Particle and Radiation Detectors

- Design of Particle-Physics Detectors -

PART-II

2022-July-19
Vietnam School on Neutrino 2022

Yoshiaki Fujii
High-energy accelerator research organization
J-PARC Neutrino Experimental Facility

For the Higgs discovery

We need

- Excellent γ–γ mass reconstruction.
  For this,
  excellent EM calorimeters for excellent energy/direction measurement of γ,
  and good hadron calorimeters and trackers for non-γ rejection.

- Excellent muon measurement.
  For this,
  excellent trackers, excellent calorimeters, good muon detector,
  thick material as muon filter, and precise magnetic field mapping

For the precision Higgs study

We need

- Excellent jet reconstruction capability
  - trackers with heigh momentum resolution and multi-track reconstruction capability for collimated jet tracks,
  - calorimeters with good energy resolution and excellent granularity

- Excellent flavor tagging
  - vertex detector of excellent position resolution and multi-track capability for collimated jet
  - Dedicated particle-ID detectors

4. Interaction of particle with matter

and

5. Operation principle of detectors

Interaction of particle with matter and operation principle of detectors

At the reaction of interest, we need to know
what kind of particles are emitted to **which direction** with **what energy** .

There are many types of detectors to achieve the purpose above.

Need to decide which to use, taking into account ;
- **Performances** ; energy, position, timing, efficiency, contamination,,,
- Mechanical feature ; Size, strength, material thickness, stability,,,
- Cost
- Elaborating-ness
- Matured technology or needs more R&D

→ Need to know operation principle of each detector
→ Need to know interaction of particle with matter

4. Interaction of particles with matter

- charged particle
- Photon
- Hadron

4. Interaction of particle with matter

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

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

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

Photon

- Photo-electric effect
- Compton scattering
- Pair creation
- Electromagnetic Shower

Neutral Hadron

- Nuclear reaction
- Hadronic shower

There are many types of detectors.
→ Need to know interaction of particle with matter

Interaction of **charged particle**

- Ionization
- Electromagnetic Shower
- Hadronic Shower

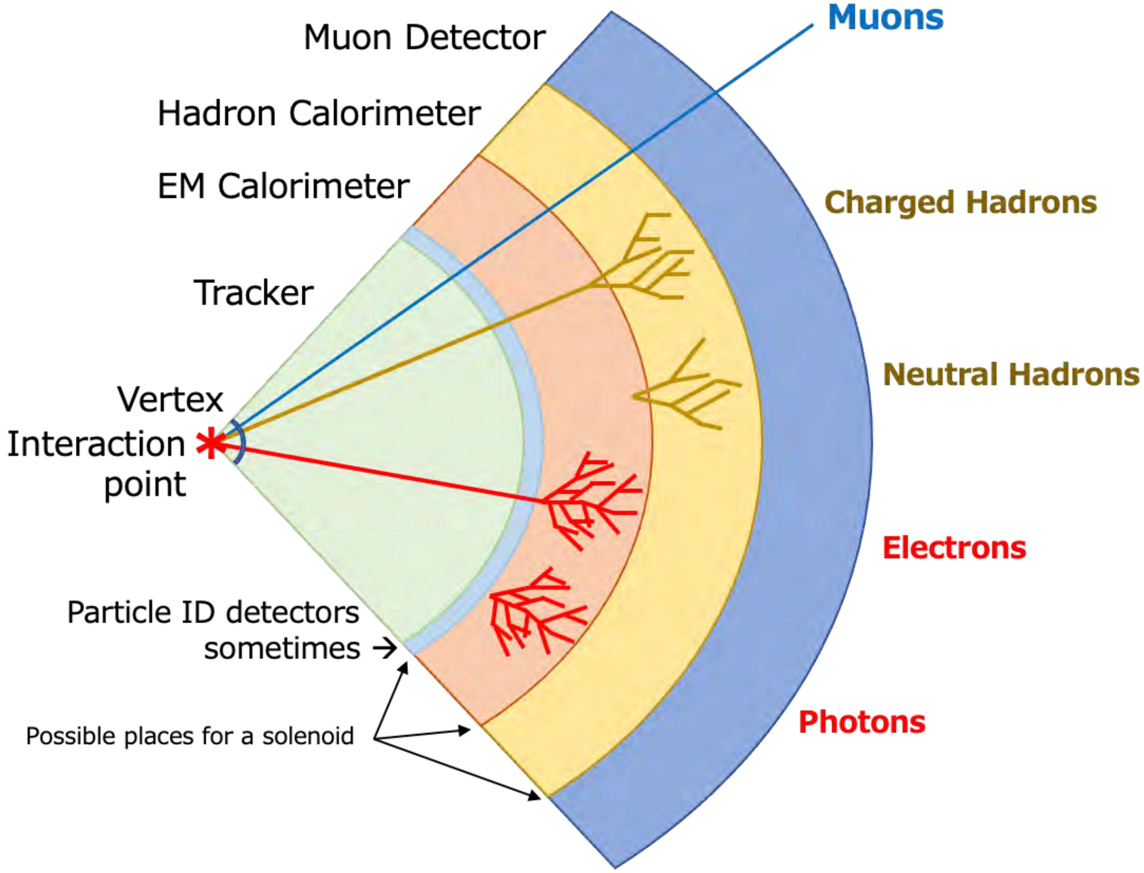
Interaction of **neutral particle**

Photon

- Electromagnetic Shower

Neutral Hadron

- Hadronic shower

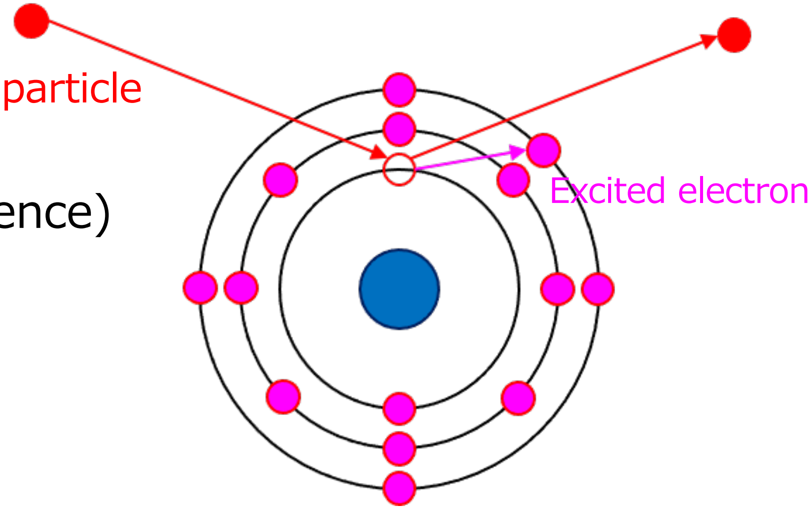


Different interaction mechanisms are used in combination for Particle ID.

- Ionization
- Cherenkov Radiation
- Transition Radiation

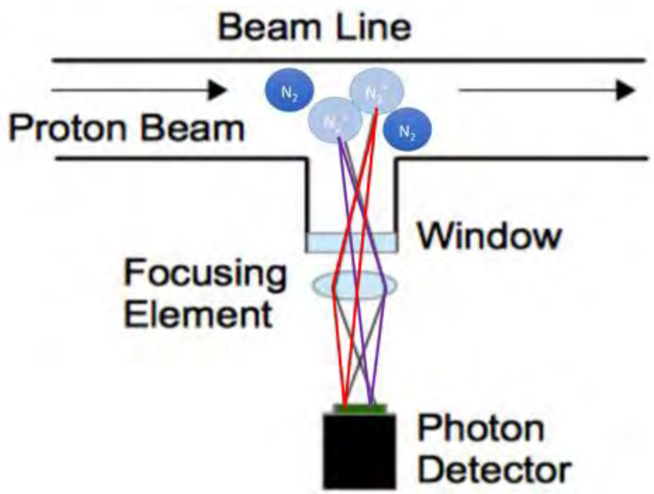
Interaction of charged particle with matter/atom

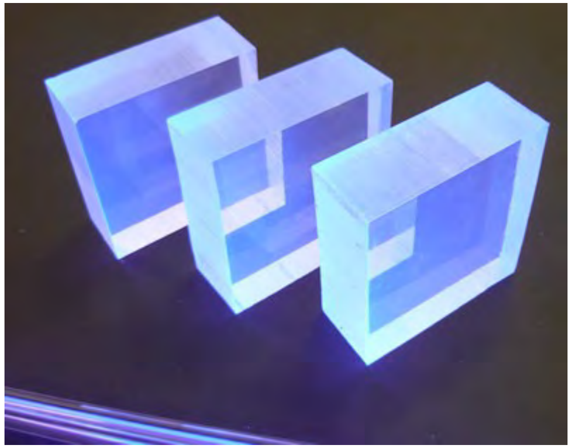
- **Excitation → fluorescence**
- Ionization

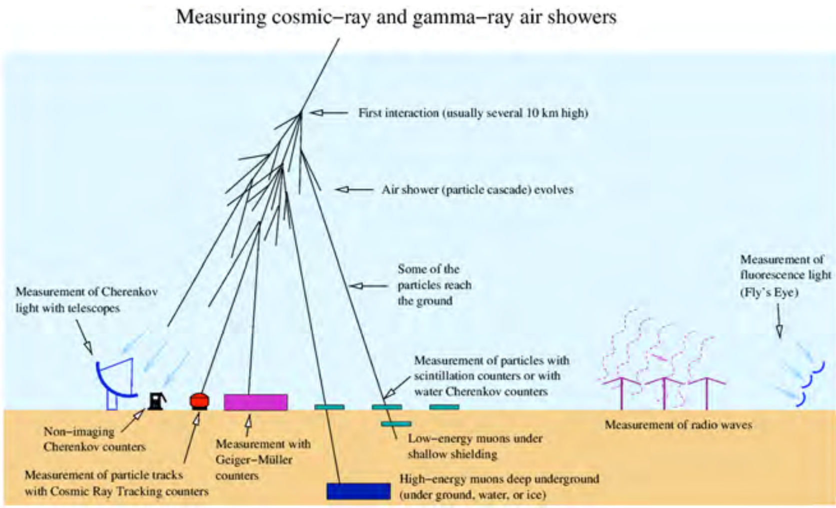


Excited atom emits photon (fluorescence) when it returns to the ground state.
→ This photon is used for detection of particle passage.

Also contribute to the energy loss of incoming particle.



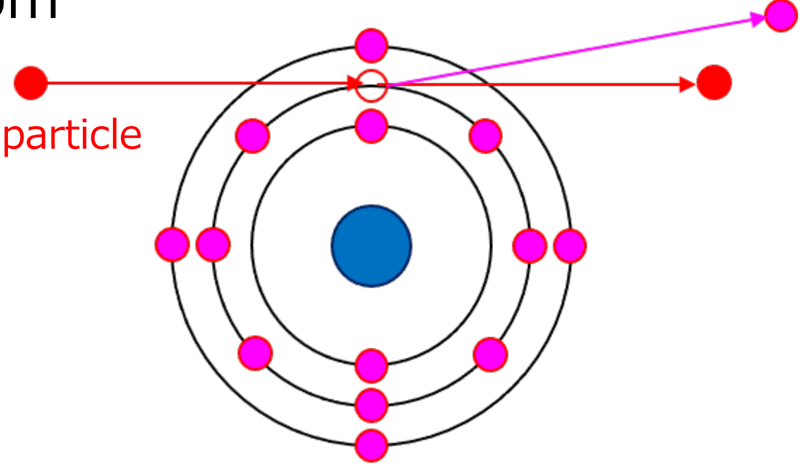




4. Interaction of particle with matter ; charged particle

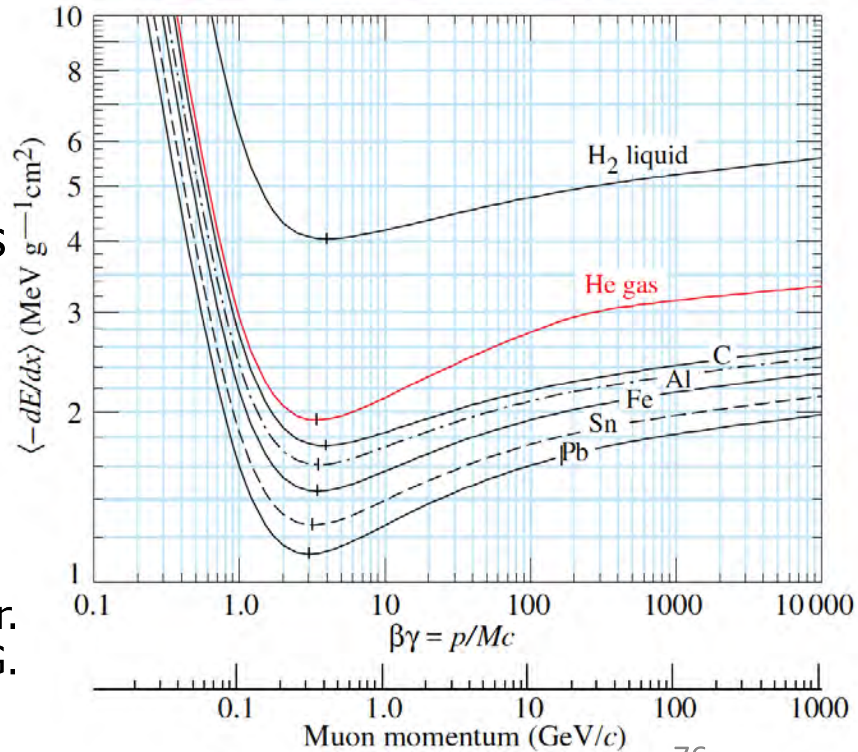
Interaction of charged particle with matter/atom

- Excitation
- **Ionization**



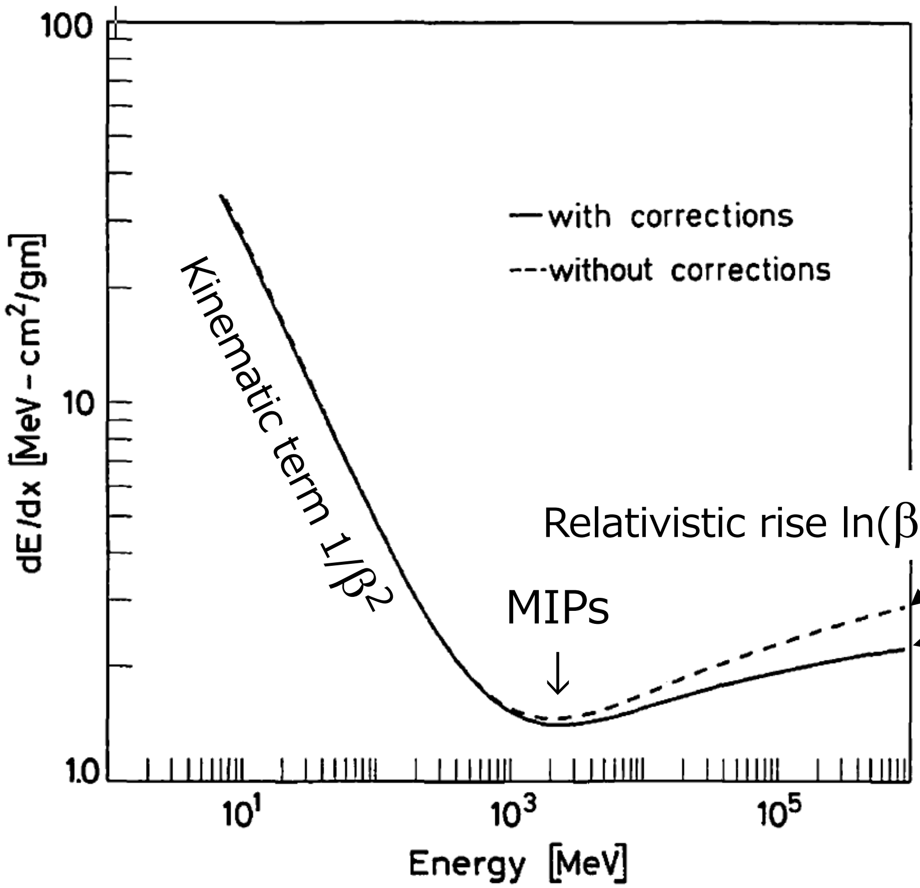
All of thee objects are useful for particle detection;
- ionized atom
- emitted electron
- energy loss of the incoming particle ; d*E*/dx

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 ; dE/dx



Energy loss in copper for Bohr and BB equations.
Taken from W.R.Leo.

General behaviour 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

Bohr's classical calculation

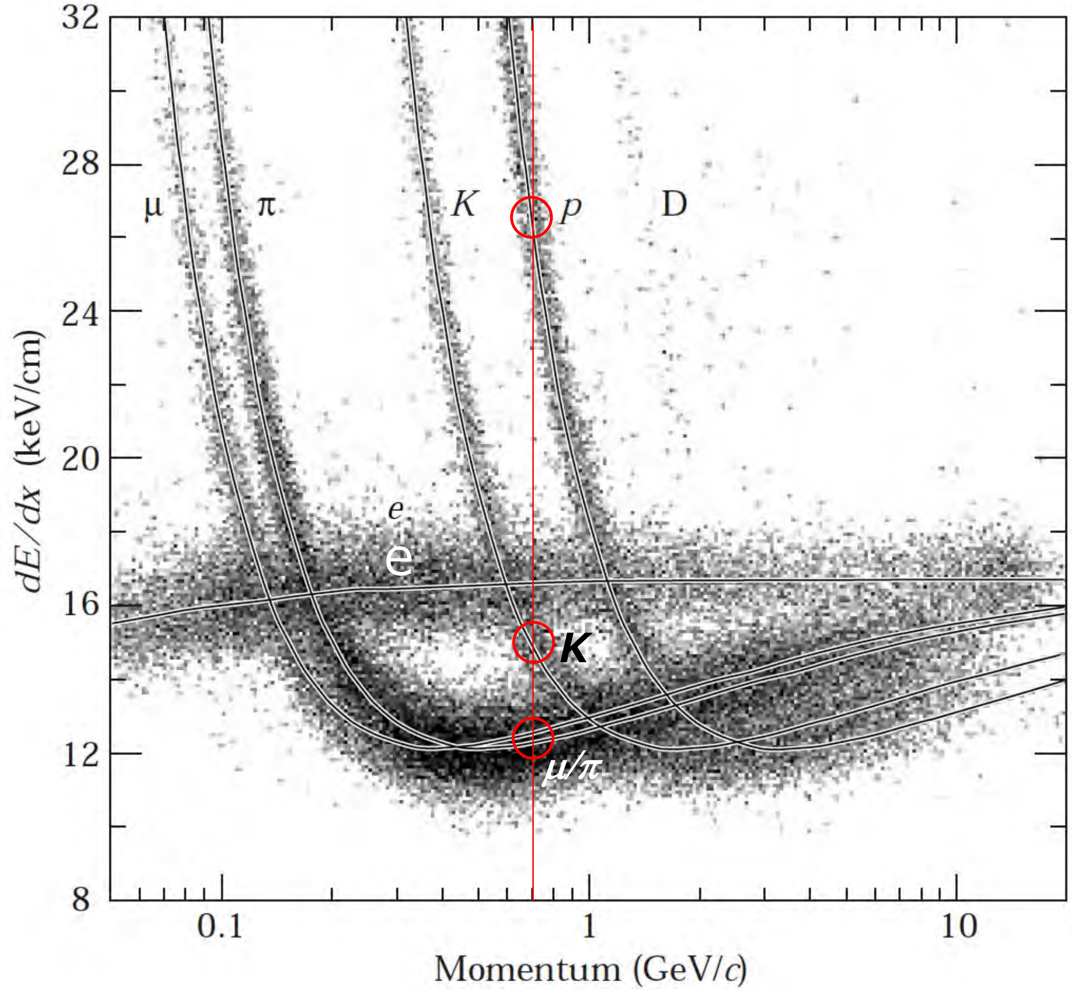
$$-\frac{dE}{dx} = \frac{4\pi N_e z^2 r_e^2 m_e c^2}{\beta^2} \ln\left(\frac{2m_e c^2 \beta^2 \gamma^2}{I}\right)$$

Bethe-Bloch QED calculation
- density effect δ - shell effect C

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

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 ; dE/dx



Energy loss for various particles.
Taken from PDG.

By measuring dE/dx and momentum, one can distinguish particle species at certain momentum region.

Interaction of charged particle with matter/atom

- **Cherenkov Radiation**
- Transition Radiation
- Bremsstrahlung
- Nuclear reaction

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

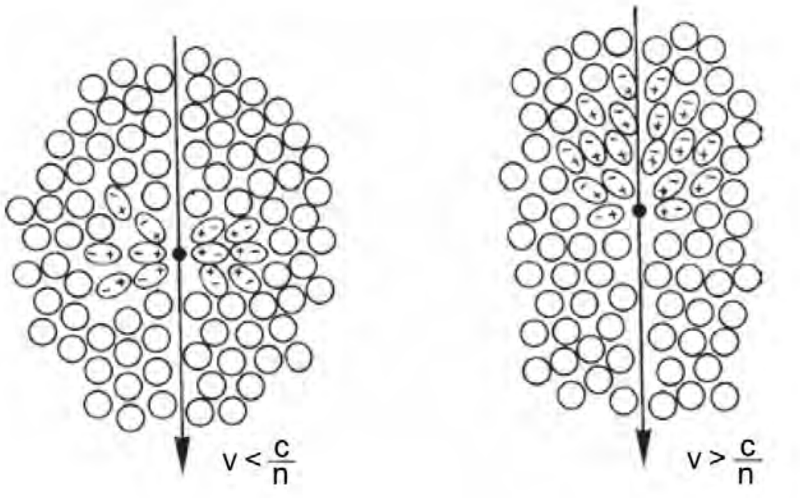


Fig. from Grupen.

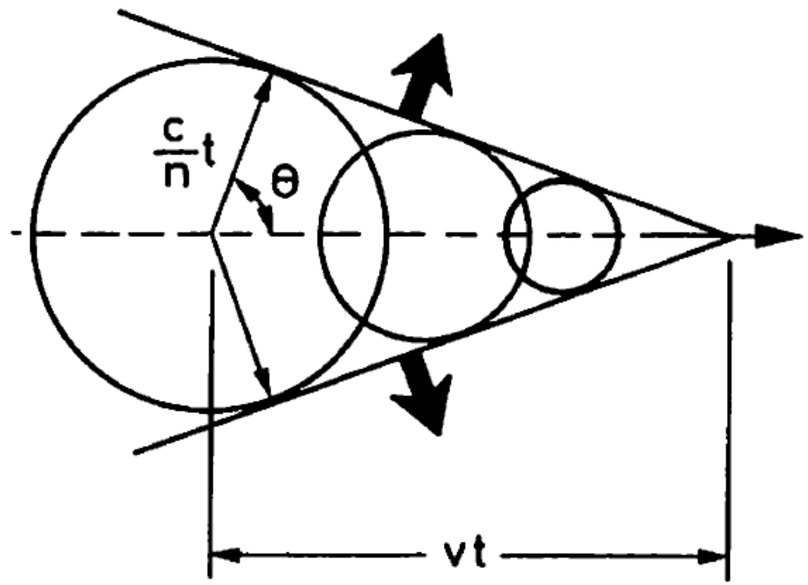


Fig. from W.R.Leo.

Mechanism of Cherenkov radiation generation. Polarization of material atom lines up for v>c/n, and dipole radiation becomes coherent.

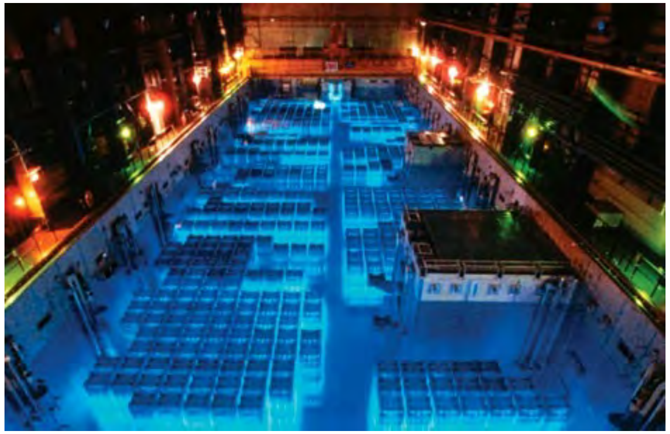
Cherenkov generation condition is $n\beta>1$, and radiation angle θ is $\cos\theta = 1/n\beta$.

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

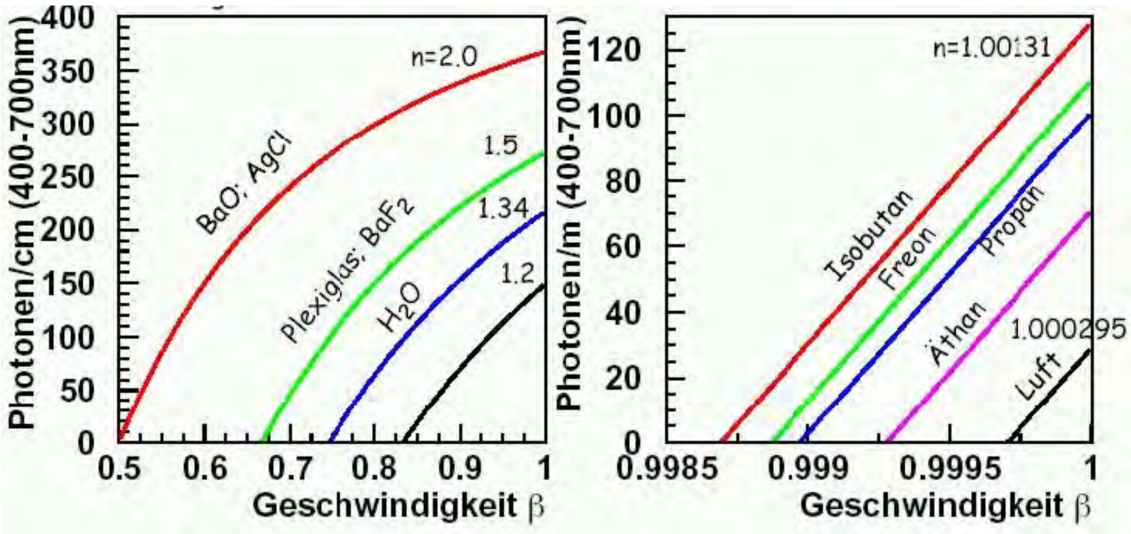
Number of generated photons are:

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



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

Integrate over certain range gives
↓ ↓



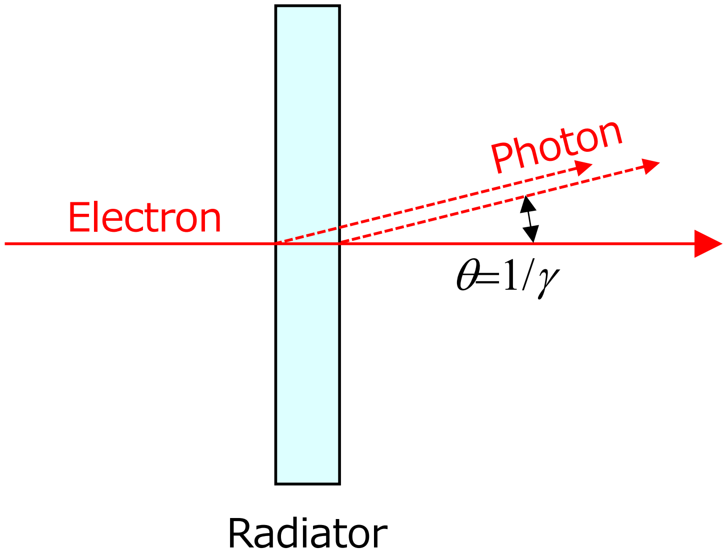
material	n	β threshold	Nphoton
He	1.000 0349	0.99997	0.03/cm
N2	1.000 298	0.9997	0.3/cm
Pentane	1.0017	0.9983	7/cm
Aerogel	1.007-1.13	0.993-0.884	tens/cm
Water	1.33	0.75	210/cm
Polystyrene	1.60	0.63	

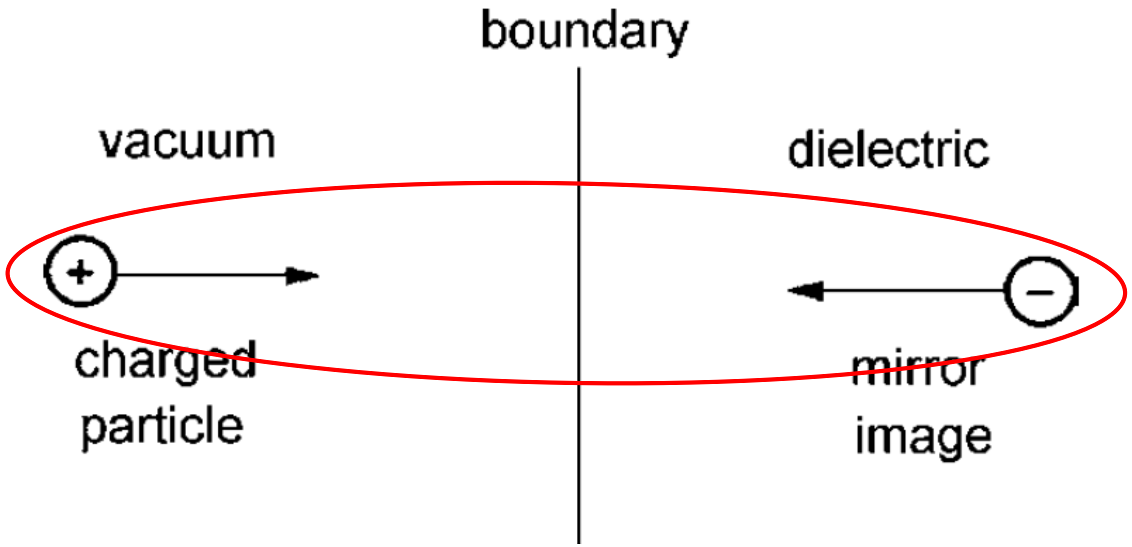
from "Cherenkov Radiation" by K.Muller

Interaction of charged particle with matter/atom

- Cherenkov Radiation
- **Transition Radiation**
- Bremsstrahlung
- Nuclear reaction

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.

Transition Radiation

Emitted energy *S*

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

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 $1/\gamma$.

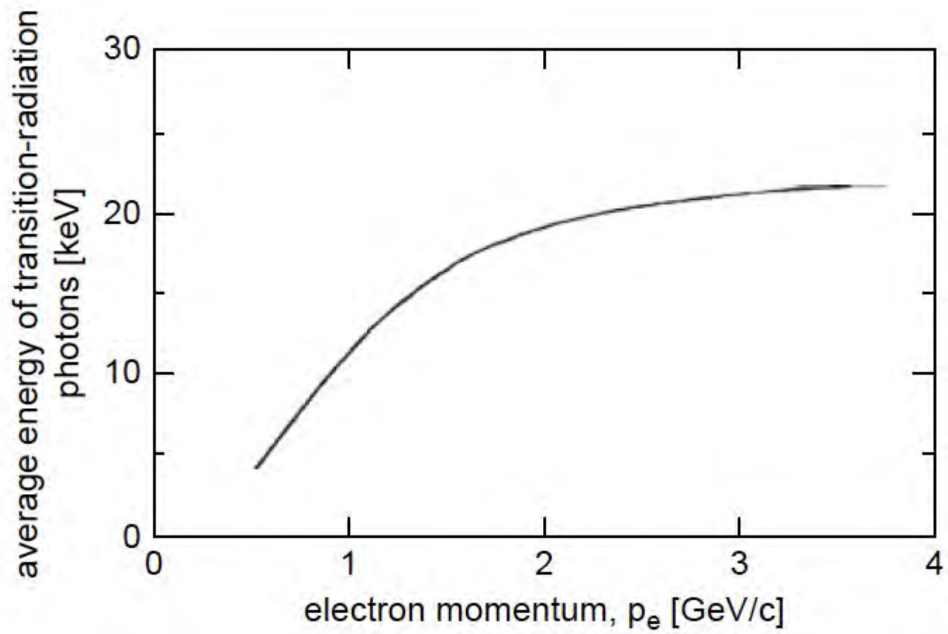
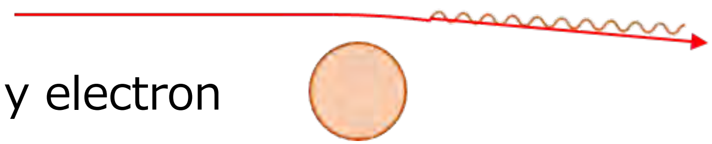


Fig. from Grupen.

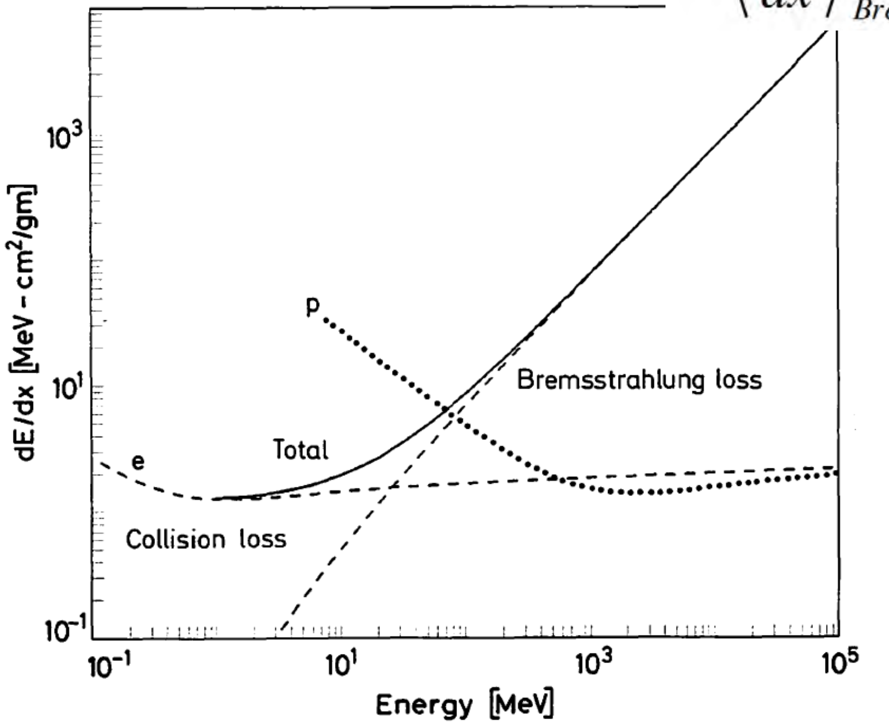
Interaction of charged particle with matter/atom

- Cherenkov Radiation
- Transition Radiation
- **Bremsstrahlung**
- Nuclear reaction

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

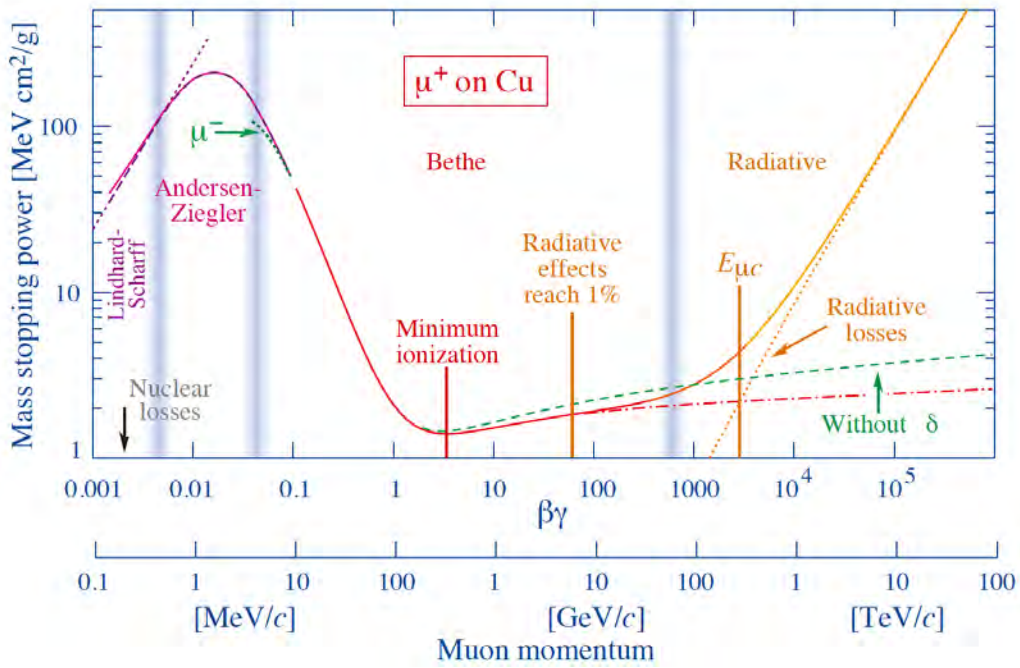


$$-\left\langle \frac{dE}{dx} \right\rangle_{Brems} \propto \frac{E}{m^2}$$; for mainly electron



High-energy electrons lose its energy dominantly through bremsstrahlung.
taken from W.R.Leo.

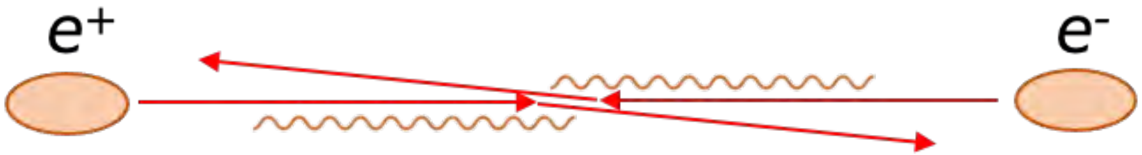
Even muons lose its energy dominantly through bremsstrahlung at ultra-high-energy.
taken from PDG.



Interaction of charged particle with matter/atom

- Cherenkov Radiation
- Transition Radiation
- **Bremsstrahlung**
- Nuclear reaction

At the linear collider, colliding beams feels strong field of incoming beam, and generate bremsstrahlung.
This reduces √S of the event,
and affects recoil mass reconstruction or momentum-balance analysis.

