Development of silicon semiconductor tracking devices for the High-Luminosity LHC experiment

Koji Nakamura (KEK)

Contents

- Introduction
  - Motivation of High Luminosity LHC and Future collider
  - Schedule and design
- Challenge of detector design
  - Requirement to the HL-LHC detector
  - Introduction of semiconductor tracking detector
- Japan group development
  - Planar type fine pixel pitch detector
  - Future technology for the timing sensitive detector.
- Conclusion

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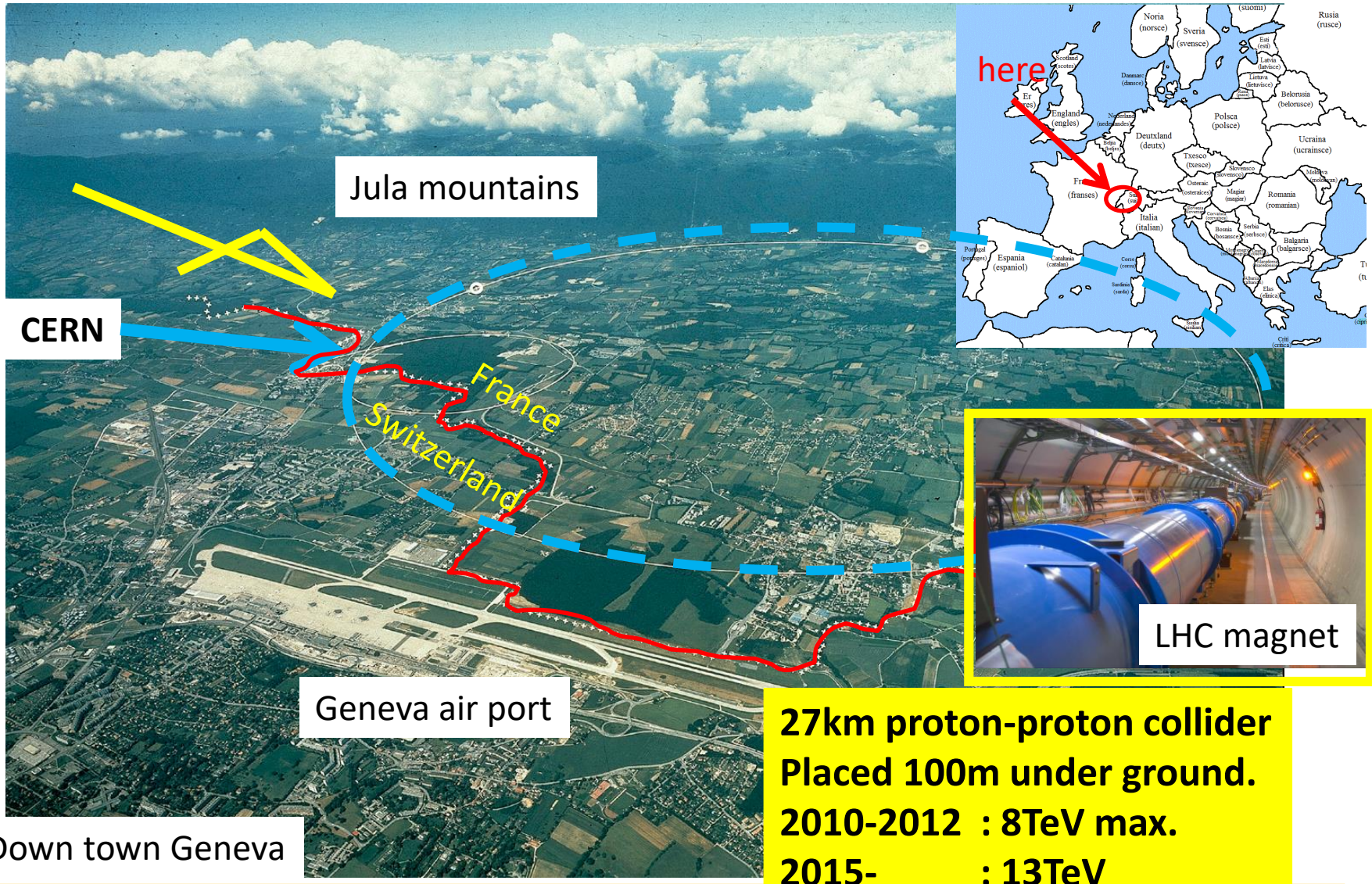
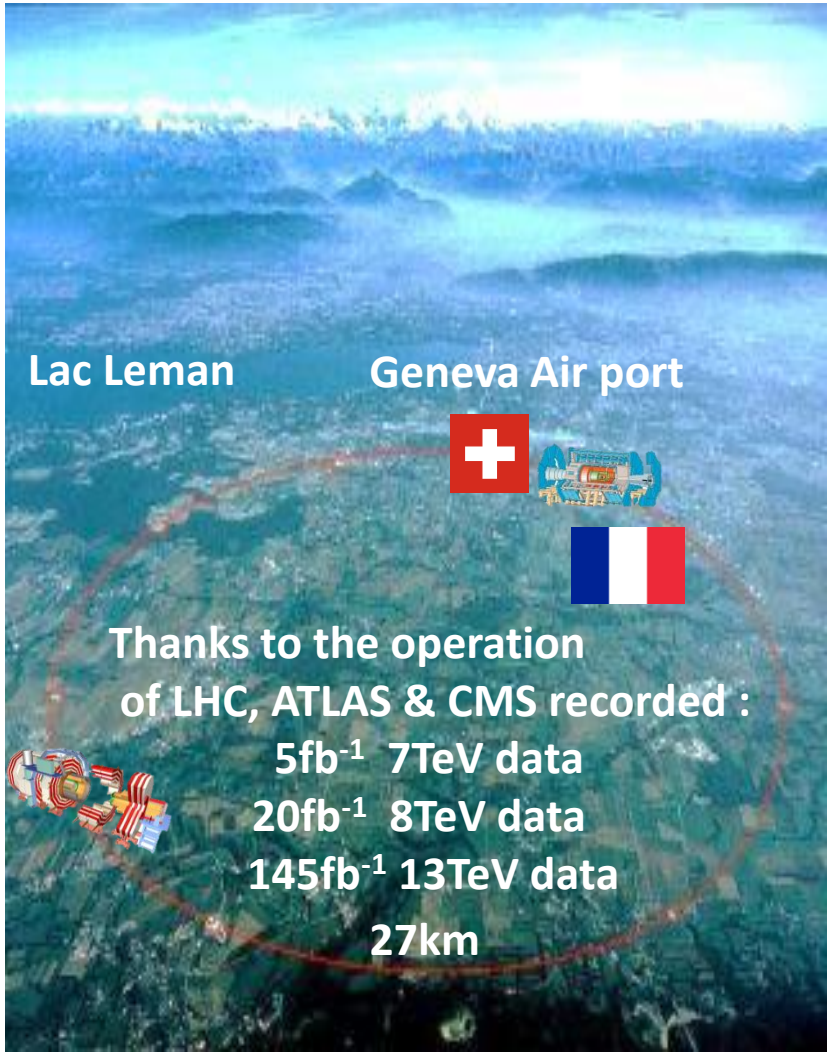
Large Hadron Collider (LHC)

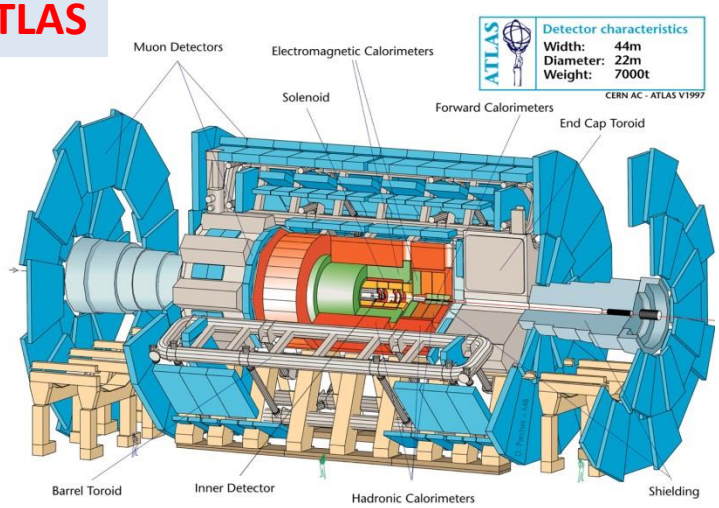


27km proton-proton collider
Placed 100m under ground.
2010-2012 : 8TeV max.
2015- : 13TeV

