高能物理偵測器

Stathes Paganis (NTU)

TWHEP 台南, 21 January 2021

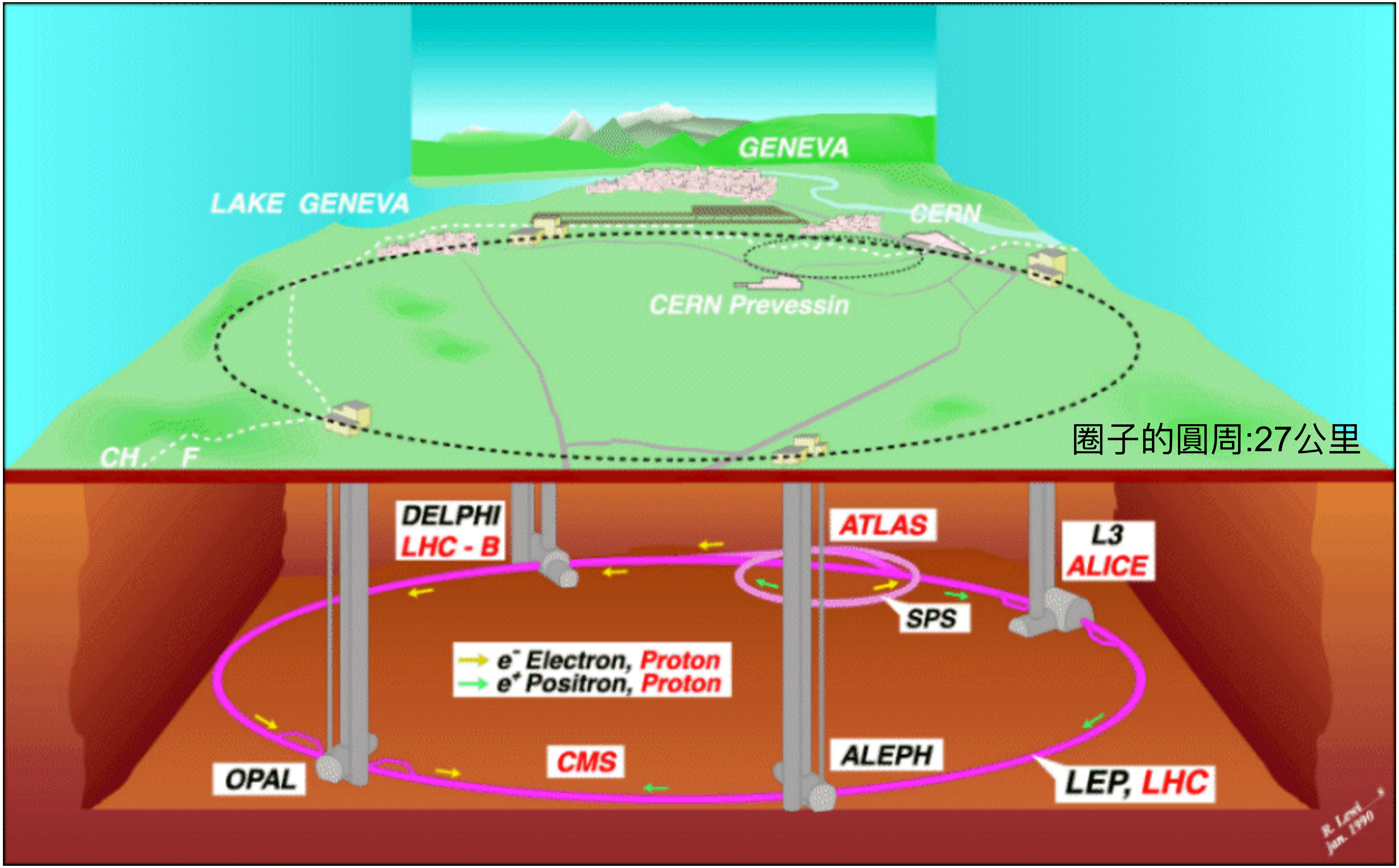
兩個大類 (HEP=高能物理)

- 對撞機實驗偵測器
  - Gas Chambers, Silicon trackers, Calorimeters
- 非對撞機實驗偵測器 (台灣)
  - Germanium blocks
  - Very Large custom PMTs
  - 其他 (參閱昨天的演講)

- γ-ray 伽瑪射線偵測器: 100KeV to few MeV
  - Crystals (NaI, LYSO, …) + PMT
- UV 紫外線，X-光 (few eV to few KeV)
- CMOS 技術 back illuminated (down to 250eV)
- Near IR (includes single photon) 紅外線
  - Silicon (MPPCs) （矽）
  - Super-conducting nano-wires (to λ=1.5μm)
- Far IR (down to λ=1000μm)
  - TES Bolometers (Superconducting)

Applications：
- Medical Imaging,
- Quantum Optics,
- Quantum Information R&D
- Quantum Cryptology
- Deep Space Commun.
- Dark Matter Search
- Astronomy, etc.

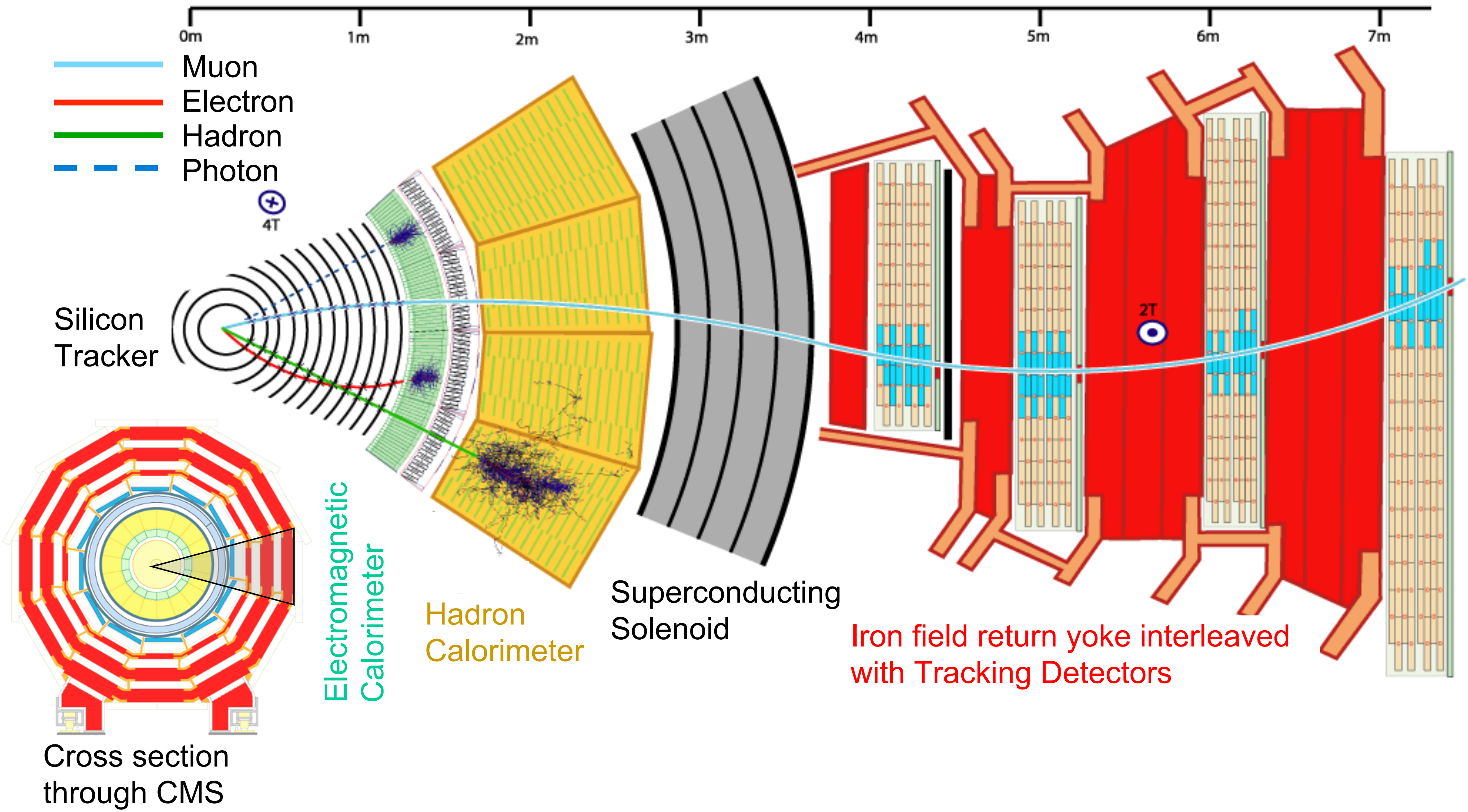
大型強子對撞機 (LHC)



圈子的圓周:27公里

+ BELLE (日本），STAR，sPHENIX （美國）

對撞機 實驗: ATLAS, CMS, BELLE, STAR



請參閱這會議的相關演講

非對撞機實驗: TEXONO, CDEX, Juno 等

TEXONO Program: HEP-Hardware Plans (2020—2030)

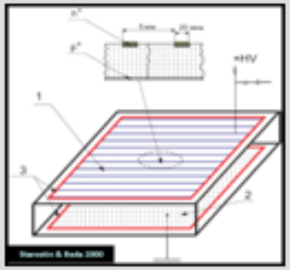
[not including Gravity Physics Programs]

TEXONO

CDEX

Upgrade of Electro-cooled O(100 eV) Threshold Germanium Detectors

⇨ νN scattering at Kuo-Sheng Reactor or elsewhere ; Light WIMP searches at China Jinping Underground Laboratory



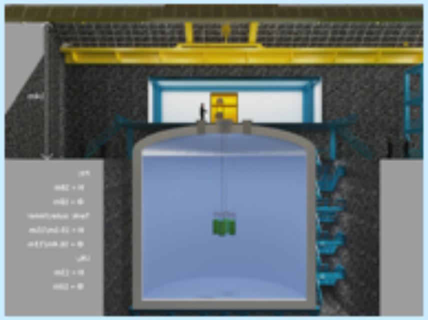
GEMADARC
Germanium Materials and Detectors Advancement Research Consortium

R&D towards Germanium Detector with Internal Amplification.

