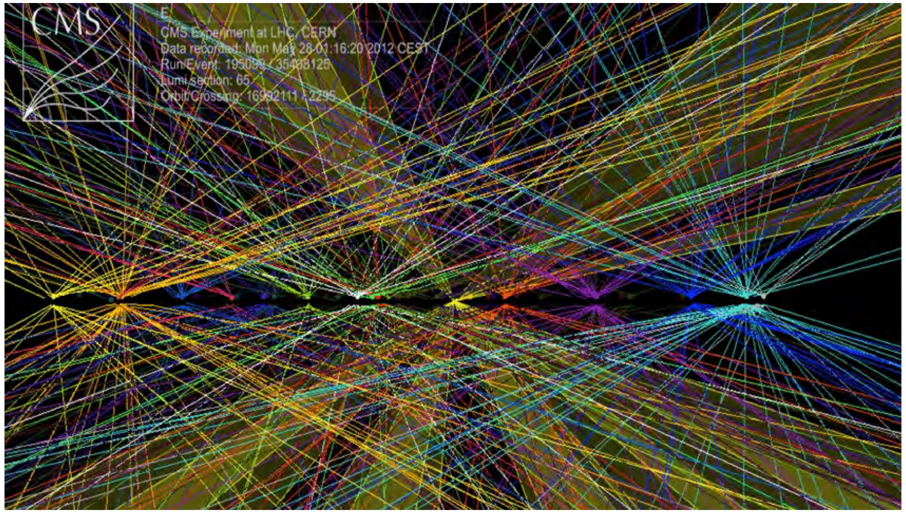
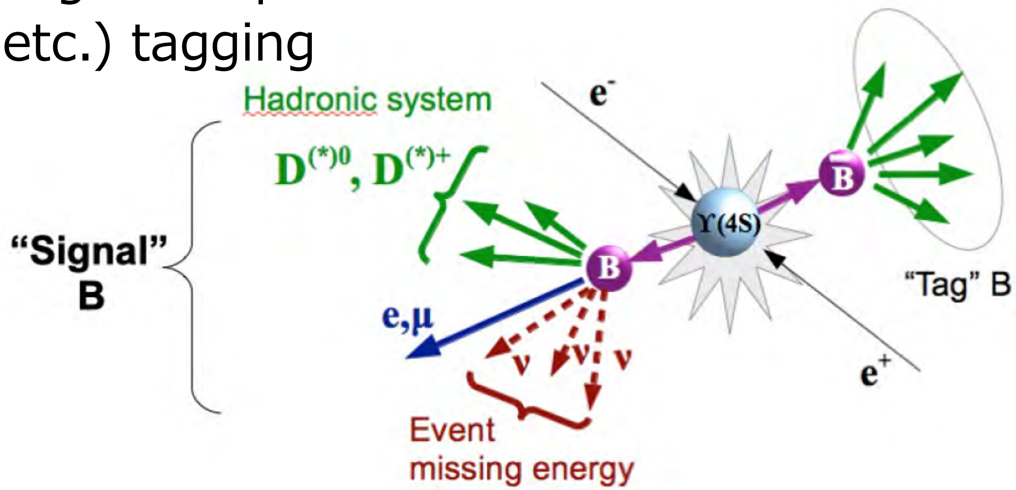
Detectors for High-Energy Experiments
- Day 2 -

High Energy Accelerator Research Organization/J-PARC
Yoshiaki Fujii

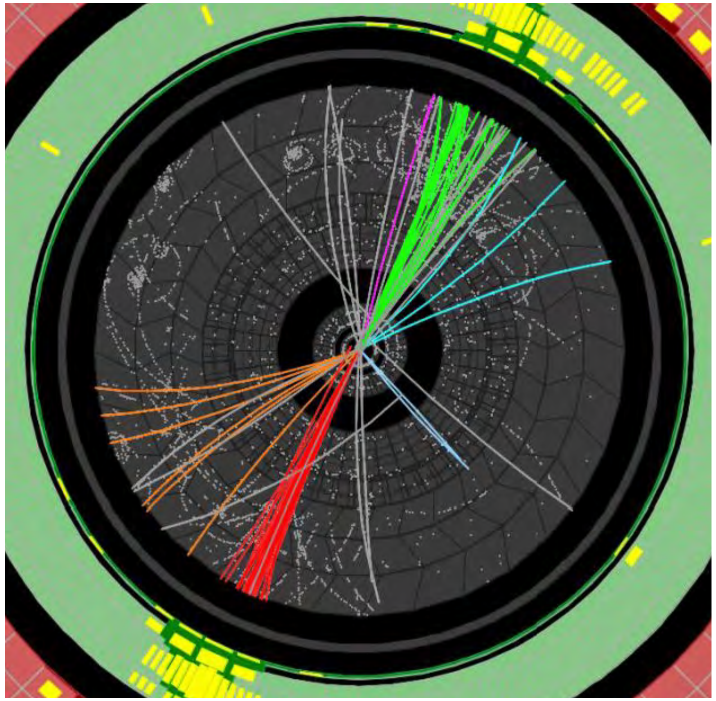
Silicon Trackers for Vertexing

- 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



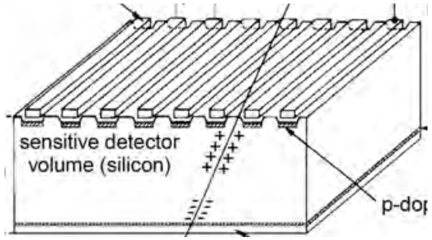
Silicon Trackers for Vertexing

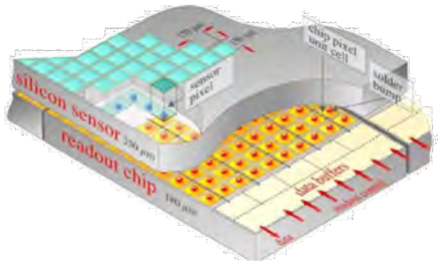
- Primary vertexing : resolve multiple-crossing overlap
- Secondary vertexing : short-lived (b, c, t etc.) tagging
- Tracking of collimated jets

Inner layer ; pixel to isolate collimated tracks

Outer layer ; micro-strip

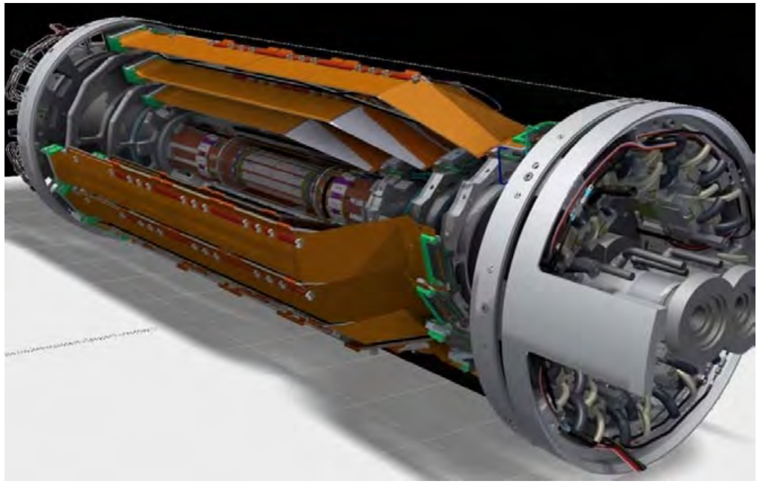
Strip



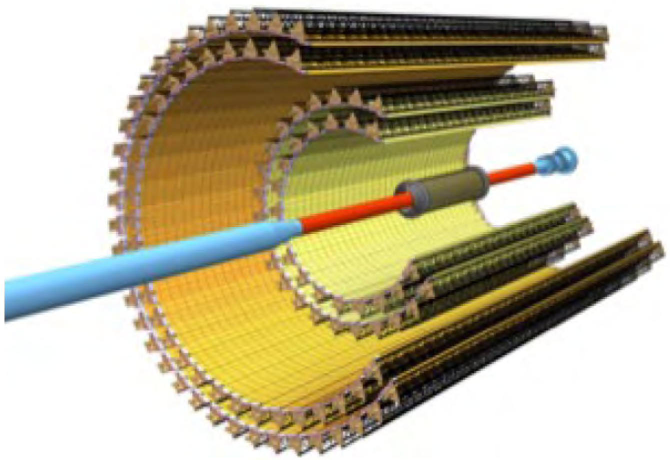


PIXEL

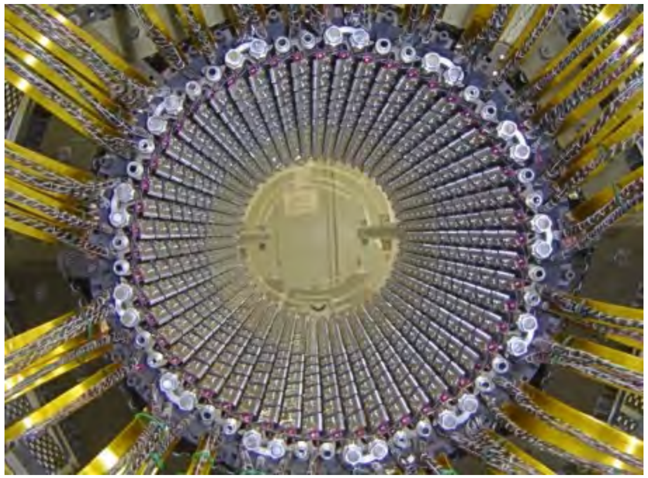
Belle-II



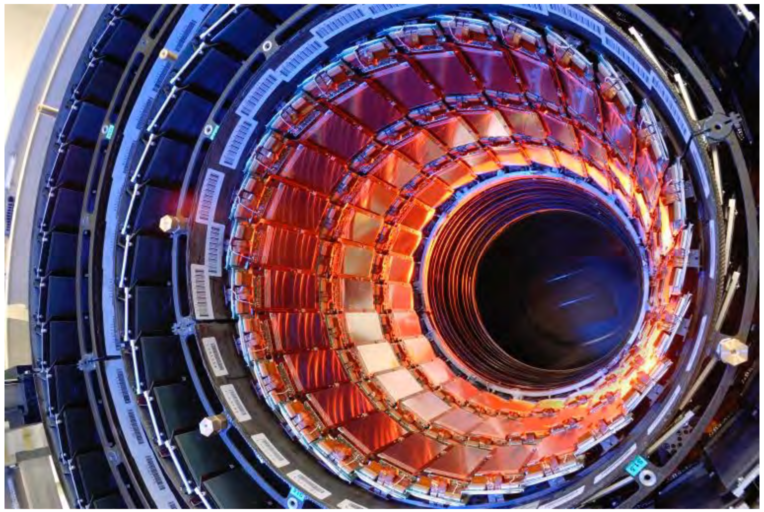
ALICE



ATLAS

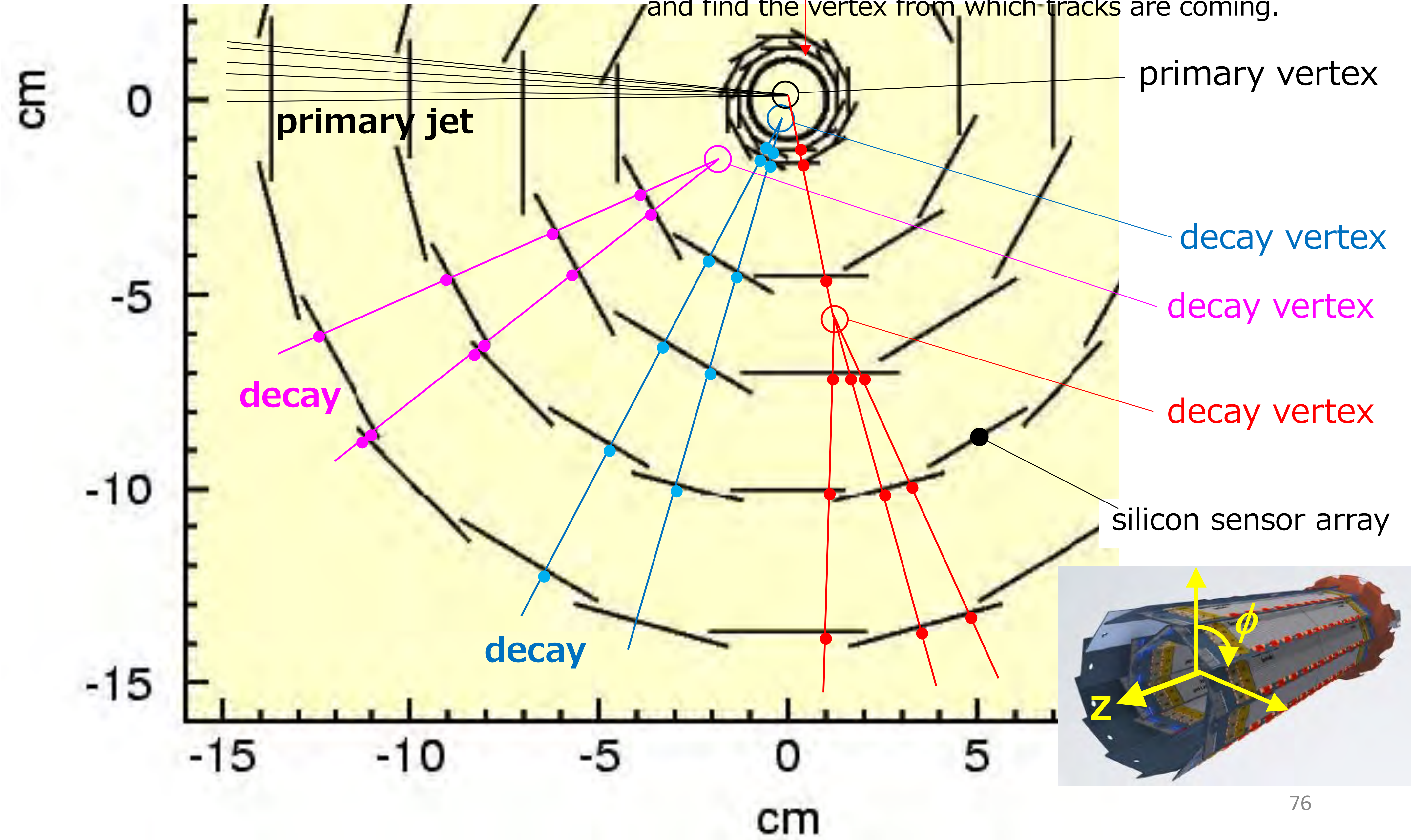


CMS

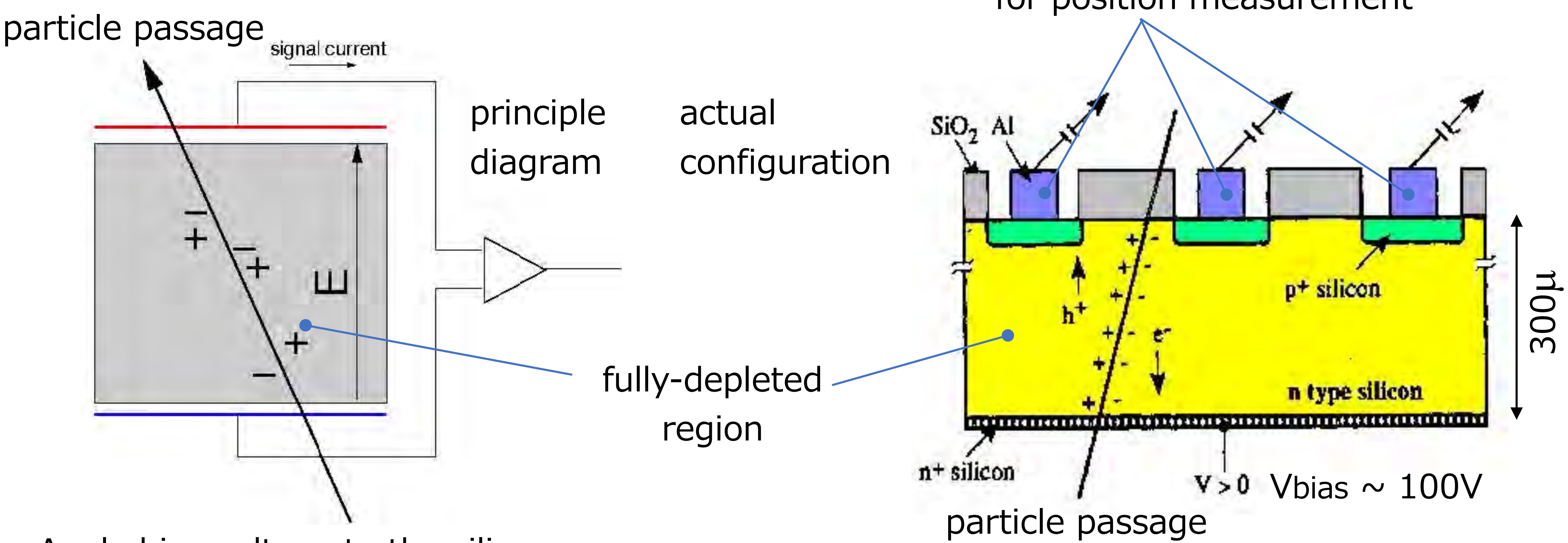


Silicon Trackers for Vertexing

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.



Signal generation



- Apply bias voltage to the silicon sensor.
- Carriers (electrons or holes) swept out and depleted region is generated.

A charged particle passes through the silicon

- Electron-hole pairs are generated along a track.
- Electrons and holes drift and are collected to the electrodes and signal picked up.

Typical Signal Amplitude :

Energy Loss ~ 0.1MeV

(1.5MeV/(g/cm2) x2.3g/cm3 x0.03cm)

Neh ~ 30,000pairs (1pair/3.6eV)

~ 5×10^{-14} C, needs excellent amplifier.

Si-Strip Detector

Two-dimensional position measurement :

Stereo layers

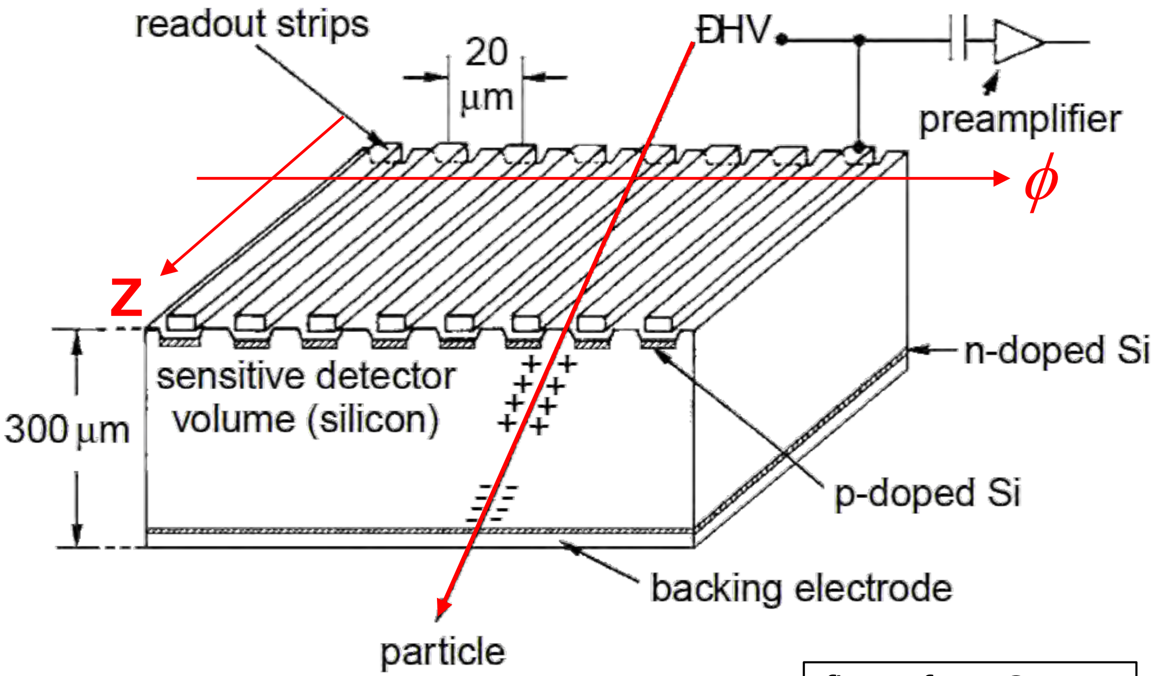
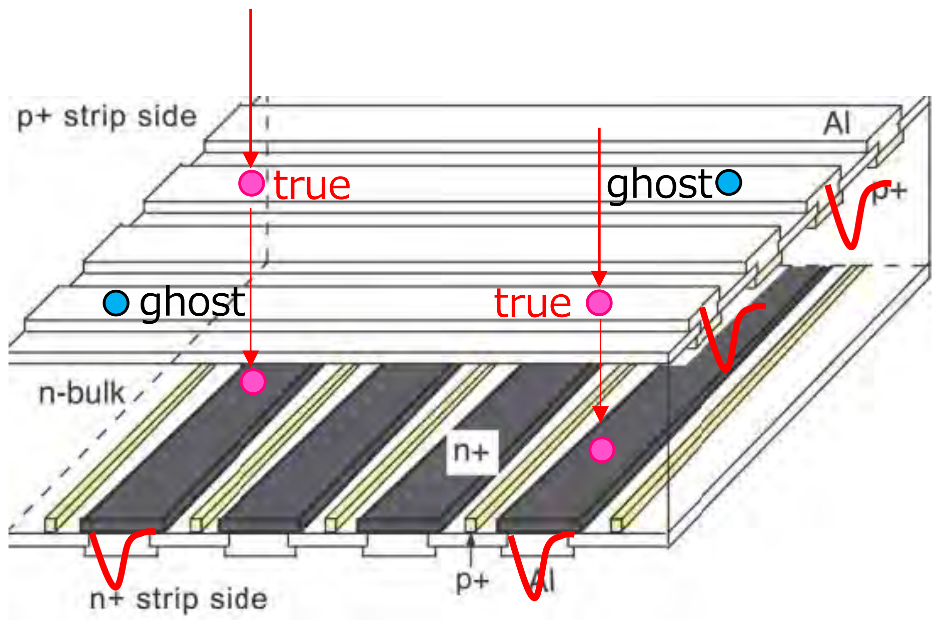


figure from Grupen

Schematic structure of silicon-strip detector.

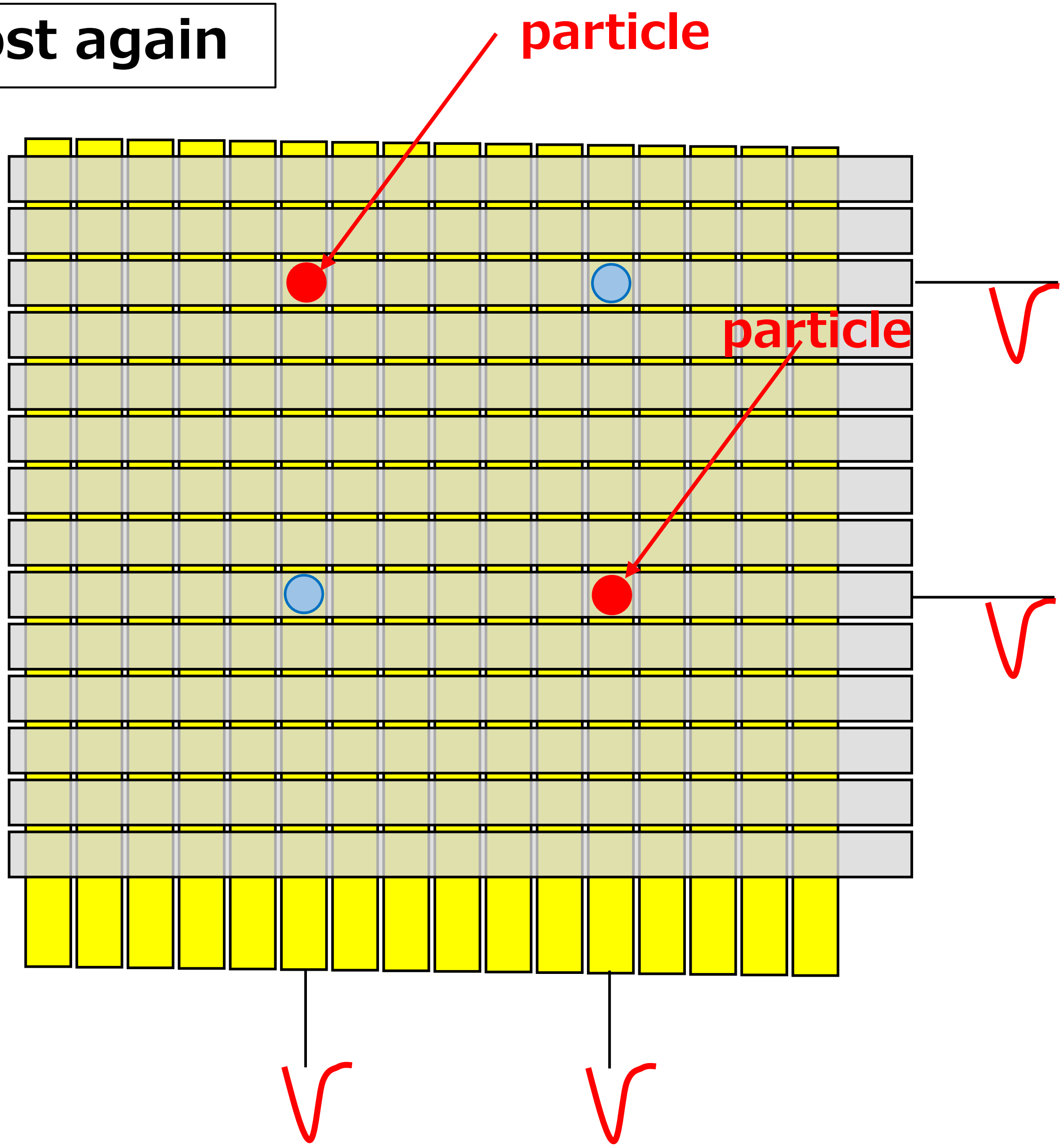
- φ position can be measured.
- Read-out electronics can be located naturally at the end of the strips.

Double-sided sensors



Schematic structure of
double-sided silicon-strip detector.
φ and z-position can be measured.
Ghost-hits appear
if plural particles come.

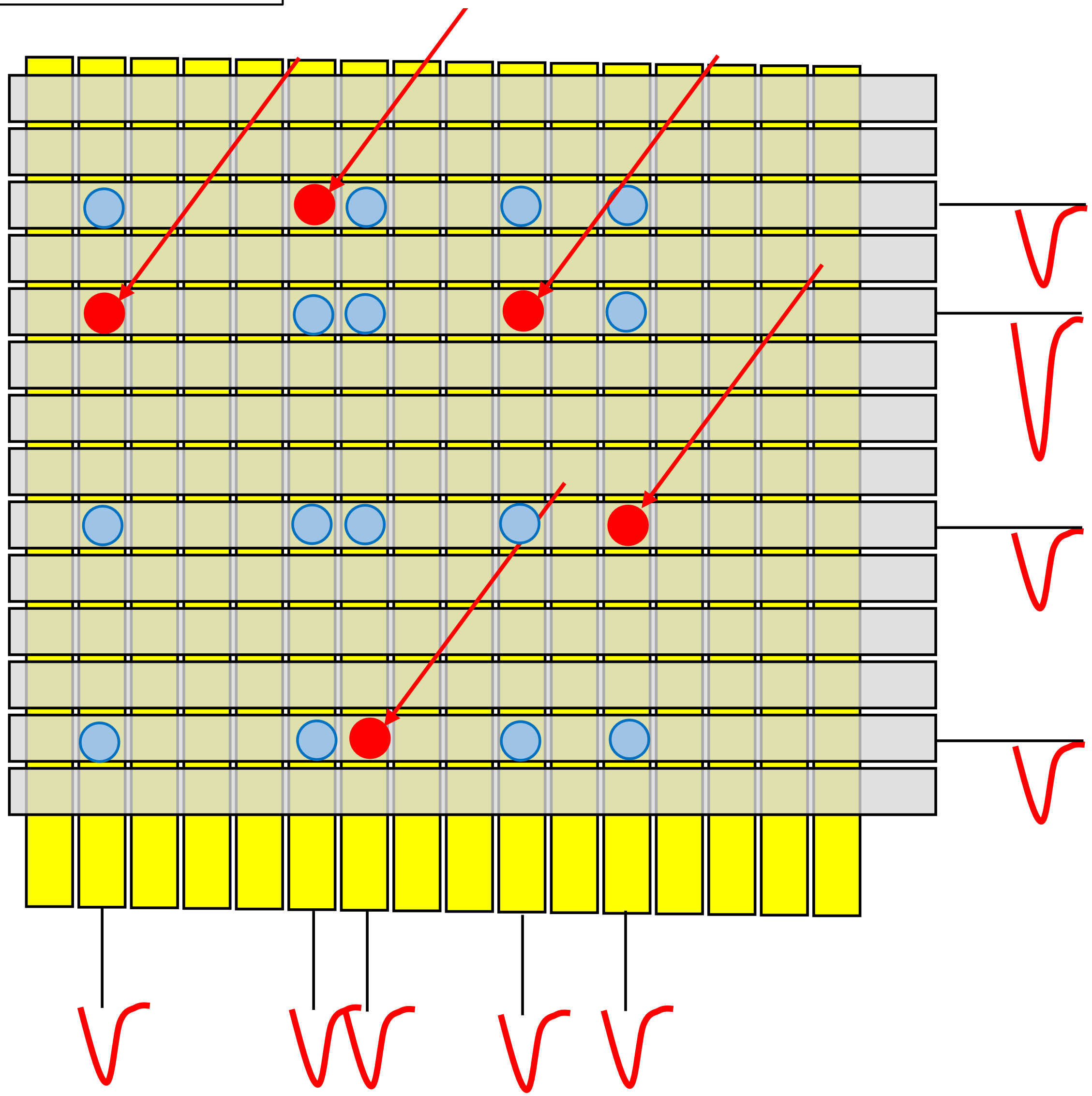
Ghost again



Ghost-hits appear if plural particles come in to one section.
You need to solve it by installing plural detector layers.

Ghost again

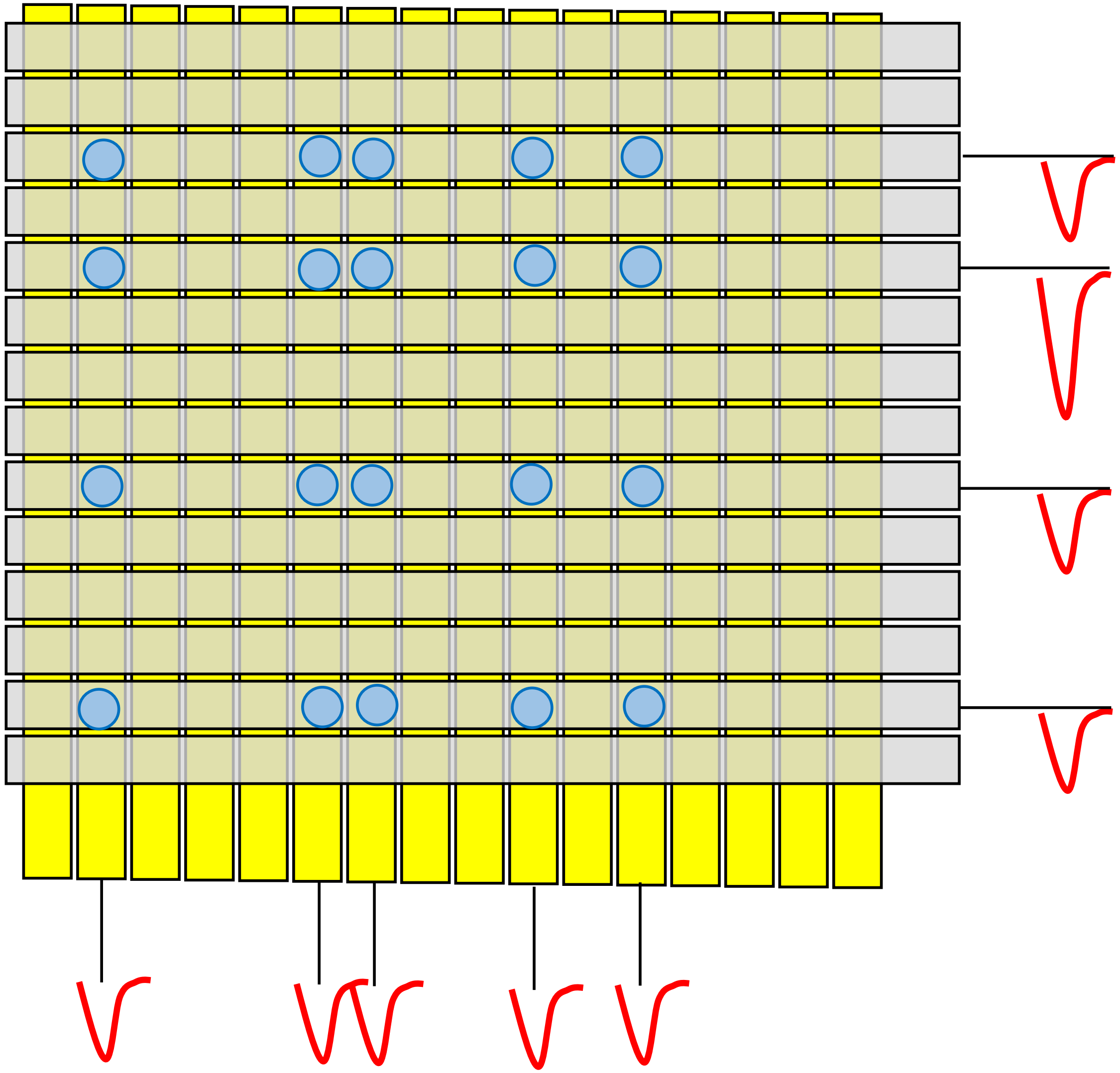
Five particles generate 20 hits in this case.



Ghost-hits appear.
It can not be solved
if occupancy is high,
even if you have several
layers of detector planes.

Ghost again

No way to pin down which are the true hits.



Ghost-hits appear.
It can not be solved if occupancy is high, even if you have several layers of detector planes.

Better resolution does not help.

Finer pitch and more read-out channel does not help, either.

You need
true two-dimensional detector
to solve ghost problem.

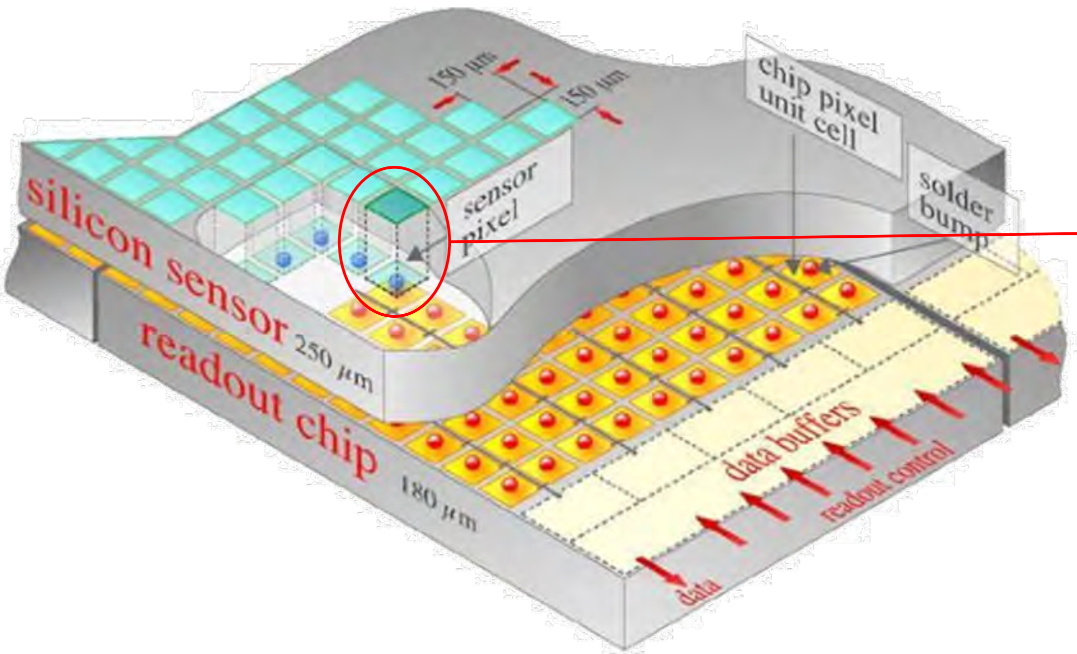
Pixel Detector

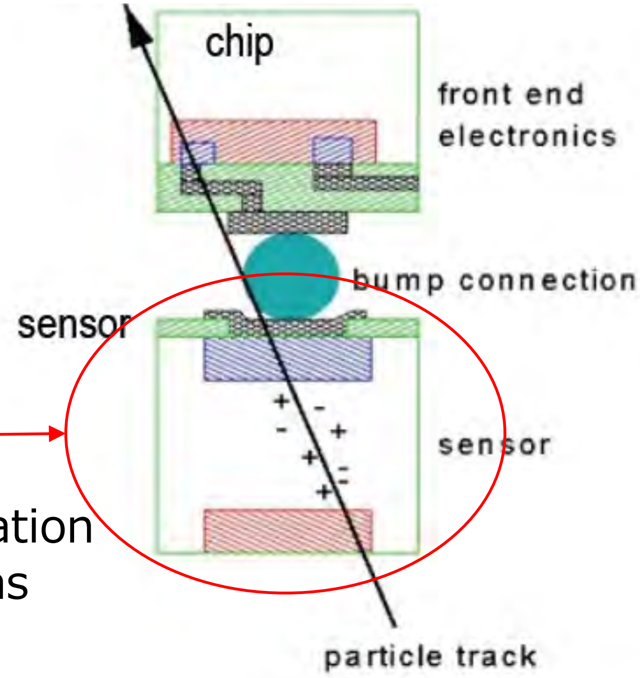
2D-measurement by orthogonal strips screws up due to ghosts if tracks are too many.

→ Pixel detector gives true 2-D position measurement free from ghost.

Read-out electronics layout is complicated.

Read-out electronics layer is overlayed on the pixel sensor layer and bonded face-to-face.





Signal generation is the same as strips.

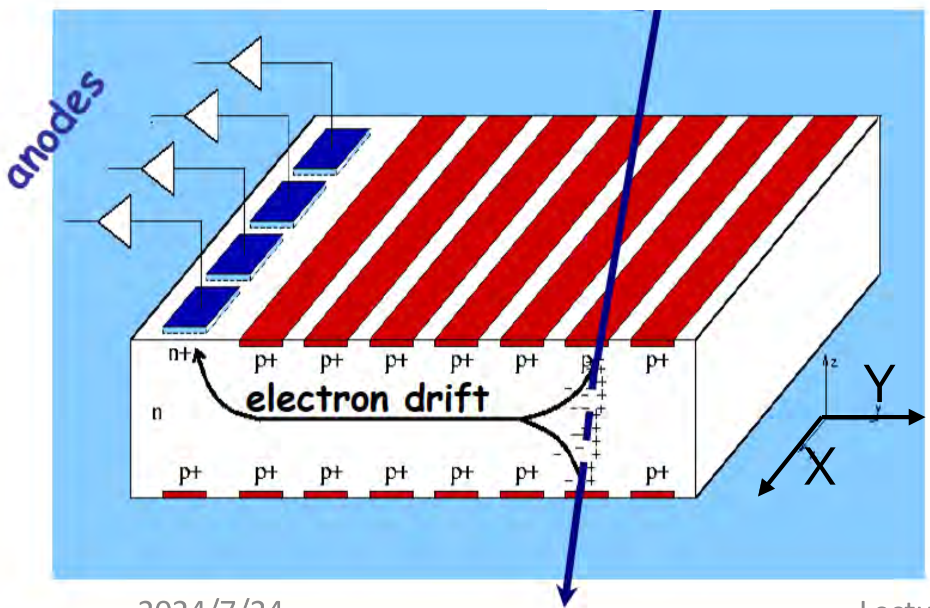
Problem is thicker material.

