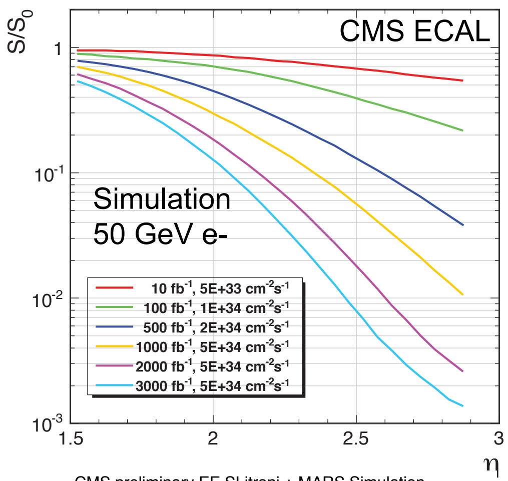
The CMS Endcap Calorimeter Upgrade

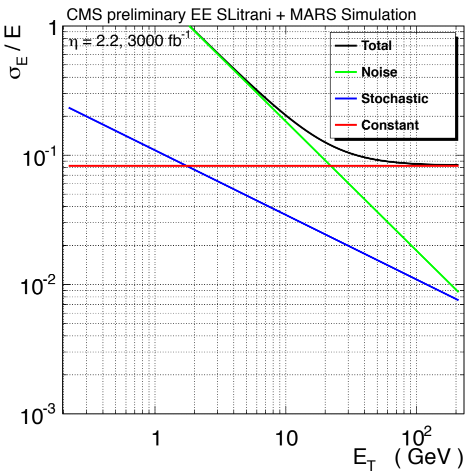
P.Bloch /CERN
On behalf of the CMS collaboration

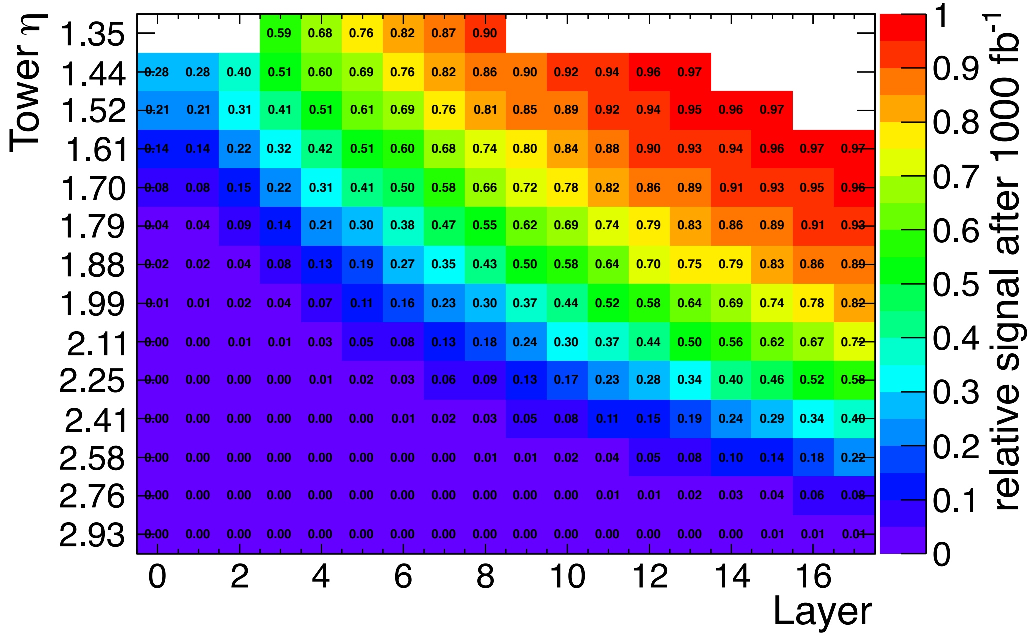
3rd ECFA Workshop October 2016

A brief recap why we have to upgrade

The replacement of CMS Endcap calorimeters is required due to radiation-induced effects [see CMS TP: LHCC-2015-10, p 72-82]







Expected relative signal after 1000 fb-1 for the existing Hadronic Endcap Calorimeter

Relative response (top) and expected energy resolution (bottom) of the existing Endcap Electromagnetic Calorimeter after 3000 fb^{-1}.
The resolution is O(10%) at the end of HL-LHC

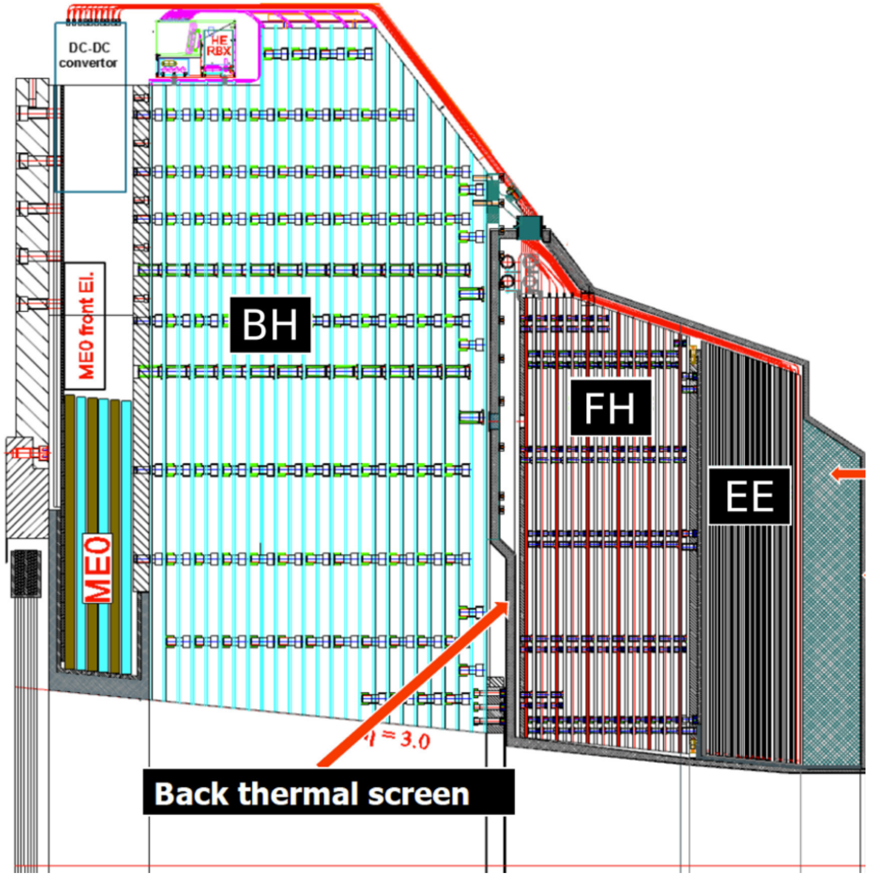
HGCAL

In May 2015, the CMS collaboration chose a Silicon-based calorimeter for HL-LHC Upgrade

- Extensive R&D in the past 20 years for Trackers and Pixels have led to development of Si-sensors which can sustain the high radiation levels
    - Fluence at η=3 in HGCAL ~ same as pixel inner layer
    - Radiation effects are well understood and reproducible
    - can be partly mitigated by low T operation
- High granularity and 3D imaging help mitigate pileup effects
- Fast signal collection (<10 ns) and fast timing capability (few tens of ps)
- Electronics in 130/65nm allows low noise and low power readout Front-End (10-15 mW/channel) even for large dynamic range
- Affordable cost

- Large experience accumulated in Si detectors construction/operation at Hadron Colliders over the last 20 years
- Synergy with developments for Linear Collider(s) detectors which all plan to use Silicon calorimetry for their electromagnetic calorimeters (CALICE)

TP Calorimeter Design



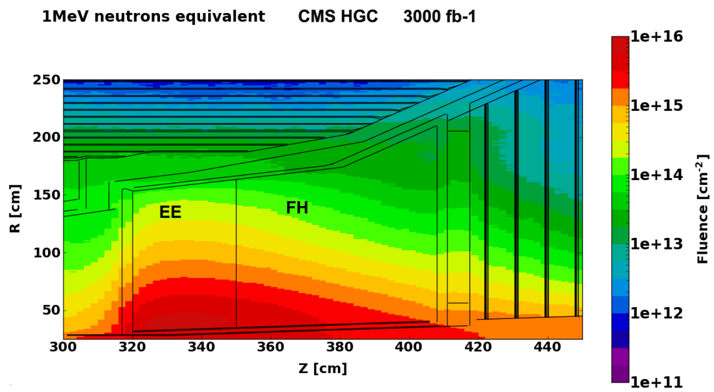
Construction:
- *Hexagonal Si-sensors built into modules.*
- *Modules with a W/Cu backing plate and PCB readout board.*
- *Modules mounted on copper cooling plates to make wedge-shaped cassettes.*
- *Cassettes inserted into absorber structures at integration site (CERN)*