⇨ Potential O(10 eV) threshold for nN scattering and Light WIMP searches

LEGEND
Large Enriched Germanium Experiment for Neutrinoless ββ Decay

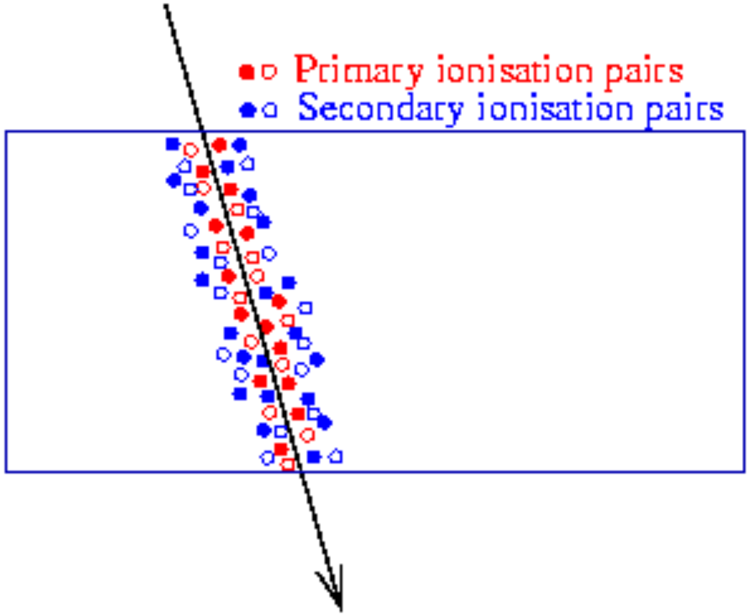
R&D Towards Formulation of Ton-scale Neutrinoless Double Beta Decay Experiments at China Jinping Underground Laboratory as part of LEGEND Program



參閱相關演講

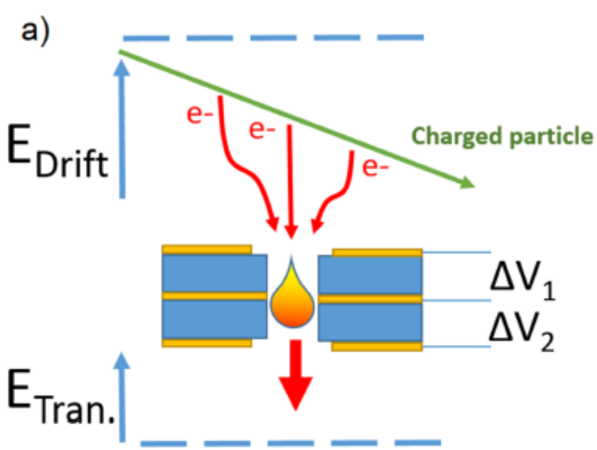
Gaseous Tracking Detectors

- Multi Wire Proportional Chambers
- Drift Chambers
- Time Projection Chambers
- MSGC, GEMS and moving on to Silicon

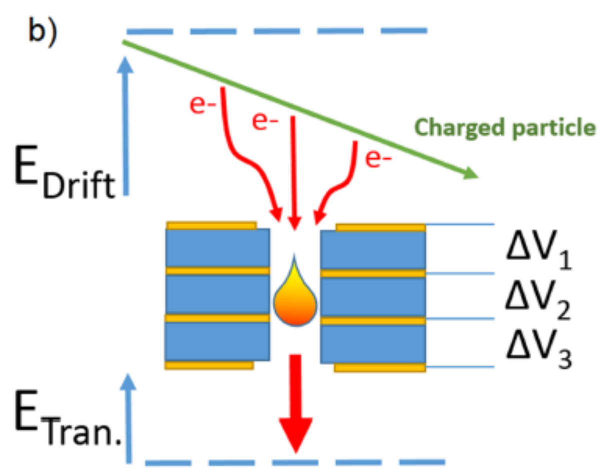


Thick GEMs (THGEM), are becoming mainstream in HEP: applications?

➔ Towards “Gaseous PMTs”

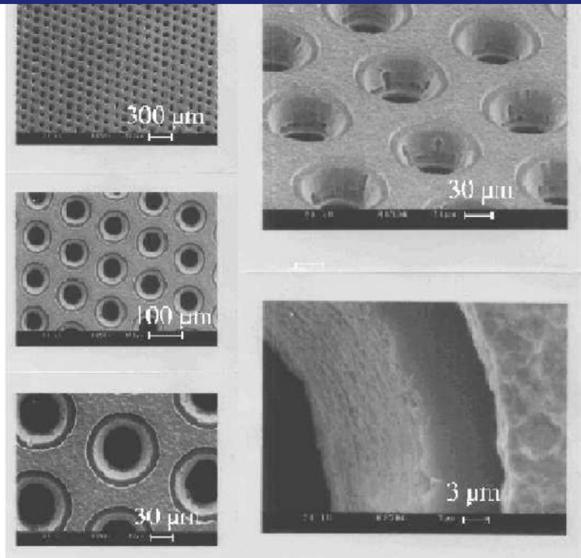


2-layer THGEM



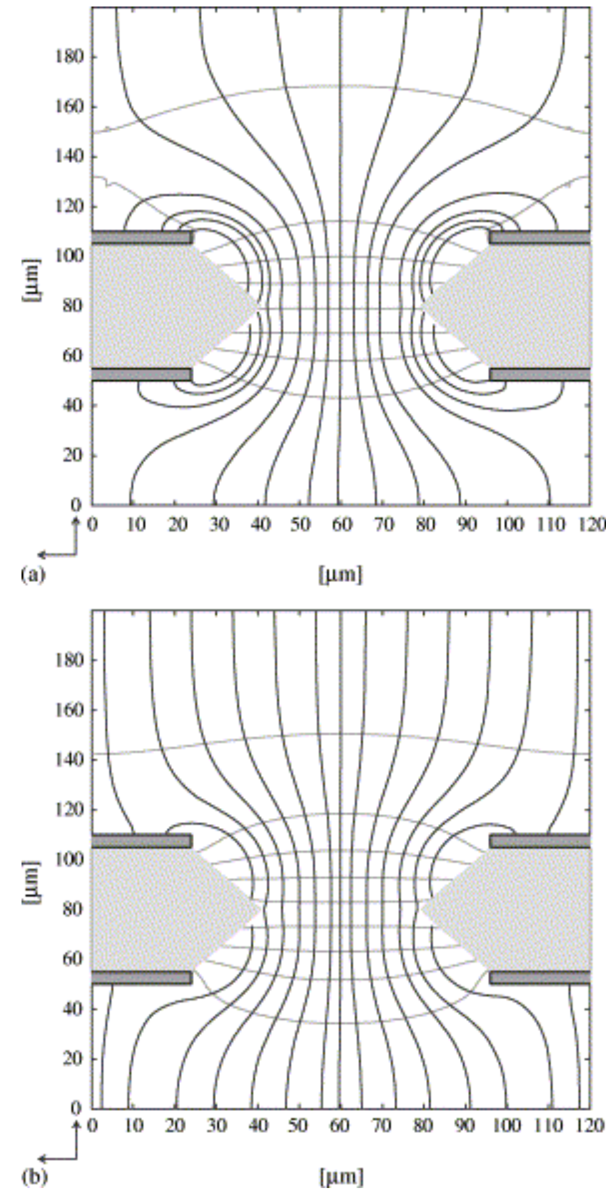
3-layer THGEM

Gas electron multipliers (GEM)

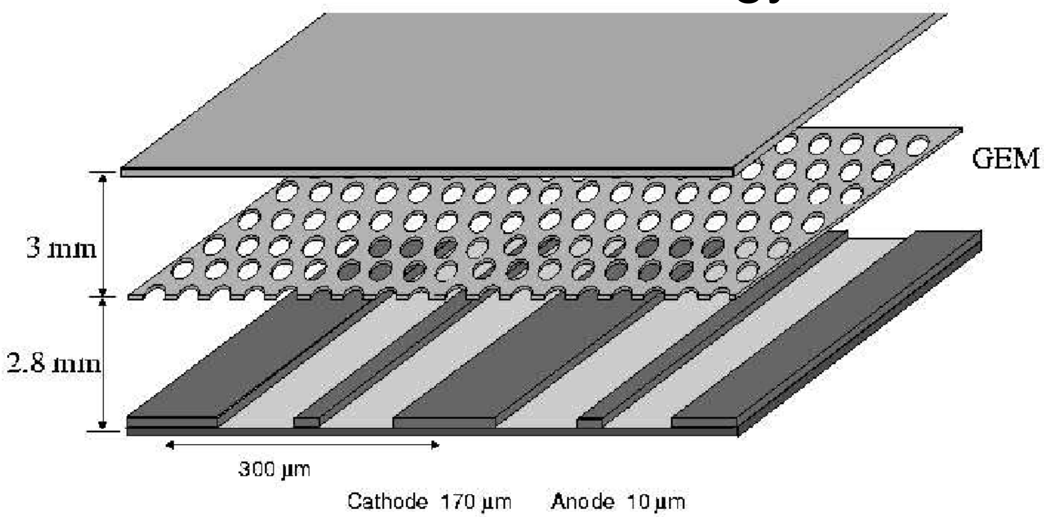


Thin perforated kapton foil, metal clad on both sides. (~500V)

Field lines squeezed through small gaps. This causes gas amplification in the gap.



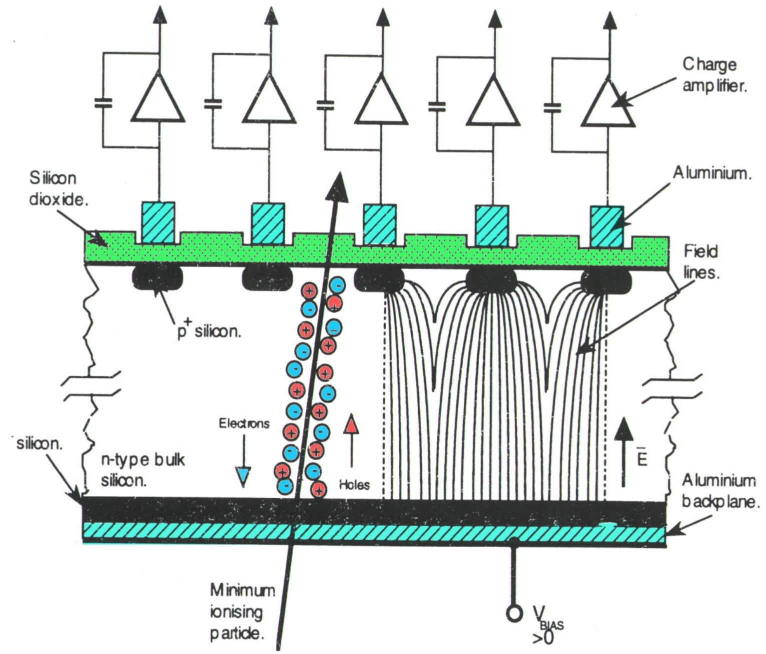
Less gas amplification needed near the anode strips.
Invented to rescue MSGC technology.

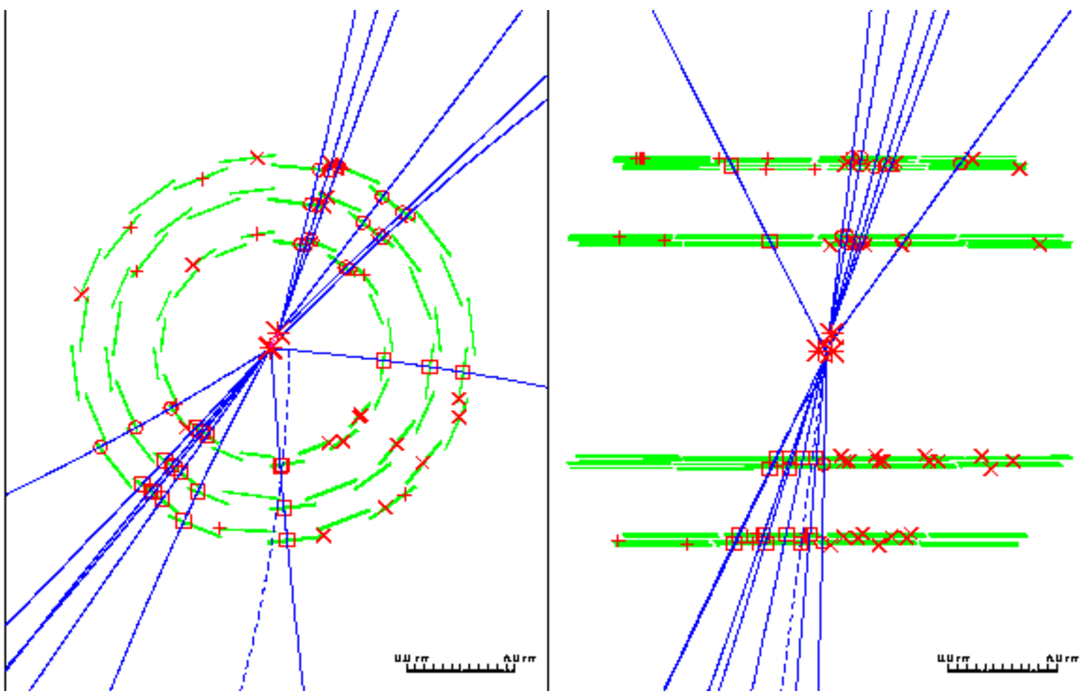


Advantage: with multiple GEM foils no need for charge multiplication near anode.

