Particle and Radiation Detectors

- Design of Particle-Physics Detectors -

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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
- Knoll ; Radiation Detection and Measurement, by Glenn E. Knoll
- Lang ; Basic Elements of Particle Radiation Detectors at VSON2017, by Karol Lang
- Nakaya ; Particle and Radiation detectors at VSON2019, by Tsuyoshi Nakaya
- Erika ; Lecture "The Physics of Particle Detectors", by Erika Garutti
- Joram ; CERN Summer Student Lectures 2003, by Christian Joram

and many slides on the experiment reports.

Contents

Introduction 1/2 (probably)

Main topics 2/2 (probably)

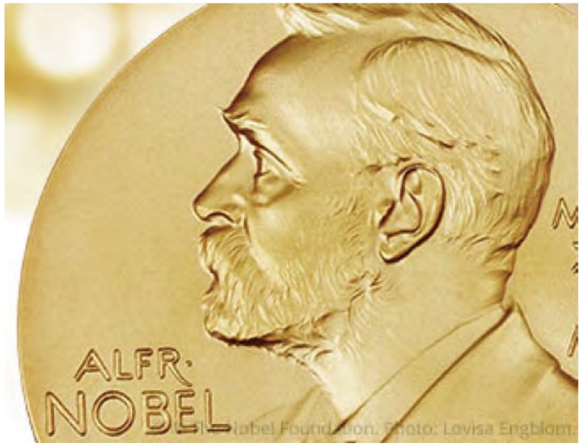
1. Pick up Reactions to Measure

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



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

Therefore, you must achieve both discovery and precision study.

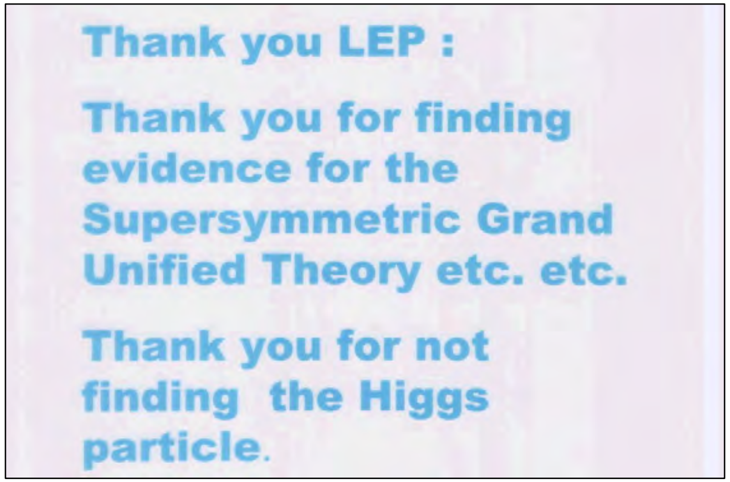
1. Pick up Reactions to Measure : Let's discover and study Higgs at LHC/ILC

<u>Assumed Situation</u> (like at the end of 20th century) ;

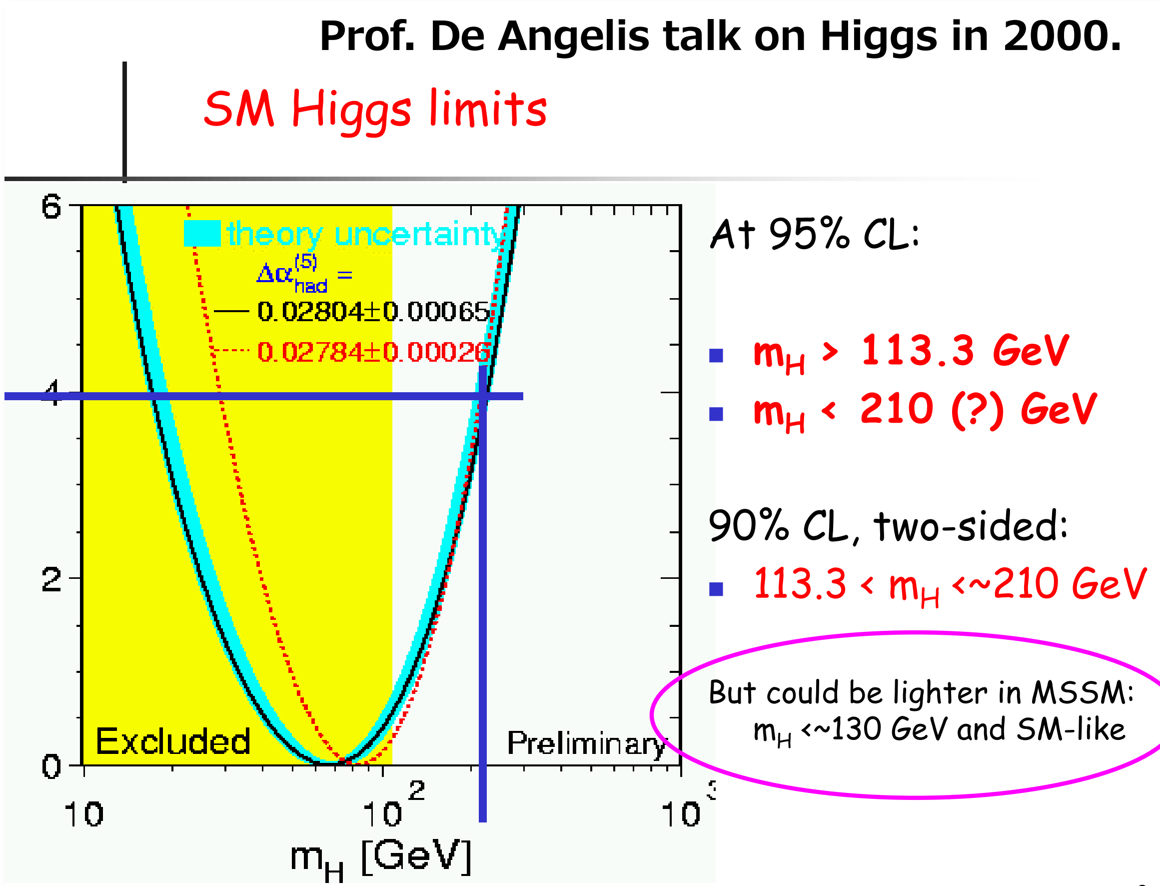
- Forget the actual discovery of Higgs at LHC in July 2012
- LEP saw something at ~115GeV

We know everything on the Standard Model Higgs except for its mass, but 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



Prof.Sugawara's remark at Osaka 2000 conference



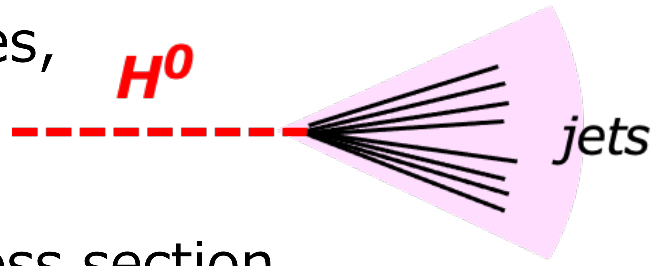
1. Pick up Reactions to Measure

First of all,
Let's discover Higgs

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.

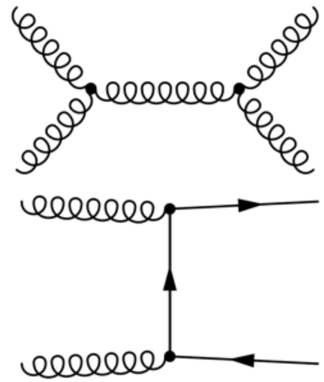
・Pick up decay mode with large branching ratio, easy reconstruction, and small background reaction.

Better S/N, faster discovery, cross-cut to the Nobel Prize.

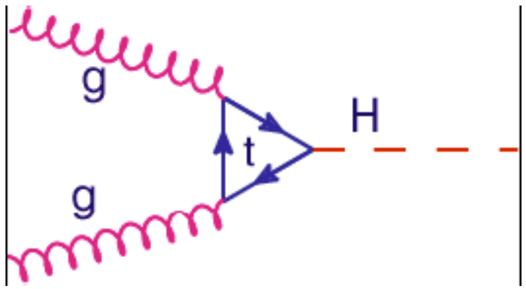
1. Pick up Reactions to Measure : Discover Higgs at LHC

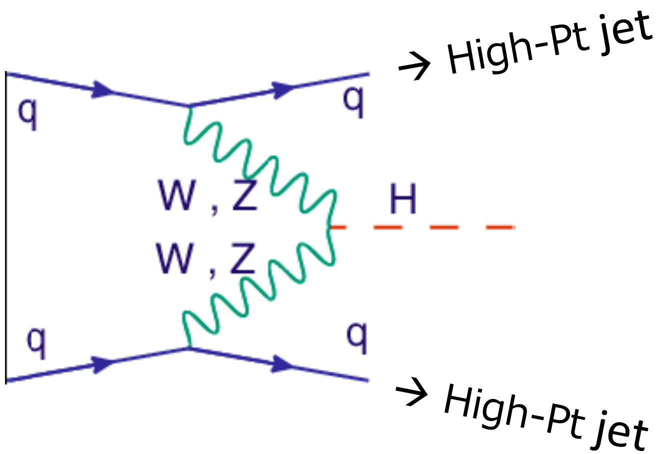
Higgs Production

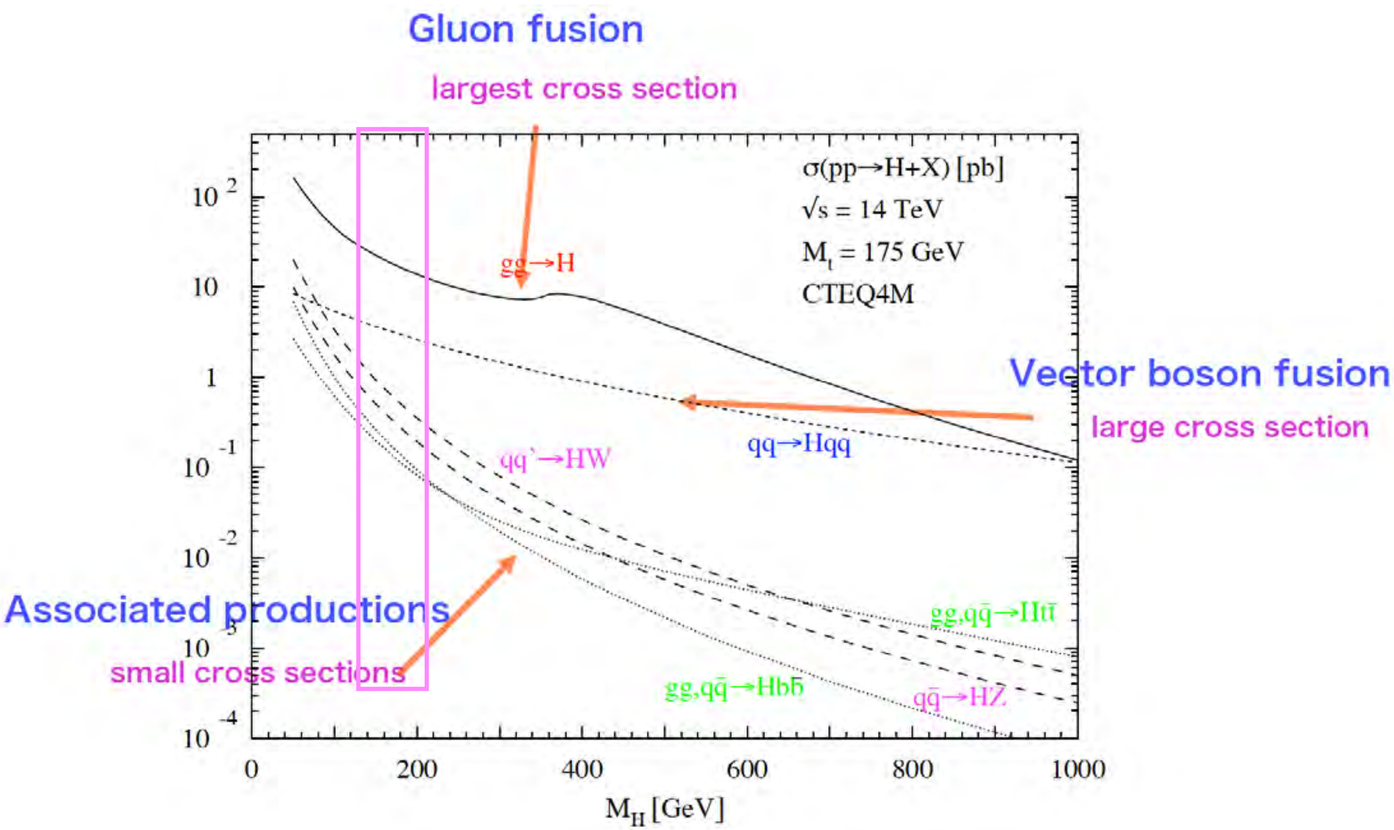
- $g + g \rightarrow H^0$ is dominant for m_H=113~210GeV
  We should choose clear decay mode of H^0
  since there are no associated particles to characterize this reaction.
- $q+q \rightarrow q+q+H^0$ has the second-largest cross section.
  Outgoing qq can be used for reaction tagging.
  A bit complicated decay mode could be used.



QCD Background reaction generates hundreds of low-energy particles.





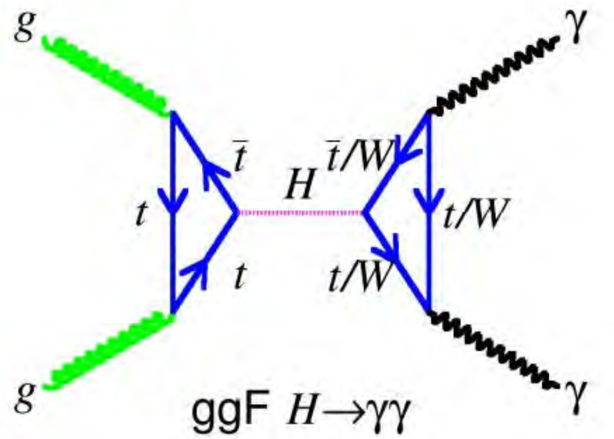


1. Pick up Reactions to Measure : Discover Higgs at LHC

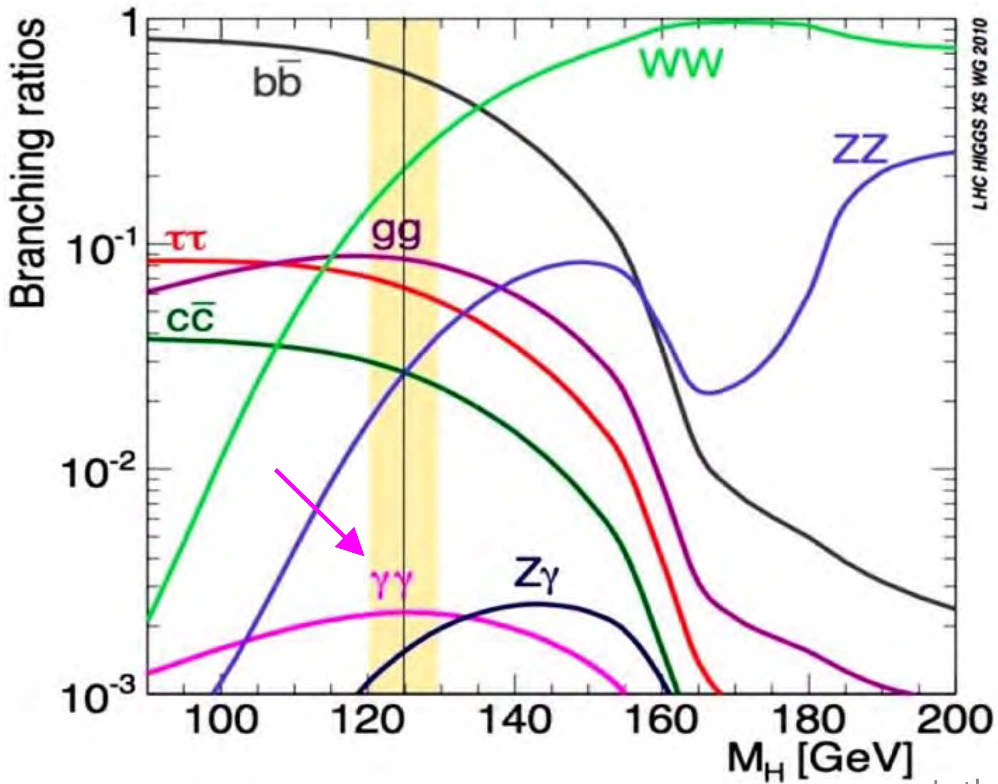
Decay mode

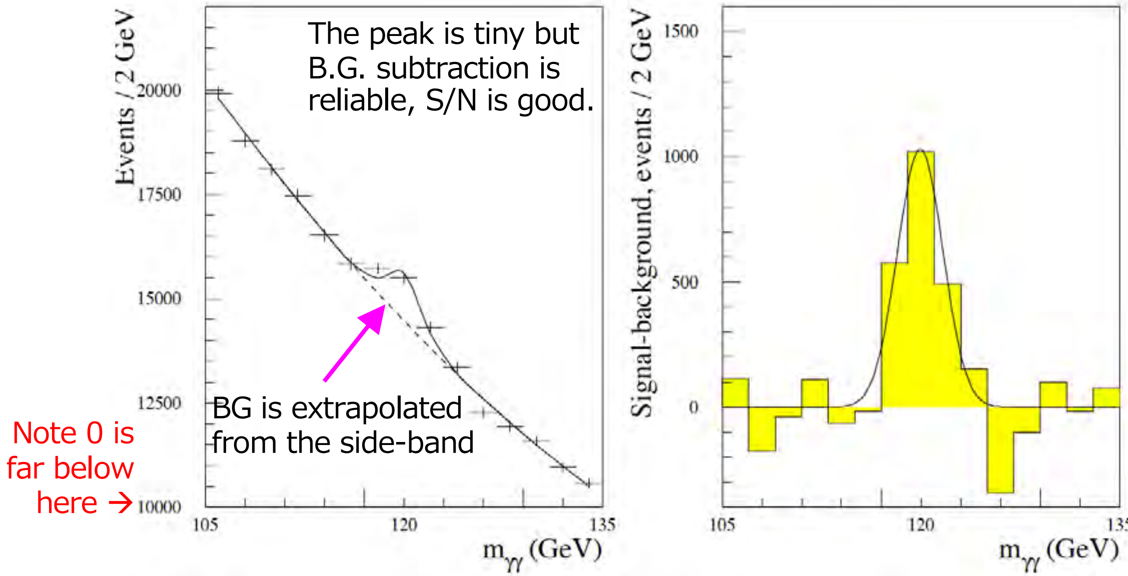
$H^0 \rightarrow \gamma\gamma$ (for light H^0)

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



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

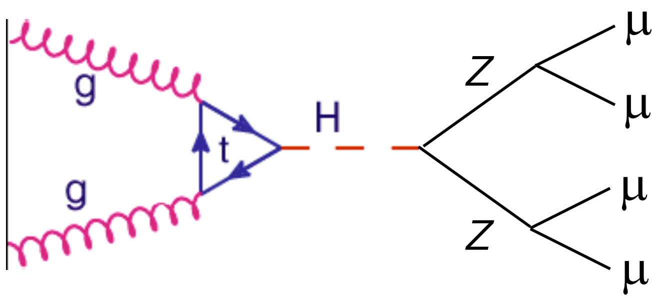


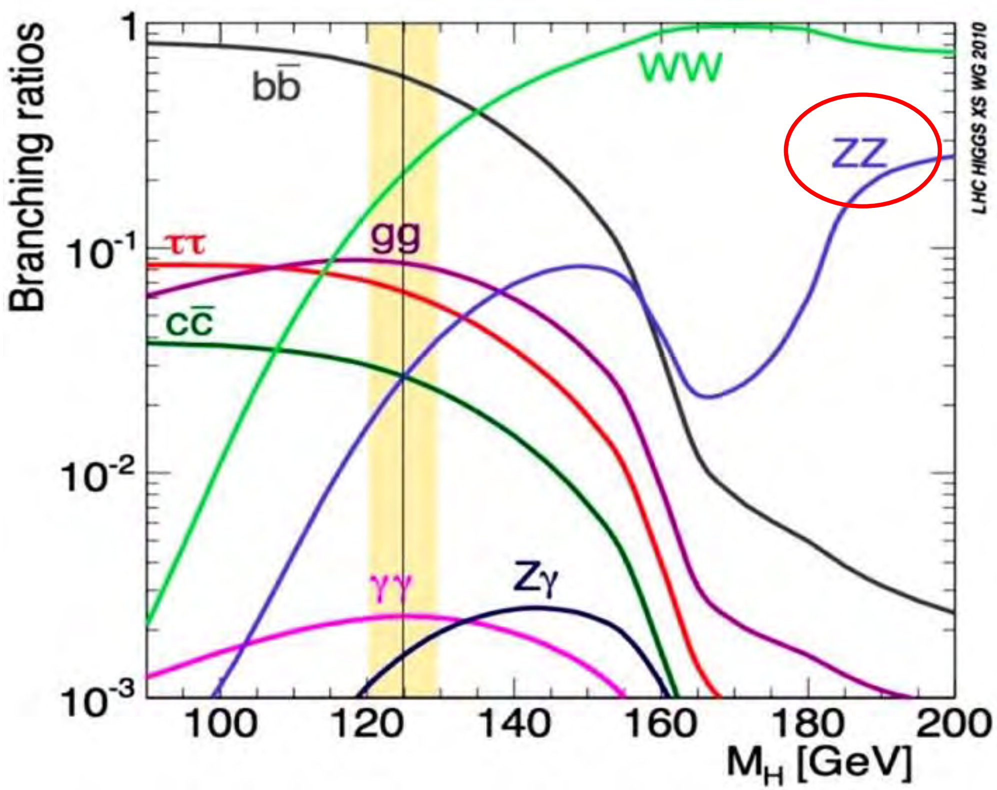


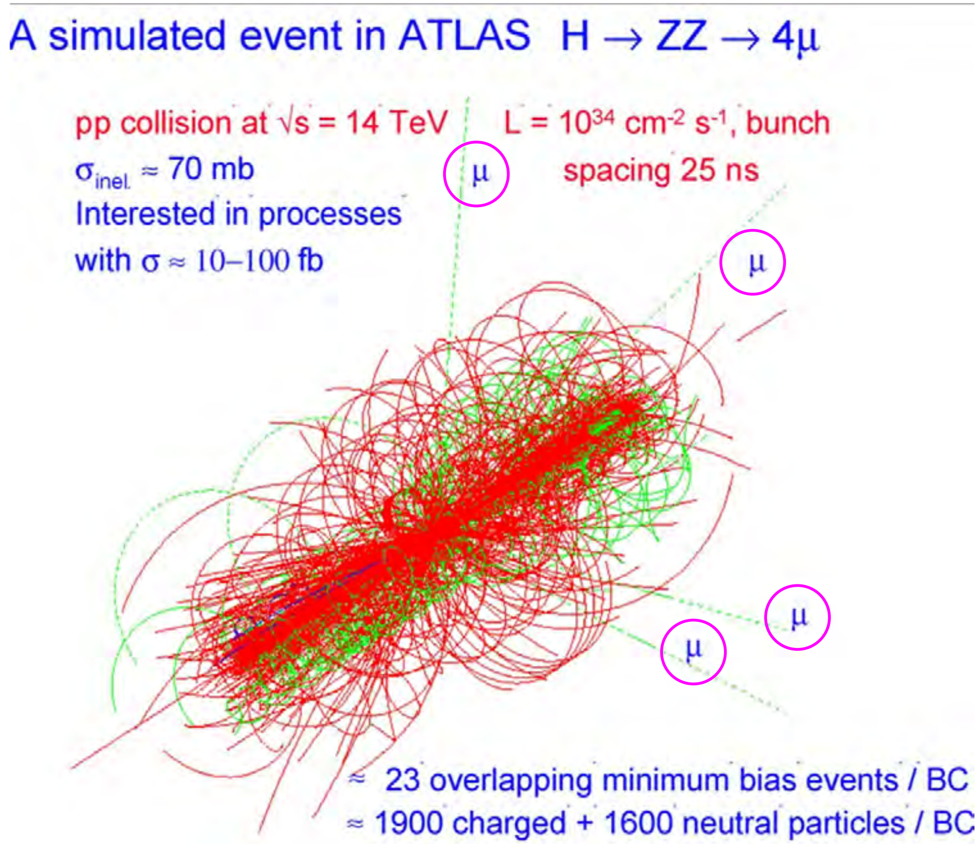
$\gamma\gamma$-mass (simulation in ATLAS TDR)

Another Decay mode

Higgs → ZZ* → 4μ (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→ZZ→4μ ~0.01%)
  since Z-decay to μμ is only 3.4%.







