Detector developments

ICFA Seminar

Ottawa, November 2017

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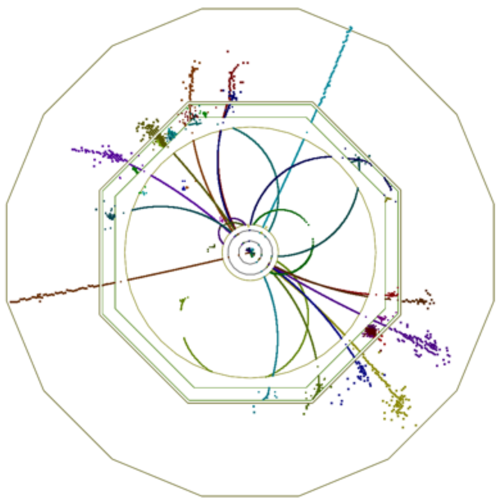
- **Introduction**
- **Silicon detectors**
- **Micro pattern gaseous detectors (MPGD)**
- **Photon sensors**
- **Particle Flow calorimetry**
- **Summary**

Disclaimer

– I am **NOT** an expert of individual detector technologies. My talk is automatically at "**colloquium**" level for non-experts, just as Jon asked speakers by email.
– I will talk about only some highlights (maybe biased), and will not cover electronics, triggers, DAQ, and so on.
– My apologies: many important works are not mentioned.
– Many things are taken from slides at various conferences that were held in recent years. Sorry and thanks a lot.

Particle detectors

We want to understand what is happening in particle collisions, ideally at the level of Feynman diagrams.



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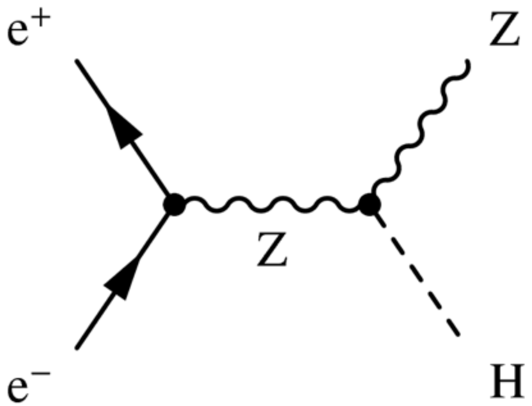
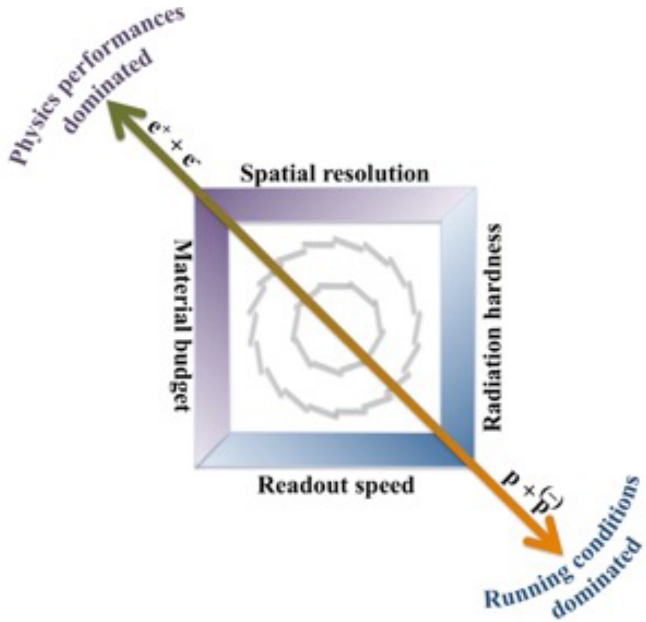
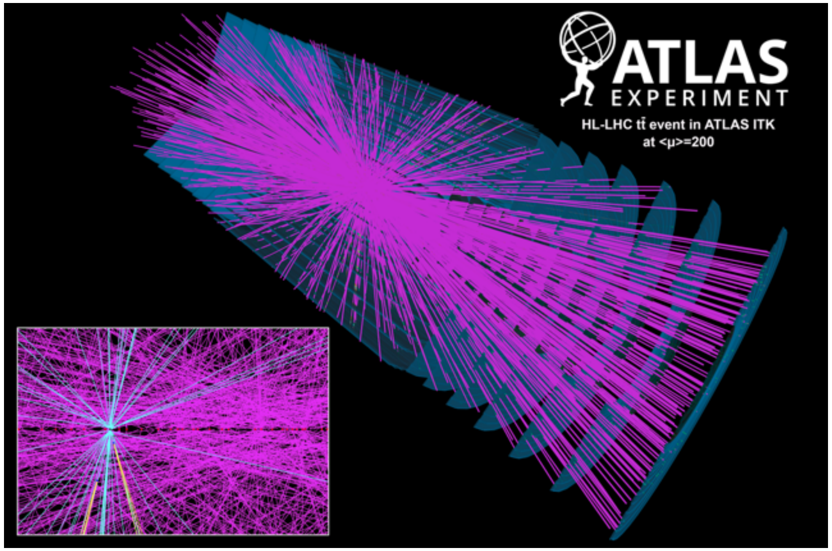
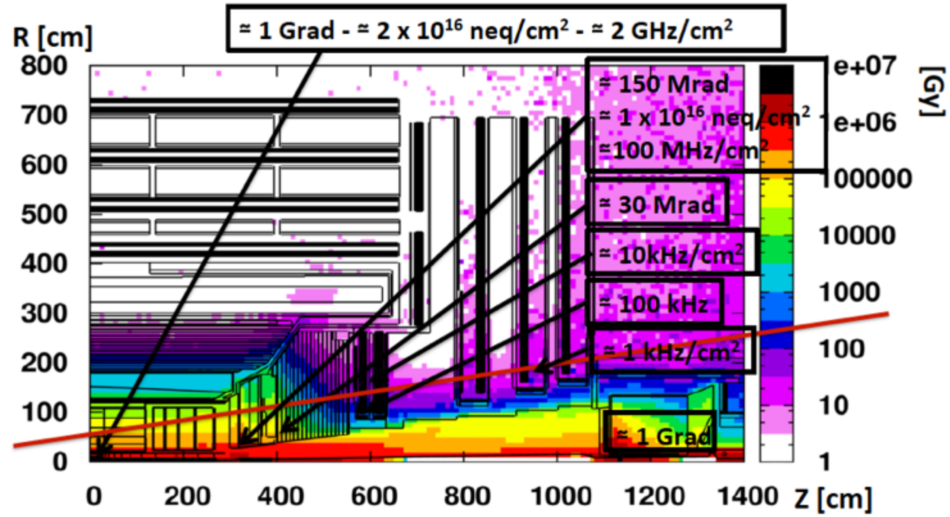


- **Future experiments require very challenging detectors in many aspects.**
- **The requirements depend on collision types, energies, and luminosities.**



Challenges of HL-LHC experiments





Maintain physics performance in extremely hard experimental conditions

- Peak luminosity 7.5x10^{34} cm^{-2}s^{-1}, Integrated luminosity 4 ab^{-1}

High occupancy and pile up

- Average pile up 140 (maximum 200): we will suffer from
  - increases of the combinatorial complexity and rate of fake tracks
  - extra energy to calorimeter measurements
- **Granularity** and **timing** are the keys to mitigate pile-ups
- Improvement of trigger and readout capability is necessary

Radiation damage

- Detector elements and electronics are exposed to high radiation dose (10 x LHC)
- **More radiation hardness** is required for trackers and endcap/forward detectors

Challenges of future lepton colliders

Maximize physics performance in much cleaner experimental conditions

- Moderate radiation level: ~ 100 kRad+10^{11} n_{eq}/cm^2 at inner vertex layer (ILC)

--> Pursue ultimate detector performance

$\sigma_{IP} = a \oplus b/p\sin^{3/2}\theta$

x	LEP	SLC	LHC	ILC
a [μm]	25	8	12	5
b [μm GeV/c]	70	33	70	10

Vertex Detector:

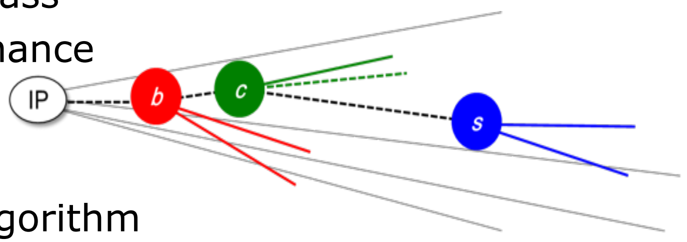
- Excellent IP resolution for efficient b, c jet tagging
- Much smaller pixel size, much less material budget

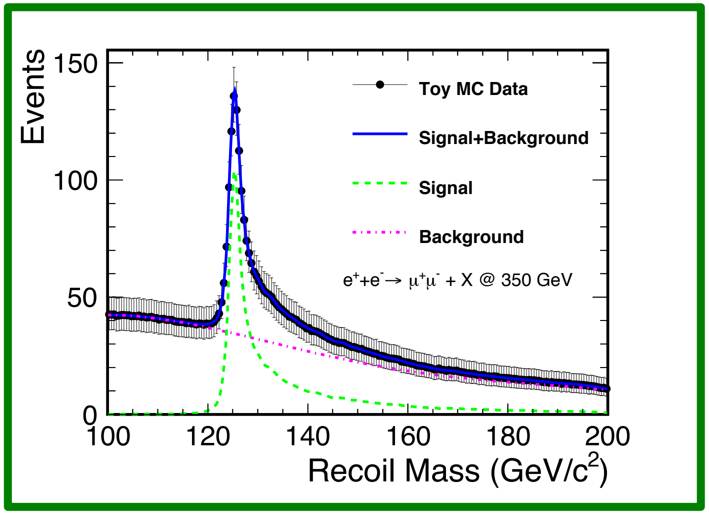
Central Tracker:

