The CMS High-Granularity Calorimeter for Operation at the High-Luminosity LHC

Florian Pitters

florian.pitters@cern.ch

CERN
Vienna University of Technology

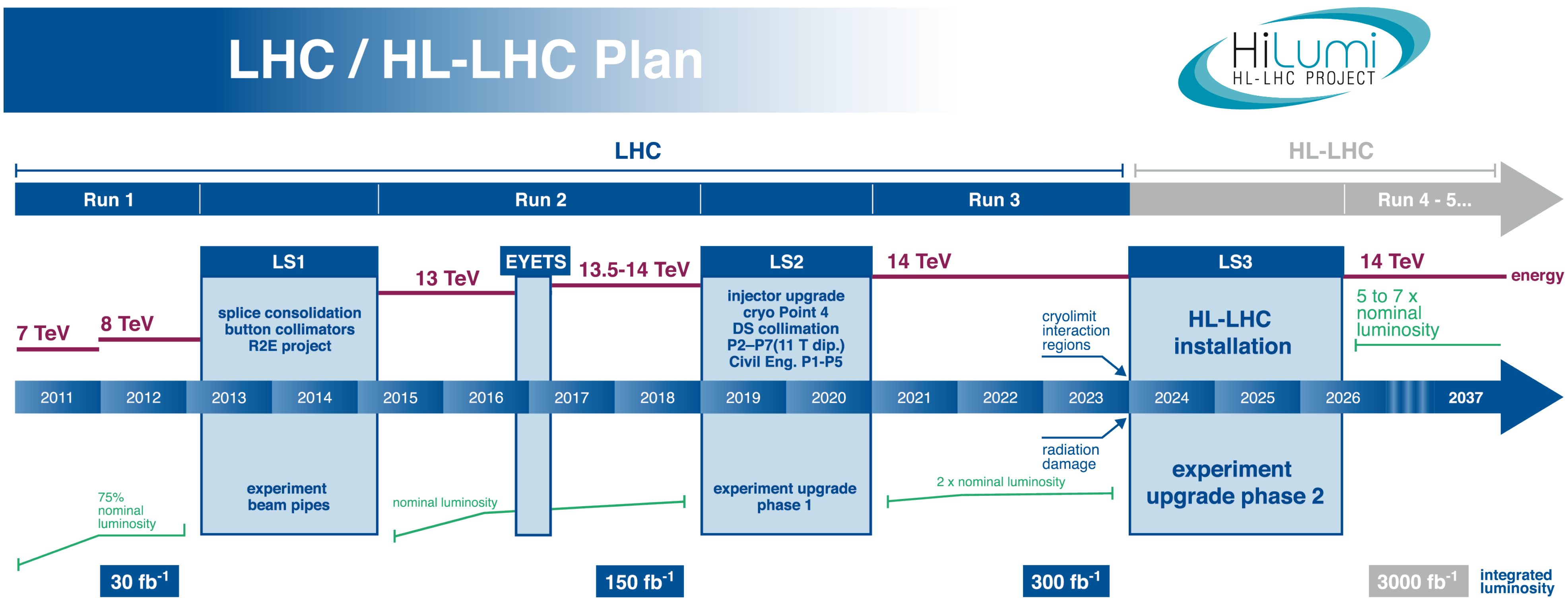
on behalf of the CMS collaboration

TIPP 2017 @ Beijing

The HL-LHC Upgrade

From around 2026 onwards LHC instantaneous luminosity will increase by a factor 5 to 7 and integrated luminosities of 3000 fb^{-1} are planned.

A major challenge for the detector design!

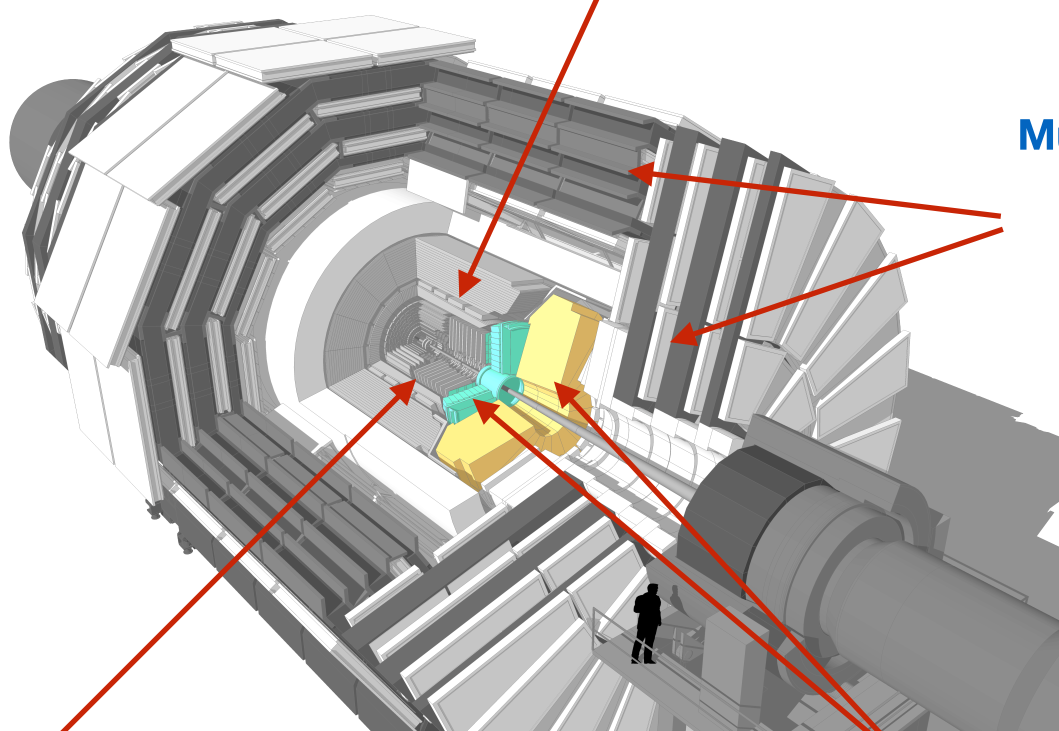


The CMS HL-LHC Upgrades

Trigger/HLT/DAQ
- Track information at L1 trigger
- L1 trigger: 12.5 μm latency - output 750kHz
- HLT: output 7.5 kHz

Barrel EM calorimeter
- Replace FE/BE electronics
- Lower operating temperature to 8°C

Muon system
- Replace DT & CSC FE/BE electronics
- Complete RPC coverage in $1.5 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$

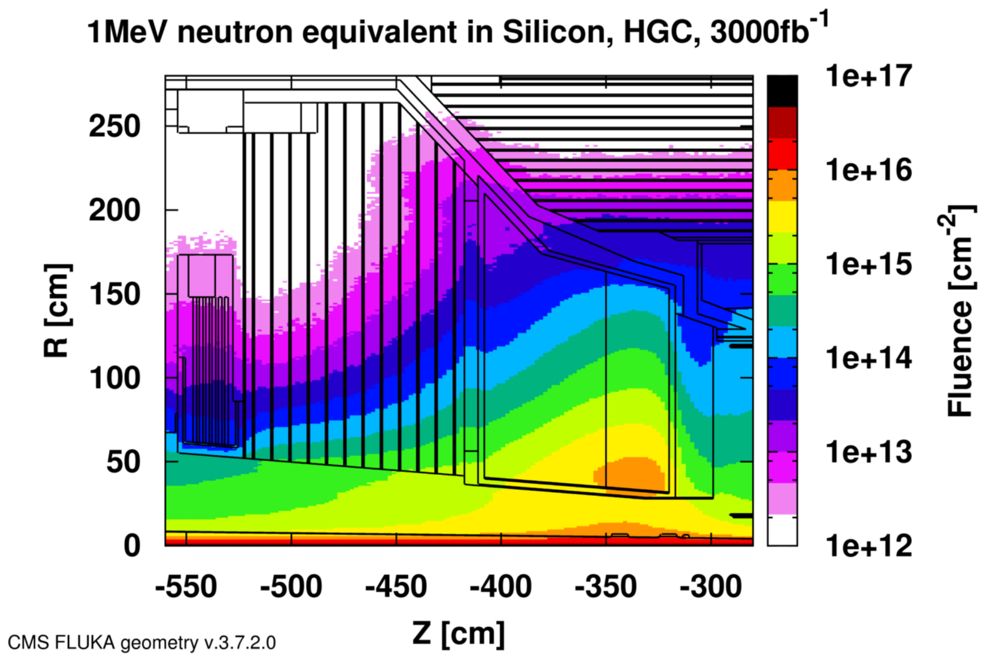


Replace tracker
- Rad. tolerant - higher granularity - significant less material
- 40 MHz selective readout ($p_T > 2$ GeV) in outer tracker for L1 trigger
- Extend coverage to $\eta = 3.8$

Replace endcap calorimeters
- Rad. tolerant – high granularity
- Mitigate pileup – 3D tracking
- Operate at -30°C

Detector Environment

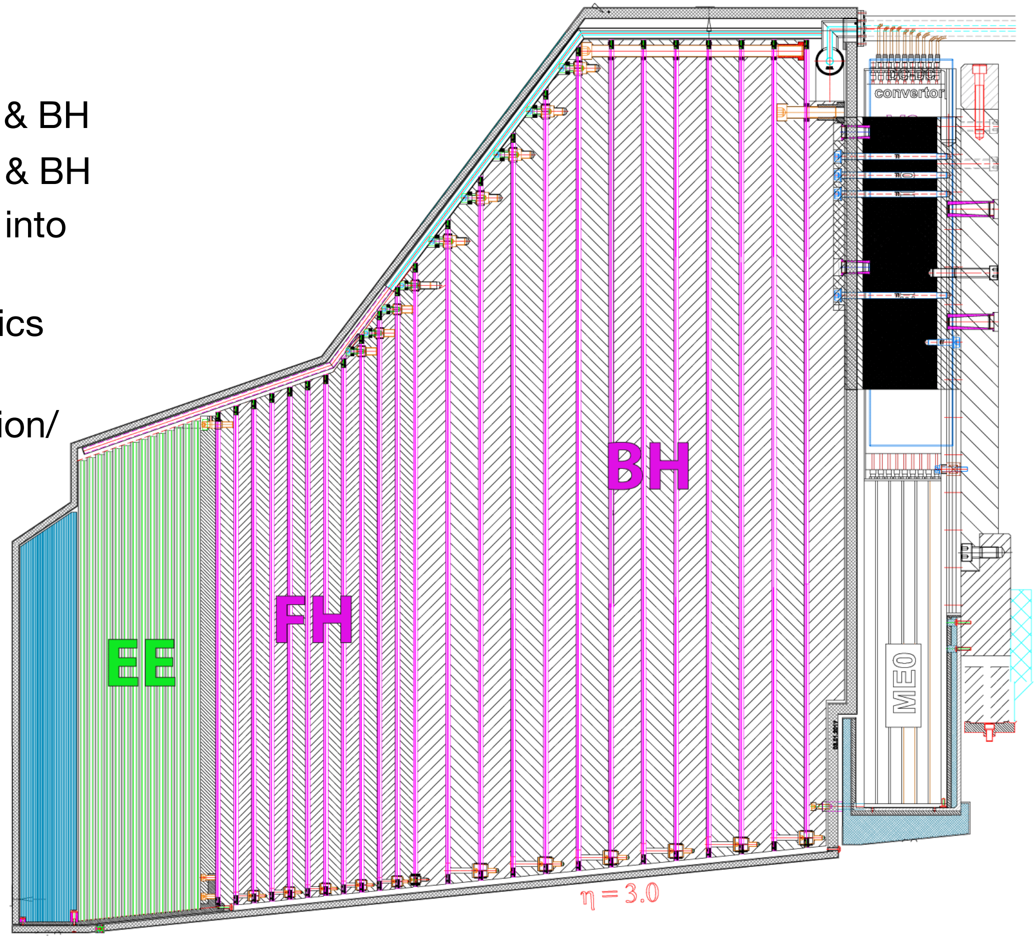
- After the HL-LHC upgrade, the CMS end-cap will operate in an unprecedented **radiation environment**
  - Fluences of up to **10^{16} neq/cm^2** and doses of up to **1.5 MGy**
  - Pile-up of up to **200 collisions/crossing**
- Use silicon detectors to survive with high granularity and precise timing of ~50ps on cell level