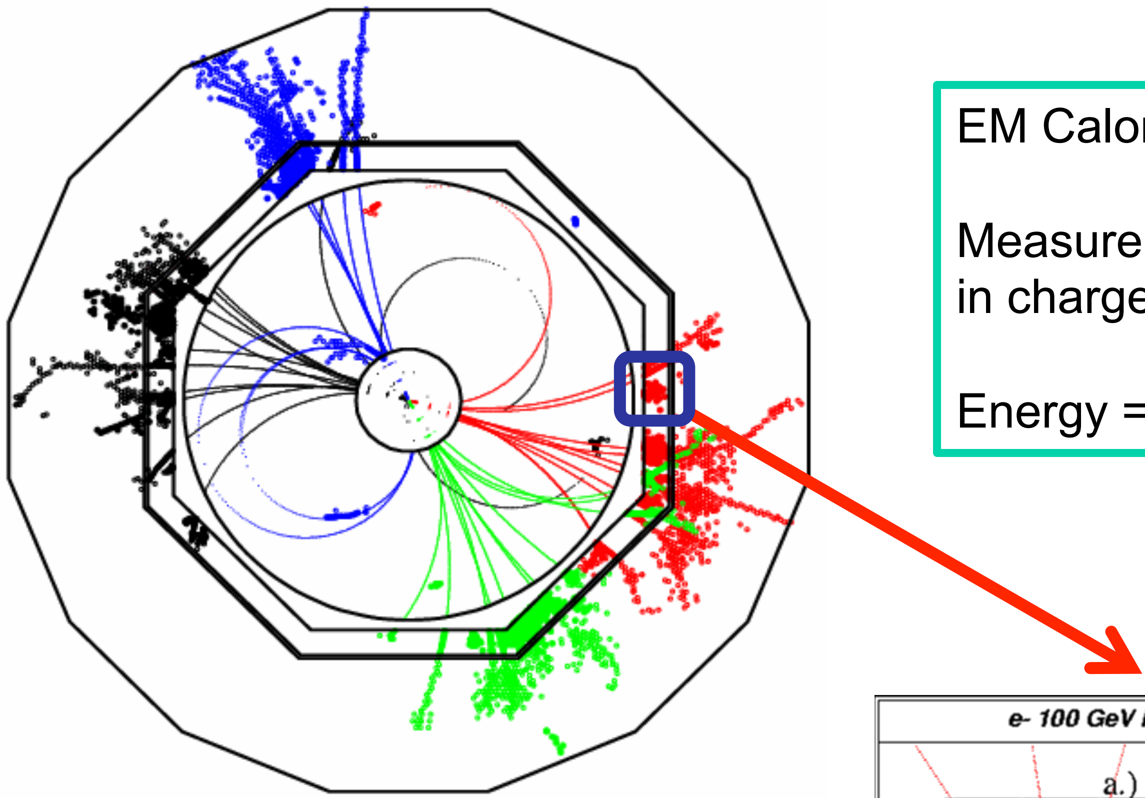
Solid-state tracking detectors （矽）

- Semi-conductors: reverse-bias *pn*-junction diode
  - **Strip detectors**
  - Pixel detectors
  - CCD detectors
  - **Pad detectors (HGCAL)**





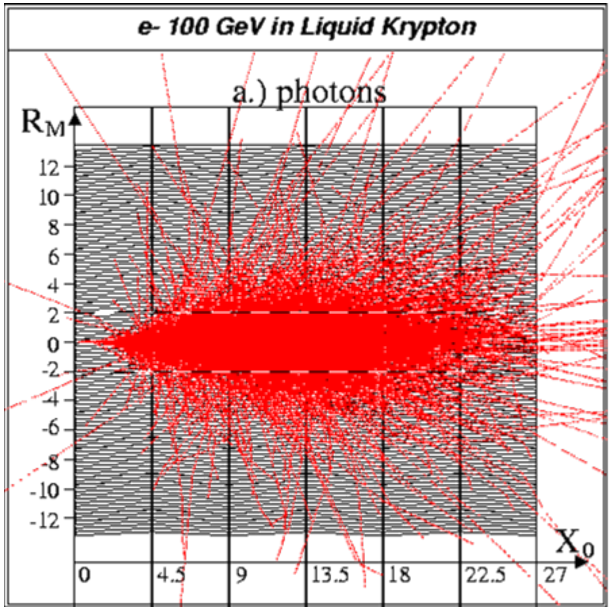
Calorimeters

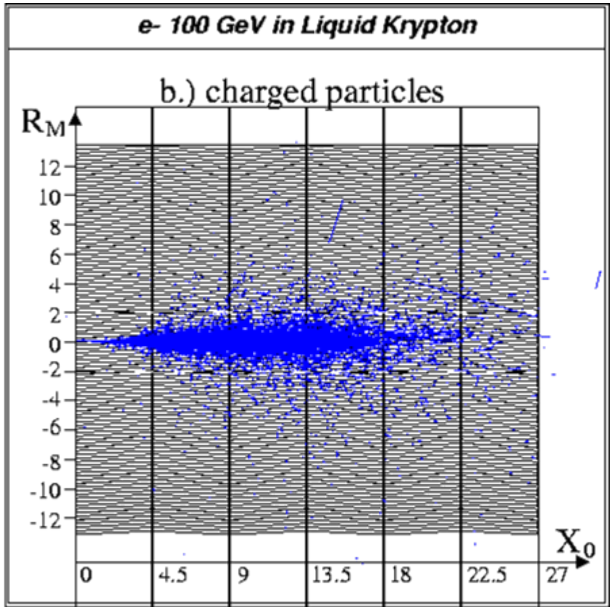


EM Calorimeters: “totally” absorb/stop **e** and γ

Measure energy of particle by summing signals in charge sensitive detectors.

Energy = constant × (Charge collected)





Other cutting-edge Technologies

- **SPAD**: Single Photon Avalanche Diodes
  - Timing: 100ps, large dead time (200ns), up to MHz rate.
  - Cover large energy range

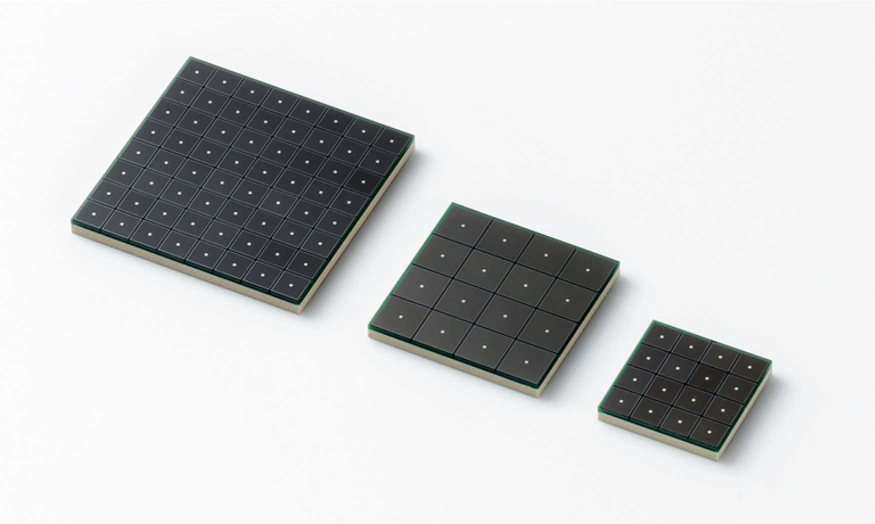
- **SiPMs**: Silicon Photomultipliers and arrays (MPPC)
  - Work only in the optical range (450nm), QE=20-50%
  - Expensive to cover large area (pixels)

- **SC Nanowire S**ingle-**P**hoton **D**etectors (**SNSPDs**)
  - Photon energy sensitivity tunable (sensitive down to λ~1μm)
  - QE: 90% (or better)
  - Timing: 10-100ps
  - Rates: 100MHz (at max QE)
  - Insensitive to gamma rays, X-rays!

SiPMs: 可見光 到 near 紅外線

- SiPMs: Silicon Photomultipliers.
  - Work in the optical range (450nm), QE=20-50%
  - Expensive to cover large area (pixels)

- Multi-Pixel Photon Counters, MPPC.



These are arrays of SiPMs

Range of sensitivity:
~300nm to 900nm (HPK)

Various SC single photon sensors

- transition edge sensors (**TES**) (jitter 100ns, duration ~μsec)
- superconducting tunnel junctions (**STJ**),
- microwave kinetic inductance detectors (**MKID**),

- superconducting nanowire single-photon detectors (**SNSPD**).
  (jitter 10ps, no dead time, λ~1μm)

However, no sensitivity at λ=10μm

- Secure quantum optical communications systems often rely on transmission through optical fibers. (https://www.laserfocusworld.com/)
- However, certain applications, such as military communications, will require free-space versions of such systems. Because of atmospheric transmission windows in the mid-infrared (λ~10μm), they require high-speed mid-IR single-photon detectors.
- Dark Matter Searches

1KPixel SNSPD array (1x1mm^2)

Wollman et al, Optics Express 35279 (2019)

