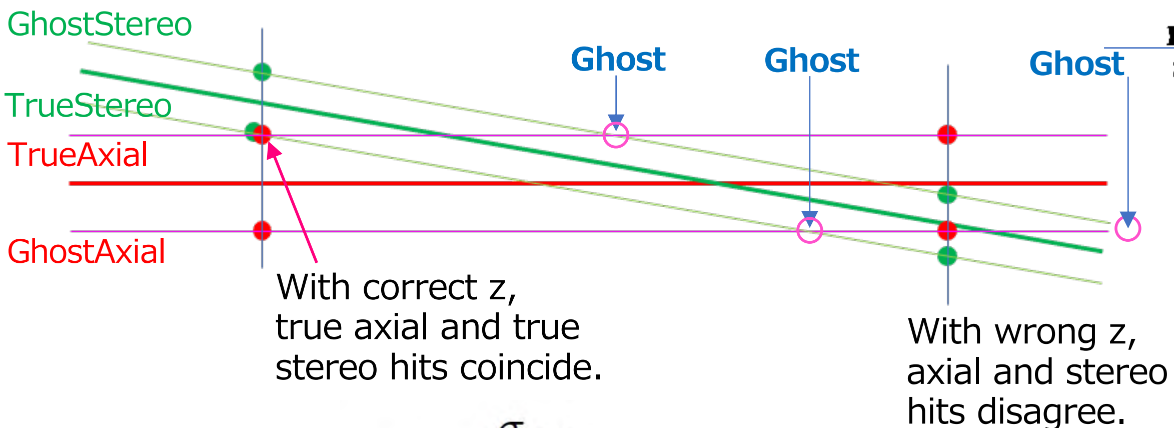
Taken from "DEVELOPMENT OF THE ZEUS CENTRAL TRACKING DETECTOR", NIM A283(1989).

Jet chamber

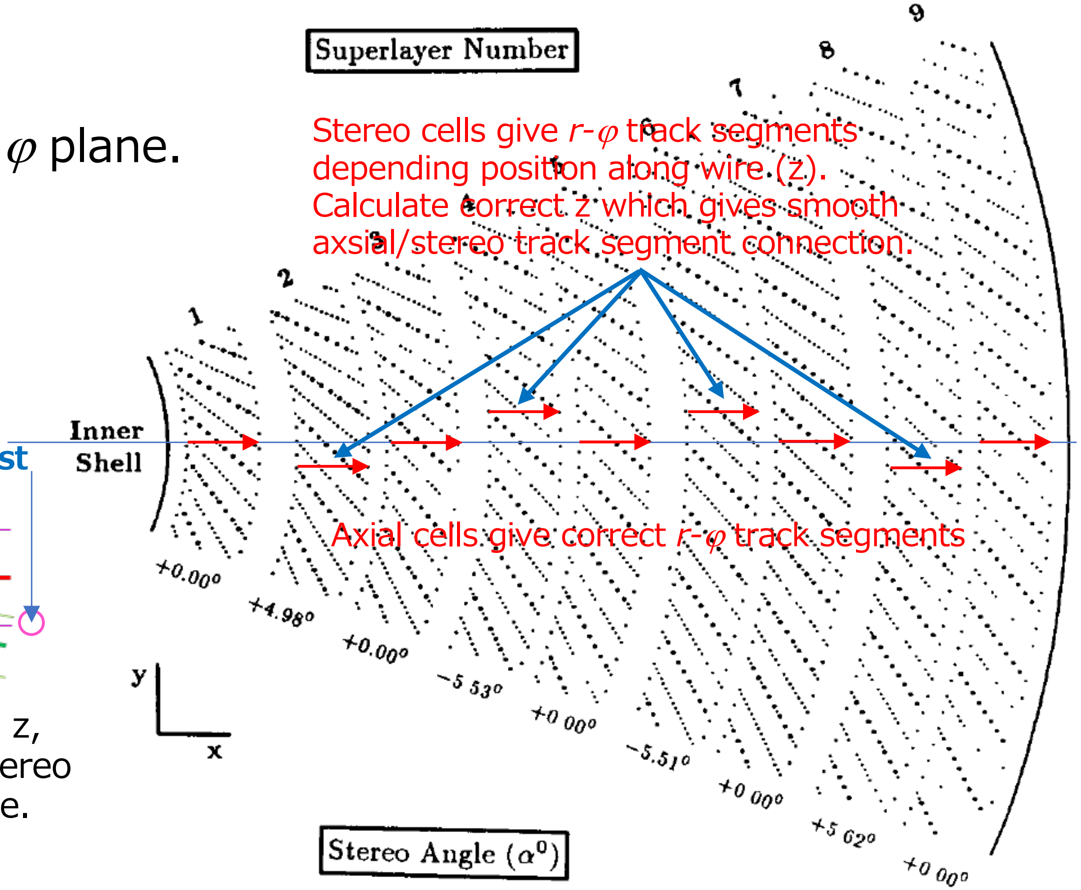
- Jet cell just measures track projection to the r-φ plane.