expected neutron equivalent fluences

The CMS HGCal Upgrade

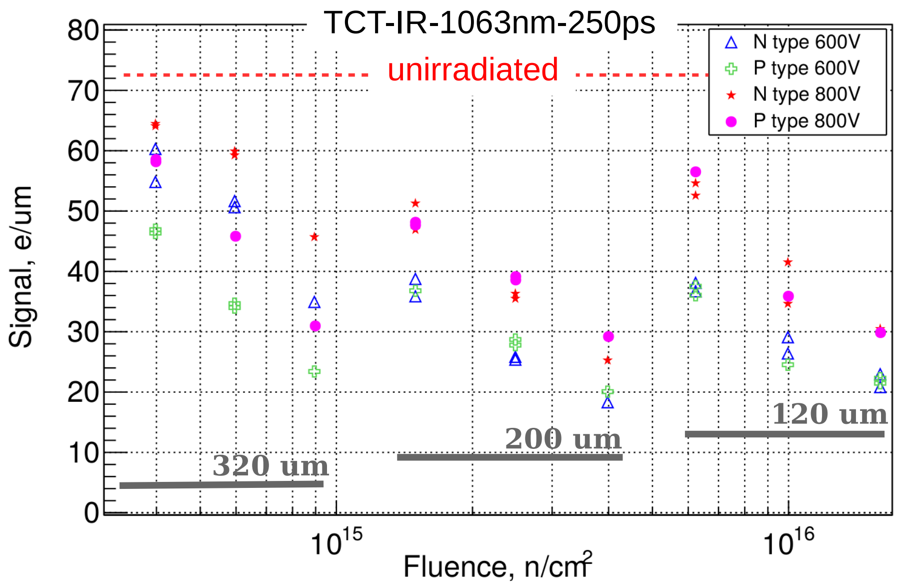
- Key facts:
  - **High granularity throughout the calorimeter**
  - **Hexagonal silicon sensors** in EE and high-radiation FH & BH
  - **Scintillating tiles** with SiPM readout in low-radiation FH & BH
  - Sensors with W/Cu backing plate and readout PCB built into **modules**
  - Modules will be mounted on cooling plates with electronics and absorbers to make up **cassettes**
  - Goal is **~50 ps timing** on cell level for vertex reconstruction/ pile-up rejection
- Key parameters:
  - HGCAL covers 1.5 < η < 3
  - **Full system** maintained **at -30°C**
  - **~ 600 m² of silicon**
  - ~ 500 m² of scintillators
  - ~ 6M silicon channels, ~0.5 and ~1 cm² cell-size
  - Power at end of life ~120 kW of which ~20% is sensor leakage current

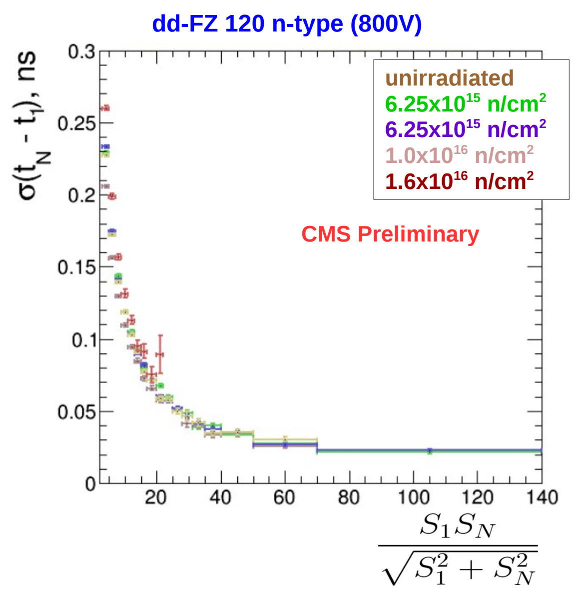


Endcap Electromagnetic calorimeter (EE): Si, Cu & CuW & Pb absorbers, 28 layers, 25 X_0 & ~1.3 λ
Front Hadronic calorimeter (FH): Si & scintillator, steel absorbers, 12 layers, ~ 3.5 λ
Backing Hadronic calorimeter (BH): Si & scintillator, steel absorbers, 12 layers, ~ 5 λ

Why Silicon?

- Relatively good understanding of and handle on **mitigating radiation damage**
  - Can mitigate leakage current noise contribution by **cooling to -30°**
  - Can mitigate signal loss by going to **thinner sensors and higher bias voltage**
- Potential to reach **intrinsic time resolution of O(25ps)**
  - Behaviour **depends only on S/N** even at 10^{16} n/cm^2
- Allows for a compact calorimeter with high granularity

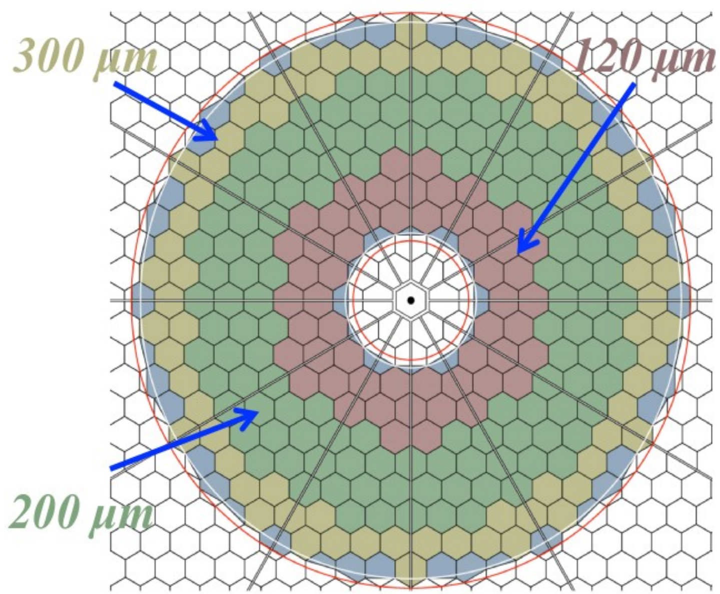




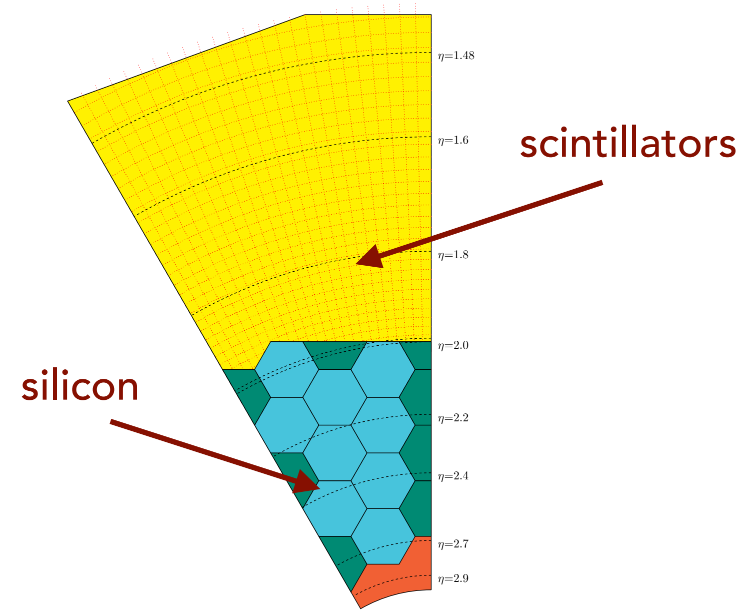
Use thin sensors in the inner most layers, operate cold and at higher voltage.

Layout

- Choose **silicon sensor thickness according to expected radiation dose**
  - Depending on 120 µm, 200 µm & 300 µm active thickness
  - Reduce cell size for thinner sensors to keep similar capacitance
- Intersection and exact geometry between scintillator and silicon regions will be evaluated in the coming months
  - **SiPM-on-tile** is the **baseline option** (analogous to CALICE AHCAL)
  - **Granularity has to be optimised** with respect to physics performance and cost



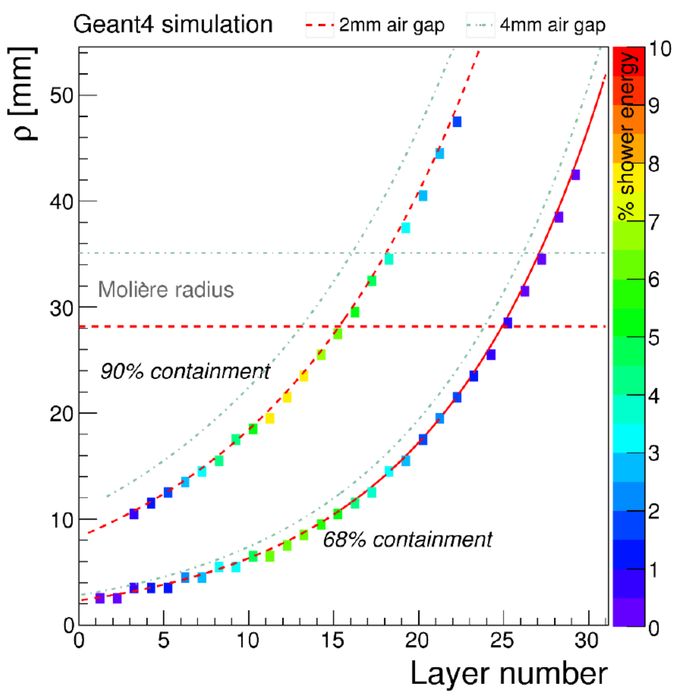
Different regions in EE



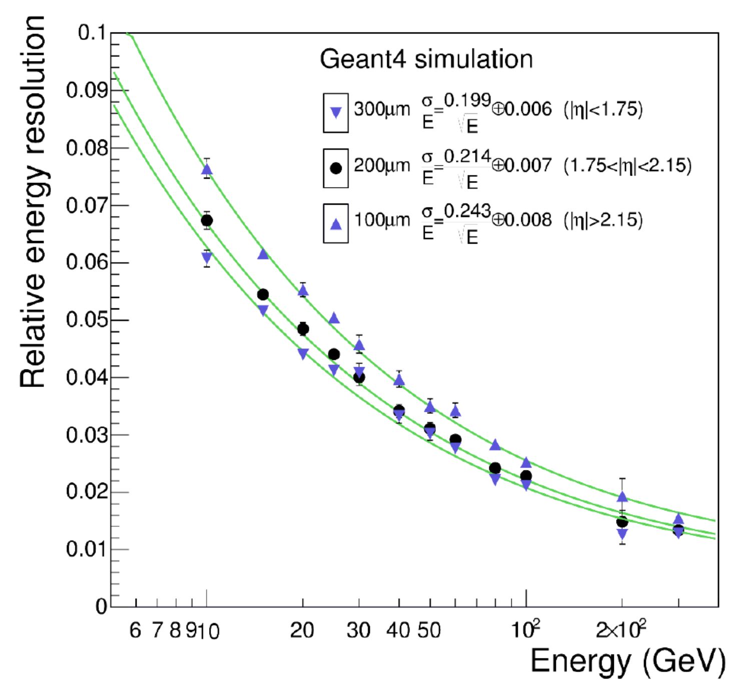
Mockup of a mixed 30° cassette for FH

Expected Performance

- Compact design and chosen materials result in **narrow showers**
  - Together with high granularity allows for good **particle separation and particle flow**
  - **Pile up rejection** can be done within the first layers
- Good energy resolution
  - Stochastic term of ~20% and constant term of ~1%