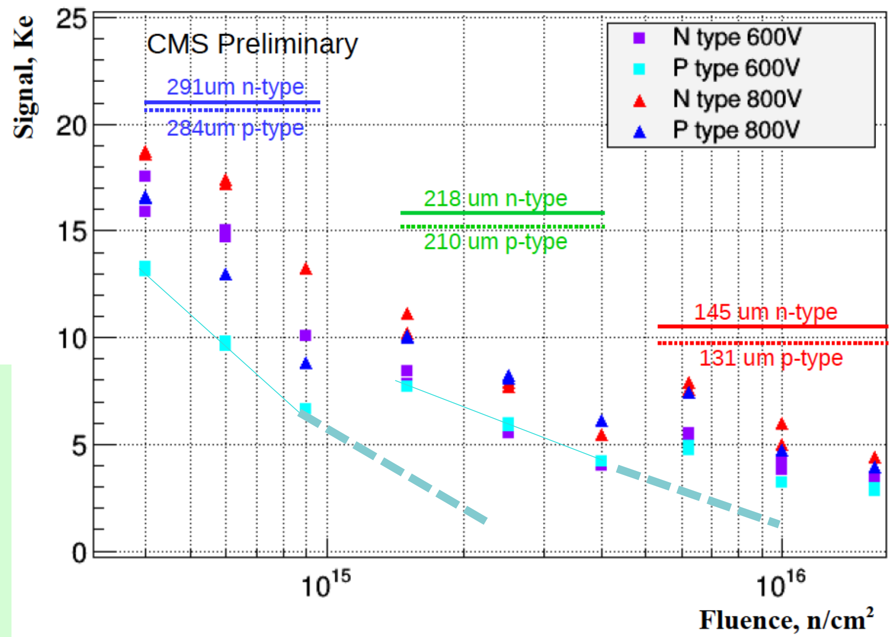
Key parameters:
- *593 m^2 of silicon*
- *6M ch, 0.5 or 1 cm^2 cell-size*
- *21,660 modules (8" or 2x6" sensors)*
- *92,000 front-end ASICS.*
- *Power at end of life 115 kW.*

System Divided into three separate parts:

EE – Silicon with tungsten absorber – 28 sampling layers – 25 X_o (~1.3 λ)
FH – Silicon with brass (now stainless steel) absorber – 12 sampling layers – 3.5 λ
BH – Scintillator with brass absorber – 11 layers – 5.5 λ

EE and FH are maintained at – 30^{o}C. BH is at room temperature.





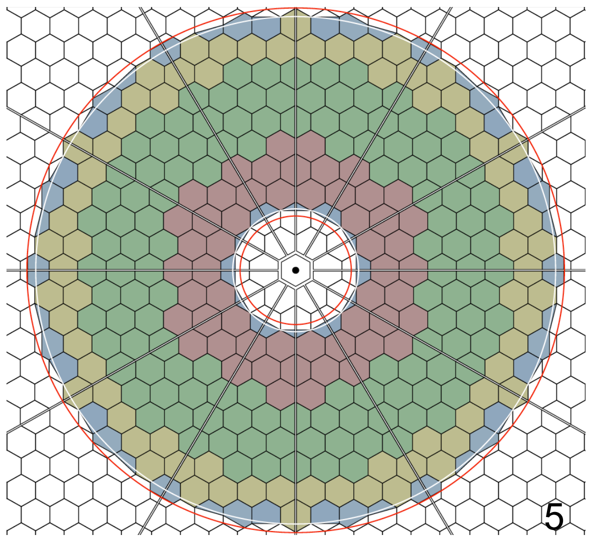
Thickness of Si sensors should be reduced for high fluence regions:

$I_{leak} \propto$ Volume . Φ decreases

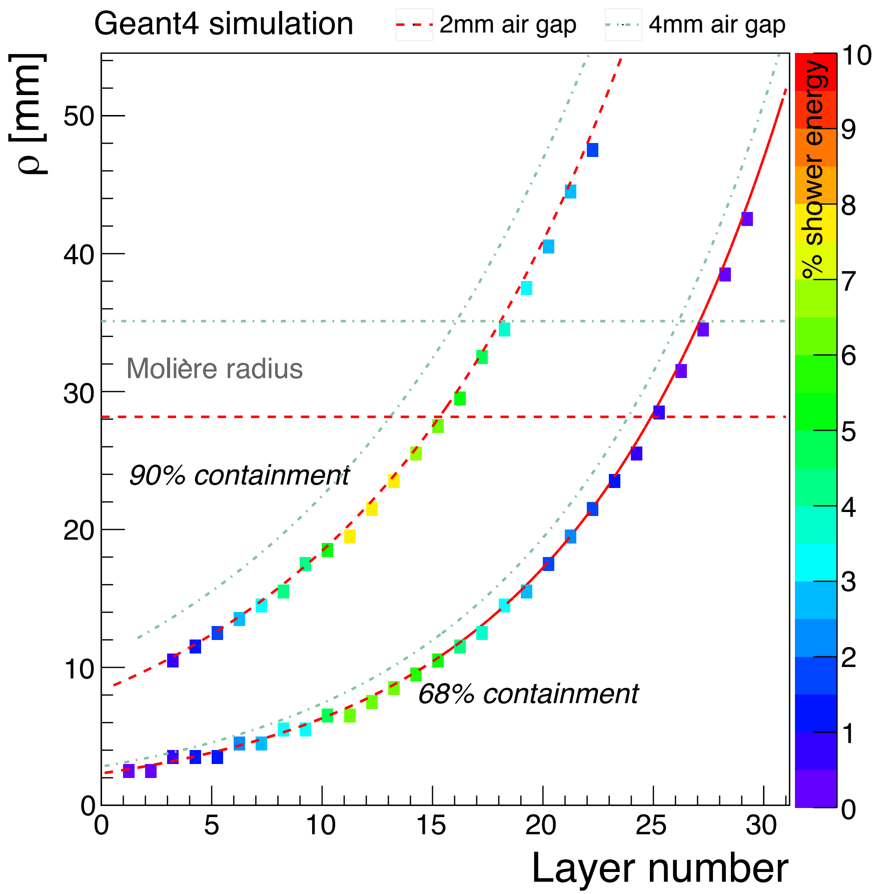
Collected Charge improves at high Φ

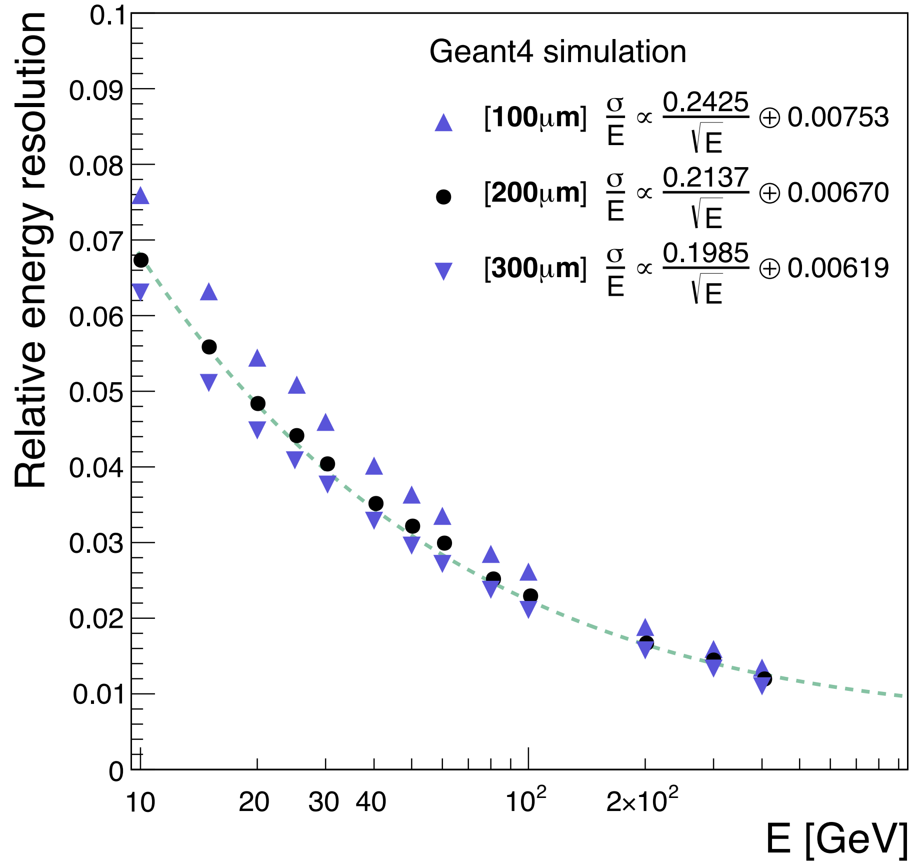
Requires cell size reduction to maintain moderate capacitance.