→ To reconstruct track in 3-dimensional space, z-measurement is needed.

→ Stereo wires (tilted wires) or charge division



$$\sigma_z = \frac{\sigma_{r,\varphi}}{\sin\gamma}$$



ZEUS jet chamber axial/stereo configuration. From NIM A283.

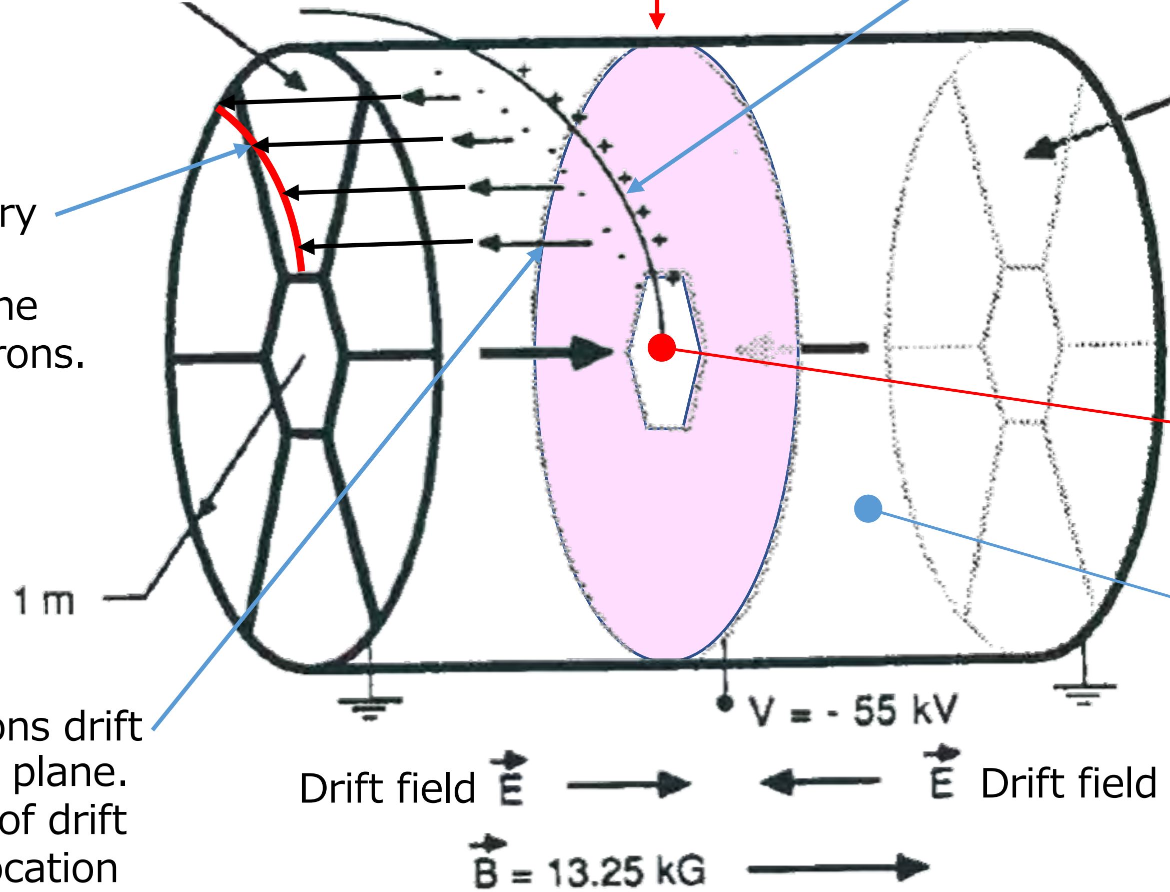
Expected performance

- good r-φ position resolution ~100μ, good z-resolution ~1.2mm