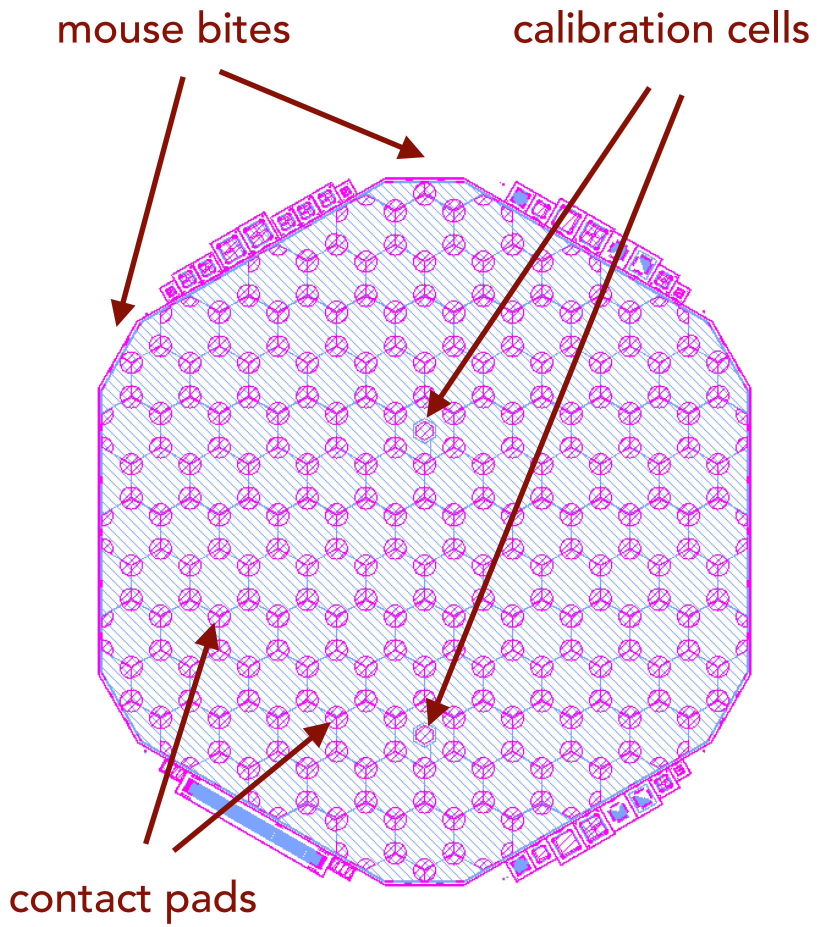
transverse shower size



relative energy resolution

Silicon Sensors

- **Hexagonal geometry** as largest tile-able polygon
  - **6” and 8”** sensors considered
  - Cell sizes of **~0.5 cm^2 and ~1 cm^2**
  - Cell capacitance of **~50 pF**
  - Will most likely need n-on-p for inner layers
- Some design goals
  - **1kV sustainability** to mitigate radiation damage
  - **Four quadrants** to study inter-cell gap distance and its influence on V_{bd}, C_{int} and CCE
- A few more details about those sensors
  - Active thickness by **deep diffusion or thinning**
  - Inner **guard ring is grounded**, outer guard ring is floating
  - Truncated tips, so called **mouse bites,** for module mounting
  - **Calibration cells** of smaller size for single MIP sensitivity at end of life

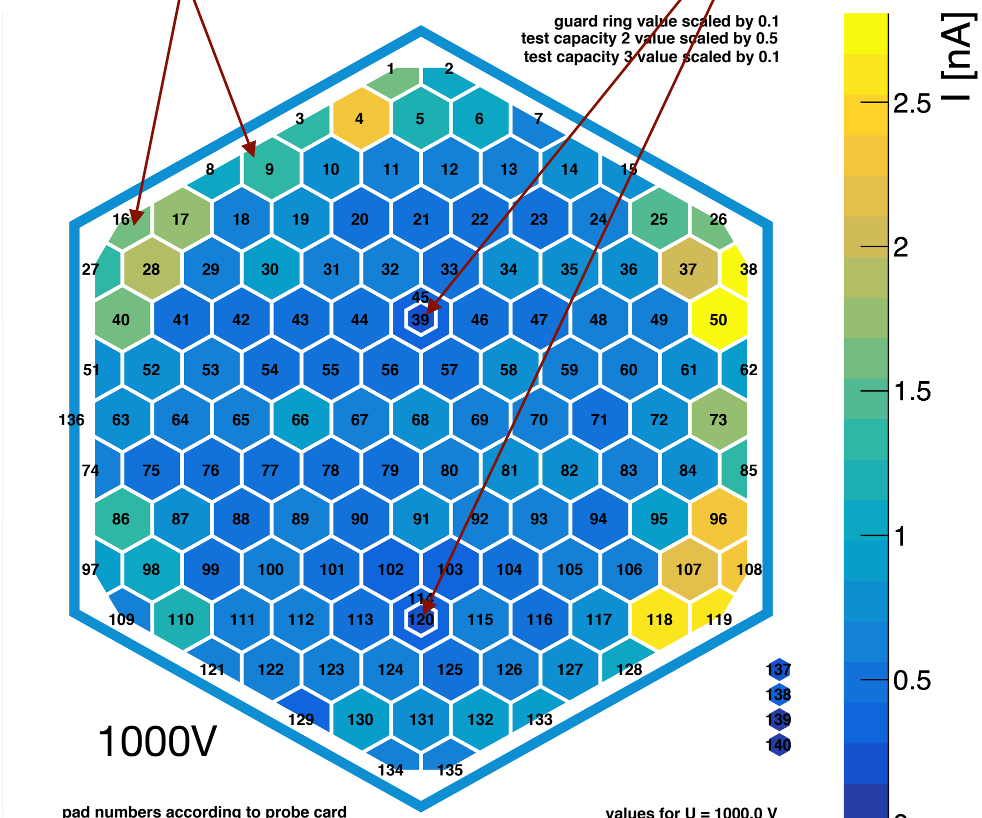


Hamamatsu 6” 128ch design

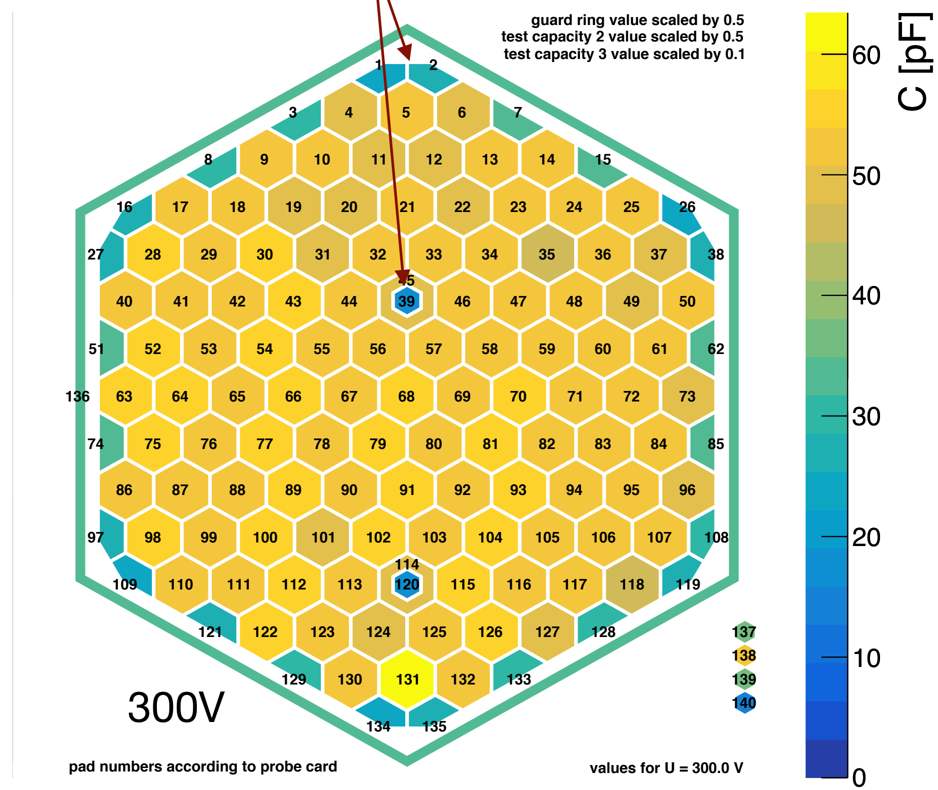
Example Results

higher leakage currents at the edge region

lower leakage currents in the calibration cells



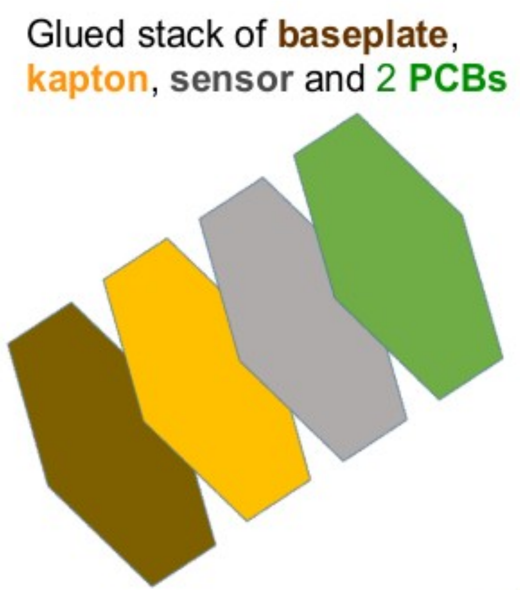
mouse bites & calibration cells show lower capacitances than full cells (smaller size)



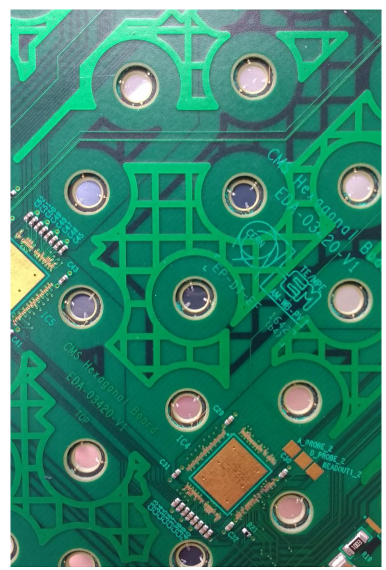
IV and CV example measurements done with probe card plus external switching unit