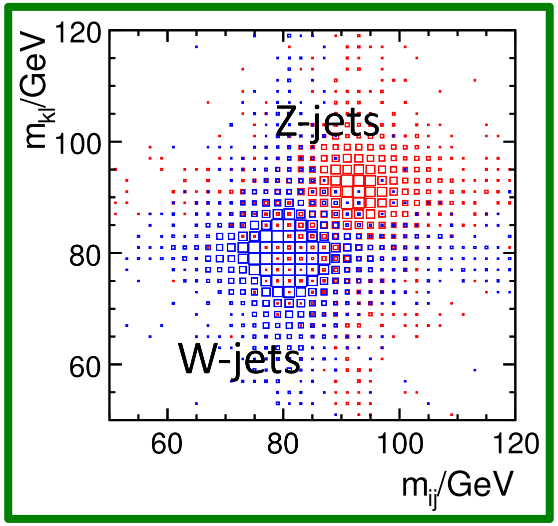
- High momentum resolution to reconstruct Higgs recoil mass
- Low material budget, not to degrade calorimeter performance

Calorimetry:

- High jet-energy resolution to separate W-jets and Z-jets
- A promising solution: high granularity for particle flow algorithm

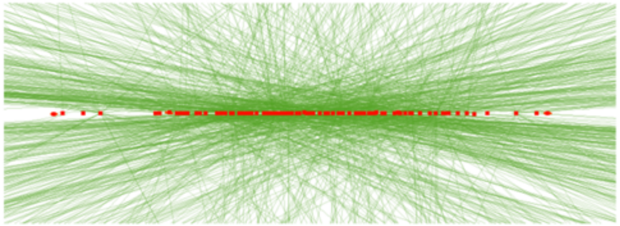




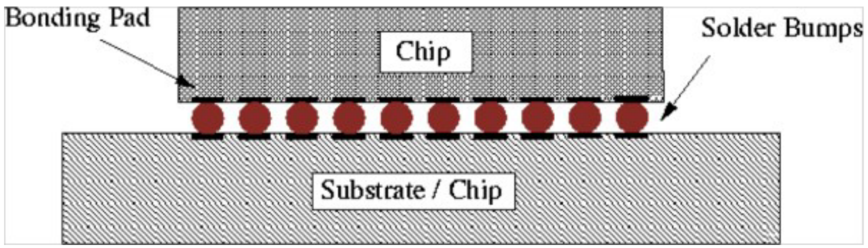


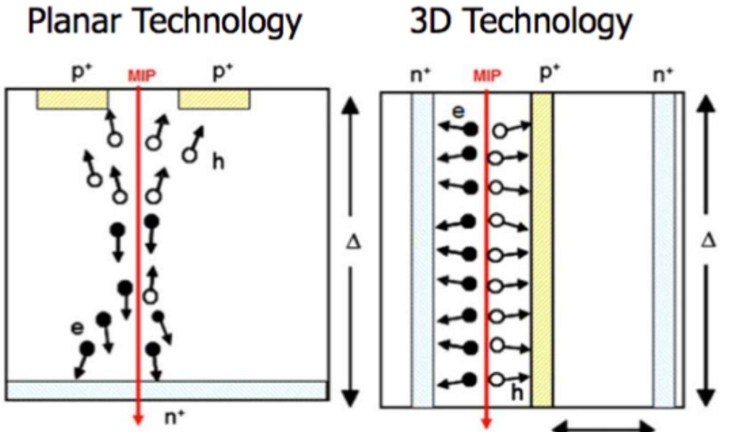
Silicon detectors

Pixel detectors for HL-LHC



- Challenges for pixel detectors
  - Radiation hardness (factor 10 x LHC)
  - Readout, Trigger, Size, Production cost, …
  - Similar approaches by ATLAS and CMS
- **Baseline**: Classical **hybrid** pixel detectors with bump bonding
  - **n-in-p planar sensors**: more radiation-hard than p-in-n sensors
  - **3D sensors**: columnar electrodes inside the sensor bulk: electrode distance can be shorter than sensitive detector thickness → more tolerance against radiation



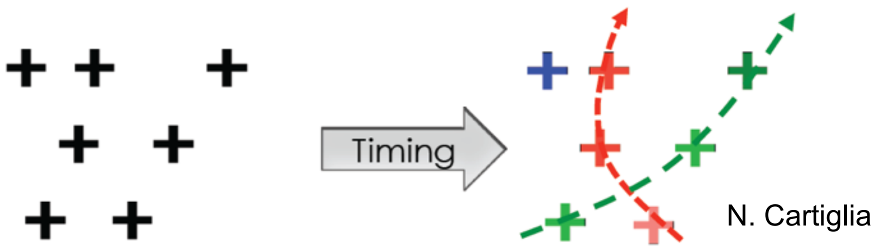


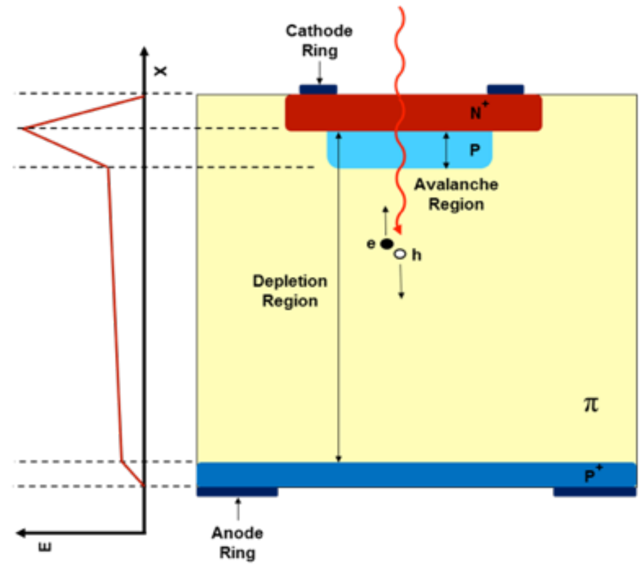
C. Da Via et al., NIM A 694 (2012) 321

- Different pixel sizes being tested: 50x50 μm^2 and 25x100 μm^2
- Readout chip designed in RD53 collaboration
  - TSMC 65 nm CMOS process
  - Radiation hardness: 1 Grad, 2×10^{16} n_{eq}/cm^2 over 10 years

Low-Gain Avalanche Diode (LGAD)

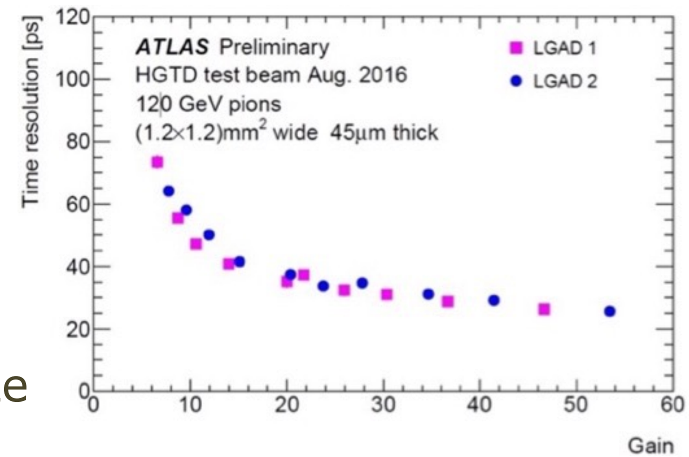
Precision timing of each point along the track can mitigate pile-ups
→ Use only "time-compatible points" for pattern-recognition





LGAD: **thin** silicon detector with **low gain** multiplication for **precise timing** measurement

- High electric field to accelerate electrons for multiplication, by highly doped p^+ region
- Moderate internal gain to reduce shot noise.
- 4 suppliers: **CNM**, FBK, HPK, Micron
- Both strip and pad detectors are possible

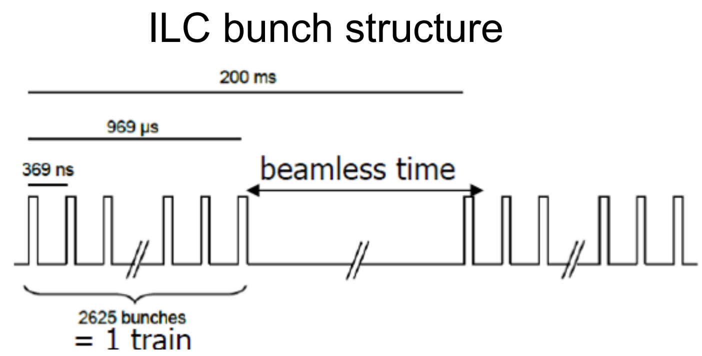


ATLAS HGTD (High Granularity Timing Detector) in front of endcap calorimeter

- 4 LGAD layers with 1.3 x 1.3 mm² sensor size
- Goal: 30 ps resolution for MIP

Pixel detectors developed for ILC/CLIC

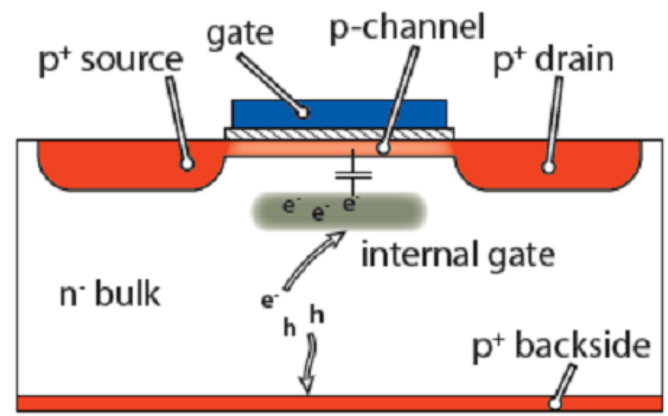
- Pixel sensors for ILC/CLIC need to have
  - Extremely good spatial resolution
  - Low material budget
  - Must deal with the **special bunch structure**
- Several technologies under development, some are used for real experiments
  - FPCCD, DEPFET, CMOS, Chronopix, SOI, 3D