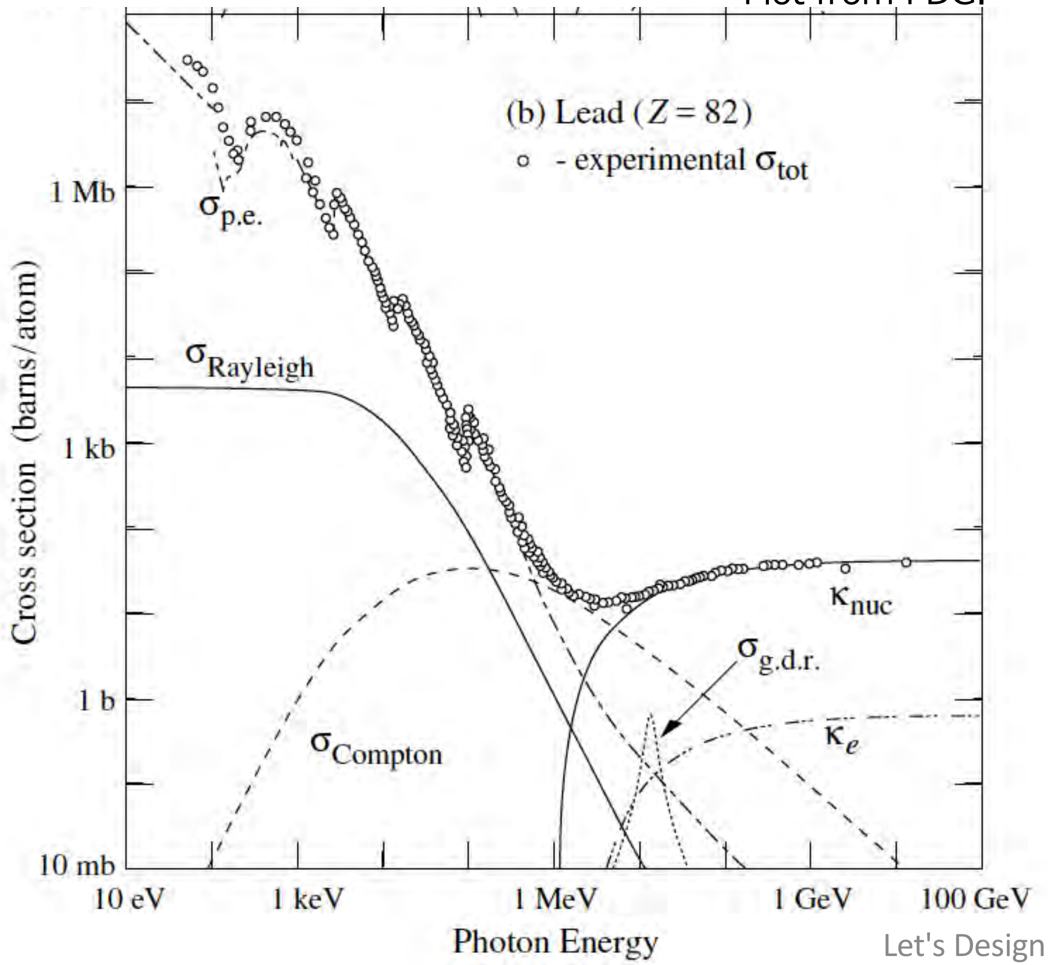


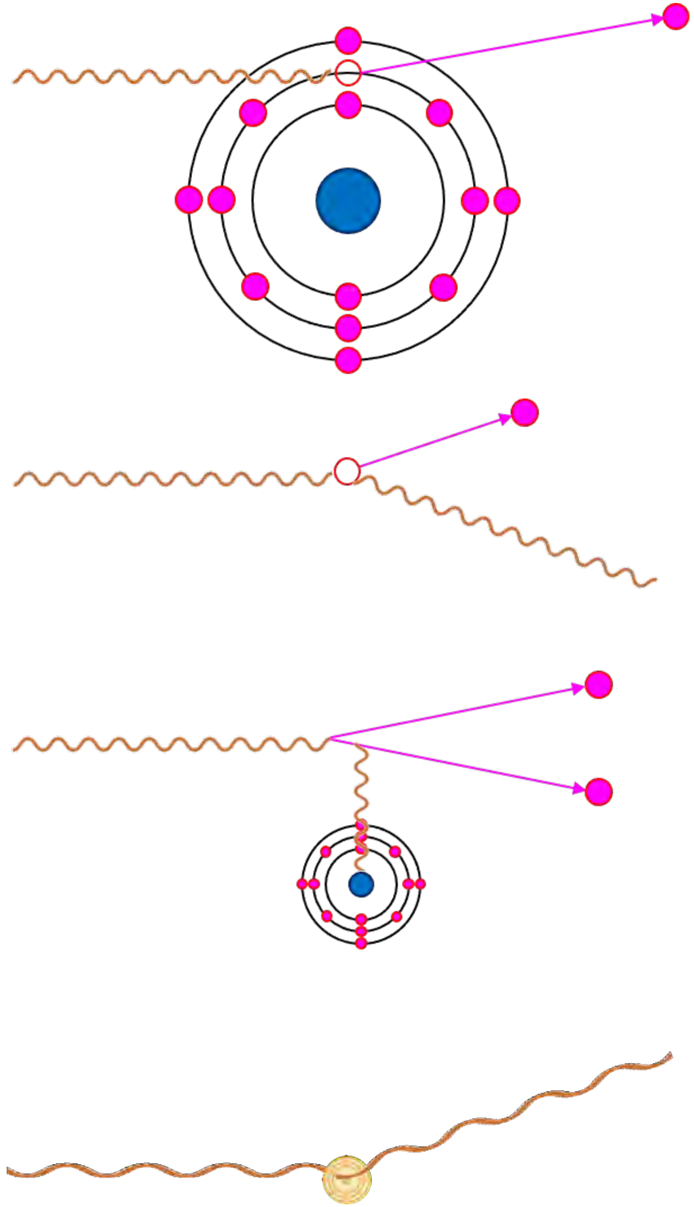
Sometimes called Beamstrahlung

Interaction of photon with matter/atom

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

Plot from PDG.





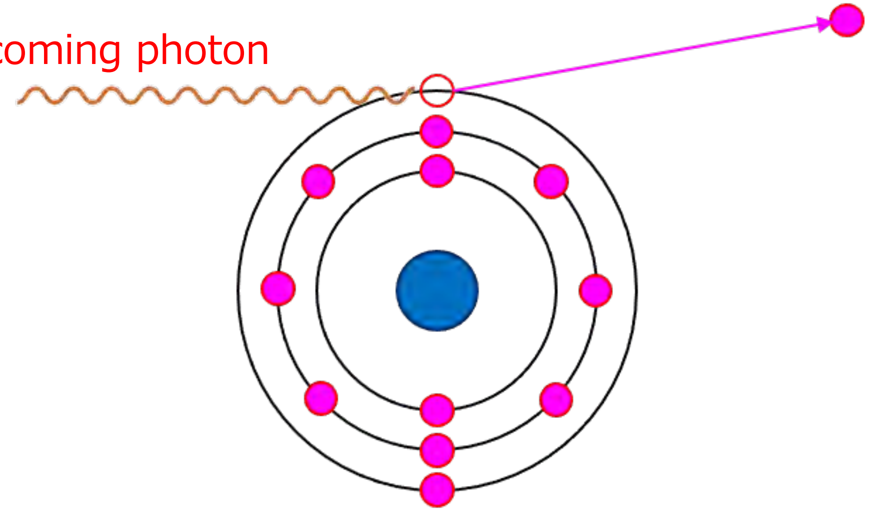
4. Interaction of particle with matter ; photon

<u>Photo-electric effect</u> ; Einstein's Nobel prize in 1921.

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

I_b = Nuclear binding energy

Has strong Z dependence.



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

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

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

$$\sigma^{e}_{\text{Th}} = \frac{8}{3} \pi r_e^2$$

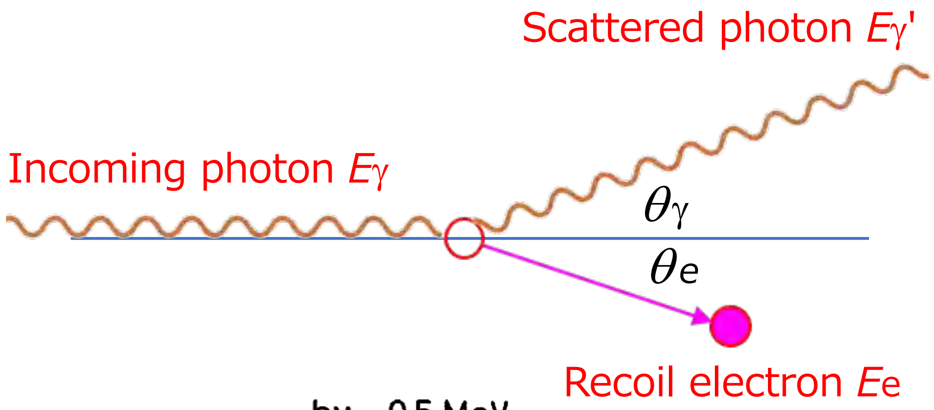
Cross section of photoelectric effect
for low-energy photon (upper) and
for high-energy photon ($\varepsilon >> 1$, lower).
σ^{e}_{Th} is Thomson-scattering cross section.
Equations from Grupen.

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

Molecule analysis etc.

Compton scattering ;

- Photon scattering by quasi-free atomic electrons
- Binding energy of electrons << Photon energy



Exact probability by Klein-Nishina;

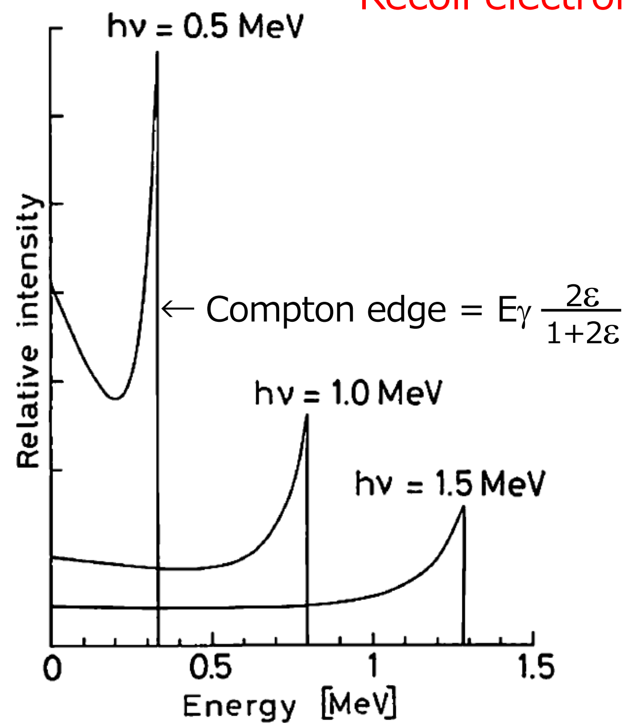
$$\phi_c(E_\gamma, E'_\gamma)\,dE'_\gamma = \pi r_e^2 \frac{N_A Z}{A} \frac{m_e c^2}{E_\gamma} \frac{dE'_\gamma}{E'_\gamma} \left[1 + \left(\frac{E'_\gamma}{E_\gamma}\right)^2 - \frac{E'_\gamma}{E_\gamma}\sin^2\theta_\gamma\right]$$

And some useful kinematic values;

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

$$E_{kin} = E_\gamma - E'_\gamma$$

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.

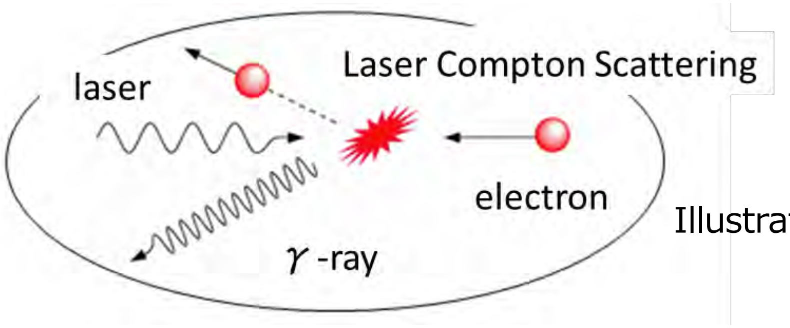
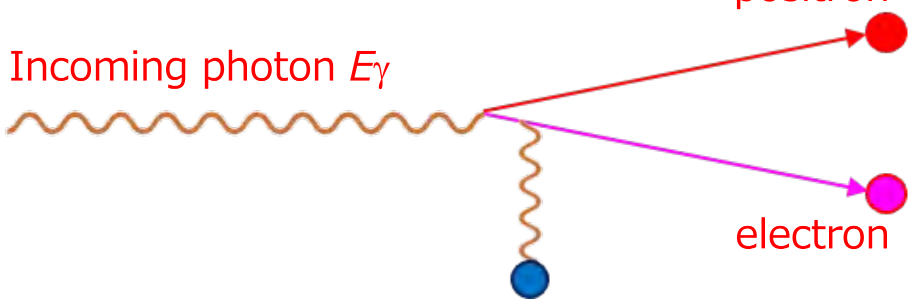


Illustration from QST-web.

4. Interaction of particle with matter ; photon

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 ;

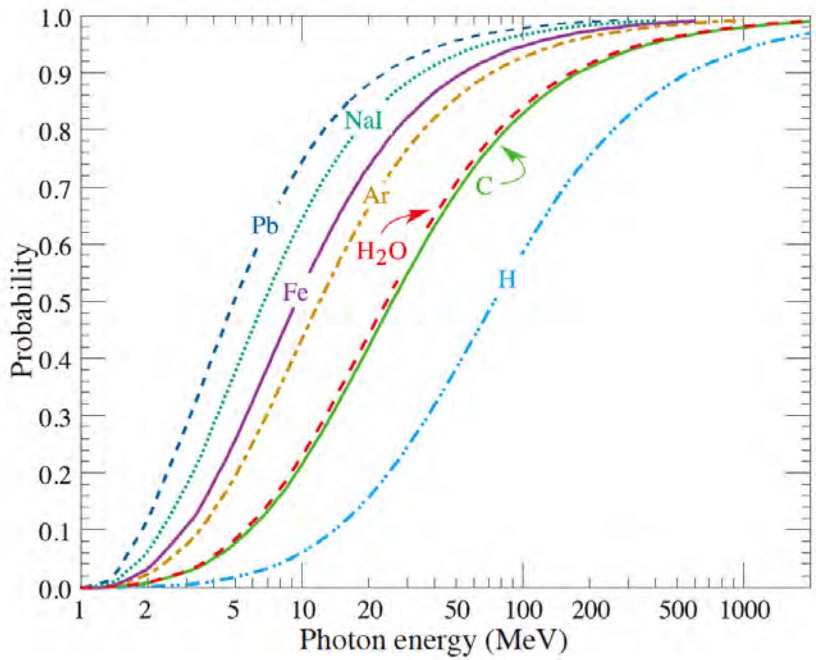
$$\sigma_{\rm pair} = 4\alpha r_e^2 Z^2 \left(\frac{7}{9}\ln 2\varepsilon - \frac{109}{54}\right)$$ at low energy

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

At very high energy, it asymptotically approaches to

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

Formula from Grupen.



Plot from PDG.

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

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

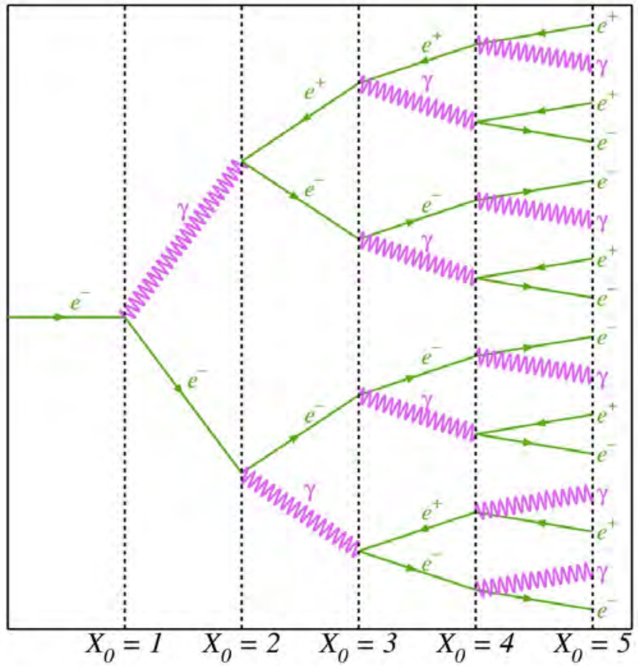
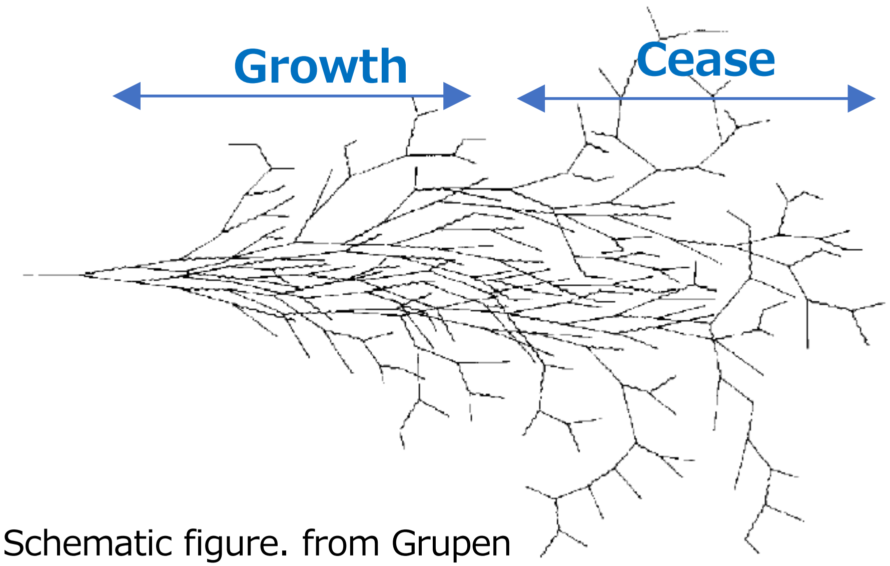
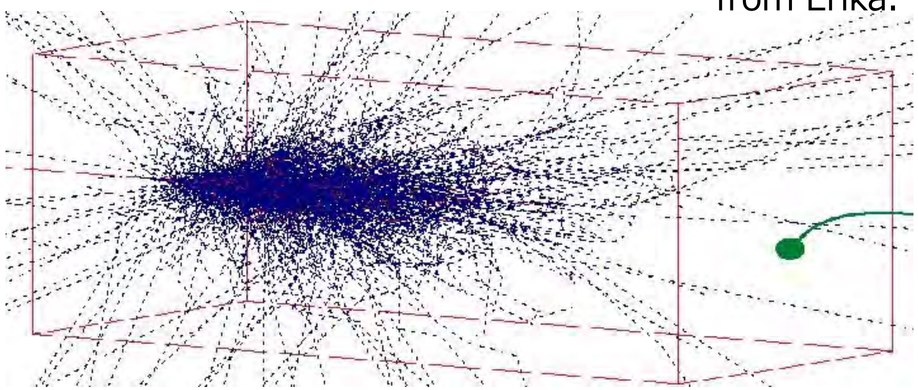


Figure from K.Lang.



Schematic figure. from Grupen

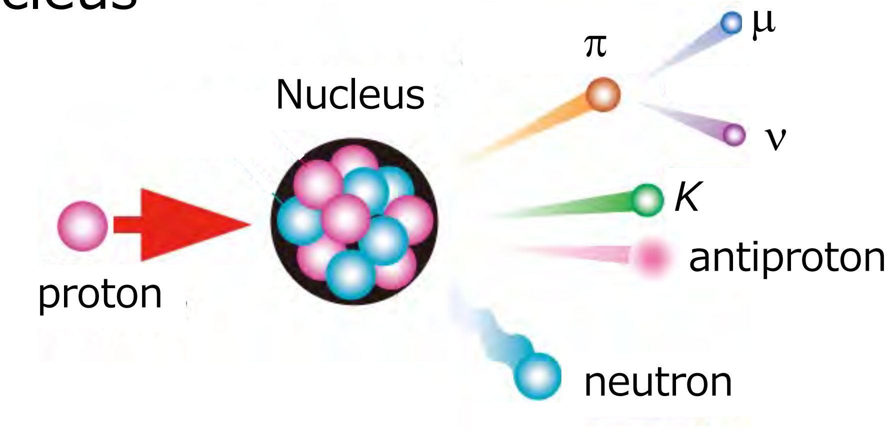
GEANT simulation EM shower. Quite dense and crowded. from Erika.

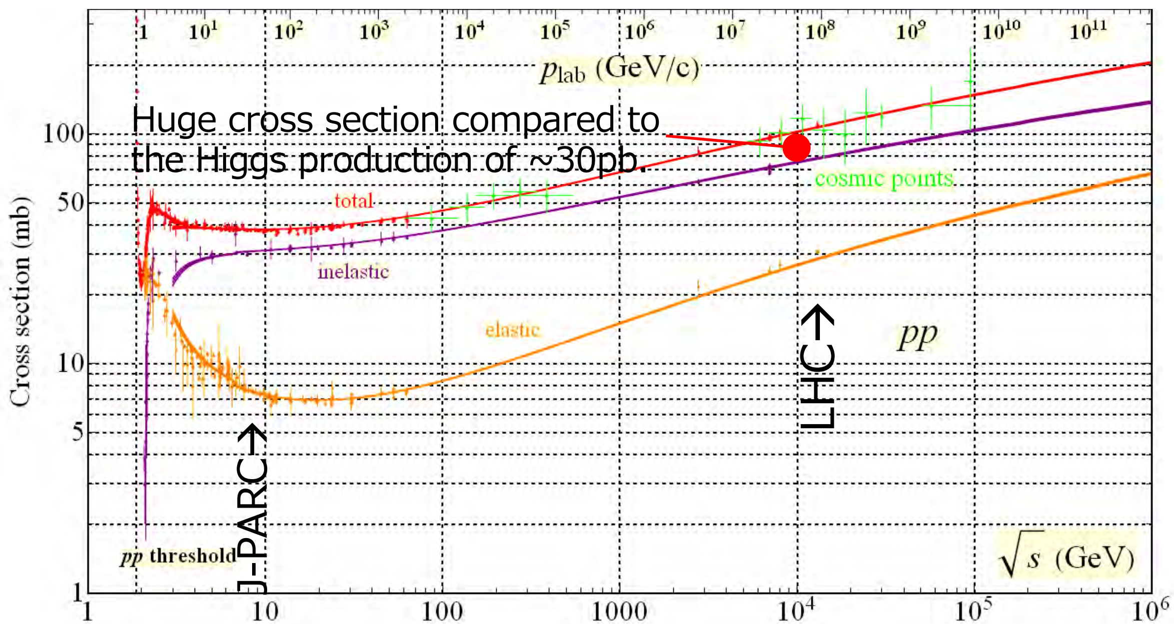


Interaction of Hadron with matter/atom/nucleus

- Nuclear reaction
- Hadronic shower

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

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

4. Interaction of particle with matter ; Hadron

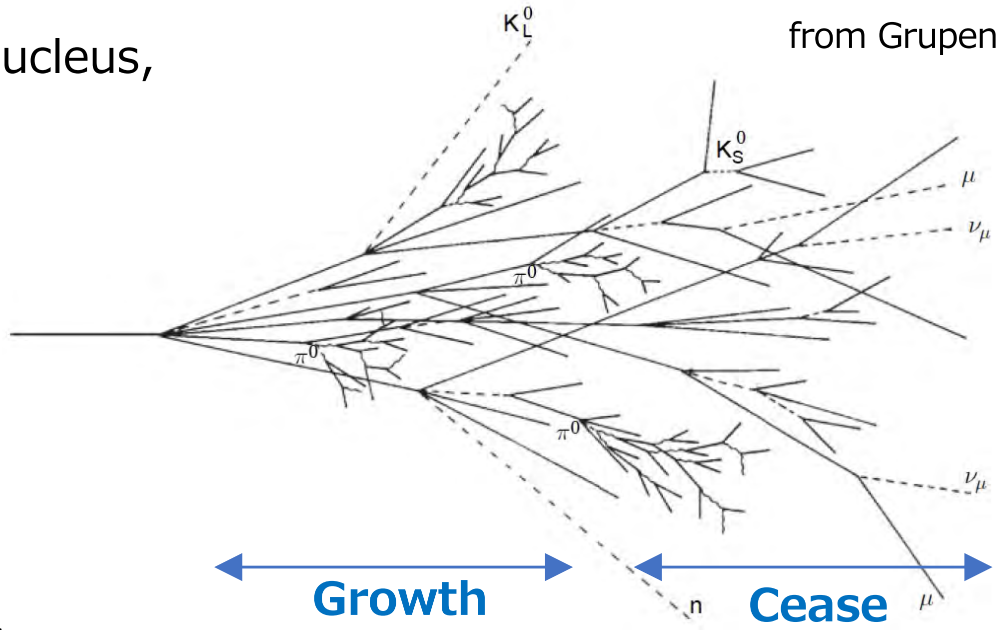
Hadronic shower

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

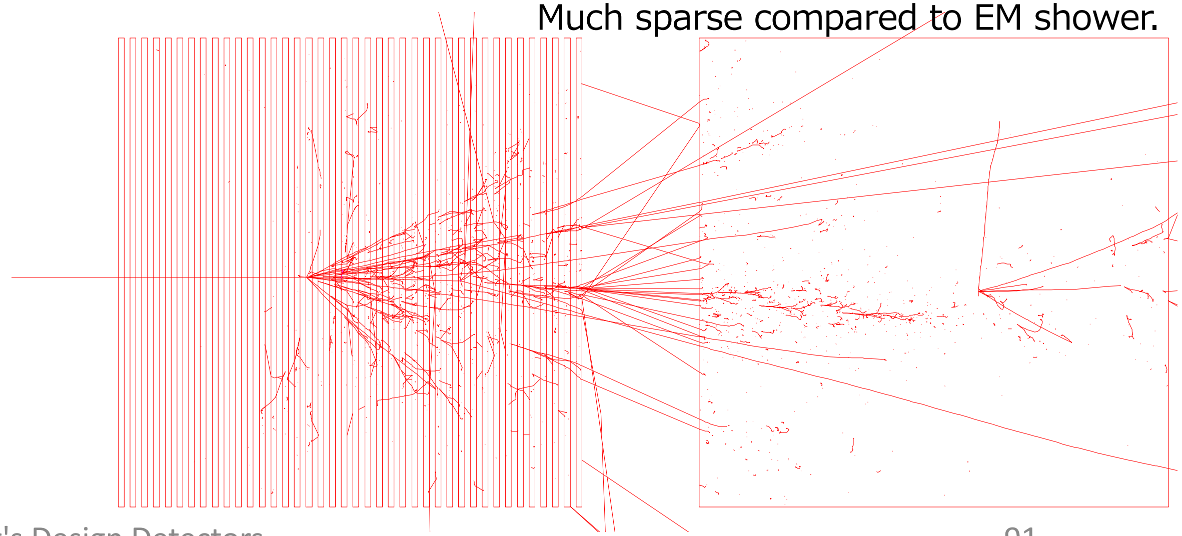
As shower growth, number of particles increases, and energy of each particle decreases.
Eventually their energy become too low to generate particles any more, and cascade ceases.

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.



4. 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 **Neutral Hadron** with matter/atom

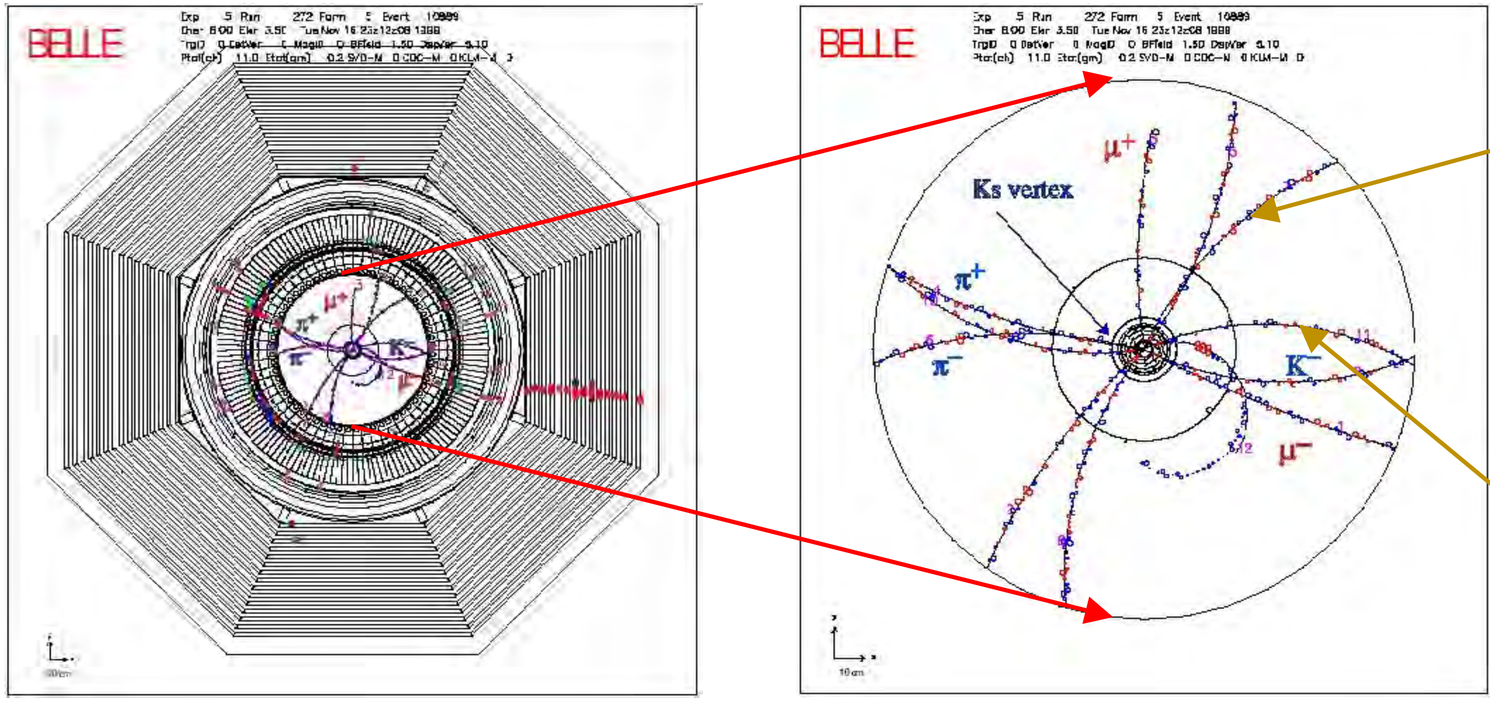
- Nuclear reaction

and Hadronic shower

5. Operation of detectors

- Trackers → to which direction
- Calorimeters → with what energy
- Photo-sensors (important device)
- Particle Identification → what kind of particle

Trackers measure particle direction and momentum.



Points are measurement. Lines are drawn by the computer.

Particle track bends in magnetic field.

- Measure space points of charged particle passages.
- Connect space points, do fitting, reconstruct the track, and obtain radius of the track.
- With magnetic field B and track radius, momentum can be calculated.
- Various Trackers for different cases (multiplicity, jet collimation, , ,)

  Multiwire drift chambers → Belle-II, BaBar,,,

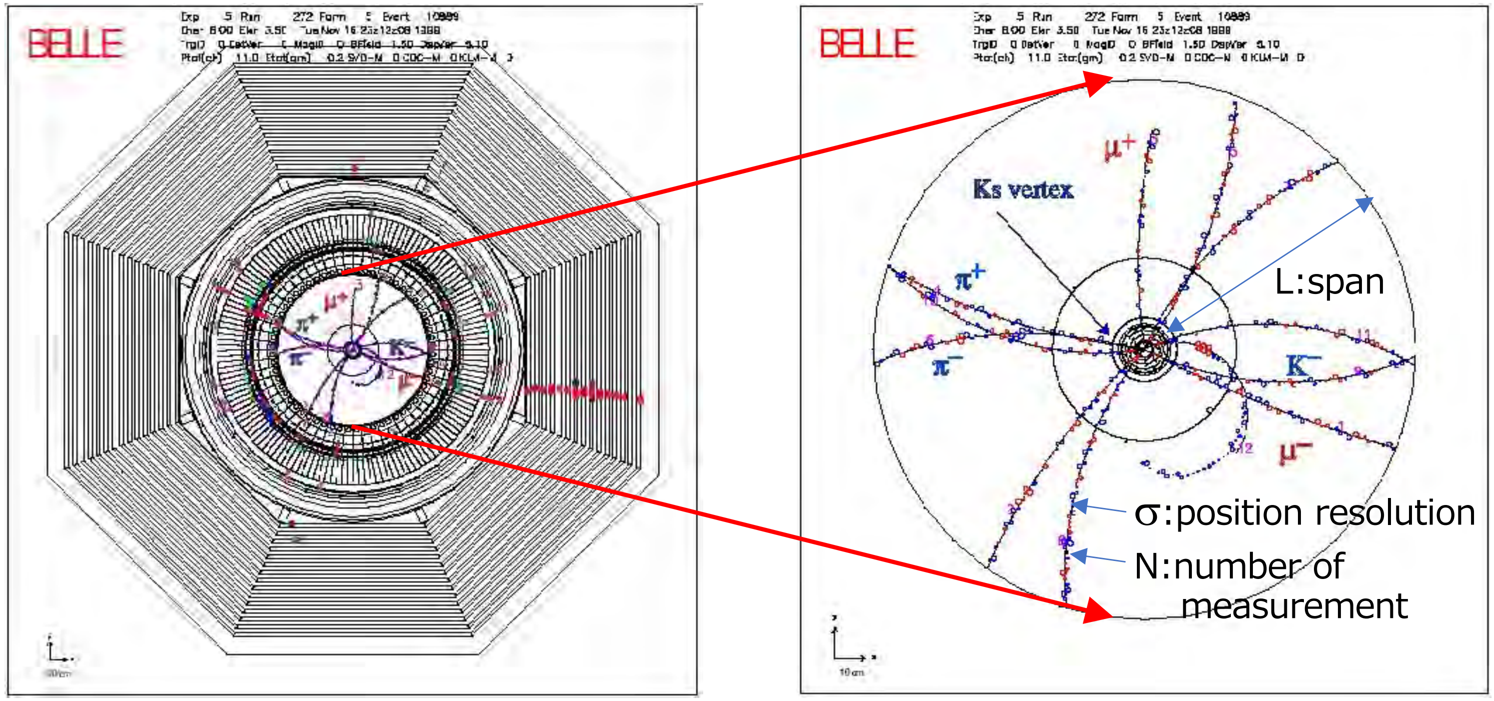
  Jet Chambers → OPAL, H1, ZEUS,,,

  Time Projection Chambers → ILD, ALICE, ALEPH, DELPHI,,,

  Silicon Tracker → ATLAS, CMS, SiD,,,

5. Operation of detectors ; Trackers

Trackers measure particle direction and momentum.



Approximately

P [GeV]$=0.3B\rho$ [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 (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 valuable for particle-ID.
- Low mass to avoid scattering inside the tracker and to avoid disturbing ECAL measurement

In case of jets:

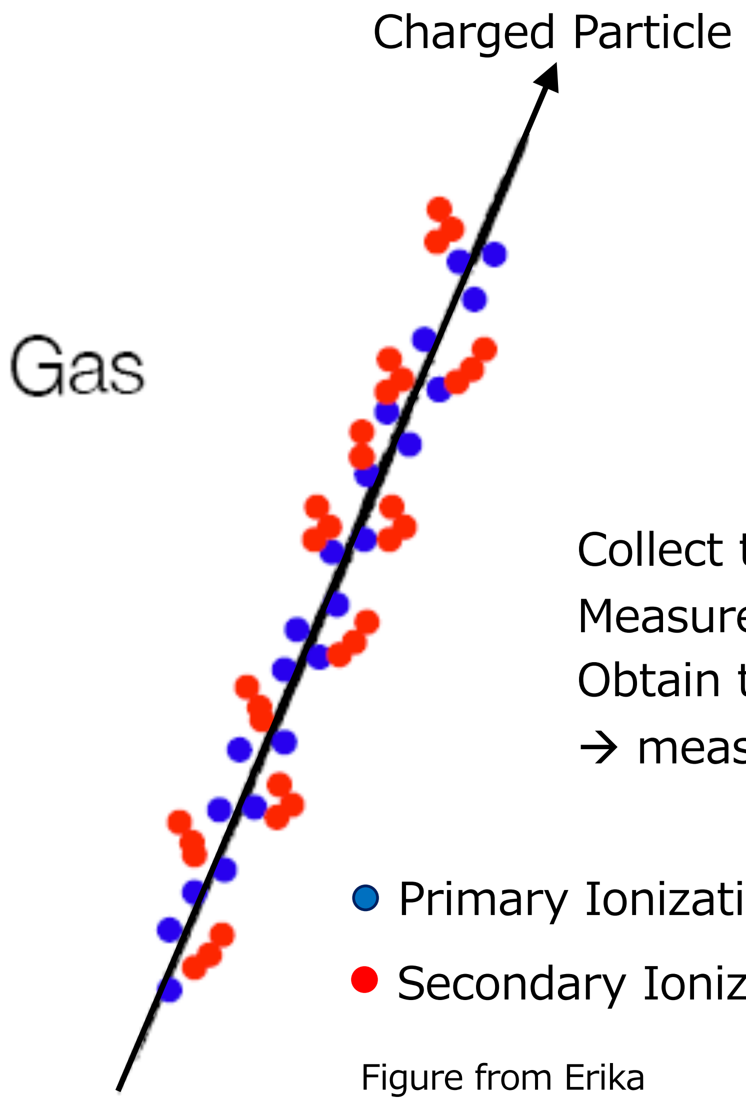
- Many tracks close to each other. Need excellent two-track separation, fine pitch to relax occupancy.
- Need to avoid double counting of track and cluster → precise track-cluster correspondence needed
  → P&E resolution, precise track extrapolation, two-track separation, fine granularity,

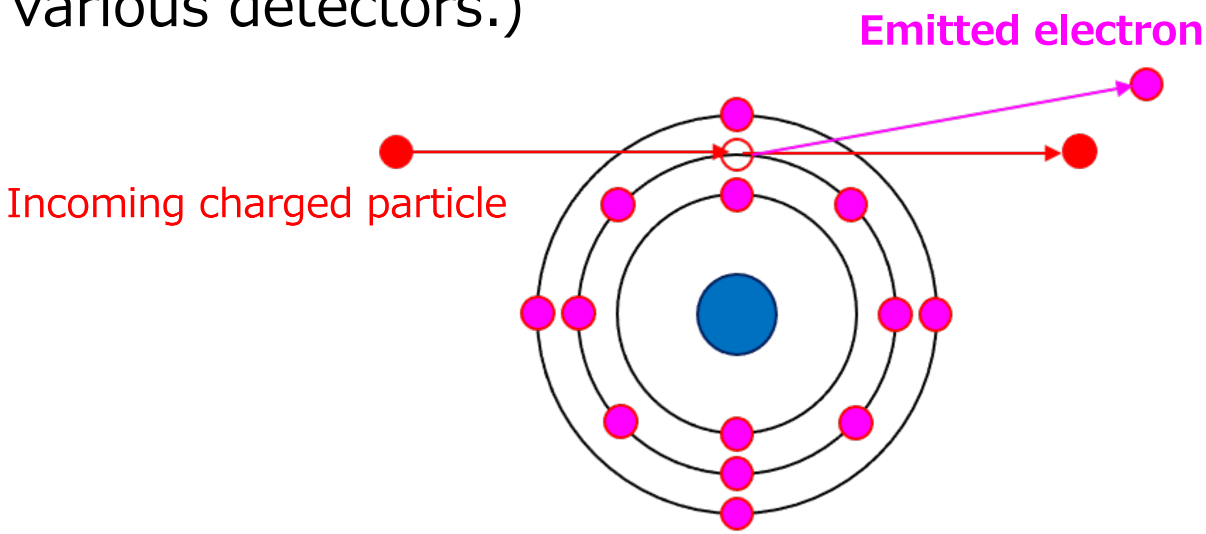
How trackers measure space points ?