Module Integration

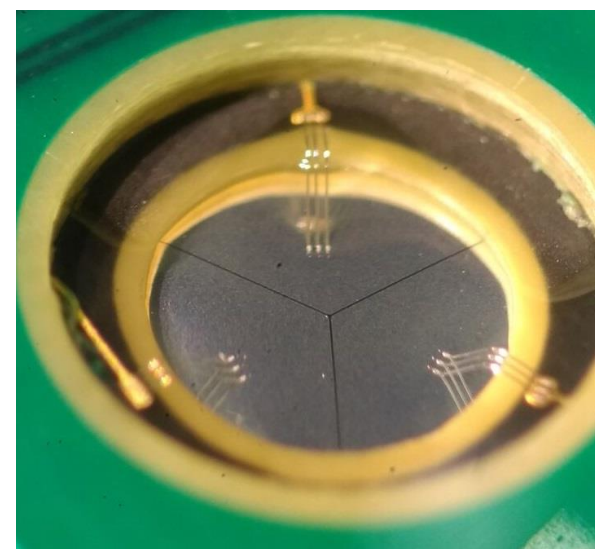
- Preliminary module design is as following
  - First, the **sensor** is glued unto **W/Cu baseplate covered with Au/Kapton foil**
  - Then, the **readout PCB** is glued unto the sensor
  - **Wire bonds through holes in the PCB** connect readout board to sensor cells
- Per hole in the PCB, we can connect to 3 cells compared to 4 with squares
  - Makes routing more difficult. Investigating sensor design features that could help.



module design



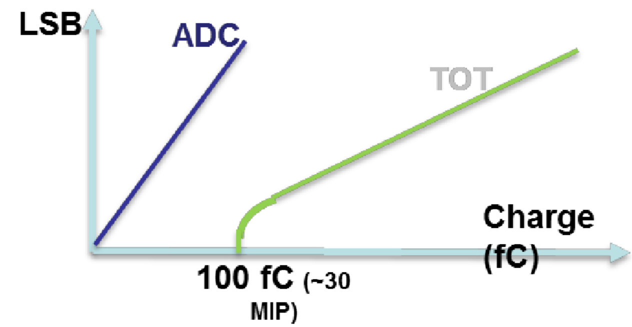
readout PCB



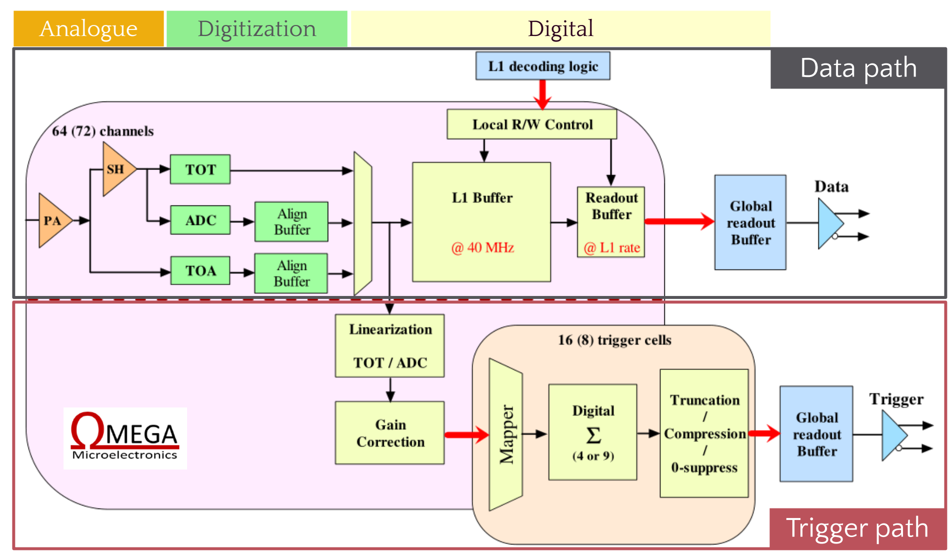
wire bonds

Front End Readout

- Requirements
  - **Large dynamic range of 0.4 fC to 10 pC**
  - Low power budget of 10 mW/channel
  - **Timing information** with 50 ps accuracy
  - Low noise of ~ 2ke$^-$
  - **High radiation resistance**
- Baseline
  - **TSMC 130nm** technology
  - **ToA with 50 ps binning** for timing
  - ToT with 12 bit for 0.1 to 10 pC
  - ADC with 10 bit for 0 to 0.1 pC
  - Large buffers to accommodate 12.5 μs latency of L1 trigger
- Status
  - Skiroc2CMS designed for testbeam
  - **First HGROC version** to be submitted by mid 2017



ADC and ToT



VFE layout

For more information see talk by Johan Borg at Thursday 11h in the R3 session.

Trigger

Front End

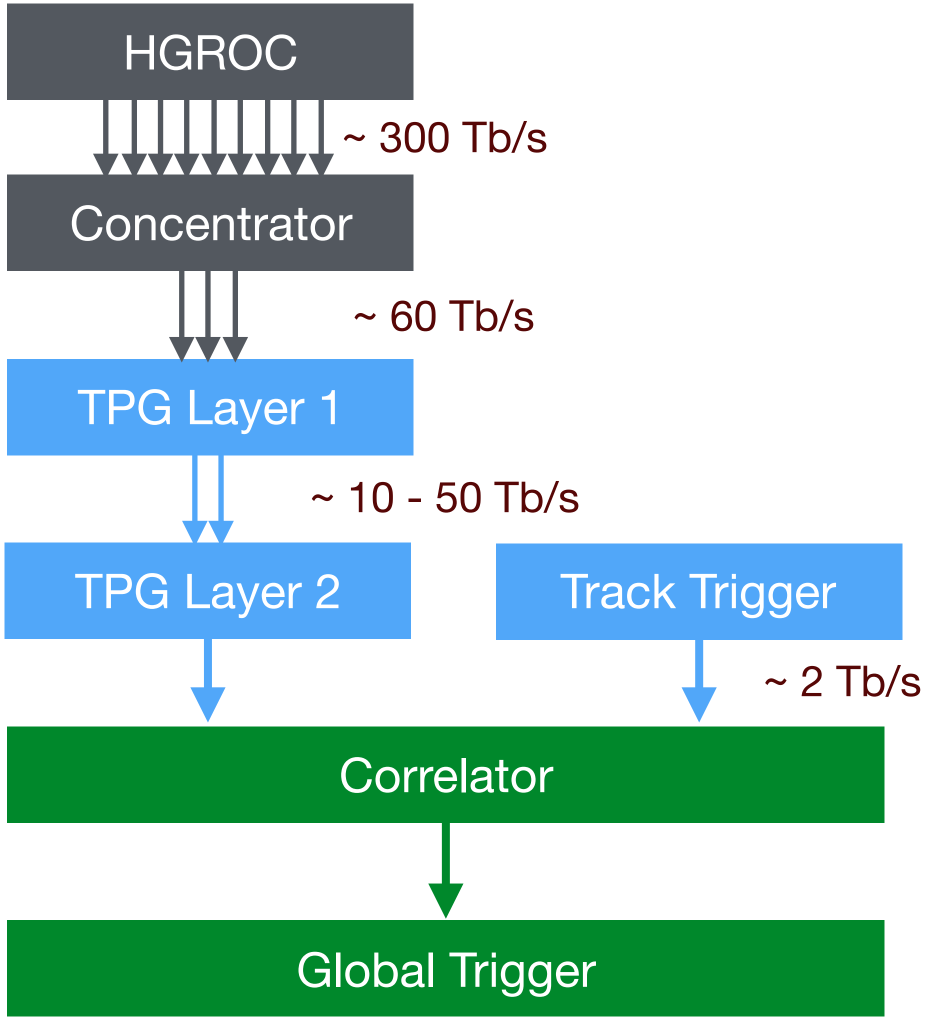
- HGROC reduces granularity and energy resolution
- Concentrator selects a fraction of trigger cells from several modules

HGCAL Backend

- Clustering of energies
- Build 2D cluster
- Link 3D clusters

CMS Backend

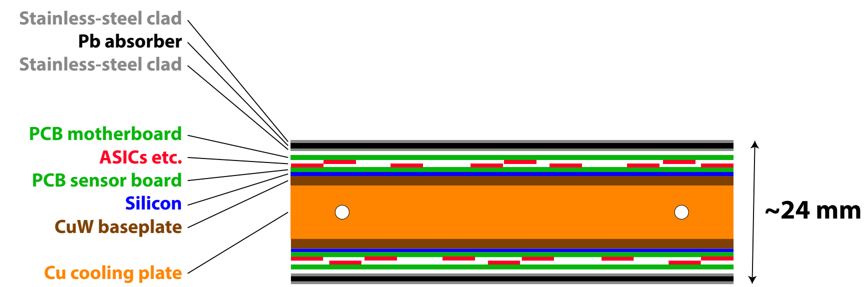
- Combination with other CMS subdetectors
- L1 trigger decision

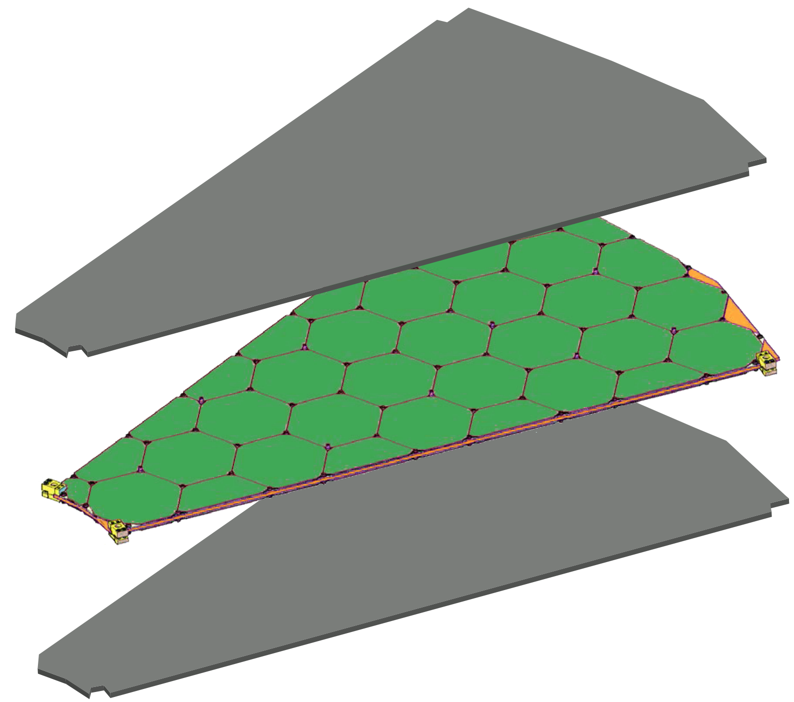


For more information see talk by Johan Borg at Thursday 11h in the R3 session.