Silicon "Drift Chamber"

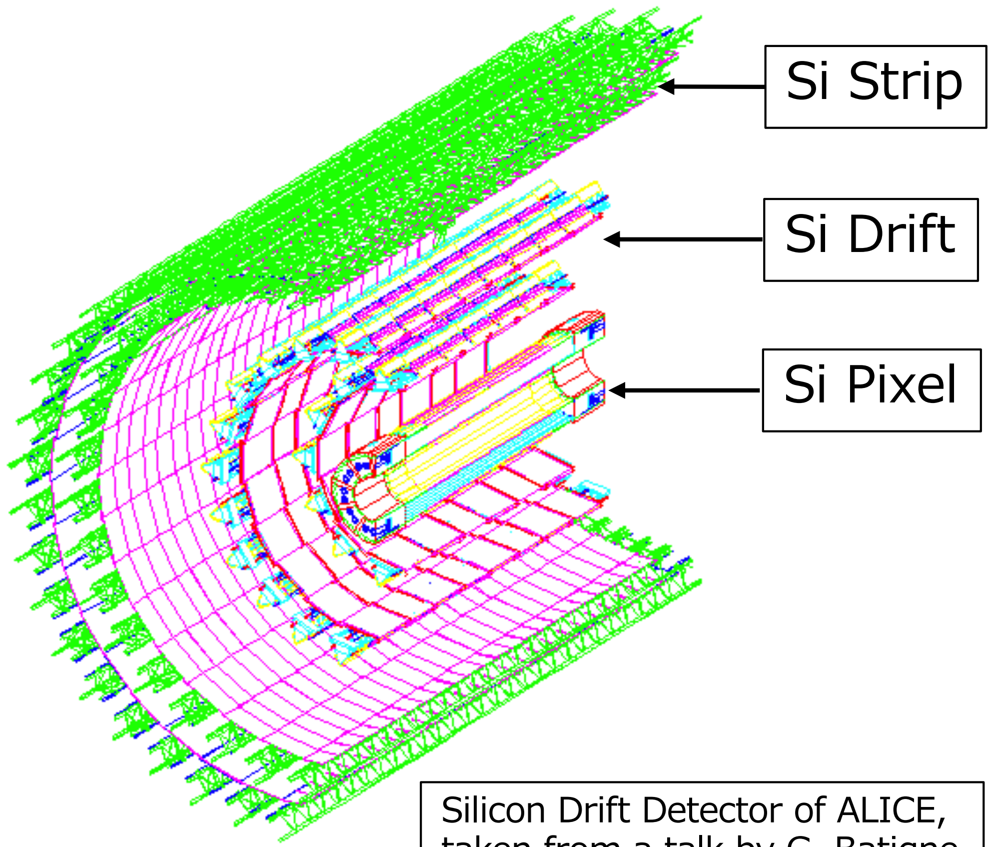
Can make a drift chamber with silicon using the same method as gas drift chambers.

Anode strips measure X position ~ 25μm
Drift time measures Y position ~ 30μm
(Except for the region close to the anodes).
Precise temperature control (0.1K) necessary.

Particle

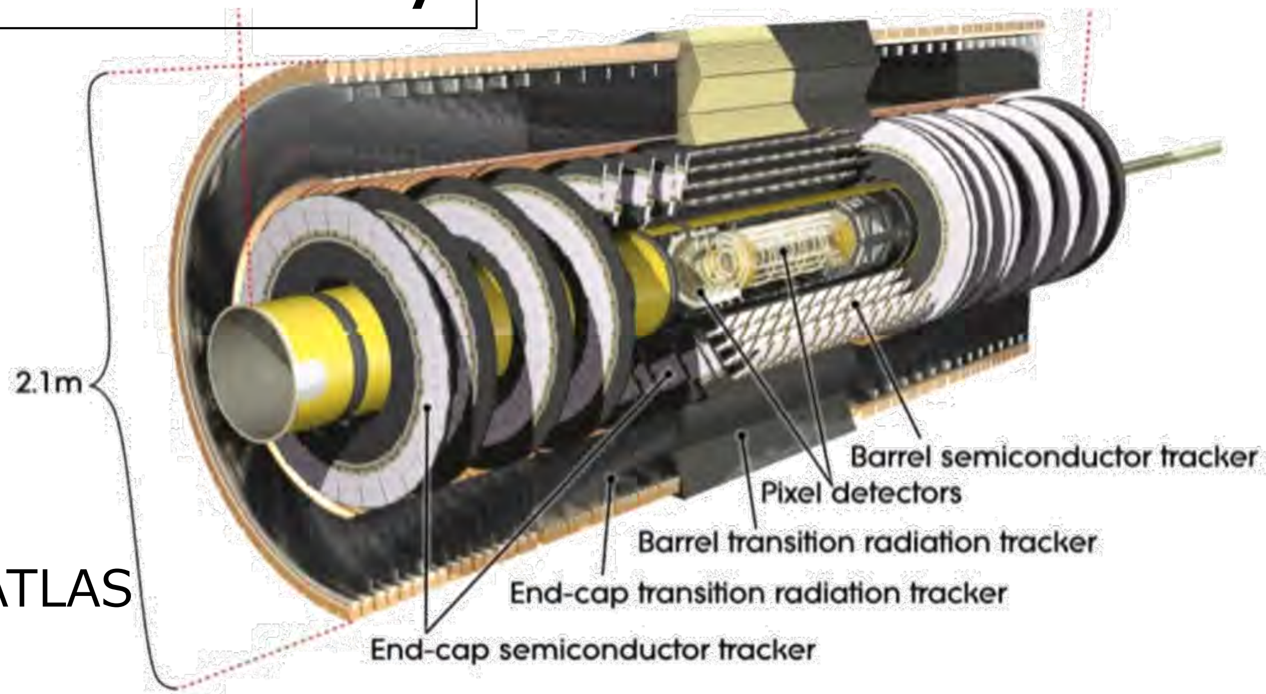


Layout of Si detectors at ALICE (heavy-ion collision exp.)
Outer layer ; Si-strip
mid layer ; Si-drift
Innermost : Si-pixel to handle dense jets

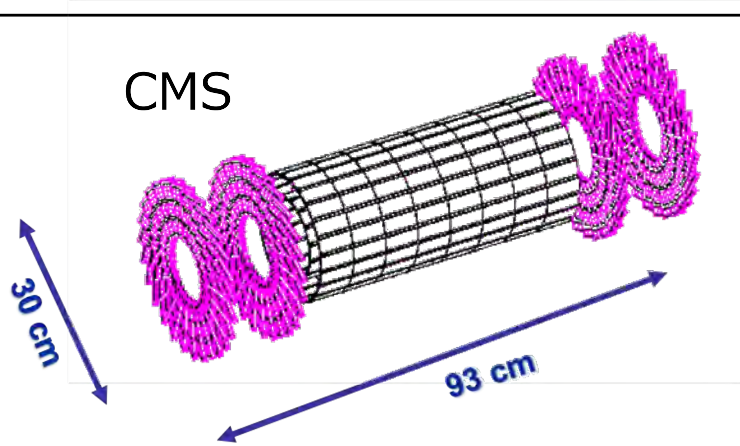


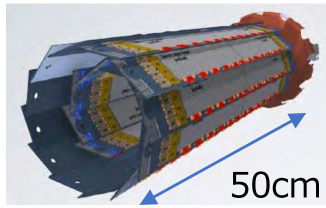
Silicon Drift Detector of ALICE, taken from a talk by G. Batigne

Vertex Summary



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	

4. Particle Identification

Measure the velocity（β or γ）of the particle,
and together with momentum measured by tracker,
identify particle species.
Do not disturb particle's travel
so as not to affect the measurement of following calorimeter.

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 are 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.

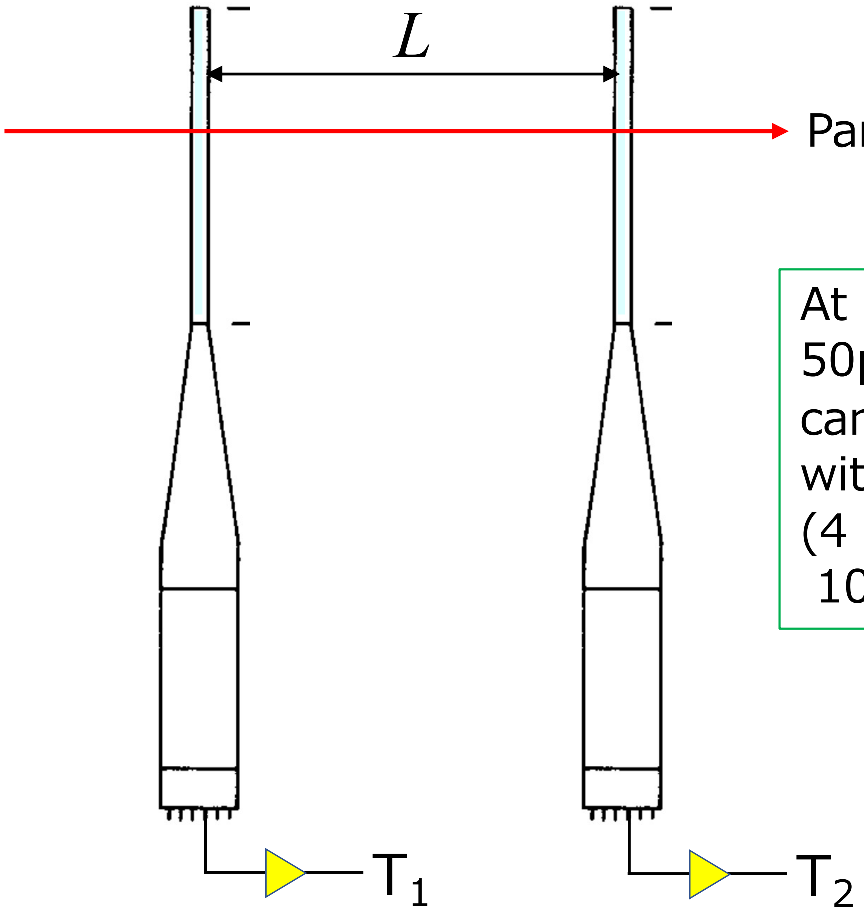
Combination of various observables

- ToF
- dE/dx
- Cherenkov Light
- Transition Radiation
- and so on ...

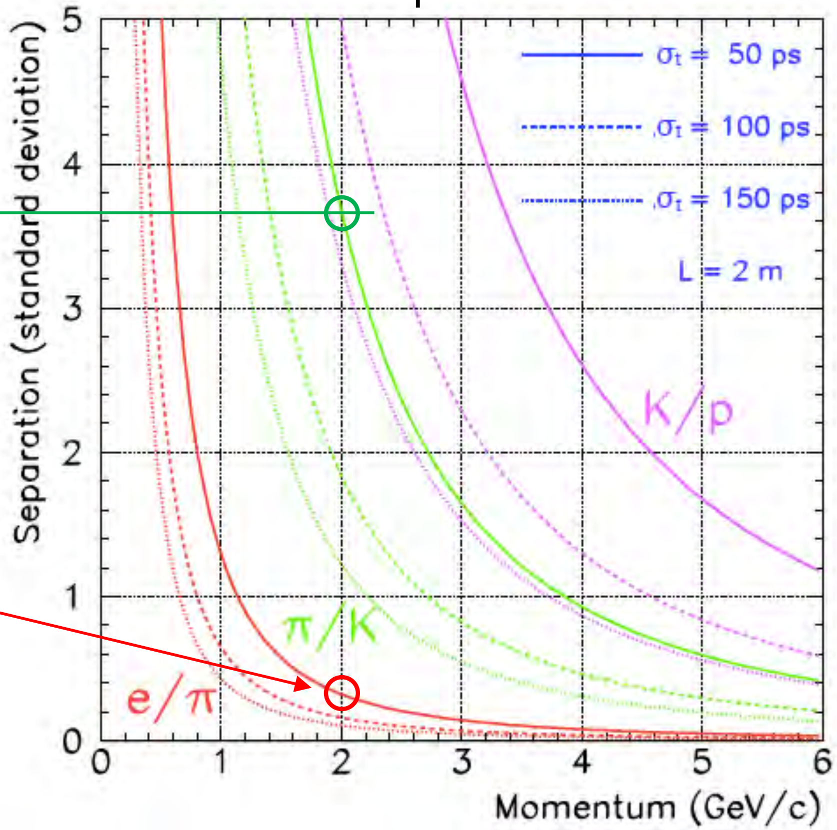
Particle ID --> Basically measure velocity (β , γ) of the particle

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

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



Particle separation curves



At 2GeV,
50ps-resolution ToF can separate π and K with $3.6\sigma \sim 99.96\%$ (4 mistakes in 10,000 samples.)

Separate e and π with ToF is very difficult.

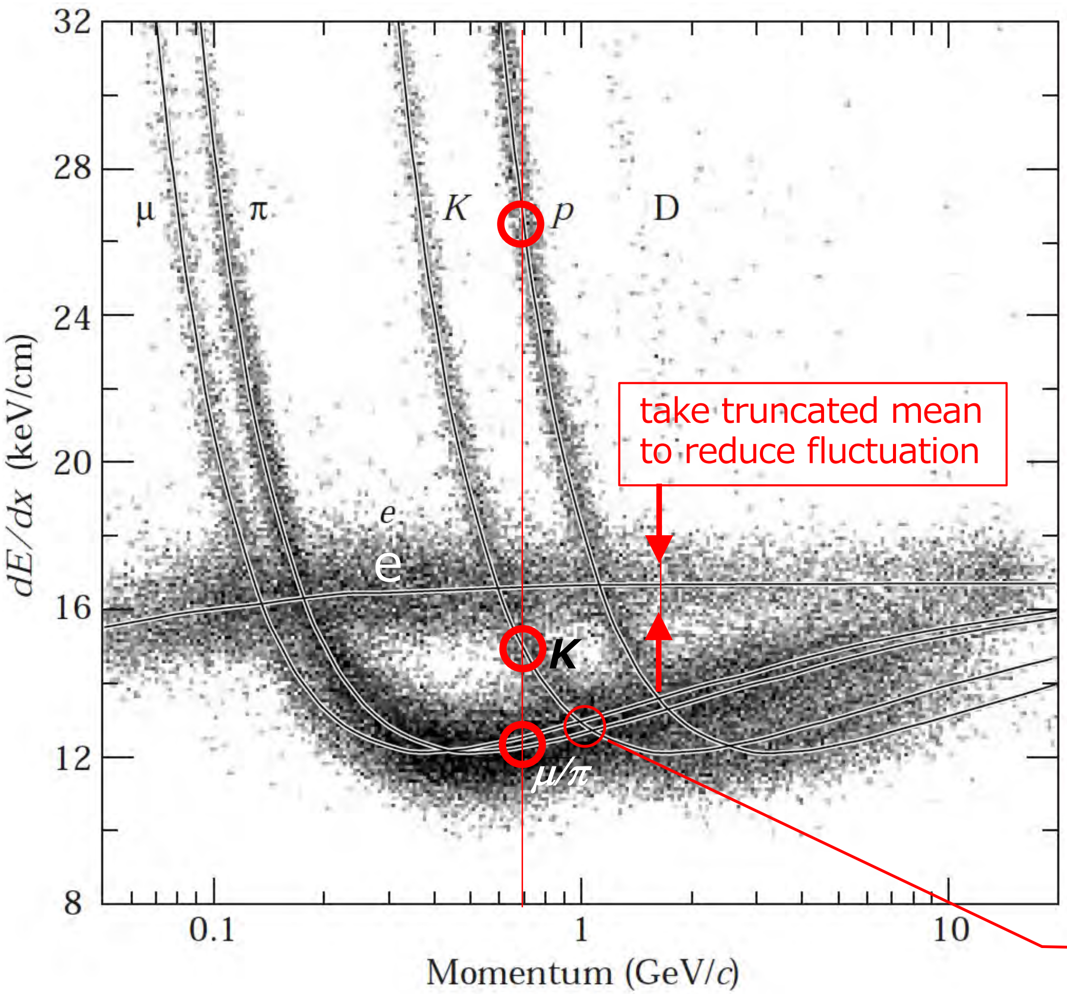
taken from Erika

4. Operation of detectors ; Particle Identification

Energy Loss 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 differences becomes small → not useful at high energy.



Below ~800MeV/c,

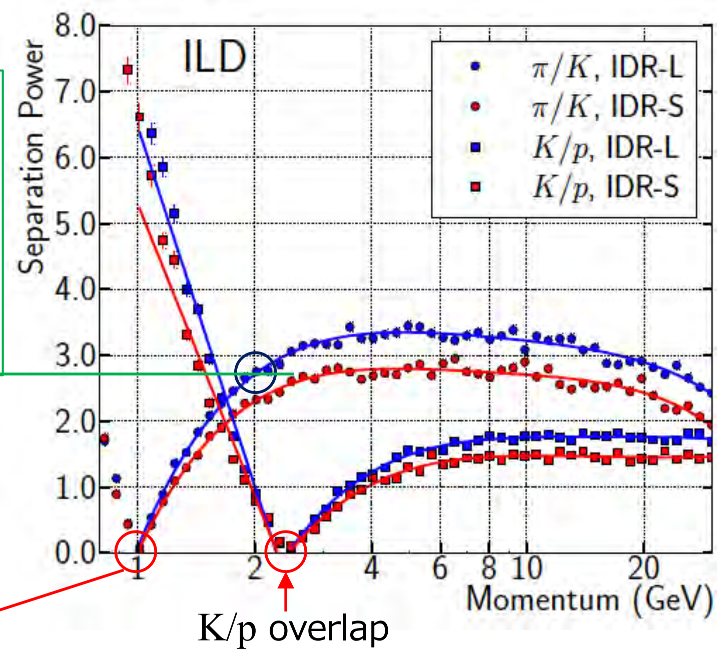
π/K can be separated but μ/π can not be.

Truncated mean of many dE/dx measurement improves the separation.

→ Useful at low-E fixed-target experiment.

At 2GeV, dE/dx can separate π and K with 2.8σ ~99.3%

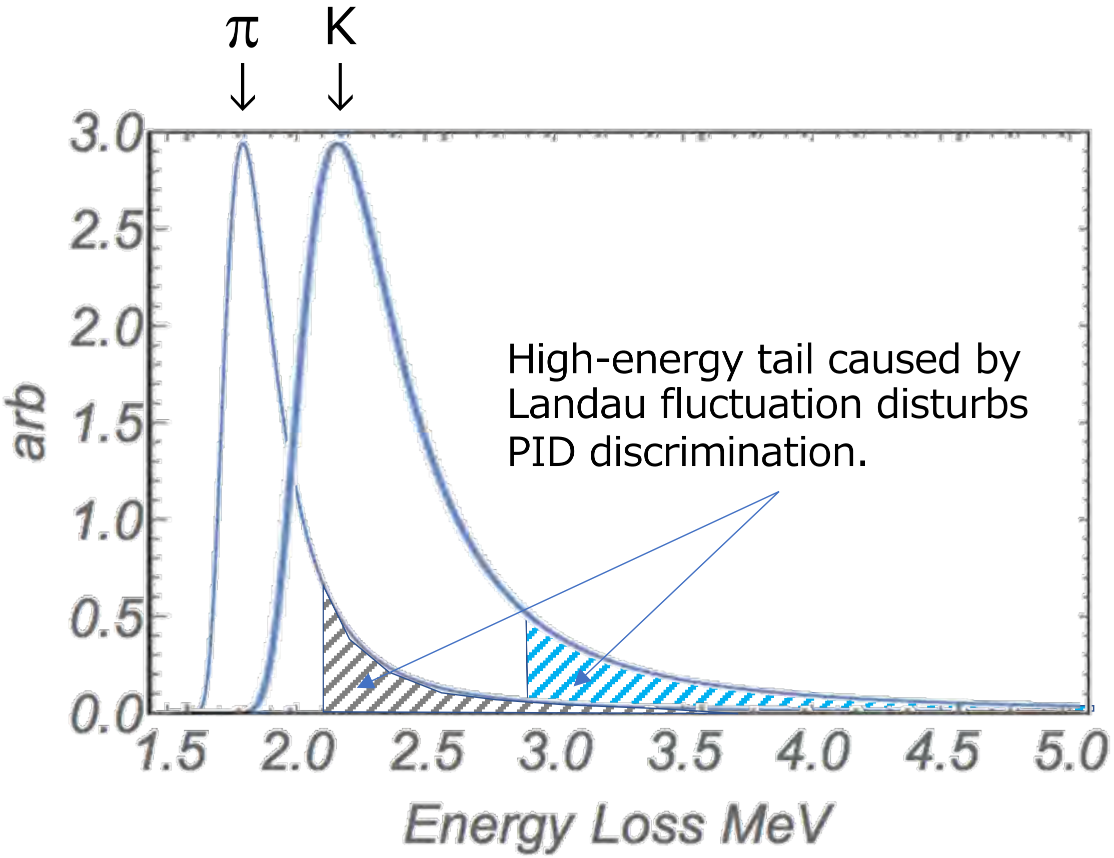
At 1GeV, dE/dx of π and K overlaps and can't be distinguished.



Taken from「Charged Hadron Identification with dE/dx and Time-of-Flight at Future Higgs Factories」by U.Einhous

Energy Loss dE/dx

Energy loss has large fluctuation tail → **Truncated mean** is commonly used.



Amongst many energy loss measurement, discard highest-30% data (for example) and calculate average energy loss in order to reduce effect of Landau fluctuation tail.

This improves particle discrimination score using energy loss measurement.

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

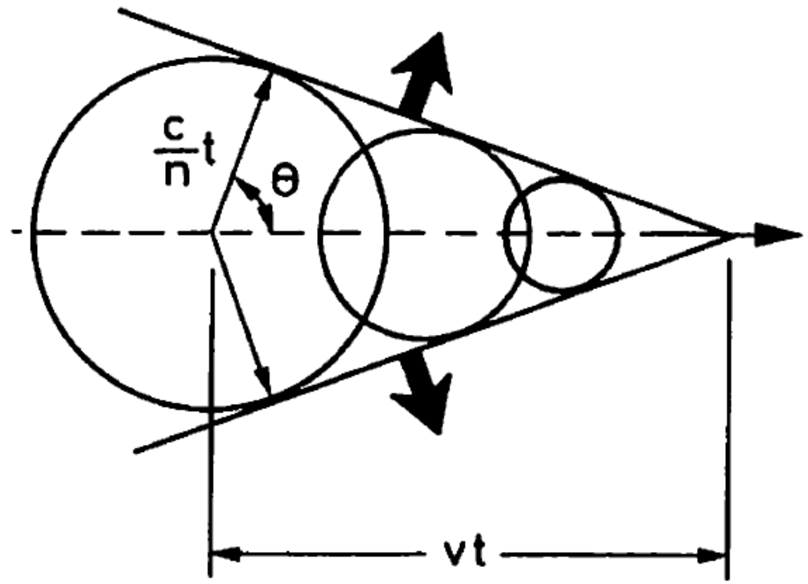
Cherenkov Light

n ; refraction index of the material.

Cherenkov generation condition ; **$\beta > 1/n$**

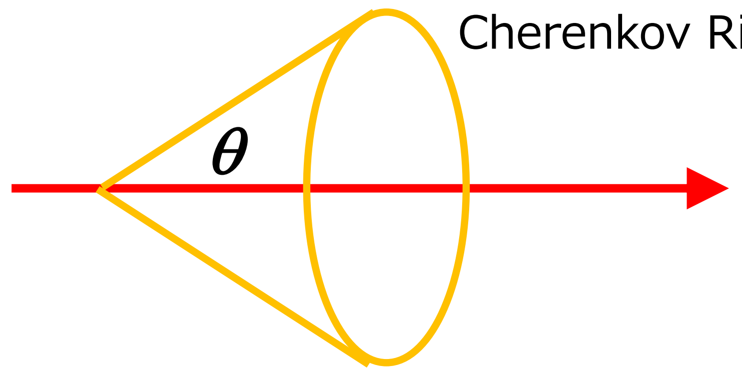
Radiation angle θ ; **$\cos\theta = 1/n\beta$**.

→ have sensitivity to β.



- Threshold type
  Detect Cherenkov photon emission exists or not for several n, and narrow-down the β range and particle species.

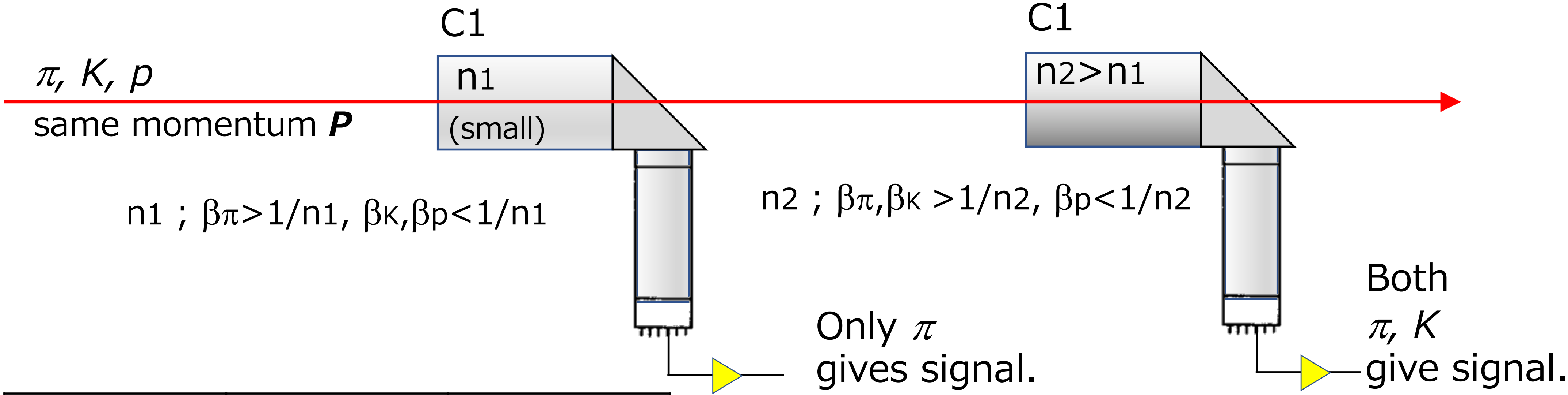
- Cone angle θ measurement tyle
  measure the ring image of the Cherenkov light, determine β, and pin-down the particle species.



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.

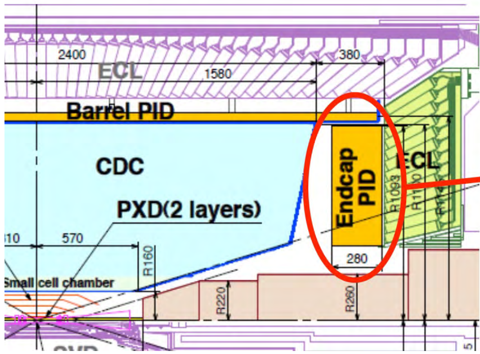
C1	C2	Particle
ON	ON	pion
Off	ON	kaon
Off	Off	proton

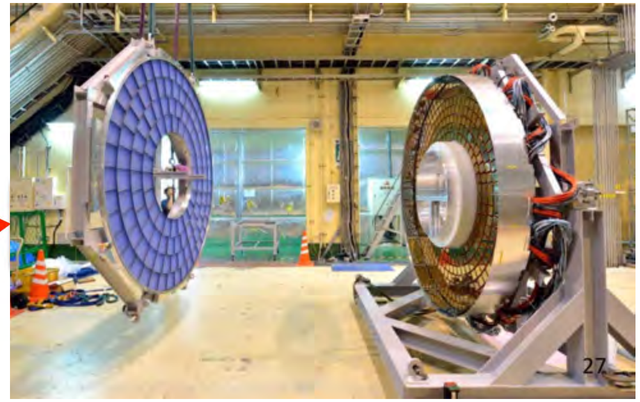
An example of $\pi/K/p$ identification

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

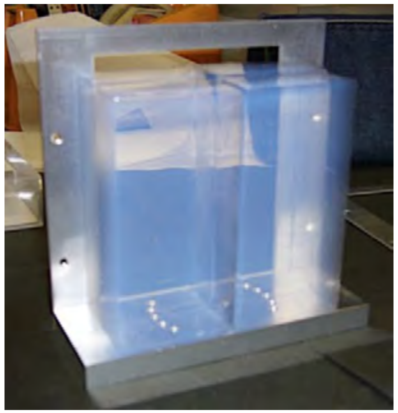
Cherenkov Light

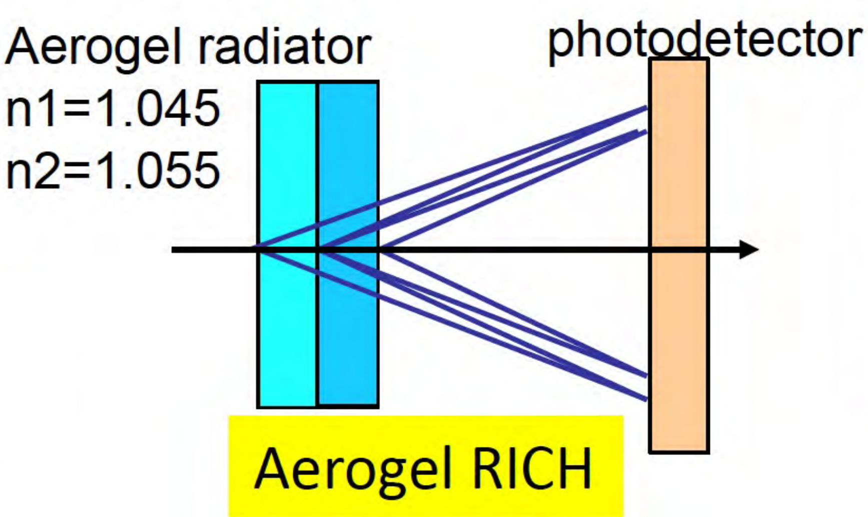
Cone angle θ measurement type
measure the ring image of
the Cherenkov light, measure β,
and pin-down the particle species.

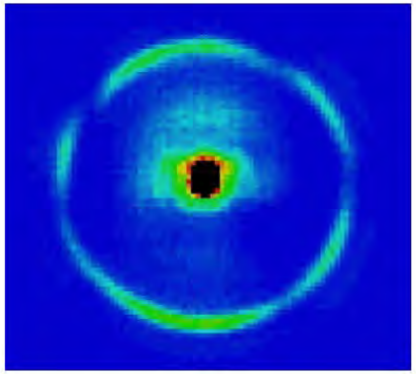


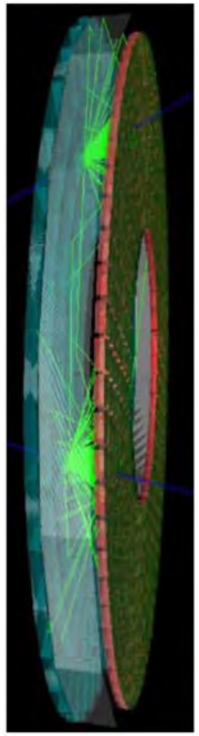


Belle-II Aerogel Ring-Image Cherenkov Counter









π/K separation by θ measurement.
"Focus" the images by double-radiator configuration.

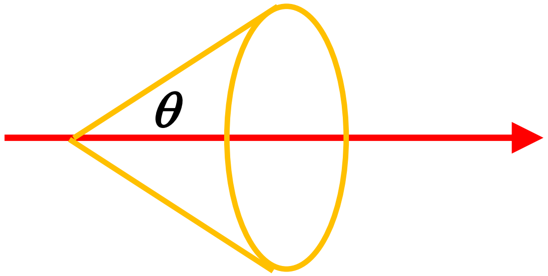
Super-Kamiokande Water Cherenkov Detector

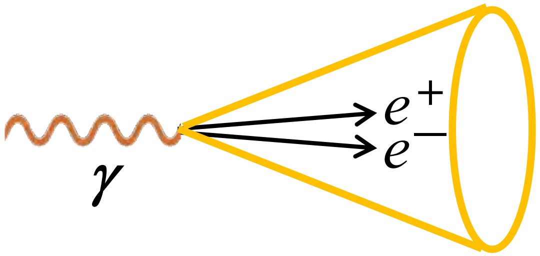
Cone angle θ measurement type

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

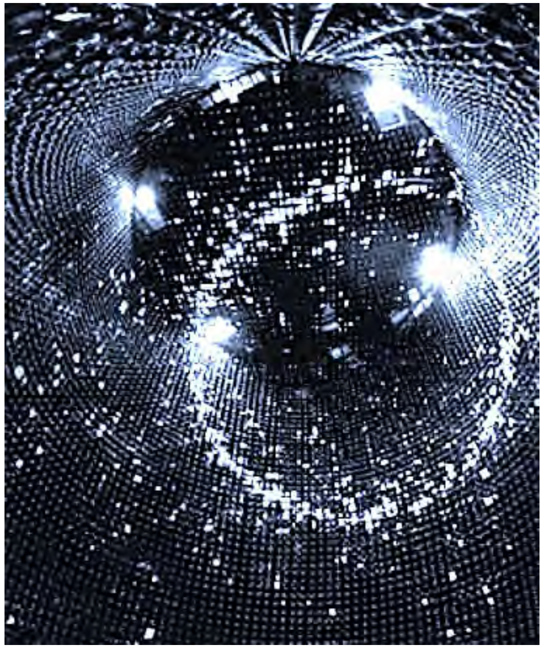
e,μ identification with θ and ring image analysis.

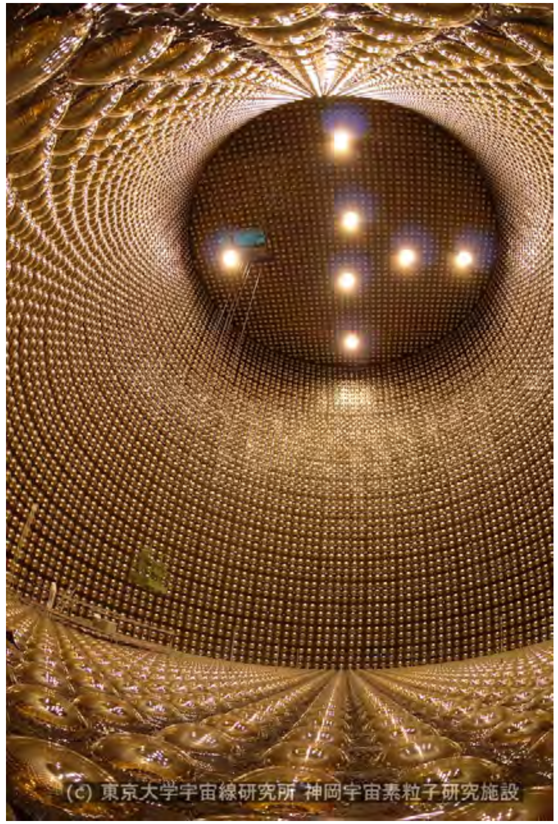
Timing of PMTs → vertex position
Distance and ring radius → emission angle θ
θ and ring image → e,μ identification
Ring charge → particle β obtained.





γ can also be detected.