- multi-track measurement with multi-hit TDC. 2-track separation ~ 2mm
- dE/dx measurement ~4%
- sensitive to B-field (<2Tesla)
- large size possible

Time Projection Chamber（TPC)

Essentially three-dimensional track measurement.

Large gas cage and no wires in drift volume.



PEP4 TPC

Base figure from Joram

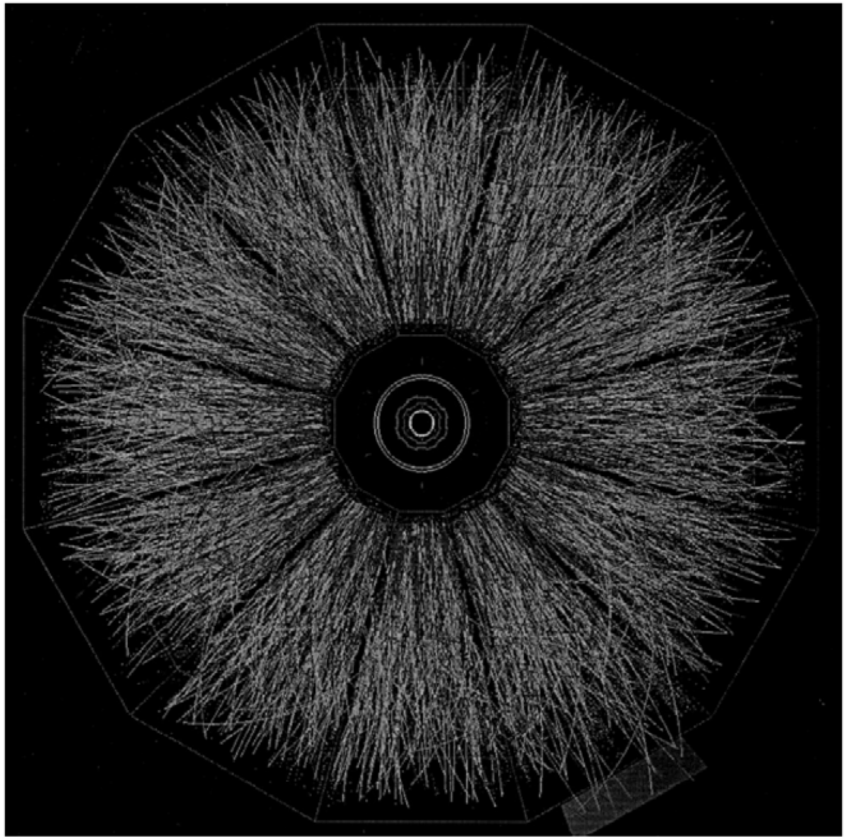
Time Projection Chamber（TPC）

Characteristic features;