Mechanical Design

- **Absorber structure will be built in full disks** rather than in sectors
  - Better physics performance as there are no gaps/ overlaps
  - Assembly was evaluated to be easier
  - Costs slightly lower
  - Mechanical strength and feasibility has been demonstrated with adequate safety factor
- Absorber material will be
  - **Lead** in steel mantle for EE
  - **Steel** for FH and BH
  - Plus some Cu and W from base and cooling plates
- **Cassettes with active modules**
  - Integrated into absorber structure for EE
  - Inserted into absorber structures for FH+BH

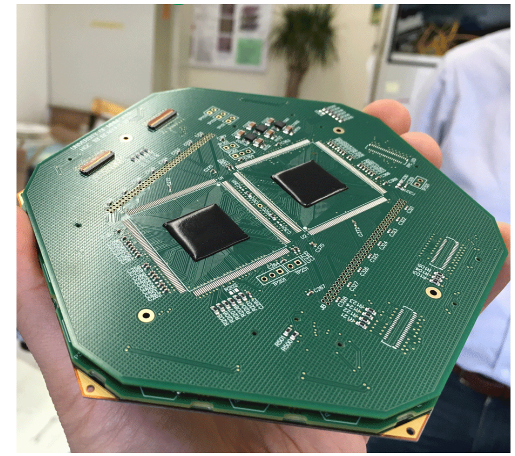




preliminary cassette design

Testbeam & Prototyping

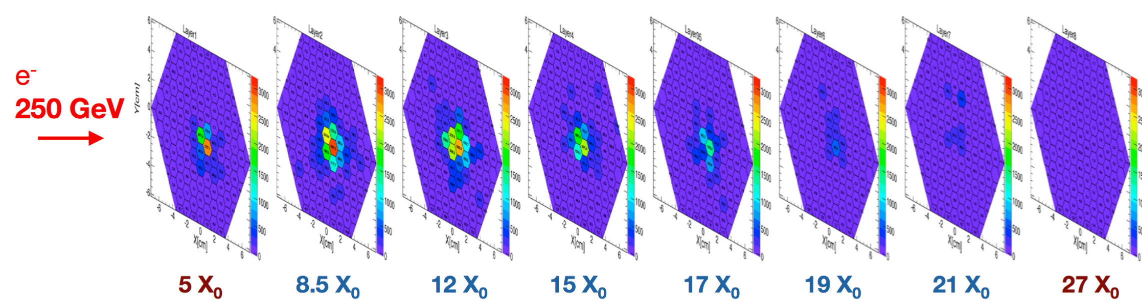
- Several testbeams at FNAL and CERN with **up to 16 HGCAL modules in 2016**
- **Proof of concept** of the baseline design with a closely spaced stack of modules
  - **Test** the design of a compact detector module with the proposed **wire-bonding scheme**
  - Learn what can go wrong
  - Reach good **agreement between simulation and experiment**



Module prototype for testbeam

- Many properties studied
  - Pedestal and noise stability
  - MIP calibration and S/N
  - Response to electrons
  - Energy, position and time resolution
- Another intensive period planned for 2017!

CERN: **250 GeV electrons** passing through **27 X_0**.

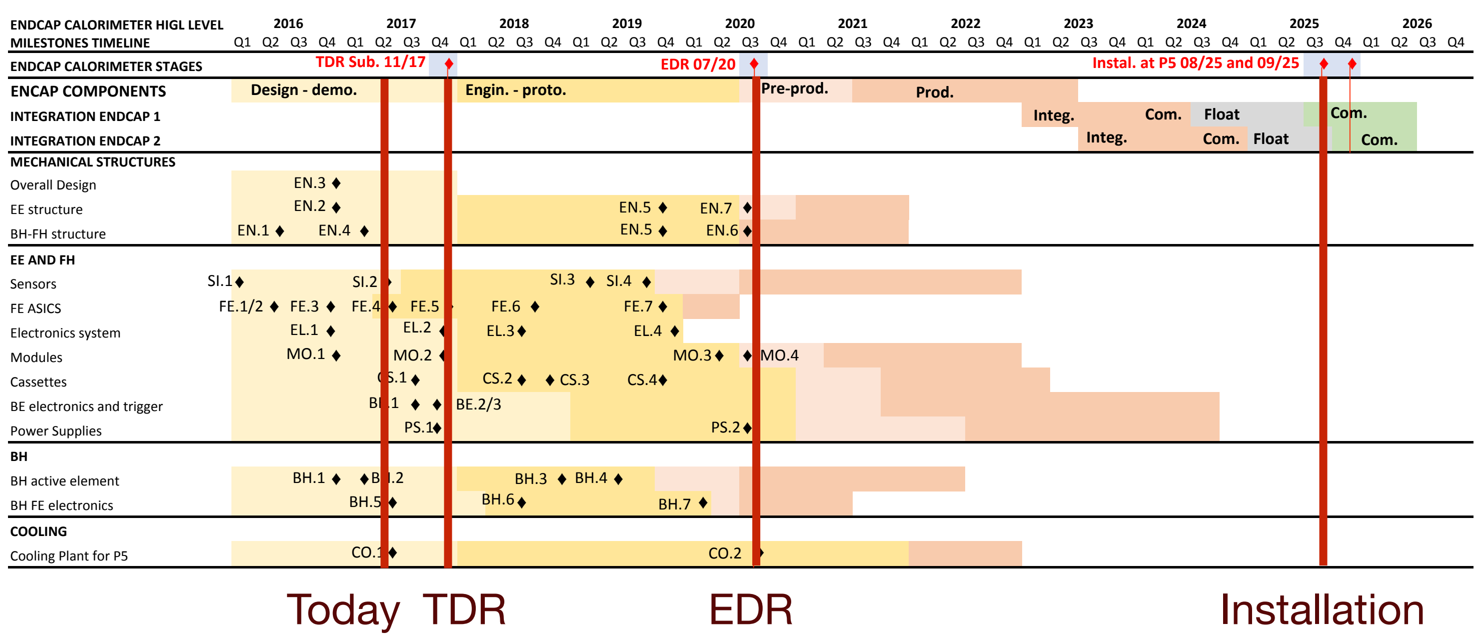


Event display from CERN TB

For more information see talk by Francesco Romeo today 14h20 in the R1 session.

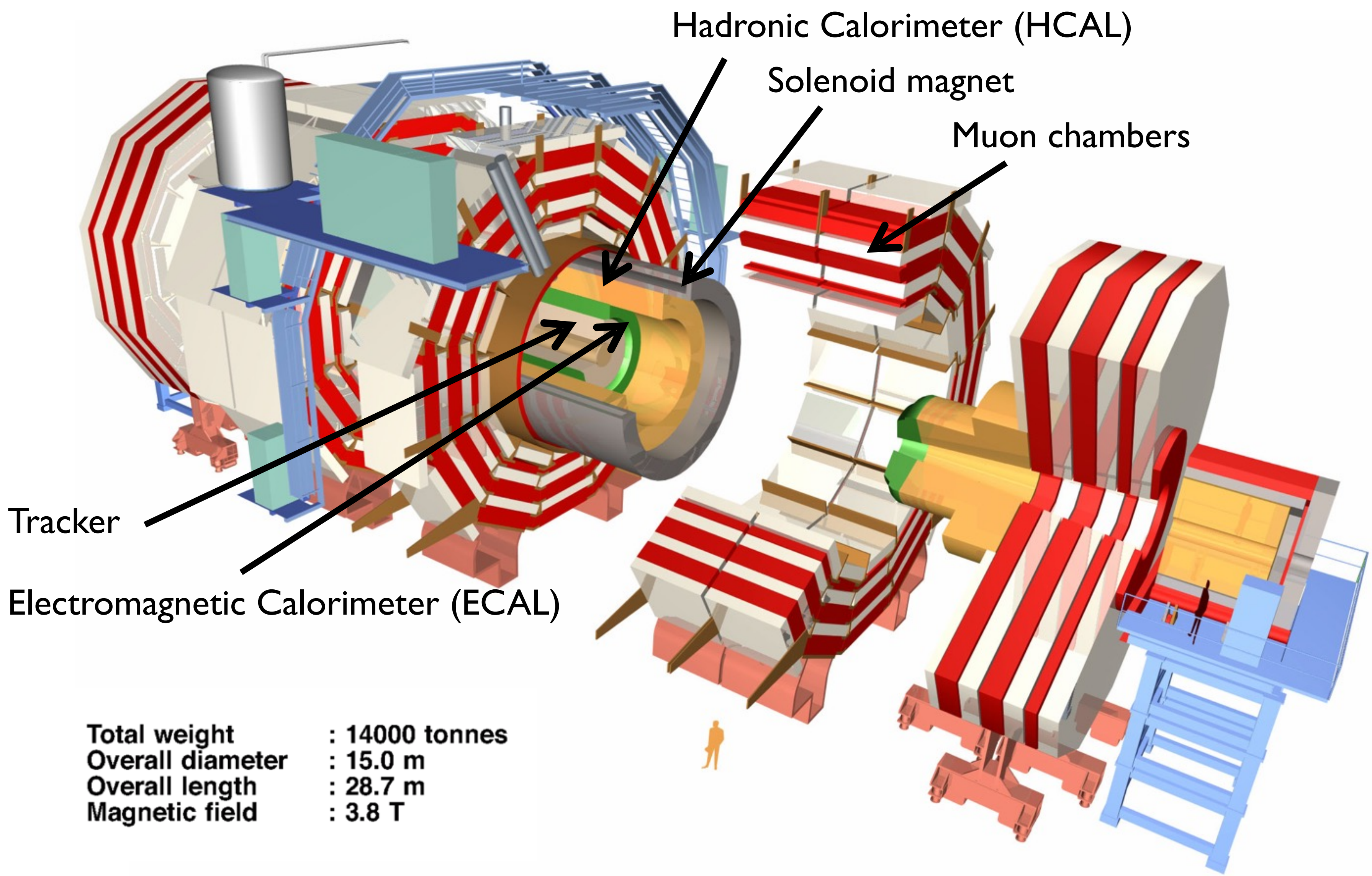
Outlook

- Basic design of the detector has been validated and we are making good progress towards the final design and construction of a highly granular silicon calorimeter
  - We benefitted a lot from the work of CALICE and ILC/CLIC communities
- TDR will be written at the end of 2017 with many design choices to be made until then
  - A lot of work is being done and has already been done to guide these decisions
  - A fast growing, international community is essential to this effort!