Transition Radiation Detector

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

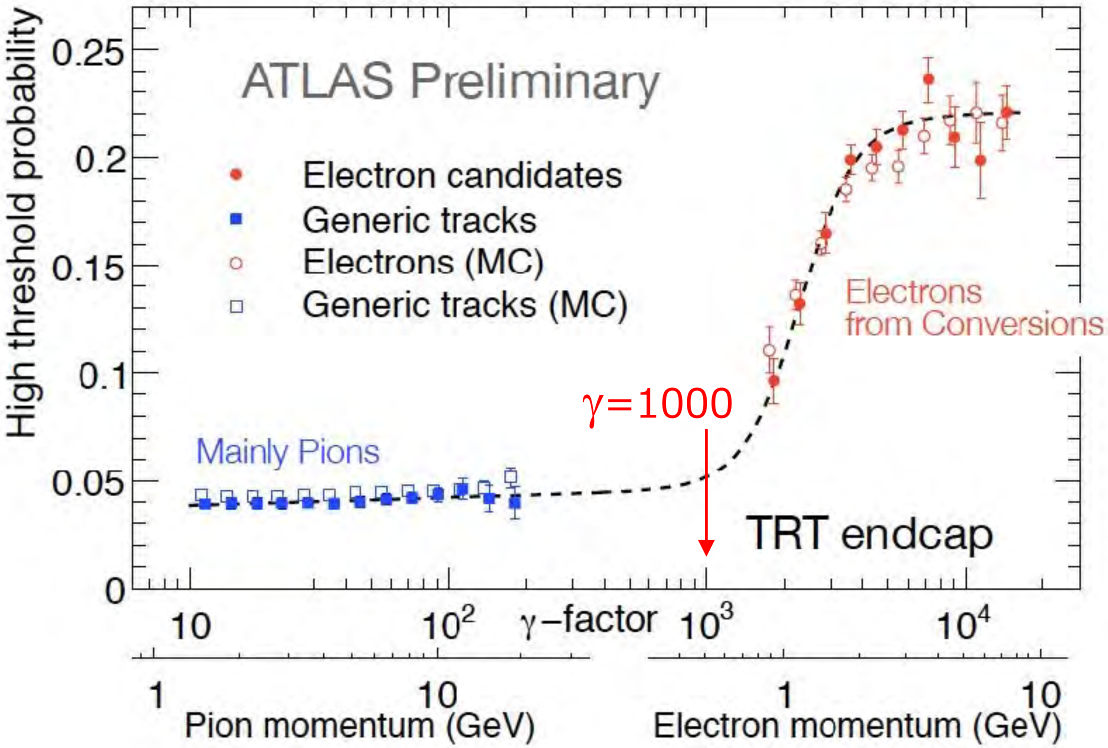
Emitted energy *S* is proportional to γ

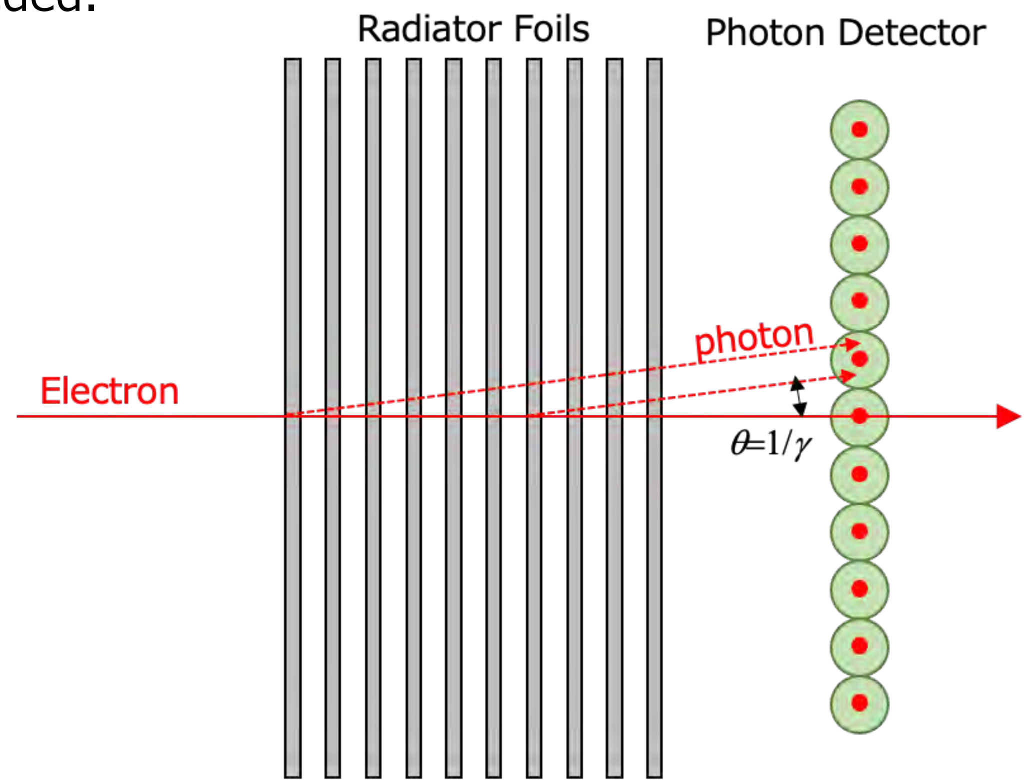
$$S = \frac{1}{3}\alpha z^2 \hbar\omega_{\rm p}\gamma \;,\; \hbar\omega_{\rm p} = \sqrt{4\pi N_e r_e^3 m_e c^2/\alpha}$$

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

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

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





Transition Radiation Detector

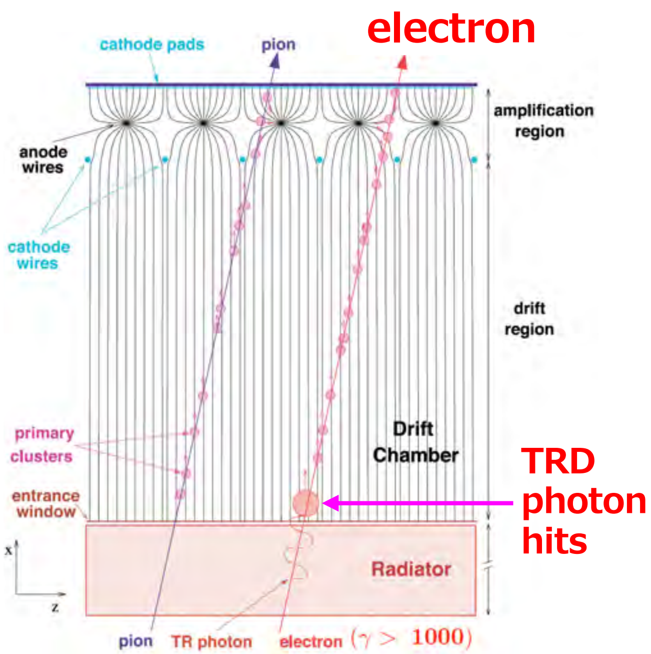
ALICE TRD

ALICE TRD : electron–ID and tracking

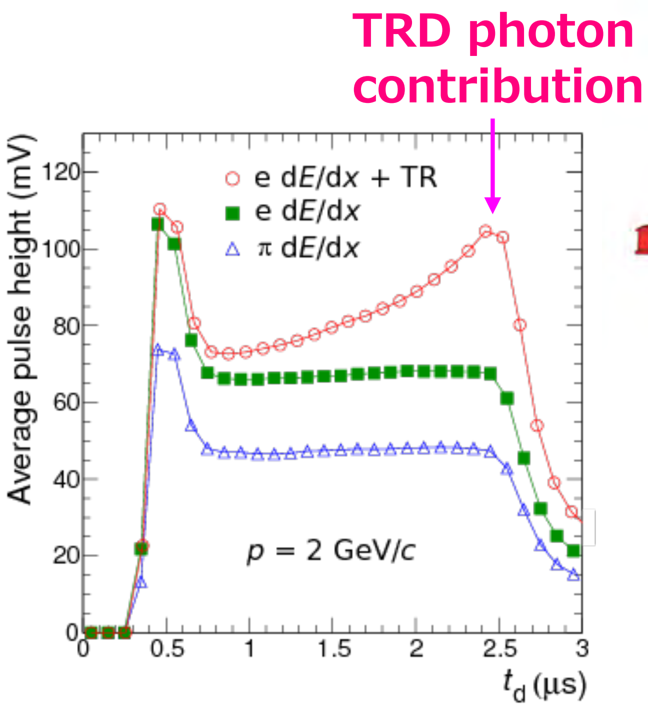
Catch $J/\phi, \Upsilon \rightarrow e^{+}e^{-}$

Radiator : Polypropylene fiber of 17μϕ

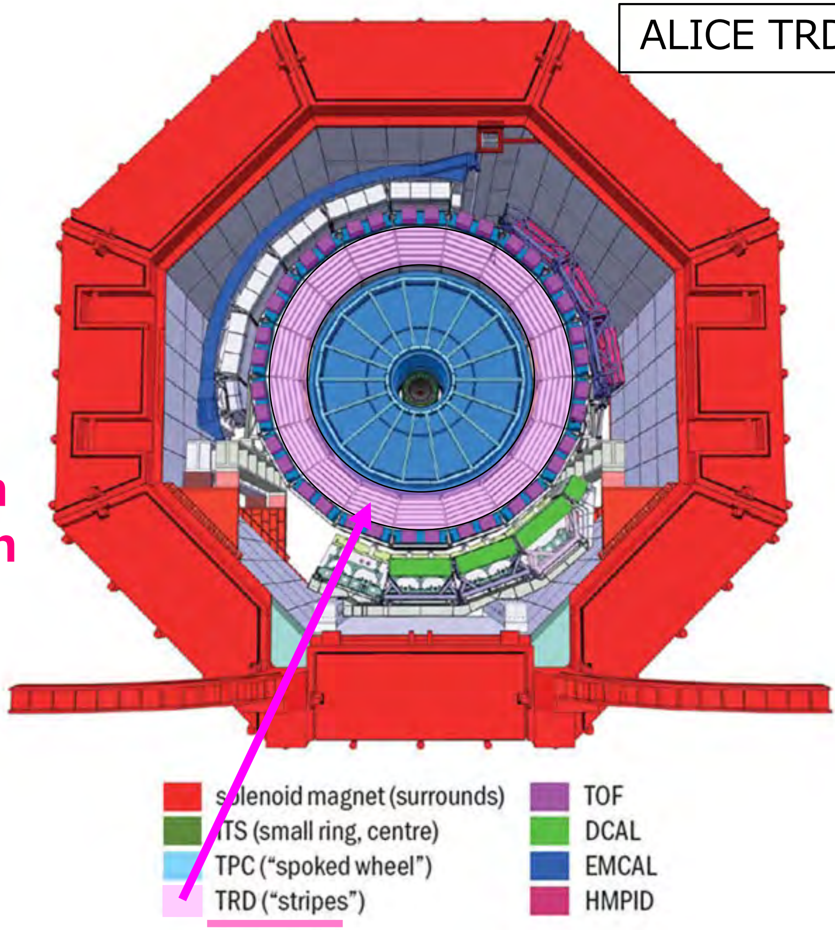
Detector ; drift chamber with Xe/CO2-gas

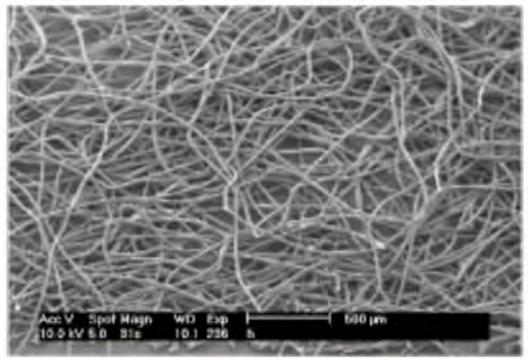


Layout of TRD, and X-ray conversion and tracks.



Signals from pions and from electrons.





Fiber radiator

Figures taken from M.J.Kweon, QM09

5.Calorimeter

Measure total energy of the particle by
absorbing all its energy by "shower" interaction.
Muons only can penetrate the calorimeter
and be measured by following muon detector.

Electromagnetic Shower

When an electron (or a γ) enters into material, it initiates cascade shower and deposits all its energy to the material.

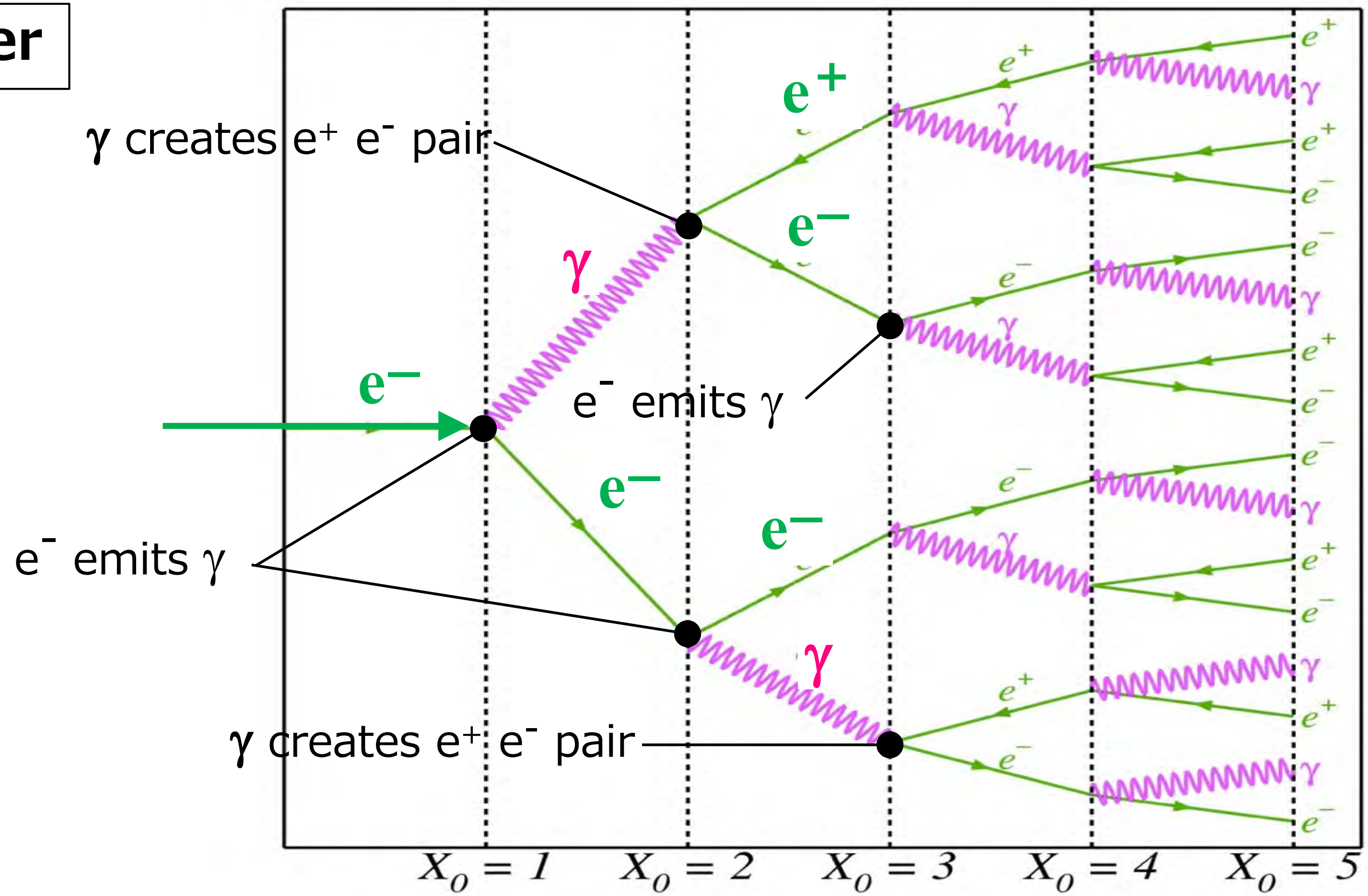


Figure from K.Lang.

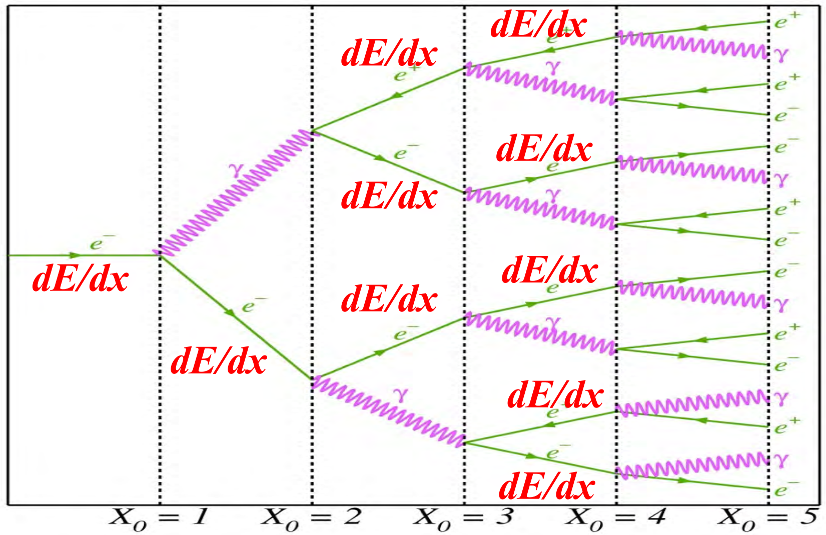
High-energy electron emits **γ**,
→ Emitted **γ** creates electron-positron pair,
→ Pair-created electron/positron again emits **γ** , , ,

This way, number of e+/e-/γ rapidly increases.
→ electromagnetic cascade = **shower**

Electromagnetic Shower

Cascade shower deposits all its energy to the material by energy loss of electron/positron.

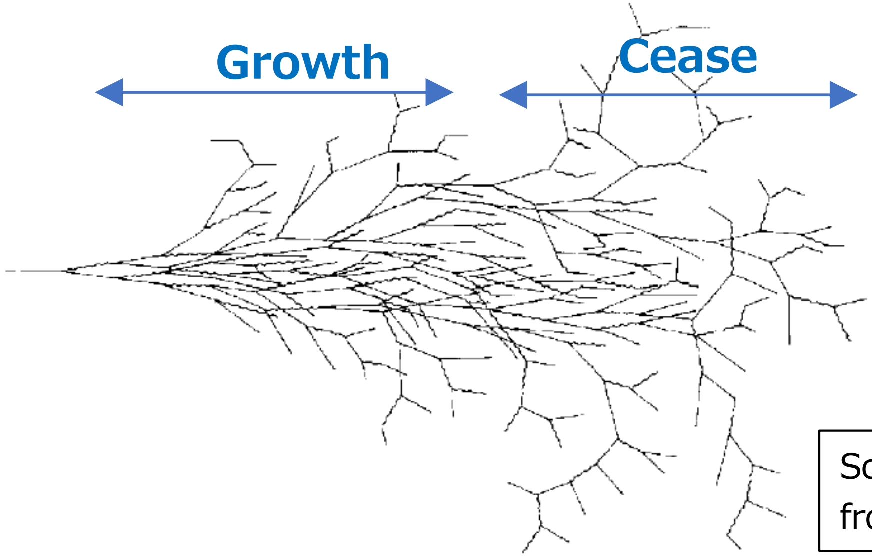
→ Electromagnetic shower is used to measure total energy of electron and γ.



Measure dE/dx of electrons and sum up.

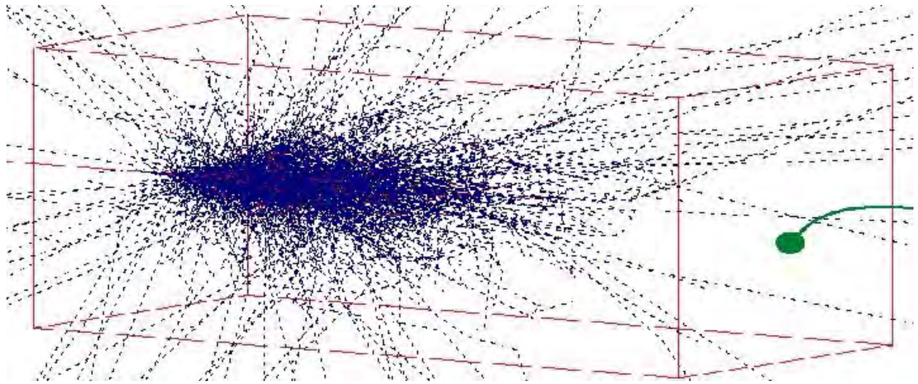
E = C・Σ (dE/dx) / sampling fraction

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.



Schematic figure from Grupen

GEANT simulation EM shower. Quite dense and crowded.



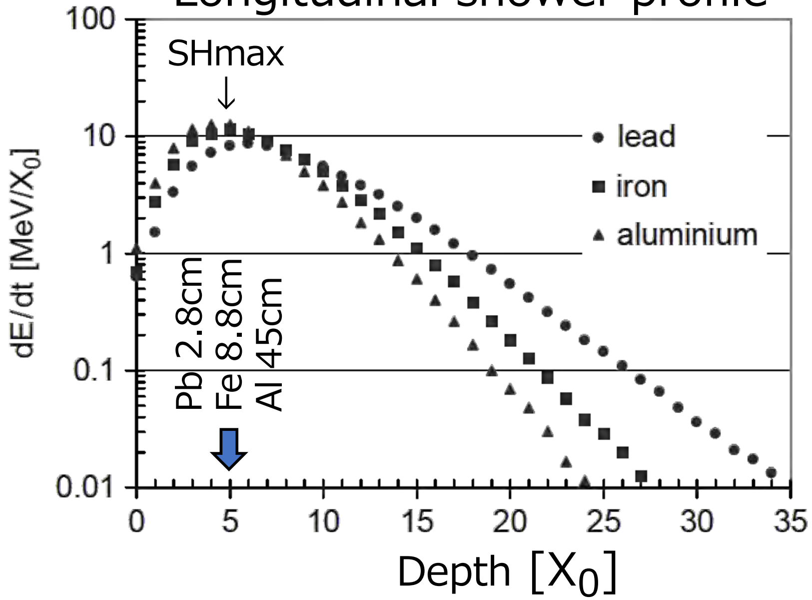
from Erika.

ElectroMagnetic Calorimeter

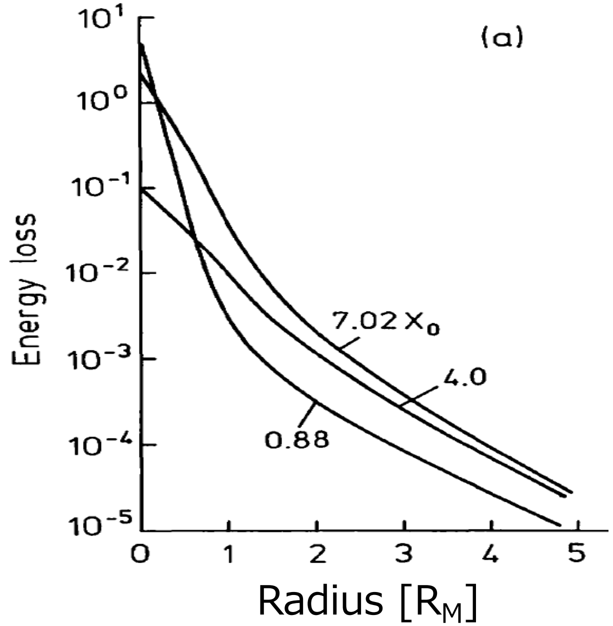
Calorimeter measures particle energy through cascade shower phenomenon.

- Dense material immediately initiate shower and develop cascade quickly.
  → Dense material is better for calorimeters.
- Shower size characterized by
  - radiation length X_0 (longitudinal size)
  - Molier radius R_M (transverse size).
- Sizes depend on material.
  Heavier material gives compact shower size.

Longitudinal shower profile



Transverse shower profile at different depth



There are two types of configurations;

1) Sampling calorimeter

Separate material to develop cascade (absorber) and material to measure energy (active media), and interleave them.
→ heavy metal used as absorbers, and free for active media.

2) Homogeneous calorimeter

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

ElectroMagnetic Calorimeter

a) Sampling Calorimeter

Interleave active layers and absorber layers.

- Active media (signal-readout layers)
  scintillator, silicon,
  noble liquid, gas chamber, , ,
  Energy loss in the active layers are measured and summed up.
- Absorber
  Lead, Iron, Tungsten, Copper, , ,
- Geometry
  sandwich, spacal, accordion, shashlik, , ,

Structural parameters are determined by required performance and shower sizes ;

- total thickness
- granularity/segmentation
- sampling frequency
- absorber thickness
- readout method/geometry etc.

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

Active layer.
Measure energy of passing charged particles.

Energy deposit by e-/e+ are summed up and converted to the total energy, corrected by sampling fraction.

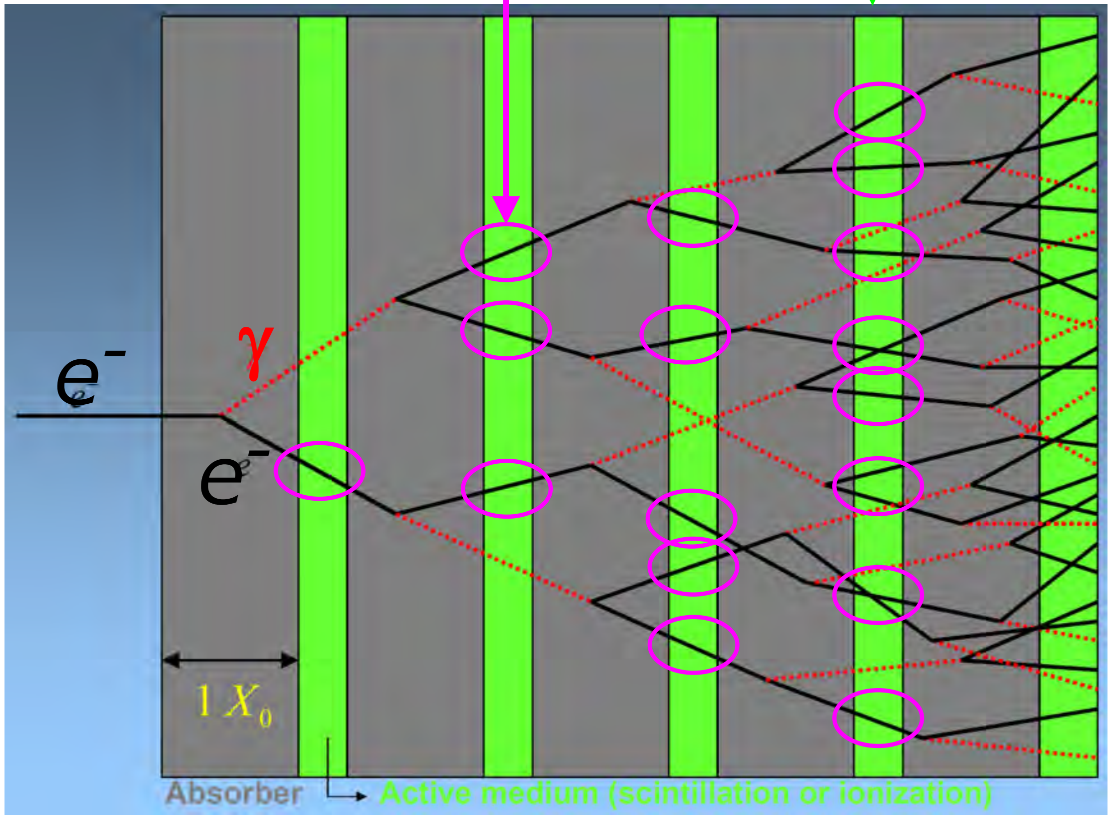


figure from P.Krieger, "ATLAS calorimetry"

ElectroMagnetic Calorimeter

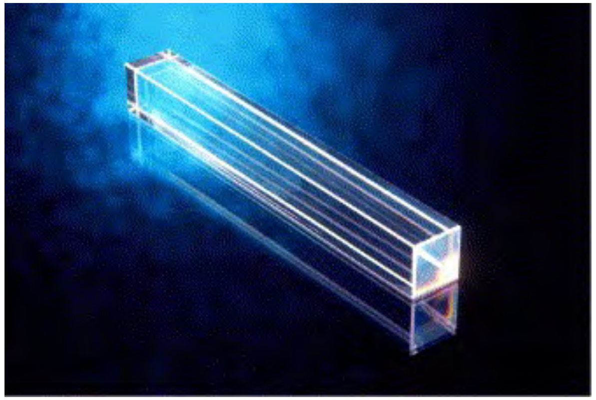
b) Homogeneous Calorimeter

The material initiates/develops shower and measure energy loss.

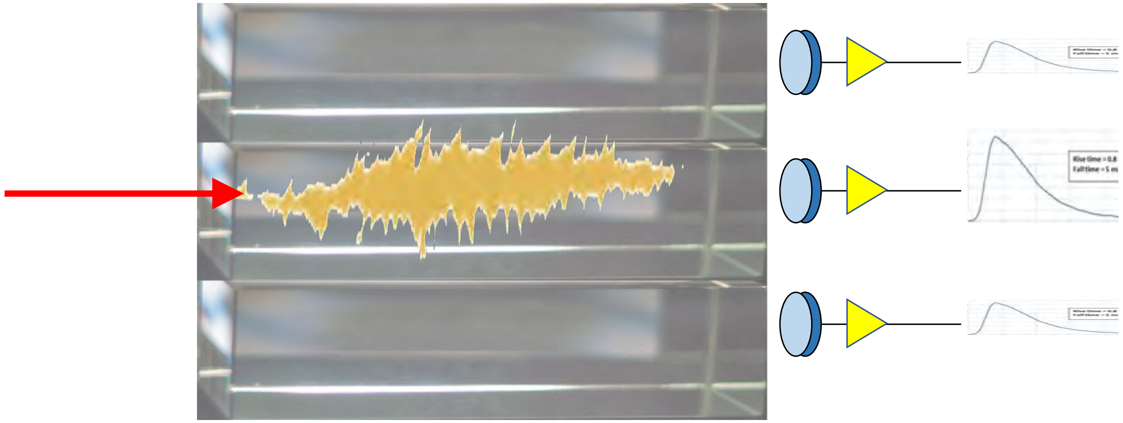
- crystals (use photons) or
- noble liquid (ionization or photon)

Structural parameters are determined by required performance and shower sizes ;

- total thickness
- granularity/segmentation size
- readout method/geometry 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

b ; noise term

c ; constant term
- shower leakage → thick calorimeter, no gap
- dead material → thinner tracker
- imperfection → quality control
- etc.

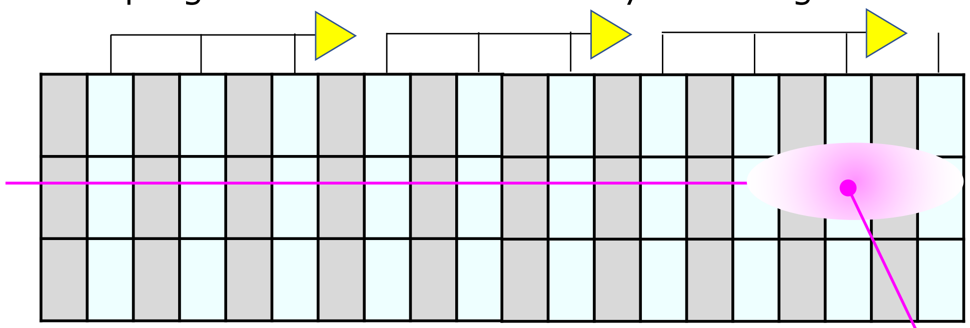
Structural parameters are determined by required performance and shower sizes ;
- total thickness → shower leakage → linearity, resolution(constant term)
- granularity/segmentation → position measurement, cluster separation, PID
- active material choice → signal size → resolution(stochastic term, noise term)
- active material thickness → signal size → resolution(stochastic term, noise term)
- absorber material choice → shower size → position measurement, cluster separation, PID
- absorber plate thickness → signal size → resolution(stochastic term, noise term)
- sampling frequency → fluctuation → resolution(stochastic term)

Segmentation/Granularity

- 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.

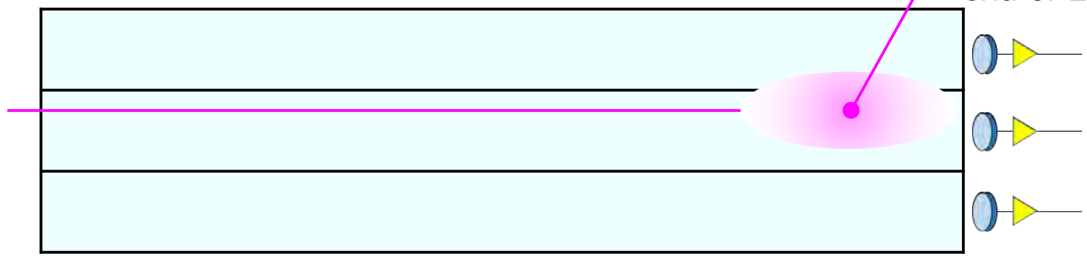
→ Dense (small R_M) material and fine segmentation

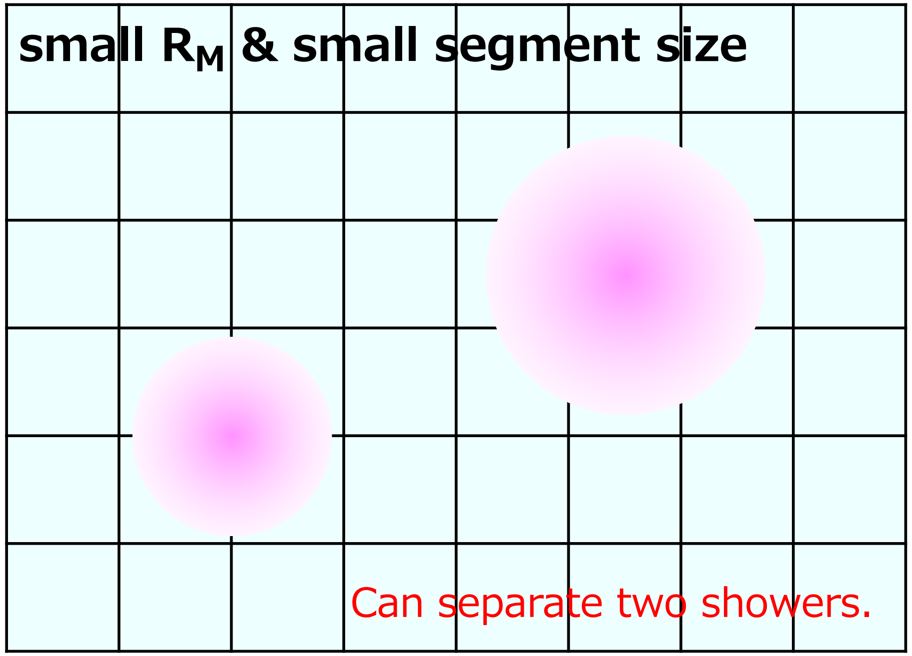
Sampling calorimeters can naturally have longitudinal segmentation.

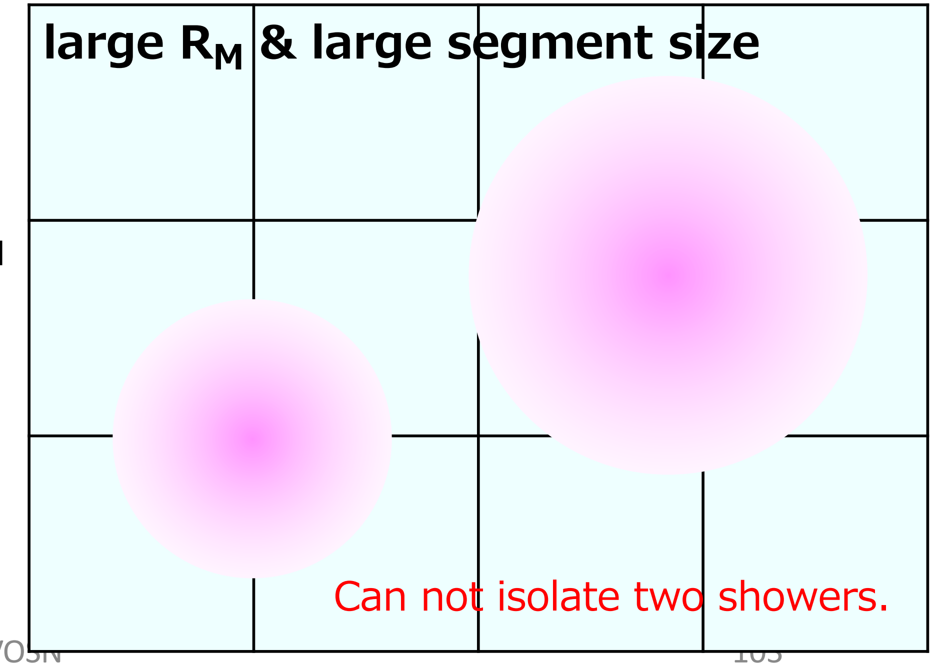


A hadron initiated shower near the end of EMcal.

Longitudinal segmentation is difficult for crystals.

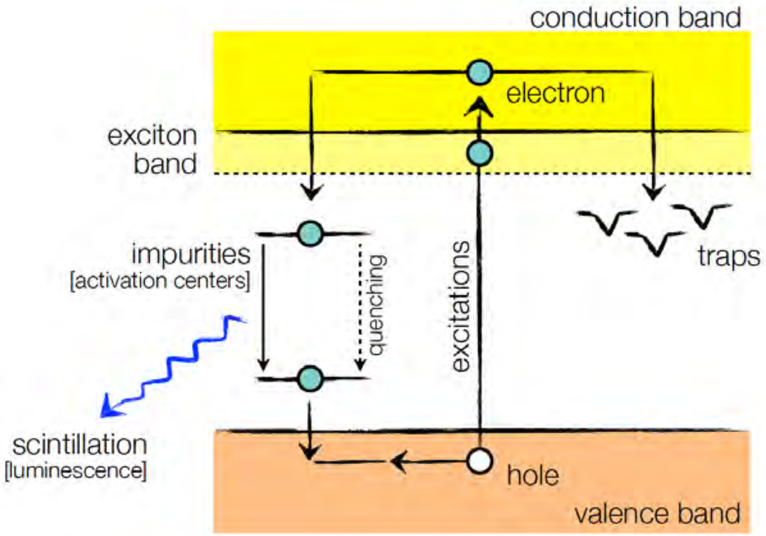


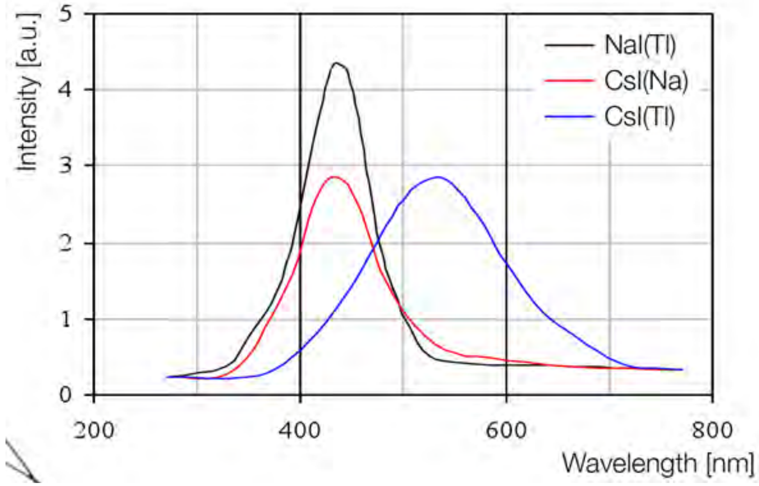




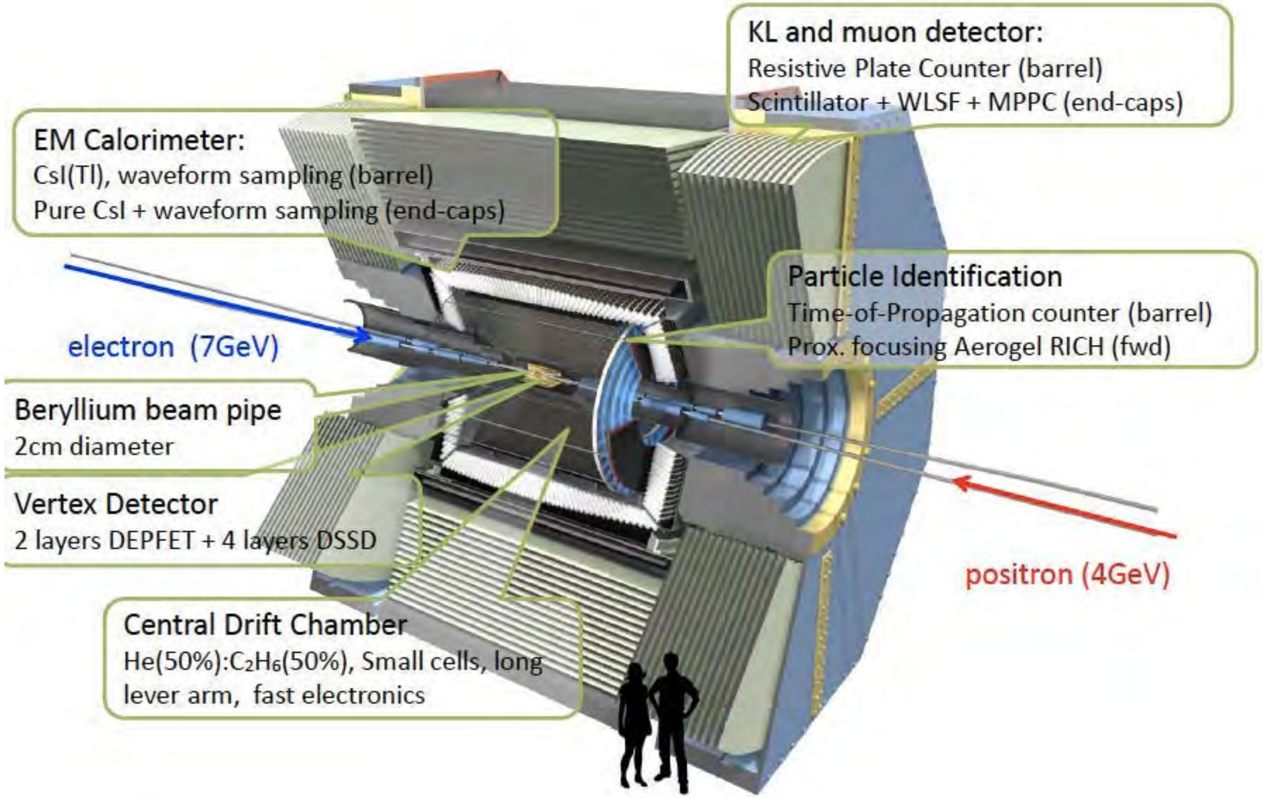
Homogenous Calorimeter

Belle-II ; CsI (Tl-doped)





taken from Erika

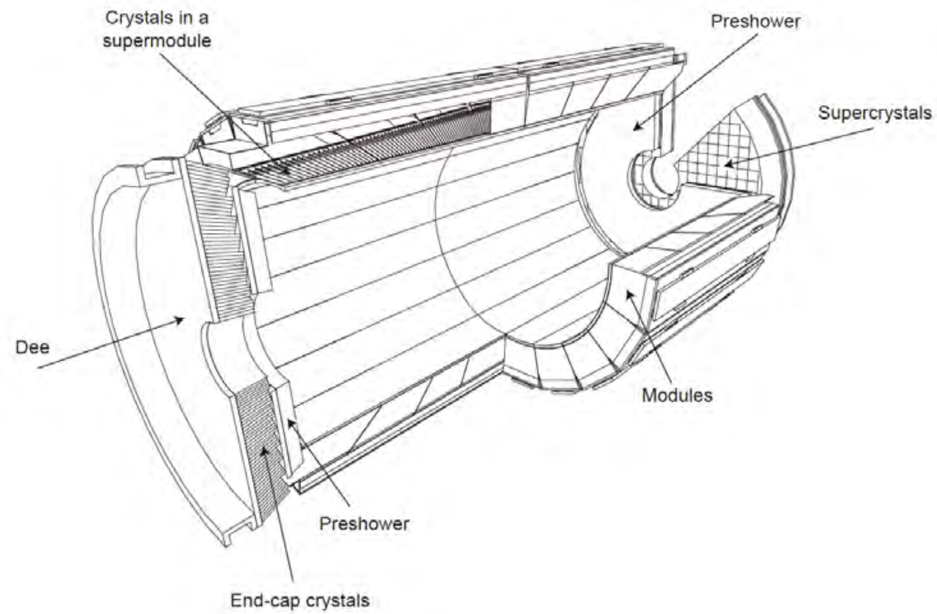


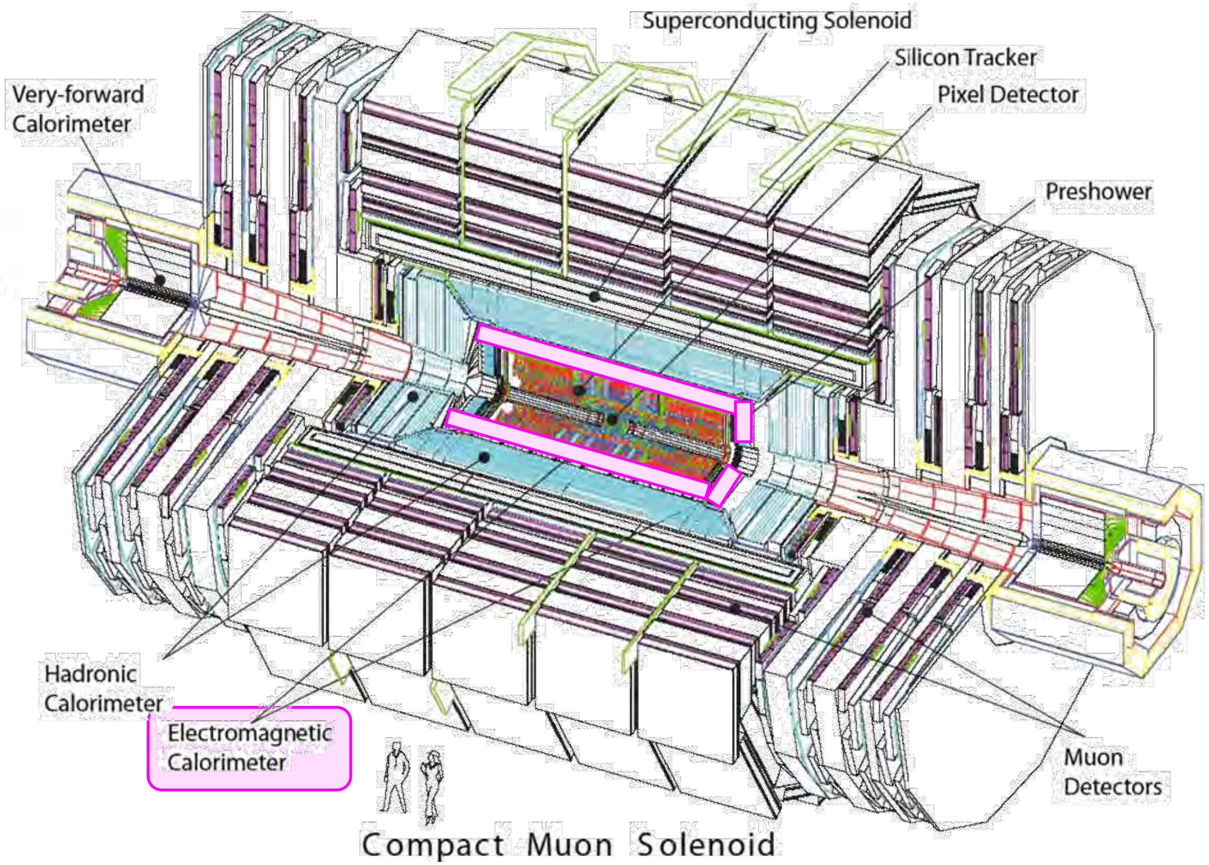
$$(\sigma_E / E = 0.066\% / E \oplus 0.81\% / E^{1/4} \oplus 1.34\%)$$

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 (a bit slow)

5. Operation of detectors ; Calorimeters

Homogenous Calorimeter
CMS ; PbWO4



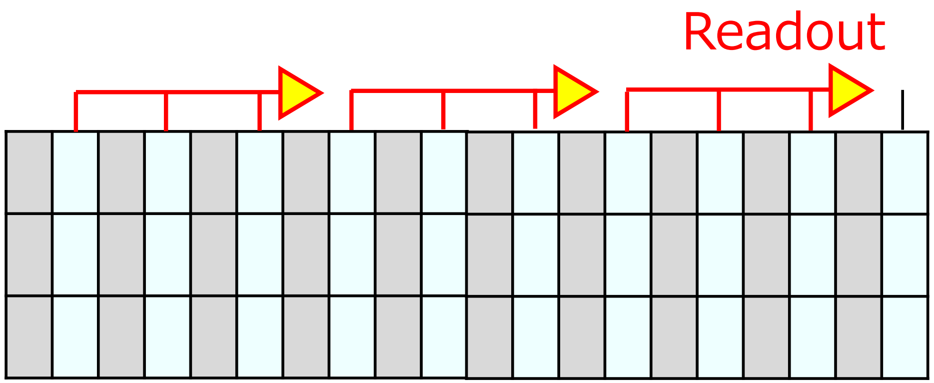


$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{3.37\%}{\sqrt{E}}\right)^2 + \left(\frac{0.107}{E}\right)^2 + (0.25\%)^2$$

PbWO4 x 76,000 crystals, 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 : very fast → necessary for LHC rate.

