CMS Endcap calorimetry: Past, Present and the Future

International Conference on Microworld Physics Problems

Grodno, Belarus,
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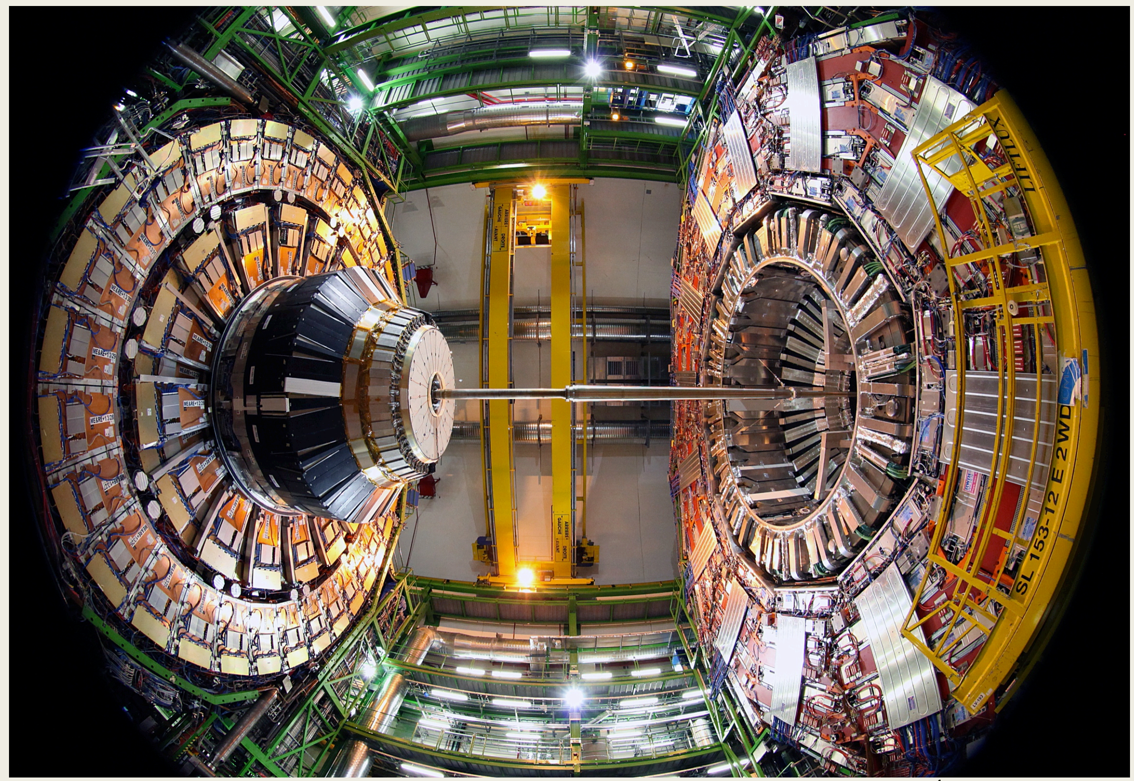
University of Rochester, USA



dedicated to memory of Professor Nikolai M. Shumeiko important stages of the participation of the Republic of Belarus in the CMS project during the work and under the leadership of Professor Nikolai Maksimovich Shumeiko in the National Center for Particle and High Energy Physics in Minsk.

1990's :	HCAL endcap absorber
1990's :	ME1/1 FE electronics R&D
1998-2001:	ME1/1 FE AFEB (anode readout front-end board): R&D, preproduction, PCB production, assembling, testing/calibration
2012-2012:	ME1/1 LV on-chamber LVDB7 board. PCD design and preproduction, PCB production, assembling, testing
2014-2016:	HCAL upgrade (Phase 1) elements and nodes of mechanical constructions of the hadronic calorimeter of the CMS experiment HE and HB readout boxes preproduction and production

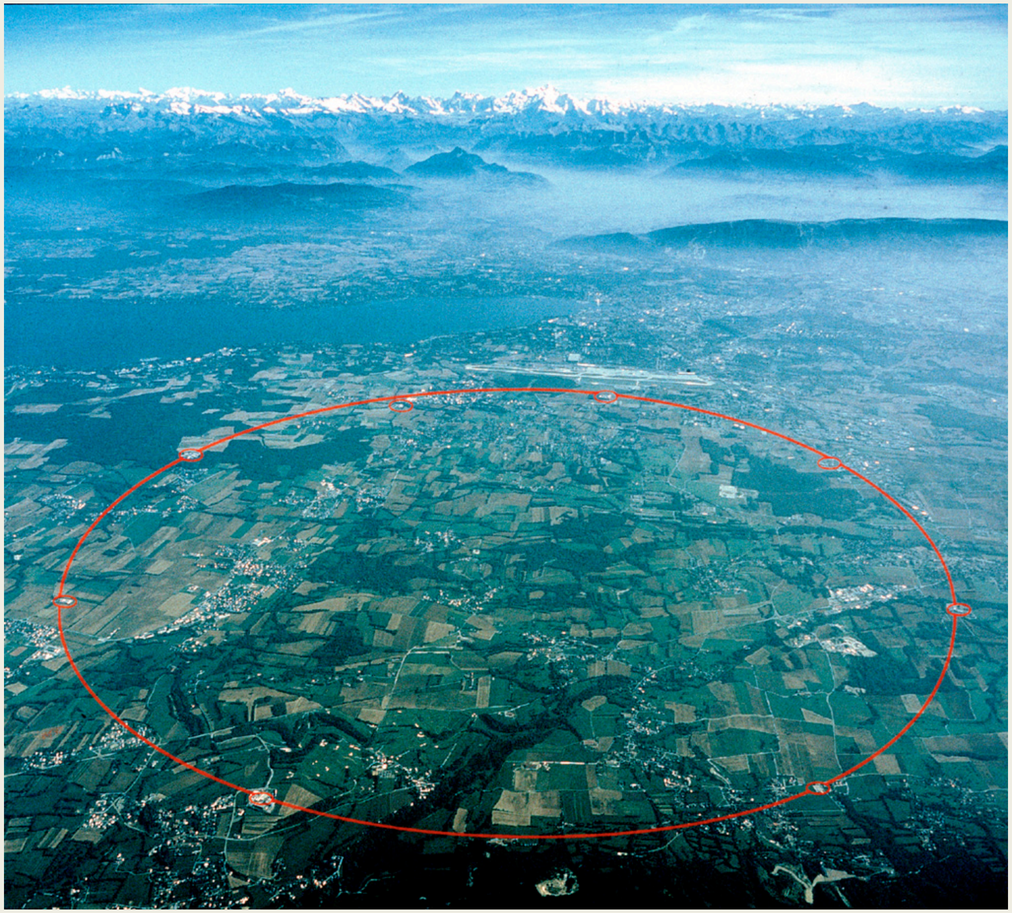
now his pupils and scientific staff of the Institute from Belarus (the Minsk Group: Vladimir Chekhovsky, Alesandr Litomin) and the enterprises of Minsk actively participate in the current (Phase1) and future (Phase2) upgrades of CMS detectors

Large Hadron Collider (LHC) at CERN, Geneva

Target start date: 2007

E_{CM}=14 TeV

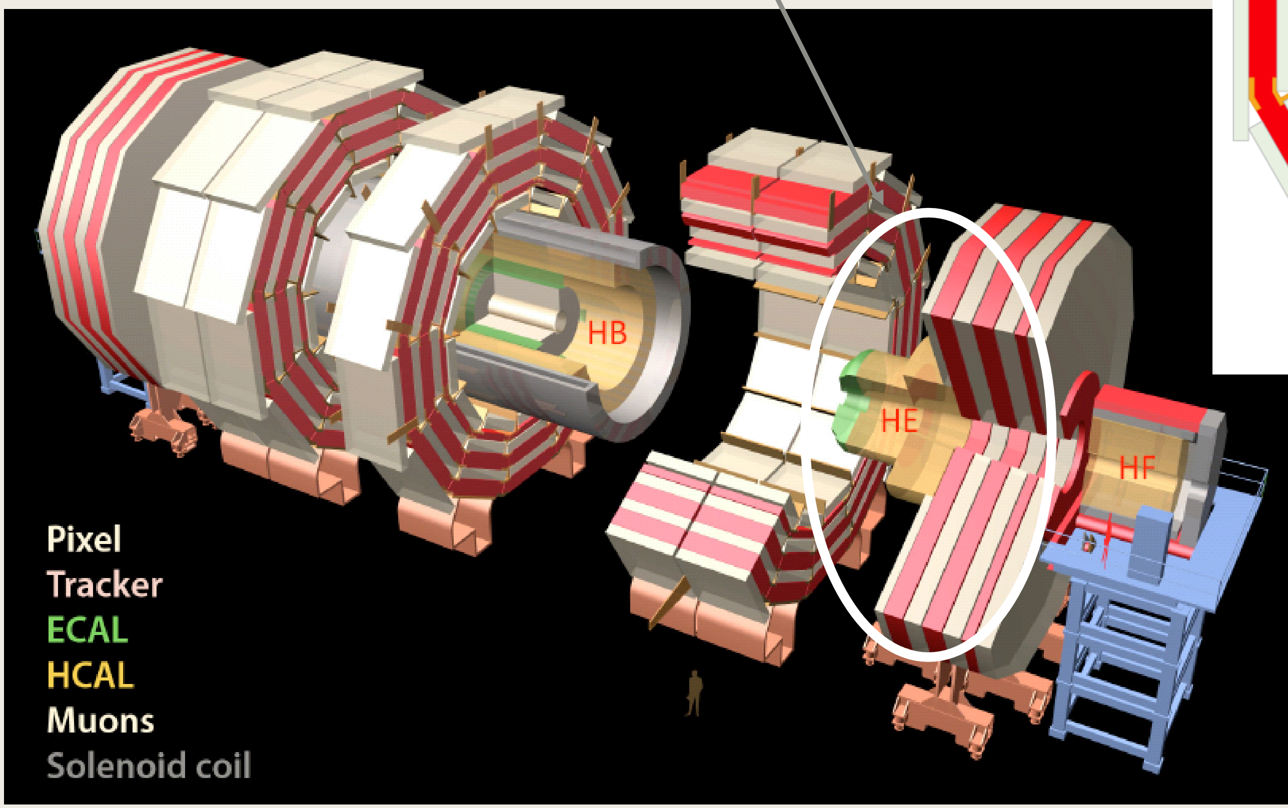
~25 ns bunch crossing time.