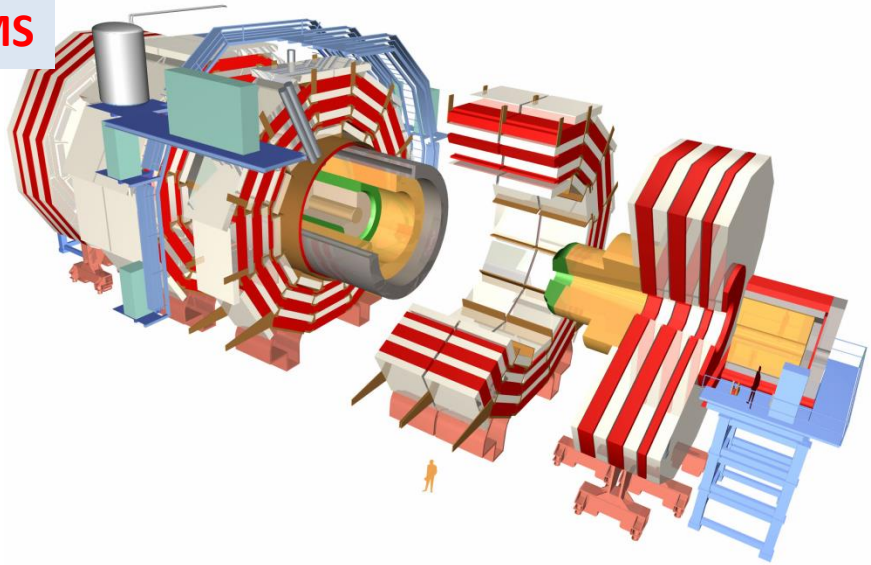
LHC and ATLAS/CMS experiment



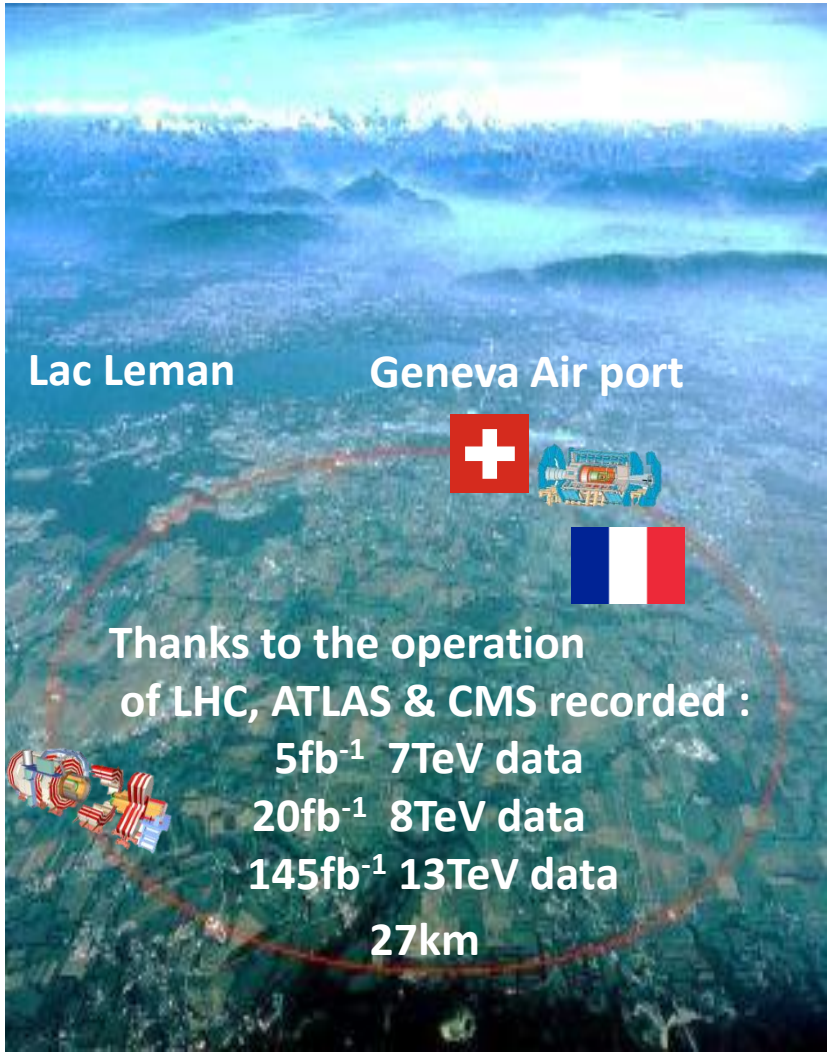
ATLAS



CMS

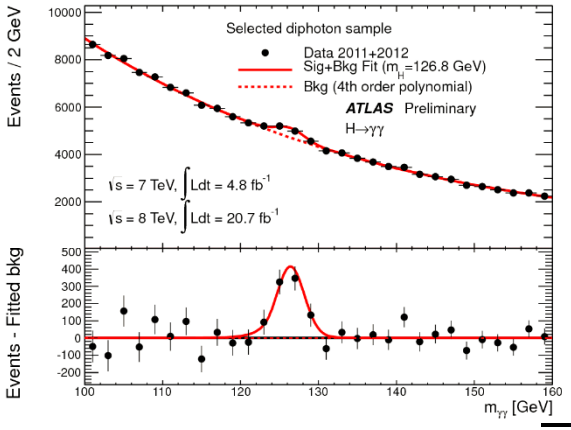


LHC and ATLAS/CMS experiment

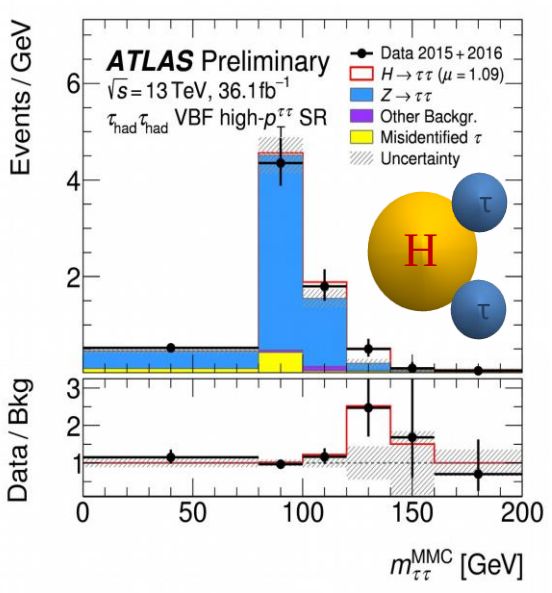


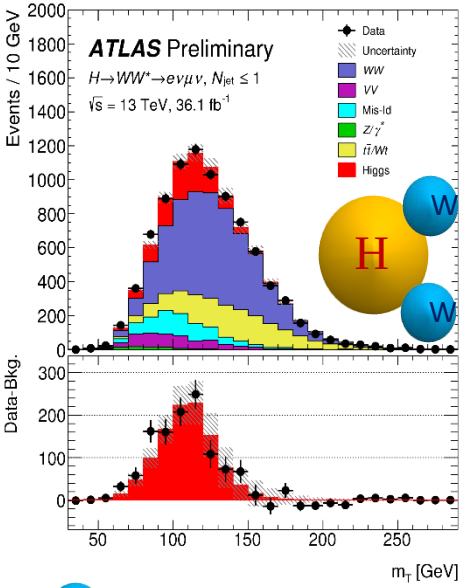
Great achievement :

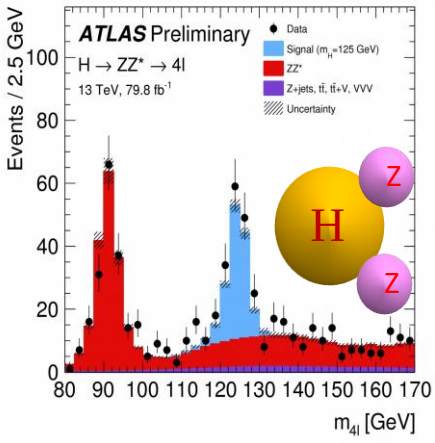
Higgs observation



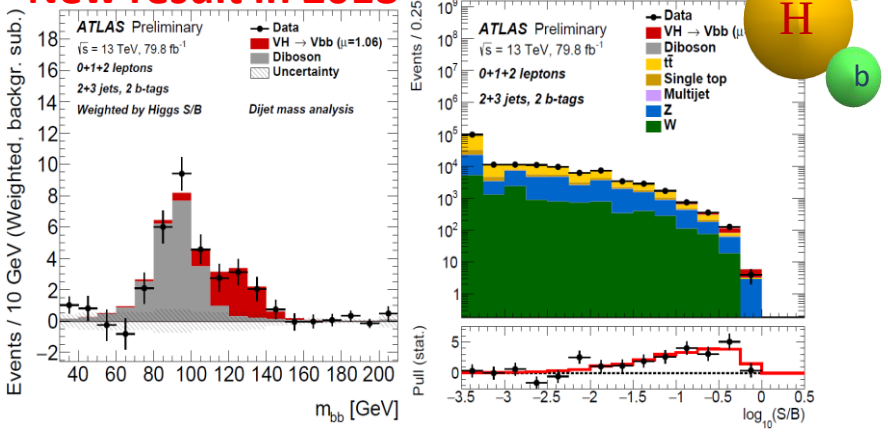
Observation of Higgs couplings







New result in 2018



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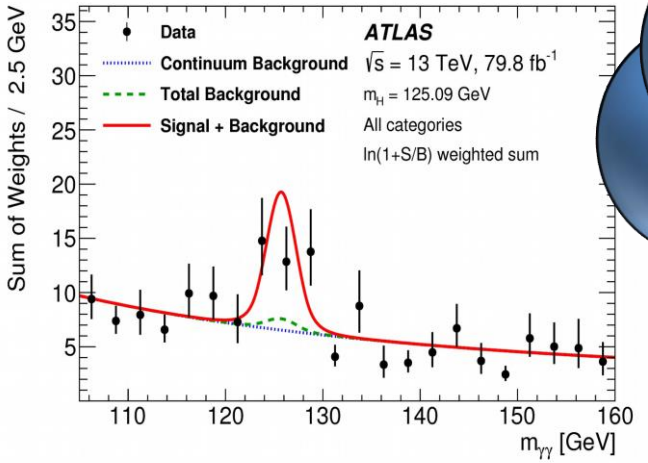
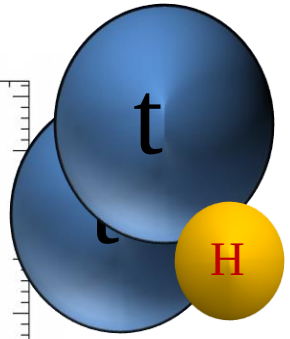
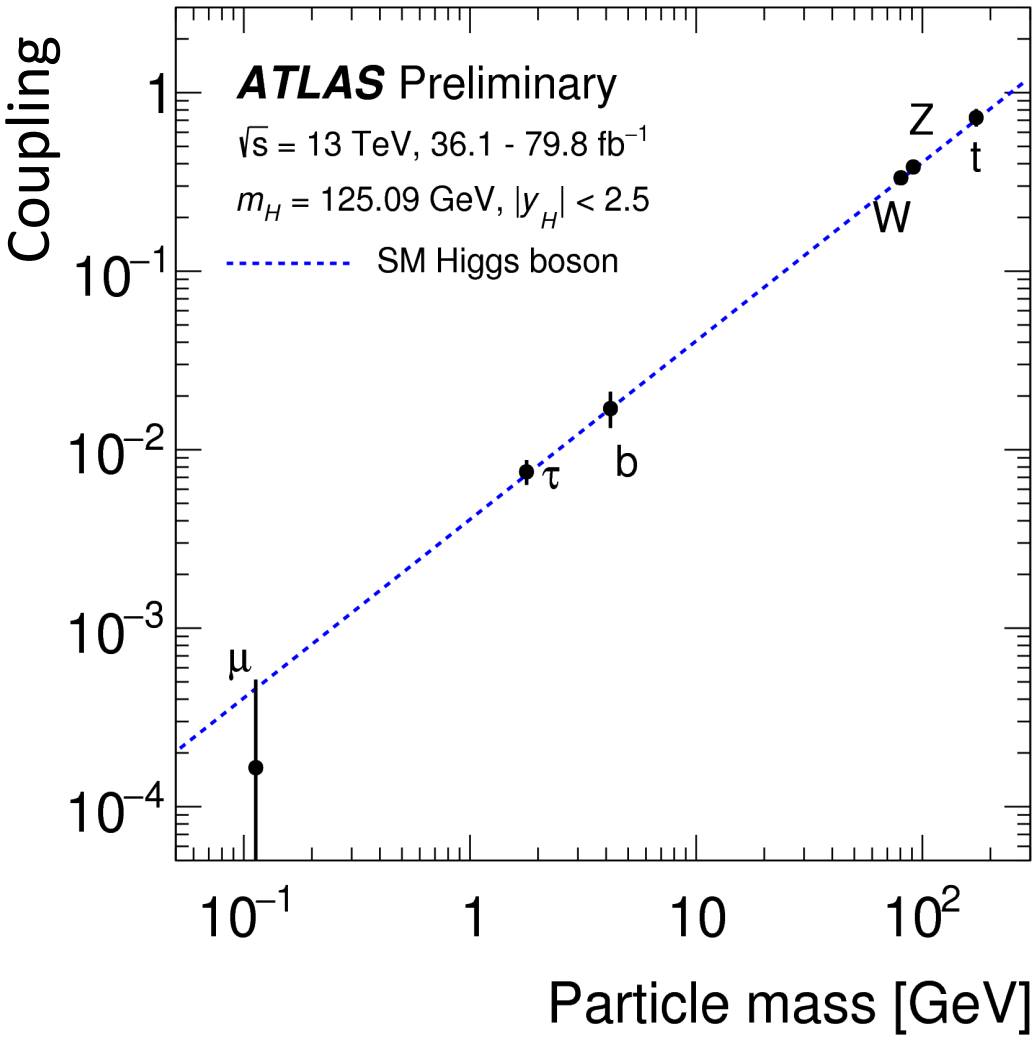




What we are now?