Readout of sampling calorimeters

Active media to measure charged particle passage;



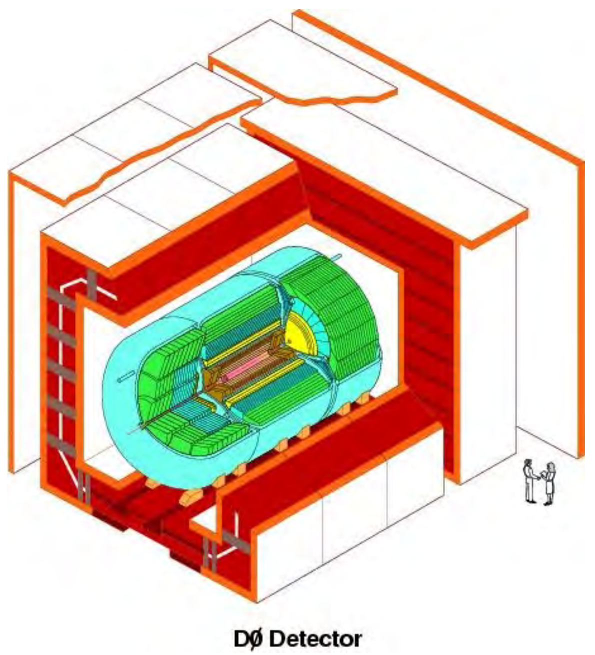
By ionization
- gas chamber
- silicon
- noble liquid
  - Use liquid Ar/Xe instead of gas.
  - Operation and configuration quite similar to the gas chambers.

By light (photons)
- plastic scintillator
  - variety of photon sensors ; PMT, Si, APD, SiPM/MPPC, Hybrids,,
  - readout method ; direct-couple, WLS-fiber/plate
- noble liquid

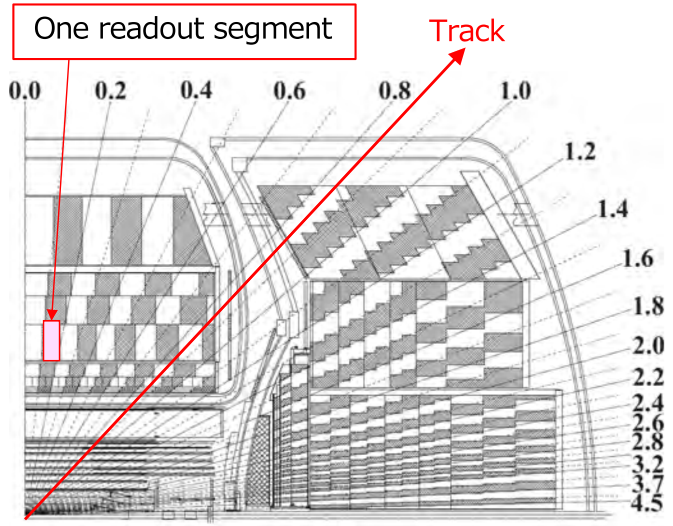
Readout of sampling calorimeter

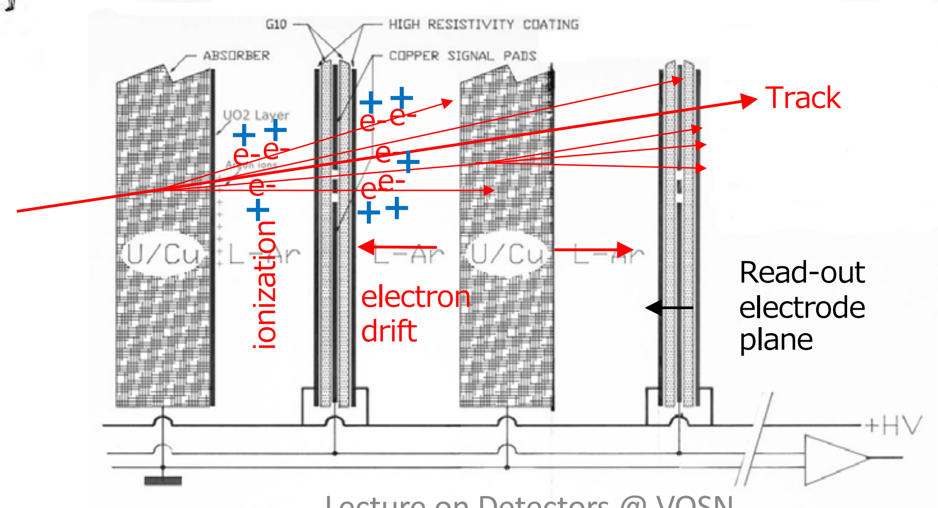
Noble Liquid ionization

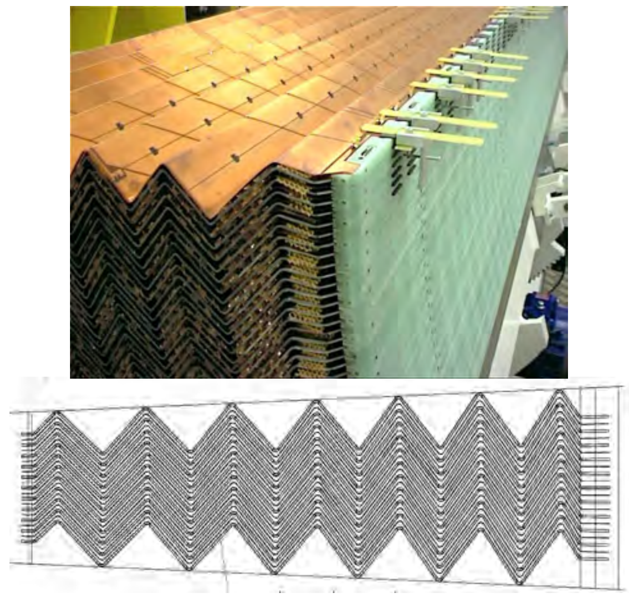
- Use liquid Ar/Xe instead of gas.
- Operation and configuration quite similar to the gas chambers.



D0 detector at Tevatron
Uranium-liq.Ar
sandwich calorimeter

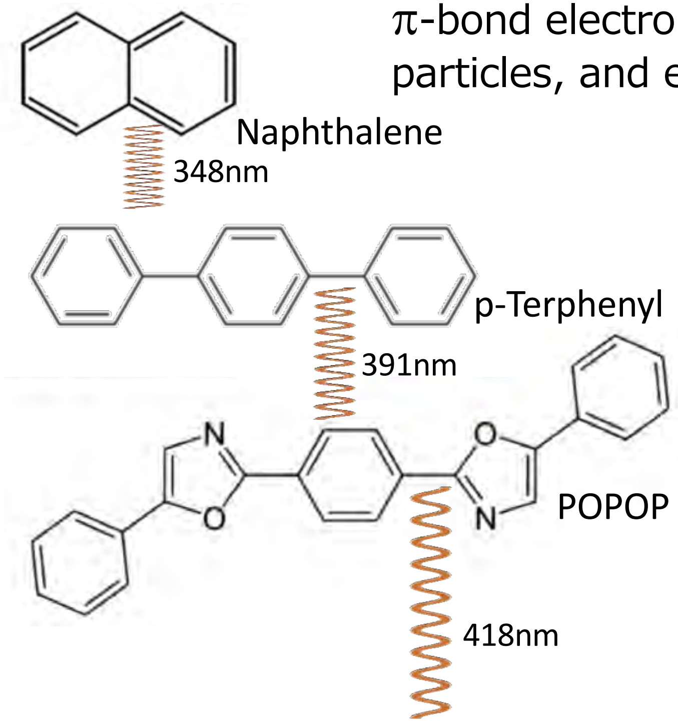






ATLAS liq.Ar EMCAL
Accordion shape absorbers to eliminate inter-segment gaps and to reduce inductance.
Can read out from back-end.

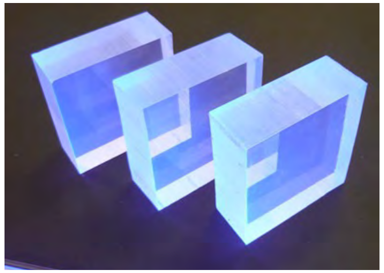
Organic Scintillator as active media



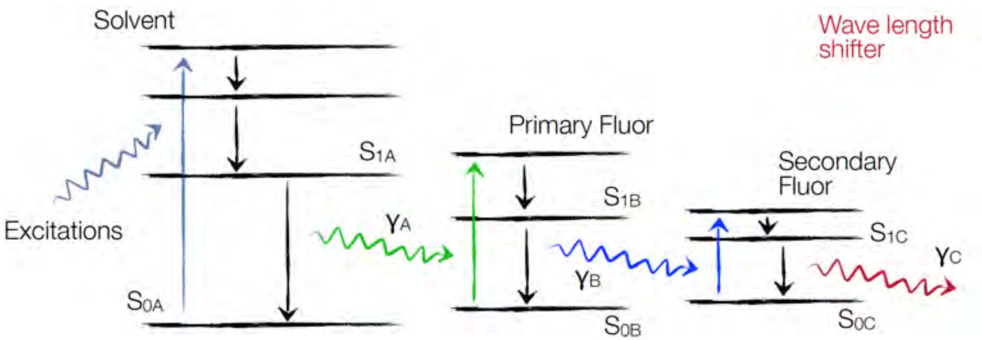
π-bond electrons are excited by charged particles, and emit photons when de-excited.

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.

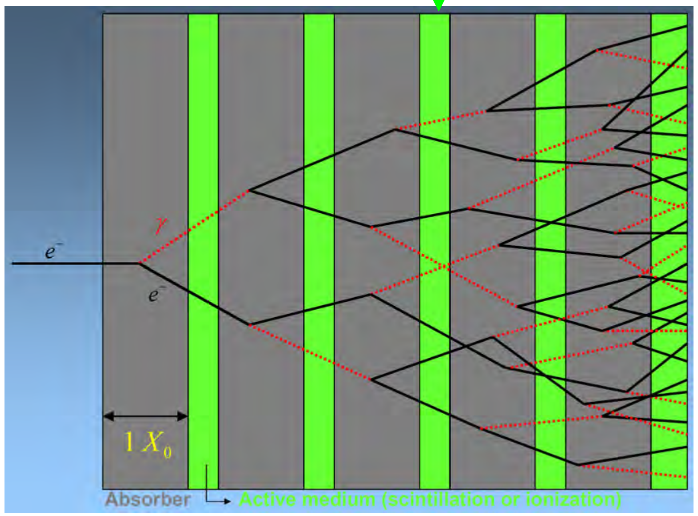


Plastic scintillators generate light when charged particles pass. Amount of light proportional to the energy loss. Measure the light by photo-sensors. Popularly used as read-out media.



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

Active plate. Measure energy of passing charged particles.

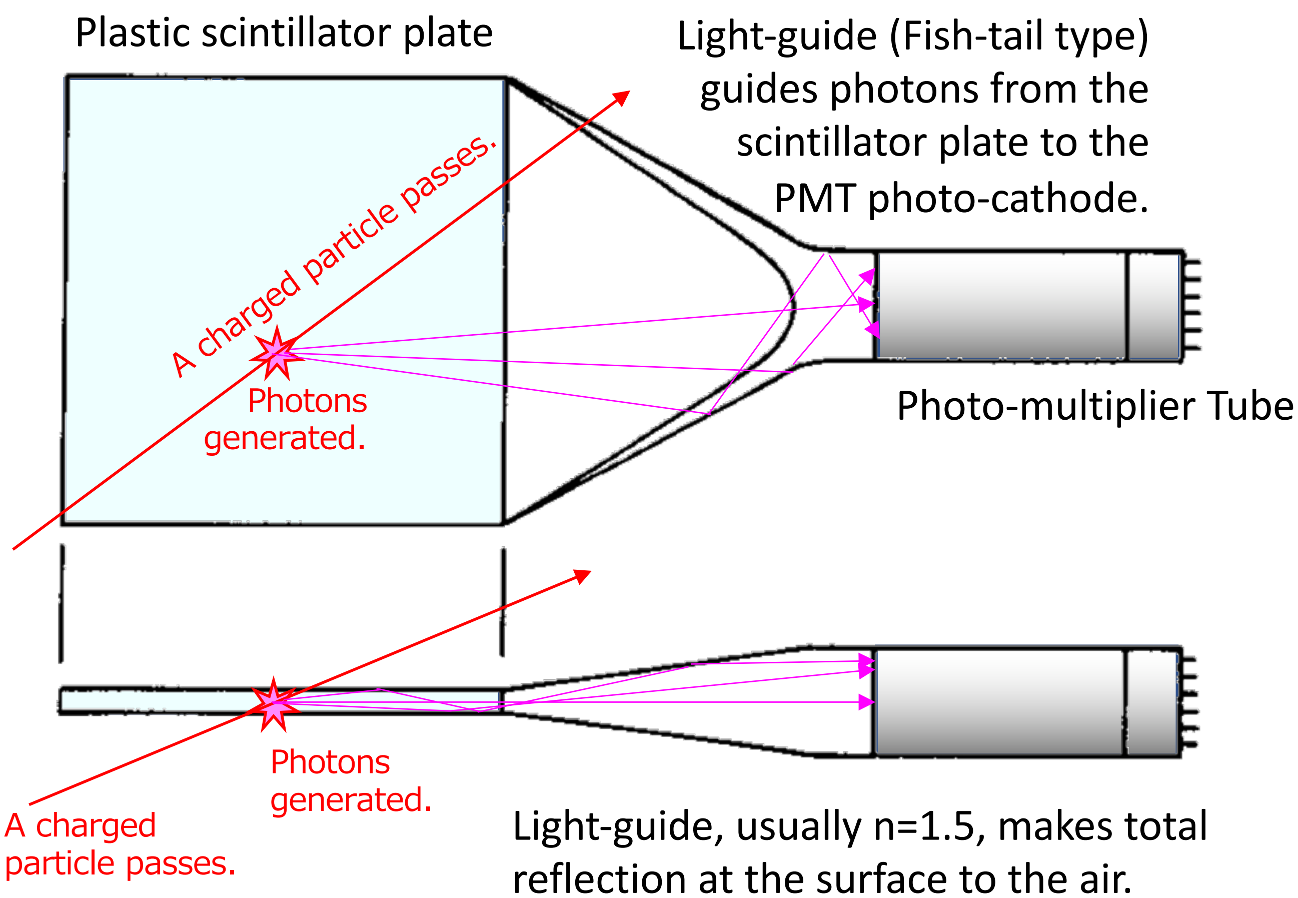


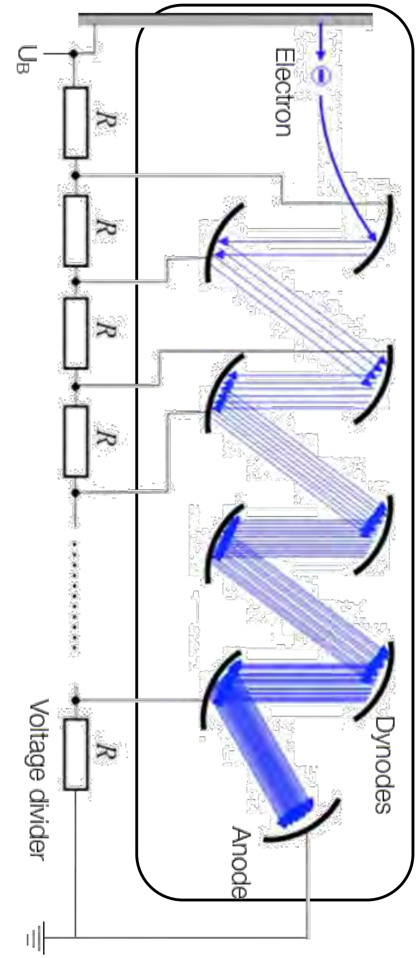
Scintillator + light-guide + PMT direct readout

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

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.

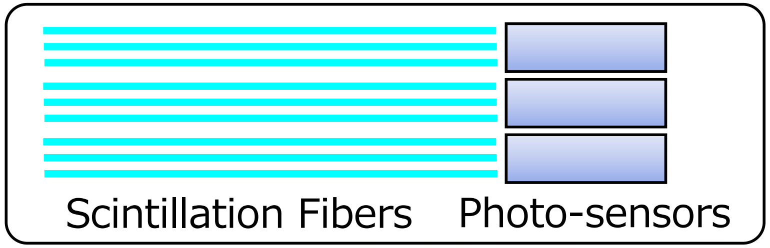


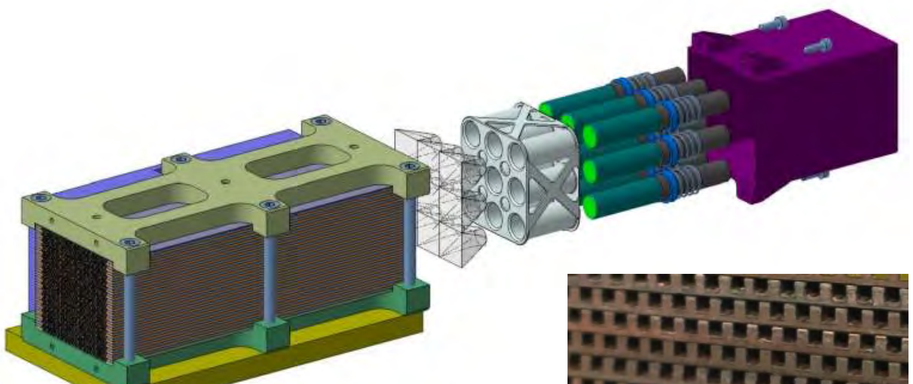


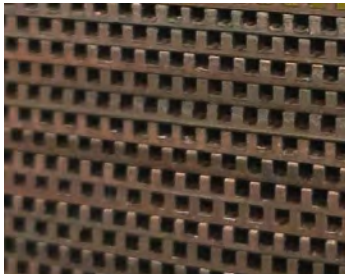
Scintillating-fiber direct readout : SPACAL

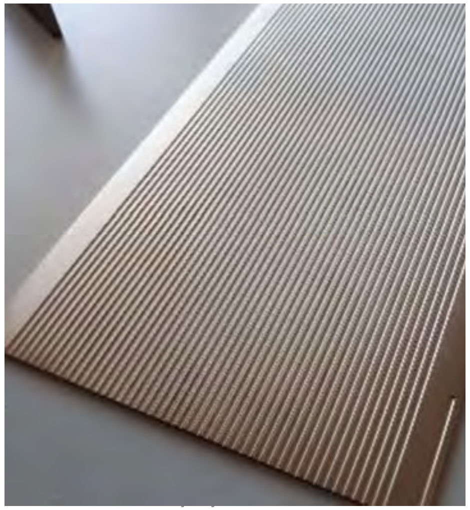
Fibers made of scintillators are embedded into grooves made on the absorber plate.
Back-end of the scintillation fibers are directly coupled to the photo-sensors.

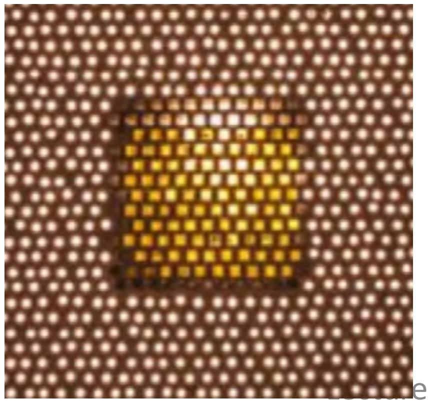
- Good transverse segmentation
- Longitudinal segmentation not easy.

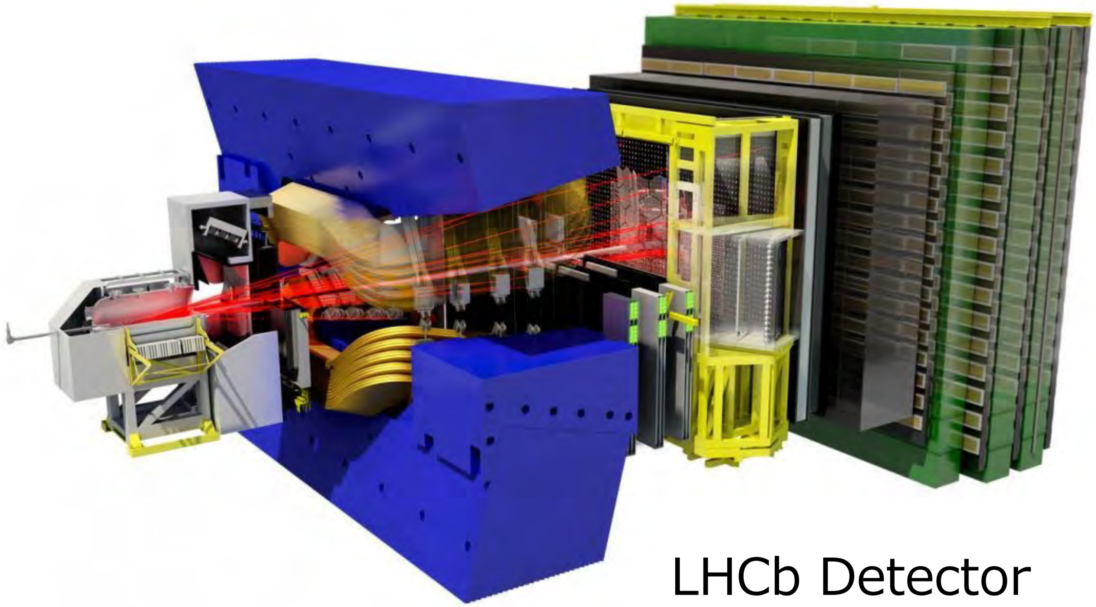












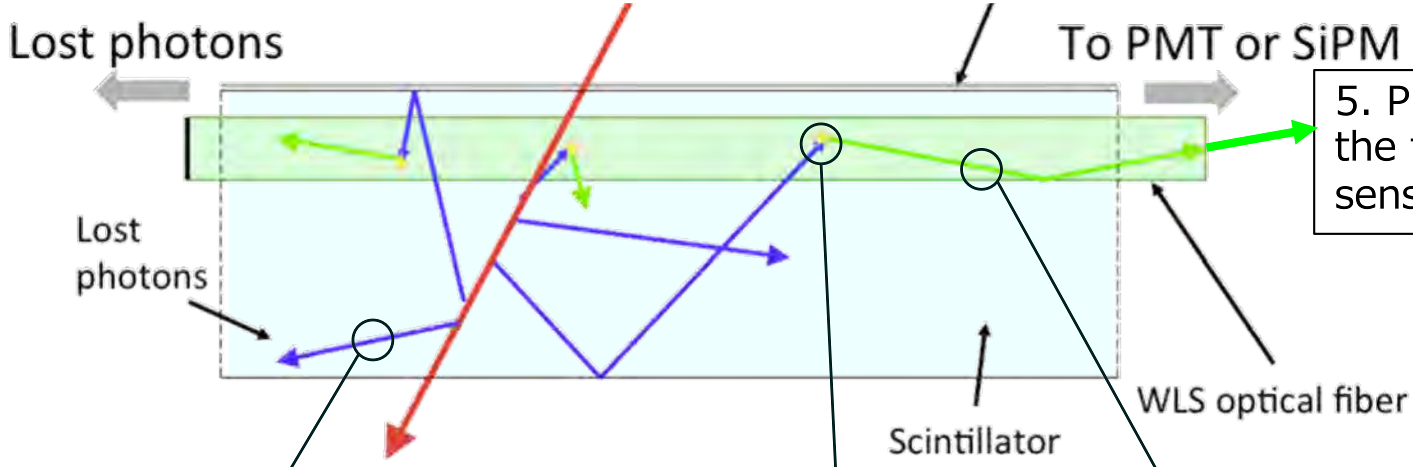
LHCb Detector

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.

1. A charged particle passes through.



5. Photons reached to the end of the fiber enters attached photo-sensor and generate a signal.

Photo-sensor has Q.E. of 20-40% → 10 electron signal.

2. Fluorescence photons are generated along the particle passage and travels to all directions.

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

3. Some of the photons enter the WLS fibers and re-emits secondary photons.

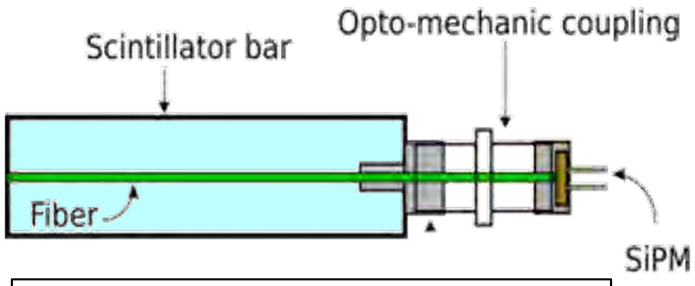
Depends on geometry, but typically a few % → 400 photons

4. Some of the re-emitted photons are trapped in the WLS fiber and travels to the end.

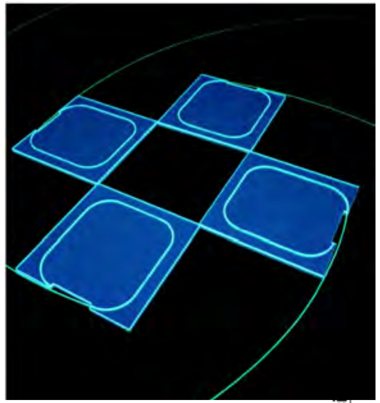
Typical double-clad WLS traps 5% → 20 photons,

WLS fiber/plate readout

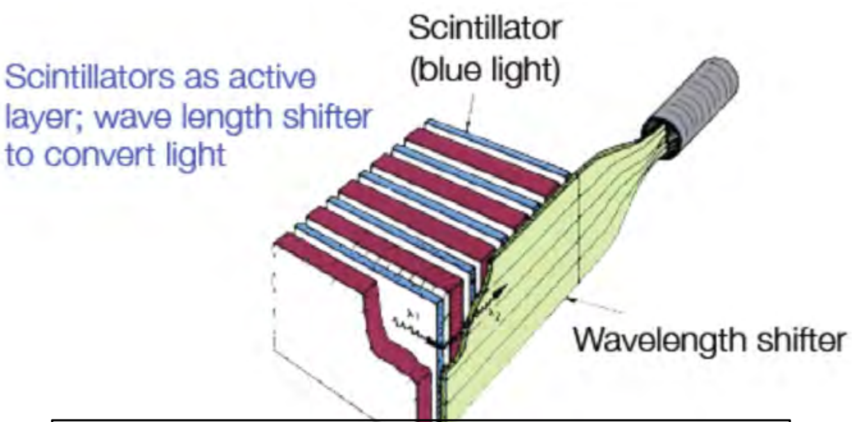
There are many of ways to couple scintillator plates and WLS fibers/plates



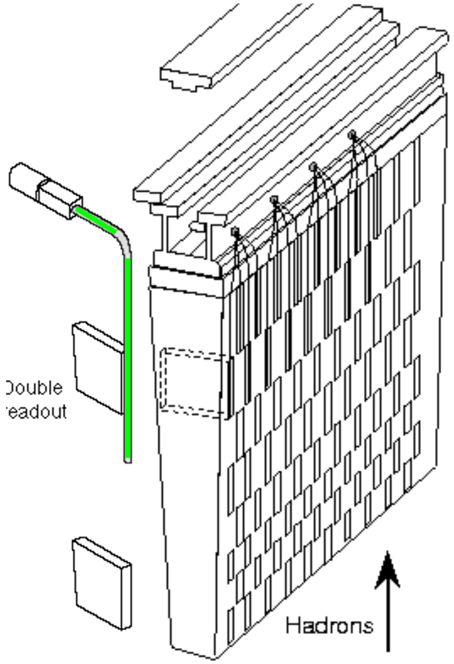
General scheme
A fiber in a scintillator bar.



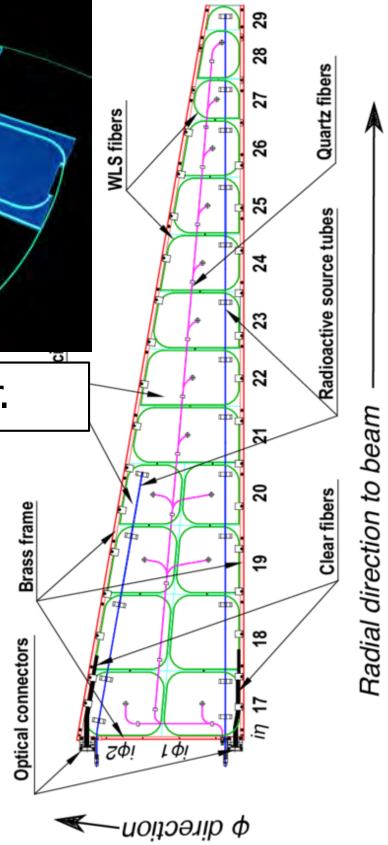
CMS tile-fiber.



ZEUS CAL
WLS-plates put both sides of tiles.



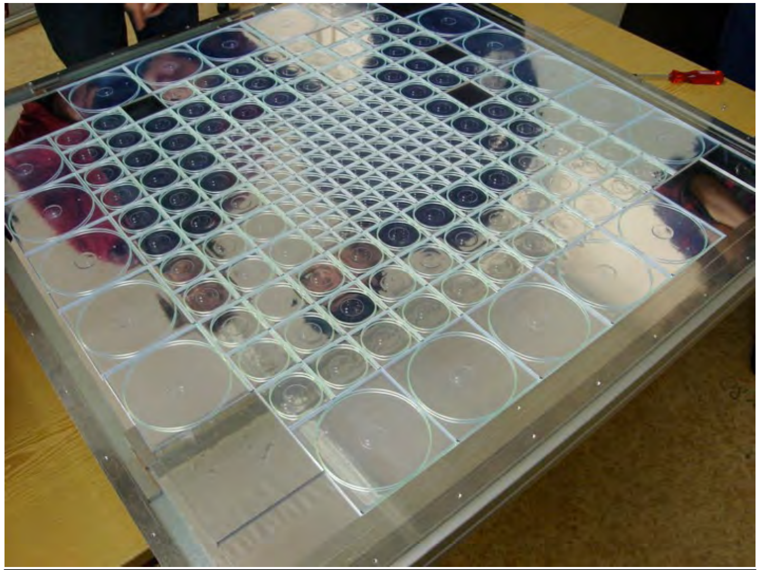
ATLAS HCAL
WLS-fiber put side of tiles.



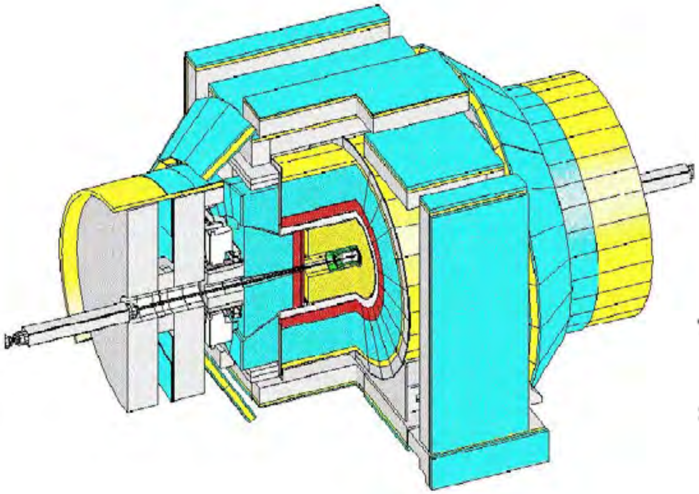
CDF mega-tile
WLS-fiber put in a groove.

Plastic Scintillator + WLS fiber sandwich

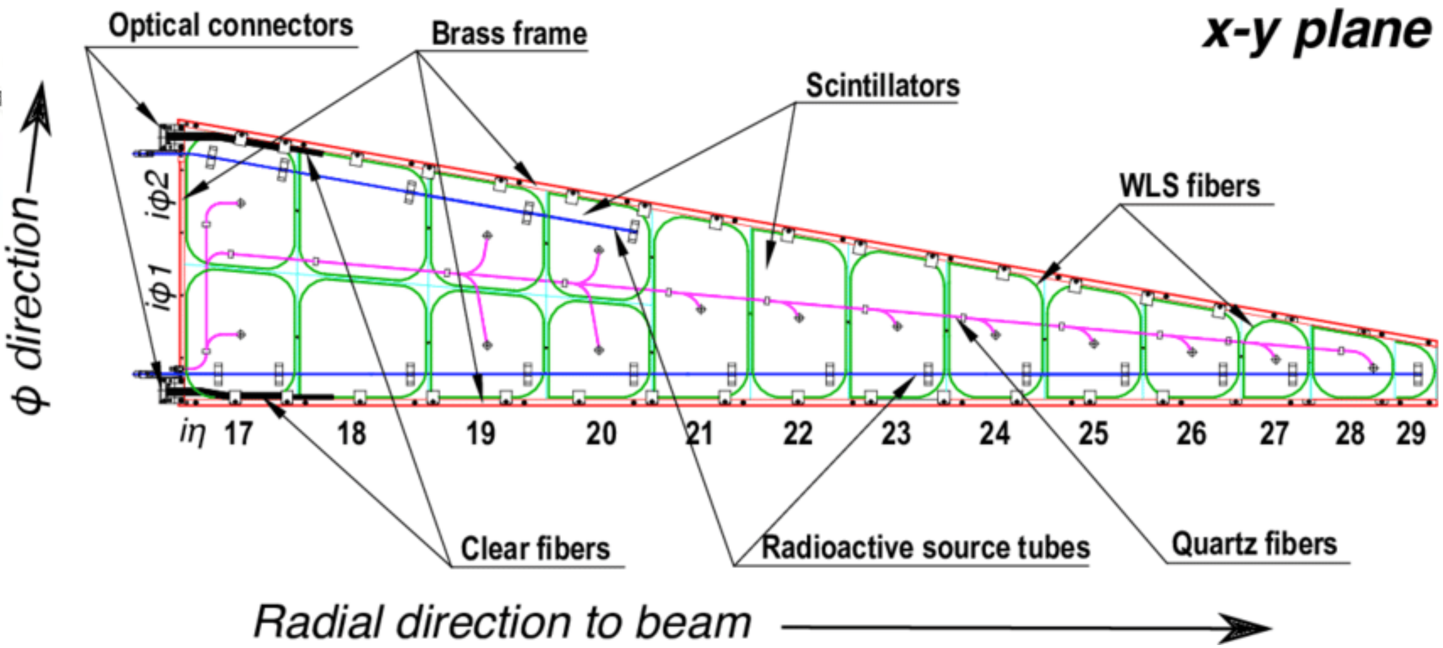
CDF/CMS calorimeter design: Tile-fiber
- A WLS fiber is put in a circular groove machined in a tile.
- Many tiles machined at once using large scintillator plate.
- WLS fibers are routed through another plate with grooves overlayed on the scintillator plate.



ILD mega-tile with varying tile size.