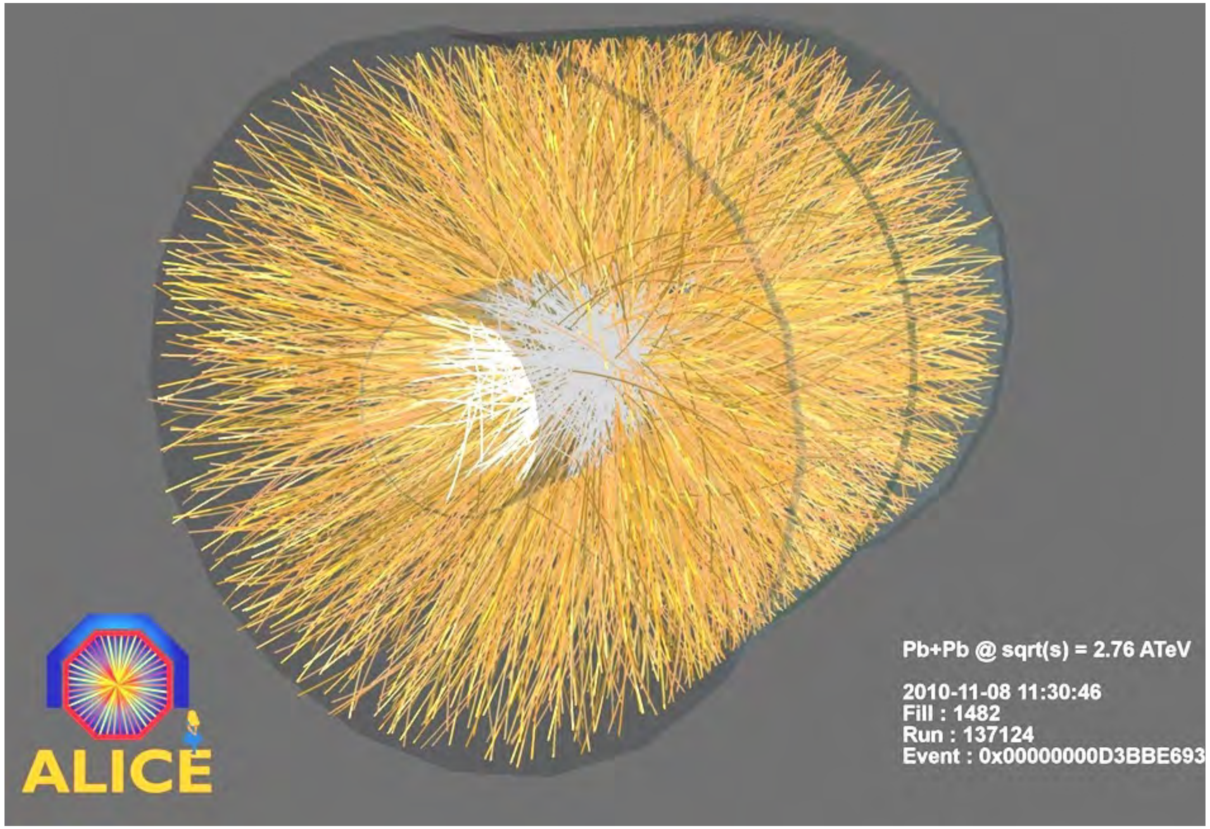
- Essentially three-dimensional track measurement
- Can measure extremely high multiplicity event.

→ results in incredible data flow of 3.5TB/s from TPC (ALICE)

RHIC STAR Au+Au reconstructed tracks.



LHC ALICE Pb+Pb reconstructed tracks.



Time Projection Chamber（TPC)

Characteristic features;

- Essentially three-dimensional track measurement
- Excellent two-track separation and high-multiplicity capability
  → suitable for jet measurement
- dE/dx measurement with many sampling points and pressurized gas
- No wires in tracking volume gives homogeneous tracking volume (no kink)
- Very long drift distance of a few m
  - Needs very high voltage to drift electrons along long path
  - Gas diffusion is significant even with containment by axial magnetic field
- Highly uniform magnetic field needed.