Coupling proportional to the particle mass

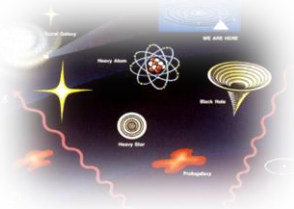
→This is the evidence of

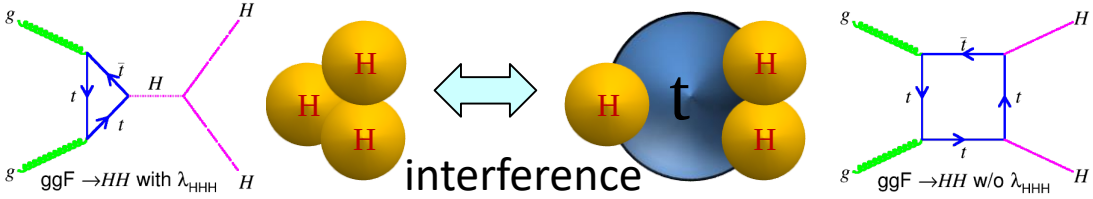
"Higgs give the mass of particles"

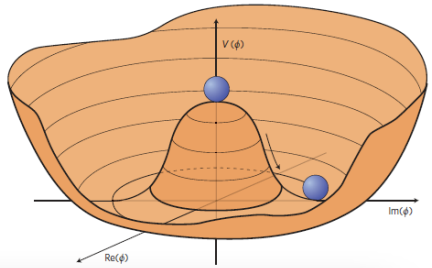
What we want to know next?

- ***"Vacuum"***
  - "Vacuum" is nothing? Filled by Higgs boson?
  - How Higgs boson/field condensed to the "Vacuum"?
  - Need to determine/observe the shape of Higgs Potential.

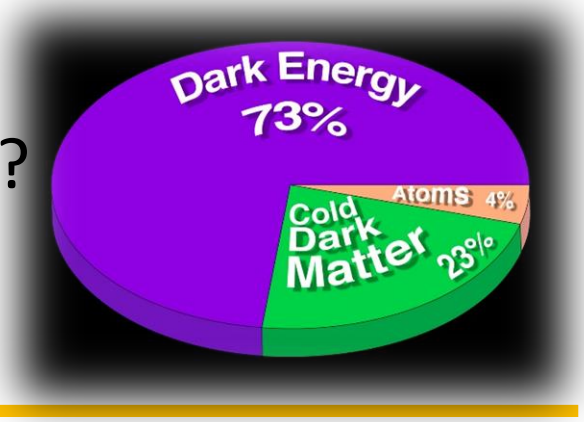
  →Observe/measure "Higgs self coupling".





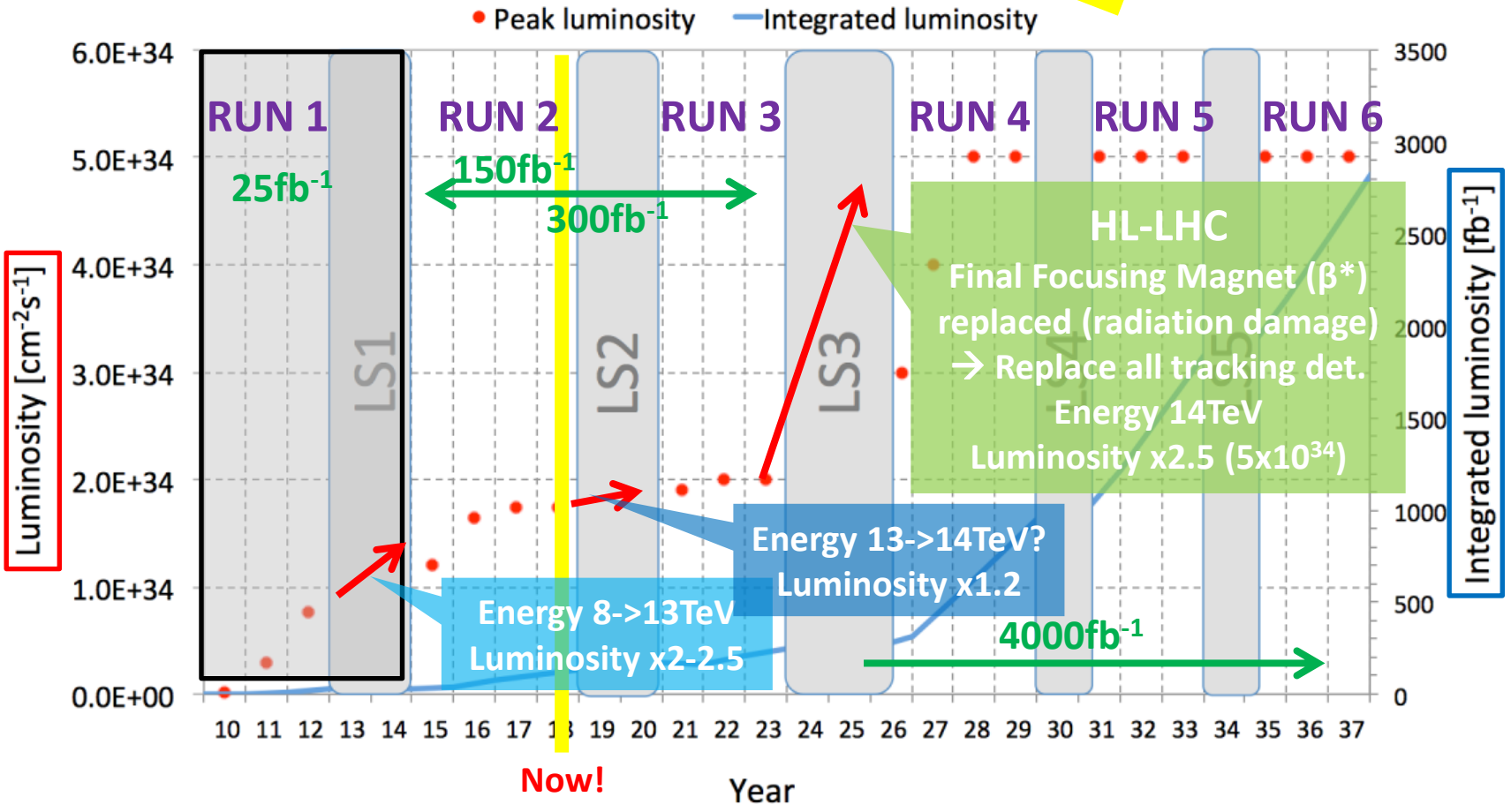


- ***"Dark Matter/Energy"***
  - We only know 4%. What's the others?
  - Beyond the Standard Model?
    - Super Symmetry?



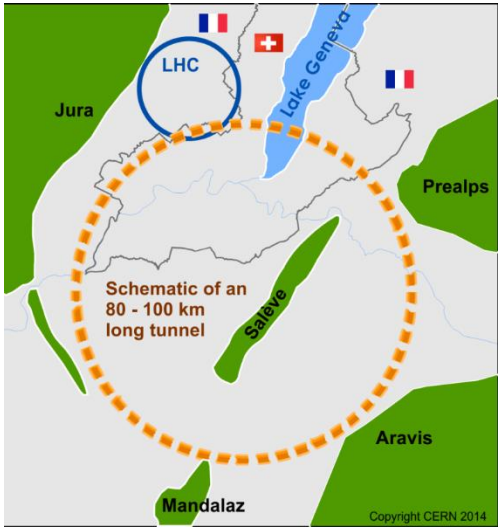
Future Hadron Collider

- Need "Higher Luminosity" and/or "Higher Energy"
  - ***High Luminosity LHC (HL-LHC)*** **Approved!**



Future Hadron Collider

- Need "Higher Luminosity" and/or "Higher Energy"
  - ***High Luminosity LHC (HL-LHC)*** Approved!
    - 20 times more data than currently taken (~3000-4000fb^{-1})
    - Plan : Start at 2026
  - ***High Energy LHC (HE-LHC)*** Discussion Started
    - Use Super Conducting Magnet with Higher Magnetic field(16T)
    - 28TeV collider in the same tunnel as LHC.
  - ***Future Circular Collider (FCC)*** Discussion Started
    - Use Super Conducting Magnet with Higher Magnetic field(16T)
    - 100TeV collider with 100km tunnel at CERN.



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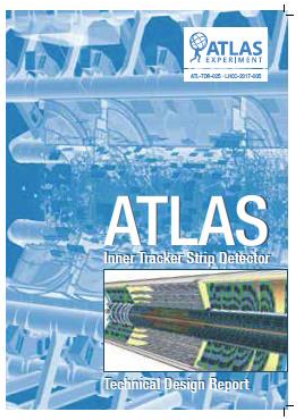
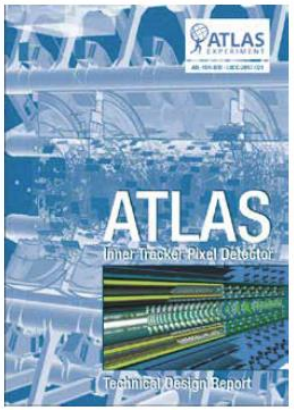
Technical Design Report for HL-LHC



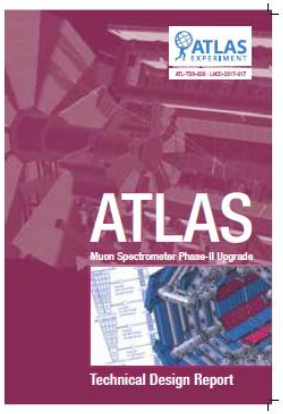
ITk strip tracker

Submission: Dec 2016
Approval: June 2017



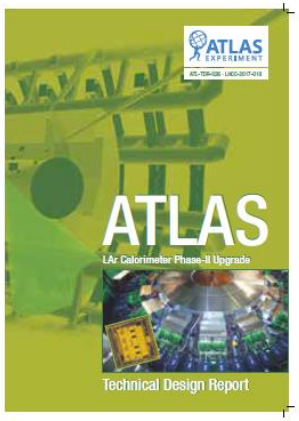
ITk pixel tracker

Submission: Dec 2017
Approval: April 2018



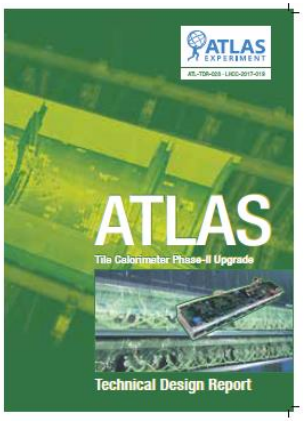
Muon spectrometer

Submission: July 2017
Approval: Dec 2017



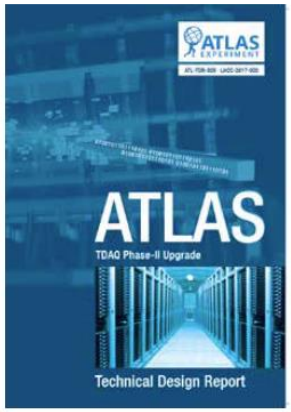
Liquid Argon Calorimeter

Submission: Sep 2017
Approval: March 2018



Tile Calorimeter

Submission: Sep 2017
Approval: March 2018



Trigger / Data Acquisition

Submission: Dec 2017
Approval: April 2018

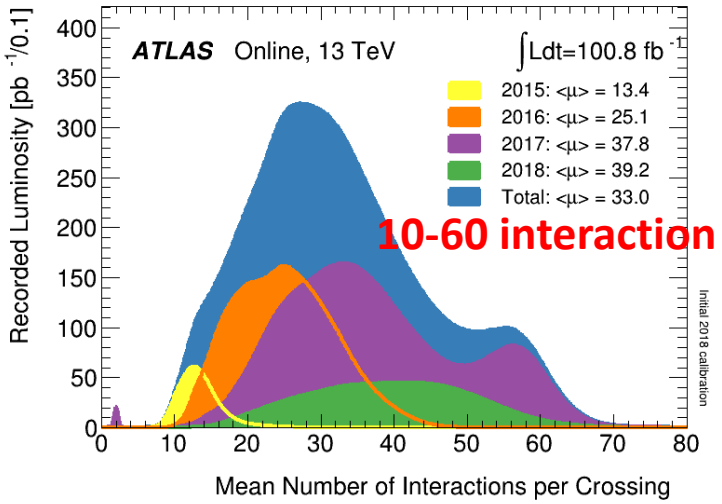
- Detector design for High Luminosity LHC is almost final.
- **Released 6 Technical Design Reports**
- Production for the silicon detectors start very soon.
- **Getting ready for mass production**