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

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





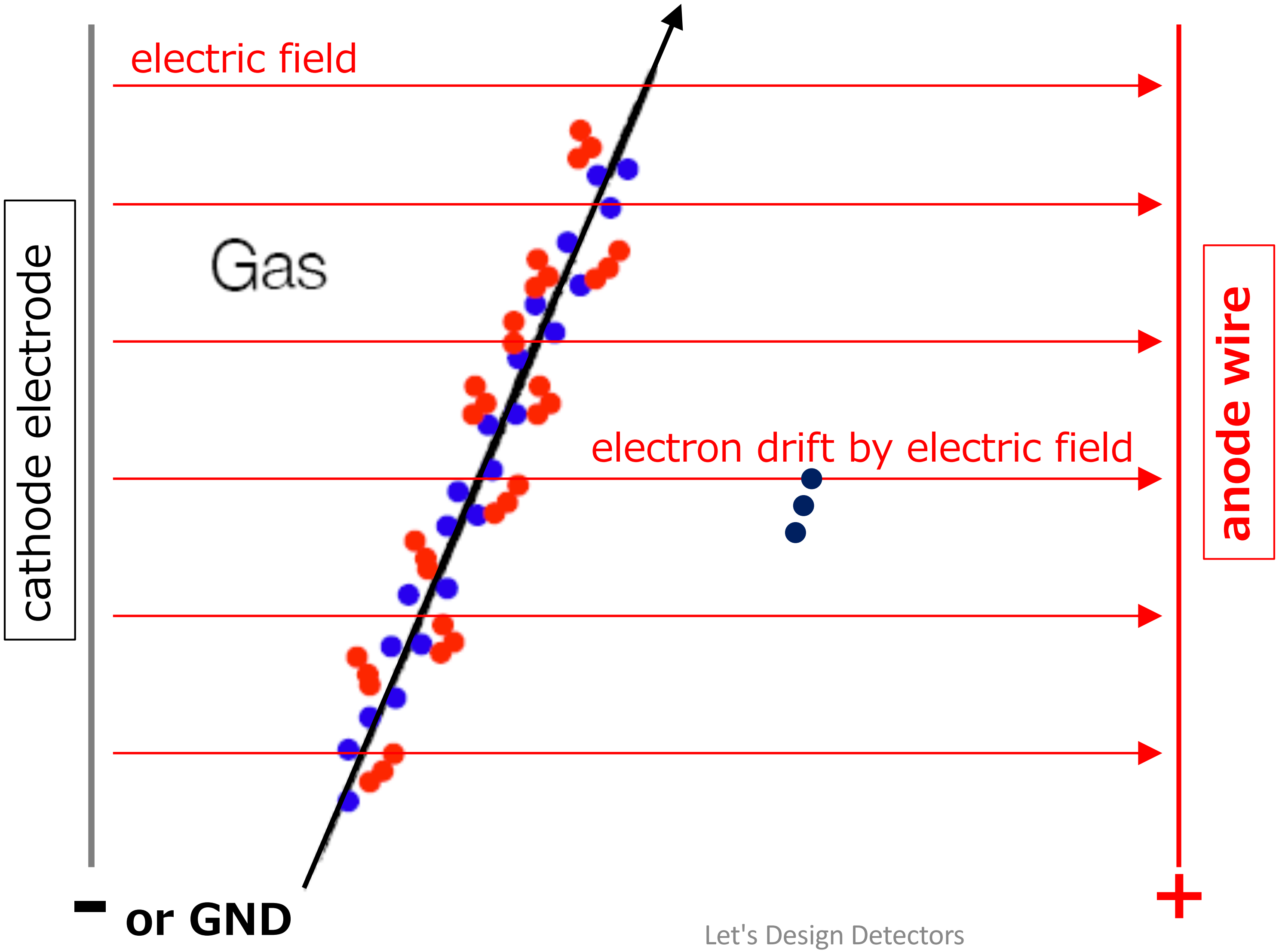
Collect the charge generated by ionization (somehow)
Measure the collected charge (somehow)
Obtain the space coordinate of the ionization point (somehow)
→ measure the space-points of the particle

- Primary Ionization
- Secondary Ionization (by δ-ray)

Figure from Erika

Operation principle of gas chambers

- wire chamber ; **drift of emitted electrons** and avalanche multiplication



Operation principle of gas chambers

- wire chamber ; drift of emitted electrons and **avalanche multiplication**

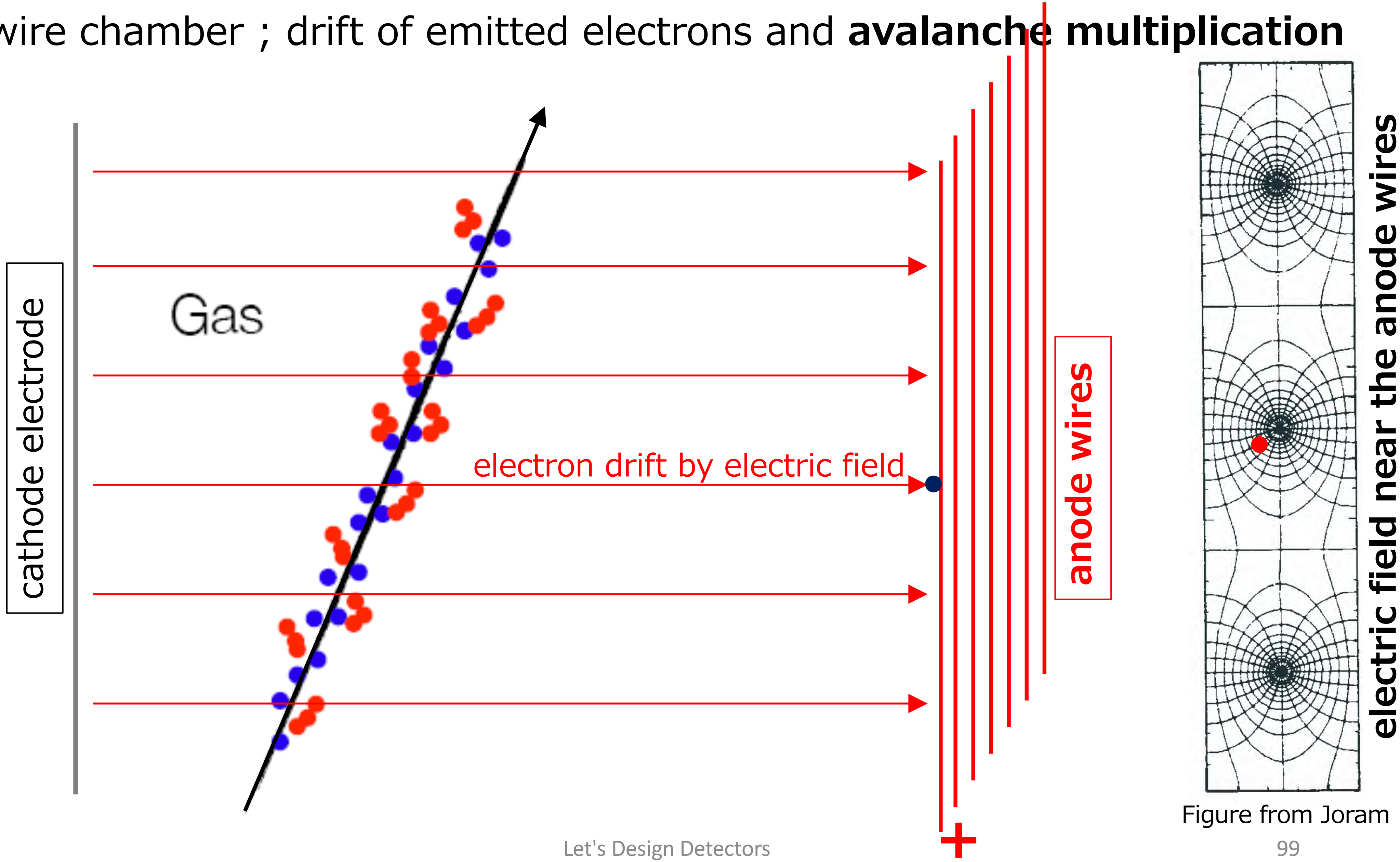
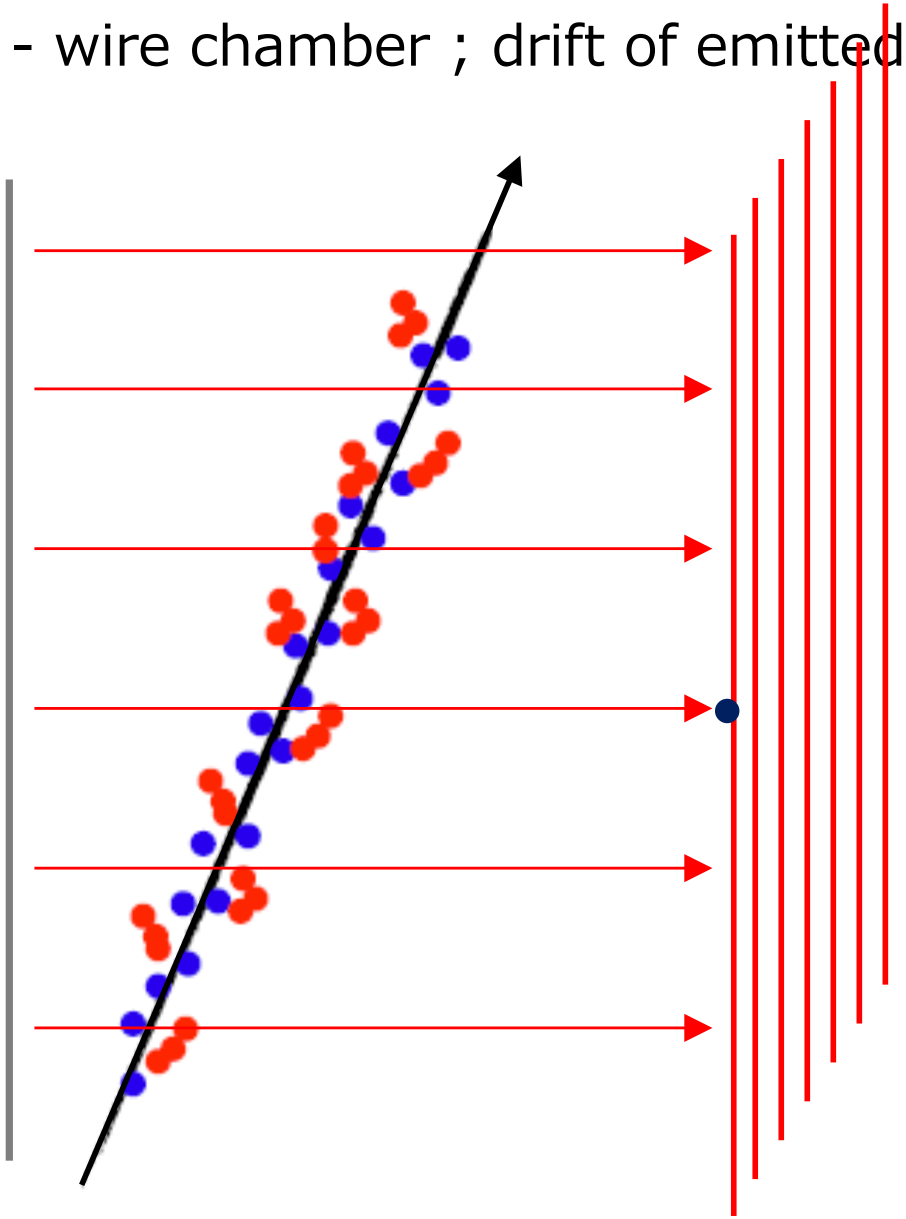


Figure from Joram

Operation principle of gas chambers

- wire chamber ; drift of emitted electrons and **avalanche multiplication**



Strong electric field near the wire.

⇩

Drift electrons are accelerated.

⇩

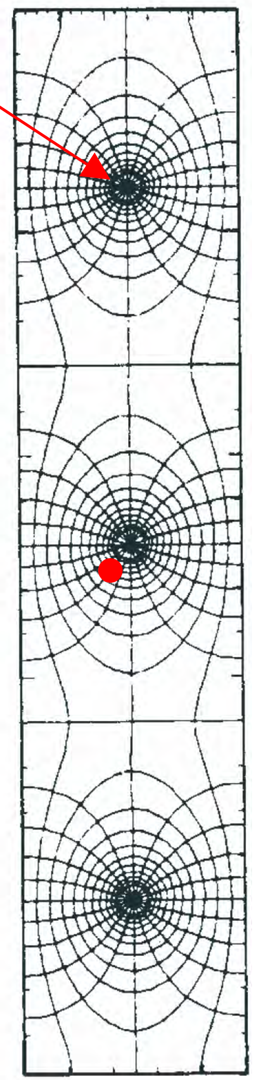
Drift electrons ionize gas atoms.

⇩

Ionized electrons are also accelerated and further ionize.

⇩

A lot of ionization generated
→ **avalanche**



electric field near the anode wires

Avalanche multiplication of electrons

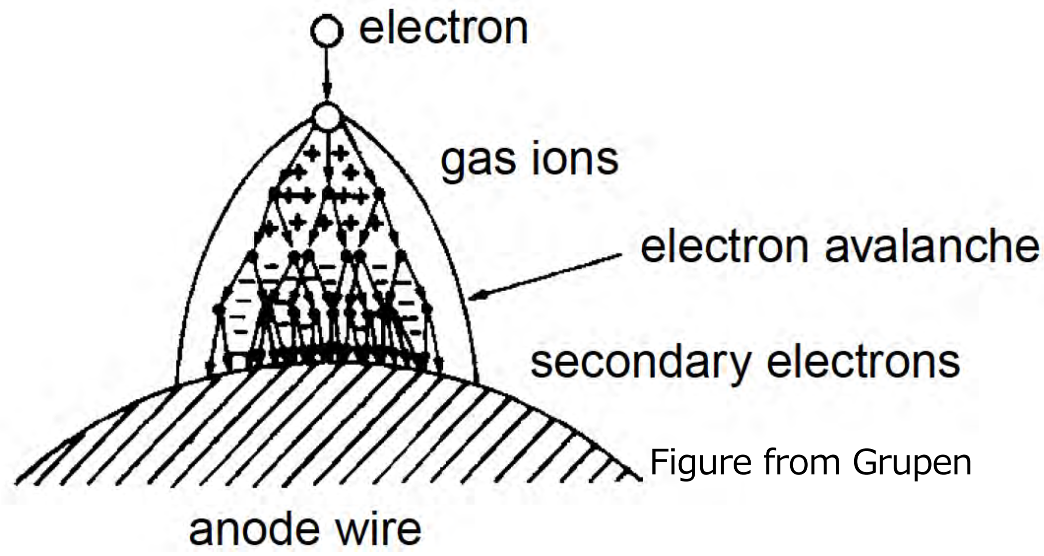
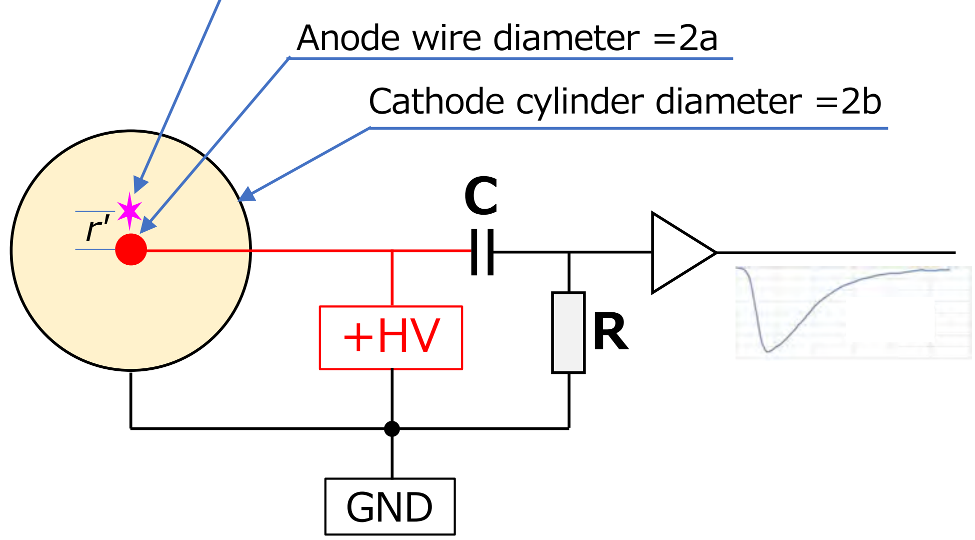


Figure from Grupen



Signal generation at the wire

- Electrons move to the wire and induce charge.
  They 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 ; $V_{ion} >> V_{electron}$
- 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

5. 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, , , ,
- wire readout or pad readout or micro-pattern gas detectors, , , ,
- on/off or pulse-height or timing (single-hit or multi-hit or FADC or , , ,)

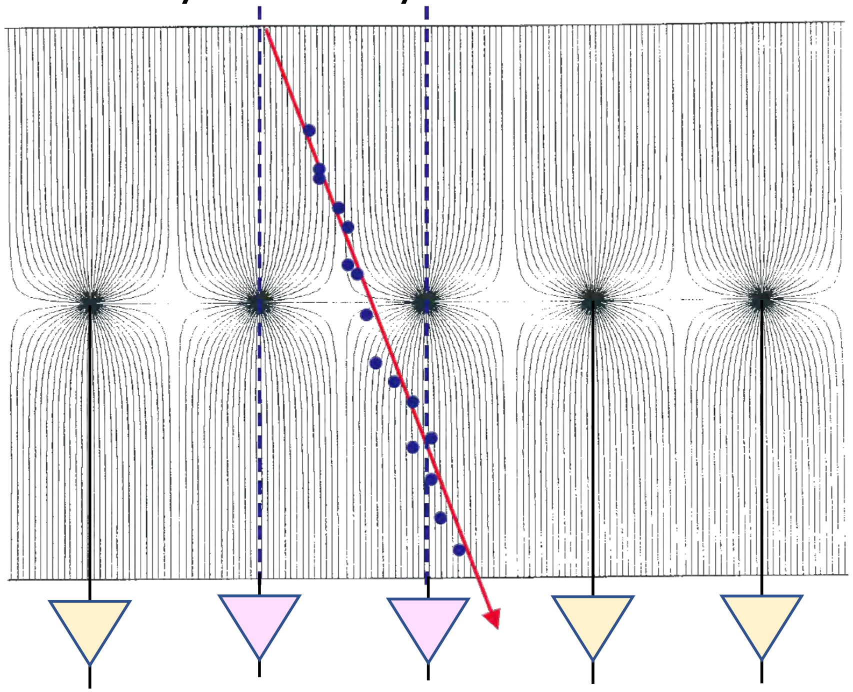
Related Performances are;

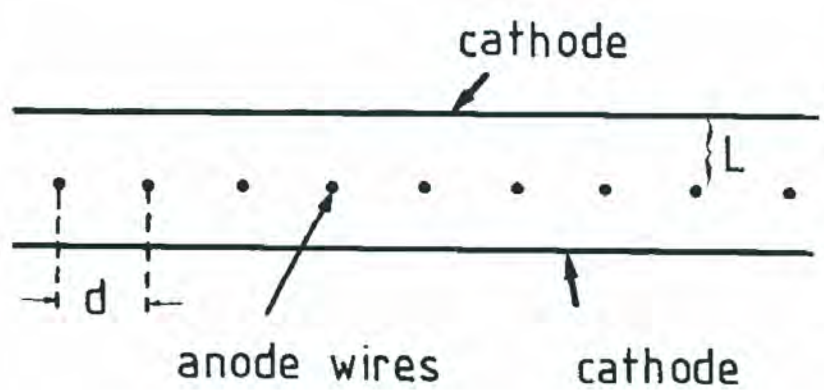
- timing resolution
- position resolution
- energy-deposit measurement
- occupancy
- two-track (hit point) separation
- material thickness
- available size
- cost

and so on...

Multi-wire Proportional chamber

Array of many wires and measure the position





Figures from Joram

Expected performance

- position resolution = d/√12 ~0.6mm ; 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

Pad/Strip Analog Read-out

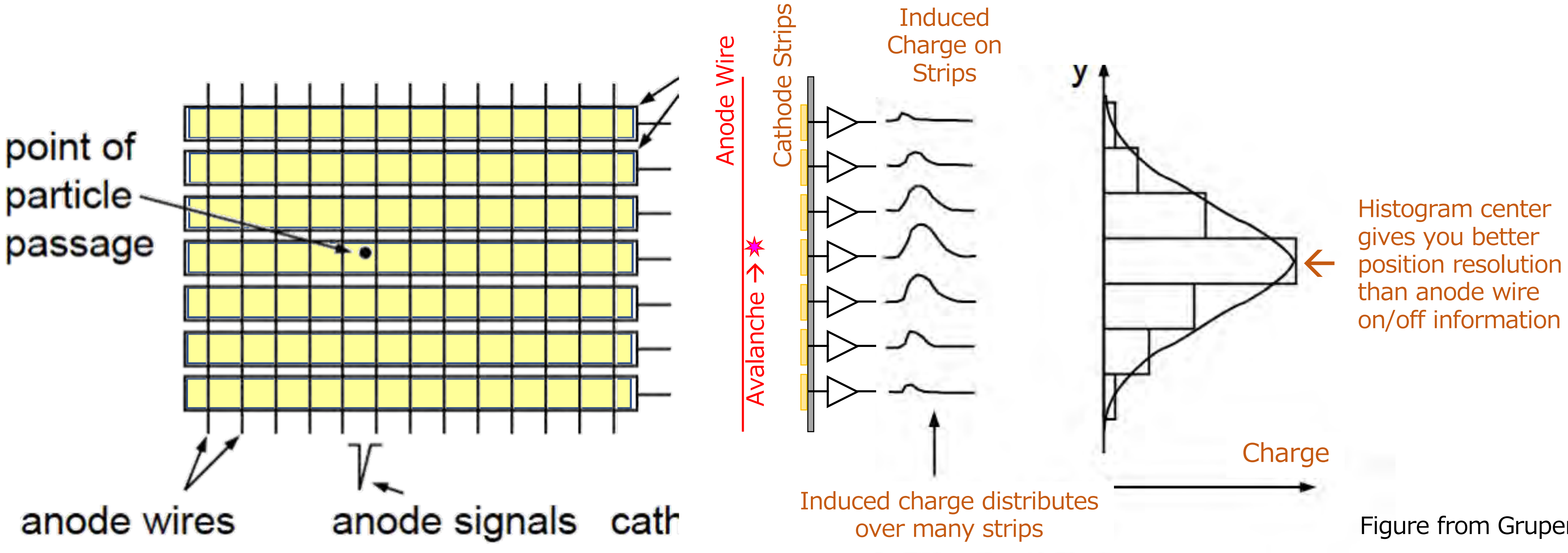
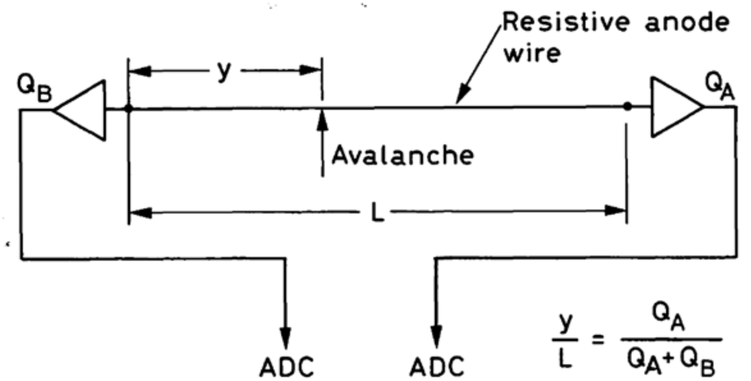


Figure from Grupen

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).

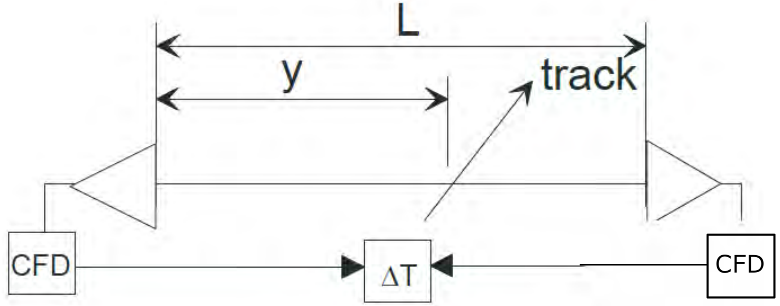
Multi-wire Proportional chamber : Two-dimensional Read-out



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

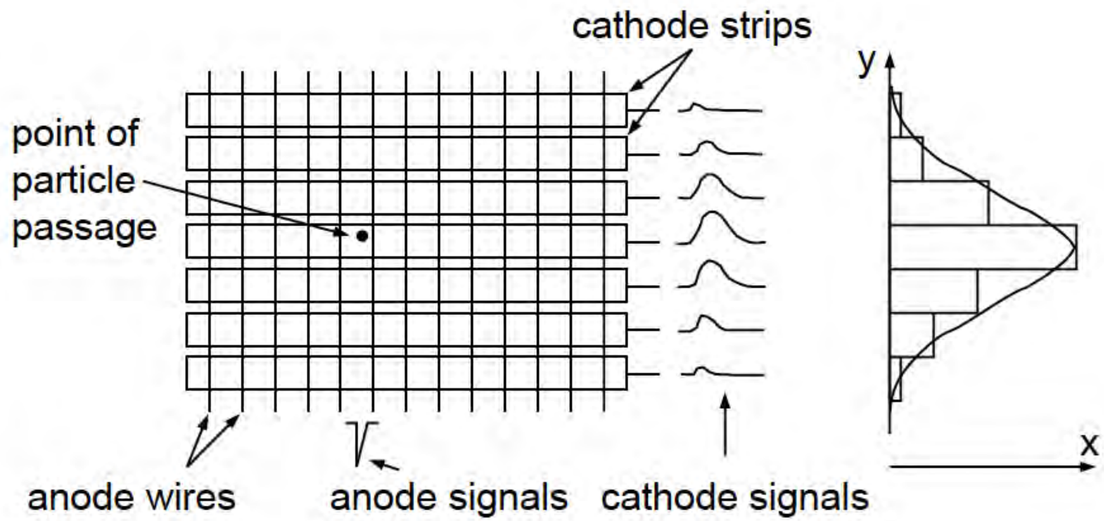
from W.R.Leo



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

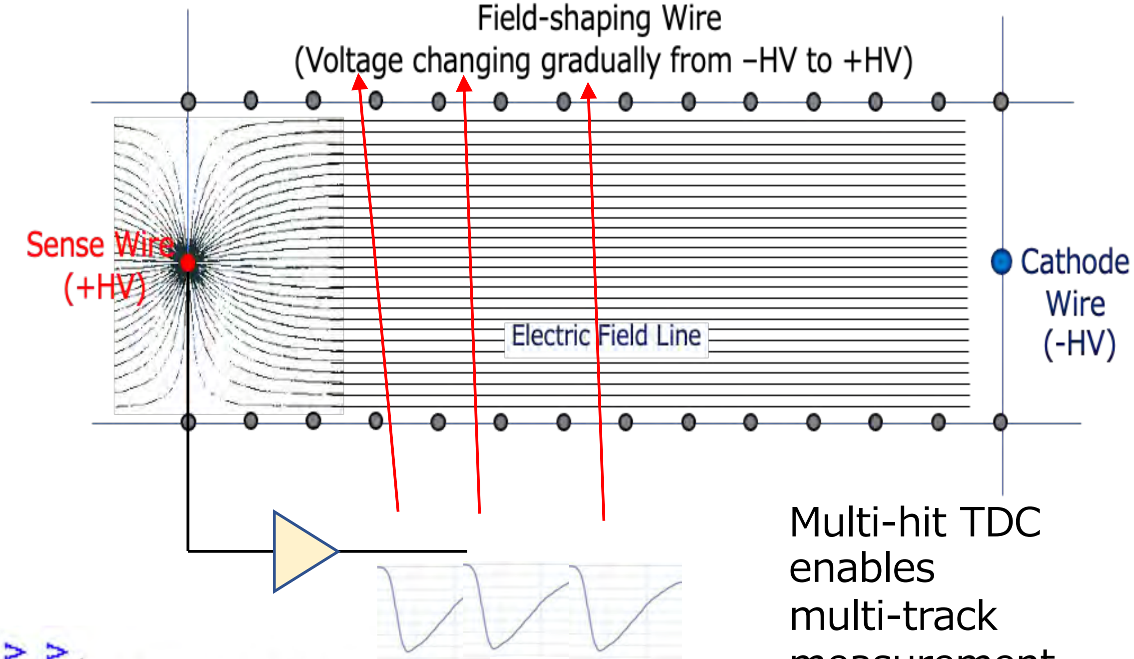


Pad/strip (direction orthogonal to the wires)
gives position information of another direction.

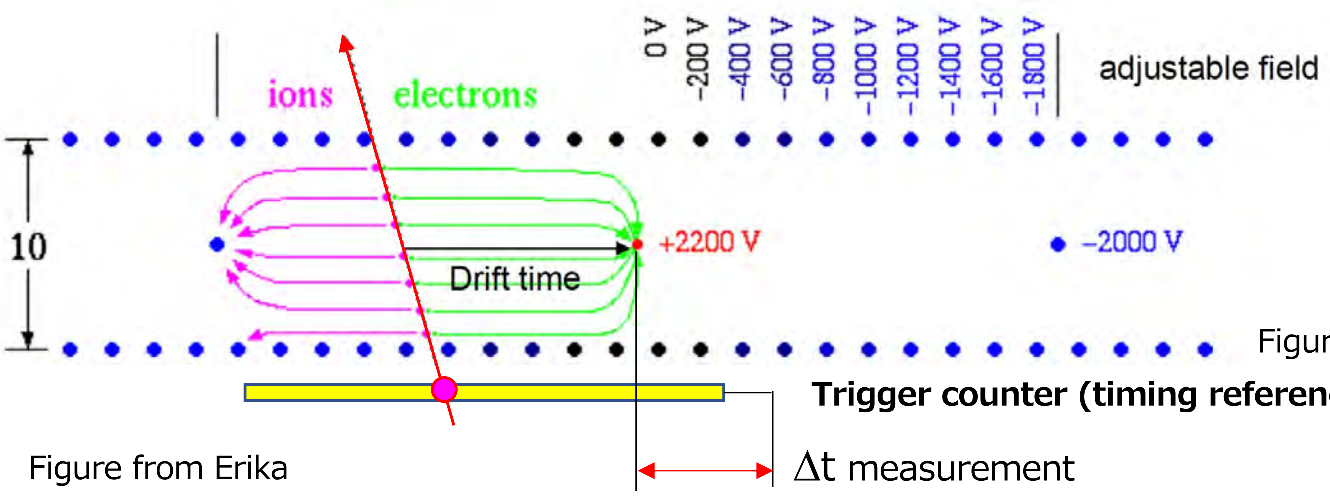
Drift chamber

- Uniform drift electric field is made by field shaping wires with appropriate voltage gradient.
- Ionized electrons (and ions)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)



Multi-hit TDC enables multi-track measurement.



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

Figure from Erika

Trigger counter (timing reference)

Figure from Erika

Δt measurement

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 needs to be solved
→ multi-layer configuration

Drift chambers just gives you distance from the wire
→ one is true, the other is a ghost.

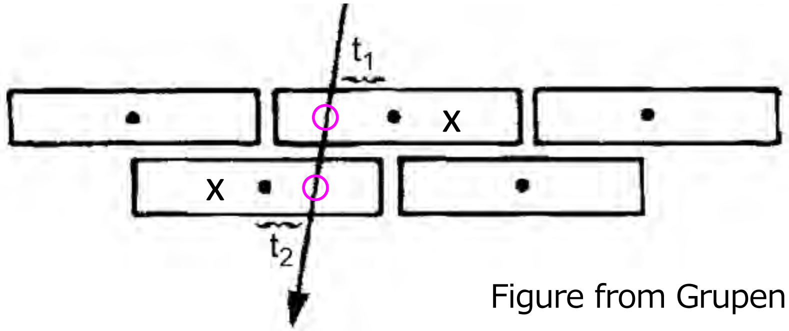
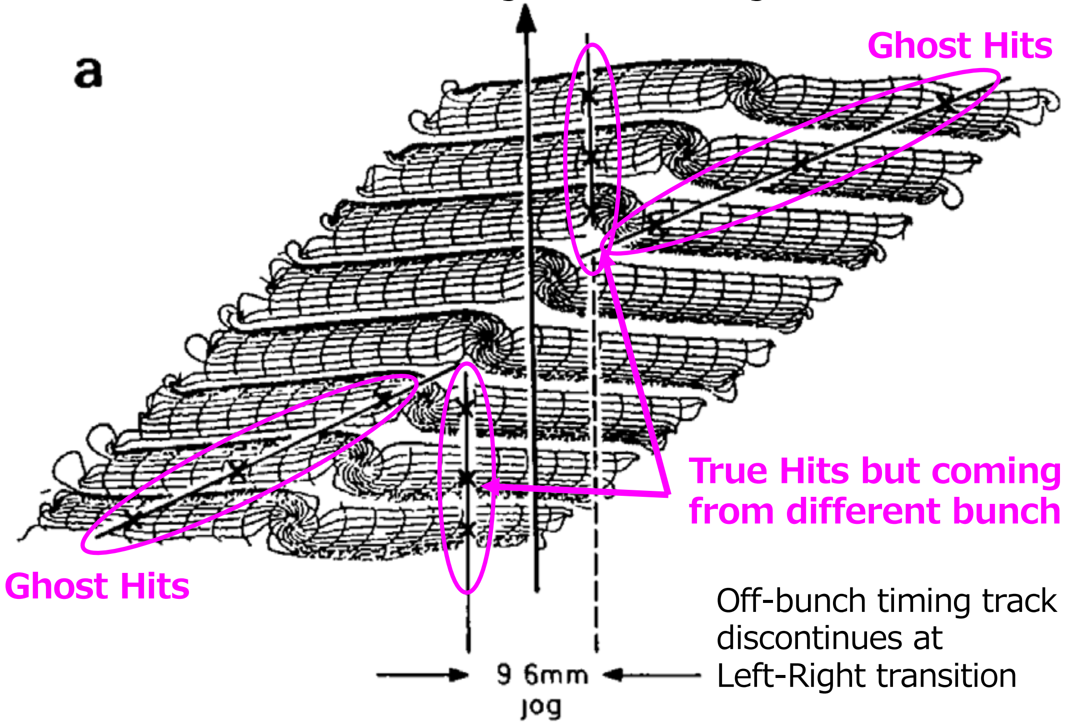


Figure from Grupen

On-bunch timing track be straight.



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).

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

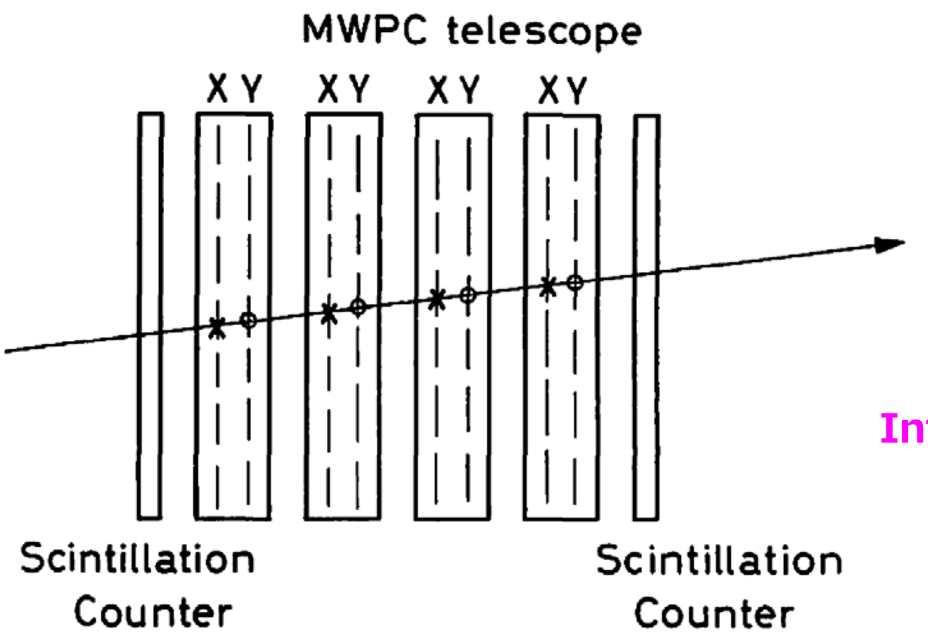


Figure from W.R.Leo

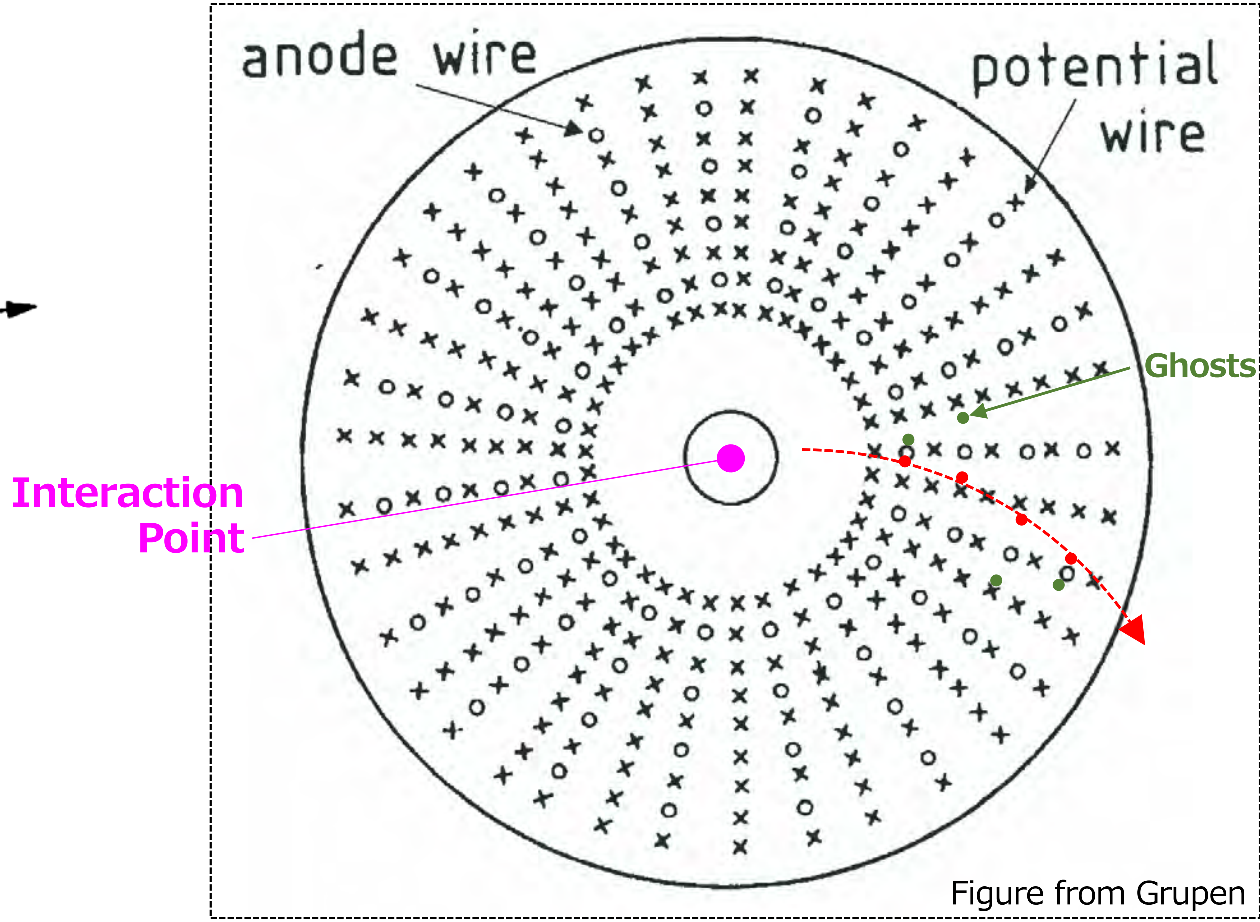
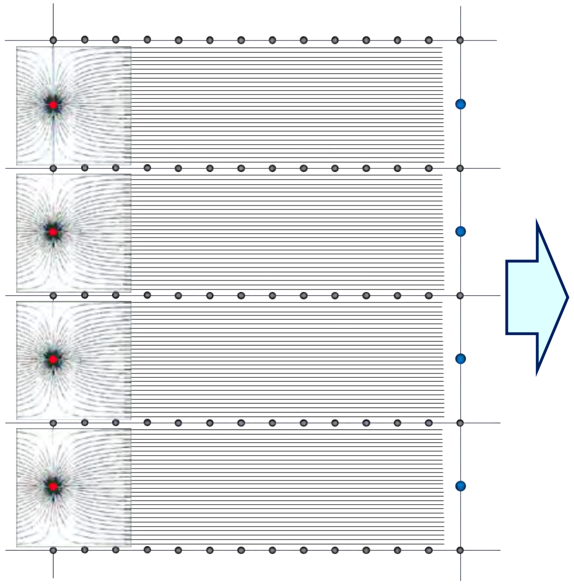


Figure from Grupen

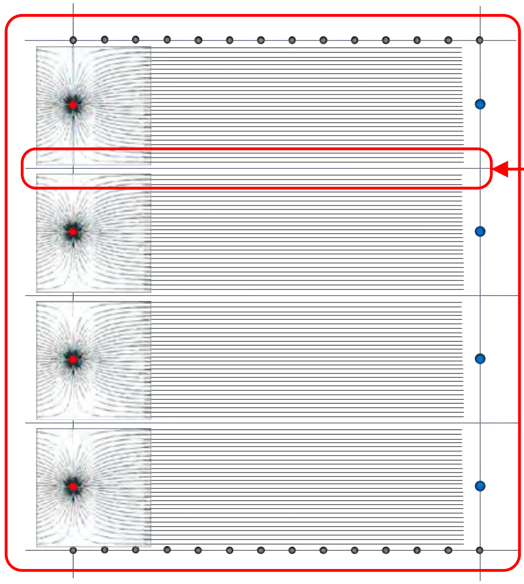
"Cylindrical Drift Chamber" ;
cylindrically multi-layered drift chamber.

Jet chamber

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

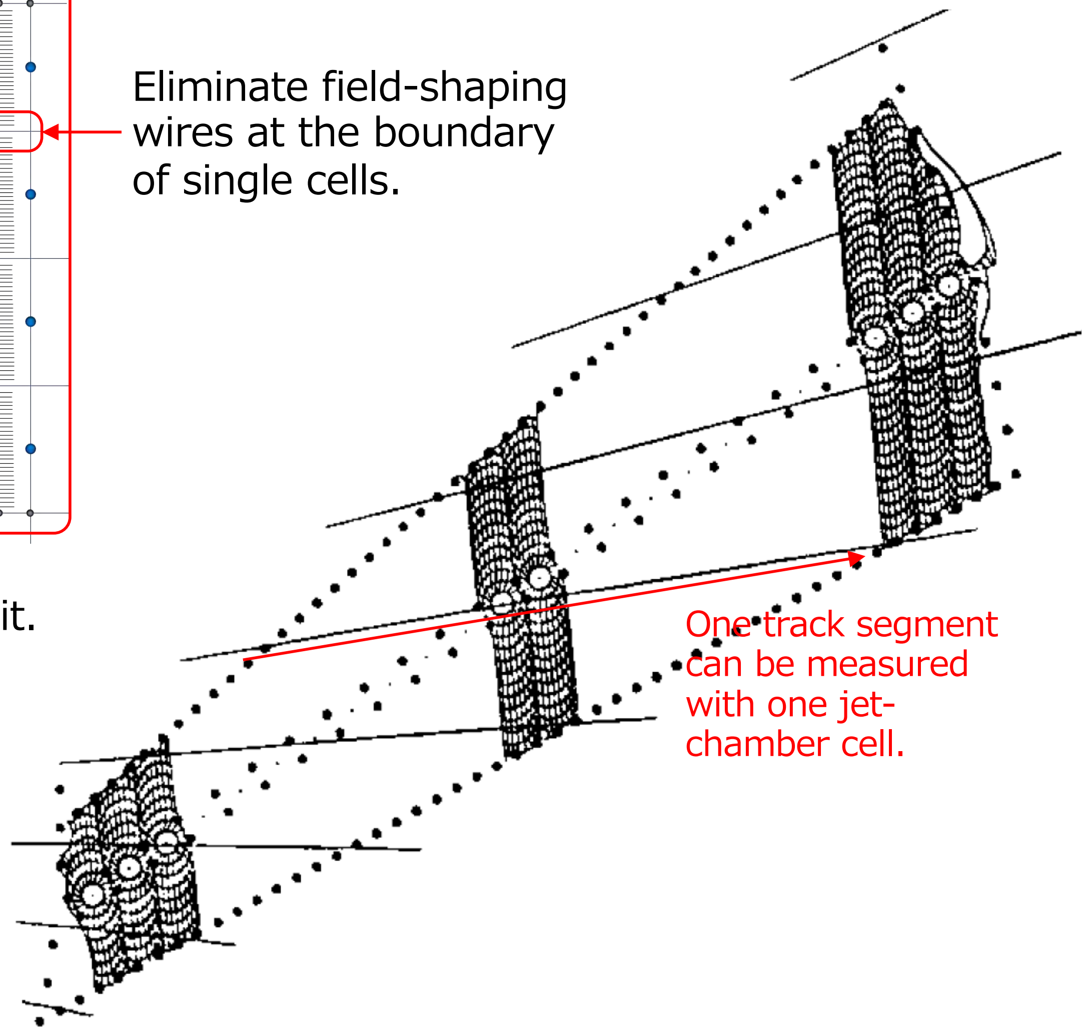


Stack many layers of single-cell drift chamber.