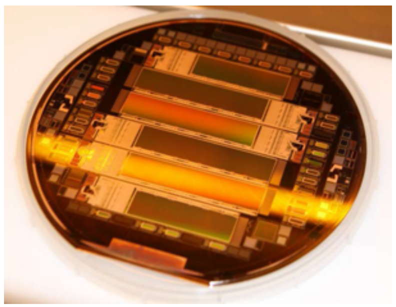


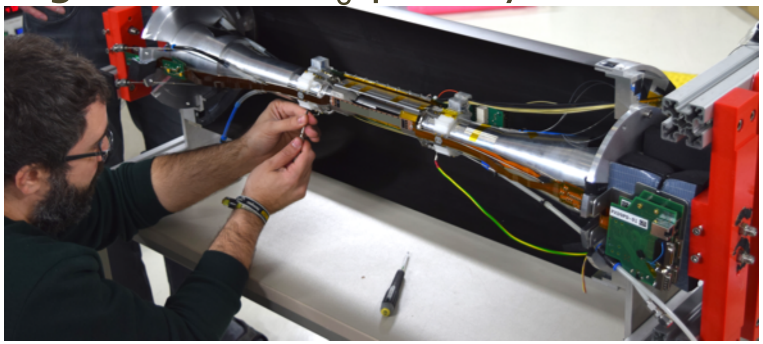
DEPFET

Depleted p-channel Field Effect Transistor

- Signal electrons accumulate in the internal gate (potential minimum) and modulate the transistor current
- Belle-II PXD:
  - Pixel size ~75x50 μm^2
  - Material budget 0.21% X_0 per layer





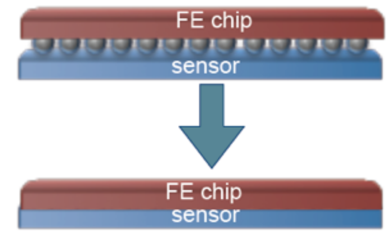


Belle II phase 3
FY2018 ~

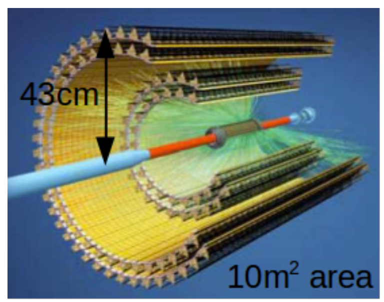
CMOS pixel sensors

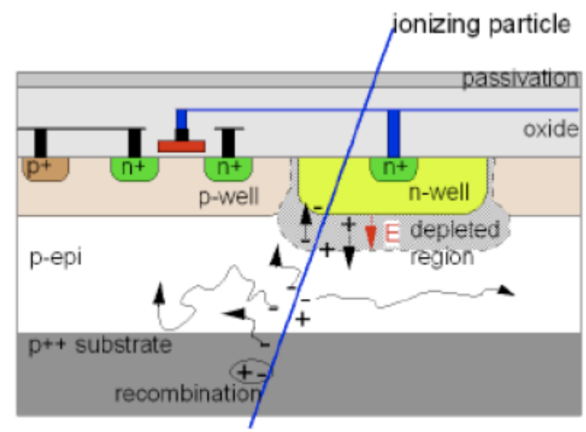
Monolithic Active Pixel Sensors (MAPS)

- sensor and signal processing electronics are integrated in a same silicon wafer
- commercial CMOS technologies (low cost)
- granularity: pixels of ~ 10x10 μm^2
- material budget: total thickness < 50 μm
- charge collection through thermal diffusion
- used in EUDET telescope, STAR PXL, ALICE ITS upgrade



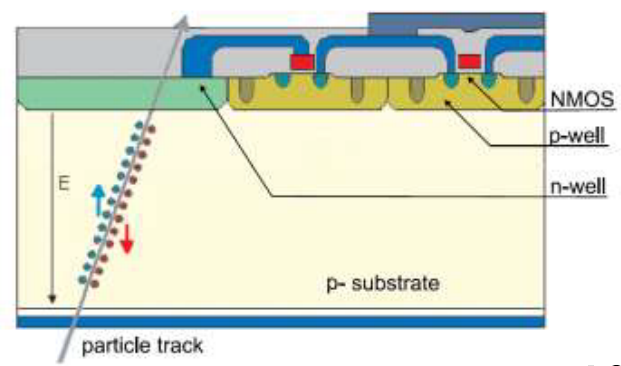
Monolithic = front-end electronics on same substrate as active sensor





HV/HR-CMOS sensors under development for HL-LHC

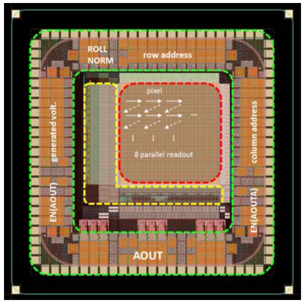
- depletion through high voltage (HV) or high resistivity (HR) substrate
- charge collection by drift, good for radiation tolerance



SOI and 3D sensors

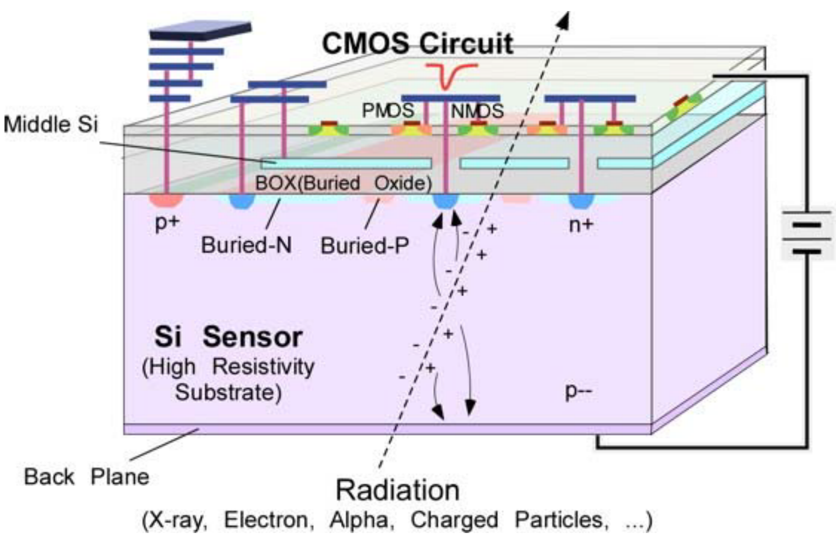
Next generation technologies

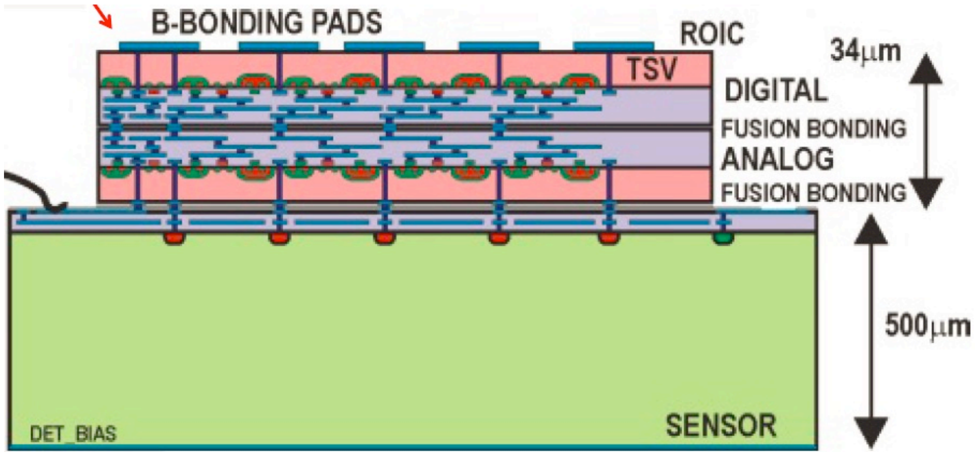
- **SOI**: Silicon On Insulator
  - CMOS circuit fabricated on buried oxide (BOX)
  - CMOS circuit fully isolated from wafer (bulk) silicon
  - Fully depleted CMOS sensors possible
  - FPIX2 chip with 8 μm pixel size tested at FNAL TB
    → **intrinsic spatial resolution < 1 μm** achieved for the first time !!



FPIX2 chip

- **3D sensor**
  - comprised of two or more layers of semiconductor devices, which have been thinned, bonded together, and interconnected to form a "monolithic" circuit.
  - Optimal process can be used for each layer (analog, time stamp, …)
  - The move to 3D is driven by industry.