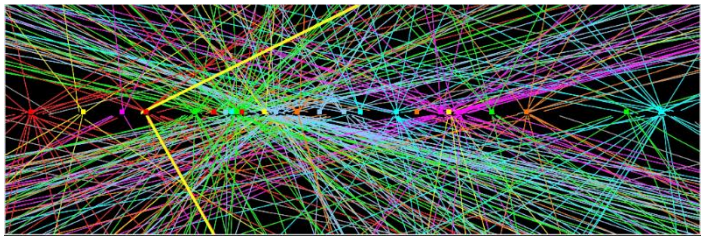
Challenge for Detector building

- Design Luminosity of HL-LHC
  - Current LHC: $L=2x10^{34}cm^{-2}s^{-1}$
  - HL-LHC : **$L=7x10^{34}cm^{-2}s^{-1}$**

3-4 times higher

Number of Interaction per Crossing





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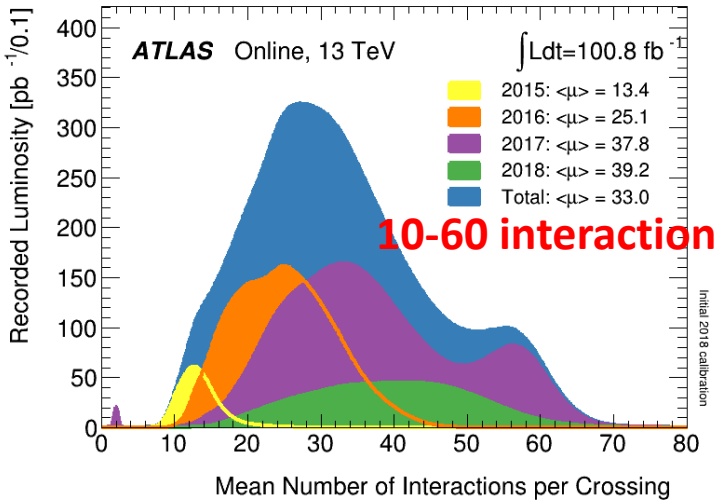
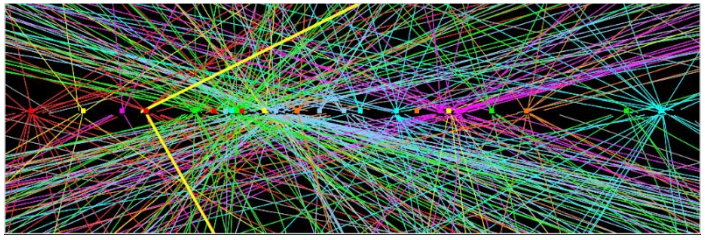
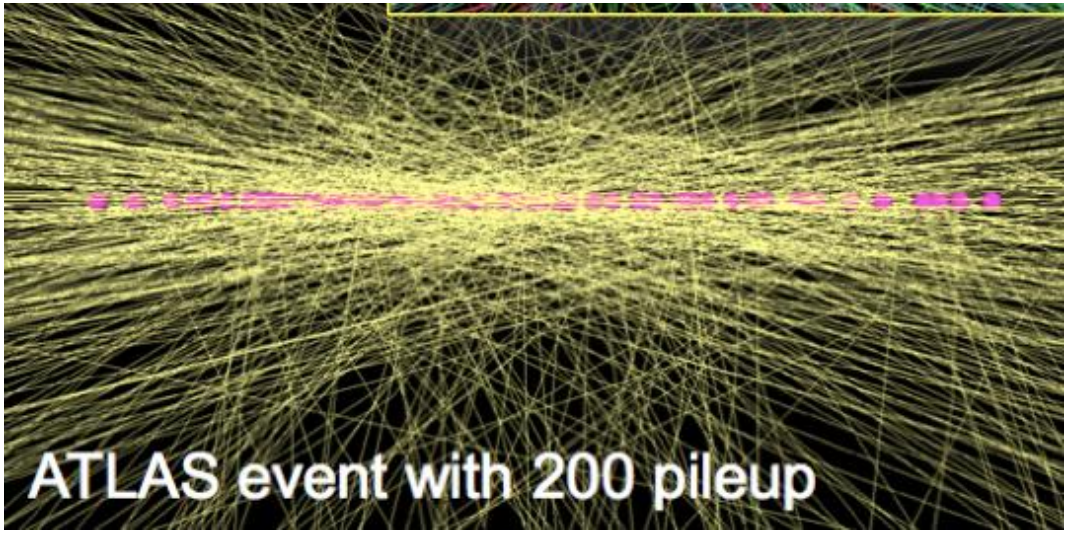




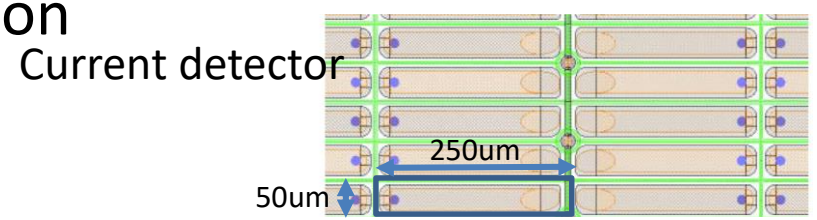
HL-LHC : 140 interaction per bunch crossing

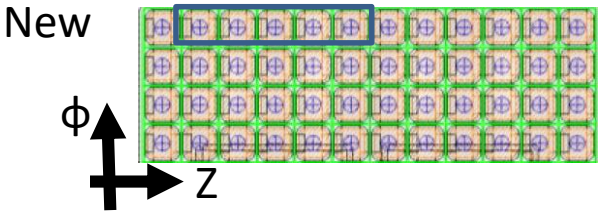


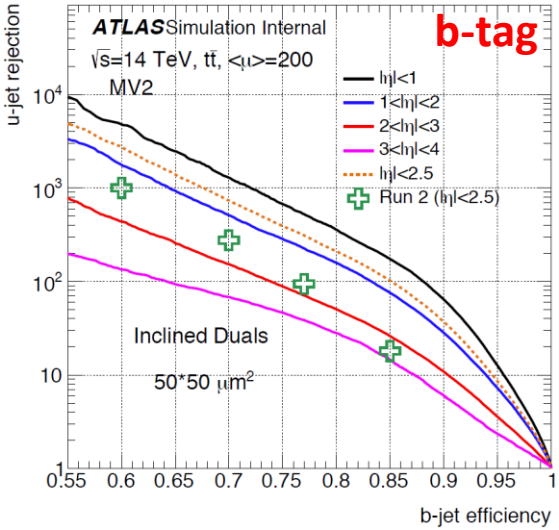
Need to identify the primary vertices to reduce Pileup oriented background

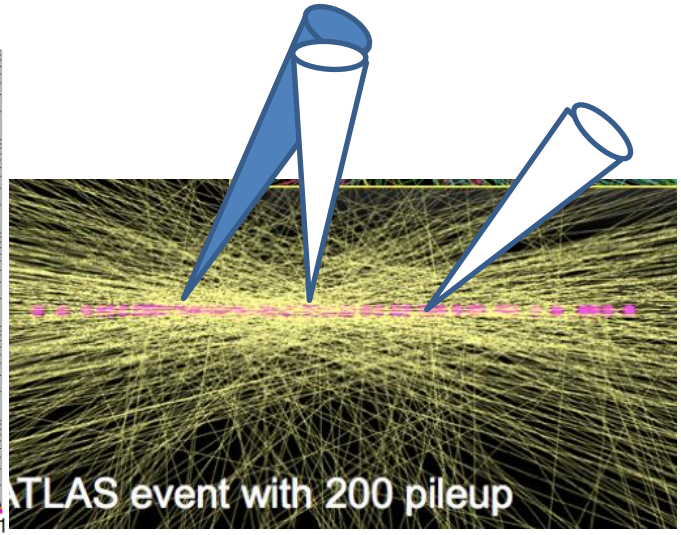
Specification for Upgrade detector

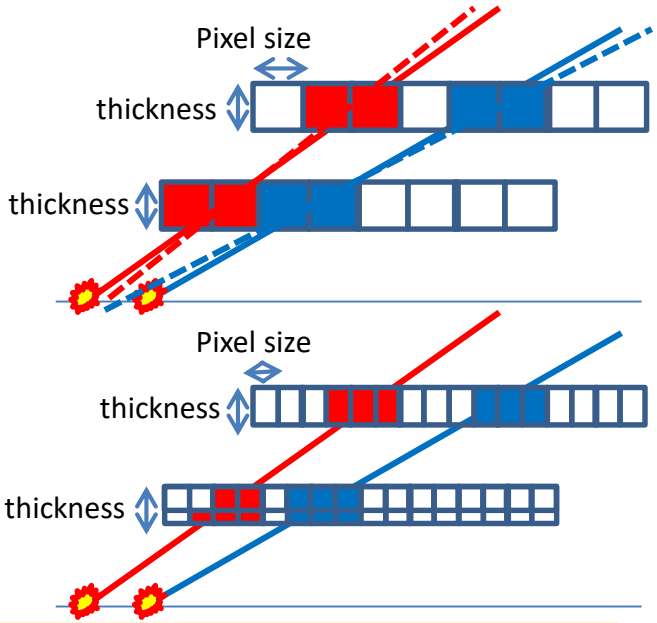
- Pixel size for charged particle detection
  - 5 times finer pixel size
  - **50um x 50um or 25um x 100um**
- Sensor thickness
  - Thinner sensor could reduce occupancy.
  - **1st and 2nd layer 100um, the others 150um**
  - Need 100um thickness to have enough charge (~7000 e-/h pair)







