Detector Complex
at Large High-Energy Experiments

- Let's design Particle-Physics Detectors -

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Vietnam School on Neutrino 2023

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J-PARC Neutrino Experimental Facility

Preface

There are many types of particle physics experiments:

- High-energy to low-energy
- High event rate to low event rate, even down to rare event search
- High-multiplicity event to low-multiplicity event

Neutrino experiments are experiment of
medium energy, low event rate, low-multiplicity event.

On the opposite side, collider experiments exist. Let me introduce how collider detectors look like, and how they are designed.

Self-introduction

Yoshiaki Fujii

High-energy accelerator research organization

and J-PARC Neutrino Experimental Facility

Currently working on T2K experiment and neutrino experimental facility

After obtaining Ph.D,

1986-1995 AMY experiment at TRISTAN e+e- collider

1991-2004 Linear-collider R&D

2004-now Neutrino Experiment

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
- Erika ; Lecture "The Physics of Particle Detectors", by Erika Garutti
- Joram ; CERN Summer Student Lectures 2003, by Christian Joram

and many slides on the reports by ATLAS, CMS, ILC.

Contents

1. Pick up Reactions to Measure
2. Overview the various detector configuration
   - Get Common sense of the detector configuration
3. Requirements to the detectors
   - What is required for the detectors for our study ?

7/26
(probably)

4. Operation of detectors
   - Trackers
   - Vertex Detectors
   - Calorimeters
   - Particle identification
5. Further Improvement (HL-LHC)

7/27
(probably)

1. Pick up Reactions to Measure

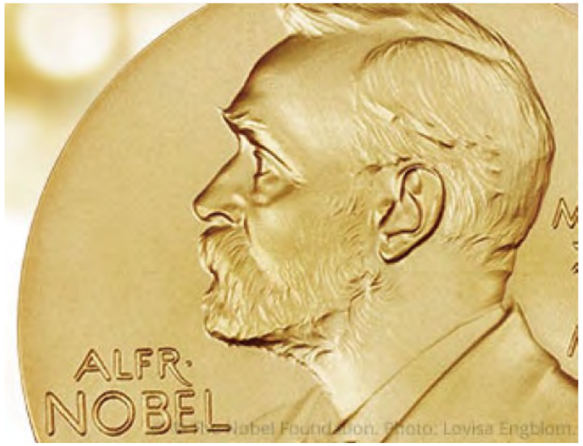
1. Pick up Reactions to Measure

Let's discover and study Higgs at collider experiments

Discovery of a new particle is one of the most important object of particle physics

Precision study of the new particle is the essence of the particle physics.
Discovery is just start of the huge new physics.

However . . . . .
Nobel prize is always given to the discovery,
not to the precision study.



<u>Therefore, you must achieve both discovery and precision study.</u>

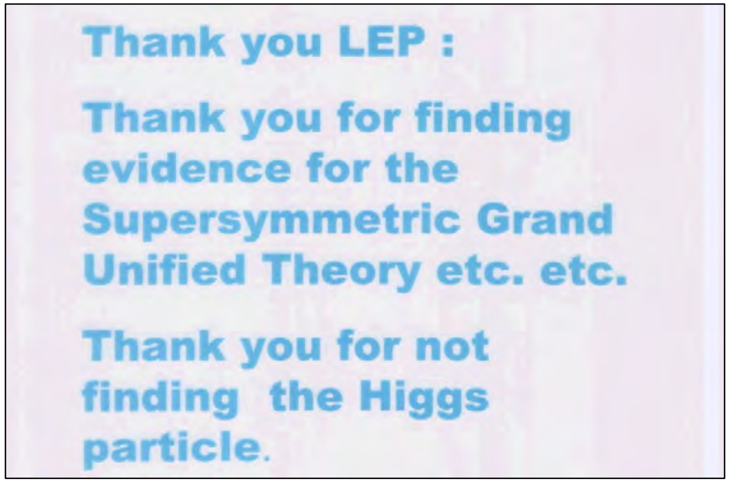
1. Pick up Reactions to Measure : Let's discover and study Higgs at LHC/ILC

Assumed Situation (like at the end of 20th century) ;

- Forget the actual discovery of Higgs at LHC in July 2012
- LEP saw something at ~115GeV

We know everything on the Standard Model Higgs except for its mass.
The allowed region is pretty clear, and we think it should not be heavy.

LEP
e+ e- collider at CERN.
1989-2000, and gave way to LHC construction.
ECM = 90GeV- 209GeV
Precision Study of Z and search for Higgs
Four experiments; ALEPH, DELPHI, L3, OPAL



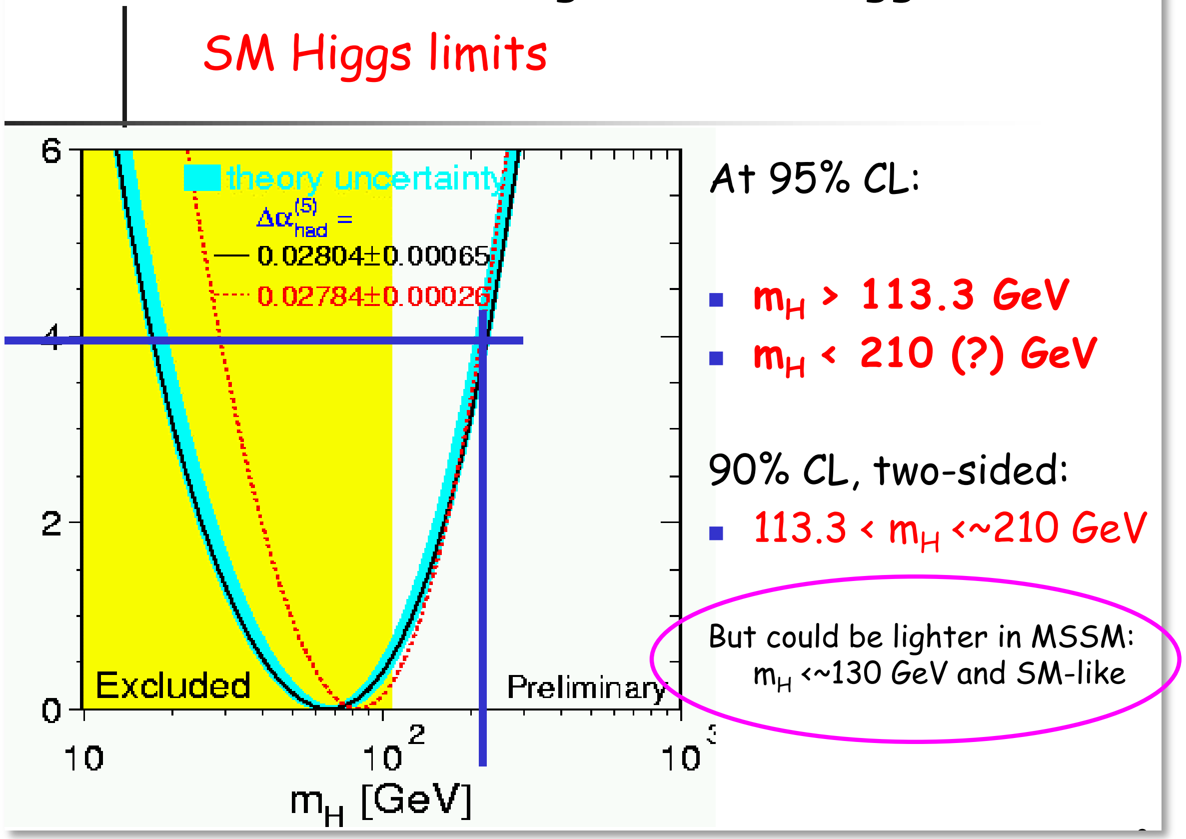
Thank you LEP :

Thank you for finding evidence for the Supersymmetric Grand Unified Theory etc. etc.

Thank you for not finding the Higgs particle.

Prof.Sugawara's remark at Osaka 2000 conference

Prof. De Angelis talk on Higgs in 2000.



SM Higgs limits

At 95% CL:

- $m_H > 113.3$ GeV
- $m_H <$ 210 (?) GeV

90% CL, two-sided:

- $113.3 < m_H <\sim 210$ GeV

But could be lighter in MSSM:
$m_H <\sim 130$ GeV and SM-like

1. Pick up Reactions to Measure

First of all,

Let's discover Higgs

1. Pick up Reactions to Measure

Once you decide your physics target,
you need to carefully examine characteristics of the reaction process,
and set design criteria of your detector **appropriately**.
Over-spec is waste of resources ; more budget, more effort, and more time.
Don't waste your time to build too fancy detectors.
You should be the first one. There is no second discovery.

In 1974, the new particle J/ϕ was reported by three groups.
- S.Ting's BNL experiment ; Phys.Rev.Lett.33,1404-1406 (1974Nov12)
- B.Richter's SLAC experiment ;Phys.Rev.Lett.33,1406-1408 (1974Nov13)
- G.Bellettini's Frascati experiment ;Phys.Rev.Lett.33,1408-1410(1974Nov18)

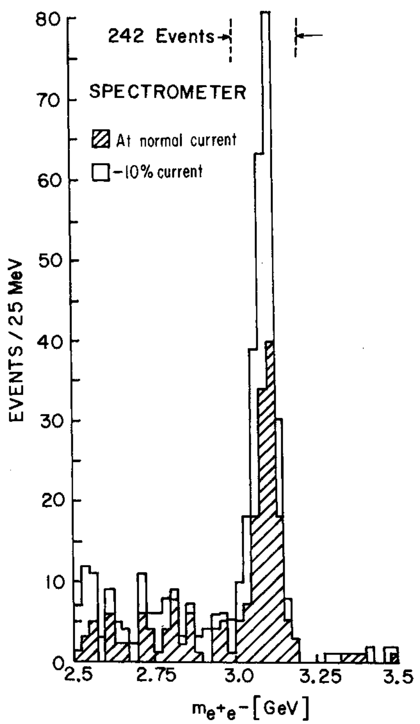
The Nobel prize of 1976 was given to S.Ting and B.Richter.

In 1983, two experimental groups reported discovery of W-boson
- UA1 ; Physics Letters B 122, 103-116 (1983 Feb.24)
- UA2 ; Physics Letters B 122, 476-485 (1983 March 13)

C.Rubbia of UA1 won the Nobel prize. UA2 could not.

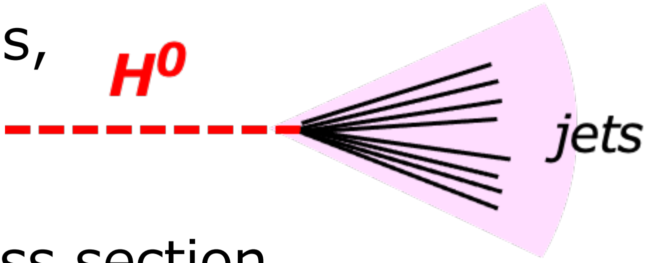
Please recall the neutrino oscillation discovery in Oyama-san's lecture and rush of θ_{13} repoorts in 2011-2012.

Incredibly narrow peak.
Discovery of the 4th quark "c-quark"



1. Pick up Reactions to Measure : Let's discover Higgs

We know everything on the SM Higgs except for its mass.
- The mass should be 113GeV ~ 210GeV.
- We know SM H^0 production cross section of various channels.
- We know SM H^0 decay branching ratio of all decay modes.



- Make invariant mass of expected H^0 decay particles, and find a peak.

- Pick up production channel of large production cross section. Better to have associated particles which characterize the reaction to suppress background.

- Pick up decay mode with large branching ratio, easy reconstruction, and small background reaction.

Better S/N, faster discovery, express ticket to the Nobel Prize.

1. Pick up Reactions to Measure : Discover Higgs at **ILC**

Let's discover Higgs at LHC

- Make invariant mass of Higgs decay particles, and find a peak.
- Choose Higgs production channel and Higgs decay channel with reasonable event rate and low background reaction, better to have characterizing associated particle.
- Better S/N, faster discovery, cross-cut to the Nobel Prize.

1. Pick up Reactions to Measure : Discover Higgs at **LHC**

Higgs Production

- *g* + *g* → H^0 is dominant for m_H=113~210GeV

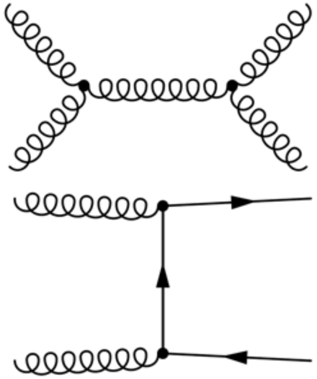
  We should choose clear decay mode of H^0

  since there are no associated particles to characterize this reaction.

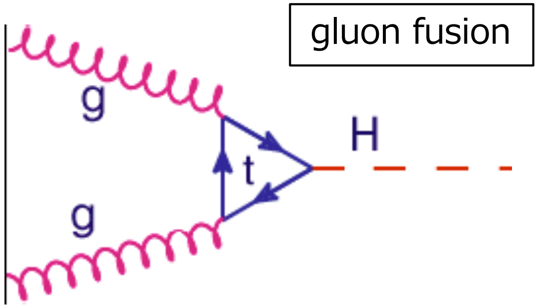
- *q*+*q* → *q*+*q*+H^0 has the second-largest cross section.

  Outgoing *qq* can be used for reaction tagging.

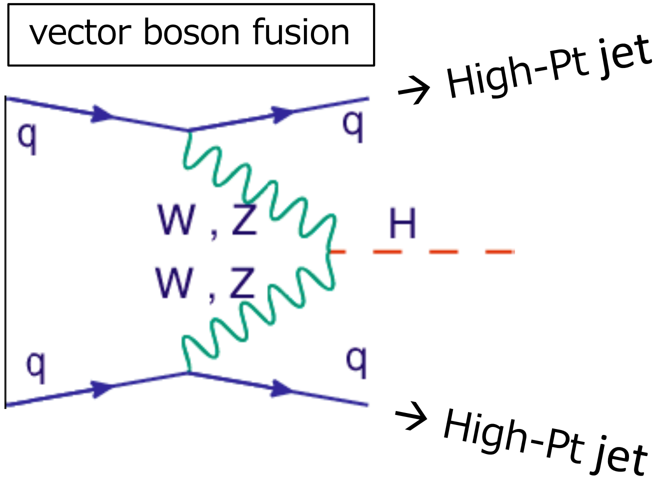
  A bit complicated decay mode could be used.



QCD Background reaction generates hundreds of low-energy particles.



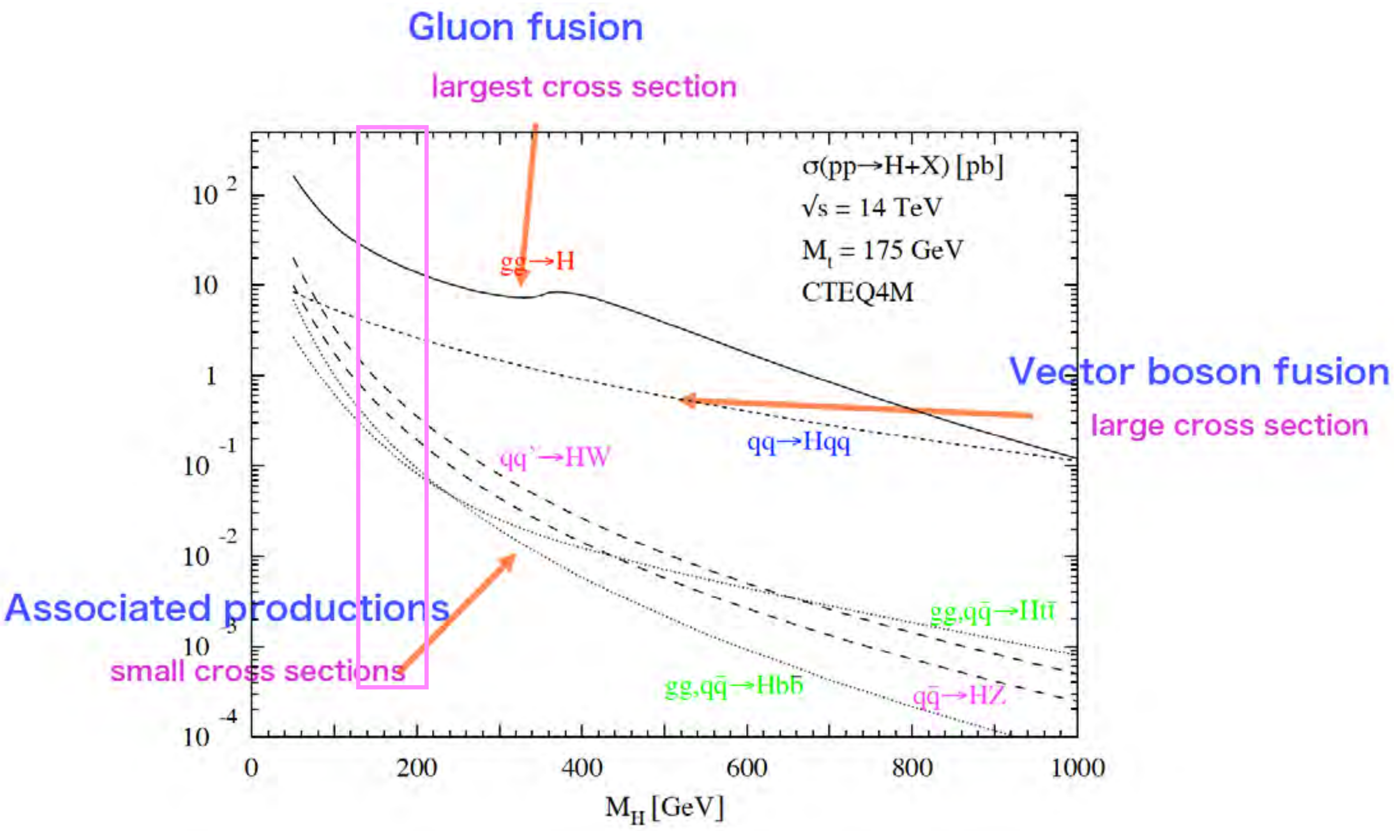
gluon fusion



vector boson fusion

→ High-Pt jet

→ High-Pt jet



Gluon fusion

largest cross section

Vector boson fusion

large cross section

Associated productions

small cross sections

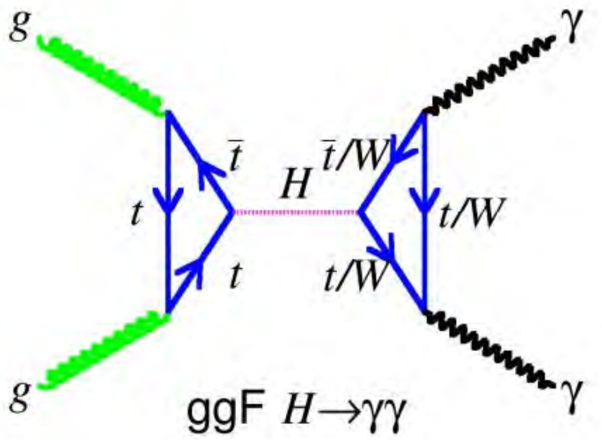
1. Pick up Reactions to Measure : Discover Higgs at **LHC**

LHC

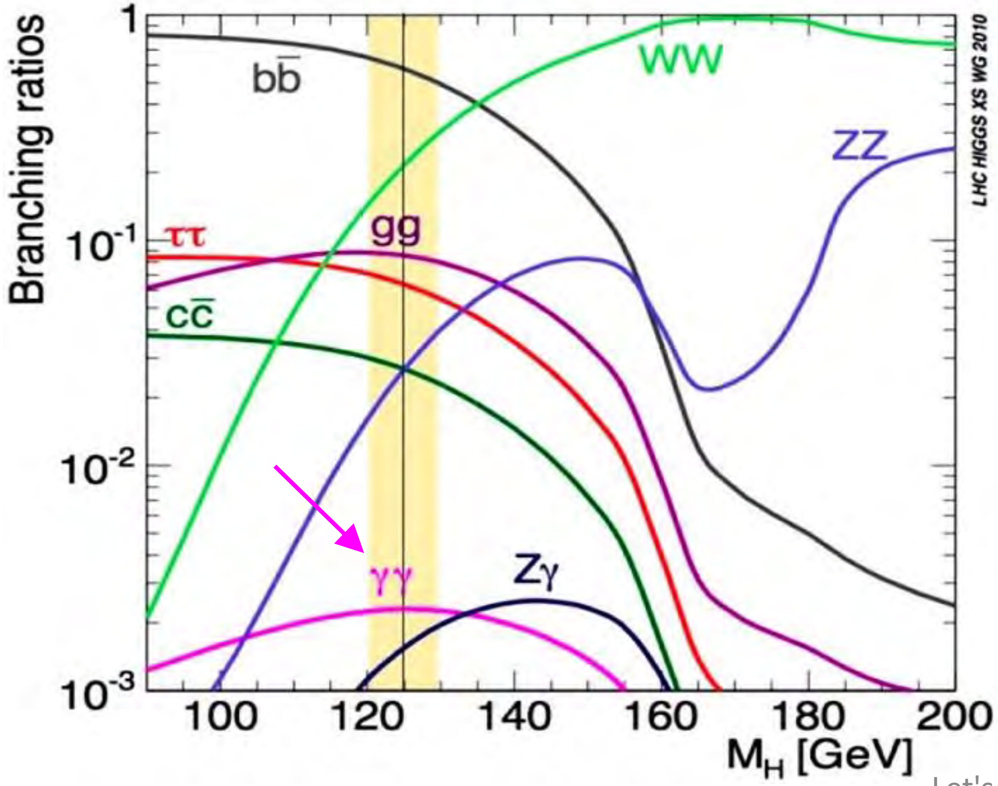
Higgs Decay mode

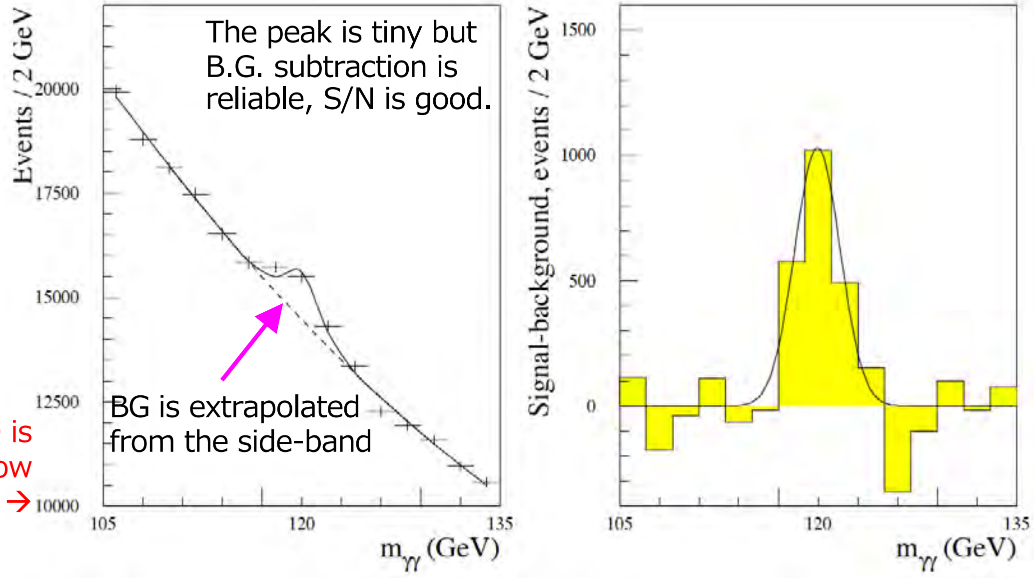
$H^0 \rightarrow \gamma\gamma$ (for light H^0)

- Just reconstruct $\gamma\gamma$ invariant mass and find a peak.
- Branching ratio is small (0.23%) but
  good S/N and good mass resolution expected, and
  background is model independent (use side-band).
- Signal γ is high energy and isolated.



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





The peak is tiny but B.G. subtraction is reliable, S/N is good.

BG is extrapolated from the side-band

Note 0 is far below here →

γγ-mass (**simulation** in ATLAS TDR)

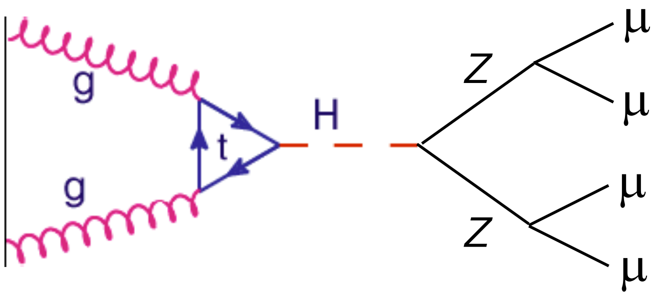
1. Pick up Reactions to Measure : Discover Higgs at **LHC**

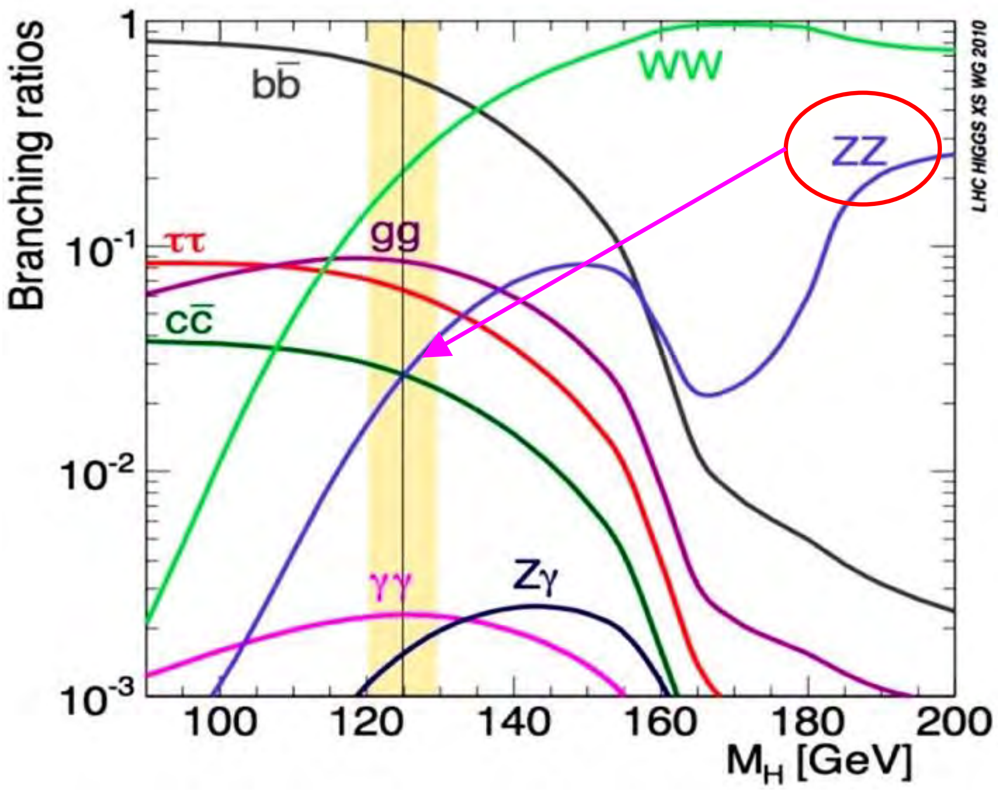
LHC

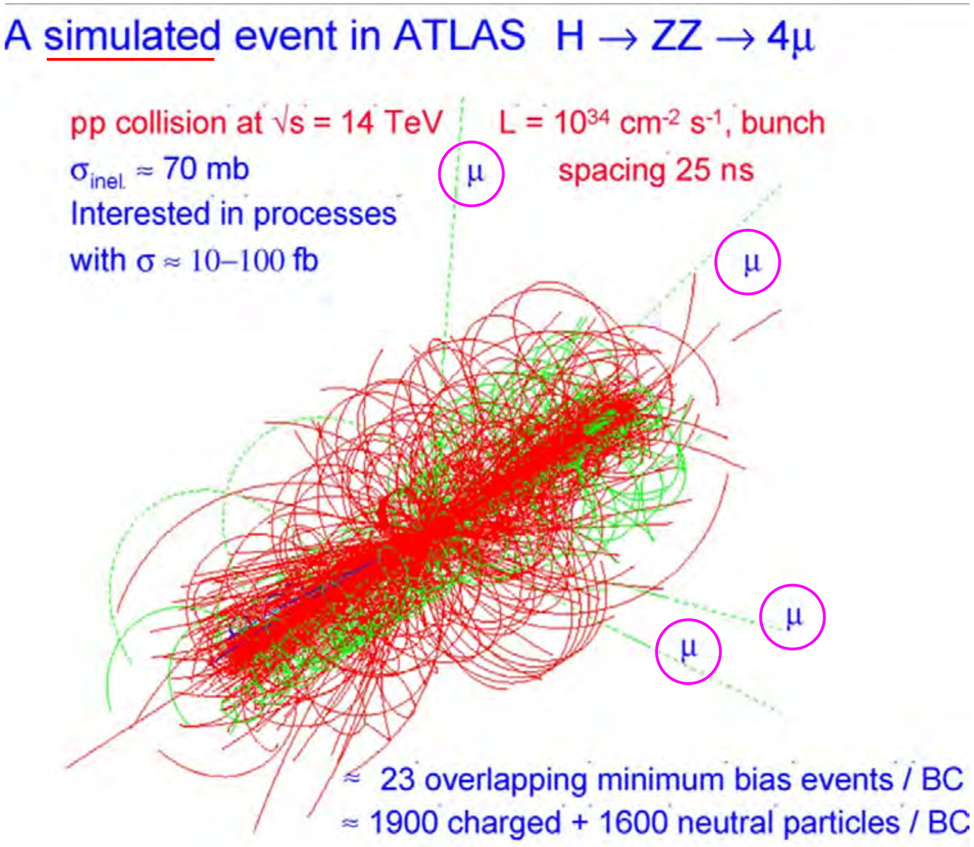
Another Decay mode

Higgs → $ZZ^* \rightarrow 4\mu$ (for not so light H^0)

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







A simulated event in ATLAS $H \rightarrow ZZ \rightarrow 4\mu$

pp collision at $\sqrt{s}$ = 14 TeV L = 10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns

$\sigma_{inel.} \approx$ 70 mb

Interested in processes with $\sigma \approx$ 10–100 fb

≈ 23 overlapping minimum bias events / BC

≈ 1900 charged + 1600 neutral particles / BC

1. Pick up Reactions to Measure : Discover Higgs at **LHC**

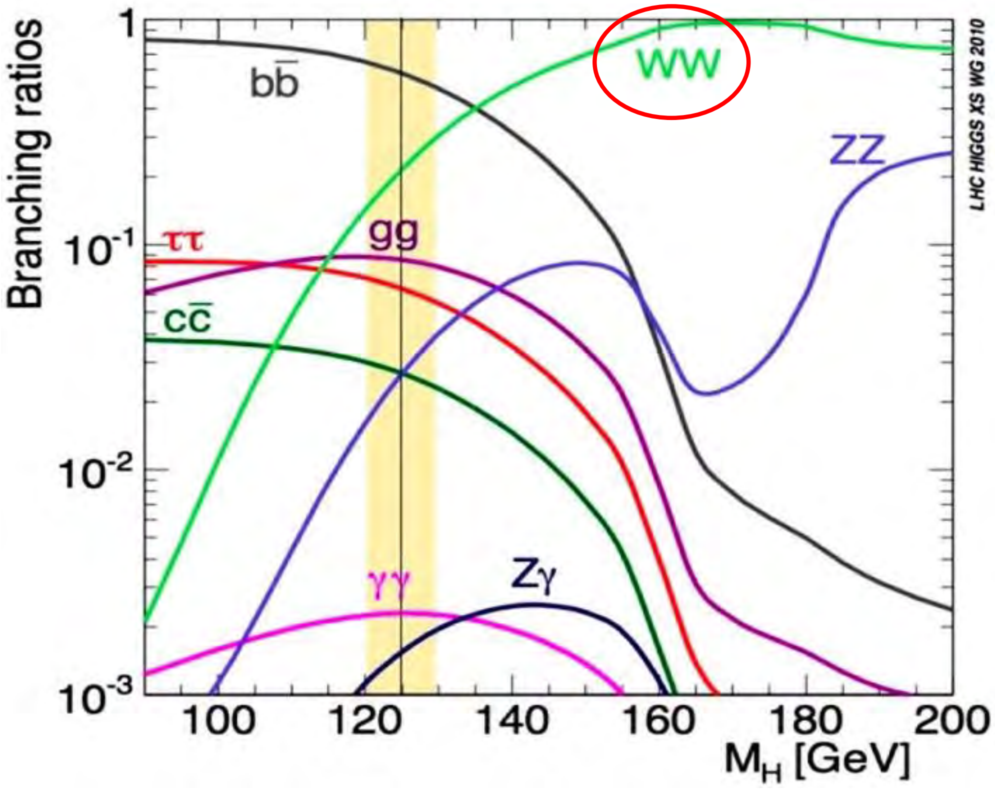
What about Other Decay modes ?

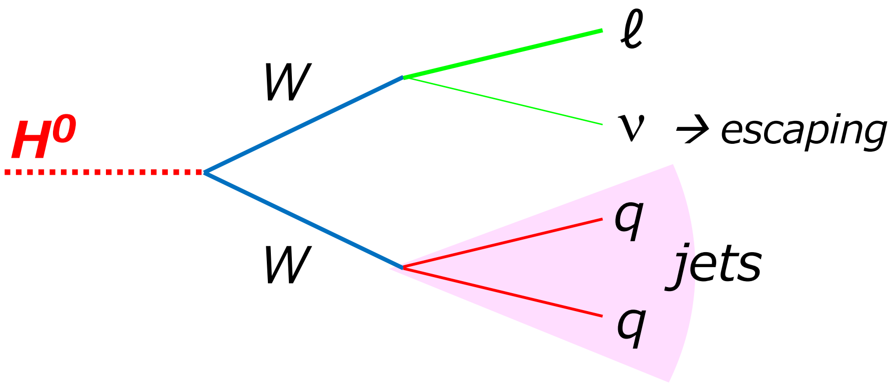
In the allowed H^0 mass region,

H^0 → WW^* has the largest branching fraction. Can we use it for discovery ?

- W decay reconstruction is difficult : hadron jets or neutrino escaping.
  - → Can't be narrow peak → not suitable for quick discovery

H^0 is likely to be light. → WW is not the top priority channel for H^0 search.





1. Pick up Reactions to Measure : Discover Higgs at **LHC**

In order to discover Higgs at LHC,

$H^0 \rightarrow \gamma\gamma$ and $H^0 \rightarrow 4\mu$ channels are promising.

For above, we need

- Excellent gamma measurement
- Excellent muon measurement

Let's discover Higgs at ILC

- Make invariant mass of Higgs decay particles, and find a peak.
  In addition, there is another way at ILC.
- Choose Higgs production channel and Higgs decay channel with reasonable event rate and low background reaction, better to have characterizing associated particle.
- Better S/N, faster discovery, cross-cut to the Nobel Prize.

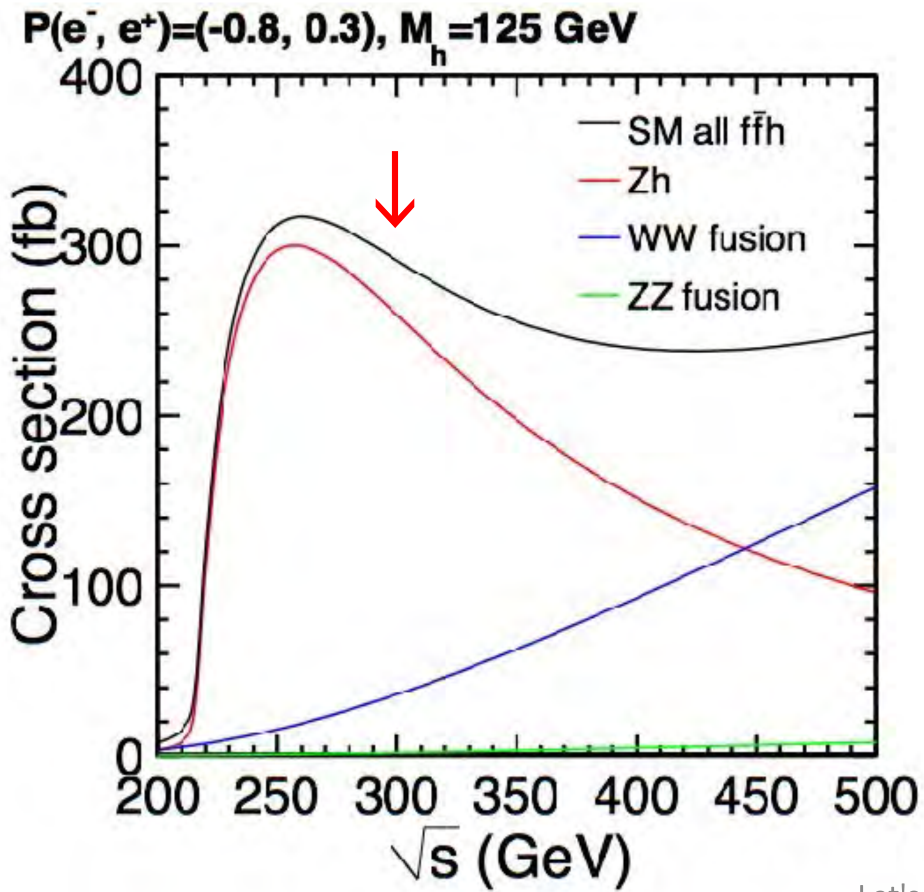
1. Pick up Reactions to Measure : Discover Higgs at **ILC**

Discovery mode

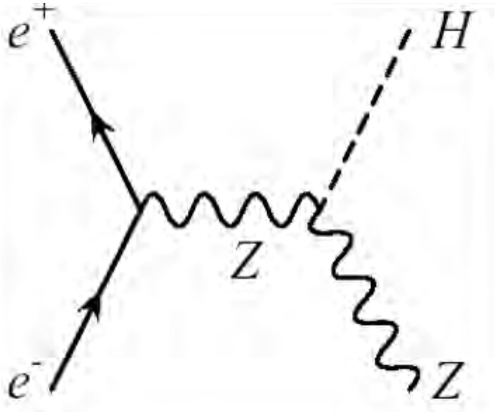
Production Channel is, no doubt,

$e^+ e^- \rightarrow Z^0H^0$; dominant production process

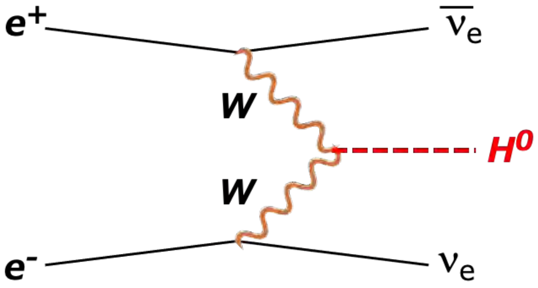
Let's discover Higgs at ILC √S=300GeV



Z^0H^0

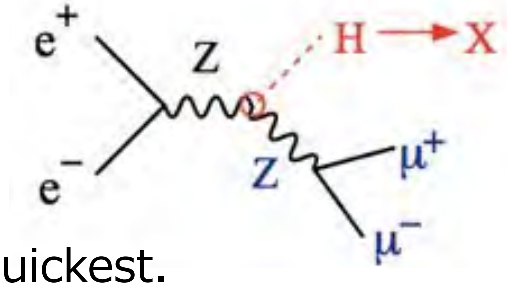


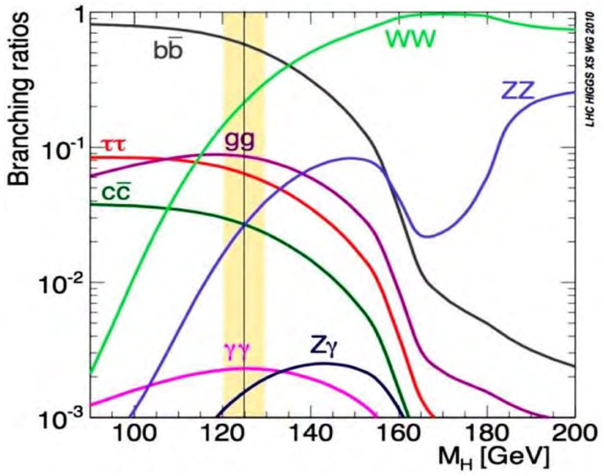
W-fusion



1. Pick up Reactions to Measure : Discover Higgs at **ILC**

Decay mode of Z^0/H^0 to search for ;





e+ e- → Z^0H^0

a) H^0 → *bb* (largest branching ratio of 58%)

Z^0 → anything

Reconstruct H^0 *b* decay explicitly.

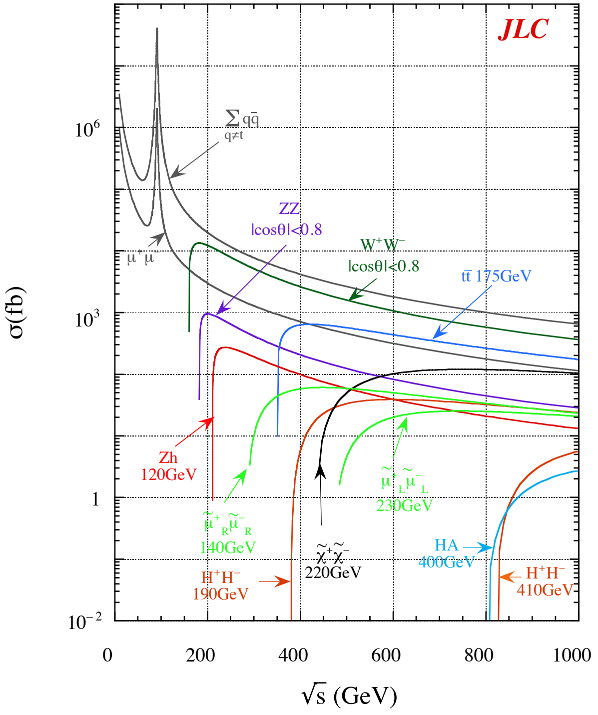
- ✓ *b* jet reconstruction is not the easiest/quickest.
- ✓ Higgs may not be SM Higgs. *bb* may not be the largest.

b) $Z^0 \rightarrow \mu^+\mu^-$ (unambiguous decay channel)

H^0 → anything

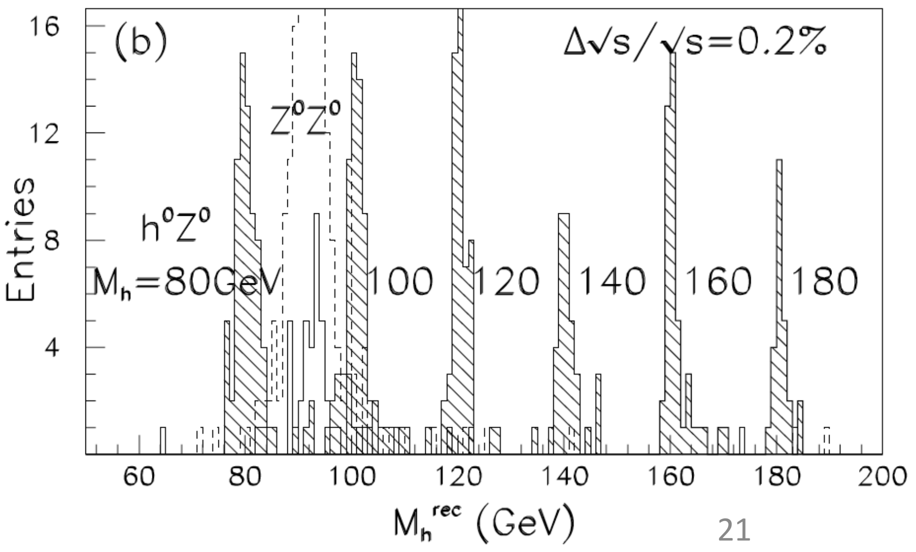
Reconstruct recoil mass of μμ from Z^0 decay and find a peak. → Can work for any Higgs.

e+e- collider has well-defined initial state. → P/E balance can be used in analysis.



$e^+ e^- \rightarrow Z^0 Z^0$ has larger cross section and becomes background, but clearly separated thanks to the excellent μμ mass reconstruction resolution.

Recoil mass of Z^0 (simulatiuon)



1. Pick up Reactions to Measure : Discover Higgs at **ILC**

In order to discover Higgs at ILC, we pick up

$e+ \ e- \rightarrow Z^0H^0$,

$Z^0 \rightarrow \mu^+\mu^-$,

$H^0 \rightarrow$ anything

For above, we need

- Excellent muon measurement

Muons are always the key to carry new physics.

Let's study Higgs at LHC/ILC

Discovery is just a start of Higgs Physics.

For precision study of Higgs, we need to measure couplings of Higgs to all species of the particles.

→ All Higgs decay particles should be detected precisely
and Higgs should be reconstructed for variety of decay channel.

1. Pick up Reactions to Measure : Study Higgs at LHC

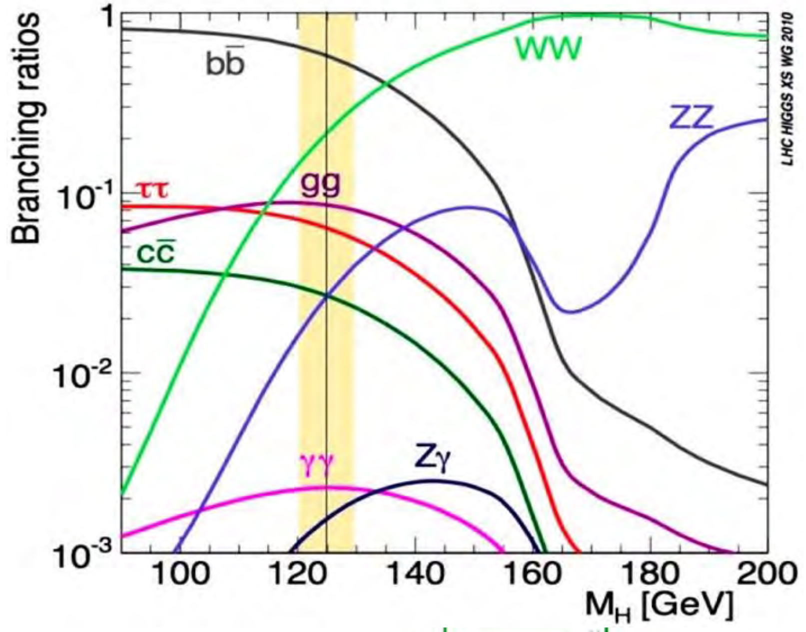
LHC

Detailed study

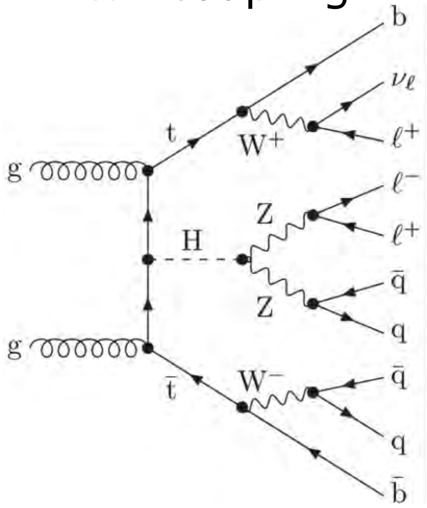
- Confirm spin/parity
- Explicitly reconstruct all H^0 decays modes to confirm coupling of particles to Higgs.
  - Coupling to top, Z, W needs study of associated production.
- Hadronic decay of H^0 and hadronic decay of associated t/Z/W suffer huge QCD background.
  → needs signature to distinguish H^0 production from background reaction

  exl. $q+q \rightarrow Z^0+H^0$;

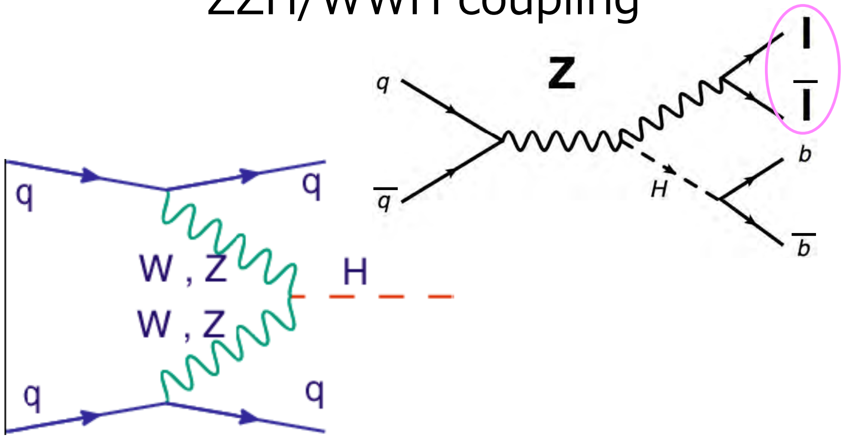
  Z^0 leptonic decay for event signature.

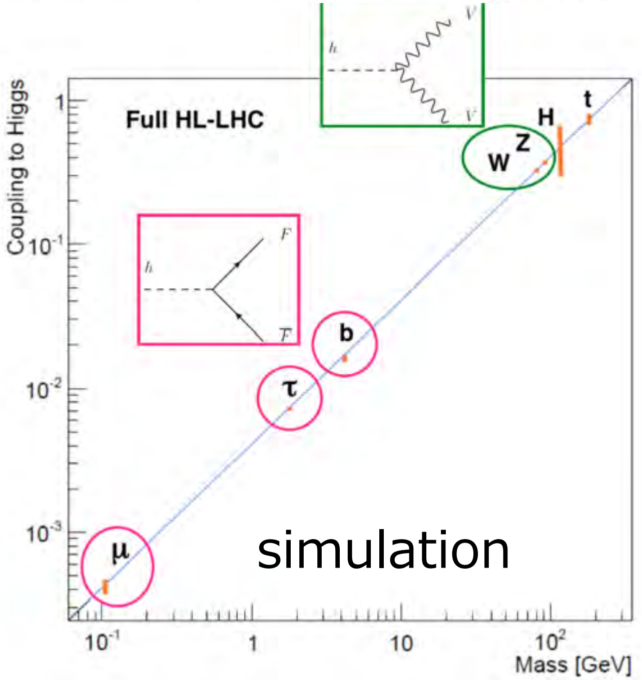


ttH coupling



ZZH/WWH coupling





simulation

1. Pick up Reactions to Measure : Study Higgs at LHC

LHC

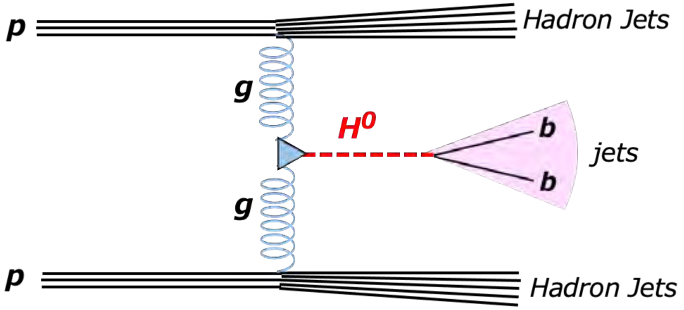
Detailed study

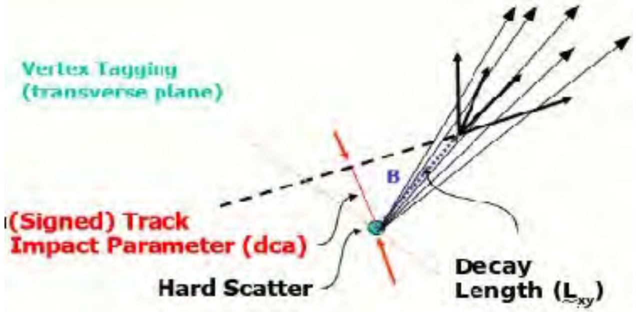
Quarks and Z/W mostly decay into "hadron jets".

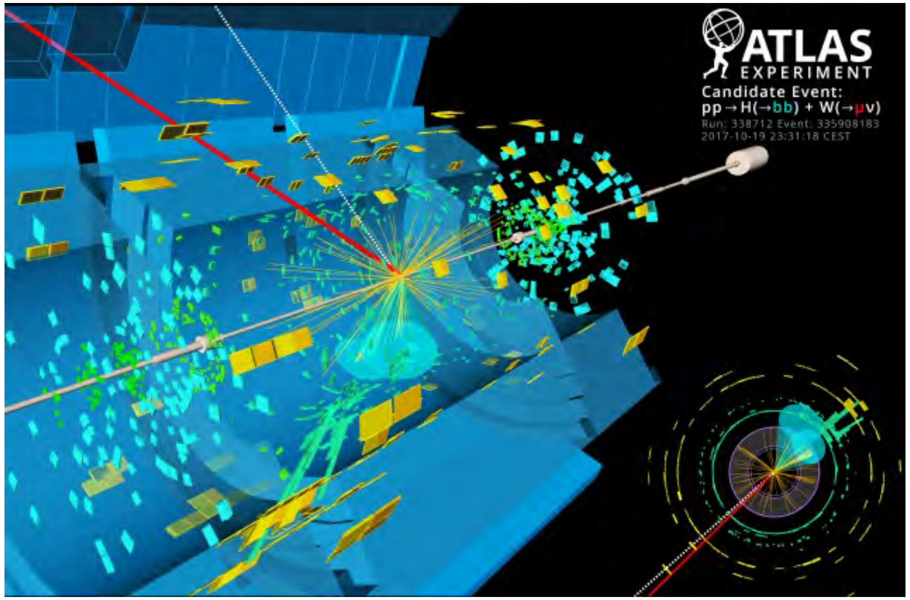
- Excellent jet reconstruction needed
- Excellent hadron flavor identification needed
- Hadronic decay of H^0 suffers huge QCD background
  - → needs characteristic associating particles to distinguish H^0 production from background reaction

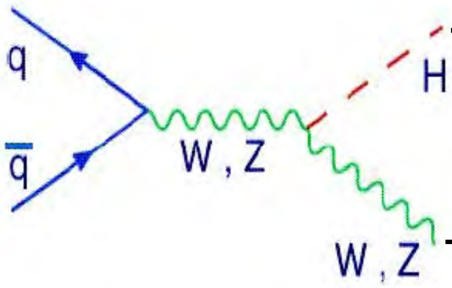
ex.; $q+q \rightarrow W/Z^0+H^0$;

W/Z0 decay particles for event signature









→ *bb*

→ ℓ ν or ℓ ℓ ; 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)

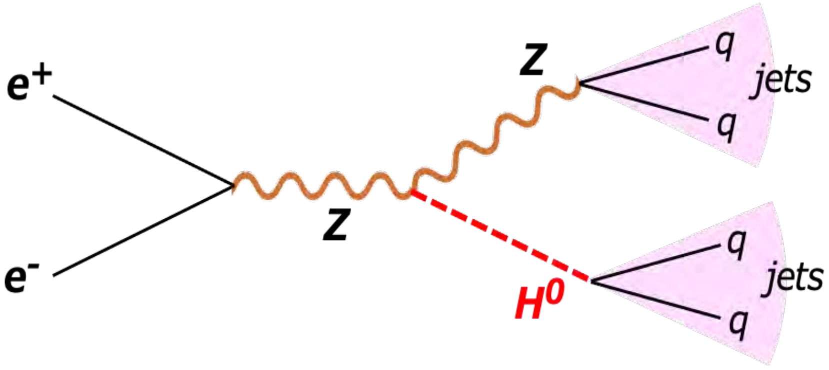
1. Pick up Reactions to Measure : Study Higgs at ILC

ILC

$e^+ e^- \rightarrow Z^0 H^0$

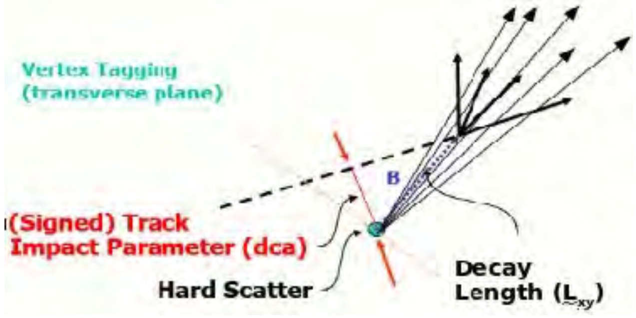
$Z^0 \rightarrow qq, \ell\ \ell$

$H^0 \rightarrow qq, \ell\ \ell, \gamma\gamma, WW^*, ZZ^*$



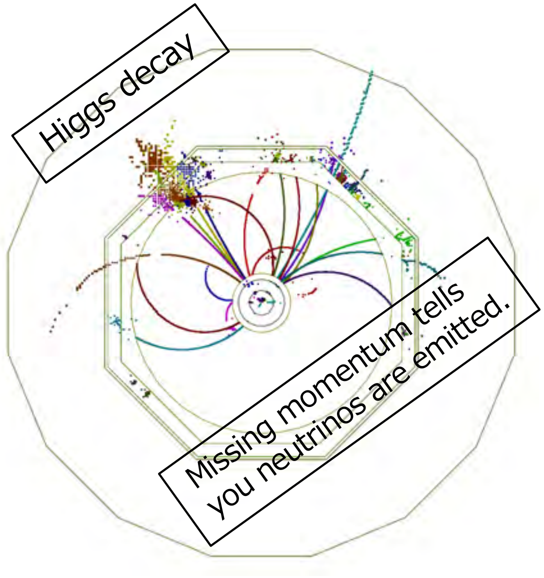
Detailed study

- Quarks and Z/W bosons mostly decay into "hadron jets".
  → Excellent jet reconstruction needed
- Excellent hadron flavor identification needed



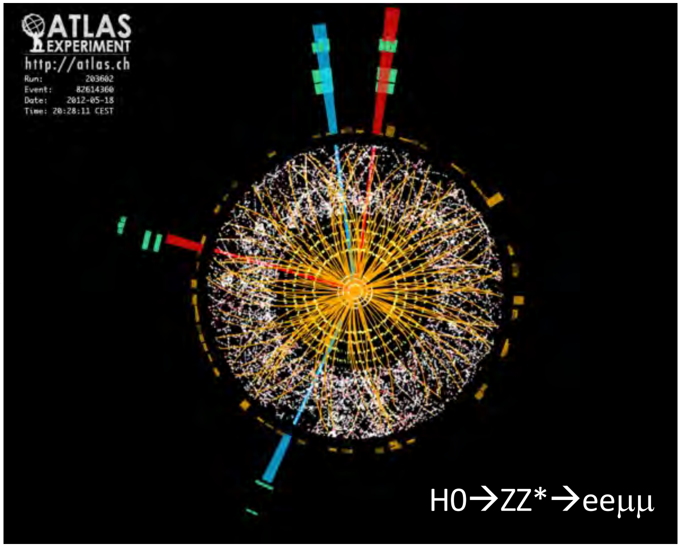
Advantage of e+e- collider over hadron colliders :

- Well-defined √S of the reaction, and P/E conservation applicable.
- Multiplicity is moderate.
- Beam polarization can be used.
- Background process not overwhelming



Higgs decay

Missing momentum tells you neutrinos are emitted.