Interconnection by through-silicon vias (TSV)

MPGD

Micro Pattern Gaseous Detector

- In general, gaseous detectors are cost-effective, capable of covering a large area, and operating stably over a broad range of conditions
  - Widely used: MWPC, Drift Chambers, RPC, …

Advantages of MPGDs (as 2D gas amplifiers)

- High rate capability
- High space resolution
- Good timing resolution
- Good energy resolution
- Radiation hardness

and

- Ion Back Flow reduction
- Photon feedback reduction

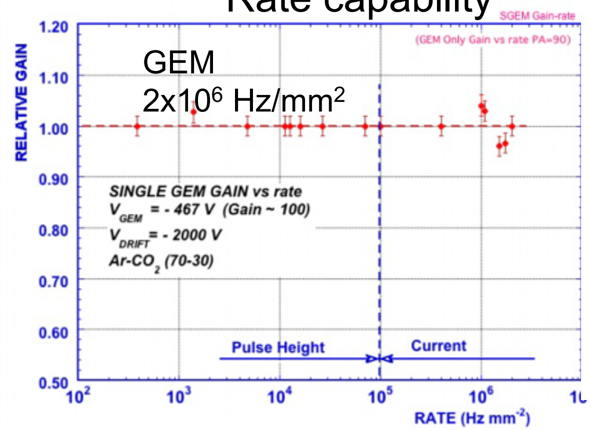
Limitations

- Production not trivial
- Sparks at high gain

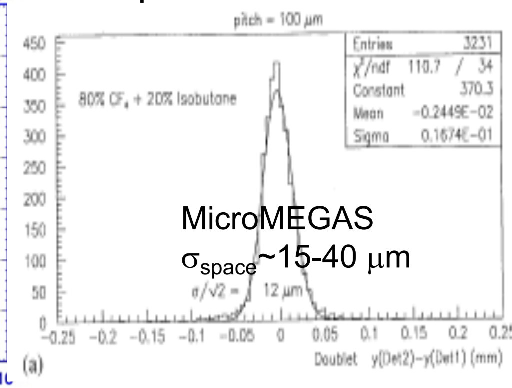
Several technologies under Development

- MicroMEGAS
- GEM
- Thick-GEM
- μ-PIC
- Ingrid

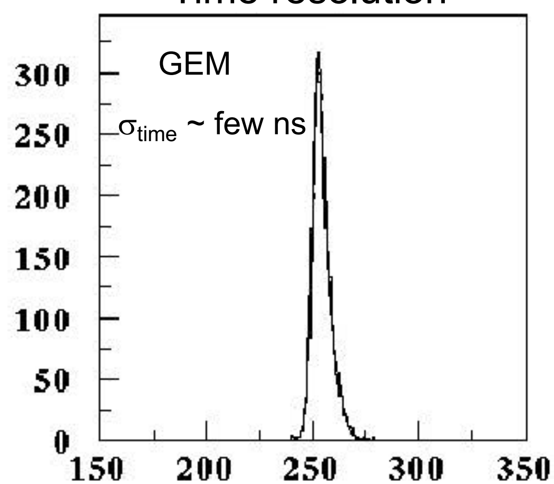
Rate capability



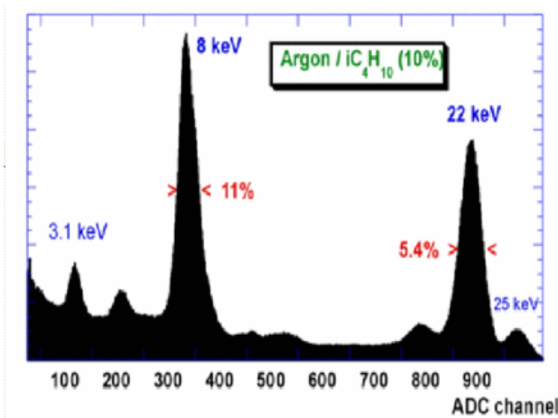
Spatial resolution



Time resolution



Energy resolution



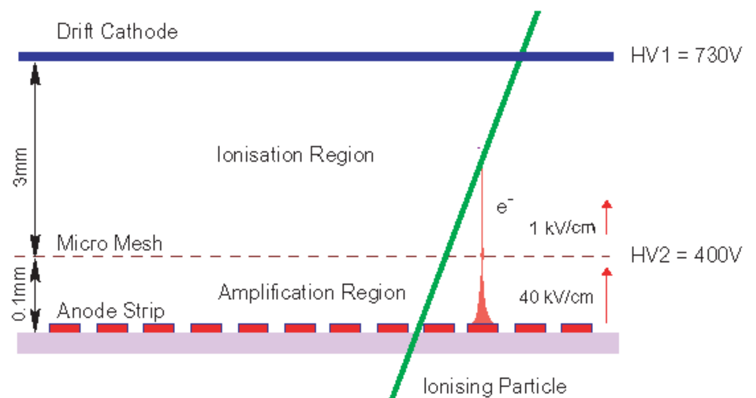
MicroMEGAS and GEM

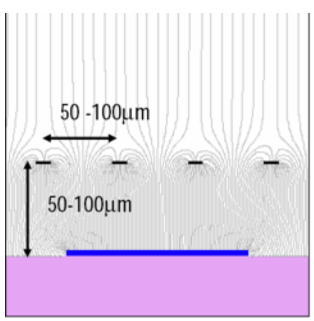
MicroMEGAS

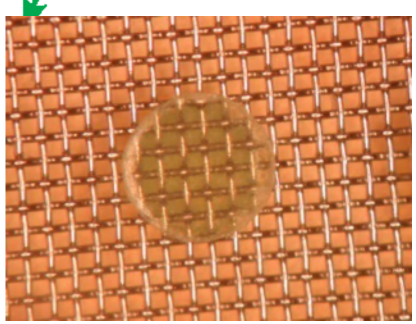
- Micromesh with pitch 50-100 μm
- Gap height 50-100 μm
  - must be uniform
- Amplification at in the gap
- Sparks are present at high gain, but manageable

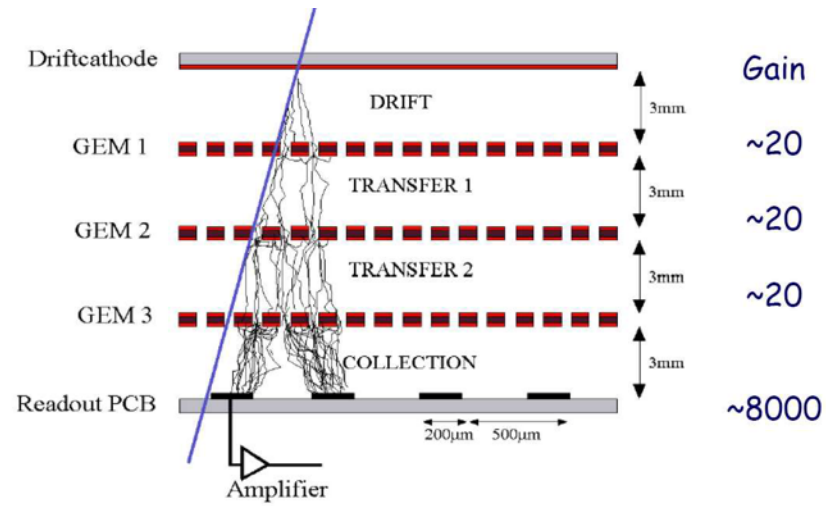
GEM (Gas Electron Amplifier)

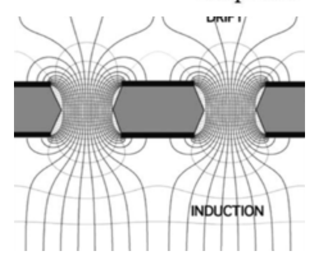
- Two copper foils on both sides of kapton layer of ~ 50 μm thick
- Amplification at the holes
- Readout by anode pads/strips
- Usually used in multi-layers at low gain, to dramatically reduce the spark rate

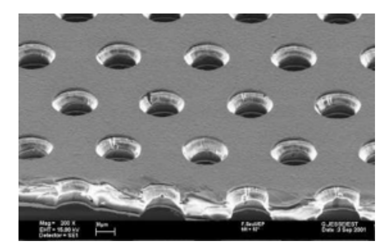




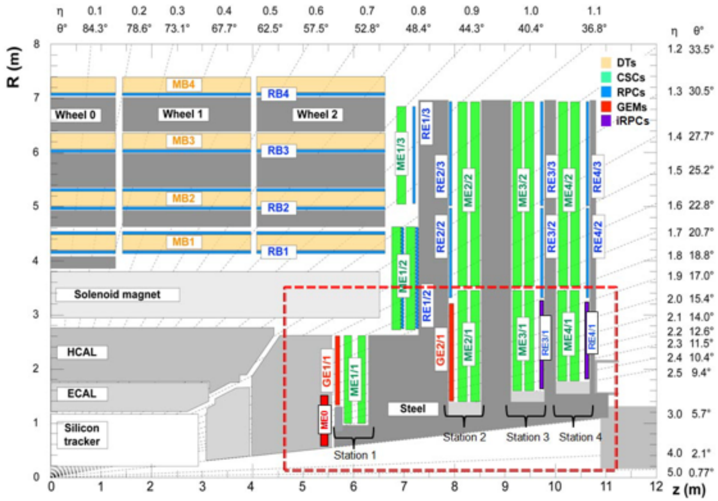


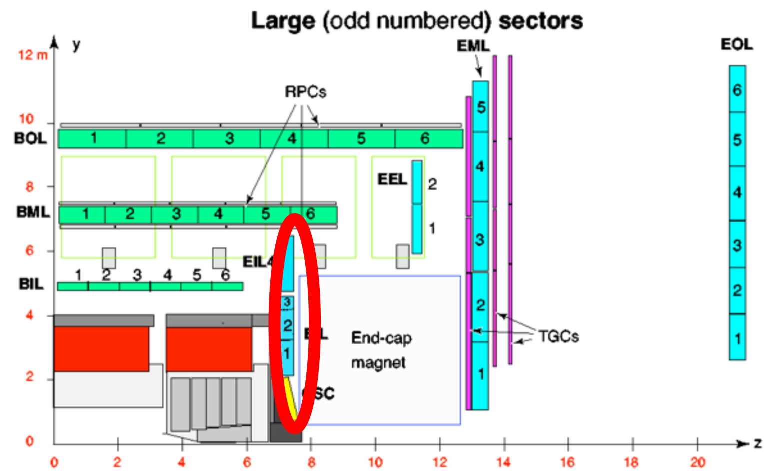






MPGD for muon detectors



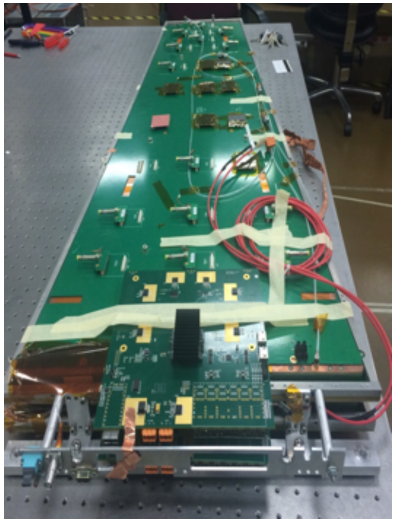


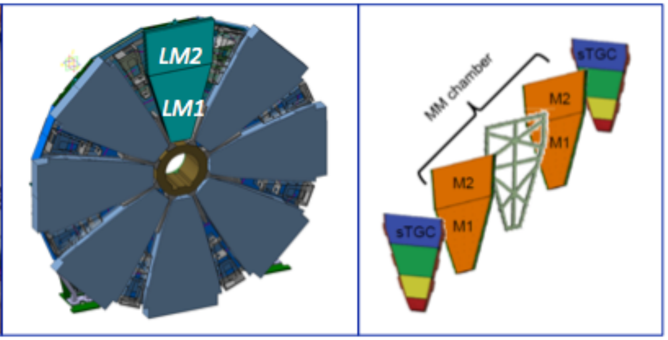
- GEM will be used in the Phase-II CMS muon system