Large Jet-Cell with many sense wires in it.

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



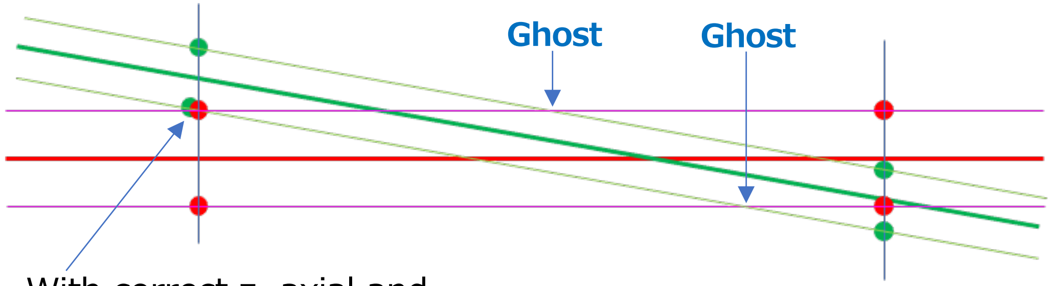
One cell of H1 jet chamber. Straight lines are pointing interaction point. Drift field is designed to be perpendicular to the I.P. pointing lines under 30° Lorentz angle. Taken from "THE CENTRAL JET CHAMBER OF THE HI EXPERIMENT", NIM A279(1989).

Jet chamber

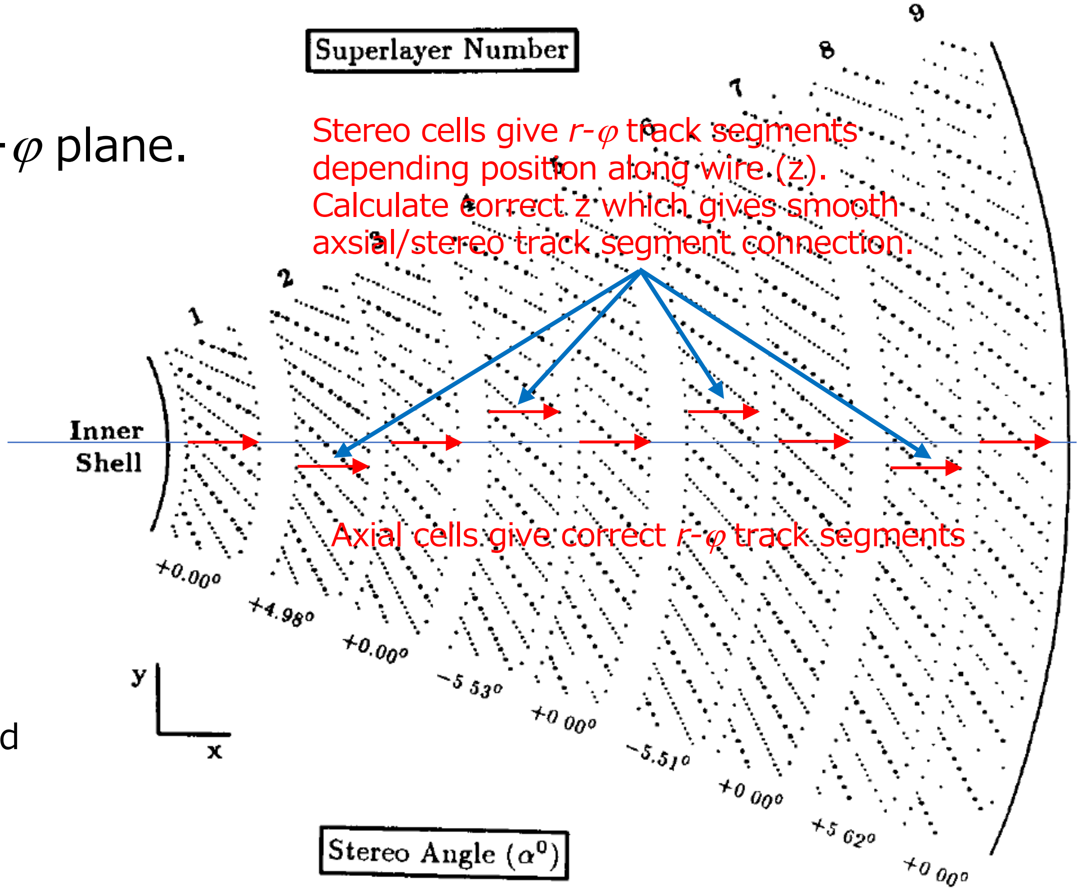
- Jet cell just measures track projection to the r-φ plane.

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

→ Stereo wires (tilted wires) or charge division



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

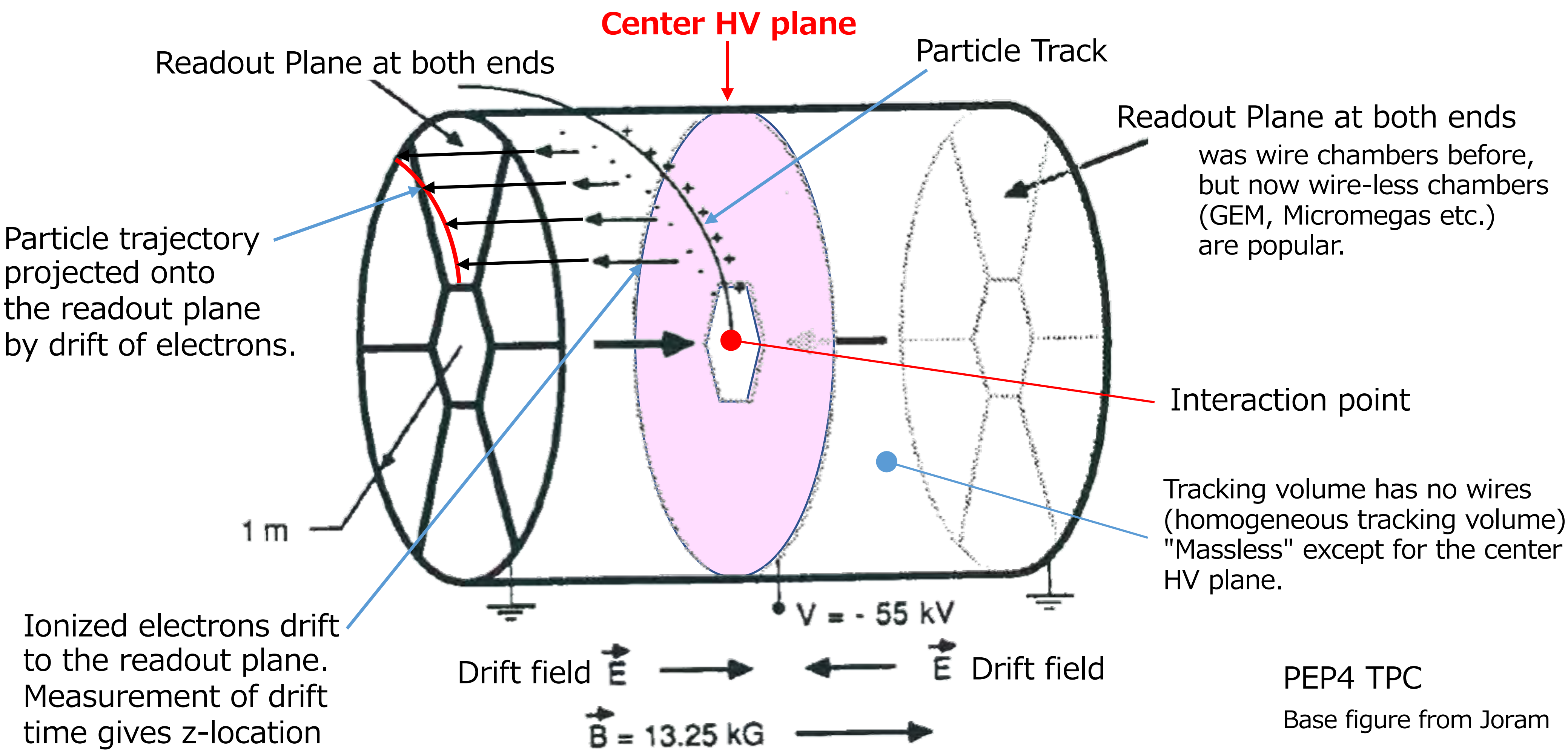


ZEUS jet chamber axial/stereo configuration. From NIM A283.

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

Essentially three-dimensional track measurement



PEP4 TPC

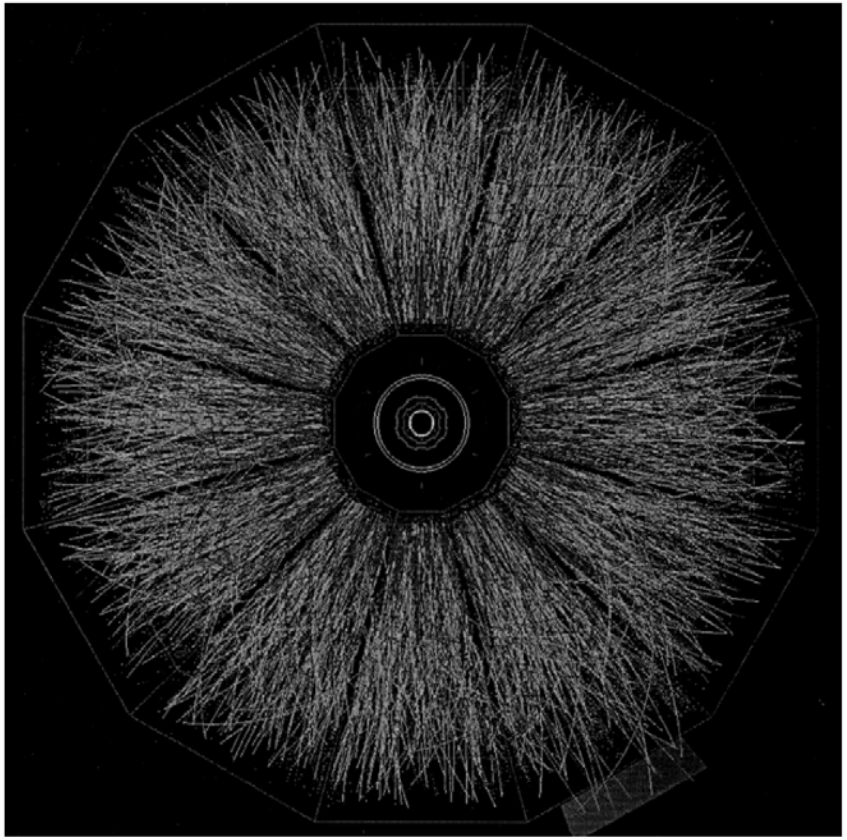
Base figure from Joram

Time Projection Chamber

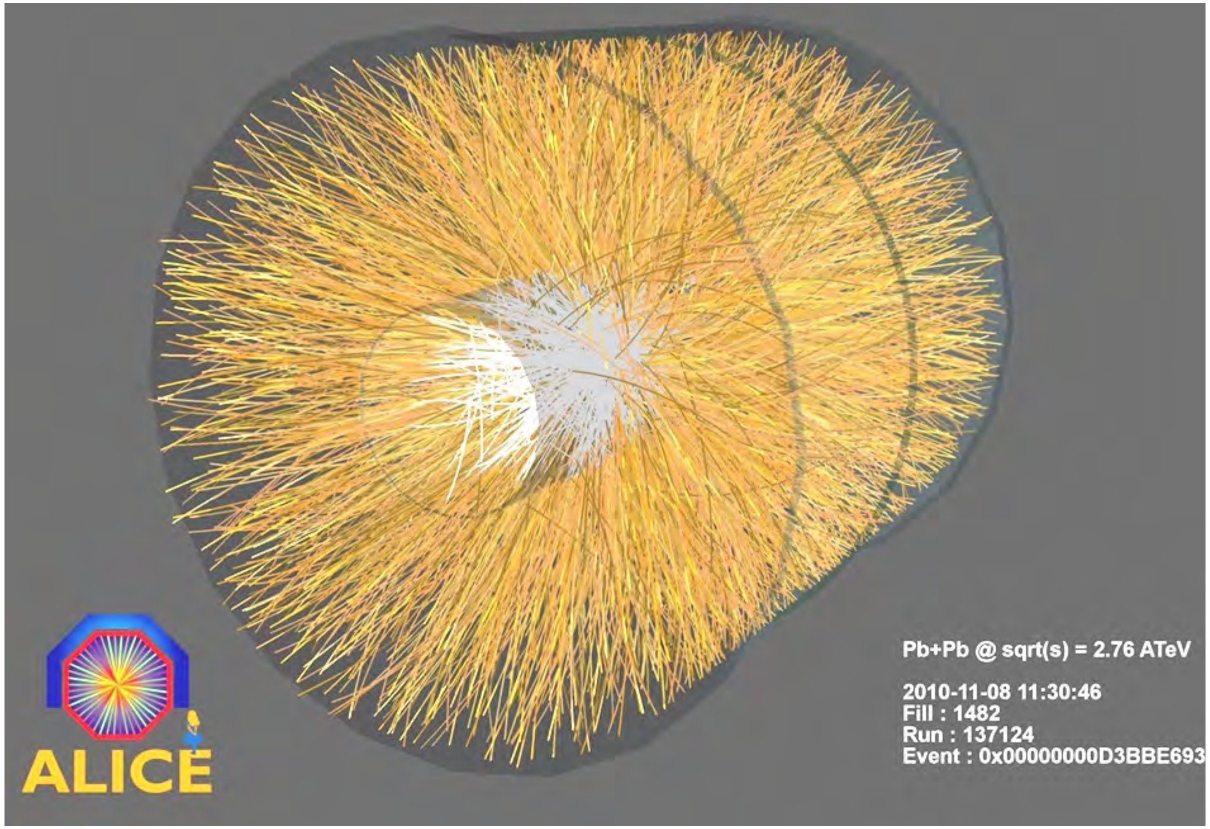
Characteristic features;

- 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

Characteristic features;

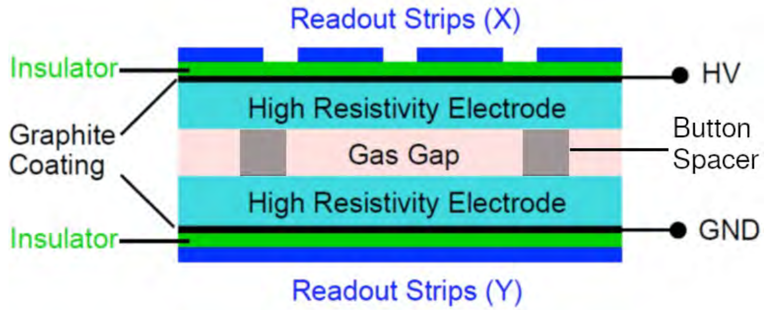
- Essentially three-dimensional track measurement
- Excellent two-track separation and high-multiplicity capability
  → suitable for jet measurement
- dE/dx measurement with many sampling points and pressurized gas
- No wires in tracking volume gives homogeneous tracking volume (no kink)
- Very long 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

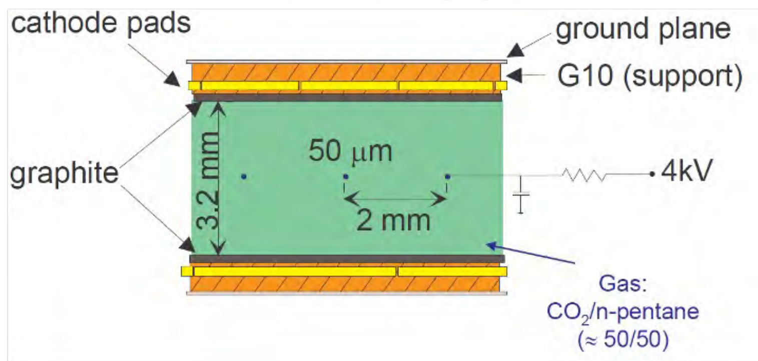
- r-φ position resolution 200~300μ, z-resolution ~1mm
- 2-track separation ~ 10mm
- dE/dx measurement ~5%
- large size possible

Varieties of gas chamber

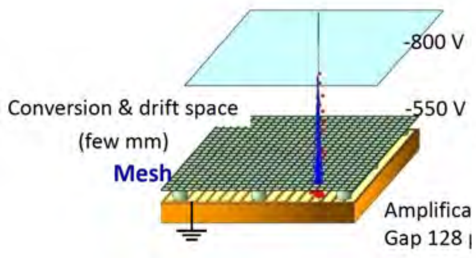
- RPC (resistive plate chamber)
  - Pad readout of streamer discharge between two parallel plates
  - Excellent time resolution (30-50ps), inexpensive,
  - Long recovery time ~ sec.

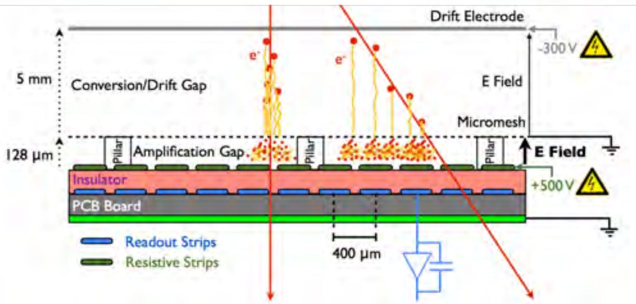


- Thin-gap chamber
  - Pad readout of MWC in avalanche mode
  - High-rate capability

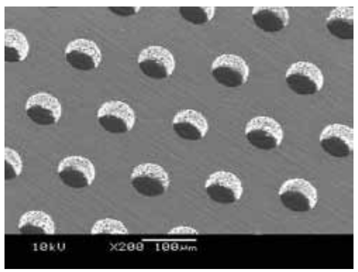


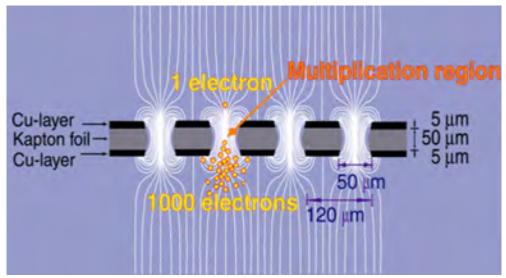
- MPGD (micro-pattern gas detector)
  - MicroMegas
    Apply HV to a fine mesh and realize avalanche.





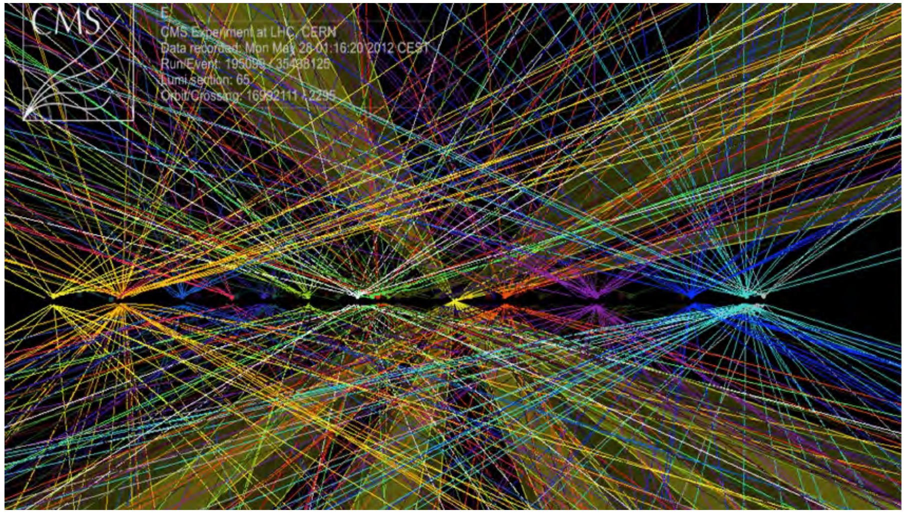
  - GEM
    Apply HV between upper and lower sides of copper-layered insulator sheet with many small holes. Avalanche occurs inside of the small holes.

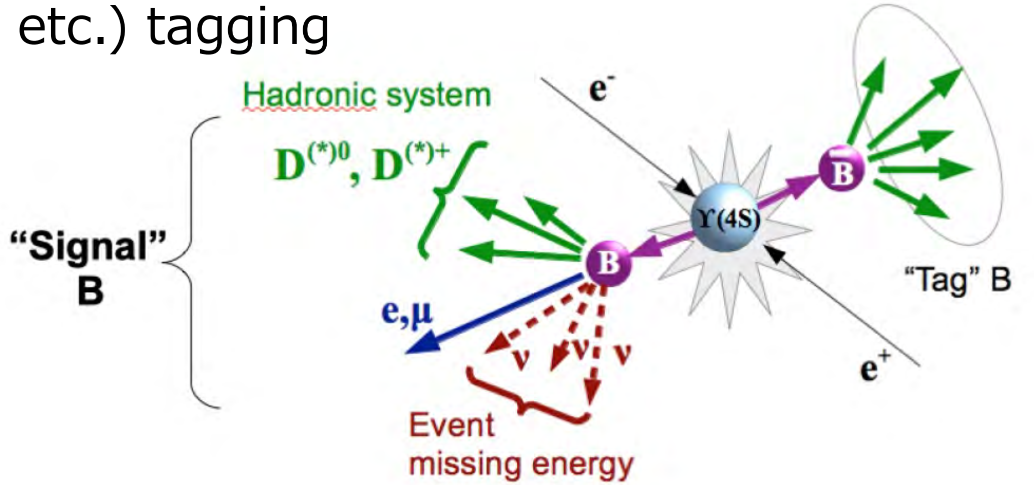




Silicon Trackers for Vertexing

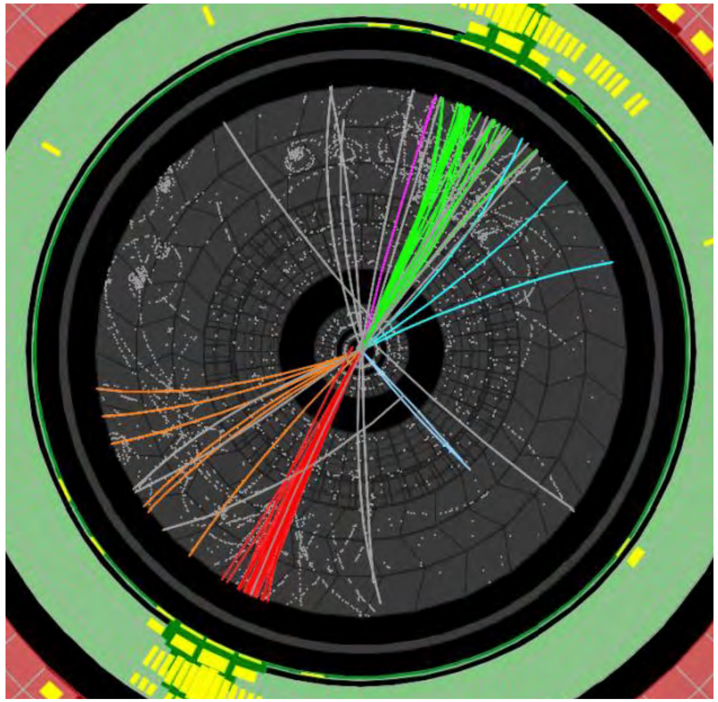
- Primary vertexing : resolve multiple-crossing overlap
- Secondary vertexing : short-lived (b, c, t etc.) tagging
- Tracking of collimated jets





Characteristics;

- Excellent position resolution and 2-track separation
- Low ionization energy
- Low occupancy even at high multiplicity
- huge number of read-out channels
- timing resolution ~ns
- thicker material
- radiation tolerance required



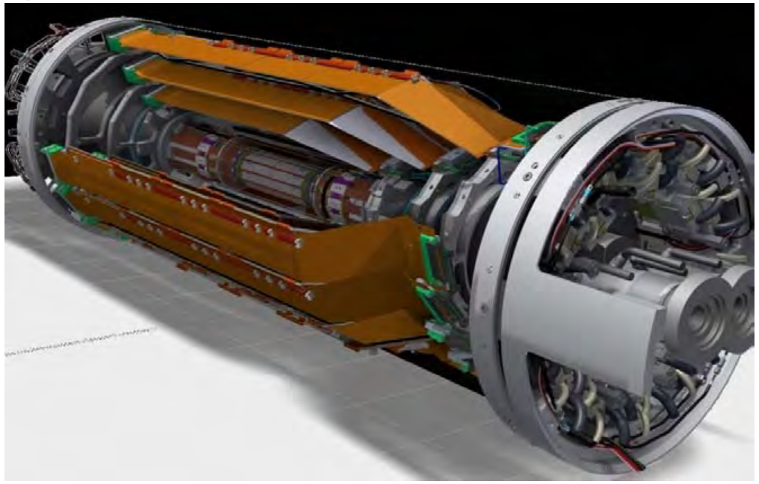
Silicon Trackers for Vertexing

- Primary vertexing : resolve multiple-crossing overlap
- Secondary vertexing : short-lived (b, c, t etc.) tagging
- Tracking of collimated jets

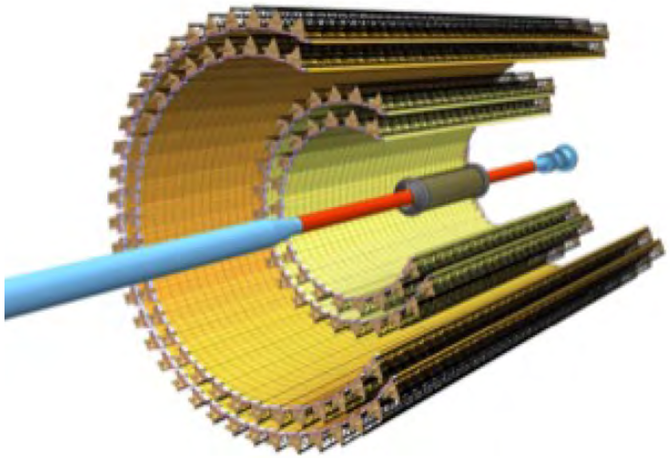
Inner layer ; pixel

Outer layer ; micro-strip

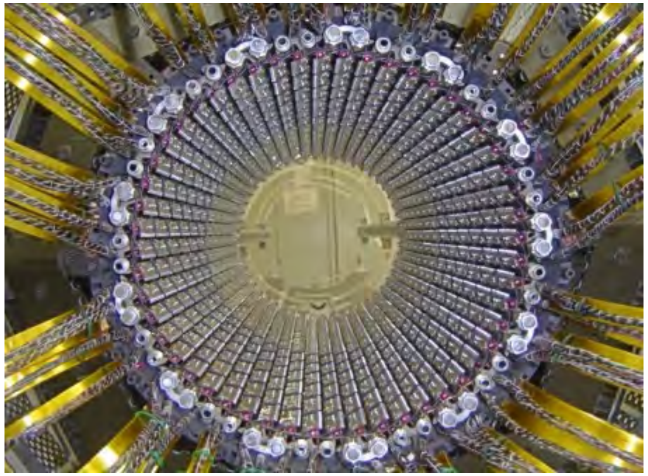
Belle-II



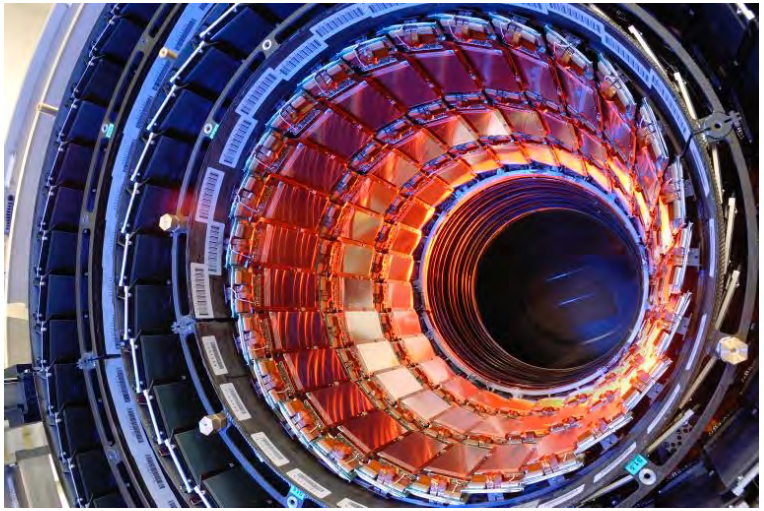
ALICE



ATLAS

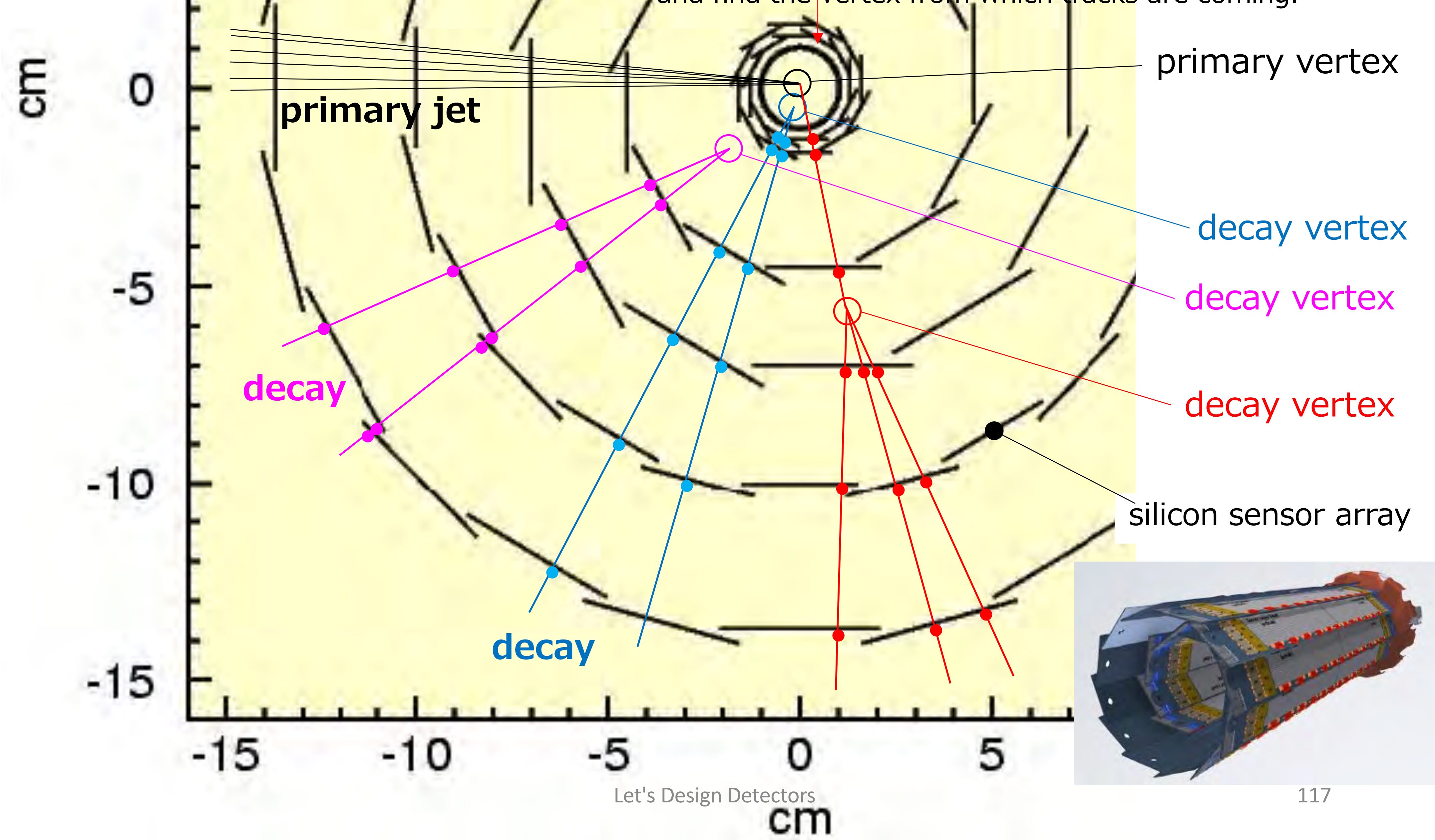


CMS

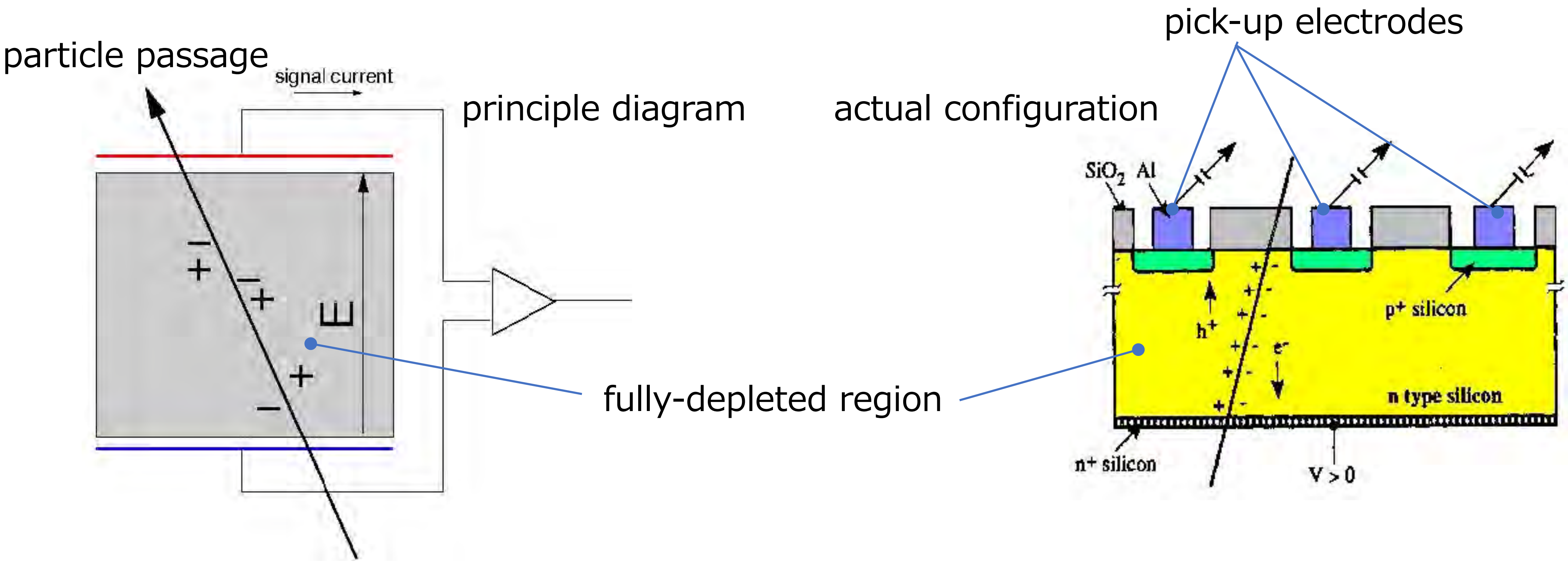


Silicon Trackers for Vertexing

Belle-II innermost vertex locates 14mm from the beamline.
Connect hit points, extrapolate to the interaction point,
and find the vertex from which tracks are coming.



Silicon Trackers ; Signal generation



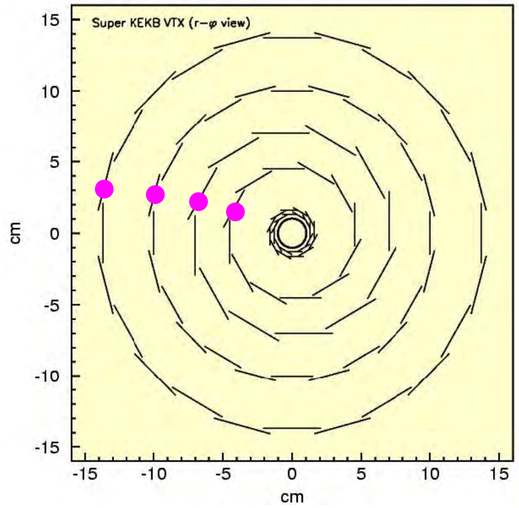
A charged particle passes through the fully-depleted region of silicon

- Apply bias voltage to the silicon sensor.
- Electrons swept out and depleted region is generated.
- Electron-hole pairs are generated
- Electrons and holes are collected to the electrodes and signal picked up.

Silicon Trackers for Vertexing

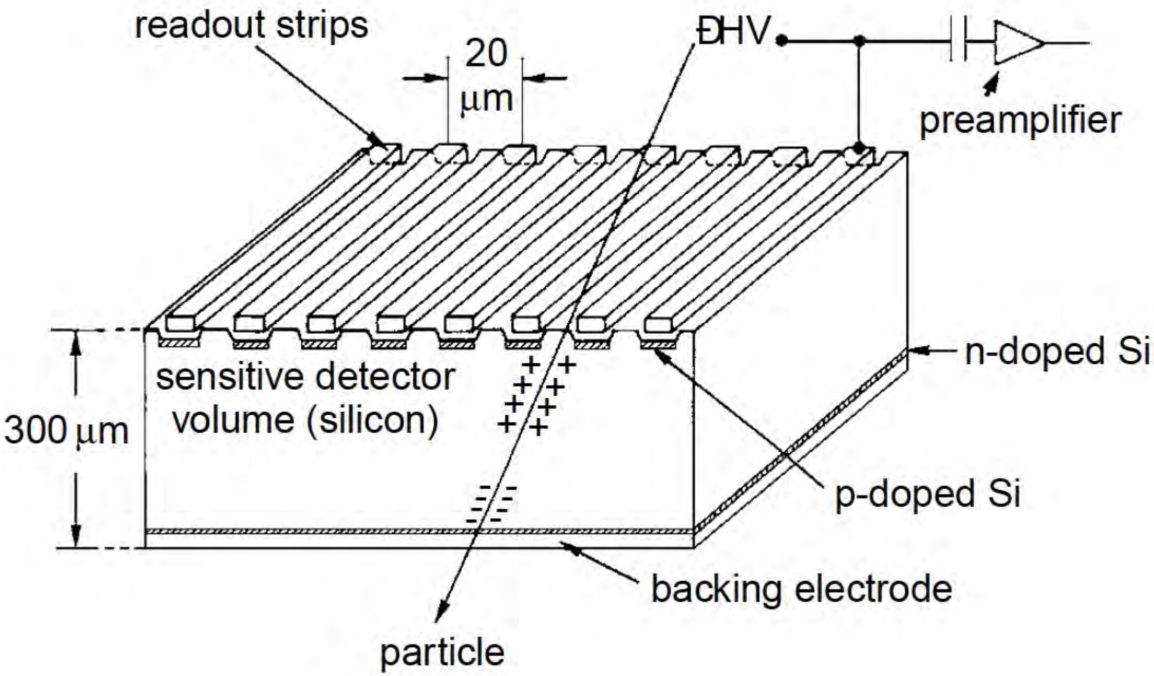
- Strip Detector

- Pixel Detector



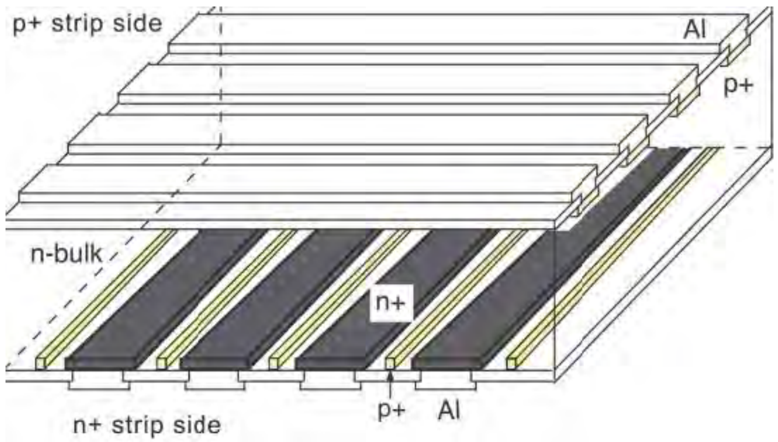
Silicon strip sensor layout. Hit points give r-φ position of the track.