Thickness	300 μm	200 μm	100 μm
Maximum dose (Mrad)	3	20	100
Maximum n fluence (cm^{-2})	6×10^{14}	2.5×10^{15}	1×10^{16}
EE region	$R > 120$ cm	$120 > R > 75$ cm	$R < 75$ cm
FH region	$R > 100$ cm	$100 > R > 60$ cm	$R < 60$ cm
Si wafer area (m^2)	290	203	96
Cell size (cm^2)	1.05	1.05	0.53
Cell capacitance (pF)	40	60	60
Initial S/N for MIP	13.7	7.0	3.5
S/N after 3000 fb^{-1}	6.5	2.7	1.7



Expected performance





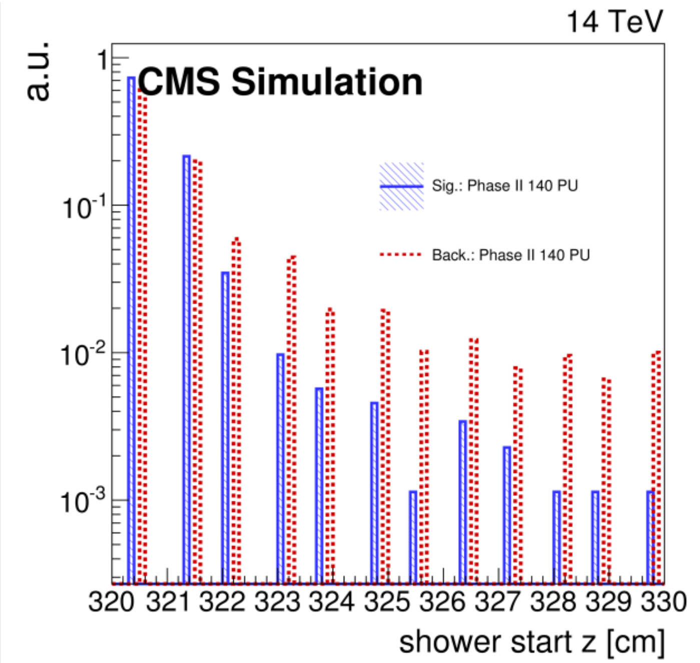
Electromagnetic showers very narrow in the first layers
-> pileup rejection,
-> good particle separation for PFlow approach

Stochastic Term ~ 20%
Small constant term (target < 1%)
(in the forward region, a moderate p_T corresponds to a high energy)

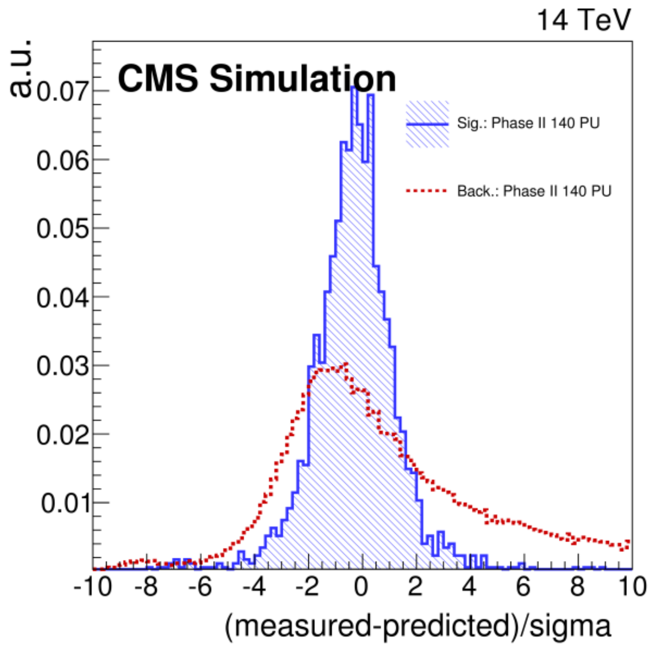
Examples of use of longitudinal information

Improved e/hadron separation

Blue: Z/γ*->ee E_T>10 GeV   Red: single pions



Shower starting layer



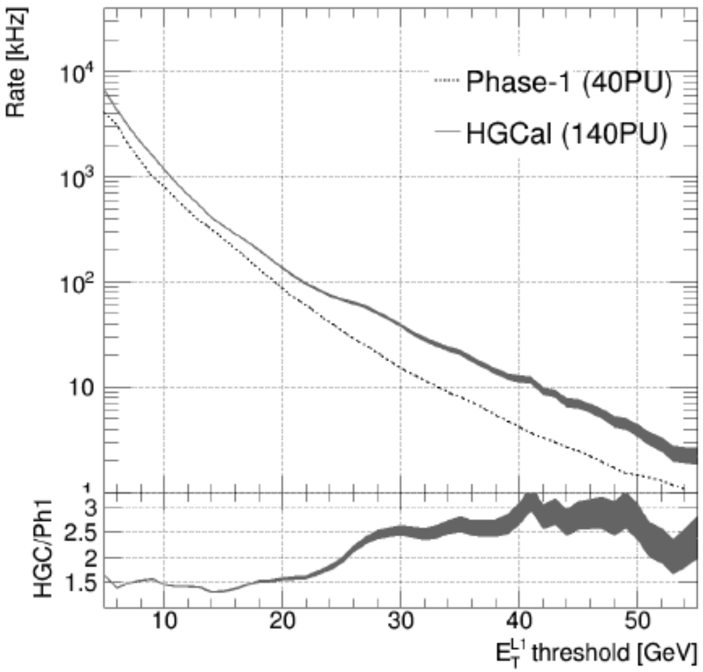
Shower length

Trigger

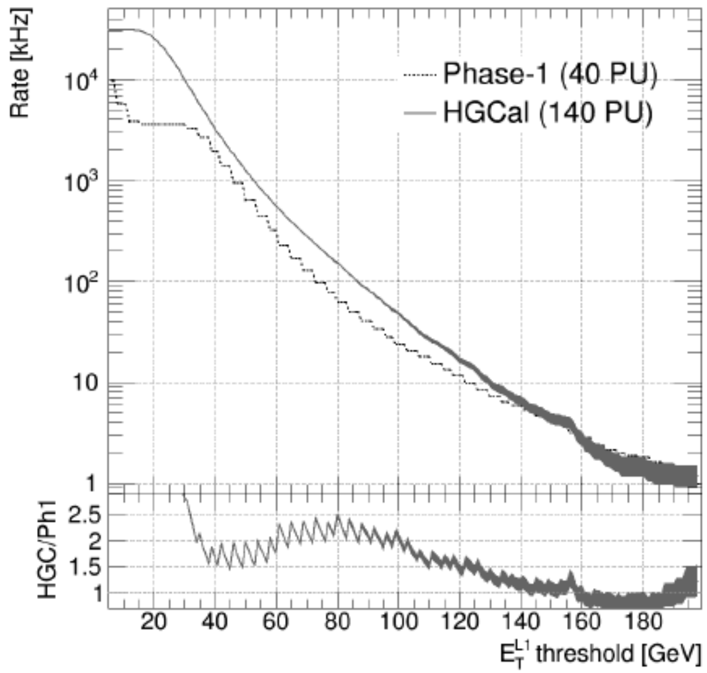
The longitudinal information allows for efficient pileup mitigation techniques

For an increase of the luminosity by a factor 3.5 compared to Phase-1, the background rate is increased by less than a factor 2.5-3, with similar signal efficiency (close to 100%)