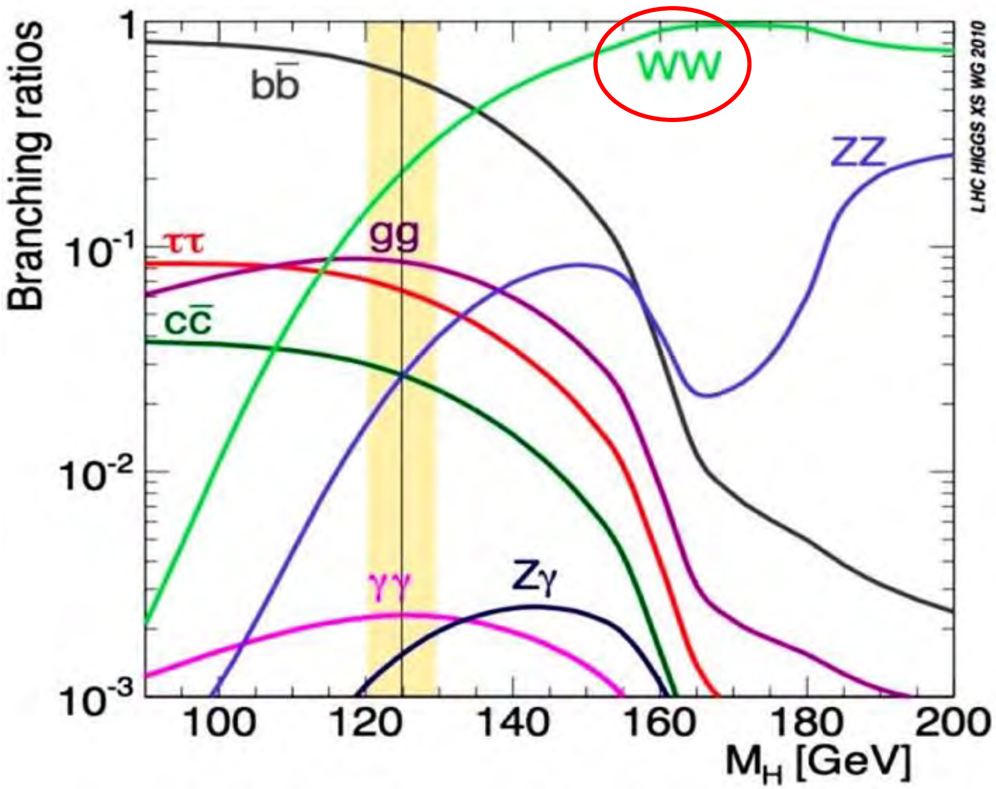
What about Other Decay modes ?

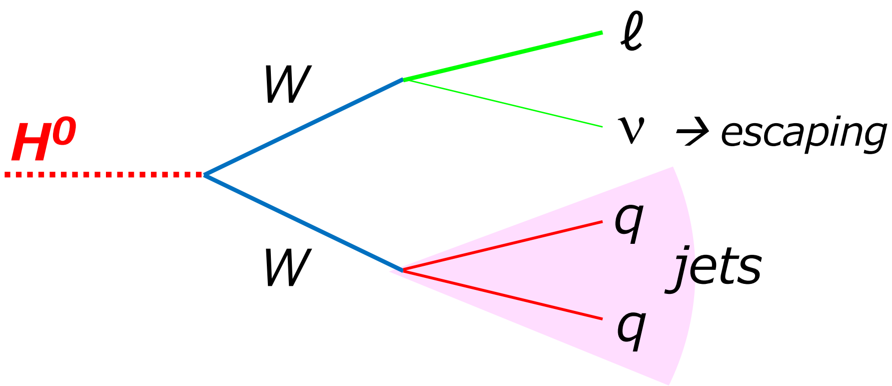
In the allowed H^0 mass region,

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 promissing.

For above, we need

- Excellent gamma measurement
- Excellent muon measurement

1. Pick up Reactions to Measure

Let's discover Higgs at ILC

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.

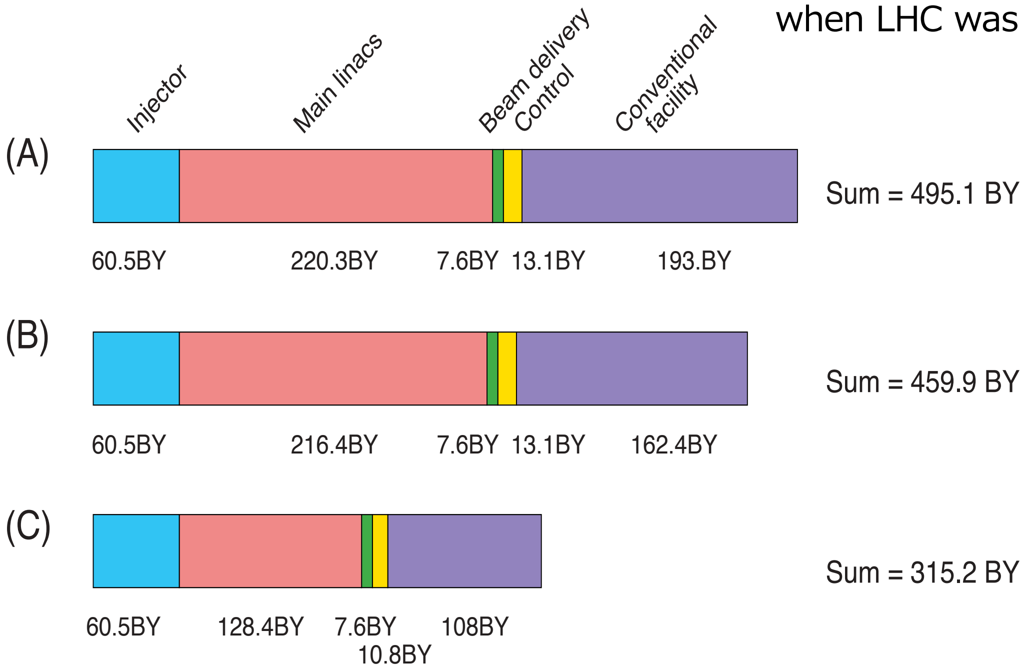
Better S/N, faster discovery, cross-cut to the Nobel Prize.

Let's discover Higgs at ILC √S=300GeV

a) Make invariant mass of Higgs decay particles, and find a peak, like LHC case.

b) There is another way at ILC:
Reconstruct recoiling system of Higgs and make recoil mass spectrum.

JLC 300GeV version was on the table as of 2003, when LHC was under construction.



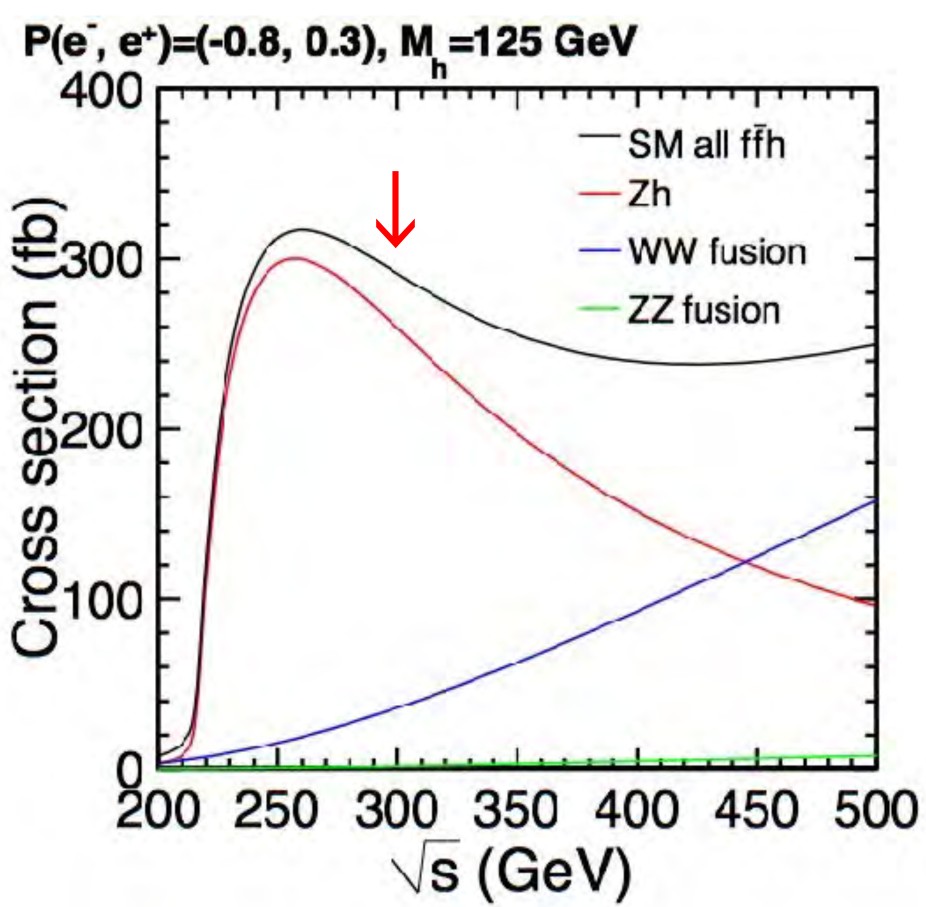
- The base design is for Ecm=500 GeV using X-band (tunnel for 1 TeV).
- Ecm=500 GeV (tunnel for 500 GeV)
- Ecm=300 GeV (tunnel for 300 GeV)

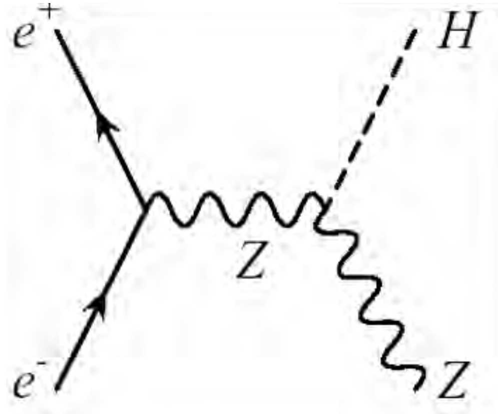
1. Pick up Reactions to Measure : Discover Higgs at ILC

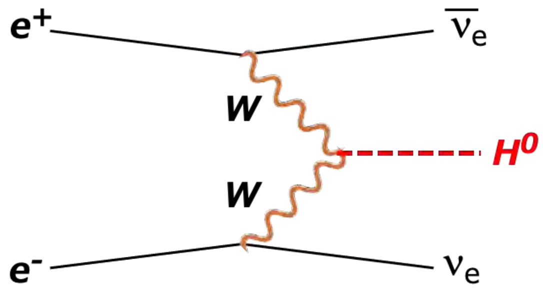
Discovery mode

Production Channel is, no doubt,

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







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

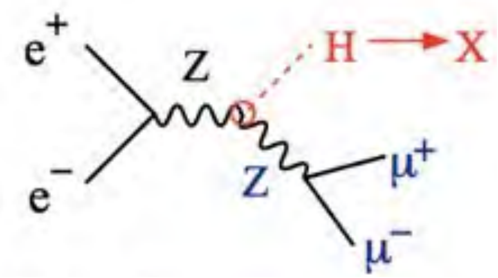
e+ e- → Z^0H^0

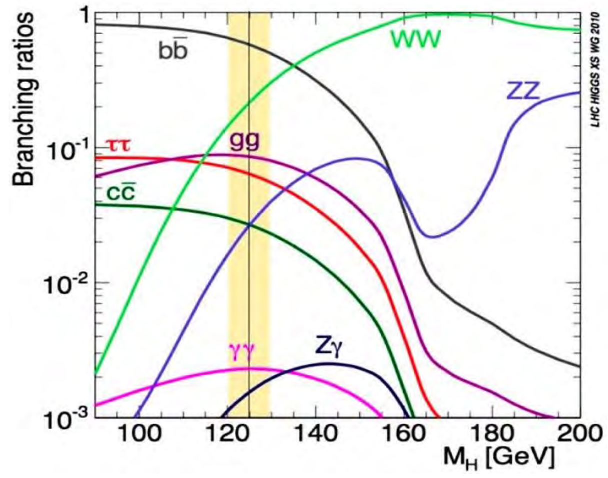
a) H^0 → *bb* (largest branching ratio of 58%)

Z^0 → anything (do not analyze)

Reconstruct H^0 *b* decay explicitly.

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



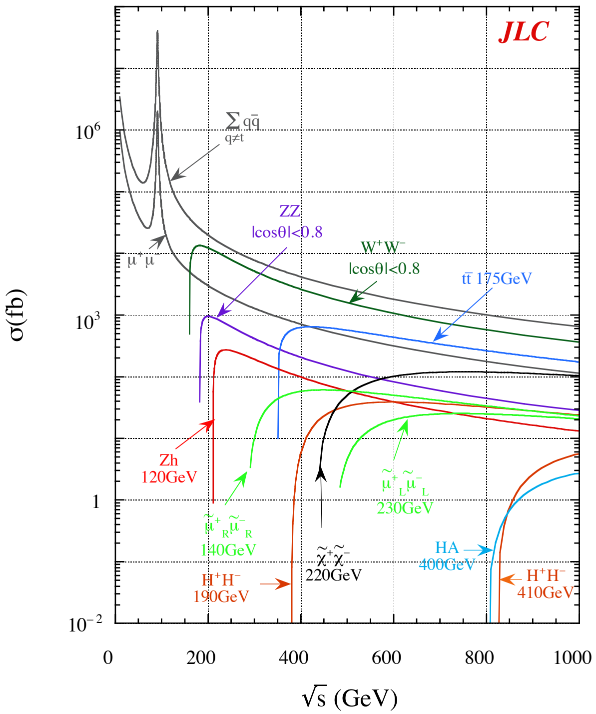


b) Z^0 → $\mu^+\mu^-$ (unambiguous decay channel)

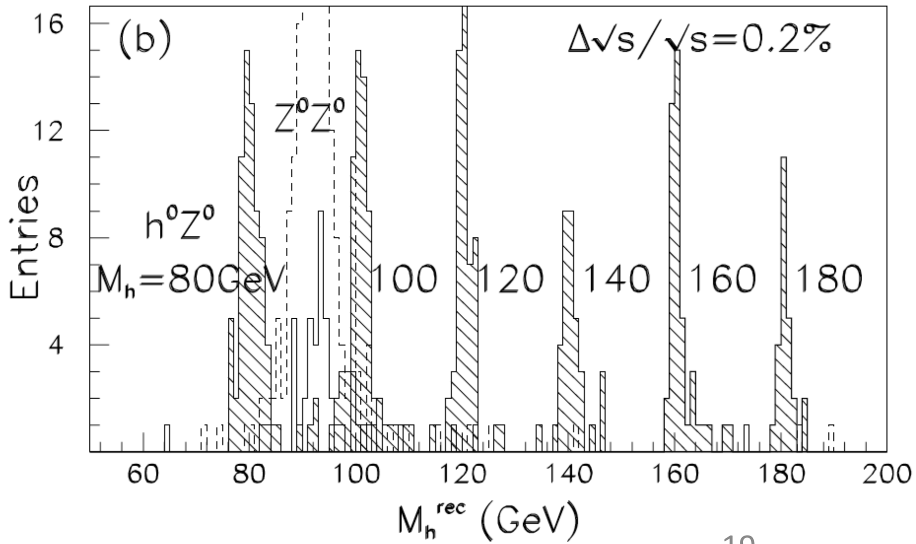
H^0 → anything (do not analyze)

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.



In order to discover Higgs at ILC, we pick up

e+ e- → Z^0H^0 ,

Z^0 → $\mu^+\mu^-$,

H^0 → anything

For above, we need

- Excellent muon measurement

Muons are always the key to carry new physics.

1. Pick up Reactions to Measure

Let's study Higgs at LHC/ILC

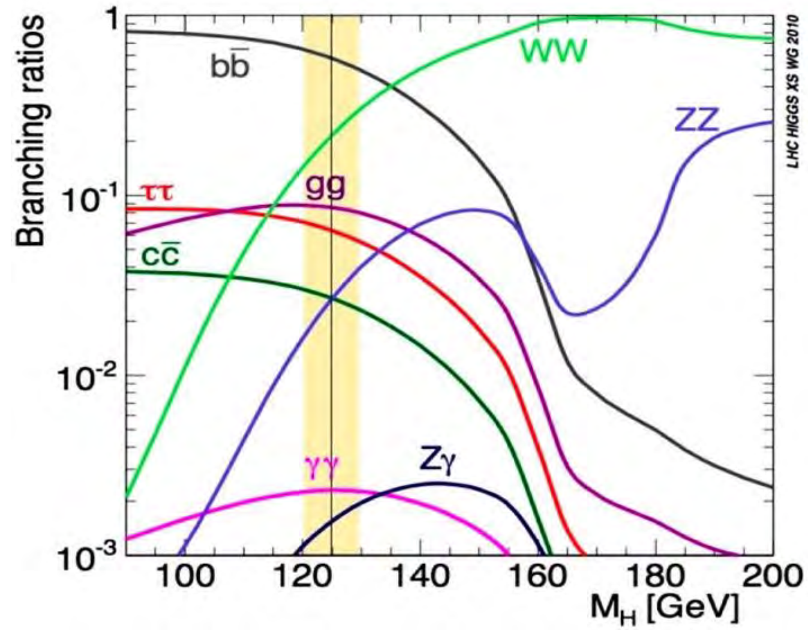
Discovery is just a start of Higgs Physics.

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

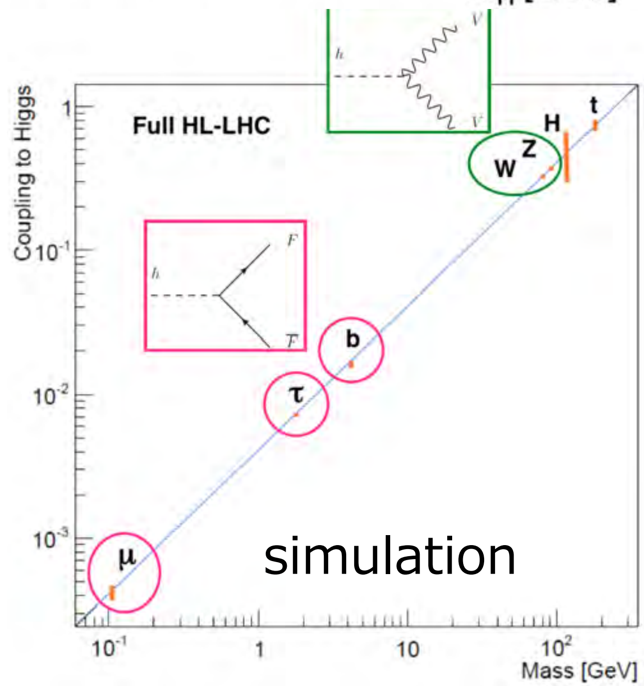


Detailed study

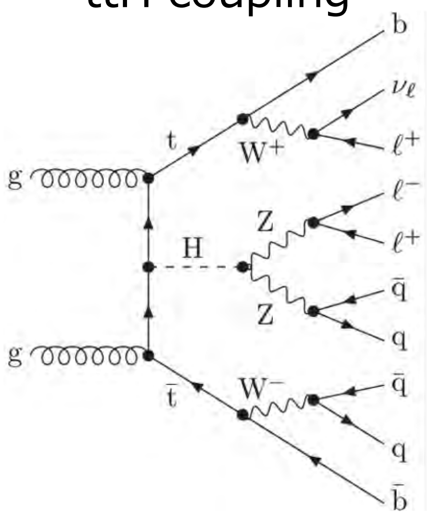
- Confirm spin/parity
- Explicitly reconstruct all H^0 decays modes to confirm coupling of particles to Higgs.
  - Coupling to top, Z, W needs study of associated production.
- Hadronic decay of H^0 and hadronic decay of associated t/Z/W suffer huge QCD background.
  → needs signature to distinguish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

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

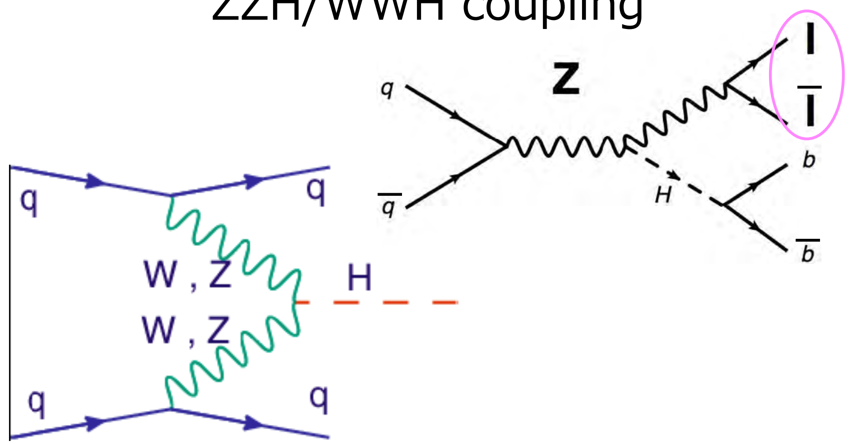
  Z^0 leptonic decay for event signature.



ttH coupling



ZZH/WWH coupling



Detailed study

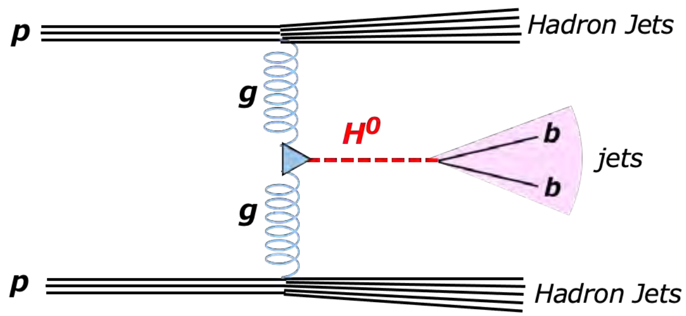
Quarks and Z/W mostly decay into "hadron jets".