MicroMEGAS will be used for New Small Wheels of ATLAS muon system

- 1200 m^2 total detector surface,
- Operational at rate > 15 kHz/cm^2,
- spatial resolution <100 μm

CMS GEM chamber

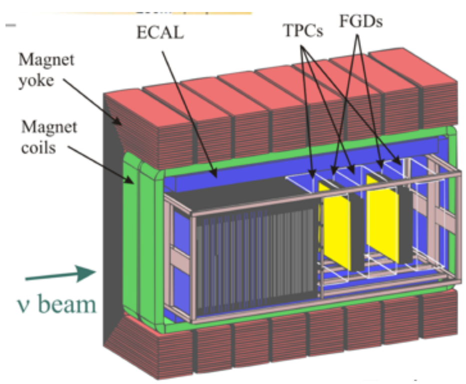


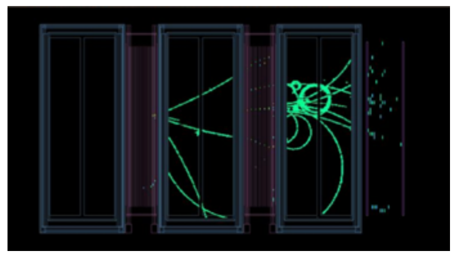


MPGD for TPC endplate

T2K TPC (MicroMEGAS)

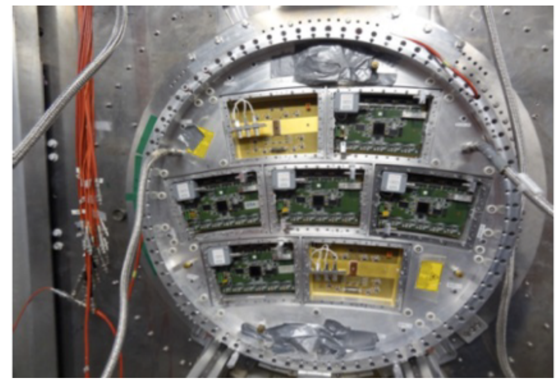
- The first large TPC using MPDG
- Spatial resolution: 0.6 mm
- dE/dx: 7.8% for MIP





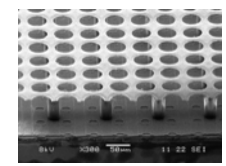
LC-TPC R&D (MicroMEGAS, GEM, Ingrid)

- Large TPC prototype with versatile endplate
- Several test beam campaigns at DESY



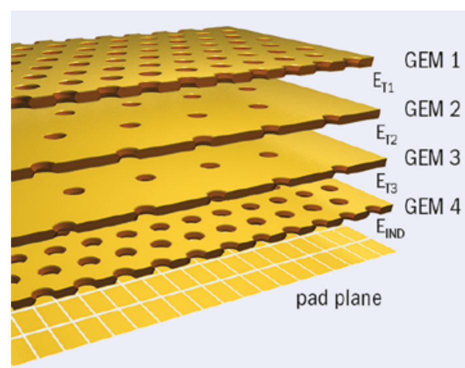

GEM

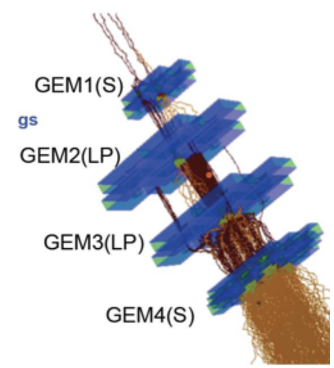

MicroMEGAS

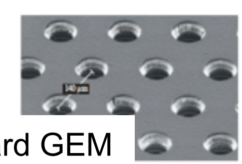

Ingrid

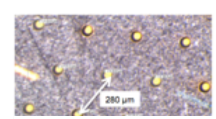
ALICE TPC upgrade (GEM)

- Continuous readout for 50 kHz Pb-Pb collisions without using gate-grid
- Replace MWPC with 4-GEM to limit space charge effects
- Maintain physics requirements:
  Ion Back Flow < 1%, $\sigma(E)/E<12\%$ for ^{55}Fe

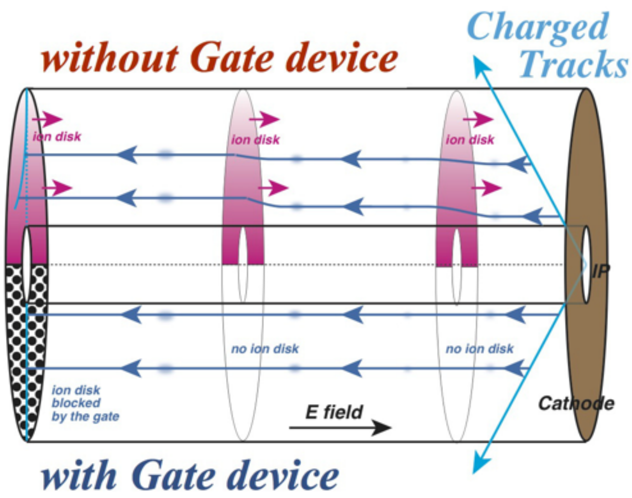





Standard GEM


Large pitch GEM

Gating GEM for LC-TPC

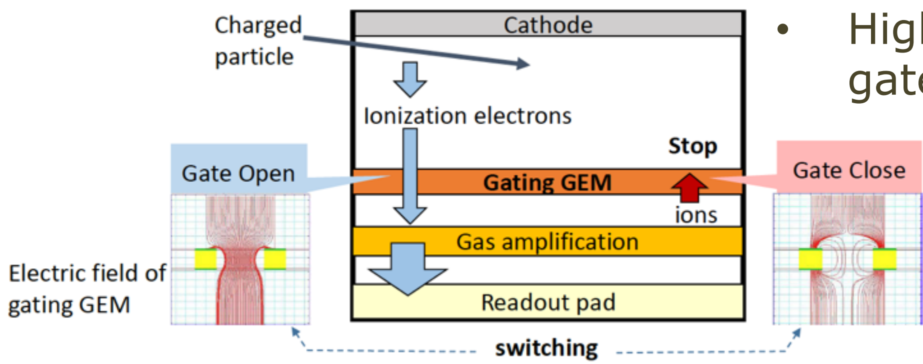


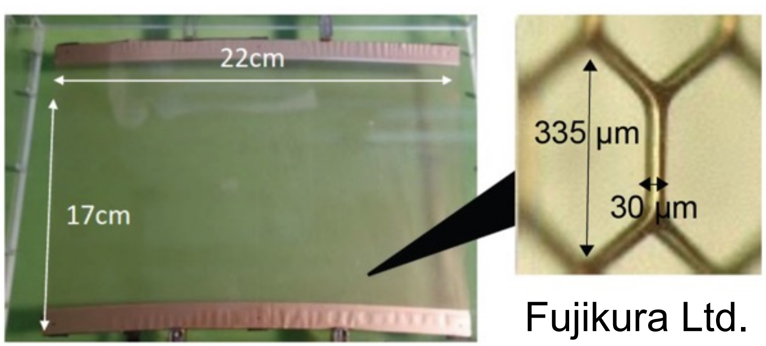
ILC has a special bunch structure (5 Hz, 1ms bunch train)

- 3 disks of IBF may slowly move from anode to cathode → distortion of the electric field
- **IBF must be completely blocked** (<0.01%) to achieve spatial resolution < 100 μm

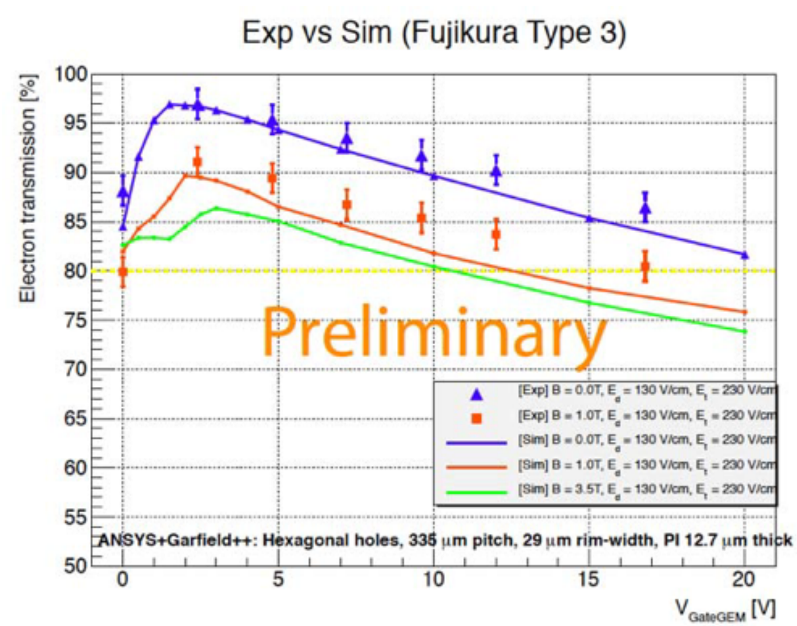
Gating GEM above the MPGD is developed

- High electron transparency (> 80 %) when the gate is OPEN.
- High blocking power for positive ions when the gate is CLOSED.