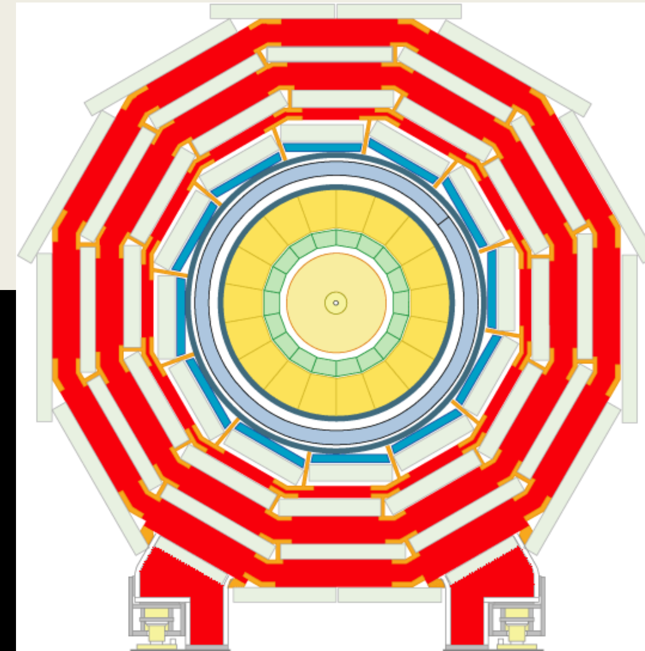


CMS experiment, Cessy, France

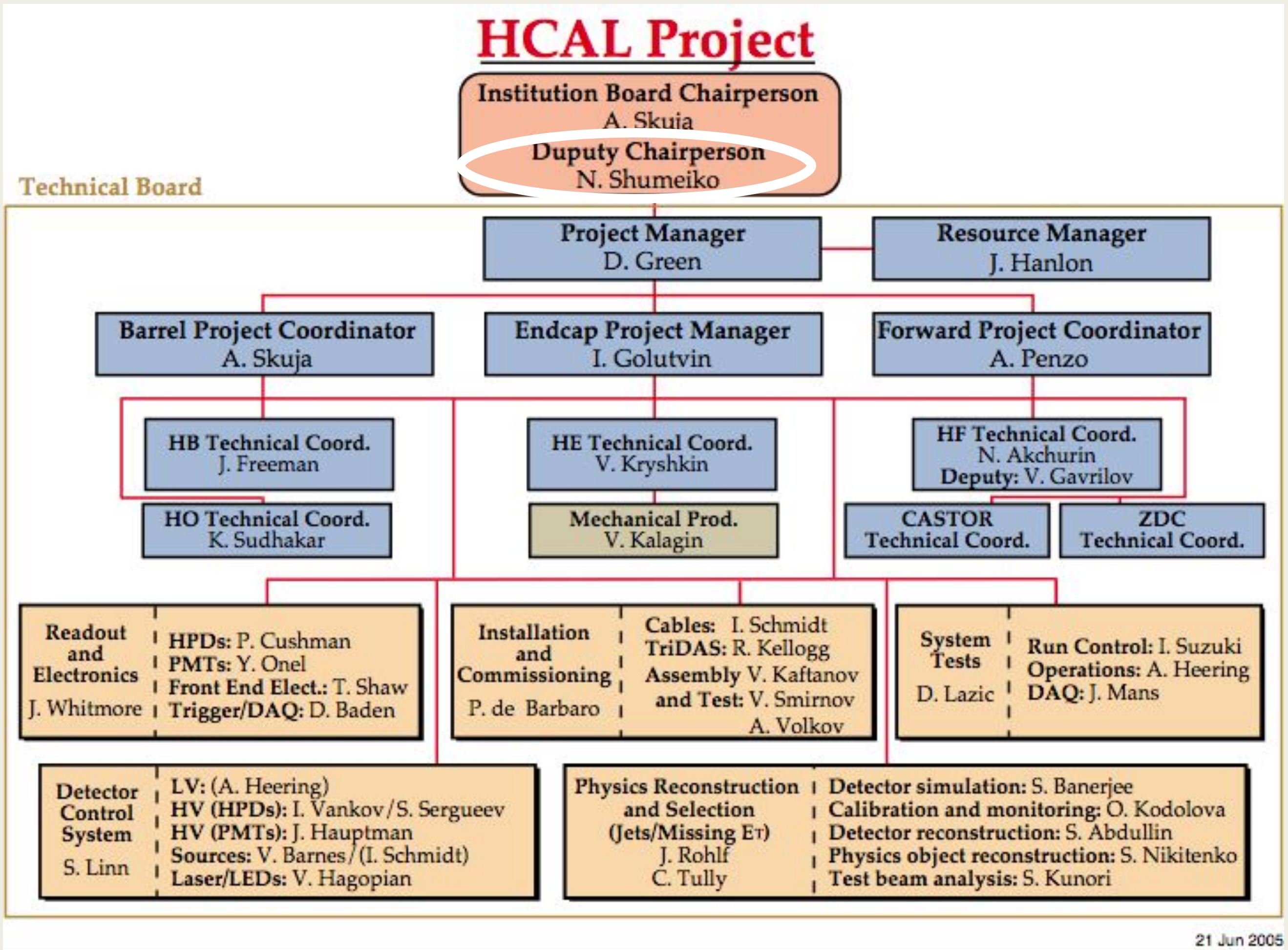
The CMS Detector and HCAL

RMDS, and Minsk group in particular, contributed to design, construction
And commissioning of CMS Hadron Endcap calorimeter

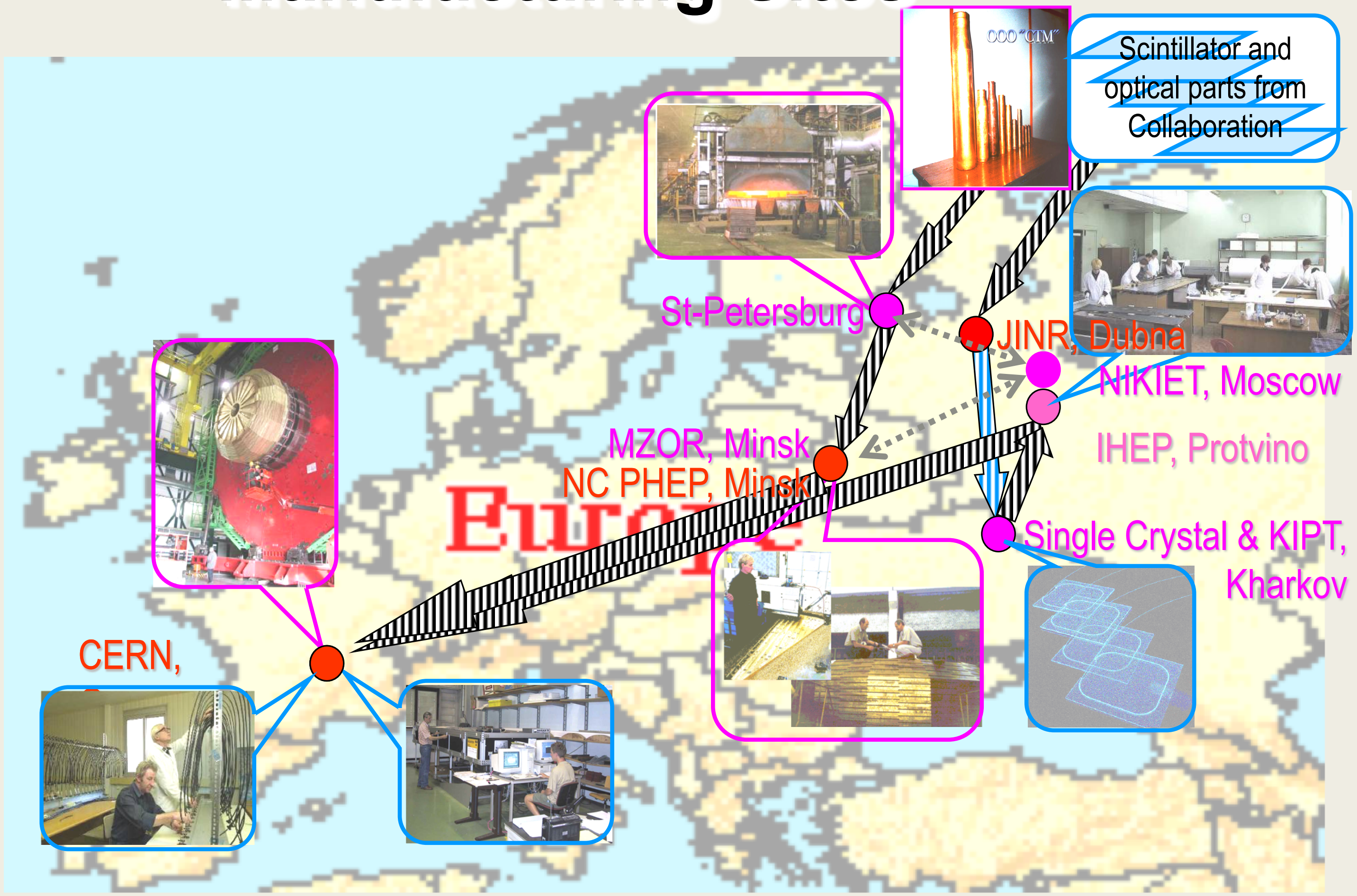




HCAL Org Chart during Installation (2005)