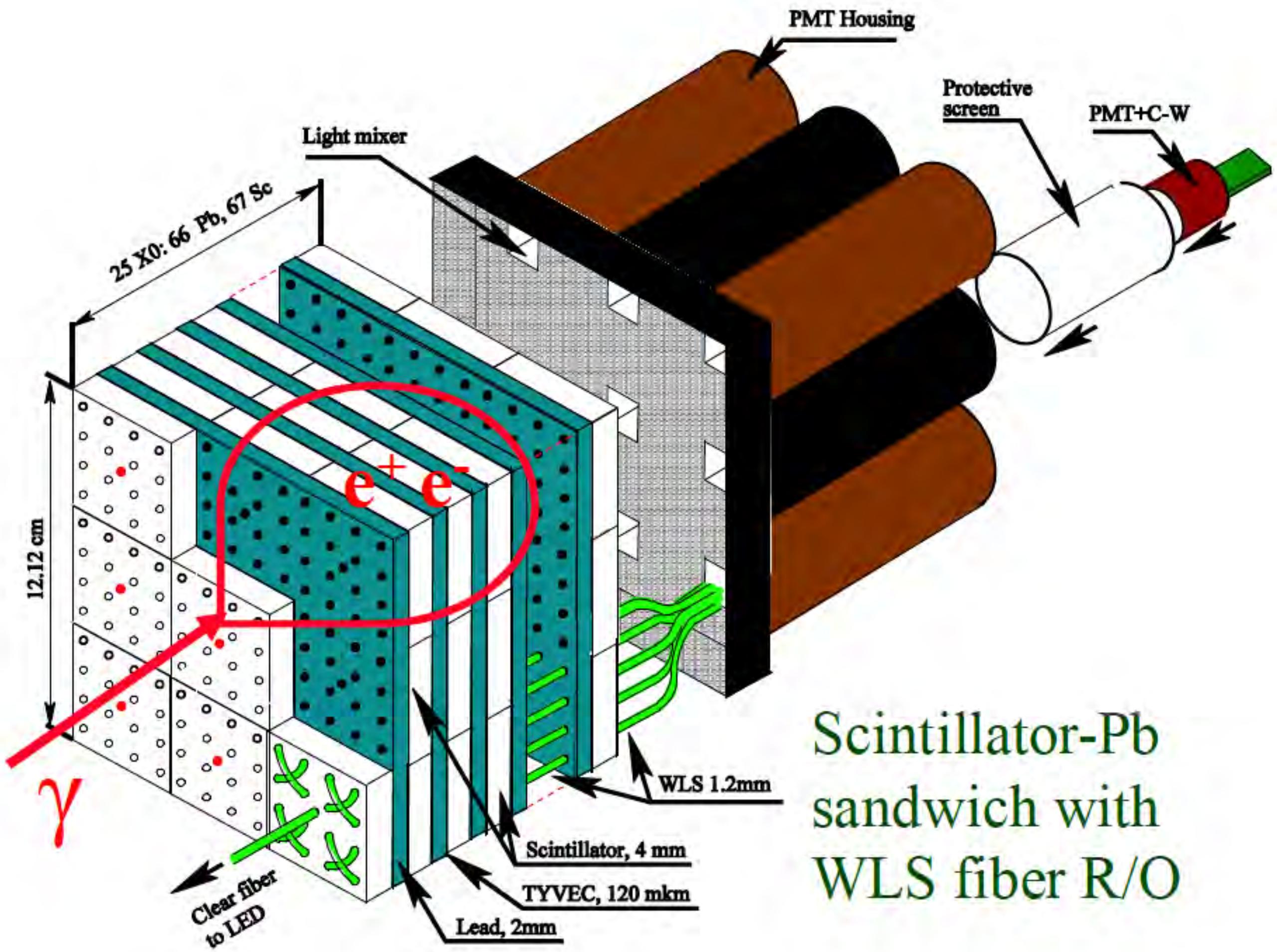


Basic parameter ;
density, Rshower, Nphoton,



Plastic Scintillator + WLS fiber shashlik

Shashlik design
- A WLS fibers run through holes machined in a tile.
- WLS fibers naturally reach to photo-sensors at the back.



Electron/γ identification with high-efficiency, low contamination

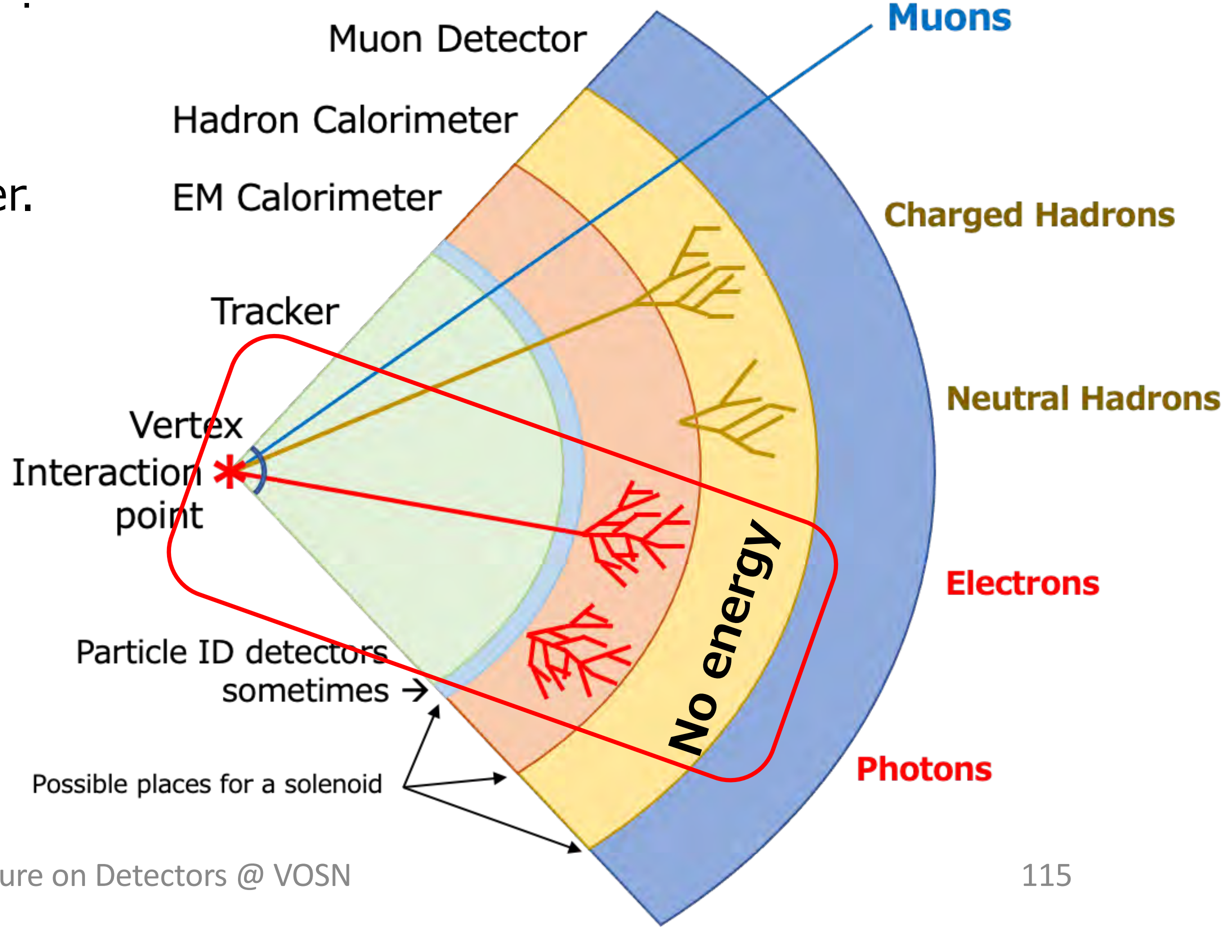
$H^0 \rightarrow \gamma\gamma$ channel was the highway to the Higgs discovery.
γ is a pure EM calorimeter cluster
without corresponding charged track nor following hadron calorimeter cluster behind.

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

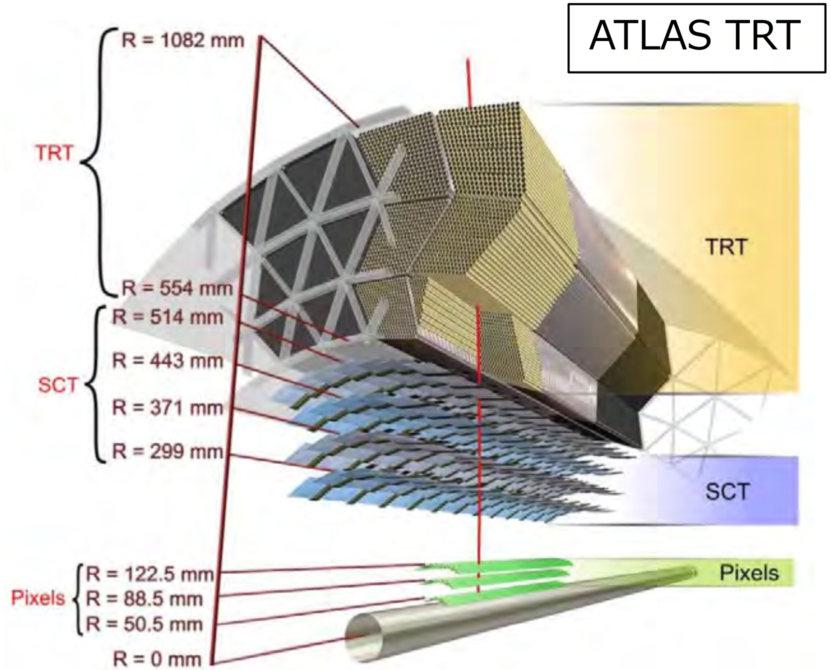
Additional e-ID with TRD



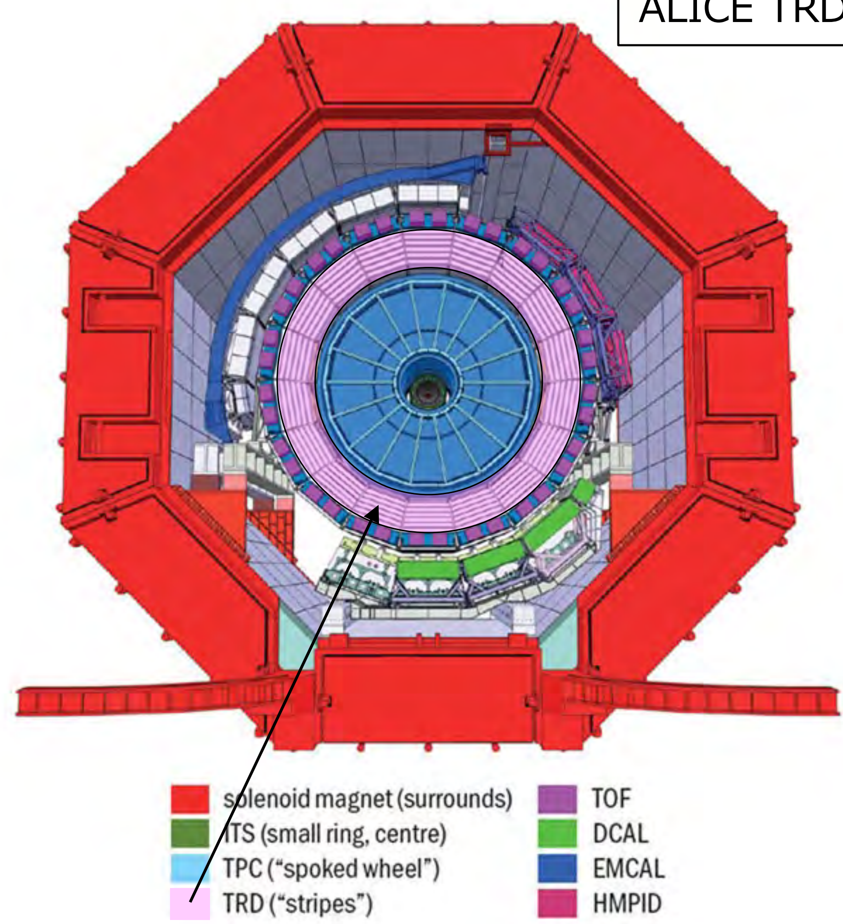
Electron identification with high-efficiency, low contamination

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

ATLAS TRT



ALICE TRD



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%

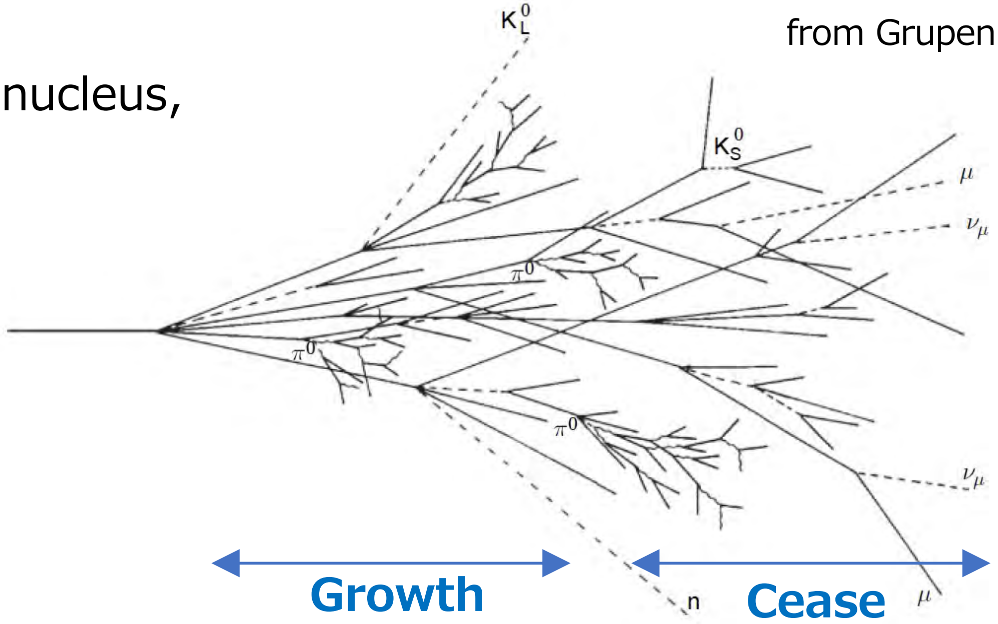
Hadronic shower

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

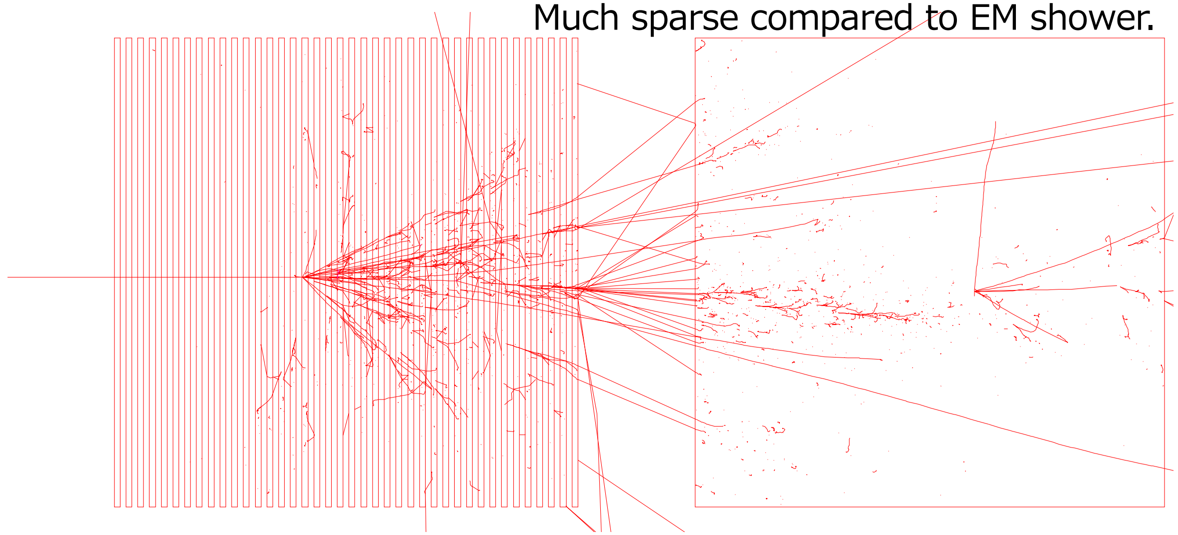
As shower growth, number of particles increases, and energy of each particle decreases.
Eventually their energy become too low to generate particles any more, and cascade ceases.

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.



5. Operation of detectors ; Hadron Calorimeters

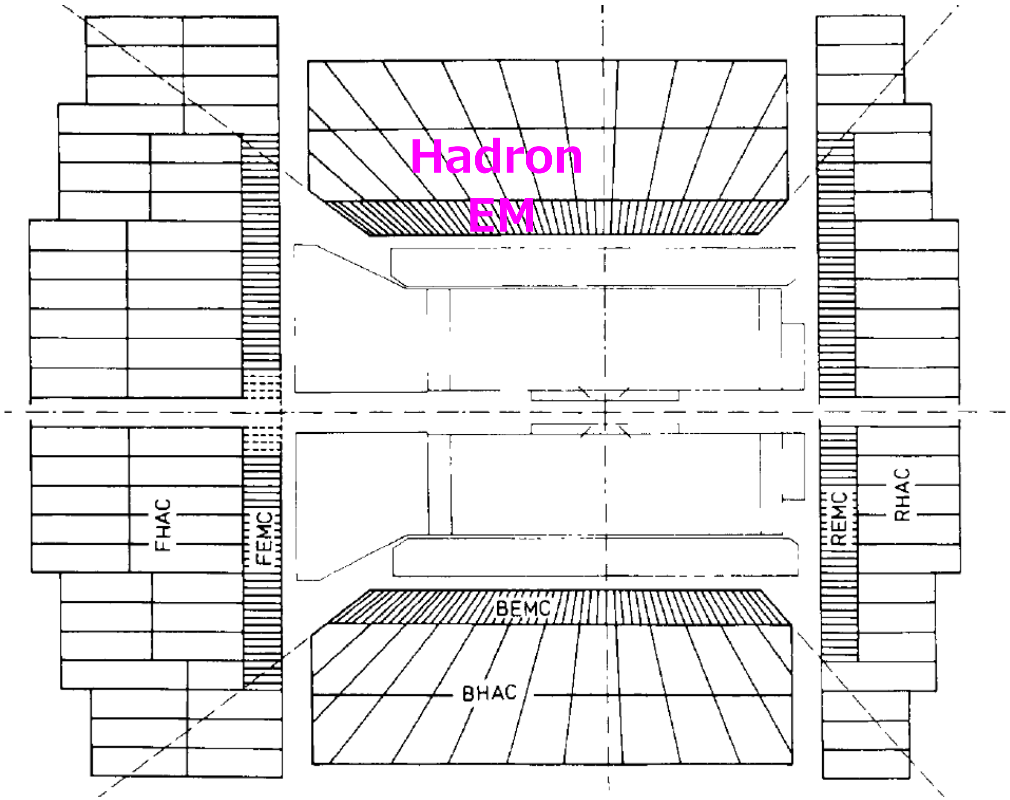
Hadron Calorimeter

Structure similar to EMcal.
Larger sizes since hadron shower is larger.
- Homogeneous ; none made 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
- Compensation ;
  Invisible energy spent on nuclear reaction
  is recovered by fission energy of 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)

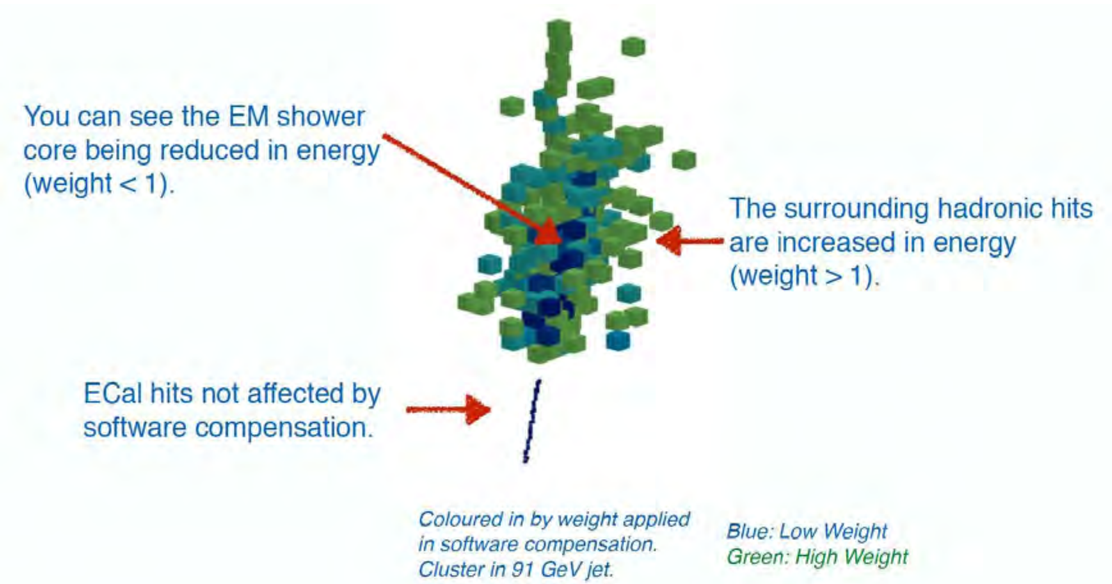
Energy calculation by counting track length (number of hits) in a shower.

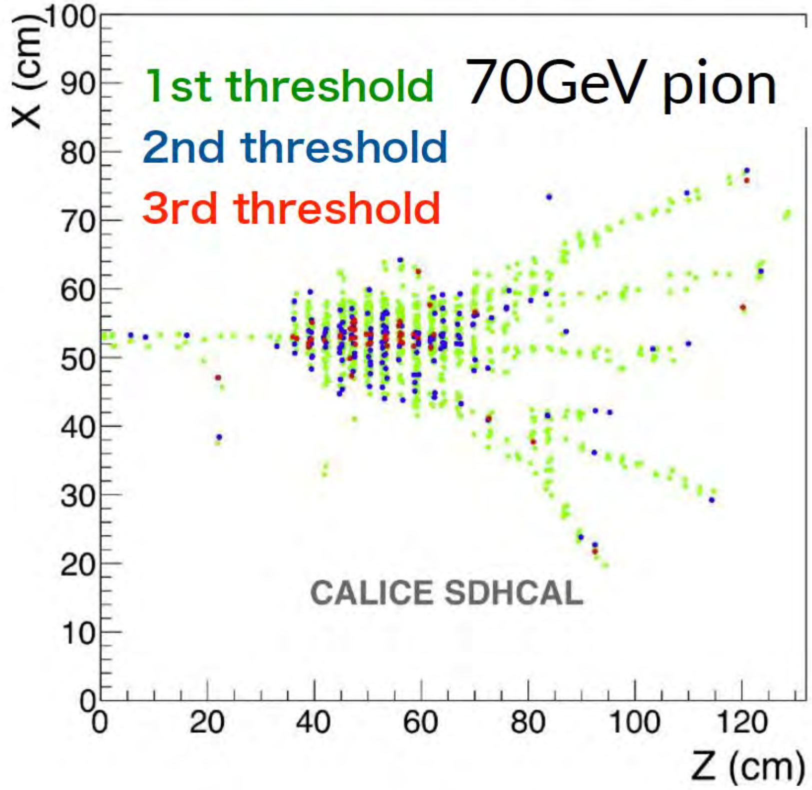
→ No energy measurement but hit on/off information only.

→ Digital HCAL (CALICE)

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

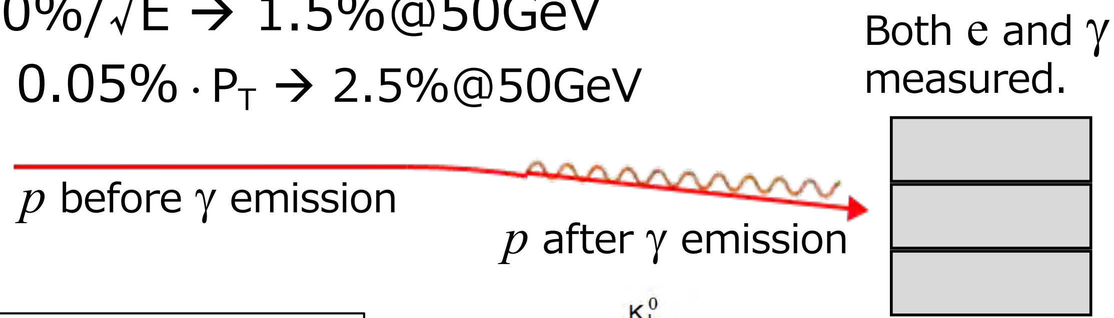
Super-high granularity also enables "software compensation".





Neutral particle detection

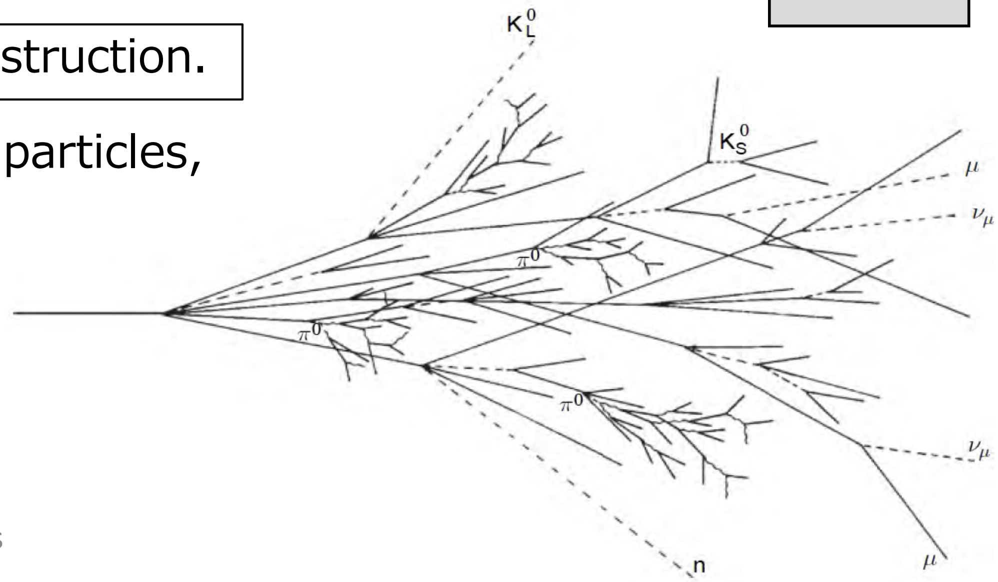
- Calorimeters measure total energy of all particles except muons and neutrino.
  Best to measure neutral particle energy with calorimeters,
  while trackers measure charged particle momentum.
- Very high energy electron energy can be better measured by calorimeters
  due to worse-P measurement of trackers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



Excellent calorimeter needed for the best jet reconstruction.

Initiate shower, absorbs all energy of all cascade particles,
and converts the energy into signal.

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



6. Muon Detector

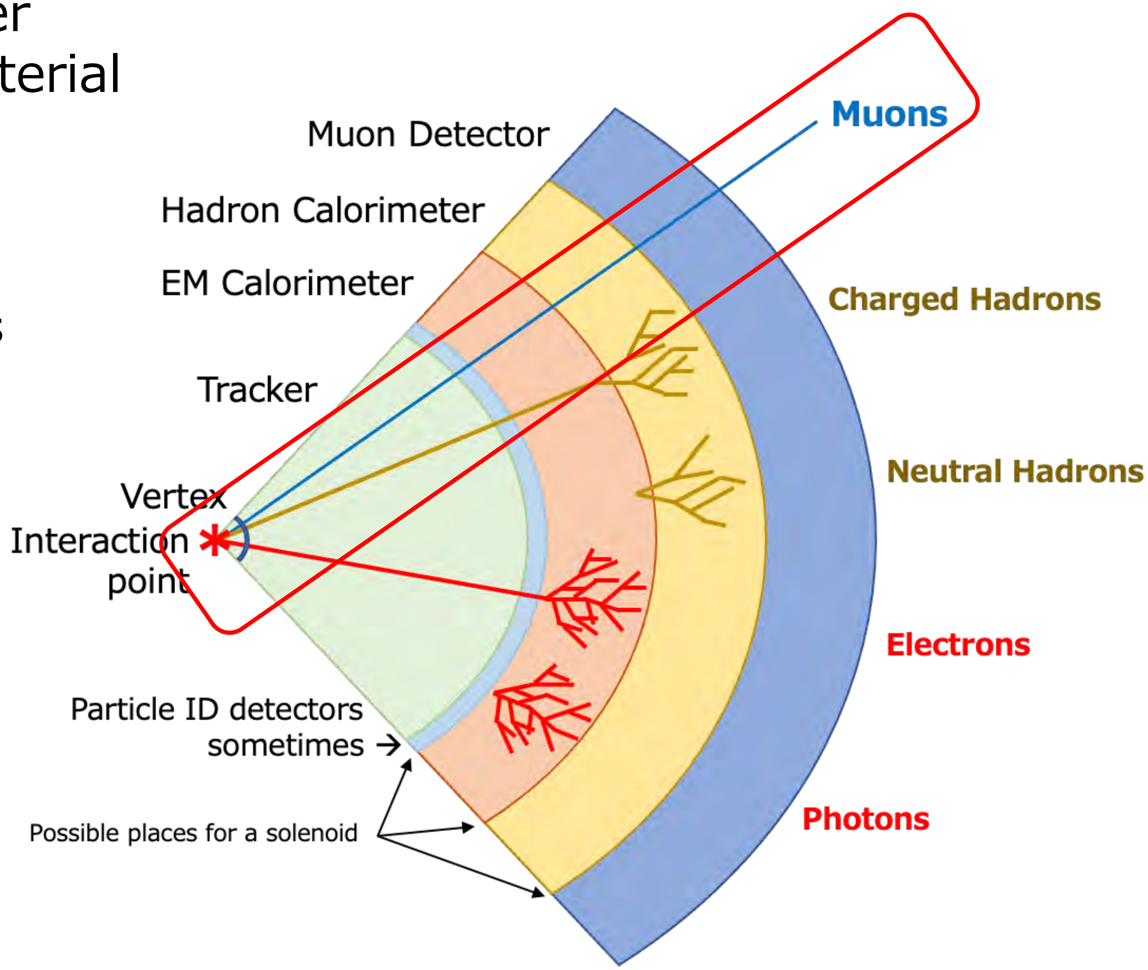
Only muons can give signal to the muon detector
behind thick absorber
due to their highest penetration capability.

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
- Leaves charged track in a tracker

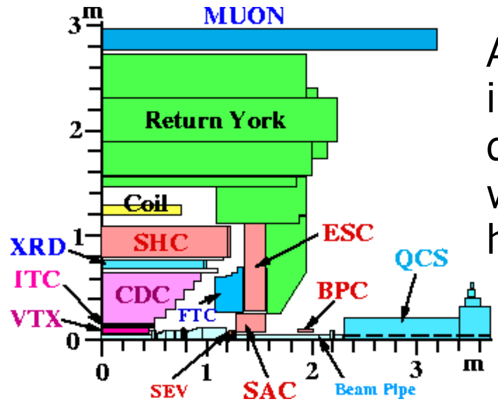
Typical configuration;
interleaved of absorber and detection layers
- Absorber
  mostly iron plate to work as flux return.
- Detection layers
  mostly gas chambers
  several choices for various emphasis
  - timing resolution
  - position resolution
  - large size
  - cost



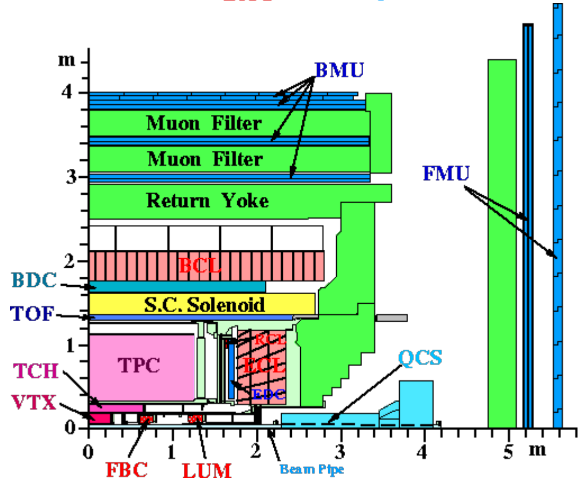
6. Operation of detectors ; Muon Identification

Design guidelines

- Use thick iron return york of magnetic field as muon filter.
- Precise and high-efficiency position measurement after passing the filtering iron to tag muon.
- In order to precisely connect to tracks in trackers ;
  - Better to have detector layer interleaved with filtering iron
  - Precise field mapping, especially in filtering iron region
  - timing information



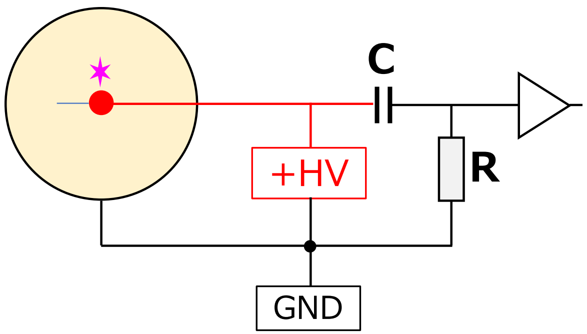
AMY has no interleaved detector, while TOPAZ has them

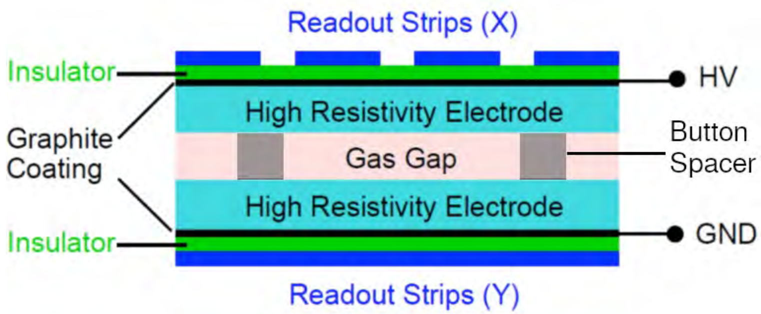


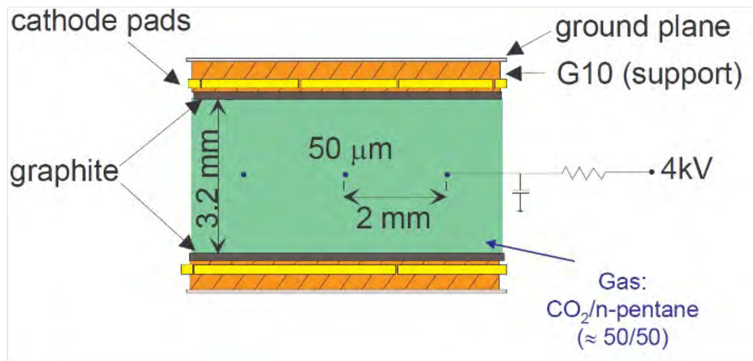
For detector layer choice

- Need to cover large area
- Low cost
- Do not need high-occupancy capability
- Do not need high double-track resolution

Candidates are; SWDC, RPC, TGC , , ,







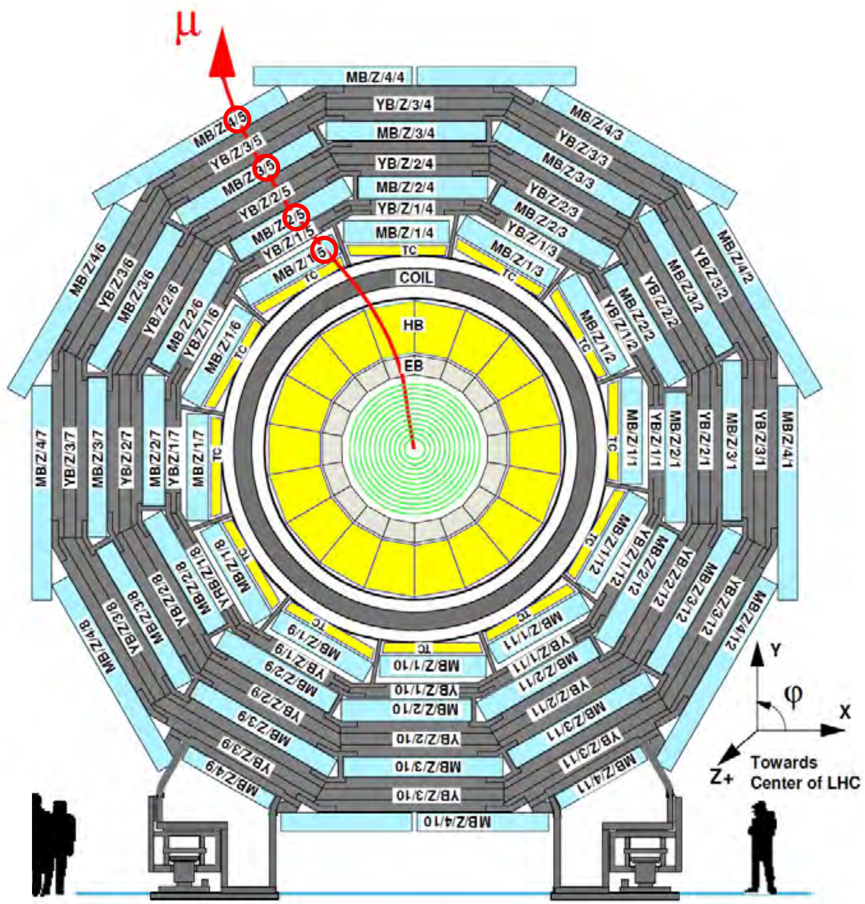
6. Operation of detectors ; Muon Identification

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

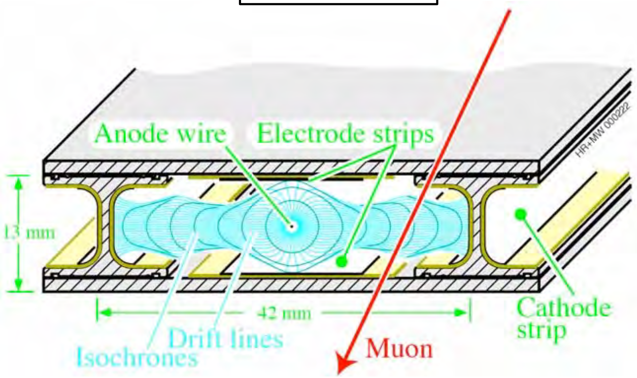
Design parameters are
- 12Tm bending field for good momentum resolution
- Thick iron absorber of 1.5m

Large detector area ~25000m2

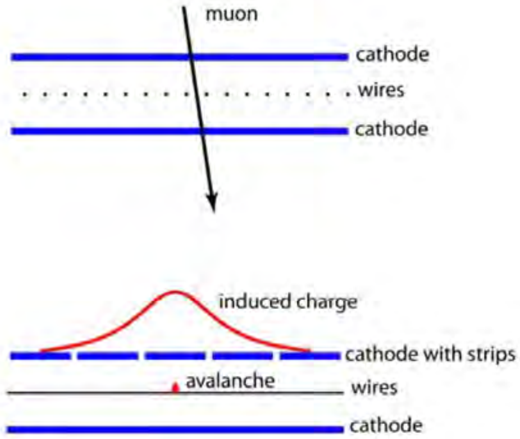
→ inexpensive detector needed
- Array of single-wire drift chamber (barrel)
- MWPC with cathode-strip readout (EC)
- RPC for trigger (fast response)



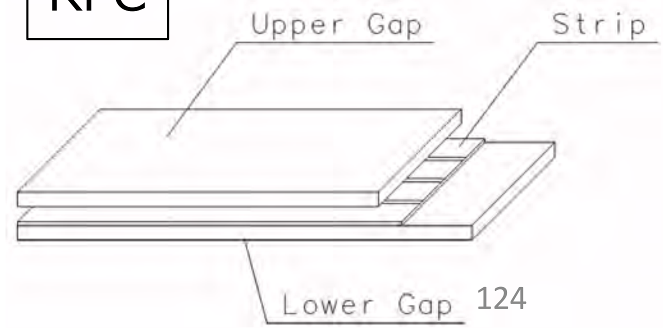
SWDC



MWPC



RPC



7. Photon Sensors

Scintillating photons and Cherenkov photons
are widely used at PID-detectors and calorimeters.
Variety of photon sensors are invented for various applications.