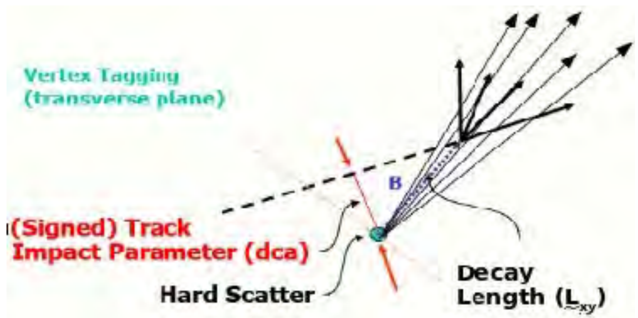
- Excellent jet reconstruction needed
- Excellent hadron flavor identification needed
- Hadronic decay of H^0 suffers huge QCD background

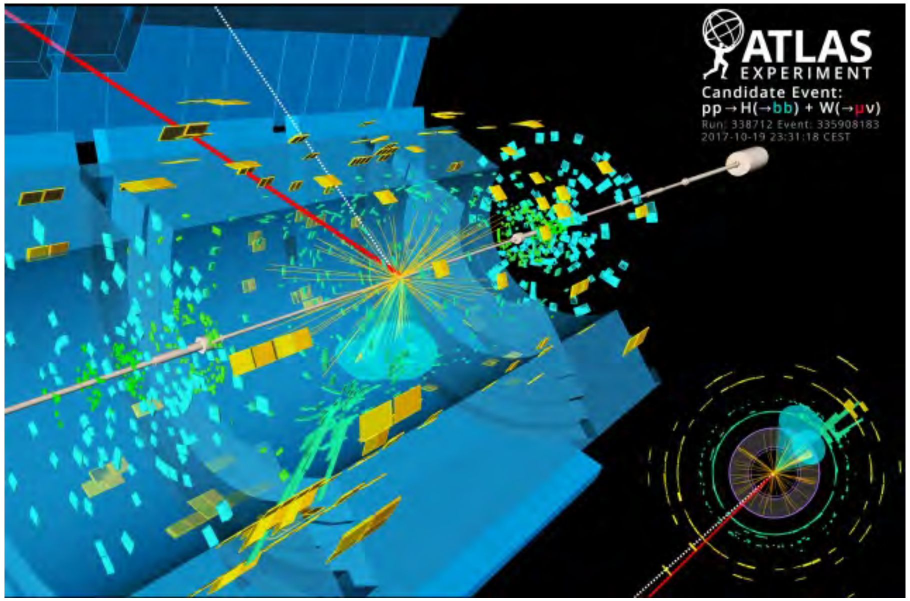
  → needs characteristic associating particles to distinguish H^0 production from background reaction

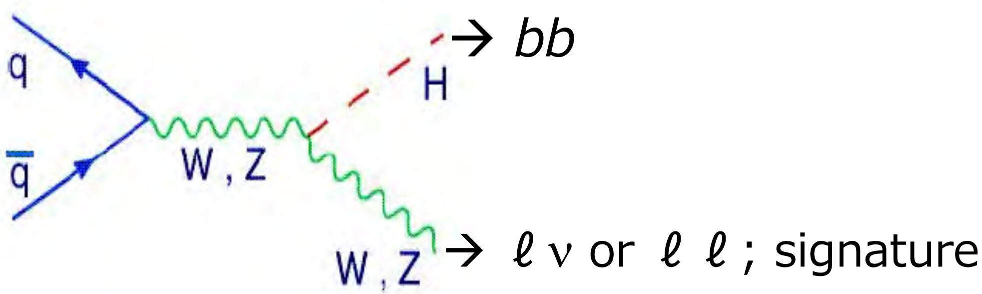
  ex.; $q+q$ → W/Z^0+H^0 ;

  W/Z0 decay particles for event signature









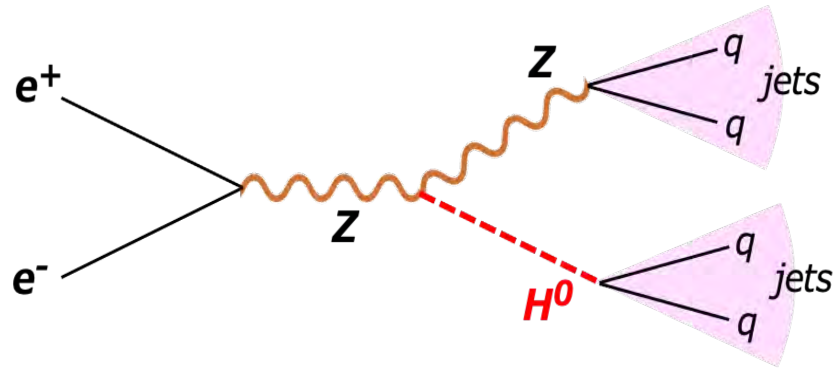
A candidate event display for the production of a Higgs boson decaying to two *b*-quarks (blue cones), **in association with a W boson** decaying to a muon (red) and a neutrino. The neutrino leaves the detector unseen, and is reconstructed through the missing transverse energy (dashed line). (Image: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

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

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

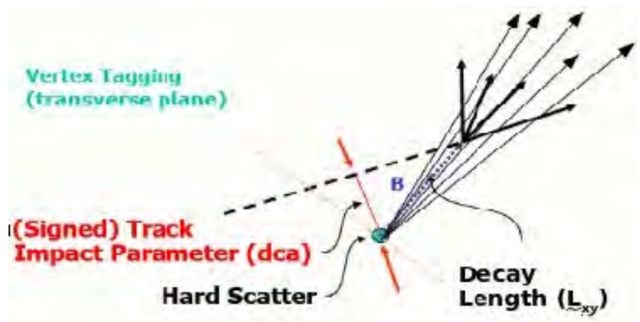
$Z^0 \rightarrow qq, \ell\ \ell$

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



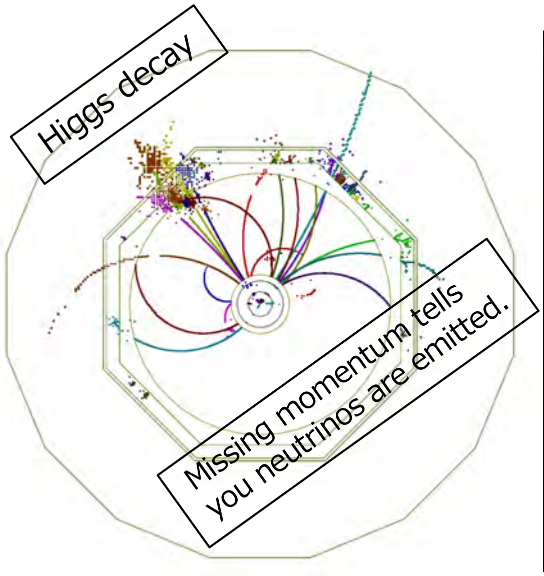
Detailed study

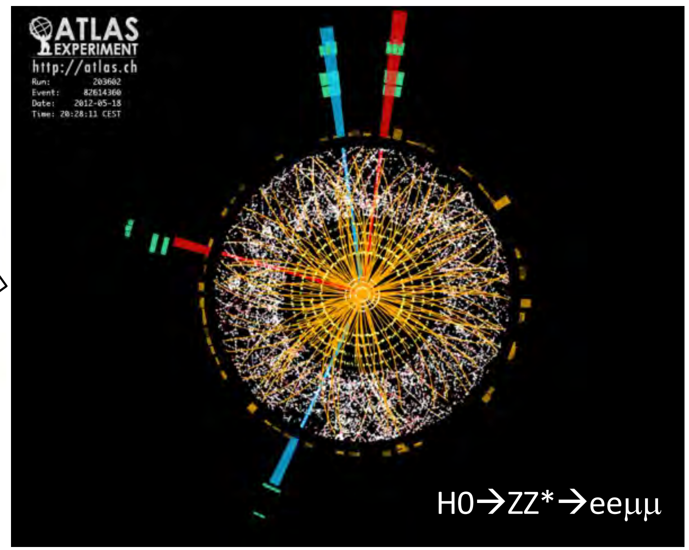
- Quarks and Z/W bosons mostly decay into "hadron jets".
  → Excellent jet reconstruction needed
- Excellent hadron flavor identification needed



Advantage of e+e- collider

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





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 hadron flavor tagging
- production channel associated with characteristic particles

2. Overview 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.

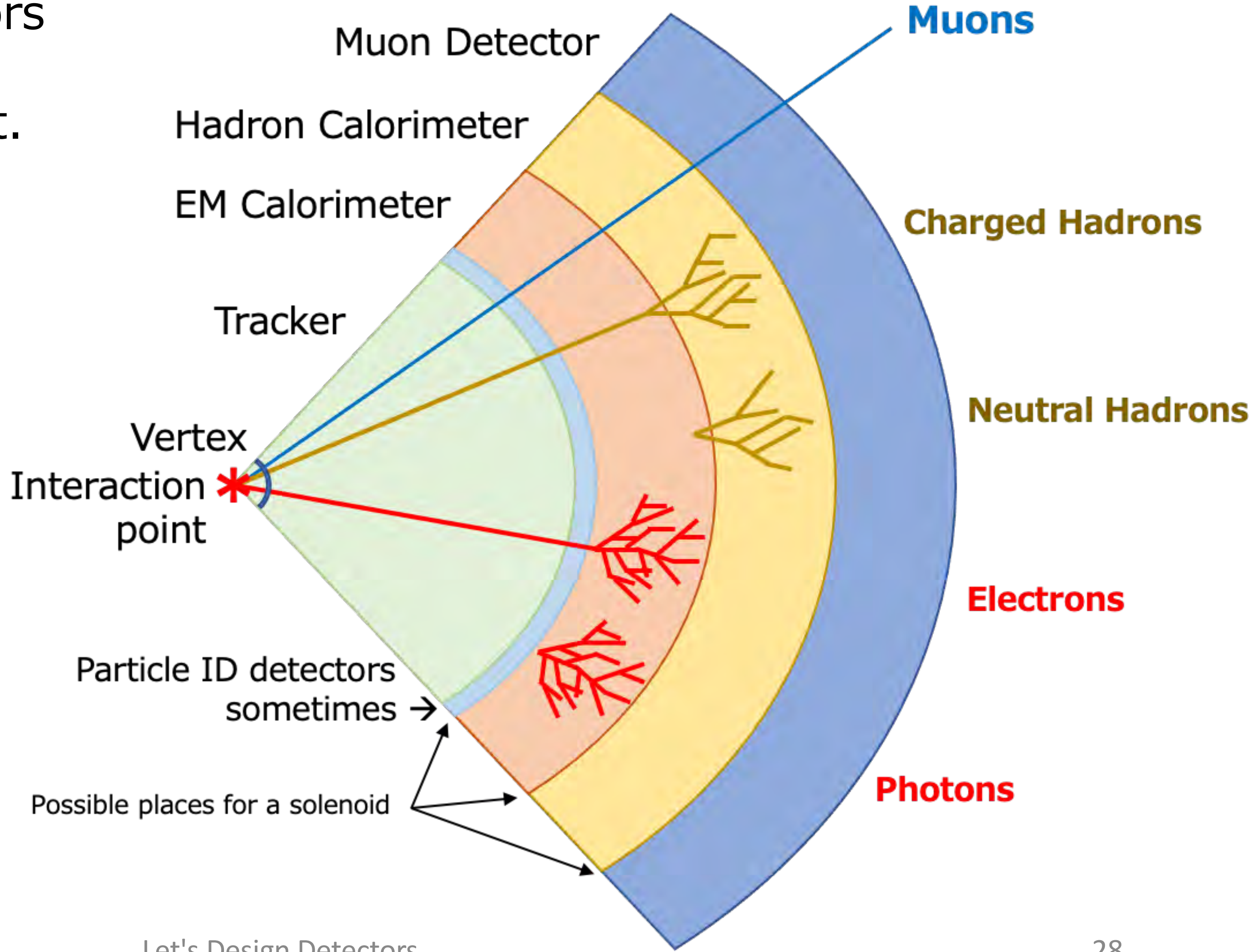
Necessity of particle identification is different exp. by exp.

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

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 ?



Common feature of the detector system

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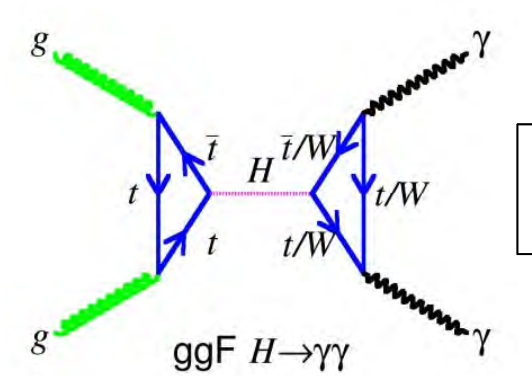
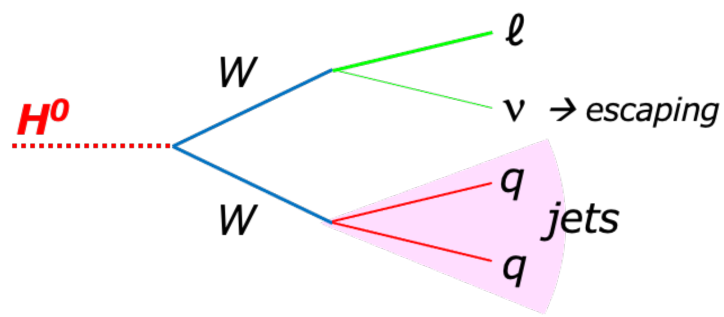
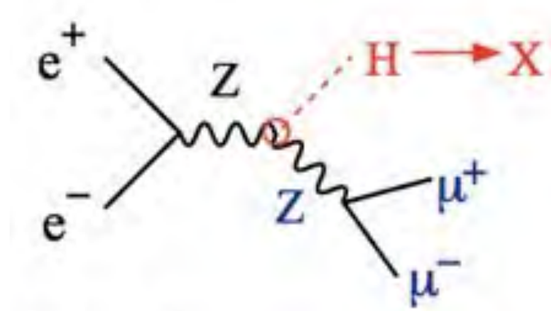


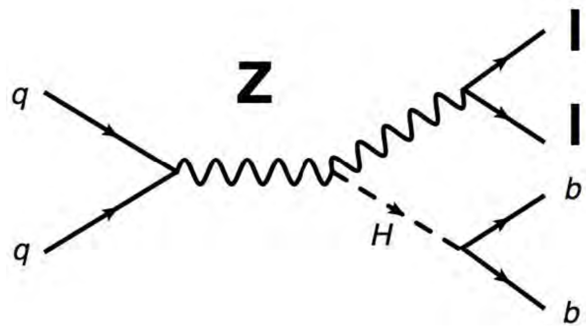
γs measured by EM calorimeters



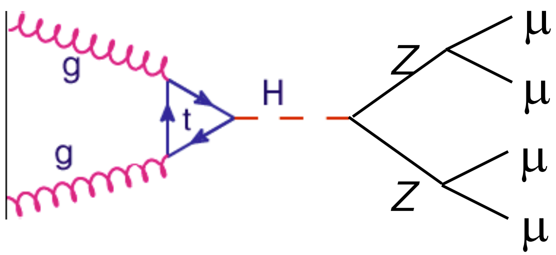
Jets measured by trackers and calorimeters

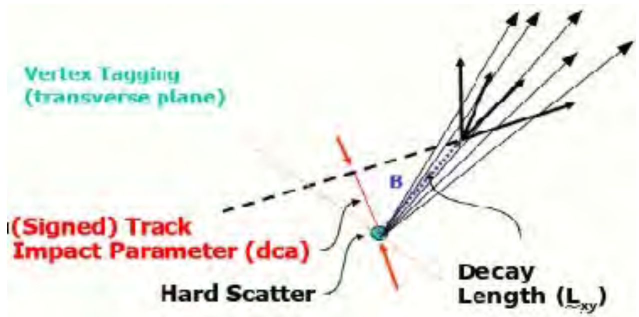


jets



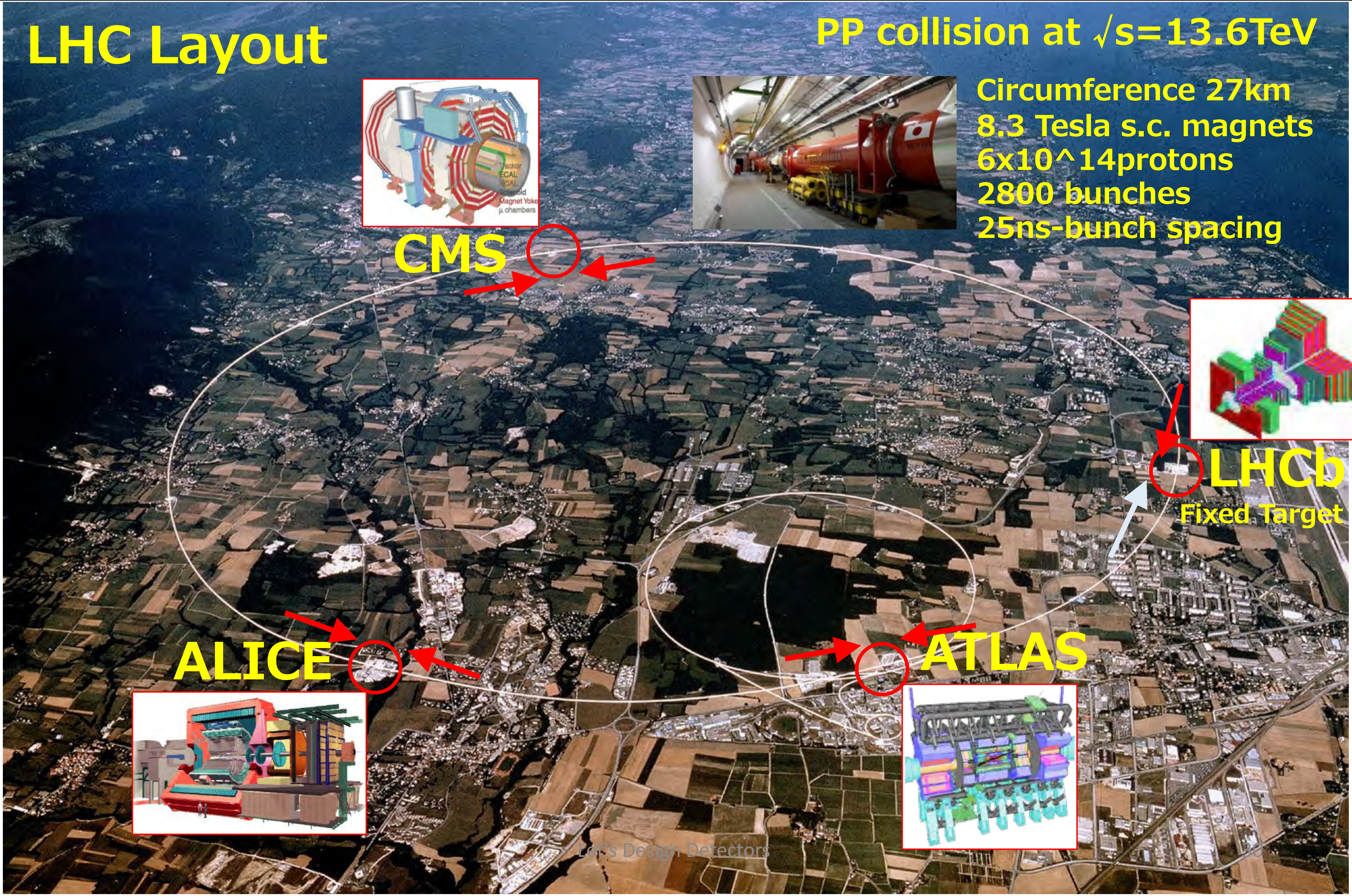
μs measured by muon detectors and trackers



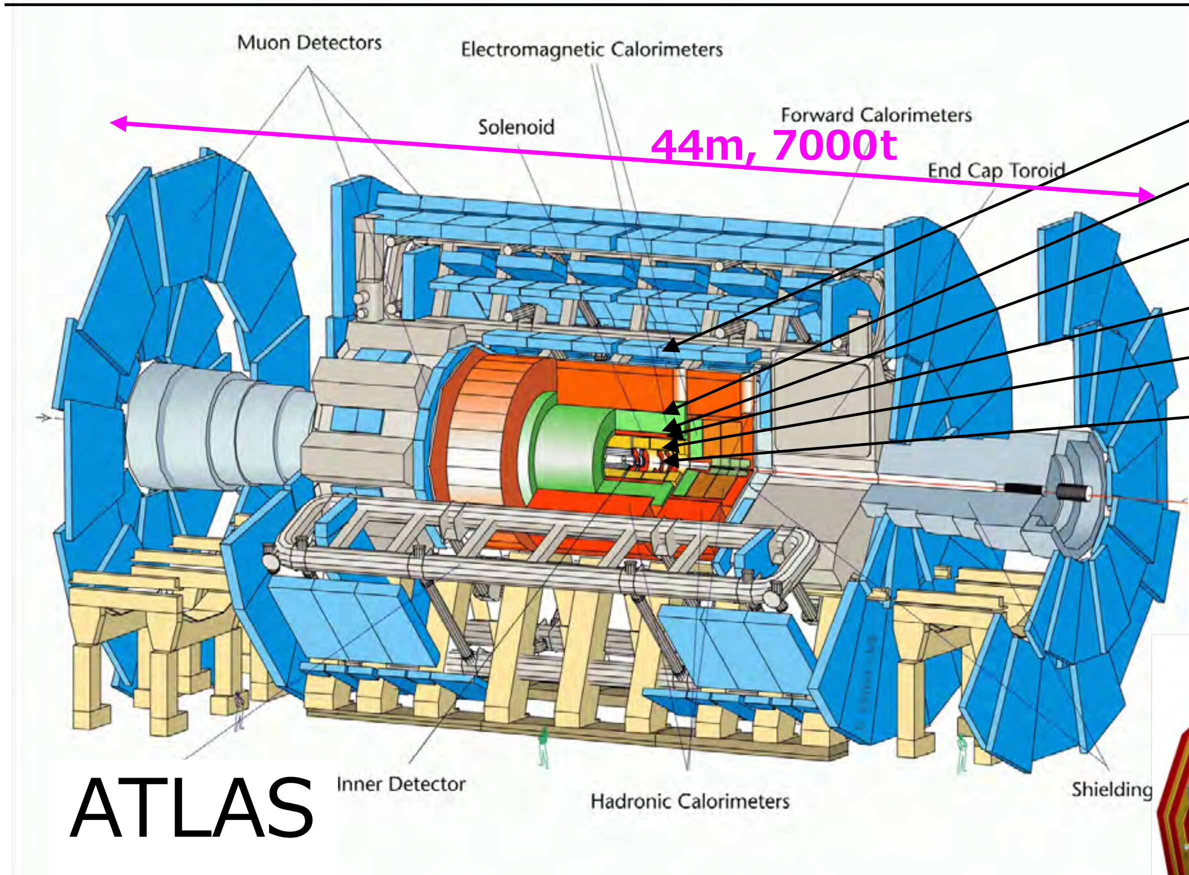


b-quarks identified by vertex detectors.

2. Overview the various detector configuration : LHC

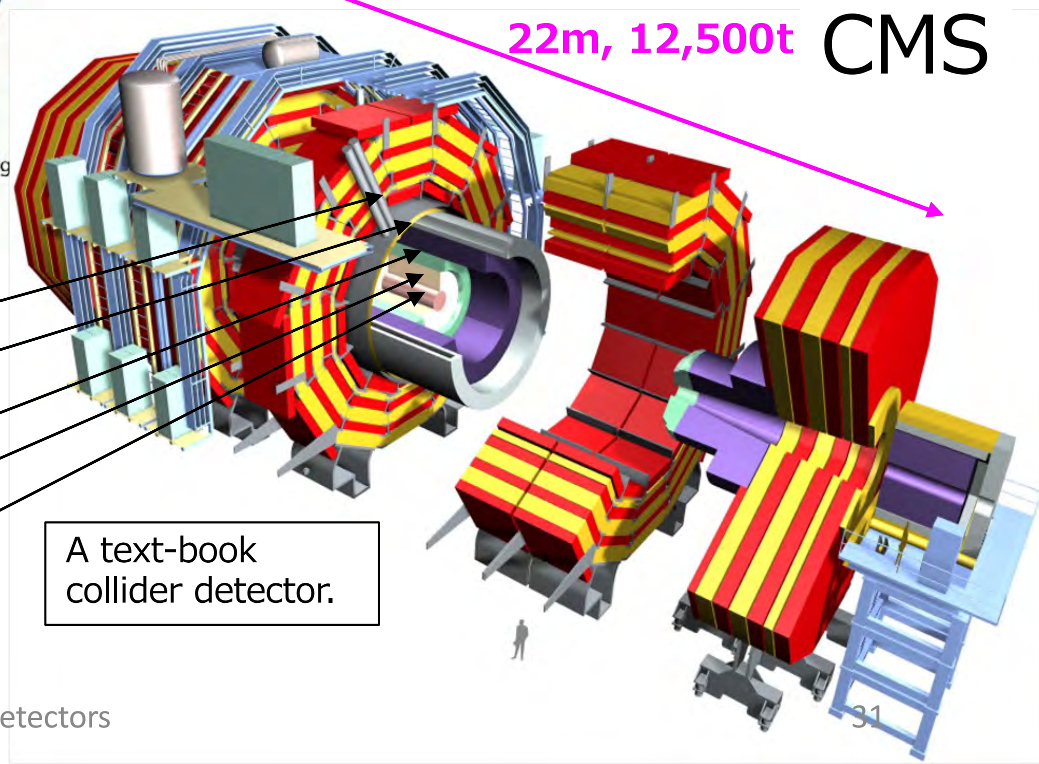


2. Overview the various detector configuration : LHC



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

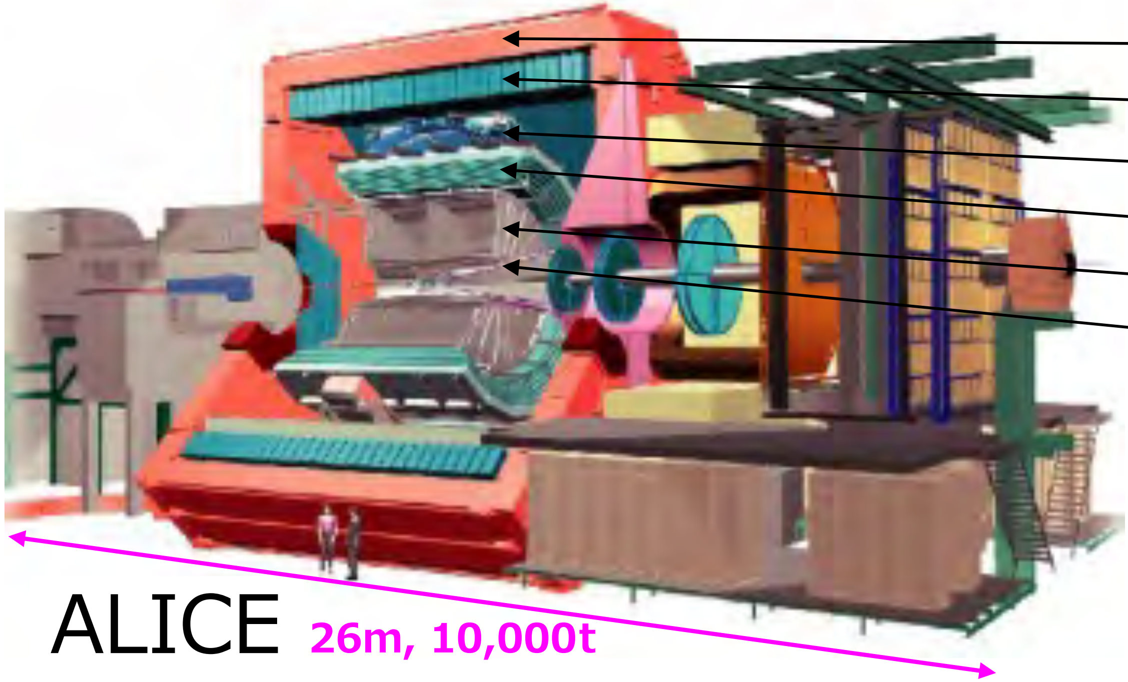
Additional electron identification detector used since thick solenoid is in front of calorimeters.