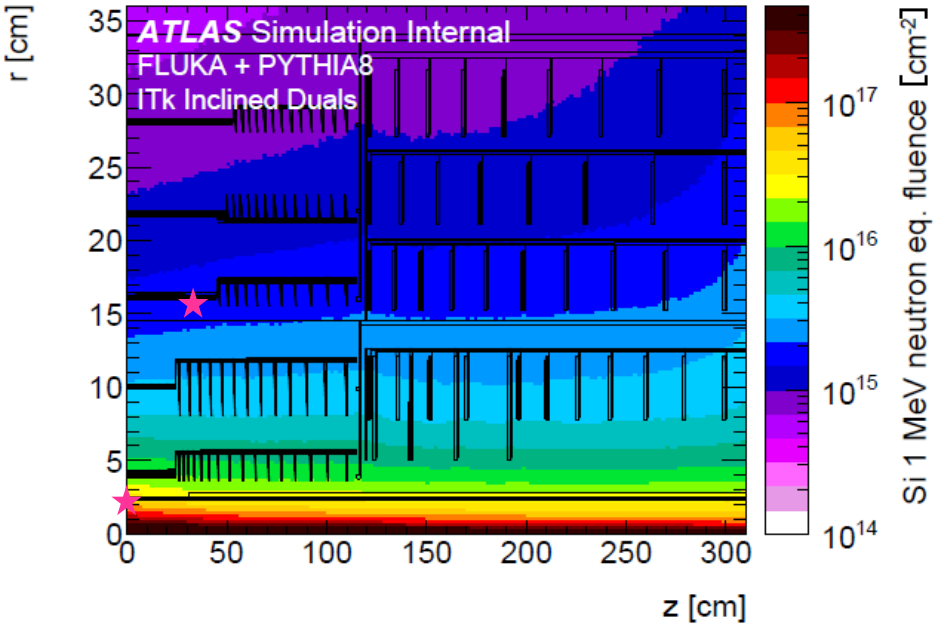


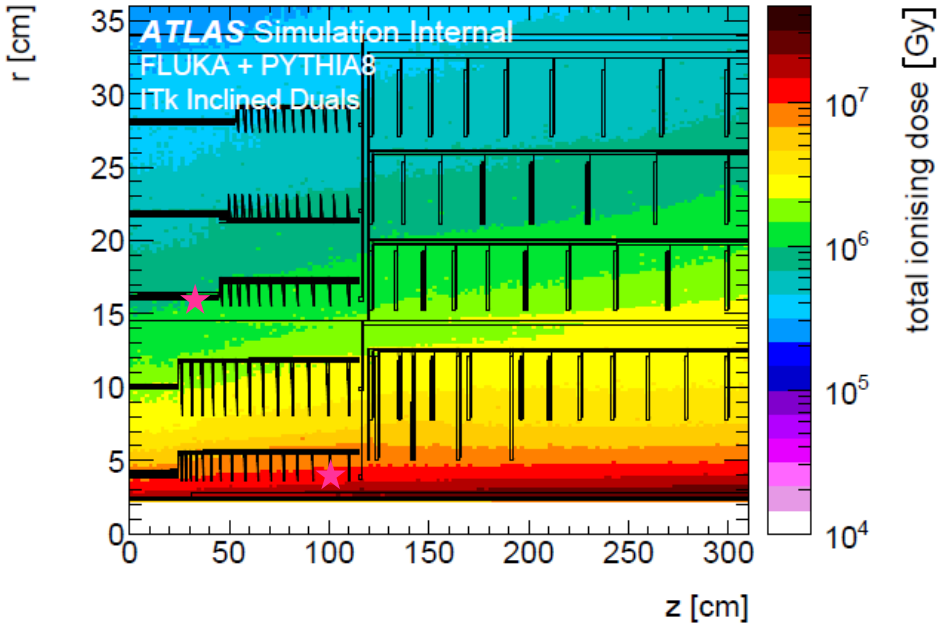


Radiation environment

- Expected radiation level for 4000fb^{-1}
  - Non Ionizing Energy Loss (NIEL):
    - 3rd layer: 2.8x10^{15} n_{eq} /cm^2 1st layer : 2.6x10^{16}neq/cm^2
  - Total Ionizing Dose (TID) :
    - 3rd layer : 1.6MGy 1st layer : 19.8MGy

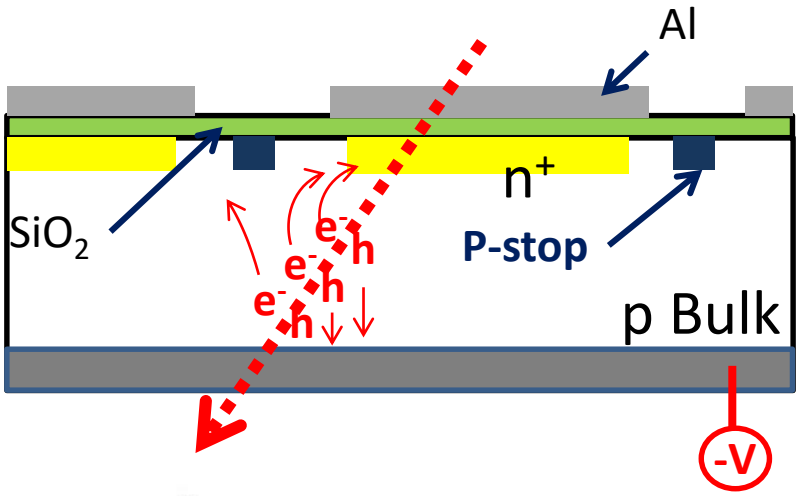
Could replace detector at the middle of runs.

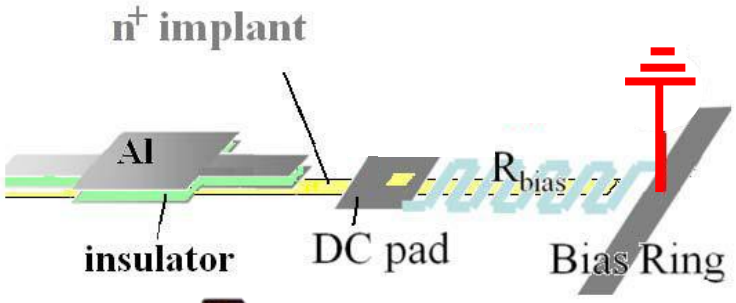




Semiconductor tracking detector

- Basic principle :
  - Backside is negative bias and n+ is ground.
  - Detect electron-hole pairs created by ionizing energy loss from MIP particle.
- Strip detector
  - **n+ can easily ground at the end of strip.**
  - Readout usually via **"wire bonding"** strips to the readout ASIC.





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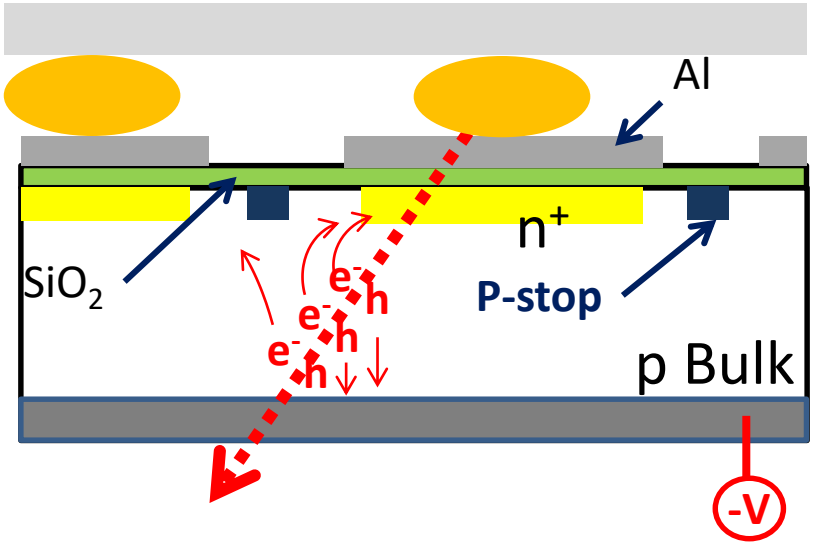
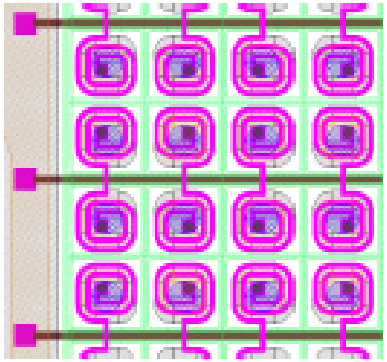
  - Readout usually via **"wire bonding"** strips to the readout ASIC.
- Pixel detector (new technology)
  - **Electrode placed two dimensionally.**
  - To ground all pixels, high resistivity biasing grid is necessary.
  - Readout ASIC is connected by **"bump-bonding"**.





4 chip module

Our development is together with Hamamatsu Photonics K.K (HPK)

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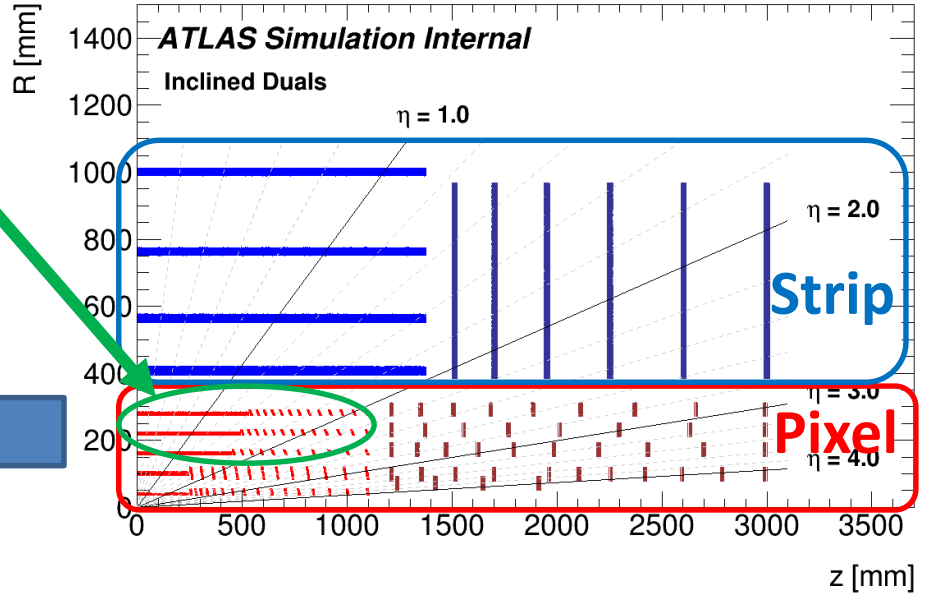
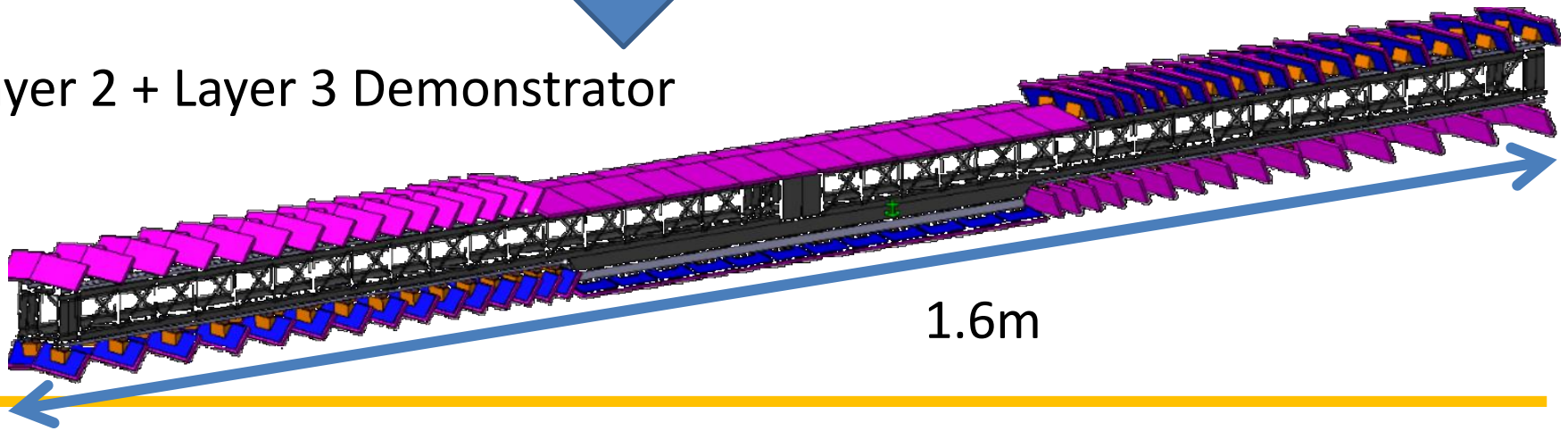
ATLAS Pixel Detector Upgrade