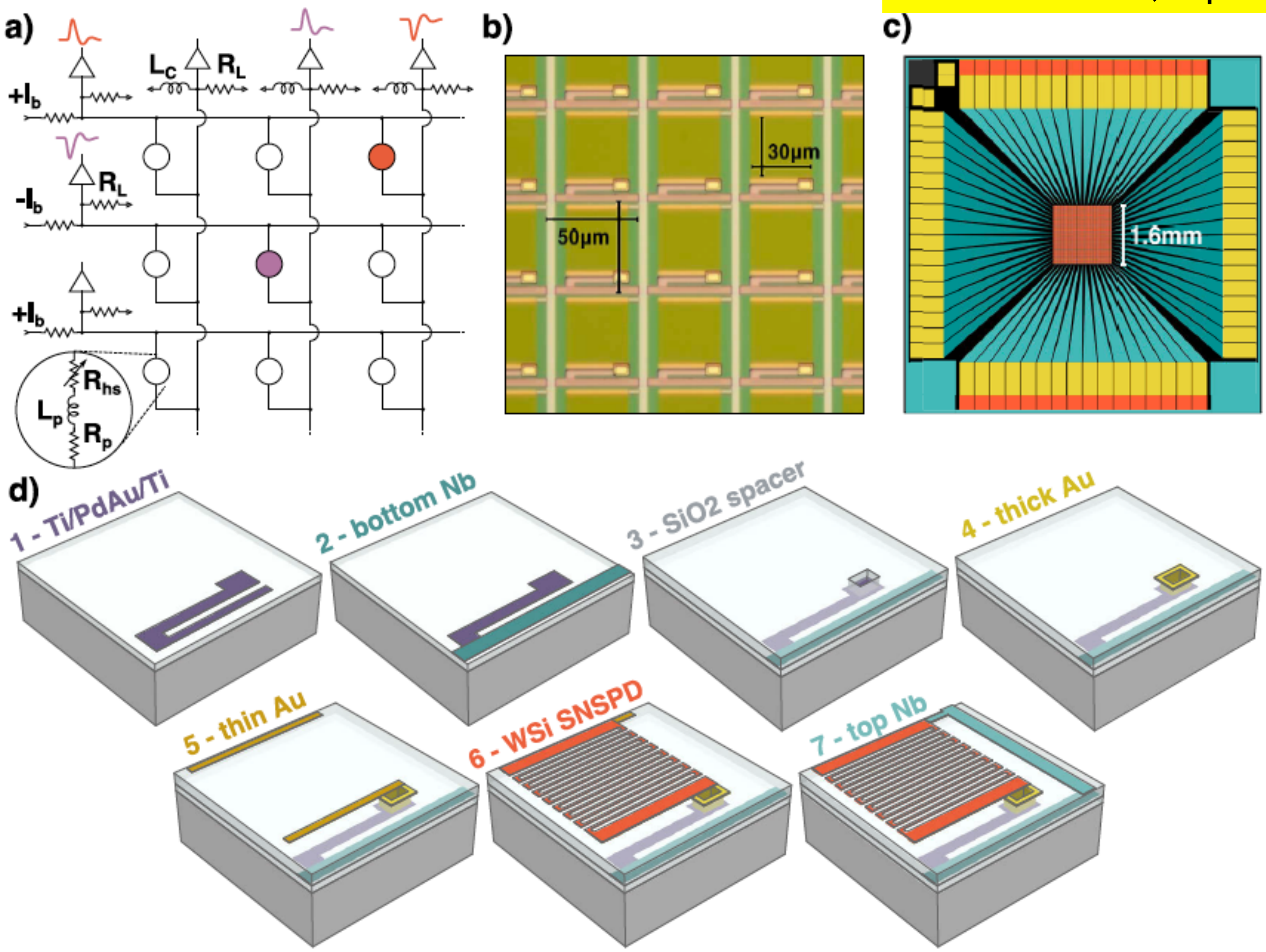


Fig. 1. a) Schematic of the row-column array. b) Optical micrograph of the fabricated array showing the pixel pitch and size. c) Chip-scale layout of the array showing the Nb leads (teal), Au bond pads (yellow), and WSi column inductors (red). d) Fabrication flow, as described in the text. The SNSPD meander and layer thicknesses are not shown to scale.

Dark Matter

Astronomy

Quantum Imaging

Quantum Information (Cryptography)

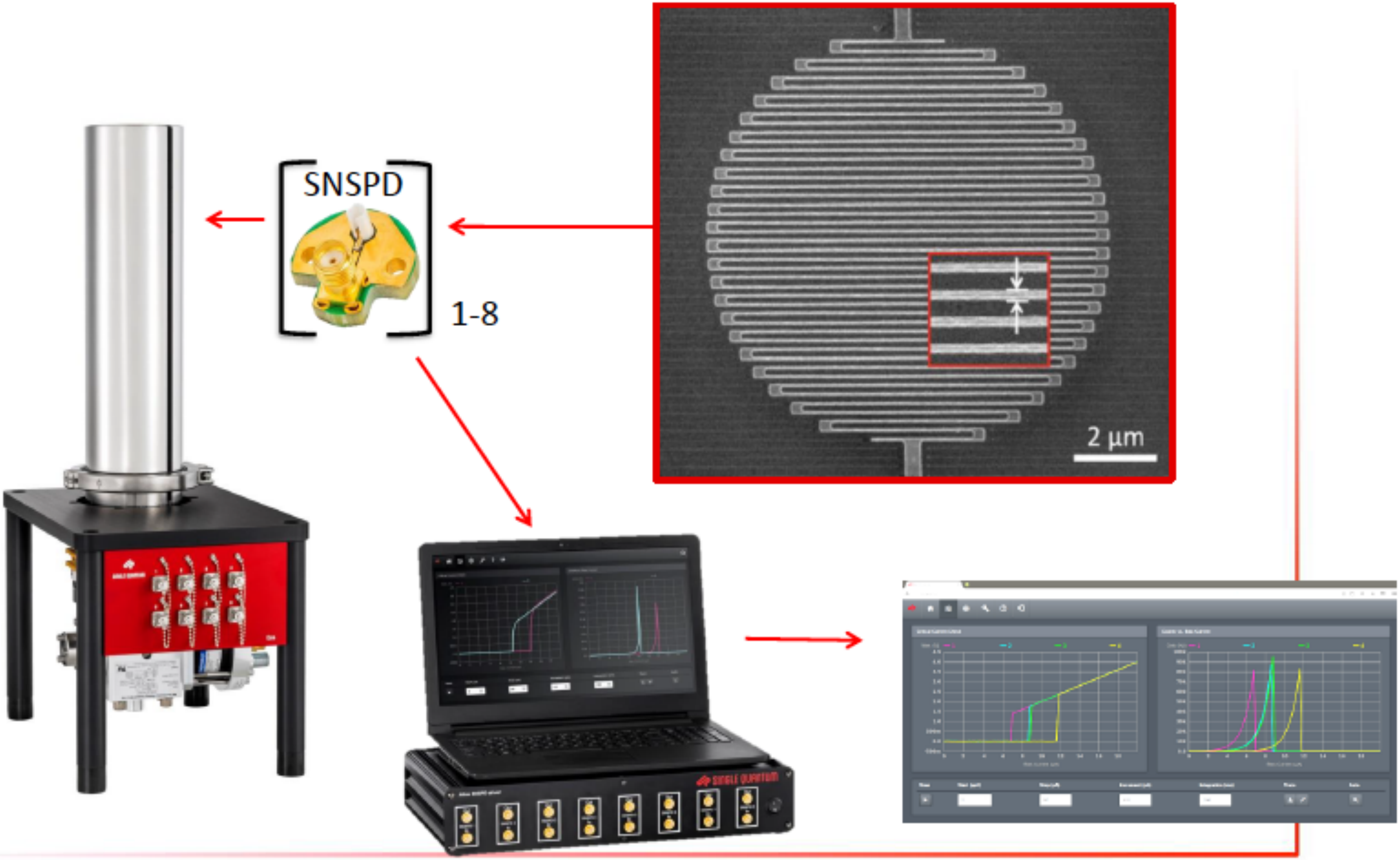
Summary

- In Taiwan we have expertise in various technologies, not only Silicon.
- I very briefly summarized some “old” and new technologies that are now leading to important real-life applications.
- Please follow the relevant presentations in this and other sessions.

請參閱這會議的相關演講

Extra Slides

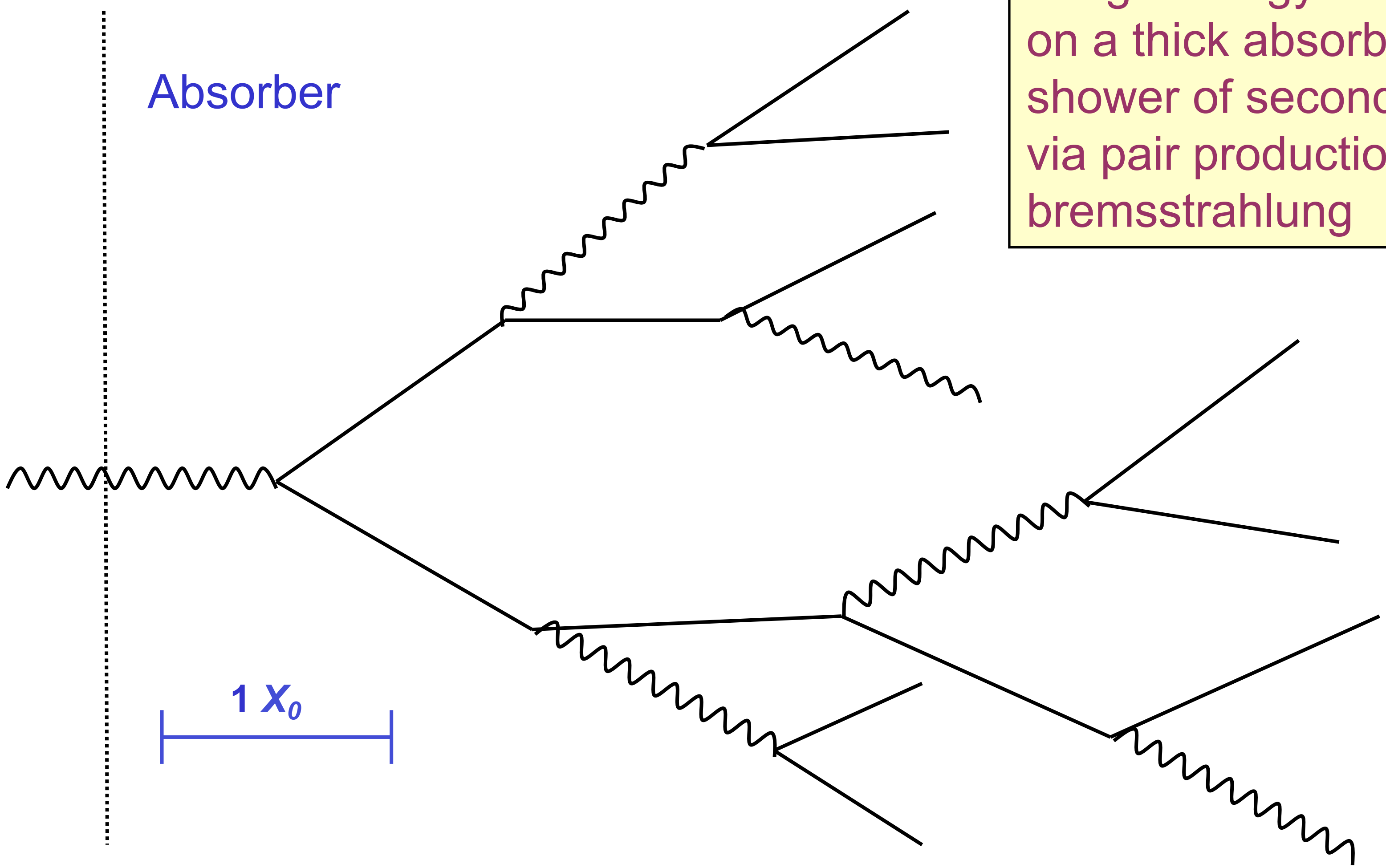
Commercial SNSPD



SINGLE QUANTUM

Excellence in photon detection

Electromagnetic Cascade



A high energy e or γ incident on a thick absorber initiates a shower of secondary e and γ via pair production and bremsstrahlung

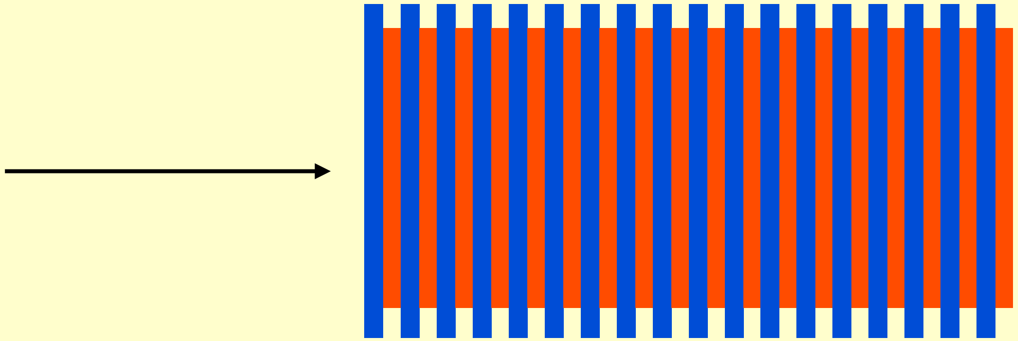
Courtesy: RM.Brown (RAL)

Calorimeter Types

There are two general classes of calorimeter:

Sampling calorimeters:

Layers of passive absorber (such as Pb, or Cu) alternate with active detector layers such as Si, scintillator or liquid argon



Homogeneous calorimeters:

A single medium serves as both absorber and detector, eg: liquified Xe or Kr, dense crystal scintillators (BGO, $PbWO_4$ **.......**), lead loaded glass.