Double-sided sensors give z-position along the beam direction also.



Schematic structure of silicon-strip detector.
r-φ position can be read-out.
Natural layout of read-out electronics at the end of the strips.

figure from Grupen

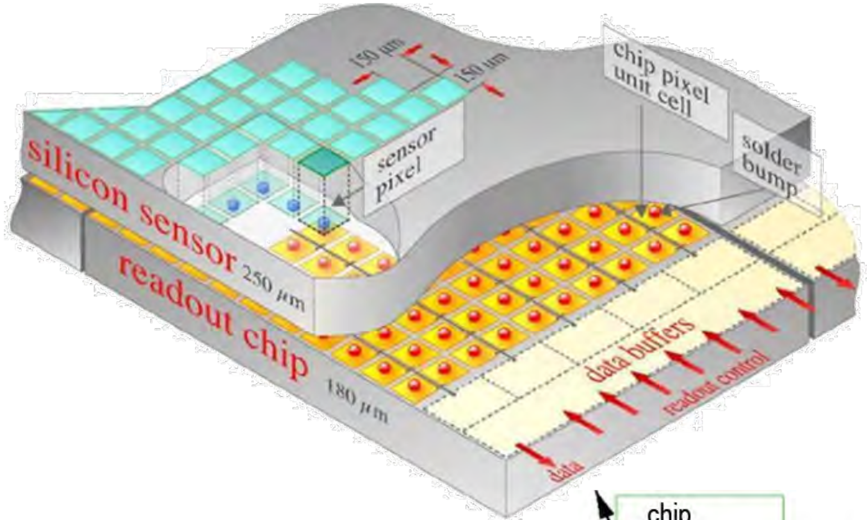


Schematic structure of double-sided silicon-strip detector. 3d-position, r-φ and z-position, can be read-out.
Ghost-hits appear if occupancy is high.

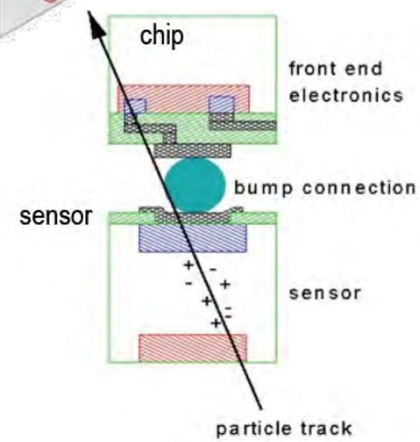
Silicon Trackers for Vertexing

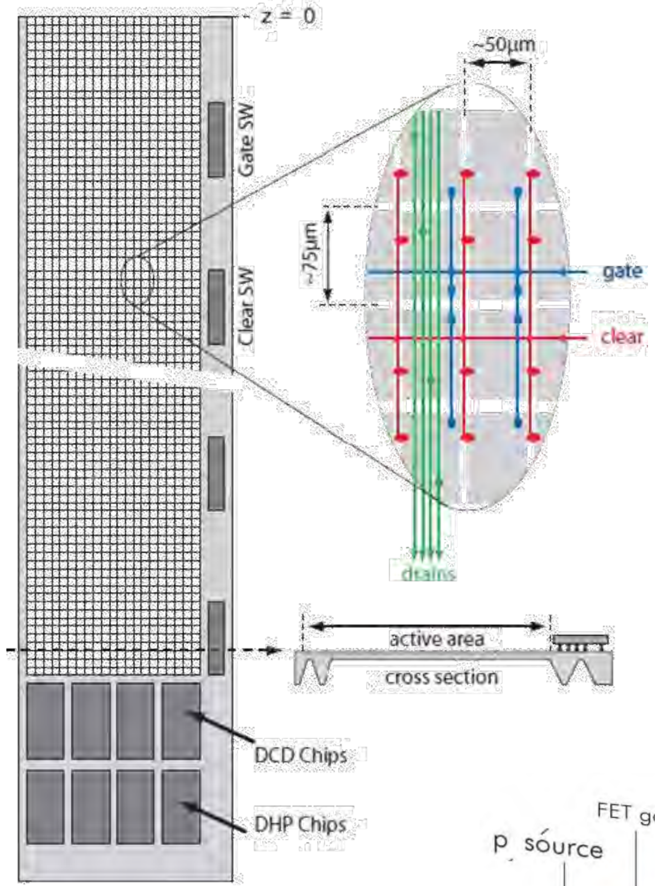
- Strip Detector
- **Pixel Detector**

True 3-d position measurement free from ghost.
Read-out electronics layout is complicated.

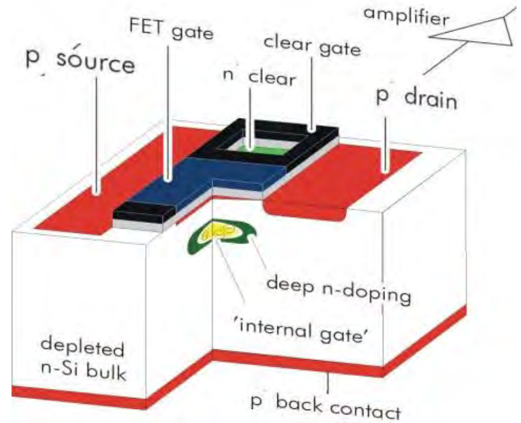


Pixel sensor layer and read-out electronics layer bonded face-to-face.



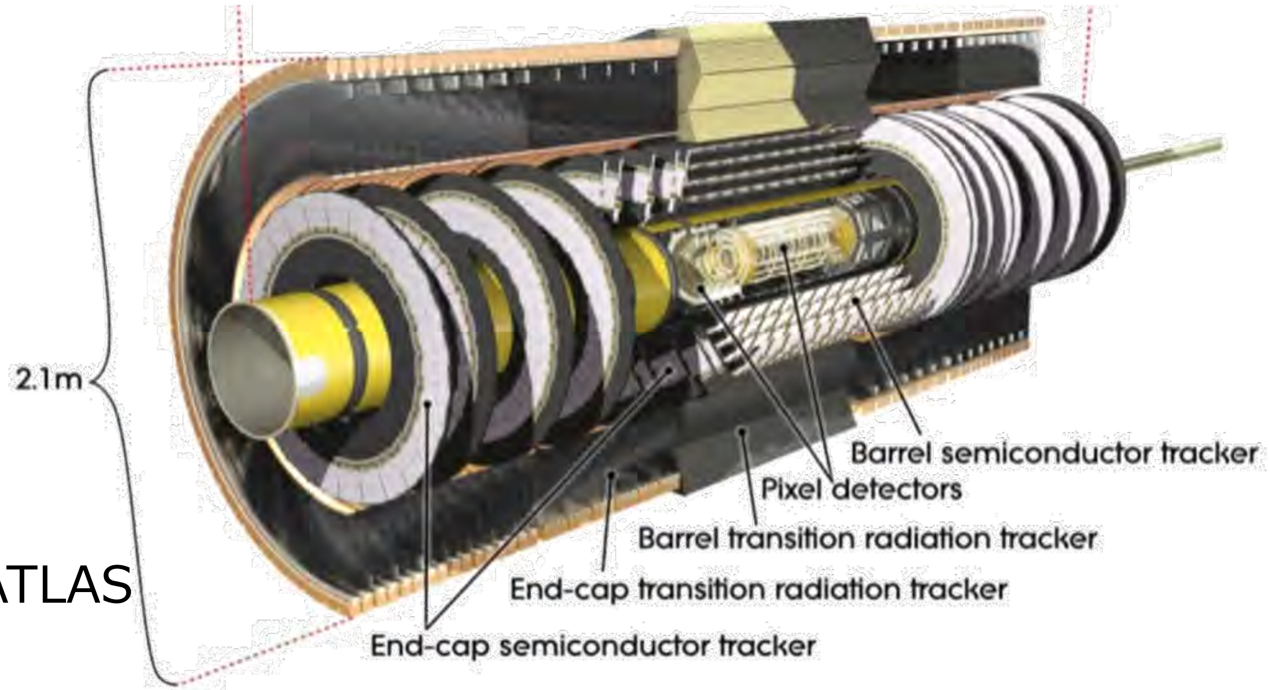


Read-out electronics chips are placed peripheral of pixel sensor chips.

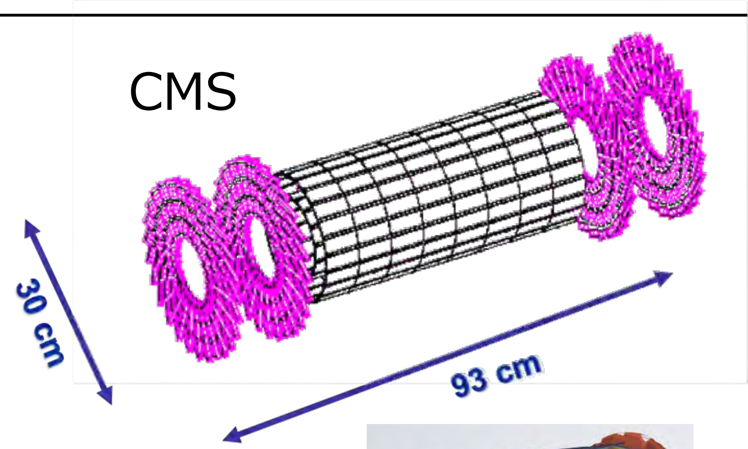


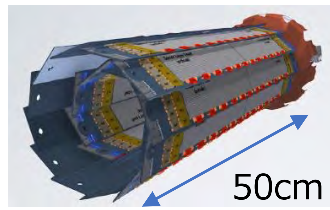
5. Operation of detectors ; Trackers ; Silicon Trackers

Vertex Detectors



ATLAS





Belel-II

	Belle-II		ATLAS		CMS	
	Strip	Pixel	Strip	Pixel	Strip	Pixel
size [μm]	50-75	50x55	80	40x400	80-120	100x150
resolution [μm] rϕ/z		15	16/580	10/115	15/50	~20
number of readout channel	0.2M	7.7M		80M		66M
closest R [mm]	38	14	300	50	255	44
Impact Parameter [μm]			~20μm @20GeV		~20μm @20GeV	

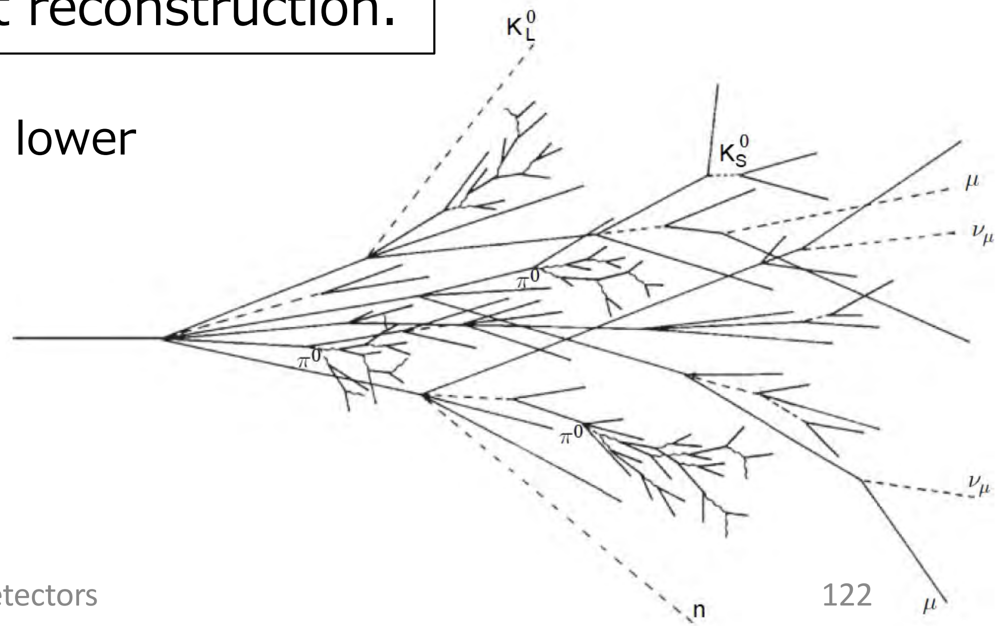
Neutral particle detection

- Calorimeters measure total energy of all particles except muons and neutrino.
  Best to measure neutral particle energy,
  while trackers measure charged particle momentum.
- Very high energy electron energy can be better measured by calorimeters
  due to better-E/worse-P measurement and photon radiation
  - calorimeter energy resolution ; $\sigma_E/E \sim 10\%/\sqrt{E}$ → 1.5%@50GeV
  - tracker momentum resolution ; $\sigma_{PT}/P_T \sim 0.05\% \cdot P_T$ → 2.5%@50GeV
  - brems-photon energy measured by CAL

Excellent calorimeter needed for the best jet reconstruction.

Initiate shower, make individual particle energy lower
to contain in a reasonable detector volume,
absorbs all energy of all cascade particles,
and converts the energy into signal.

・Two ways to convert energy to signal;
  - ionization
  - photon



ElectroMagnetic Calorimeter

- Dense material quickly initiate shower and grow cascade quickly.
  → Dense material is better for calorimeters in most of the cases.
- Shower size characterized by
  radiation length X_0 (longitudinal size) and Molier radius R_M (transverse size).
- X_0 and R_M depends on material.

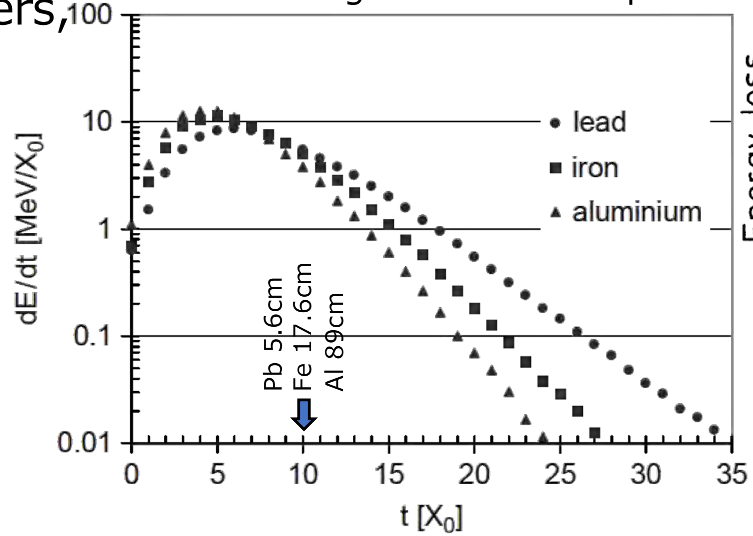
Config. 1) Sampling calorimeter

Separate material to develop cascade (absorber) and to measure energy (active media)
→ heavy metal can be used as absorbers, and free to choose active media.

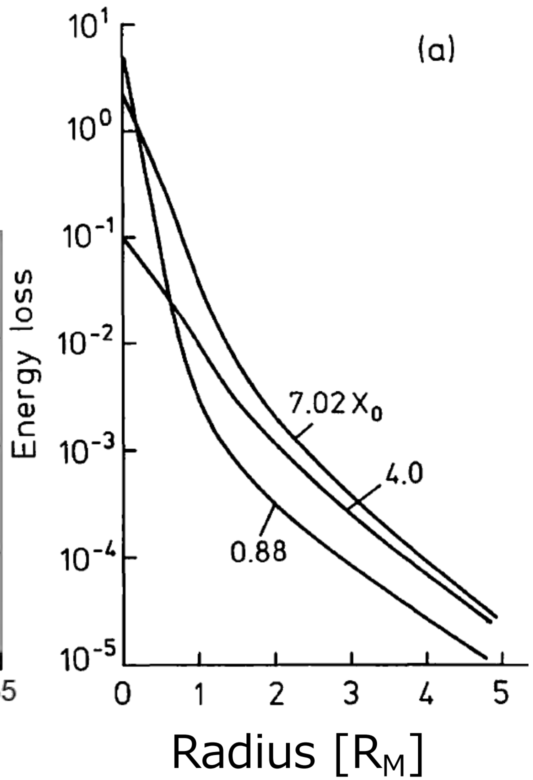
Config. 2) Homogeneous calorimeter

Absorber and active media are the same material.
Better resolution achieved, but need special material, heavy and can generate signal

Longitudinal shower profile



Transverse shower profile



ElectroMagnetic Calorimeter

a) Sampling Calorimeter (right figure)

- Active media
  plastic scintillator, noble liquid, silicon
- Absorber
  Lead, Iron, Tungsten, Copper, , ,
- Geometry
  sandwich, spacal, accordion, shashlik,

b) Homogeneous
crystals (use photons) or
noble liquid (ionization or photon)

Structural parameters determined by required performance and shower sizes ;

total thickness
granularity/segmentation
sampling frequency
absorber thickness etc.

Absorber plate,
thickness of 1Xo for example.
One interaction in a plate on average
and grow cascade.

energy deposit by
electrons are summed
up and converted to the
total energy, corrected
by sampling fraction.

Active plate.
Measure energy
of passing
charged particles.

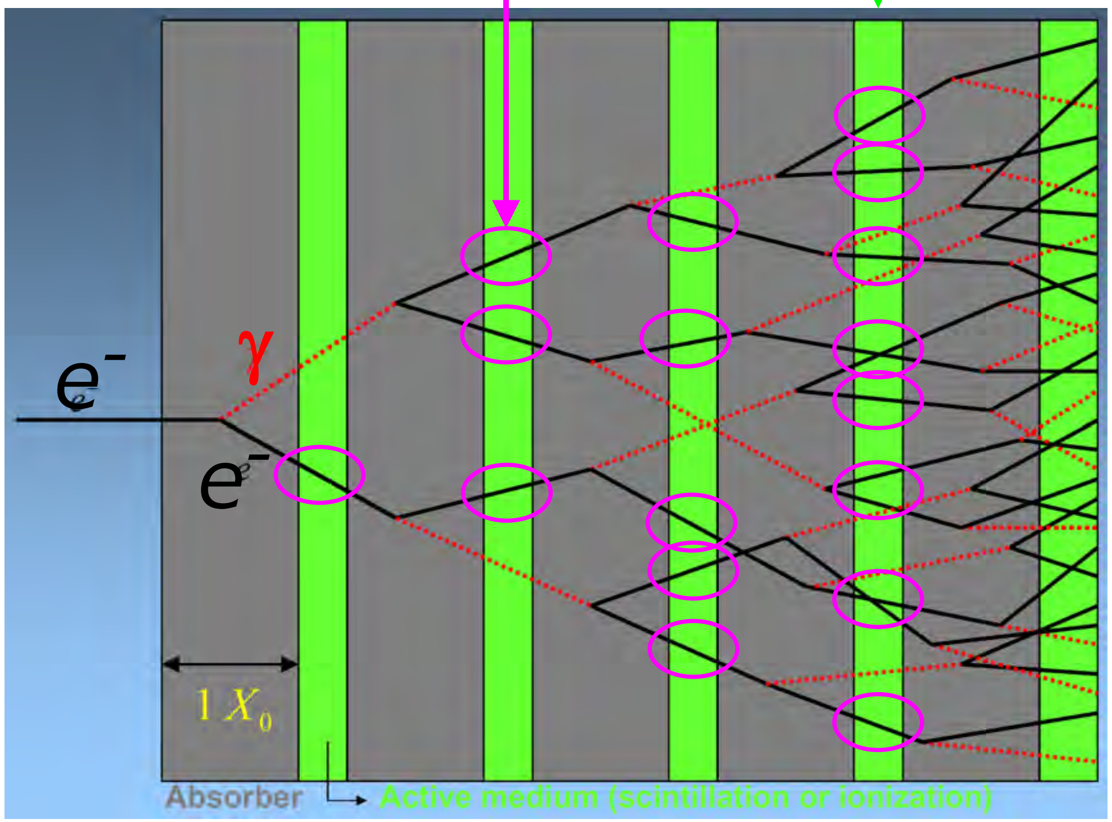


figure from P.Krieger, "ATLAS calorimetry"

ElectroMagnetic Calorimeter

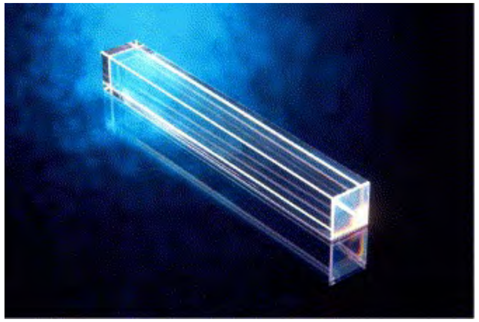
a) Sampling
- Active media
  plastic scintillator, noble liquid, silicon
- Absorber
  Lead, Iron, Tungsten, Copper, , ,
- Geometry
  sandwich, spacal, accordion, shashlik,

b) Homogeneous Calorimeter

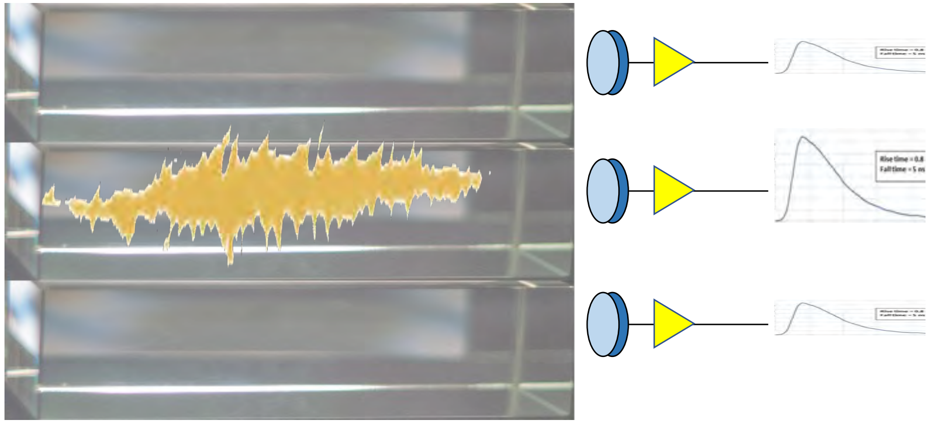
crystals (use photons) or
noble liquid (ionization or photon)

Structural parameters determined by required performance and shower sizes ;

total thickness
granularity/segmentation
sampling frequency
absorber thickness etc.



Crystals which generate light on particle passage is used for homogeneous calorimeters.



Make an array of crystals,
light-shielded to each-other,
and read out photons from each crystal.

5. Operation of detectors ; Calorimeters

Energy resolution can be expressed as;

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

a ; stochastic term

statistical fluctuation of shower → homogeneous
sampling fluctuation → frequent sampling
signal fluctuation → more ionization pairs, more photons
etc.

b ; noise term

c ; constant term

shower leakage → thick calorimeter, no gap
dead material → thinner tracker
imperfection → quality control
etc.

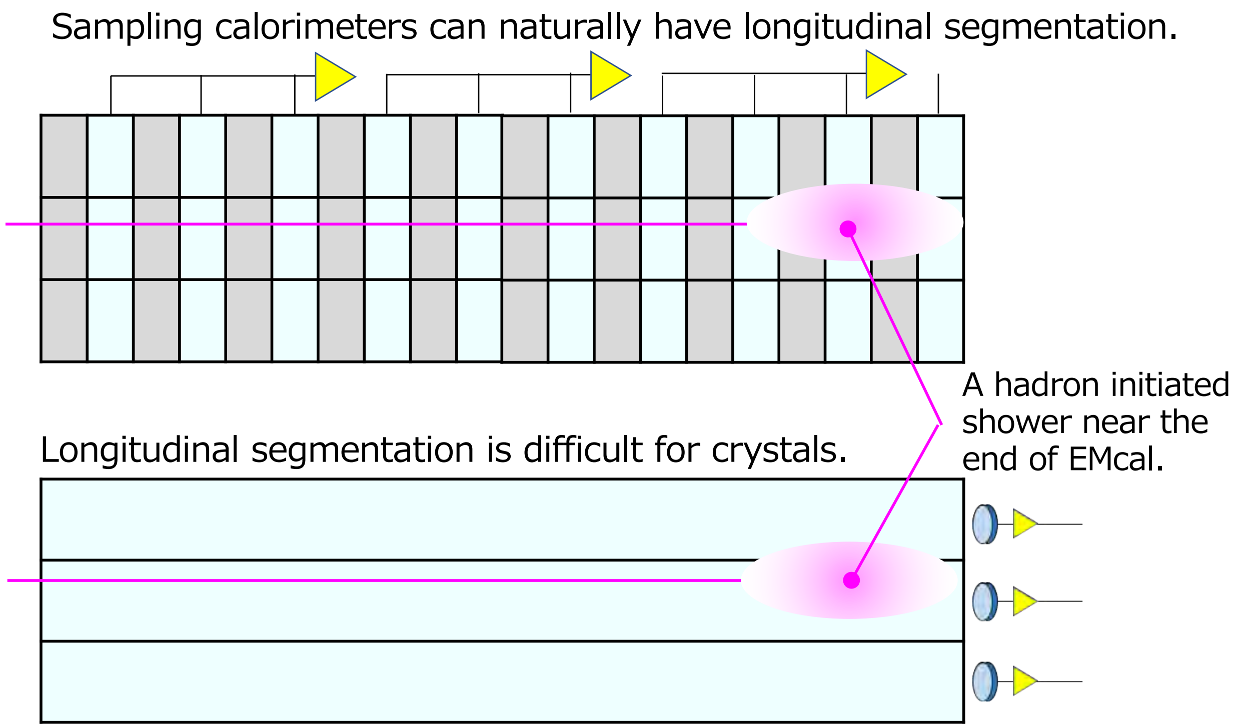
Structural parameters are determined by required performance and shower sizes ;

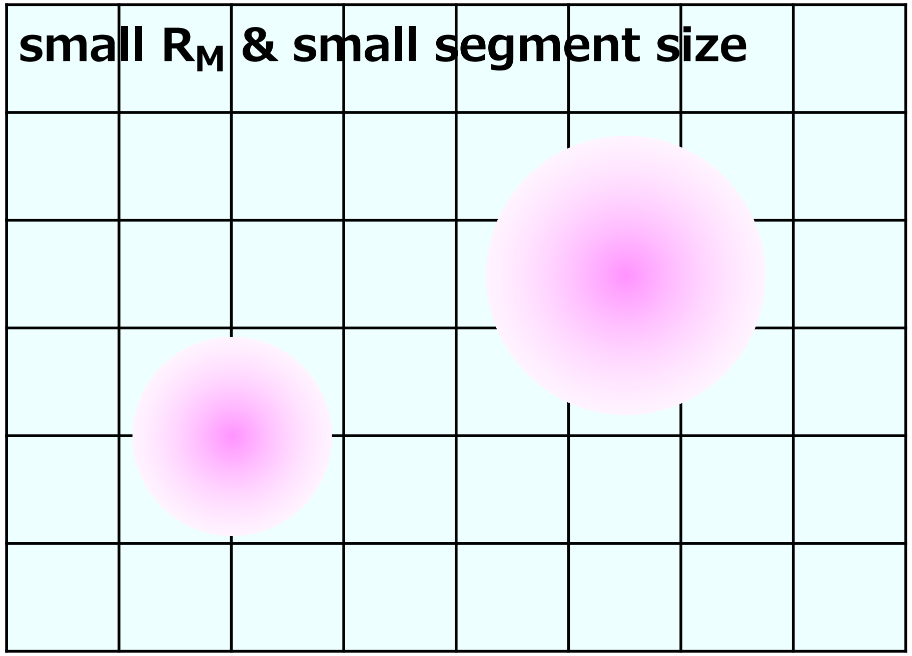
- total thickness
- active material choice
- granularity/segmentation
- sampling frequency
- absorber plate thickness etc.

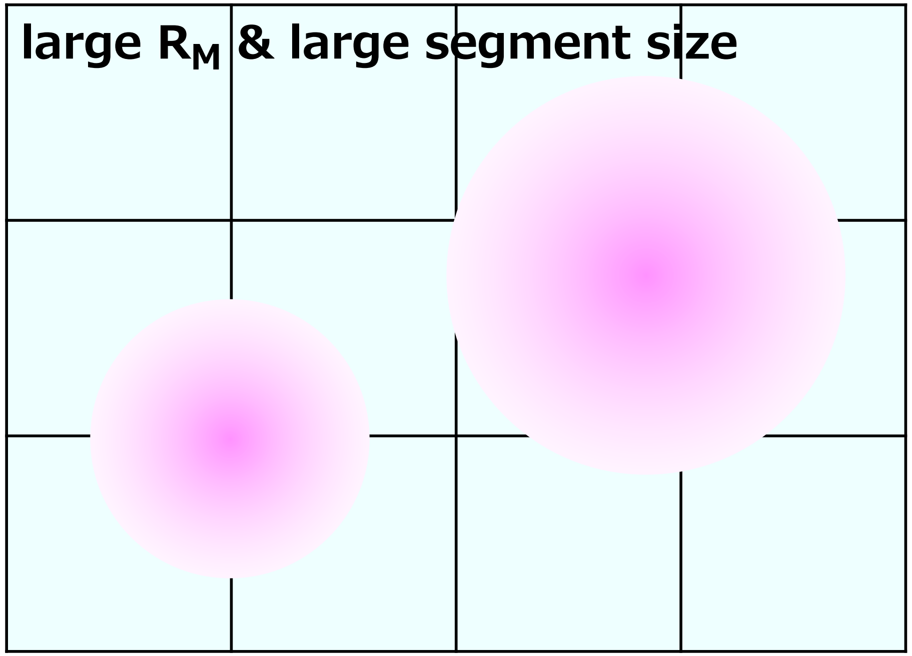
Segmentation/Granurality

- Need transverse segmentation
  and shower be shared by plural segments.
- For better two-cluster separation,
  plural clusters should not merge.
- Better to have longitudinal segmentation
  for EM/hadron identification.

→ Dense (small R_M) material and fine segmentation

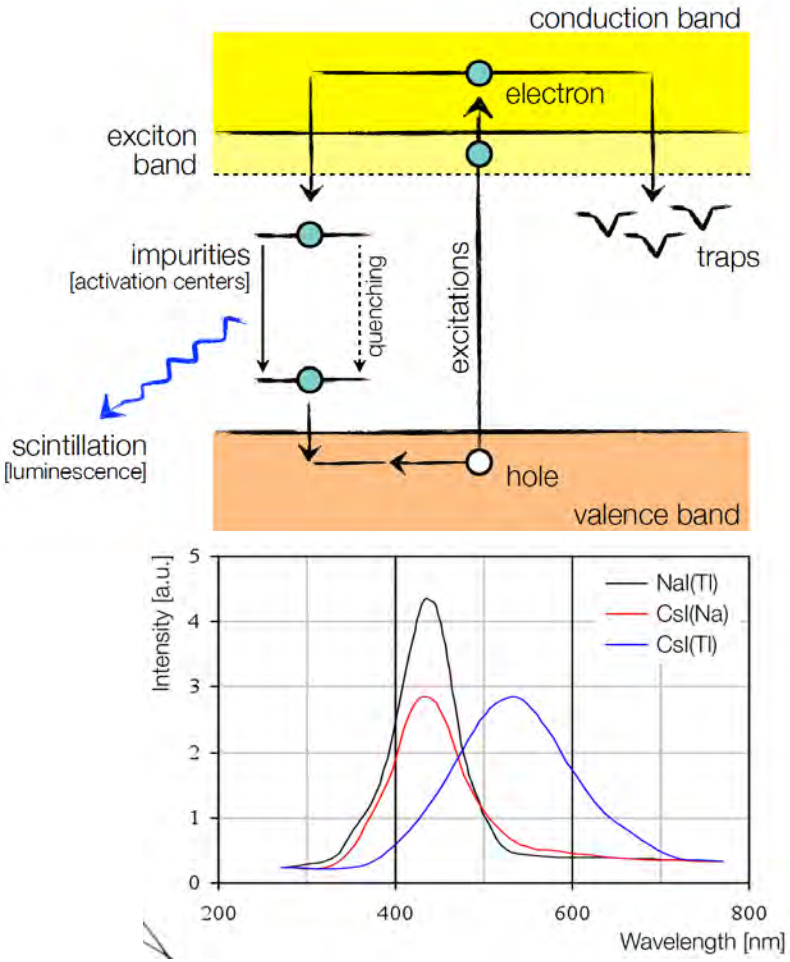




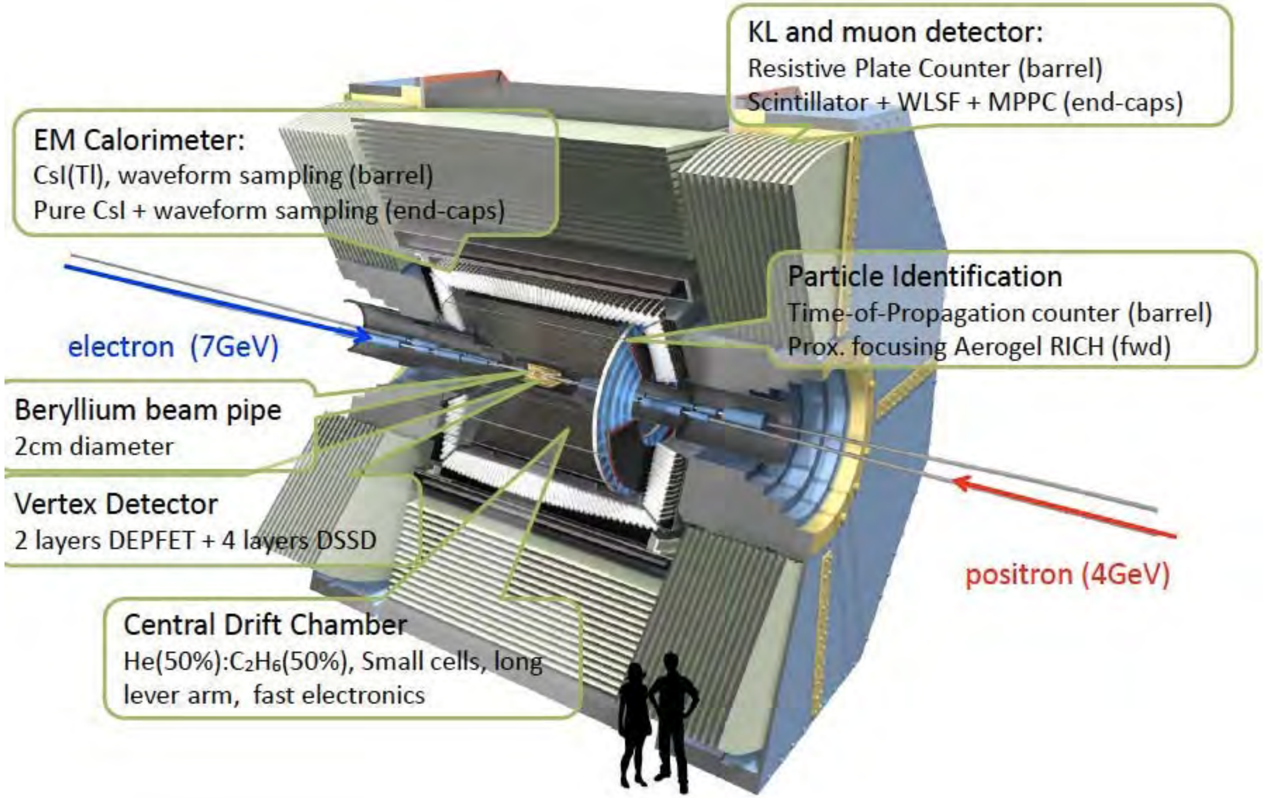


Homogenous Calorimeter

Belle-II ; CsI



from Erika



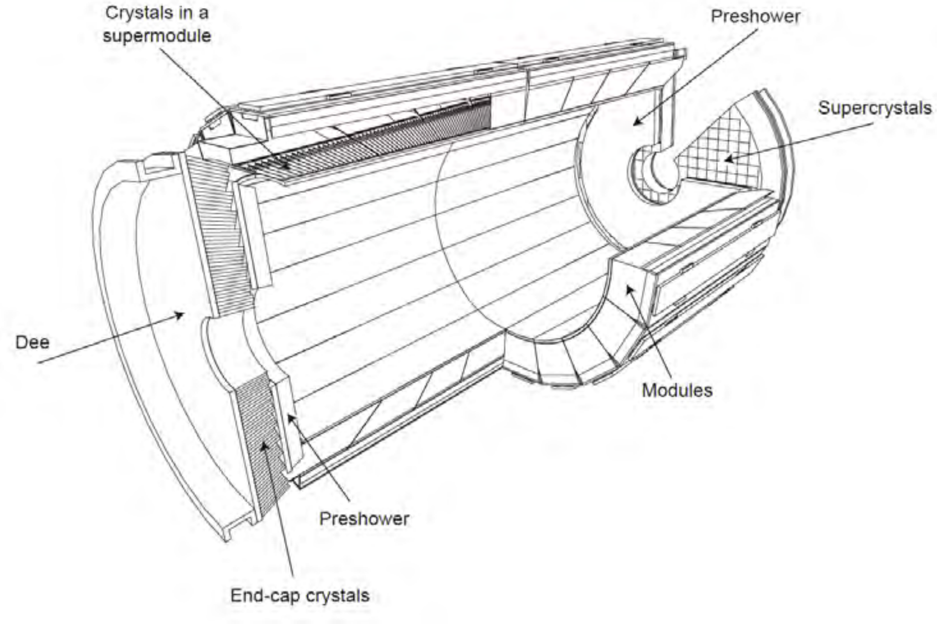
$$(\sigma_E / E = 0.066\% / E \oplus 0.81\% / E^{1/4} \oplus 1.34\%)$$

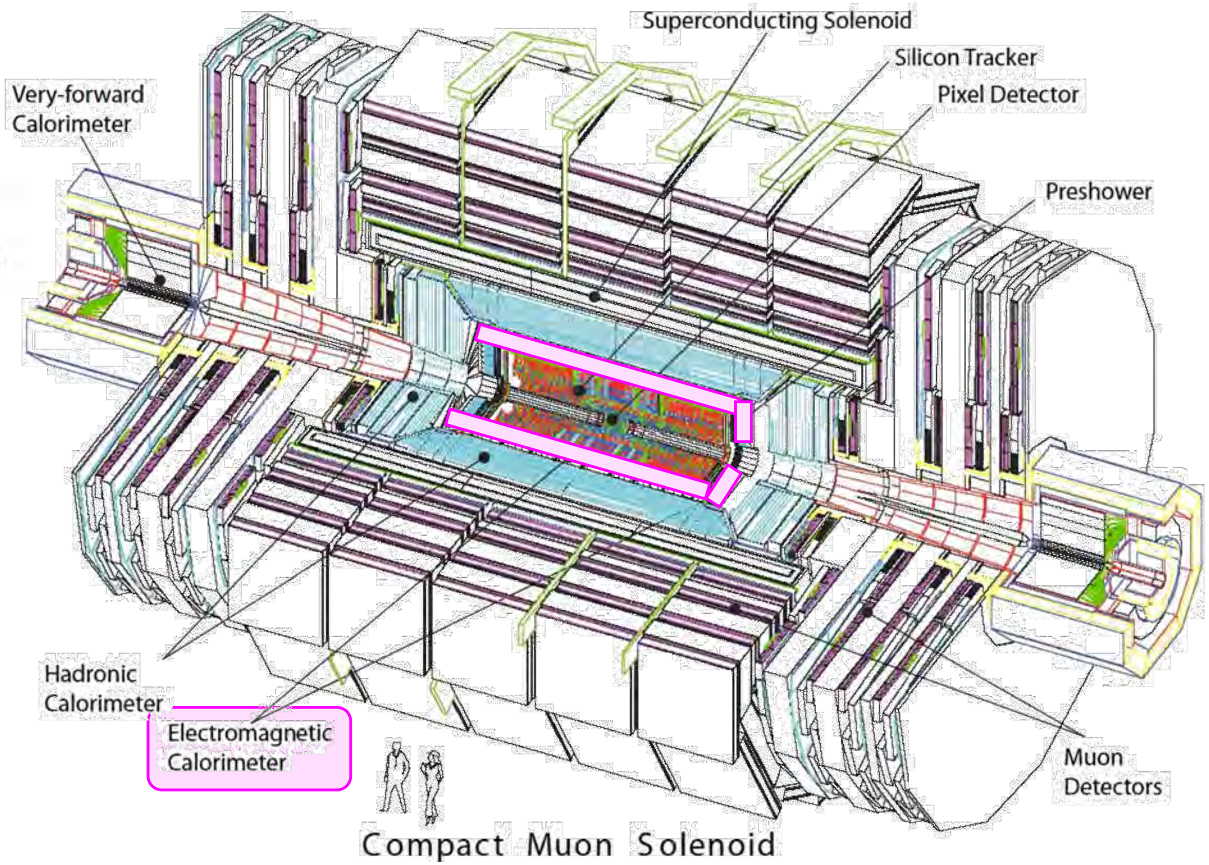
CsI(Tl) x 8,700 crystals, 6cmx6cmx30cm(16Xo)
Basic parameter of CsI (Tl)
density 4.5g/cm3, Xo 1.85cm, R_M 3.8cm,
N_{photon} 110k/MeV (40% of NaI)
λ=565nm
decay time ~1μs

5. Operation of detectors ; Calorimeters

Homogenous Calorimeter

CMS ; PbWO4





$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{3.37\%}{\sqrt{E}}\right)^2 + \left(\frac{0.107}{E}\right)^2 + \left(0.25\%\right)^2$$

PbWO4 x76,000crystals, 22mmx22mmx230mm(25.8Xo)

Basic parameter of PbWO4

density 8.3g/cm3, Xo 0.89cm, RM 2.2cm, N_{photon} 1/100 of NaI

decay time ~10ns

Readout of sampling calorimeter

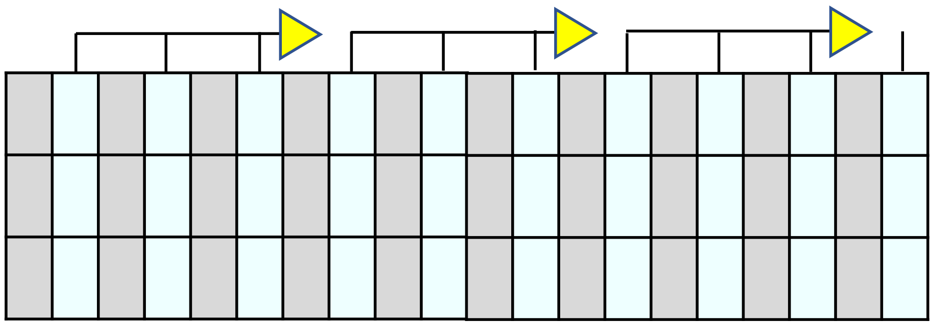
Active media to measure charged particle passage;

By ionization

- gas chamber ; see previous slides
- silicon ; see previous slides
- **noble liquid**

  Use liquid Ar/Xe instead of gas.