- Japan group : Pixel Detector development
  Target : 3rd – 5th layers
  - High Efficiency Sensor design
  - Readout ASIC and DAQ development
  - Sensor – ASIC attachment
  - Flex PCB design and assembly
  - Module loading to the support



Contributing to all steps
Build detector in Japan

Layer 2 + Layer 3 Demonstrator



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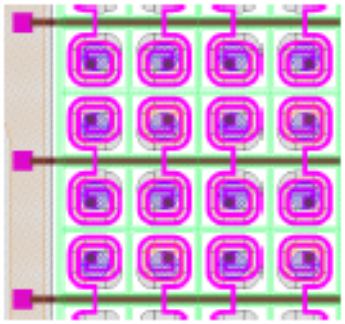
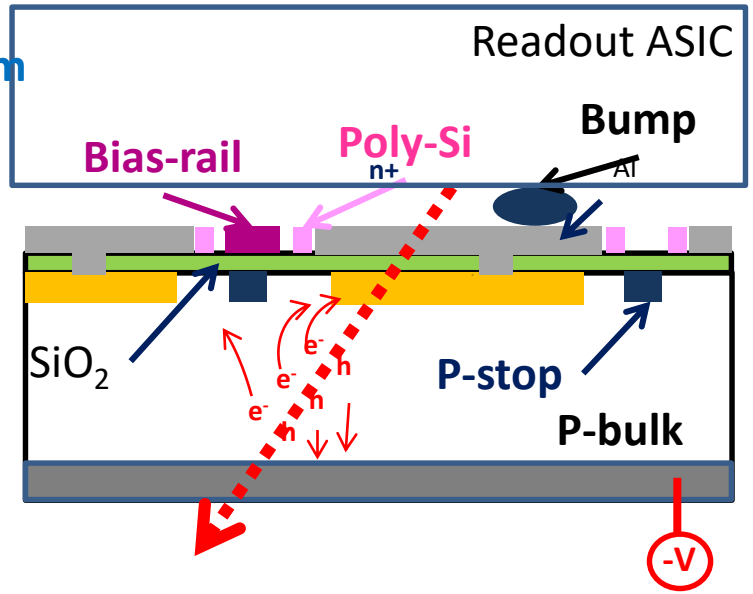
HPK: n+ in p type
Pixel Size : 50umx50um
Requirement :
97% after irradiation
($3x10^{15} n_{eq}/cm^2$)



Efficiency measurement at testbeam
Irradiation test by proton beam
→After irradiation >99% efficiency

Planar type Pixel module



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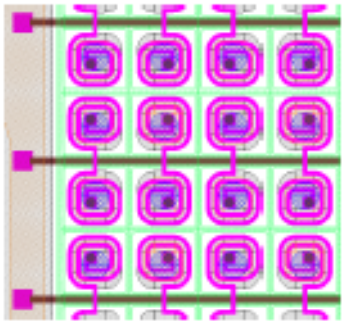
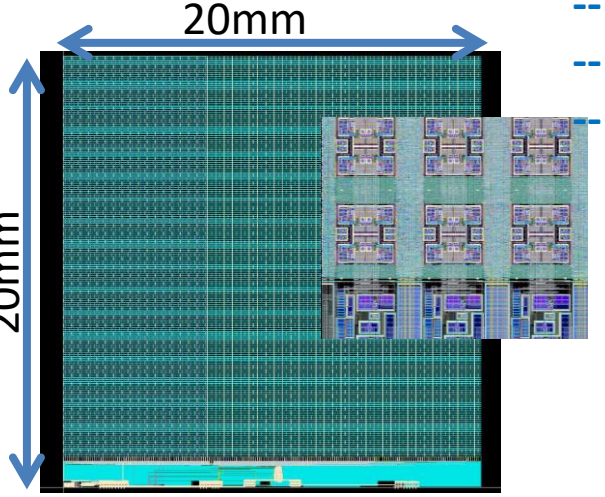
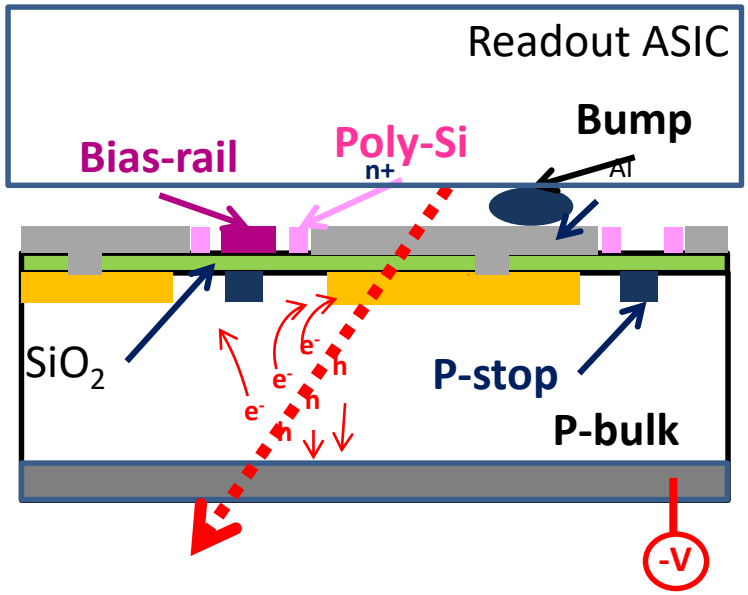


RD53 Collaboration
(ATLAS+CMS)
65nm CMOS process



½ size prototype available
DAQ development with US
-- 5.12Gbps / ASIC readout
-- 400x384 pixel matrix
-- Low noise (<100 e)

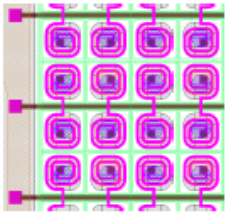
Planar type Pixel module



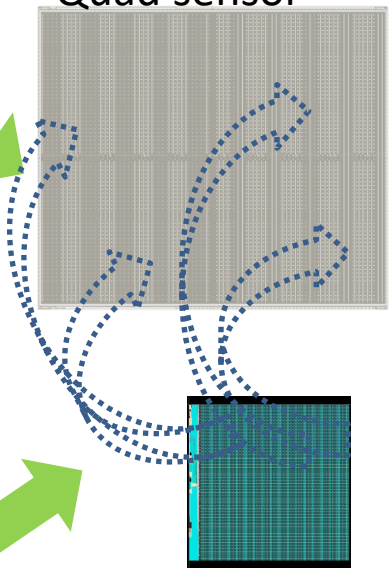
ATLAS Pixel Detector Upgrade

- Japan group : Pixel Detector development
  Target : 3rd – 5th layers
  - High Efficiency Sensor design
  - Readout ASIC and DAQ development
  - **Sensor – ASIC attachment**
  - Flex PCB design and assembly
  - Module loading to the support

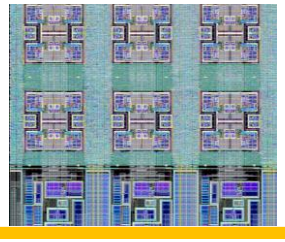
HPK Sensor



Quad sensor



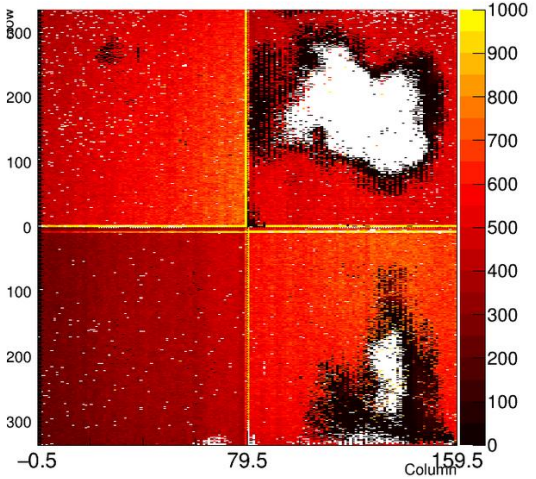
Readout ASIC
(TSMC)



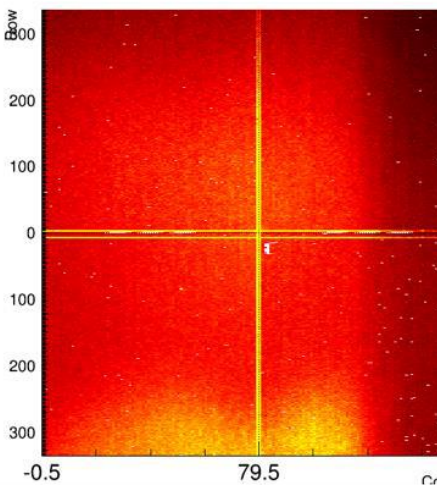
Bump bonding @ HPK
SnAg solder bump
no flux / no support wafer
Thickness sensor/ASIC
→150um/150um

Established in 2016
High production Yield
ready for mass production

^{90}Sr Source test (beginning)



^{90}Sr Source test (improved)



ATLAS Pixel Detector Upgrade

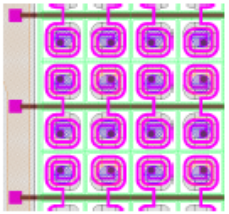
- Japan group : Pixel Detector development

  Target : 3rd – 5th layers

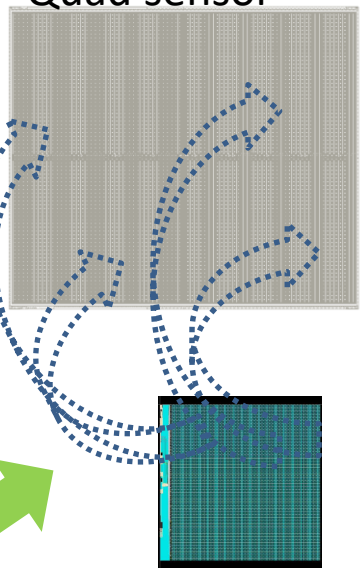
  - High Efficiency Sensor design
  - Readout ASIC and DAQ development
  - Sensor – ASIC attachment
  - **Flex PCB design and assembly**
  - Module loading to the support