- 

Hadron Endcap calorimeter (HE) Manufacturing Sites

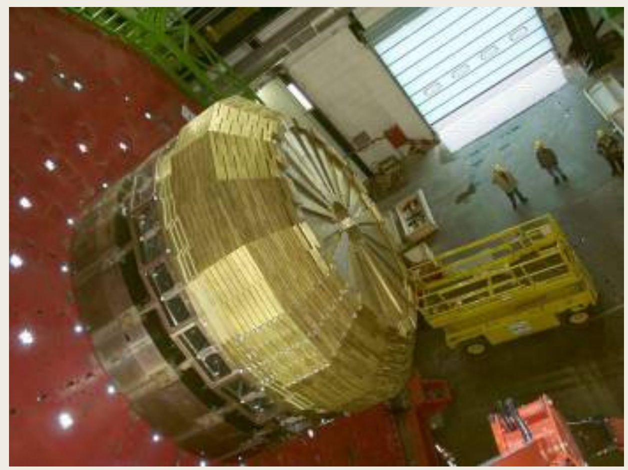


RDMS and Hadron Endcap (HE)

The RDMS groups made major contributions to the design and construction of HE (mechanics and optics) and mechanics of Hadron Forward (HF).

For HE

- **Mechanical design by NIKIET including connection to endcap yoke**
- **Brass absorber plates were rolled in IZHORA of St. Petersburg**
- **Machined and pre-assembled in MZOR of Minsk**
- **Scintillator megatiles machined at Kharkov**
- **Megatiles assembled and tested in Protvino**

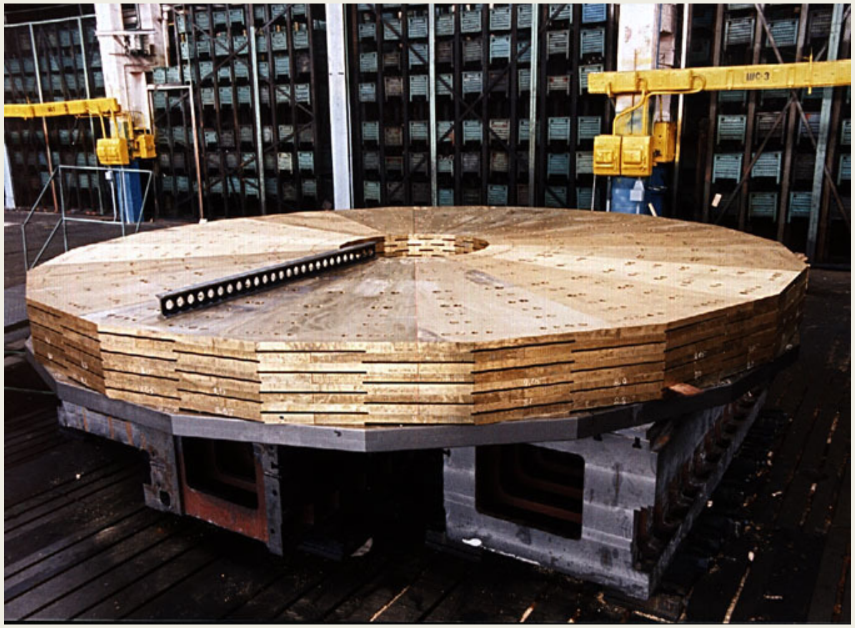


HE Absorber Plates & Cartridge Brass

> And he shall judge among the nations, and shall rebuke many people: and they shall beat their swords into plowshares, and their spears into pruninghooks: nation shall not lift up sword against nation, neither shall they learn war any more. (Isaiah 2:4).

- **The HE brass indeed consisted of reconstituted cartridge shells.**
- **RDMS supplied this cartridge brass. US paid for ½ of the HE brass.**
- **V. Kaligin of Dubna had overall coordination responsibility.**
- **NIKIET (Moscow) had design responsibility**
- **IZHORA (St. Petersburg) manufactured the plates**
- **MZOR of Minsk machined and pre-assmebled the plates (under the leadership of Nikolai Shumeiko)**
- **Plates then shipped and assembled at CERN with final assembly performed vertically (under RDMS supervision)**

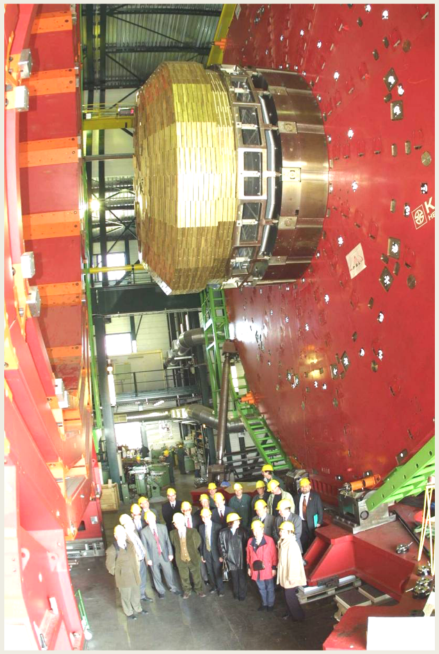
HE Preassembly in Minsk (MZOR)

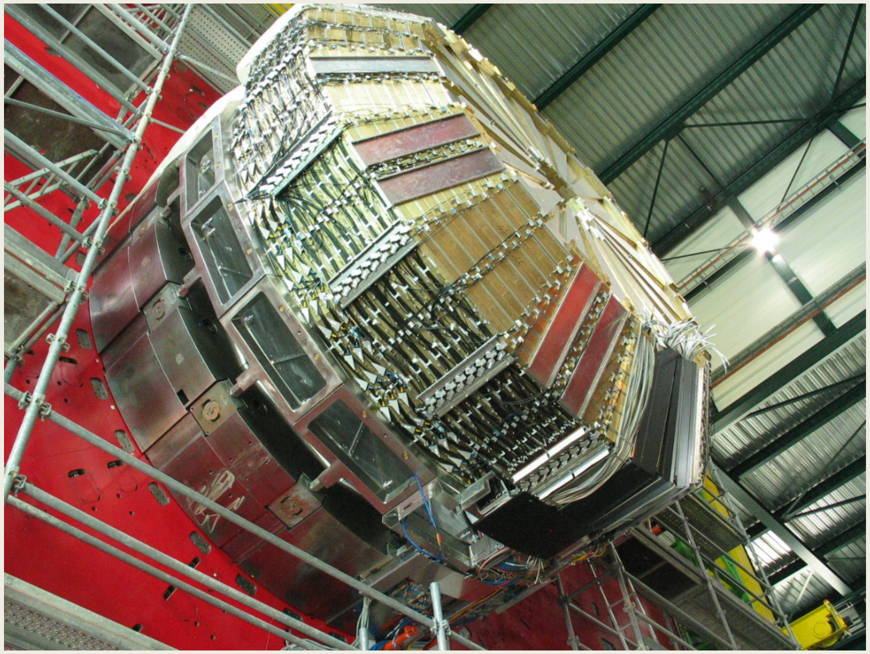


HE Installation at CERN

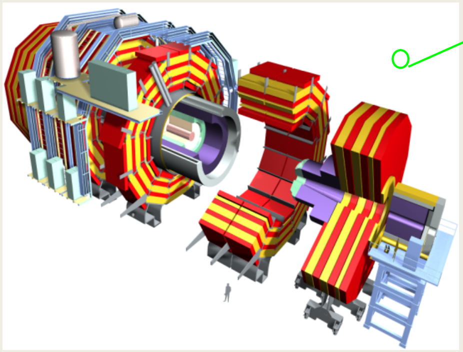
The HE installation team was lead by Vitali Kaftanov of Moscow – ITEP. His team included V. Smirnov (engineer from Dubna, Alexander Vishnevsky (also an engineer) and A.Volkov (physicist from Protvino)

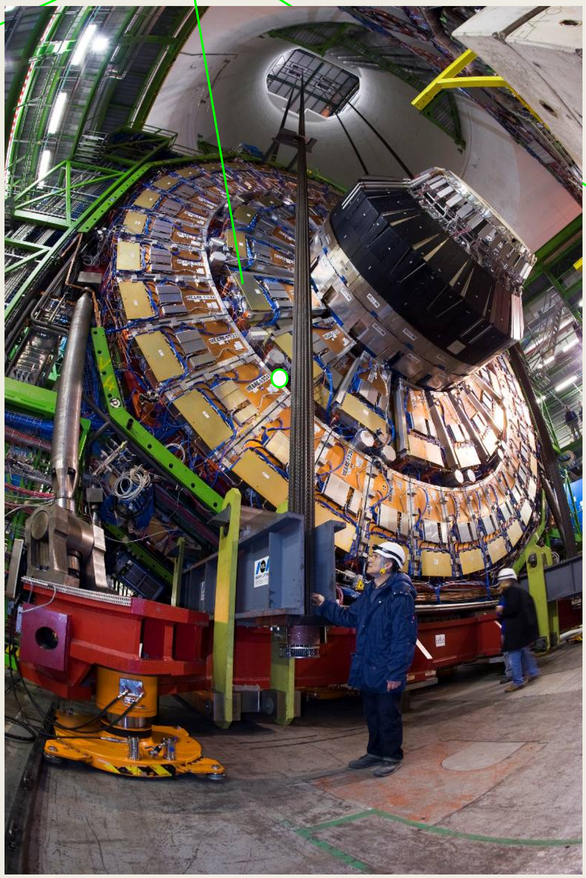
The Megatiles were installed into the slots of the brass Matrix. The WLS fiber was Connected to Readout Boxes (RBXs) via clear fiber.