EM Calo energy resolution

$$\frac{\sigma_E^2}{\langle E \rangle^2} = \text{Noise}^2 + \text{Stochastic}^2 + \text{Constant}^2$$

<u>Example</u>

$$\text{Noise} = \frac{N[\text{GeV}]}{\langle E \rangle}$$

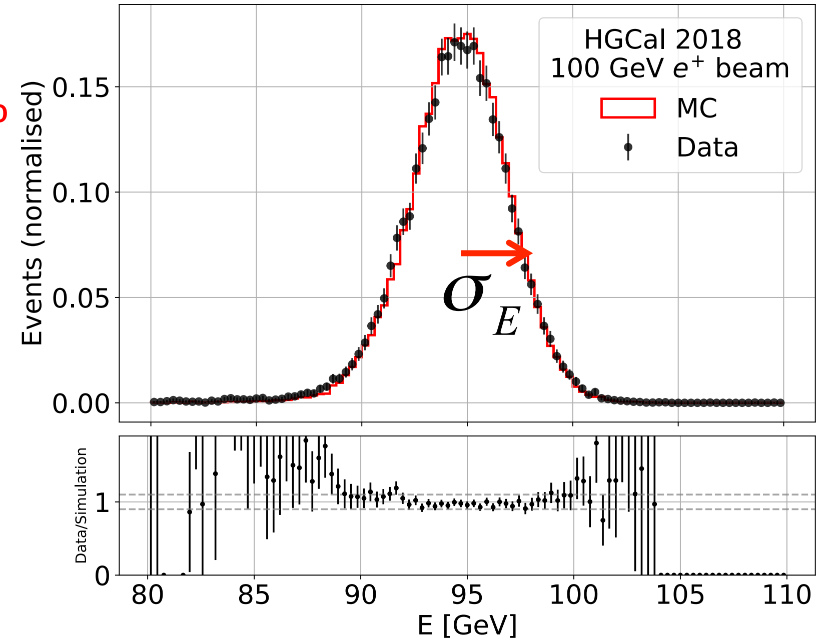
0.1GeV/100GeV=0.1%

$$\text{Stochastic} = \frac{S\left[\%\sqrt{\text{GeV}}\right]}{\sqrt{\langle E \rangle}}$$

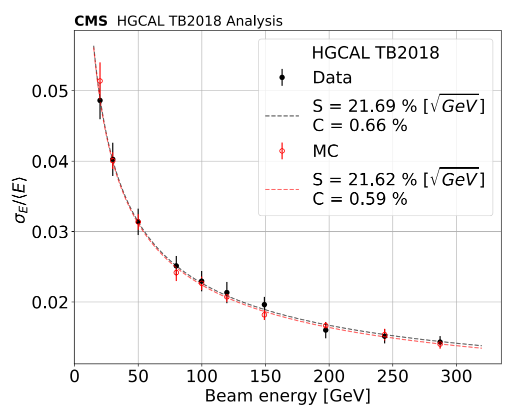
20%/sqrt(100)=2%

$$\text{Constant} = \text{C}[\%]$$

0.5%



$\langle E \rangle$



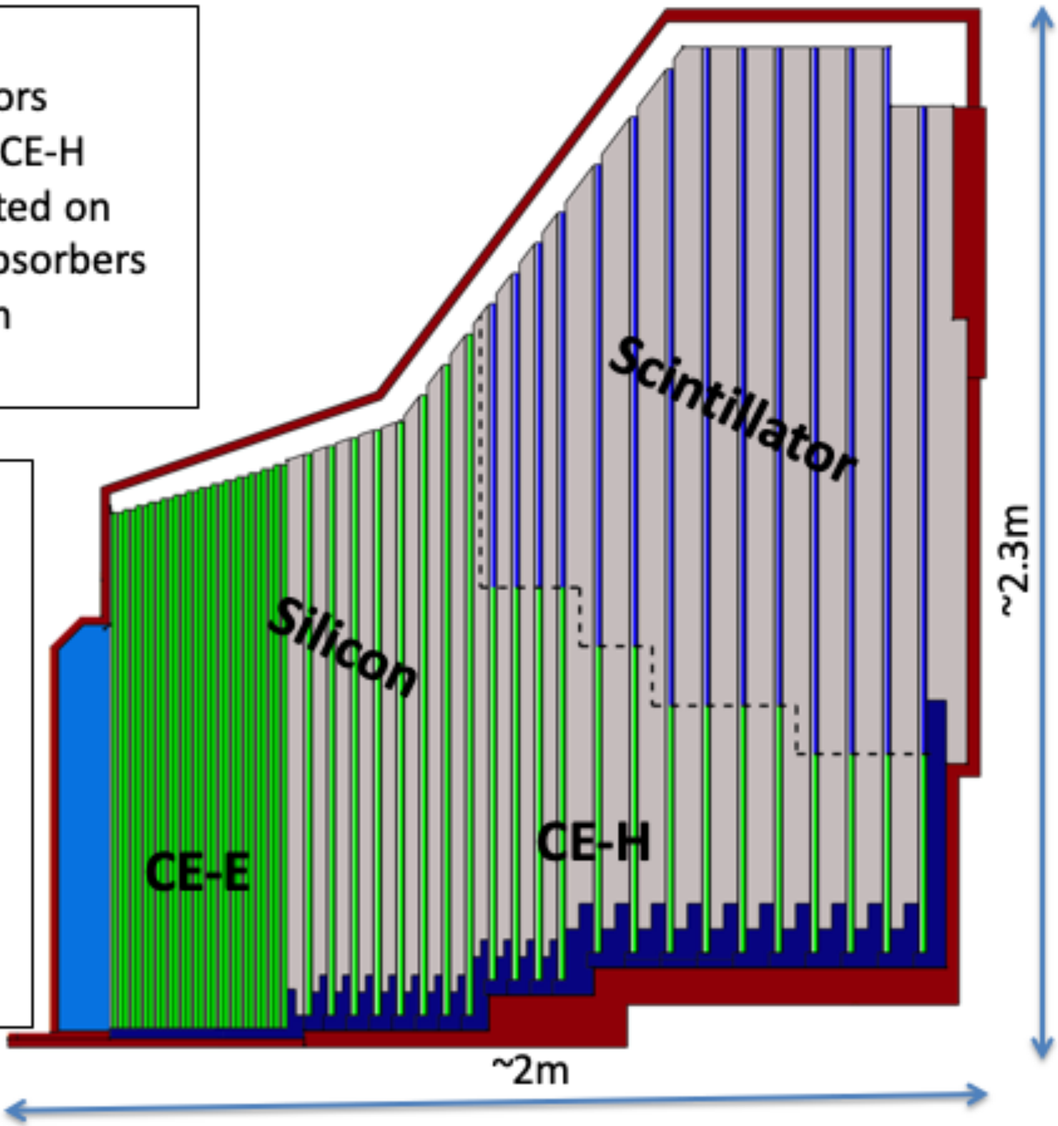
CMS High Granularity Calorimeter

Active Elements:

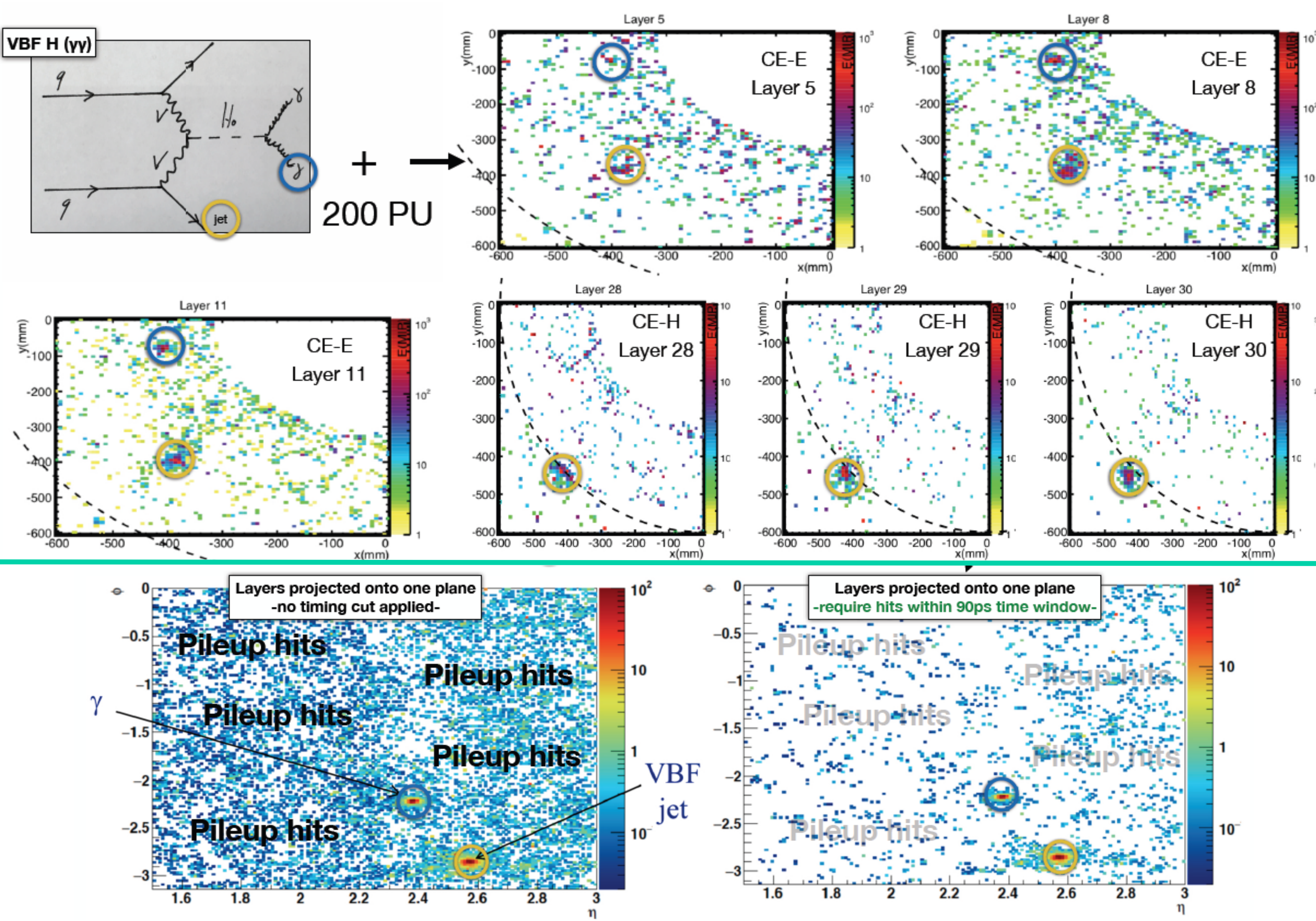
- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- "Cassettes": multiple modules mounted on cooling plates with electronics and absorbers
- Scintillating tiles with SiPM readout in low-radiation regions of CE-H