Development of Assembly jig
Radiation Tolerance test for Glue
Wire bonding

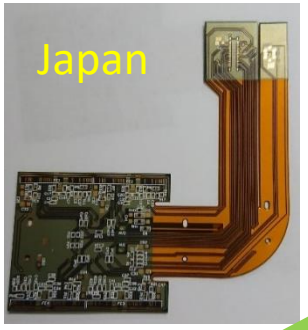
HPK Sensor



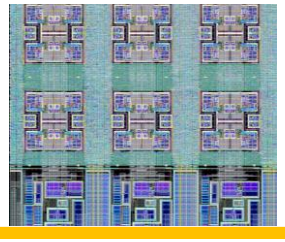
Quad sensor



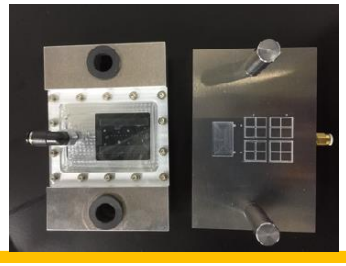
Module Flex

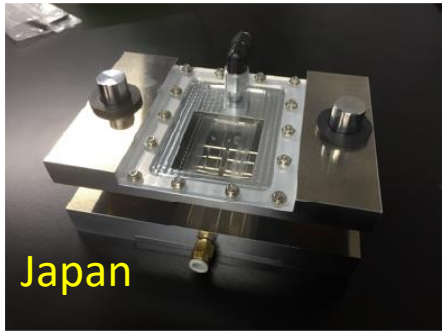


Readout ASIC
(TSMC)



Assembly jig





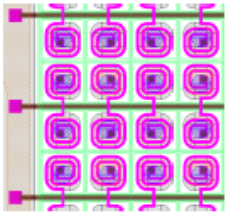
ATLAS Pixel Detector Upgrade

- Japan group : Pixel Dete
  Target : 3rd – 5th layers
  - High Efficiency Sensor
  - Readout ASIC and DA
  - Sensor – ASIC attachm
  - Flex PCB design and a
  - **Module loading to the support**

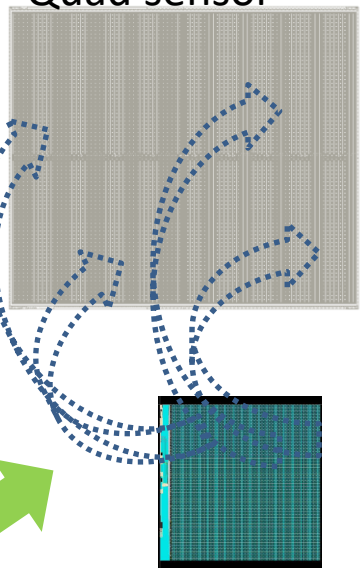
Installation

bending

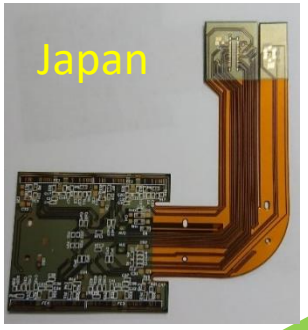
HPK Sensor



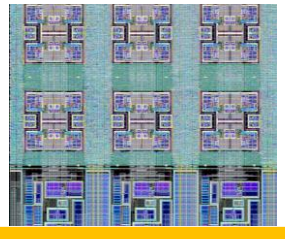
Quad sensor



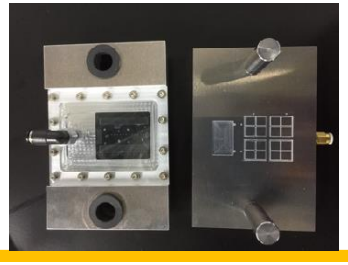
Module Flex

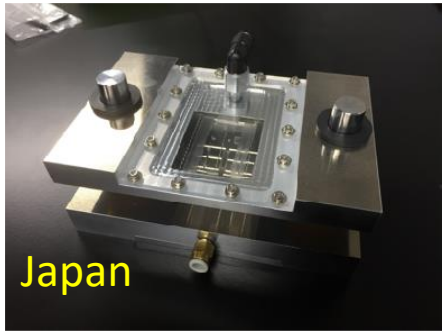


Readout ASIC
(TSMC)



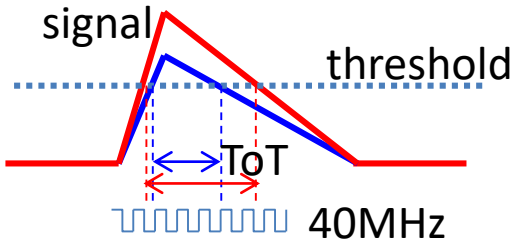
Assembly jig

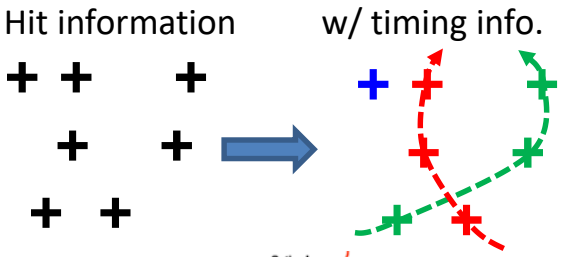


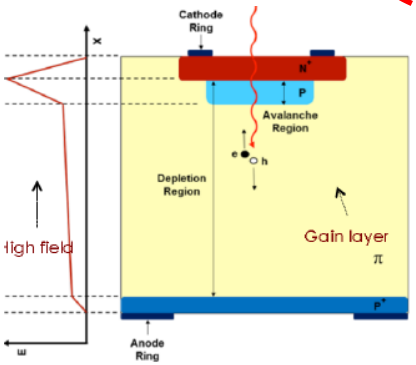


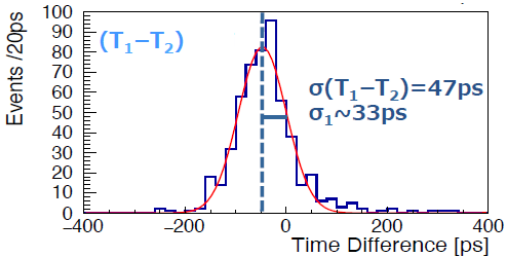
Signal readout and timing resolution

- Current Pixel detector
  - Amplifire and shaper are in ASIC
  - Time over Threshold (ToT) based ADC
    - Considering readout speed(5Gbps/ASIC), one of the best approach.
    - Time walk require less than 25ns (1 clock) to identify bunch of collision.
  - Once hit positions are obtained, reconstruct track as the best chi-square combination of hits.
    - **Timing information helps. 30ps ~ 1mm**
- Low Gain Avalanche Detector (LGAD)
  - Create High Electric Field to have huge mobility of e/h pairs.
  - **HPK device : ~30ps time resolution achieved!**



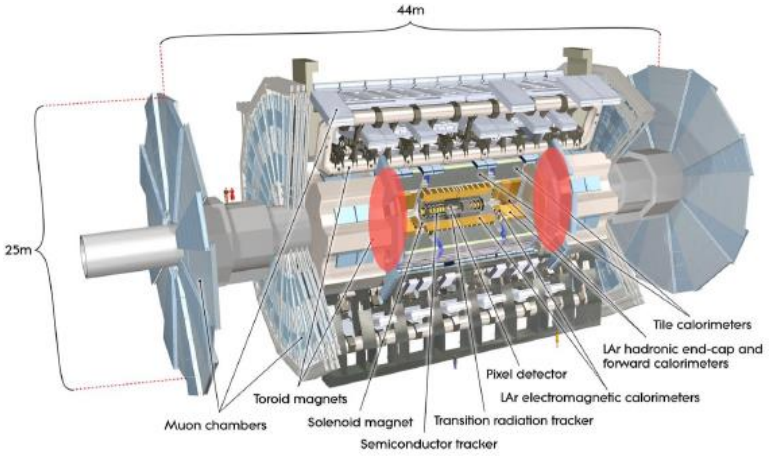


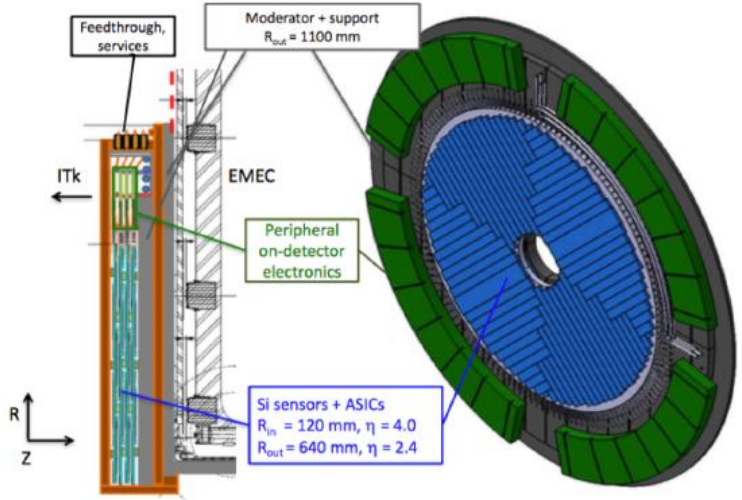




Future application of LGAD detector

- HL-LHC upgrade
  - Pad detector will be installed





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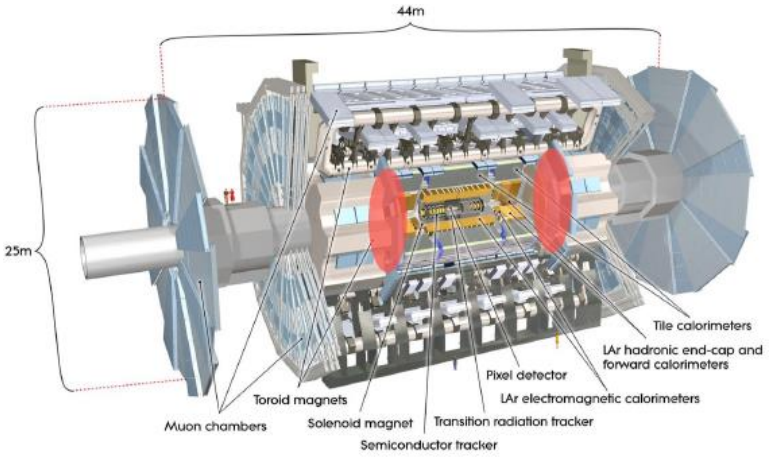
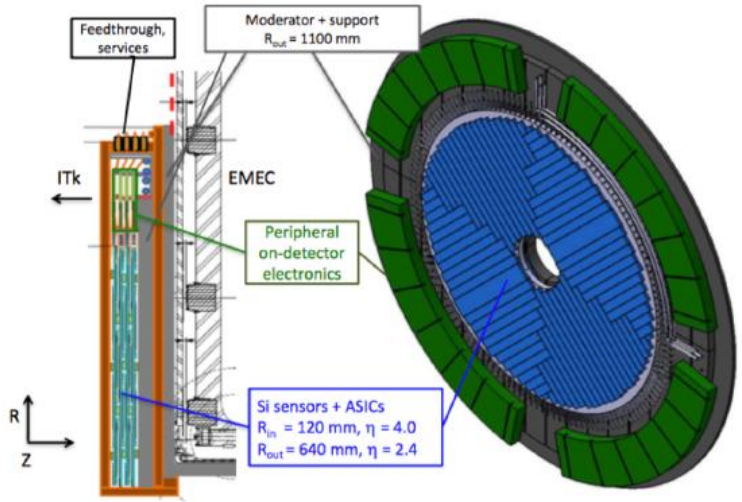


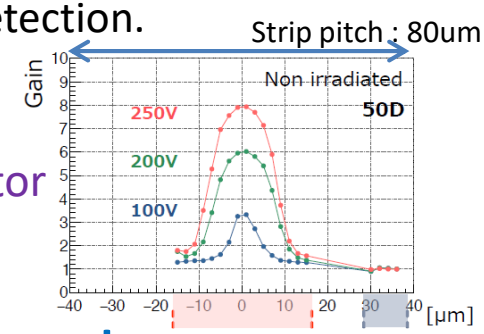


- Future improvement:

① **Better granularity :**

- The position detection.