H0→ZZ*→eeμμ

1. Pick up Reactions to Measure : Study Higgs at LHC/ILC

For Higgs precision study,
we need to reconstruct all H^0 decay modes;
$H^0 \rightarrow qq, \ell\ \ell, \gamma\gamma, WW, ZZ$

We need
- excellent jet reconstruction
- Excellent flavor tagging
- production channel associated with characteristic particles

2. Overview of the various detector configuration

2. Overview the various detector configuration

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

The detector system should measure
what **kind of particles** are emitted, to which **direction**, with what **energy**.

For this purpose;

- **direction of the particles** → Trackers
- **momentum of the particles** → Trackers & magnetic field
- **energy of the particles** → Calorimeters
- **species of the particles** → Vertex, Muon, CAL, and dedicated PID detectors

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

Necessity of particle identification is different exp. by exp.

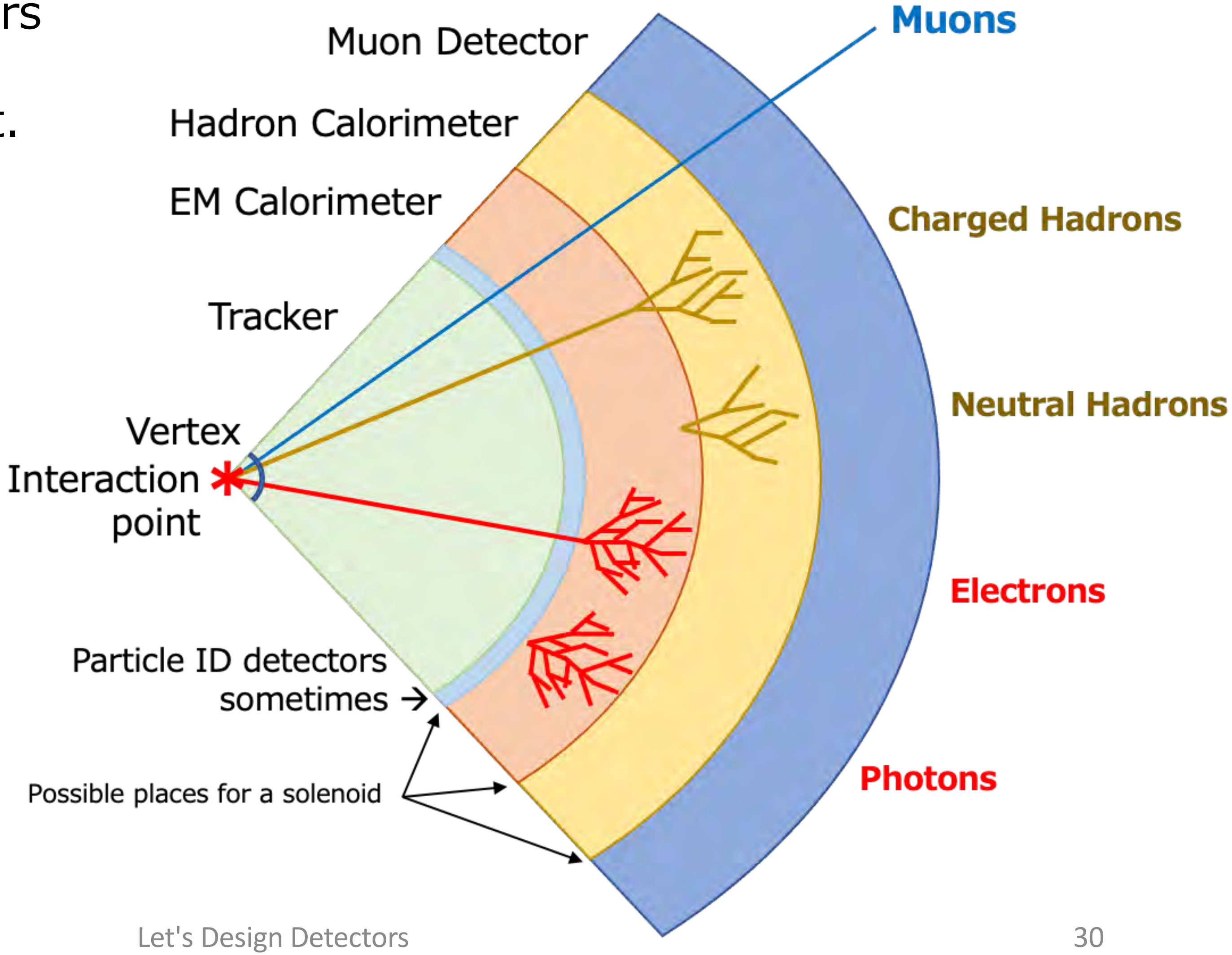
for all decay particles,
being separated from the background particles.
Combinations of various detectors can give you above information.

2. Overview the various detector configuration

Common feature of the detector system

- General layout as shown is almost common to many experiments.
- Use characteristics of interaction of particles with matter to measure aimed particle.
    → Will be explained later.
- Particle identification detectors strongly reflect the physics to explore at the experiment.
    →Variety of Particle-ID detectors used.

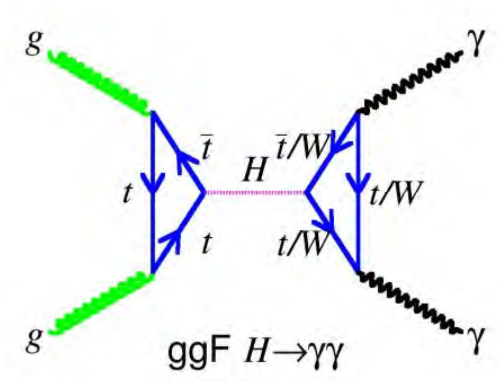
    - ● Want to separate kaons from pions ?
    - ● The best electron identification needed ?



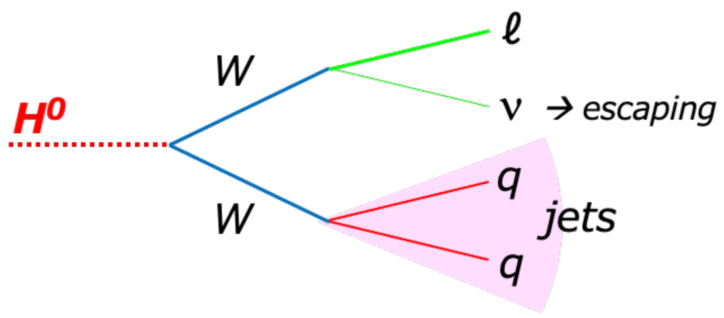
2. Overview the various detector configuration

Common feature of the detector system

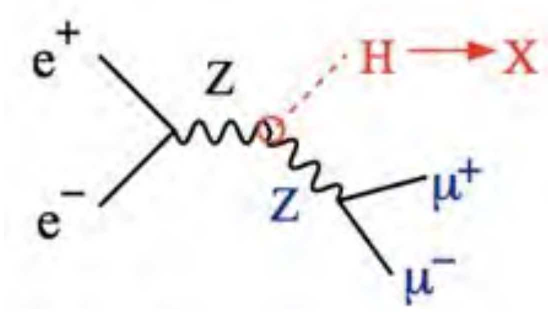
- General layout is almost common to many experiments.
- Use characteristics of interaction of particles with matter to measure aimed particle.
- Particle-ID detectors strongly reflect the physics to explore at the experiment.



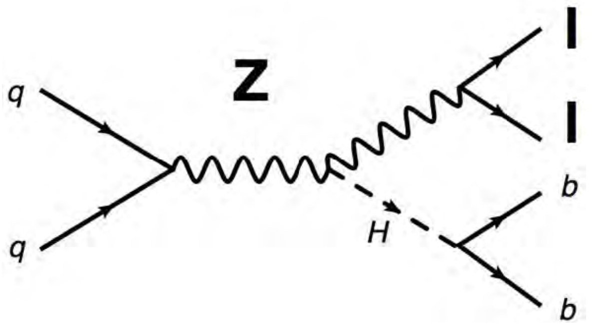
γs measured by EM calorimeters



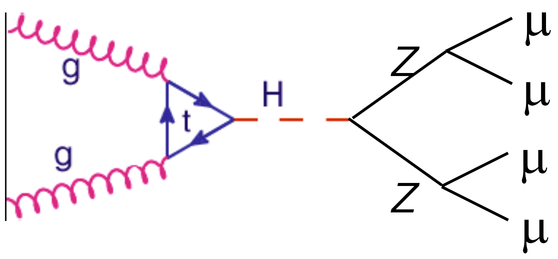
Jets measured by trackers and calorimeters

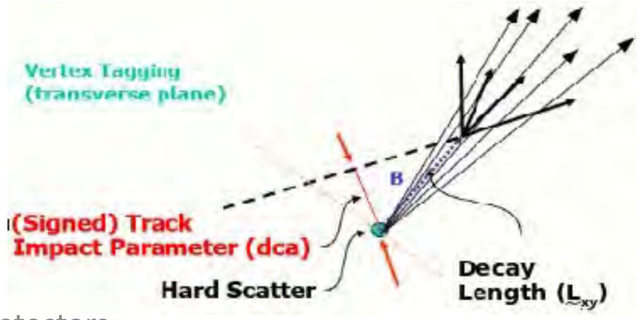


jets



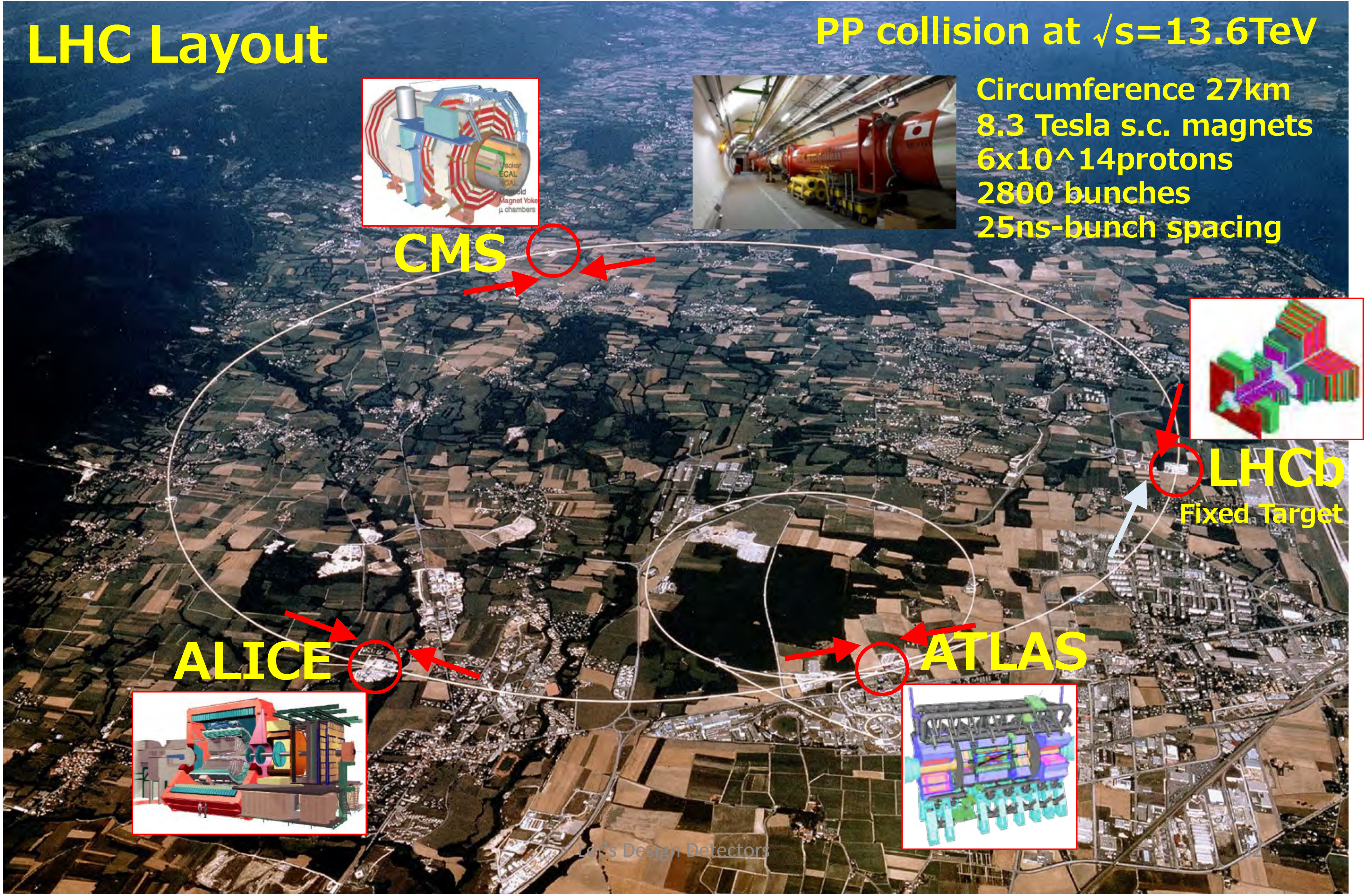
μs measured by muon detectors and trackers





b-quarks identified by vertex detectors.

2. Overview the various detector configuration : LHC

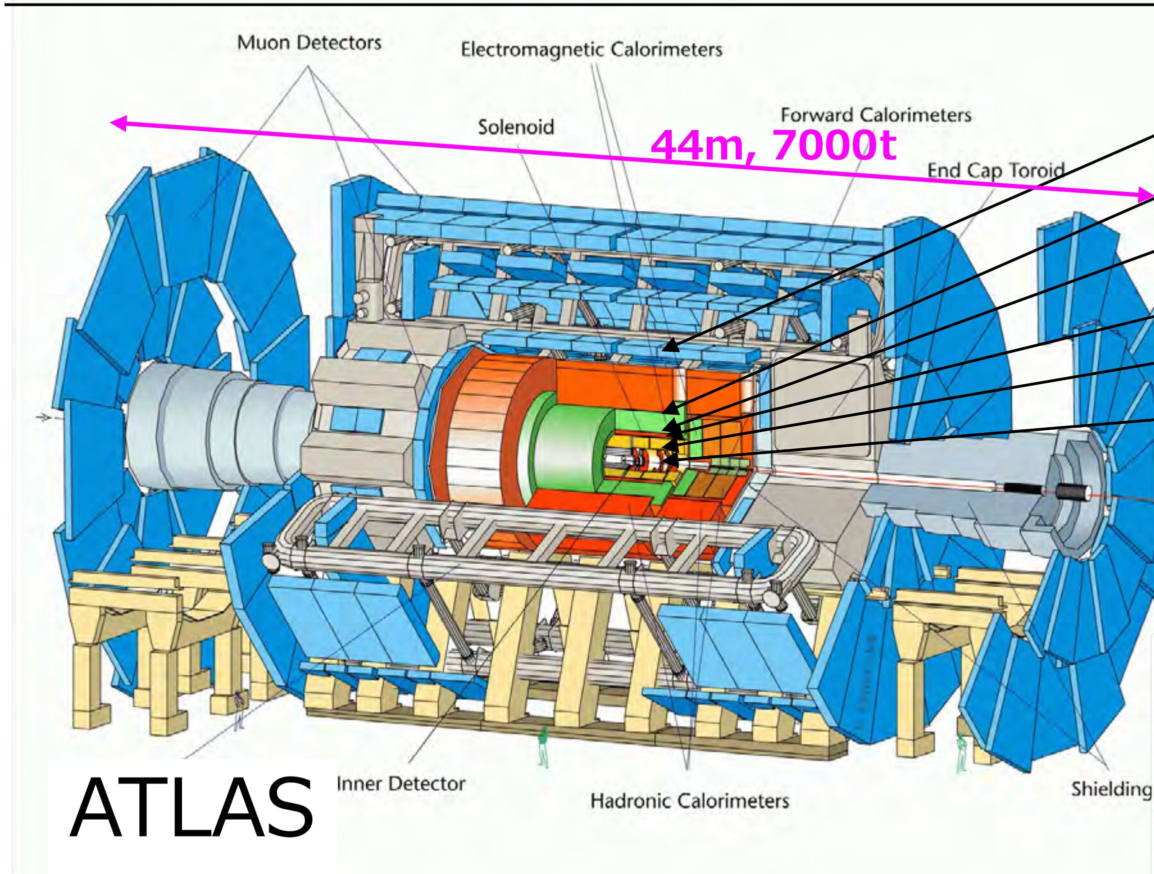


LHC Layout

PP collision at √s=13.6TeV

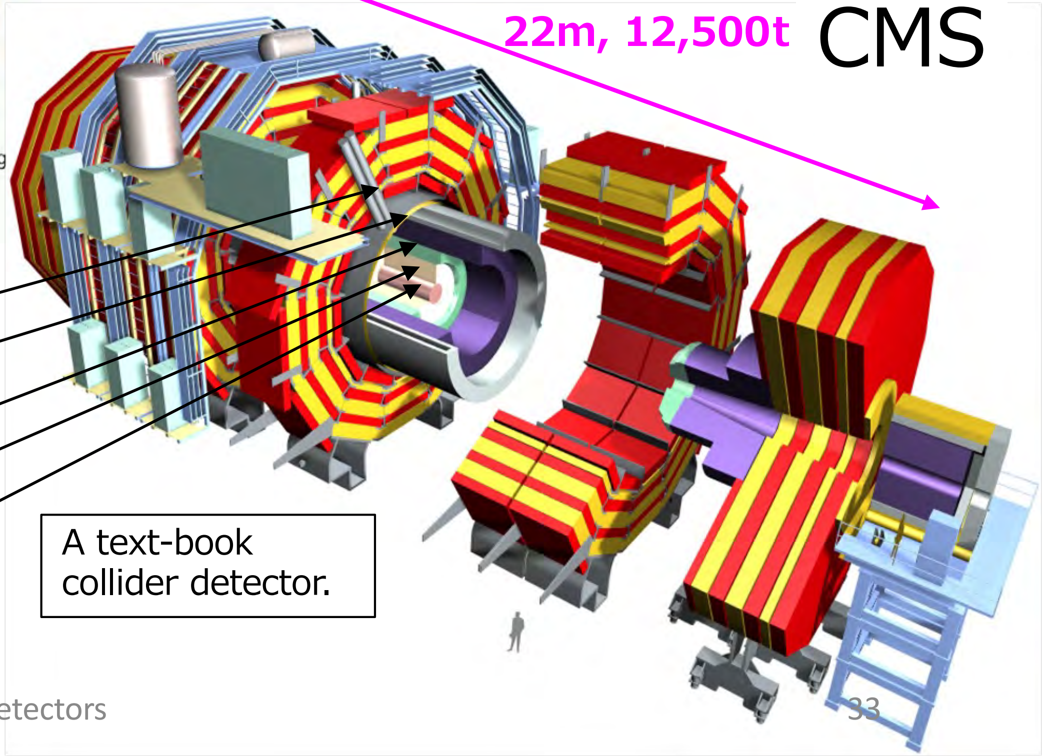
Circumference 27km
8.3 Tesla s.c. magnets
6x10^14protons
2800 bunches
25ns-bunch spacing

2. Overview the various detector configuration : LHC



Muon detector & Troid magnet
Calorimeter
Solenoid
e-ID
Tracker
Vertex detector

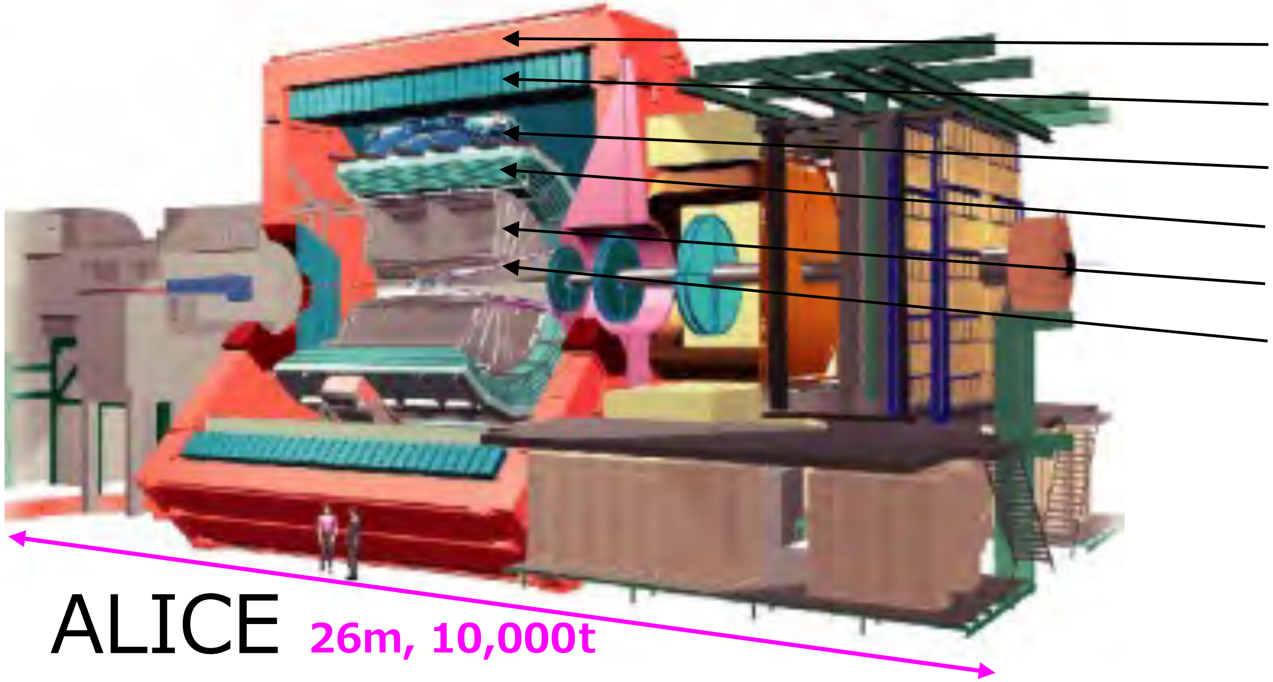
Additional electron identification detector used since thick solenoid is in front of calorimeters.



Muon detector
Solenoid
Calorimeter
Tracker
Vertex detector

A text-book collider detector.

2. Overview the various detector configuration : LHC

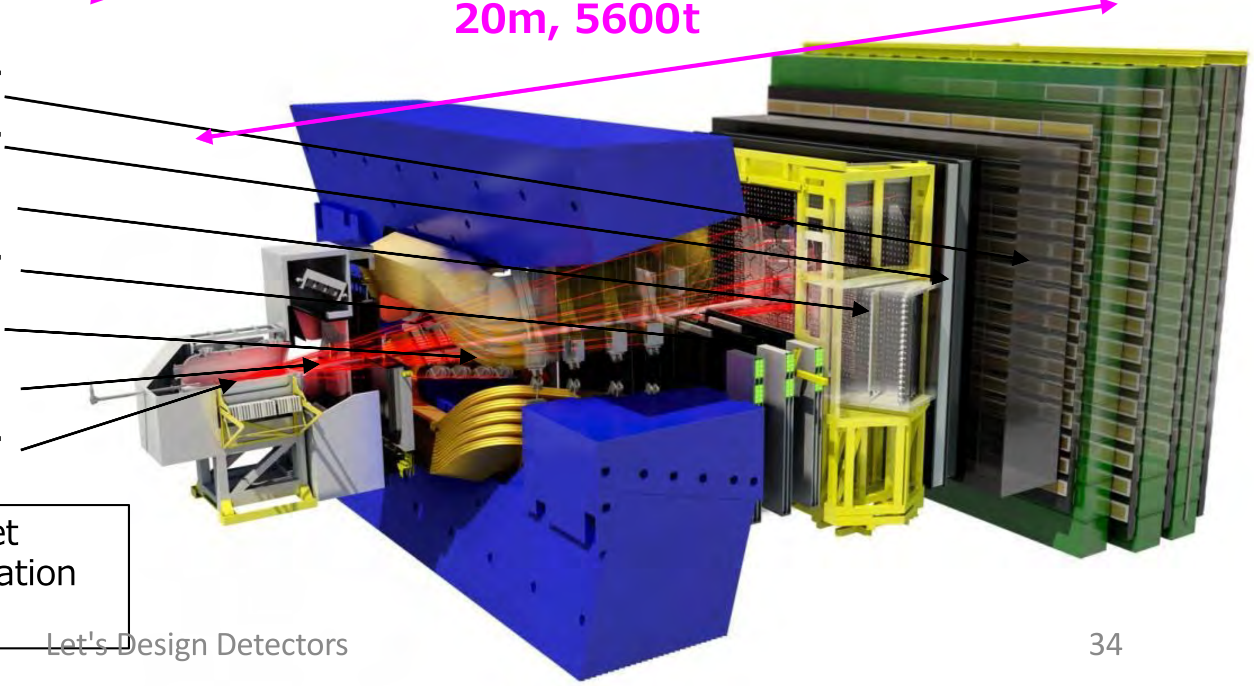


Muon detector
Solenoid
Calorimeter
e-ID
Tracker
Vertex detector

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

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

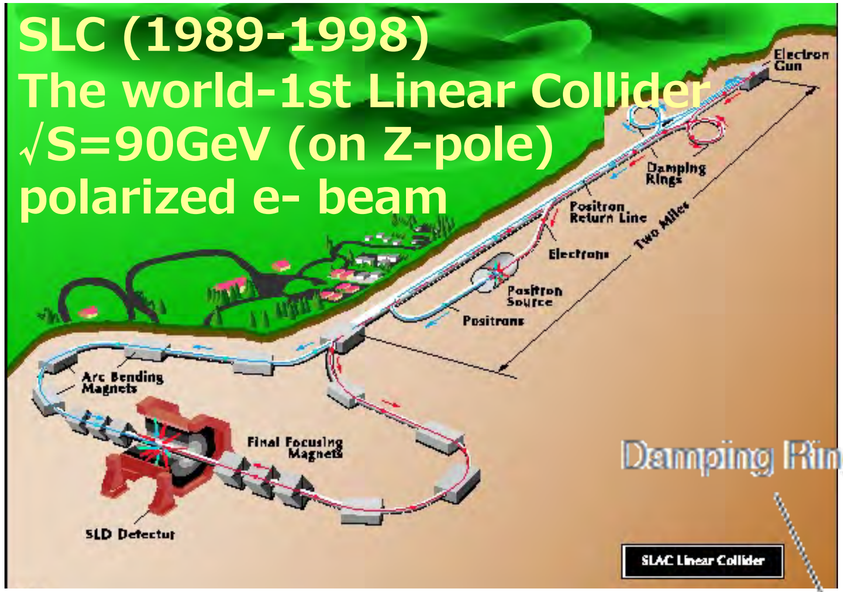
LHCb **20m, 5600t**



Muon detector
Calorimeter
PID
Tracker
Magnet
PID
Vertex detector

A detector for fixed-target experiment, but configuration is almost the same.

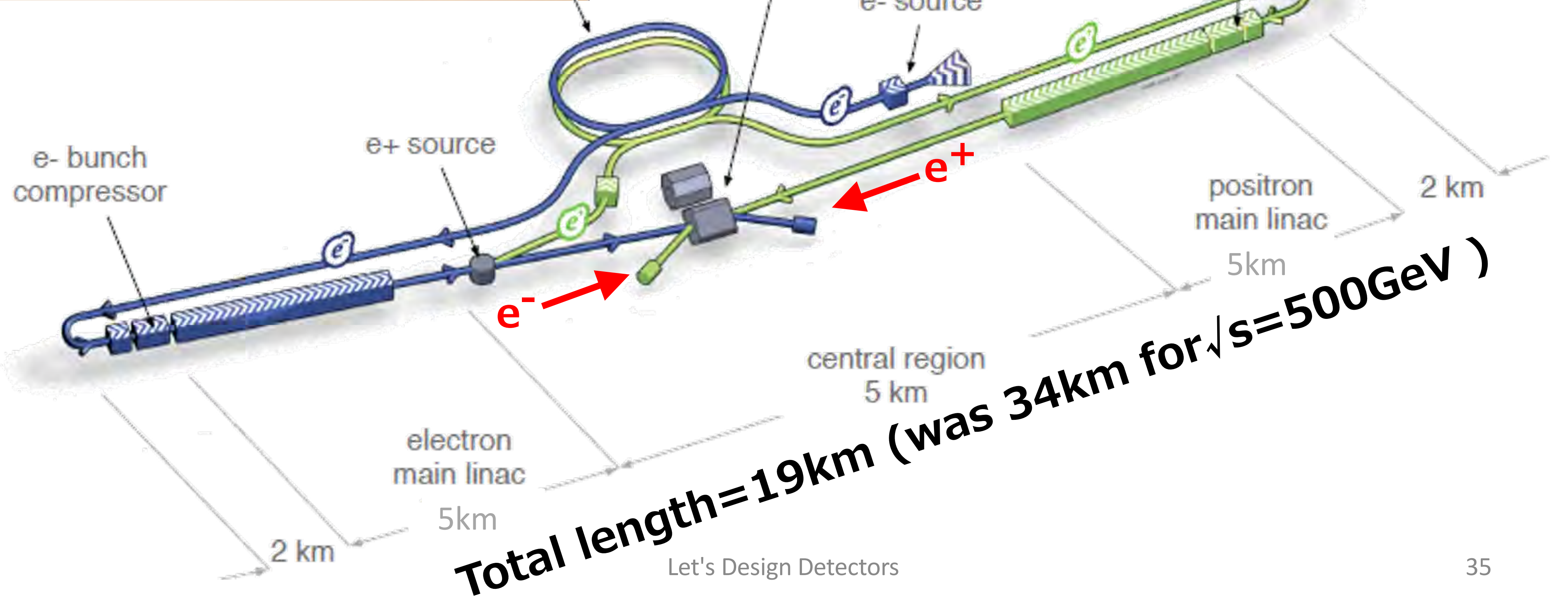
2. Overview the various detector configuration : Linear Colliders



SLC (1989-1998)
The world-1st Linear Collider
√S=90GeV (on Z-pole)
polarized e- beam

Linear Collider Layout

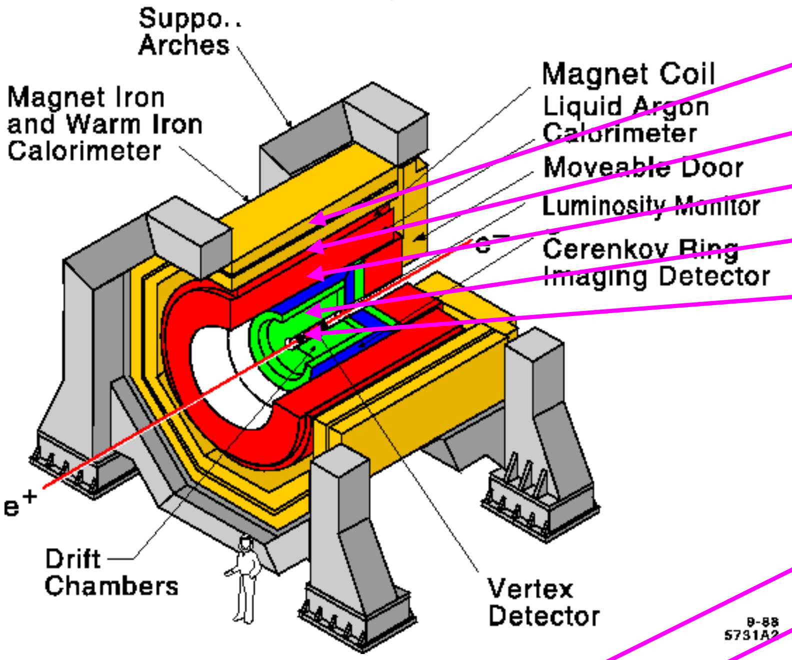
ILC as of 2018
e+e- collision at √s=250GeV
Beam sizes ; V=7.7nm, H=515nm
Pulse Rep.Rate ; 5Hz
Bunch-space ; 554ns
1312 bunches/pulse



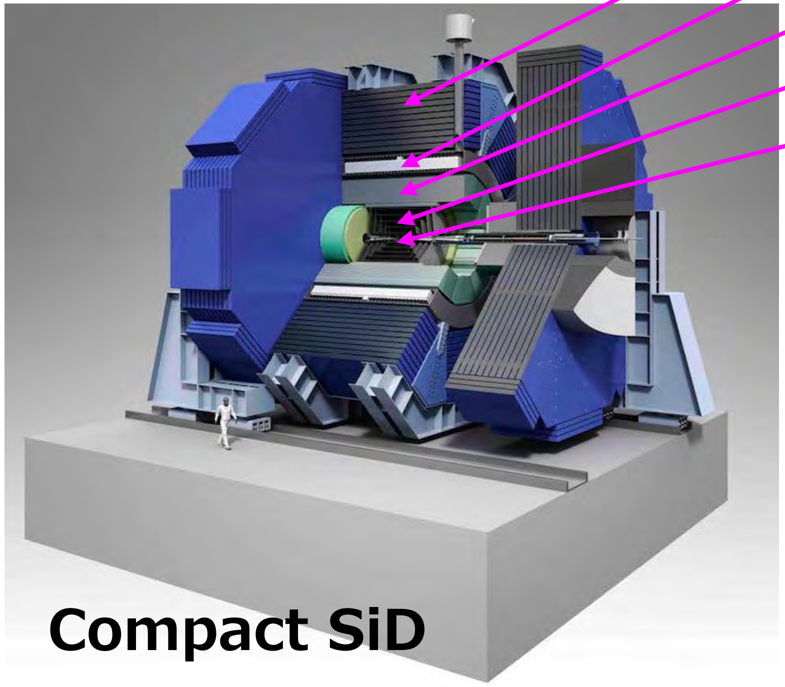
Total length=19km (was 34km for√s=500GeV)

2. Overview the various detector configuration : Linear Colliders

SLD @SLC



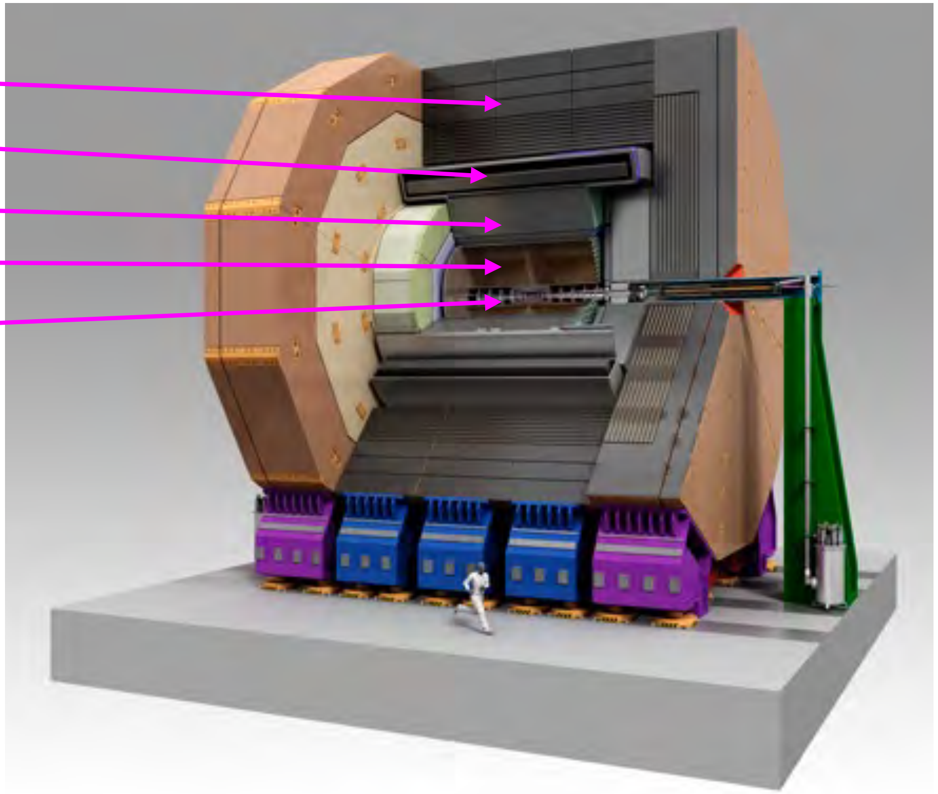
Muon detector
Solenoid
Calorimeter
Tracker
Vertex detector



Muon detector
Solenoid
Calorimeter
Tracker
Vertex detector

Compact SiD

Concept similar
to CMS.

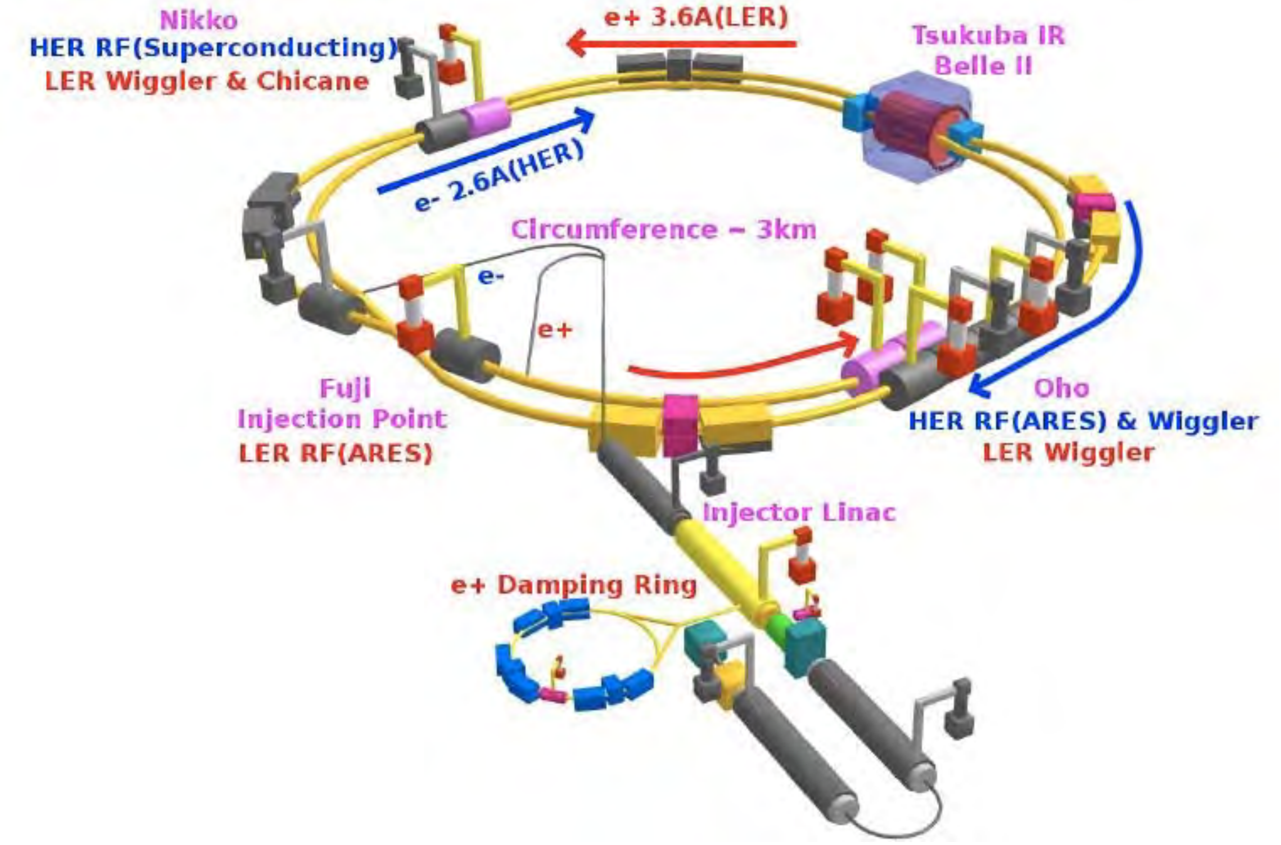


General-purpose LCD

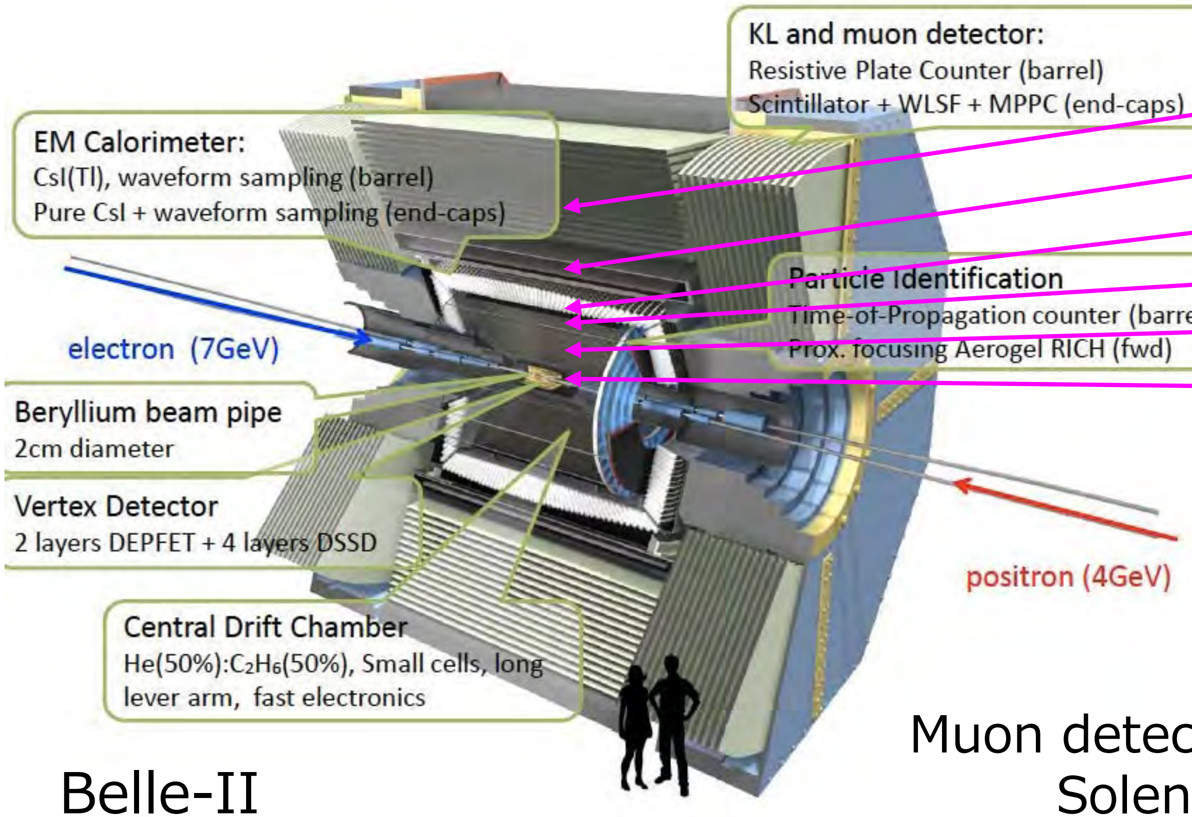
A text-book
collider detector.

SuperKEKB Accelerator

SuperKEKB
asymmetric e+e- collider
e-=7GeV, e+=4GeV, $\sqrt{s}$=10.58GeV (Y4S)
Beam sizes ; V~0.05μm, H~10μm
Bunch-bunch spacing ; 4ns
2400 bunches in a ring of 3km-circumference



2. Overview the various detector configuration ; B-Factory

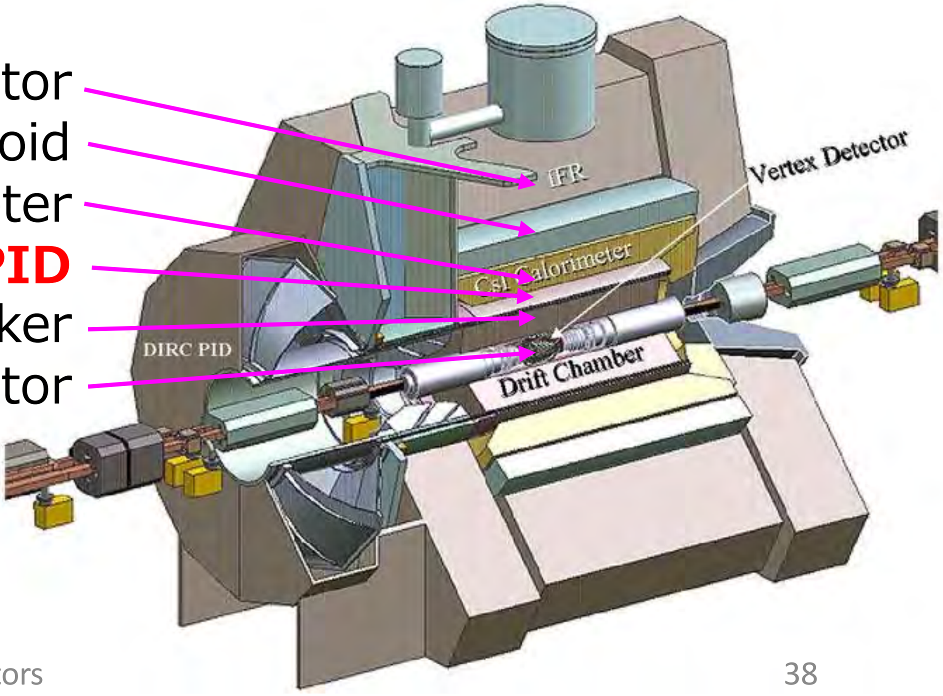


Muon detector
Solenoid
Calorimeter
PID
Tracker
Vertex detector

Belle-II

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

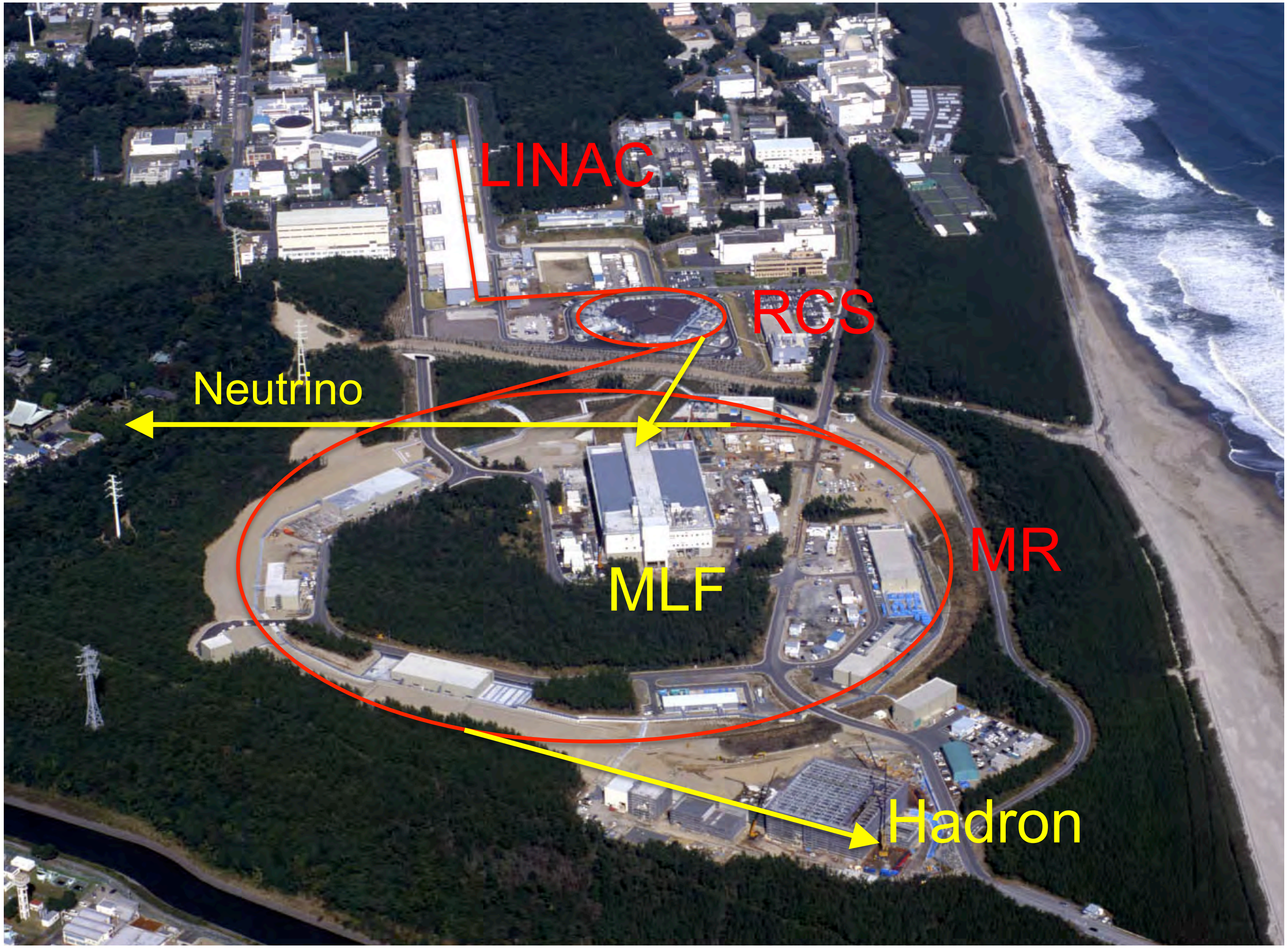
Babar



Muon detector
Solenoid
Calorimeter
PID
Tracker
Vertex detector

2. Overview the various detector configuration ; J-PARC

J-PARC Accelerator



400MeV LINAC
3GeV RCS
  → MLF
  → MR
30GeV MR
  → Neutrino
  → Hadron

MR parameters

- 1.5km circumferene
- 30GeV (K.E.)

For neutrino;

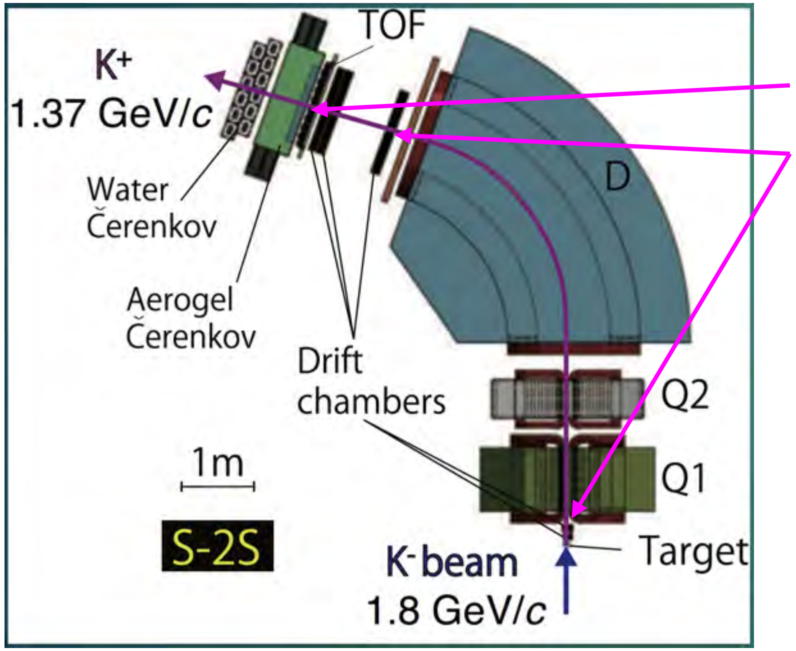
- 1.36sec cycle upgrading to 1.16sec.
- 510kW in operation upgrading to 1.3MW.

For hadron

- 5.2sec cycle
- 64kW in operation upgrading to 100kW.

2. Overview the various detector configuration ; J-PARC

J-PARC Detectors : fixed-target detectors



PID

Tracker

No vertex
No Muon

Hyper-nucleus experiment

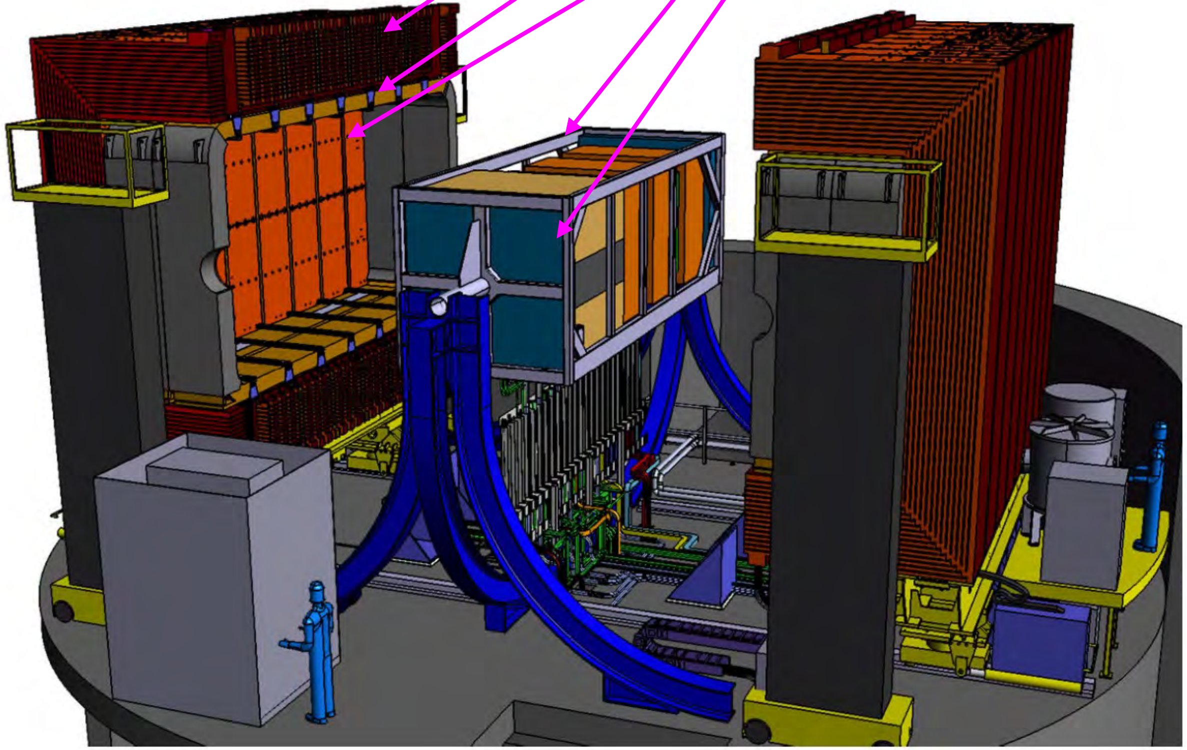
Strong interaction of s-quark hadrons.
Low-energy low-multiplicity events,
s-qurk tagging (π/K separation) important.