Key Parameters:

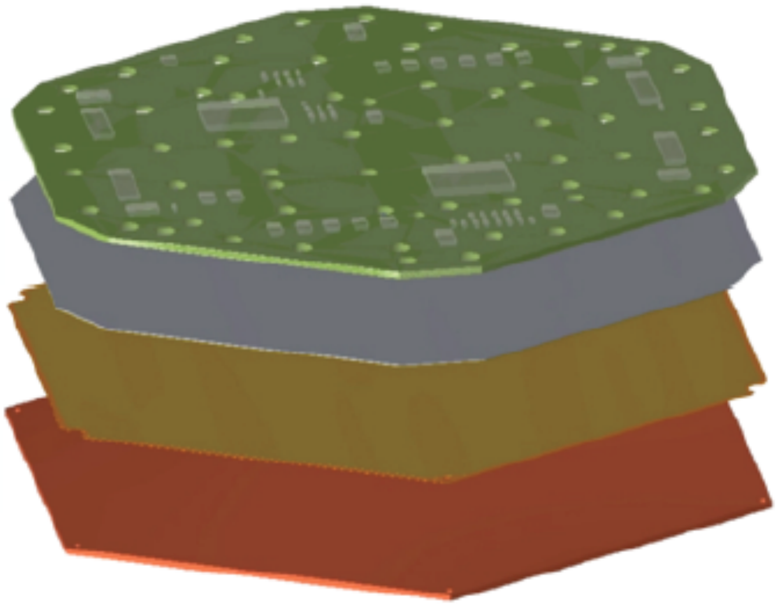
Coverage: $1.5 < |\eta| < 3.0$
~215 tonnes per endcap
Full system maintained at -30°C
~620m^2 Si sensors in ~30000 modules
~6M Si channels, 0.5 or 1cm^2 cell size
~400m^2 of scintillators in ~4000 boards
~400k scint. channels, 4-30cm^2 cell size
Power at end of HL-LHC:
~125 kW per endcap

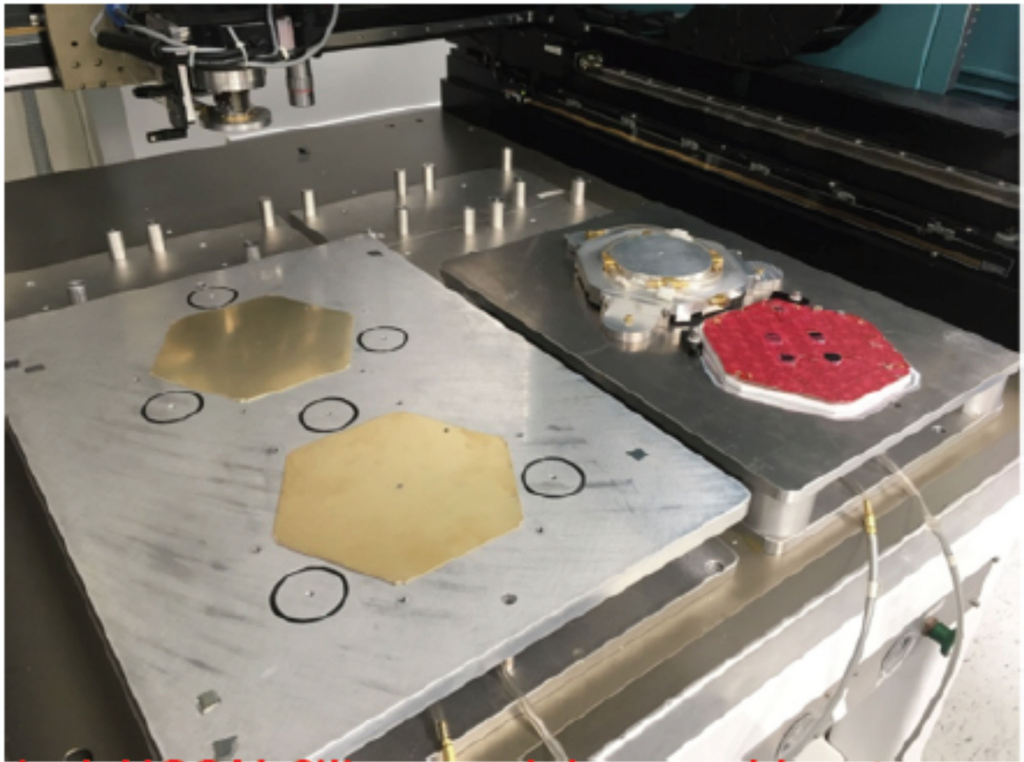


Electromagnetic calorimeter (**CE-E**): **Si**, Cu & CuW & Pb absorbers, 28 layers, 25 X_0 & ~1.3λ
Hadronic calorimeter (**CE-H**): **Si** & **scintillator**, steel absorbers, 22 layers, ~8.5λ

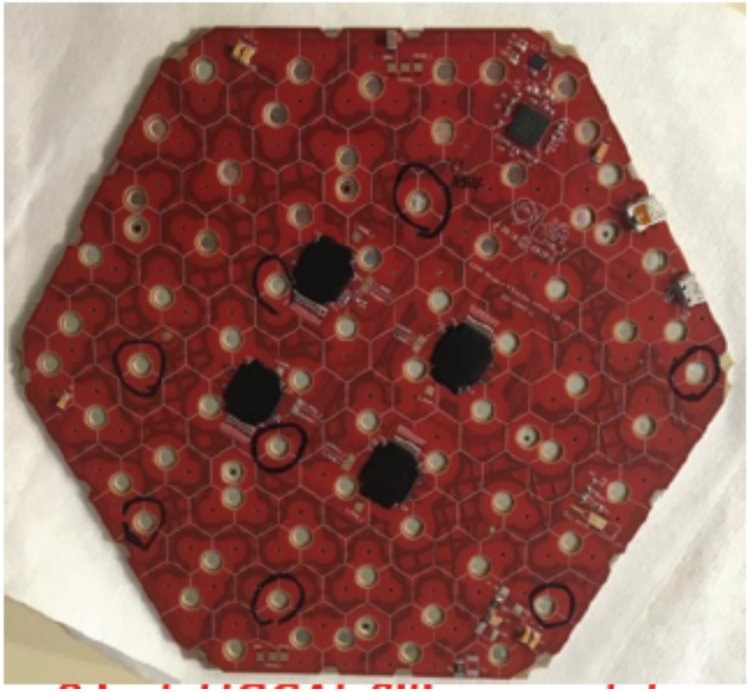

VBF H (γγ)
jet
+
200 PU
CE-E
Layer 5
CE-E
Layer 8
CE-E
Layer 11
CE-H
Layer 28
CE-H
Layer 29
CE-H
Layer 30
x(mm)
y(mm)
E(MIP)
Layers projected onto one plane
-no timing cut applied-
Pileup hits
Pileup hits
Pileup hits
Pileup hits
Pileup hits
γ
VBF
jet
Layers projected onto one plane
-require hits within 90ps time window-
η
φ