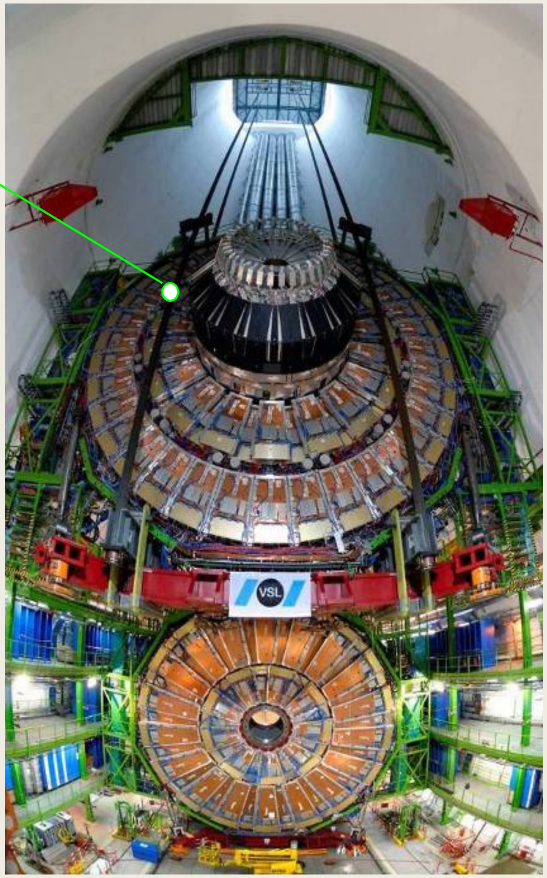




HCAL – Endcaps in CMS Cavern underground







HCAL – HE Design

1. Design of HE first prototypes and 20degree PPT2
2. Design of HE absorbers
3. Design of HE/YE1interfaces and Integration
4. Design of tiles, megatiles, and optical system - cables
5. Design of laser control system
6. Design of stands for pig tail and megatile quality test
7. Design of megatron stand for Al-coat of the fiber ends
8. Radiation calculations

PROTVINO-IHEP
1. Abramov Victor
2. Korablev Andrey
3. Korneev Yury
4. Krinitsyn Alexander
5. Krychkin Victor
6. Turchanovich Leonid
7. Volkov Alexey
8. Levine Andrey
9. Sourkov Alexandre
10. Evdokimov V.
11. Markov A.
12. Potapov V.
13. Sasov A.
14. Simonova Z.
15. Skvortsova E.
16. Uzunian Andrey
17. Azhguirei Igor

MINSK-NCPHEP
1. Emeliantchik Igor
2. Litomin Aliaksandr
3. Shumeiko Nikolai
4. Stefanovitch Roman

et al

DUBNA
1. Ershov Yuri
2. Golutvin Igor
3. Gramenitski Igor
4. Kalagin Vladimir
5. Lysiakov Vadim
6. Kosarev Ivan
7. Melnitchenko Igor
8. Moisenz Petr
9. Sergeev Sergey
10. Volodko Anton
11. Zarubin Anatoli

et al

MOSCOW-RDIPE
1. Druzhkin Dmitry
2. Ivanov Alexander
3. Kudinov Vladimir
4. Orlov Alexandre
5. Smetannikov Vladimir

et al

KHARKOV-ISC
1. Grinev Boris
2. Lyubynskiy Vadym
3. Senchyshyn Vitaliy

et al

KHARKOV-KIPT
1. Levchuk Leonid
2. Nemashkalo Anatoly
3. Sorokin Pavel

et al

HCAL – Endcap Manufacture

1. **Manufacturing of brass for absorbers in "Krasny Vyborzhets"**
2. **Manufacturing and pre-assembly of HE absorbers in Minsk MZOR**
3. **Manufacturing of HE/YE1 Interface in Minsk MZOR**
4. **Supervision and quality acceptance control for mechanics manufacturing**
5. **Production of tiles and megatiles**
   - **Production of stands for fiber ends coat, pig tail, and megatile and pig tails quality test and control**
   - **Production and quality test of megatiles during production and after transportation at CERN**
6. **Production of laser control system and optical cables**
7. **Production of HE prototypes**
8. **Production of HV system**

DUBNA
1. Golutvin Igor
2. Kalagin Vladimir
3. Melnitchenko Igor
4. Volodko Anton
5. Zarubin Anatoli

et al

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et al

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2. Nemashkalo Anatoly
3. Sorokin Pavel

et al

PROTVINO-IHEP
1. Goncharo Petr
2. Korablev Andrey
3. Korneev Yury
4. Krinitsyn Alexander
5. Krychkin Victor
6. Markov A.
7. Pavlov S.
8. Talov Vladimir
9. Tyurin Nikolai
10. Turchanovich Leonid
11. Volkov Alexey
12. Zaichenko Alexander

MINSK-MZOR
1. Chernyavsky Boris
2. Krivomaz Mikhail

SOFIA-INRNE
1. Genchev Vlado
2. Vankov Ivan

et al

HCAL – Craftsmen in Brass/Bronze

PROTVINO-IHEP
1. Abramov Victor
2. Kalinin Alexey
3. Khmelnikov Alexander
4. Korablev Andrey
5. Korneev Yury
6. Krinitsyn Alexander
7. Krychkin Victor
8. Levine Andrey
9. Sourkov Alexandre
10. Talanov Vadim
11. Talov Vladimir
12. Tyurin Nikolay
13. Volkov Alexey

MOSCOW-RDIPE
1. Druzhkin Dmitry
2. Ivanov Alexander
3. Kudinov Vladimir
4. Orlov Alexandre
5. Smetannikov Vladimir

DUBNA
1. Ershov Yuri
2. Golutvin Igor
3. Gramenitski Igor
4. Kalagin Vladimir
5. Konoplyanikov Viktor
6. Korenkov Vladimir
7. Kurenkov Alexander
8. Lysiakov Vadim
9. Malakhov Alexander
10. Melnitchenko Igor
11. Moisenz Petr
12. Sergeev Sergey
13. Smirnov Vitaly
14. Vishnevskiy Alexander
15. Volodko Anton
16. Zarubin Anatoli

MINSK-NCPHEP
1. Chekhovsky Vladimir
2. Emeliantchik Igor
3. Litomin Aliaksandr
4. Mossolov Vladimir
5. Shumeiko Nikolai
6. Stefanovitch Roman
7. Tikhonov Anton
8. Zazyulya Fedor

MINSK-MZOR
1. Chernyavsky Boris
2. Krivomaz Mikhail

KHARKOV-ISC
1. Grinev Boris
2. Lyubynskiy Vadym
3. Senchyshyn Vitaliy

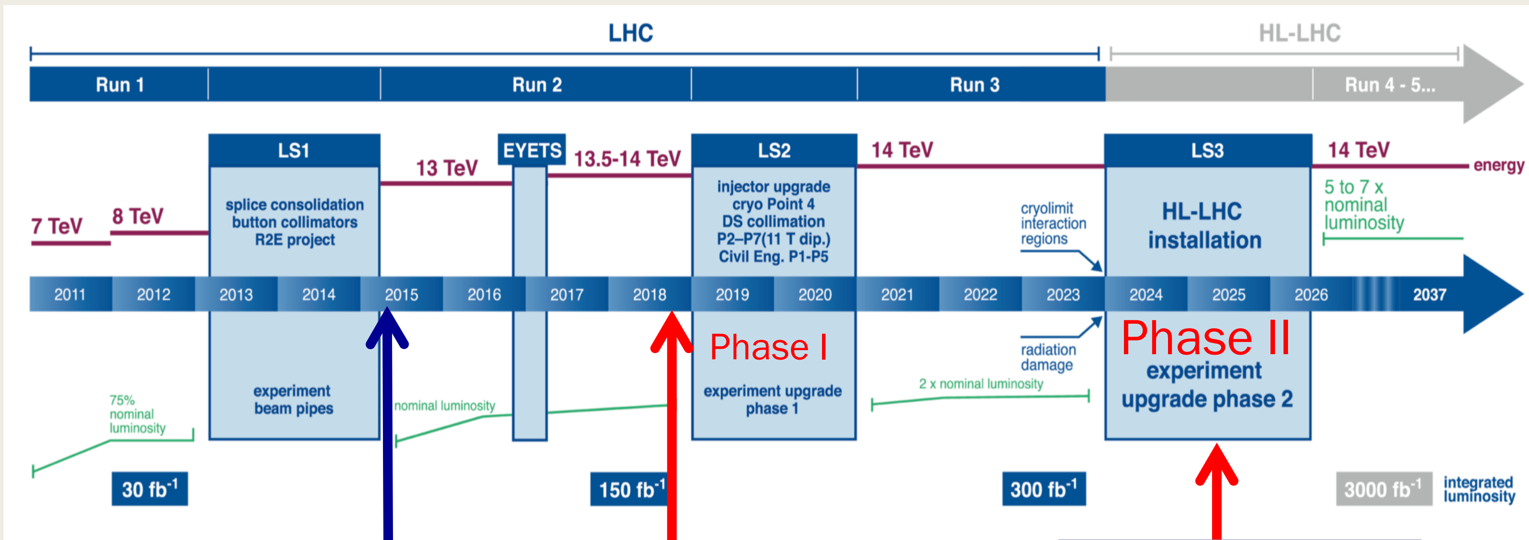
KHARKOV-KIPT
1. Levchuk Leonid
2. Nemashkalo Anatoly
3. Sorokin Pavel