T2K ND280

Neutrino oscillation study and lepton CPV.
Low-energy low-multiplicity events.

No vertex detector

Muon detector
Magnet
Calorimeter
Tracker

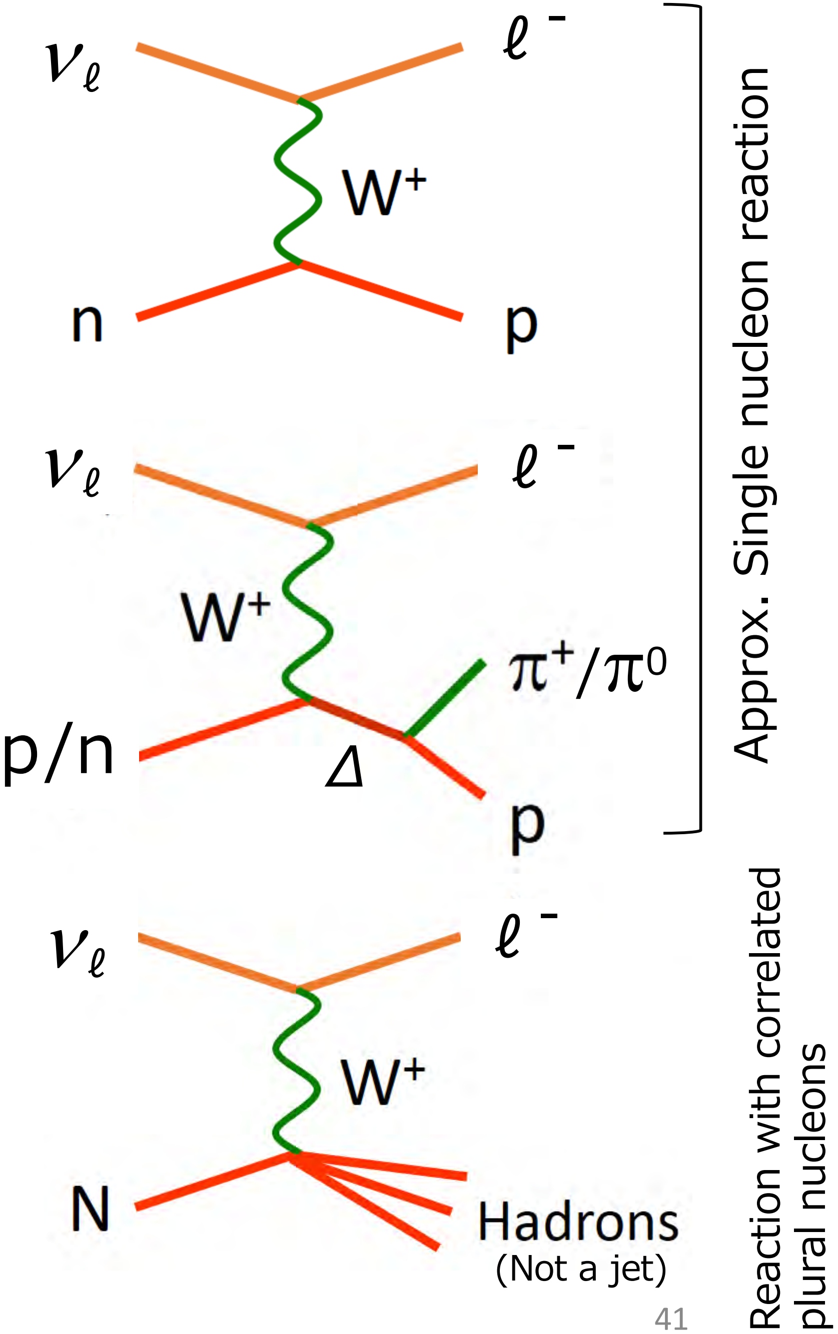


2. Overview the various detector configuration ; Neutrino Far Detectors

Must be a "Target Detector"
- Very small cross section, very low event rate
  - → Huge mass needed.

Neutrino Event topology is simple
- Just several tracks
- No jets

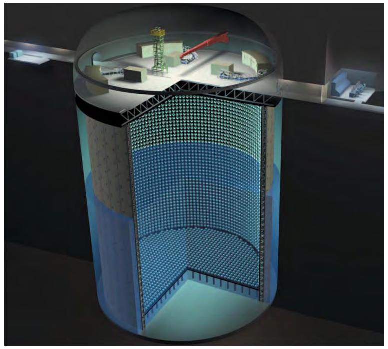
Requirement to the detector is **unique**
- modest granularity
- modest energy/momentum resolution
- Particle ID is important
  - pion ID (especially pi0)
  - e/mu separation
- low-energy proton detection favoured
- High purity of active media
  - (water, liq.Ar, liq.Scint.)

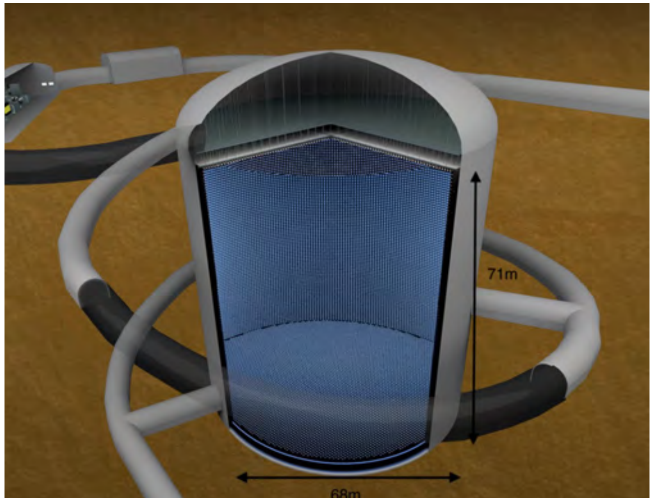


2. Overview the various detector configuration ; Neutrino Far Detectors

Accelerator-ν

Super-K
(Water-Cherenkov)
40x40m,
22.5kt (50kton)

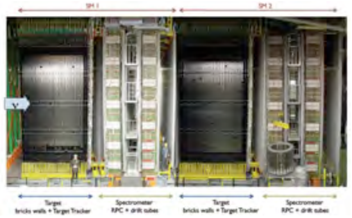




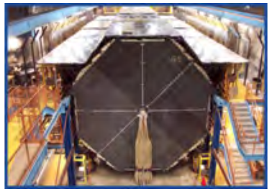
Hyper-K
(Water-Cherenkov)
68x71m ,
190kton (260kton)

Dune (Liq.Ar)
18x19x66m, 17kton x4modules

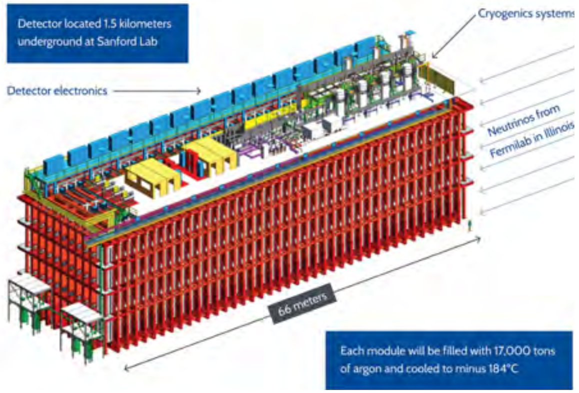
OPERA (Emulsion)
10x10x20m, 1.3kton



MINOS (Scintillator)
8x8x30m, 5.4kton

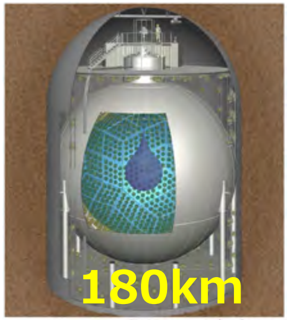


NoVA (Liq.Scintillator)
16x16x67m, 14kton



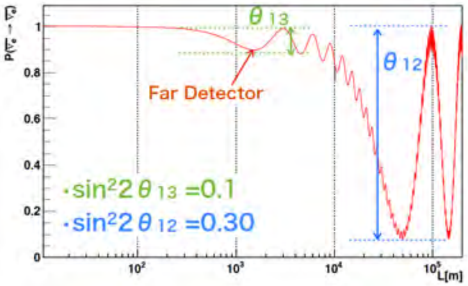
Reactor-ν

Kamland (Liq.Scintillator)
18mx20m, 1kton (4Kton)

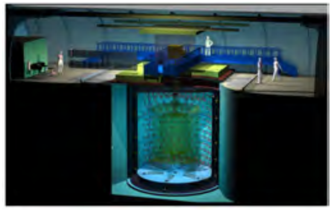


180km

Distance is another key.

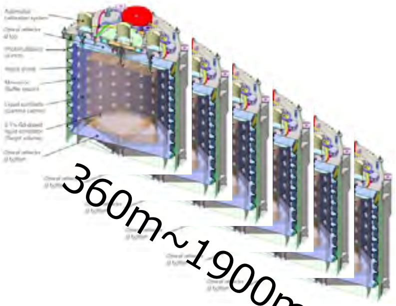


DoubleChooz (Liq.Scint.)
7mx7m, 10m3(140m3)



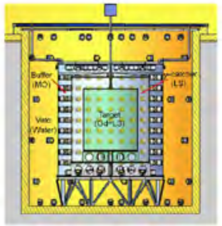
1km

DayaBay (Liq.Scint.)
5mΦ, (20t (80ton))x6



360m~1900m

RENO (Liq.Scint.)
9mx8m,16t (80tons)



1.3km

2. Overview the various detector configuration ; Neutrino Far Detectors

Accelerator-based
Neutrino Oscillation
Experiments

Super-K
Hyper-K

NUMI/MINOS,NOvA

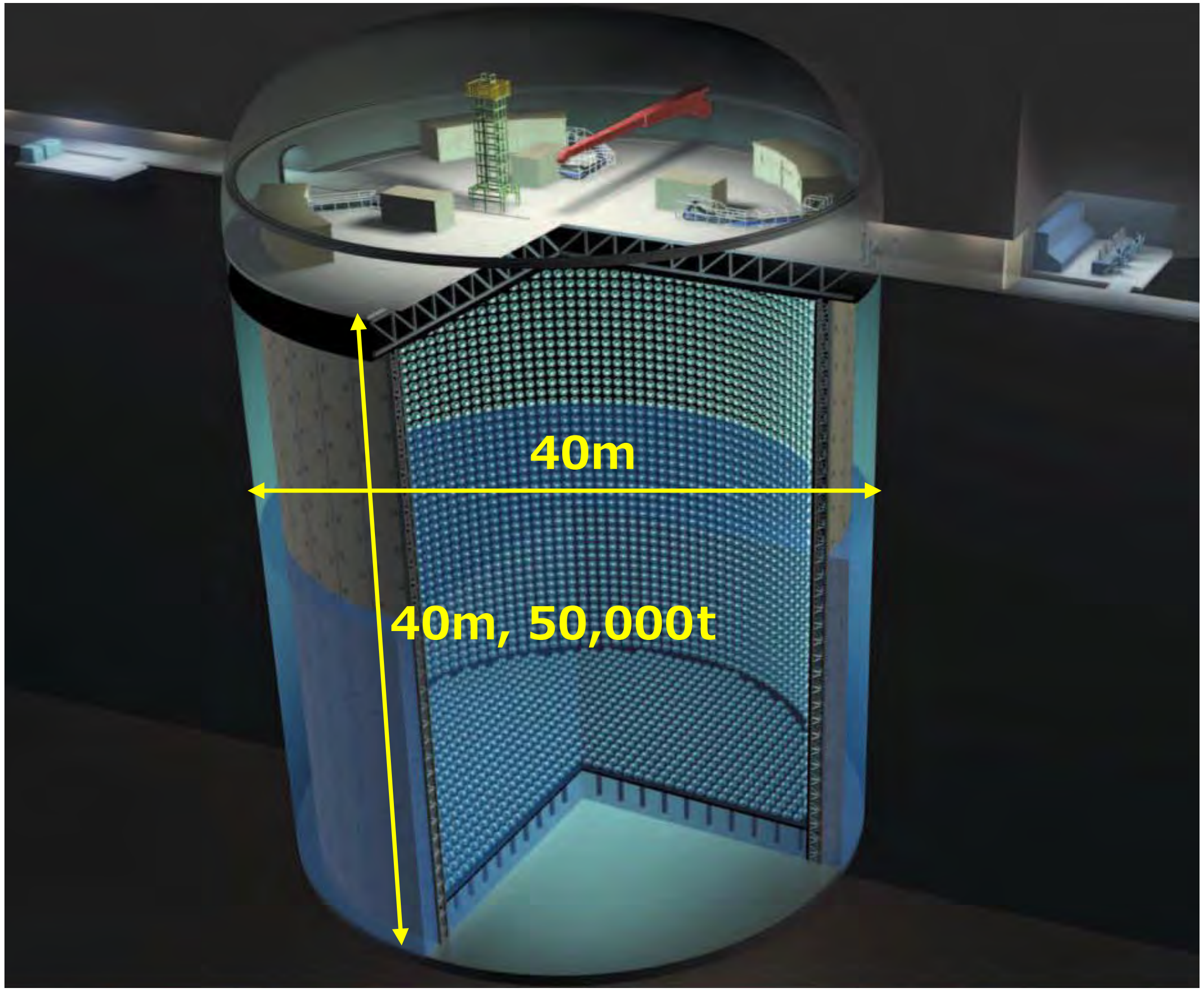
CNGS/OPERA

LBNF/DUNE

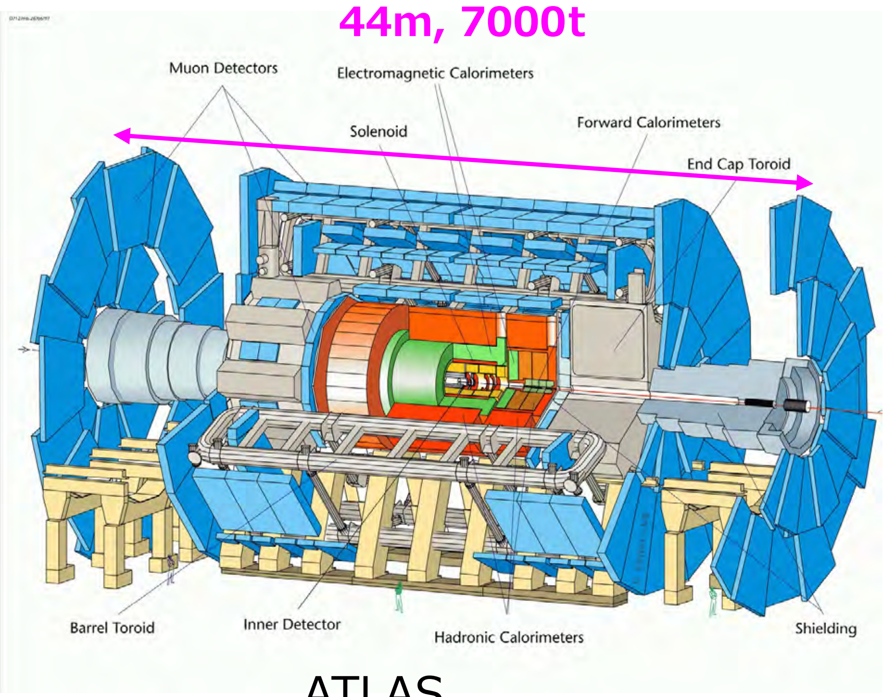
Distance is another key.

2. Overview the various detector configuration ; Neutrino Far Detectors

Super-Kamiokande was unprecedentedly huge when it was built in 1996.
LHC detectors now, however, are not far behind.
Hyper-K will be the Monarch again.



Super-Kamiokande ; Constgruction cost ~10 B-yen



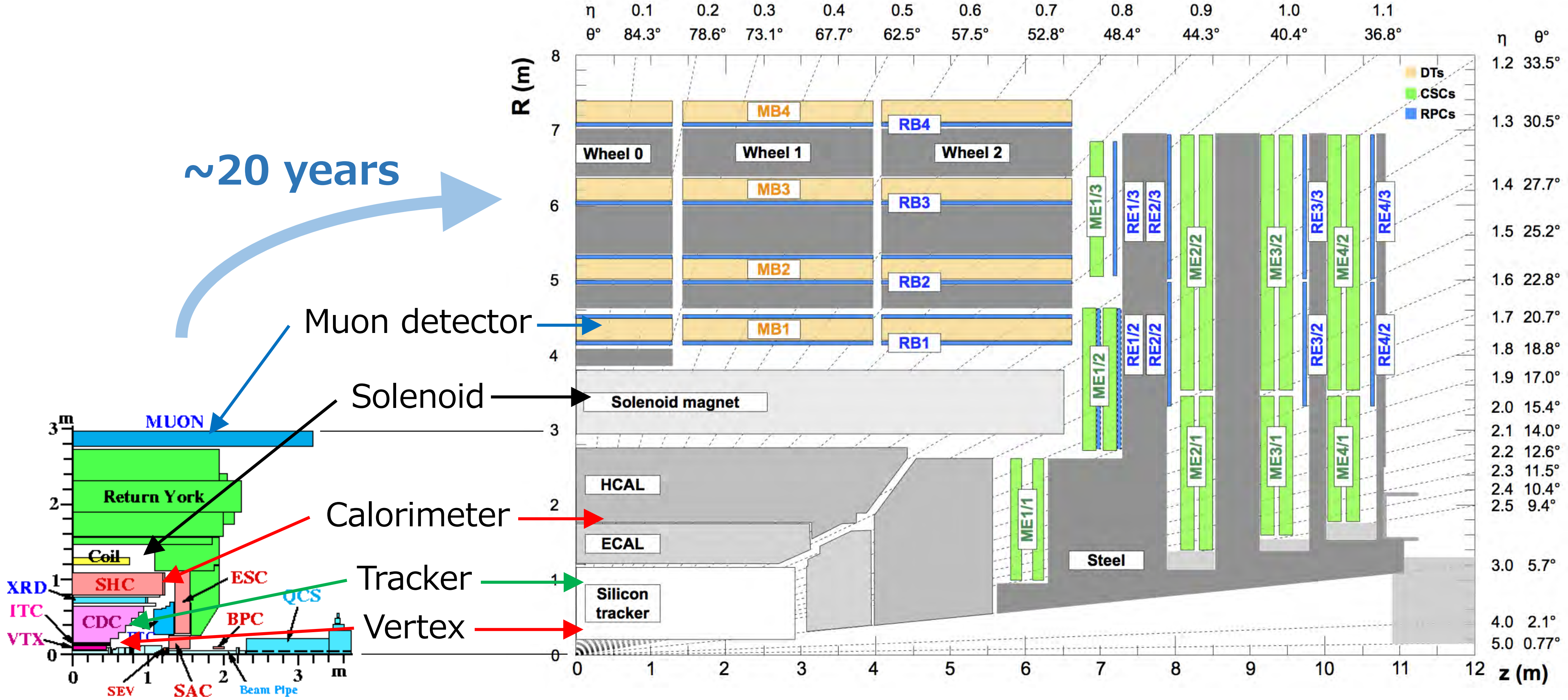
ATLAS
Construction cost
- LHC ~500B-yen
- ATLAS ~54B-yen

HL-LHC upgrade
- LHC ~170B-yen
- ATLAS ~31B-Yen

2. Overview the various detector configuration

Common feature of the detector system

- Sizes are different corresponding to the √S, but configuration is the same from inside to outside.



Muon detector

Solenoid

Calorimeter

Tracker

Vertex

AMY detector made in 1986
√S=60GeV, R=3m, 700tons

CMS detector made in 2008
√S=14TeV, R=7.5m, 12,500tons

3. Requirement to the detectors

3. Requirement to the detectors

For the picked up "Benchmark" reactions,
we examine what kind of detectors are needed,
and clarify the required performances
to detect and analyze the reaction.

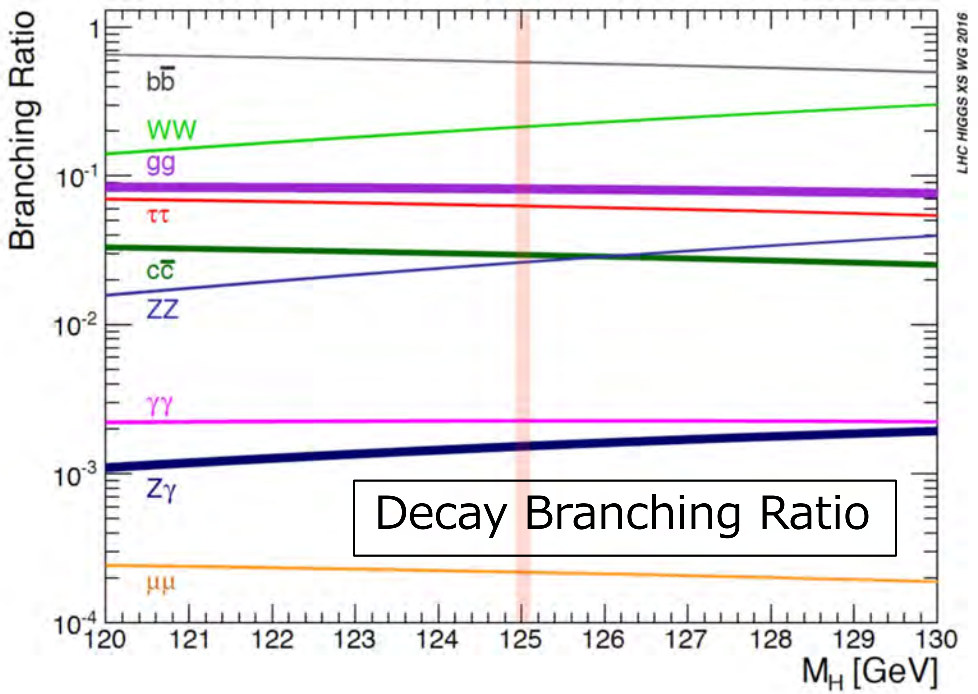
"Better is better" is not the optimum way.

3. Requirement to the detectors ; Higgs discovery at LHC

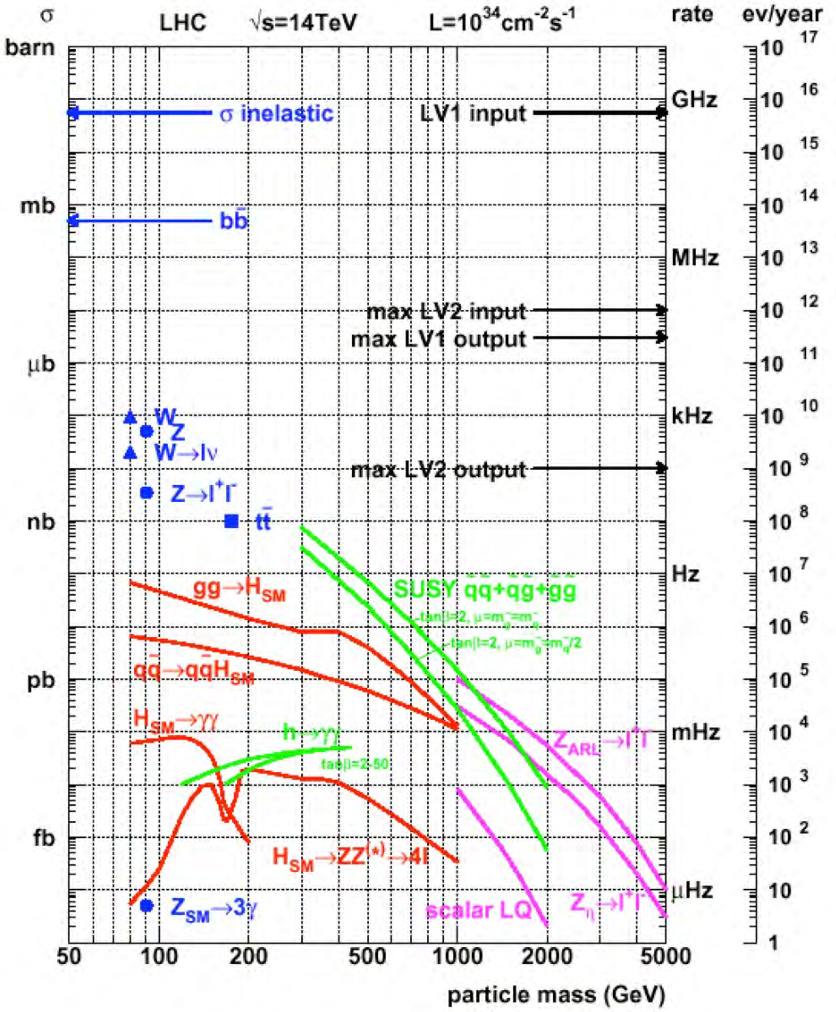
Discover Higgs at LHC.

You know everything but it's mass.

- you know production mechanisms and their cross sections.
- you know decay branching ratios.
- you know SM background processes which overlap overwhelmingly, but need to know how much reduction you can achieve.



Decay Branching Ratio



Production and
B.G. cross sections

3. Requirement to the detectors ; Higgs discovery at LHC $\gamma\gamma$

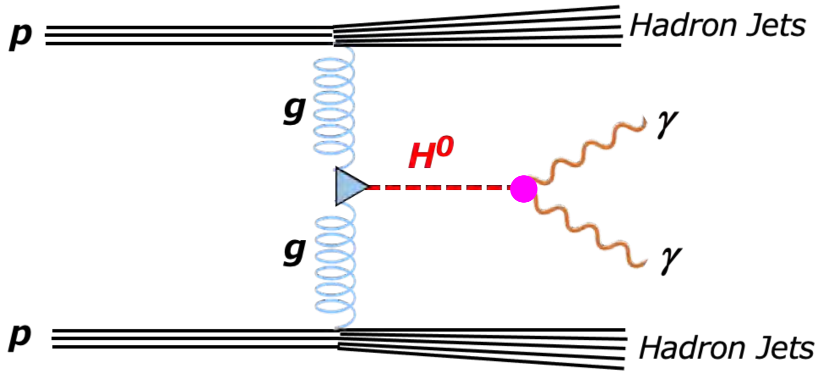
$g + g \rightarrow H^0$, $H^0 \rightarrow \gamma\gamma$

Calculate mass of $\gamma\gamma$

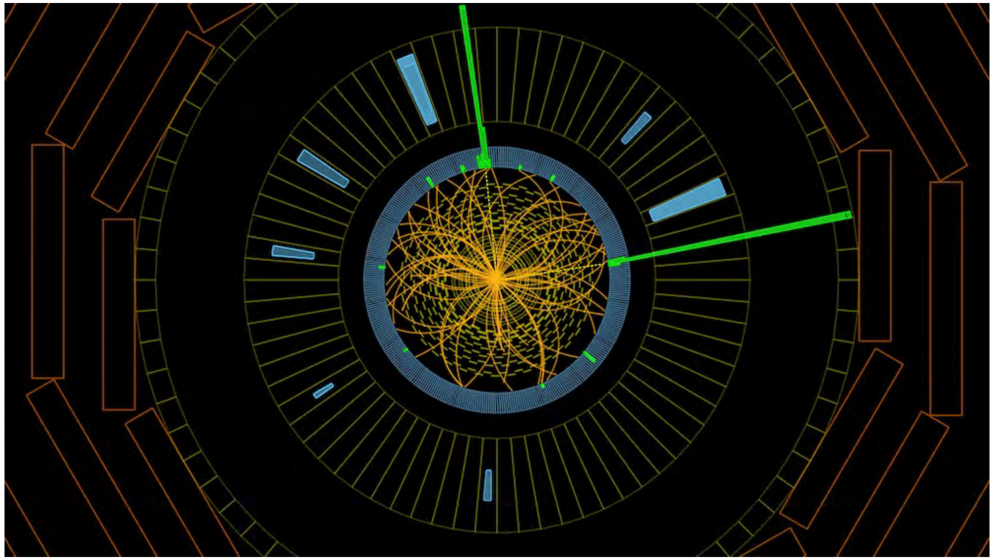
→ a clear peak on huge background → discovery

- γ is "isolated" ; not buried in remnant jet.
  → Do not rely on associating key particles
- Background from side-band of spectra
  → model-independent estimation.
- Good energy and position resolution
  → narrow mass peak → good S/N

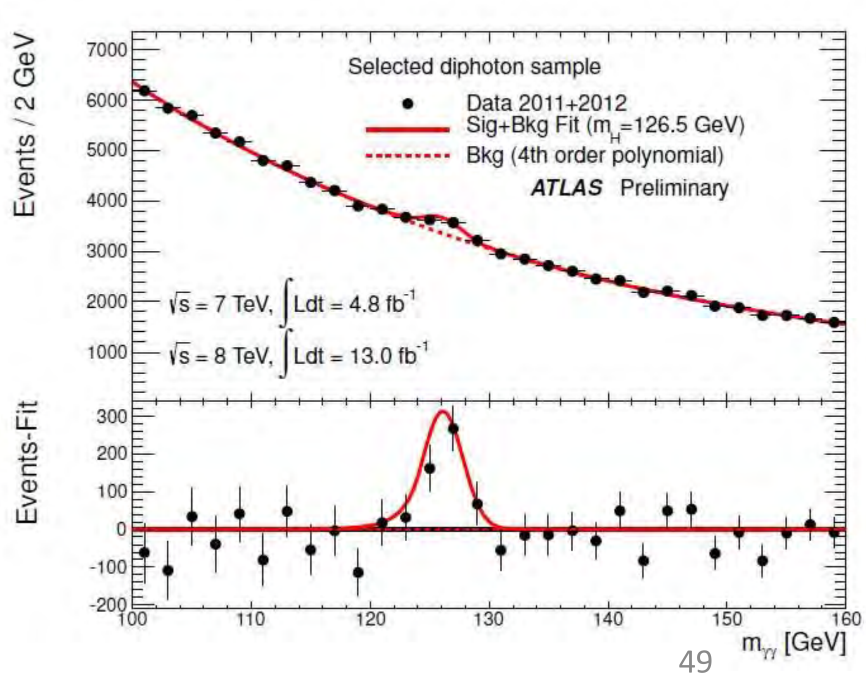
∗Just high-performance EM calorimeter !



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



CMS H0→2γ event. γs (green bars) are clearly identified by EM calorimeter.



3. Requirement to the detectors ; Higgs discovery at LHC $\gamma\gamma$

$H^0 \rightarrow \gamma\gamma$

Calculate invariant mass of $\gamma\gamma$

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

Natural width of Standard Model Higgs is just 4MeV (for light Higgs).

→ Performance of 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
Type	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

3. Requirement to the detectors ; Higgs discovery at LHC $\gamma\gamma$

$H^0 \rightarrow \gamma\gamma$

Design parameters of EM calorimeter for required performance;
(Needs simulation for quantitative estimation.)

- Energy resolution ; light yield, shower fluctuation
  structure ; homogeneous or sampling
  sampling ; sampling fraction, sampling frequency,
  absorber material, active media,,,
- Position resolution
  → Transverse segmentation (or granularity)
- 2γ separation → granularity, density
  (→ shower size → separation, containment)
- Efficiency ; light yield,
  structure (material budget, crack,,,)
- Contamination
  electron rejection → track-cluster matching
  → position resolution
  hadron rejection → segmentation (or granularity)
  π^0 rejection → granularity

and

- fast (timing separation) → signal generation mechanism and read-out device

Schematic example of a sampling calorimeter

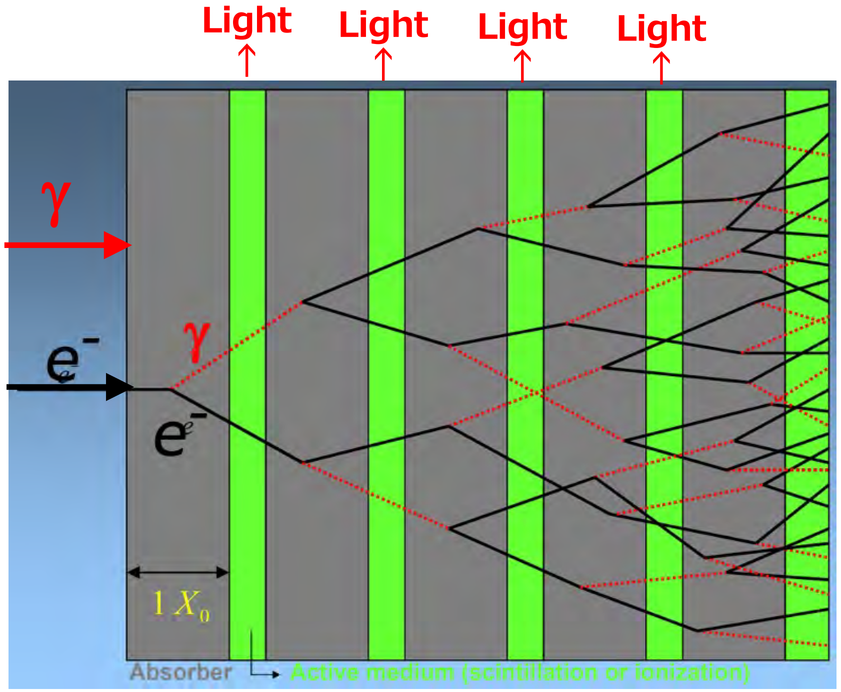


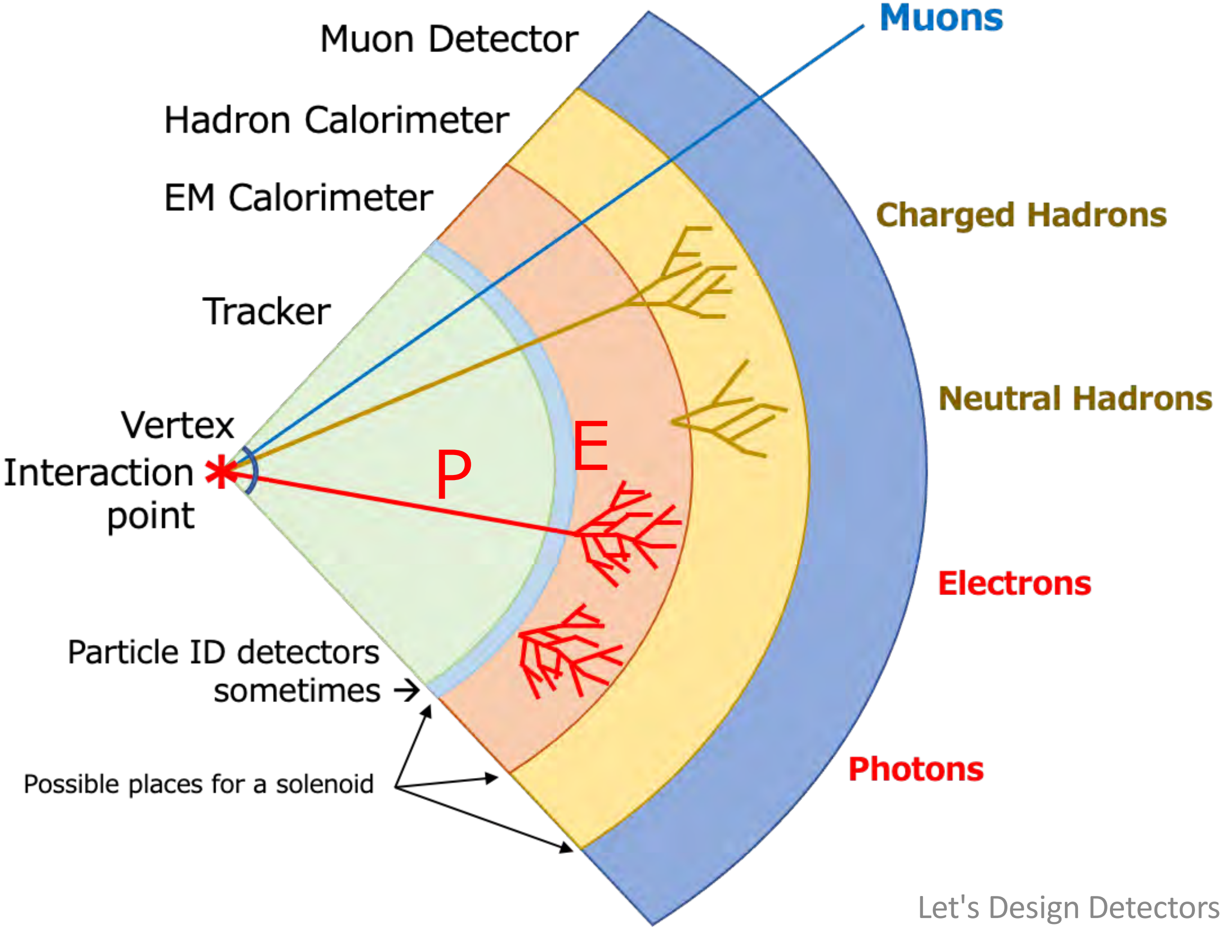
figure from P.Krieger, "ATLAS calorimetry"

3. Requirement to the detectors ; Higgs discovery at LHC $\gamma\gamma$

High-performance EM calorimeter

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

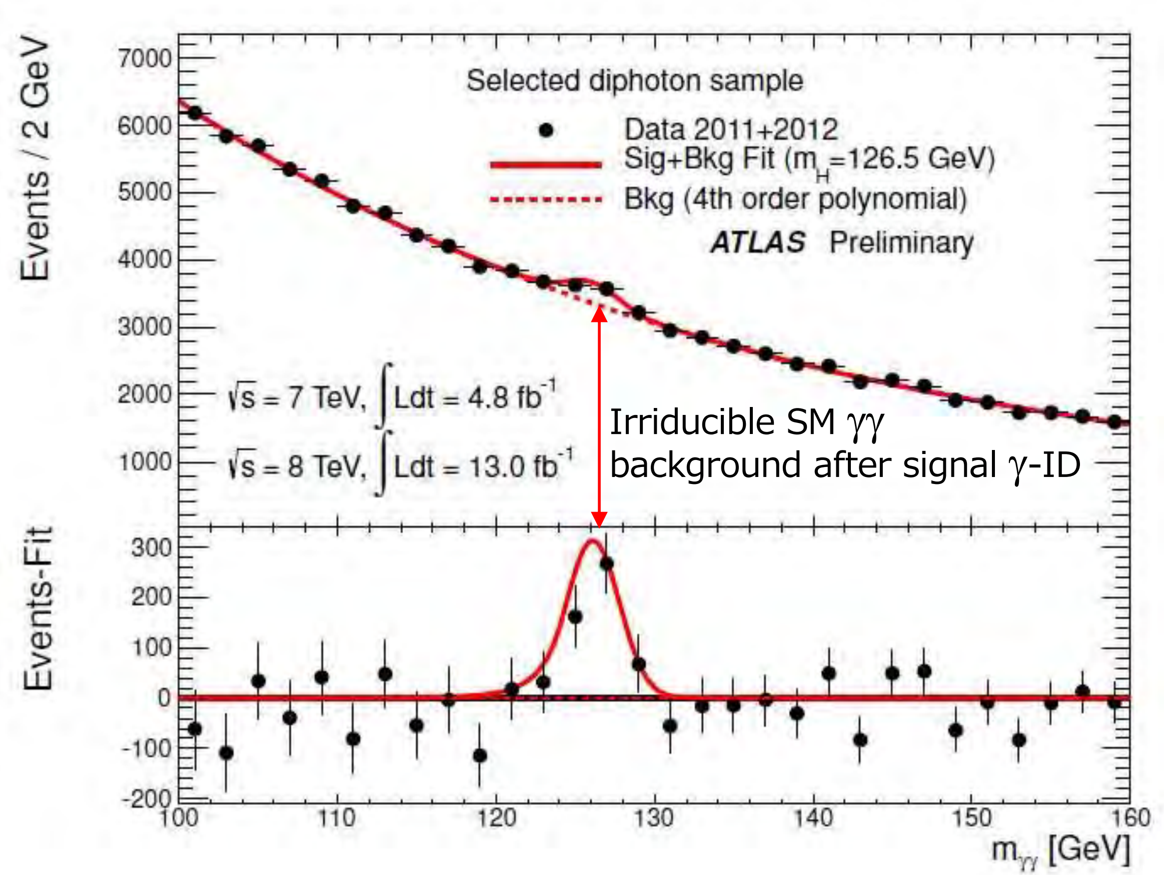
Needs good **energy/momentum/position** measurement and very careful calibration/analysis.

3. Requirement to the detectors ; Higgs discovery at LHC $\gamma\gamma$

High-performance EM calorimeter

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



Irridicible SM $\gamma\gamma$ background after signal γ-ID

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.

3. Requirement to the detectors ; Higgs discovery at LHC γγ

$H^0 \rightarrow \gamma\gamma$

Examples of parameters/performance of EMcal for excellent γ measurement

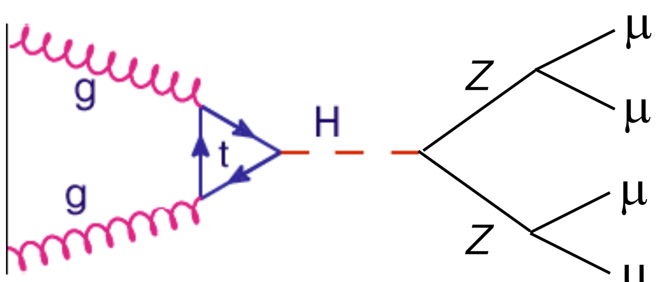
- Energy resolution (material in front of EM also matters)
- Granularity (Position resolution → θ resolution, 2γ separation)
- timing (resolve event overlapping)

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 γγ mass resolution	1.4GeV	0.9GeV	?

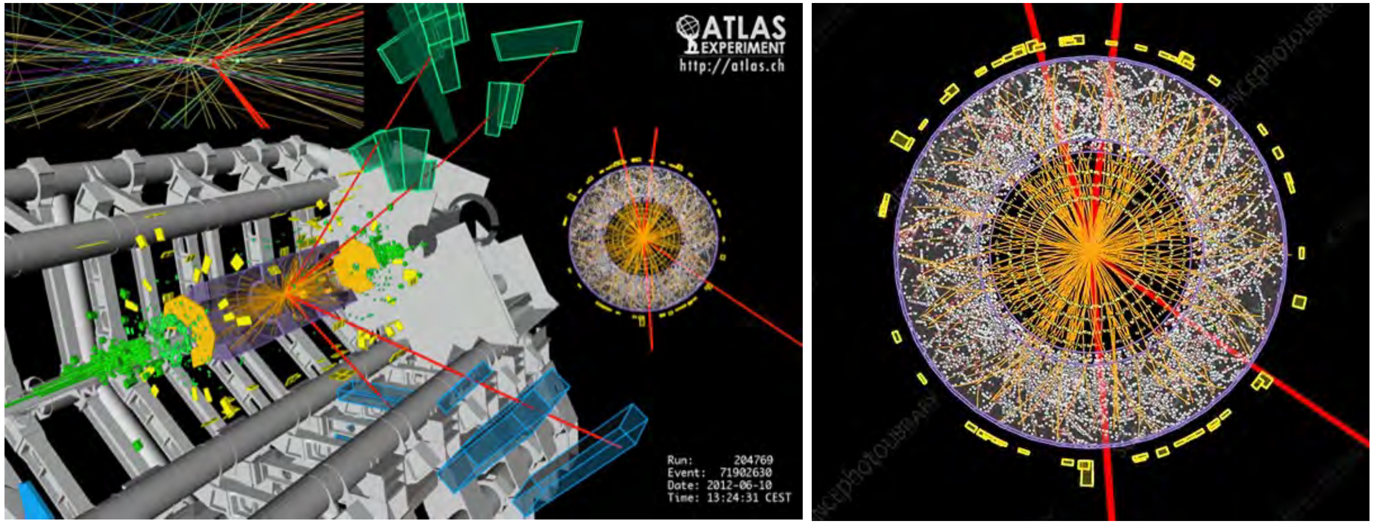
3. Requirement to the detectors ; Higgs discovery at LHC 4μ



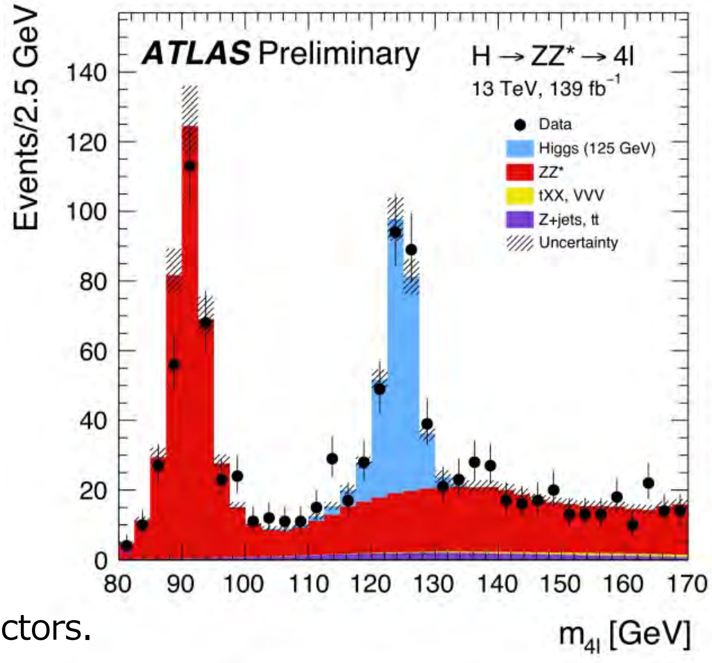
Higgs → ZZ → 4μ

- Very clean event signature but
  Very low event rate (H^0→ZZ→4μ ~0.01%)
- Calculate mass of 4μ
  → A clear peak on background → **discovery**
    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→4μ event. Muons (red lines) are clearly identified by outer-most muon detectors.

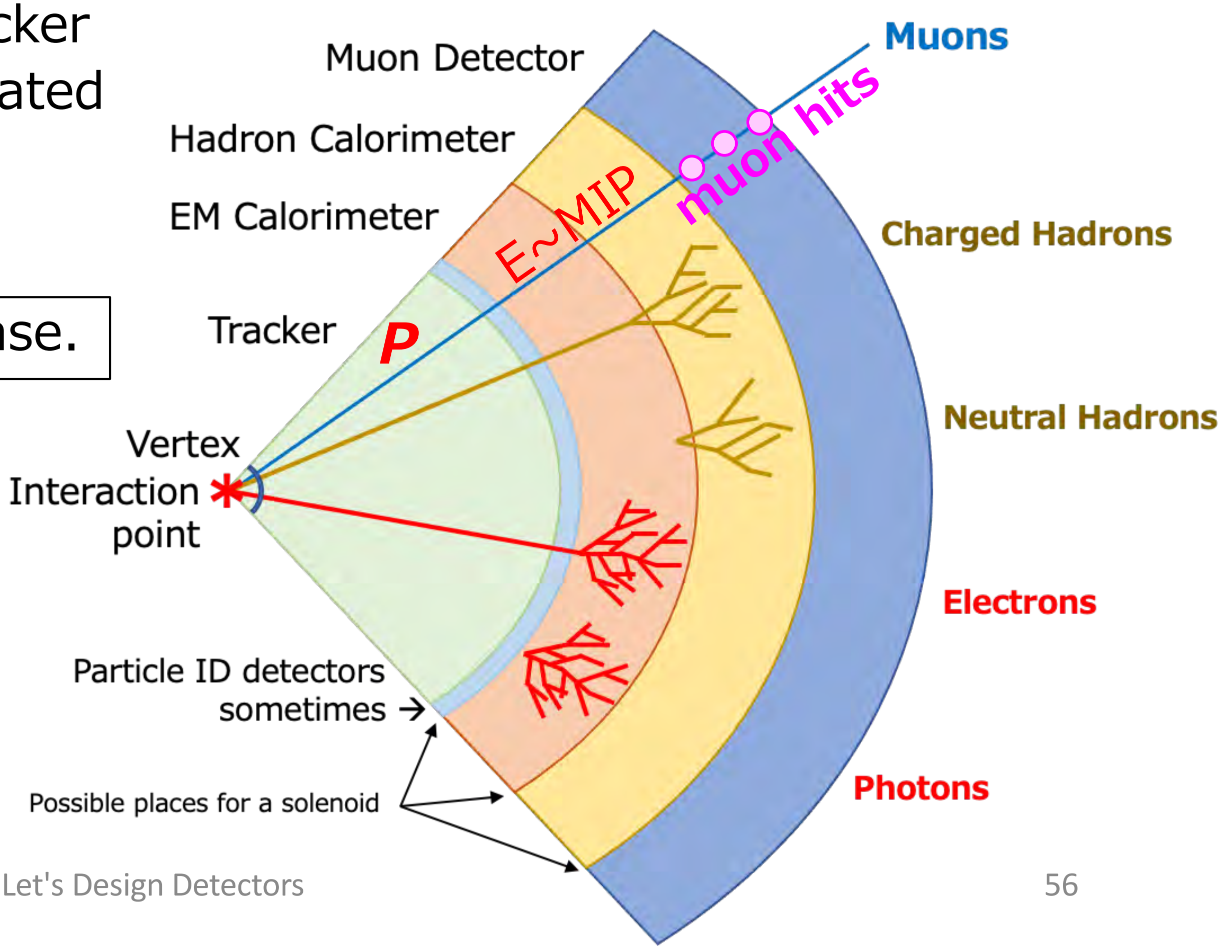


3. Requirement to the detectors ; Higgs discovery at LHC 4μ

High-performance muon measurement

- Identify the particles as muon
  - Have hits in muon detectors
  - Energy deposit in CAL consistent to muons (no showers in CAL)
- Precise measurement of momentum ***P***
  - Precise track reconstruction and extrapolation to muon detector
  - Momentum resolution of the tracker
  - Precise matching of the extrapolated track and muon detector hits.

Will be described in detail at ILC case.

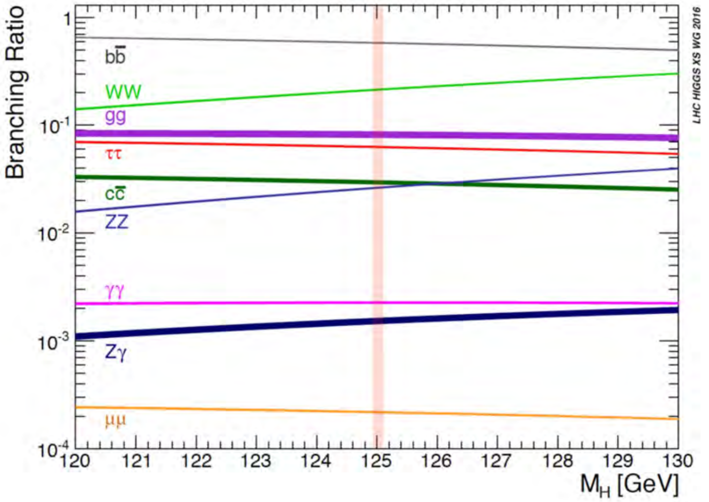


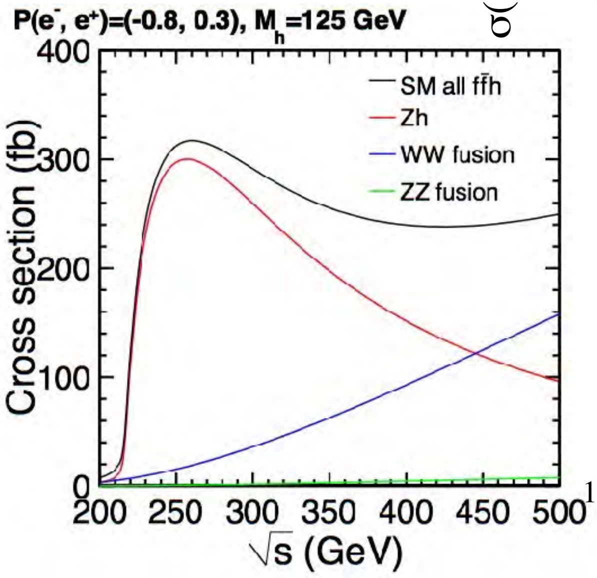
3. Requirement to the detectors ; Higgs discovery at ILC

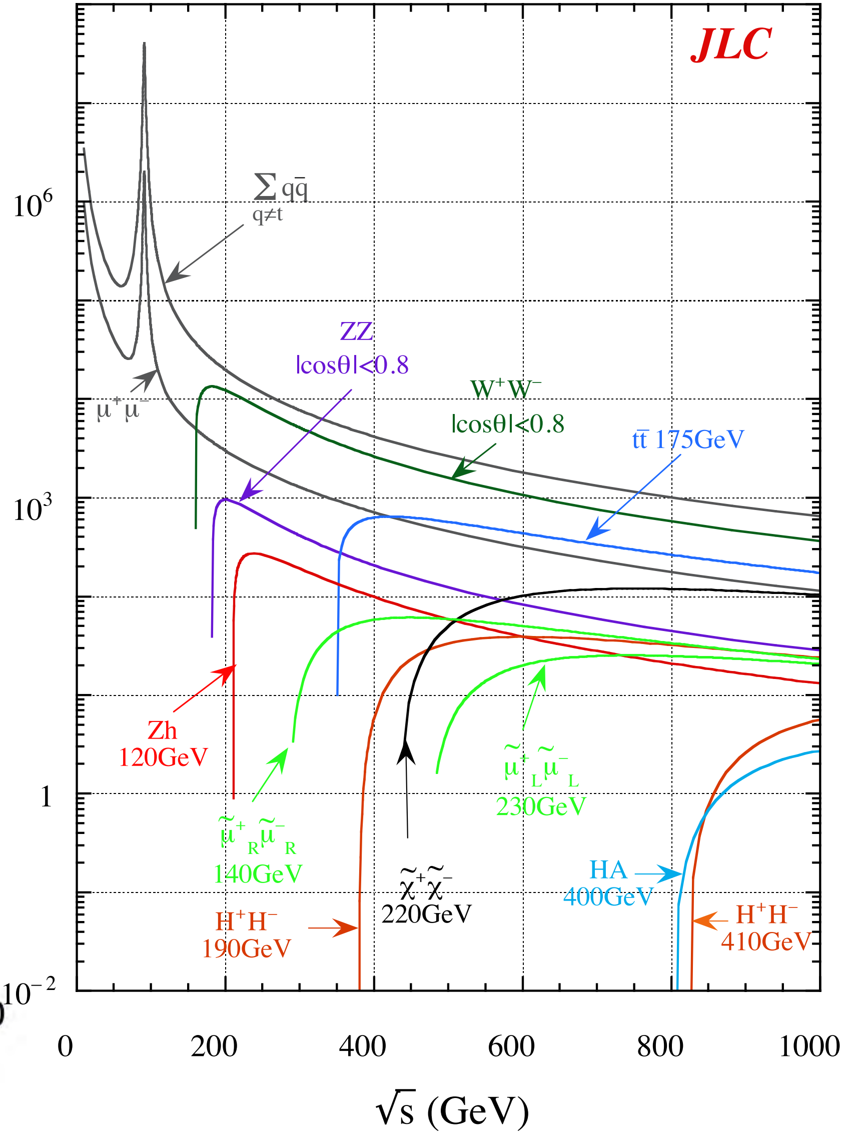
Let's discover Higgs at ILC

You know everything but it's mass.

- you know production mechanisms and their cross section.
- you know decay branching ratios







Large ZZ and WW background over ZH production can be distinguished by mass reconstruction.