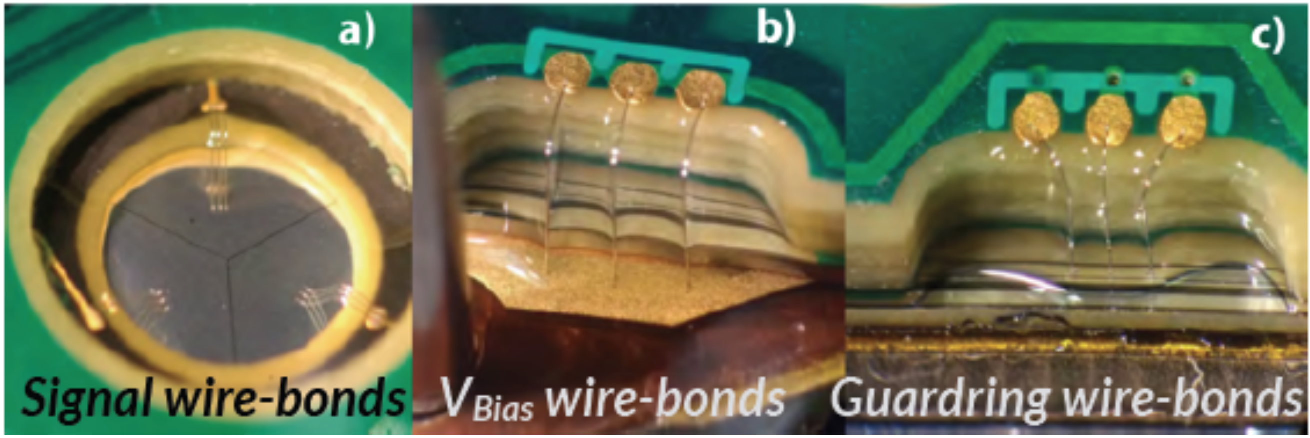
HGCAL Modules



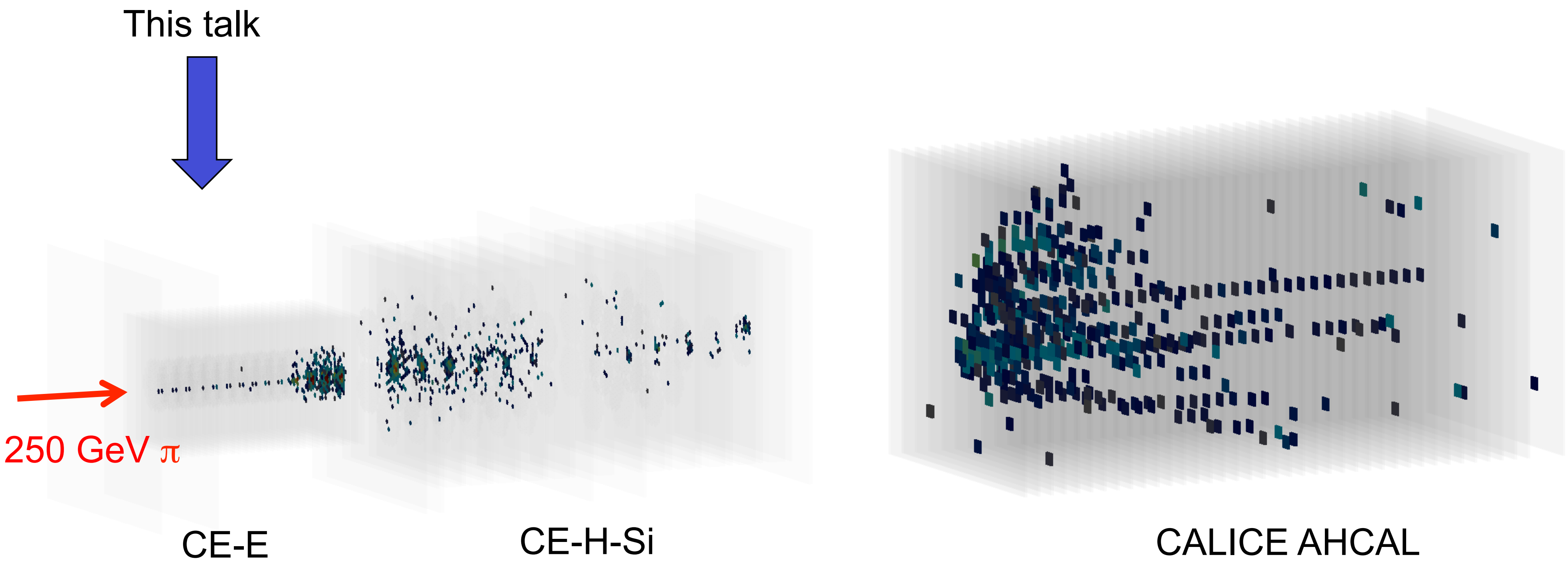


8 inch HGCAL Silicon module assembly set-up
(At one of the 6 module assembly centers worldwide)

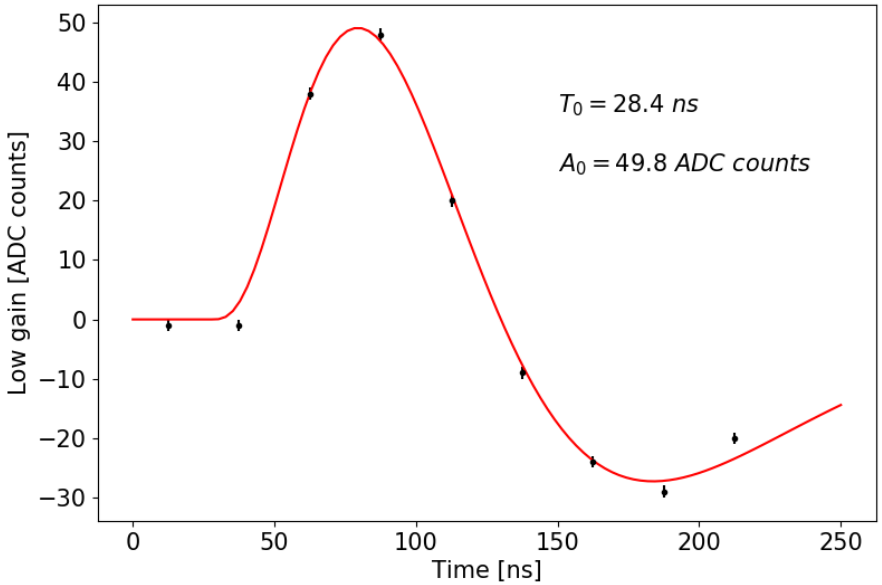


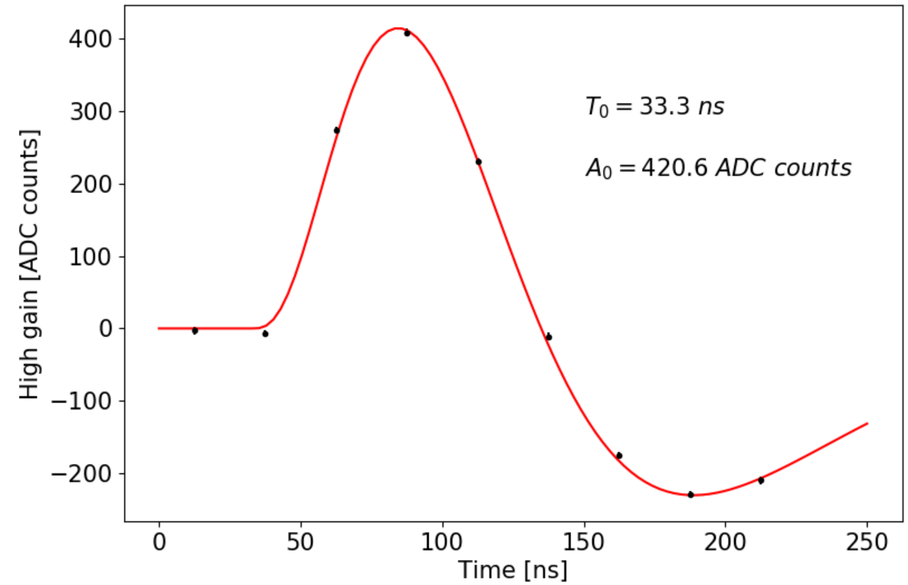


HGCAL is an imaging Calo

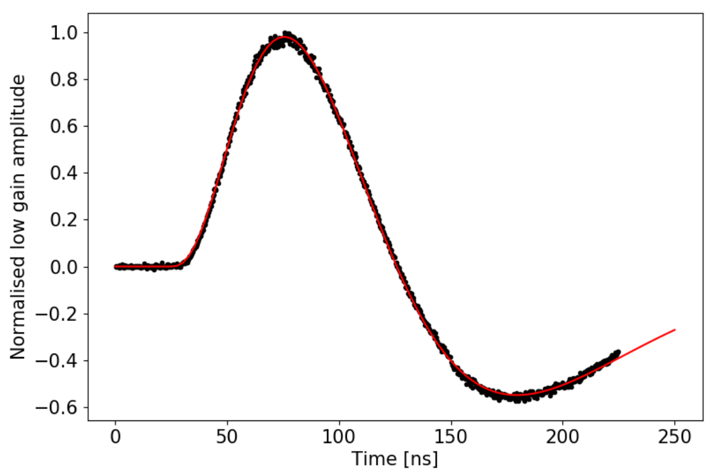


Real-time fast electronics





Low gain shaper pulse (left) vs High Gain pulse (right) for 300GeV electrons.
The model pulse has been extracted by sampling pulses at 1nsec.



$$S(t) = \begin{cases} A_0\left[\left(\frac{t-t_0}{\tau}\right)^n - \frac{1}{n+1}\left(\frac{t-t_0}{\tau}\right)^{n+1}\right]e^{-\alpha(t-t_0)/\tau} & \text{if } t > t_0 \\ 0 & \text{otherwise} \end{cases}$$

Dedicated injection runs on test stands with waveforms sampled at 1nsec.

Step 5: use muons to get ADCperMIP

- The hit energy is estimated using a preliminary HG-MIP calibration.
- Hits with more than 0.5 MIP, corresponding to 20-25 HG ADC of the reconstructed waveform amplitude are visualised.
- (A hit-energy-colour bar could be added.)

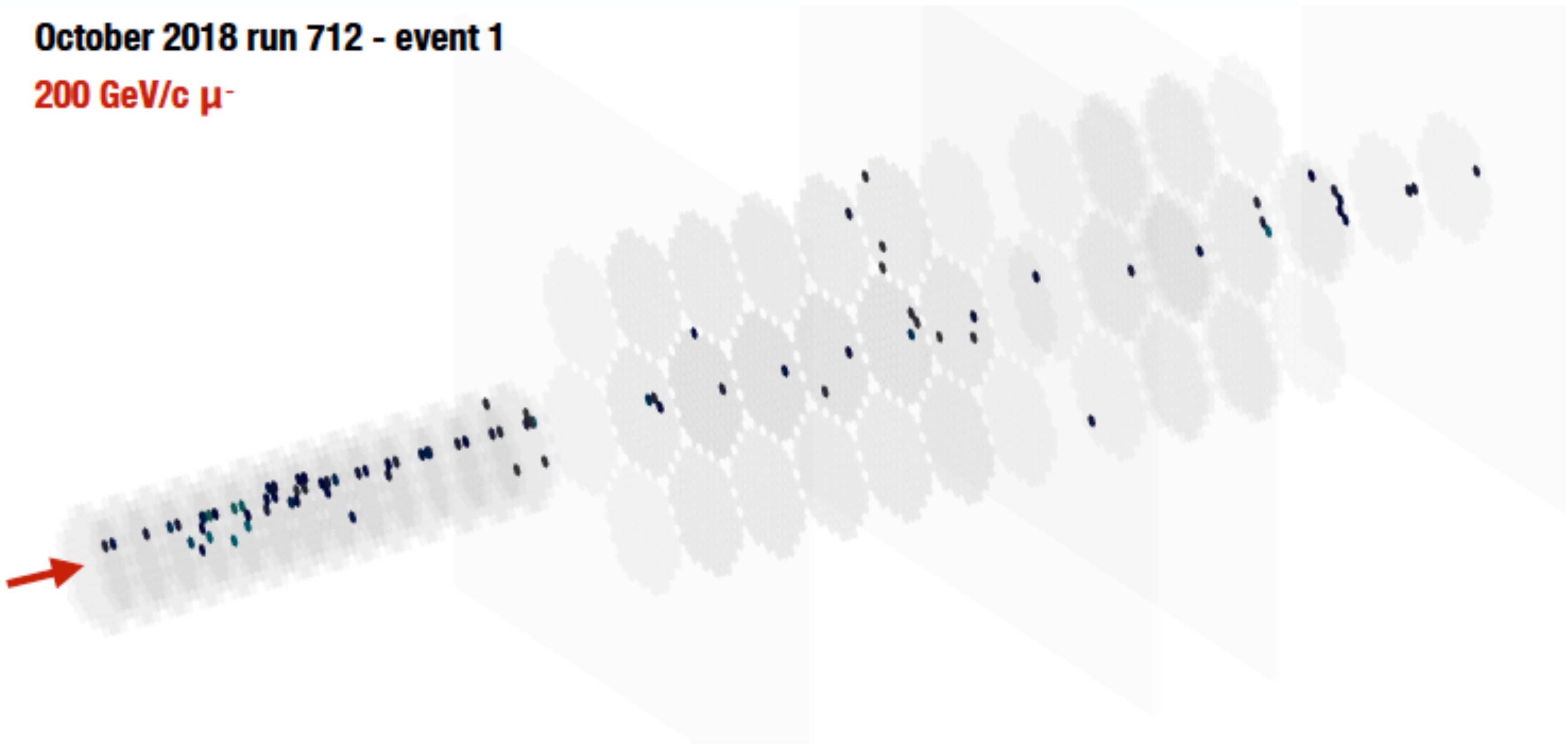
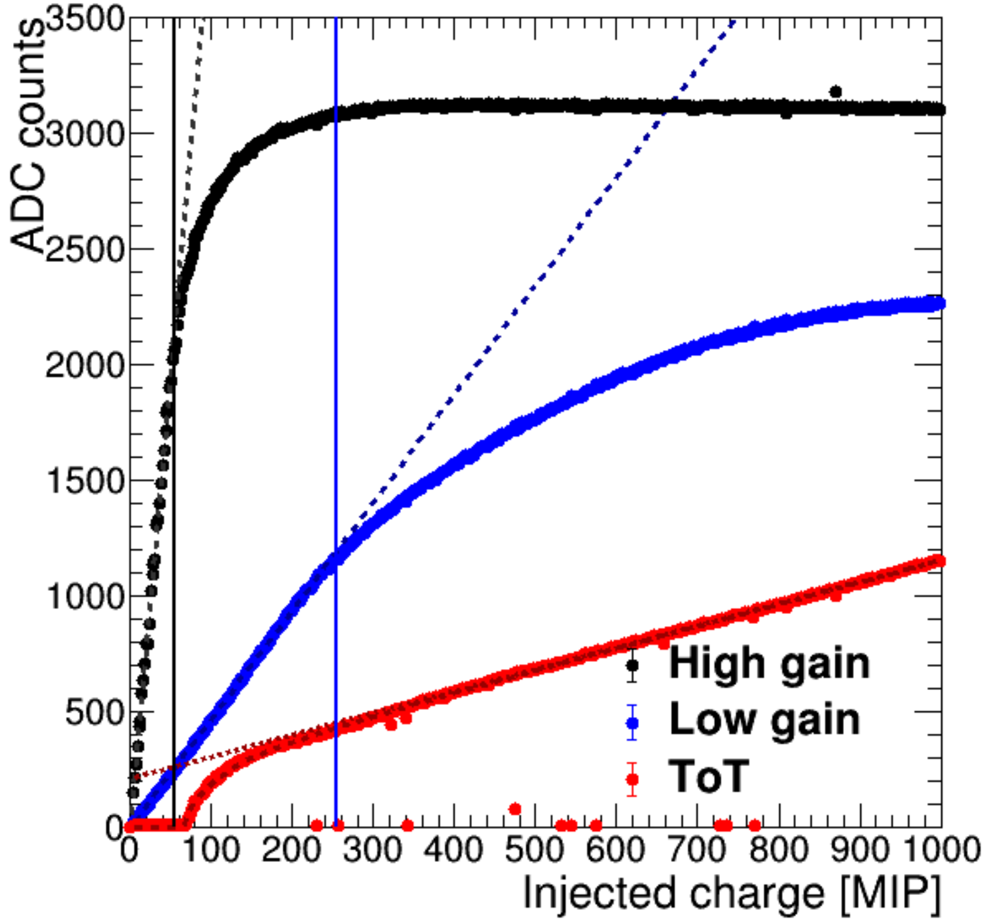