Backup

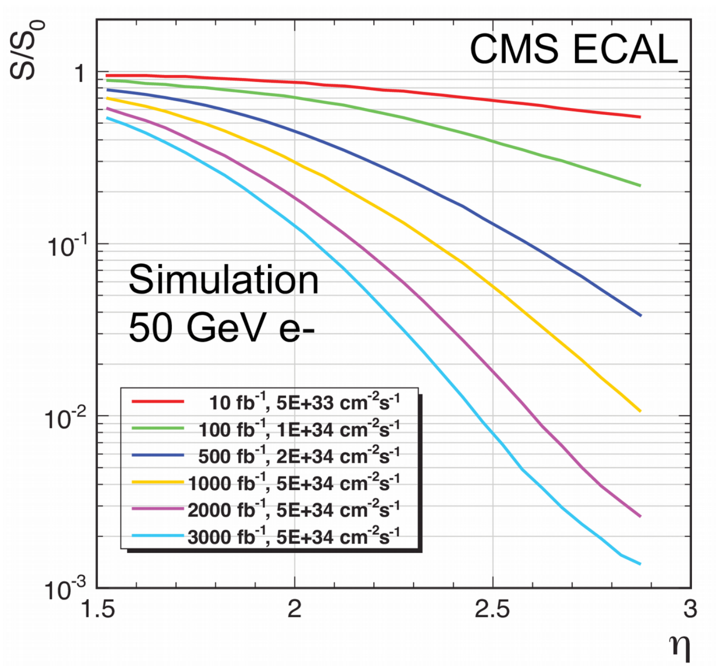
CMS Today



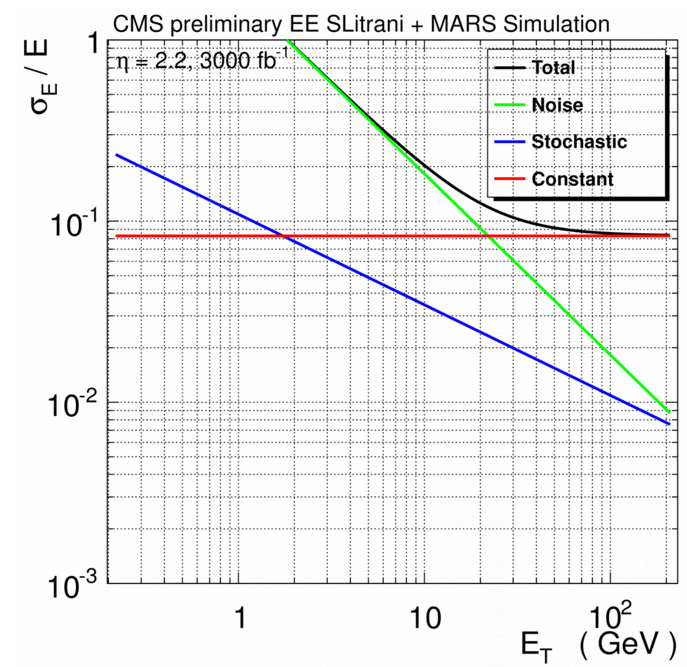
Total weight	: 14000 tonnes
Overall diameter	: 15.0 m
Overall length	: 28.7 m
Magnetic field	: 3.8 T

Effects on Current Endcap

- Current endcap is made of $PbWO_4$ crystals
- Radiation damage results in **deteriorated signal yield**
  - Formation of colour centres that cause light absorption
  - Laser monitoring mitigates this but only to a certain point
  - **Energy resolution constant** term after 3000 fb^{-1} expected to be ~**9%**



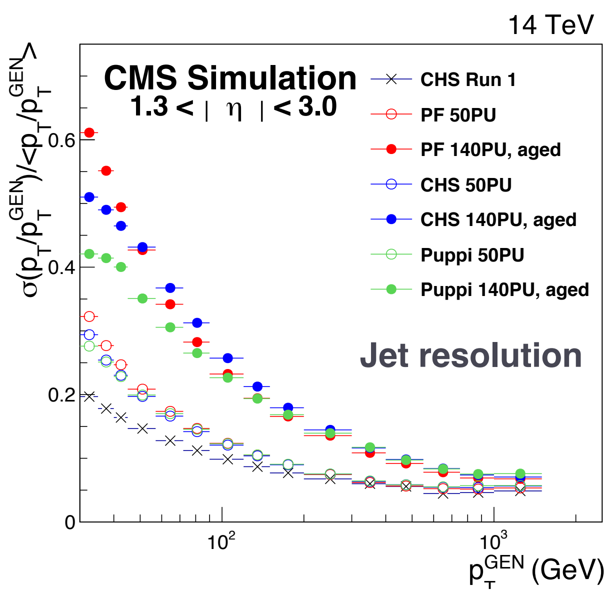
signal loss with eta



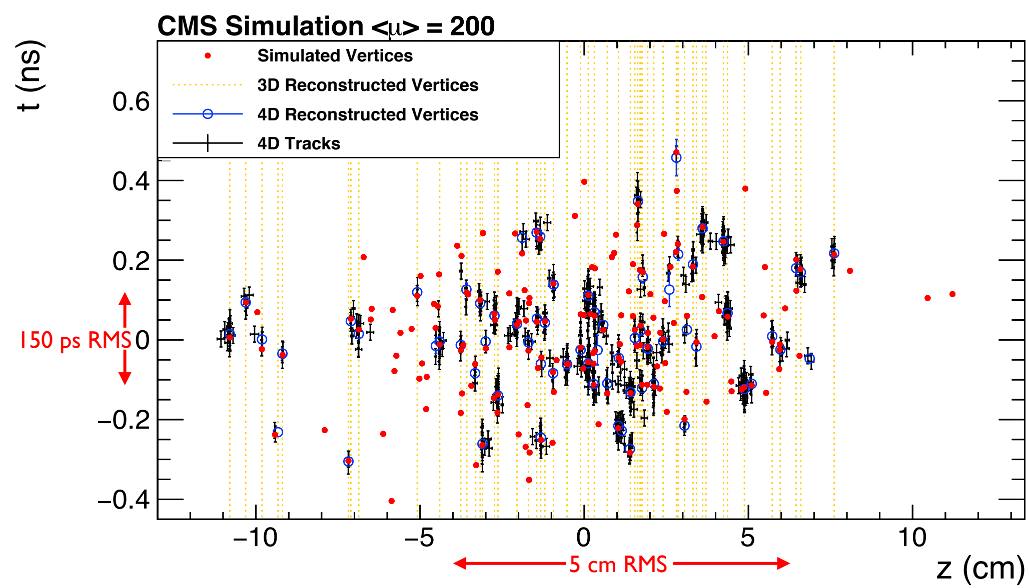
energy resolution after 3000fb^{-1} for current EC

Detector Challenge I: Pile Up

- HL upgrade will result in up to **200 collisions per bunch crossing** (from ~50)
  - For the HL-LHC baseline option, vertex density increases by a factor ~8
  - Effects on vertex reconstruction, track purity, jet energy reconstruction …
- Can be mitigated with **excellent time resolution and high granularity**
  - If beam is sliced in O(25 ps), vertex density is reduced to the level of 50 coll./bunch crossing
  - Design calorimeter for particle flow algorithms to aid particle separation



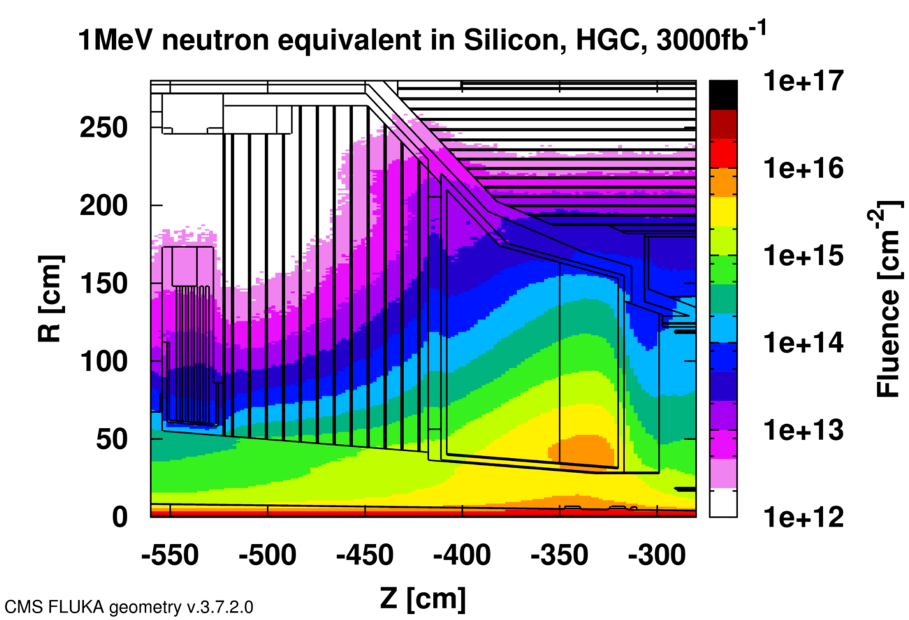
decrease of jet energy resolution with PU



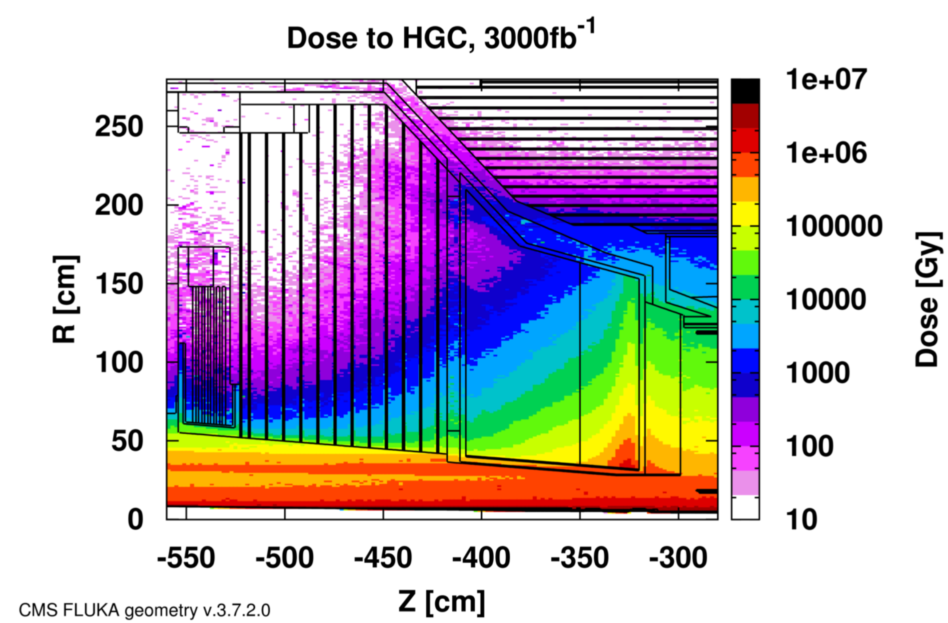
vertex reconstruction with pile-up 200

Detector Challenge II: Radiation

- After the HL-LHC upgrade, the CMS end-cap will operate in an unprecedented **radiation environment**
  - Fluences of up to **10^{16} neq/cm^2** and doses of up to **1.5 MGy**
- Will need very radiation hard detector material and readout
  - Strong dependency on |η| and |Z| suggest that **design can vary with exact location**