Electron and photon trigger



Jet trigger

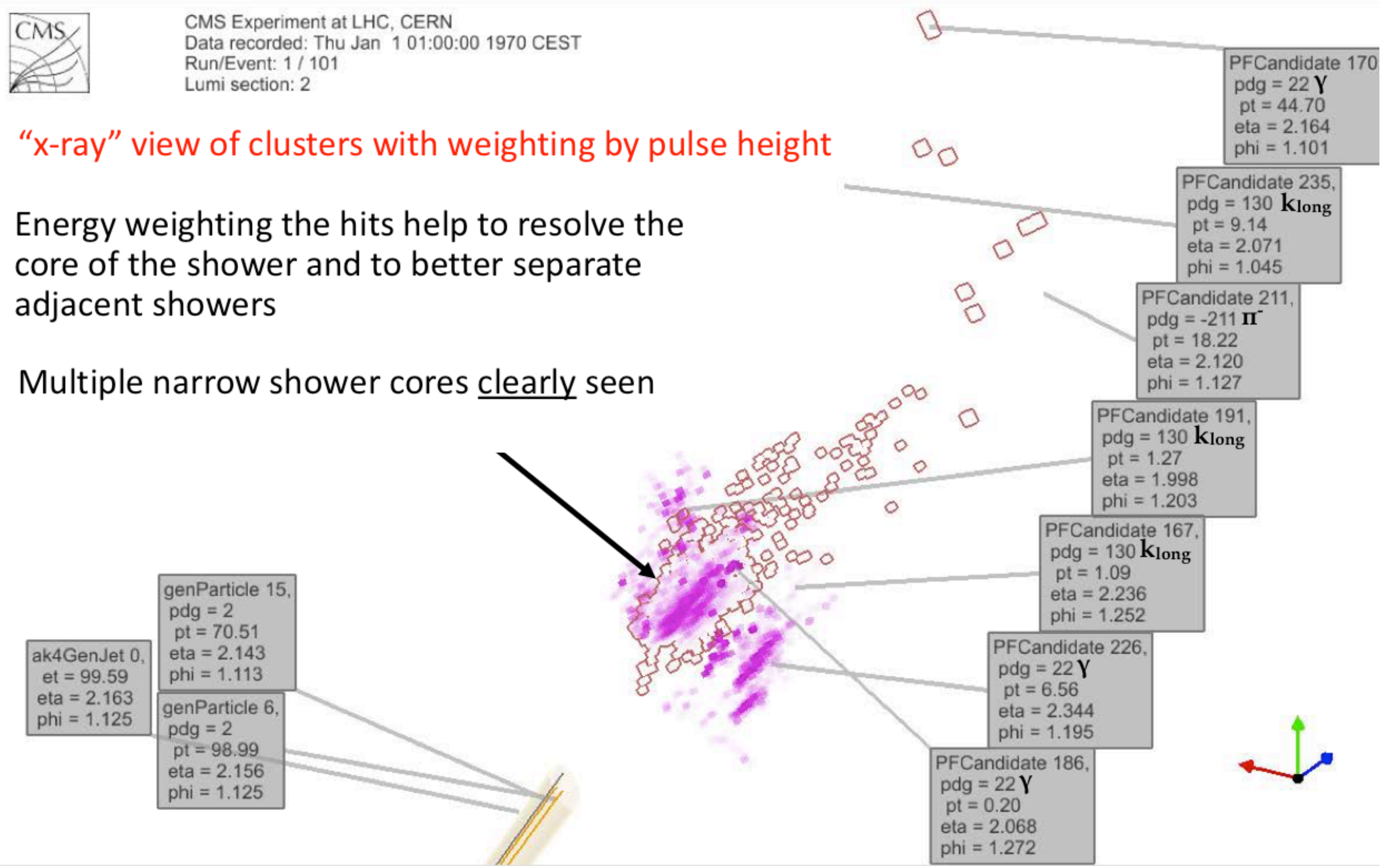


3D + Energy : “X-ray” of jets

“x-ray” view of clusters with weighting by pulse height

Energy weighting the hits help to resolve the core of the shower and to better separate adjacent showers

Multiple narrow shower cores <u>clearly</u> seen



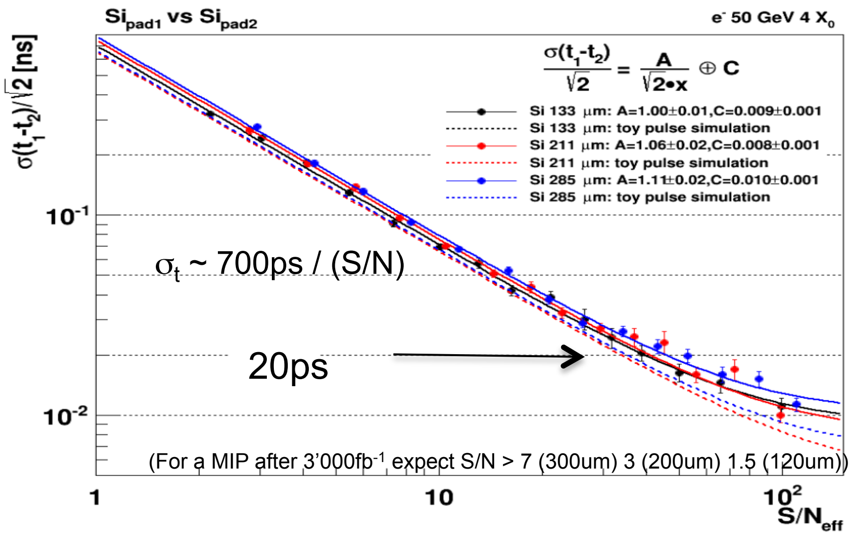
Use of fast timing

Fast timing will help to check the compatibility of different showers to originate from the same vertex and to associate them with a particular vertex.

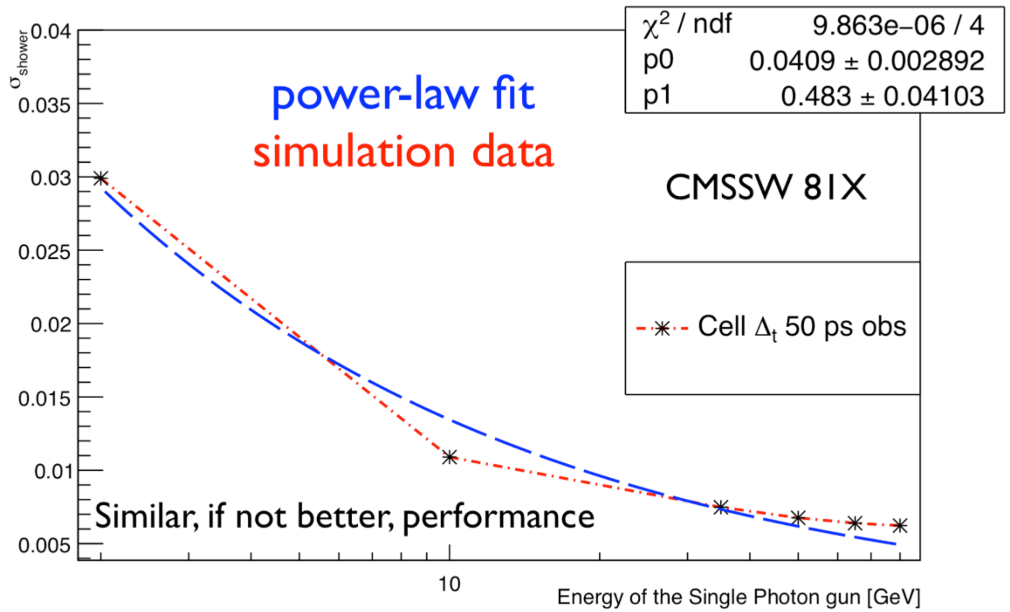
particularly useful for H->$\gamma\gamma$

Tests in beam have shown that for large enough signals in a Si cell, an intrinsic precision better than 20ps can be expected. (see following presentation of Z.Gecse)

opens the possibility to measure precise timing for em. (and large energy hadron) showers



$\sigma_t \sim$ 20ps for ~ 5 (300um) –> 20 (120um) MIPs



Target is to keep clock jitter and systematic effects (not included above) below 20ps

mechanical layout and possible evolutions (1)