ITEP/VNIITF
1. Andriash Alexander
2. Kadomtsev Alexander
3. Kretinin Yury
4. Naumenko Mikhail
5. Putnikov Igor
6. Scherbakov Alexander
7. Skripov Roman

MOSCOW-ITEP
1. Gavrilov Vladimir
2. Ilina Natalia
3. Kaftanov Vitali
4. Kiselevich Ivan
5. Kolosov Victor
6. Kossov Mikhail
7. Krokhotin Andrey
8. Kuleshov Sergey
9. Litvintsev Dmitry
10. Nikitin Arkady
11. Oulianov Alexei
12. Safronov Grigory
13. Semenov Sergey
14. Stolin Viatcheslav
15. Vlasov Evgueni

MOSCOW-MSU
1. Cherstnev Alexandre
2. Ershov Alexander
3. Gribushin Andrey
4. Kodolova Olga
5. Sarycheva Ludmila
6. Savrin Viktor

The future at CERN: High Luminosity LHC Timeline



HGC
selected
Spring 2015

today

CMS Master Schedule
HGCal to be lowered
into UX5
Autumn 2025

7 years

What makes it worthwhile to run longer an HEP experiment ?

1. Higher centre-of-mass energy
2. Higher integrated luminosity
3. Qualitatively better detectors

Reminder: Physics Questions for the LHC

1. SM contains too many apparently arbitrary features - *presumably these should become clearer as we make progress towards a unified theory.*

✓ **2. Clarify the e-w symmetry breaking sector**

SM has an unproven element: the generation of mass

Higgs mechanism ->? or other physics ?

Answer will be found at **LHC energies**

e.g. why $M_\gamma = 0$

M_W, M_Z ~ 100,000 MeV!

Jim Virdee transparency from the early 90's

3. SM gives nonsense at LHC energies

Probability of some processes becomes greater than 1 !! Nature's slap on the wrist!

Higgs mechanism provides a possible solution

4. Identify particles that make up Dark Matter

Even if the Higgs boson is found all is not completely well with SM alone:

next question is "Why is (Higgs) mass so low"?

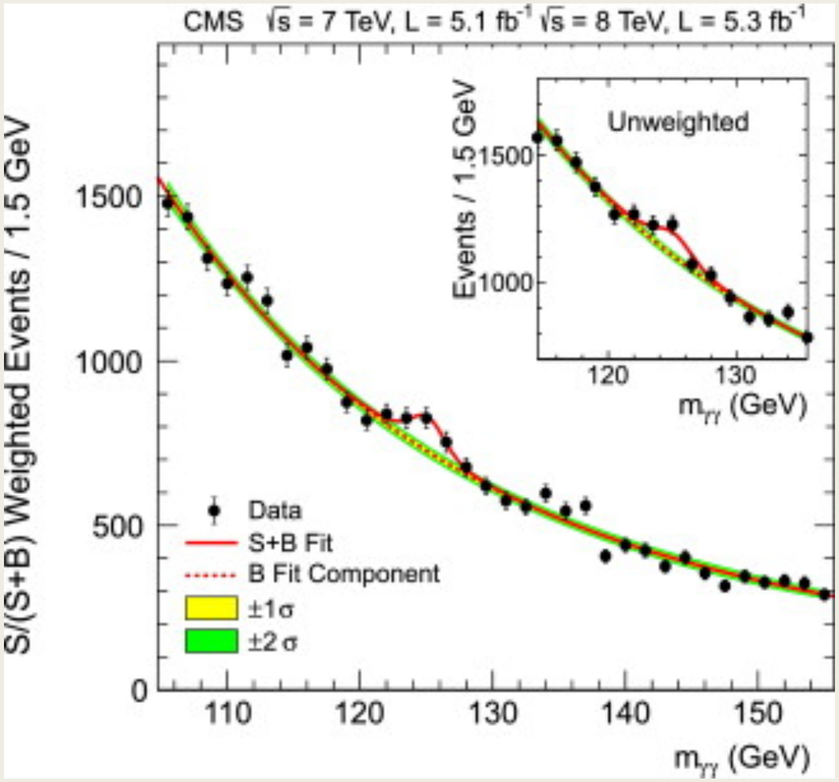
*If a new symmetry (Supersymmetry) is the answer, it must show up at O(***1TeV***)*

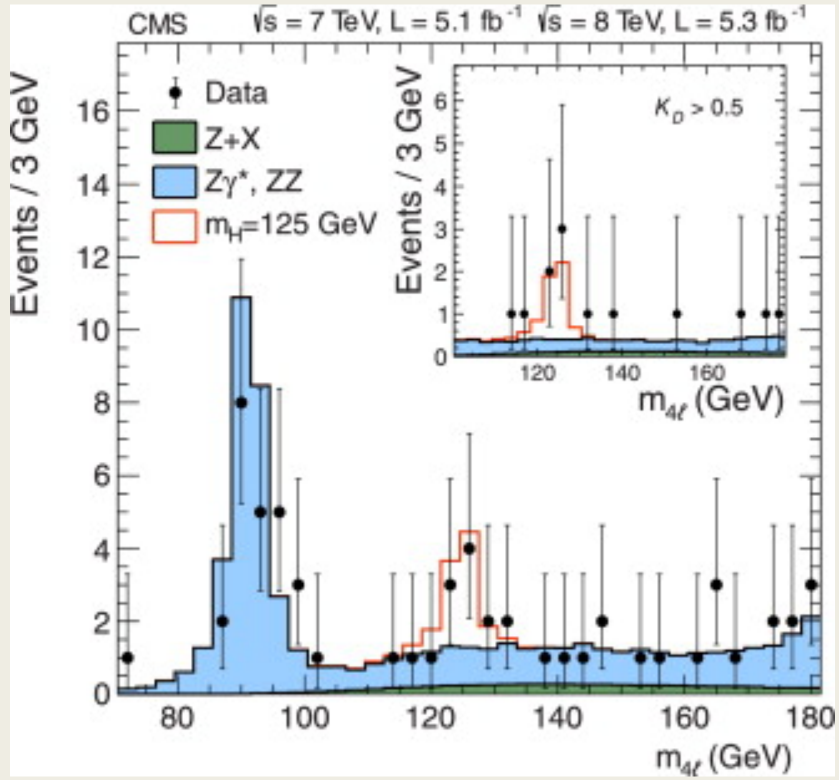
5. Search for new physics at the TeV scale

SM is logically incomplete – does not incorporate gravity

Superstring theory ⇨ *dramatic concepts: supersymmetry , extra space-time dimensions ?*

The CMS Higgs Discovery in 2014:



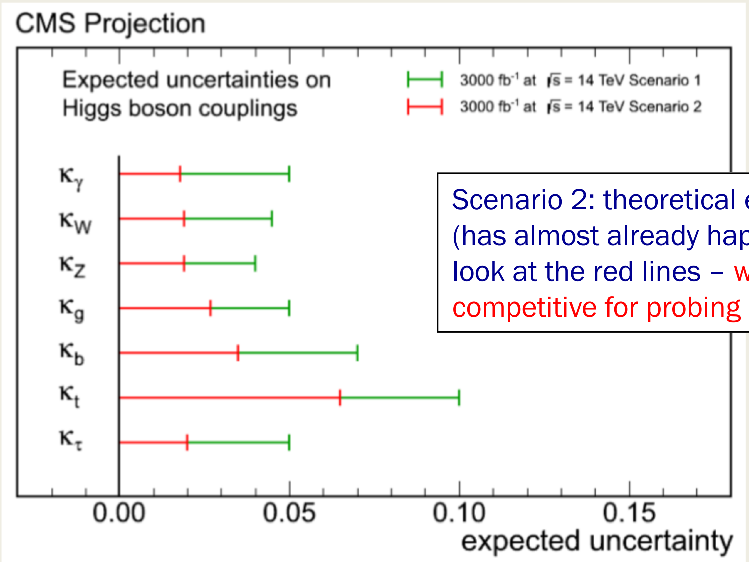


HL-LHC: Measurement of Higgs boson Parameters

HL-LHC: No. of Higgs bosons produced at $\sqrt{s}$=14 TeV for 3000 fb^{-1}

Process	No. Evts (M)
gg→ H	145
VBF	13
WH	5
ZH	2.5
ttH	1.8

- Higher statistics allows categorization of signal regions with higher S/B, regions where the systematics are better controlled,
- The balance between statistical and systematic errors changes
- e.g. VBF H→ττ: expect 200k events



Scenario 2: theoretical errors halved (has almost already happened). So look at the red lines – will be competitive for probing BSM physics

- HGCAL has particular capabilities in the areas of
- H→γγ, H→ZZ*→4e, 2μ2e, H→ττ
- VBF channels (bbar, ττ, etc.)
  (lhs plot does not take account of dedicated L1-triggers)
- Di-Higgs production
- Rare decays involving photons
  (not on lhs plot)

Expected doses and fluence in CMS endcap region after 3000 fb^{-1}

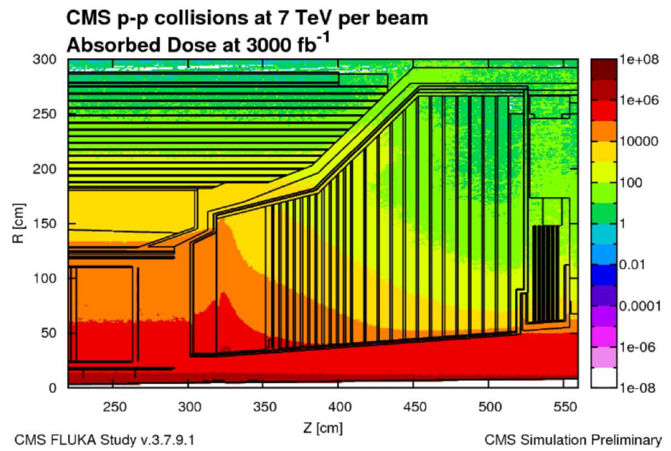


Figure 1.1: Dose of ionizing radiation accumulated in HGCAL after an integrated luminosity of3000 fb^{-1}, simulated using the FLUKA program, and shown as a two-dimensional map in the radial and longitudinal coordinates, r and z.