Figure: Event display of a 200 GeV/c muon traversing the CE-E (28 layers) and CE-H (12 layers) prototypes during the beam test of October 2018. The incoming muon enters the detector from the left-hand side.

Pad energy reconstruction: LG,HG,ToT



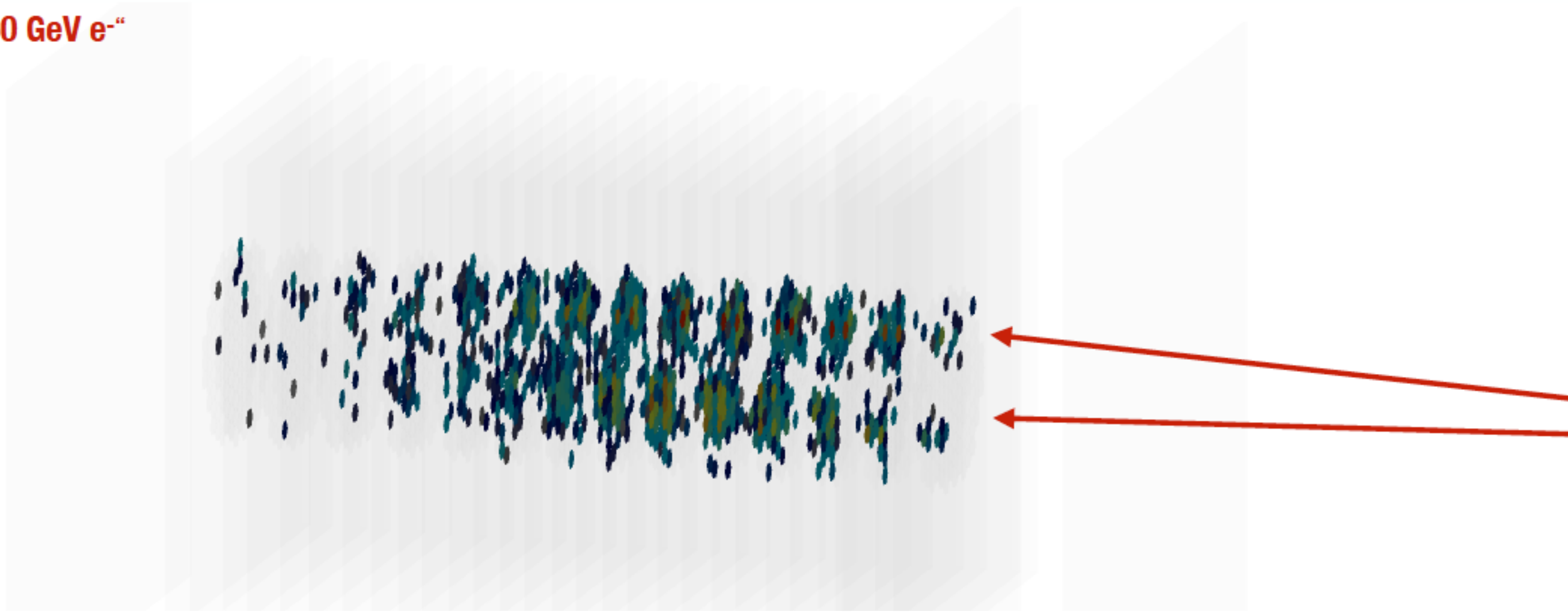
$$A'_{HG} = \begin{cases} A^{TOT} \cdot m_{LG/TOT} \cdot m_{HG/LG} & \text{, if } A^{LG} > TP_{LG} \\ A^{LG} \cdot m_{HG/LG} & \text{, else if } A^{HG} > TP_{HG} \\ A^{HG} & \text{, otherwise} \end{cases}$$

$$E^{Si}_{pad}[MIP] = A'_{HG} \cdot M_{MIP/HG},$$

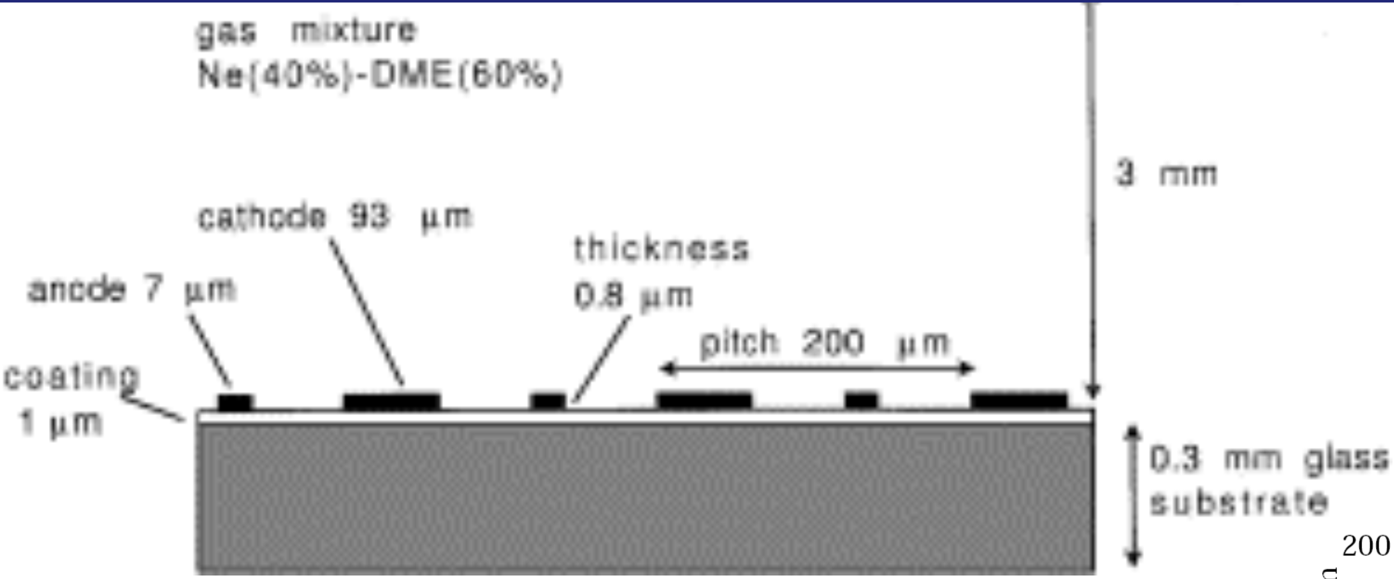
HGCAL is an imaging Calo

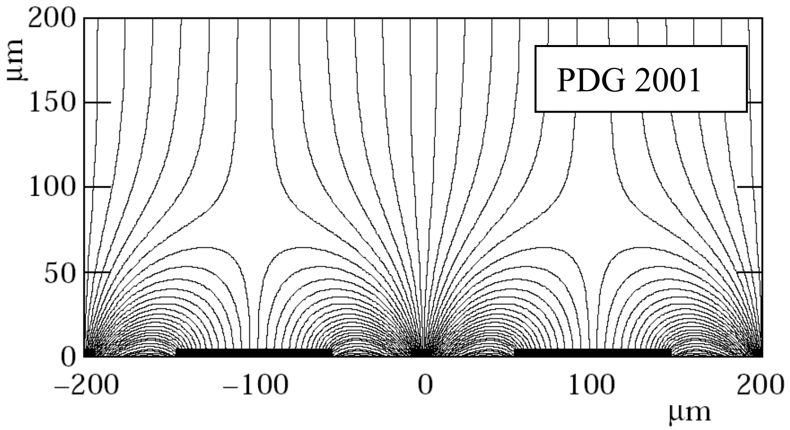
June 2018 run 407 - event 1:

"150 GeV e-"



Micro-Strip Gas Chambers (MSGC)

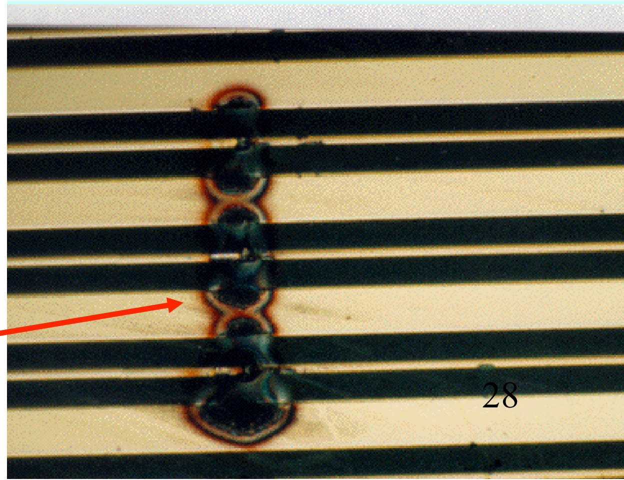




Example: CMS MCGC’s (abandoned)

MSGC’s:

- anode and cathode strips etched on glass substrate.
- cathode strips provide fast “drain” for ions from avalanche



High sensitivity to discharges, damaging strips.