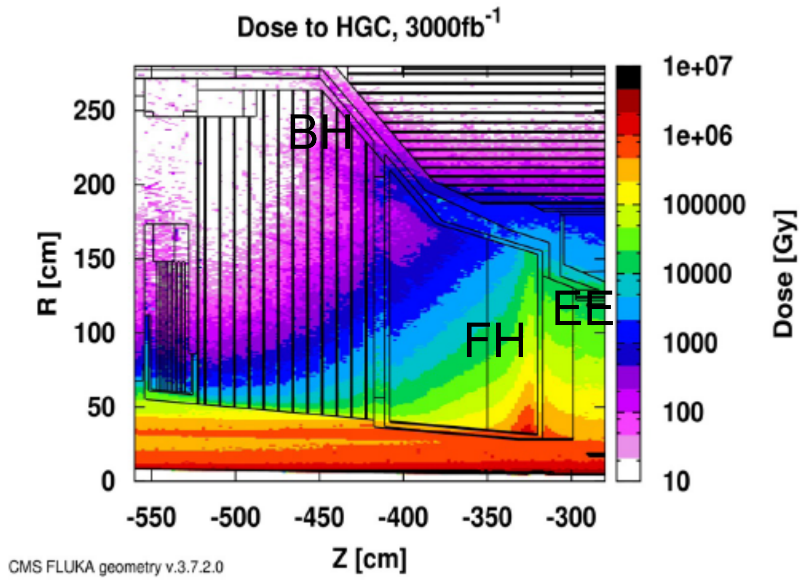
Decided to use new absorber for BH, and chose Stainless Steel (SS) for FH/BH

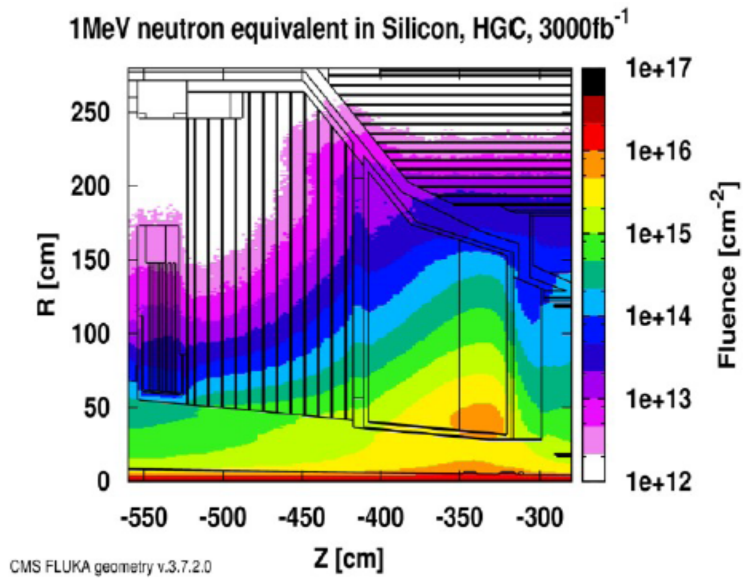
-flexibility in assembly schedule

-SS much cheaper than Brass and offers more engineering possibilities

Whole structure (including 200t BH) at cold temperature ?

- design flexibility: opening up the possibility of using Silicon in the most exposed areas and scintillator in the lower fluence regions
- opening up the possibility of SiPM on tiles for the scintillators
- warm-cold transition at the back, where there is more space for feedthroughs / manifolds



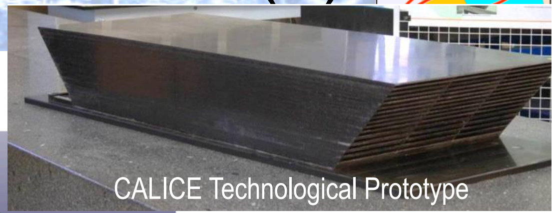


mechanical layout and possible evolutions (2)

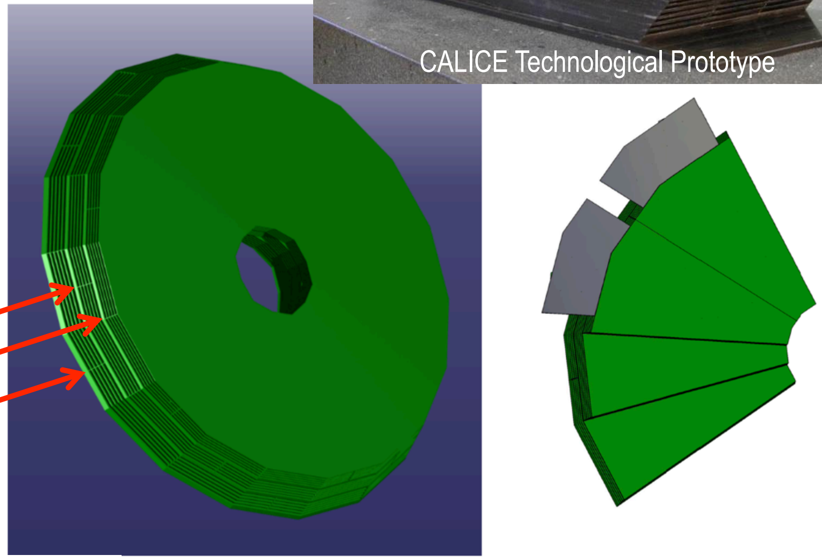
EE structure

TP design based on CALICE developments: 30° cassettes including two Si layers and a cooling plate inserted in C-Fibre pockets

Alternative: stack of (30° or larger) cassettes and W plates with spacers, compressed by front/back plates



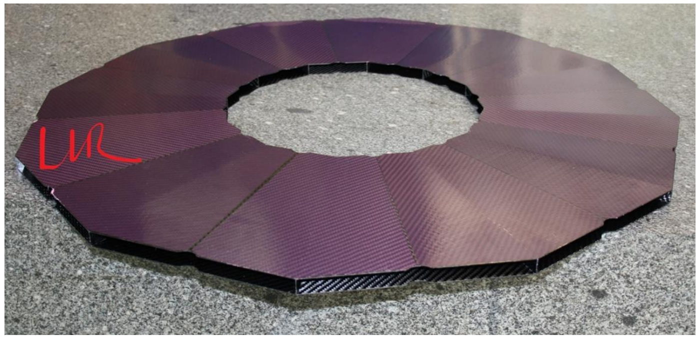
Staggered phi cracks



(Left) EE carbon-fibre structure integrating tungsten absorber plates alternatin with empty slots. (Right) Insertion of a cassette into a slot the structure.

Driving Criteria for decision

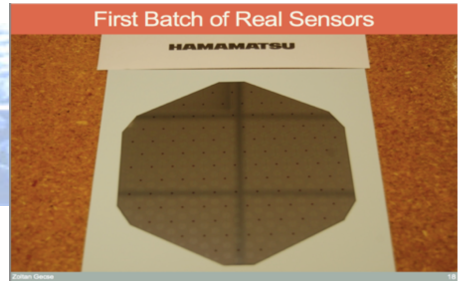
- Assembly and installation: ease, reliability, cost and time; central vs. distributed subassembly construction, …
- Risk, reliability, maintainability
- Physics: cracks, impact of inner cone, density, coverage at low- & high-η edges,..
- Mechanical behavior
- Cost



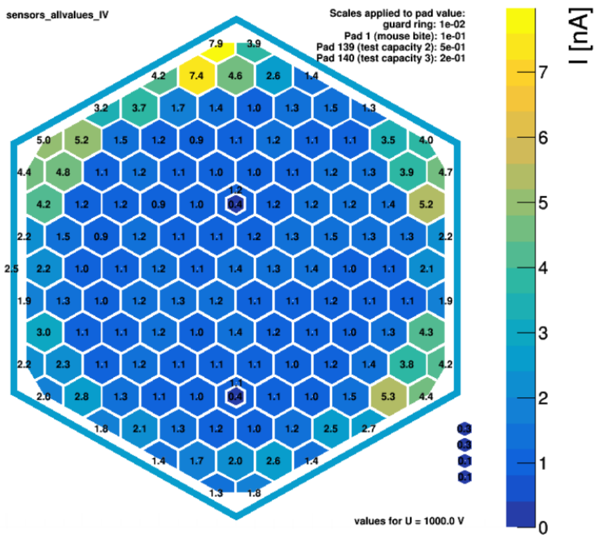
~1/3 scale prototype of CF alveolar (Sep 2016)