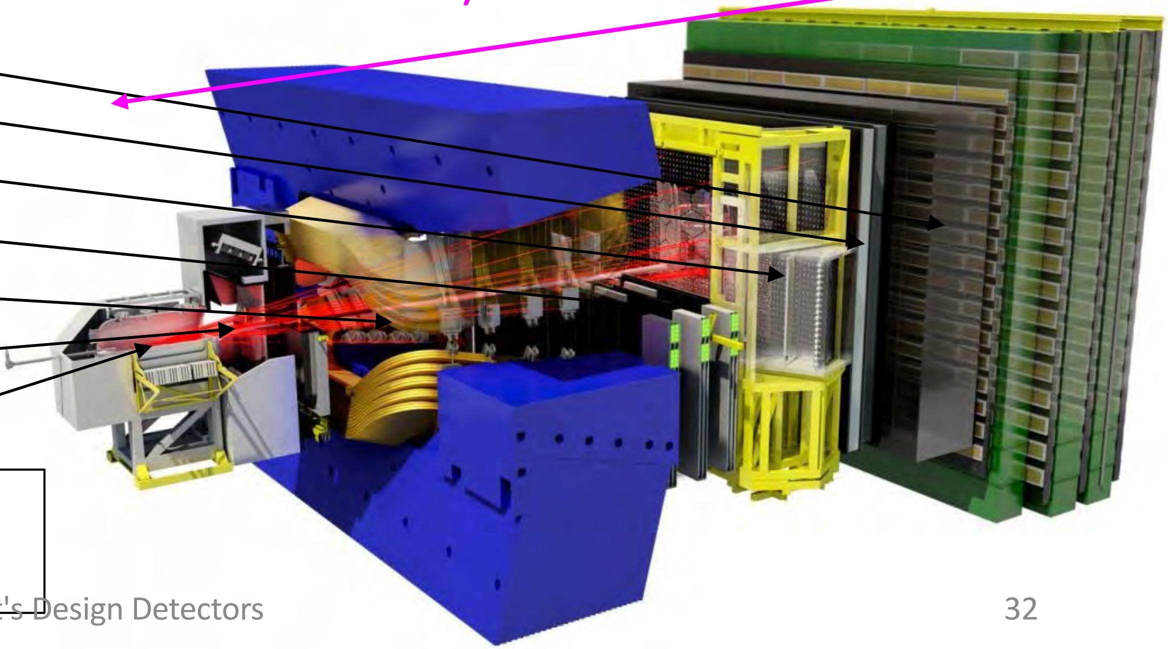
Muon detector
Solenoid
Calorimeter
Tracker
Vertex detector

A text-book collider detector.

2. Overview the various detector configuration : LHC



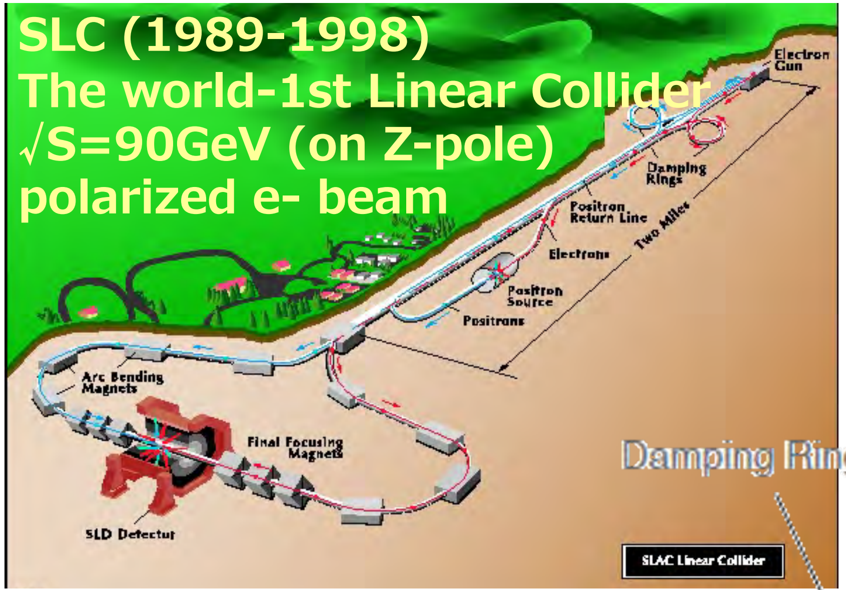
Heavy-ion collision experiment for q-g plasma. The best electron identification needed for their physics target.



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

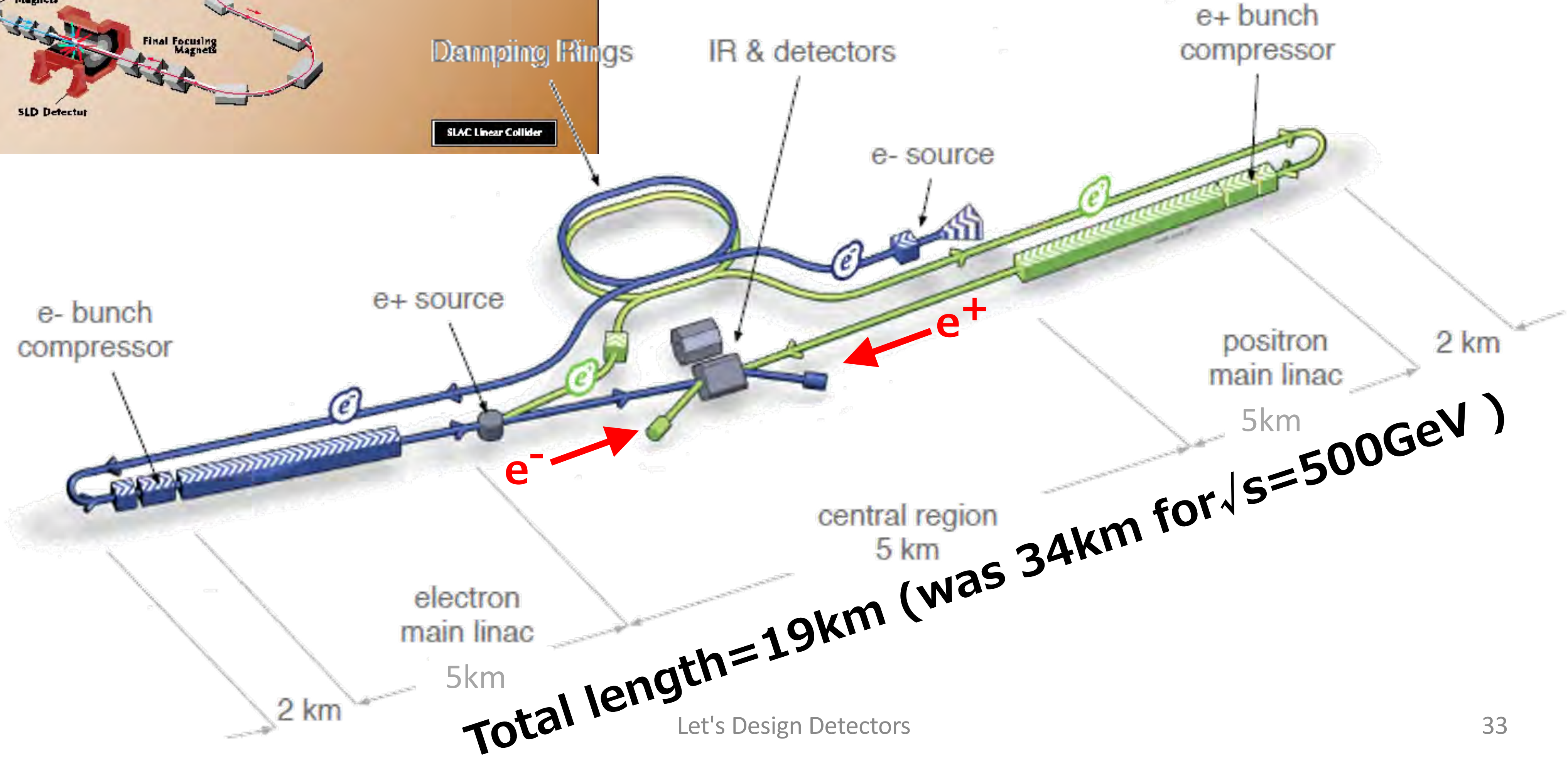
2. Overview the various detector configuration : Linear Colliders

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



Linear Collider Layout

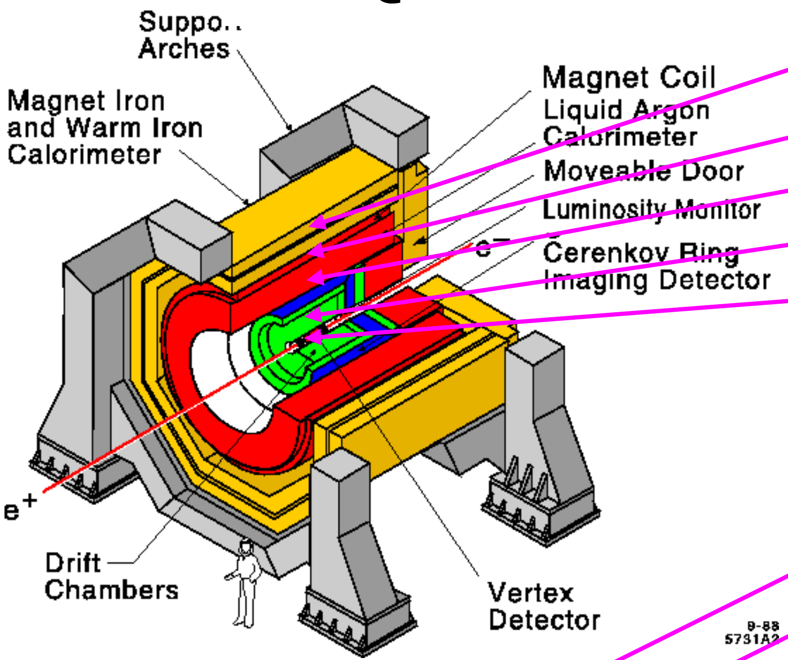
ILC as of 2018
e+e- collision at √s=250GeV
Beam sizes ; V=7.7nm, H=515nm
Pulse Rep.Rate ; 5Hz
Bunch-space ; 554ns
1312 bunches/pulse



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

2. Overview the various detector configuration : Linear Colliders

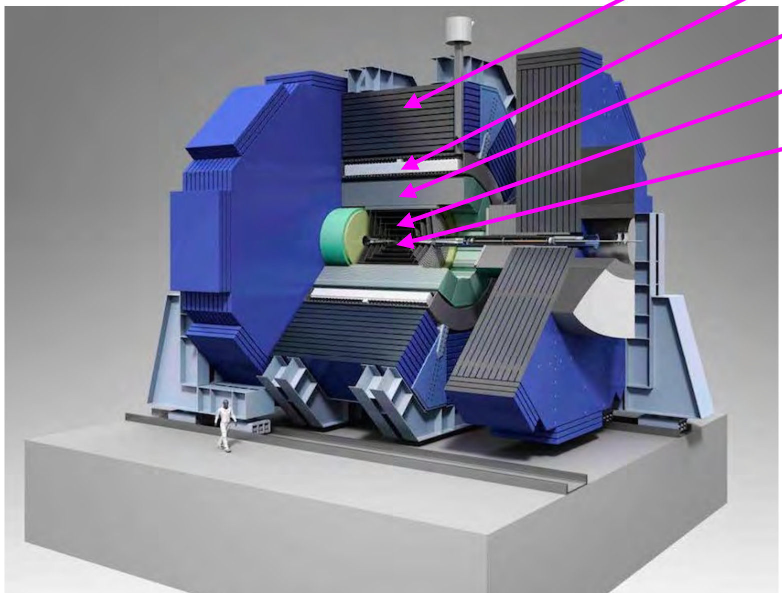
SLD @SLC



Muon detector
Solenoid
Calorimeter
Tracker
Vertex detector

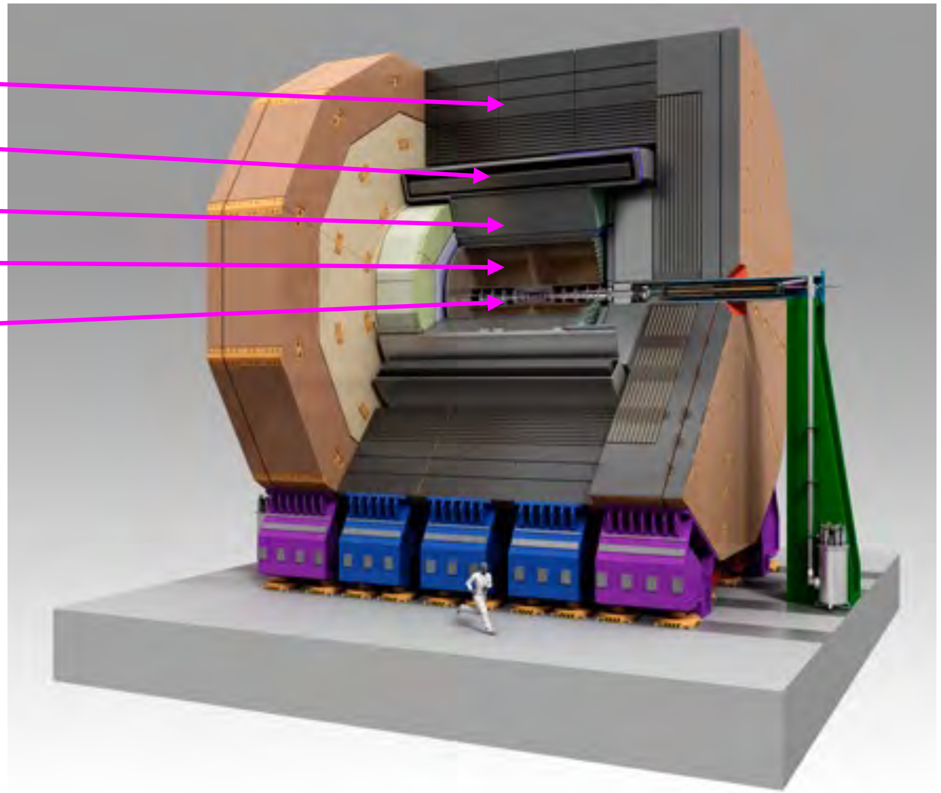
A text-book collider detector.

Muon detector
Solenoid
Calorimeter
Tracker
Vertex detector



Compact SiD

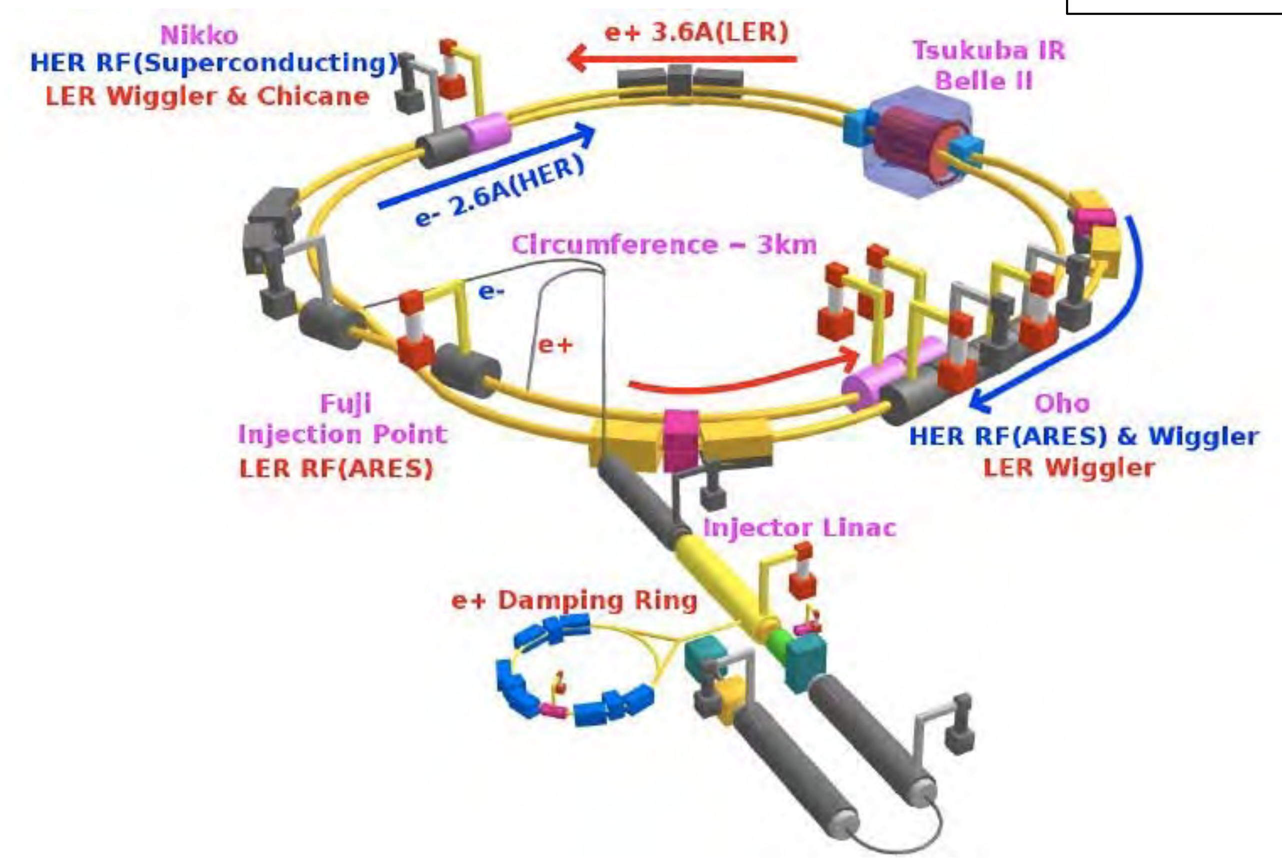
Concept similar to CMS.



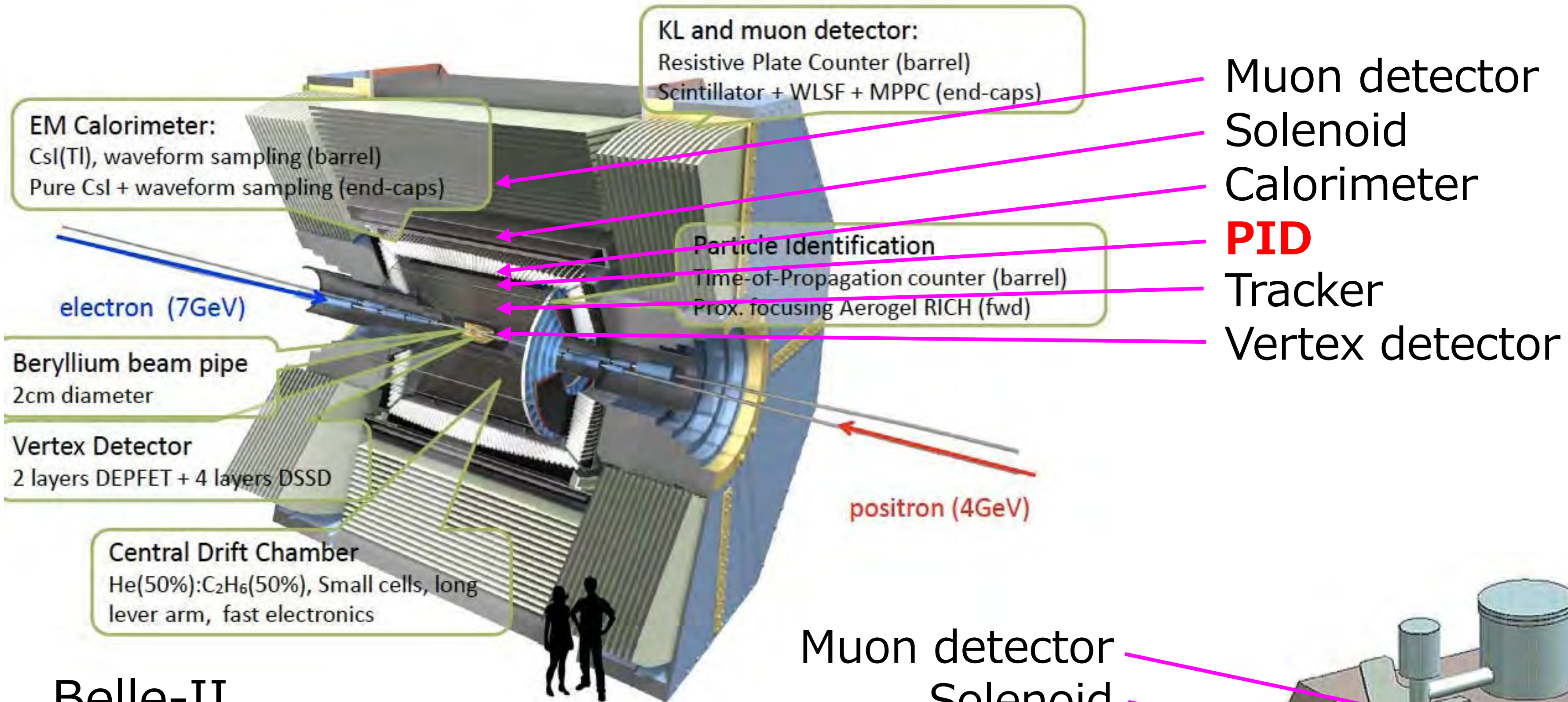
General-purpose LCD

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



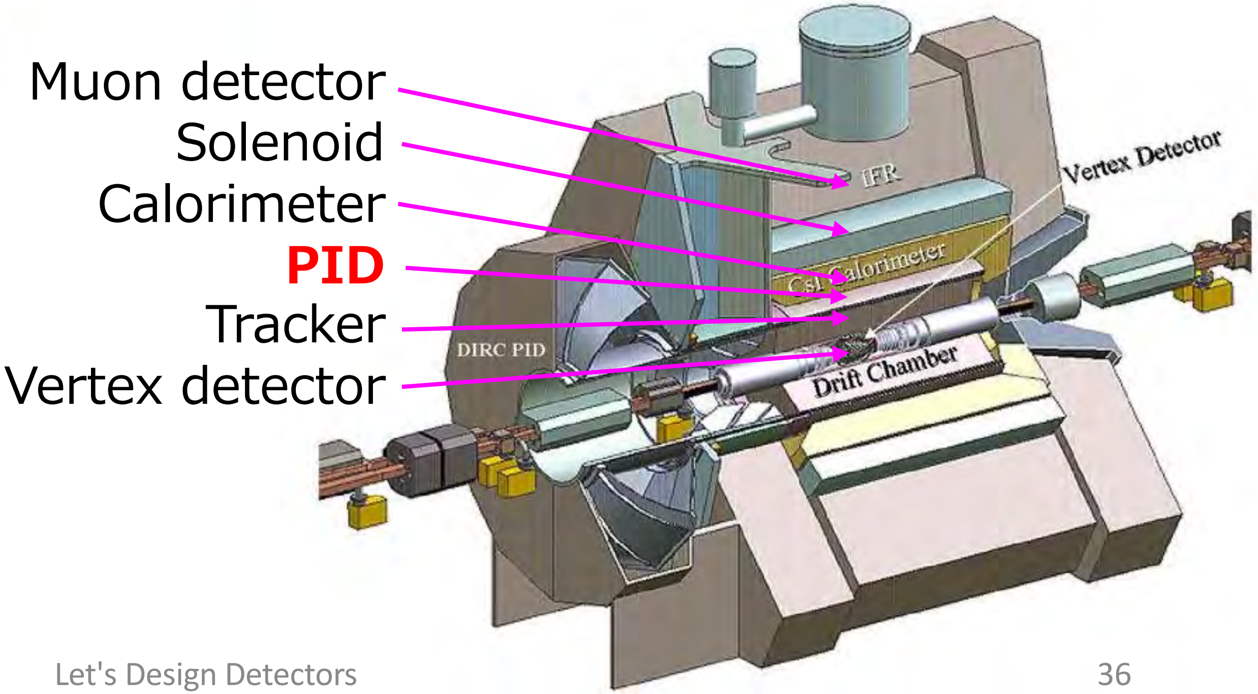
2. Overview the various detector configuration ; B-Factory