3. Requirement to the detectors ; Higgs discovery at ILC

Discovery of H^0 ; Find a peak in the recoil mass distribution of $\mu^+\mu^-$ from Z^0 decay

$e^+ e^- \rightarrow Z^0H^0$, $Z^0 \rightarrow \mu^+\mu^-$

$H^0 \rightarrow$ anything (do not care)

Just detect muons precisely and calculate recoil mass with beam e+e- 4momenta;

$$\boxed{(E,\boldsymbol{P})_{H^0} = (E,\boldsymbol{P})_{e+} + (E,\boldsymbol{P})_{e-} - (E,\boldsymbol{P})_{Z}}$$

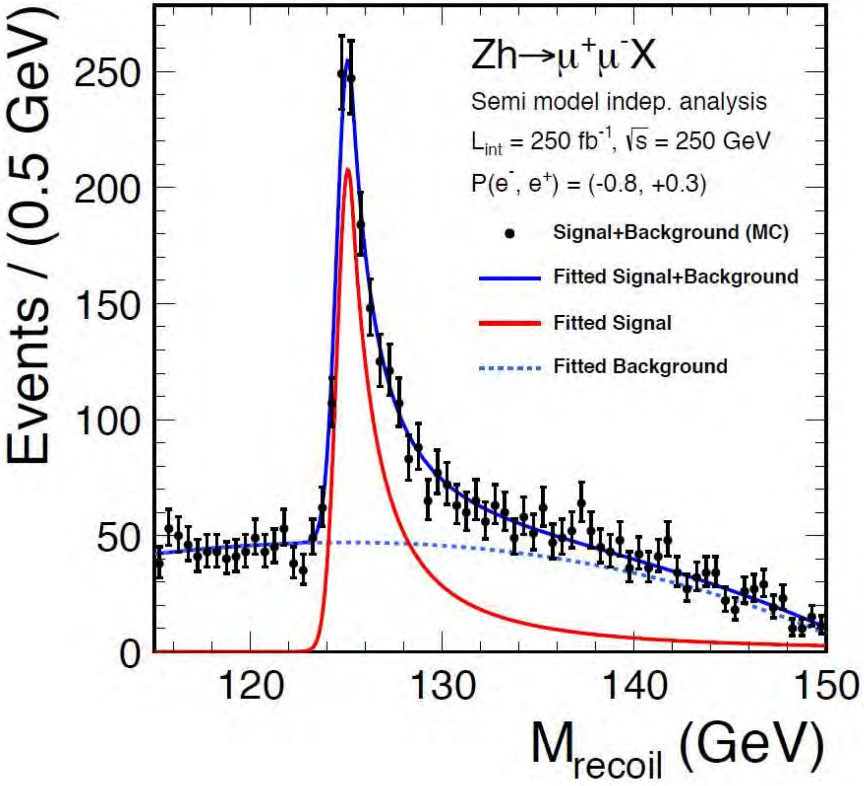
Calculate H^0 Mass ↑ ↑Suffer I.R.↑ ↑Calculate using $\mu\mu$ ***P***

Or simply $$\boxed{m^2_{\mathrm{recoil}} = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2}$$

* Recoil mass suffers initial state radiation of e+e- and shifts/has tail to higher mass.
Not suitable for precise mass determination.

Criteria :

- High-efficiency muon identification
- Precise measurement of muon momentum



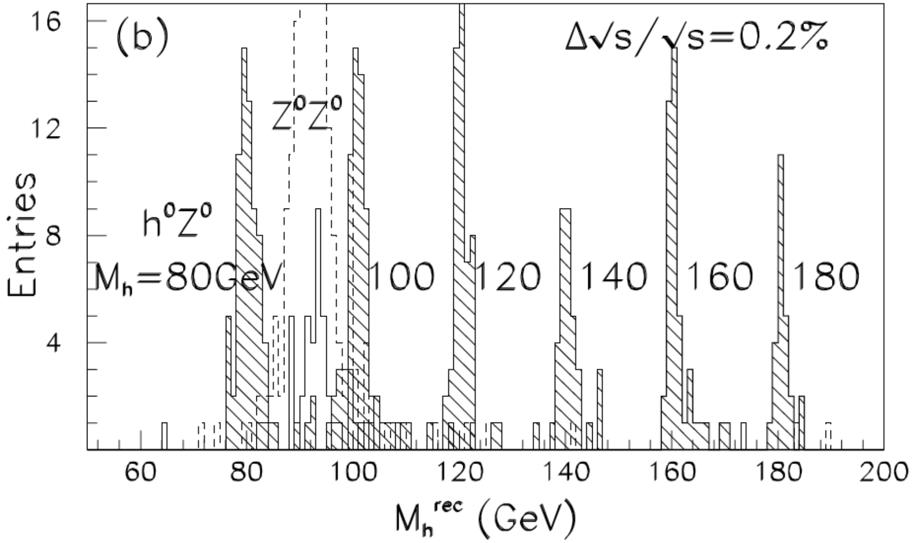
3. Requirement to the detectors ; Higgs discovery at ILC

Discovery of H^0 ; Find a peak in the recoil mass distribution of $\mu^+\mu^-$ from Z^0 decay

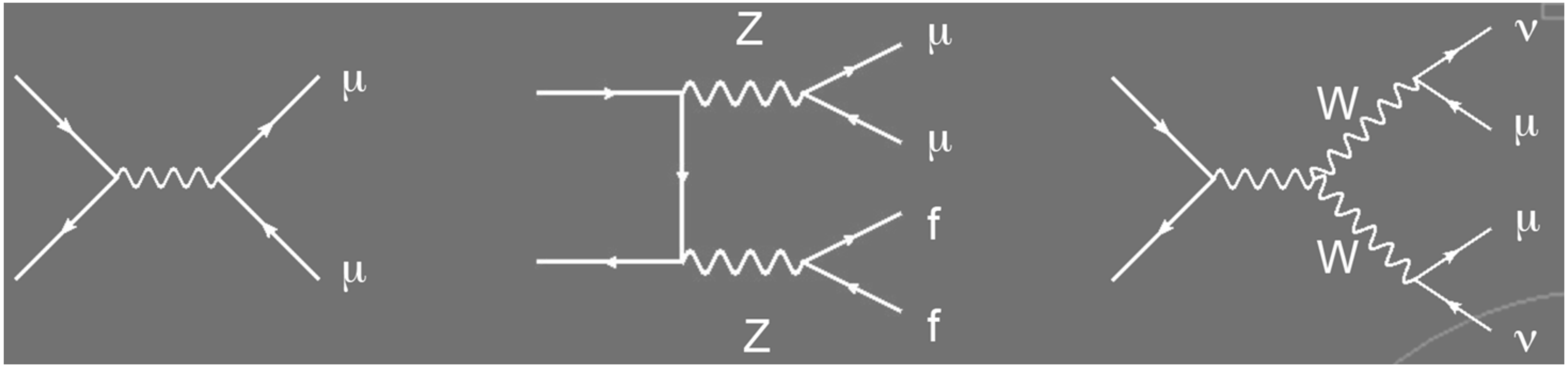
$e^+ e^- \rightarrow Z^0H^0$, $Z^0 \rightarrow \mu^+\mu^-$

$H^0 \rightarrow$ anything (do not care)

Background Processes can be distinguished from signal process by Pt cuts, di-muon mass, etc.



Background Processes



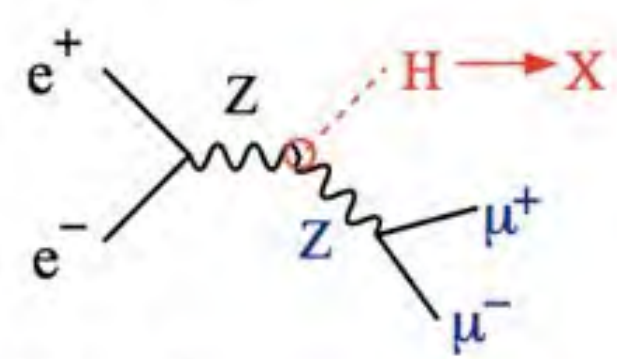
3. Requirement to the detectors ; Higgs discovery at ILC

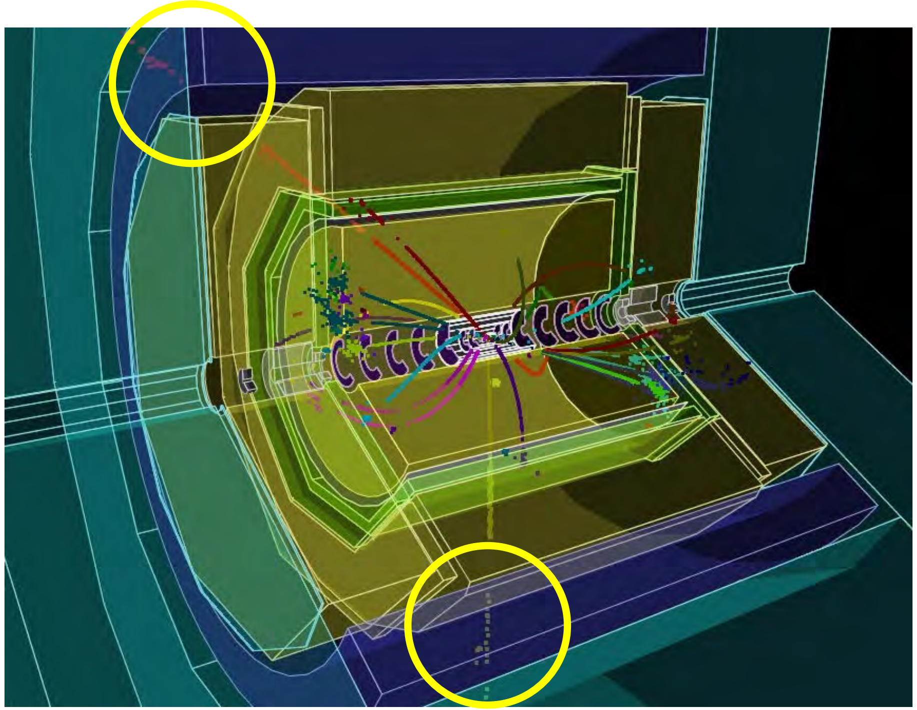
High-efficiency muon identification

How can we know the particle is muon ?

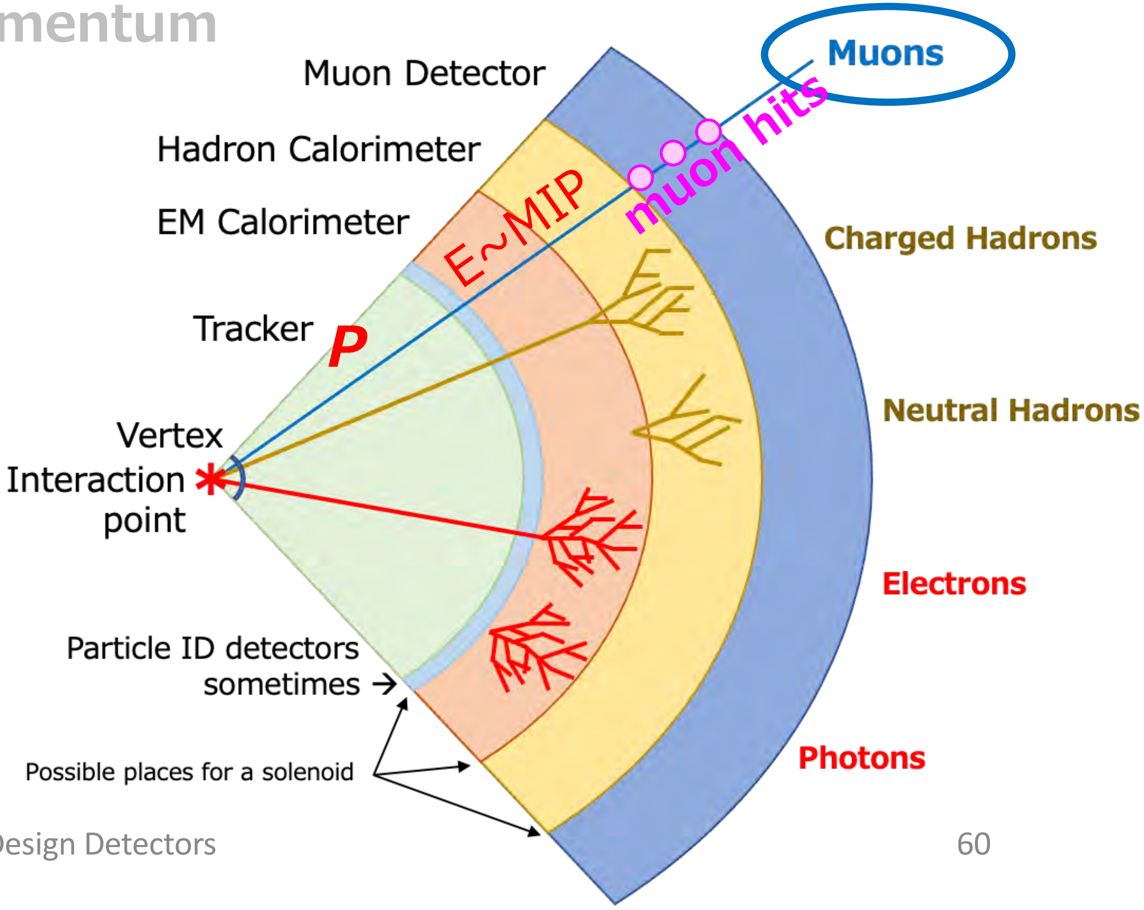
- The track penetrate through thick material and make hits in muon detectors
- Muon does not initiate EM shower
- Muon does not initiate hadron shower

- Precise measurement of muon momentum





e+e- → ZH, Z→μμ, H→*bb*

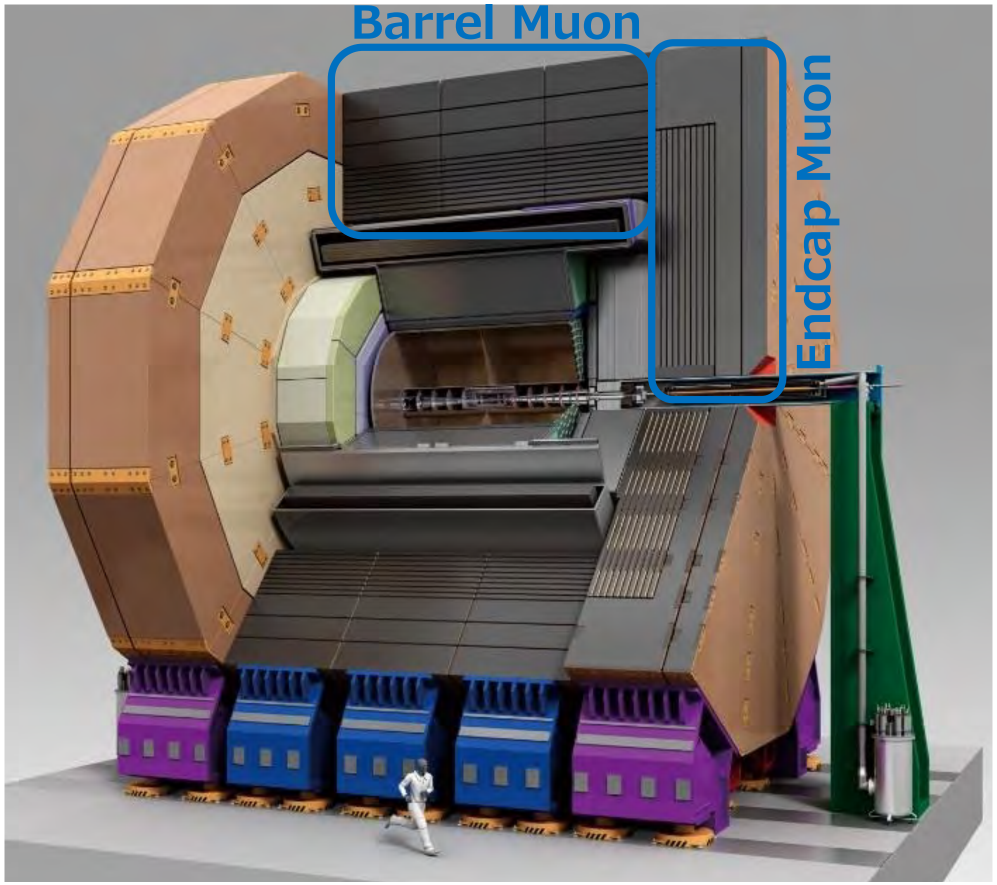


3. Requirement to the detectors ; Higgs discovery at ILC

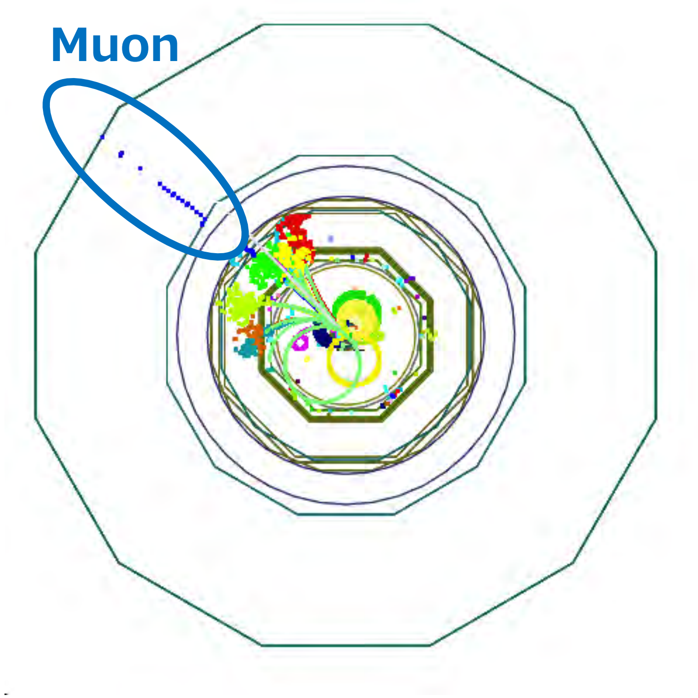
High-efficiency muon identification

→ 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



3. Requirement to the detectors ; Higgs discovery at ILC

High-efficiency muon identification

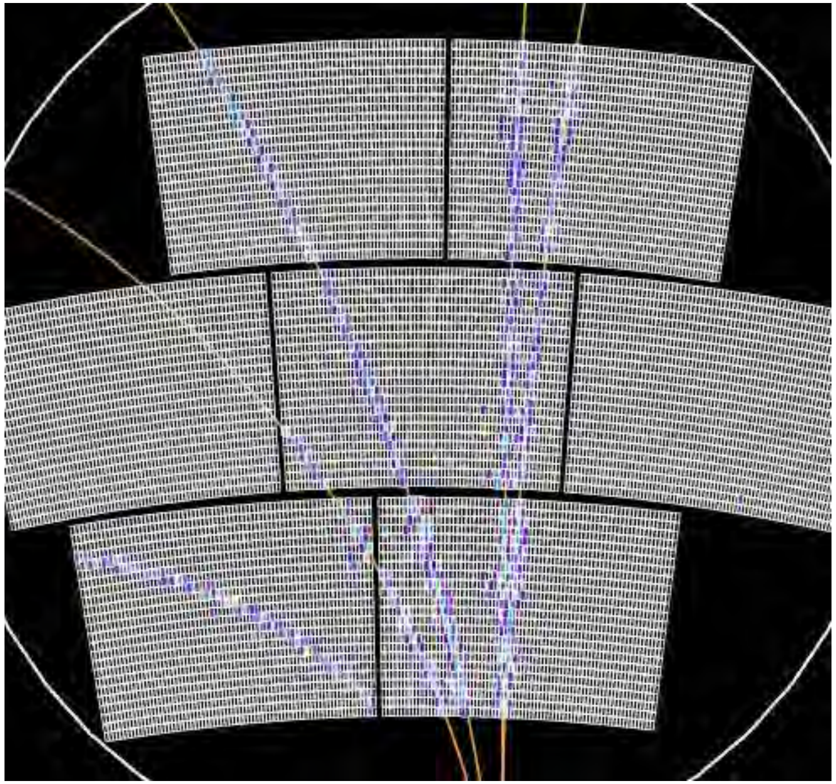
Precise measurement of muon momentum

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)

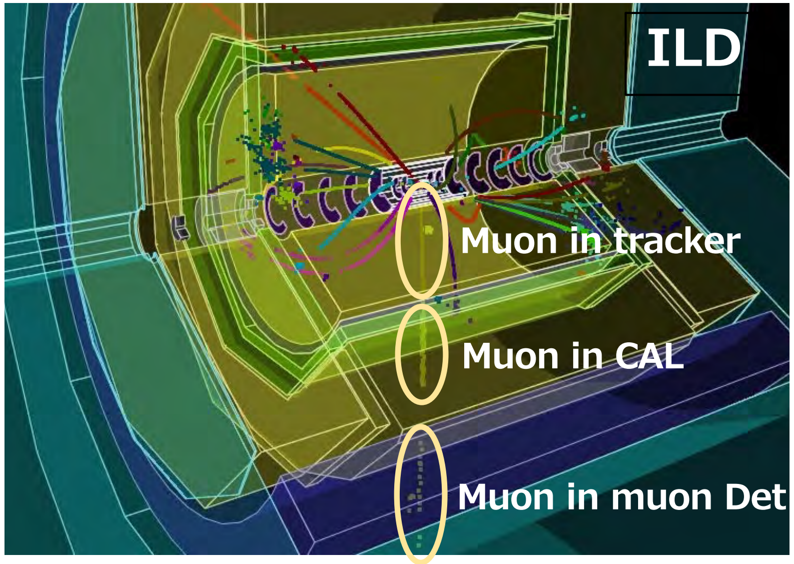
3. Requirement to the detectors ; Higgs discovery at ILC

High-efficiency muon identification

Precise measurement of muon momentum

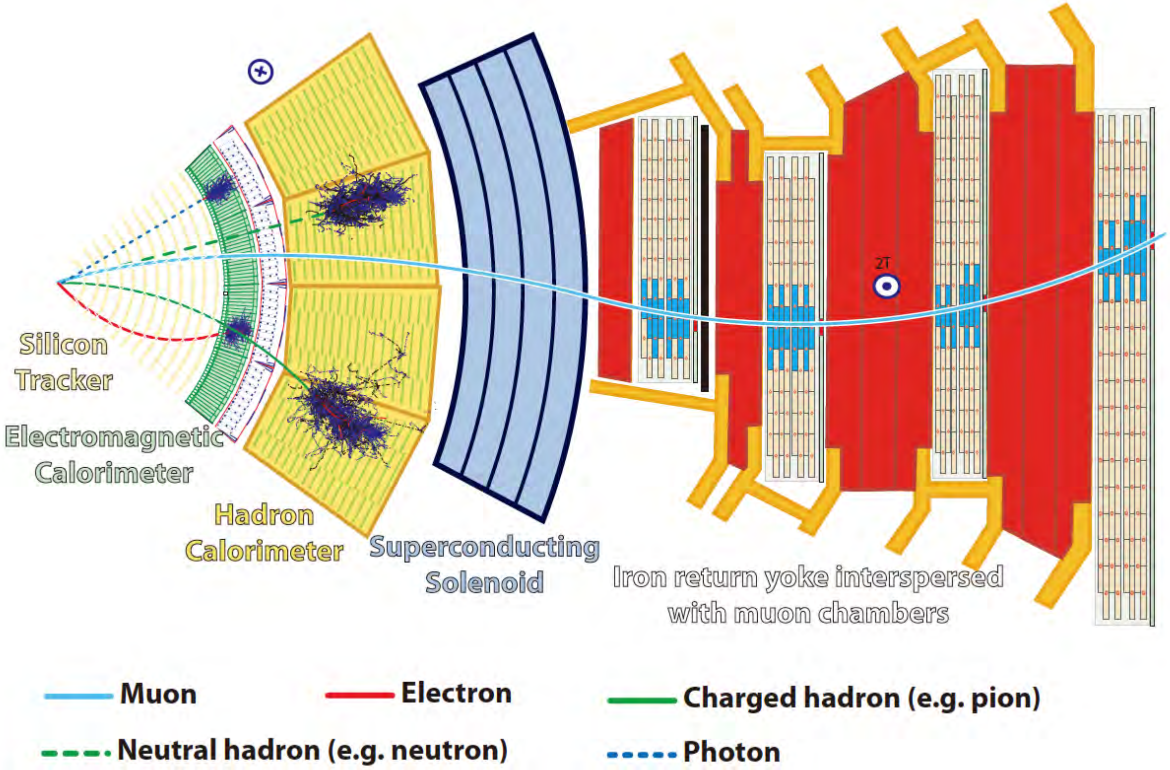
Precise correspondence between muon detector hits and tracks.

- 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.



Summary for the Higgs discovery

We need

- Excellent EM calorimeters for excellent energy/direction measurement of gammas,
  and good hadron calorimeters and trackers for non-gamma rejection
  to achieve excellent gamma-gamma mass reconstruction,

- excellent trackers, excellent calorimeters, thick material as muon filter,
  good muon detector, and precise magnetic field mapping
  to achieve excellent muon measurement

Let's study Higgs in detail at LHC/ILC

This is **the physics** we are really interested in.

We need

- Investigation of hundreds of production/decay channel combinations to discover any deviation from the Standard Model prediction.

- More Excellent Detectors not to miss tiny deviation/signal, or to verify SM prediction with high precision

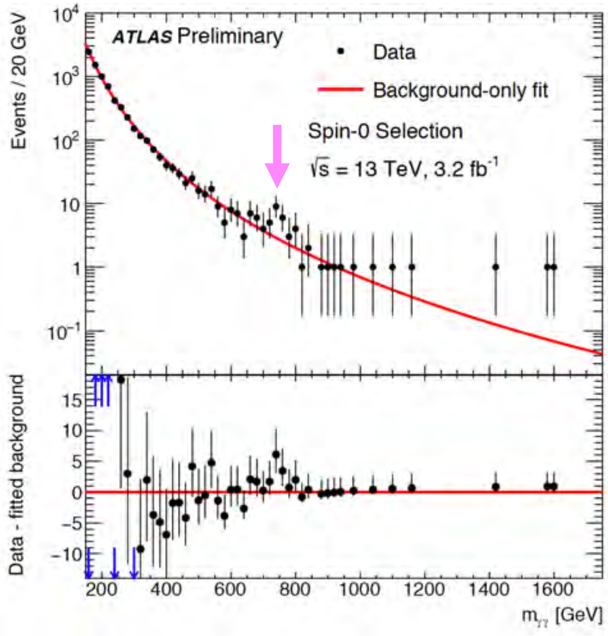
3. Requirement to the detectors ; Higgs Study at LHC/ILC

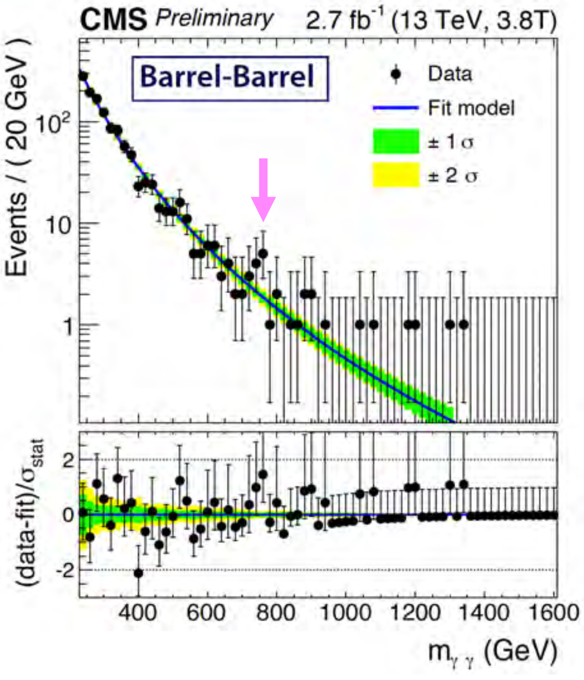
We need to investigate hundreds of channels.
→ Special care is needed on analyzing many many channels.

Remark !

If you analyze one hundred channels, in some channel, you shall find "statistically fluctuated" un-physical peak of 2.5 σ significance at some energy.

An example; In 2015, both ATLAS and CMS observed a peak at 750GeV in γγ mass spectra.





Dec.15, 14:00, talks given at a seminar.

10 papers were submitted the night,
150 papers submitted within 2 weeks,
and eventually
more than 400 papers were submitted,
to explain this by new exotic theories
until the peak disappeared in Aug.2016
at new analysis with more data.

3. Requirement to the detectors ; Higgs Study at LHC/ILC

Let's study Higgs in detail at LHC/ILC.

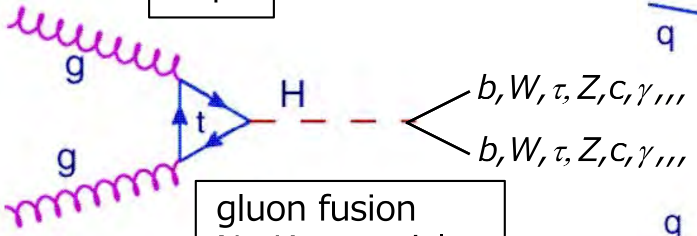
- Explicitly reconstruct all possible H^0 decay modes.

- Need to study coupling to all particles to establish Higgs-ness

- Explore various production channels, hopefully with associating 'Key' particle.

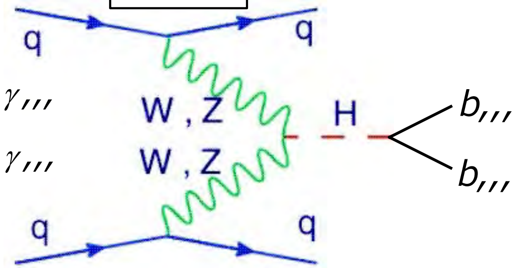
- To distinguish them from overwhelming background

50pb



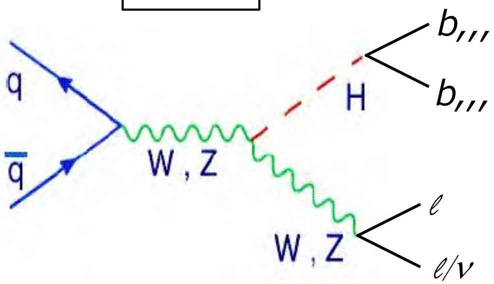
gluon fusion
No Key particles

4.2pb



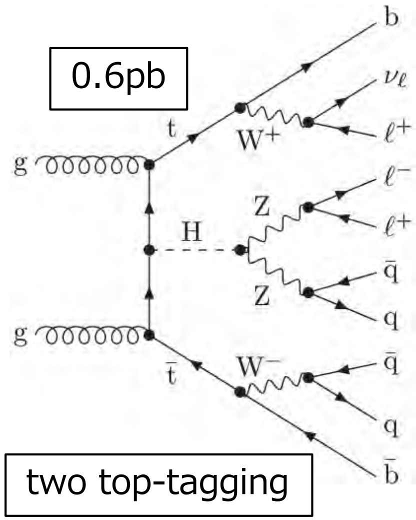
two high-Pt jets

2.4pb



Z/W-tagging

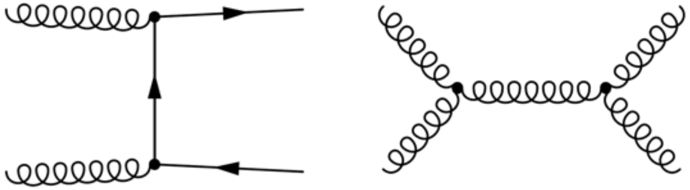
0.6pb



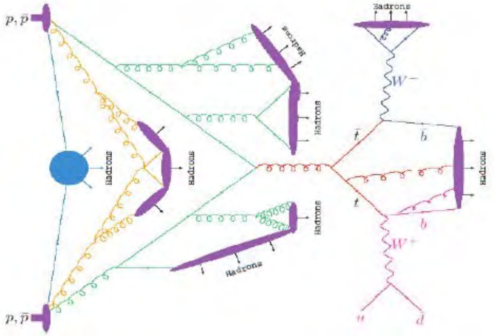
two top-tagging

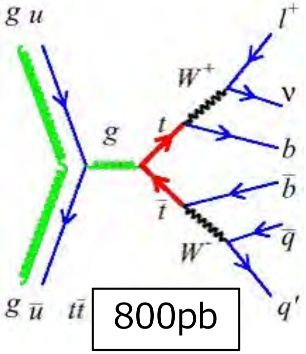
Signals

Backgrounds



high-Pt jets ~μb





800pb

3. Requirement to the detectors ; Higgs Study at LHC/ILC

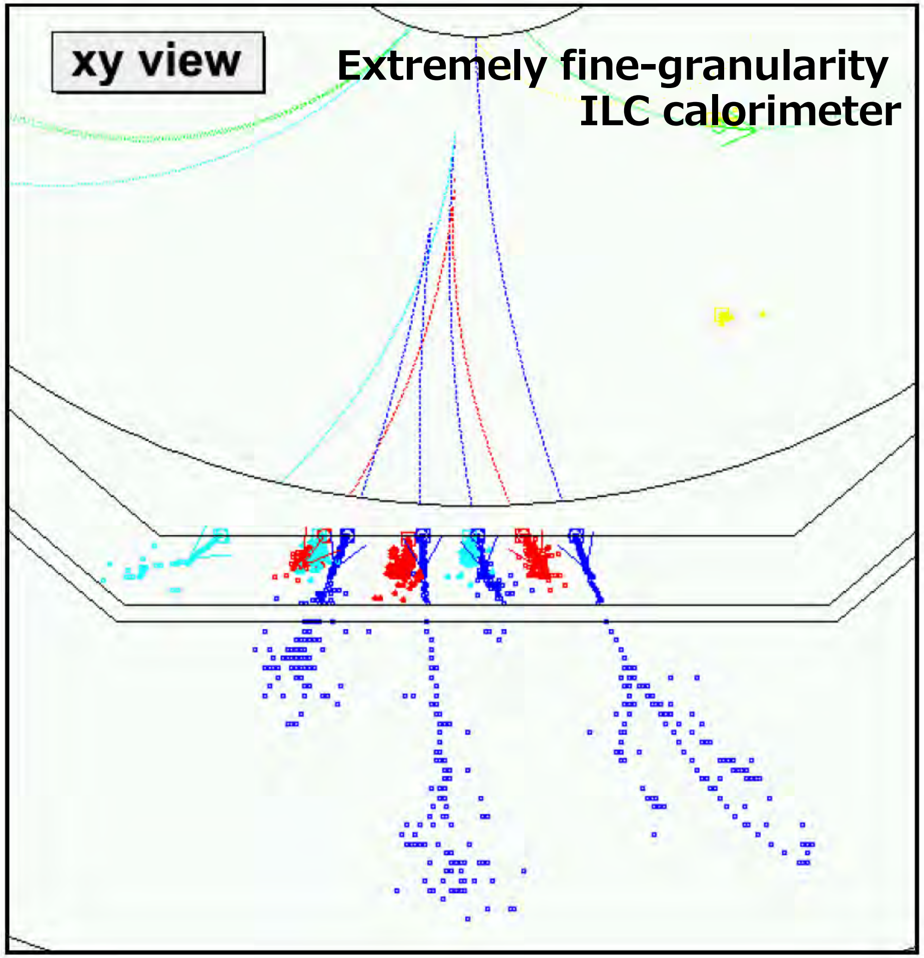
Explicitly reconstruct all possible H^0/t/b/W/Z decays.

- good resolutions ; energy, momentum, position, timing

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

  Excellent granularities 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



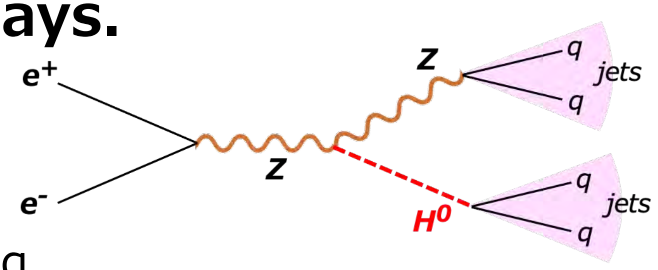
Untangle track-cluster overlap with high-granularity calorimeters, and use tracker information for charged particles.

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.

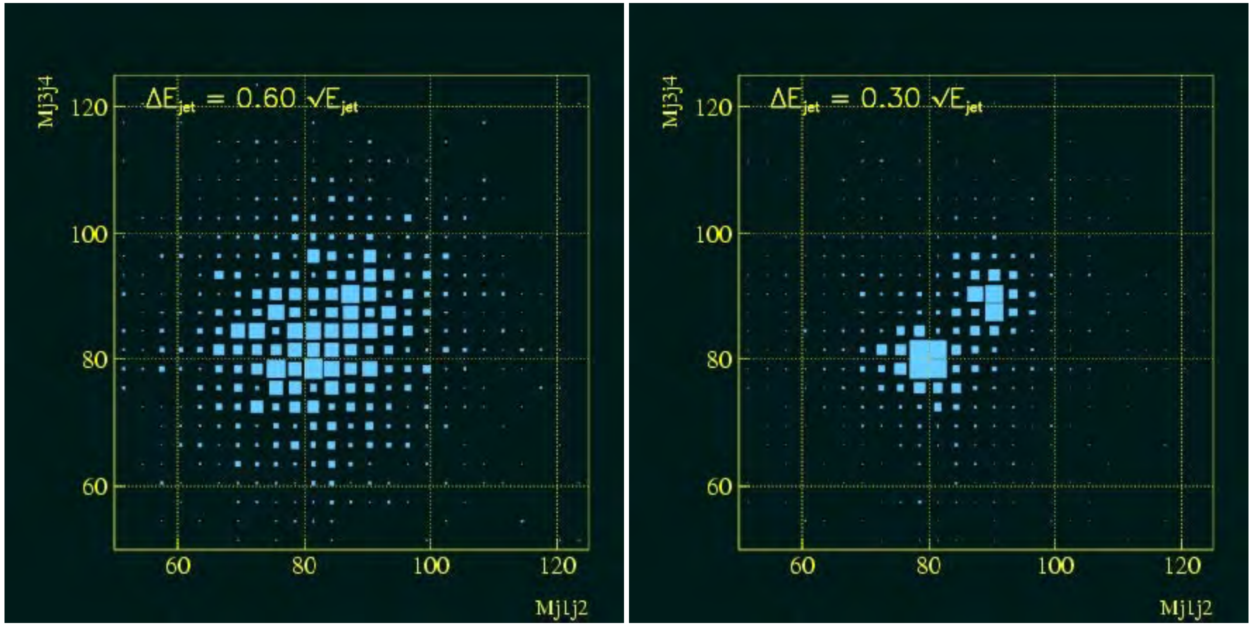
3. Requirement to the detectors ; Higgs Study at LHC/ILC

Explicitly reconstruct all possible H^0/t/b/W/Z decays.



- 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

W/Z mass reconstruction for 2-jet decay

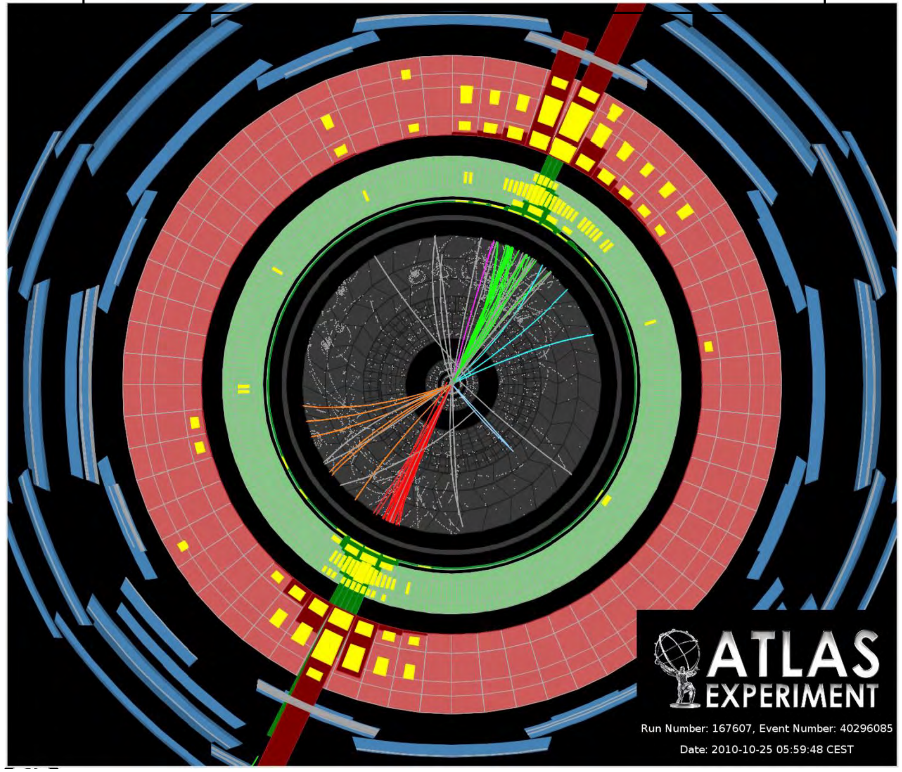


W and Z not separated
with conventional 60/√E detector.

W and Z clearly separated
with 30/√E ILC detector.

Figure taken from Aspen 2007 report by J.Brau.

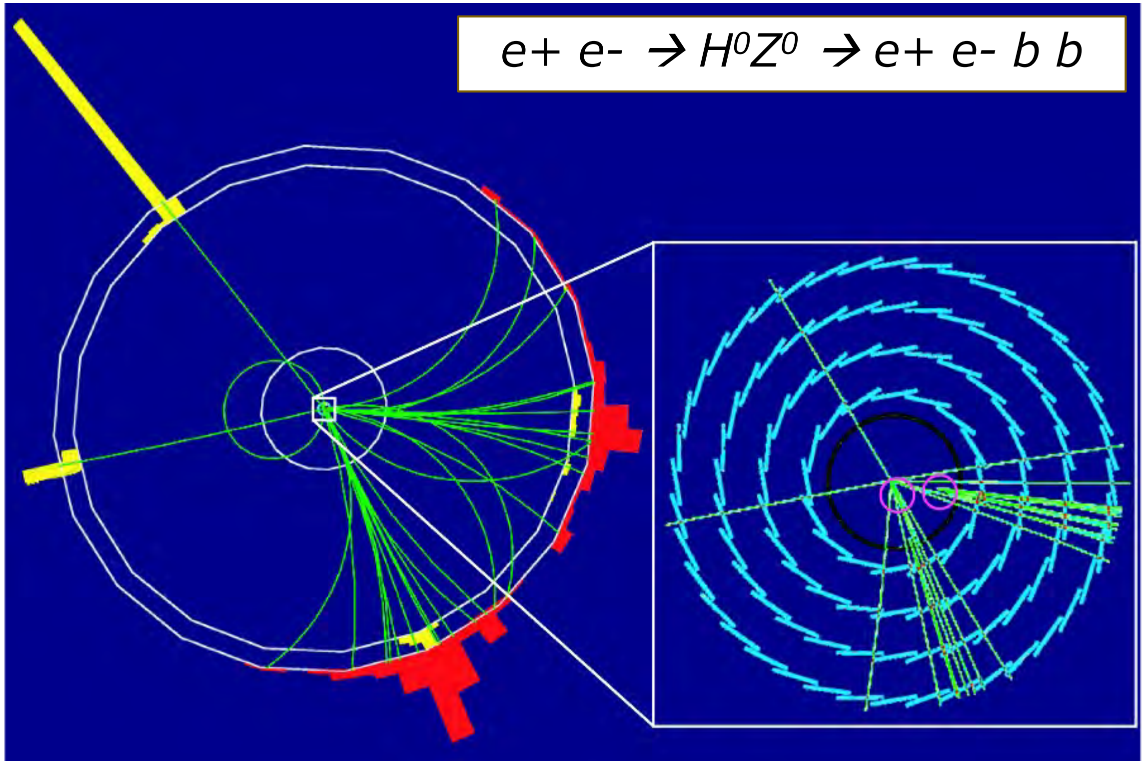
Many particle in collimated JET
should be separately reconstructed.

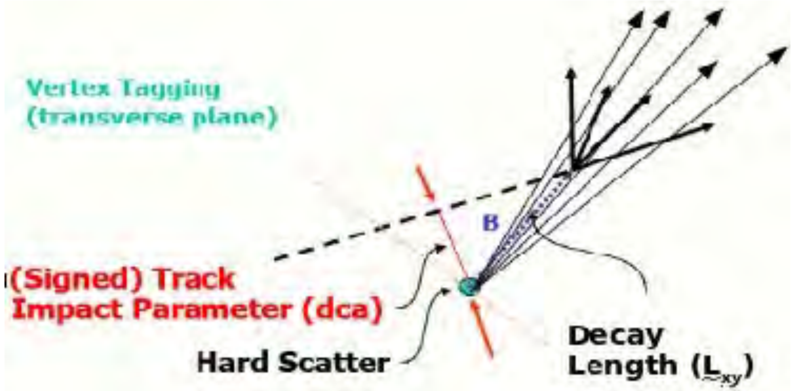


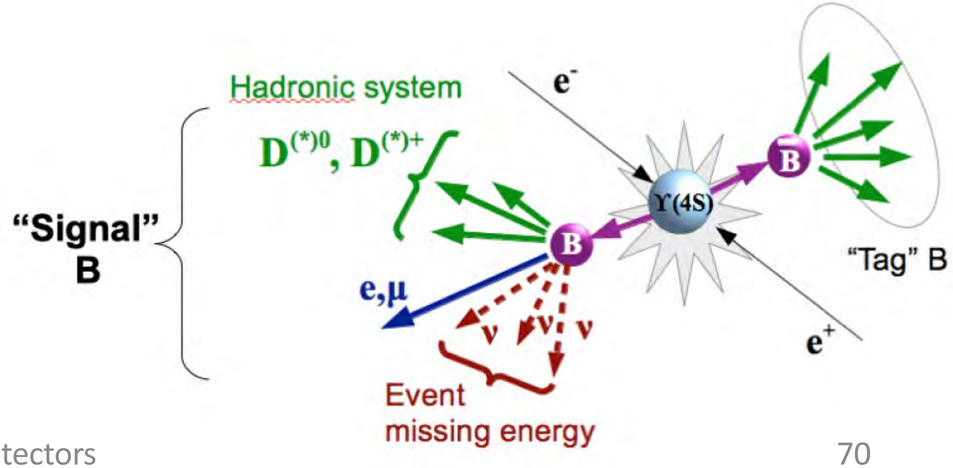
3. Requirement to the detectors ; Higgs Study at LHC/ILC

Explicitly reconstruct all possible H^0/t/b/W/Z decays.

- 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



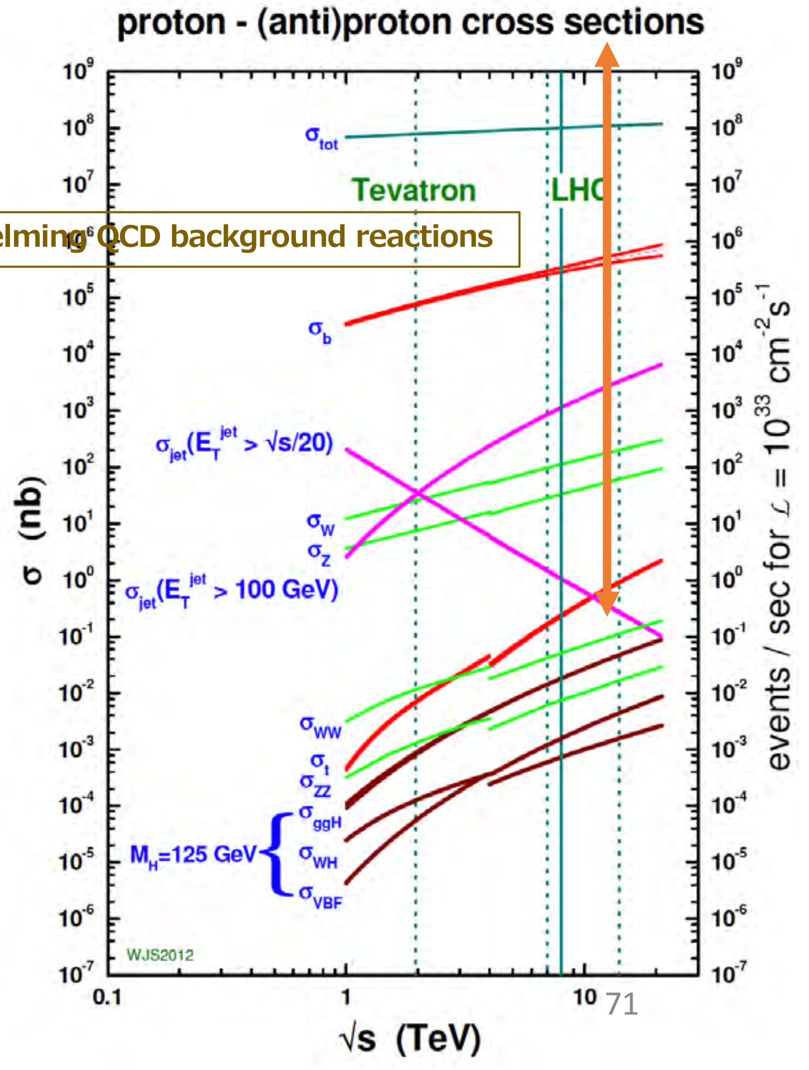




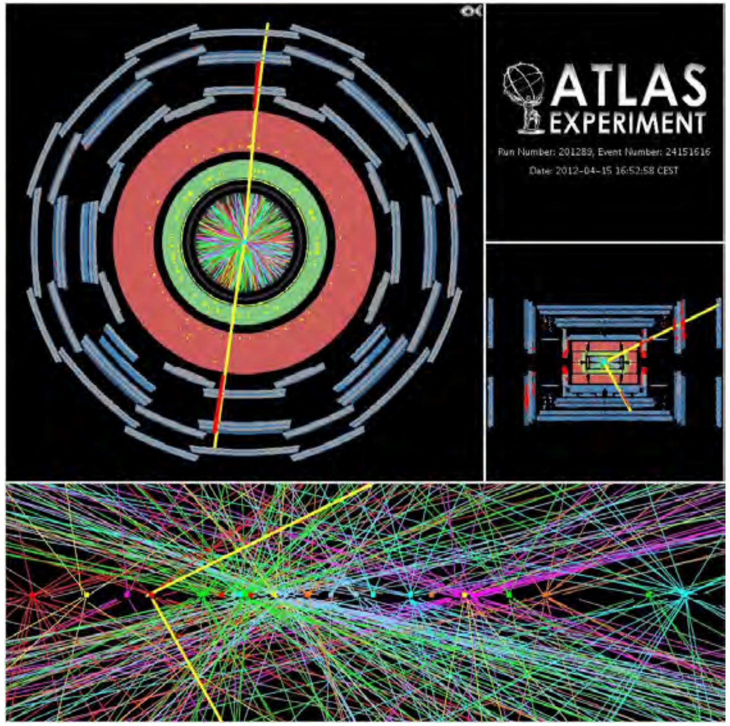
3. Requirement to the detectors ; Higgs Study at LHC/ILC

Explicitly reconstruct all possible H^0/t/b/W/Z decays.

- 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)
  as well as for primary vertexing for bunch separation
- **Reject overwhelming QCD background reactions**



Overwhelming QCD background reactions



Multi-bunch overlapping

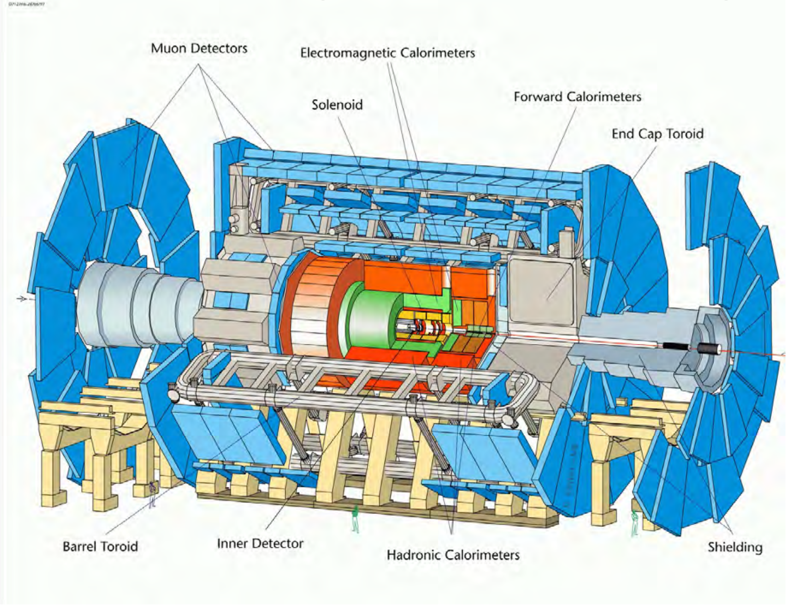
3. Requirement to the detectors ; Higgs Study at LHC/ILC

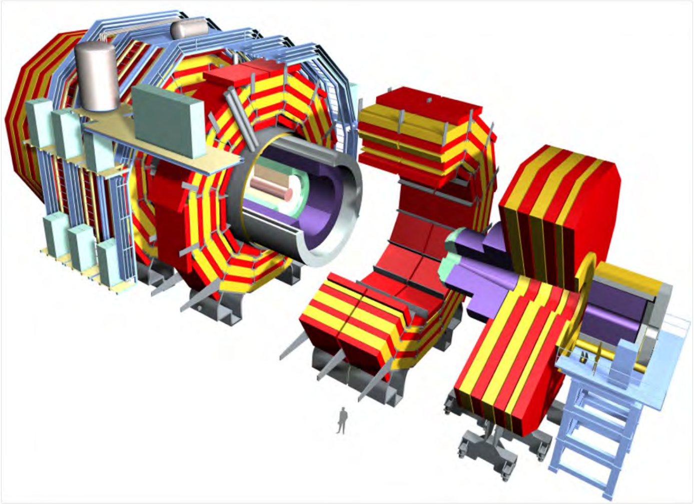
Explicitly reconstruct all possible H^0/t/b/W/Z decays.

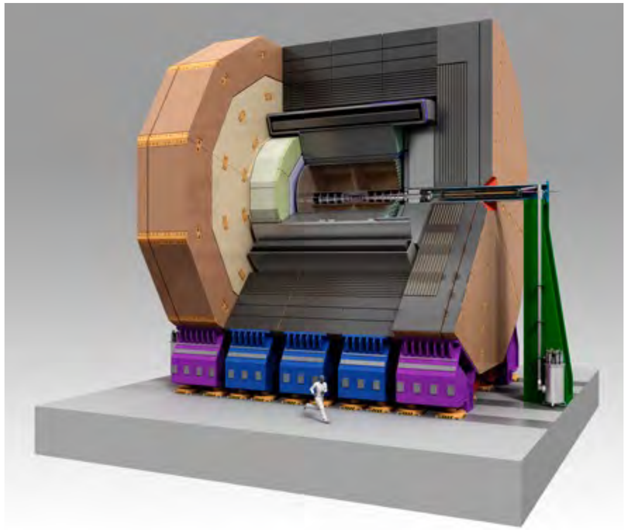
- good resolutions ; energy, momentum, position, timing
  Charged particle be measured by trackers, while neutral particles by calorimeters.
  Excellent position resolutions to untangle track/cluster overlapping.
- Jet reconstruction ; high multiplicity, high occupancy
- Precision secondary vertexing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

These were the 1st phase solutions, but more excellent ones needed now.

This is almost the solution







For the precision Higgs study

We need

- Investigation of hundreds of production/decay channel combinations to Higgs-ness of the particle.
- More Excellent Detectors not to miss any deviation/signal, or to verify SM prediction with high precision

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 excellent energy resolution and high-granularity

Excellent flavor tagging

- vertex detector of excellent position resolution and small pixel, narrow strip to reconstruct vertex point precisely even for collimated high-multiplicity jet tracks.
  This also helps tracking of collimated jet,
  and background suppression by primary vertex identification.
- Dedicated particle-ID detectors are also important for flavor tagging

That's it for today.

The second half will be given tomorrow.

Detector Complex at Large High-Energy Experiments

- Let's design Particle-Physics Detectors -

PART-II

2023-July-27
Vietnam School on Neutrino 2023

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

Remind

For the Higgs discovery

We will search for Higgs to $\gamma\,\gamma$ channel and four muon channel.

- Excellent γ–γ mass reconstruction.