  Operation and configuration quite similar to the gas chambers.



By light (photons)

- **plastic scintillator**

Read out of scintillator

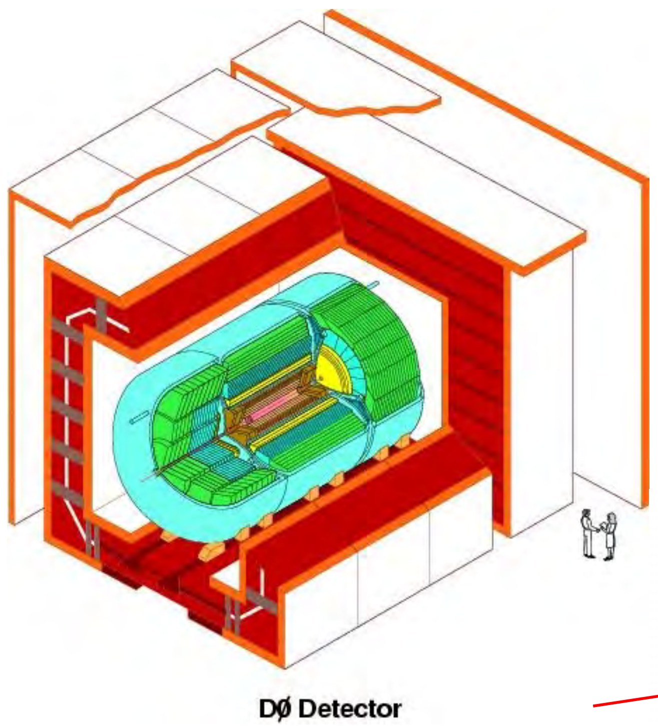
- variety of photon sensor ; PMT, Si, APD, SiPM/MPPC, Hybrids,,
- readout method ; direct-couple, WLS-fiber/plate

Readout of sampling calorimeter

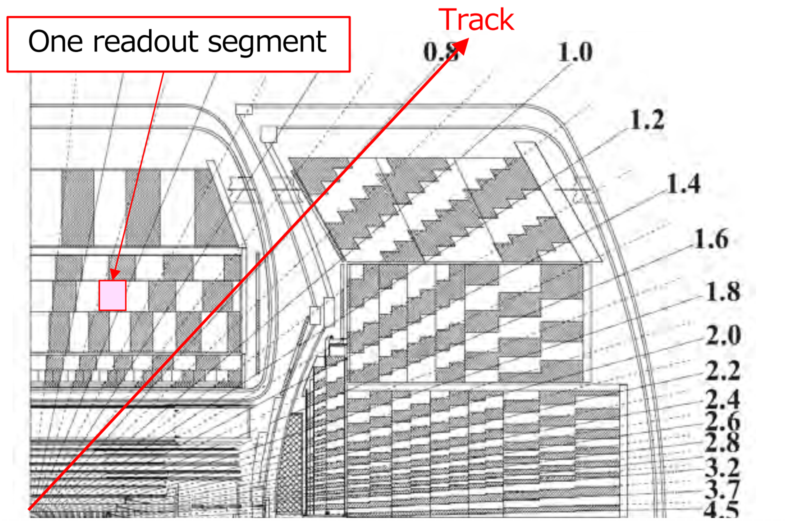
- Noble Liquid ionization

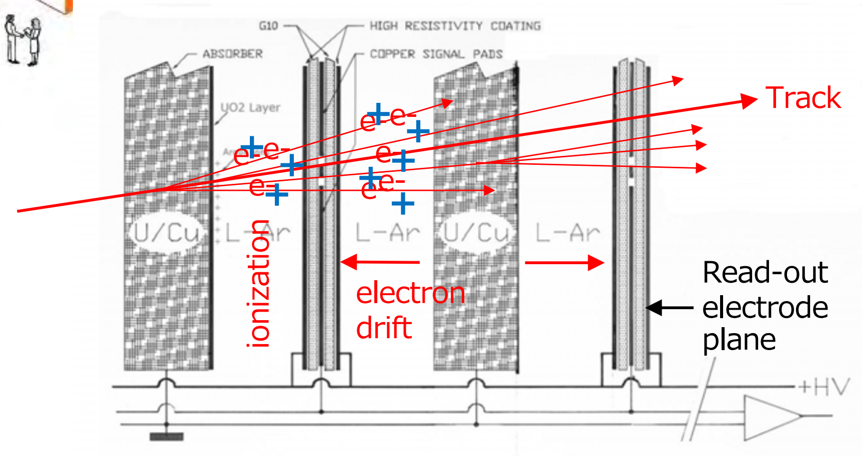
Use liquid Ar/Xe instead of gas.

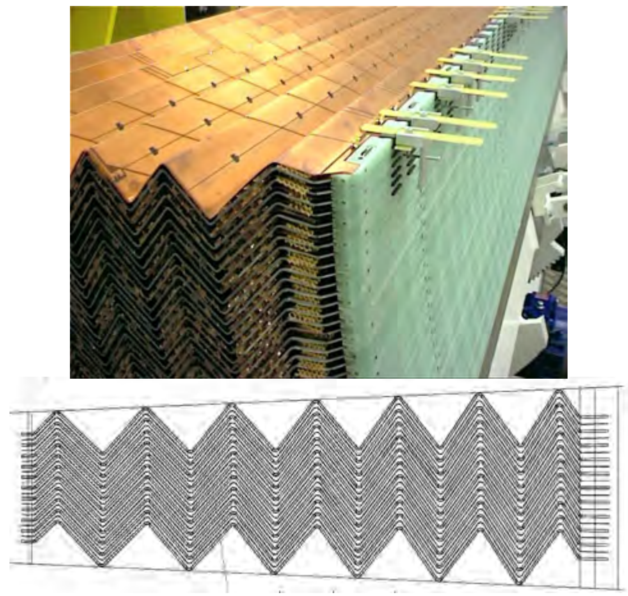
Operation and configuration quite similar to the gas chambers.



D0 detector at Tevatron
Uranium-liq.Ar
sandwich calorimeter



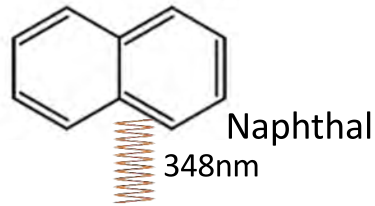


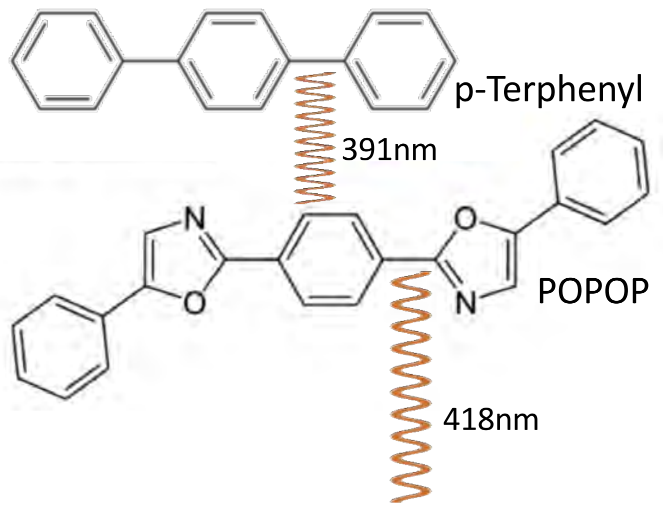


ATLAS liq.Ar EMCAL
Accordion shape absorbers to eliminate inter-segment gaps and to reduce inductance.

Organic Scintillator as active media

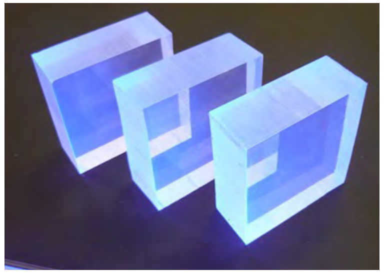
π-bond electrons are excited by charged particles, and emit photons when de-excited.



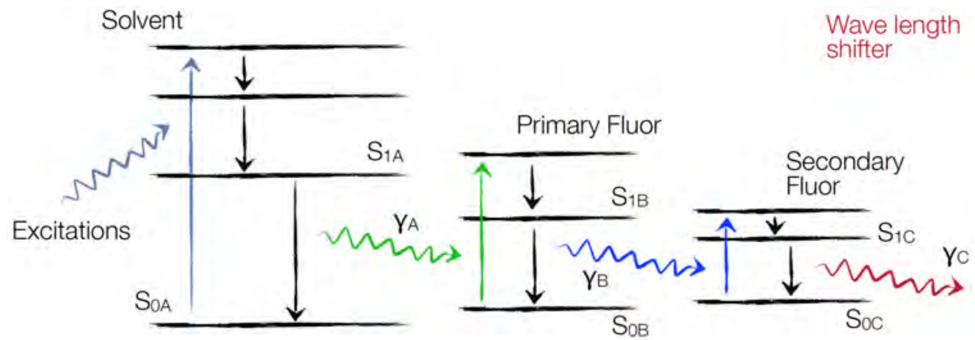


Wavelength or this primary photon is too short for most of photo-sensors.

By cascade absorption and re-emission of photon, make the wavelength longer to match spectral response of photo-sensors.

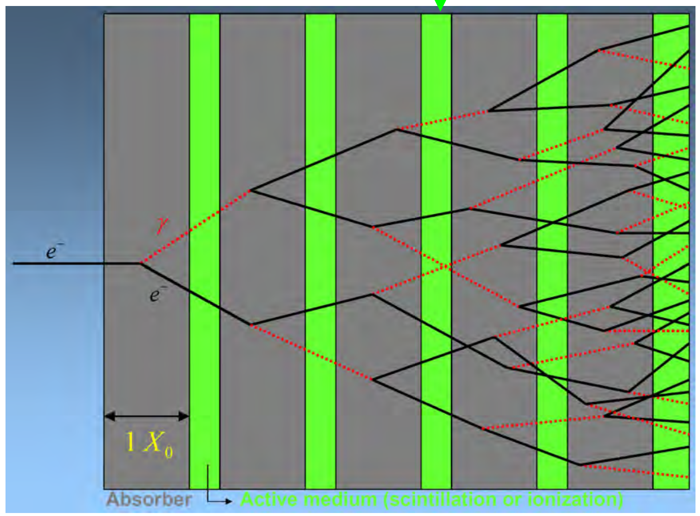


Plastic scintillators generate light when charged particles pass. Amount of light proportional to the energy loss.
Measure the light by photo-sensors.
Popularly used as read-out media.



For NE102
N_{photon}=250k/MeV
λ=424nm
τ=2.5ns

Active plate. Measure energy of passing charged particles.



Scintillator + light-guide + PMT direct readout

The most general (old-fashioned) way to read out scintillator light is to use PMT (photo-multiplier tube) coupled by a light-guide.

Plastic scintillator plate

Light-guide (Fish-tail type) guides photons from the scintillator plate to the PMT photo-cathode.

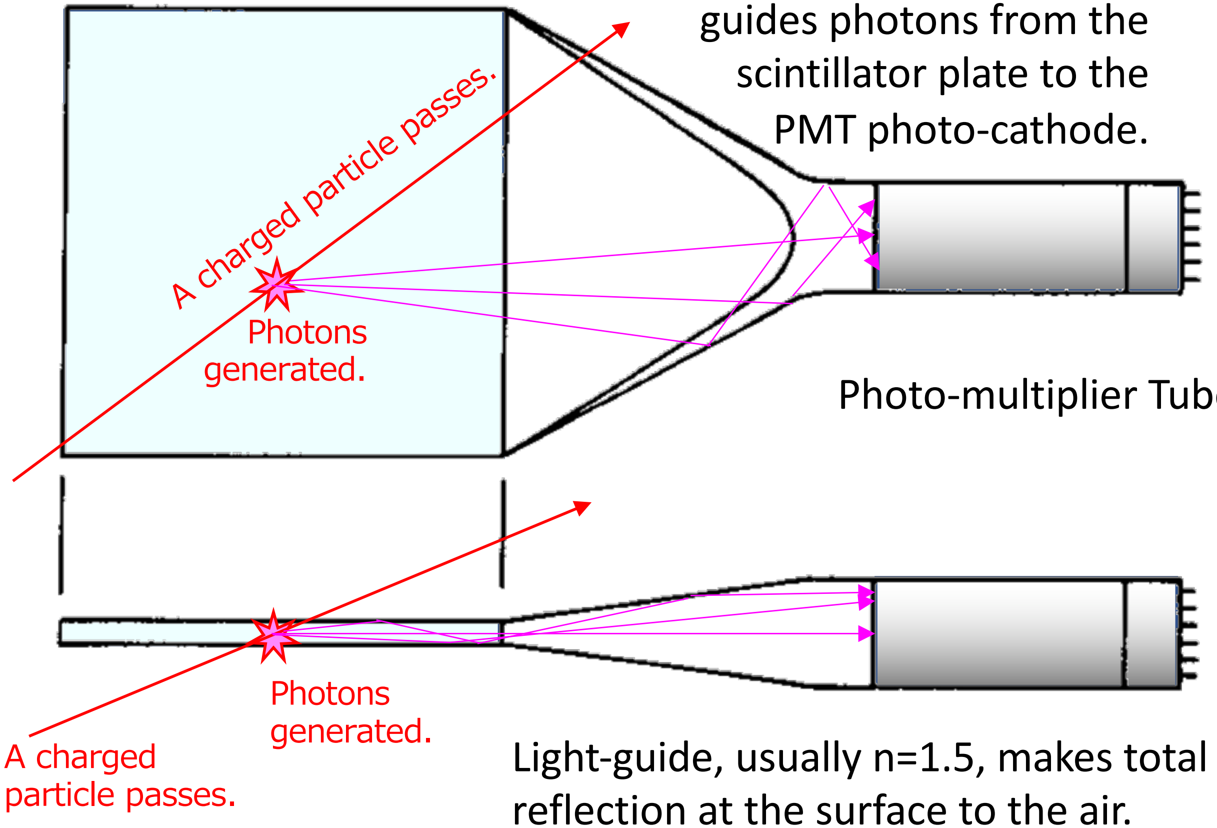
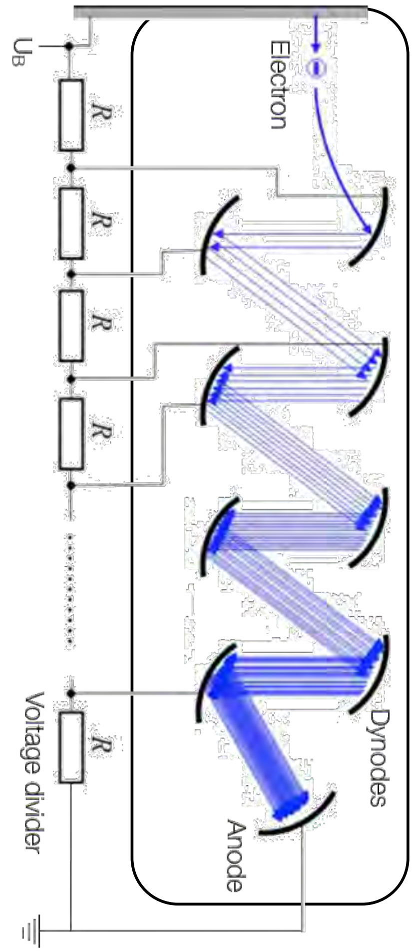


Photo-multiplier Tube

Light-guide, usually n=1.5, makes total reflection at the surface to the air.

Photo-multiplier Tube

Photo-electrons emitted from the photo-cathode are accelerated by HV, hit the dynodes, and make cascade of secondary electrons. Gain of ~10^6 available.

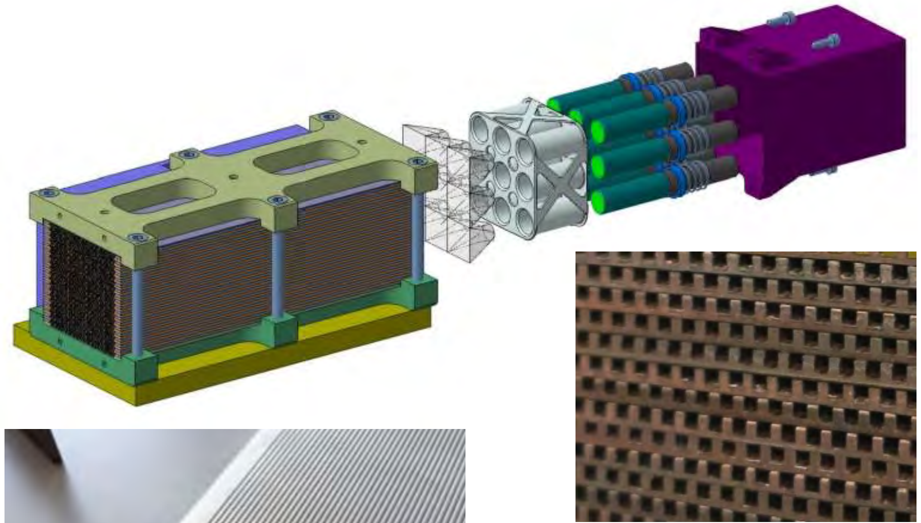


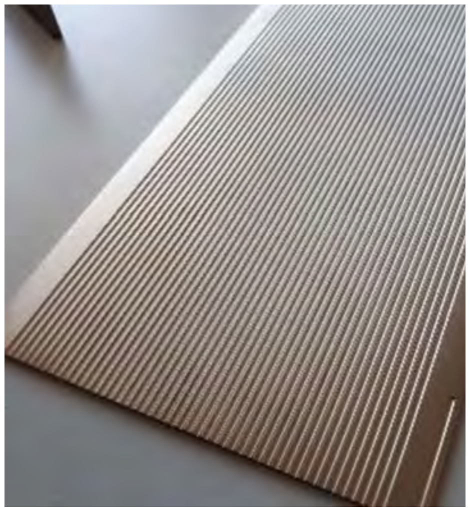
5. Operation of detectors ; Calorimeters

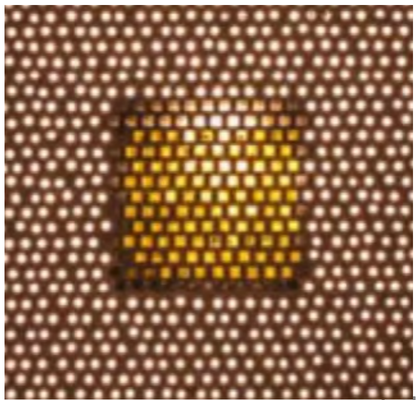
Sintillating-fiber SPACAL

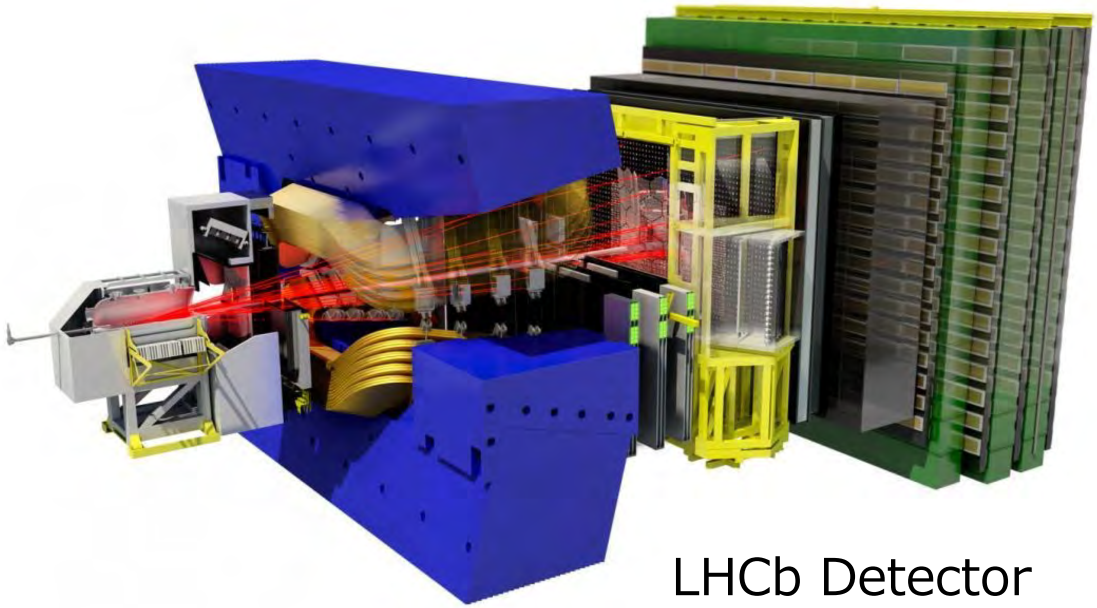
Fibers made of scintillators are embedded into grooves made on the absorber plate.
Back-end of the scintillation fibers are directly coupled to the photo-sensors.

- Good transverse segmentation
- Longitudinal segmentation not easy.







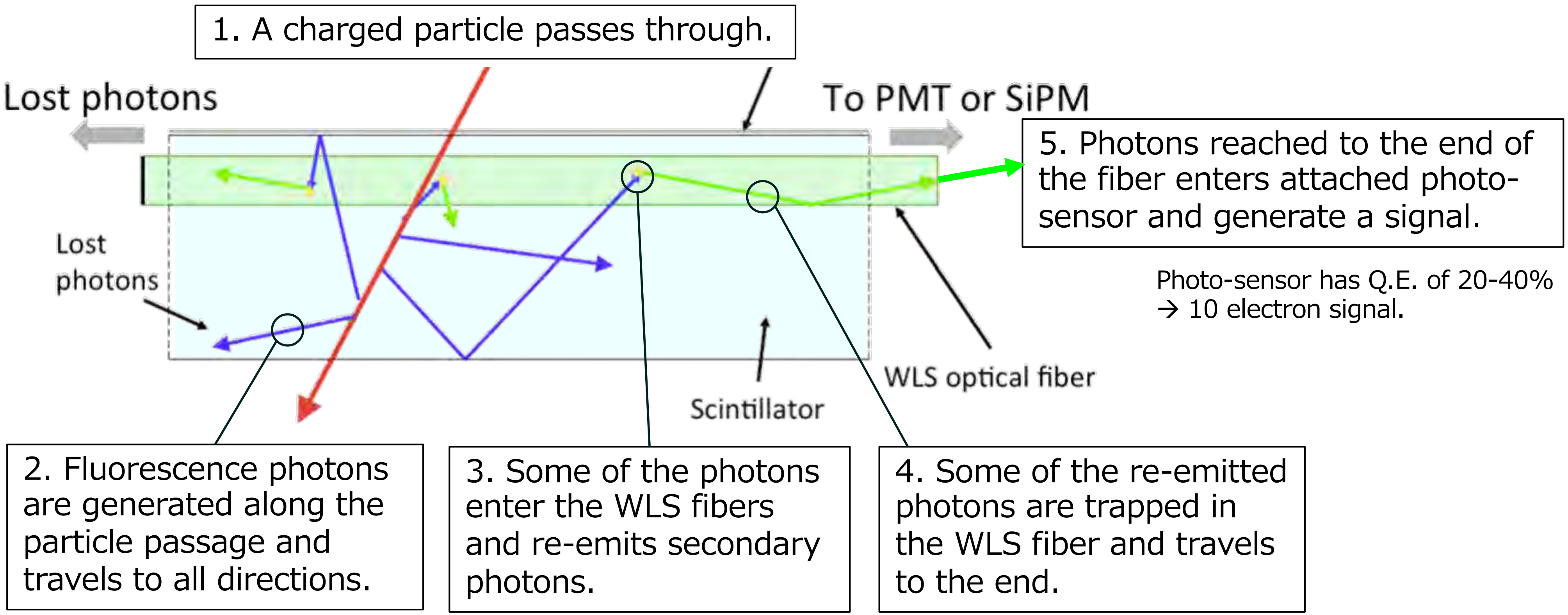


LHCb Detector

Figures taken from A.Schopper,
The LHCb ECAL upgrade(s) and ongoing R&D

WLS fiber/plate readout

Light collection from the scintillator and transfer to photo-sensors by wave-length-shifting fibers/plates has become common.



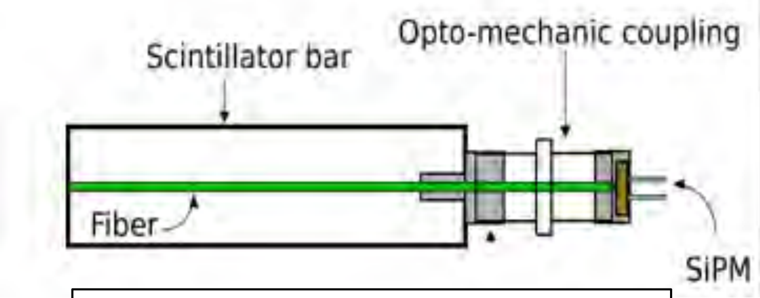
For 1cm-thick plastic scintillator, Nphoton~20,000

Depends on geometry, but typically a few % → 400 photons

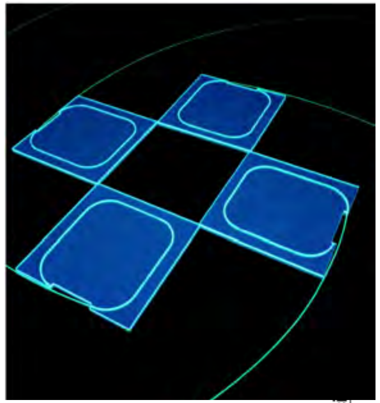
Typical double-clad WLS traps 5% → 20 photons,

WLS fiber/plate readout

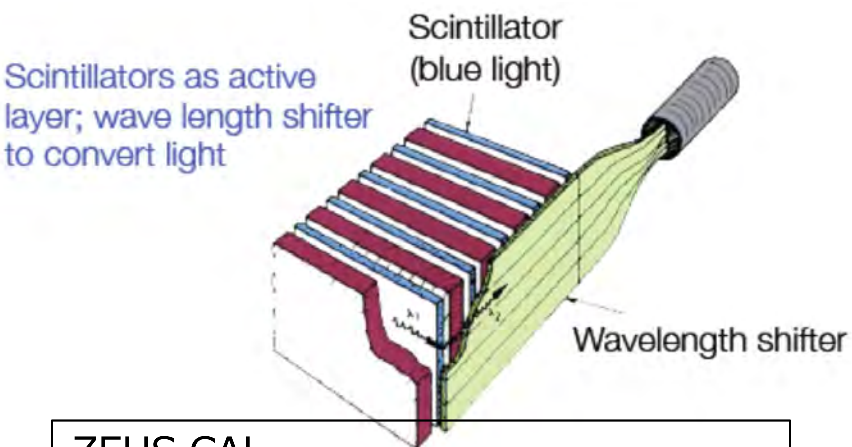
There are many of ways to couple scintillator plates and WLS fibers/plates



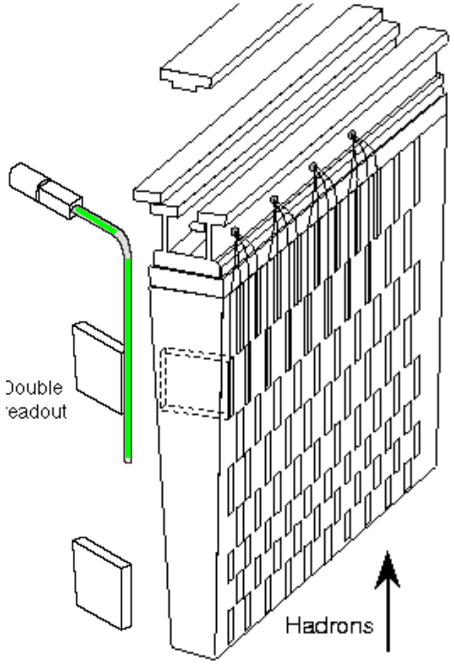
General scheme
A fiber in a scintillator bar.



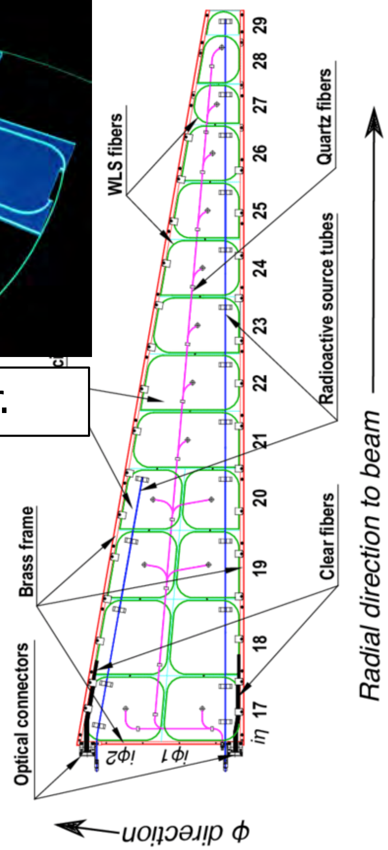
CMS tile-fiber.



ZEUS CAL
WLS-plates put both sides of tiles.



ATLAS HCAL
WLS-fiber put side of tiles.

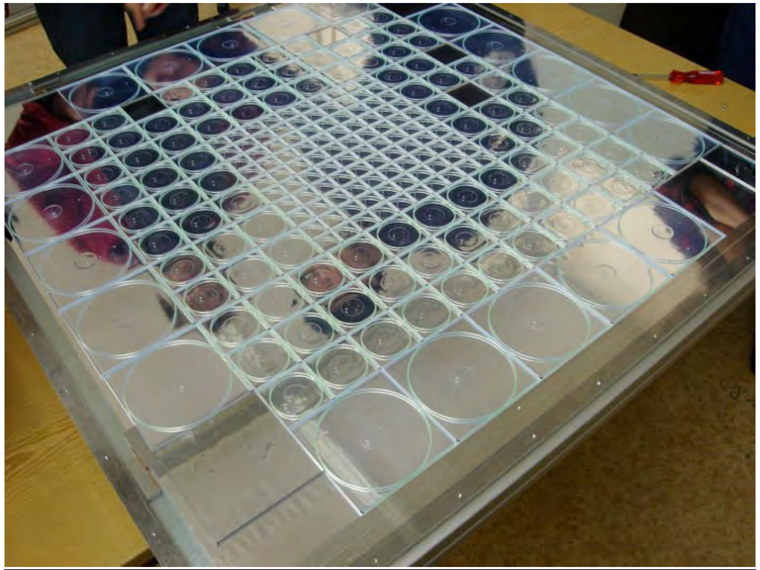


CDF mega-tile
WLS-fiber put in a groove.

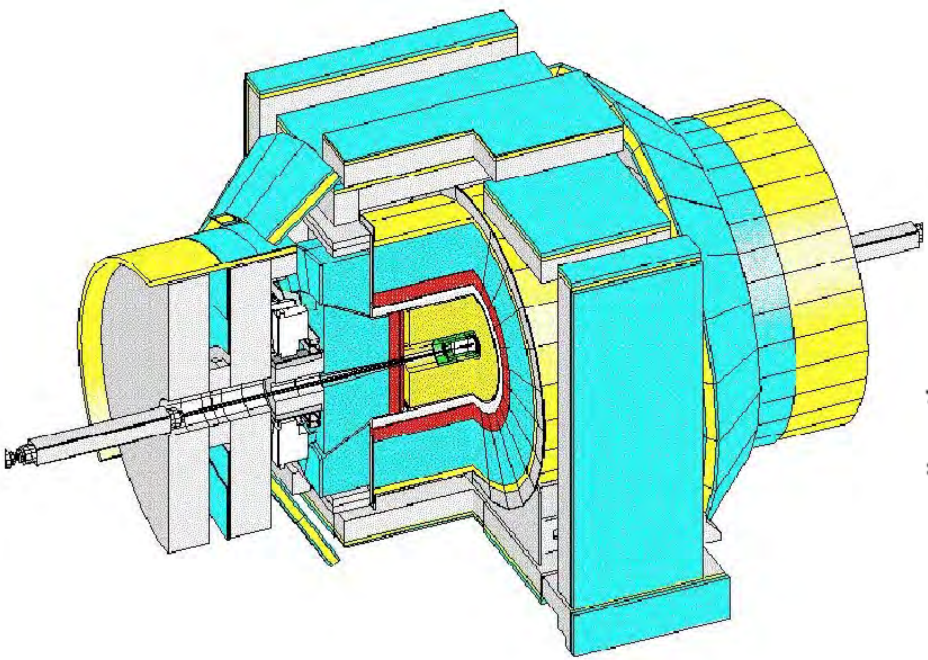
5. Operation of detectors ; Calorimeters

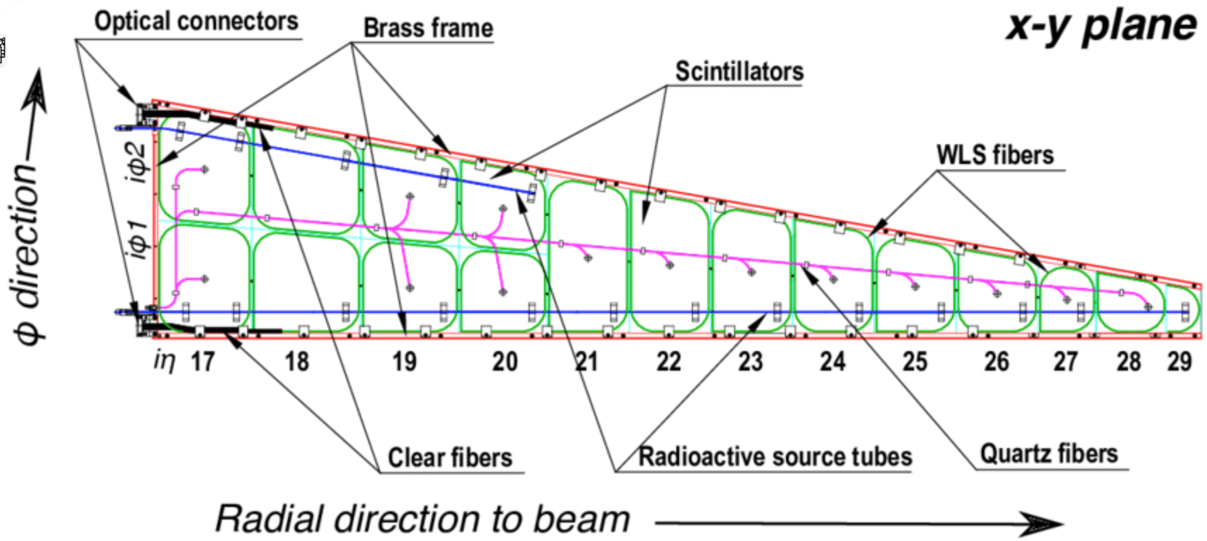
Plastic Scintillator + WLS fiber sandwich

CDF/CMS calorimeter design: Tile-fiber
- A WLS fiber is put in a circular groove machined in a tile.
- Many tiles machined at once using large scintillator plate.
- WLS fibers are routed through
  another overlayed plate with grooves.



ILD mega-tile with varying tile size.

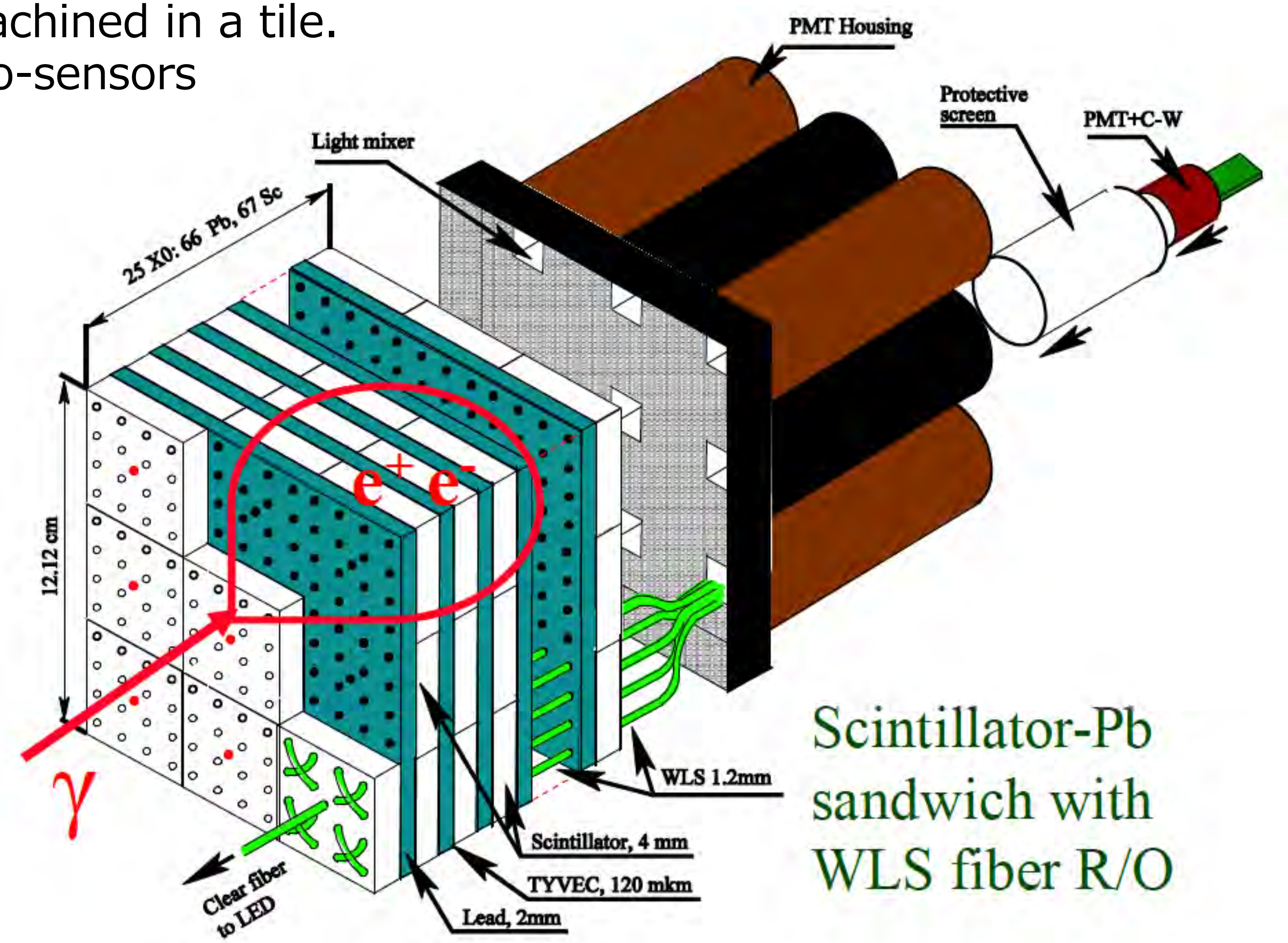




Basic parameter ; density, Rshower, Nphoton,
Characteristic of generated photon (time)

Plastic Scintillator + WLS fiber shashlik

LHCb shashlik design
- A WLS fibers run through holes machined in a tile.
- WLS fibers naturally reach to photo-sensors



Scintillator-Pb sandwich with WLS fiber R/O

Hadron Calorimeter

Structure similar to EMcal.
Larger sizes since hadron shower is larger.