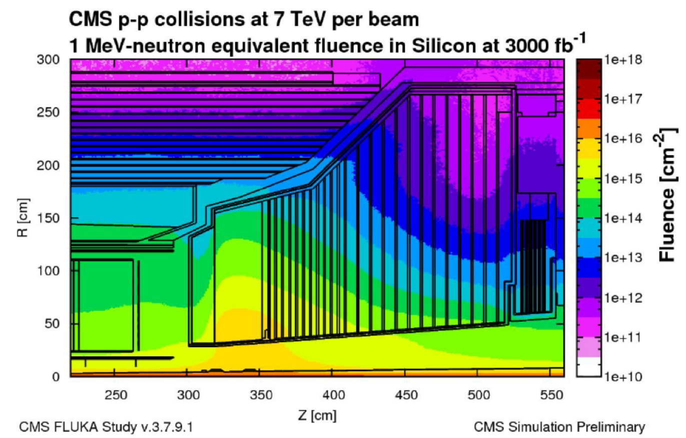


Figure 1.2: Fluence, parameterized as a fluence of 1 MeV equivalent neutrons, accumulated in HGCAL after an integrated luminosity of3000 fb^{-1}, simulated using the FLUKA program, and shown as a two-dimensional map in the radial and longitudinal coordinates, r and z.

Hadron Endcap (HE): scintillators/WLS fibers; Electromagnetic Endcap (EE): Lead tungstate crystals
Present Endcap detectors were designed for integrated luminosity of 500 fb $^{-1}$. Radiation damage to active elements of present CMS Endcap detectors much beyond this integrated luminosity would lead to performance degradation, and in effect, unacceptable loss of physics performance.

Signal loss of HE calorimeter vs Int. Luminosity

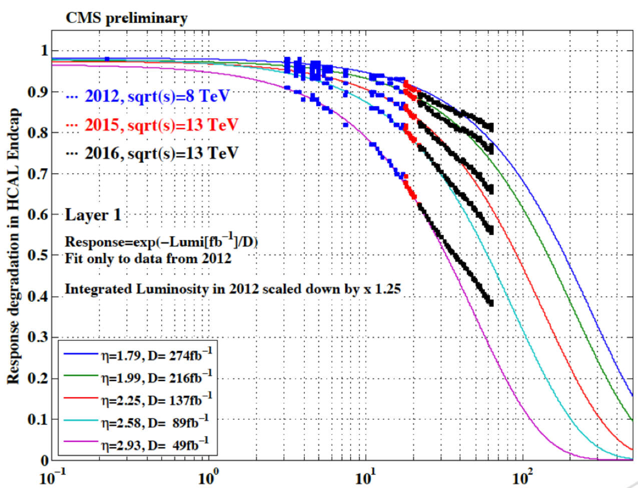


Figure 2.18: Response loss in HE Layer1 for various η towers, averaged over all ϕ towers, as a function of integrated luminosity. The response was normalized to the signal at the beginning of 2012. The normalization for Laser intensity variation was obtained using the lowest η ring.

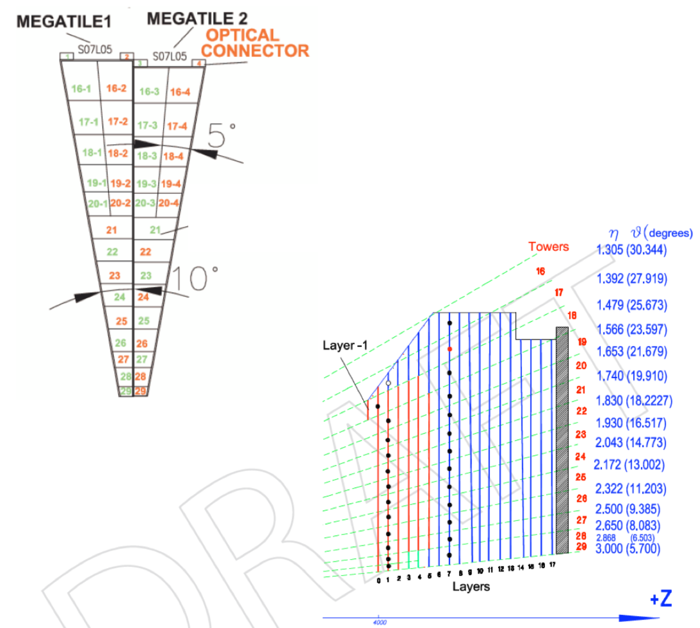


Figure A.1: Left: Example of a the transverse (η-ϕ) segmentation of two adjacent HE megatiles, covering a $\Delta\phi$ angle of 20°. Right: Longitudinal and angular segmentation of the HE calorimeter. The dashed lines point to the interaction point. Tower pseudorapidity index ieta is given in red, while η (θ) boundaries are given in blue. The two lines of dots in L1 and L7 represent the location where UV light is injected into the scintillator for calibration and monitoring.

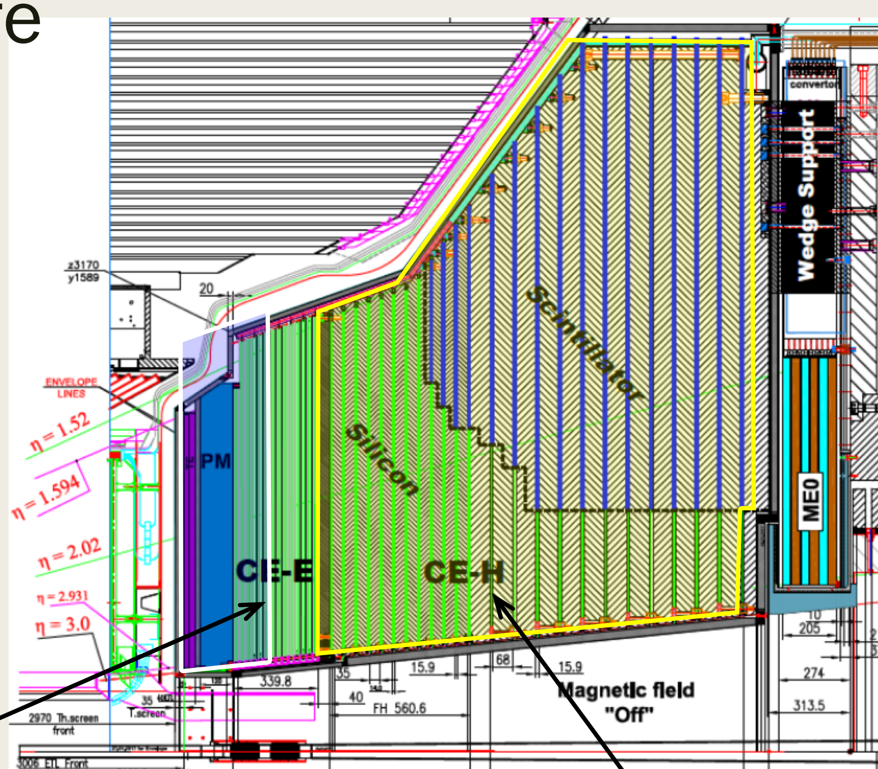
After 100 fb $^{-1}$, in the high eta region of HE, signal reduction ~ x2

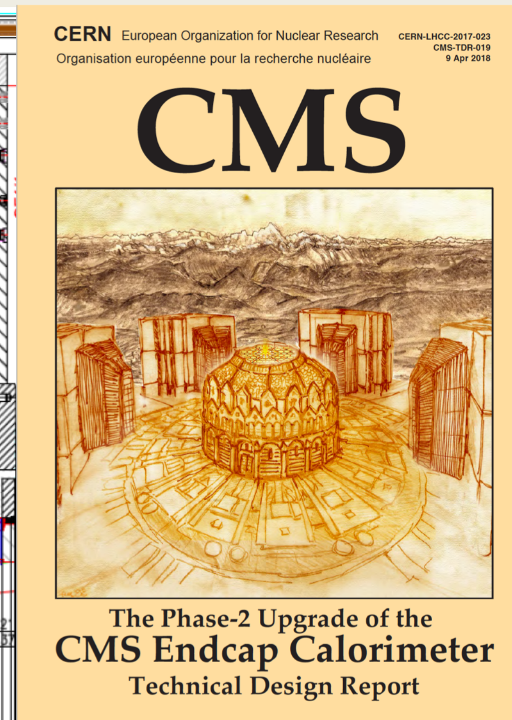
High Granularity Calorimeter (HGCAL)

Overall Structure

New detector features:

- Radiation tolerance (up to 3000 fb^{-1})
- Dense calorimeter (preserving lateral compactness)
- Fine lateral granularity (two shower separation)
- Fine longitudinal granularity (energy resolution, pattern recognition, pile-up mitigation)
- Precise measurement of the time of high energy showers (pile-up rejection, identification of the vertex of triggering interaction)
- Ability to contribute to the Level-1 triggering decision