For this,

- excellent EM calorimeters for excellent energy/position measurement of γ,
- good hadron calorimeters and trackers for rejection of non-γ.

- 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

Remind

We need

- Investigation of hundreds of production/decay channel combinations to establish Higgs-ness of the particle.
- Excellent Detectors to verify StandardModel prediction with high precision or not to miss any deviation from StandardModel.

For that purpose, in addition to the good EM calorimeter and muon measurement, 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. Operation of detectors

We set requirements on the detectors.

Let's see what kind of detectors can satisfy the requirements.

4. Operation 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 (You've learned last week).

4. Operation of detectors

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

- Trackers → direction and momentum (~energy)
- Vertex Detector → find decay point (flavour tagging ~ particle ID)
  and also do tracking
- Calorimeters → energy,
  and also do particle identification
- Particle ID. → what kind of particle
  (muon, pion/Kaon, electron, gamma,,,)

For each detector, how it woks will be examined.

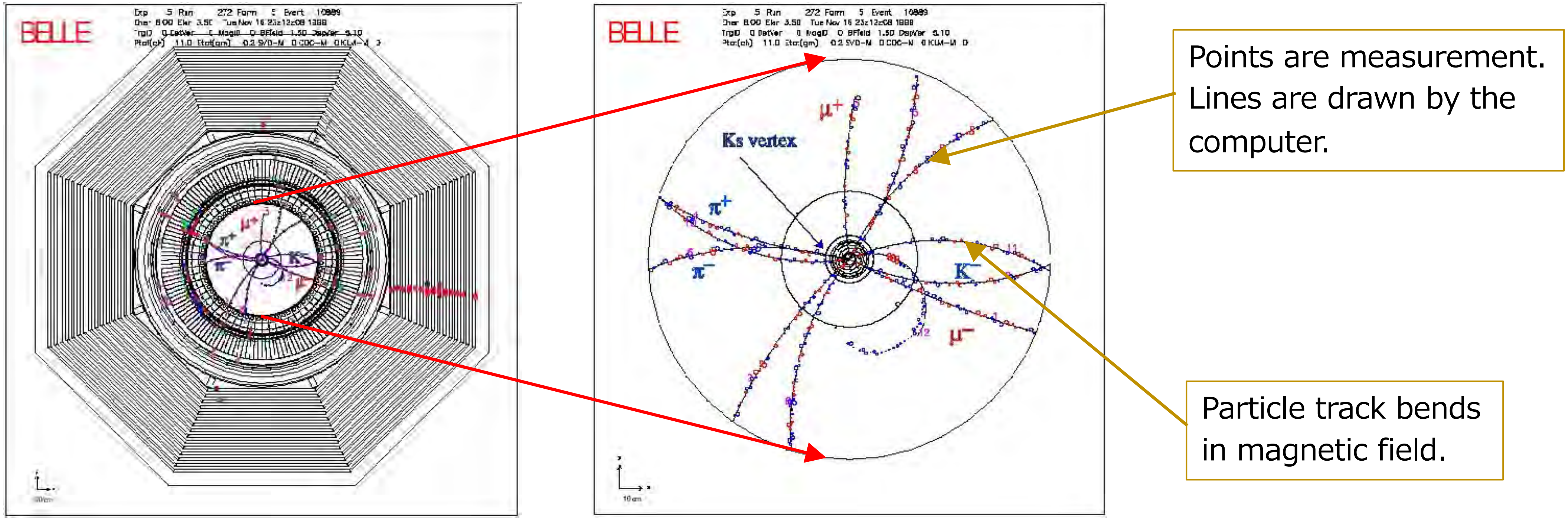
4. Operation of detectors

Trackers

Trackers measure particle direction and momentum.

4. Operation of detectors ; Trackers

Trackers measure particle direction and momentum.



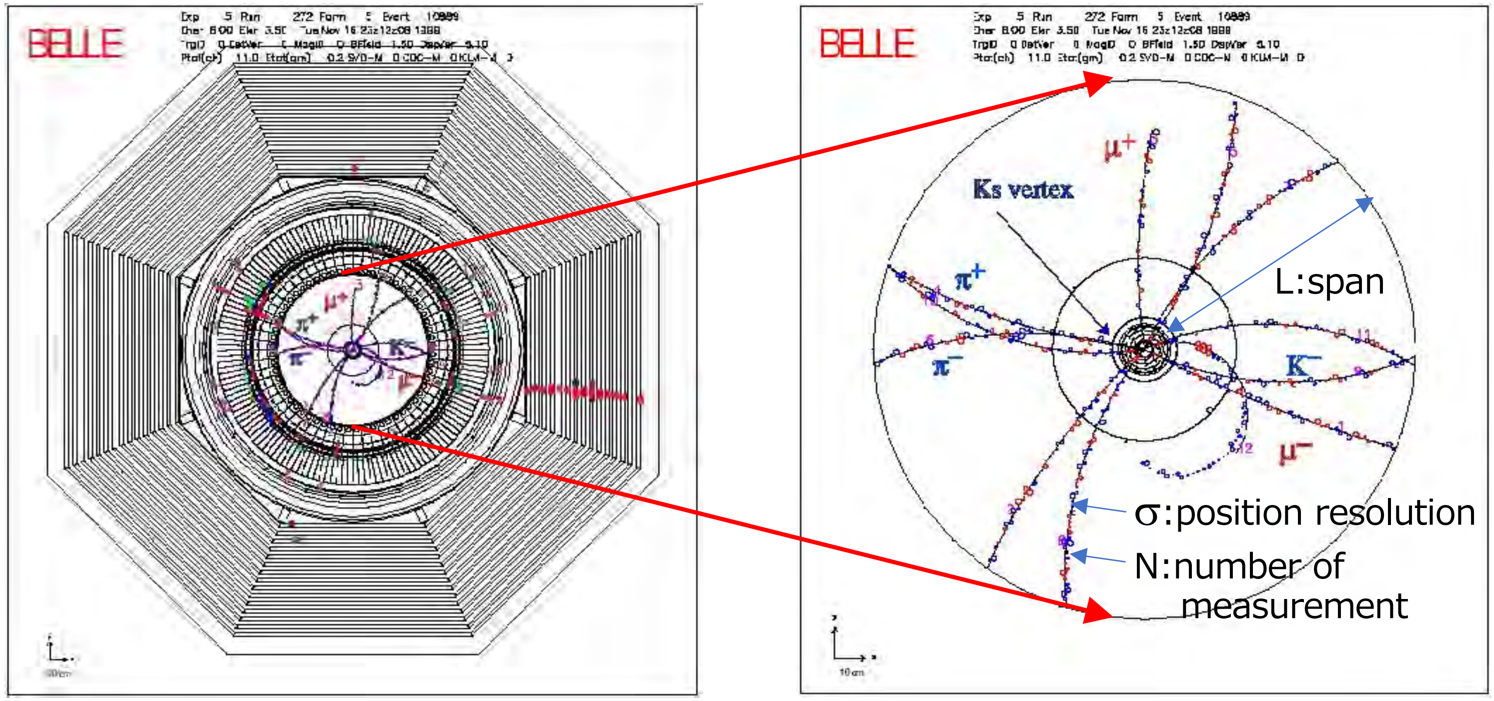
Points are measurement. Lines are drawn by the computer.

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 ρ, momentum P can be calculated. ($\sim P = 0.3B\rho$)
- 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,,,

4. Operation of detectors ; Trackers

Trackers measure particle direction and momentum.



Approximately

P [GeV]=0.3$B\rho$ [T · m]

Resolution, in general

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

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

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

ATLAS (achieved)

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

ILC (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 are valuable for particle-ID.
- Low mass is needed to avoid scattering inside the tracker and to avoid disturbing EM-CAL measurement.

In case of jets:

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

4. Operation of detectors ; Trackers

How trackers measure space points ?

Generate signal by ionization in matter : (Explained by Nakaya-san)
There are many types of trackers;

- Gas trackers
  - multi-wire chambers (~MWPC)
  - drift chambers (DC)
  - jet chambers
  - time projection chambers (TPC)
  - various unique chambers
- Silicon trackers
  - Strip-type
  - Pixel-type
  - Si Drift Chamber
- VTX detectors (main role is vertex reconstruction, but also do tracking)

4. Operation of detectors ; Trackers ; Gas Chambers

Tracking by chamber planes

Stack many layers of chamber planes
→ many position measurements
along the track
→ Track reconstruction

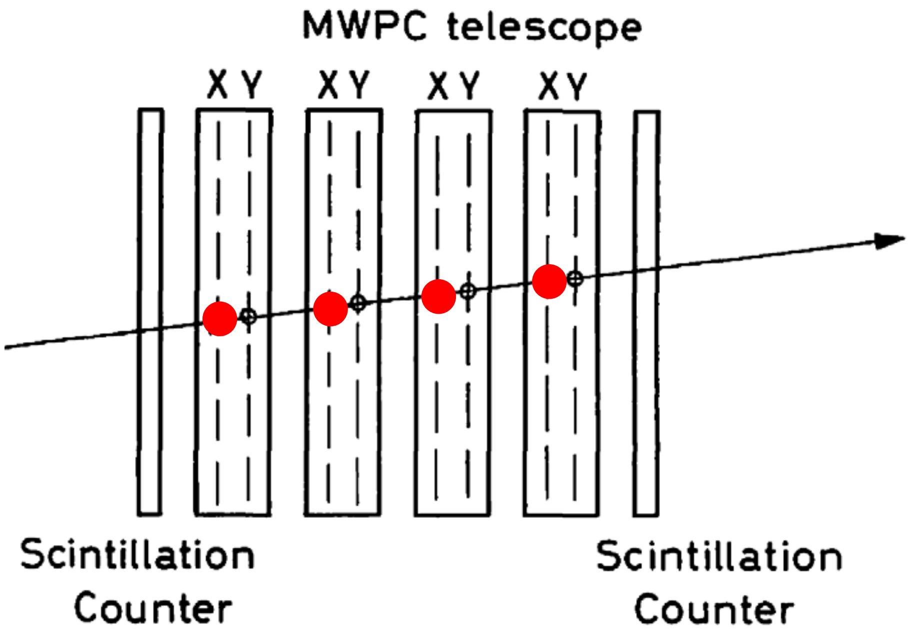


Figure from W.R.Leo

Cylindrical Drift Chamber
Cylindrically multi-layered
surrounding collision point.

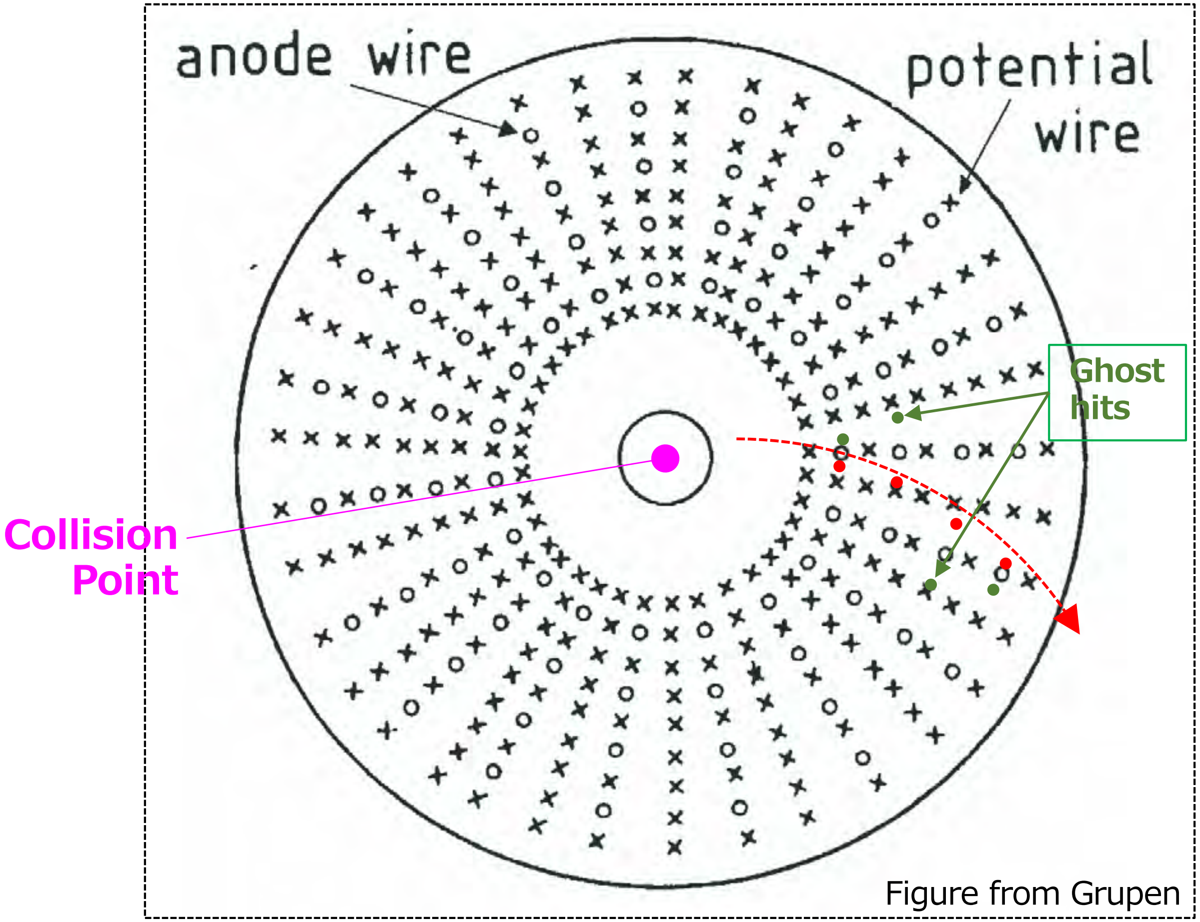


Figure from Grupen

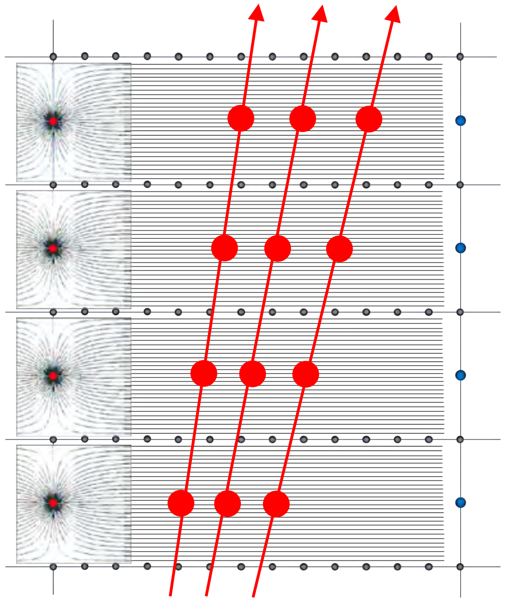
Drift chambers have left-right ambiguity, and generate ghost hits.
They do not line up, and they do not make ghost tracks.

4. Operation of detectors ; Trackers ; Gas Chambers

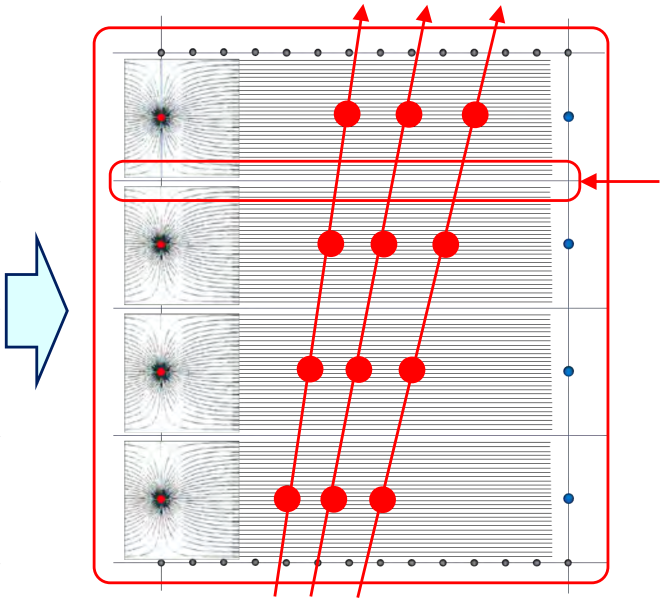
Jet chamber

- Drift chamber with many wires in a "cell" and can measure "Track Segment"
- For drift chambers, one wire can measure many points → Jet chamber can measure many tracks.

→ suitable to measure collimated tracks in a jet.

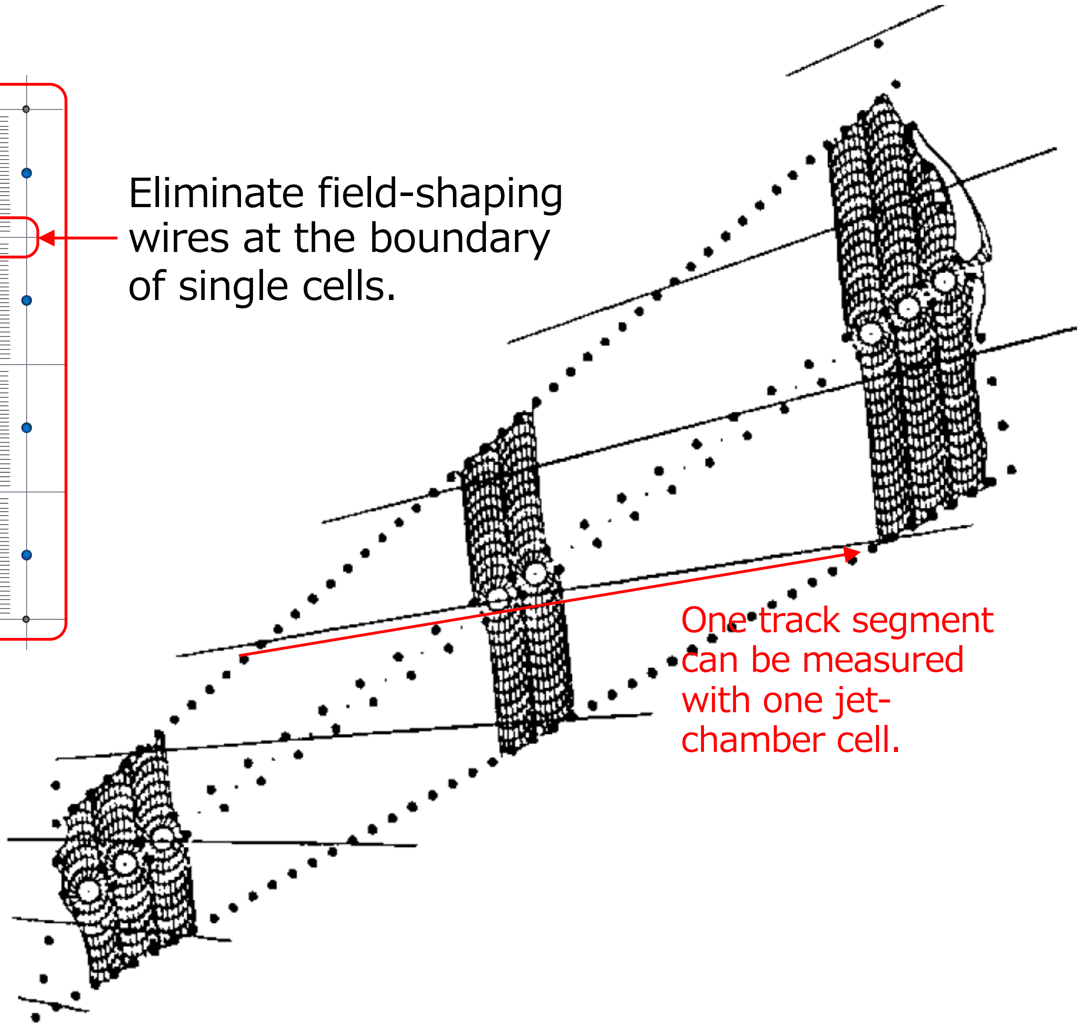


Stack many layers of single-cell drift chamber.



Large Jet-Cell with many sense wires in it.

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



One track segment can be measured with one jet-chamber cell.

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).

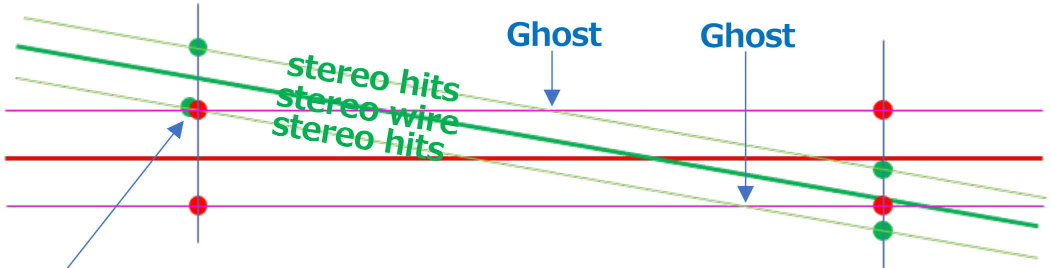
4. Operation of detectors ; Trackers ; Gas Chambers

Jet chamber

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

→ To reconstruct track in 3-dimensional space,
z-measurement (along the wires) is needed.

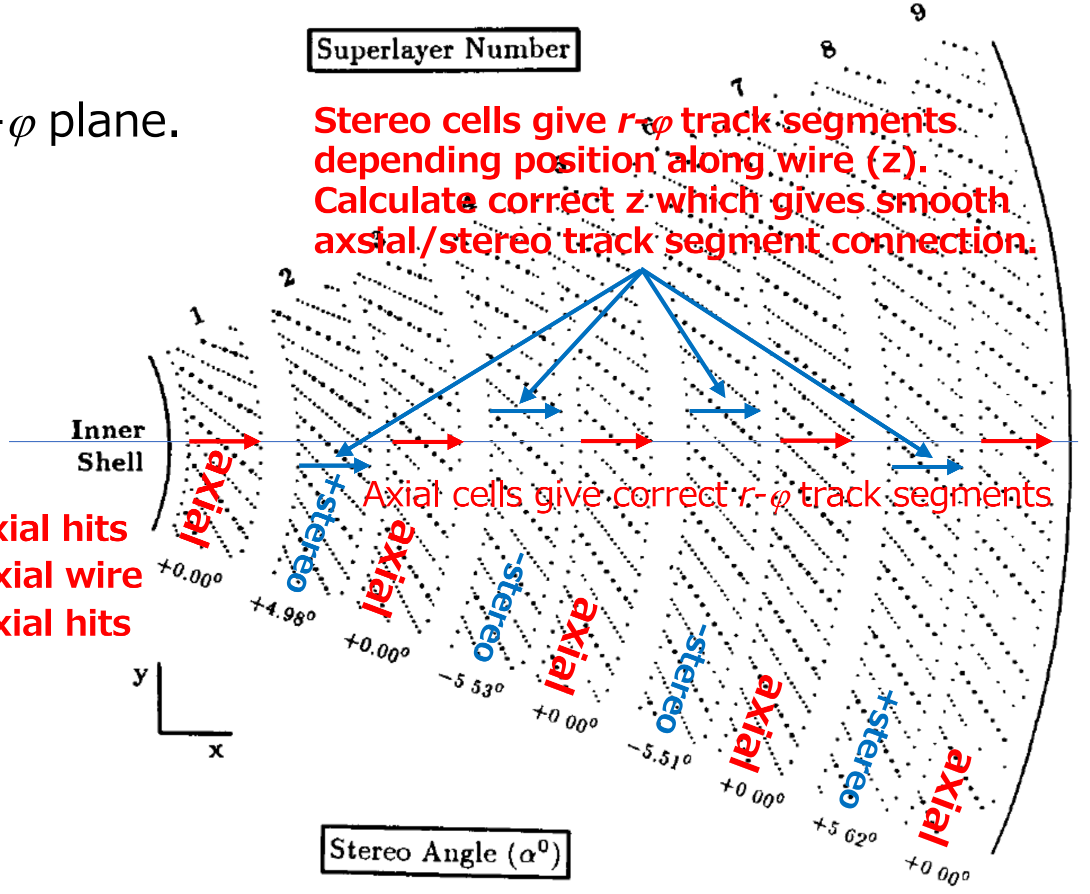
→ Stereo wires (tilted wires) or charge division



With correct z, axial and stereo hits coincide.

With wrong z, axial and stereo hits disagree.

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



Stereo cells give r-φ track segments depending position along wire (z). Calculate correct z which gives smooth axsial/stereo track segment connection.

Axial cells give correct r-φ track segments

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

Expected performance

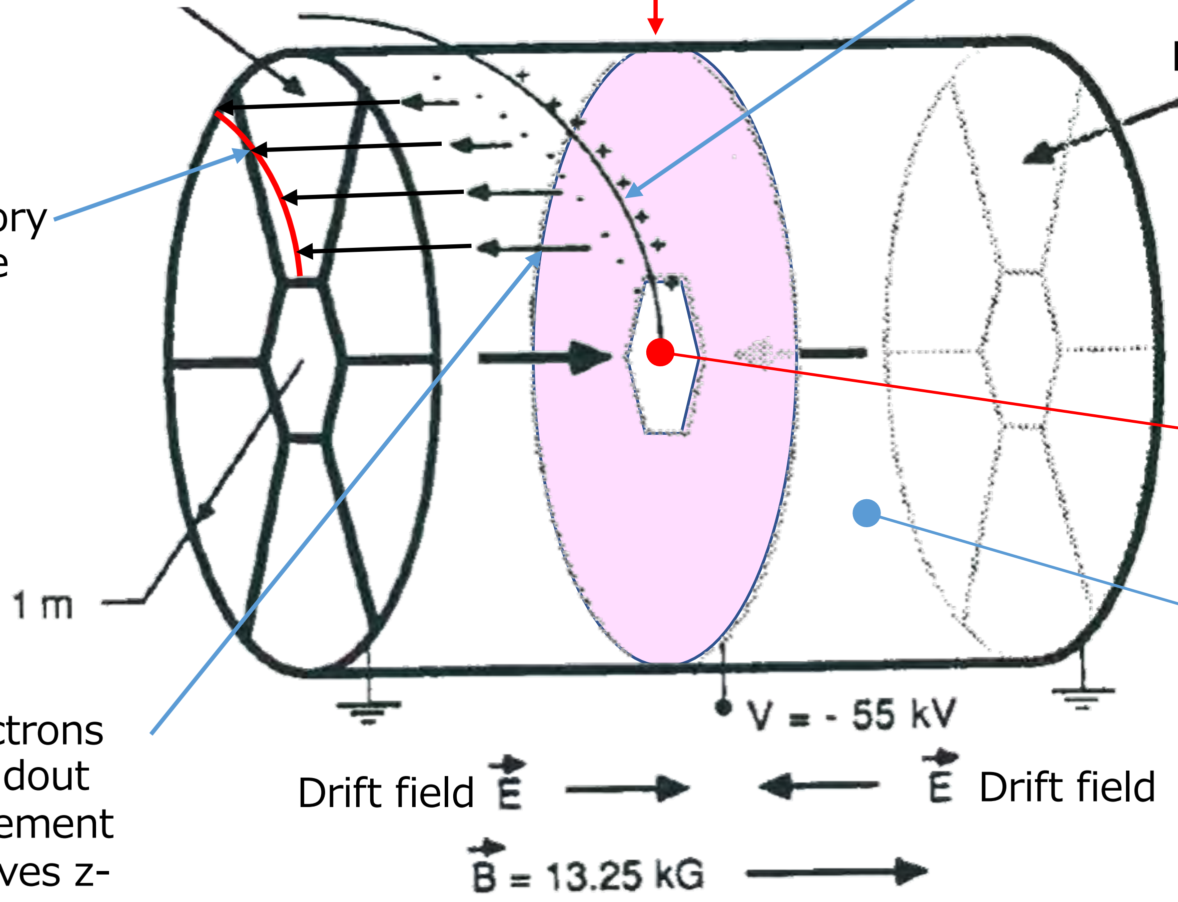
- good r-φ position resolution ~100μ, good z-resolution ~1.2mm
- multi-track measurement with multi-hit TDC. 2-track separation ~ 2mm
- dE/dx measurement ~4%
- sensitive to B-field (<2Tesla)
- large size possible

4. Operation of detectors ; Trackers ; Gas Chambers

Time Projection Chamber

A kind of drift chambers.

Essentially three-dimensional track measurement



Center HV plane

Readout Plane at both ends

1) Particle Track

Readout Plane at both ends
was wire chambers before,
but now wire-less chambers
(GEM, Micromegas etc.)
are popular.

3) Particle trajectory projected onto the readout plane by drift of electrons.

Interaction point

Tracking volume has no wires (homogeneous tracking volume) "Massless" except for the center HV plane.

2) Ionized electrons drift to the readout plane. Measurement of drift time gives z-location

PEP4 TPC

Base figure from Joram

4. Operation of detectors ; Trackers ; Gas Chambers

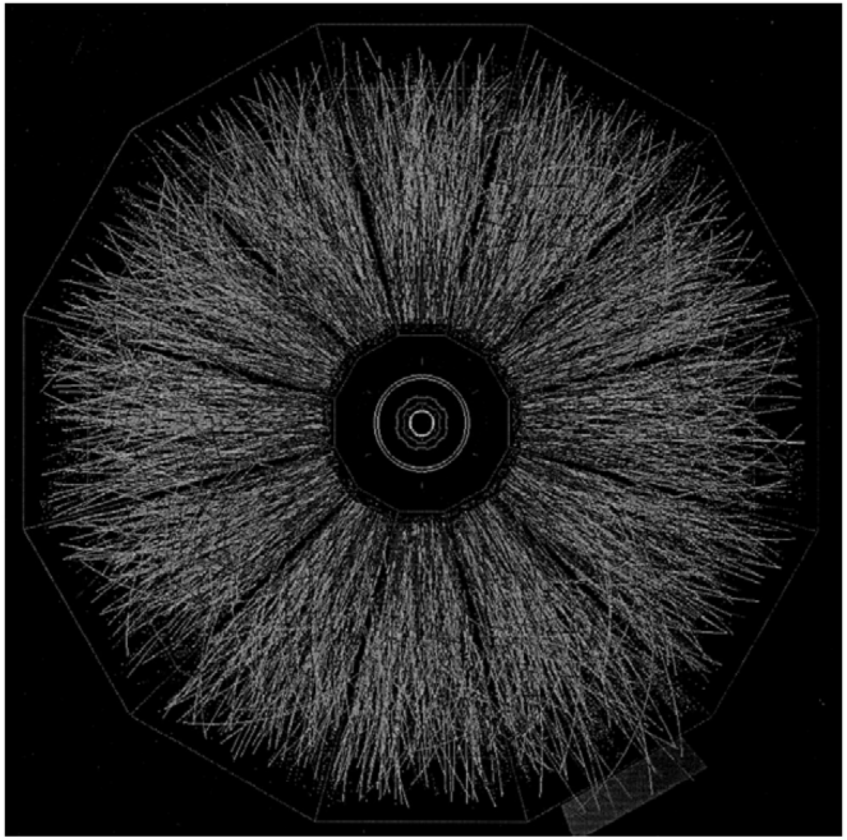
Time Projection Chamber

Characteristic features;

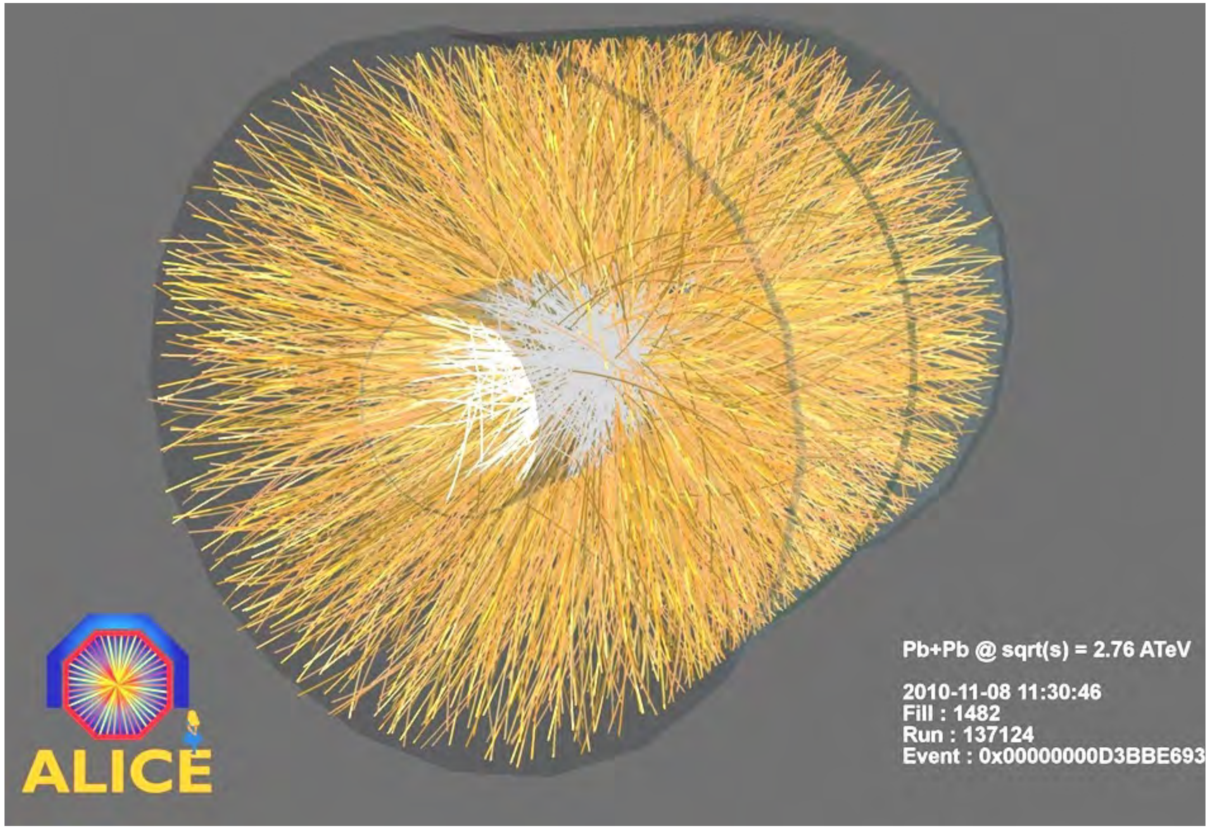
- Essentially three-dimensional track measurement
- Can measure extremely high multiplicity event.

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

RHIC STAR Au+Au reconstructed tracks.



LHC ALICE Pb+Pb reconstructed tracks.



4. Operation of detectors ; Trackers ; Gas Chambers

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 → Particle ID
- No wires in tracking volume gives homogeneous tracking volume → no track 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.

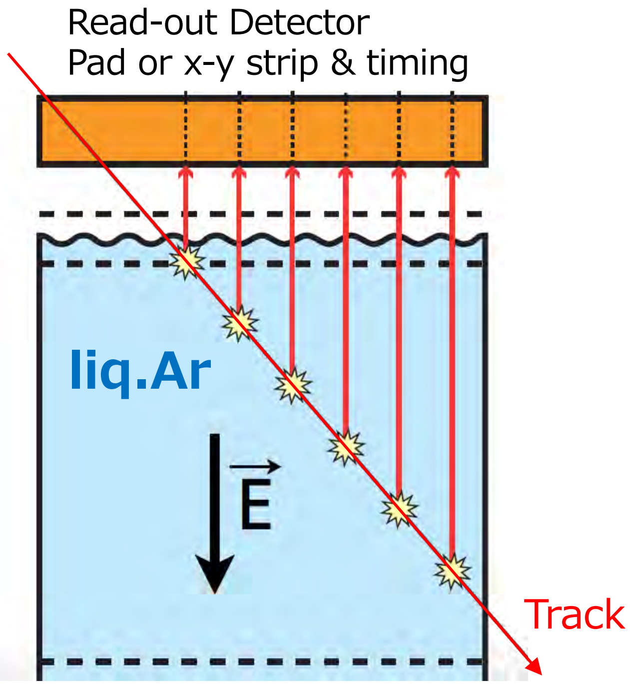
Expected performance

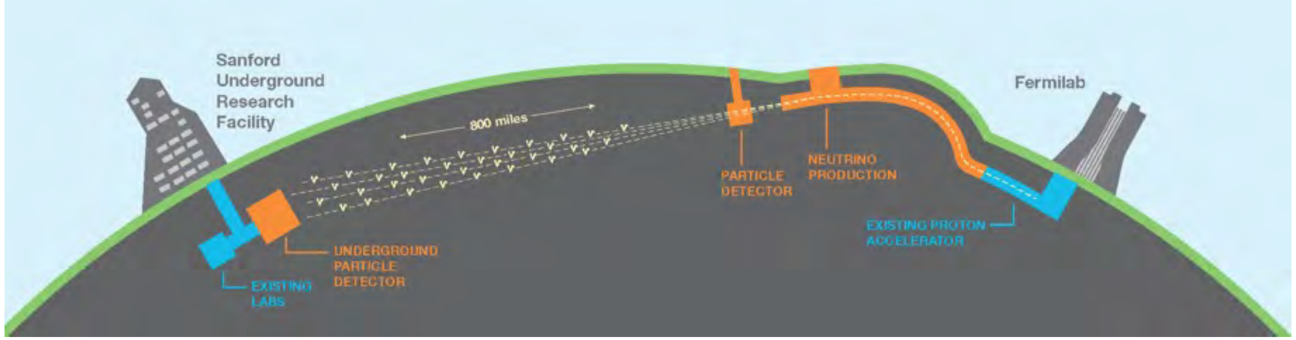
- r-φ position resolution 200~300μ, z-resolution ~1mm
- 2-track separation ~ 10mm
- dE/dx measurement ~5%
- large size possible

4. Operation of detectors ; Trackers ; Noble Liquid

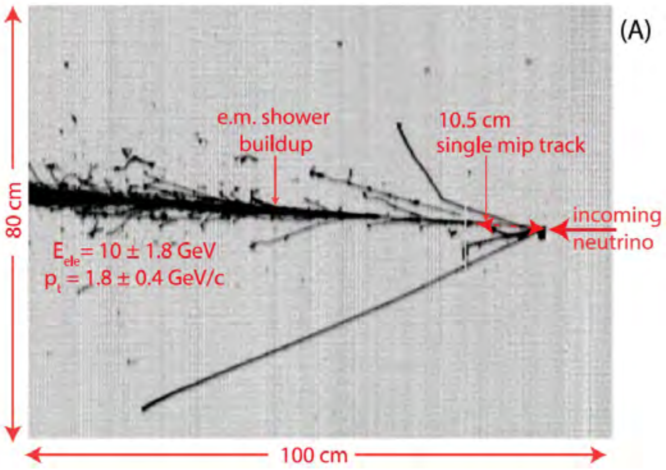
Liquid-Argon Time Projection Chamber

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





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

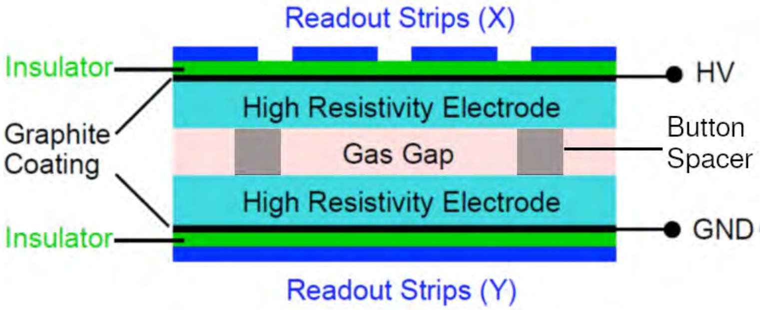


Real event of ICARUS detector.
Taken from Eur.Phys.J.C(2013)73

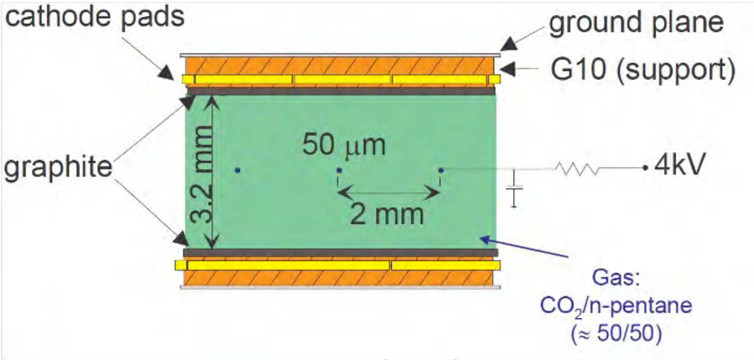
4. Operation of detectors ; Trackers ; Gas Chambers

Varieties of gas chamber

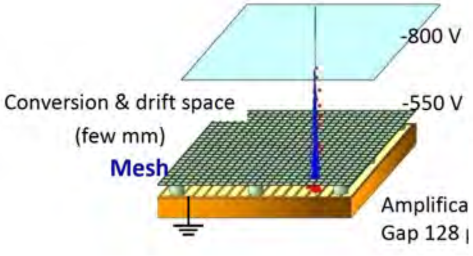
- RPC (resistive plate chamber)
  - Pad readout of streamer discharge between two parallel plates
  - Excellent time resolution (30-50ps), inexpensive,
  - Long recovery time ~ sec.

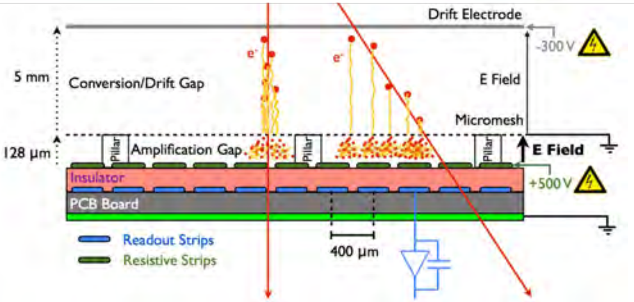


- Thin-gap chamber
  - Pad readout of MWC in avalanche mode
  - High-rate capability

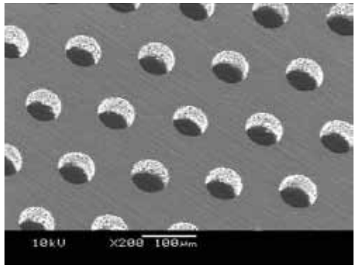


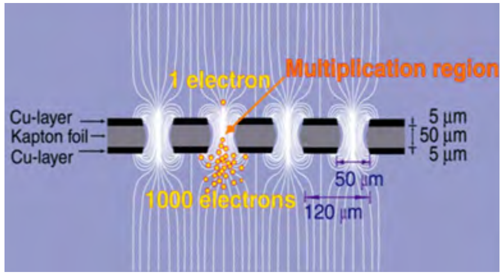
- MPGD (micro-pattern gas detector)
  - MicroMegas
    Apply HV to a fine mesh and realize avalanche.





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

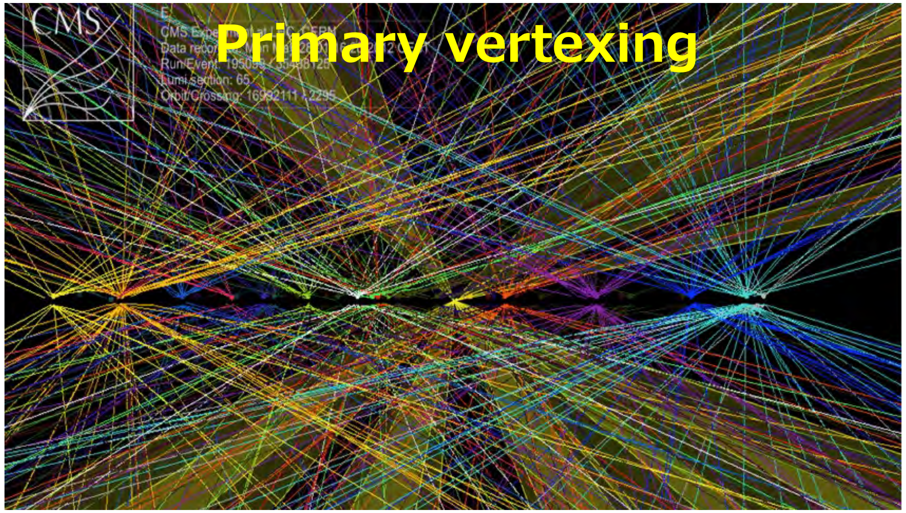




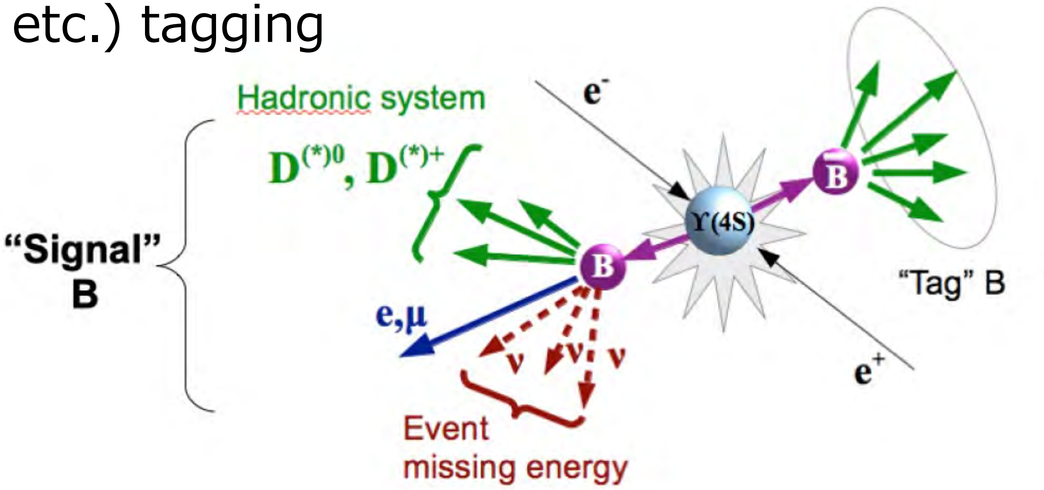
4. Operation of detectors ; Trackers ; Silicon Trackers

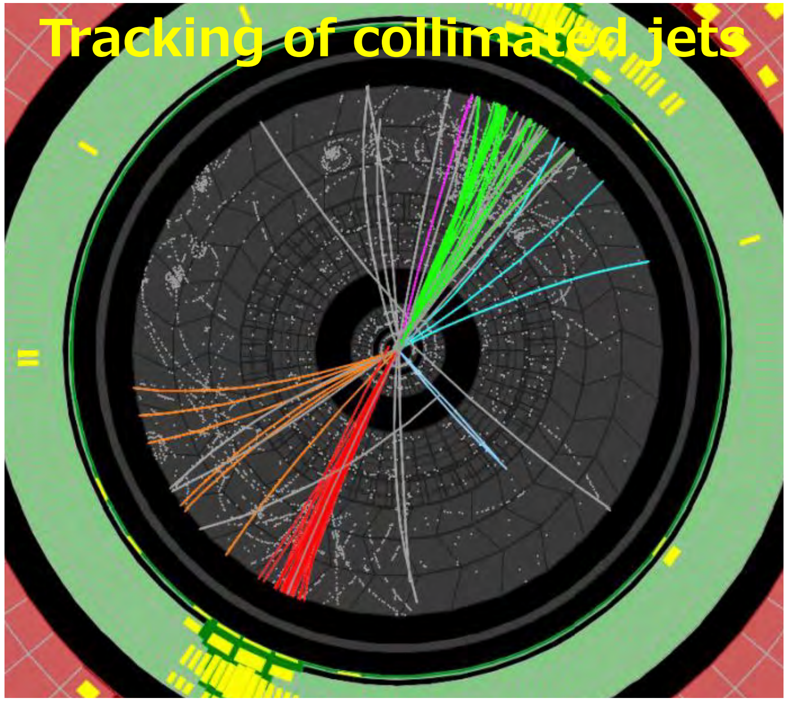
Silicon Trackers for Vertexing

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



Secondary vertexing





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

4. Operation of detectors ; Trackers ; Silicon Trackers

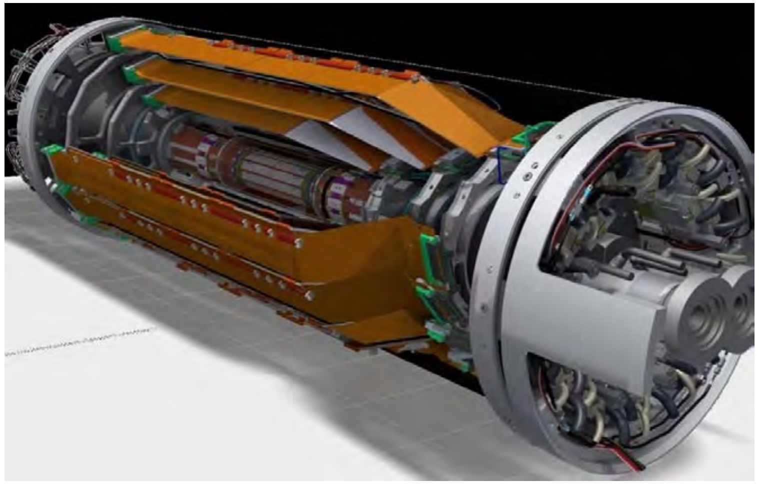
Silicon Trackers for Vertexing

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

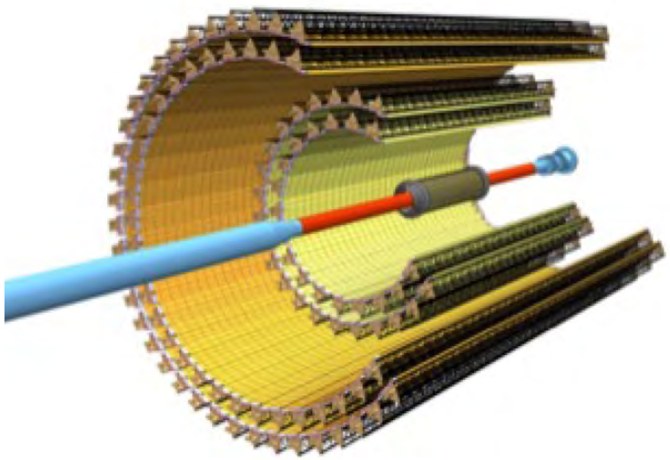
Popular configuration for various detector is;

- Inner layer ; pixel
- Outer layer ; micro-strip

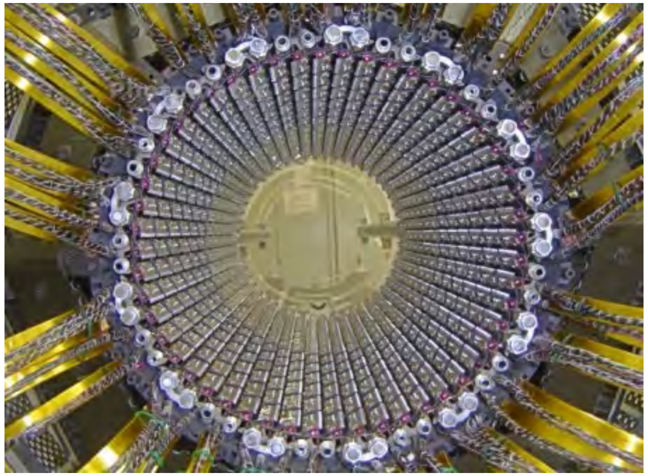
Belle-II



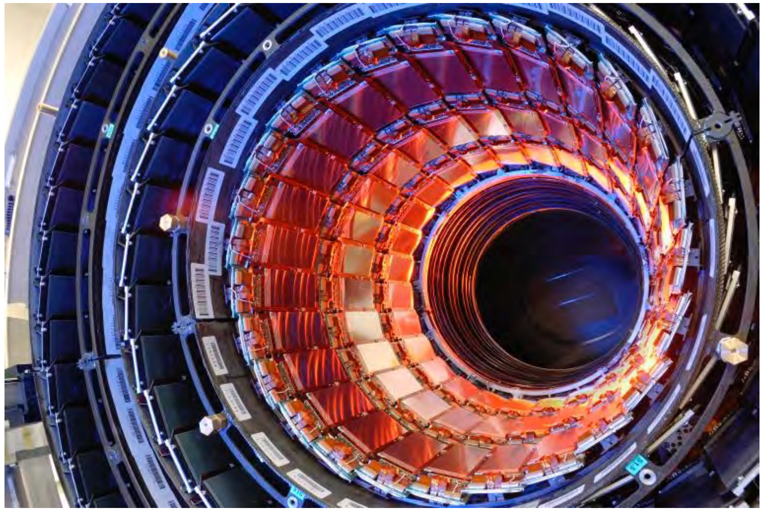
ALICE



ATLAS



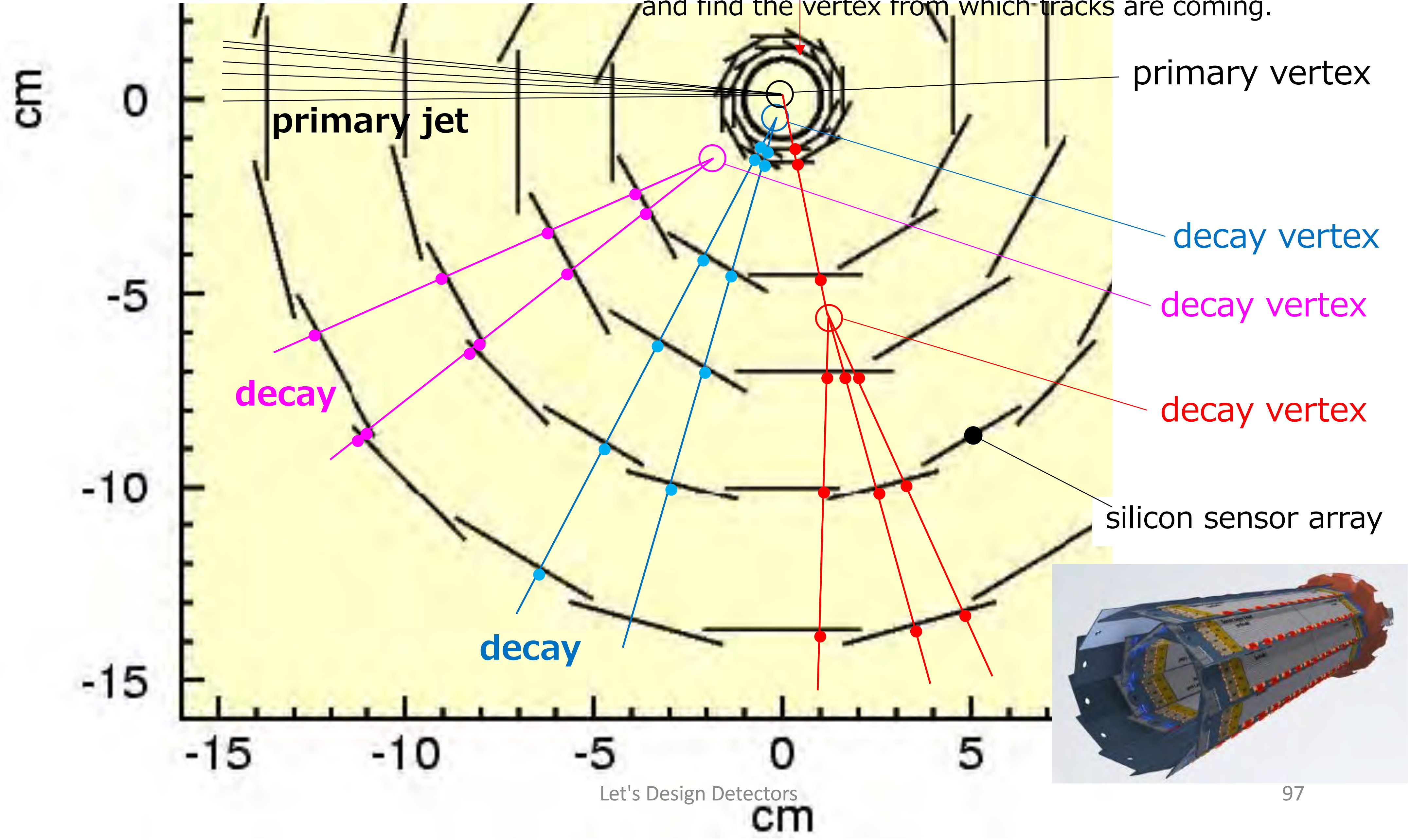
CMS



4. Operation of detectors ; Trackers ; Silicon Trackers

Silicon Trackers for Vertexing

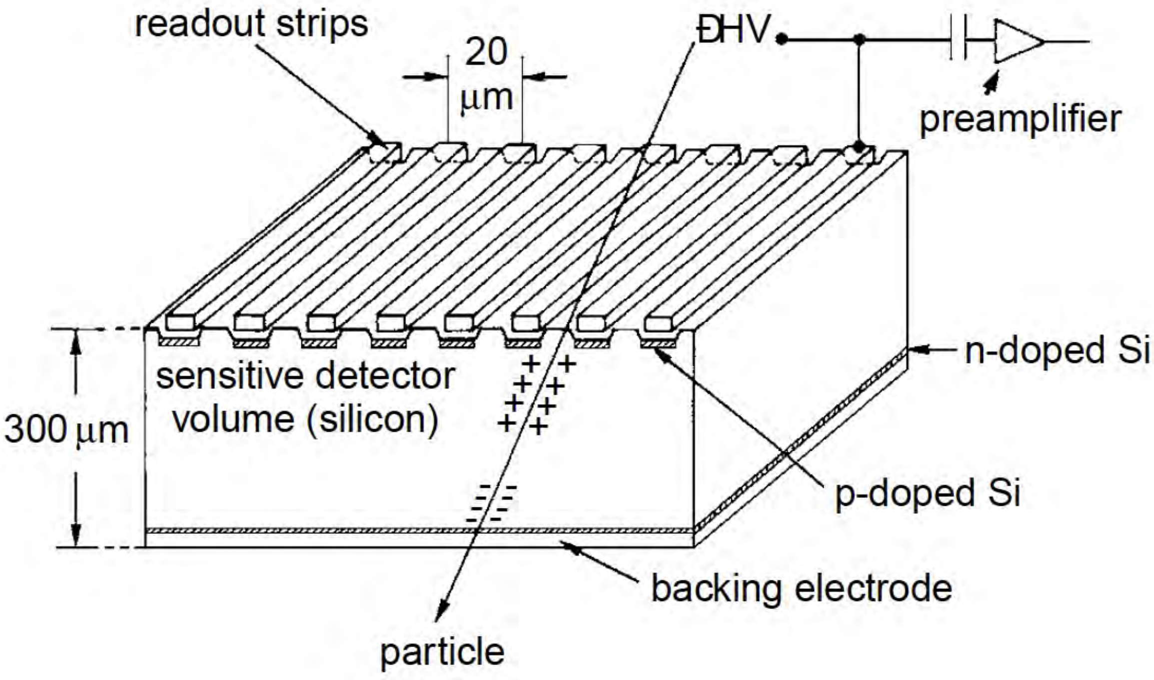
Belle-II innermost vertex locates 14mm from the beamline.
Connect hit points, extrapolate to the interaction point,
and find the vertex from which tracks are coming.