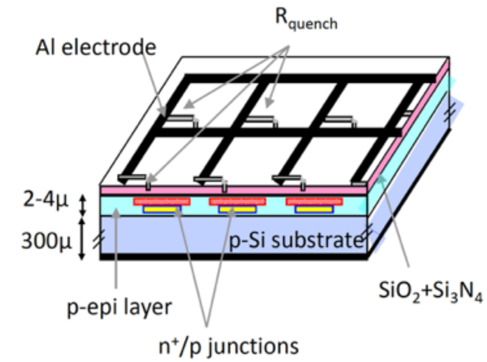
Fujikura Ltd.

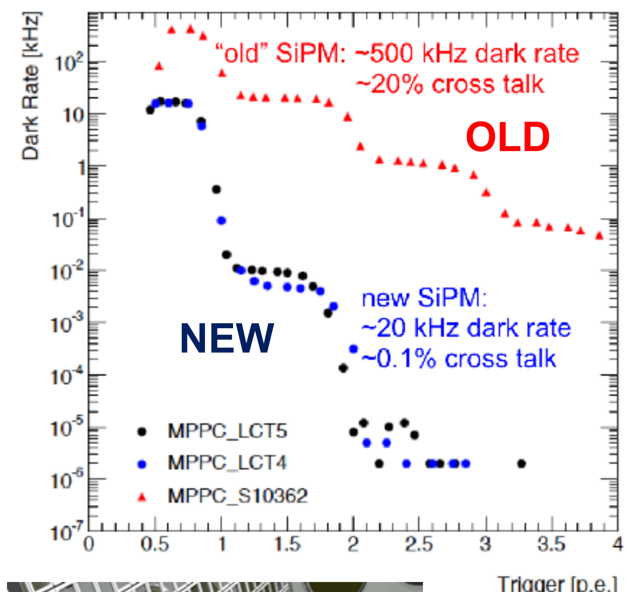


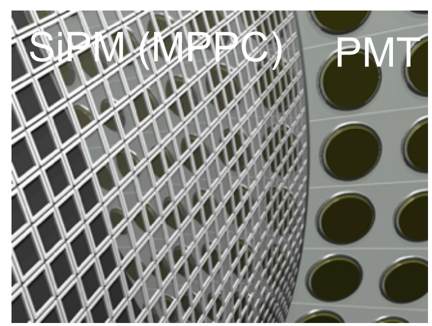
Photon sensors

Silicon Photomultiplier

- Invented in Russia, called as SiPM, MPPC, PPD, now produced worldwide
- Operate many small APDs in Geiger mode and gang the outputs.
- Properties
  - High gain ~ 10^6 at low HV (50~70 V)
  - Photon counting capability
  - Fast timing: $\sigma_t(1\gamma)$~100 ps
  - Insensitive to magnetic field
  - Compact, low cost
  - Dynamic range restricted by number of pixels
  - High dark rate /cross talk
- Already widely used for many applications
- This device is still new and improving
  - Significant reduction of dark rate / crosstalk
  - Smaller pixel pitch → more dynamic range
  - VUV sensitive → application extended to liquid Xe calorimeter







MEG II
liquid Xe
12 x 12 mm^2
50 μm pitch

Long-lived MCP-PMT

MCP-PMT is similar to ordinary PMT, with dynode replaced by MCP (MicroChannel Plate)

Advantages

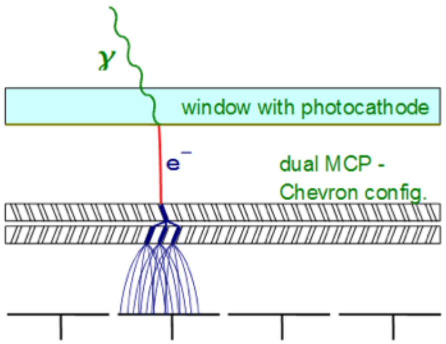
- Gain ~ 10^6, single photon counting
- Small thickness, high field→ tts ~ 50 ps or less
- Operational in magnetic field (B ~ 1.5 T)

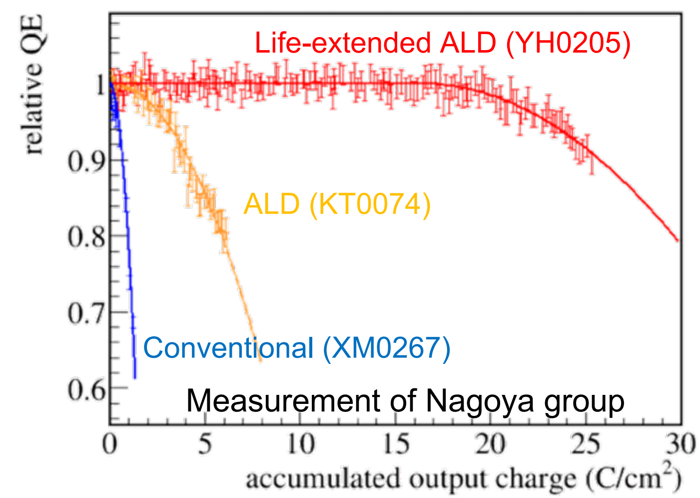
Used for many Cherenkov/TOF detectors

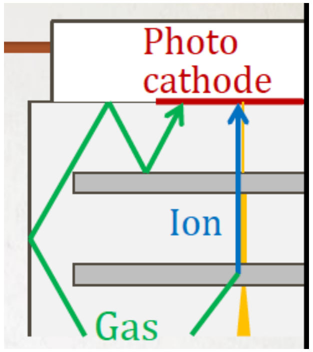
- Belle-II TOP, LHCb TORCH, PANDA DIRC, EIC DIRC, …

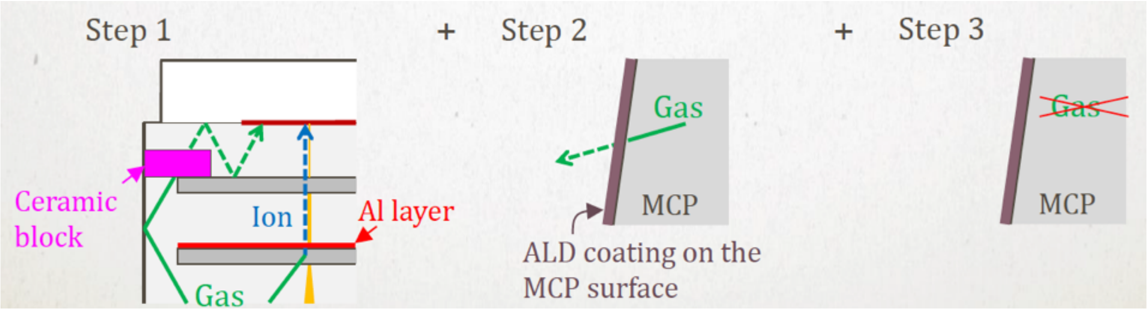
Weakness: **Ageing of the photo-cathode**, where QE is degraded by the gas/ion desorbed from large surface of MCP. To reduce the effect:

1. Block the gas/ion from reaching the photocathode
   - Conventional MCP-PMT
2. Suppress outgassing from MCP by coating
   - ALD (Atomic Layer Deposition) MCP-PMT
3. Reduce residual gas on MCP
   - **Life-extended ALD MCP-PMT**







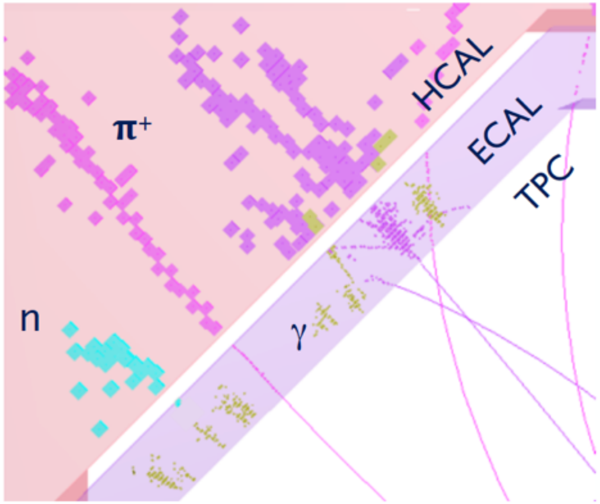


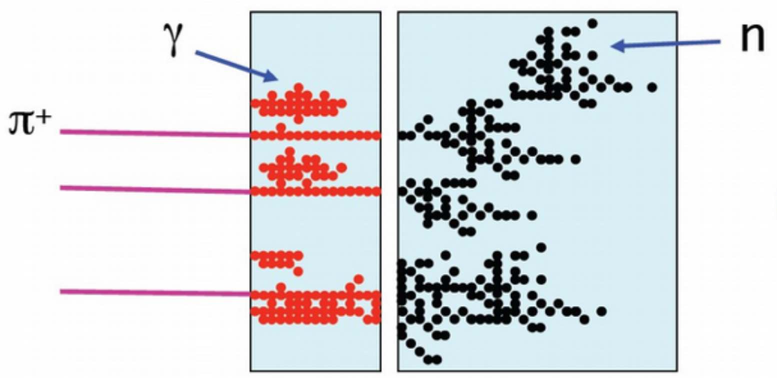
PFA calorimetry

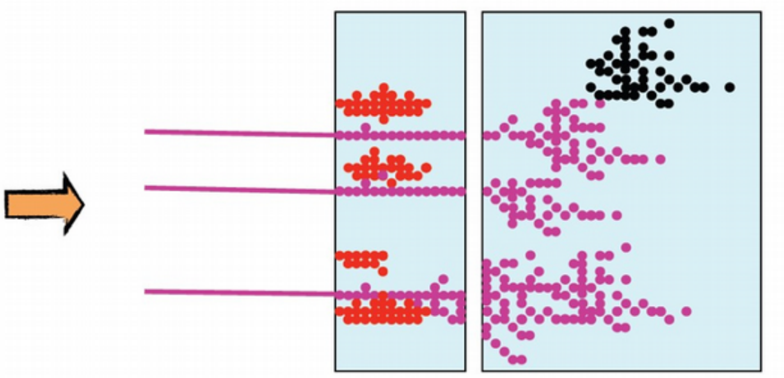
Particle flow approach

PFA uses best energy measurement for each particle to reconstruct **jet energy** with no overlaps:

- **Charged tracks (~60%)**
  - **→ tracker: $\sigma_{1/pT} \approx 2 \times 10^{-5}$ (GeV)**
- **Photons (~30%)**
  - **→ ECAL: $\sigma_E/E \approx 15\% / \sqrt{E}$ (GeV)**
- **Neutral hadrons (~10%) → HCAL: $\sigma_E/E \approx 60\% / \sqrt{E}$ (GeV)**







$$E_{JET} = E_{ECAL} + E_{HCAL} \qquad E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$$

It is essential to separate calorimeter clusters at particle level

→ Calls for highly granular calorimeters

Granularity is the key

Jet energy resolution

$$(\sigma_{jet})^2=(\sigma_{tracks})^2+(\sigma_{ECAL})^2+(\sigma_{HCAL})^2+(\sigma_{loss})^2+\mathbf{(\sigma_{confusion})^2}$$

Confusion term originates from overlap of shower clusters in calorimeter

Material for absorbers

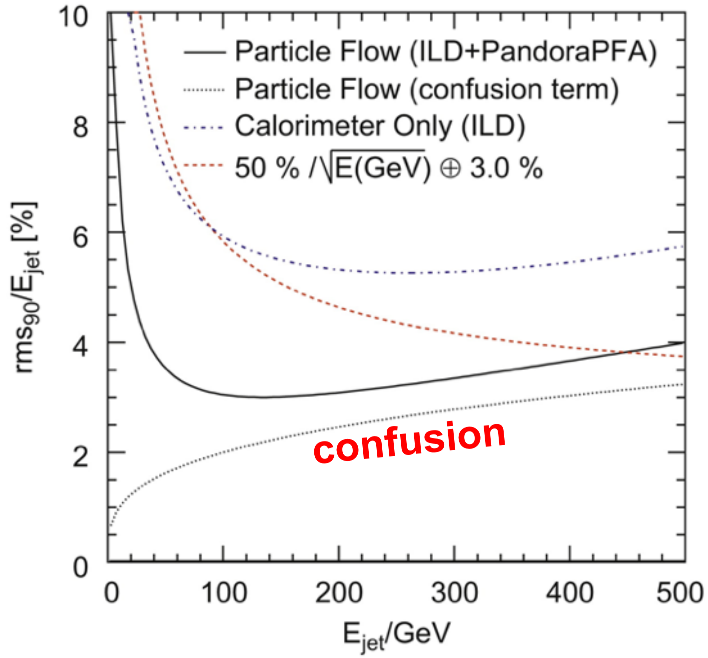
- ECAL: Tungsten
- HCAL: Steel or Tungsten

Thin active layers

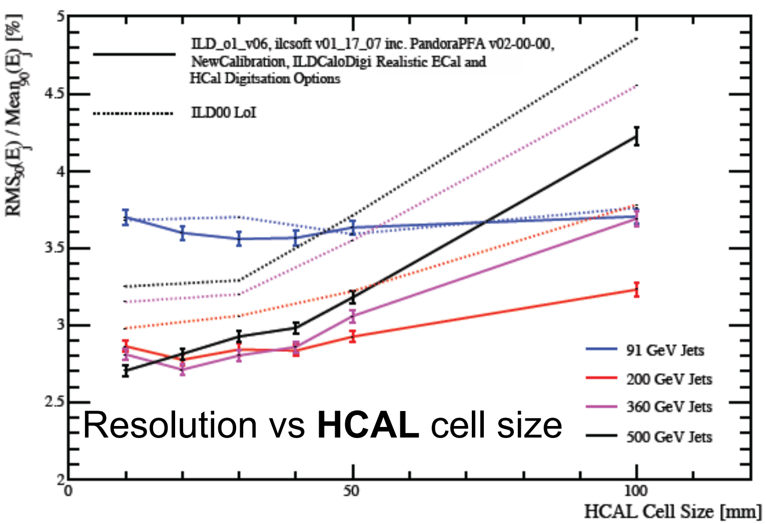
- Sensor and frontend electronics integrated

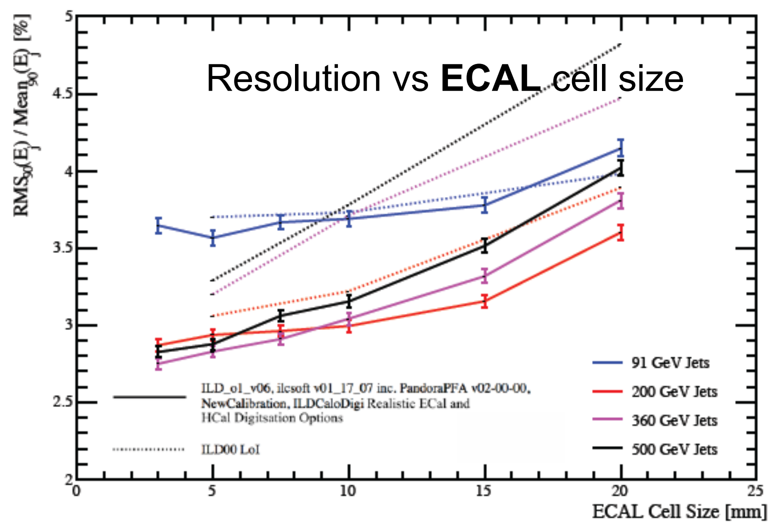
Optimized granularity (cell size) for ILC

- ECAL ~ 0.5x0.5 cm^2
- HCAL ~ 3x3 cm^2 (analog readout)



From M.A. Thomson
Nucl. Instrum. Meth. A611 (2009) 25.

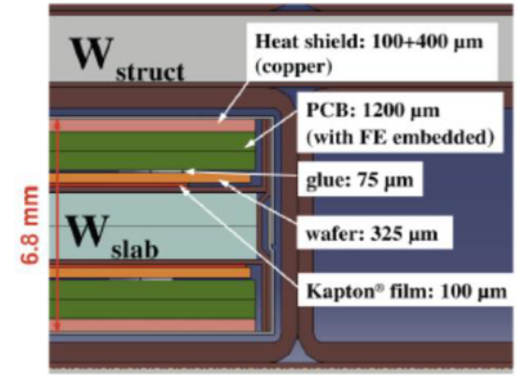


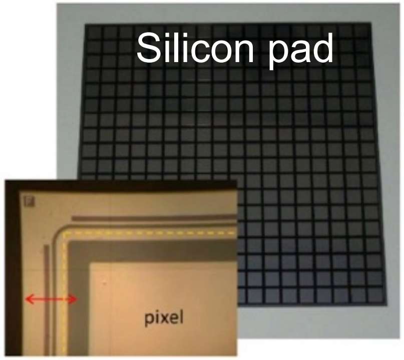


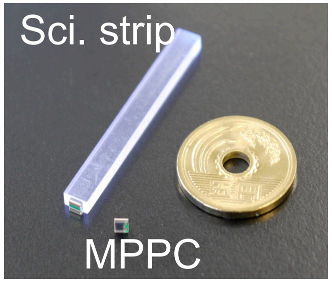
S. Green
LCWS15

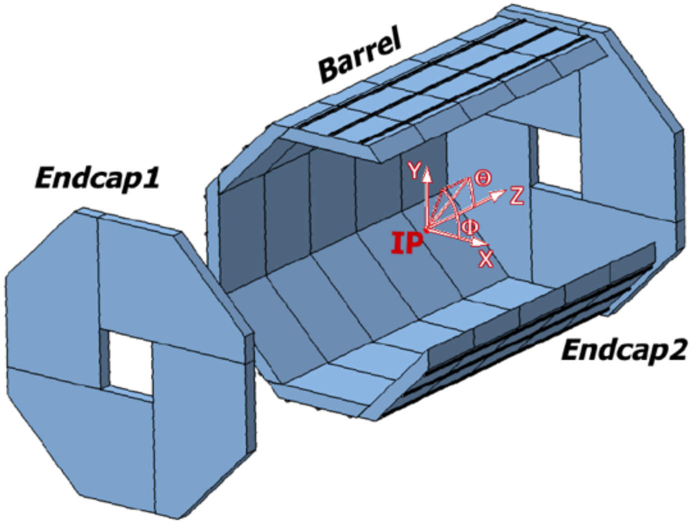
High granularity ECAL

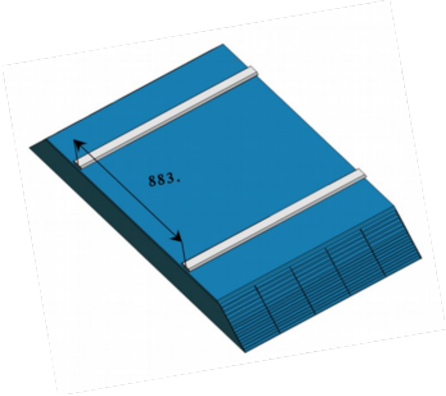
- Each module = carbon-fiber + W structure with alveoli where detector elements (slabs) slide in.
- Slab = Si matrices of PIN diodes (5 x 5 mm^2) glued to PCB with embedded electronics (SKIROC) on both sides of W wrapped into carbon fiber.
- Alternative idea is to use scintillator strips with SiPM readout for sensitive layers
- SiD ECAL will use highly segmented hexagonal Si sensors with readout by KPiX ASIC