Expected performance

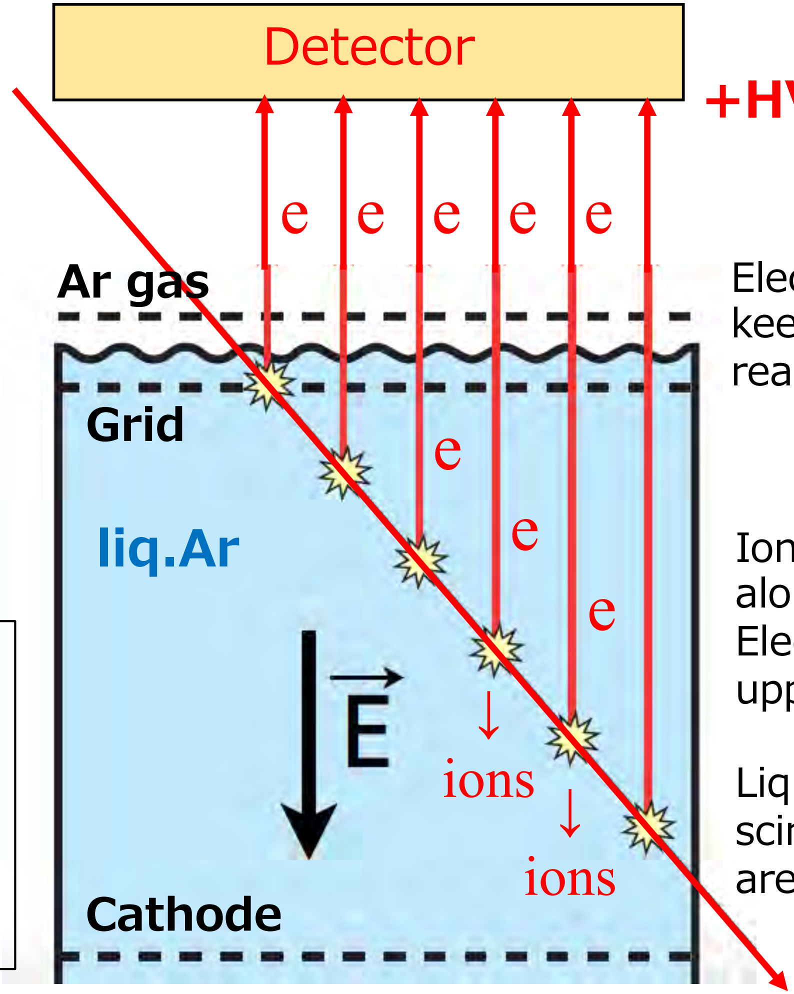
- r-φ position resolution 200~300μ, z-resolution ~1mm
- 2-track separation ~ 10mm
- dE/dx measurement ~5%
- large size possible

3. Operation of detectors ; Trackers ; Noble Liquid

Liquid-Argon Time Projection Chamber

TPC with liq.Ar instead of gas
- Work as target material
  → Excellent neutrino target/detector
- Excellent 3D tracking
- Calorimetric energy measurement
- dE/dx measurement gives PID
- Purity of liq.Ar is far more important than gas TPC.

Read-out Detector with gas high gain like chambers. Charge measurement with Pad or x-y strip and timing measurement for drift distance.



+HV makes electrons jump up from liq.Ar. to gas.

Electrons in gas region keep traveling to read-out detector.

Ionization along the track. Electron travels toward upper gas region.

Liq.Ar also generate scintillation light, and are used for timing.

Benchmark performance
- *x,y,z* position resolution ~1mm
- 2-track separation ~ ??mm
- dE/dx measurement
- EM shower energy resolution ~3%/√E
- HD shower energy resolution ~30%/√E

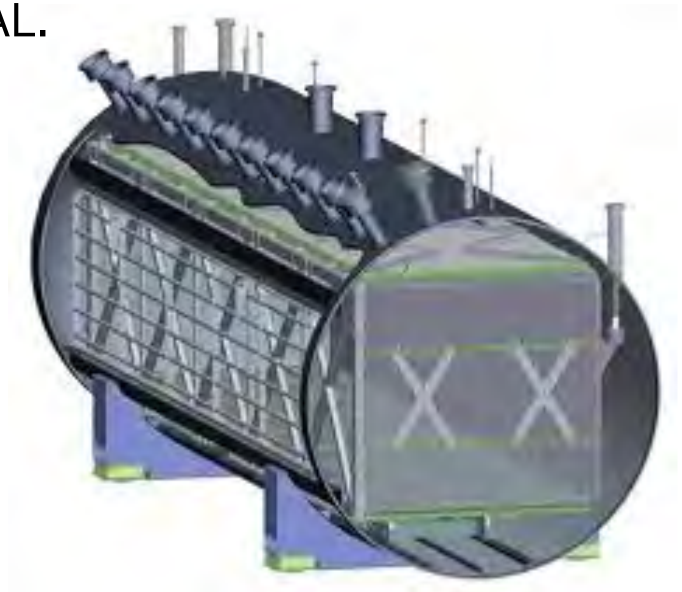
Taken from「Development of liquid argon TPCs at CERN」by L.Epprecht