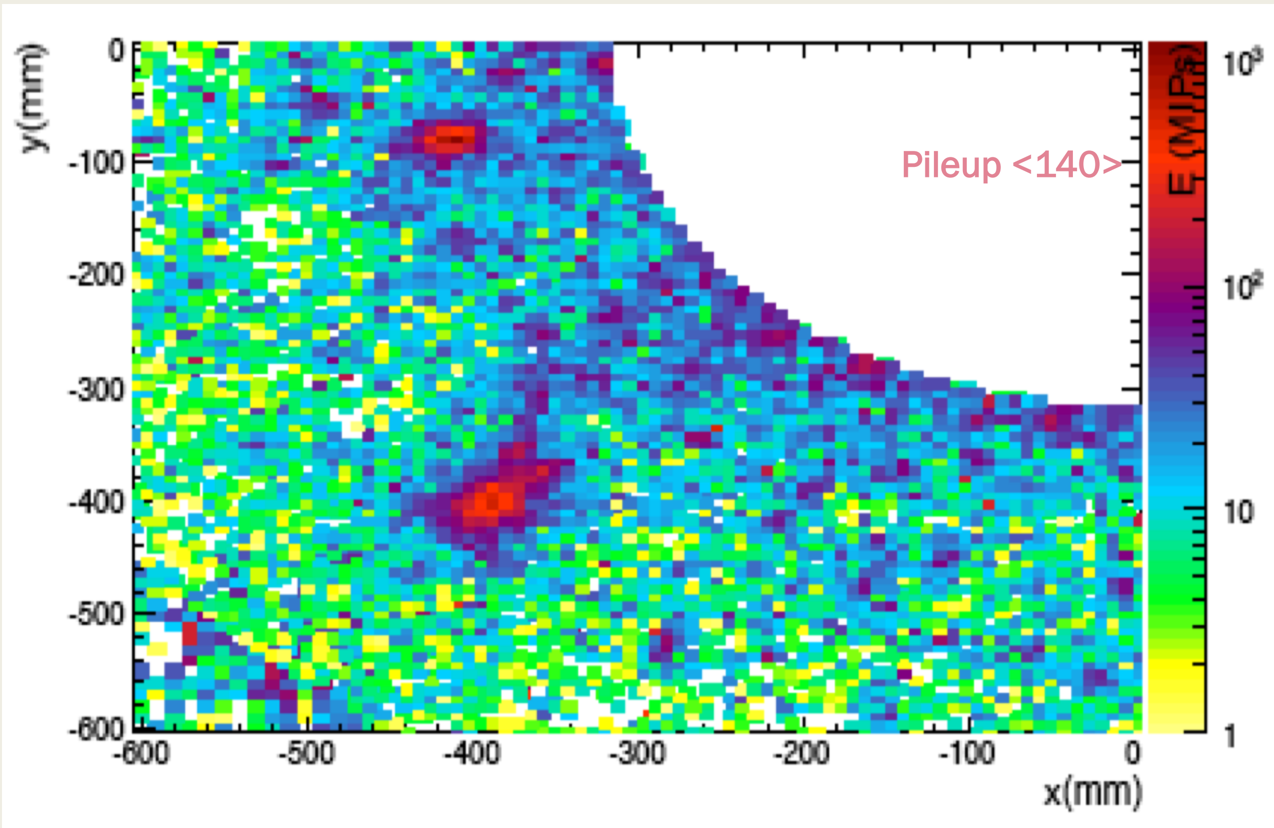
EM Cal … Less conventional structure

- Pb/SS absorbers are part of cassettes
- Cassettes stacked directly on top of each other

Hadron Cal … Conventional structure

- Steel absorber plates with gaps
- Active detectors (cassettes) inserted into gaps

Event Display of VBF Jets (VBF H→γγ)



E (MIPs)

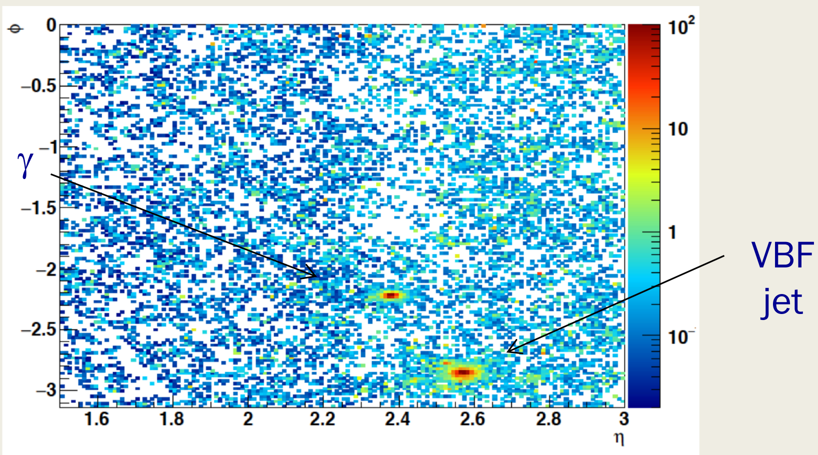
Use of Timing: One aim - Event "Cleanup"

Arises naturally from the choice of CE parameters and electronics

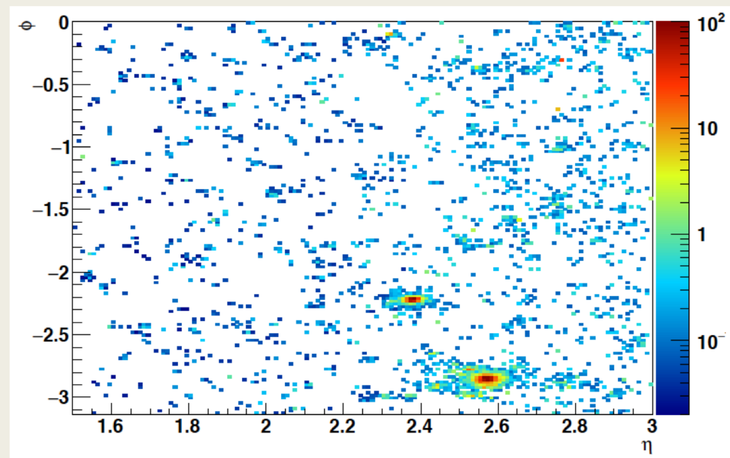
Figure of Merit: pileup mitigation (illustrative)

VBF (H→γγ) event with one photon and one VBF jet in the same quadrant,

PU=200 events: No timing cut



PU=200 evts: Cut Δt < 90ps (3σ at 30ps)

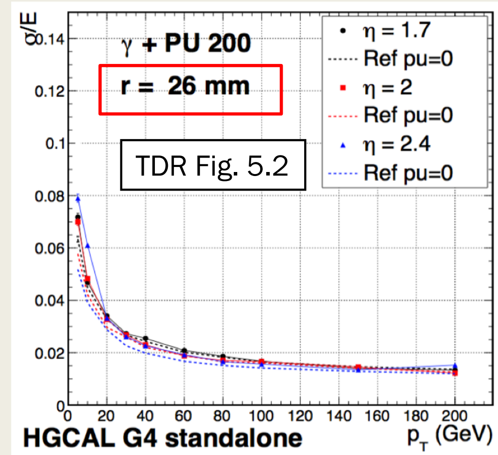


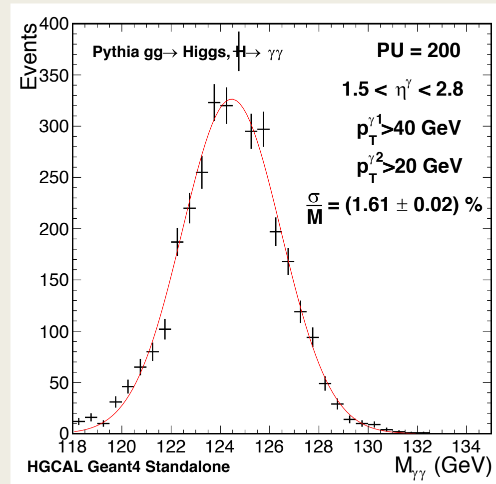
Plots show cells with Q > 12fC (threshold for timing measurement) projected to the front face of the endcap calorimeter.

Aim: Preserve adequate em energy resolution

- The **number of longitudinal samplings** is driven by the desire not to worsen the $H \rightarrow \gamma\gamma$ mass resolution ($\sigma_{M\gamma\gamma}/M_{\gamma\gamma}$ <1.5%)
    - noting that, for a given p_T, energies in the endcap are much higher than in the barrel
    - silicon sensors constitute a 'thin' sampling medium

- The chosen thicknesses of silicon (for radiation tolerance reasons), and baseline choice of the number of layers (28) satisfies the above desire.
- The stochastic term is ~ 25%/√E.