5. Operation of detectors ; Trackers ; Silicon Trackers

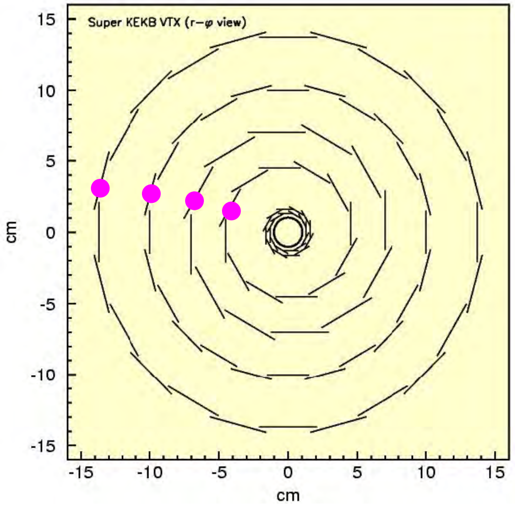
Silicon Trackers for Vertexing

- **Strip Detector**
- Pixel Detector
- Si Drift Chamber



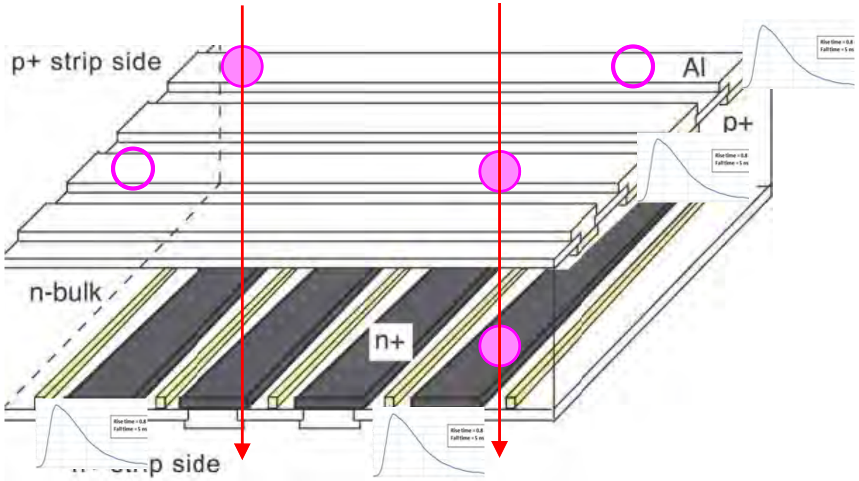
Schematic structure of silicon-strip detector.
Position perpendicular to strips can be measured.
Natural layout of read-out electronics at the end of the strips.

figure from Grupen



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

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



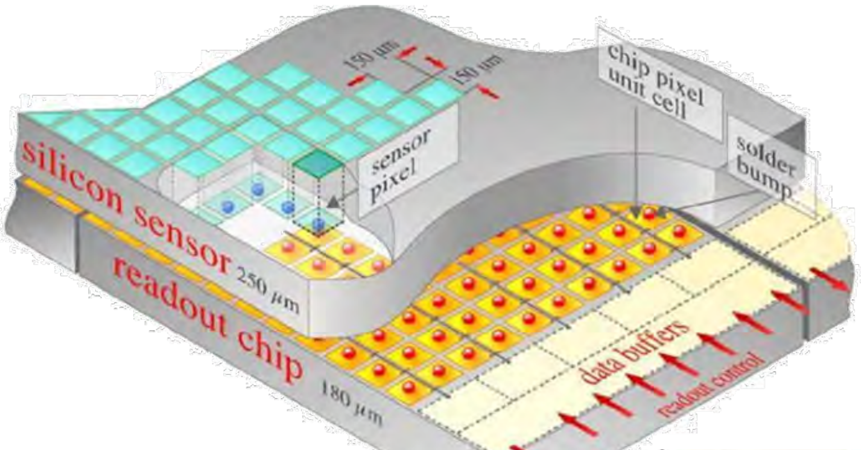
Schematic structure of double-sided silicon-strip detector. 2D-position, φ and z, can be measured.
r is given by plate location.
Ghost-hits appear if occupancy is high.

4. Operation of detectors ; Trackers ; Silicon Trackers

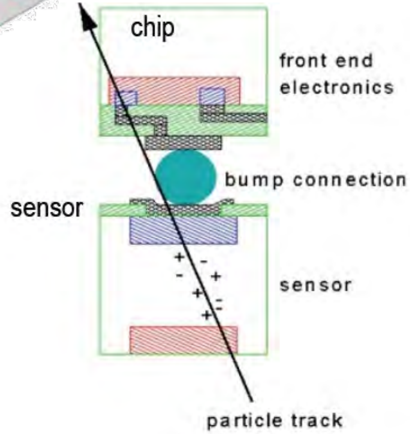
Silicon Trackers for Vertexing

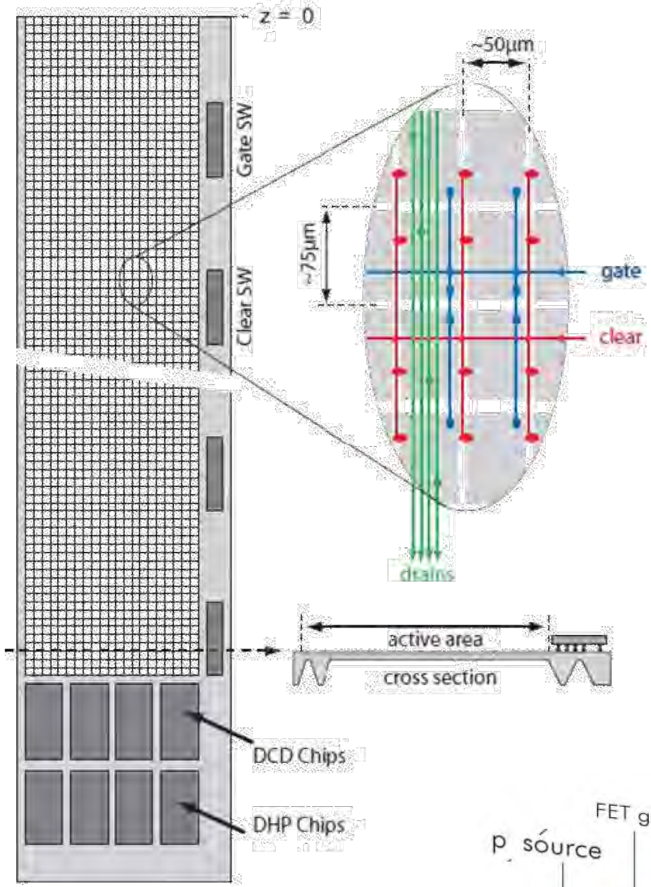
- Strip Detector
- **Pixel Detector**
- Si Drift Chamber

True 2-D position measurement free from ghost.
Read-out electronics layout is complicated.

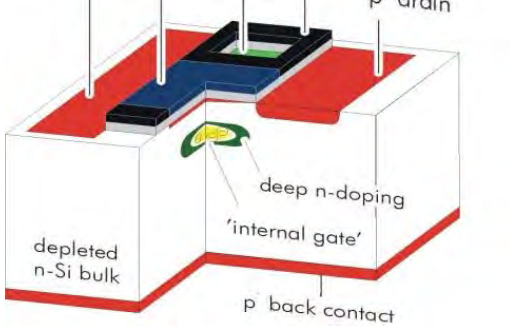


Pixel sensor layer and read-out electronics layer bonded face-to-face.





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

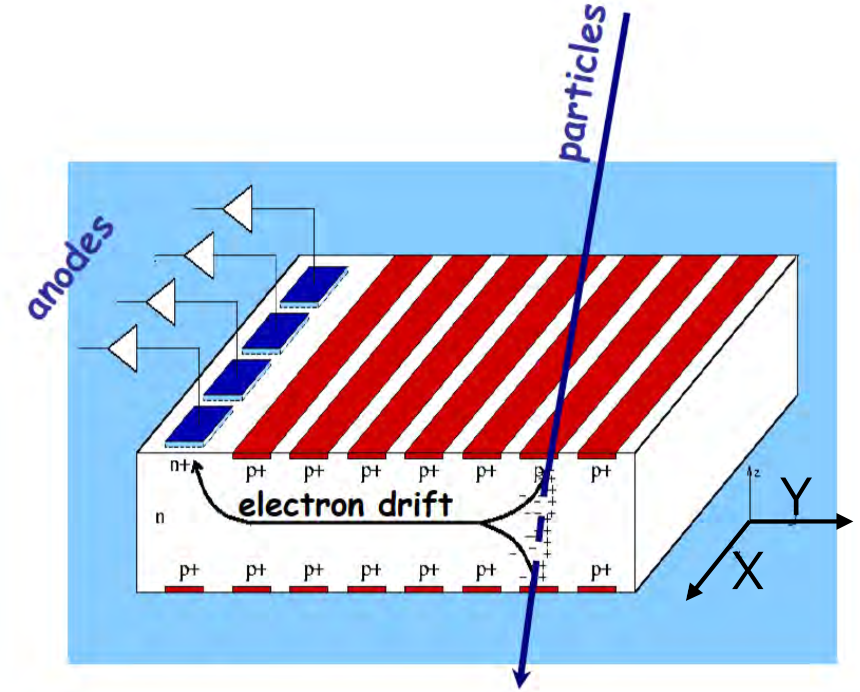


4. Operation of detectors ; Trackers ; Silicon Trackers

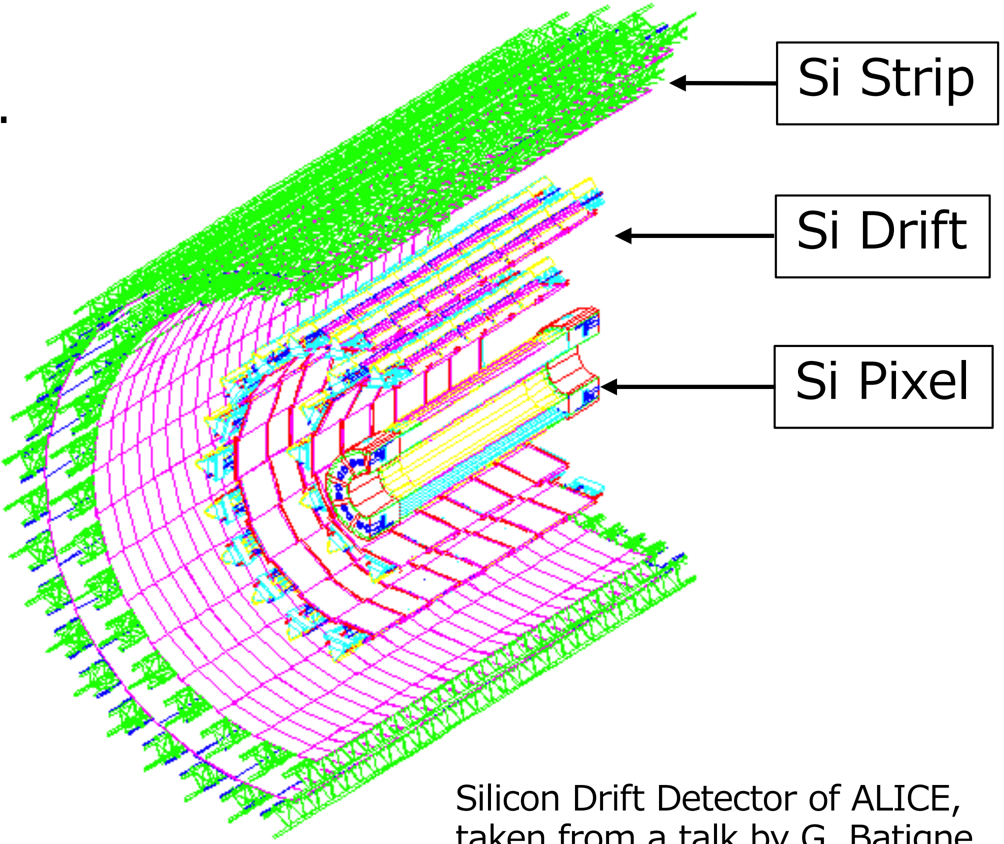
Silicon Trackers for Vertexing

- Strip Detector
- Pixel Detector
- **Si "Drift Chamber"**

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.



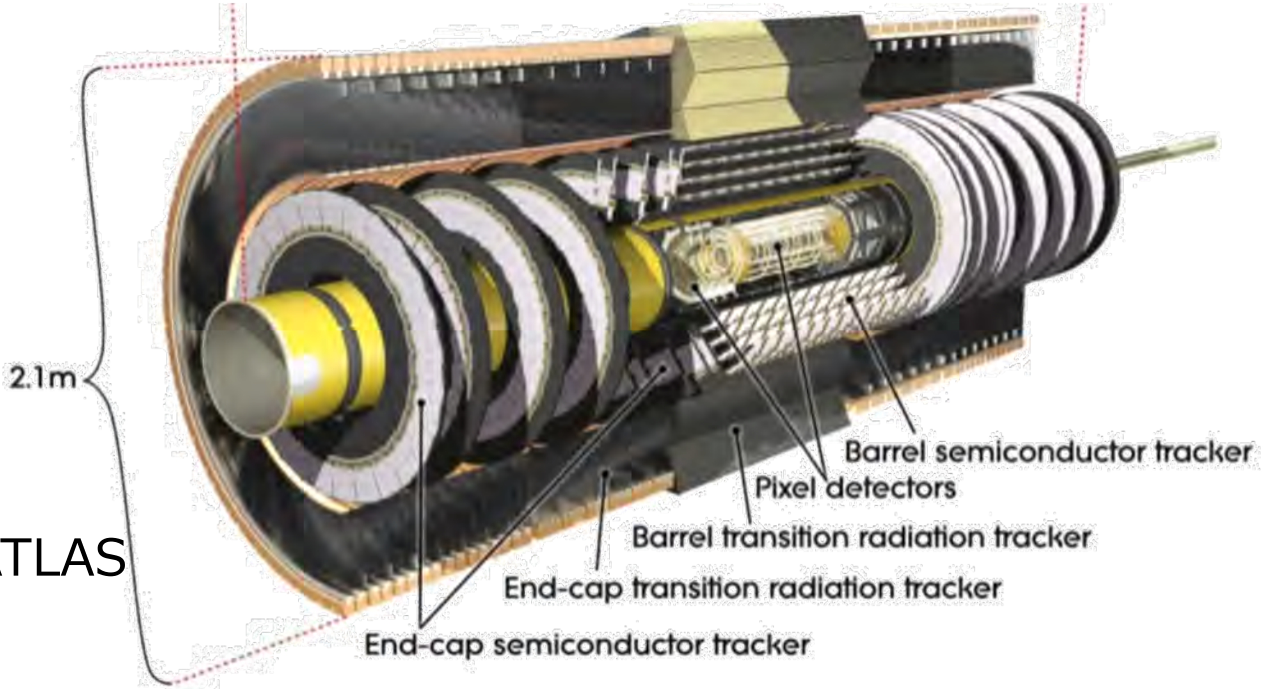
Principle of silicon DC of ALICE,
taken from a talk by G. Batigne



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

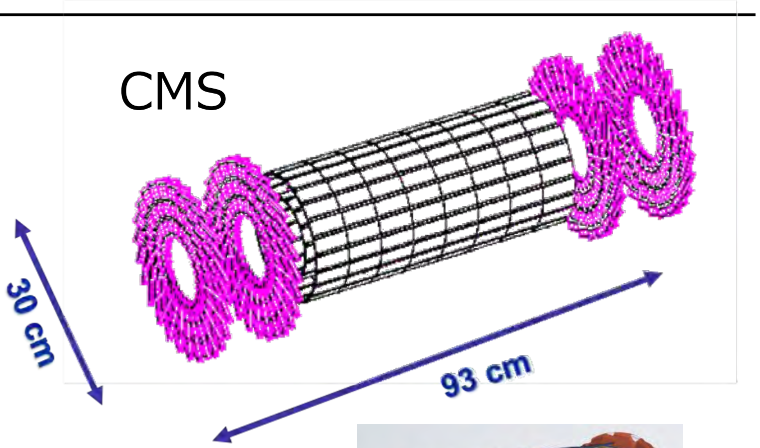
4. Operation of detectors ; Trackers ; Silicon Trackers

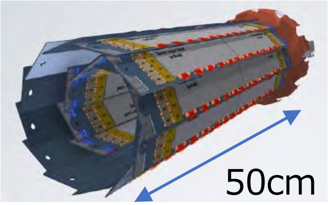
Comparison of Vertex Detectors



ATLAS

CMS





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. Operation of detectors

Calorimeters

measure energy of both charged and neutral particles.

4. Operation of detectors ; Calorimeters

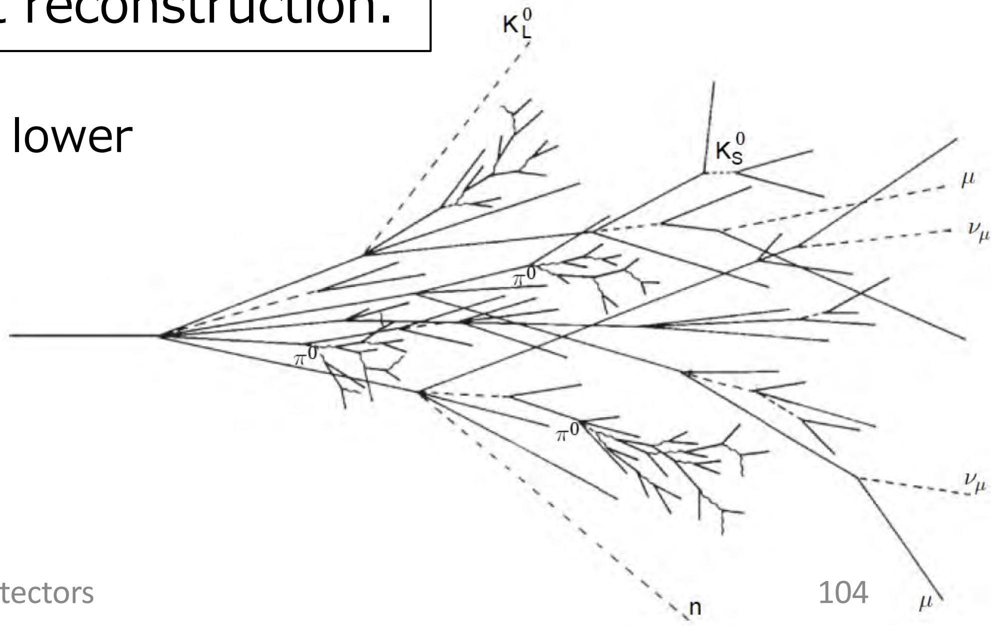
Neutral particle detection

- Calorimeters measure total energy of all particles except muons and neutrinos.
  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 ; $\sigma_E/E \sim 10\%/\sqrt{E} \rightarrow 1.5\%@50\mathrm{GeV}$
  - tracker momentum resolution ; $\sigma_{PT}/P_T \sim 0.05\% \cdot P_T \rightarrow 2.5\%@50\mathrm{GeV}$
  - 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.

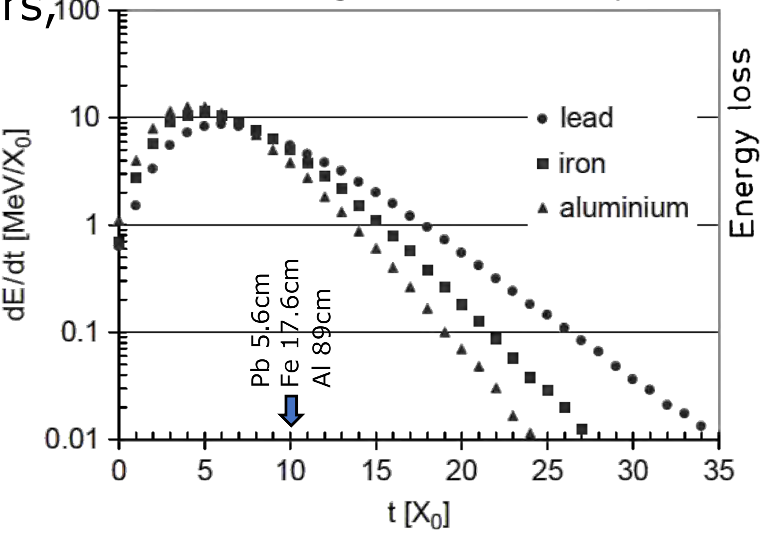
Config. 1) Sampling calorimeter

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.

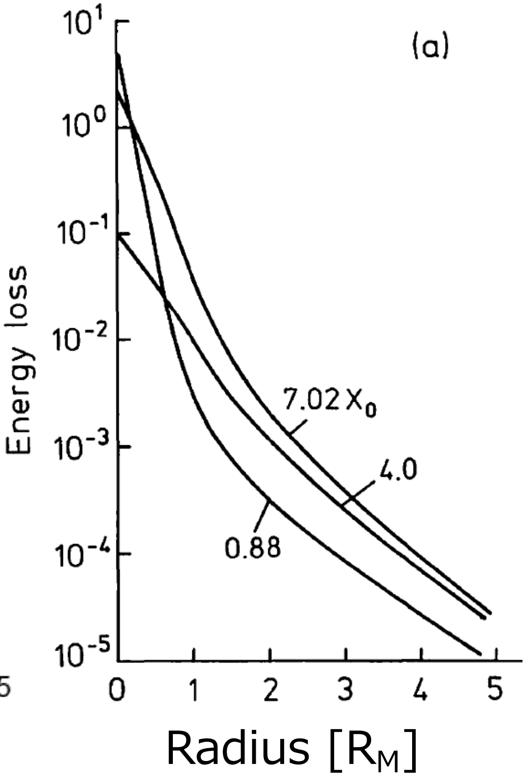
Config. 2) Homogeneous calorimeter

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



4. Operation of detectors ; Calorimeters

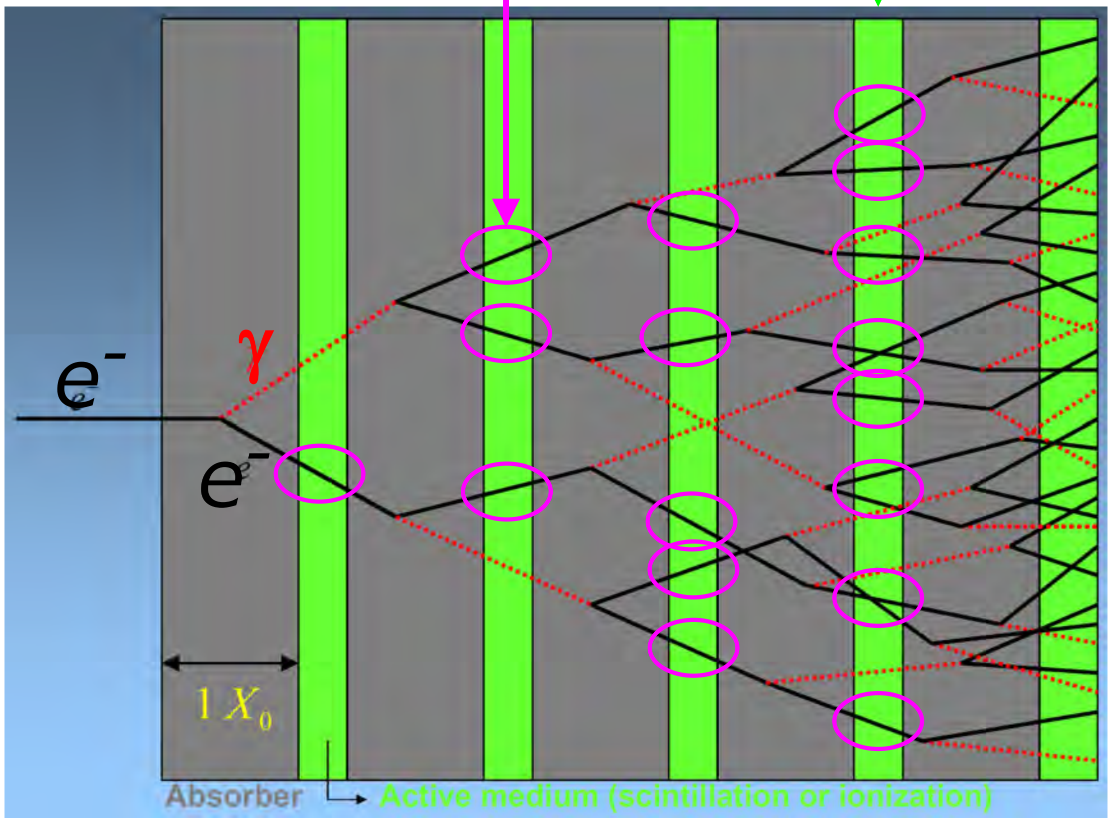
ElectroMagnetic Calorimeter

a) Sampling Calorimeter (right figure)

- Active media
  plastic scintillator, noble liquid, silicon
- Absorber
  Lead, Iron, Tungsten, Copper, , ,
- Geometry
  sandwich, spacal, accordion, shashlik,
- Energy resolution not excellent because
  only a small portion of energy measured.

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.

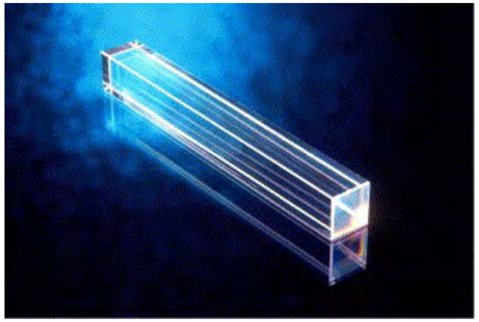
Active plate.
Measure energy
of passing
charged particles.

figure from P.Krieger, "ATLAS calorimetry"

4. Operation of detectors ; Calorimeters

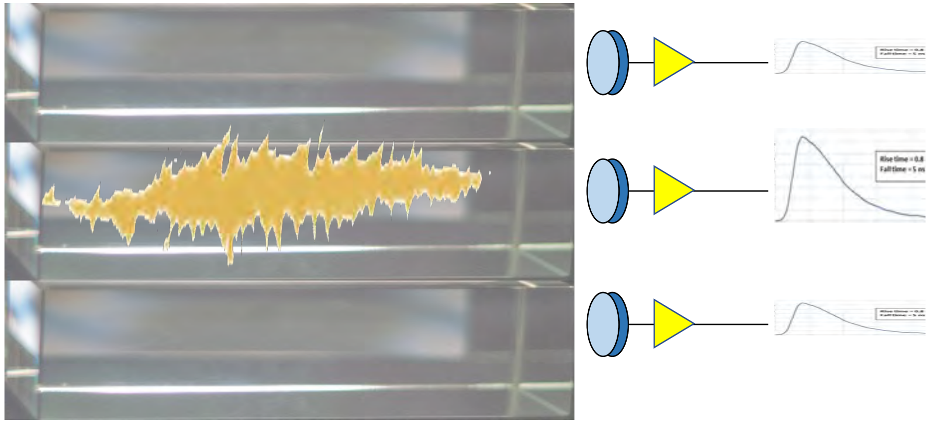
ElectroMagnetic Calorimeter

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



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

b) Homogeneous Calorimeter
- crystals (use photons) or
  noble liquid (ionization or photon)
- Excellent energy resolution since
  all the deposit energy can be measured.



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

Structural parameters determined by required performance and shower sizes ;
- total thickness
- granularity/segmentation
- sampling frequency
- absorber thickness etc.

4. Operation of detectors ; Calorimeters

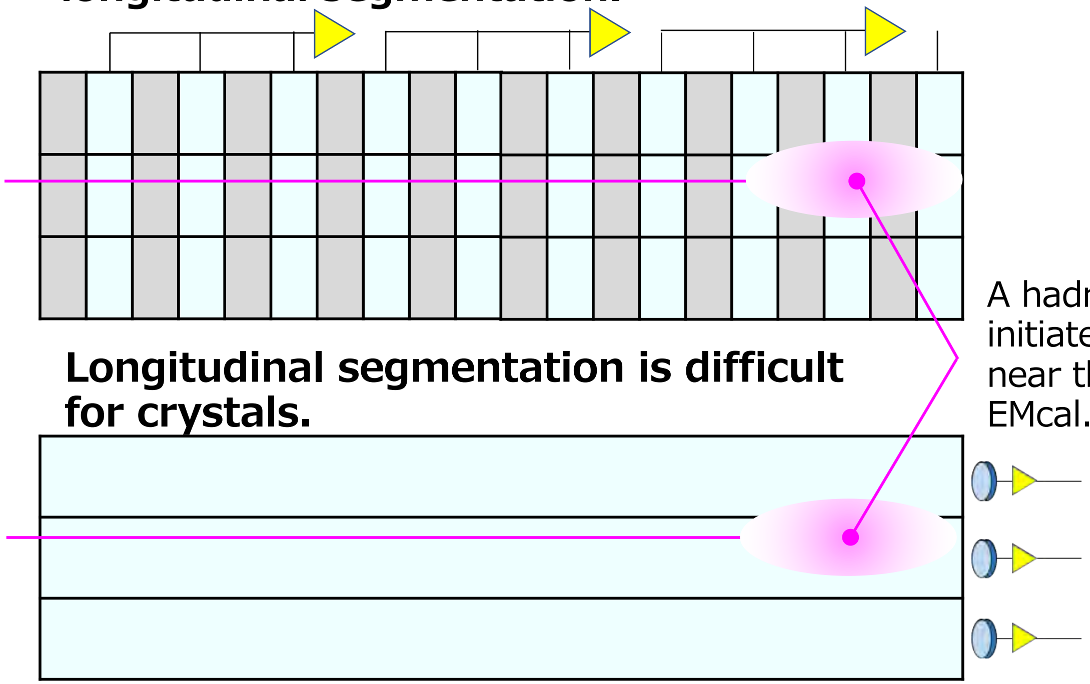
Segmentation/Granurality

For better two-cluster separation,
plural clusters should not merge.

- Make fine transverse segmentation
- Use dense material to make shower size compact.
- Better to have longitudinal segmentation for EM/hadron identification.

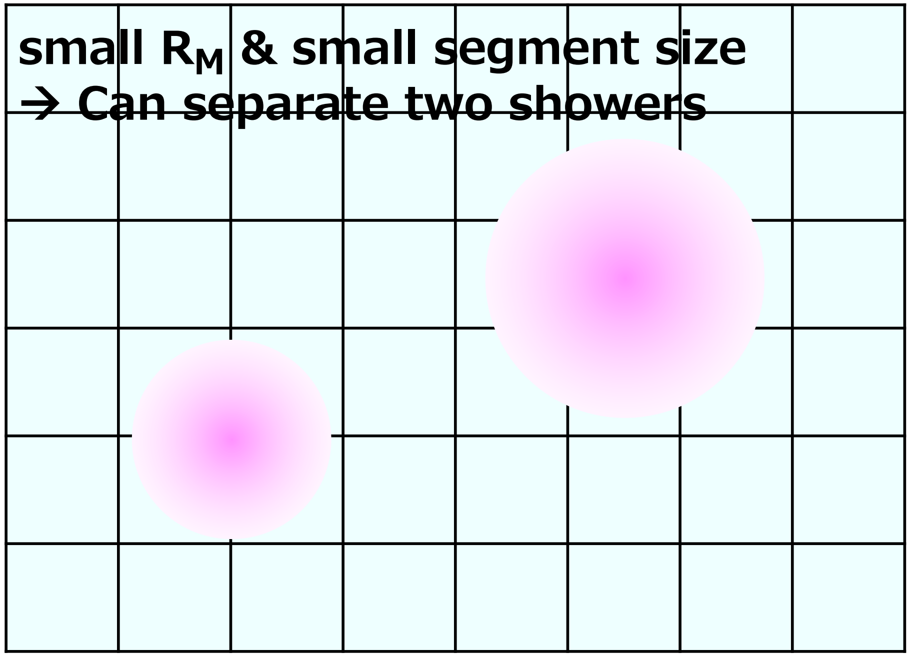
→ Dense material and fine segmentation

Sampling calorimeters can naturally have longitudinal segmentation.

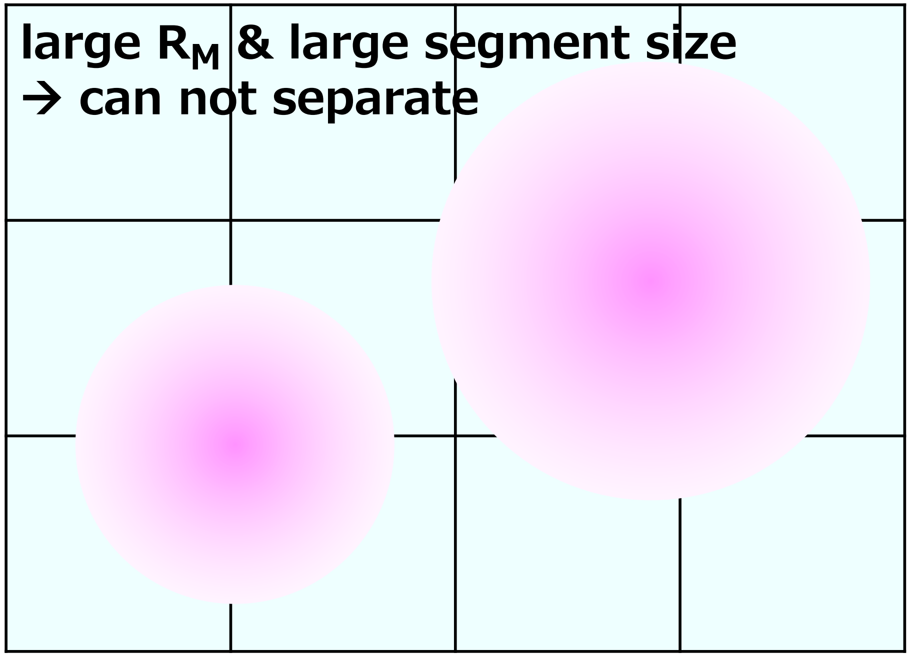


Longitudinal segmentation is difficult for crystals.

A hadron may initiate shower near the end of EMcal.



small R_M & small segment size
→ Can separate two showers



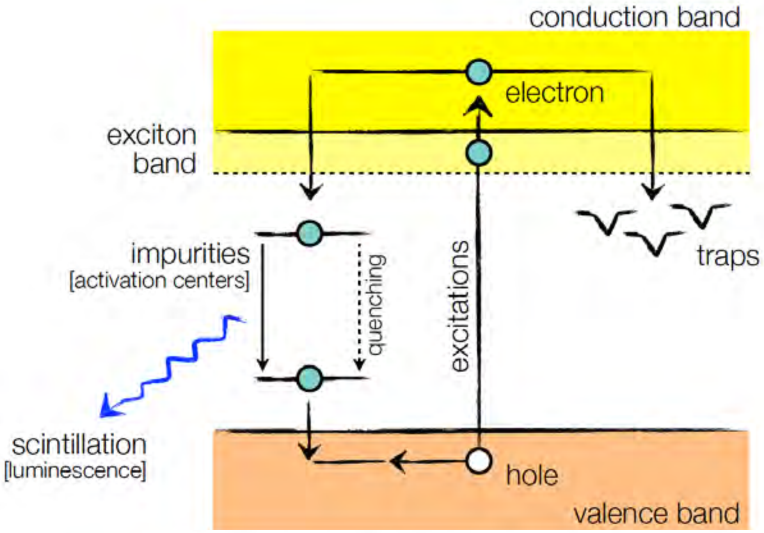
large R_M & large segment size
→ can not separate

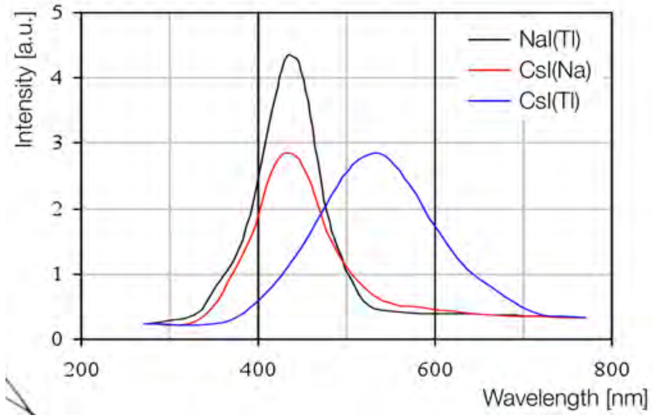
4. Operation of detectors ; Calorimeters

Homogenous Calorimeter

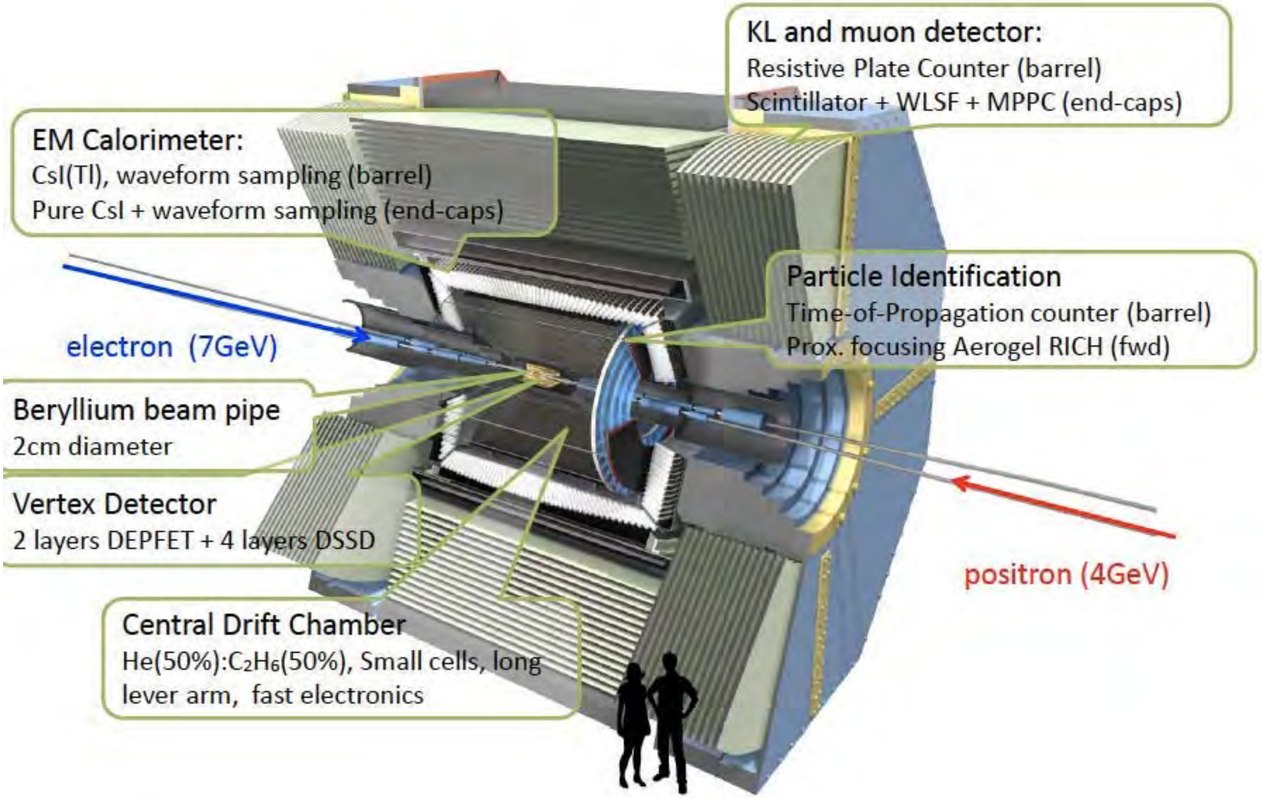
Belle-II ; CsI crystal

Energy is low. Large signal is important.





from Erika



KL and muon detector:
Resistive Plate Counter (barrel)
Scintillator + WLSF + MPPC (end-caps)

EM Calorimeter:
CsI(Tl), waveform sampling (barrel)
Pure CsI + waveform sampling (end-caps)

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

electron (7GeV)

Beryllium beam pipe
2cm diameter

Vertex Detector
2 layers DEPFET + 4 layers DSSD

positron (4GeV)

Central Drift Chamber
He(50%):C_2H_6(50%), Small cells, long lever arm, fast electronics

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

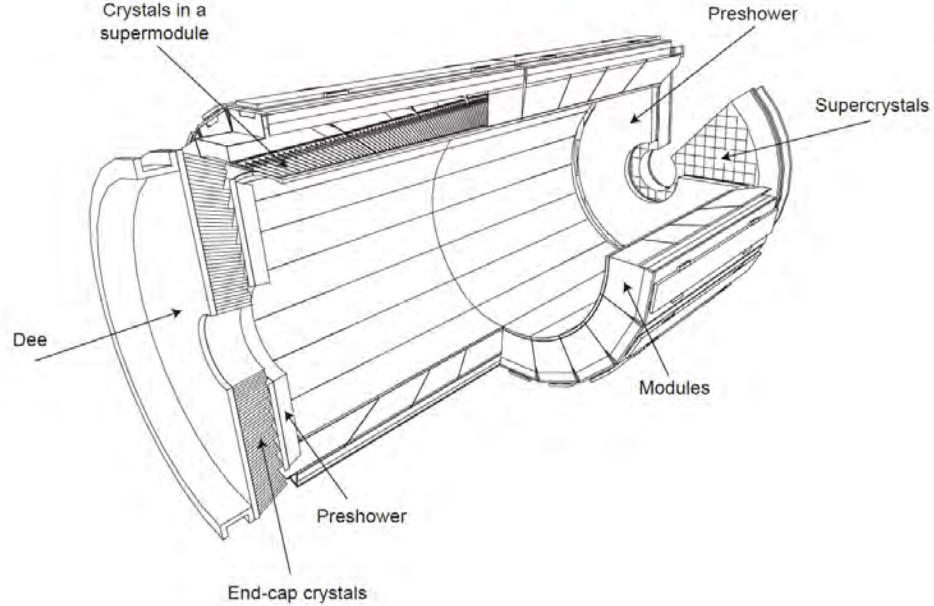
CsI(Tl) x 8,700 crystals, 6cmx6cmx30cm(16Xo)
Basic parameter of CsI (Tl)
density 4.5g/cm3, Xo 1.85cm, R_M 3.8cm,
N_{photon} 110k/MeV (40% of NaI)
λ=565nm
decay time ~1μs

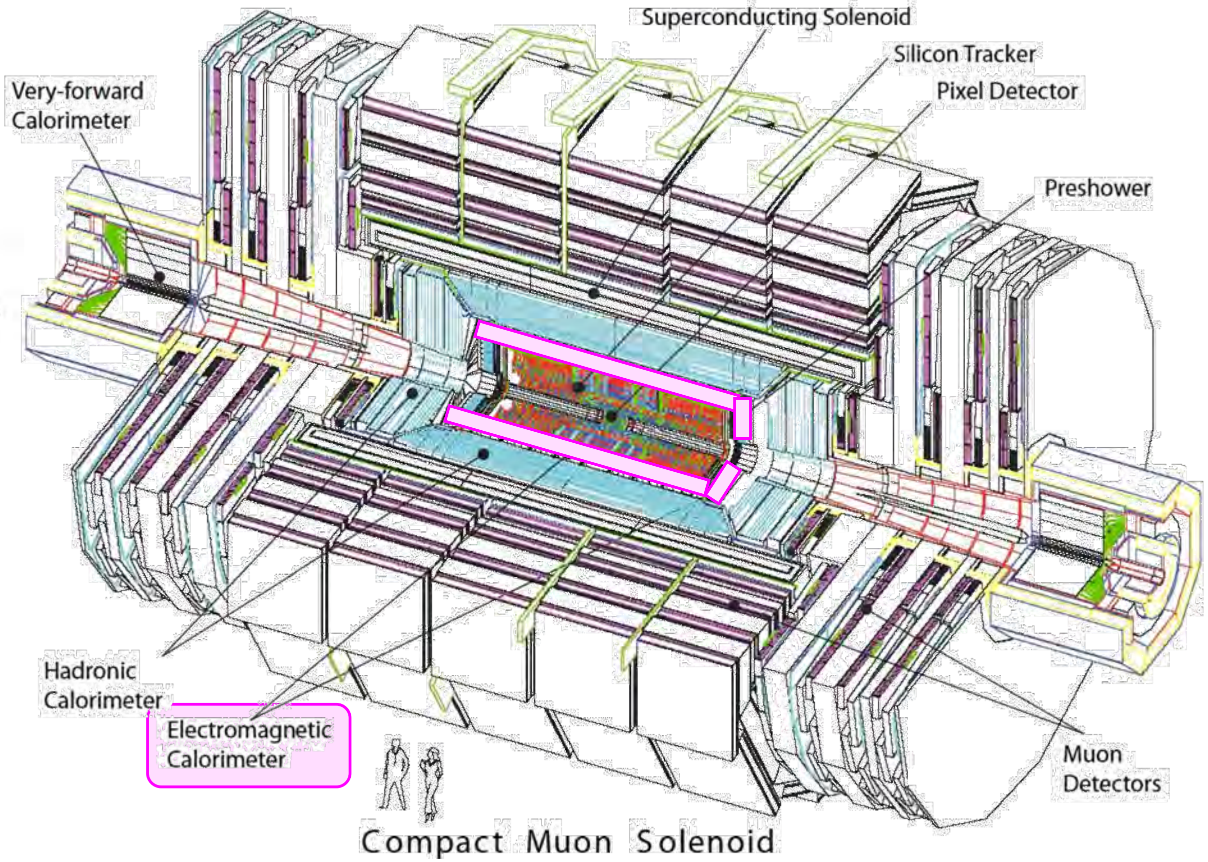
4. Operation of detectors ; Calorimeters

Homogenous Calorimeter

CMS ; PbWO4 crystals

High Energy. Small signal is OK. Be FAST.





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

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

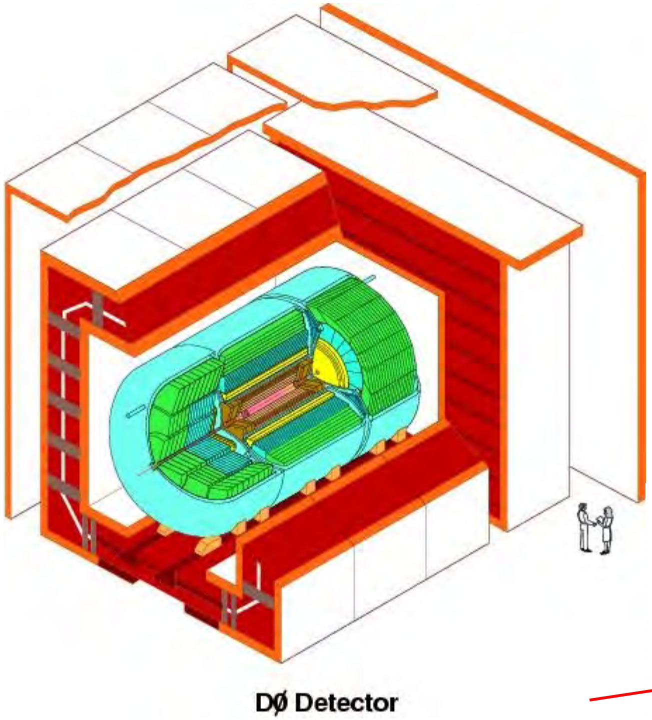
decay time ~10ns

4. Operation of detectors ; Calorimeters

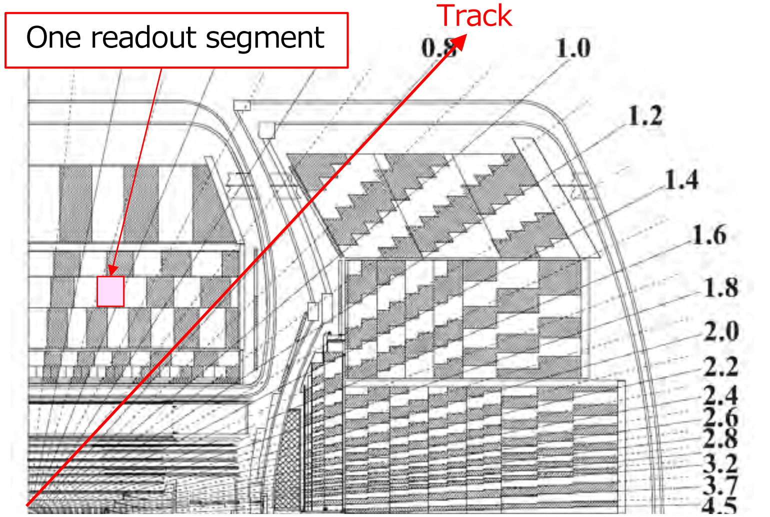
Sampling Calorimeter

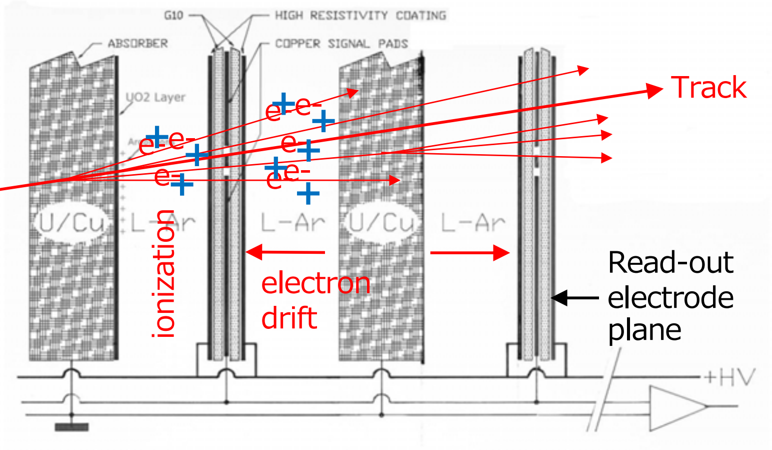
Noble Liquid Calorimeter

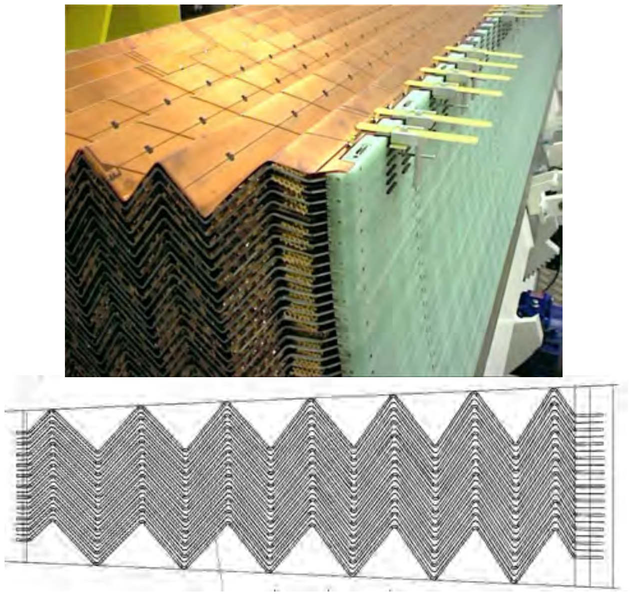
- Use liquid Ar/Xe instead of gas. Better energy resolution than gas chambers.
- Operation and configuration quite similar to the gas chambers but needs cryostat.



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.