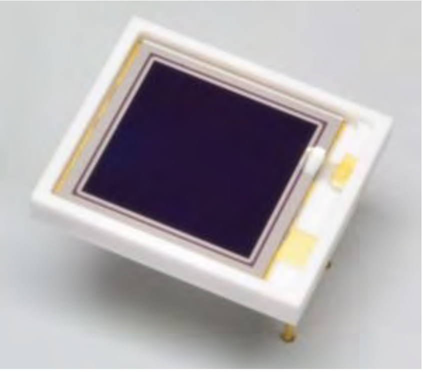
7. Operation of detectors ; Photon Sensors

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

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

PMT

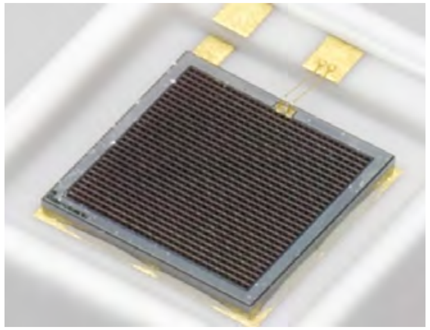
MCP



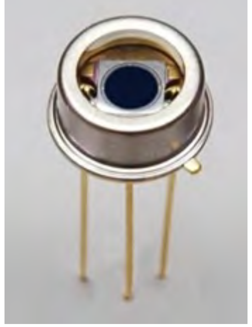
Si

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

and so on.



SiPM/MPPC



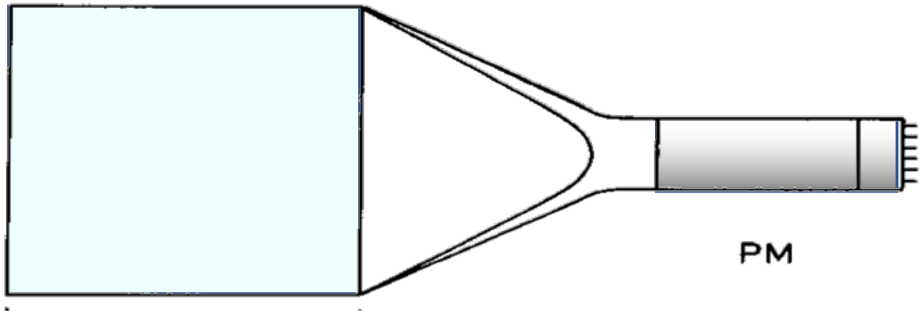
APD

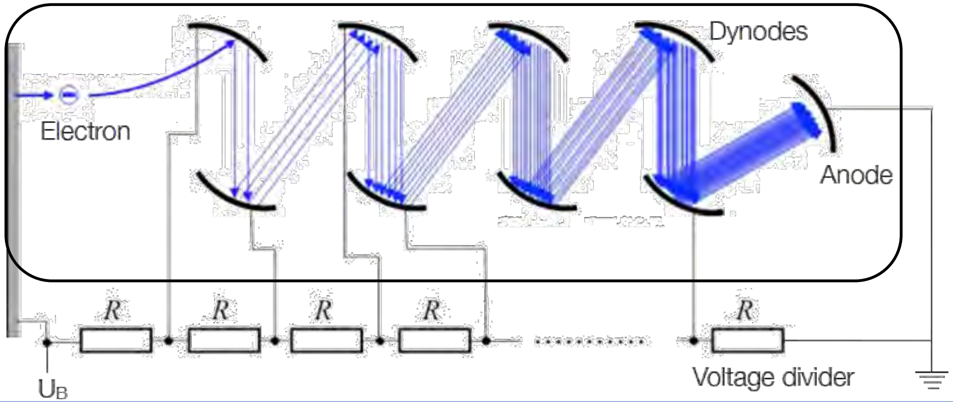
HAPD

7. Operation of detectors ; Photon Sensors

Photo-multiplier Tube

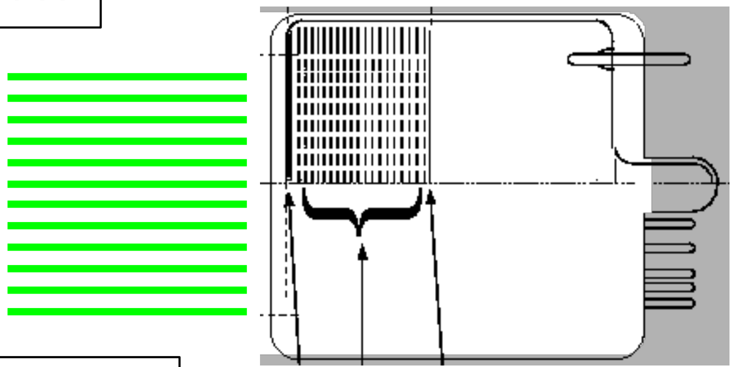
- High-gain, low noise, wide dynamic range
- Large photo-sensitive area.



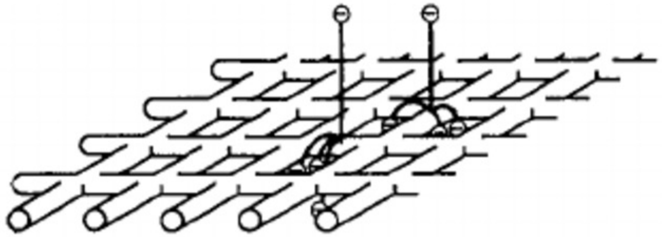


Fine-mesh PMT

Fiber-bundle readout

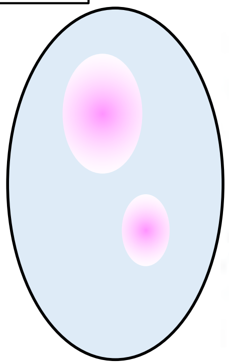


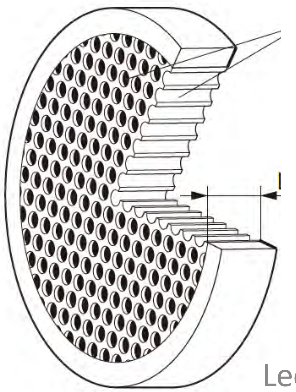
- Operational in B~1T
- Multi-anode available→ position measurement

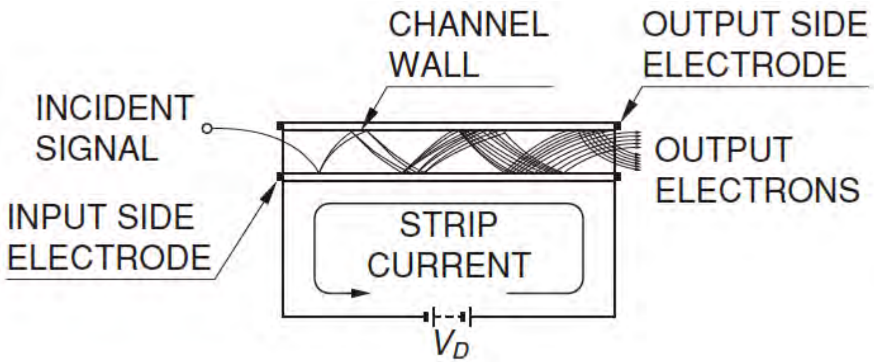


Micro-channel plate

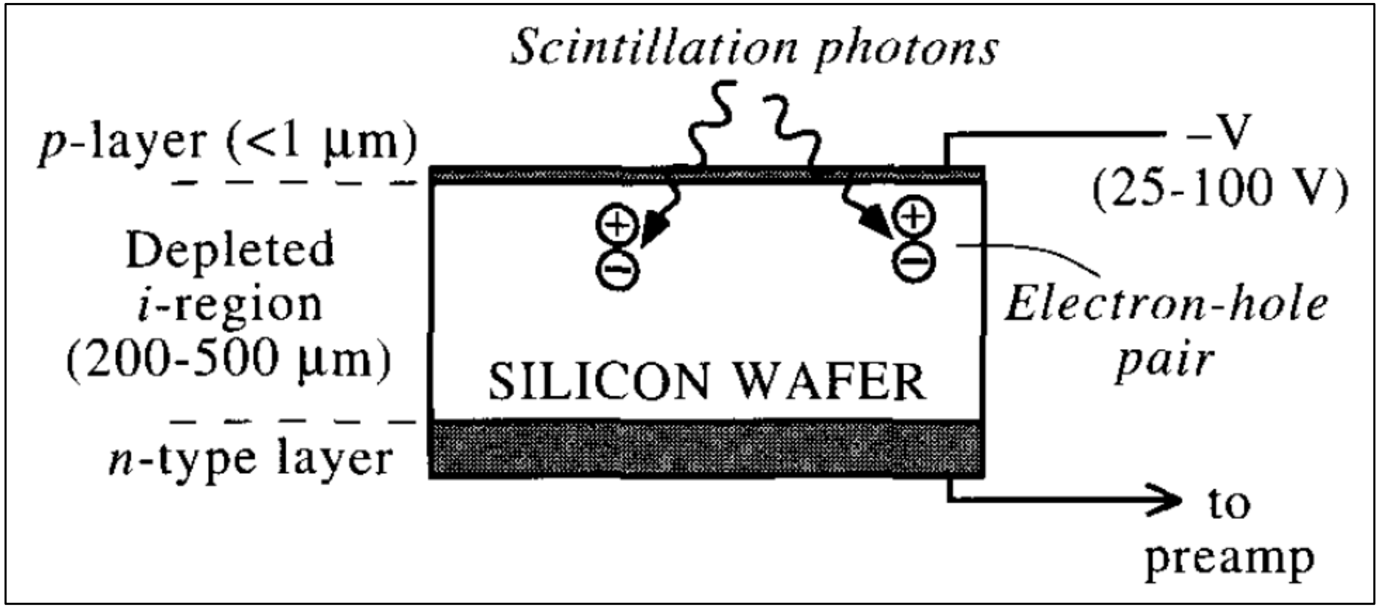
Imaging



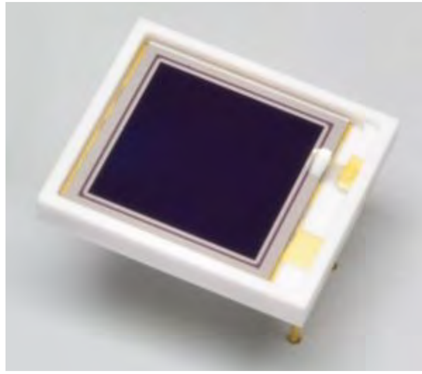




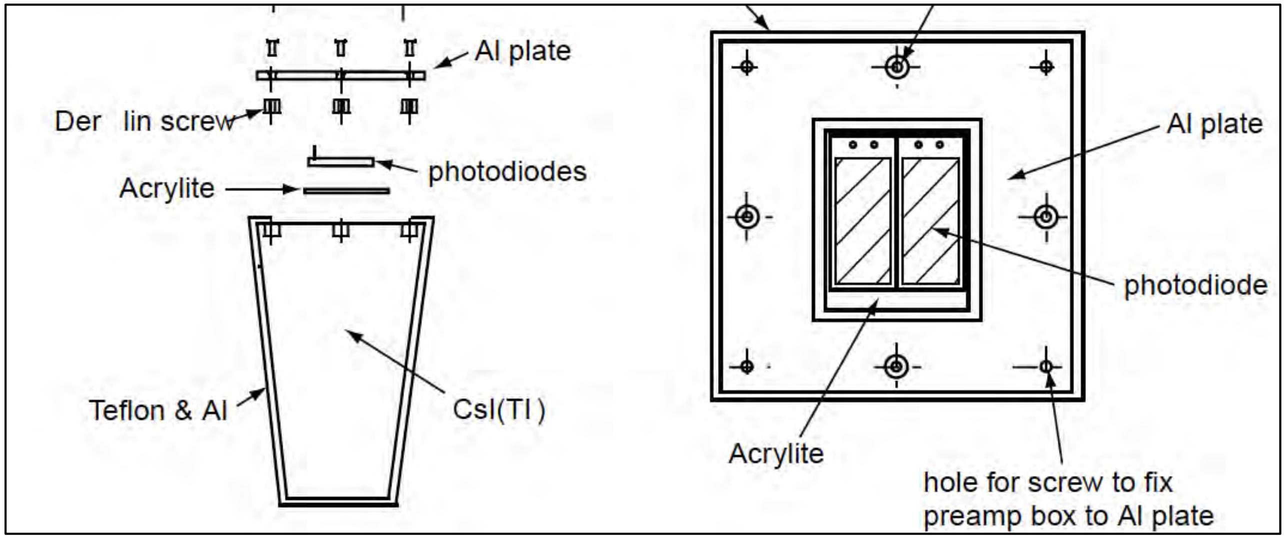
PIN silicon photodiode



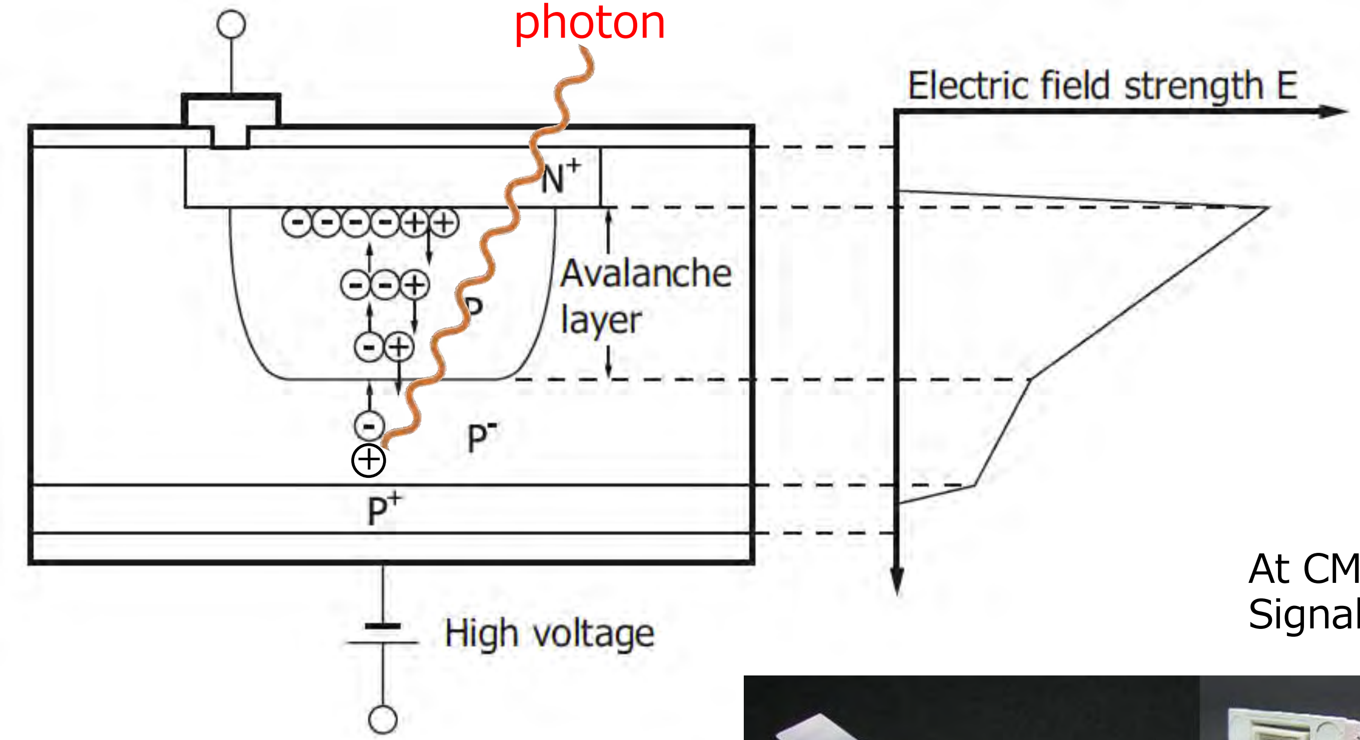
The same structure as Si for tracking. A photon generate one electron-hole pair (3.6eV needed), thus no gain (no amplification).



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

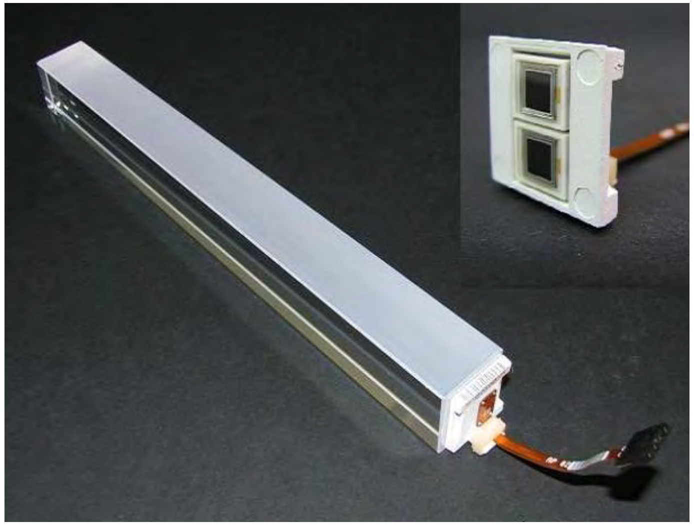


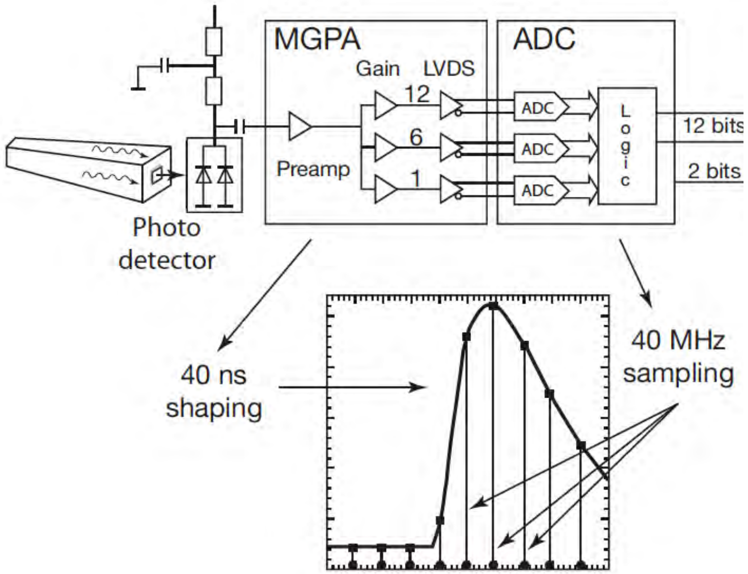
Avalanche Photodiode



One photon generate one e-h pair. Drifted electron is accelerated by strong electric field of avalanche region, and e-h creaction cascade occurs.

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



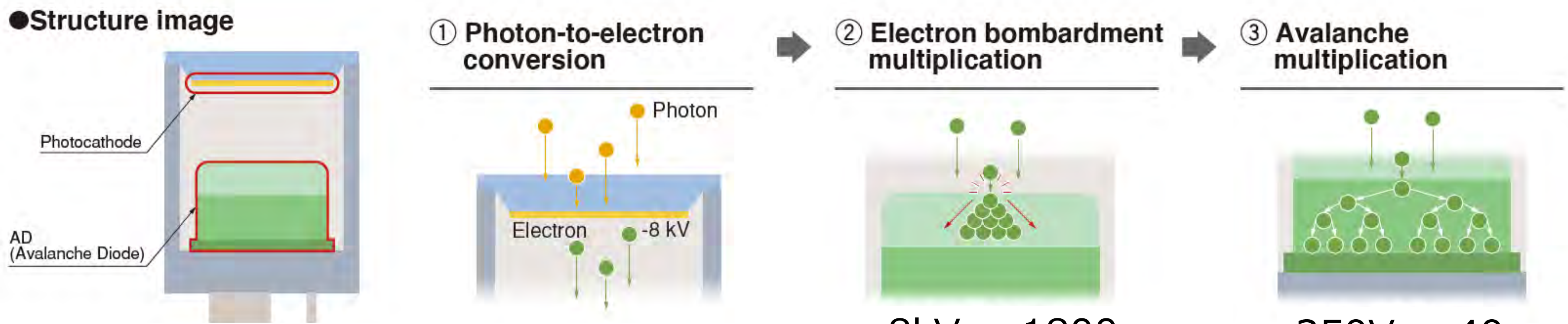


CMS-APD ; V ~400V
Gain ~50
Typically, V=150~500V
G= 50~400
Area = 1~10mmΦ

7. Operation of detectors ; Photon Sensors

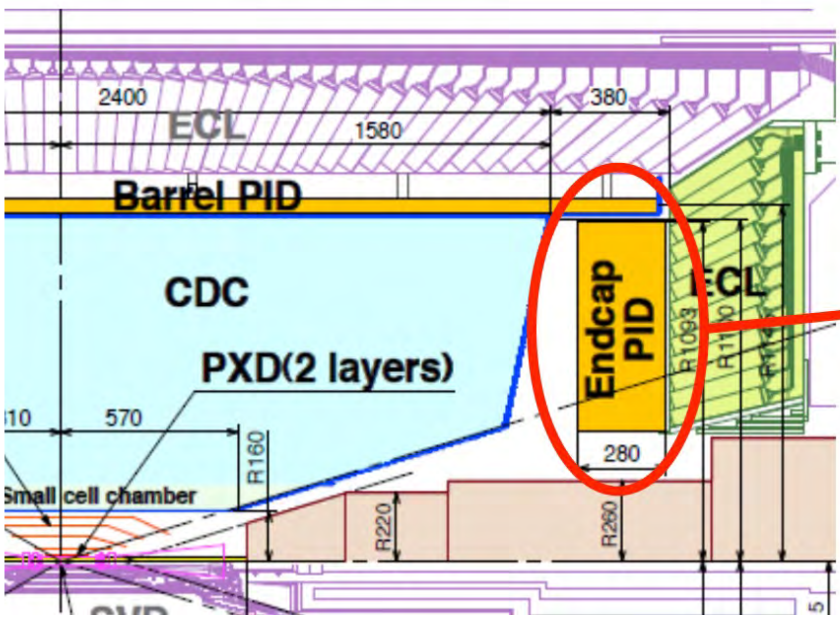
HAPD（Hybrid-APD）

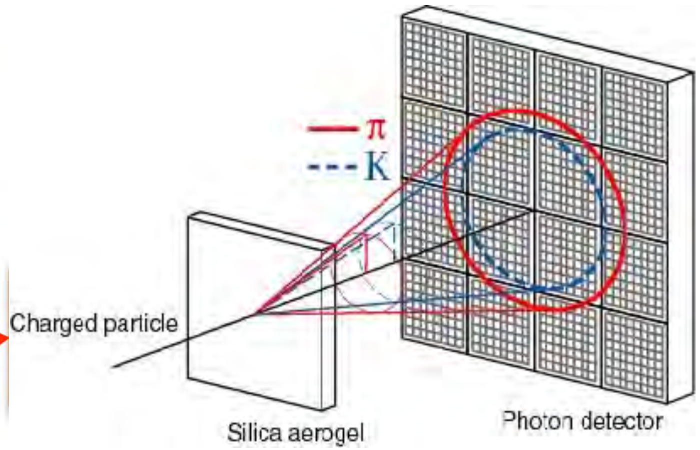
HV acceleration gain and APD gain gives high gain.



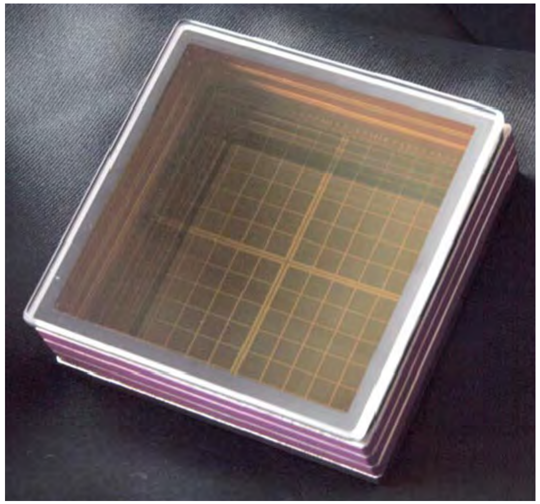
-8kV～x1800

350V～x40



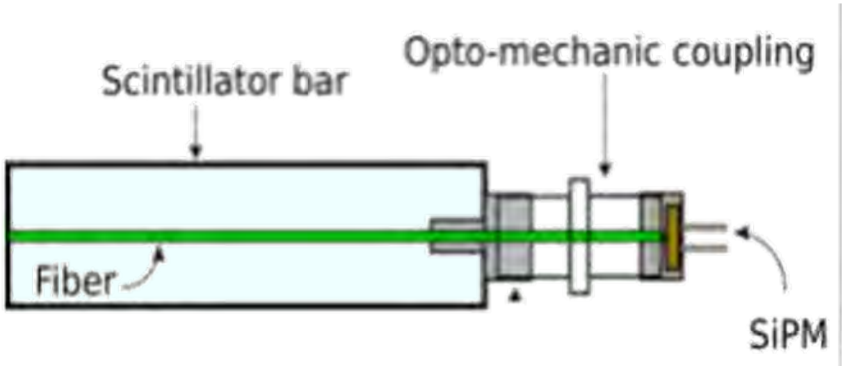


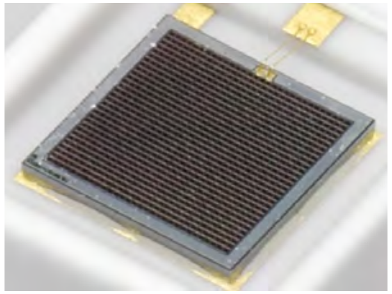
Belle-II ARICH HAPD
5mmx5mm pixel,
144 pixel/module,
gain =~10^5(1800x40)

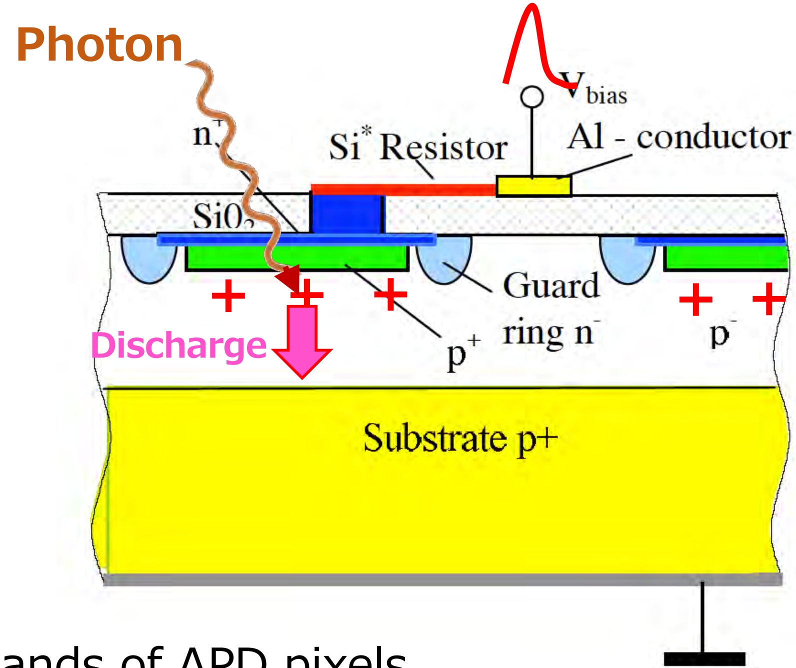


7. Operation of detectors ; Photon Sensors

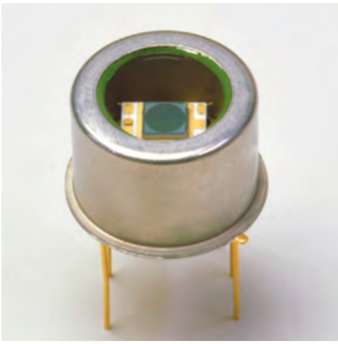
SiPM/MPPC

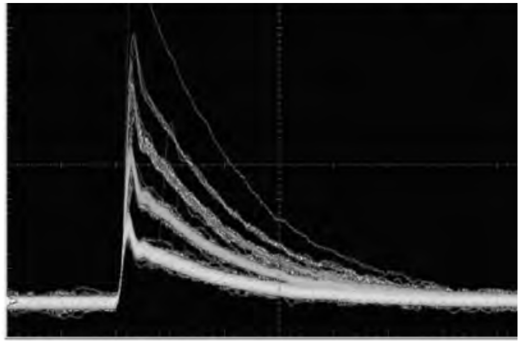






Best to couple with WLS fibers.





One sensor has thousands of APD pixels.
Each APD 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.

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

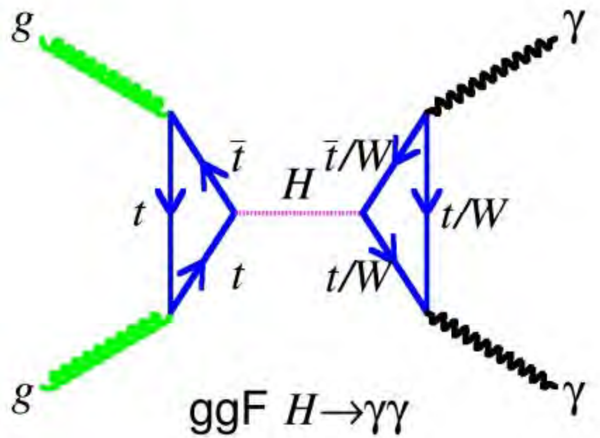
Single-photon sensitivity.
Fast rise time, slightly slow fall time due to quenching.
Operational in strong magnetic field.
Pixel-size/number of pixel be carefully chosen.

8. Actual Detector Design and Performance

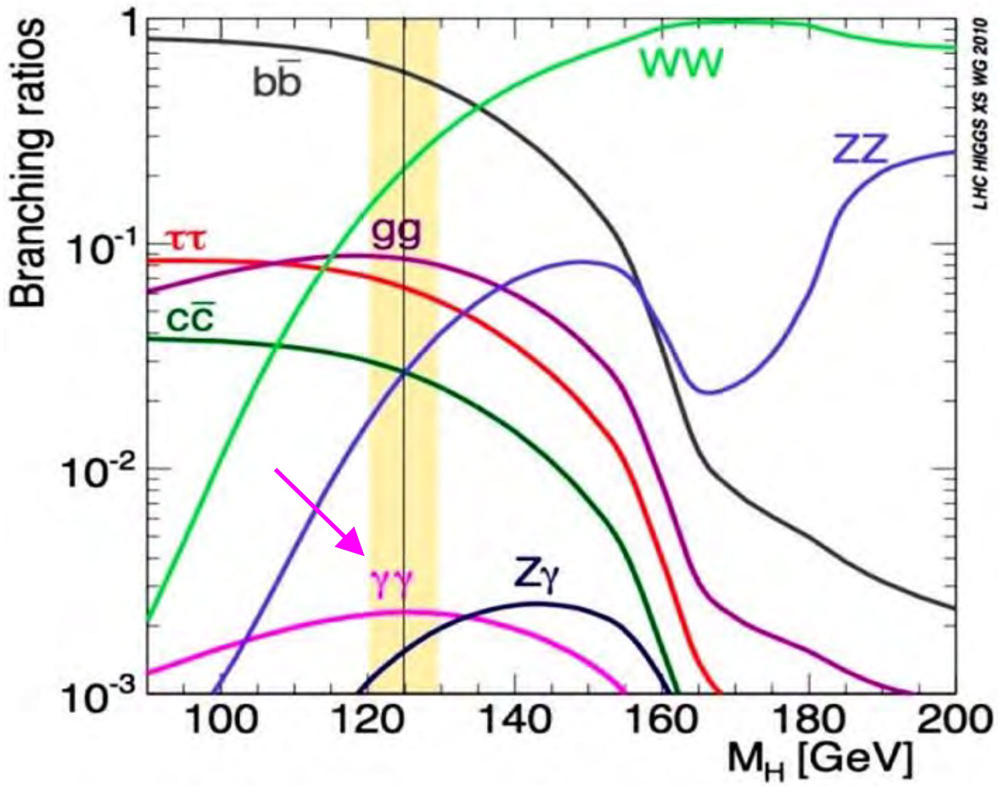
8. Actual Detector Design and Performance

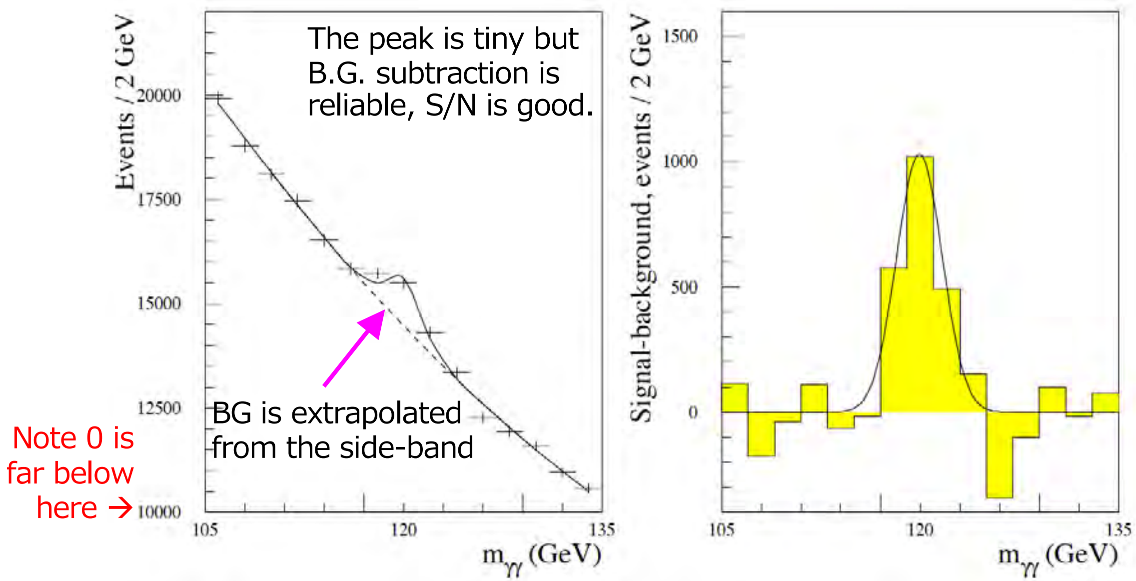
$H^0 \rightarrow \gamma\gamma$ as benchmark of calorimeter performance

- Just reconstruct $\gamma\gamma$ invariant mass and find a peak.
- Branching ratio is low (0.23%) but
  good S/N and good mass resolution expected,
  background is model independent (use side-band).
- Signal γ is "isolated" (not buried in jets).



Detect γ in huge hadronic background, and make γ–γ mass





$\gamma\gamma$-mass (simulation in ATLAS TDR)

8. Actual Detector Design and Performance

$H^0 \rightarrow \gamma\gamma$ as benchmark of calorimeter performance

Calculate invariant mass of $\gamma\gamma$

$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\theta_{12})}$$

Natural width of Standard Model Higgs is just 4MeV.

→ Performance EM calorimeter determines width of reconstructed $\gamma\gamma$ mass.

→ High-performance EM calorimeter to measure γ precisely and get narrow peak.

- energy resolution (σ_E)
- position resolution (angle θ_{12})
- 2γ separation (spatial overlap)
- high efficiency
- Low contamination
  - electron rejection
  - hadron rejection
  - π^0 rejection

and

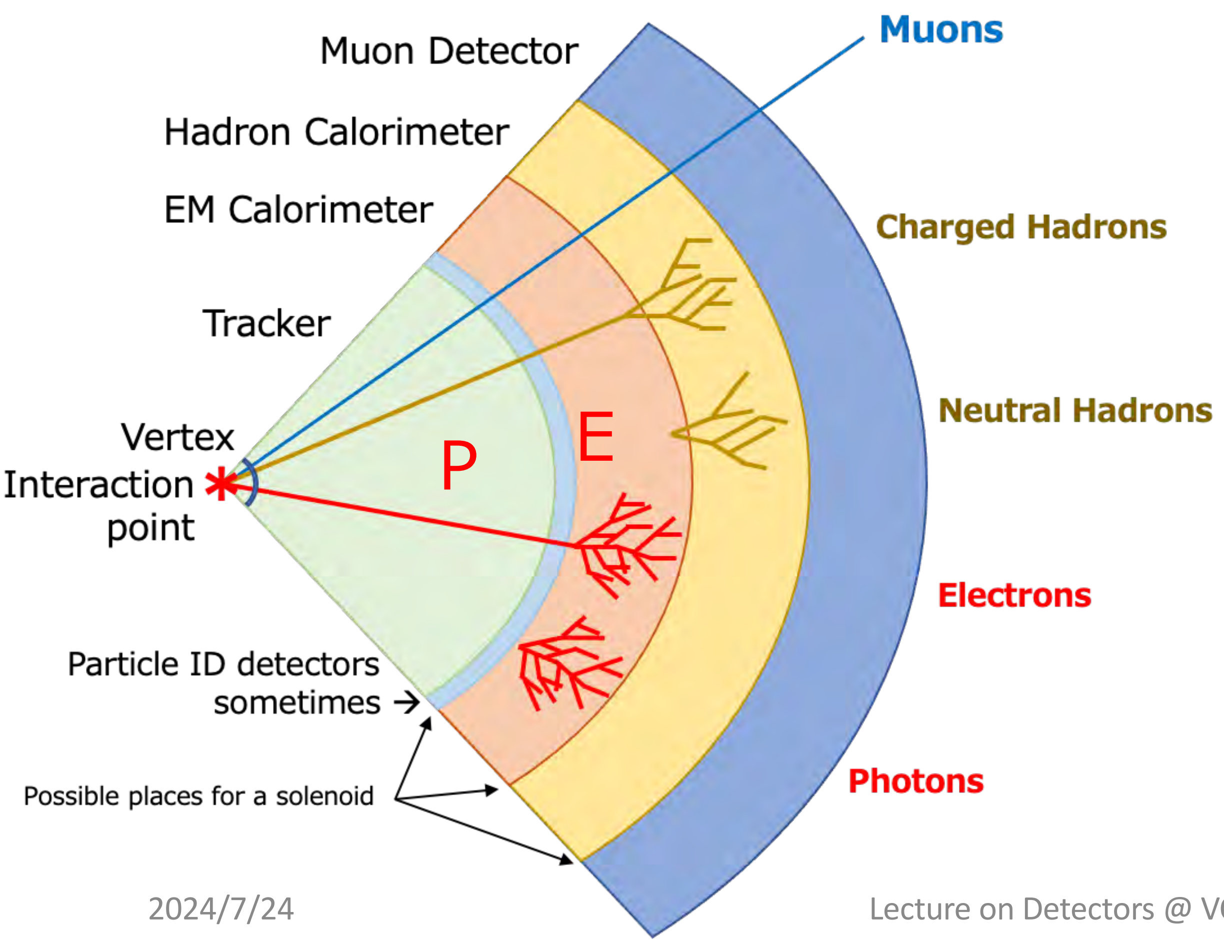
- fast (bunch-overlap separation)

	ATLAS	CMS	LCD
	Sampling	Crystal	Sampling
Energy Resolution	Medium	Excellent	Medium
Granularity (transverse)	Good	Good	Excellent
Segmentation (longitudinal)	Good	Poor	Excellent
Timing Resolution	Good	Excellent	Don't mind

8. Actual Detector Design and Performance

H^0 → γ γ as benchmark of calorimeter performance

High-performance EM calorimeter is needed ;
In addition to the excellent γ measurement, **need to reject non-γ**
・hadron rejection → shower spatial development → segmentation/granularity
・electron rejection → track-cluster matching → need excellent trackers



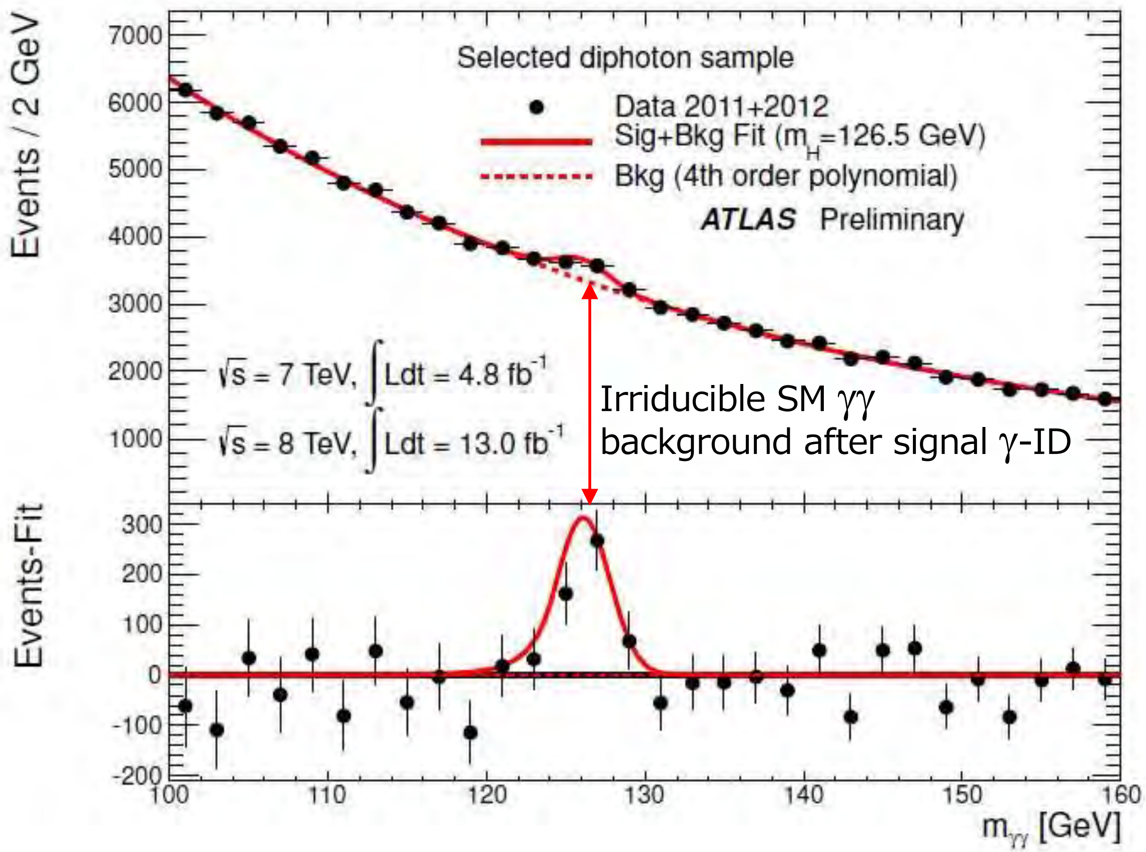
For an EM cluster;
- No corresponding track
  - No hadron cluster → γ
  - Significant HD cluster → γ + hadron overlap ?
- A track matches the cluster
  - P=E → **electron**
  - P>E → γ + hadron overlap ?
  - P<E → γ + electron overlap ?
  - Avoid double counting of P&E

Needs good **energy/momentum/position** measurement and very careful calibration/analysis.