Belle-II

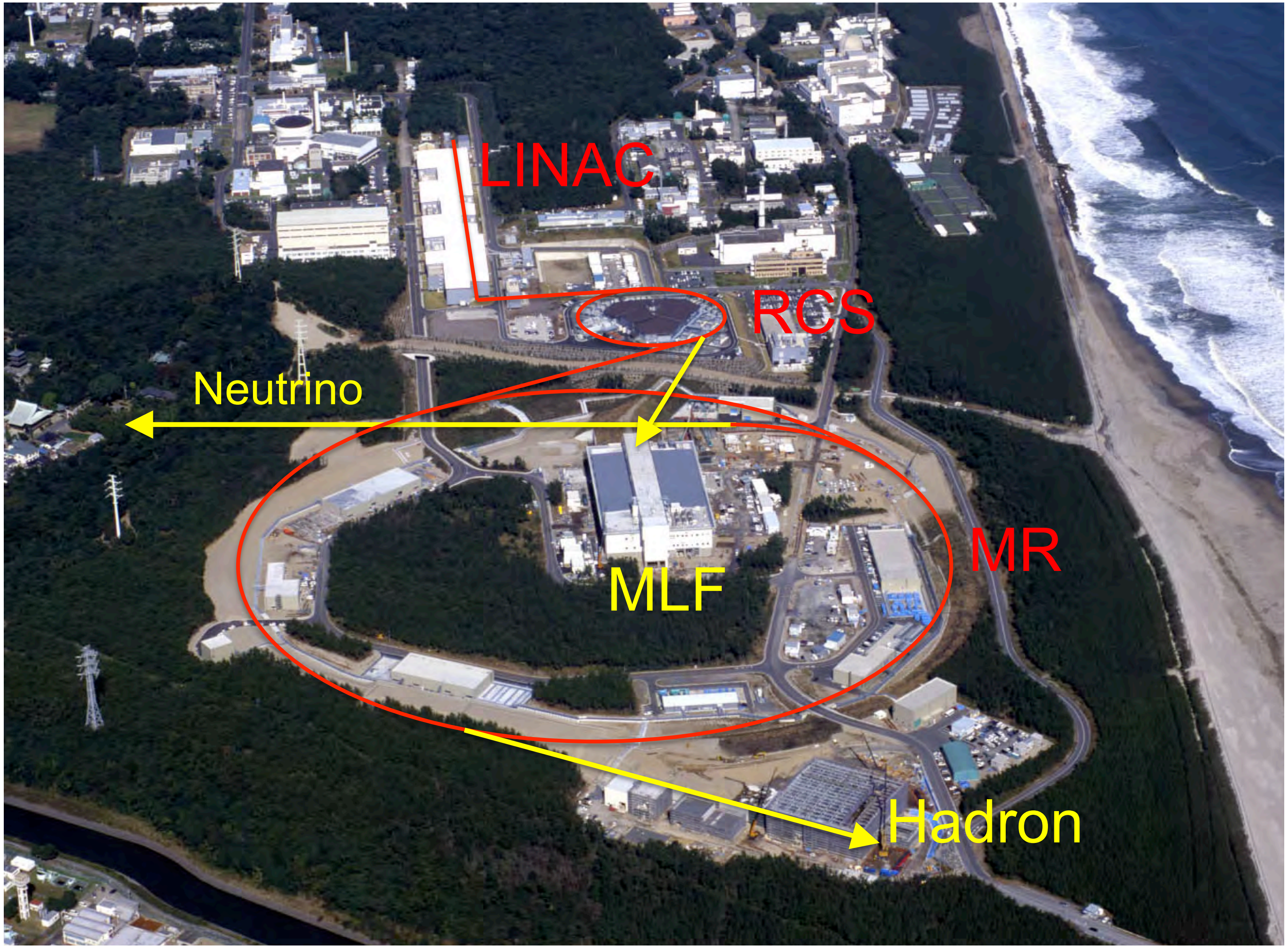
CP violation search →
Precision study of CPV and heavy flavor to explore new (BSM) physics.
Flavor tagging essential.

Babar



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;

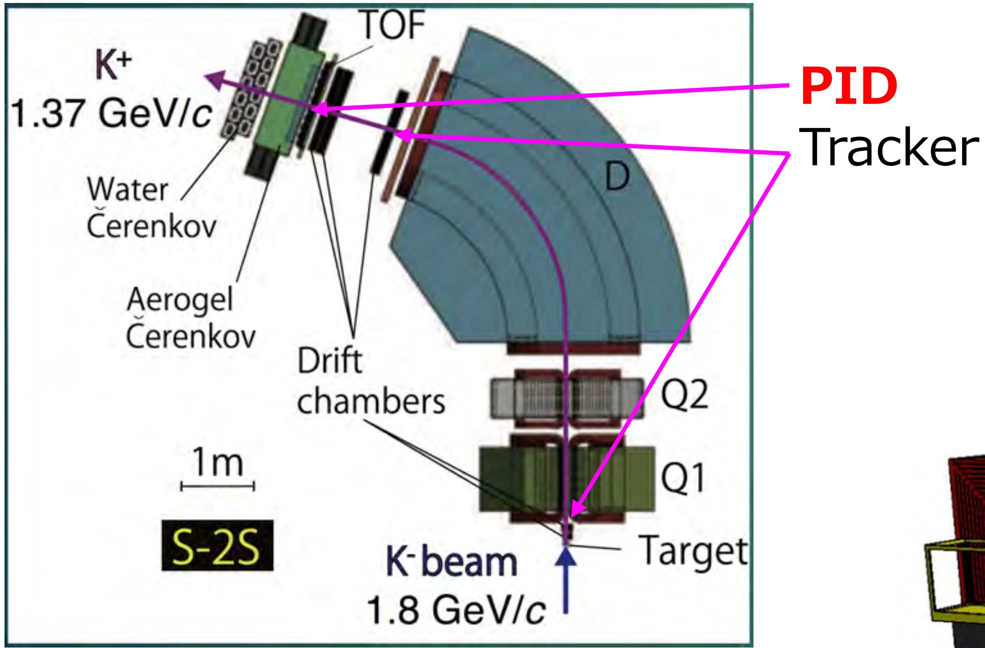
- 2.48sec cycle
  upgrading to 1.16sec.
- 510kW in operation
  upgrading to 1.3MW.

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

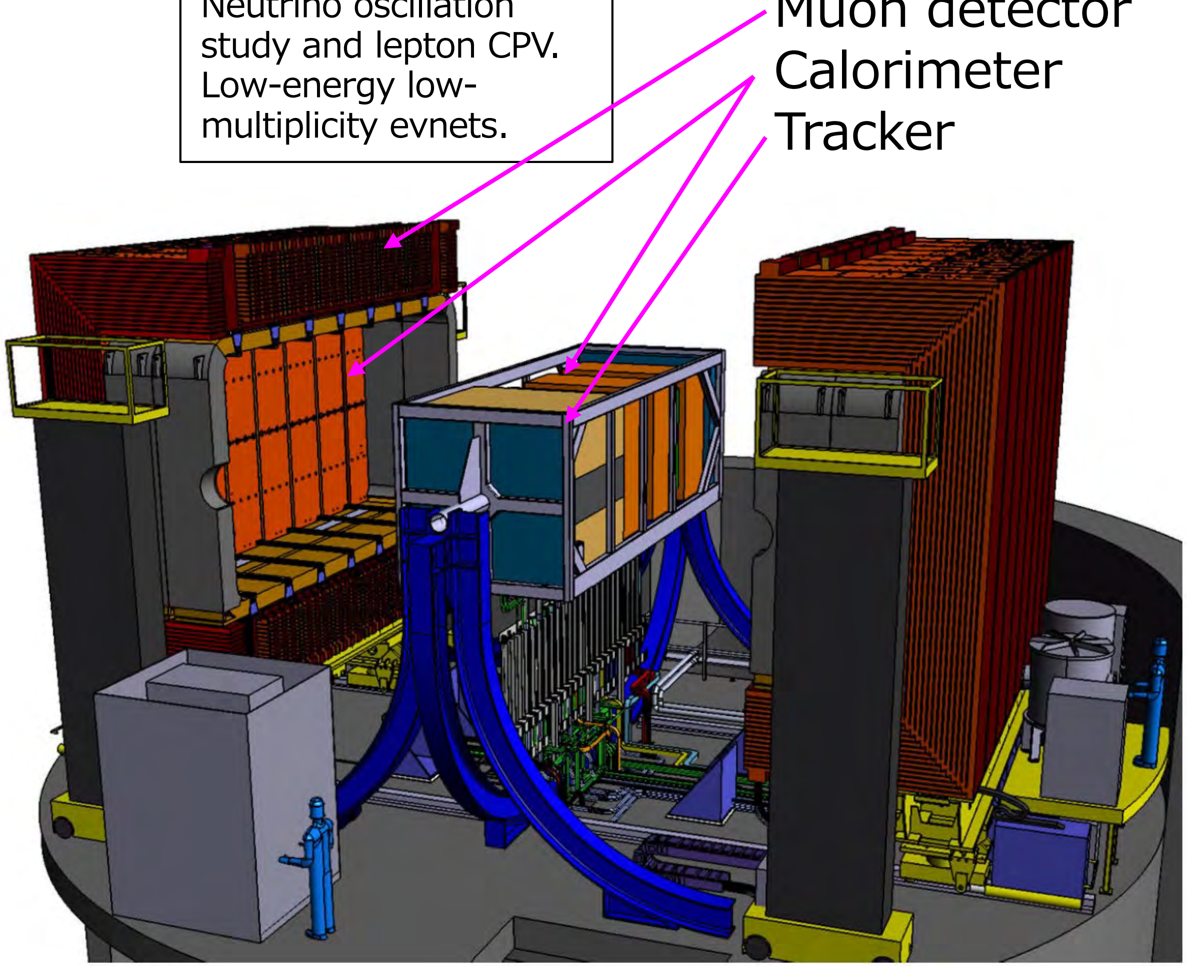


Hyper-nulceus experiment

Strong interaction of s-quark hadrons.
Low-energy low-multiplicity evnets,
flavour tagging important.

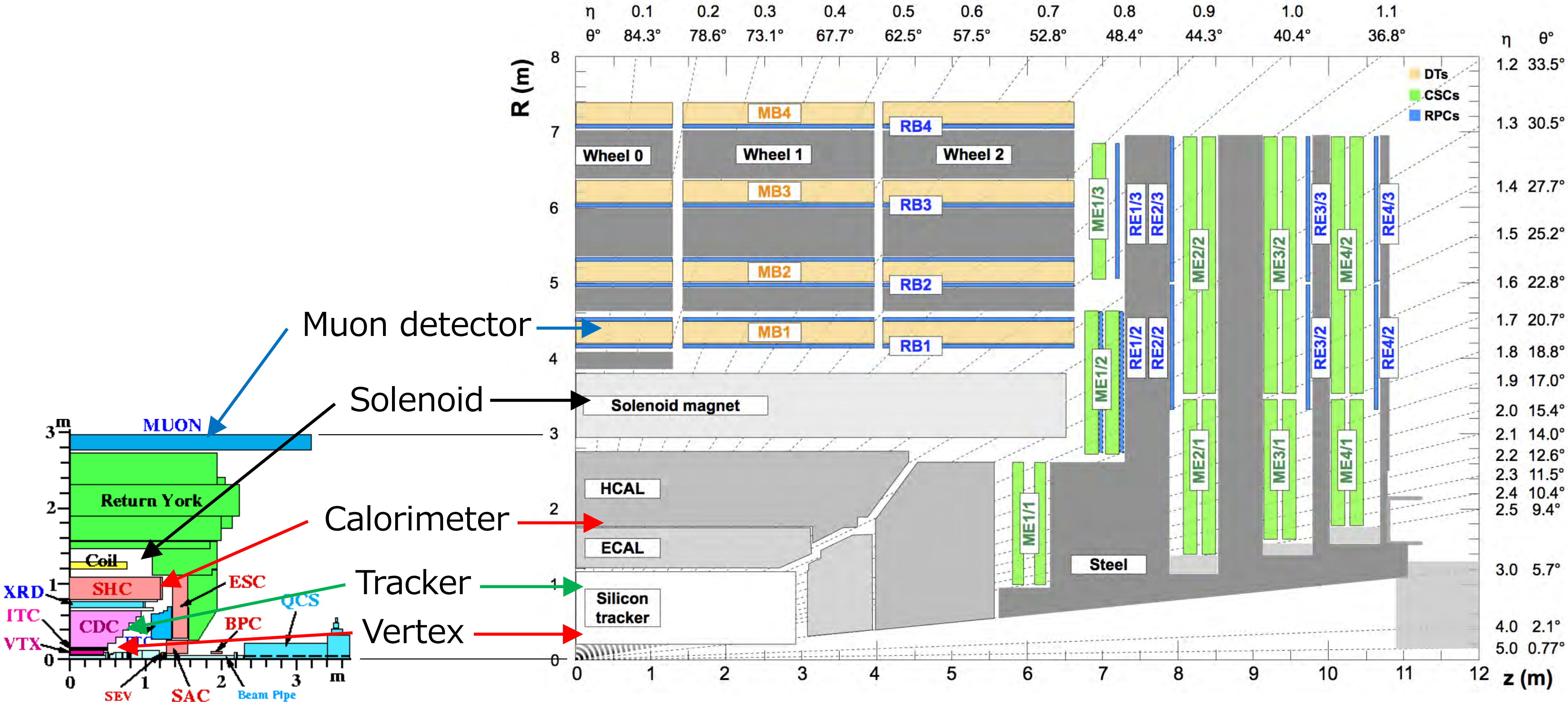
T2K ND280

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



Common feature of the detector system

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



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

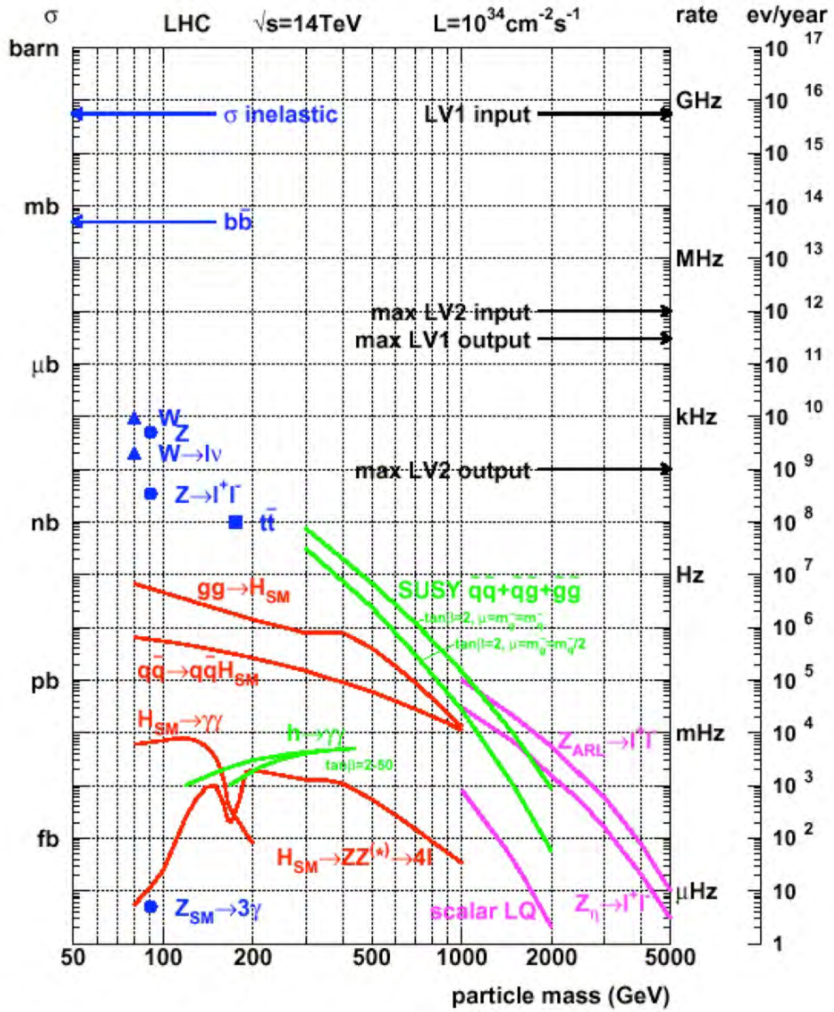
3. Requirement to the detectors

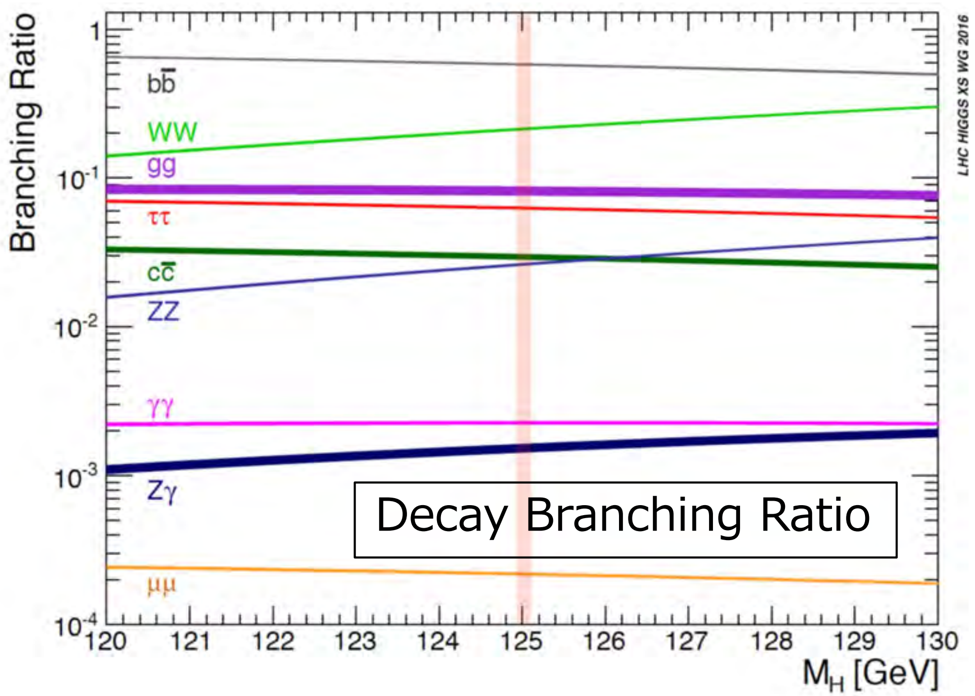
For the picked up "Benchmark" reactions,
we examine what kind of detectors and their performances
are needed to detect and analyze the reaction.

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.

Production and B.G. cross sections





3. Requirement to the detectors ; Higgs discovery at LHC

***g* + *g* → H^0 , H^0 → γ γ**

Calculate mass of γ γ

→ a clear peak on huge background → discovery

- γ is "isolated" ; not buried in remnant jet.

  → Do not rely on associating key particles

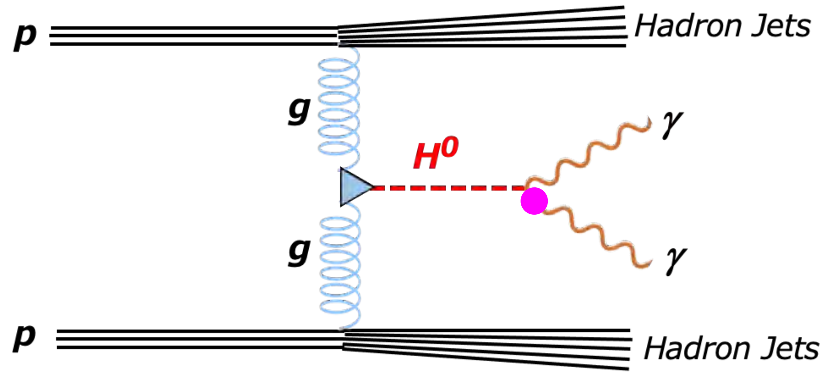
- Background from side-band of spectra

  → model-independent estimation.

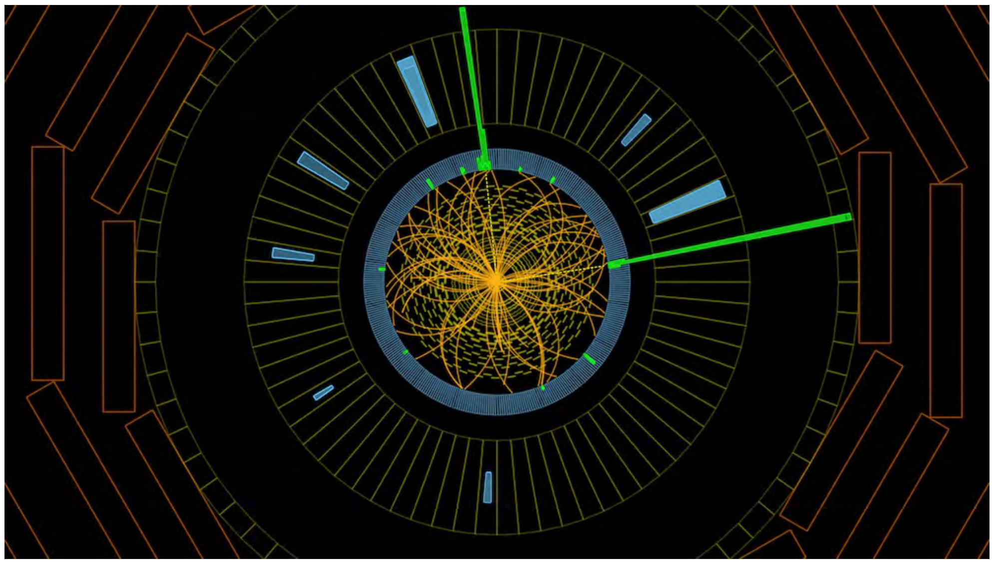
- Good energy and position resolution

  → narrow mass peak → good S/N

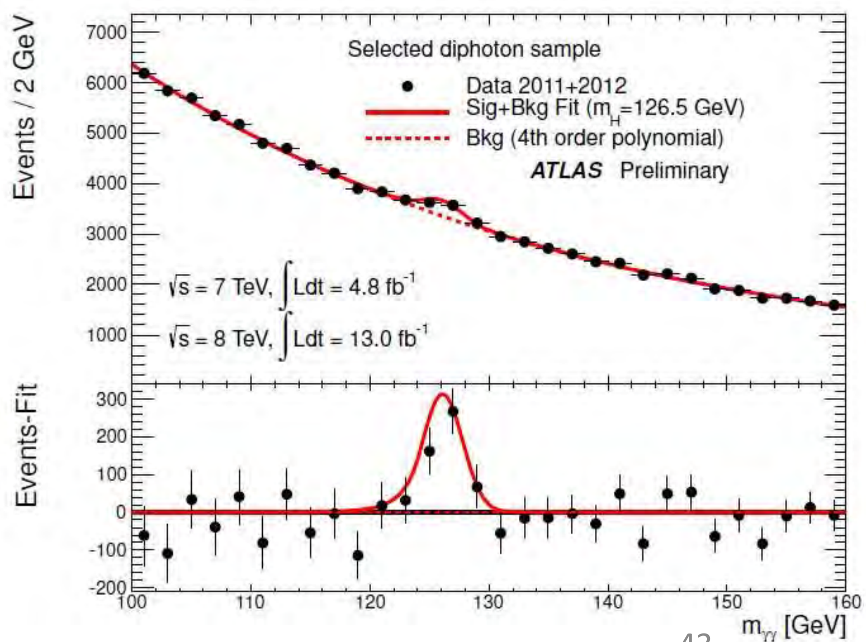
∗Just high-performance EM calorimeter !



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



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



3. Requirement to the detectors :LHC $\gamma\gamma$

$H^0 \rightarrow \gamma\gamma$

Calculate invariant mass of $\gamma\gamma$

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

Natural width of Standard Model Higgs is just 4MeV.