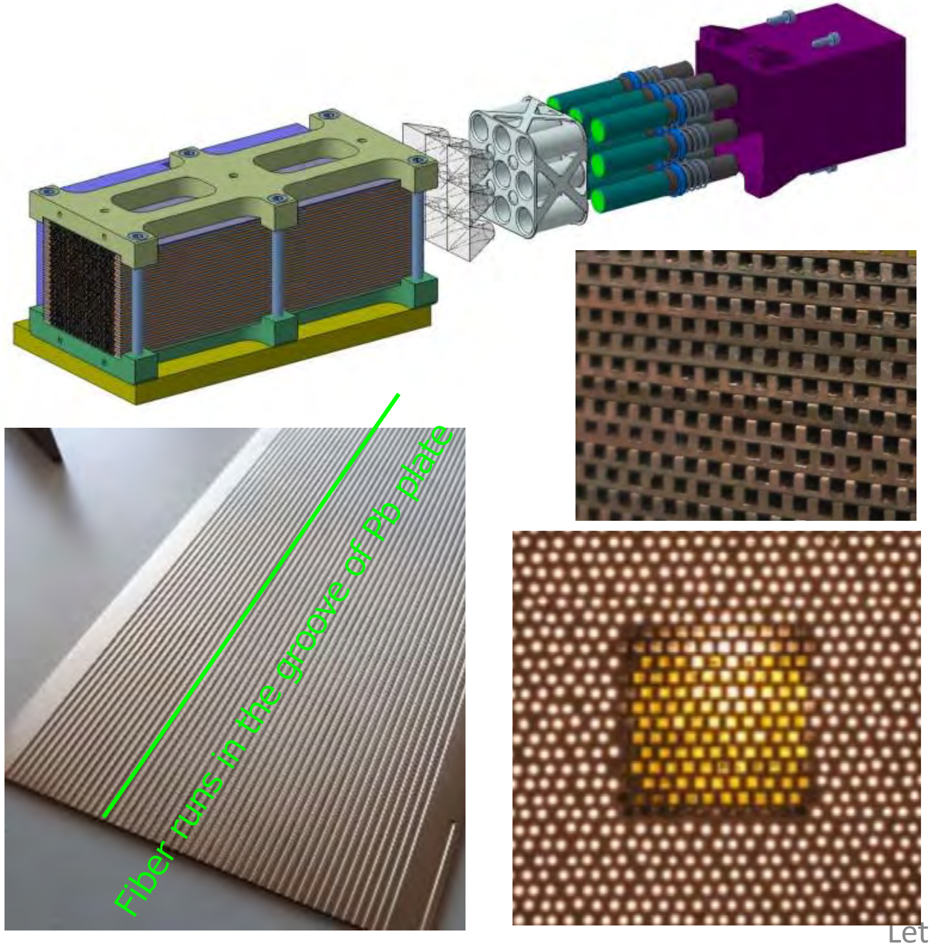
4. Operation of detectors ; Calorimeters

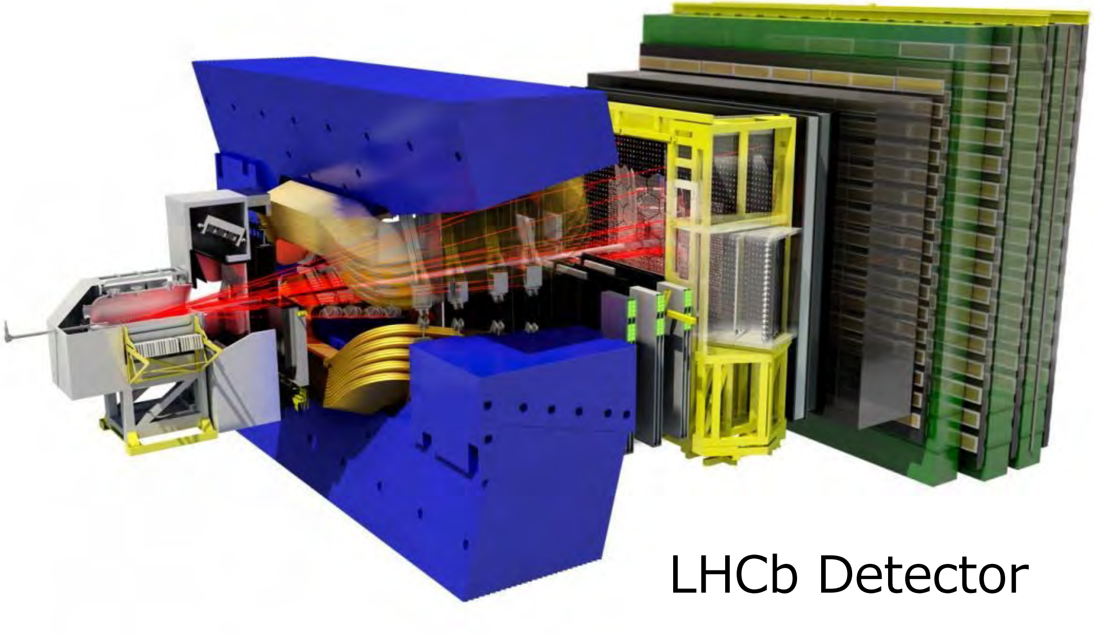
Sampling Calorimeter

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.



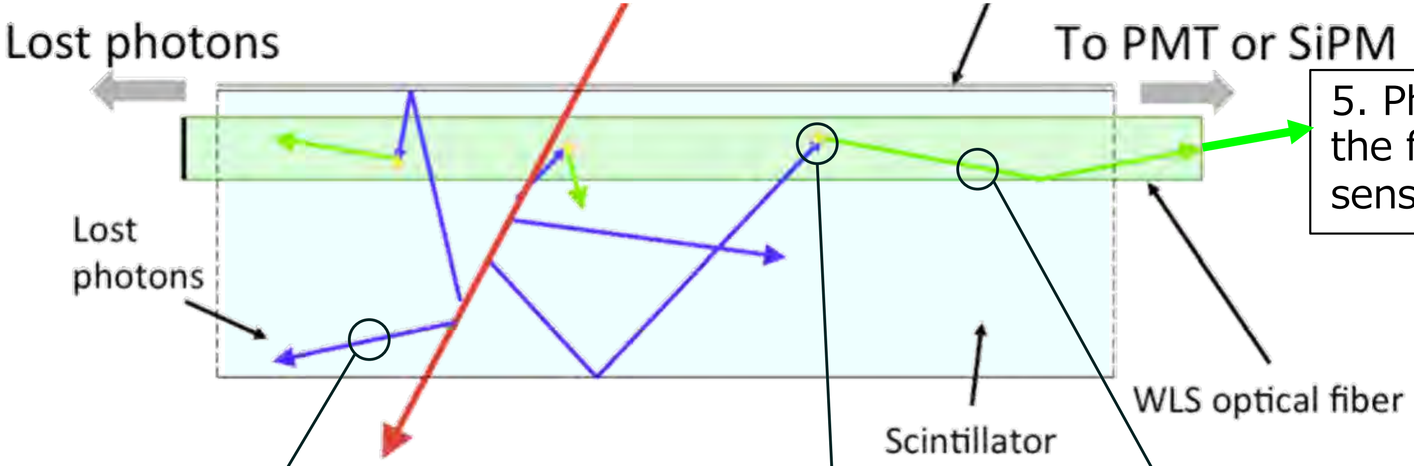


LHCb Detector

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.



1. A charged particle passes through.

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.

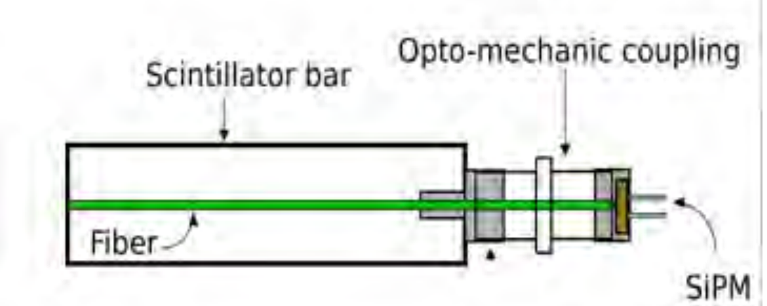
Typical double-clad WLS traps 5% → 20 photons,

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

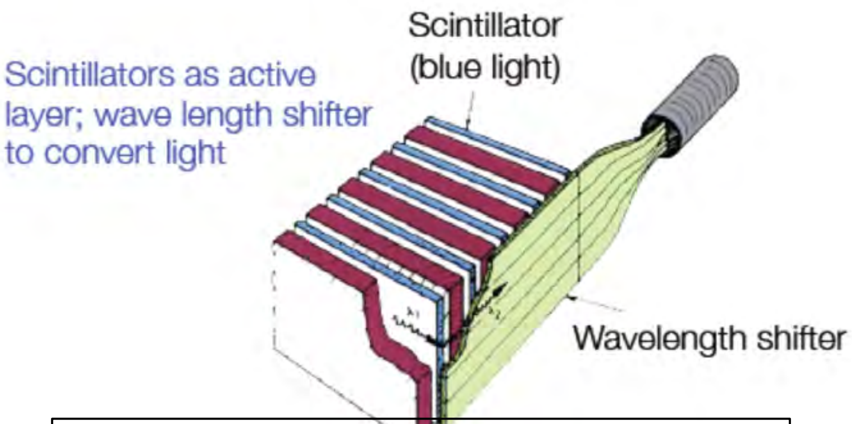
Photo-sensor has Q.E. of 20-40% → 10 electron signal.

WLS fiber/plate readout

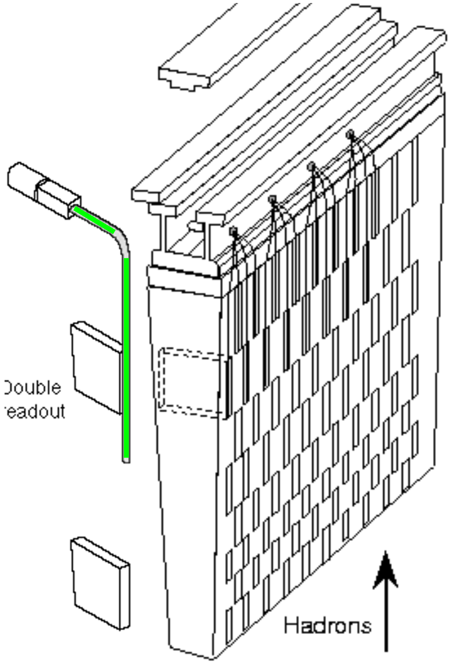
There are many of ways to couple scintillator plates and WLS fibers/plates



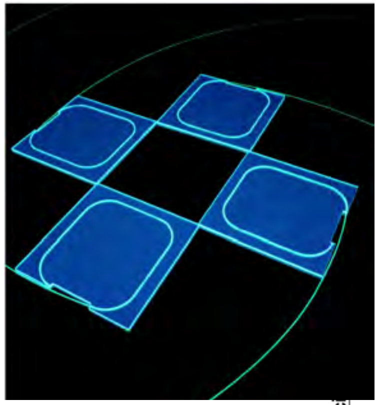
General scheme
A fiber in a scintillator bar.



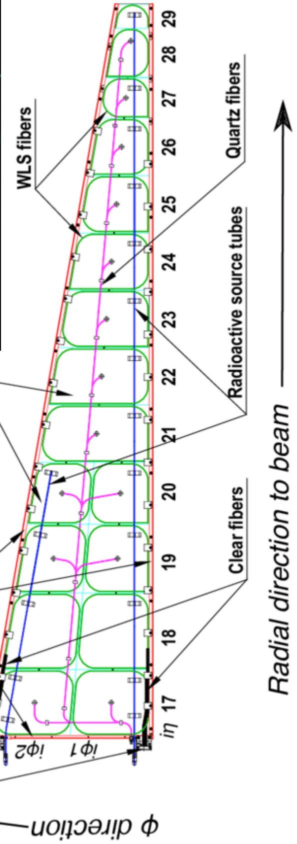
ZEUS CAL
WLS-plates put both sides of tiles.



ATLAS HCAL
WLS-fiber put side of tiles.



CMS tile-fiber.



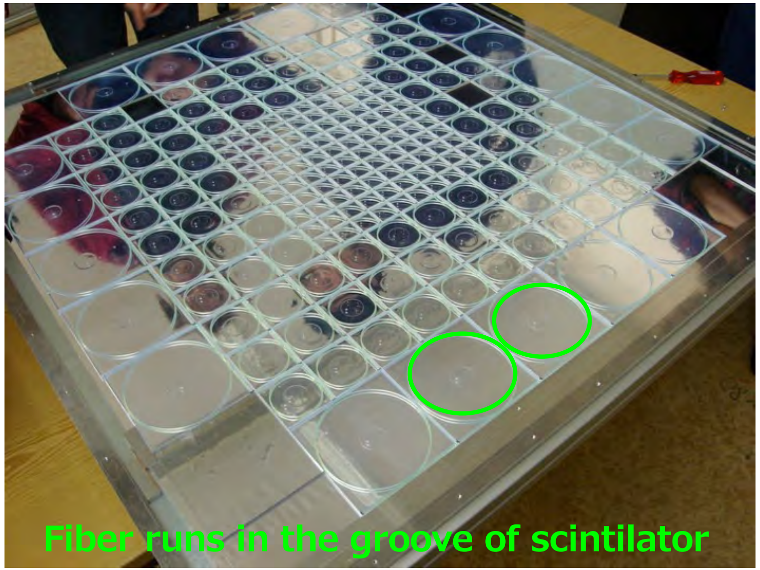
CDF mega-tile
WLS-fiber put in a groove.

4. Operation of detectors ; Calorimeters

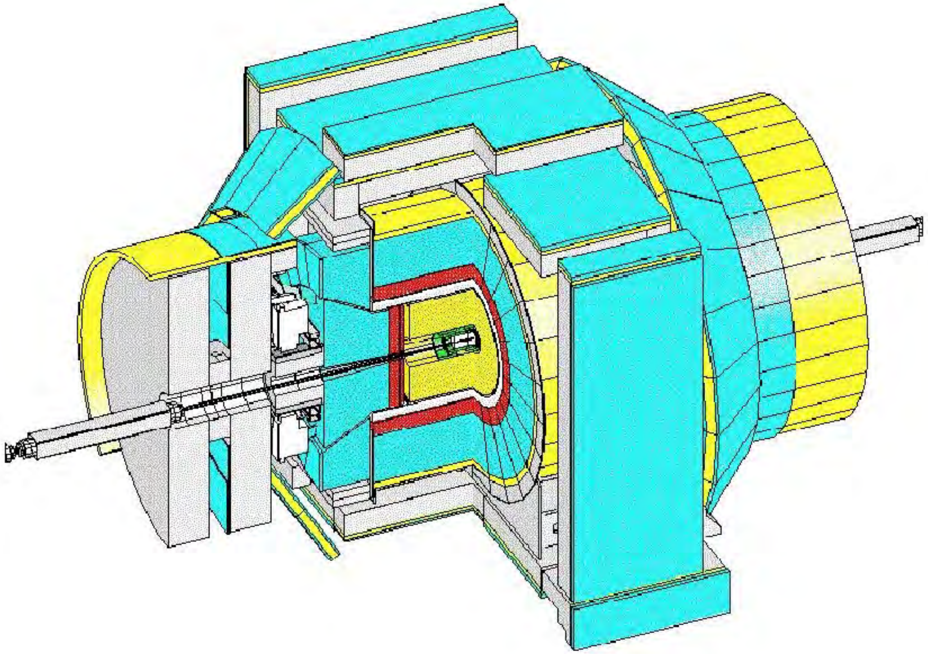
Sampling Calorimeter

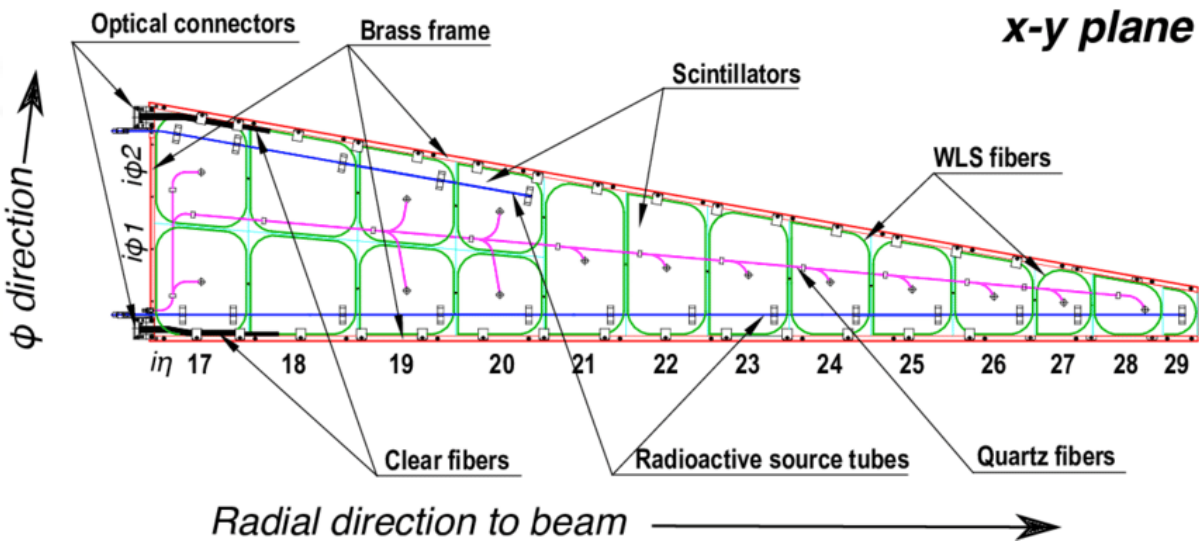
Plastic Scintillator + WLS fiber sandwich

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.


Fiber runs in the groove of scintilator

ILD mega-tile with varying tile size.



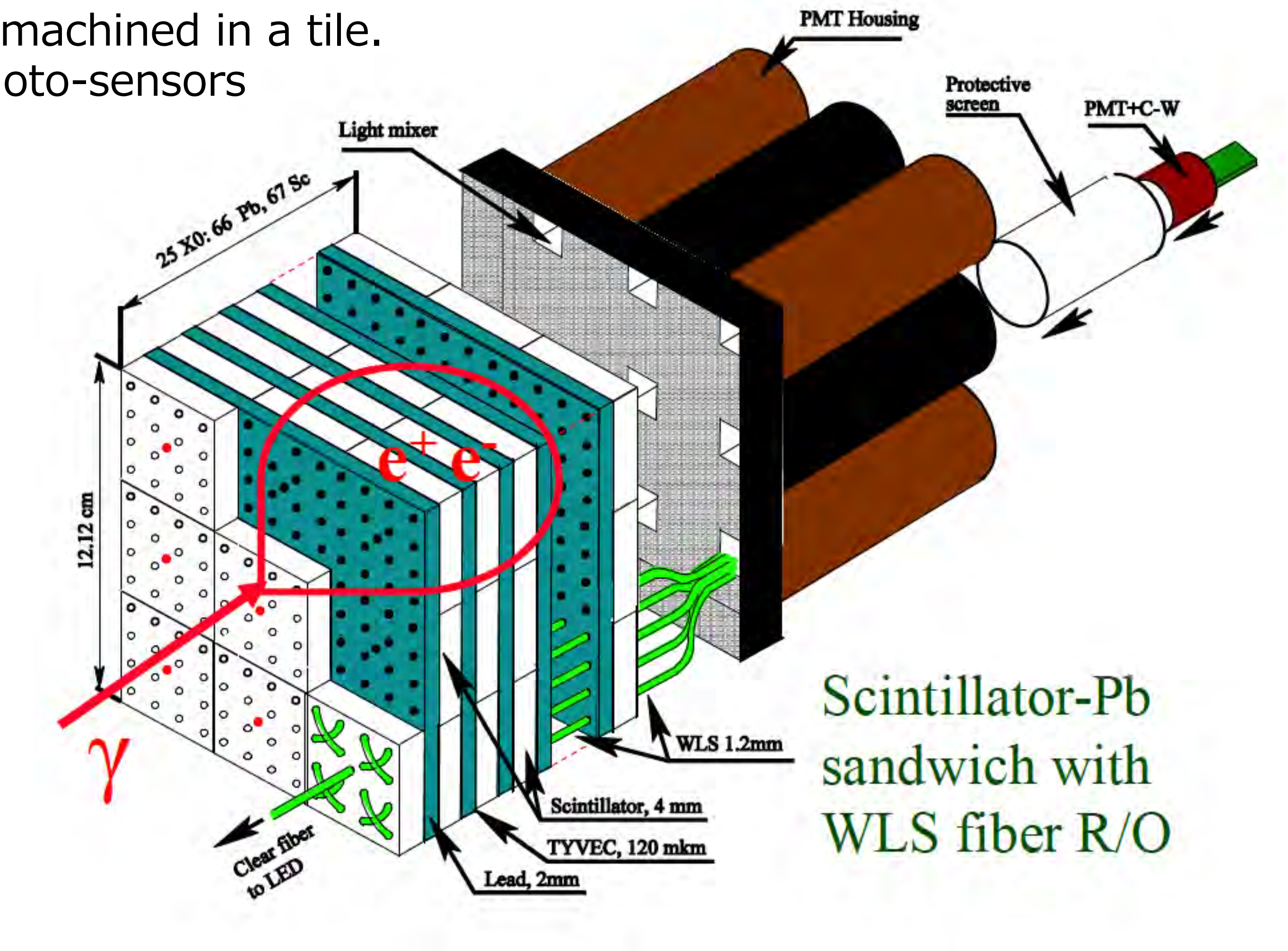


4. Operation of detectors ; Calorimeters

Sampling Calorimeter

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

4. Operation of detectors ; 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

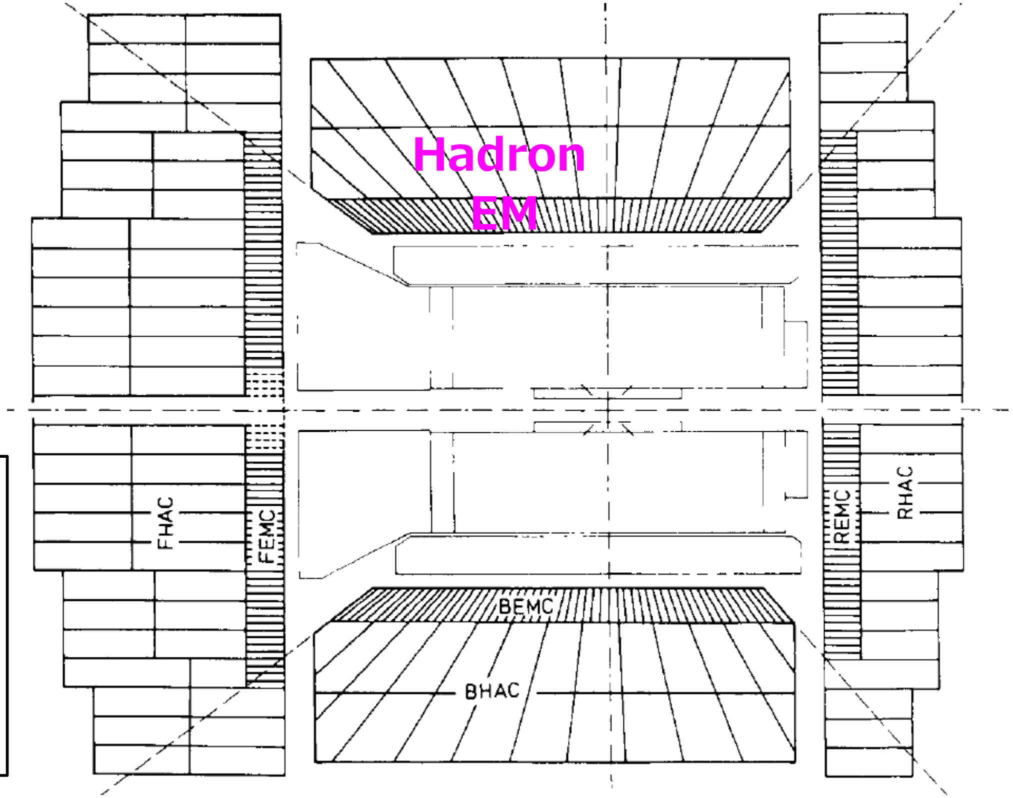
	Density [g/cm3]	Radiation Length X_0	Interaction Length λ_I
Iron	7.87	18mm	16.8cm
Lead	11.4	5.6mm	17.6cm
Tungsten	19.3	3.5mm	9.9cm
U	19.0	3.2mm	11.0cm

Strategical Unique Options

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

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.
The best hadron energy resolution ever achieved.

ZEUS calorimeter layout



4. Operation of detectors ; Calorimeters

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

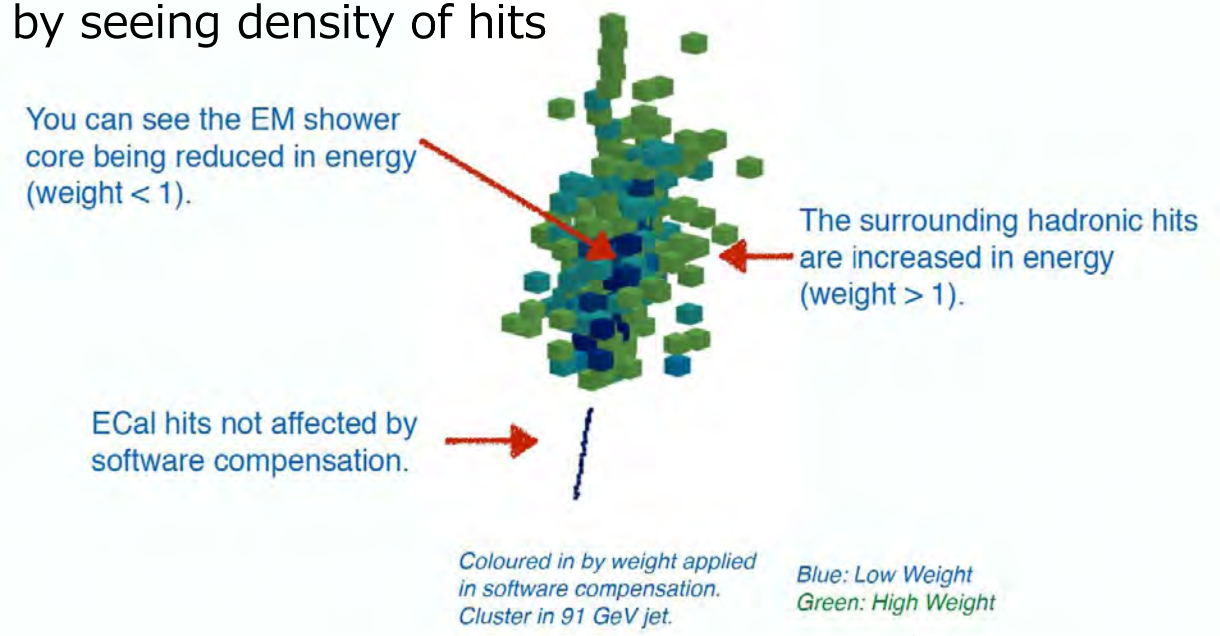
→ Digital HCAL (CALICE)

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

Super-high granularity also enables "software compensation".

- Number of read-out channels becomes huge, but nobody cares nowadays.

Software Compensation
enhance hadronic energy and reduce EM energy
by seeing density of hits



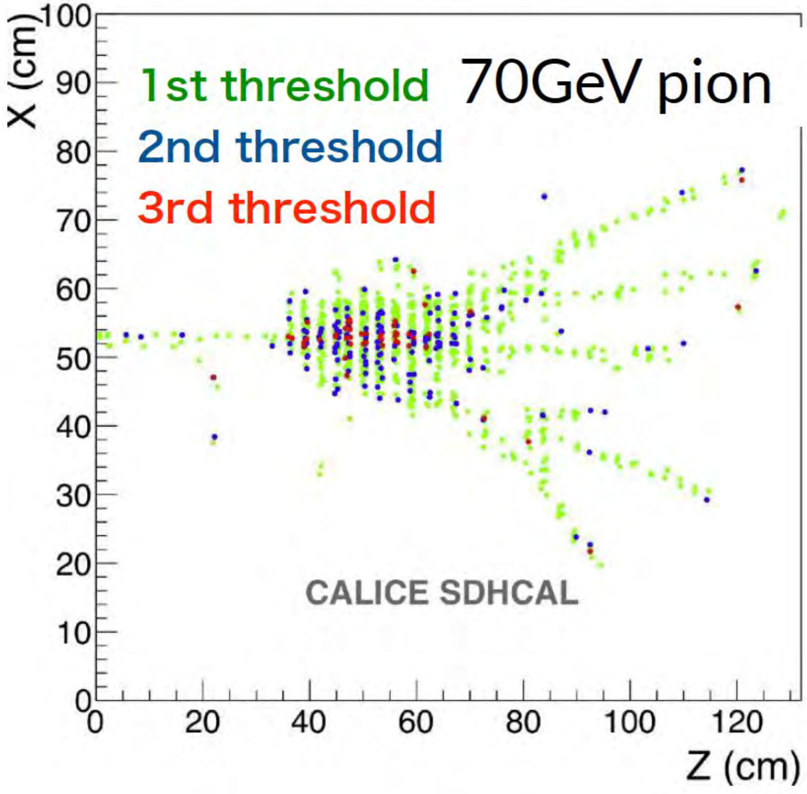
You can see the EM shower core being reduced in energy (weight < 1).

The surrounding hadronic hits are increased in energy (weight > 1).

ECal hits not affected by software compensation.

Coloured in by weight applied in software compensation. Cluster in 91 GeV jet.

Blue: Low Weight
Green: High Weight



4. Operation of detectors

Particle Identification

Identify species of the particle.
Strongly depends on your physics goal.

4. Operation of detectors ; Particle Identification

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.

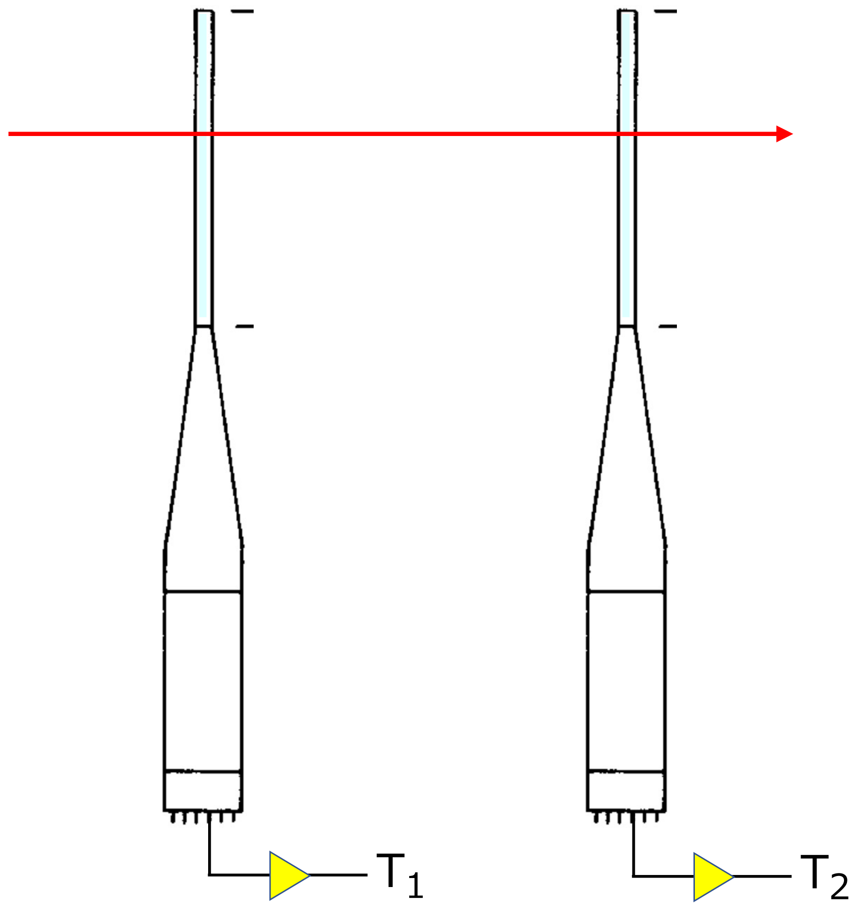
- Very important for flavour physics
- not simple nor straight ;
  Need to identify mass, but direct calculation of mass is difficult.
  → Measure velocity (β , γ) of the particle. (Momentum is known.)

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

4. Operation of detectors ; Particle Identification

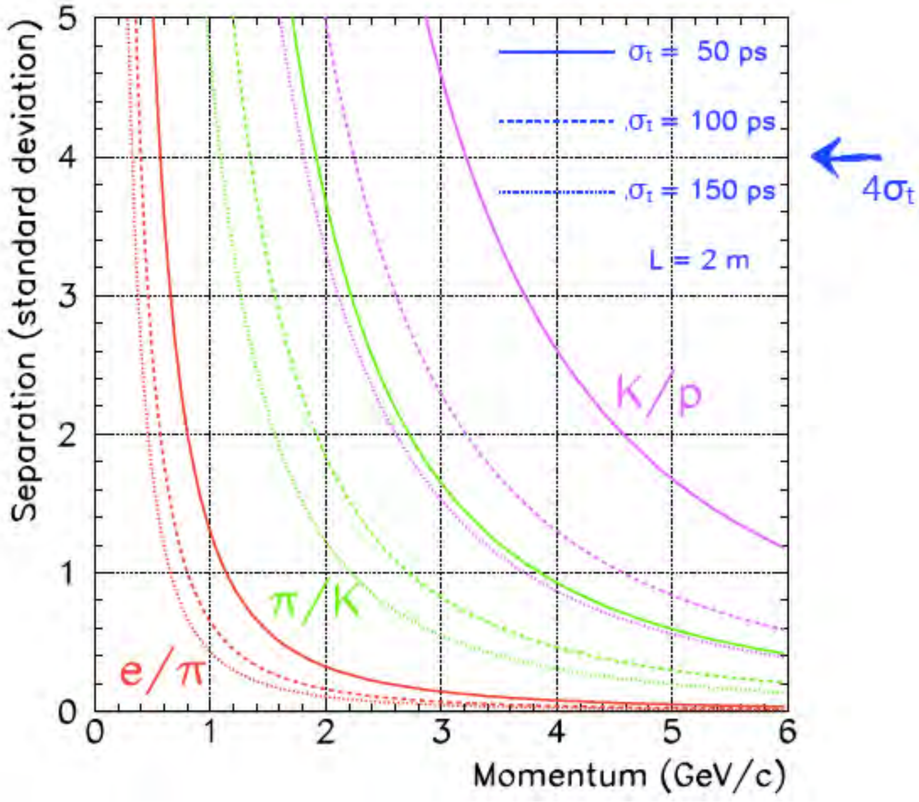
Particle ID --> Basically measure velocity (β , γ) of the particle

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



ToF = Arrival time difference $\Delta T = T_2 - T_1 = L/c\beta$
Compare ΔT at the same momentum.

Separation capability ↓ depends on momentum.



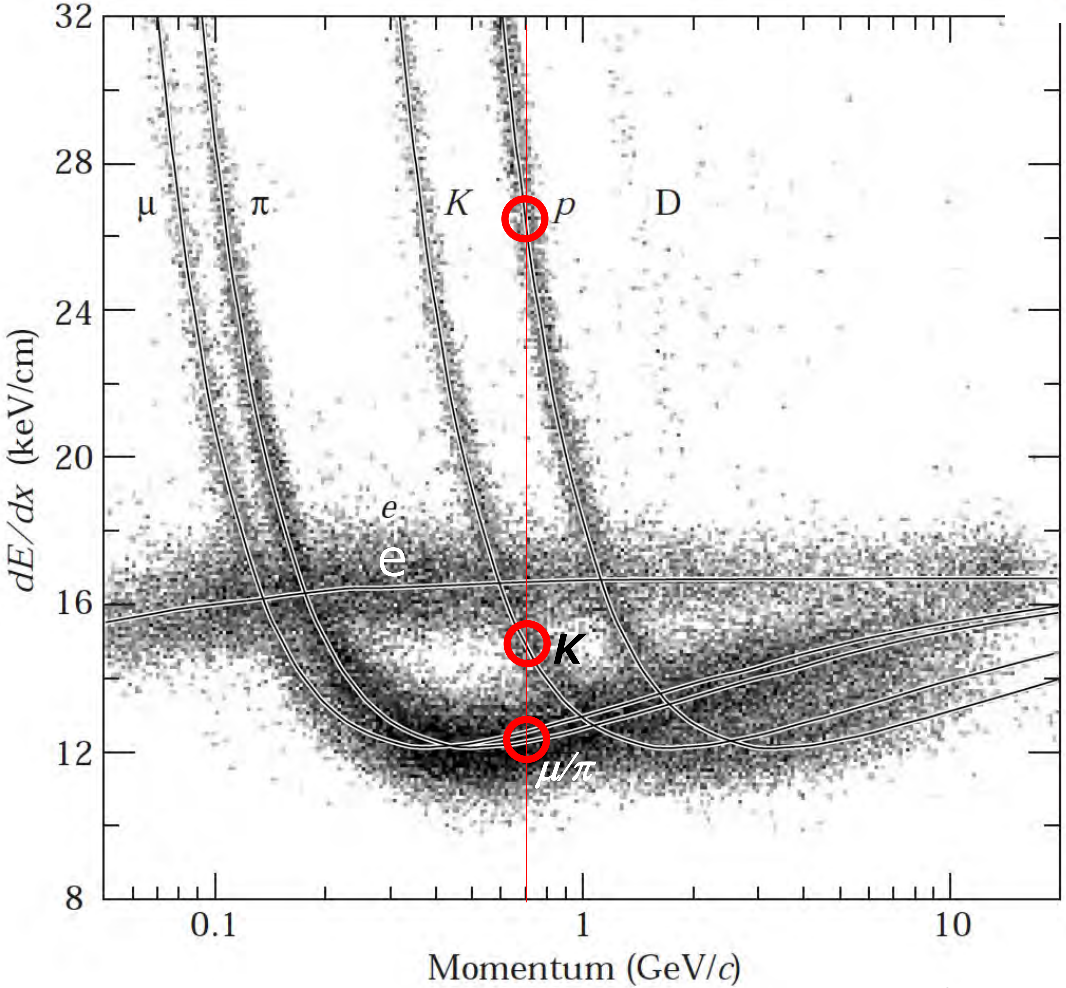
4. Operation of detectors ; Particle Identification

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.
→ Useful at low-energy.

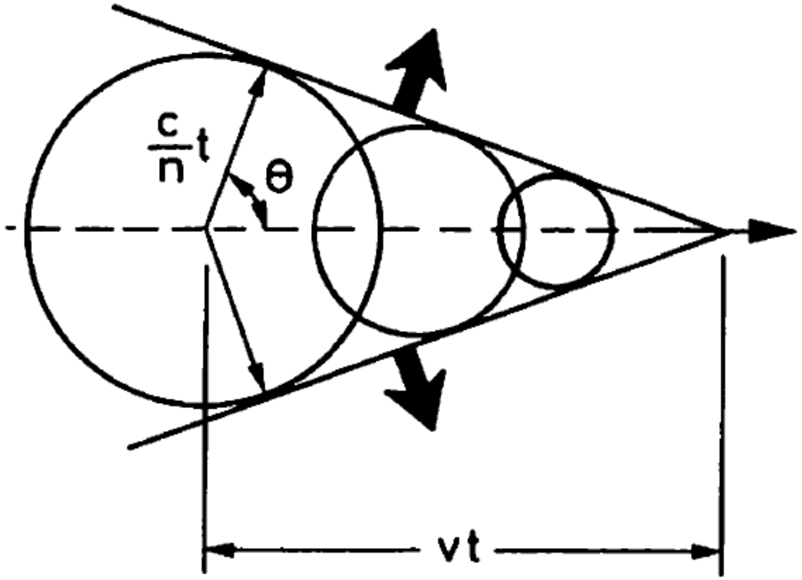
Truncated mean of many dE/dx
measurement improves the separation.

4. Operation of detectors ; Particle Identification

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

Cherenkov Light

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



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

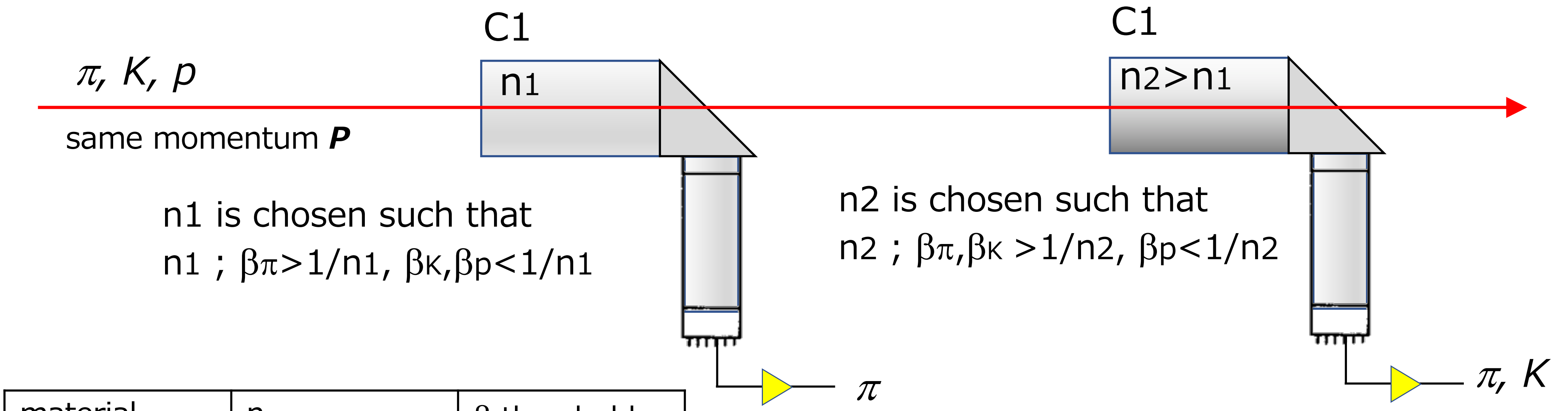
- Cone angle θ measurement tyle
  measure the ring image of the Cherenkov light, determine β, and pin-down the particle species.

4. Operation of detectors ; Particle Identification

Cherenkov Light

Threshold type

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



n1 is chosen such that
n1 ; $\beta_\pi > 1/n_1$, $\beta_K, \beta_p < 1/n_1$

n2 is chosen such that
n2 ; $\beta_\pi, \beta_K > 1/n_2$, $\beta_p < 1/n_2$

π only generate light

π, K generate light.
Protons don't.

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.

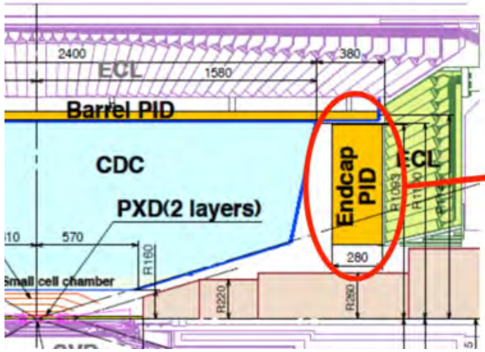
According to the momentum of the particles to measure, choose appropriate radiator, and narrow-down the β range and particle species.

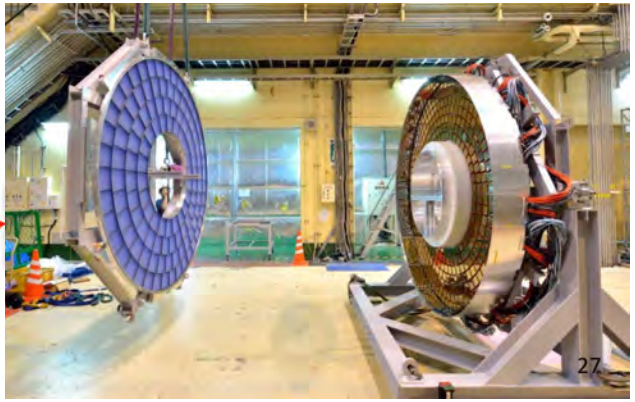
4. Operation of detectors ; Particle Identification

Cherenkov Light

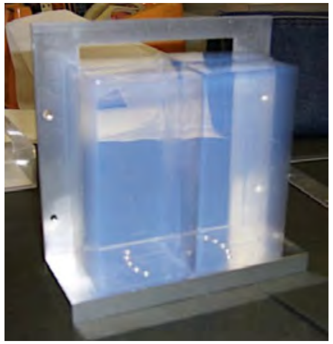
Cone angle θ measurement type

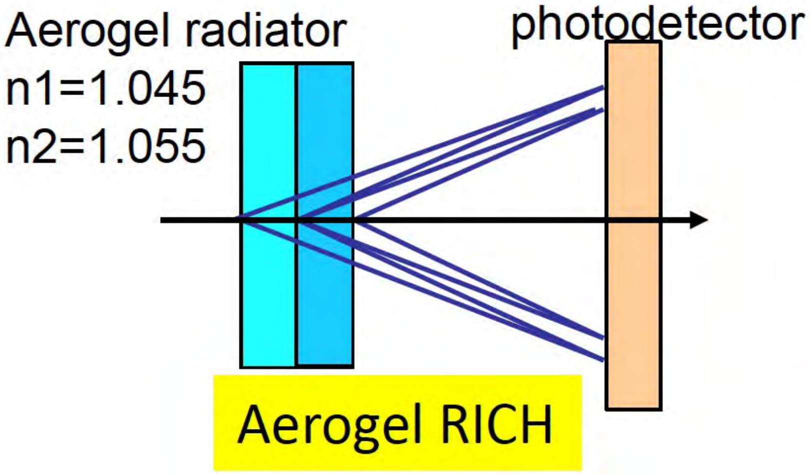
Measure the ring image of
the Cherenkov light, measure β,
and pin-down the particle species.

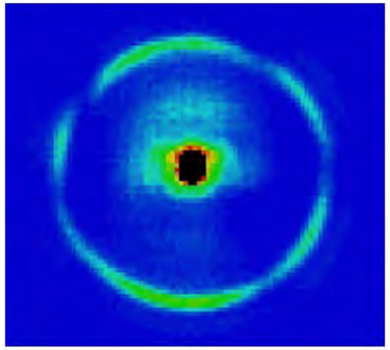


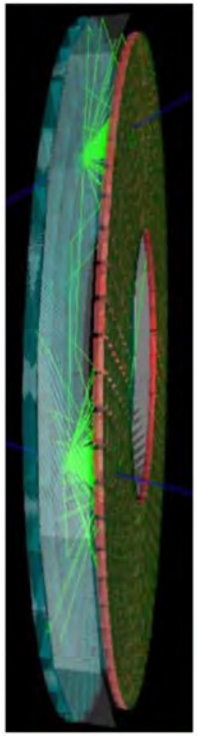


Belle-II Aerogel Ring-Image Cherenkov Counter









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

4. Operation of detectors ; Particle Identification

Cherenkov Light

Cone angle θ measurement type

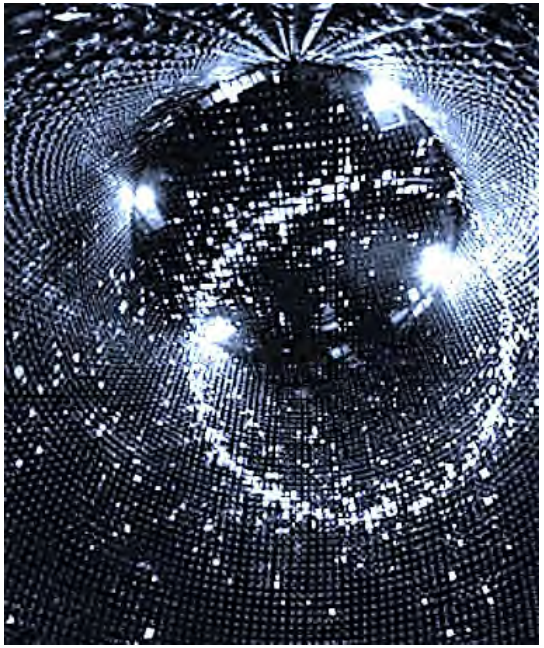
measure the ring image of the Cherenkov light, measure β, and pin-down the particle species.

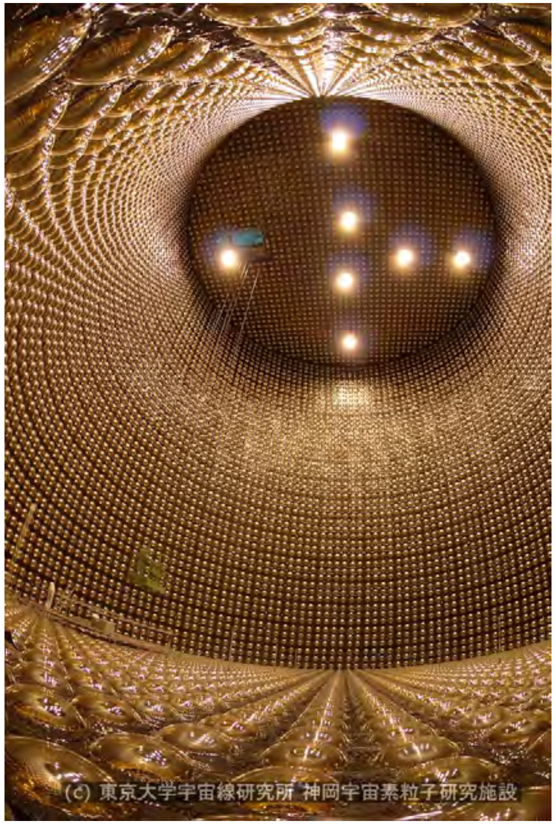
Super-Kamiokande Water Cherenkov Counter

e,μ identification with θ and ring image analysis.

Roughly speaking,
Timing of PMTs → vertex position
Vertex position and ring radius
→ emission angle θ
θ and ring sharpness
→ e,μ identification
Ring signal charge
→ particle β .

Actual analysis is multi-parameter maximum-likelihood method.





(c) 東京大学宇宙線研究所 神岡宇宙素粒子研究施設

4. Operation of detectors ; Particle Identification

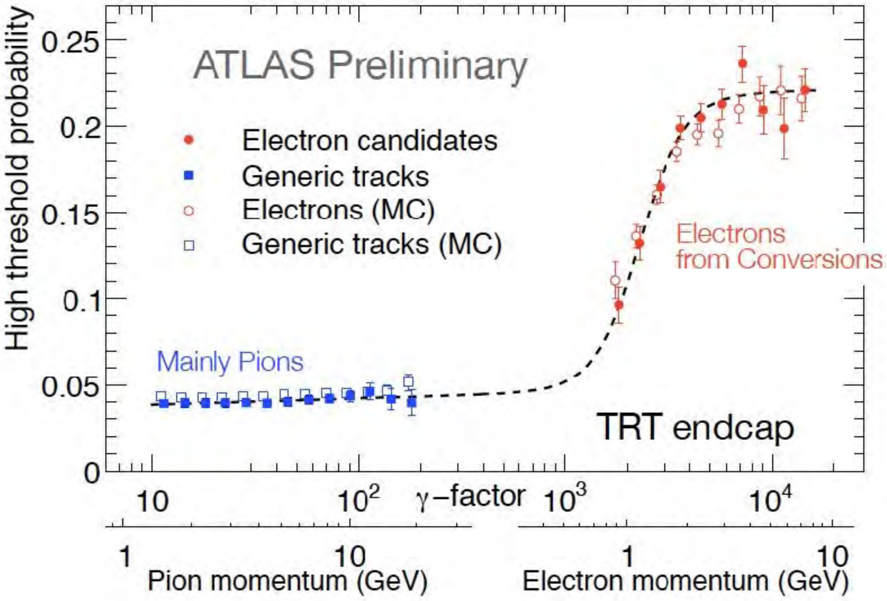
Transition Radiation Detector

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

Emitted energy *S*

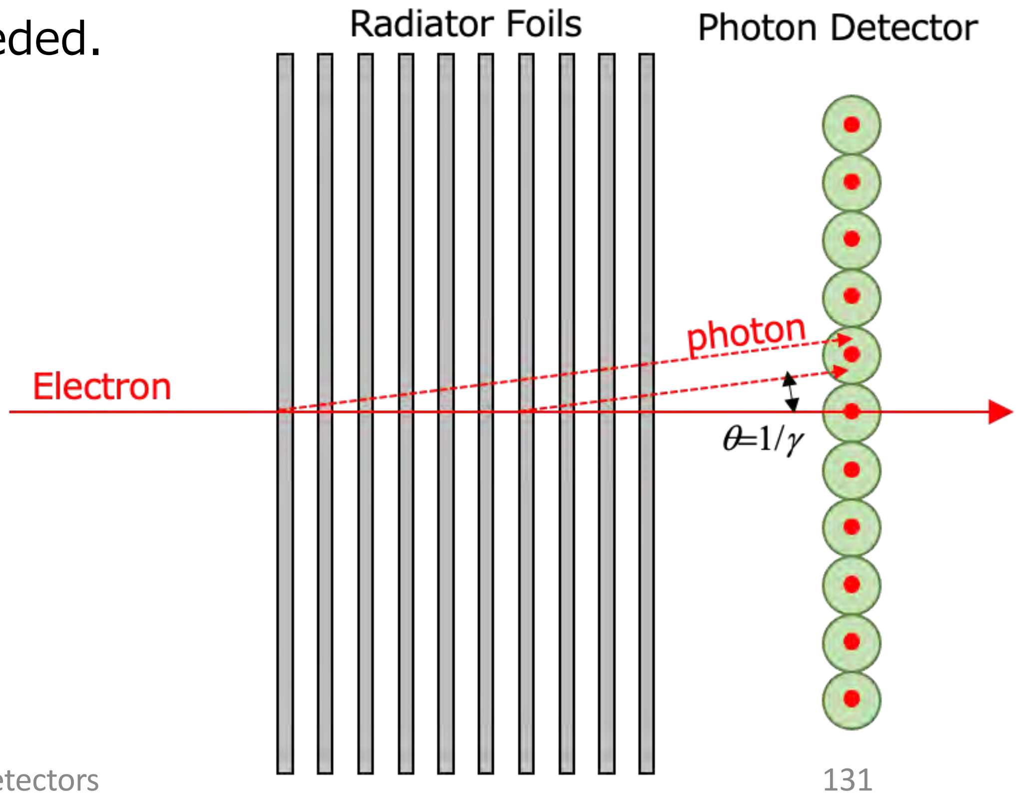
$$S = \frac{1}{3}\alpha z^2 \hbar\omega_{\mathrm{p}}\gamma \ , \quad \hbar\omega_{\mathrm{p}} = \sqrt{4\pi N_e r_e^3 m_e c^2}/\alpha$$

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



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

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



4. Operation of detectors ; Particle Identification

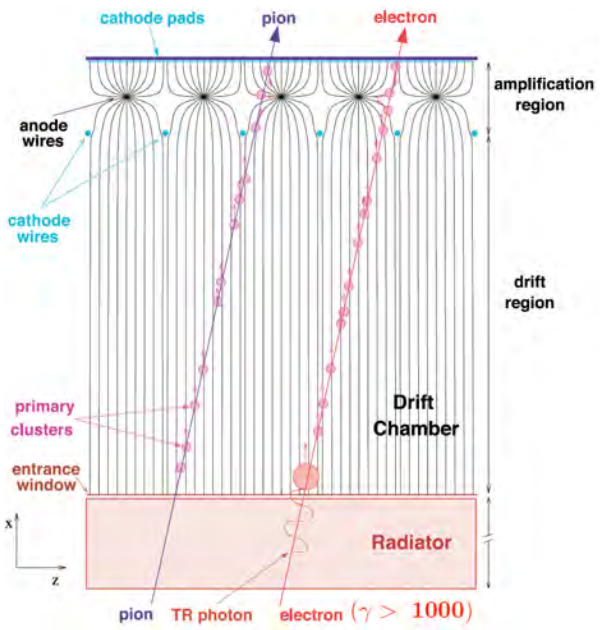
Transition Radiation Detector

ALICE TRD

ALICE TRD : electron–ID and tracking

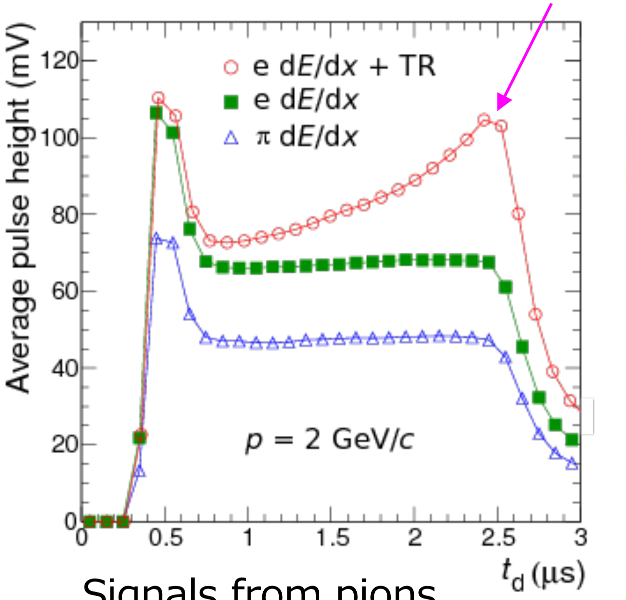
Catch $J/\phi, \Upsilon \rightarrow e^{+} e^{-}$

Radiator : Polypropylene fiber of 17μm–ϕ
Detector ; drift chamber with Xe/CO$_2$-gas



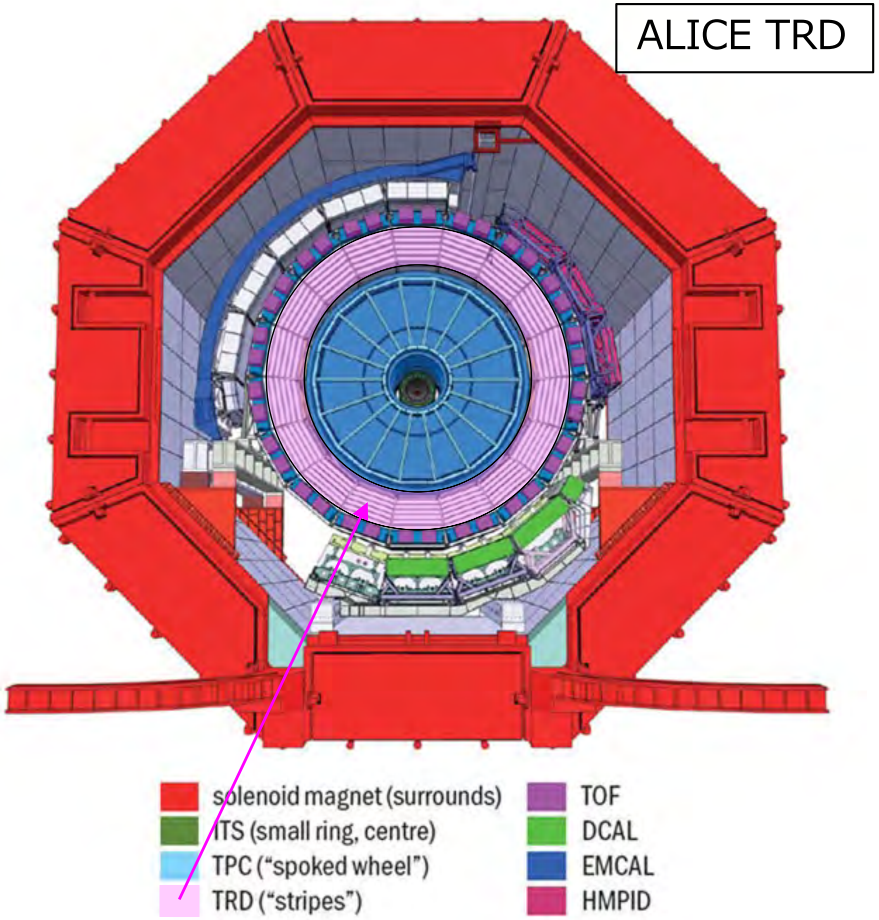
Layout of TRD, and X-ray conversion and tracks.