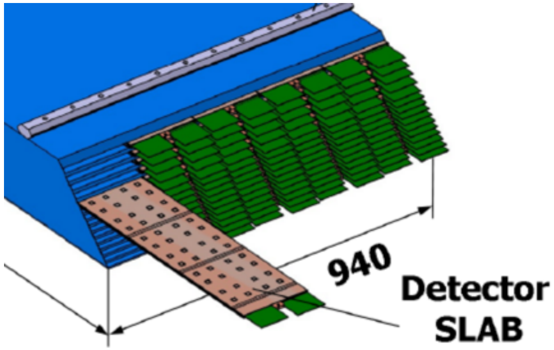








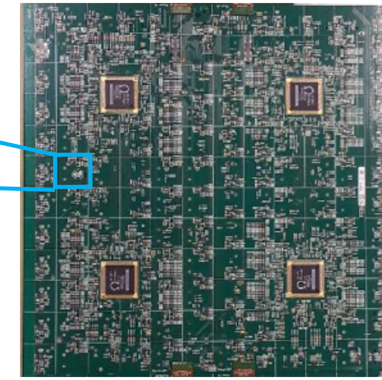




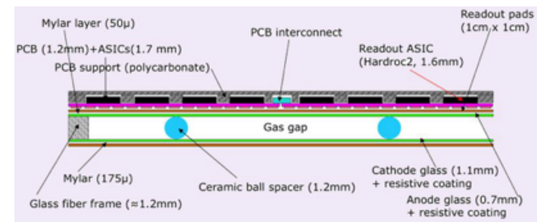
High granularity HCAL

Two promising approaches have been studied by CALICE

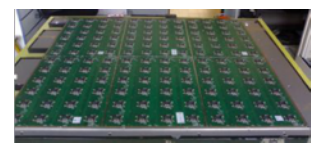
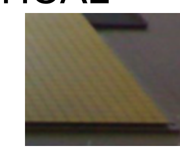
- **Analog HCAL**
  - Active layer: scintillator tiles (3x3 cm^2) readout using SiPM
  - Readout ASIC: SPIROC (OMEGA)
  - Physics prototype demonstrated performance
  - (ILD, SiD, CLIC)
- **(Semi-)Digital HCAL**
  - RPC with 1x1 cm^2 pads, with digital (1-bit) or semi-digital (2-bit) readout
  - Other detector options: MicroMEGAS, GEM, THGEM
  - Readout ASIC: HARDROC (OMEGA)
- Physics prototypes validated the concept and demonstrated performance
- Technological prototypes demonstrate scalability to the full detector

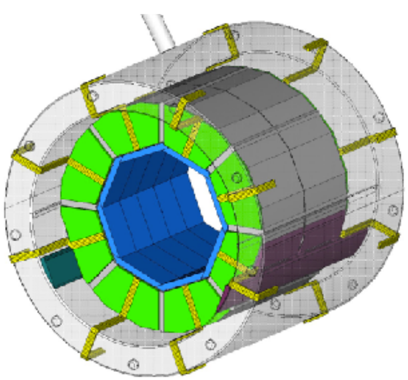
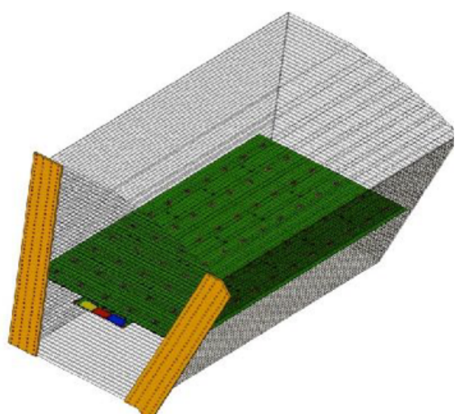
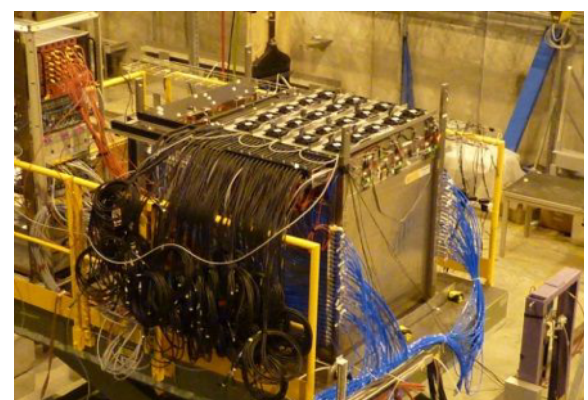



AHCAL unit

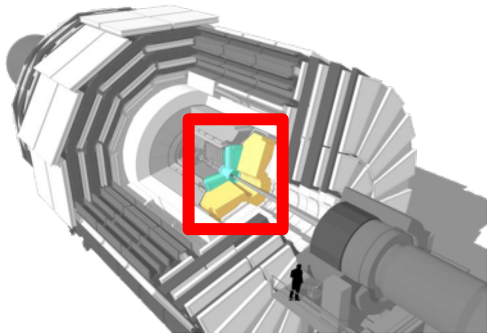


RPC for SDHCAL

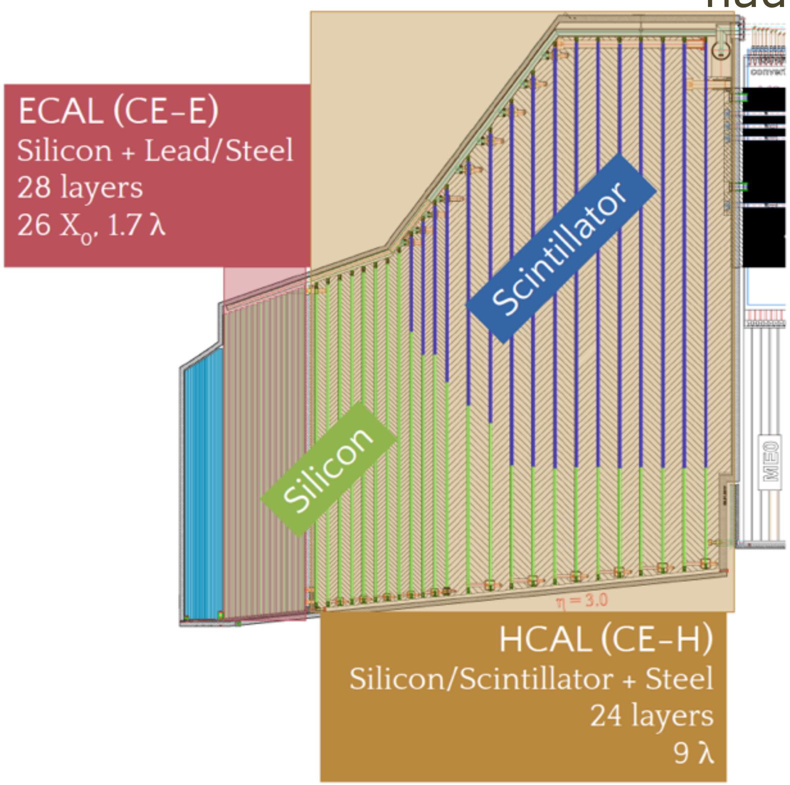



Application to HL-LHC calorimetry

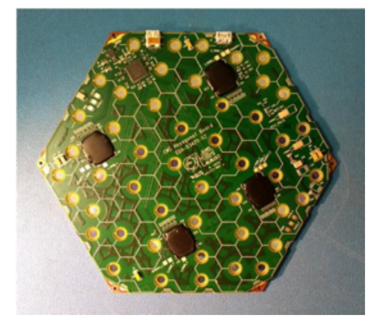


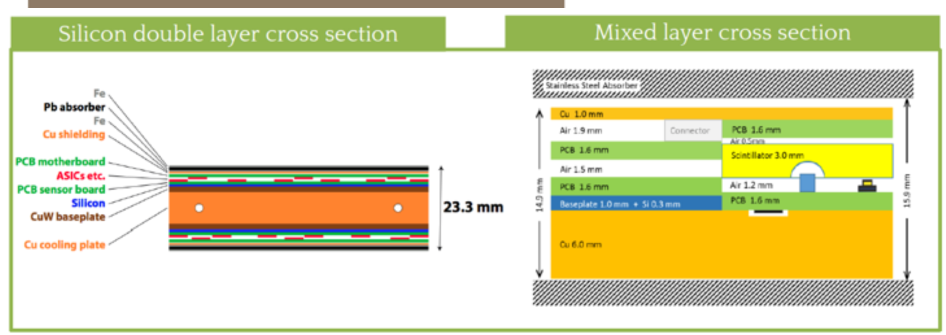
- CMS endcap ECAL and HCAL need to be replaced endue to radiation damage at HL-LHC
  - Radiation tolerant
  - Good timing resolution
  - Tracking capability (shower reconstruction)
- CMS will use **HGCAL**: inspired by the technologies developed by CALICE for a long time (a good example of synergy between hadron and lepton collider experiments)



6 million Silicon channels
≈ 600 m² ≈ 3× CMS Tracker
0.5 and 1 cm² cell sizes

Mixed layers in hadronic part
≈ 500 m² Plastic scintillator
On-tile SiPM





Summary

- Future experiments require improved detector technologies
  - Better spatial and timing resolutions
  - Tolerance against high rate and high radiation dose
  - Large coverage at low cost

- Significant advances have been made for various detector technologies, for specific experiments, and for general use in HEP and other fields.

- Development of detector technologies requires substantial investment (manpower, budget).

- The market in HEP is not large. Detector development may be accelerated if we could find more good applications in other fields → Marcel's talk

Thank you for your attention !!