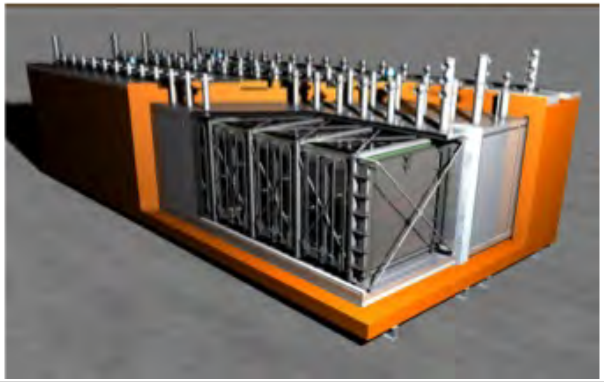
Liquid-Argon Time Projection Chamber

Work as target material
→ Excellent neutrino target/detector

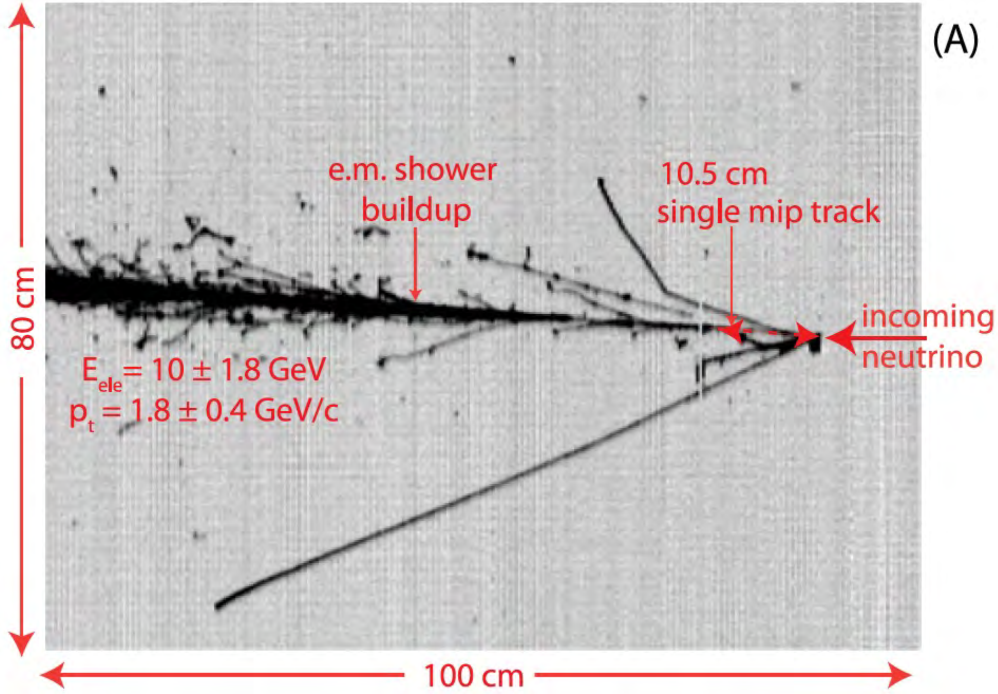
ICARUS detector (470ton Liq.Ar)
- To examine LSND sterile neutrino.
- ν beam from CERN to Rome.

MicroBoone detector (89ton Liq.Ar)
- To examine LSND sterile neutrino.
- ν beam in FNAL.