8. Actual Detector Design and Performance

$H^0 \rightarrow \gamma\gamma$ as benchmark of calorimeter performance

High-performance EM calorimeter is needed ;
In addition to the excellent γ measurement, **need to reject non-γ**
・hadron rejection → shower spatial development → segmentation/granularity
・electron rejection → track-cluster matching → need excellent trackers



For an EM cluster;
・No corresponding track
- No hadron cluster → γ
- Significant HD cluster
→ γ + hadron overlap ?
・A track matches the cluster
- P=E → **electron**
- P>E → γ + hadron overlap ?
- P<E → γ + electron overlap ?
- Avoid double counting of P&E

Needs good **energy/momentum/position** measurement and very careful calibration/analysis.

8. Actual Detector Design and Performance

$H^0 \rightarrow \gamma\gamma$ as benchmark of calorimeter performance

Examples of parameters/performance of EMcal for excellent γ measurement
- Energy resolution (material in front of EM also matters)
- Granularity (Position resolution → θ resolution, 2γ separation)
- timing

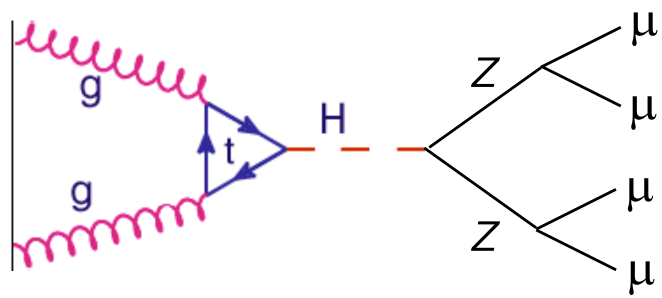
CMS EMcal clearly targets the best measurement of $H^0 \rightarrow \gamma\gamma$ discovery.

CMS ; effect of energy resolution and position resolution on mass resolution are comparable for light Higgs.
ATLAS ; energy resolution effect is larger than position resolution effect.

	ATLAS	CMS	LCD
	Pb/Liq.Ar	PbWO4	W/Si
Material in front of CAL	coil in front of EMCAL	coil outside of HCAL	coil outside of HCAL
Energy Resolution	10%/√E	3%/√E	17%/√E
Granularity (transverse)	3.8cmx3.8cm @ r=1.5m	2.3cmx2.3cm @r=1.3m	5.5mmx5.5mm @r=1.5~1.8m?
Segmentation (longitudinal)	3	1	30
Timing Resolution	~300ps	~150ps	Don't mind
Expectd $\gamma\gamma$ mass resolution	1.4GeV	0.9GeV	?

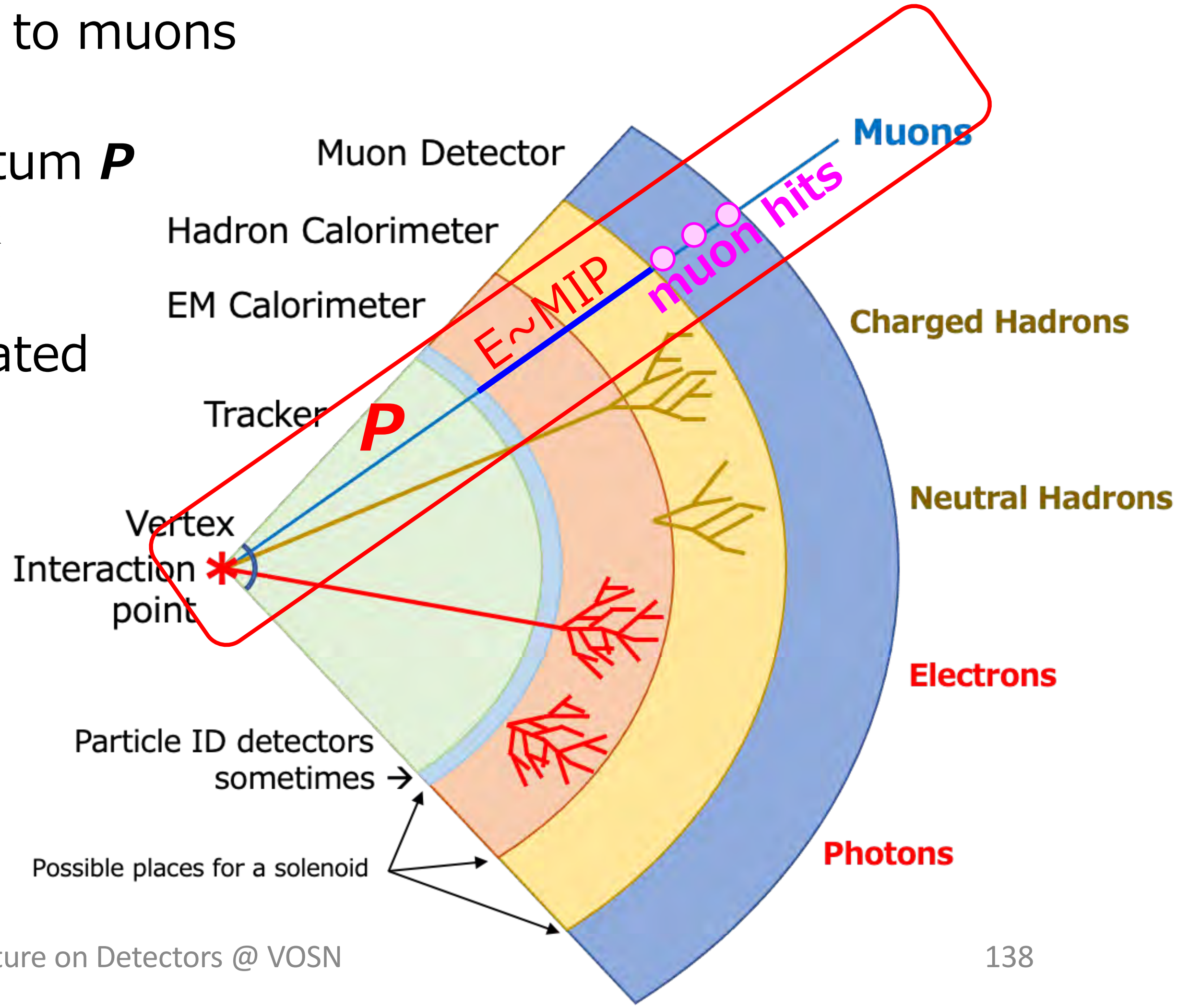
8. Actual Detector Design and Performance

Higgs → ZZ* → 4μ as benchmark of muon detector



High-performance muon measurement

- Identify the particles as muon
  - Has hits in muon detectors
  - Energy deposit in CAL consistent to muons
- Precise track reconstruction
  - Precise measurement of momentum ***P***
  - Precise extrapolation of the track to muon detector
  - Precise matching of the extrapolated track and muon detector hits.



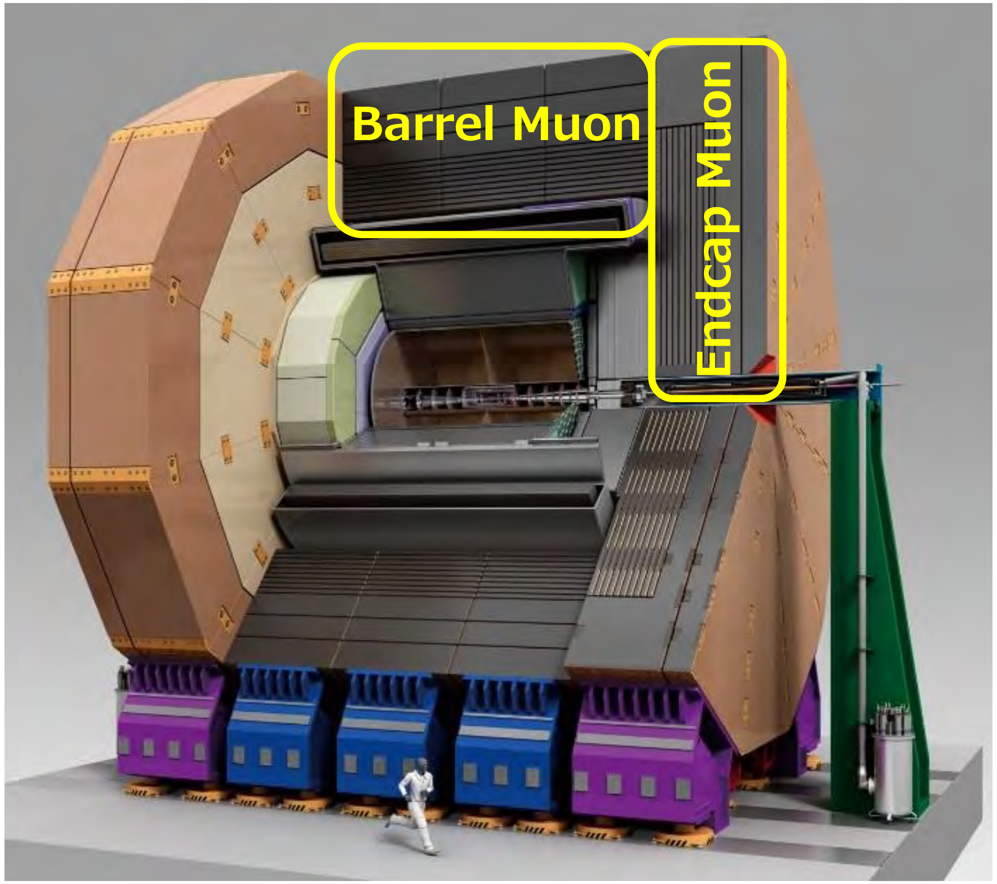
8. Actual Detector Design and Performance

Higgs → ZZ* → 4μ as benchmark of muon detector

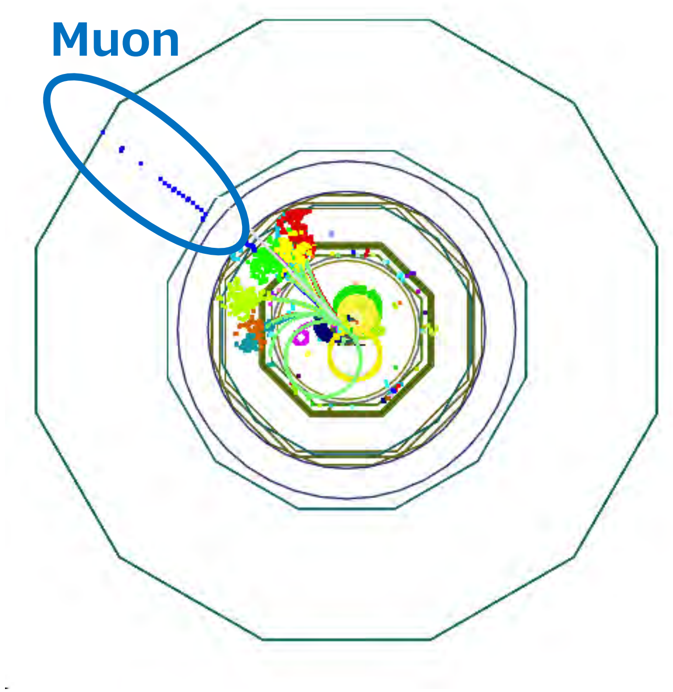
High-efficiency muon identification

→ penetration as MIP through thick material

Interleave of absorbers and chambers. Need to cover large area.



ILD muon detector
Plastic scintillator strips or RPC
as active media

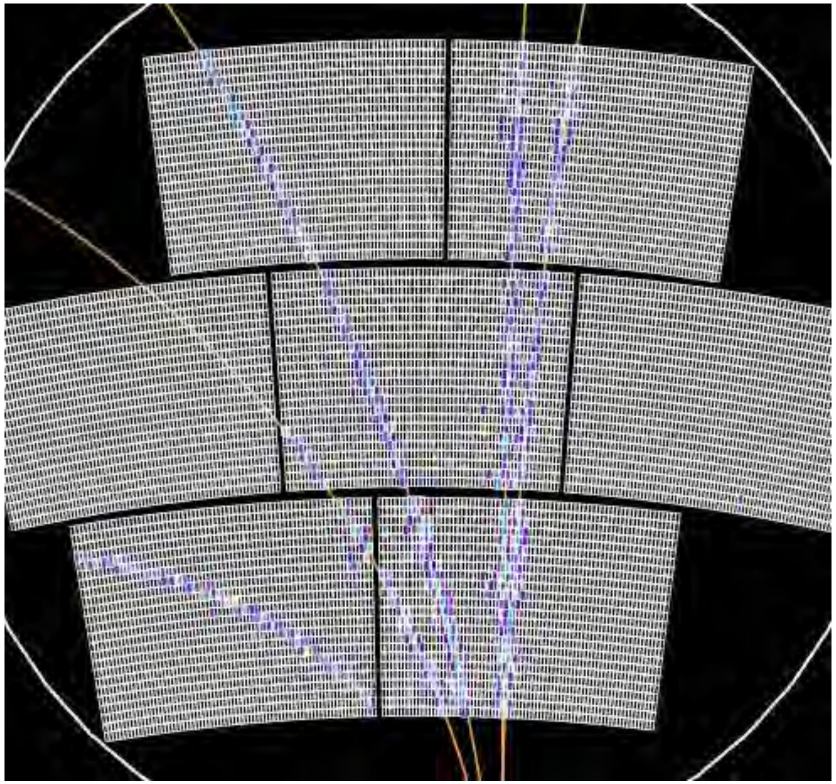


8. Actual Detector Design and Performance

Higgs → ZZ* → 4μ as benchmark of muon detector

Precise measurement of muon momentum

Tracking of space points → track curvature in B field→ momentum
→ many space points
precise position measurement of each space point
Low material to avoid scattering/energy loss



ILD central tracker TPC
Endplate MicroMegas hit point (bluish squares)
and
fitted track (yellow curve)

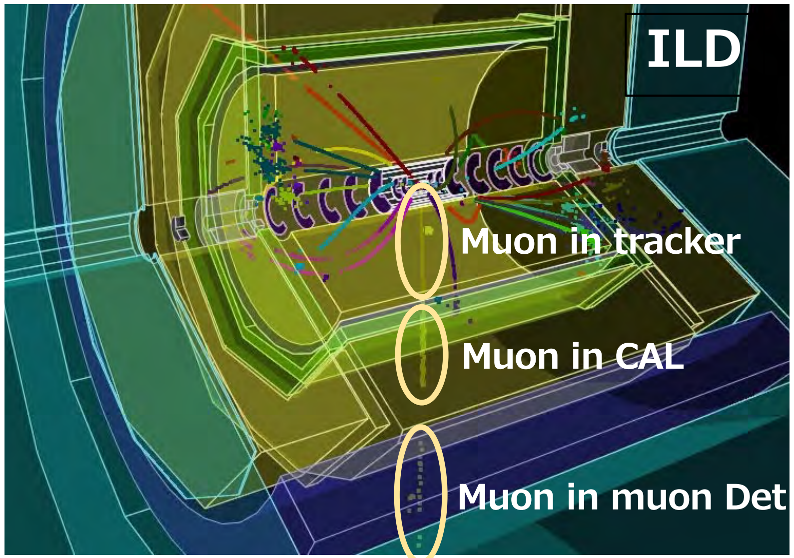
Excellent momentum resolution of
σ_{PT} /PT= 5x10^{-5} PT [GeV]
should be achieved at ILC.

8. Actual Detector Design and Performance

Higgs → ZZ* → 4μ as benchmark of muon detector

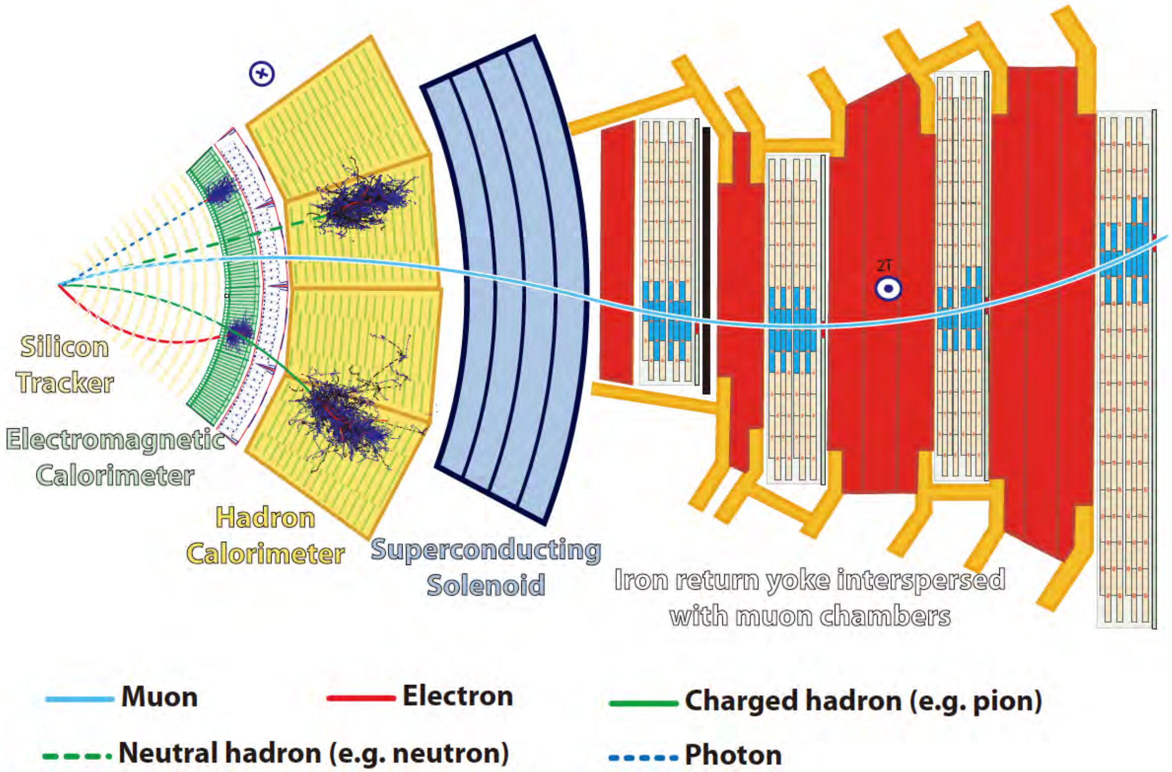
Precise correspondence between muon detector hits and tracks.

- Position matching
  - Position resolution of muon detector
  - Precise extrapolation of the candidate tracks to muon detector
    - Magnetic field mapping
    - Knowledge on material
- Timing matching



Track extrapolation and connection is simple.

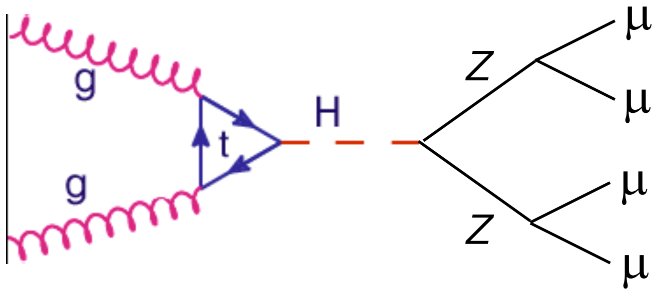
CMS ; Track extrapolation and connection is not simple.

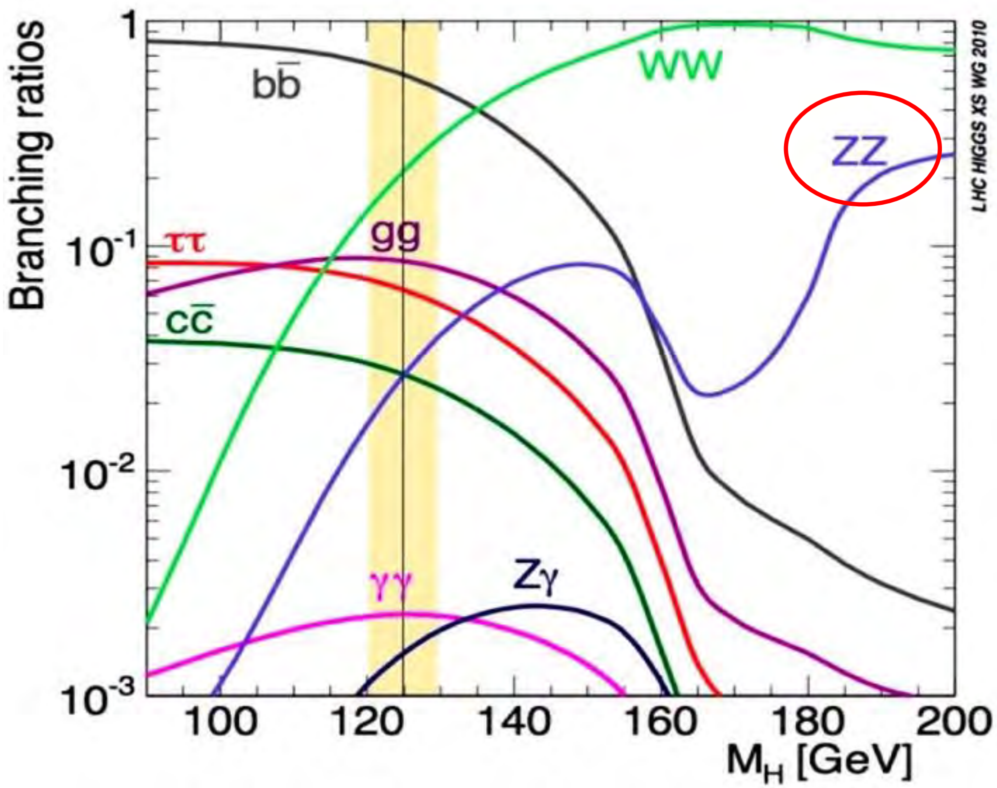


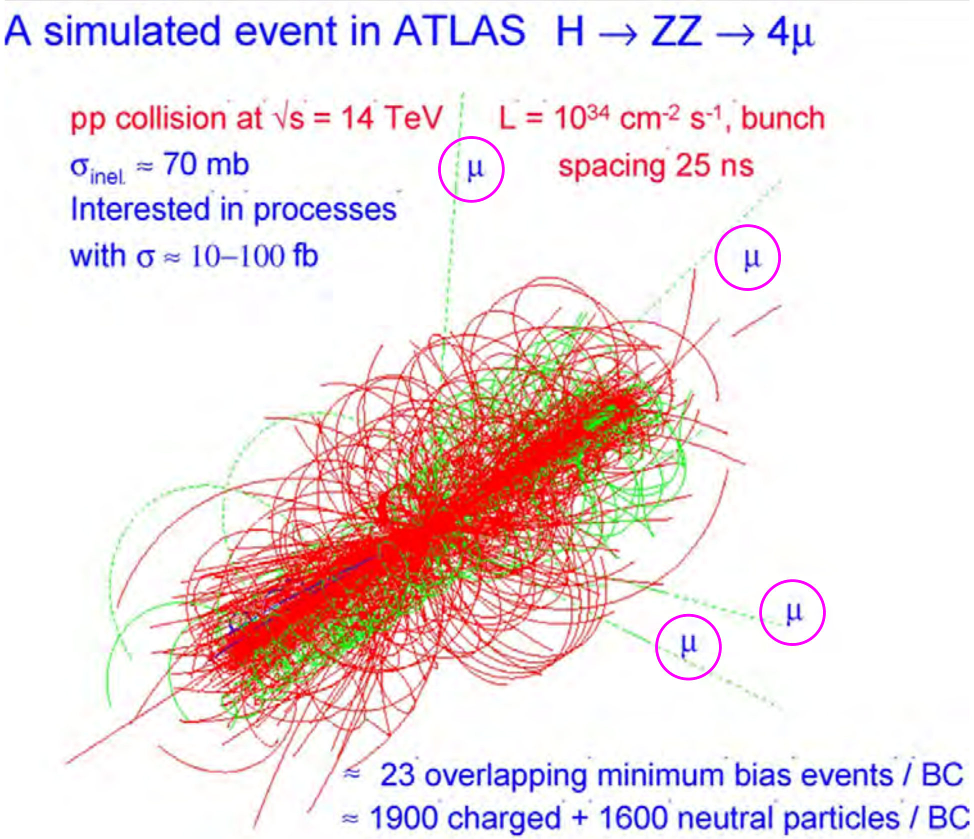
8. Actual Detector Design and Performance

Higgs → ZZ* → 4μ @LHC

- Very clean event signature.
  High-energy μ can be unambiguously identified.
- Mass reconstruction resolution is good.
- Very low event rate (H0→ZZ→4μ ~0.01%)
  since Z-decay to μμ is only 3.4%.

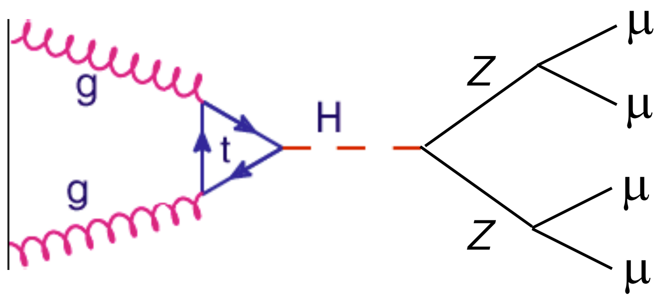






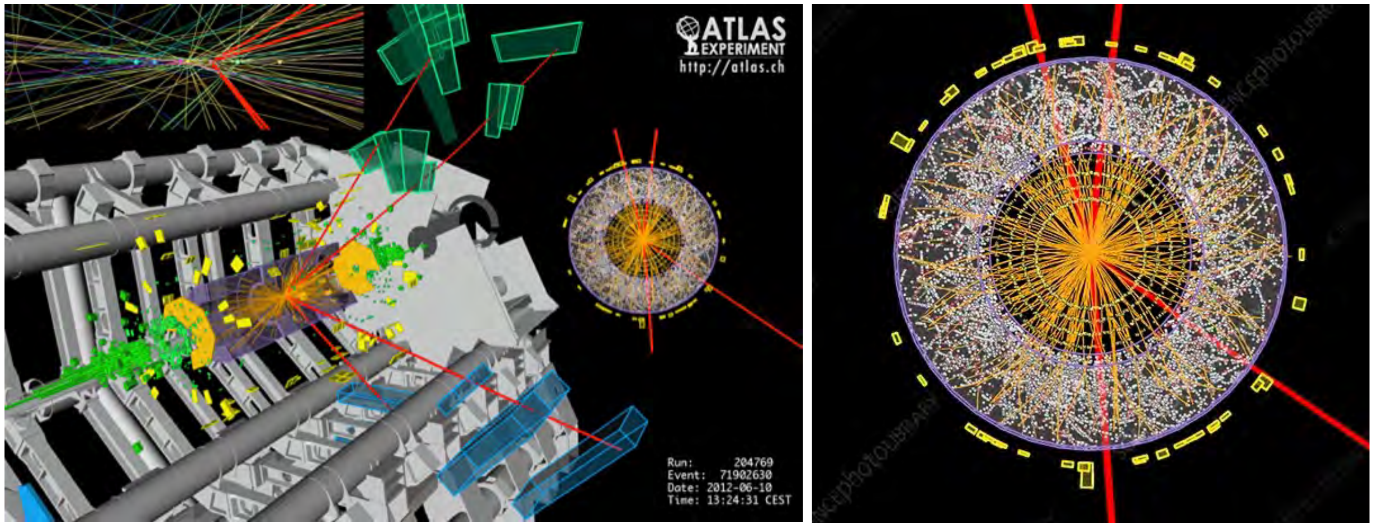
8. Actual Detector Design and Performance

Higgs → ZZ* → 4μ @LHC

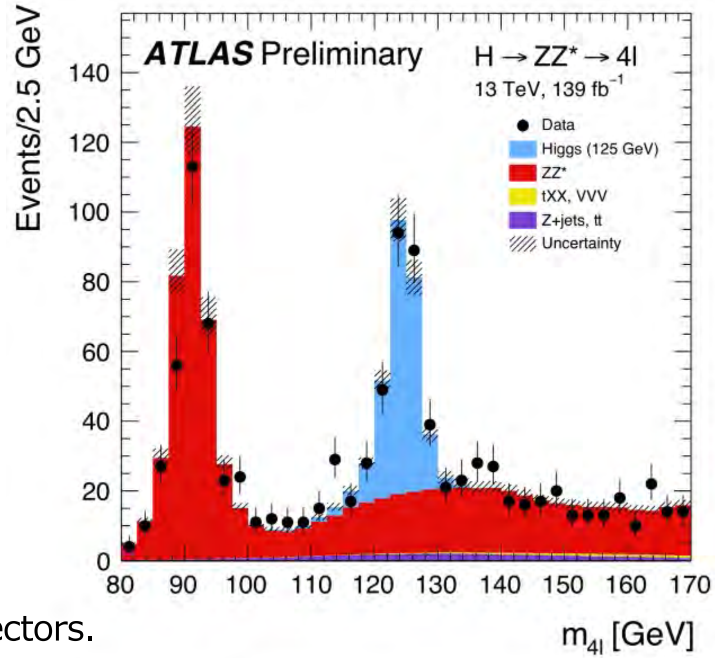


- Very clean event signature but
  Very low event rate ($H^0 \to ZZ \to 4\mu$ ~0.01%)
- Calculate mass of 4μ
  → A clear peak on background
    Background estimation needs background reaction analysis. Thus takes time.
- Do not rely on associating key particles.
- Good momentum and position resolution of μ
  → narrow mass peak → good S/N

∗ High-performance muon detector (ID & **P**) needed.

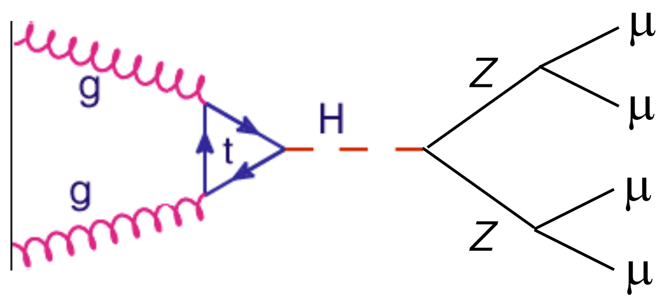


ATLAS $H^0 \to 4\mu$ event. Muons (red lines) are clearly identified by outer-most muon detectors.



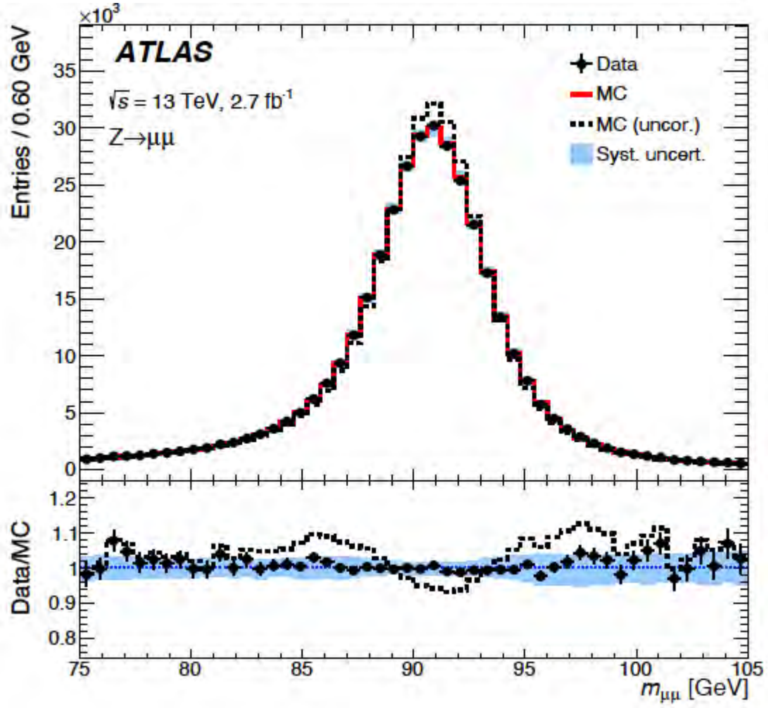
8. Actual Detector Design and Performance

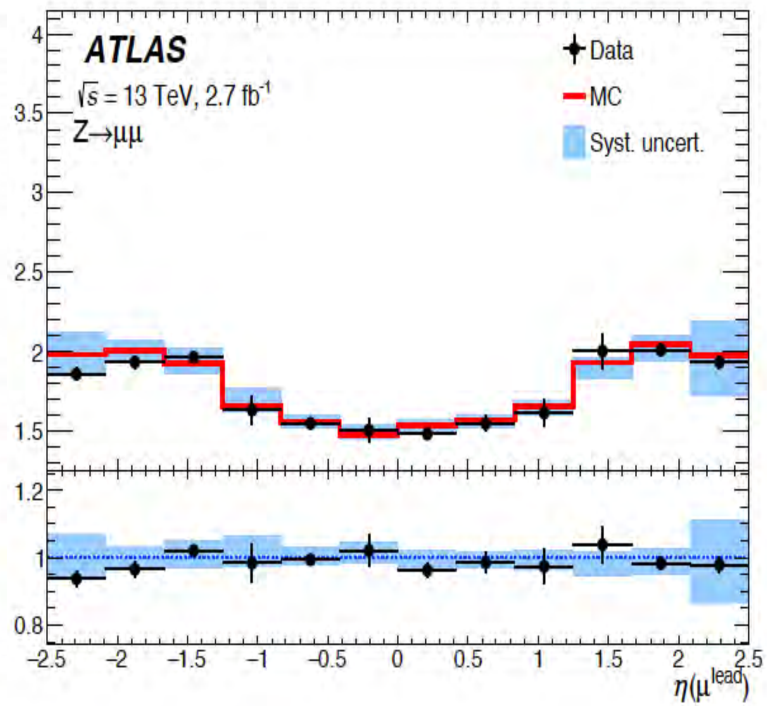
Higgs → ZZ* → 4μ @LHC

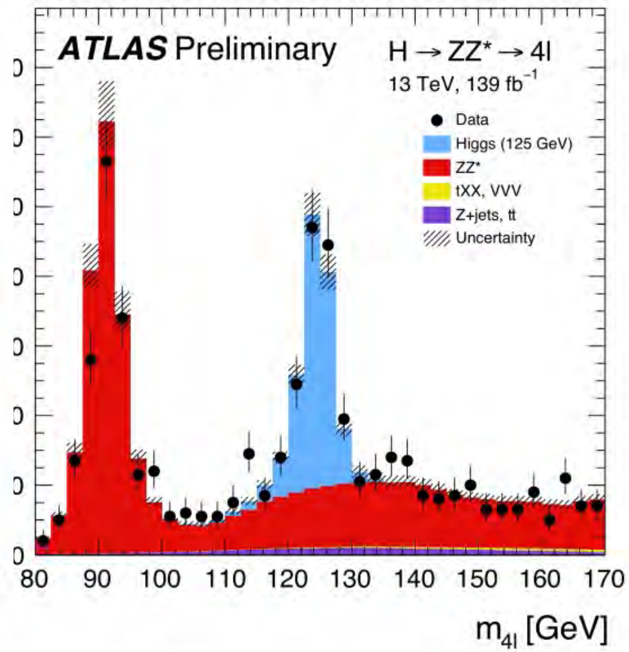


ATLAS achieves di-muon mass resolution of
1.5~2% for Z → μμ decay → ~1.5GeV for m_Z

Muon momentum resolution at 2T
$\sigma_{PT}/PT = 2\times10^{-4}$ PT [GeV] is achieved.