expected hadron fluences

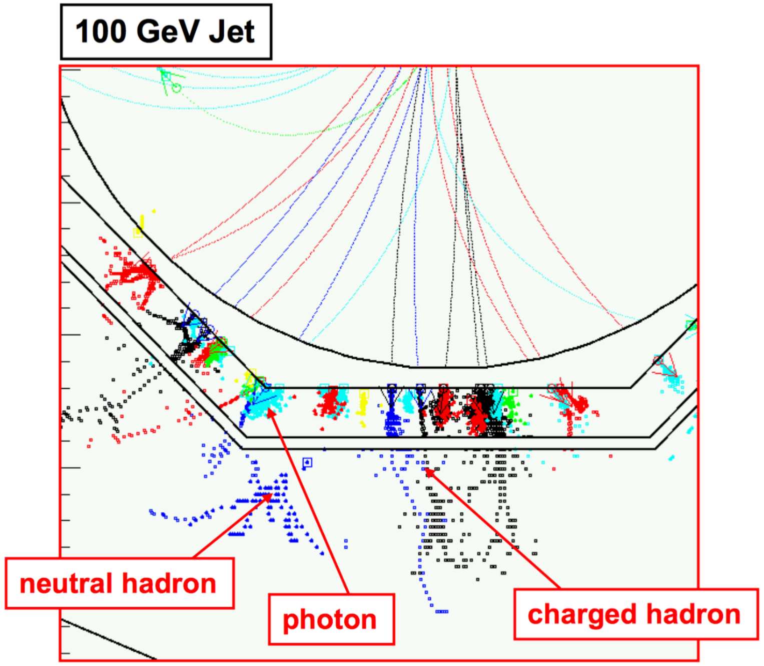


expected total dose

Particle Flow Principle

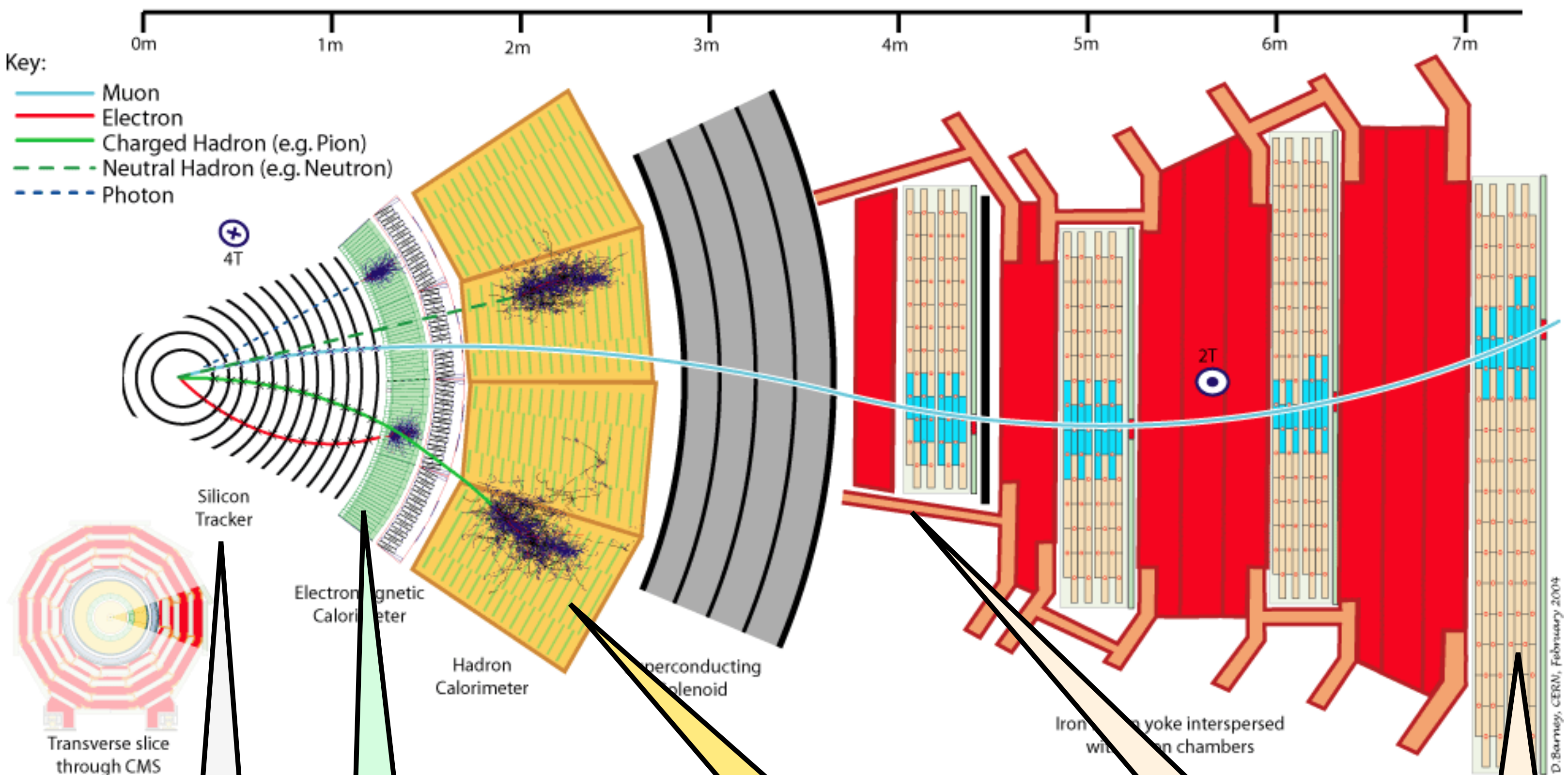
- Particle Flow Analysis aims to improve energy resolution by resolving the showers of the individual particles in a jet by combining information from various detectors
  - Link tracks and clusters
  - Utilise e.g. momentum measurement from tracks for charged hadrons for energy measurement
  - Summing up energies is replaced by a TMVA problem

- Needs technology that allows high granularity and fast timing to distinguish shower components
  - Lots of R&D by CALICE for linear collider detectors (CLIC, ILC)
  - Si/W ECAL, Sci/Fe HCAL, analog vs digital energy information, etc.



Visualisation from PandoraPFA

Particle Flow in CMS



Silicon Tracker

Position, momentum of charged particles : **$e^{\pm}$, $\pi^{\pm}$, $\mu^{\pm}$**

Electromagnetic Calorimeter

Position & ID, energy of **$e^{\pm}$, γ, π^0**

Hadron Calorimeter

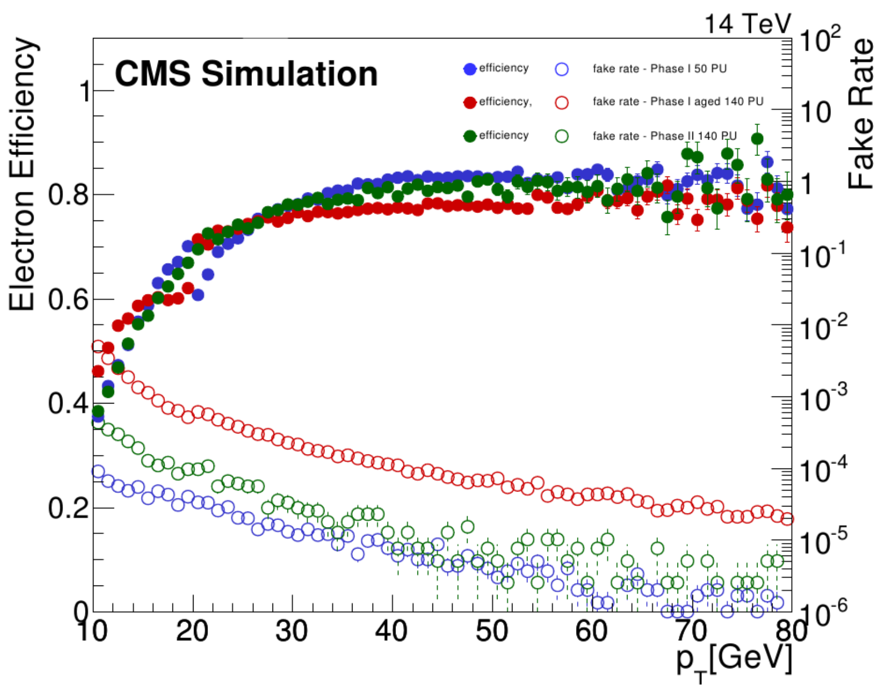
Energy of hadrons : **p, n, $\pi^{\pm}$, K ..**

Muon Chambers

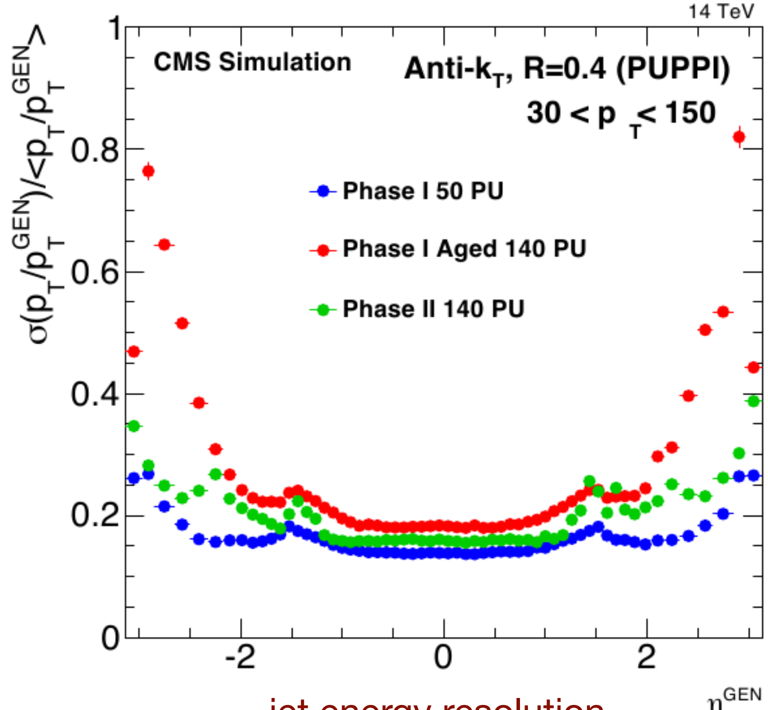
Position & momentum of **$\mu^{\pm}$**

Particle Flow in HGCAL

- Algorithms still far from optimised but already able to recovery run 1 performance
  - Electron identification
  - Jet energy resolution



electron efficiency



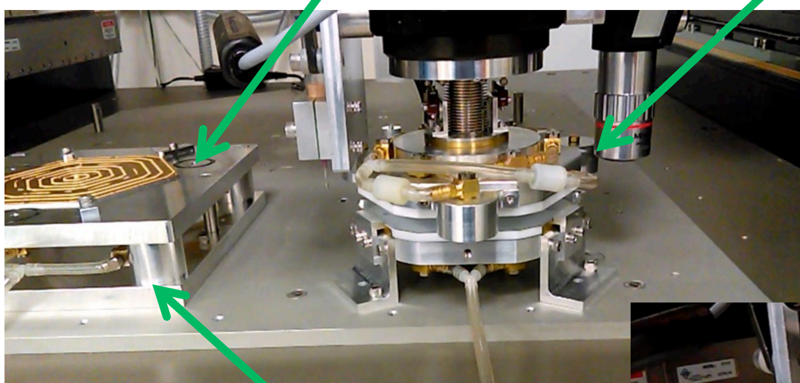
jet energy resolution

Module Assembly

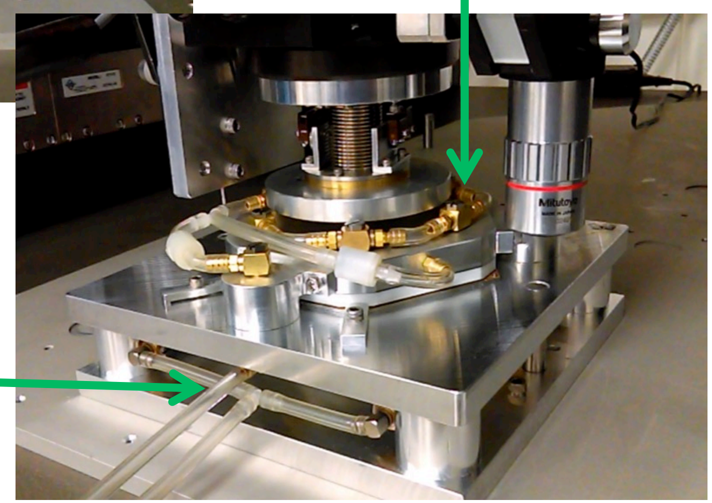
- Automatic gantry now ready at UCSB
  - Throughput of around 20 modules/day/assembly site is estimated