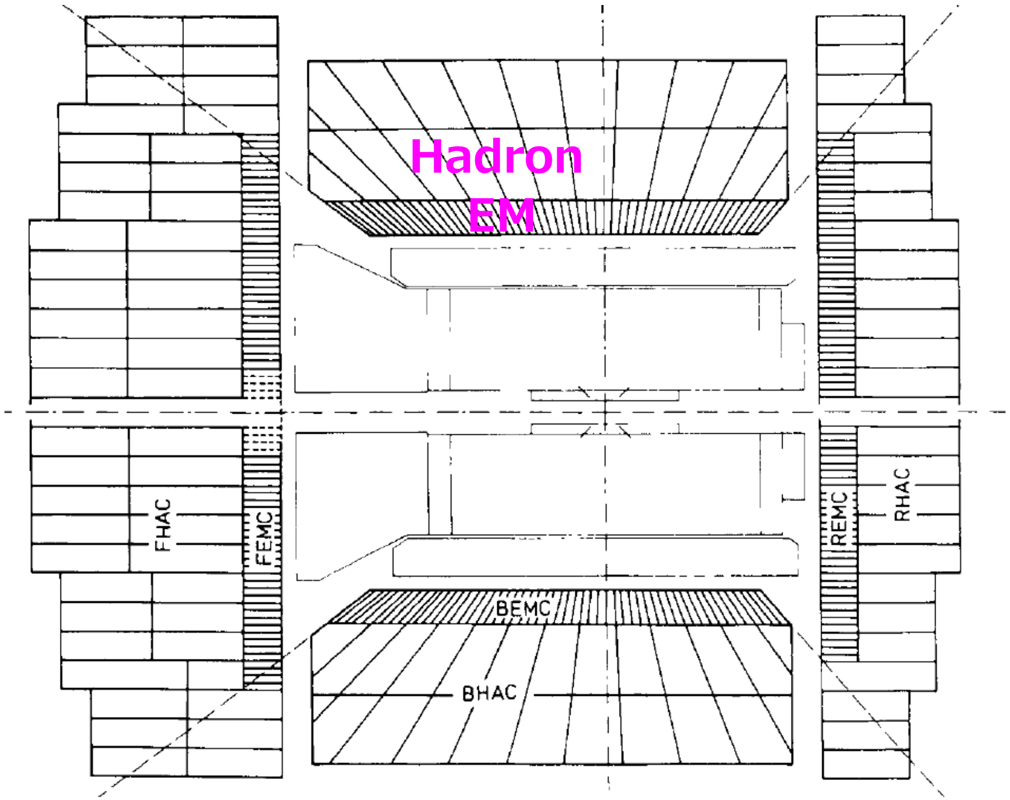
- Homogeneous ; none so far.
- Sampling
  - Active Layer ; Scintillator, Noble Liquid,,,
  - Absorber layer ; Lead, Iron, Uranium, Copper,,,
- Segmentation

	Density [g/cm3]	Radiation Length X_0	Interaction Length λ_I
Iron	7.87	18mm	16.8cm
Lead	11.4	5.6mm	17.6cm
Tungsten	19.3	3.5mm	9.9cm
U	19.0	3.2mm	11.0cm

Strategical Choice

- Tracking calorimeter ;
  Energy calculation by counting tracks in shower
- Nuclear reaction invisible energy recovery ;
  Compensation with Uranium/Lead

ZEUS calorimeter layout



ZEUS "compensated" hadron calorimeter with
3.2mm-U + 3.0mm-plastic scintillator
gives $15\%/\sqrt{E} \oplus 2\%$ for e
and $35\%/\sqrt{E} \oplus 2\%$ for hadron.

Hadron Calorimeter

Strategical Choice : Tracking calorimeter (digital calorimeter)

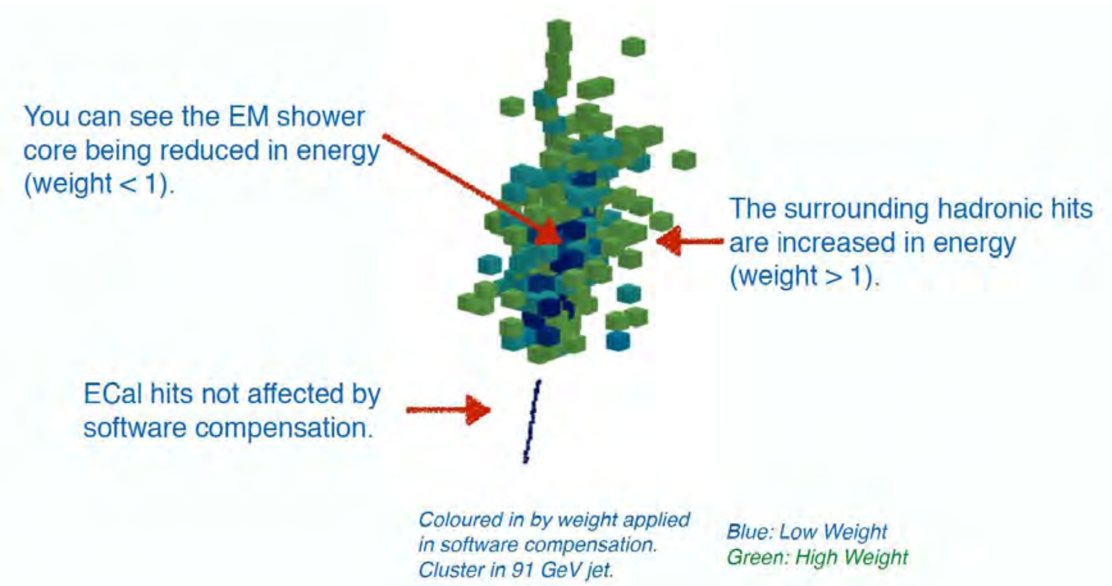
Energy calculation by counting track length (number of hits) in a shower.

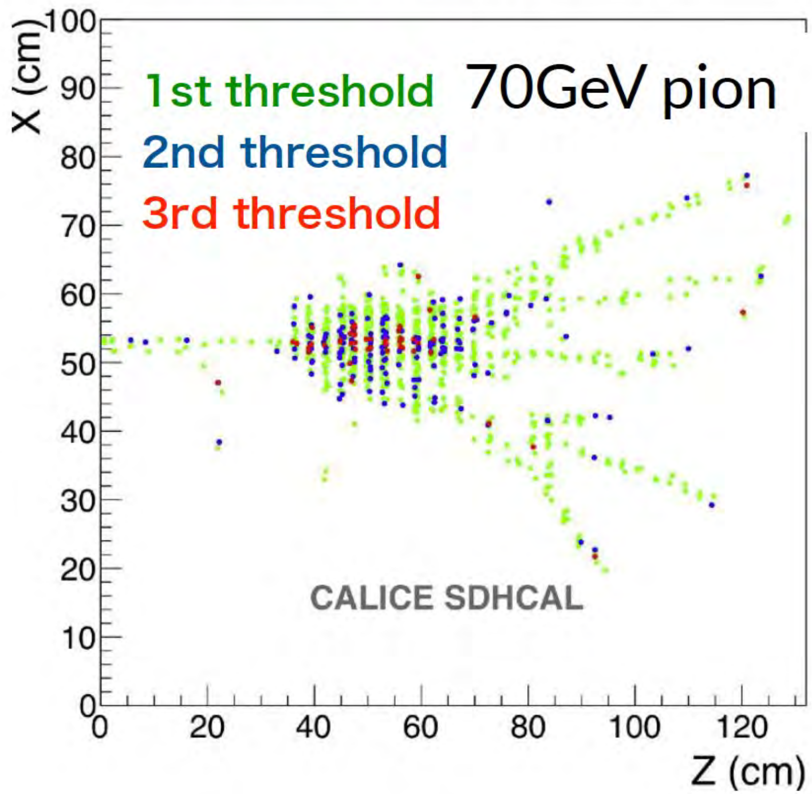
→ No energy measurement but hit on/off information only.

→ Digital HCAL (CALICE)

1.3m^3-prototype, 48 layers of RPC, 1cmx1cm pad 0.5Mch-readout being tested.

Super-high granularity also enables "software compensation".

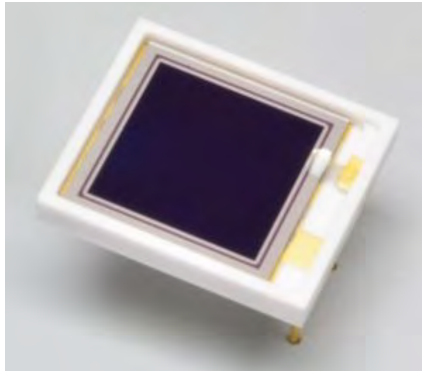


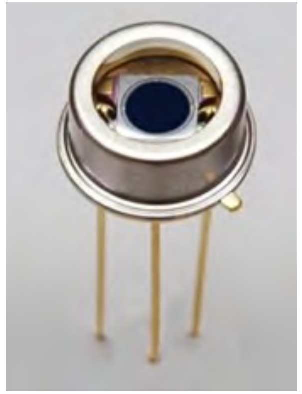


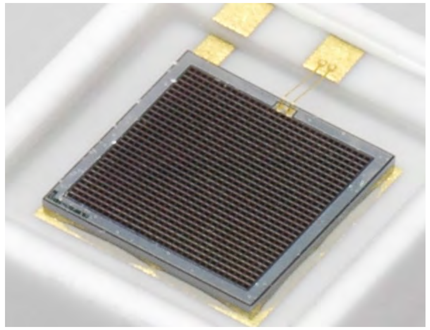
5. Operation of detectors ; Photon Sensors

Various photon sensors are used to read out scintillation light, either directly or with WLS fibers/plates.

- PMT, FM-PMT, MCP
- Si, APD
- HAPD
- SiPM/MPPC





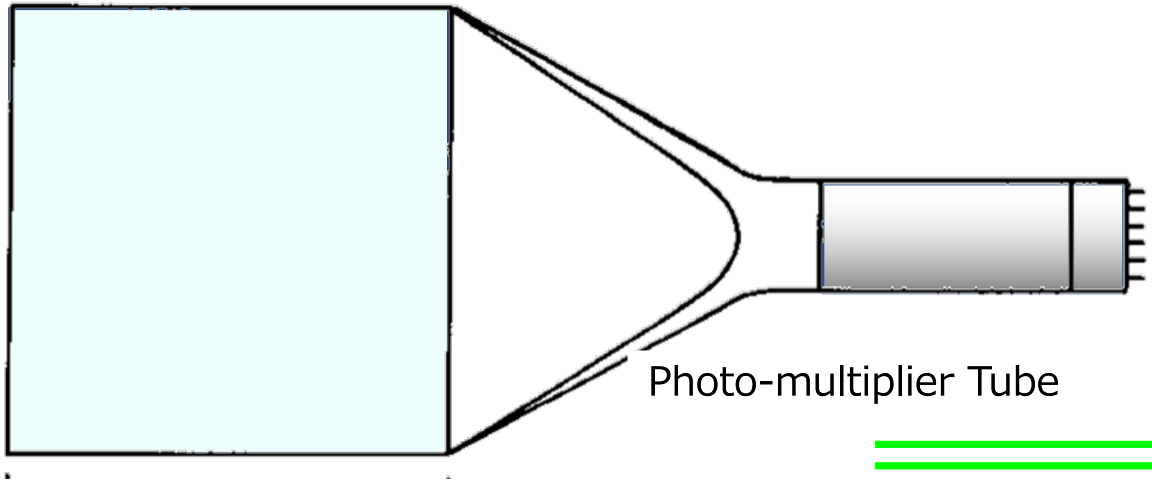


Choices are driven by
- gain, noise, dynamic range
  single-photon sensitivity,
- photo-sensitive area and spectral response
- tolerance for magnetic field
- operation volatge
- cost

and so on.

Structure, operation principle and characteristics of Various Photon sensors

PMT, FM-PMT, MCP



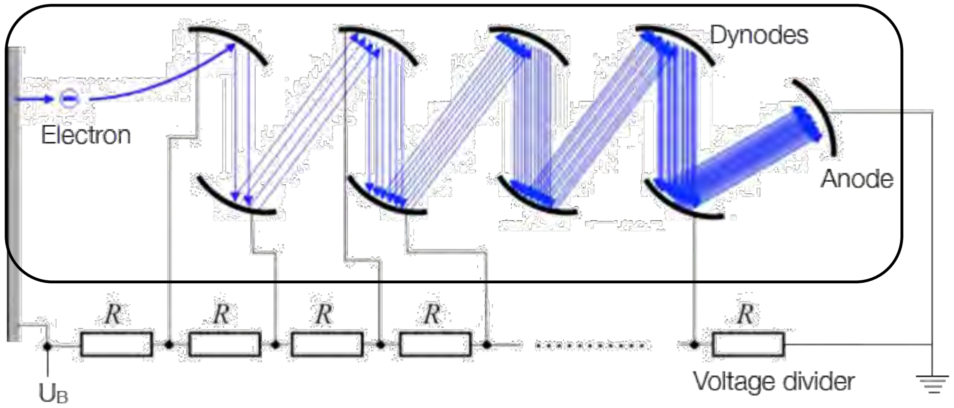
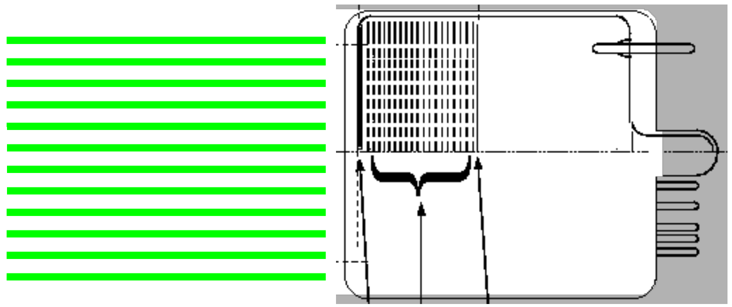


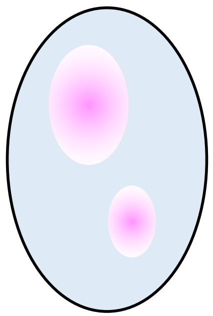
Photo-multiplier Tube

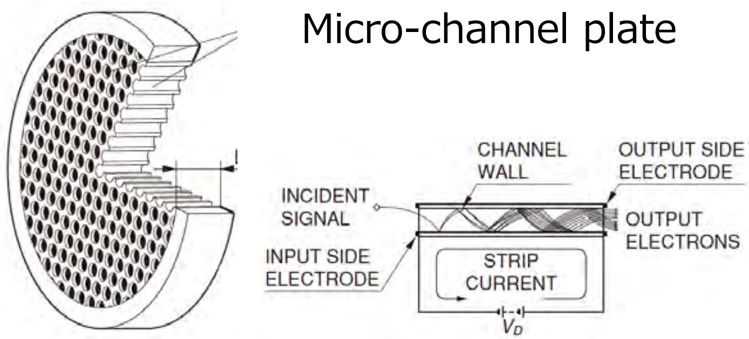
Fiber-bundle readout



Fine-mesh PMT
Operational in B~1T
Multi-anode available
→ position measurement

Imaging

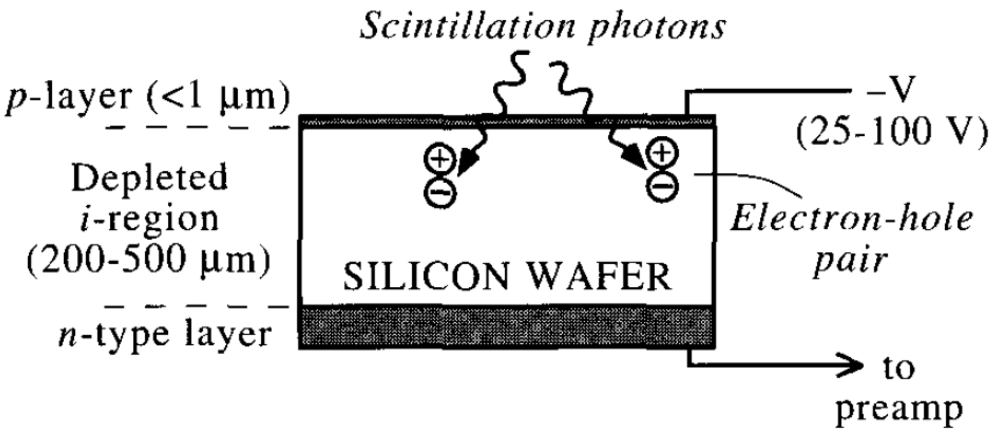




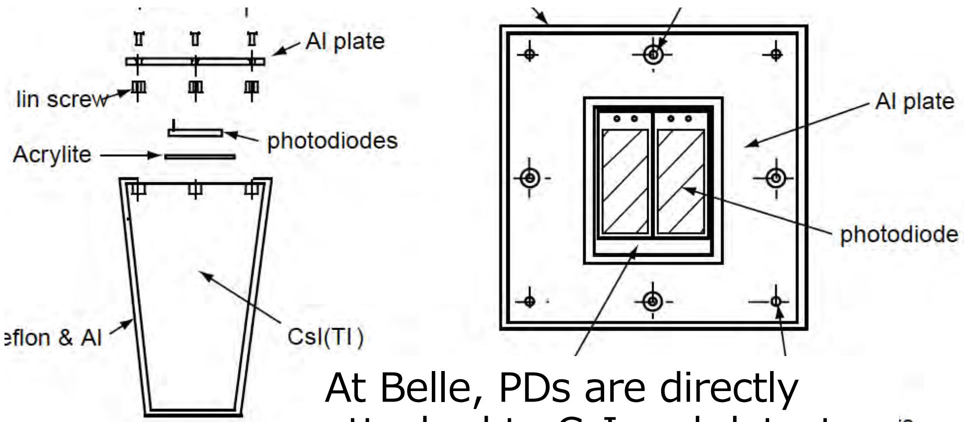
Micro-channel plate

Structure, operation principle and characteristics of Various Photon sensors

PIN silicon photodiode

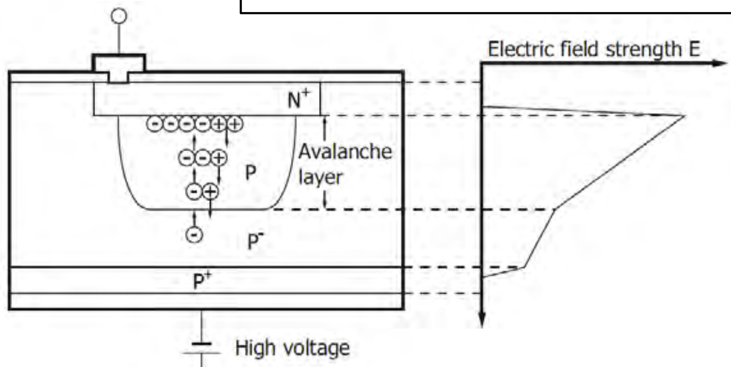


The same structure as Si for tracking.
Photons generate electron-hole pairs.



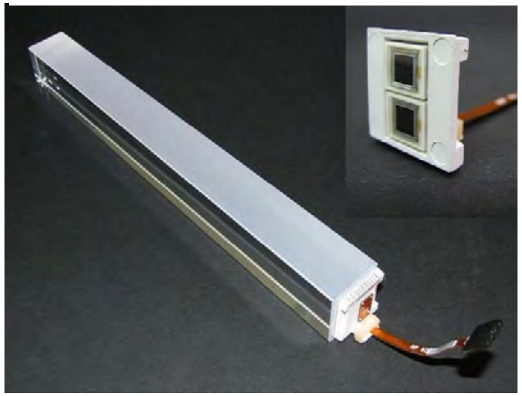
At Belle, PDs are directly attached to CsI and detect photons.

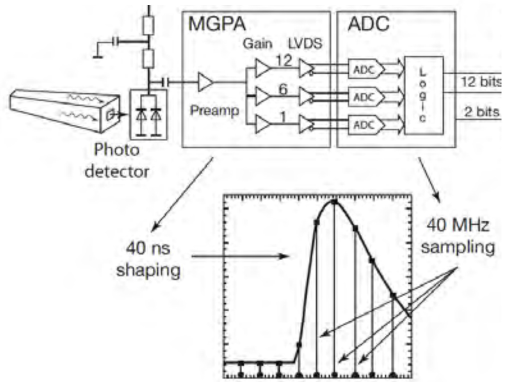
Avalanche Photodiode



As PIN-Si, photons generate e-h pairs. Drifted electrons are accelerated by strong electric field of avalanche region, and e-h cascade occurs.

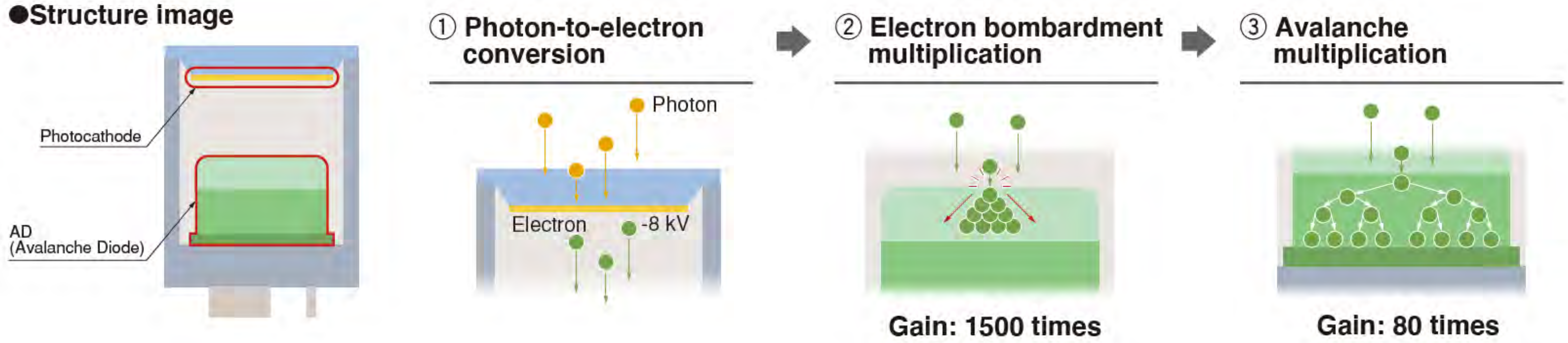
At CMS, APDs are directly attached to $PbWO_4$.
Signal is amplified and digitized by FADC.

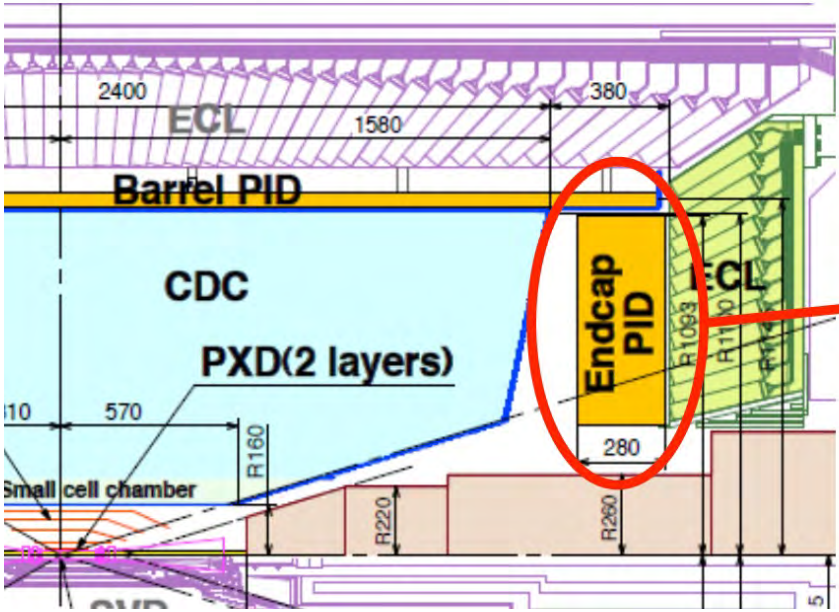


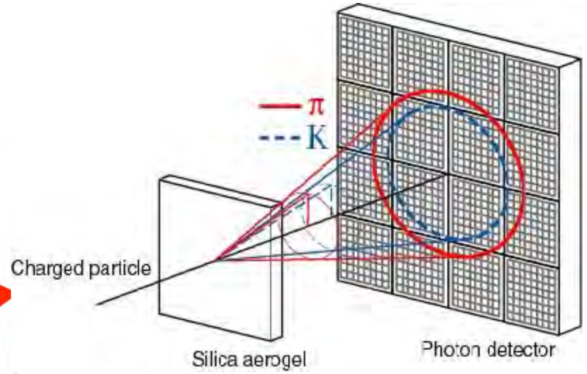


Structure, operation principle and characteristics of Various Photon sensors

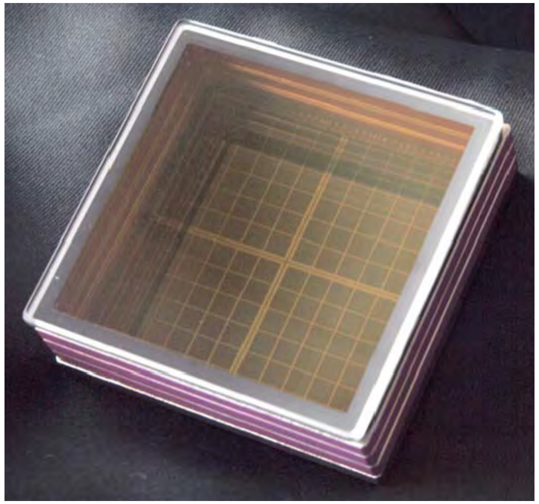
HAPD





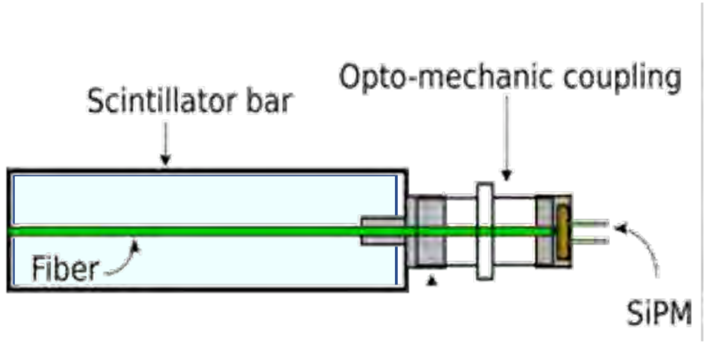


Belle-II ARICH HAPD
5mmx5mm pixel,
144 pixel/module,
gain =1400x40

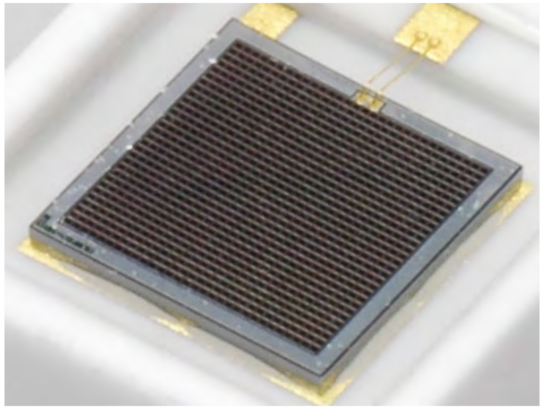


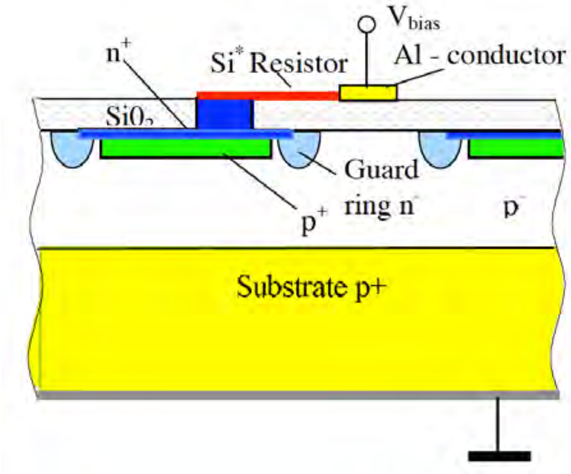
Structure, operation principle and characteristics of Various Photon sensors

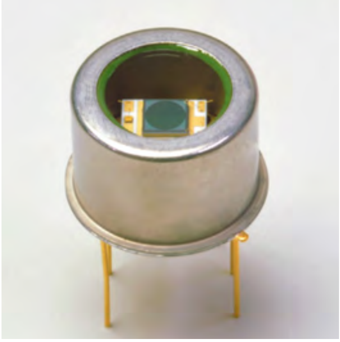
SiPM/MPPC

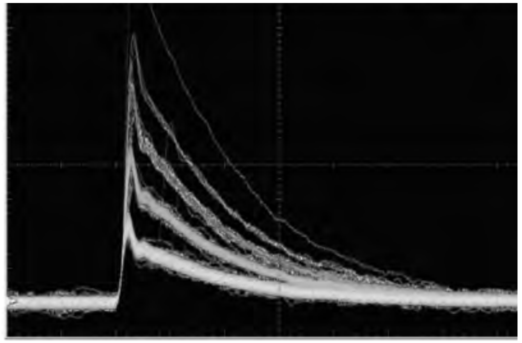


Best to couple with WLS fibers.









S14422
- 1.5mmϕ photo-sensitive area
- □25μm x 2876pixels,
- V_{BR}=40.5V
- Gain>10^5

One sensor has thousands of pixels.
Each pixel acts as Geiger-mode photon detector.
If photon hits the pixel, it generates discharge signal.
→ Each pixel gives just on/off signal.
→ Number of photons entered to the sensor is number of fired pixels, if number of photons are not too many.

Single-photon sensitivity.
Fast rise time, slightly slow fall time due to quenching.
Operational in strong magnetic field.
Pixel-size/number of pixel be carefully chosen.

Particle Identification

Identify species of charged particle (e,μ,π,p,K,,, especially π/K separation)

PID purpose strongly depends on the physics target
→ design/technology different experiment by experiment

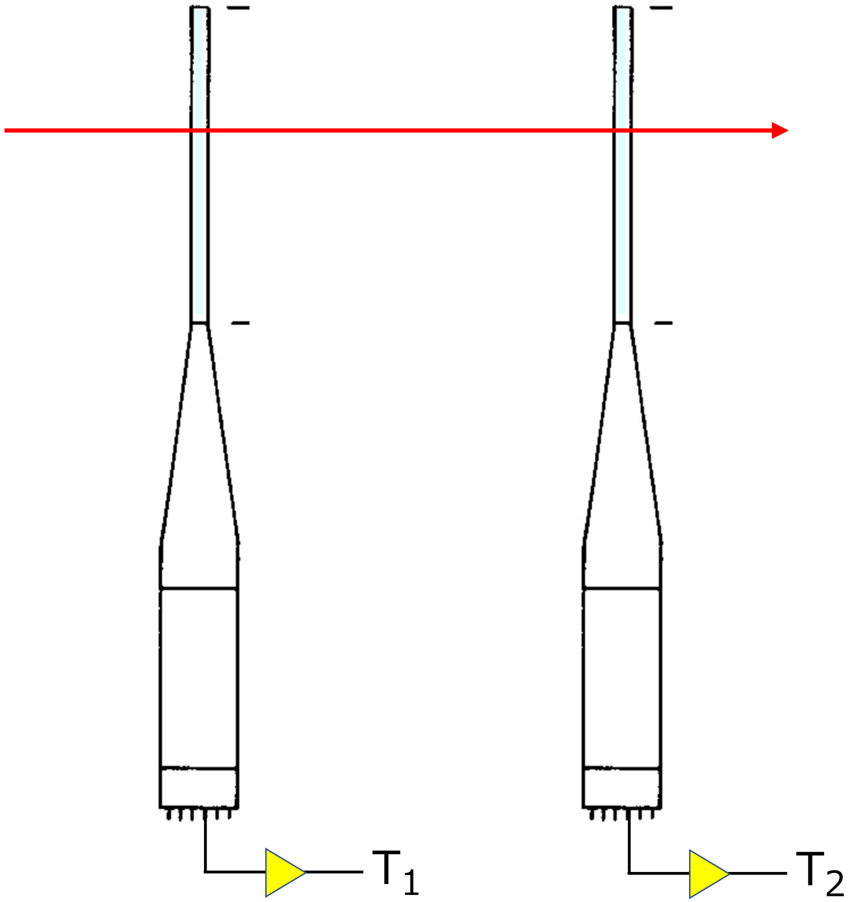
- Very important for flavour physics
- not simple nor straight ;
  Need to identify mass, but direct calculation of mass is difficult.
  → Measure velocity (β , γ) of the particle and separate them.

Combination of various observables

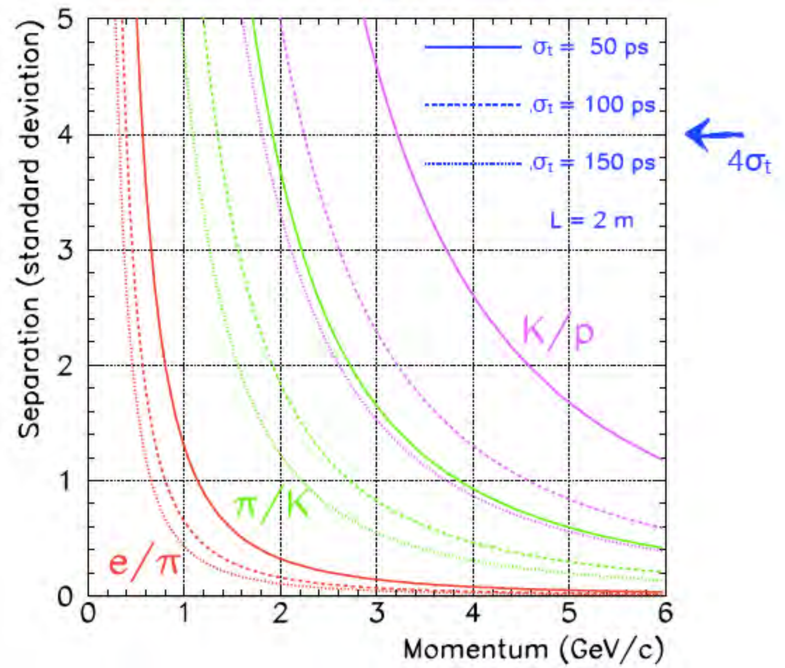
- ToF
- dE/dx
- Cherenkov Light ; many types of Cherenkov detectors
- Transition Radiation
- and so on ...

Particle ID --> Basically measure velocity (β , γ) of the particle

ToF (Time-of-Flight) ; the most straight-forward way



ToF = Arrival time difference $\Delta T = T_2 - T_1 = L/c\beta$



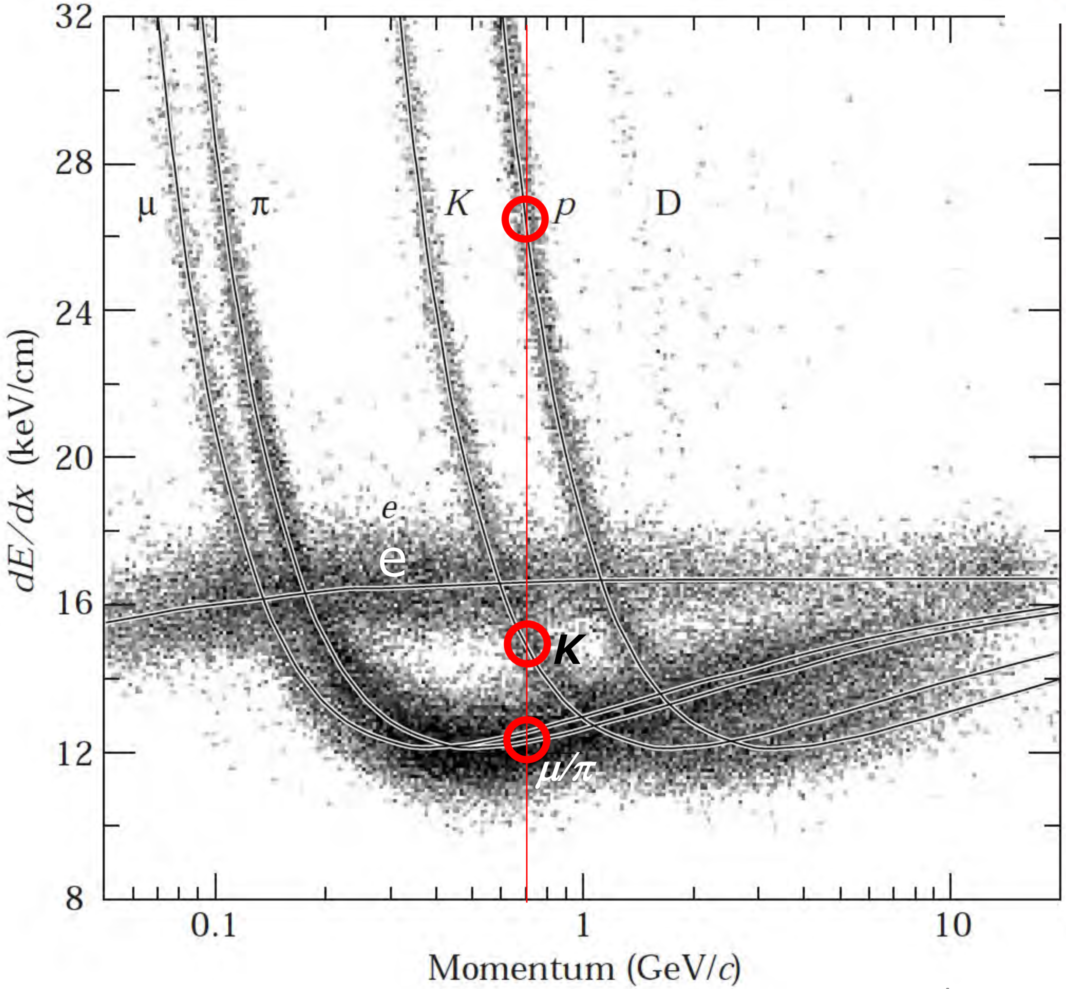
5. Operation of detectors ; Particle Identification

Particle ID --> Basically measure velocity (β , γ) of the particle

dE/dx

Energy loss is function of velocity

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



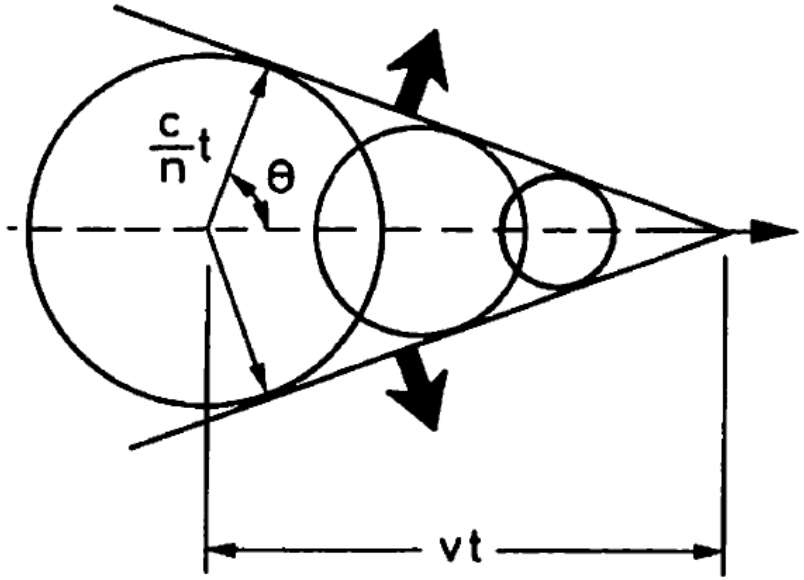
At high energy, β saturates and dE/dx has small differences → not very useful.

Below ~800MeV/c,
π/*K* can be separated but μ/π can not be.
Truncated mean of many dE/dx measurement improves the separation.
→ Useful at low-energy fixed-target experiment.