Decision by mid-December 2016

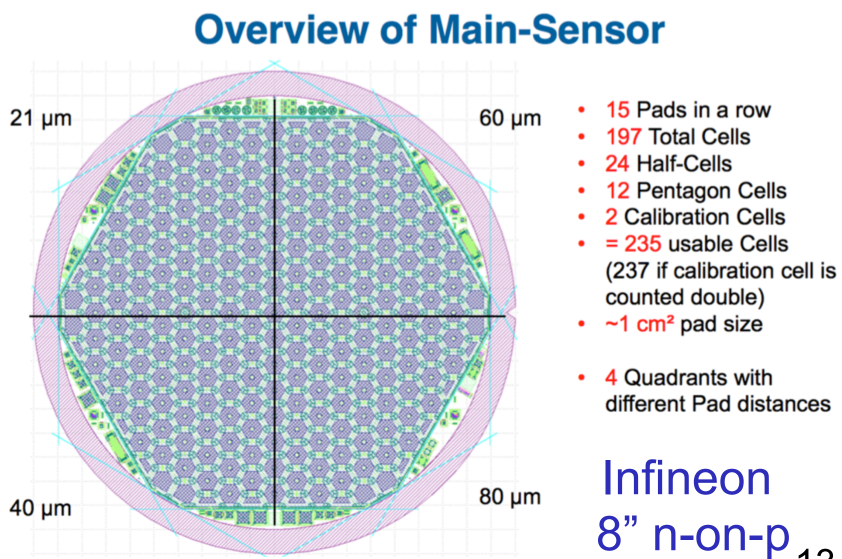
Silicon Sensors



- TP design based on 6” sensors
  - HPK 6” p-on-n 128- and 256-channel sensors, 300/200/100um – delivery completed (182 pieces). Very good quality.
  - n-on-p on order, to compare performance of both types after irradiation.
- Preference for 8” sensors due to likelihood of lower cost and less parts to assemble. Need to qualify production lines/material.
  - Infineon: 8” n-on-p 256 channel sensors – fabrication started, delivery Q4 2016
  - HPK: 8” n-on-p 256 channel sensors (using stepper) – fabrication started delivery Q4 2016
  - Novati: received half hexagonal sensors off 8” wafers.



HPK 6” p-on-n 128 channel sensors
I_{leak} @ 1000V: average for 15 sensors



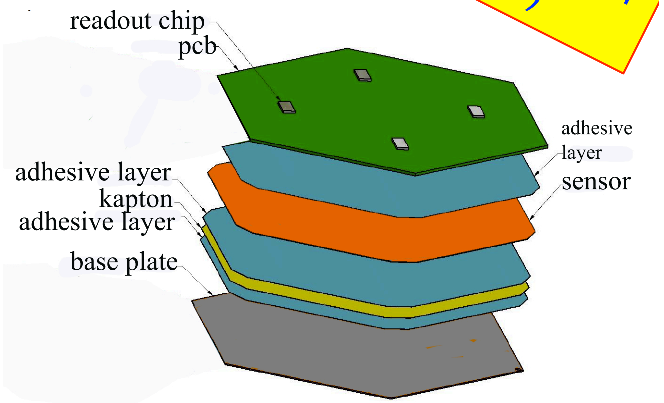
Infineon
8” n-on-p

Modules / Cooling

More on modules and tests in beam in the presentation of Z.Gecse)

Modules are assembled as a stack of base plate, kapton® insulator, Si sensor and PCB, glued together.

Rely on experience with automated module assembly from CMS Tracker



Keeping sensors at low T is essential to mitigate radiation effects

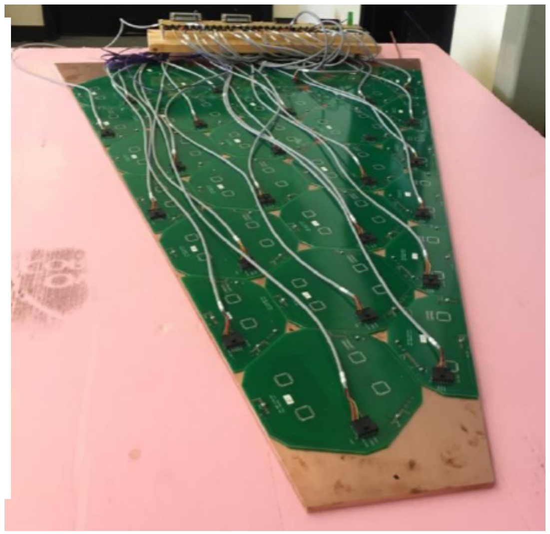
limit the leakage current (self heating $\propto I_{leak}$, noise $\propto \sqrt{I_{leak}}$)

avoid reverse annealing

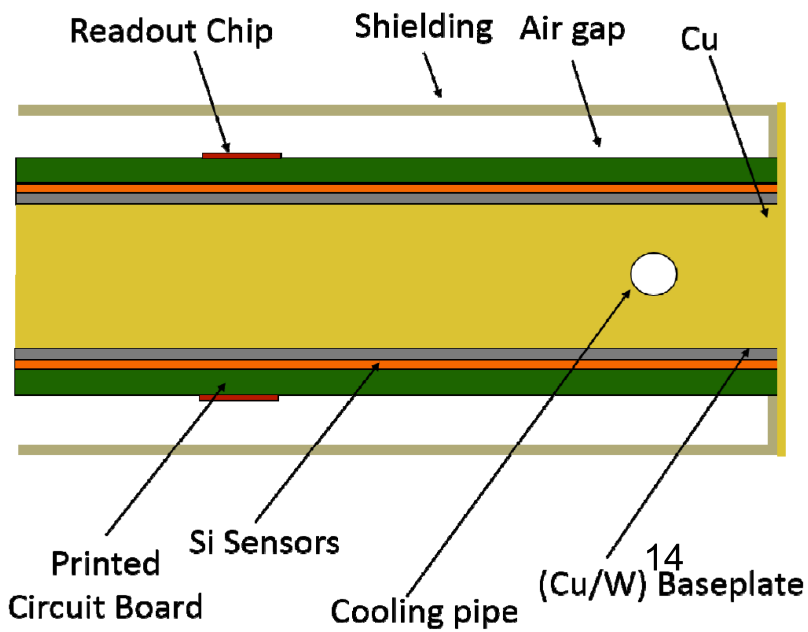
Cu cooling plate (part of absorber structure) in intimate contact with sensor module

Baseline is evaporative CO_2 cooling at $T \leq -30°C$

Results Summary (post-calibration)	Full heat load, 0.3 bar	Full heat load, 0.2 bar
Min. temp. (°C)	-30.3	-30.2
Max. temp. (°C)	-29.2	-29.0
Temp. spread (°C)	1.1	1.2
Mean (°C)	-29.8	-29.7
Standard dev. (°C)	0.225	0.226



Mockup with heaters uniform load 360 W/m²
Temperature spread within 1.2°C



Front-End Electronics

Very stringent requirements for Front-End Electronics

- Large dynamic range 0.4 fC – 10 pC (15 bits)
  noise < 2000 e- to keep MIP visibility for low thickness sensors after 3000 fb-1
- Leakage current compensation
- Low power budget < 10 mW/channel
- Timing information 50 ps accuracy
- System on chip (digitization, processing), high speed readout (>Gb/s), large buffers to accommodate 12.5μs latency of L1 trigger
- Preferably compatibility for positive and negative inputs.
- High radiation resistance (150 MRad, 10^{16} n/cm^2)

Front-End Electronics

Baseline

Charge + Time over Threshold (ToT)

Charge readout 0-100 fC 10 bits ADC

Time Over Threshold 0.1 -10 pC, 12 bits TDC

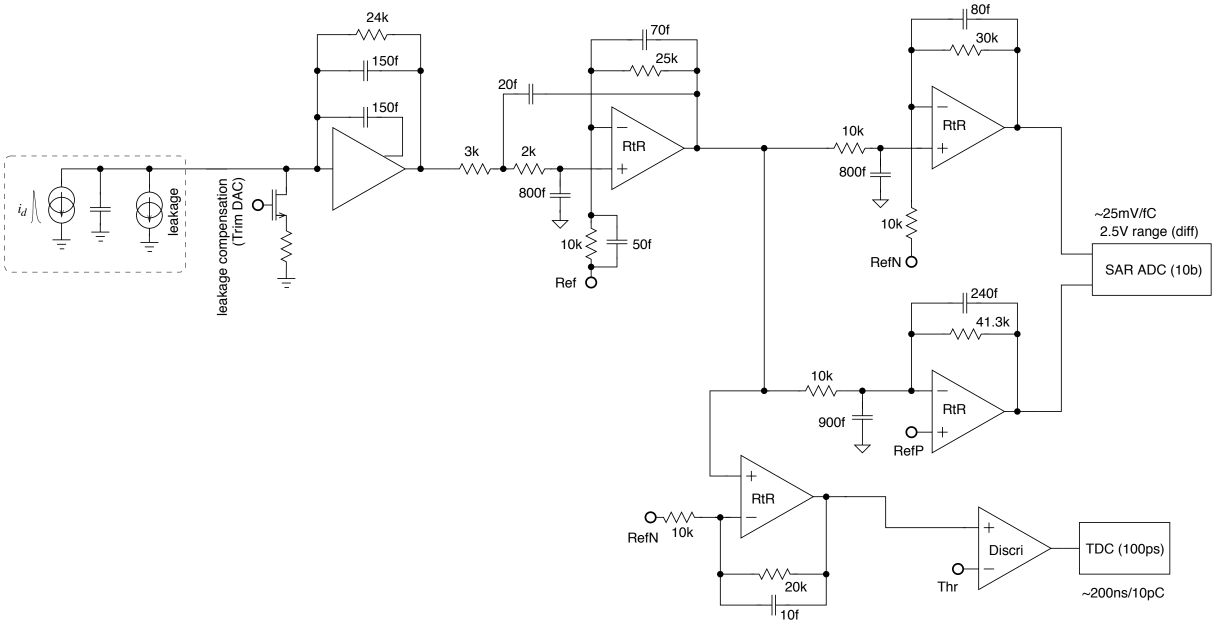
(Variants with bi-gain also studied as backup)