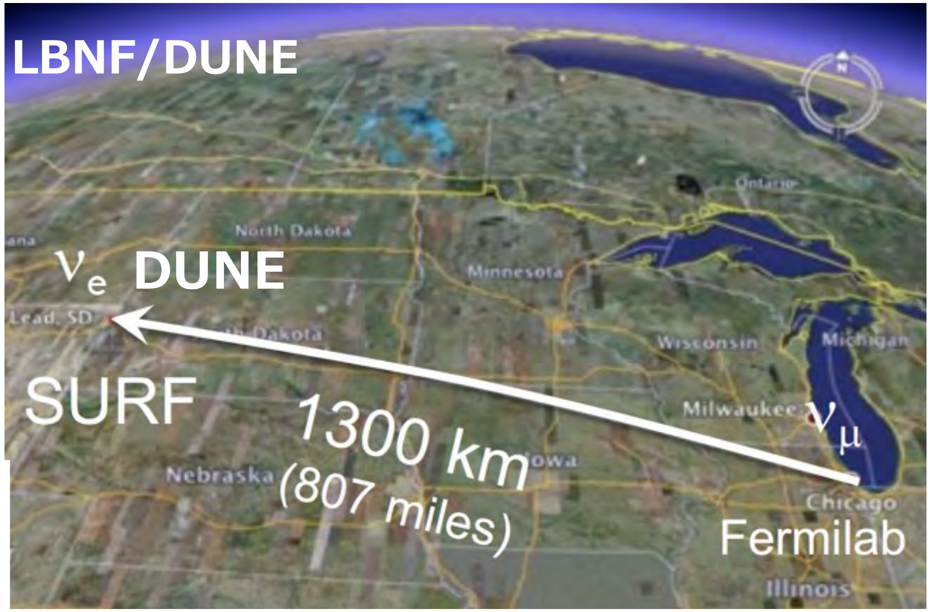


ICARUS T600 detector.
Taken from「ICARUS detector」by F.Varanini



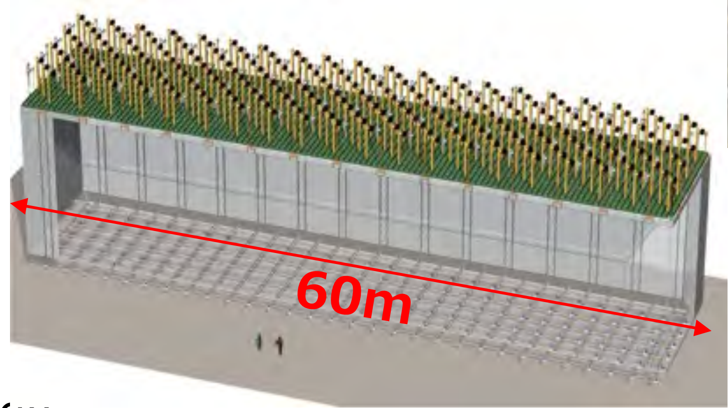
Real event of ICARUS detector.
Taken from Eur.Phys.J.C(2013)73

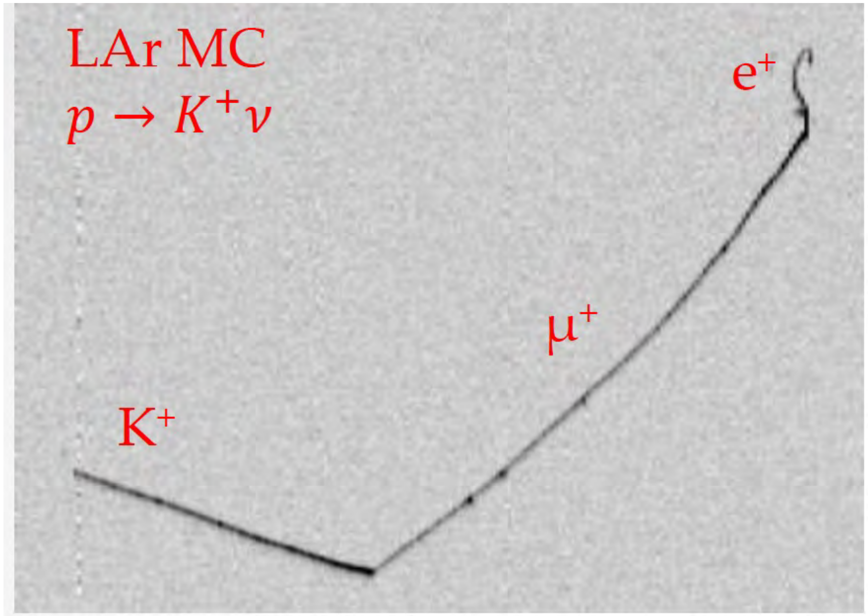
Liquid-Argon Time Projection Chamber



Dune experiment (FNAL → South Dakota)
- Near Detector ; 67ton Liq.Ar TPC + peripherals
- Far Detector ; 17.5kton Liq.Ar TPC x 4modules
  66m x 18m x 19m each.