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

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

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

and

- fast (bunch-overlap separation)

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

3. Requirement to the detectors :LHC γγ

$H^0 \rightarrow \gamma\gamma$

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

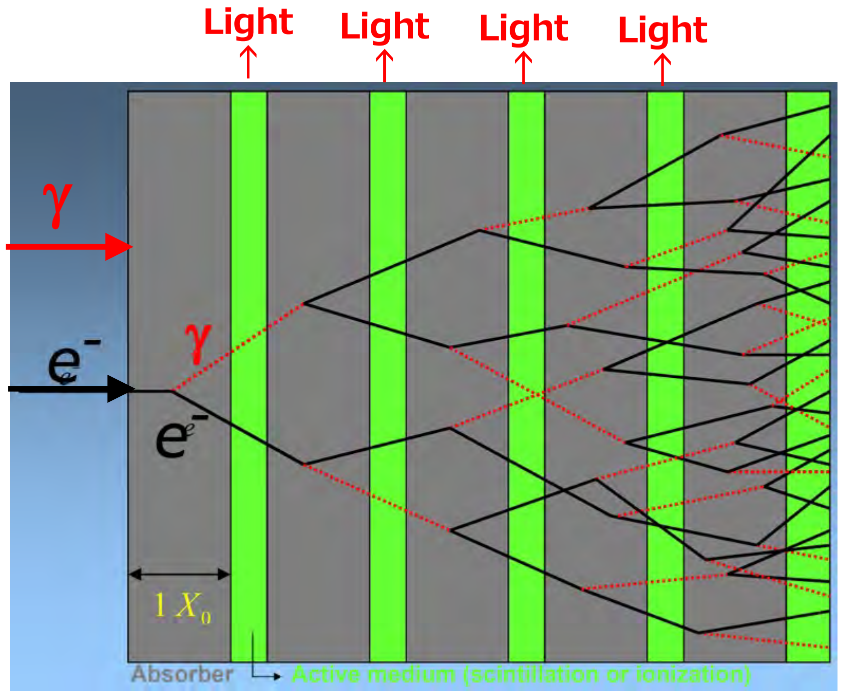


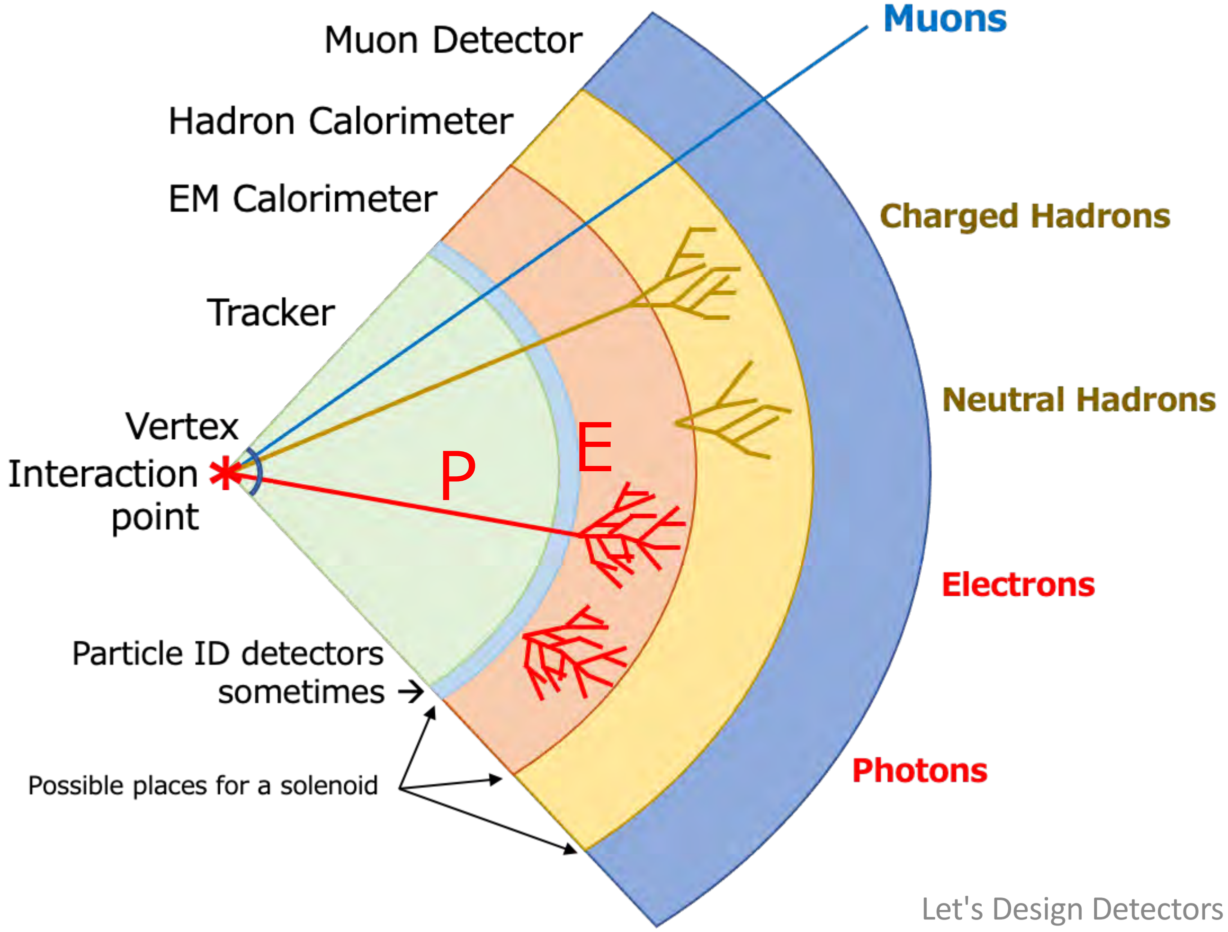
figure from P.Krieger, "ATLAS calorimetry"

3. Requirement to the detectors :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 :LHC γγ

High-performance EM calorimeter

In addition to the excellent γ measurement, **need to reject non-γ**

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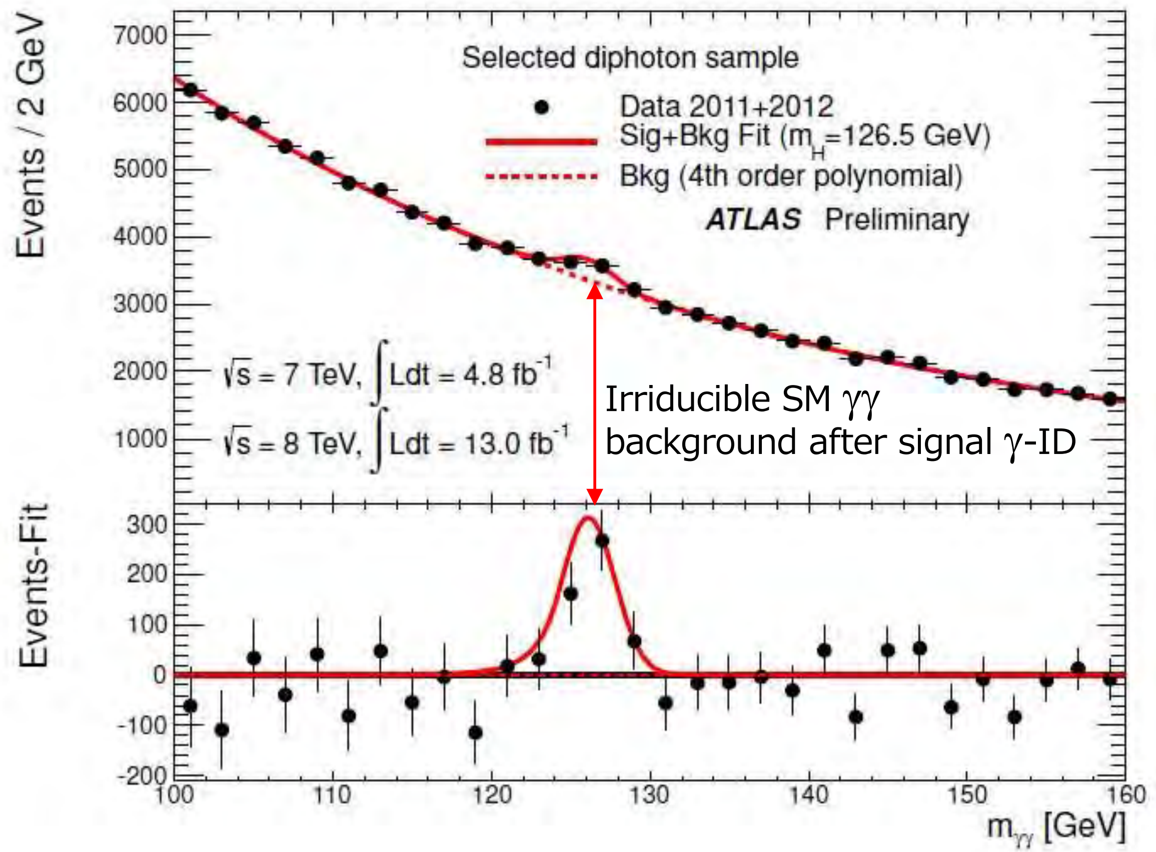

For an EM cluster;

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  - No hadron cluster → γ
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  - 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 :LHC $\gamma\gamma$

$H^0 \rightarrow \gamma\gamma$

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

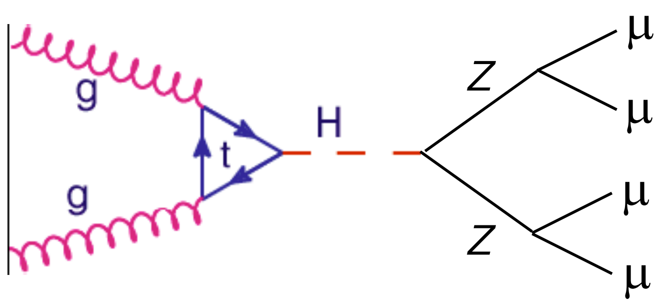
CMS EMcal clearly targets the best measurement of $H^0 \rightarrow \gamma\gamma$ discovery.

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

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

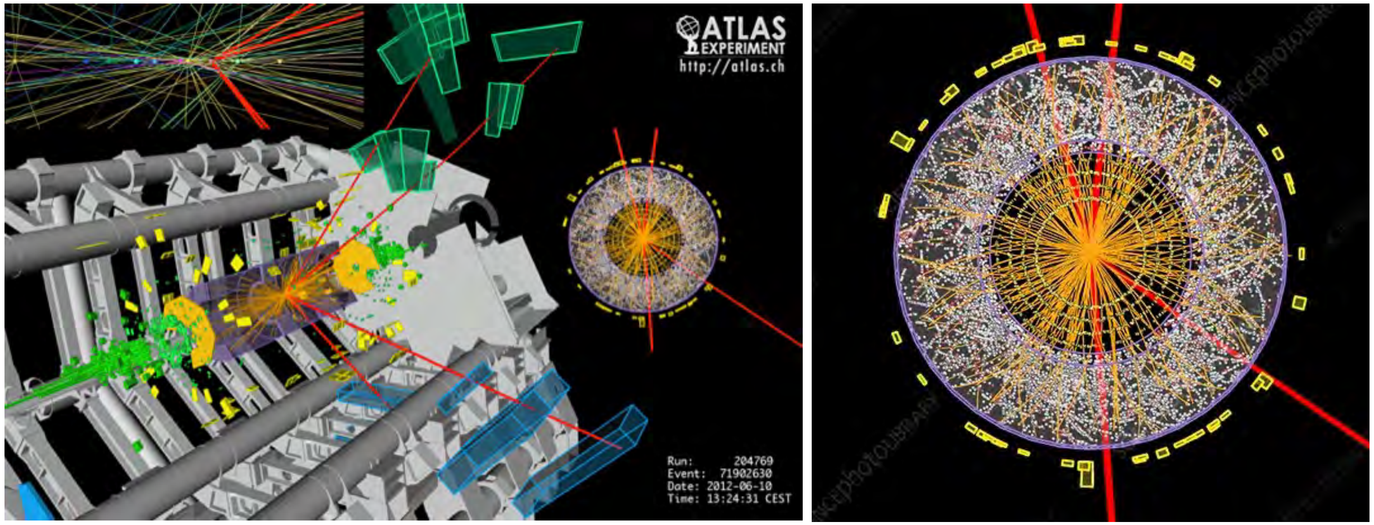
3. Requirement to the detectors ; Higgs discovery at LHC

Higgs → ZZ → 4μ

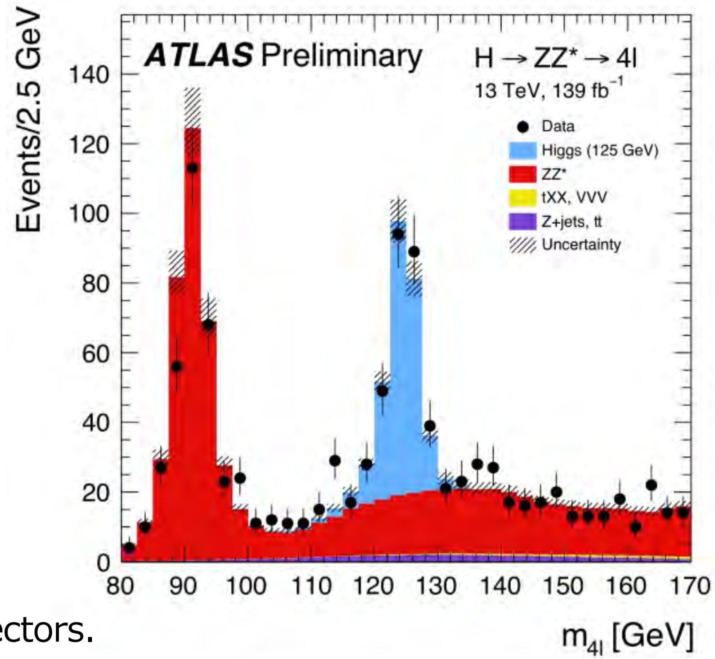


- Very clean event signature but
  Very low event rate (H^0→ZZ→4μ ~0.01%)
- Calculate mass of 4μ
  → A clear peak on background → **discovery**
  Background estimation needs background reaction analysis. Thus takes time.
- Do not rely on associating key particles.
- Good momentum and position resolution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

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



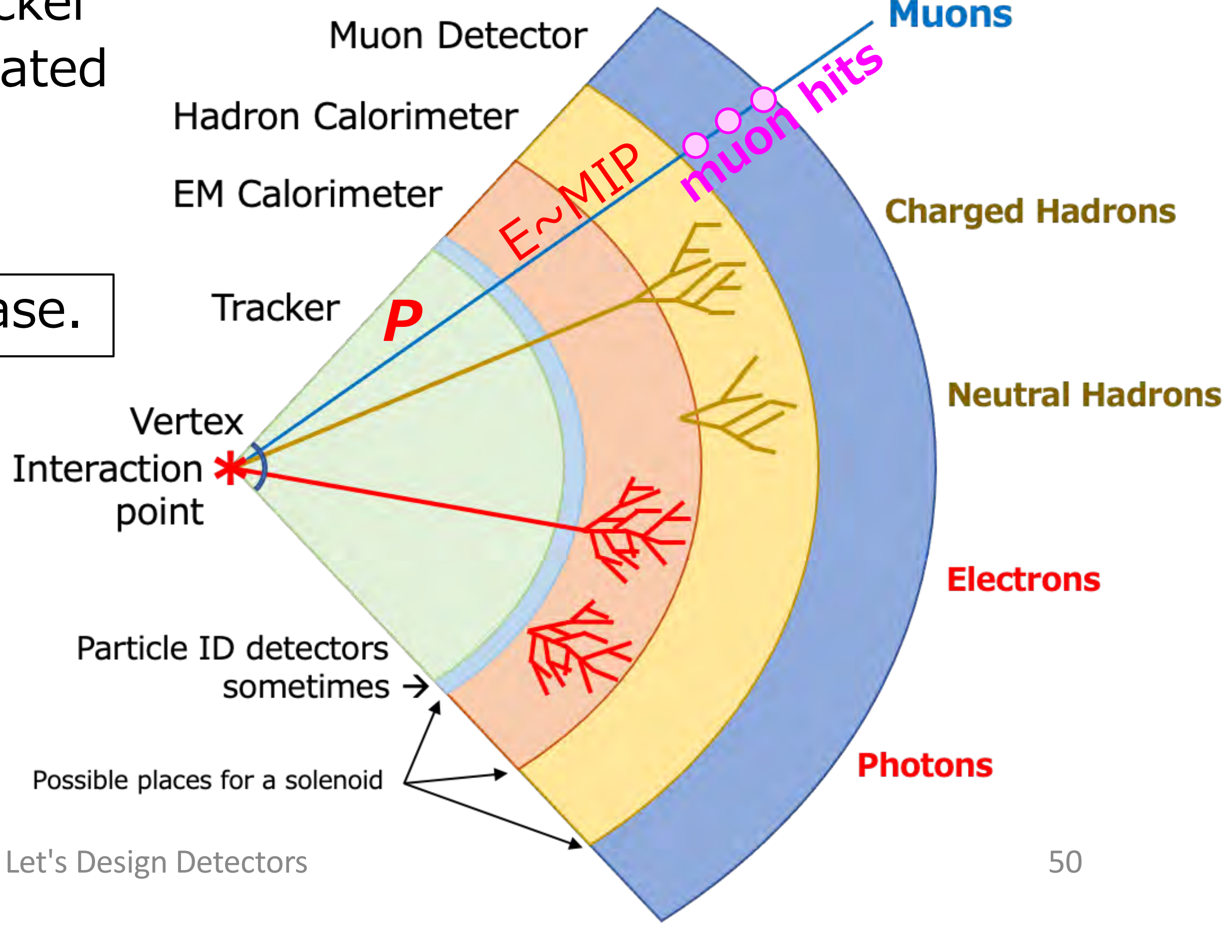
ATLAS H^0→4μ event. Muons (red lines) are clearly identified by outer-most muon detectors.



High-performance muon measurement

- Identify the particles as muon
  - Has hits in muon detectors
  - Energy deposit in CAL consistent to muons
- 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.

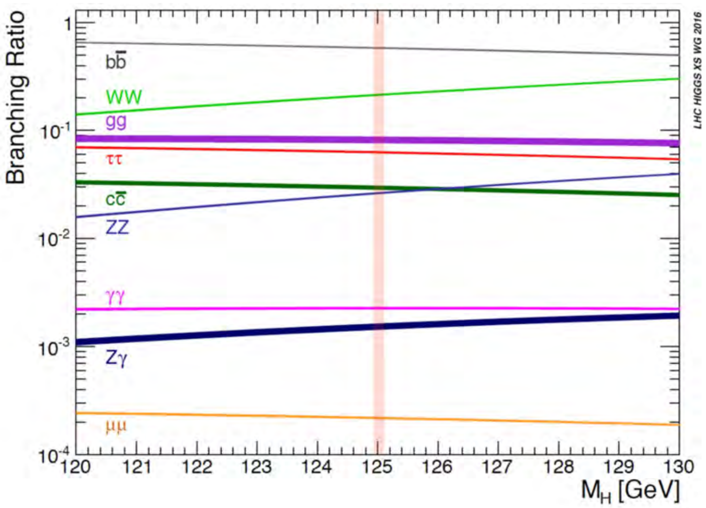
Will be described in detail at ILC case.

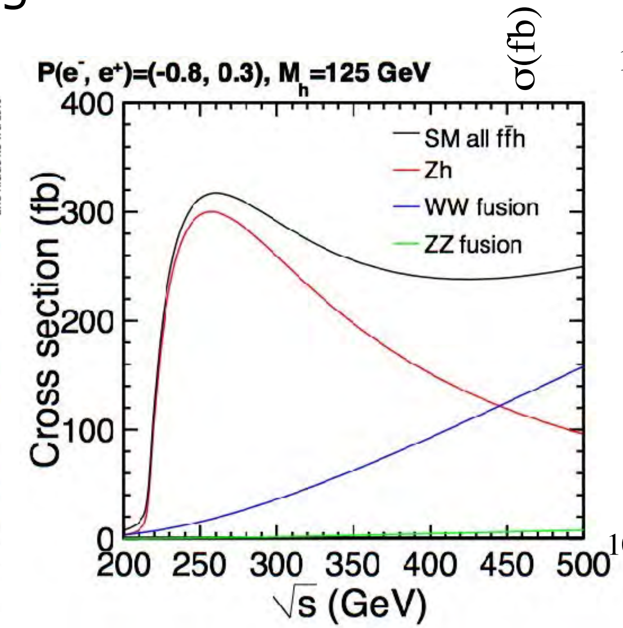


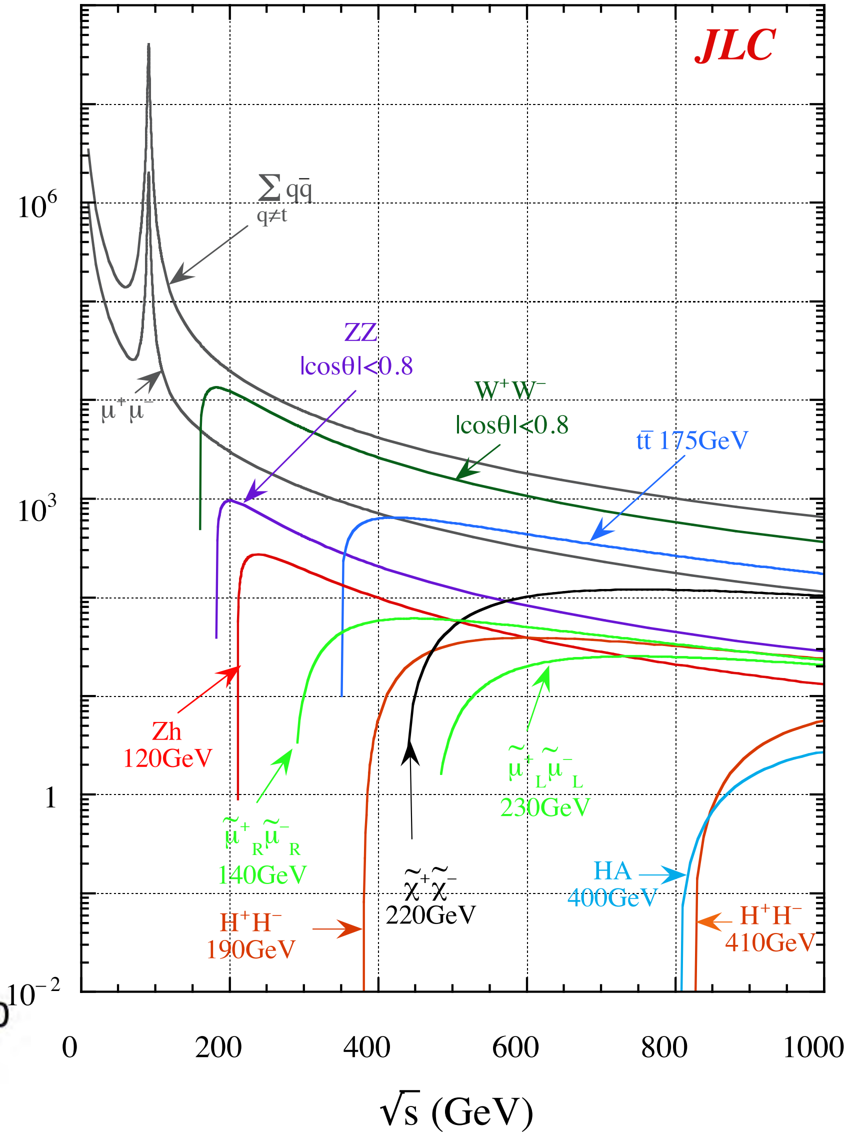
Let's discover Higgs at ILC

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- → Z^0H^0, $Z^0 \to \mu^+\mu^-$

H^0 → anything (do not care)