130nm TSMC technology

Known radiation hardness up to required dose

Higher voltage rail than 65nm (good for analogue)

Some basic blocks available



TP design
I. Kaplon/CERN

Strategy for FE electronics

1) Modify existing CALICE chip to include most of the required functionalities

Exercise functionalities such as ToT, cross calibration ADC-ToT, fast timing…

Allows study of FE printed circuit board and module assembly

Test beams 2016-2017

SKIROC2 -> SKIROC2-CMS 0.35 μm AMS (non radhard)

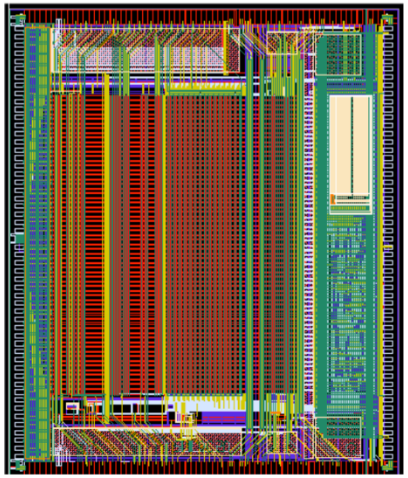
faster shaper 25ns instead of 200 ns

sampling @ 40 MHz, depth 300 ns

ToT

TDC for ToA, 20 ps binning, 50 ps jitter

Received late June, under test (see next presentation)



2) Submit Test Vehicles in 130 nm

TV1 *received* mid-September: analogue architecture, baseline + variants

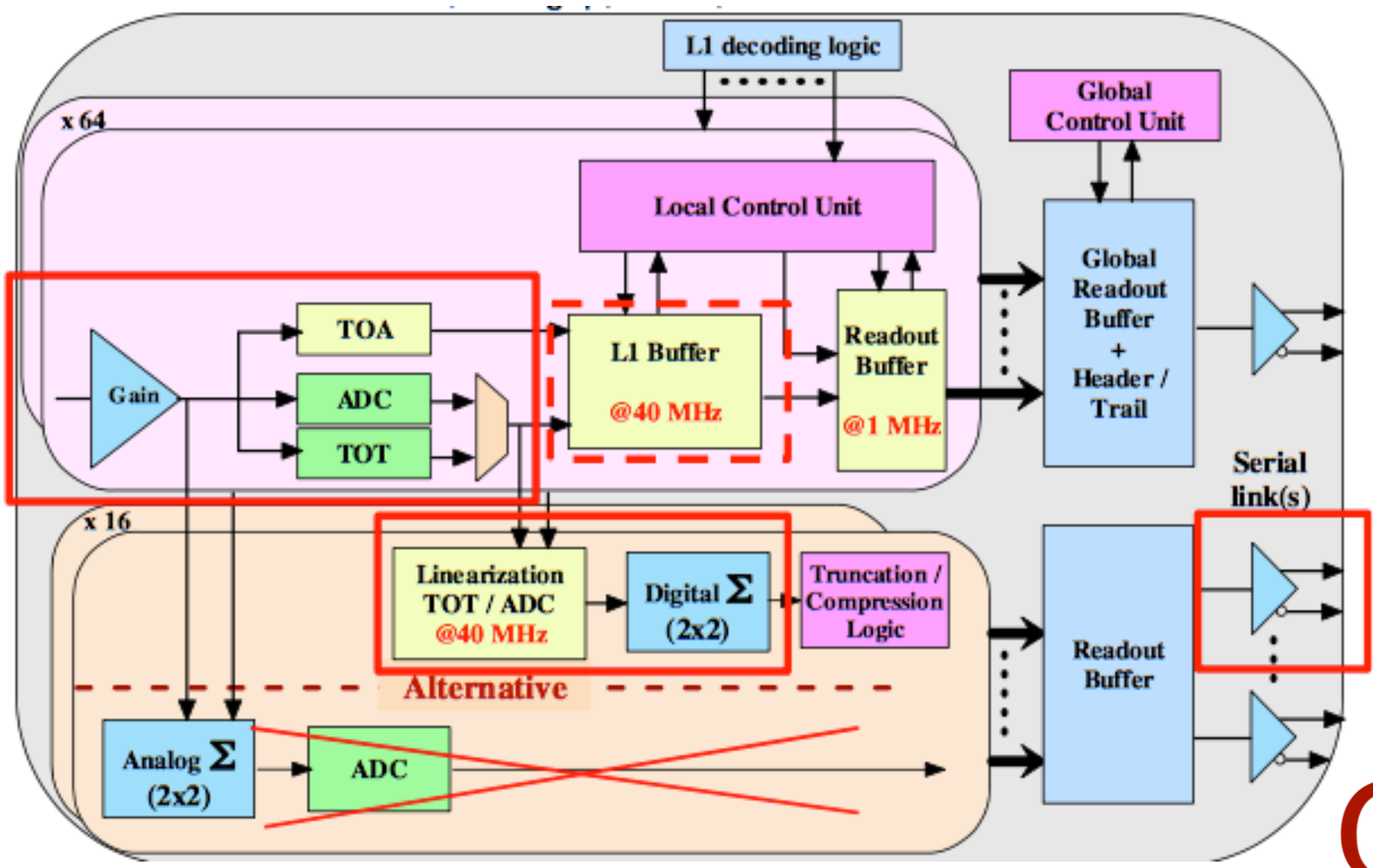
TV2 to be submitted before end 2016: 8 channels, analogue+ADC+ToT+ Trigger sums

3) Submit first “complete” ASIC June 2017

(some digital functionalities may still be incomplete)

4) Two more iterations foreseen in the overall planning

FE electronics diagram



The blocks in *red rectangles* will be included in TV2

Electronics systems

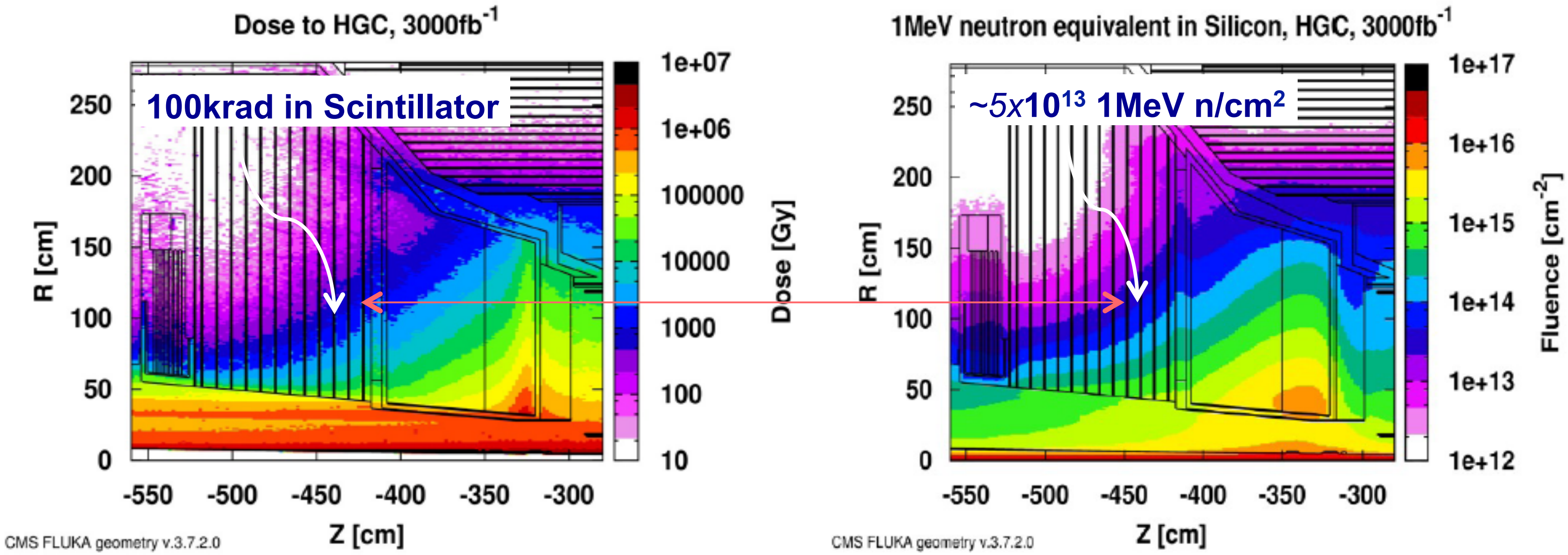
For the electronics system, the strategy is to use as much as possible common components developed for Phase-2 upgrades