(2) Glue is dispensed on the kapton covered baseplate

(3) Tool picks up the sensor



(4) Sensor is placed on the baseplate

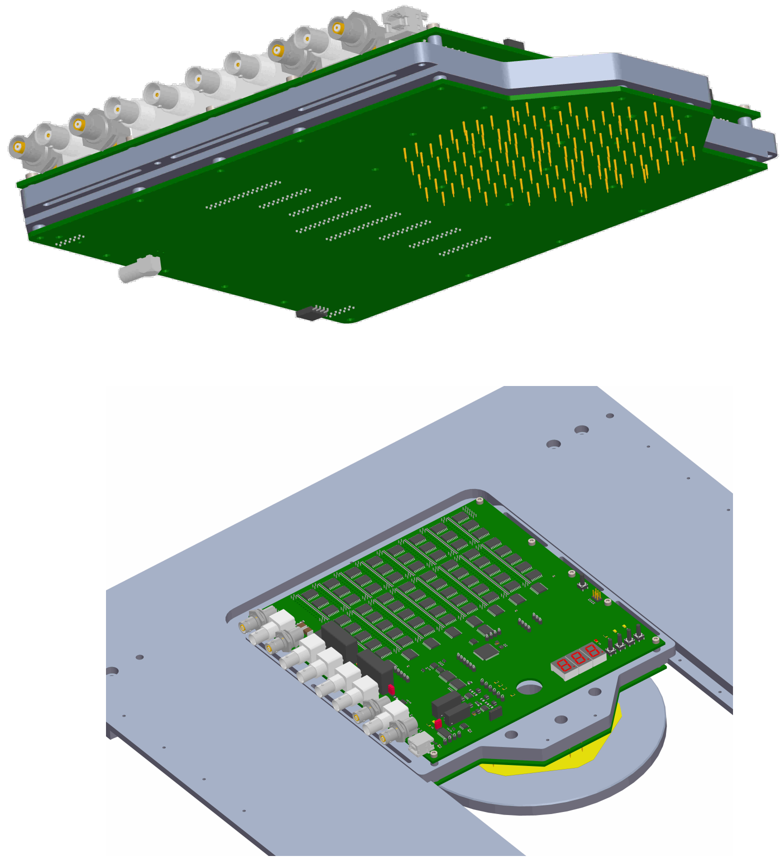


(1) Module baseplate is vacuum chucked during assembly

(5) External Vacuum holds the module during overnight curing

Sensor Testing I

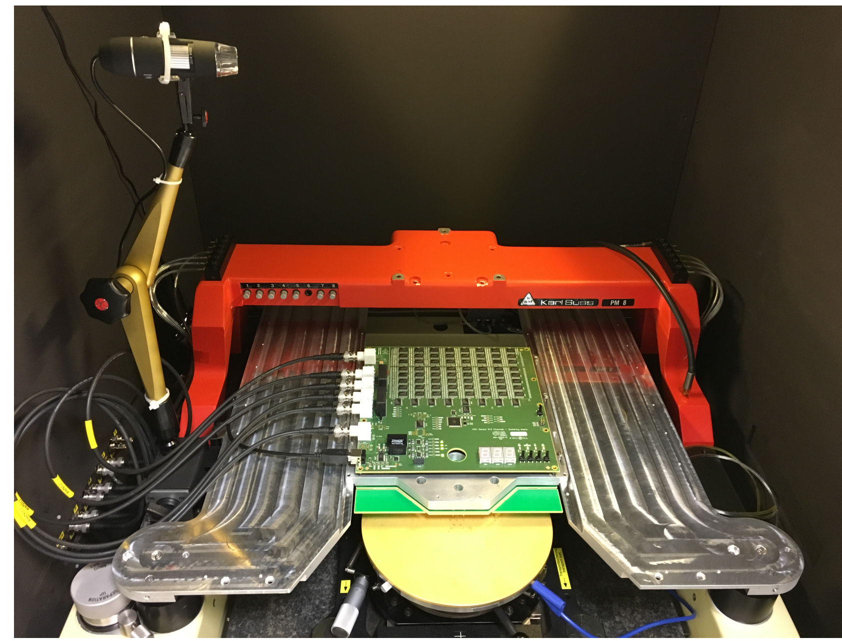
- To test the sensor IV and CV characteristics under realistic conditions, one needs to **bias all sensor cells** during the tests.
  - Electric field configuration determines V_{bd} and changes drastically with floating cells.
  - Use probe card to contact and bias all cells at the same time.
  - Spring loaded pins, so called **pogo pins**, to control uniform contact.
- Depending on the sensor layout, we need to probe **between 128 and 512 channels**.
  - Use a switching matrix to measure them one after the other
  - To avoid a large and clumsy system, **integrate the components as much as possible**
- Therefore, a high performant and fully integrated switching matrix has been designed as a plugin card that sits directly on top of the probe card.



CAD drawings of the assembled cards. Pogo pins can be seen in the top picture.

Sensor Testing II

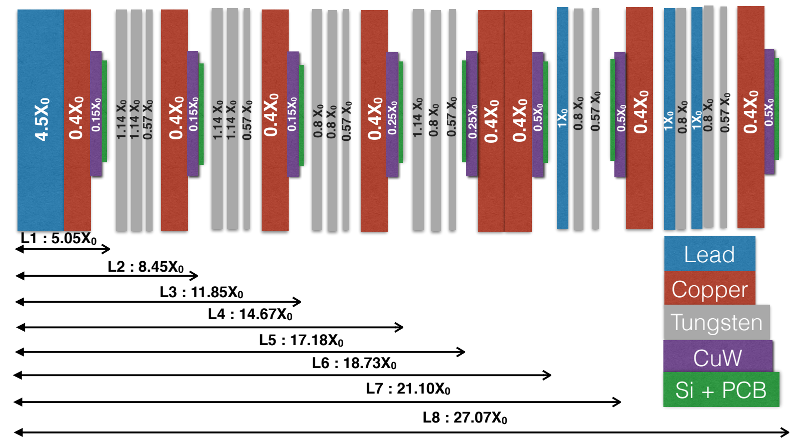
- Some details of the system
  - Low **leakage current of ~10 pA**
  - Low **parasitic capacitances of ~ 80pF @ 50kHz** in total, including traces on the probe card
  - Can handle **512 input channels**
  - Avoid hundred of coax cables from probe card to external switching matrix
- Integration into existing probestation via mounting frame that allows to adjust parallelism of cards to sensor/chuck

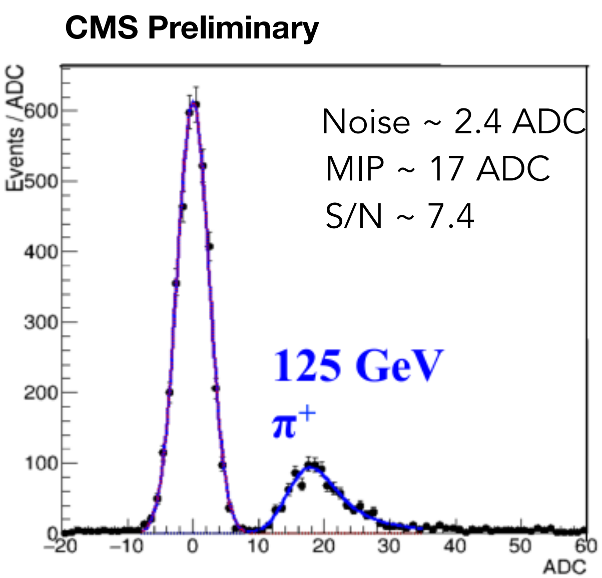


Picture of the full setup installed at CERN.
It is being tested and characterised right now.

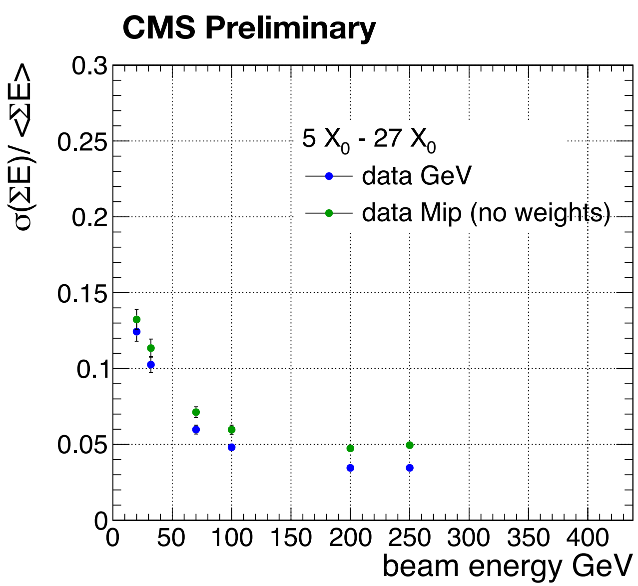
Testbeam Results

- Overall performance with Skiroc2 readout
  - **Pedestals** found to be **stable** over time
  - For MIPs we have **S/N ~ 7.4** for 200µm
  - **Energy recovery** of fraction lost in thick absorbers **via dE/dx weighting**
  - Shower development matches simulation

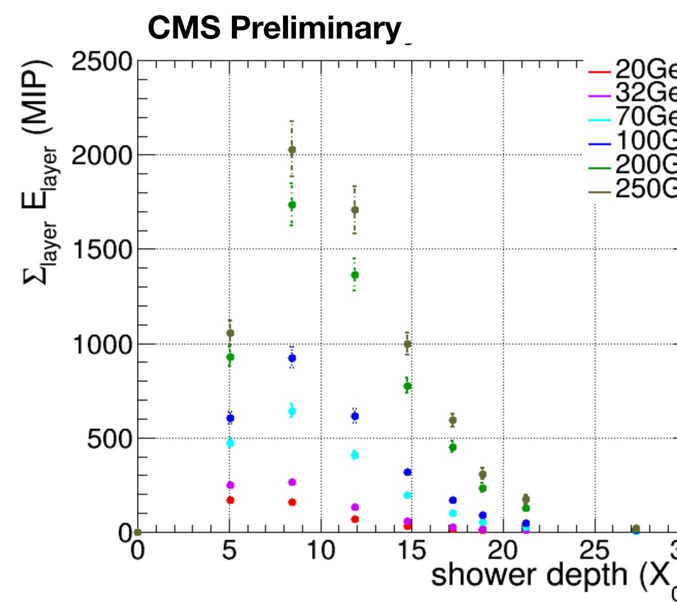




S/N for MIPs



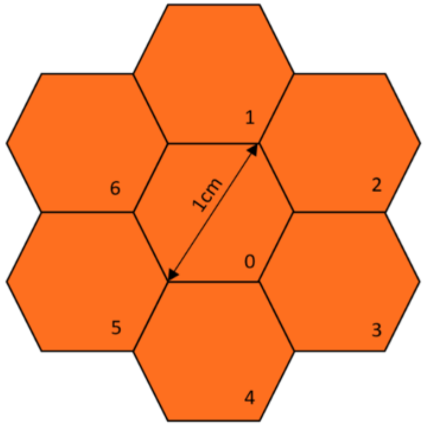
Energy resolution



Shower development

Time Resolution

- Measure the **intrinsic time resolution** one can obtain from **planar silicon sensors** in a calorimeter environment (intrinsically large signals!).
  - 25 cells of a HGCAL module readout via a **5Gs/s digitiser**
  - MCP with Δt ~ 5ps as reference timer



- Testbeam at FNAL with up to 32 GeV electrons
  - Cell level time resolution ~25ps
  - Improve to **cluster level time resolution ~15ps**
  - Many subtle effects that have to be taken care of
  - Same setup last year at CERN with up to 250 GeV electrons
  - Analysis ongoing