Particle ID --> Basically measure velocity (β , γ) of the particle

Cherenkov Light

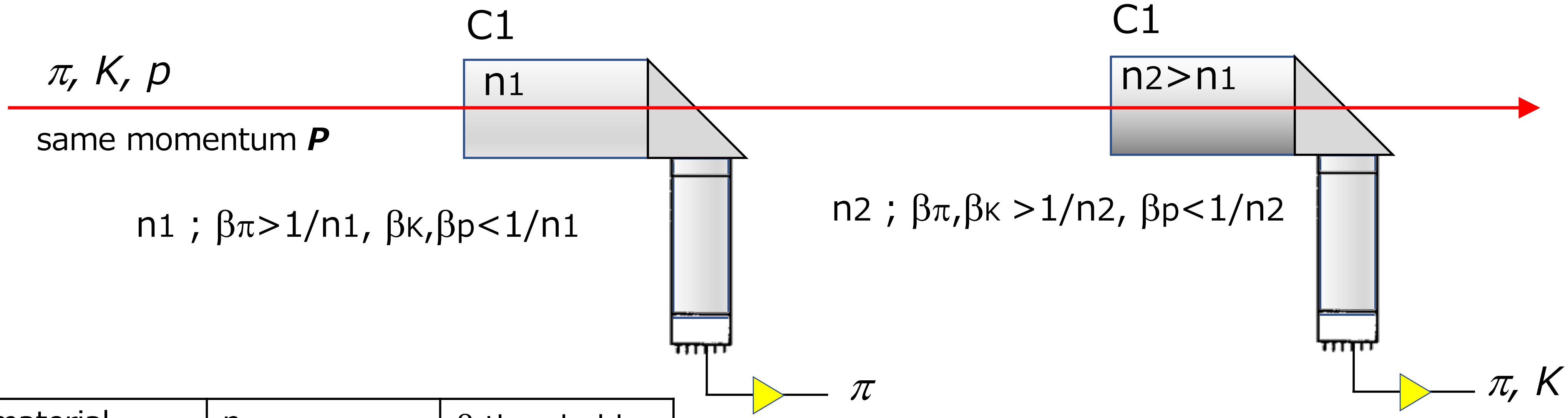
Cherenkov generation condition ; β>1/n
Radiation angle θ ; cos θ =1/nβ.
→ have sensitivity to β.
- Threshold type
  Detect Cherenkov photon emission for several n, and narrow-down the β range and particle species.
- Cone angle θ measurement tyle
  measure the ring image of the Cherenkov light, measure β, and pin-down the particle species.



Cherenkov Light ;

Threshold type

Detect Cherenkov emission for several n, and narrow-down the β range and particle species.



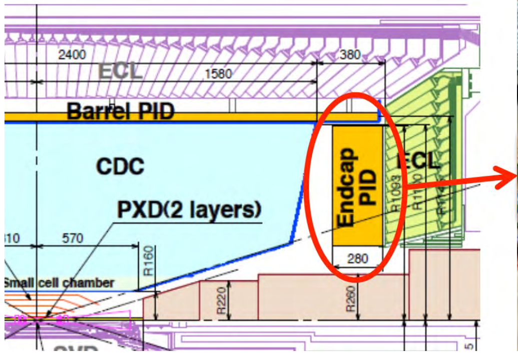
material	n	β threshold
He	1.000 034 9	0.99997
N2	1.000 298	0.9997
Pentane	1.0017	0.9983
Aerogel	1.007-1.13	0.993-0.884
Water	1.33	0.75
Polystyrene	1.60	0.63

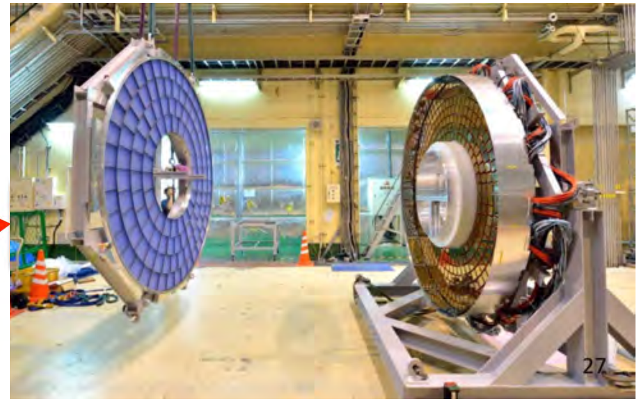
data taken from Grupen.

According to the momentum of the particles to measure, choose appropriate radiator, and narrow-down the β range and particle species.

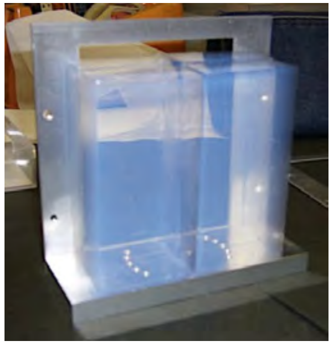
Cherenkov Light

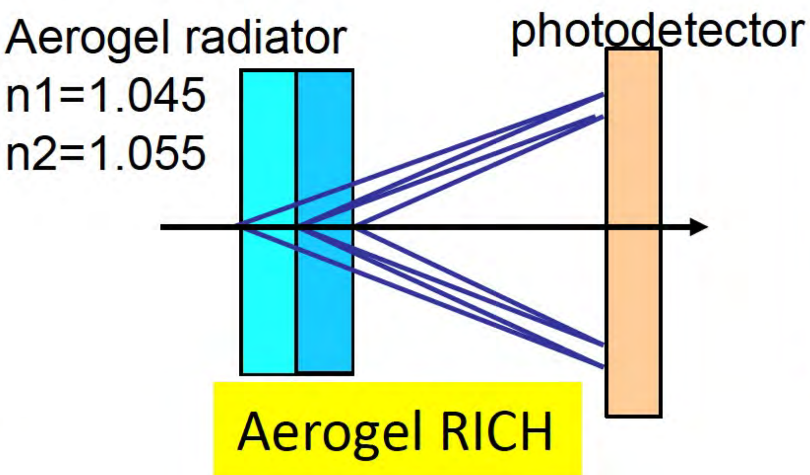
Cone angle θ measurement type
measure the ring image of
the Cherenkov light, measure β,
and pin-down the particle species.

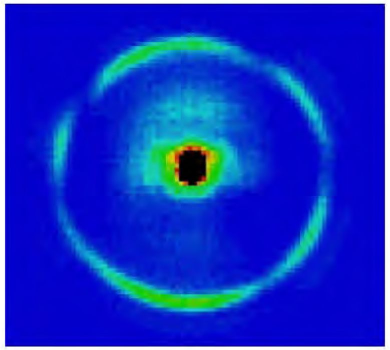


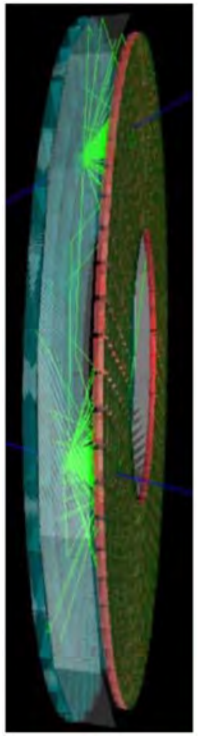


Belle-II Aerogel Ring-Image Cherenkov Counter









π/K separation by θ measurement
"focus" the image by double-radiator configuration.

Cherenkov Light

Cone angle θ measurement type

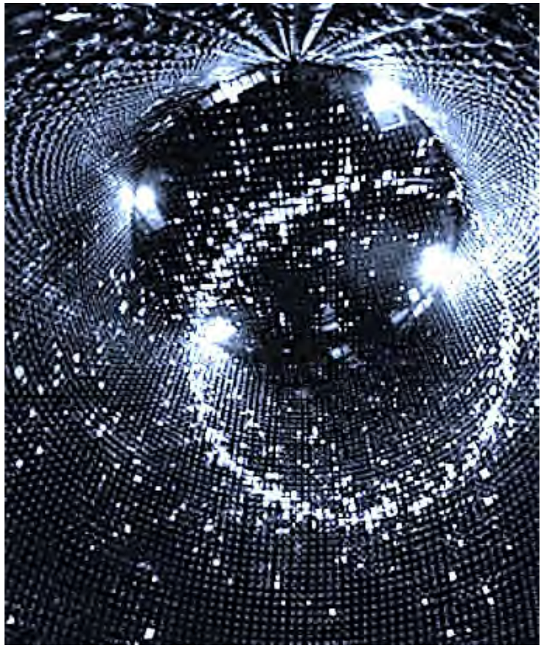
measure the ring image of the Cherenkov light, measure β, and pin-down the particle species.

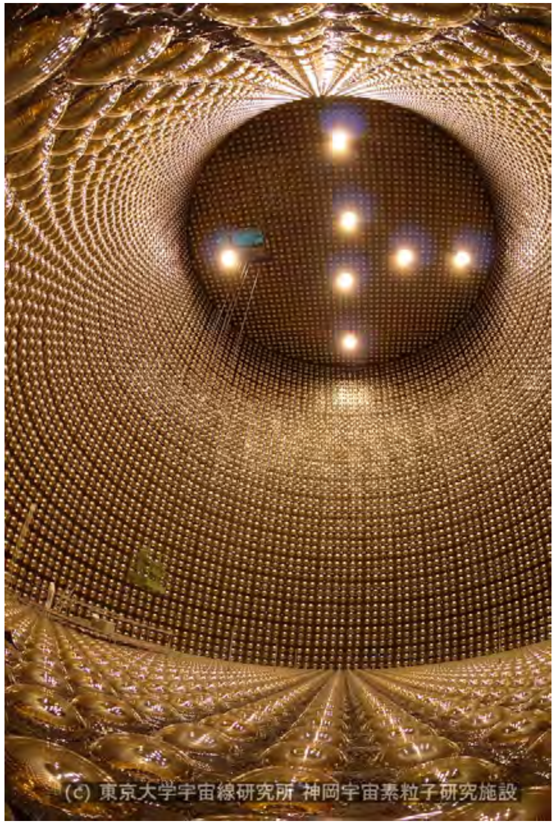
Super-Kamiokande Water Cherenkov Counter

e,μ identification with θ and ring image analysis.

Timing of PMTs → vertex position
Distance and ring radius → emission angle θ
θ and ring image → e,μ identification
Ring charge → particle β obtained.

Actual analysis is multi-parameter maximum-likelihood method with all information.





Transition Radiation Detector

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

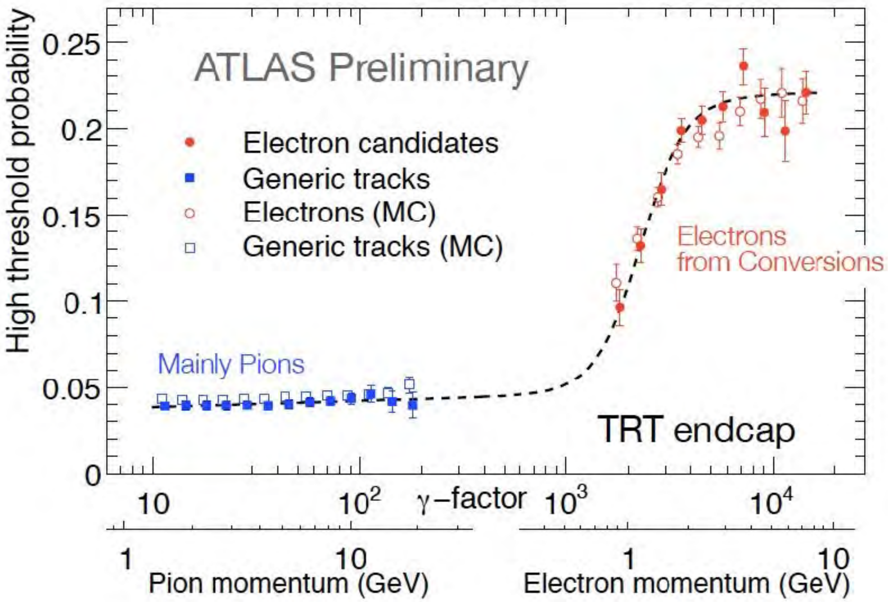
Emitted $N_{photon} \sim \alpha z^2$
~0.01 for electron

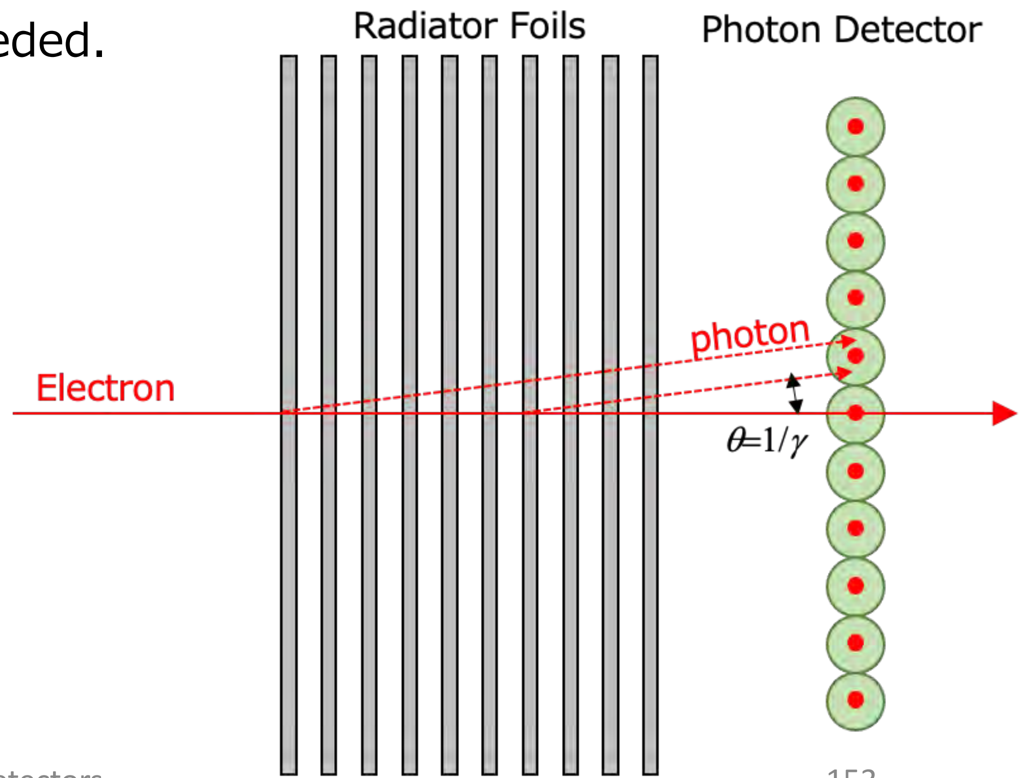
Emitted energy *S*

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

Transition radiation from single boundary is weak.
→ Use multi-layer configuration for actual detector.

To get significant energy emitted, γ >1000 is needed.
→ mainly to identify electrons

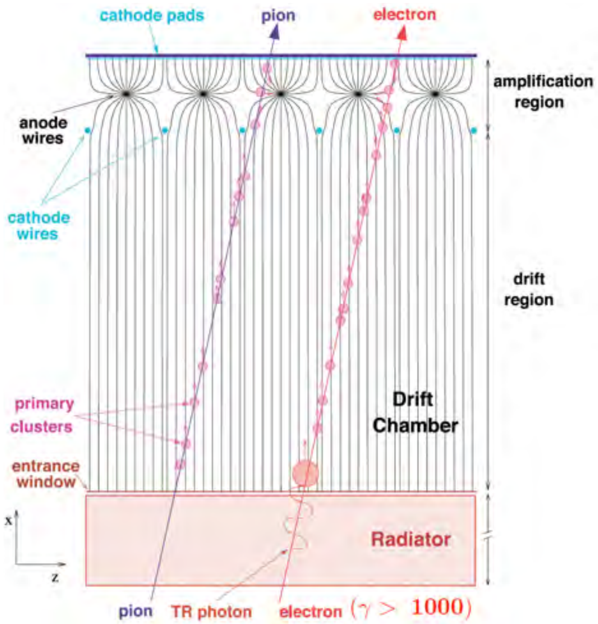




Transition Radiation Detector

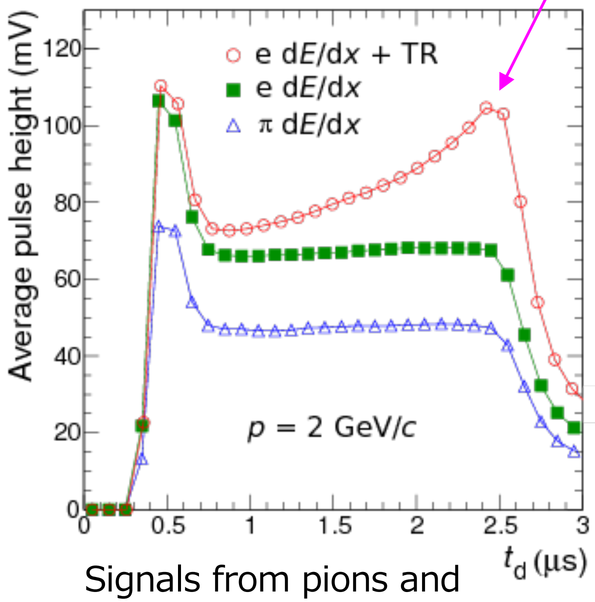
ALICE TRD

ALICE TRD : electron−ID and tracking
Catch $J/\phi, \Upsilon \rightarrow e^+e^-$
Radiator : Polypropylene fiber of 17μϕ
Detector ; drift chamber with Xe/CO2-gas

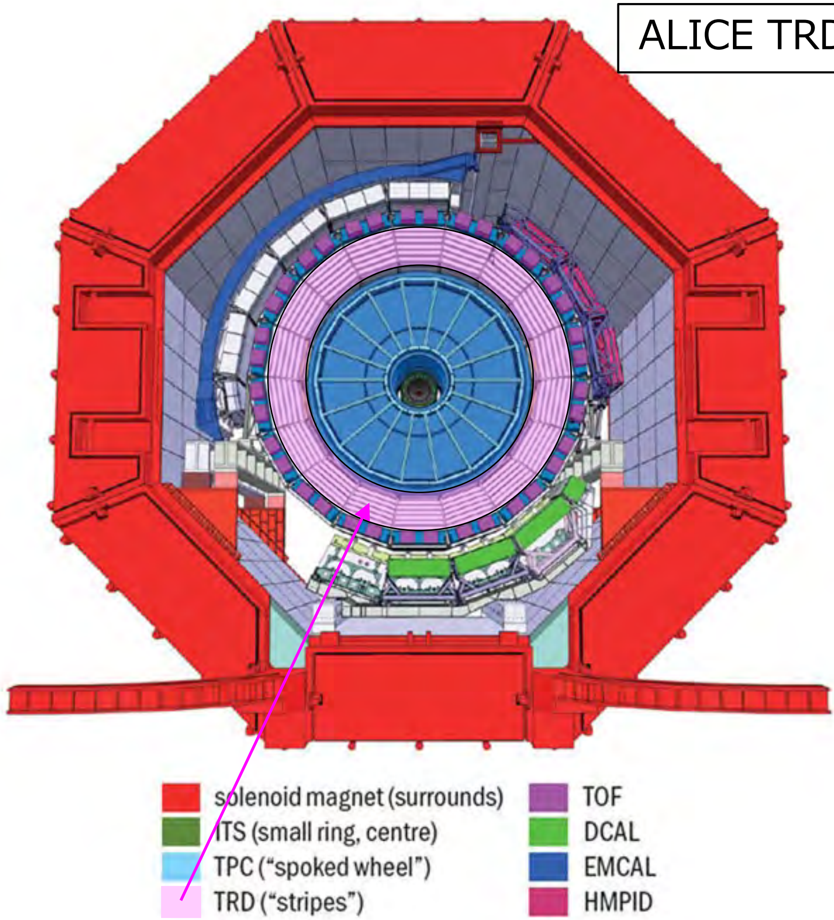


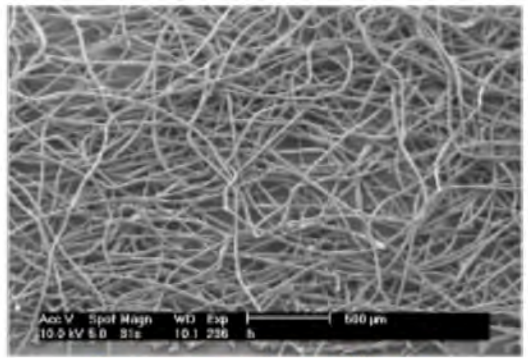
Layout of TRD, and X-ray conversion and tracks.

TRD photon contribution



Signals from pions and from electrons.





Fiber radiator

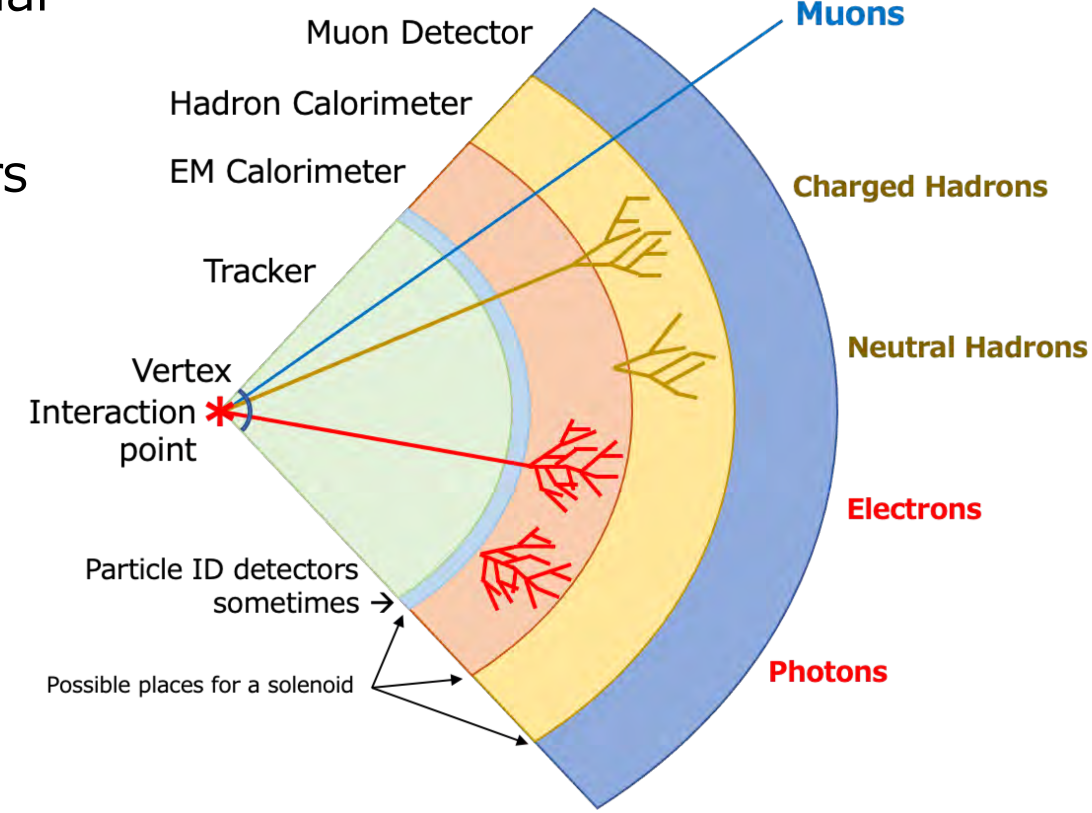
Figures taken from M.J.Kweon, QM09.

Muon identification with high-efficiency, low contamination

Muon are the key particles to search for new physics.

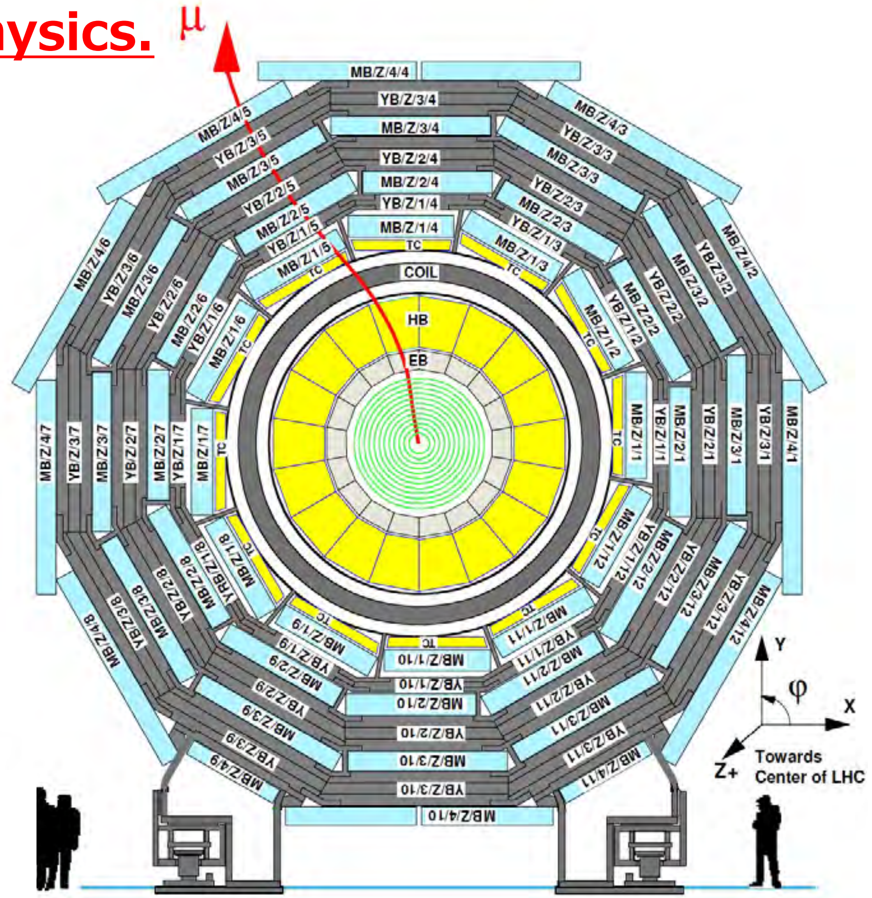
How can we know the particle is muon ?
- Muon does not initiate EM shower
- Muon does not initiate hadron shower
- Penetration as MIP through thick material

Typical configuration;
Interleave of absorber and detection layers
- Absorber
  mostly iron plate to work as flux return.
- Detection layers
  mostly gas chambers
  several choices for various emphasis
    - timing resolution
    - position resolution
    - large size
    - cost



Muon identification with high-efficiency, low contamination

Muon are the key particles to search for new physics.

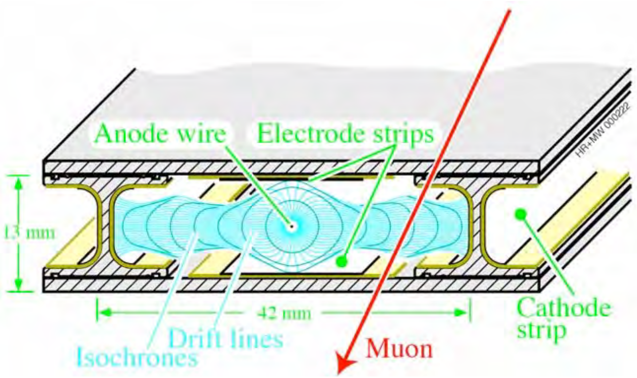


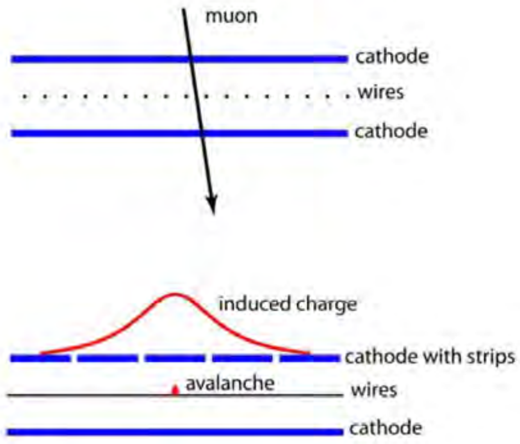
Compact Muon Solenoid (CMS) aims at
- good muon identification
- good muon momentum resolution
- good dimuon mass resolution

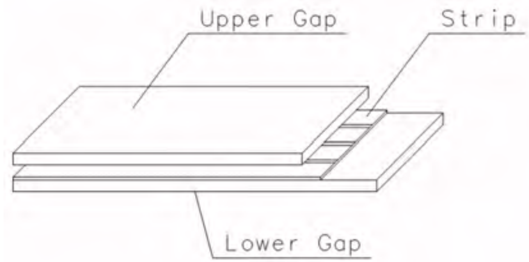
Design parameters are
- 12Tm bending field for good momentum resolution
- Thick iron absober of 1.5m

Detector area ~25000m2
→ inexpensive detector needed
- Array of single-wire drift chamber (barrel)
- MWPC with cathode-strip readout (EC)
- RPC for trigger (fast response)

mu-IDのefficiency, contamination







Electron identification with high-efficiency, low contamination

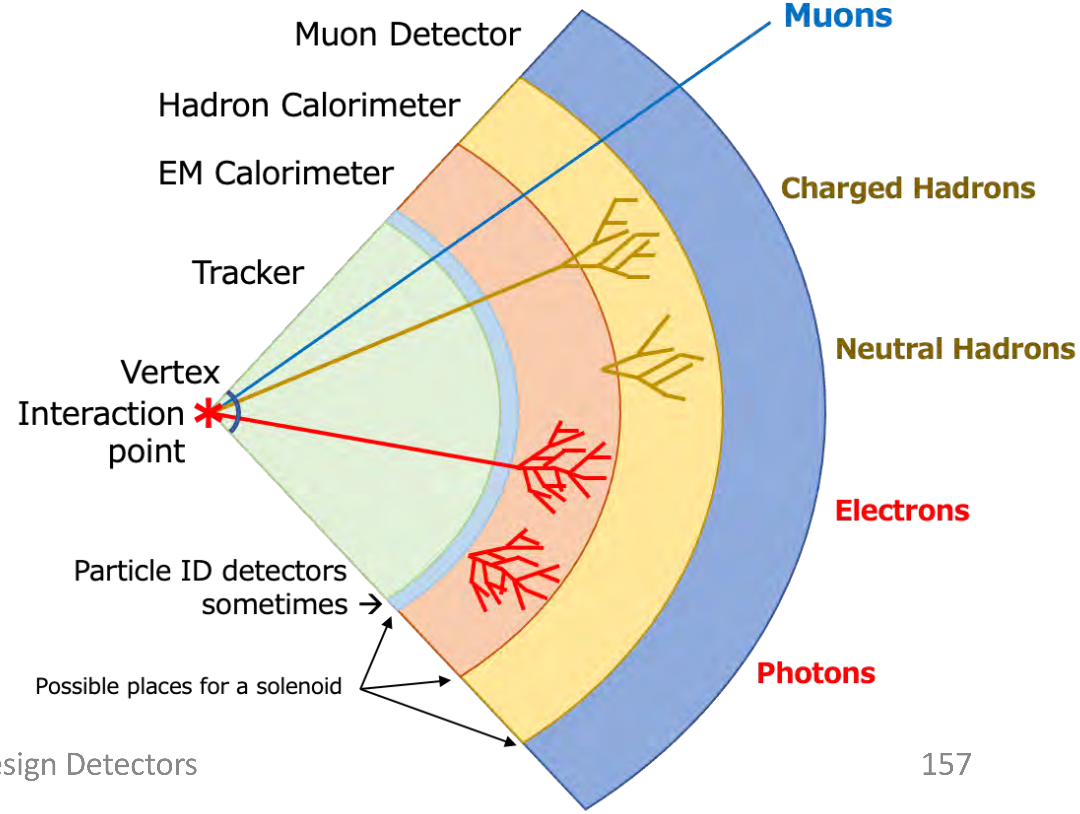
$H^0 \rightarrow \gamma\gamma$ chennel is the highway to the Higgs discovery.

How can we know the particle is electron ?

With calorimeter

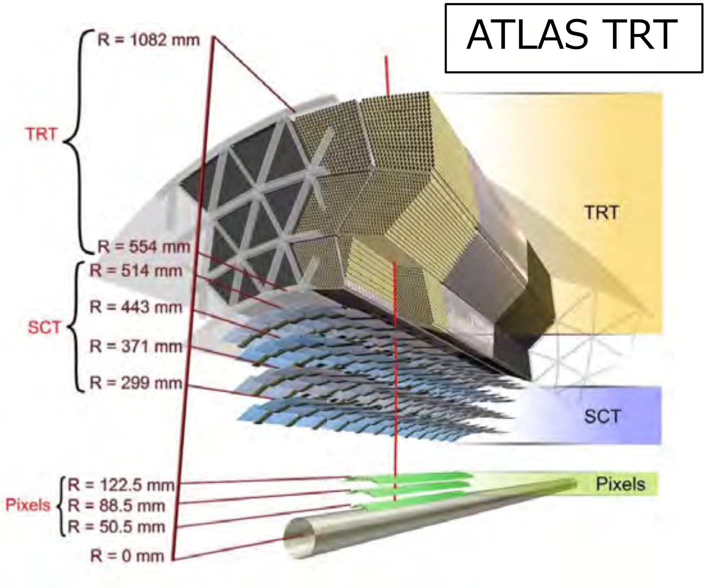
- Initiate EM shower
  - Shower profile consistent to EM shower.
  - → fine granularity is needed.
- Matches to a track (not γ, π^0)
  - Position matches
  - Energy-momentum matches
- Do not initiate hadron shower

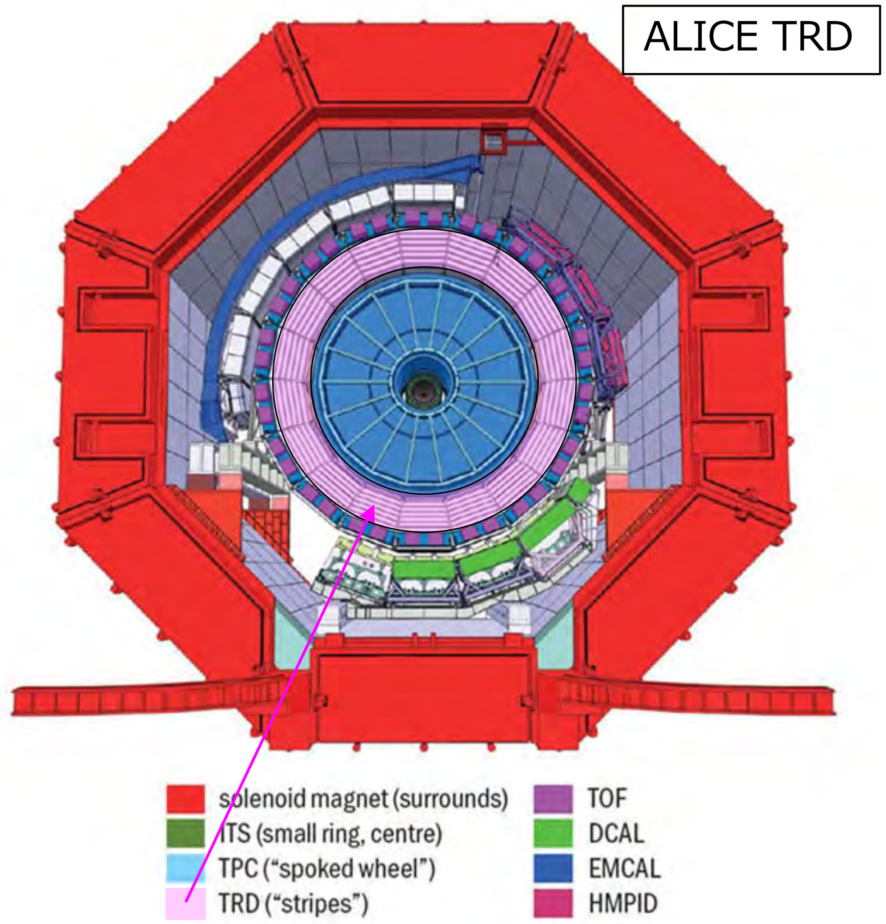
Additional e-ID with TRD



Electron identification with high-efficiency, low contamination

For the best electron ID, EM calorimeter + TRD are used.





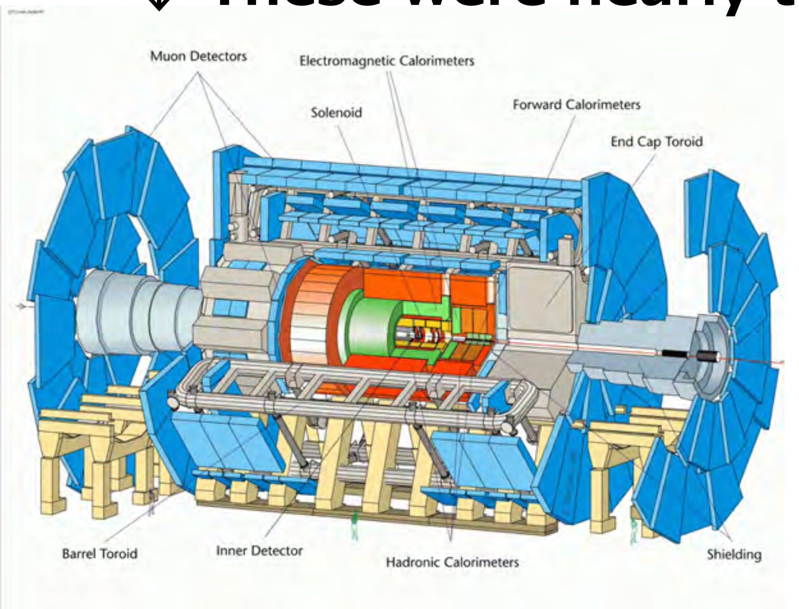
ATLAS TRT performance is;
pion rejection = 1/20 (2GeV)
pion rejection = 1/16 (20GeV)
at electron efficiency = 90%

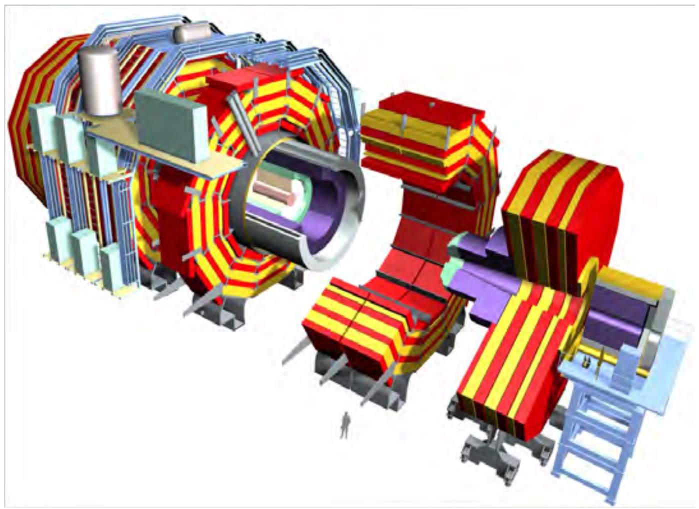
pion rejection = 1/50 (2,20GeV)
at electron efficiency = 80%

Explicitly reconstruct all $H^0/t/b/W/Z$ decays for precision study of H^0

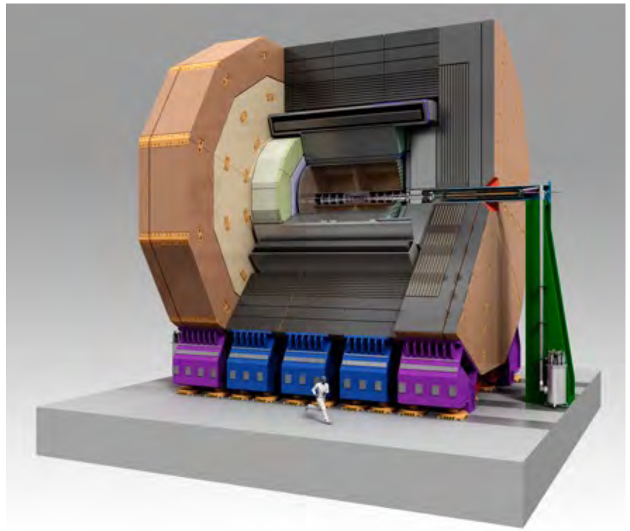
- good resolutions ; energy, momentum, position, timing
  Charged particle be measured by trackers, while neutral particles by calorimeters.
  Excellent position resolutions to untangle track/cluster overlapping.
- Jet reconstruction ; high multiplicity, high occupancy
- Precision secondary vertexing (b,c,τ-tagging) and primary vertexing (bunch separation).
- Reject overwhelming QCD background reactions

↓ These were nearly the solutions ↓





This was almost the solution



Summary

1. We pick up reactions to measure
   Higgs discovery
   Higgs precision study

2. We overviewed the detectors for particle physics

3. We specified required performance of the detectors for picked up reactions

4. We surveyed interaction of particle with matter as fundamental knowledge to design detectors

5. We surveyed operation of various detectors

References

Many ideas, explanations, figures and equations are taken from the references below;

- PDG ; Review of Particle Physics, by Particle Data group
- W.R.Leo ; Techniques for Nuclear and Particle Physics Experiments, by William R. Leo
- Grupen ; Particle Detectors, by Claus Grupen and Boris Schwartz
- Knoll ; Radiation Detection and Measurement, by Glenn E. Knoll
- Lang ; Basic Elements of Particle Radiation Detectors at VSON2017, by Karol Lang
- Nakaya ; Particle and Radiation detectors at VSON2019, by Tsuyoshi Nakaya
- Erika ; Lecture "The Physics of Particle Detectors", by Erika Garutti
- Joram ; CERN Summer Student Lectures 2003, by Christian Joram

and many slides on the experiment reports.