Developed strip detector

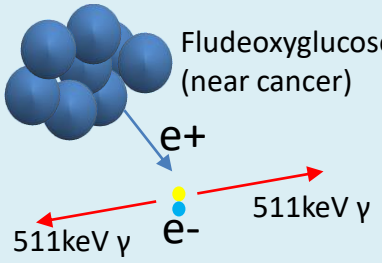


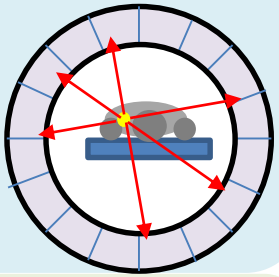
② **Higher radiation tolerance**

- Inner tracking detector.

Positron Emission Tomography (PET)

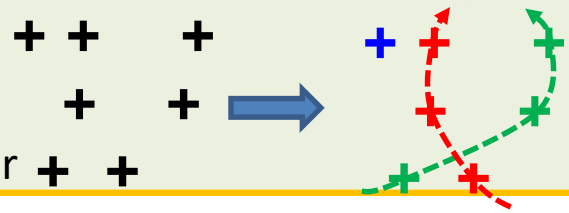
① Medical Usage (PET)





① + ②

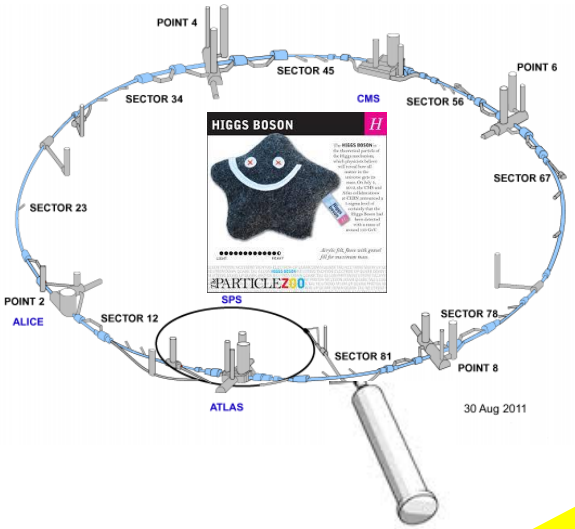
- HEP Detector
- Monitor of Nuclear Reactor



Conclusion

Conclusion

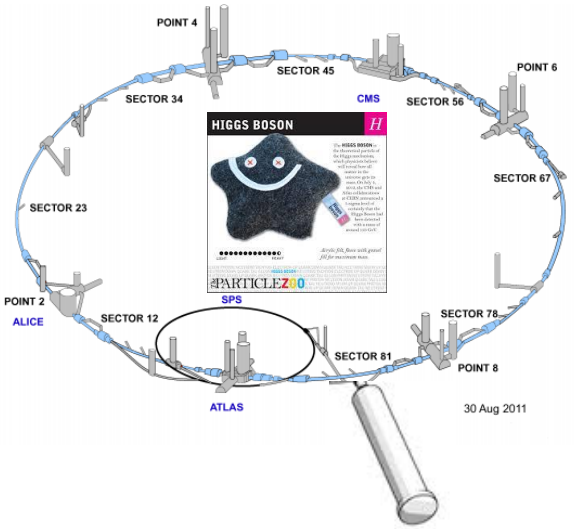
LHC



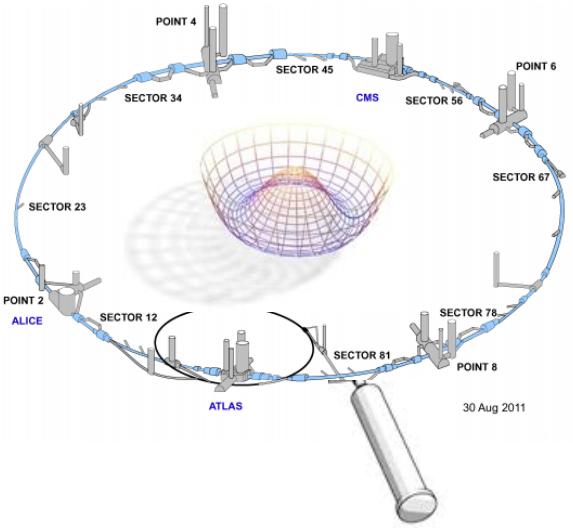
We observed Higgs boson and its couplings!

Conclusion

LHC



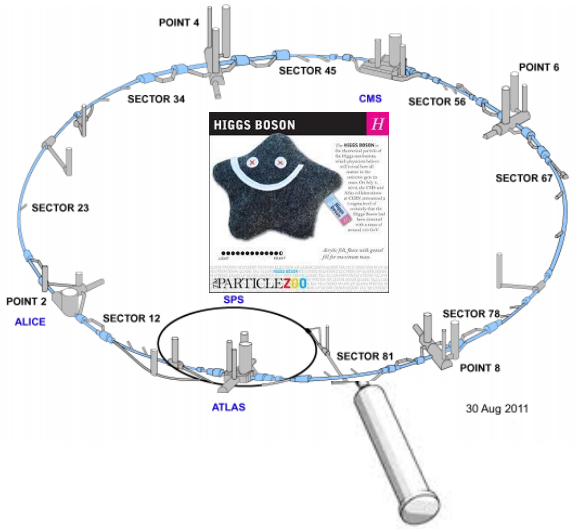
HL-LHC



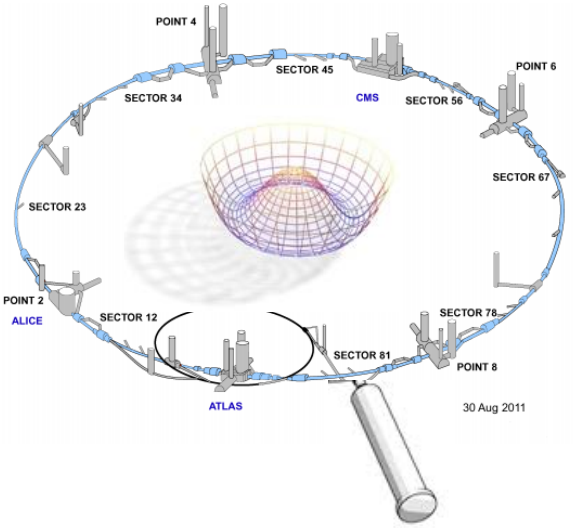
Upgrading accelerator and detectors to see more physics

Conclusion

LHC



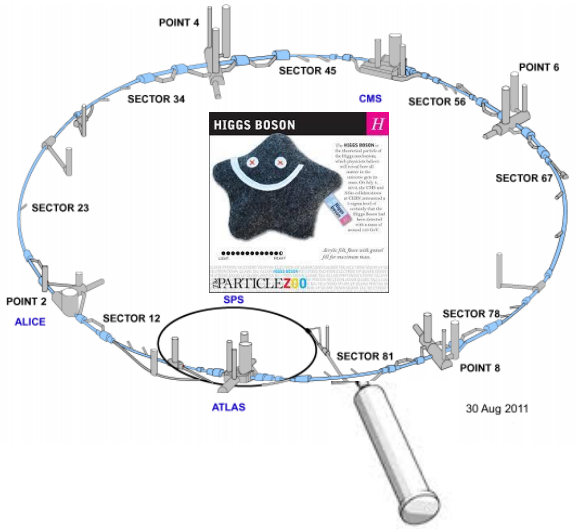
HL-LHC



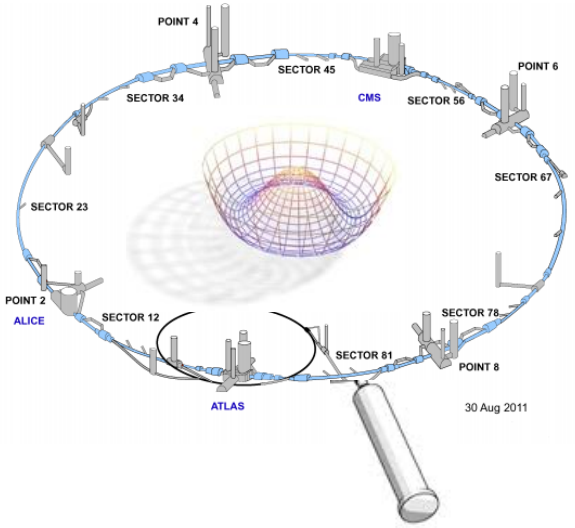
Our technology have possibility to contribute to the industry !

Conclusion

LHC



HL-LHC



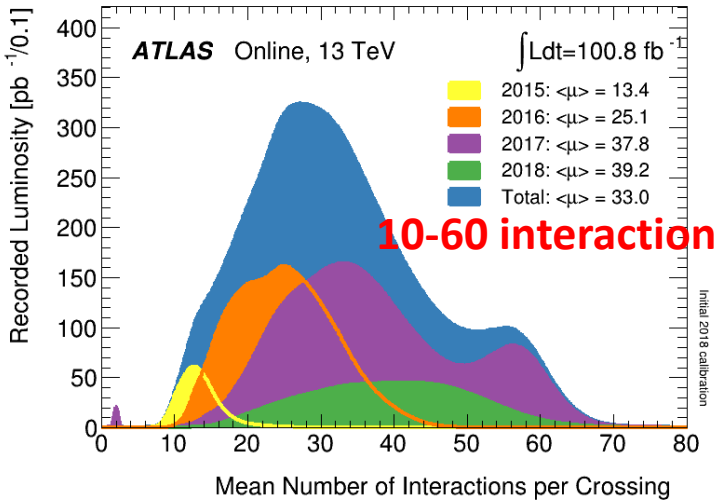
backup

Challenge for Detector building

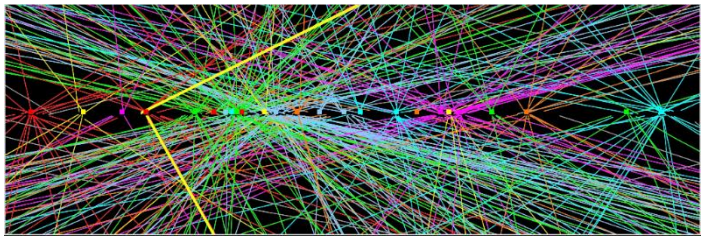
- Design Luminosity of HL-LHC
  - Current LHC: $L=2x10^{34}cm^{-2}s^{-1}$
  - HL-LHC : **$L=7x10^{34}cm^{-2}s^{-1}$**

3-4 times higher

Number of Interaction per Crossing



10-60 interaction



HL-LHC : 140 interaction per bunch crossing

HL-LHC μ=140 @ 5e34

HL-LHC++ μ=140 @ 5e34

LHC μ=40 @ 0.7e34