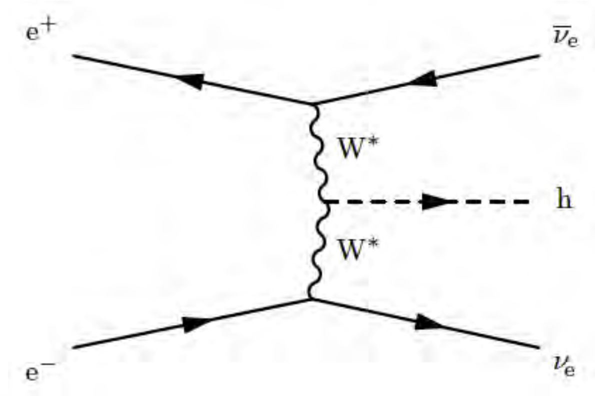




Taken from 「Muon reconstruction performance of the ATLAS detector in proton–proton collision data at ps=13 TeV」

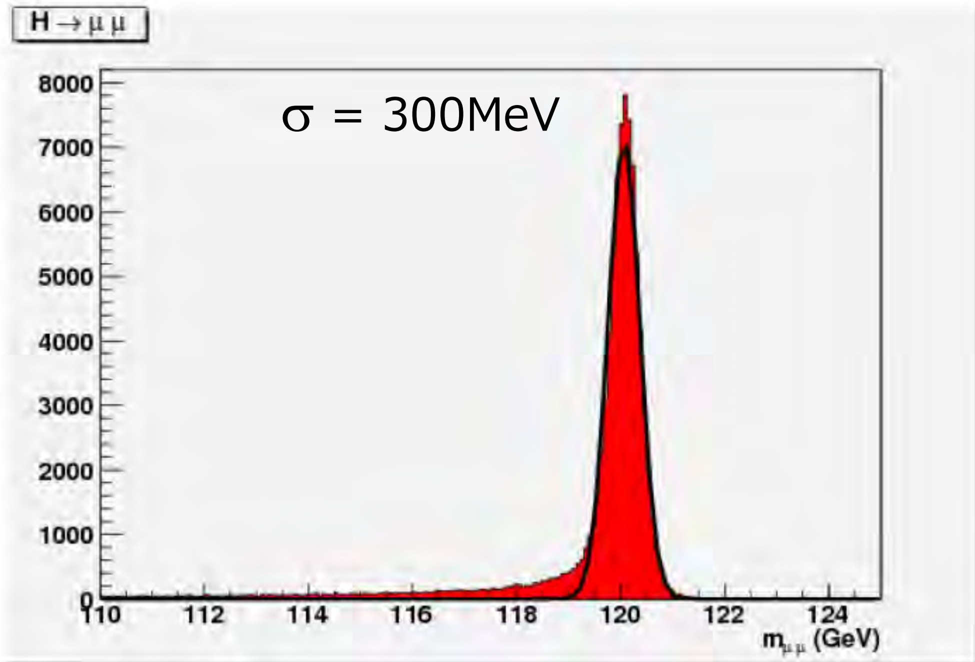
8. Actual Detector Design and Performance

Higgs → $\mu^+ \mu^-$ @ILC

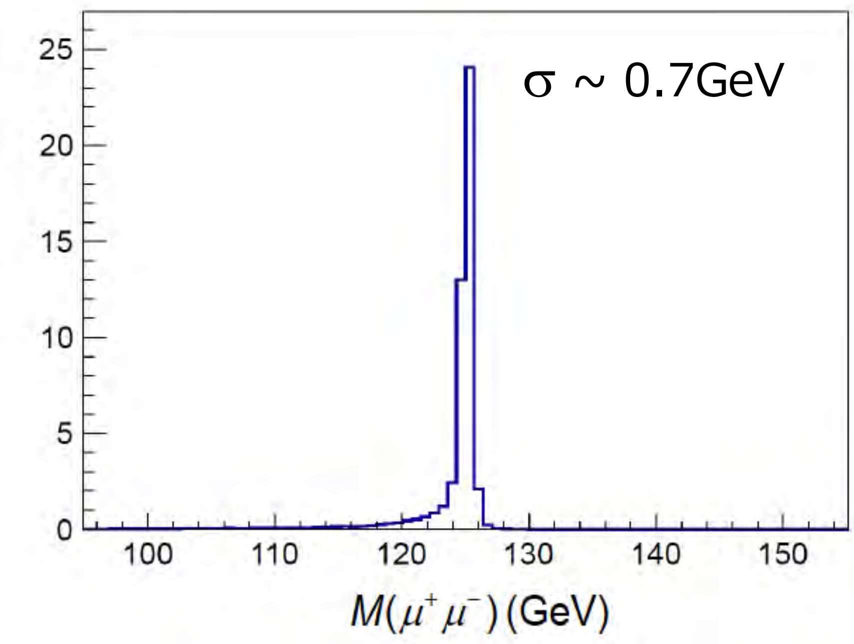


Excellent momentum resolution of ILD (5×10^{-5} PT at 3.5 or 5T) gives excellent di-muon invariant mass resolution.

Four times better momentum resolution
2~4 times better di-muon mass resolution } than ATLAS



Invariant mass of muon pair for
e+ e- → ZH^0 → $qq\mu\mu$ at √S=250GeV
Taken from SiD LoI 2009.

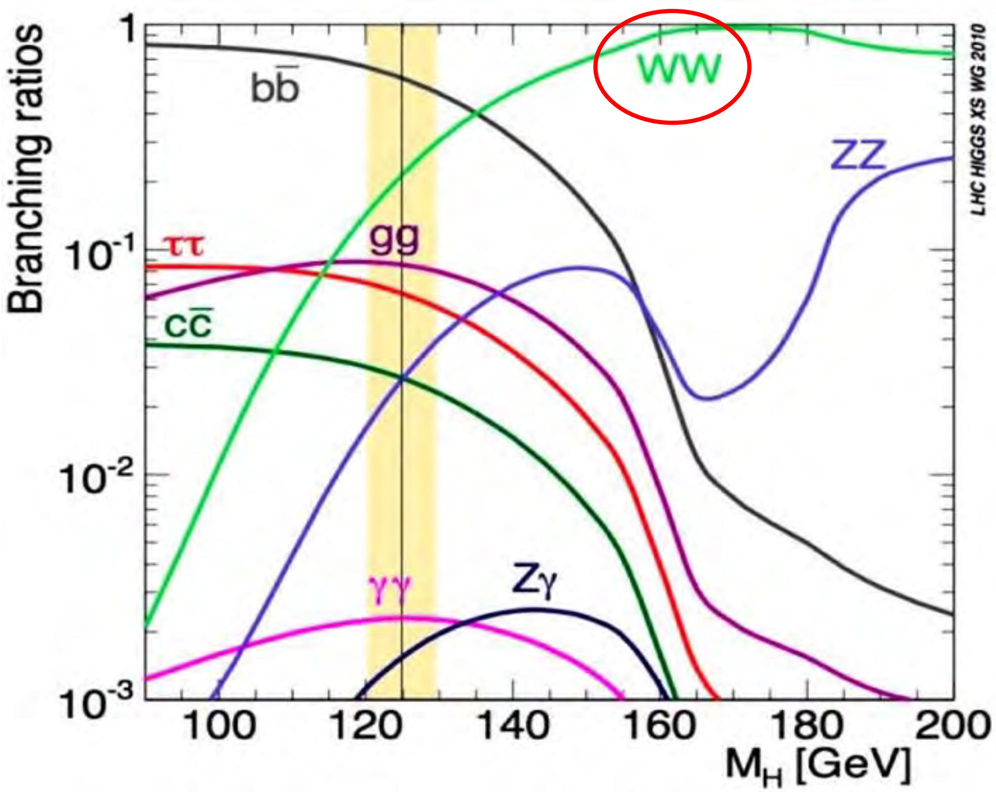


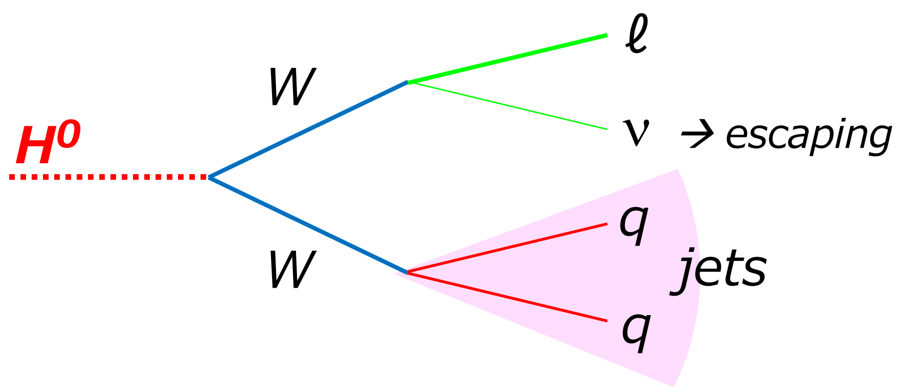
Invariant mass of muon pair for
e+ e- → $\nu\nu H^0$ → $\nu\nu\mu\mu$ at √S=1TeV
Taken from ILC Higgs Whitepaper 2013.

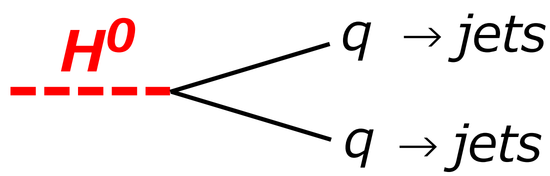
8. Actual Detector Design and Performance

Higgs → Jets as measure of total performance

In the allowed H^0 mass region,
H^0 → WW* has the largest branching fraction → Important for precision study.
H^0 → qq is essentially important to establish "Higgs-ness" of the Higgs.

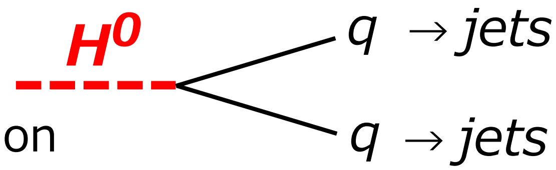






8. Actual Detector Design and Performance

Higgs → Jets as measure of total performance

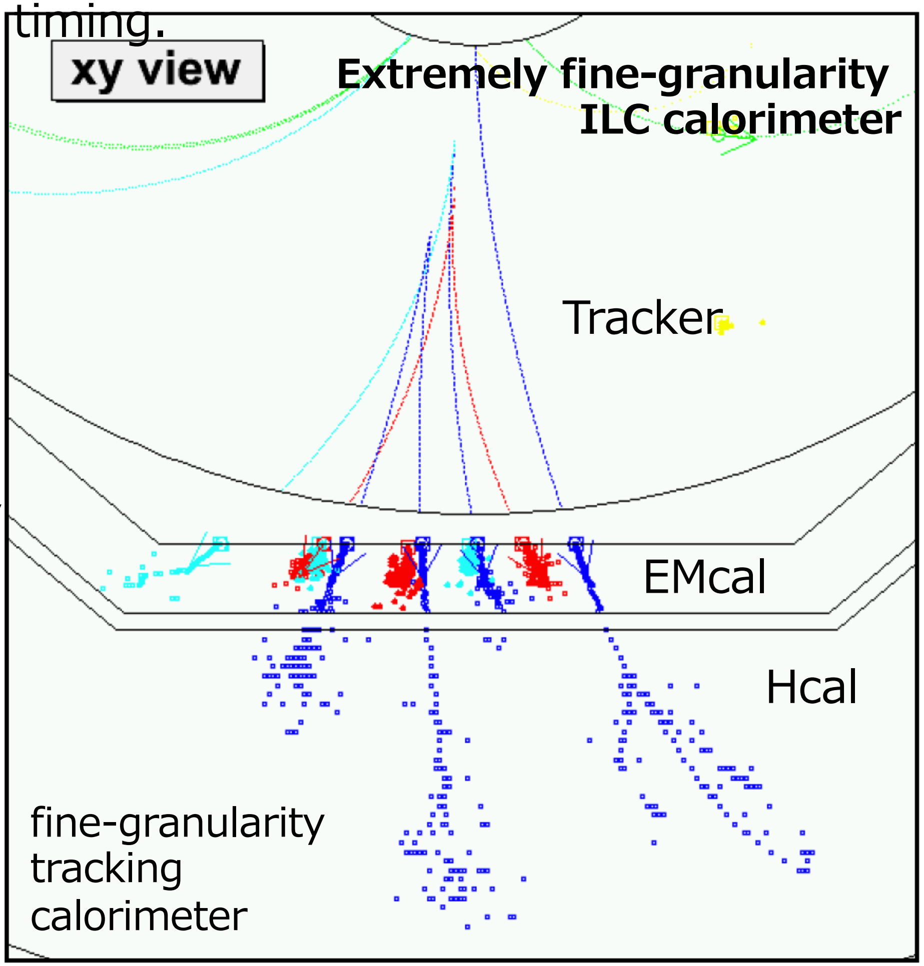


Explicitly reconstruct all possible H^0/t/b/W/Z decays by jet reconstruction

- Charged particle be measured by trackers, while neutral particles by calorimeters.

- Excellent granularities to untangle track/cluster overlapping.

- good resolutions of energy, momentum, position, and timing.
- Need to handle high multiplicity, high occupancy of jets.
- Precision secondary vertexing (b,c,τ-tagging) and primary vertexing (bunch separation).
- Reject overwhelming QCD background reactions overlapping with jets.



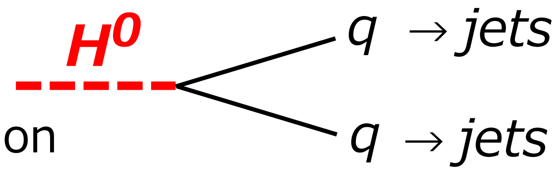
Untangle track/cluster overlap with fine-granularity calorimeters, and use tracker information for charged particles.

Particle in jets	Fraction of Energy	Detector	Resolution
Charged	65	Tracker	0.005%PT
Photons	25	EMCAL	15%/√E
Neutral Hadrons	10	HCAL	60%/√E

Table and figure taken from Aspen 2007 report by J.Brau.

8. Actual Detector Design and Performance

Higgs → Jets as measure of total performance



Explicitly reconstruct all possible H^0/t/b/W/Z decays by jet reconstruction
- Charged particle be measured by trackers, while neutral particles by calorimeters.
- Excellent granularities to untangle track/cluster overlapping.
- **good resolutions of energy, momentum, position, and timing.**
- **Need to handle high multiplicity, high occupancy of jets.**
- Precision secondary vertexing (b,c,τ-tagging) and primary vertexing (bunch separation).
- Reject overwhelming QCD background reactions overlapping with jets.

W/Z mass reconstruction for 2-jet decay

W and Z not separated with conventional $60/\sqrt{E}$ detector.

W and Z clearly separated with $30/\sqrt{E}$ ILC detector.

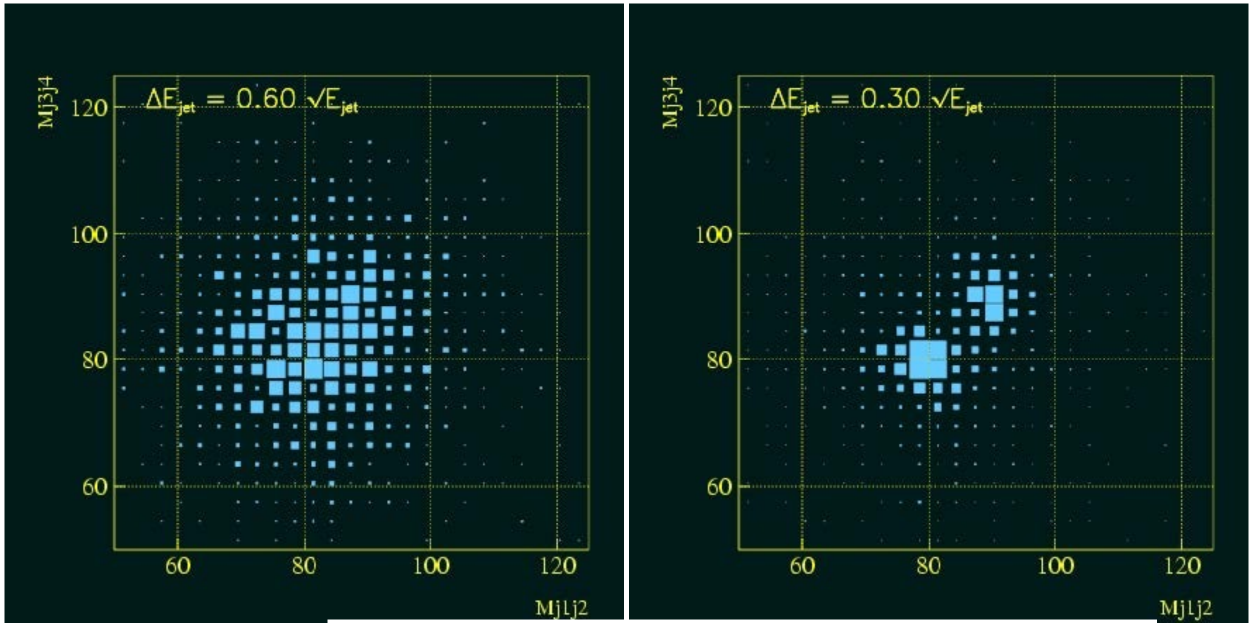
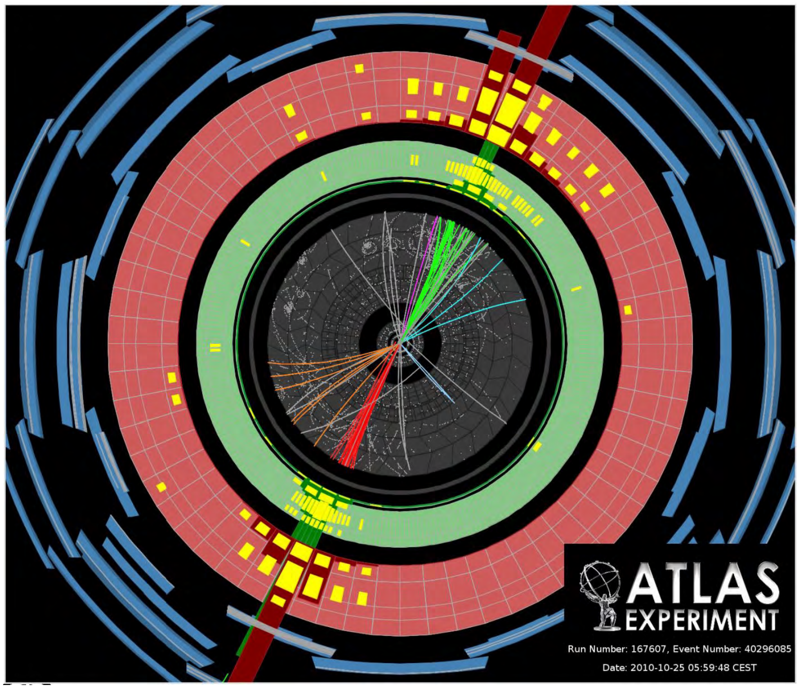


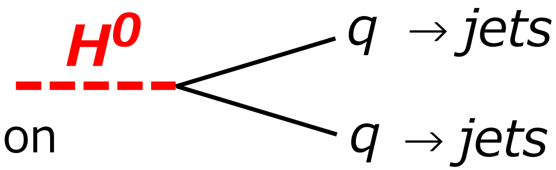
Figure taken from Aspen 2007 report by J.Brau.

Many particle in collimated JET should be separately reconstructed.

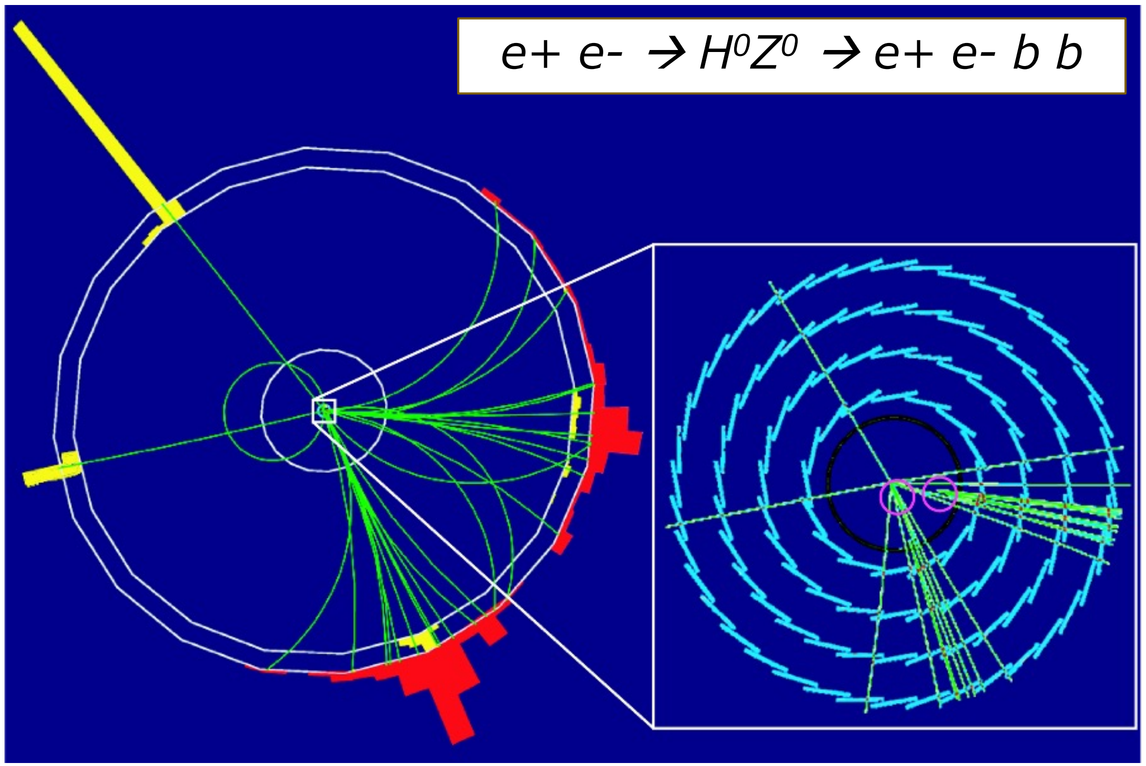


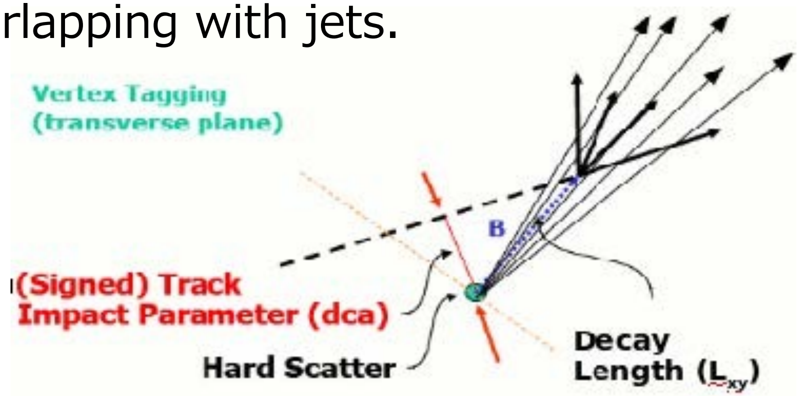
8. Actual Detector Design and Performance

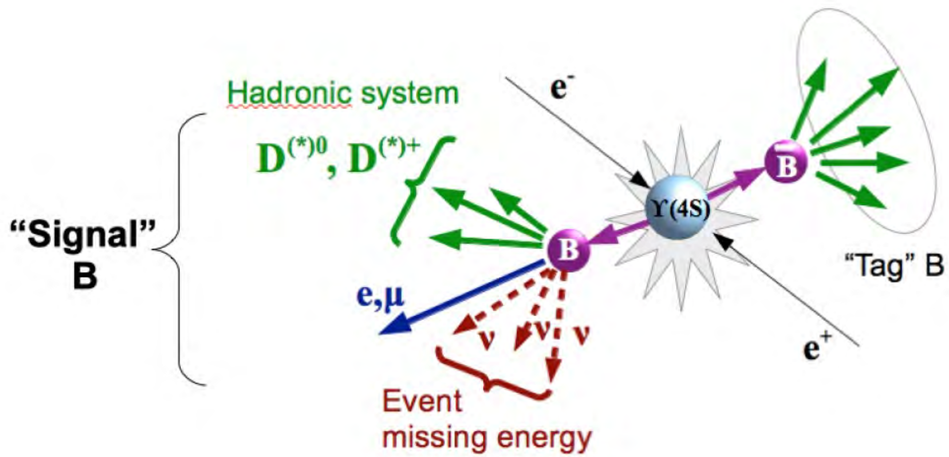
Higgs → Jets as measure of total performance



Explicitly reconstruct all possible H^0/t/b/W/Z decays by jet reconstruction
- Charged particle be measured by trackers, while neutral particles by calorimeters.
- Excellent granularities to untangle track/cluster overlapping.
- good resolutions of energy, momentum, position, and timing.
- Need to handle high multiplicity, high occupancy of jets.
- **Precision secondary vertexing (b,c,τ-tag) and primary vertexing (bunch separation).**
- Reject overwhelming QCD background reactions overlapping with jets.

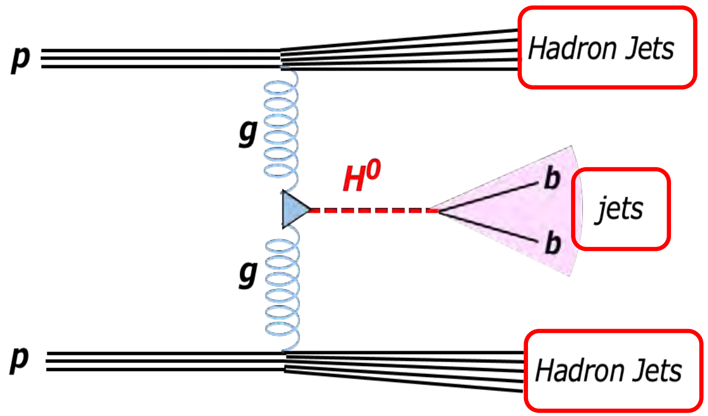






8. Actual Detector Design and Performance

Higgs → Jets as measure of total performance

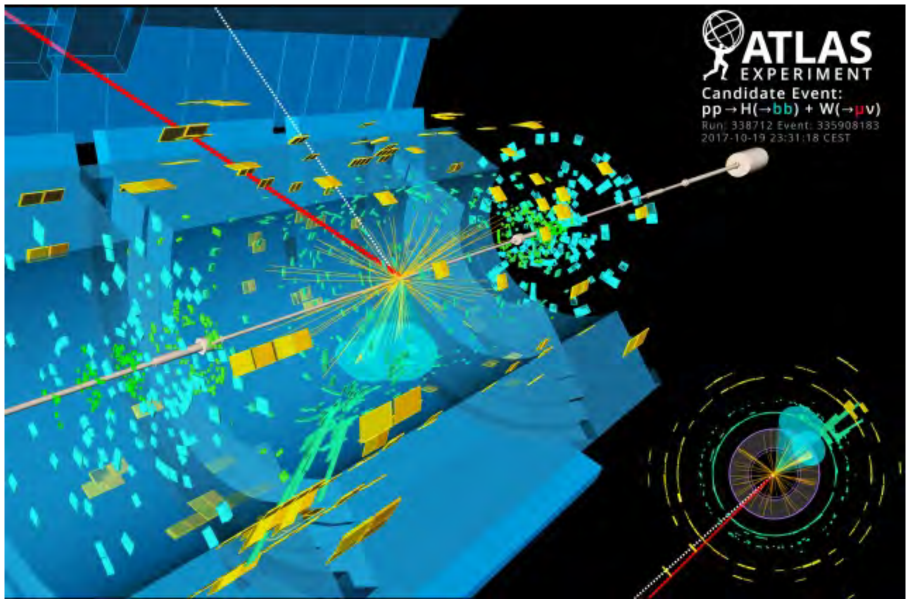


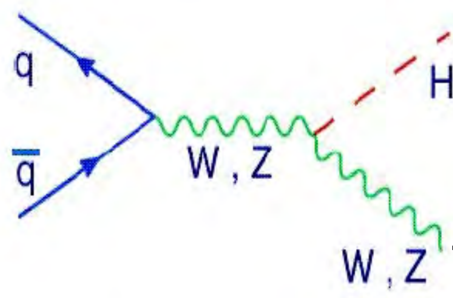
Quarks and Z/W mostly decay into "hadron jets".

- Excellent jet reconstruction needed
- Excellent hadron flavor identification needed
- **Reject overwhelming QCD background reactions overlapping with jets. .**

→ needs characteristic associating particles to distinguish H^0 production from background reaction.

ex.; $q+q$ → W/Z^0+H^0 associated production, where W/Z^0 decay particles are used for event signature.

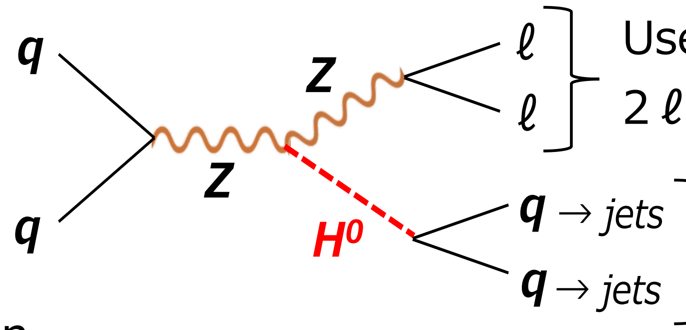




A candidate event display for the production of a Higgs boson decaying to two *b*-quarks (blue cones), **in association with a W boson** decaying to a muon (red) and a neutrino. The neutrino leaves the detector unseen, and is reconstructed through the missing transverse energy (dashed line). (Image: ATLAS Collaboration/CERN)

8. Actual Detector Design and Performance

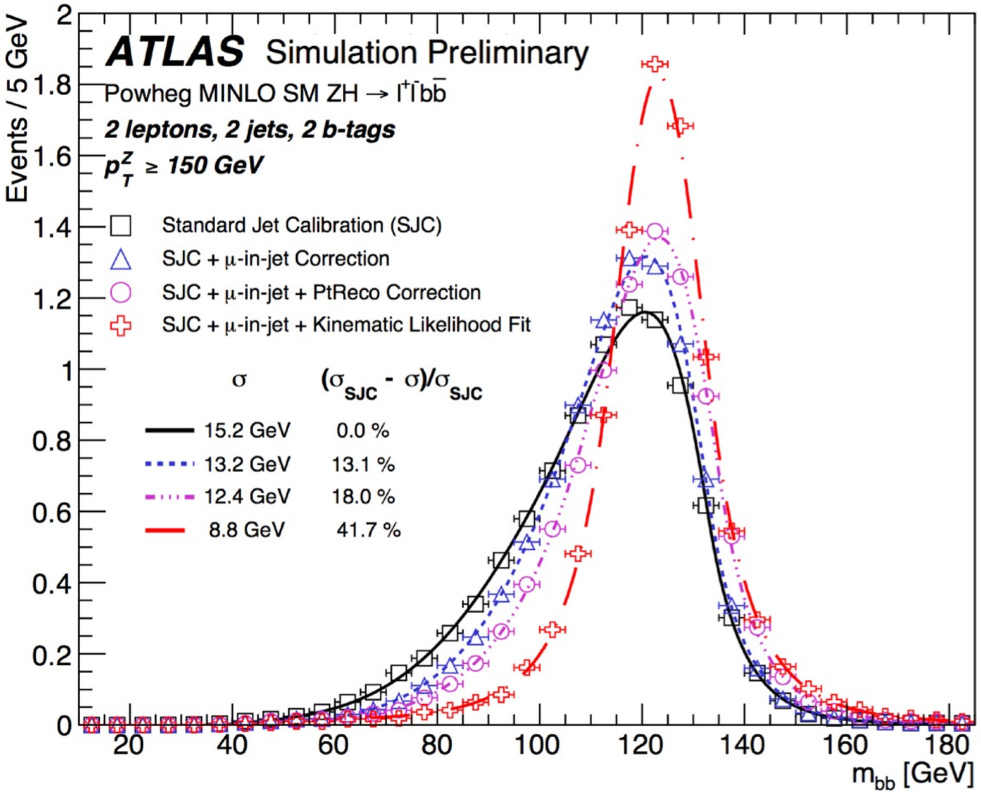
Higgs → Jets in ATLAS case



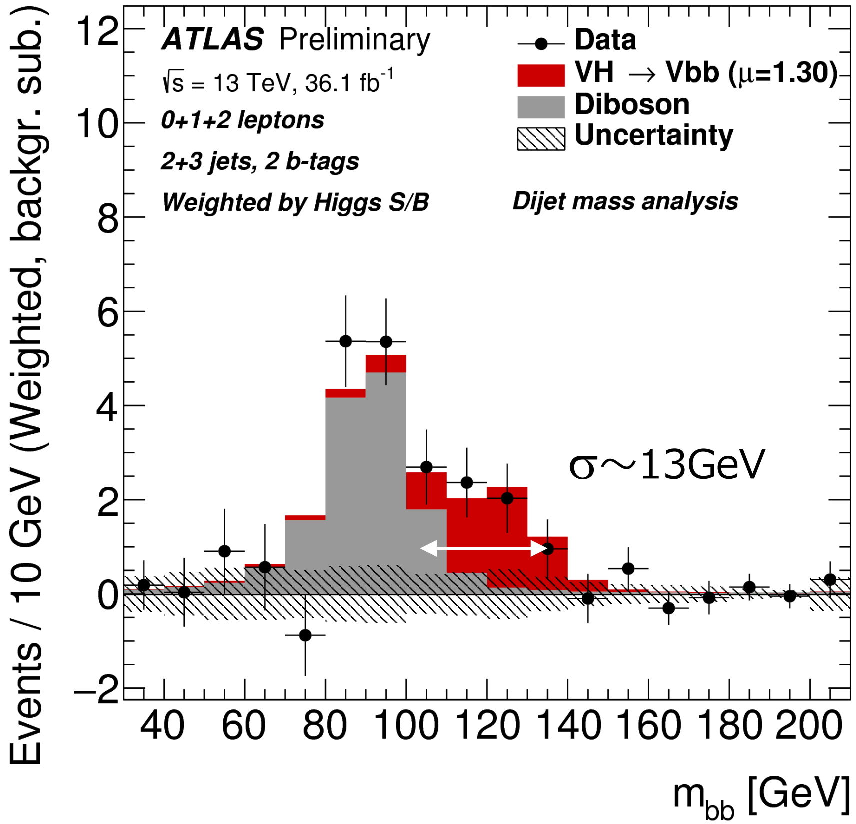
Used for constraint.
2 ℓ for Z, 1 ℓ for W, 0 for Z→νν

m_{bb} reconstructed

Simulated m_{bb} resolution
15.2GeV for simple jet mass recon.
13.2GeV with μ in b-jet correction.
8.8GeV with 2-lepton constraint.



Real data



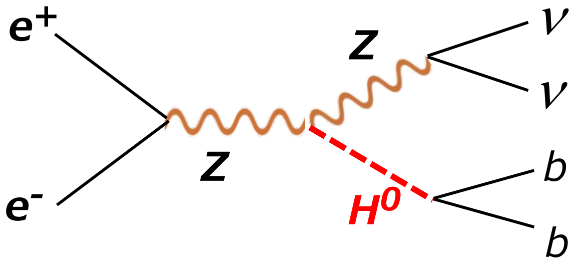
σ～13GeV

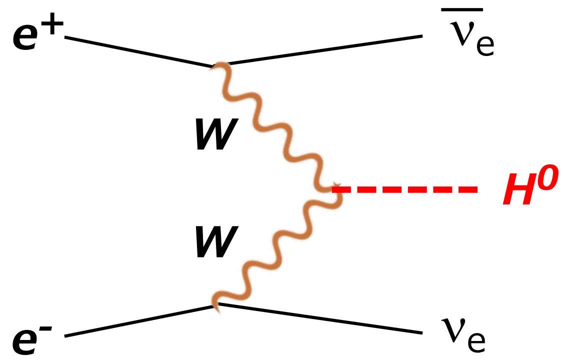
taken from T.Masubuchi「LHCでのヒッグス研究の最新結果」2017

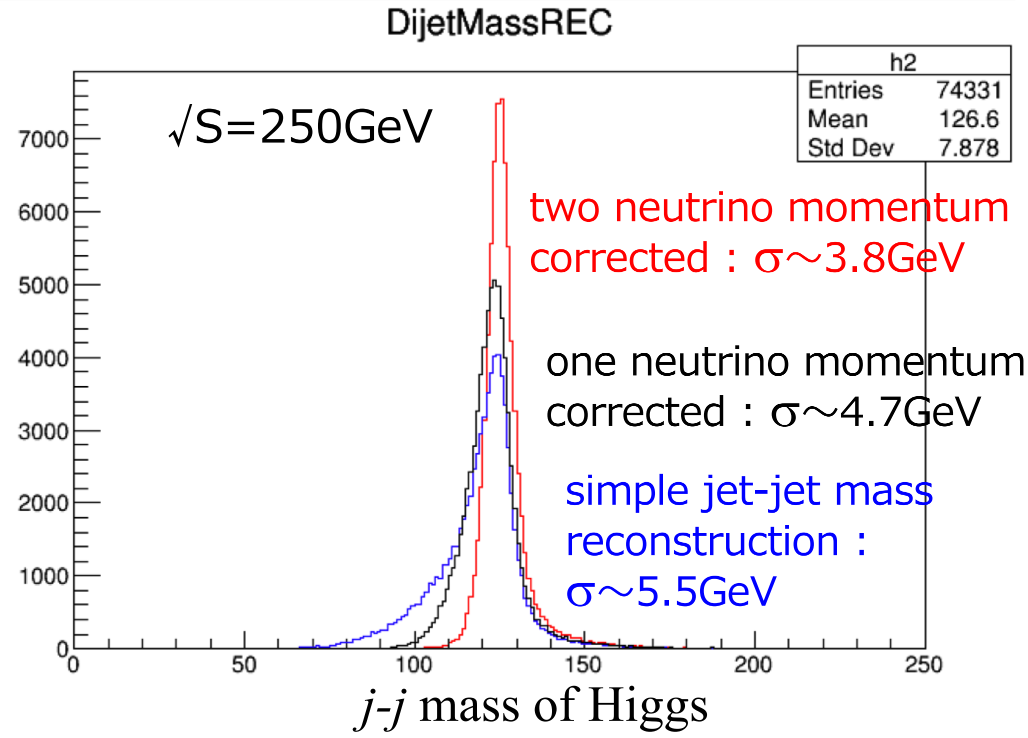
8. Actual Detector Design and Performance

Higgs → Jets in ILC case

significantly better than LHC case

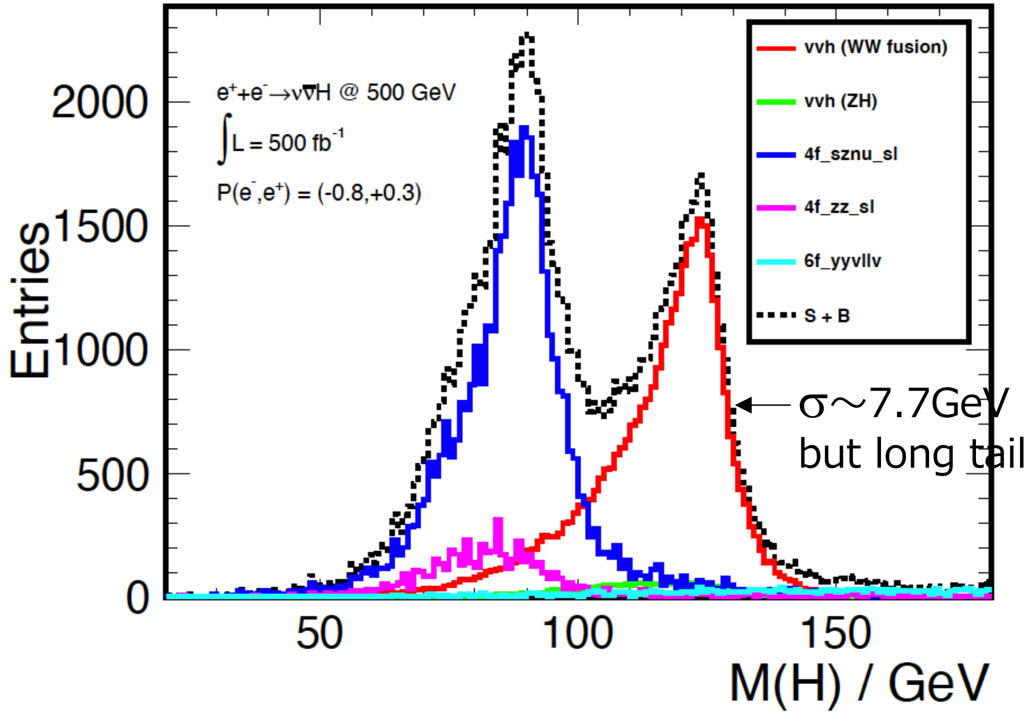






Taken from SS.Kajiwara「Improving the jet energy reconstruction for Higgs precision measurement at the ILC」2019

Event selection with missing νν applied.



taken from「ILC Higgs White Paper」2018

8. Actual Detector Design and Performance

In Summary

For Higgs/EW/top precision study,
we need to reconstruct all decay modes;
H^0 /top/W/Z → $q\ q, \ell\ \ell\ , \gamma\,\gamma, W\ W, Z\ Z$

We need
- excellent EM calorimeter : energy resolution and granularity
- excellent tracker ; momentum resolution and collimated track separation
- Excellent hadron flavor tagging ; vertex and PID
- excellent jet reconstruction ; combination of above all
- utilization of production channel associated with characteristic particles

And we have variety of detector technologies to achieve above.