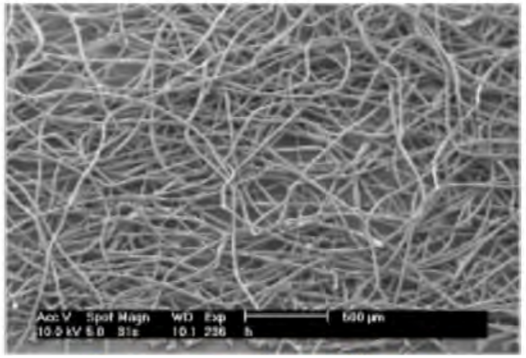
TRD photon contribution



Signals from pions and from electrons.

Larger signal is electrons.





Fiber radiator

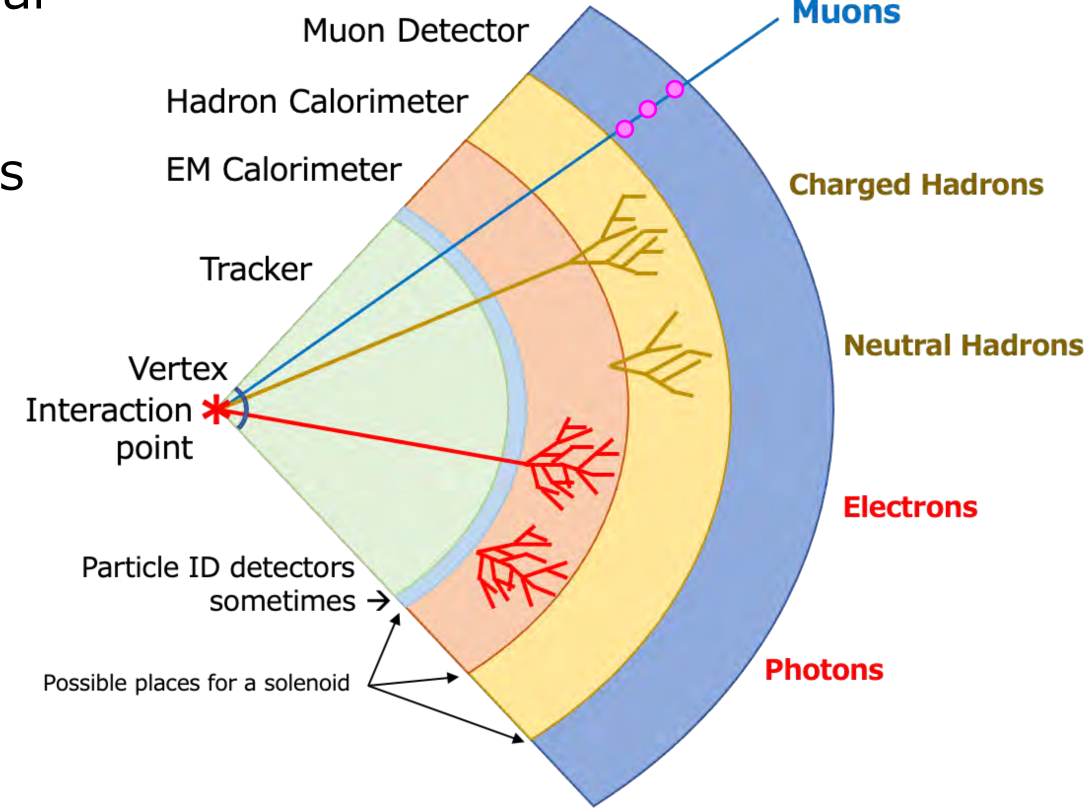
Figures taken from M.J.Kweon, QM09.

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



4. Operation of detectors ; Particle Identification

Muon identification with high-efficiency, low contamination

Muon are the key particles to search for new physics.

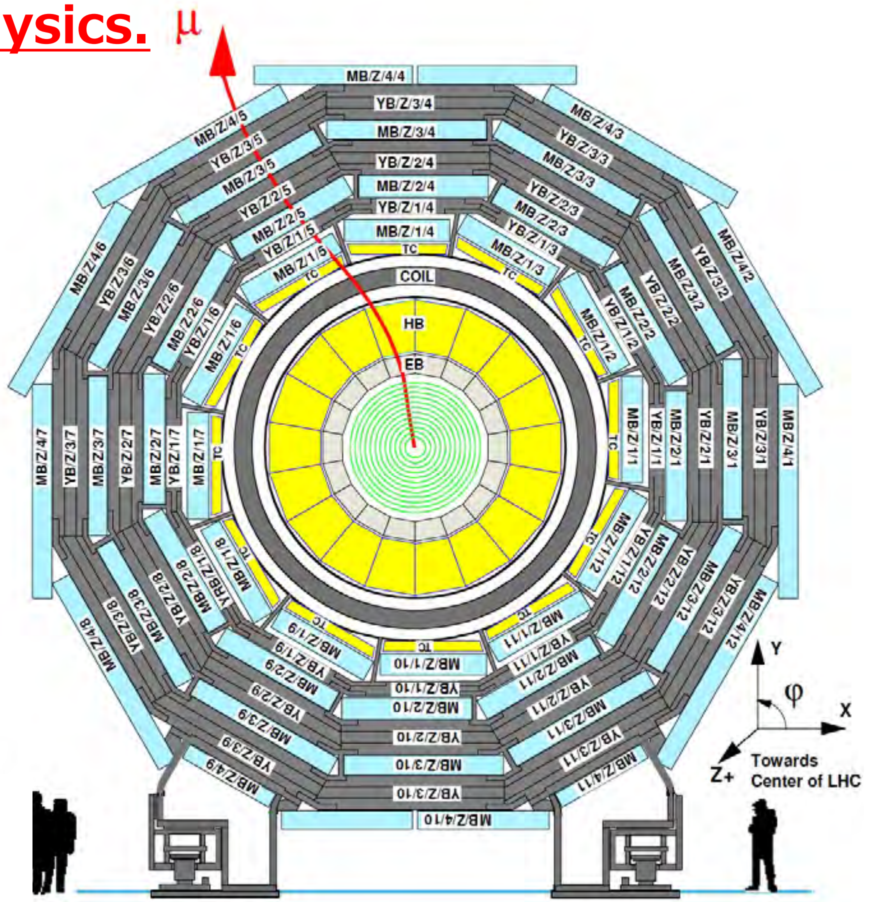
Compact Muon Solenoid (CMS) aims at
- good muon identification
- good muon momentum resolution
- good dimuon mass resolution

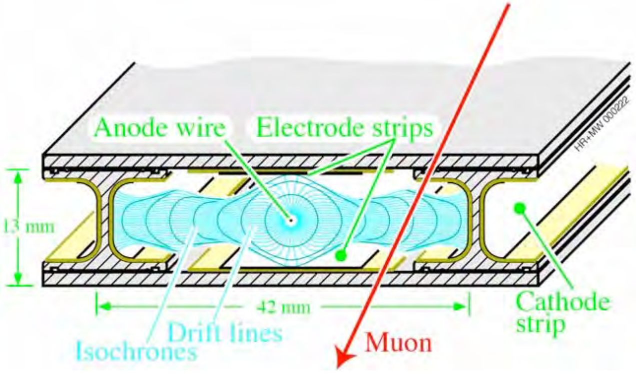
Design parameters are
- 12Tm bending field for good momentum resolution
- Thick iron absober of 1.5m

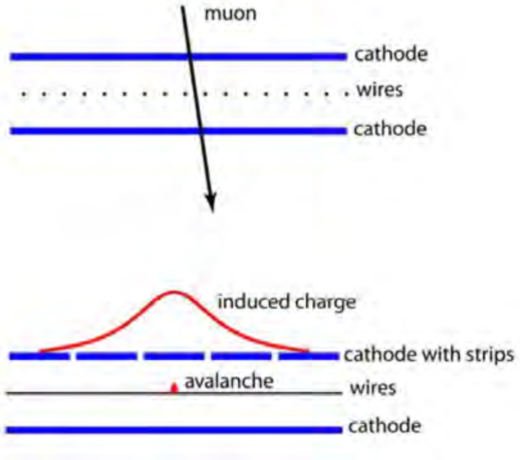
Detector area ~25000m2

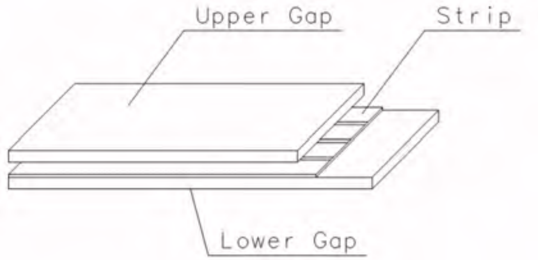
→ inexpensive detector needed
- Array of single-wire drift chamber (barrel)
- MWPC with cathode-strip readout (EC)
- RPC for trigger (fast response)

mu-IDのefficiency, contamination









4. Operation of detectors ; Particle Identification

Electron identification with high-efficiency, low contamination

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

How can we know the particle is electron ?

With calorimeter

- Initiate EM shower

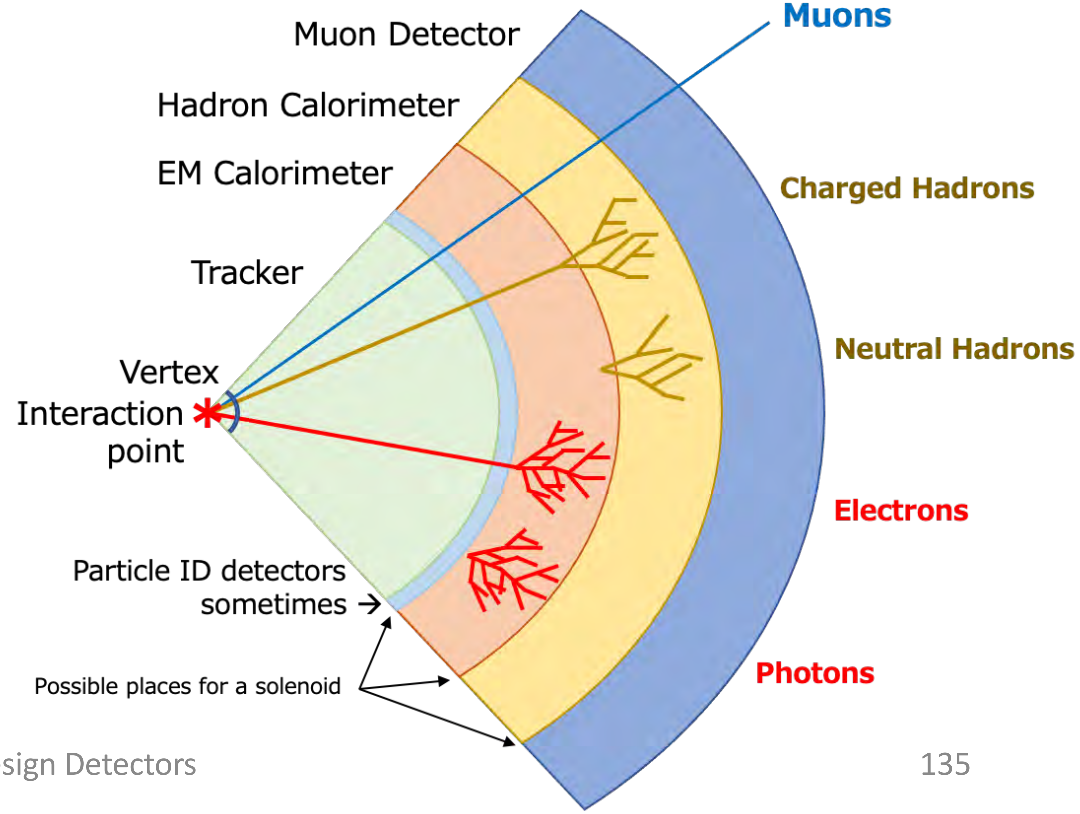
  Shower profile consistent to EM shower.

  → 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

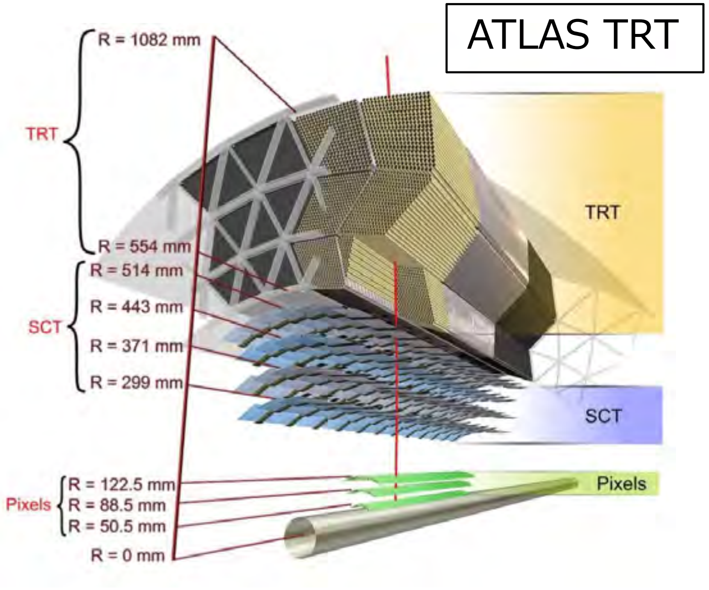


4. Operation of detectors ; Particle Identification

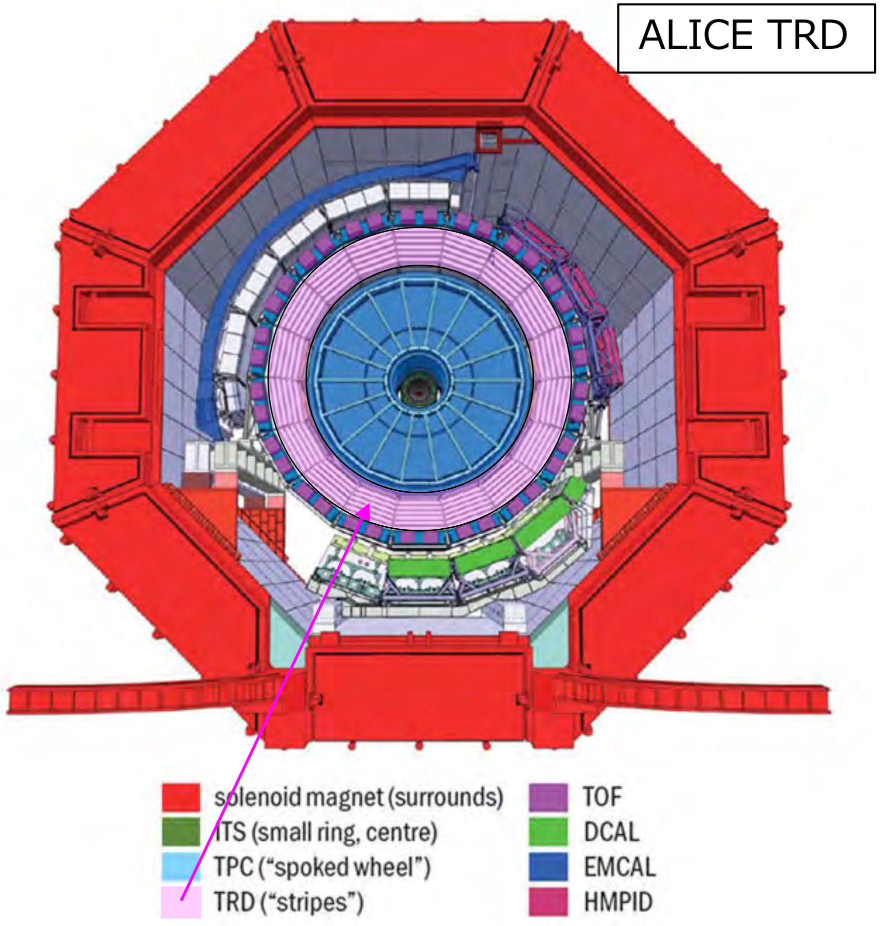
Electron identification with high-efficiency, low contamination

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%

4. Operation of detectors ; More Excellent Solutions

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

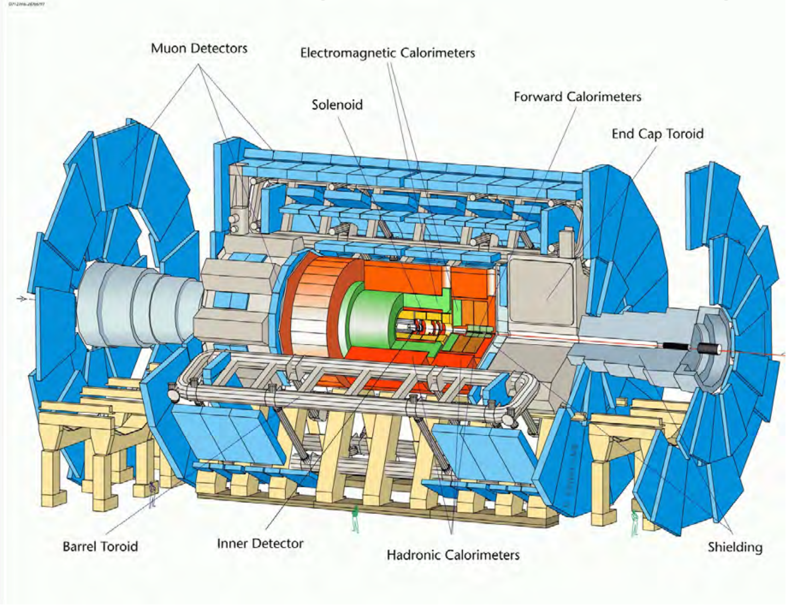
- good resolutions ; energy, momentum, position, timing

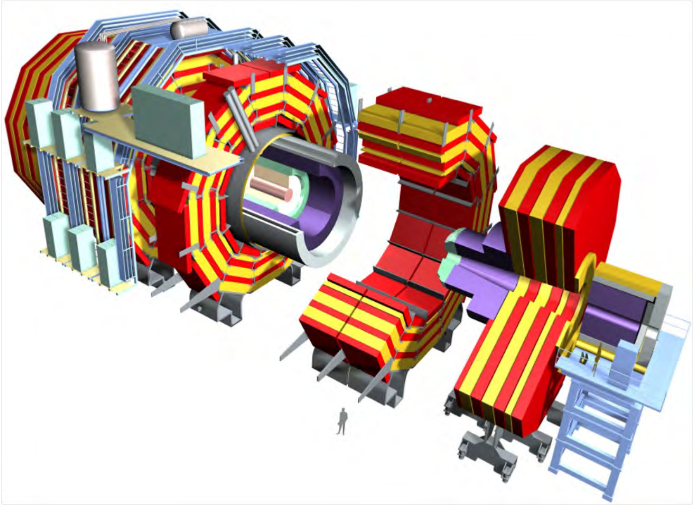
  Charged particle be measured by trackers, while neutral particles by calorimeters.

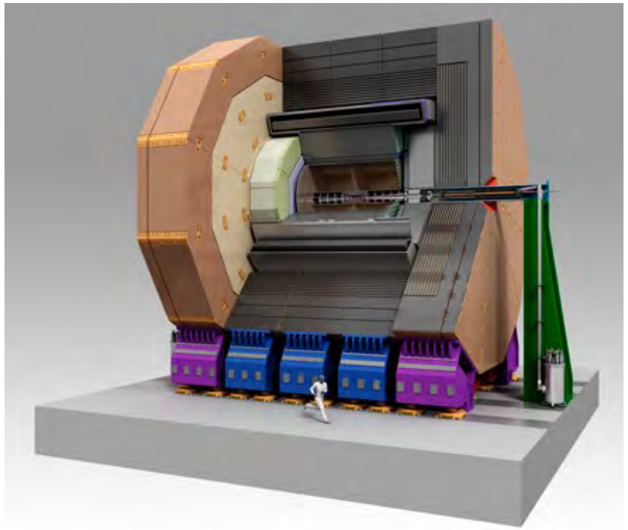
  Excellent position resolutions to resolve track/cluster overlapping.
- Jet reconstruction ; high multiplicity, high occupancy
- Precision secondary vertexing (b,c,τ-tagging) and primary vertexing (bunch separation).
- Reject overwhelming QCD background reactions

These were the 1st phase solutions, but more excellent ones needed now.

This was almost the solution







5. Further Improvement at HL-LHC

5. Further Improvement at HL-LHC

For

more precise Higgs study to detect any deviations from the SM prediction,

and

further extend the reach to search for new particles,

LHC will

- increase it's luminosity and
- increase its energy slightly, 13TeV→14TeV.

Run1		Run2		Run3		Run4
2011~2012		2015~2018		2022~2025		2029~
7~8TeV	**LS1**	13TeV	**LS2**	13.6TeV	**LS3**	14TeV
0.75x10^{34}		1~2x10^{34}		2x10^{34}		5~7.5x10^{34}
30fb-1		140fb-1		250fb-1		3000fb-1

Higgs Discovery **Higgs Study** **Higgs Precision Study**

5. Further Improvement at HL-LHC

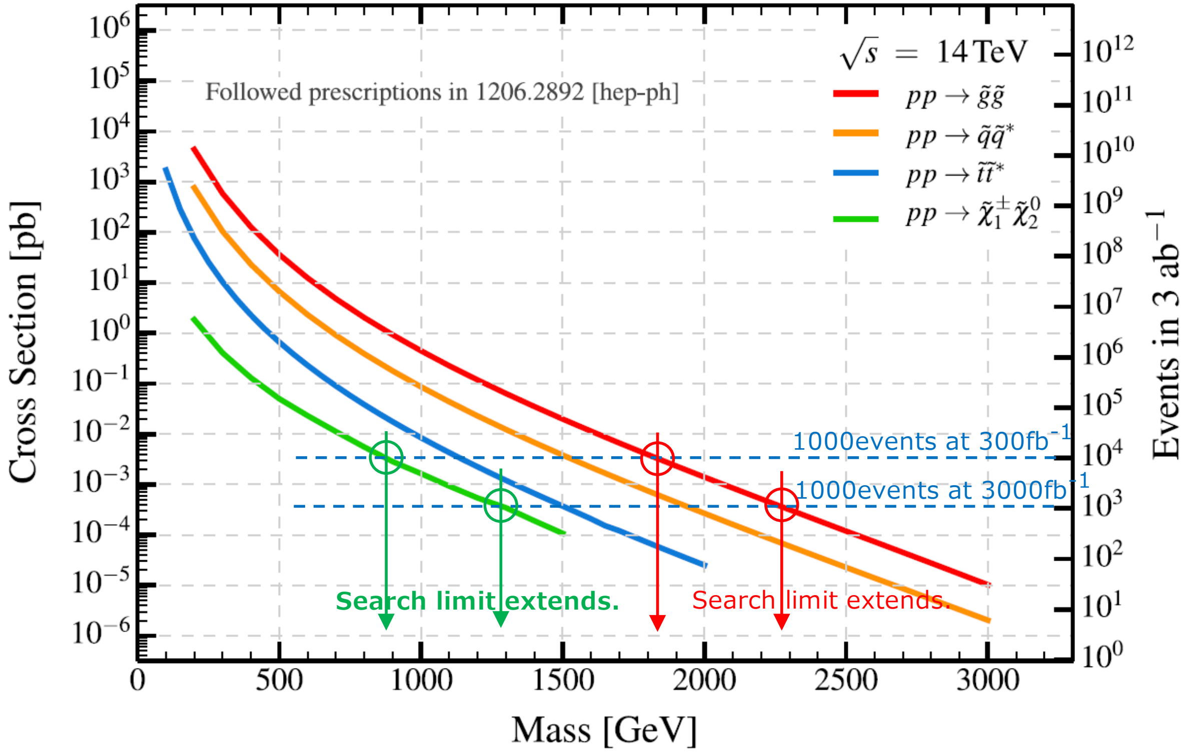
For more precise Higgs study to detect any tiny deviations from the SM prediction, and to further extend the reach to search for new particles,
LHC will **increase it's luminosity** and increase energy 13TeV→14TeV.

High Luminosity → Increase statistics

- Precision Study
- Higher sensitivity
  to deviation from SM prediction,
  to much rare processes

At the same time,
systematic error should be improved

Increase number of collisions
→ Collision of high-momentum parton (*q*/*g*) also increase.
→ Search extends to higher mass



Taken from K.Nakamura, Flavour Physics Workshop 2014

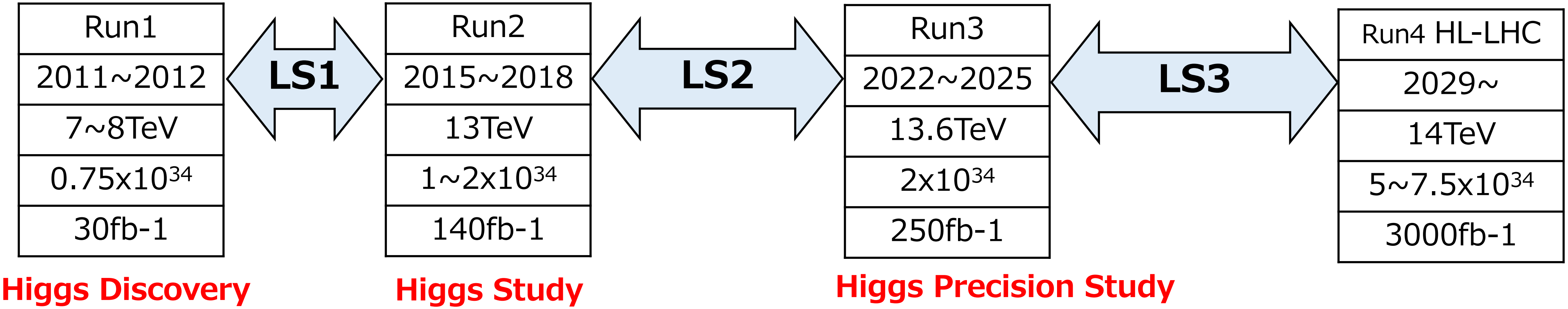
5. Further Improvement at HL-LHC

For more precise Higgs study to detect any tiny deviations from the SM prediction, and to further extend the reach to search for new particles, LHC will **increase it's luminosity** (and increase energy 13TeV→14TeV) .

To utilize extremely high luminosity
- Need to resolve overlapping events.
- Need to take huge number of events

Once overlapping events are clearly disentangled, event analysis is similar
- Basic concept of the detector stay the same.

To improve sensitivity to new physics
- Strengthen muon detectors ; Muons are always the key to the new physics.



Run1		Run2		Run3		Run4 HL-LHC
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7~8TeV		13TeV		13.6TeV		14TeV
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30fb-1		140fb-1		250fb-1		3000fb-1

Higgs Discovery

Higgs Study

Higgs Precision Study

5. Further Improvement at HL-LHC

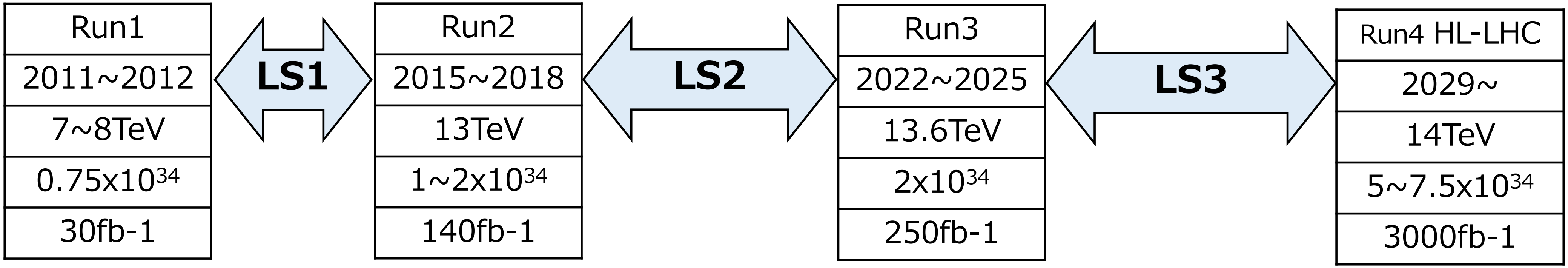
In order to resolve overlapping events
- finer granularity
- fast timing measurement

In order to take huge number of events
- fast signal processing electronics/DAQ
- high bandwidth data flow to take huge data
- excellent trigger to reduce unnecessary events and not to mis target process

And we need higher radiation-hardness

Phase-I upgrade
- ● High-granular CAL trigger
- ● New forward trigger chamber
- ● New Small Wheels Muon Detector

Phase-II upgrade
- ● All Silicon inner trackers extending to forward
- ● Forward high-granularity precision timing detector
- ● Inner-barrel muon chamber
- ● Calorimeter electronics



Run1	LS1	Run2	LS2	Run3	LS3	Run4 HL-LHC
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30fb-1		140fb-1		250fb-1		3000fb-1

Higgs Discovery

Higgs Study

Higgs Precision Study

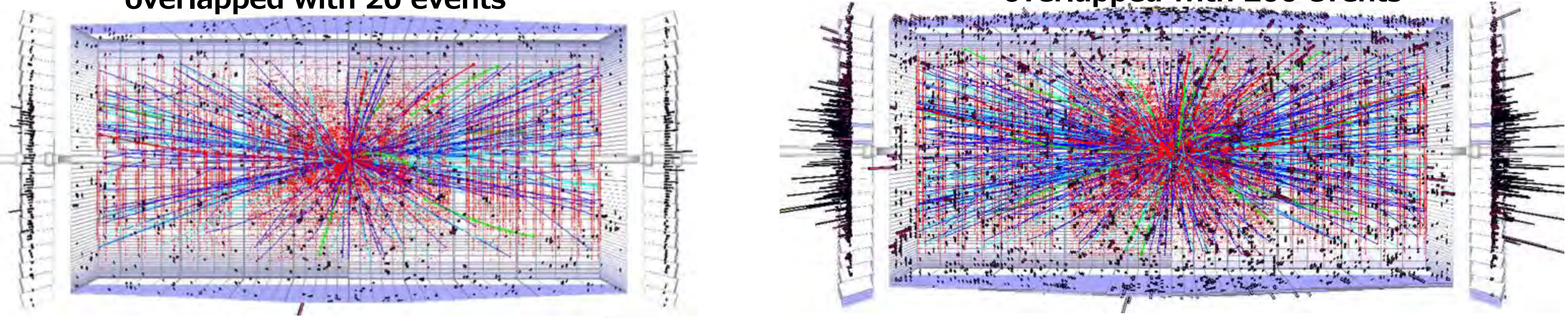
5. Further Improvement at HL-LHC

Trackers of higher granularity to resolve overlapping events

- **More pixels with finer size**
- 3D-pixels
- Fast readout
- Extend to larger η (forward)
- Radiation hardness

Just an example

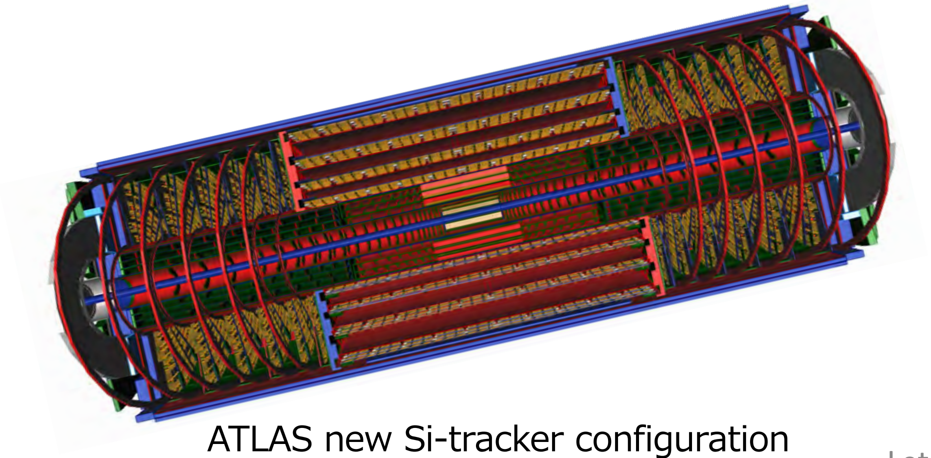
H→ZZ→eeμμ event



overlapped with 20 events

overlapped with 200 events

Figure taken from a Talk by Takubo (KEK)



ATLAS new Si-tracker configuration
taken from ATL-PHYS-PUB-2021-024

New Inner Silicon Tracker (ATLAS) ; More Pixels

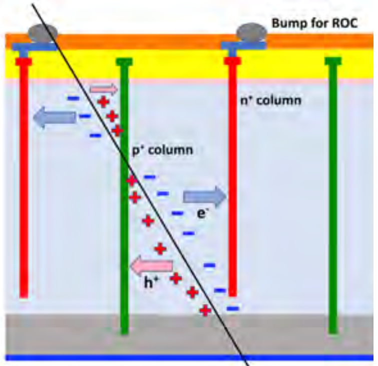
	Area (m^2)	# Modules	# channels
Pixels	13	9164	**5100 M**
Strips	165	17888	60 M

5. Further Improvement at HL-LHC

Trackers of higher granularity to resolve overlapping events

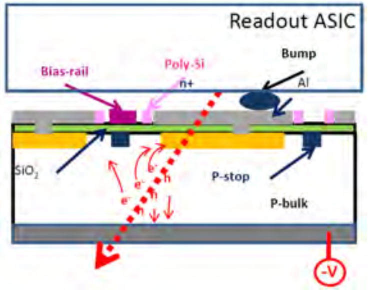
- More pixels
- **3D-pixels**
- Fast readout
- **Extend to larger η (forward)**
- Radiation hardness

Just an example



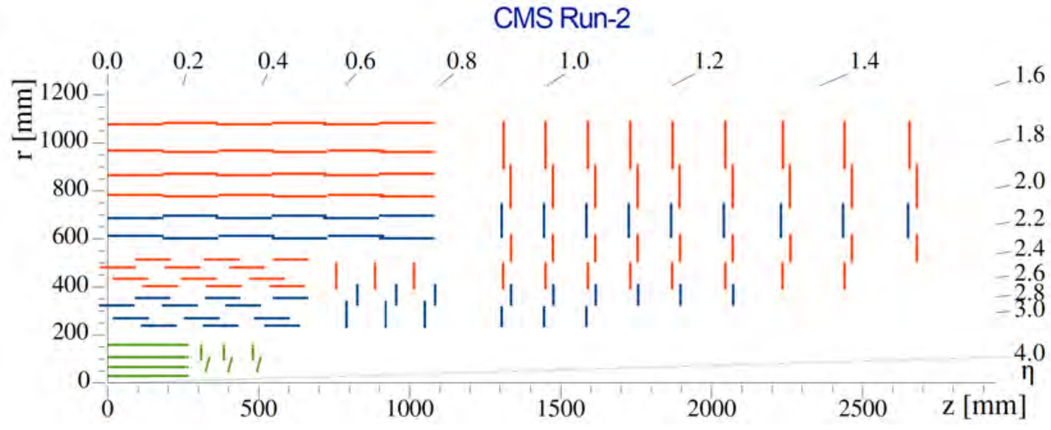
Structure of LHC 3D-pixel

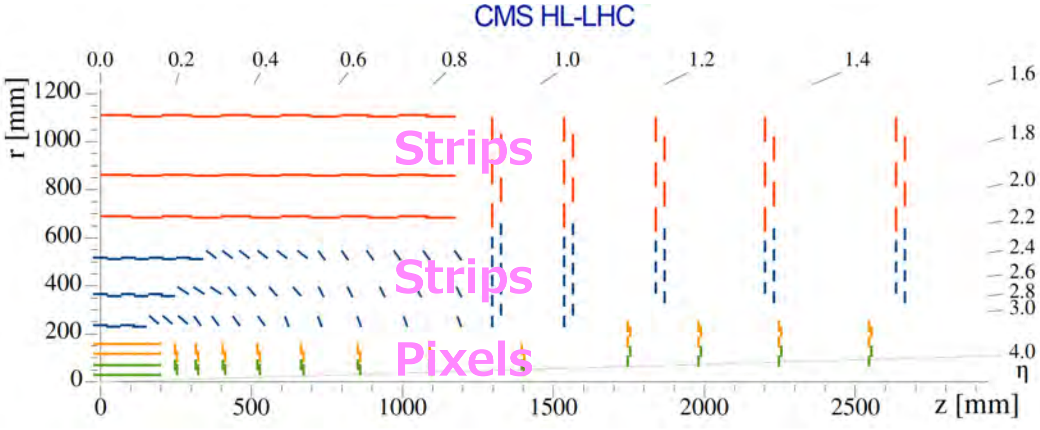
LHC 3D-pixels are NOT 3D-position measurement detector such as Si-TPC, but the structure is NOT planar as usual silicon sensors.
Can achieve smaller pixel size and higher radiation hardness.



Structure of usual planar pixel

New Silicon Tracker (CMS) ; More Forward



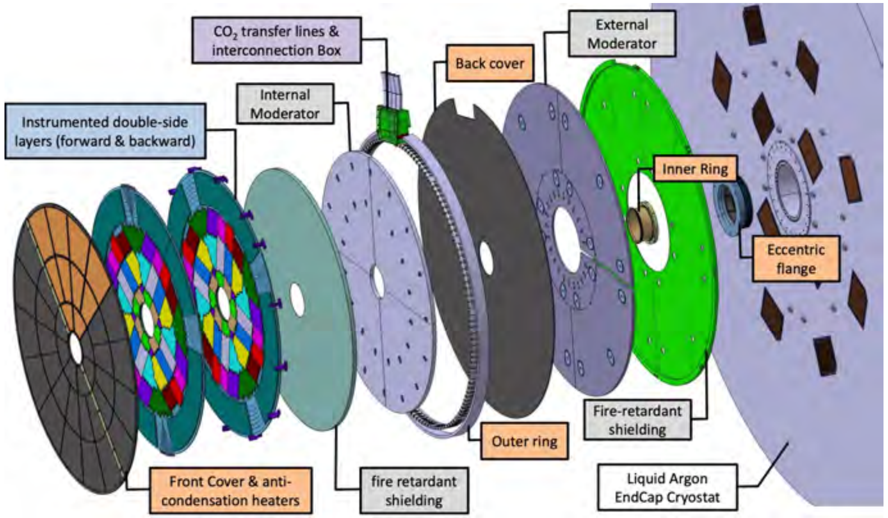


5. Further Improvement at HL-LHC

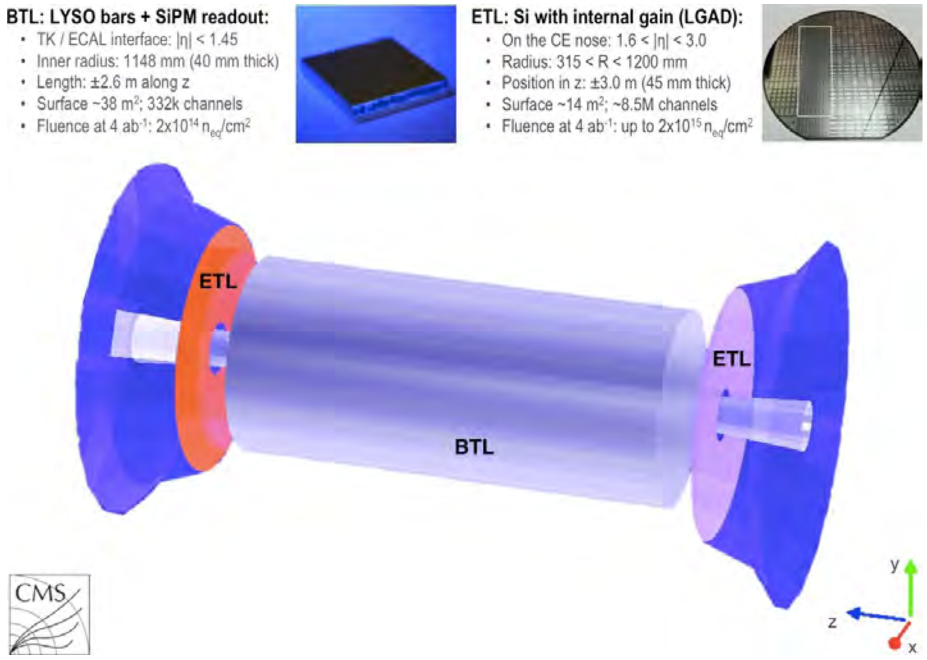
Fast Timing Detector to resolve overlapping events of a few hundreds.

ATLAS HGTD (High-Granularity Timing Detector)
- Forward region before EndCap CAL
- Four layers of LGAD (Low-Gain Avalanche Detector) gives
  - 30ps – 50ps timing resolution
  - Fine granularity of 1.3mm x 1.3mm pixels.

Just an example



taken from ATLAS-TDR-031



BTL: LYSO bars + SiPM readout:
- TK / ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: $2x10^{14}\ n_{eq}/cm^2$

ETL: Si with internal gain (LGAD):
- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: $315 < R < 1200$ mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to $2x10^{15}\ n_{eq}/cm^2$

taken from a talk by Carlos Lacasta, IFIC-Valencia

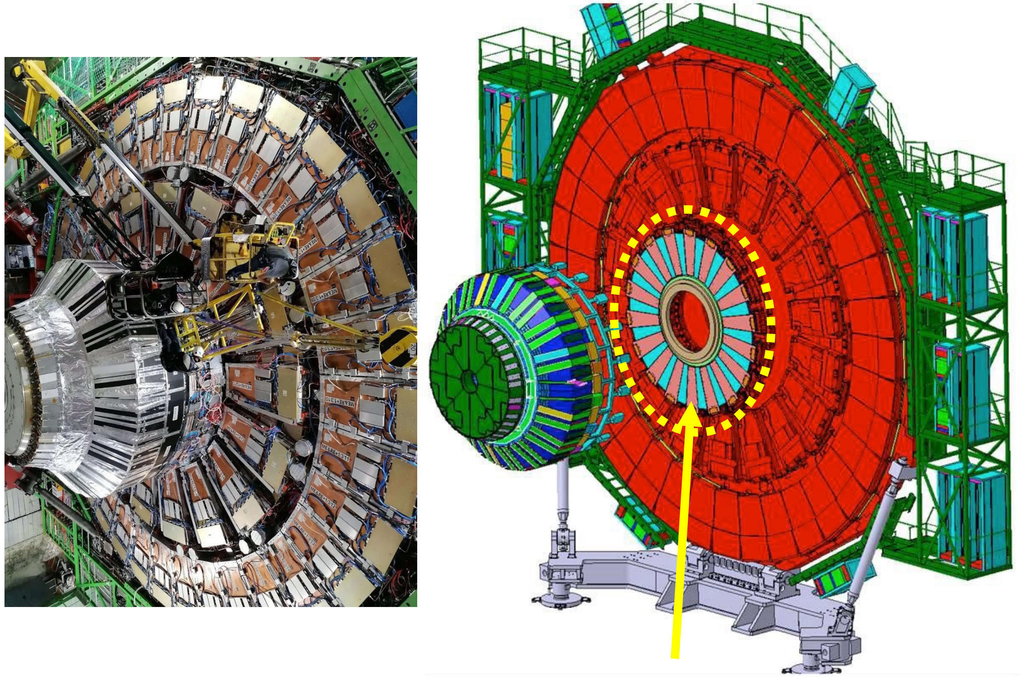
CMS
installs fast timing detector for both barrel and endcap region.
- Barrel : LYSO/LSO tiles with SiPM readout
- Endcap ; LGAD pixels
- timing resolution similar to ATLAS

5. Further Improvement at HL-LHC

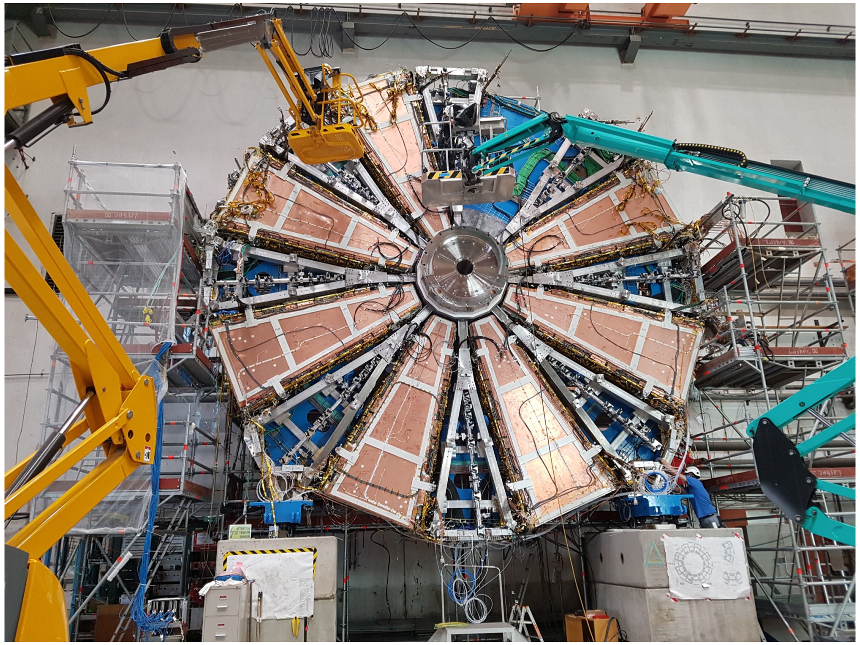
Higher Performance **Muon** for new physics

- Improve performance in forward region.
- Extend coverage to more forward region.
- Reduce fake muon triggers

Just an example



CMS : New GEM muon detector at forward region.
taken from a talk by Carlos Lacasta, IFIC-Valencia



ATLAS: New Small Wheel muon detector at forward region, consists of micromegas (for granularity), and small-strip thin gap chambers (precision timing).
taken from a talk by Maria Perganti, National Technical University of Athens

5. Further Improvement at HL-LHC

Utilize extremely high luminosity
- Need to take huge number of events

Super-improvement on
- On-detector Electronics (rad-hard, high-rate read-out, and finer granularity),
- Trigger (high-rate, better filtering for reduction/efficiency, finer granularity),
- High-speed Data-taking system, and handle huge data.

5. Further Improvement at HL-LHC

In summary, for extremely high luminosity,

- New finer-granularity detectors,
  or finer readout grouping of existing detectors
- Fast timing detectors to resolve dense event overlap.
- Fast signal processing electronics/DAQ, and high bandwidth data flow to take huge data.
- Excellent trigger to reduce unnecessary events and not to mis target process
- Higher radiation-hardness detectors and their readout electronics.

To improve sensitivity to new physics

- Strengthen muon detectors ; Muons are always the key to the new physics.

Summary

1. We pick up reactions to for
   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. Operation of various detectors are introduced.

5. Further improvement at LHC are briefly shown.

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
- Erika ; Lecture "The Physics of Particle Detectors", by Erika Garutti
- Joram ; CERN Summer Student Lectures 2003, by Christian Joram

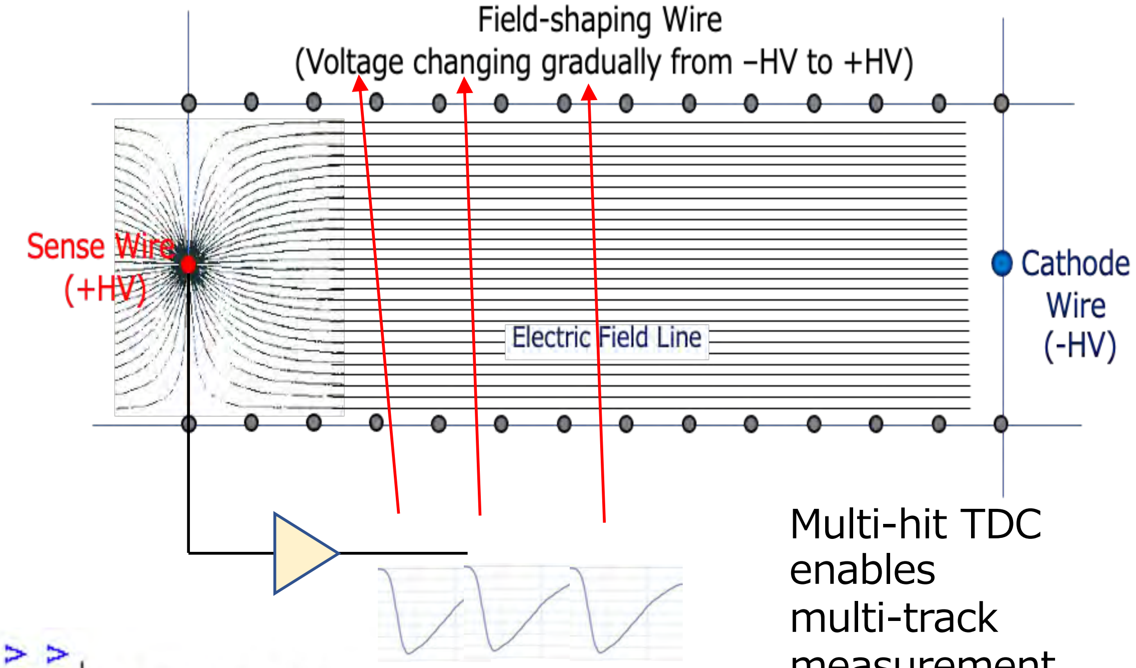
and many slides on the reports by ATLAS, CMS, ILC.

5. Operation of detectors ; Trackers ; Gas Chambers

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.

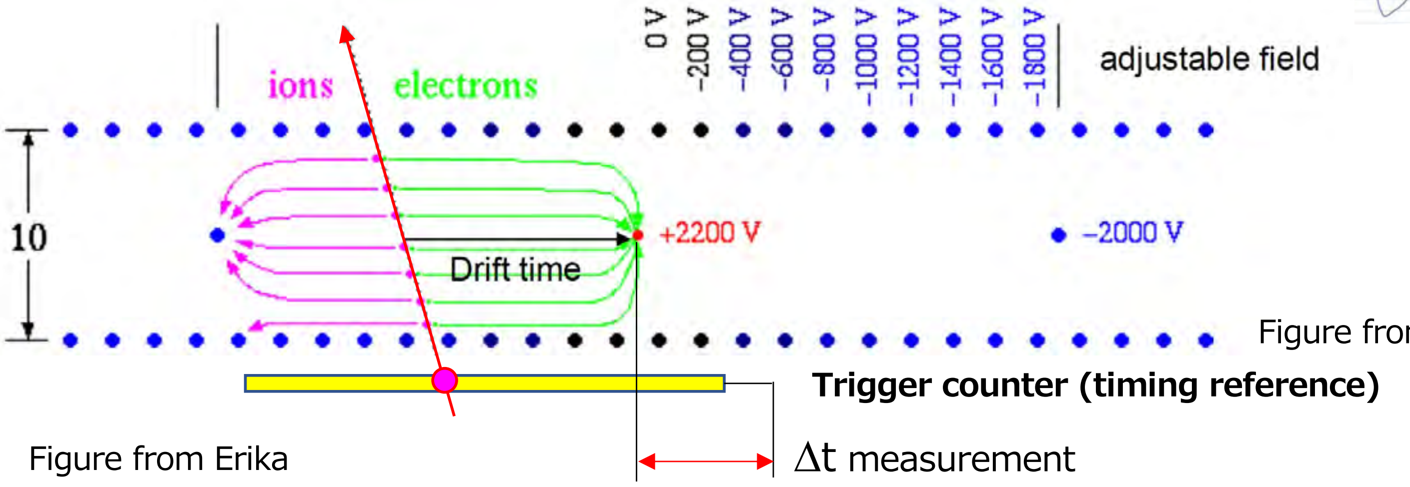


Figure from Erika

Figure from Erika

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

5. Operation of detectors ; Trackers ; Gas Chambers

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.

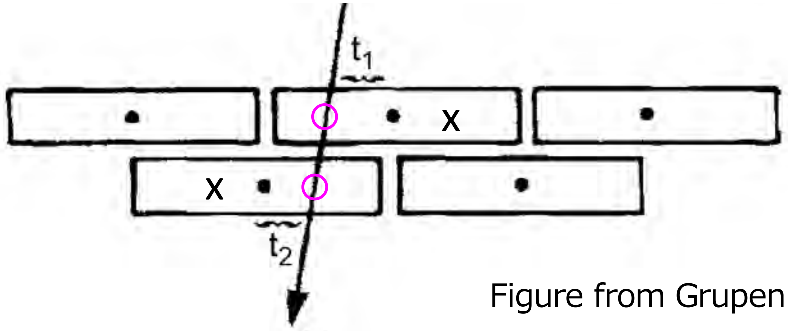
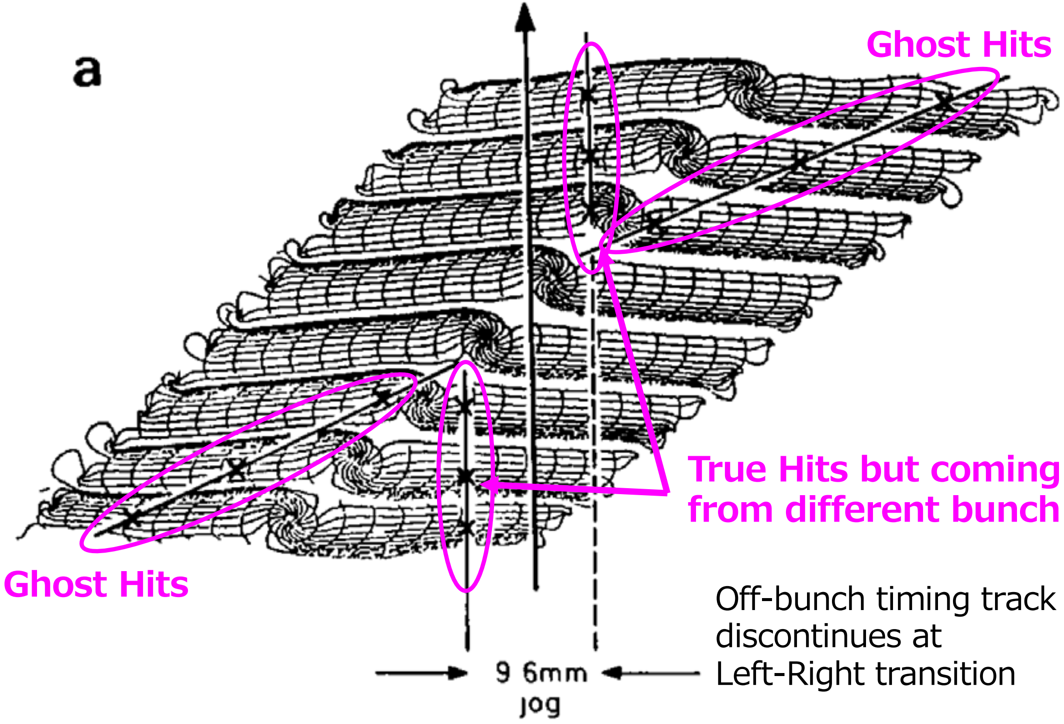


Figure from Grupen

On-bunch timing track be straight.



Off-bunch timing track discontinues at Left-Right transition

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