- LpGBT for serialisation at 10 Gb/s and electronics control
- Versatile link for electrical-to optical conversion
- DC-DC converters (probably located on the back of the calorimeter)
- Common boards within CMS for Back-End receivers and Trigger ?
- Power supplies (LV and HV) in synergy with inner Tracker
- …

The readout architecture is under study and a baseline design should be defined by mid-December 2016.

BH active material

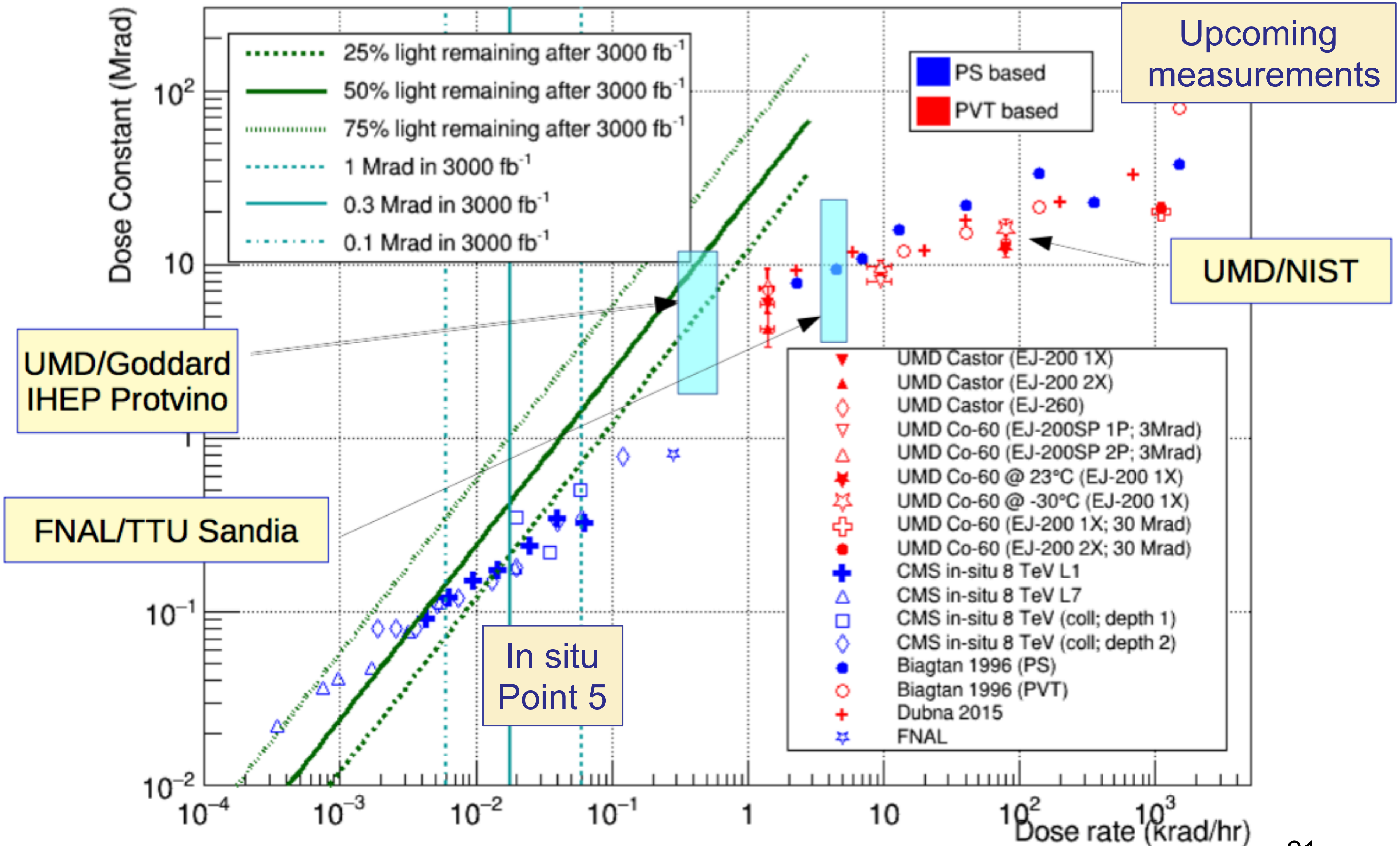
Despite being “protected” by EE+FH, the TID in BH reaches several MRads for the most inner part.



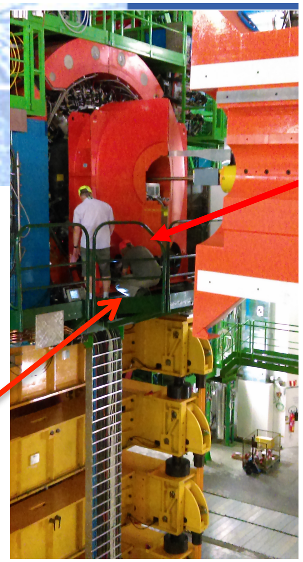
- Aim at using material which does not require any replacement during HL-LHC lifetime
- Current scintillator would lose too much light

- Large dose rate effects : Dose Constant D (defined by $S/S_0 = e^{-\text{Integrated Dose}/D}$) has a strong dependence on dose rate: smaller dose rates damage more.

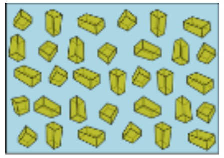
Measurements: Dose Constant v/s Dose Rate for scintillators



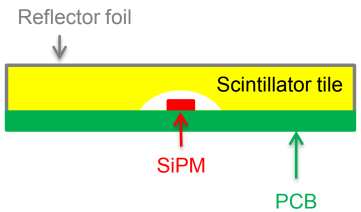
BH active material

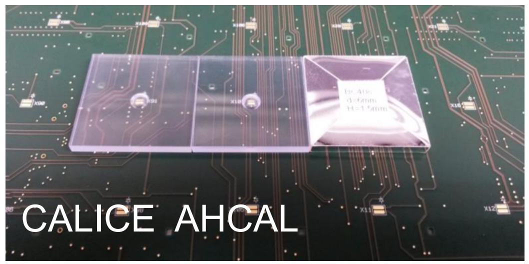


- Go to more rad hard material
  - Several campaigns of irradiations, with as-realistic-as-possible dose rates including irradiations in situ (CMS CASTOR table)
  - Includes some irradiations at cold T
  - Favoured candidate: green scintillator (such as over-doped EJ260) with orange WLS
- Use other material in the highest radiation region ?
  - Silicon ?
    - only 5-10% increase of total Si area. Requires cold endcap
  - Crystal-composite material coupled to quartz plate?



- If BH is cold, an attractive possibility is to use SiPMs on tile rather than on the periphery
    - Finer granularity
    - No complicated WLS/clear fibres
    - Extensively studied by CALICE





Summary

- CMS is preparing for a High Granularity Endcap calorimeter for Phase-2, largely based on Silicon sensors.
- This is an unprecedented and very challenging task (600 m^2 Silicon, >6M channels).
- Though Silicon Calorimetry has been extensively studied and prototyped by CALICE in the past 15 years, HL-LHC operation poses new challenges (high rate, radiation, pileup, high speed, heat load,..) which require specific (hardware and software) developments. Fitting in a existing detector is adding to the complexity.
  - A vibrant program of R&D, prototyping and tests in beam is going on
- We are carefully looking again at the proposed TP design balancing simplicity, cost-effective technical solutions, and physics performance. The main design decisions will be taken in the next months, followed by a TDR to be submitted in November 2017.