to study
- neutrino oscillation, mass ordering, and CPV
- Sterile neutrino with ND
- Proton Decay especially SUSY mode,
- Super-Nova



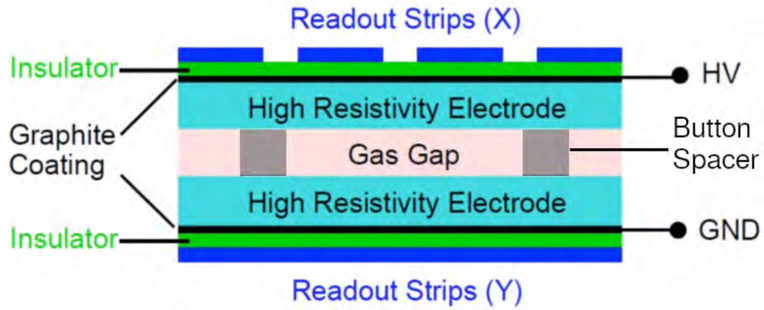


Kaon detection from $p \to \nu K^+$

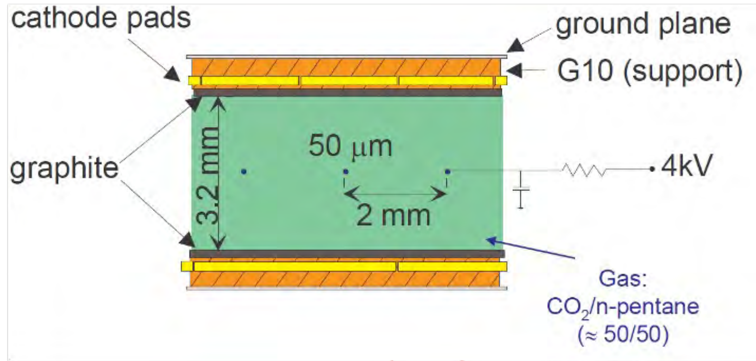
Taken f

Varieties of gas chambers

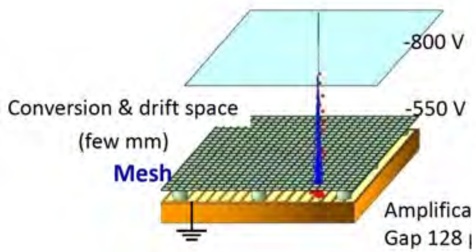
- RPC (resistive plate chamber)
  - Pad readout of streamer discharge between two parallel plates
  - Excellent time resolution (30-50ps), inexpensive,
  - Long recovery time ~ sec.

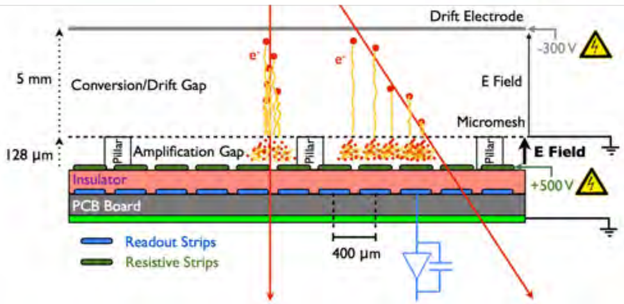


- Thin-gap chamber
  - Pad readout of MWC in avalanche mode
  - High-rate capability



- MPGD (micro-pattern gas detector)
  - MicroMegas
    Apply HV to a fine mesh and realize avalanche.





  - GEM
    Apply HV between upper and lower sides of copper-layered insulator sheet with many small holes. Avalanche occurs inside of the small holes.