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

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

Calculate H^0 Mass↑ ↑Suffer I.R.↑ ↑Calculate using μμ ***P***

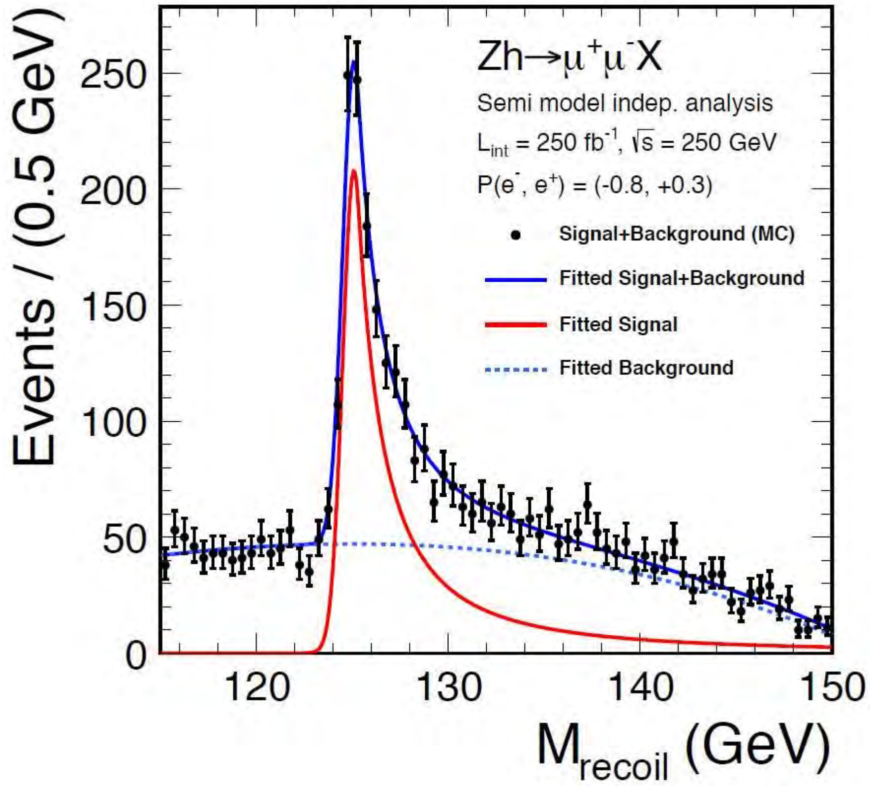
Or simply

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

* 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



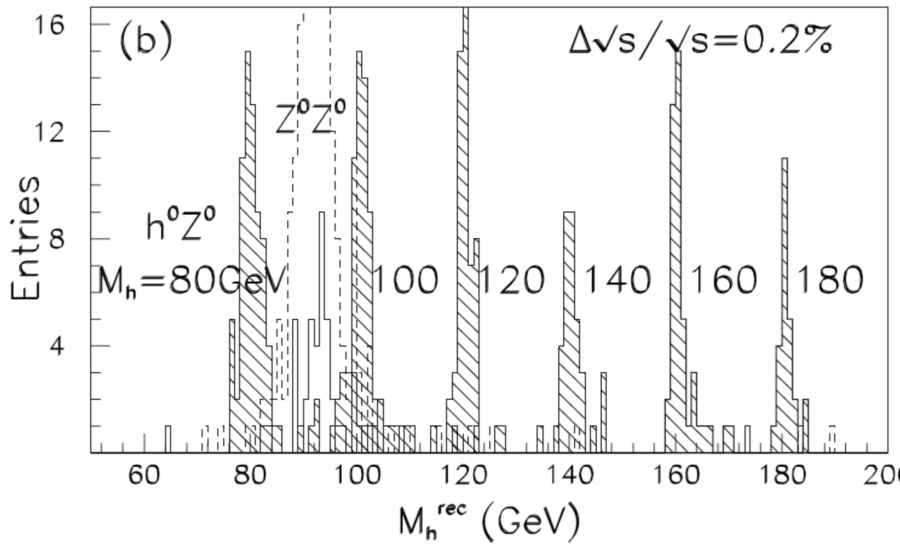
3. Requirement to the detectors ; Higgs discovery at ILC

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

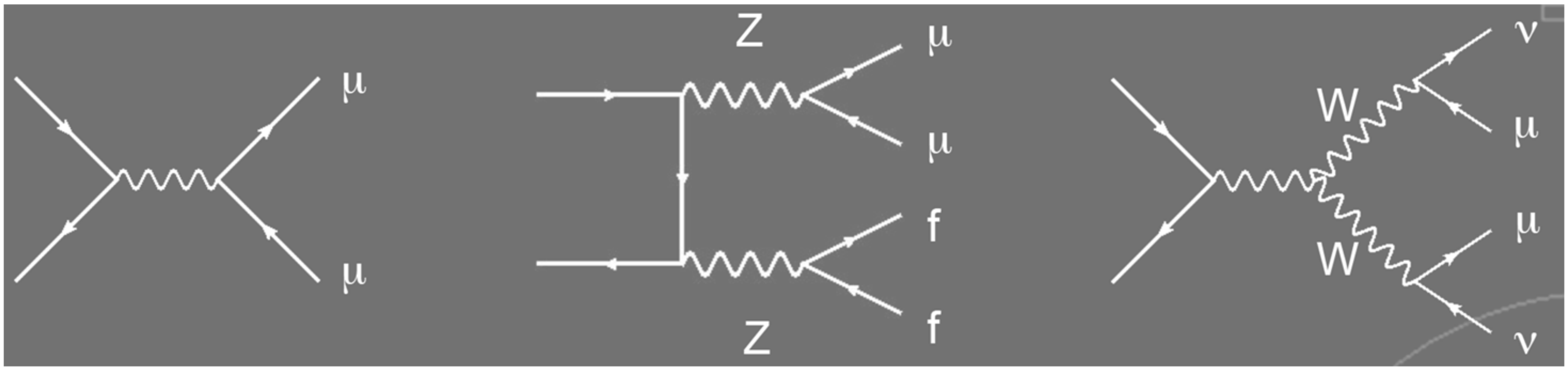
$e^+ e^- \rightarrow Z^0H^0$, $Z^0 \rightarrow \mu^+\mu^-$

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

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



Background Processes

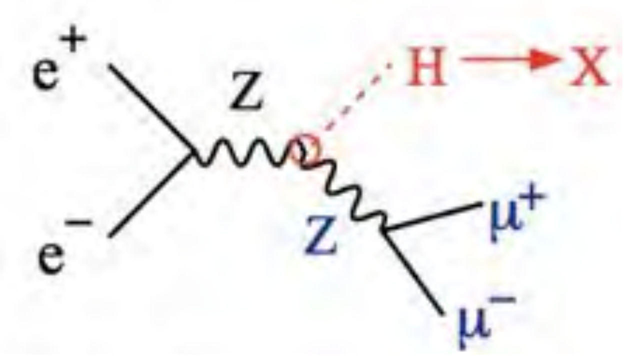


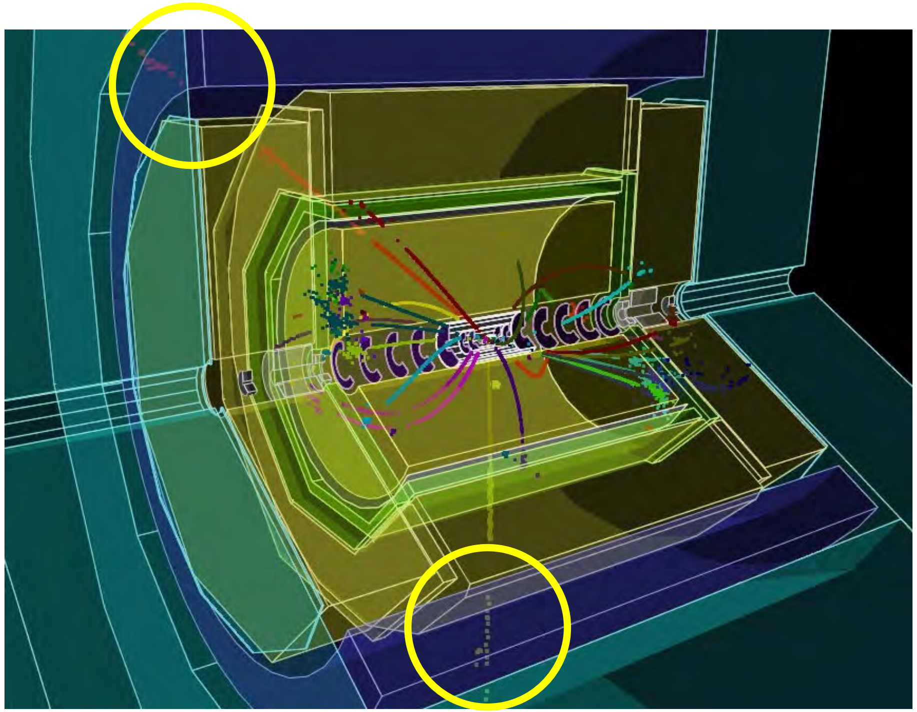
High-efficiency muon identification

How can we know the particle is muon ?

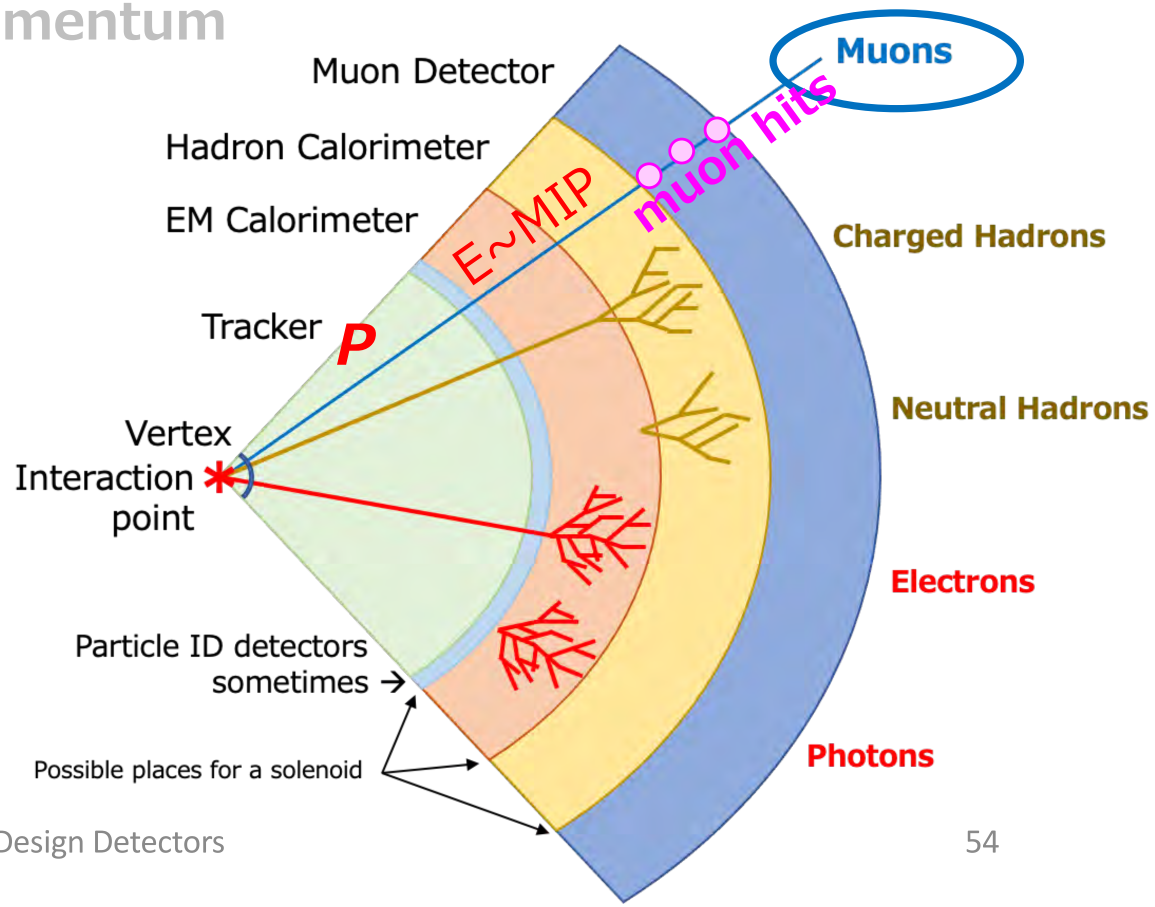
- The track penetrate through thick material and make hits in muon detectors
- Muon does not initiate EM shower
- Muon does not initiate hadron shower

- Precise measurement of muon momentum





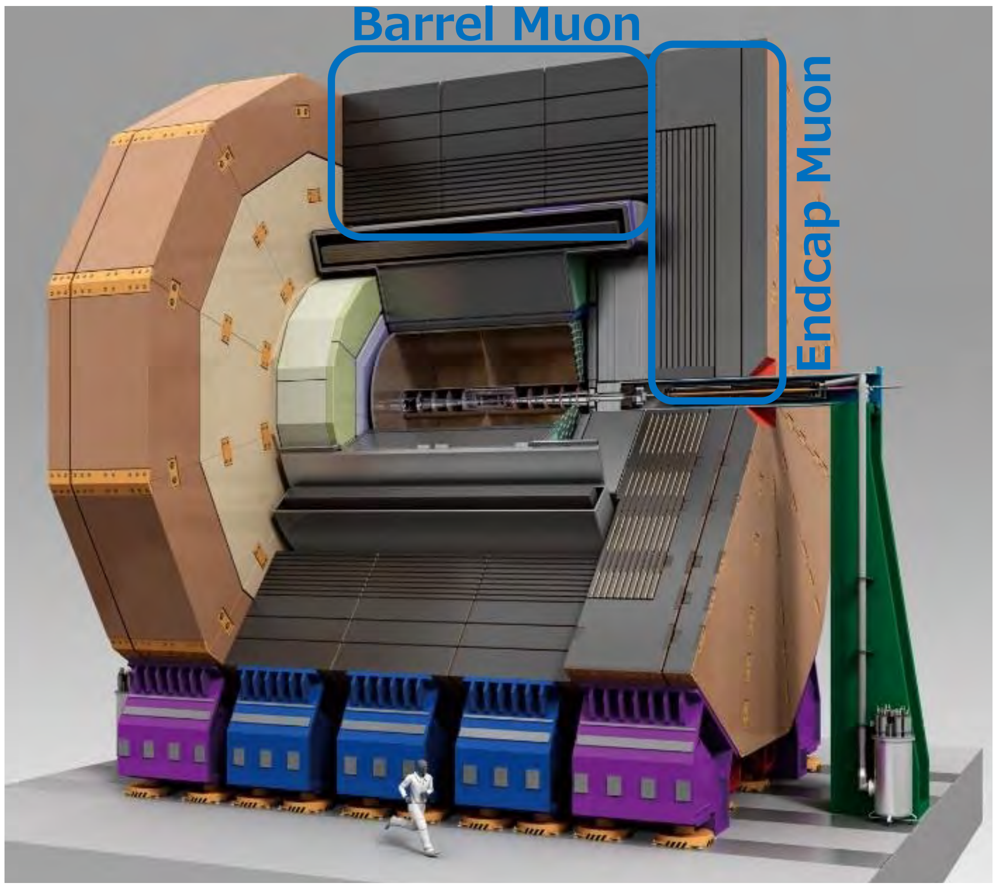
e+e- → ZH, Z→μμ, H→*bb*



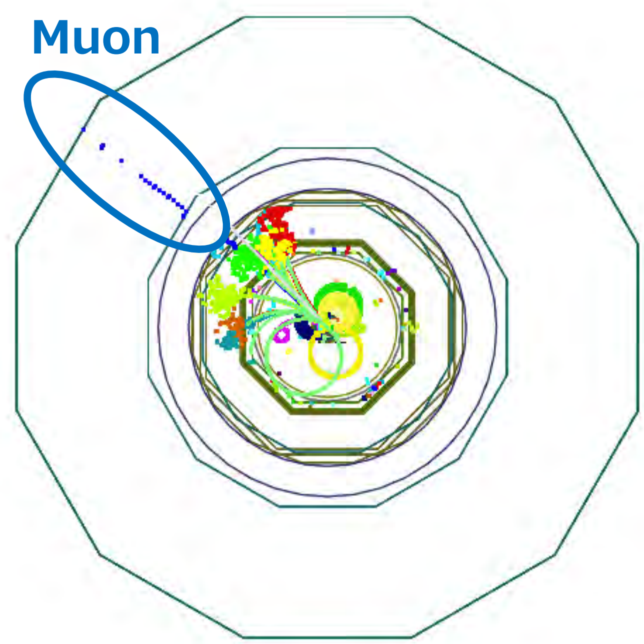
High-efficiency muon identification

→ 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

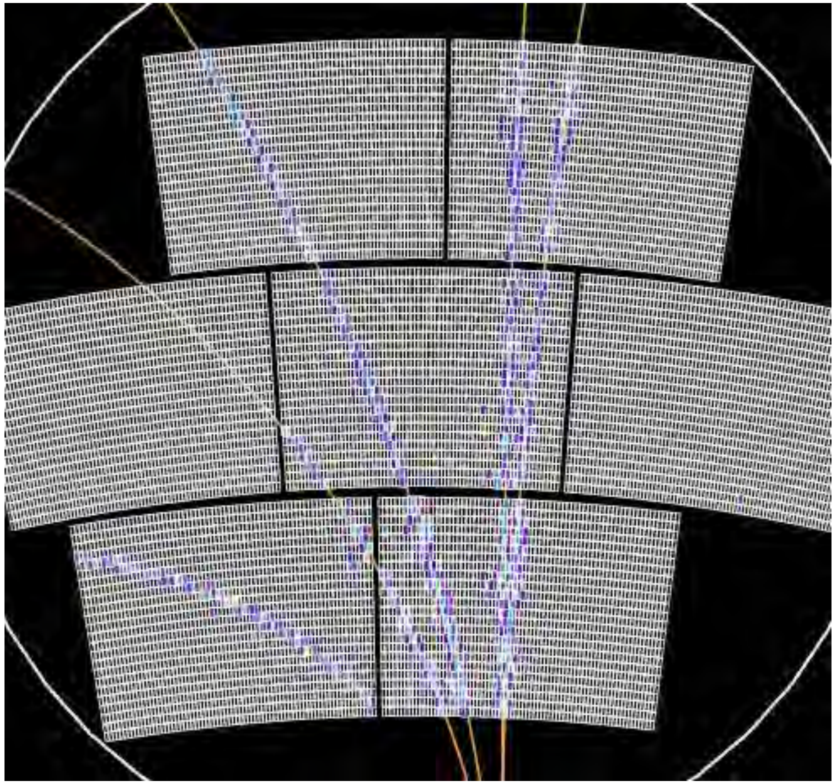


High-efficiency muon identification

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)

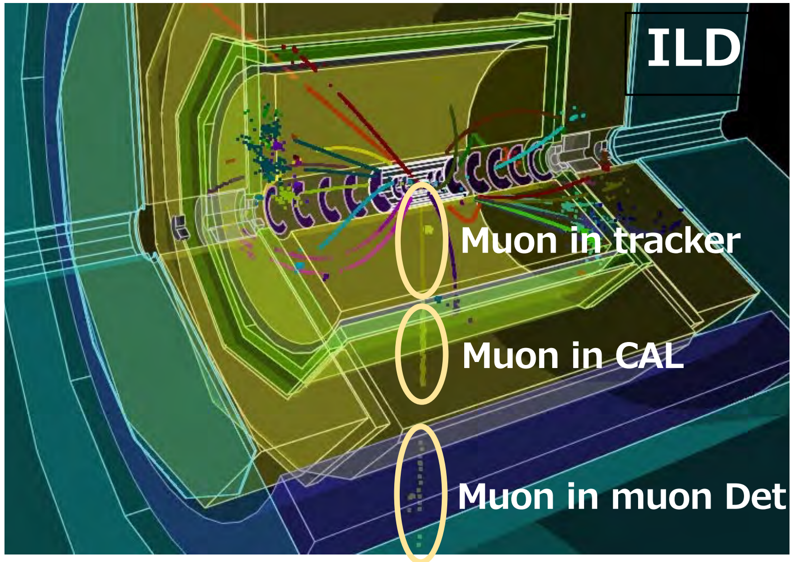
3. Requirement to the detectors ; Higgs discovery at ILC

High-efficiency muon identification

Precise measurement of muon momentum

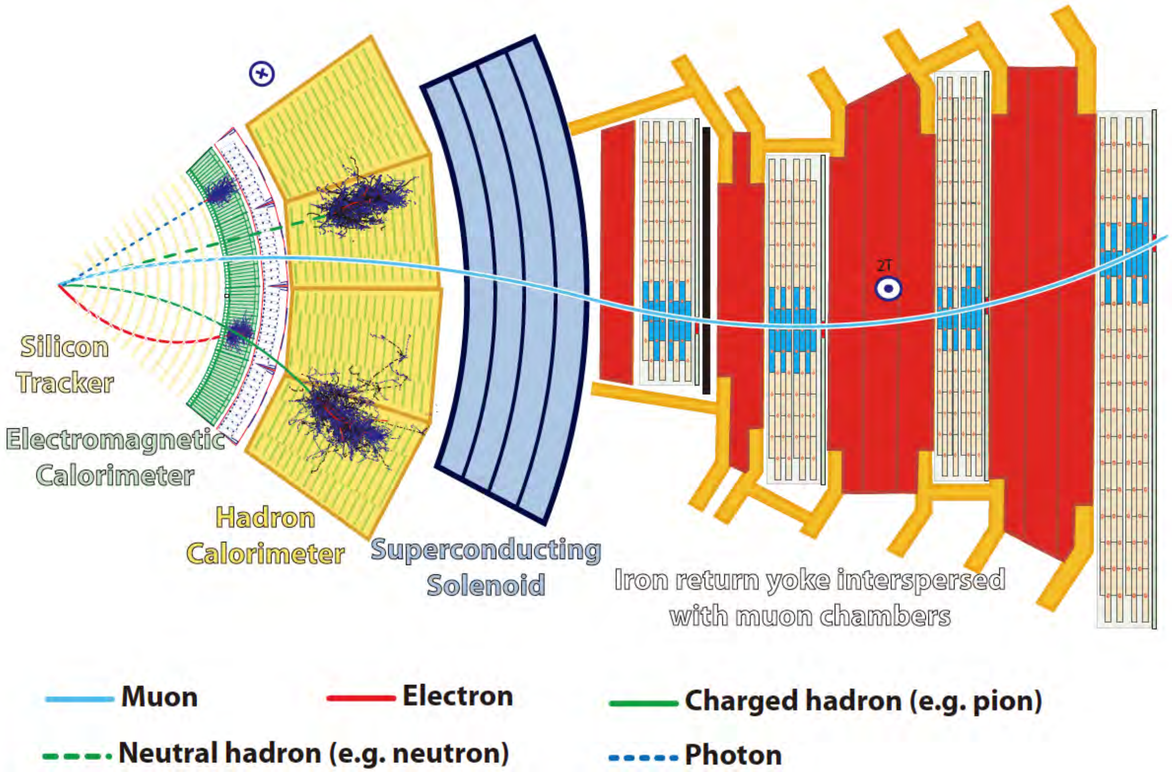
Precise correspondence between muon detector hits and tracks.

- 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.



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 need to carry through.

What kind of detectors do we need ?

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

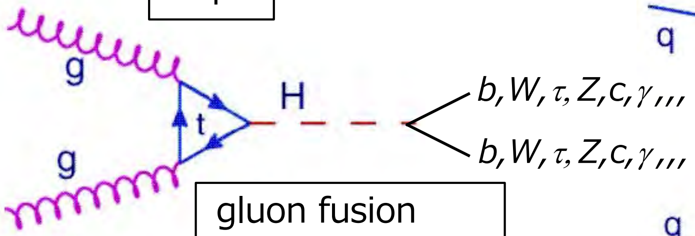
Let's study Higgs in detail at LHC/ILC.

- Explicitly reconstruct all possible H^0 decay modes.

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

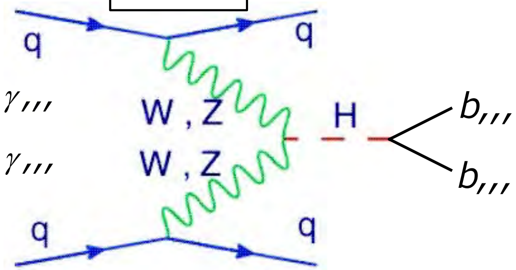
- Explore various production channels, hopefully with associating 'Key' particle.
  - To distinguish them from overwhelming background

50pb



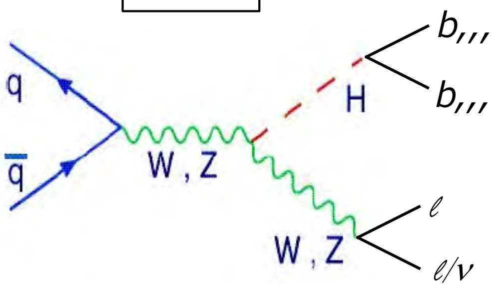
gluon fusion
No Key particles

4.2pb



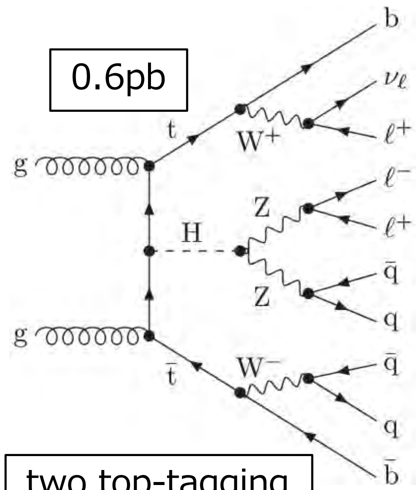
two high-Pt jets

2.4pb



Z/W-tagging

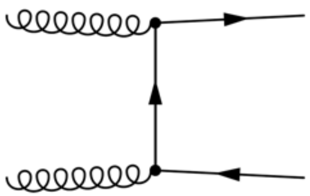
0.6pb

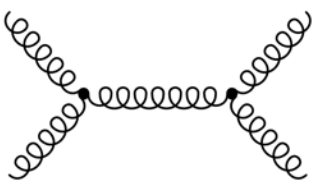


two top-tagging

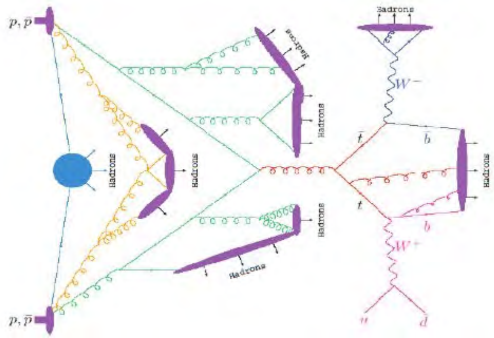
Signals

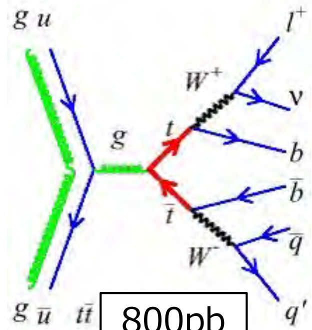
Backgrounds





high-Pt jets ~μb



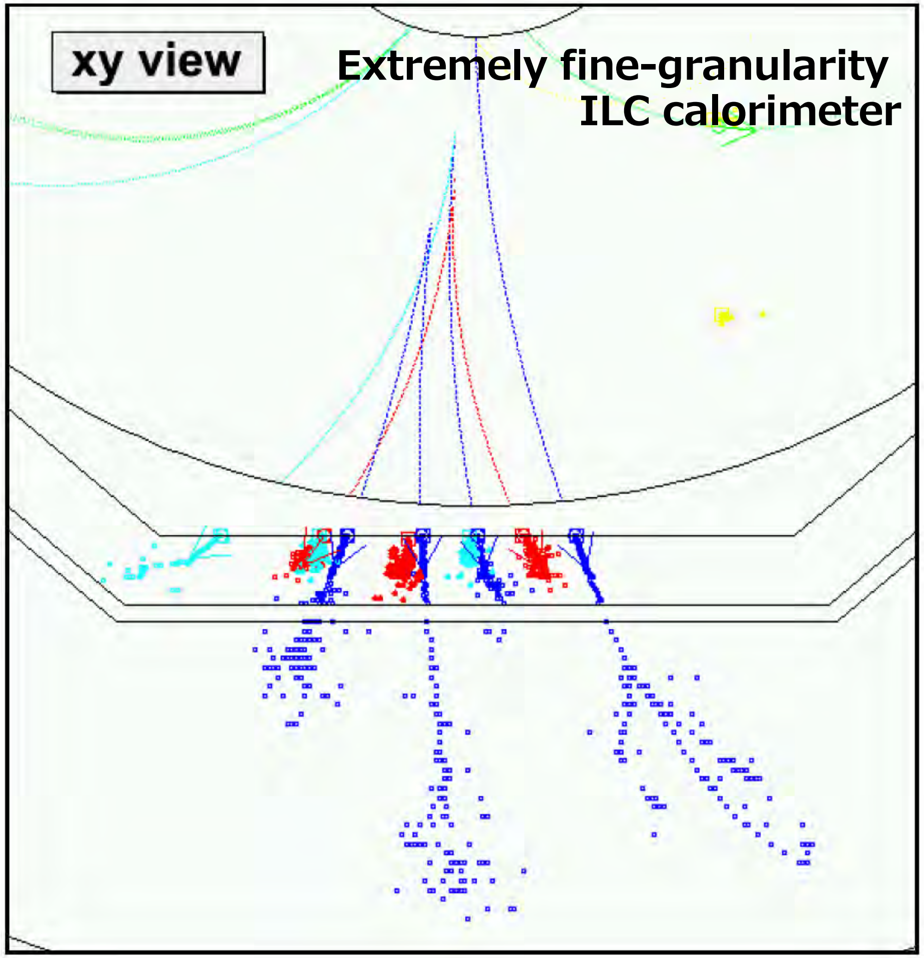


800pb

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

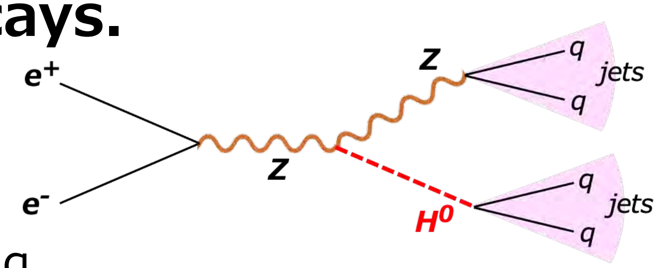


Untangle track-cluster overlap with high-granularity calorimeters, and use tracker information for charged particles.

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.

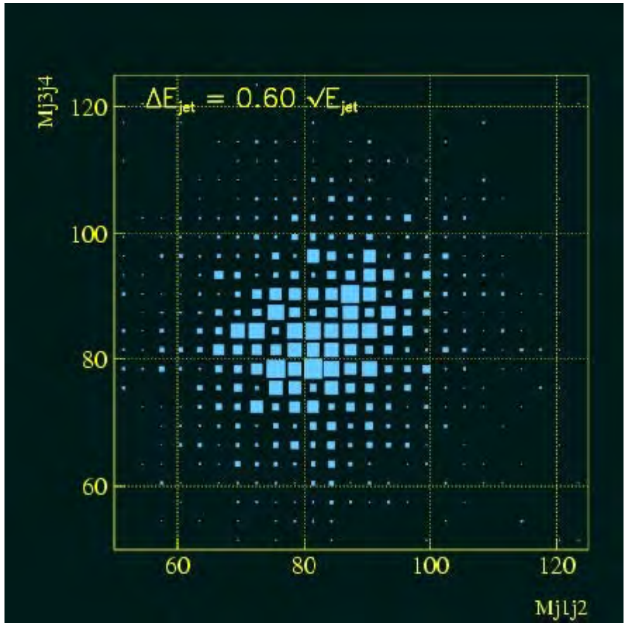
Explicitly reconstruct all possible $H^0/t/b/W/Z$ decays.



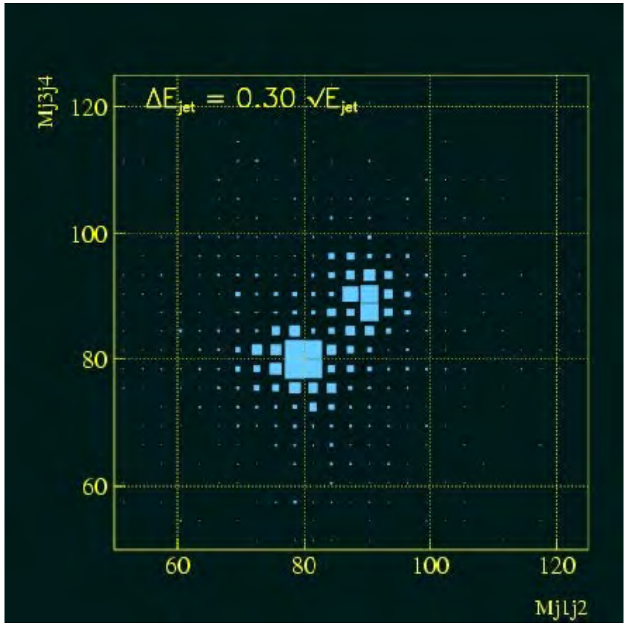
- good resolutions ; energy, momentum, position, timing
  Charged particle be measured by trackers,
  while neutral particles by calorimeters.
  Excellent position resolutions to untangle track/cluster overlapping.
- **Jet reconstruction ; high multiplicity, high occupancy**
- Precision secondary vertexing (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.



Many particle in collimated JET should be separately reconstructed.

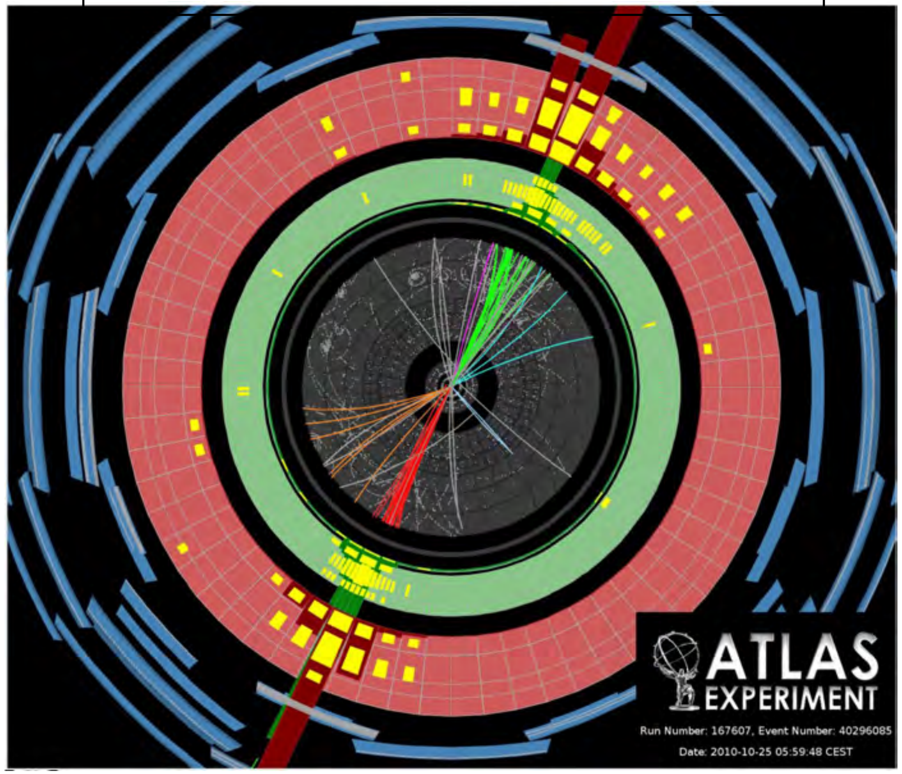
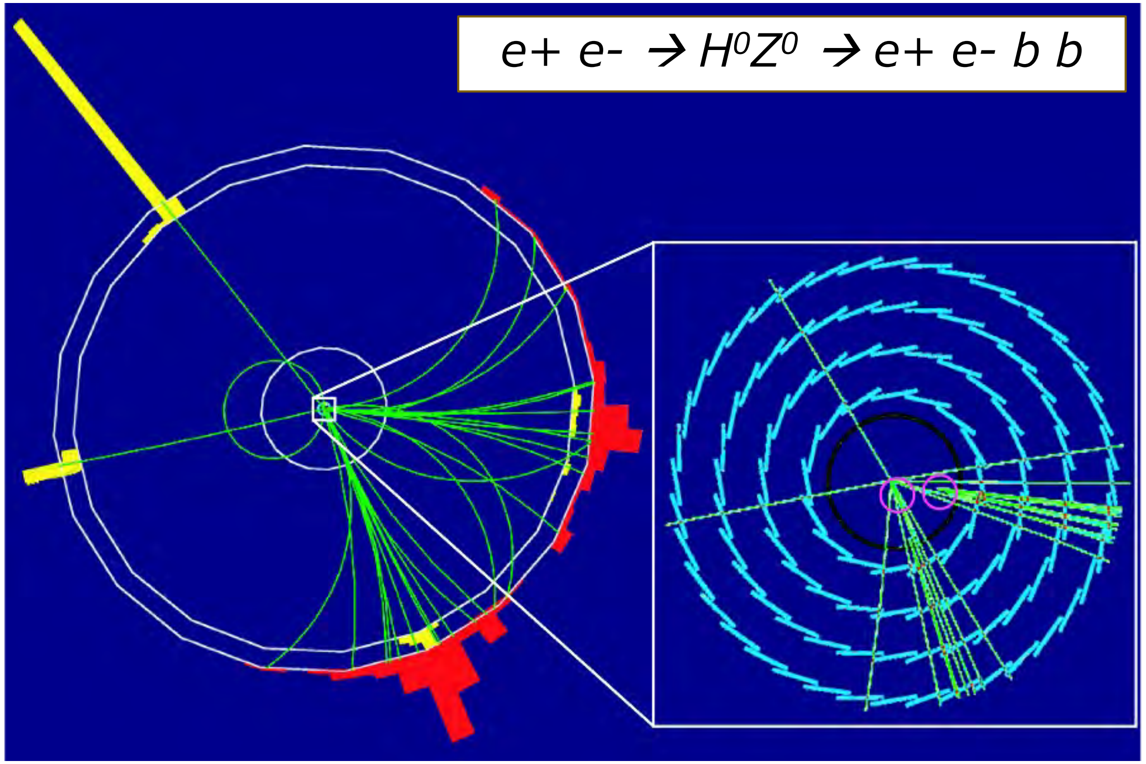
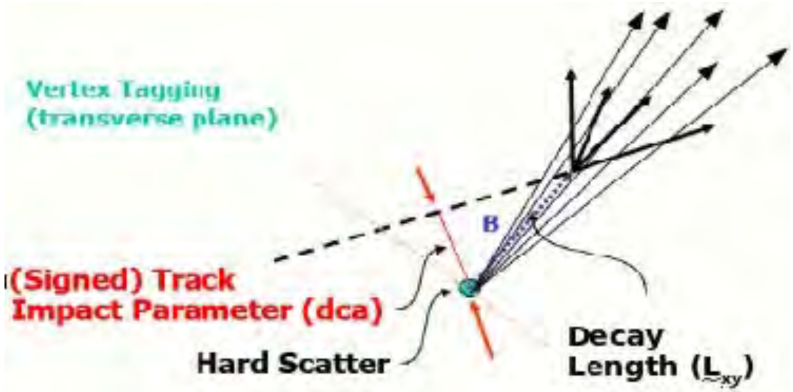


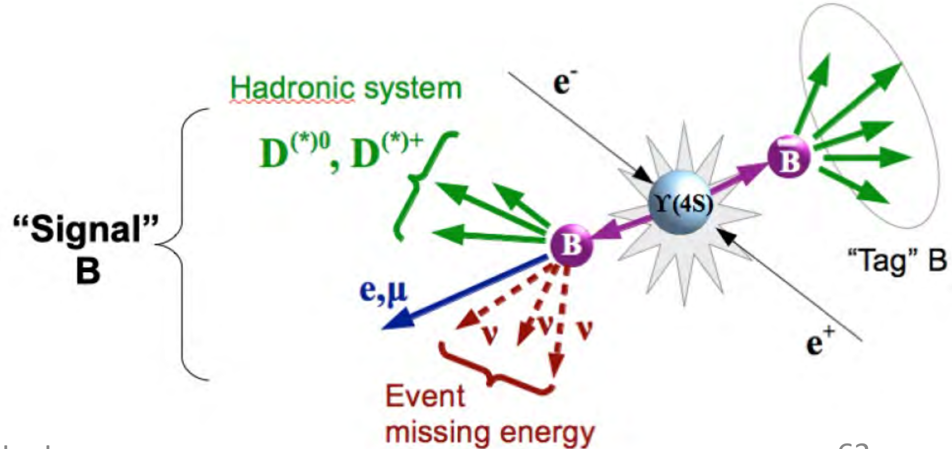
Figure taken from Aspen 2007 report by J.Brau.

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

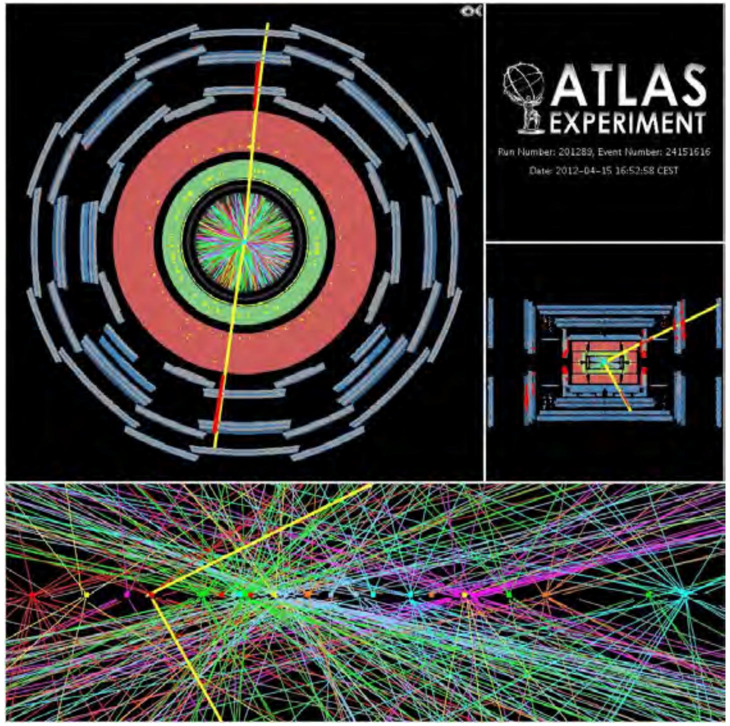




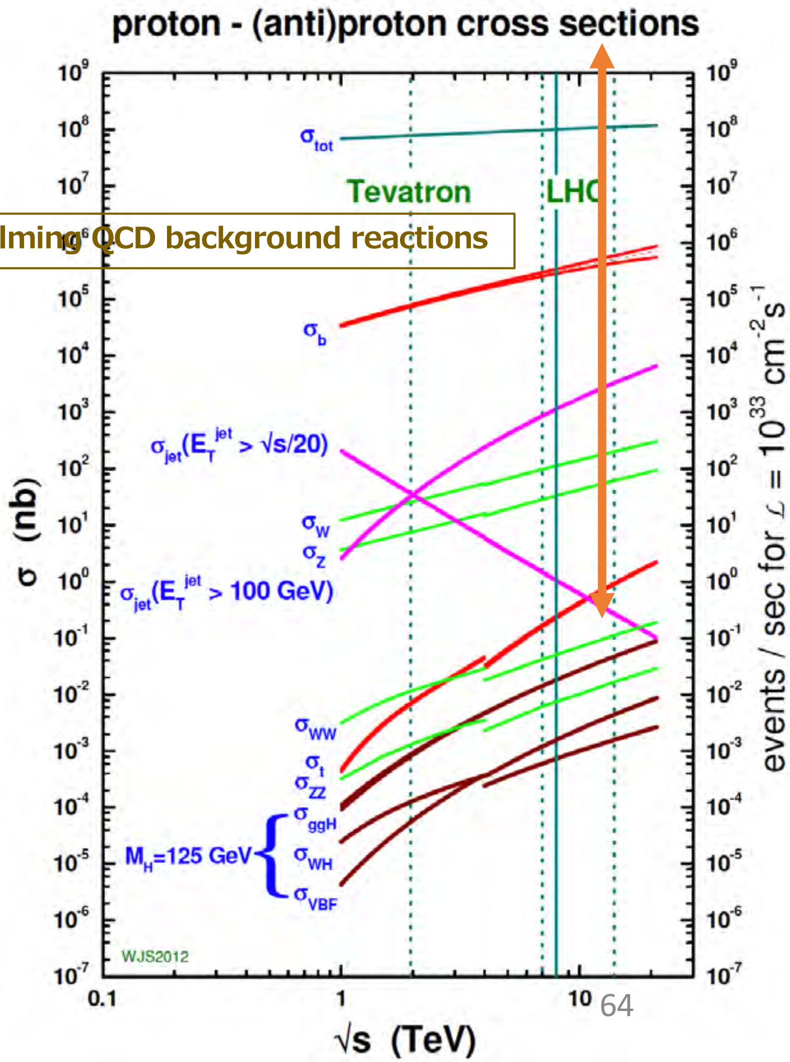


Explicitly reconstruct all possible $H^0/t/b/W/Z$ decays.

- 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**



Multi-bunch overlapping



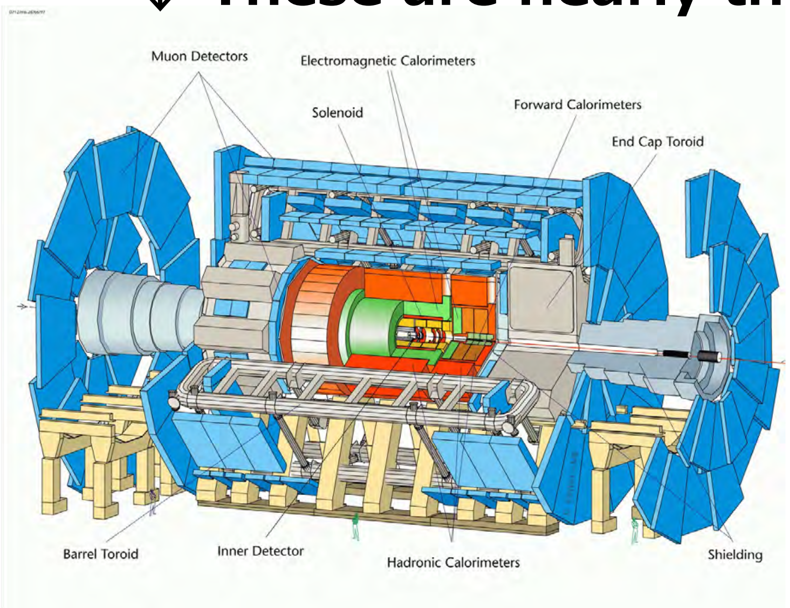
3. Requirement to the detectors ; Higgs Study at LHC/ILC

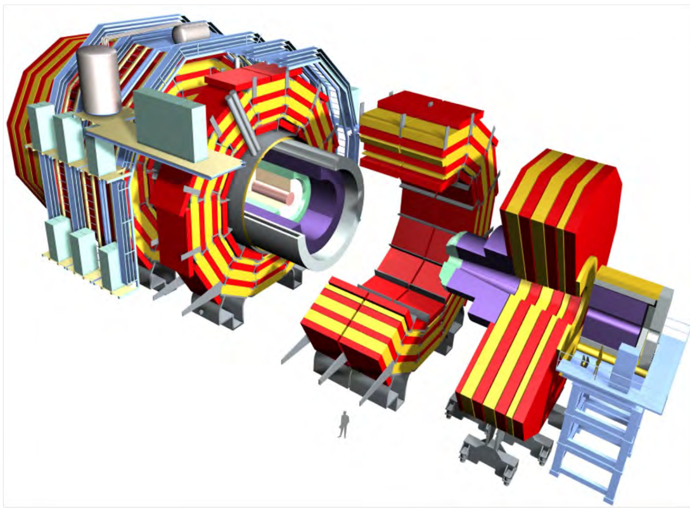
Explicitly reconstruct all possible H^0/t/b/W/Z decays.

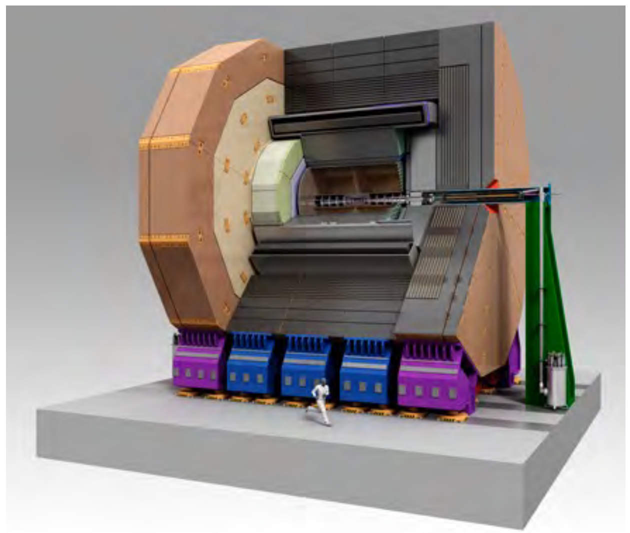
- good resolutions ; energy, momentum, position, timing
  Charged particle be measured by trackers, while neutral particles by calorimeters.
  Excellent position resolutions to untangle track/cluster overlapping.
- Jet reconstruction ; high multiplicity, high occupancy
- Precision secondary vertexing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

↓ These are nearly the solutions ↓

This is almost the solution







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

4. Interaction of particle with matter

and

5. Operation principle of detectors

Interaction of particle with matter and operation principle of detectors

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

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

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

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