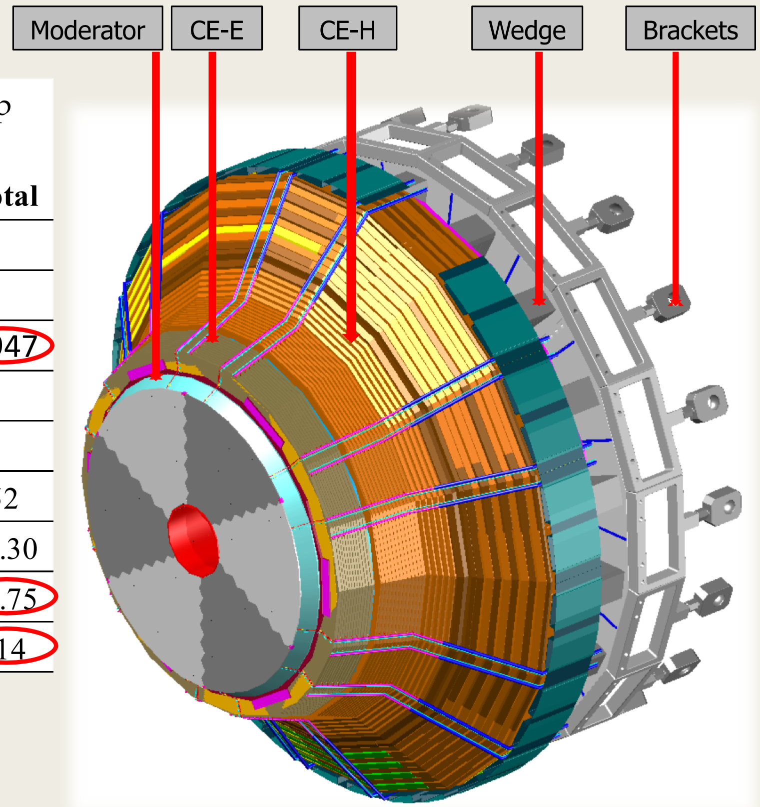




HGCAL Design Overview

Table 4.1: Size, weight, and structure of each endcap calorimeter (HGCAL)

	CE-E	CE-H (fine)	CE-H (coarse)	Total
z_{min} (mm)	3191	3530	4131	
z_{max} (mm)	3530	4131	5138	
Δz (mm)	339	601	1007	1947
r_{min} (mm)	320	357	420	
r_{max} (mm)	1680	2122	2664	
Layers	28	12	12	52
X_0 (CE-E)	26.3	-	-	26.30
λ	1.73	3.30	5.72	10.75
Mass (t)	23	36	155	214



Canter-levered structure:
C.O.M ≈1.2 m beyond support point on YE1 nose

HGCAL Longitudinal Structure

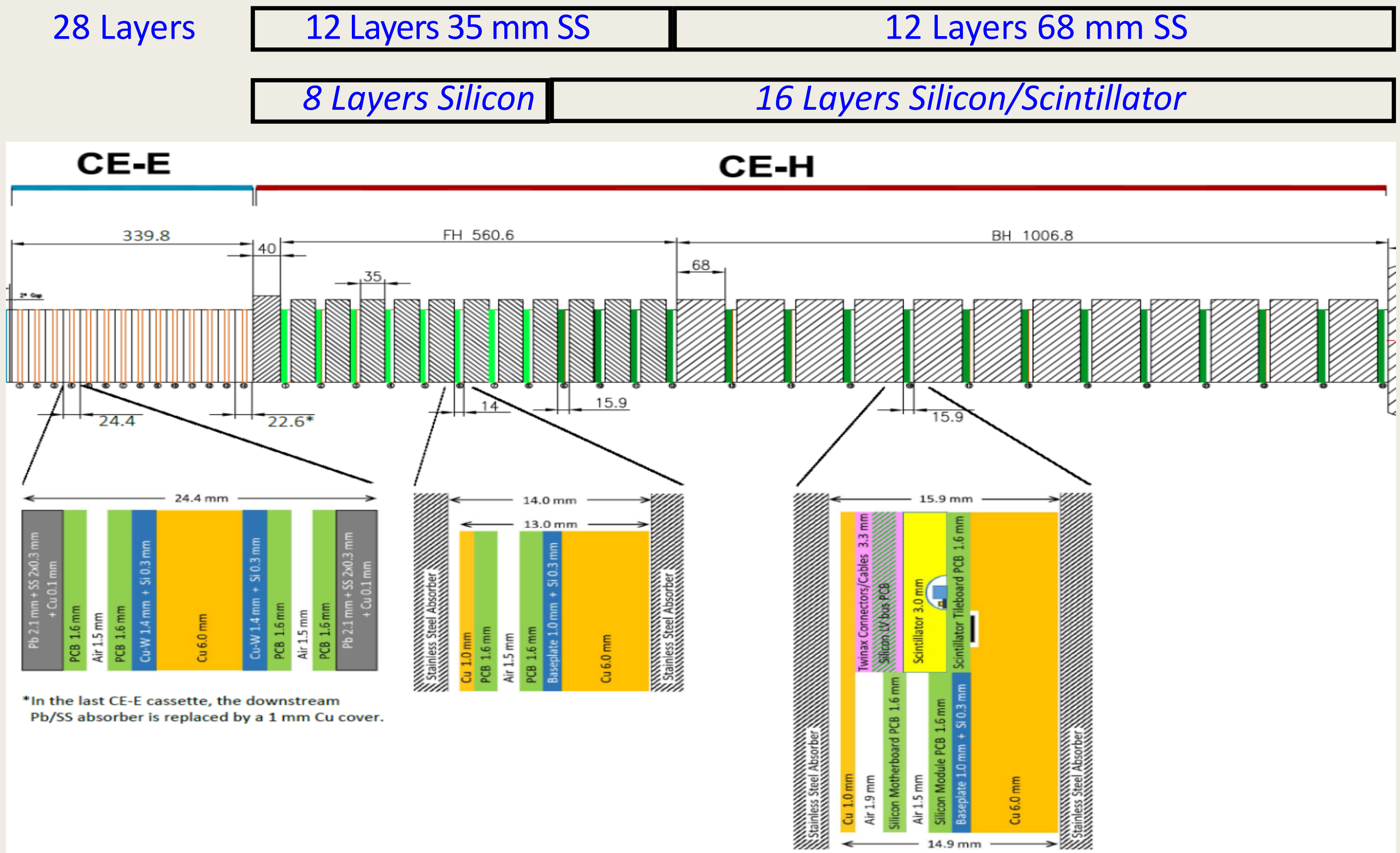
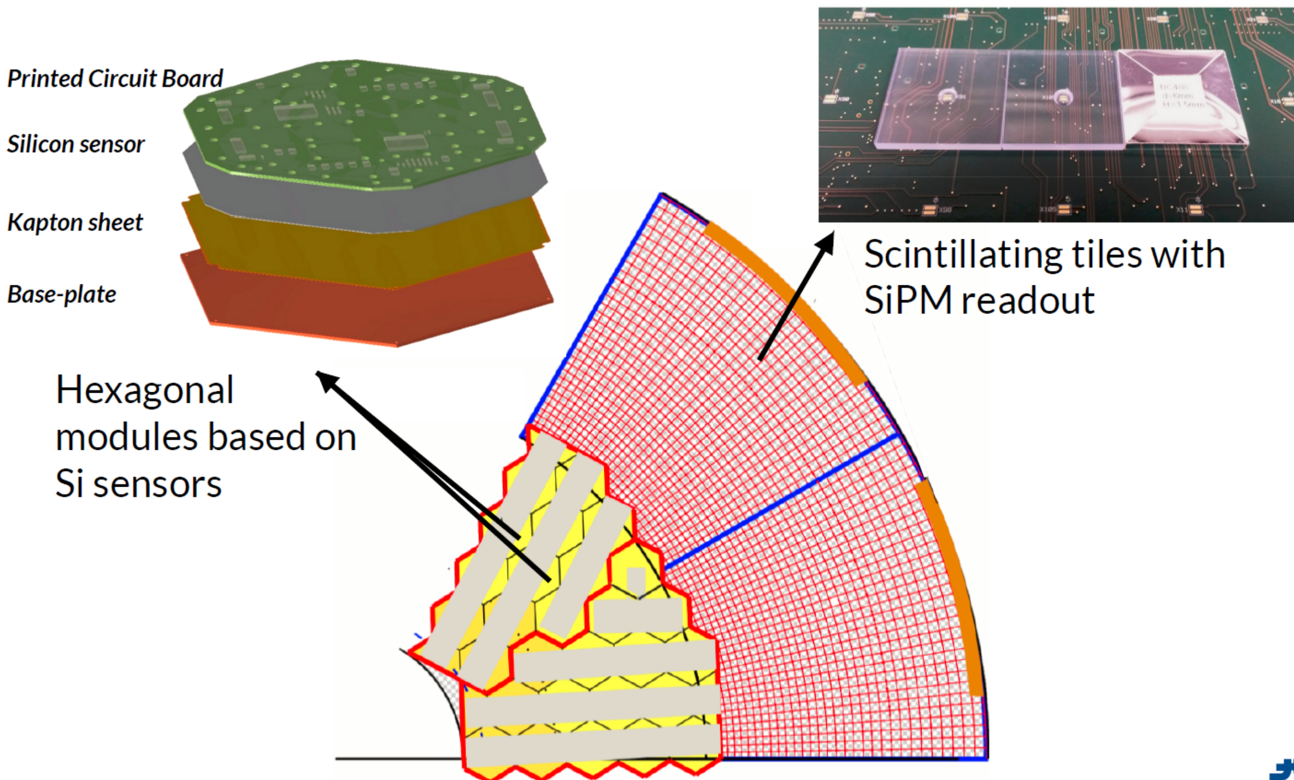


Figure 1.4: Longitudinal structure of the HGCAL, with schematic cross-sections of the three types of cassettes: CE-E cassettes, CE-H silicon sensor cassettes, and CE-H mixed silicon/scintillator cassettes. In the mixed cassettes the cross-hatched region is shared by the scintillator and silicon services in different angular regions.

HGCal Modules and Cassettes

- Cassettes provide support and cooling for the modules



Maral Alyari 4

SiPM-on-Tiles Modules

HL Milestones (2018-2019)
CE.SC.1 July 2019 Scintillator and tile board assembly technique selected

- **Scintillator tile modules (a la CALICE)**
- Scintillator (no WLS, ESR reflector
- + Tile board (~ 40x40 cm2, surface mounted SiPMs, ASICs, LEDs.

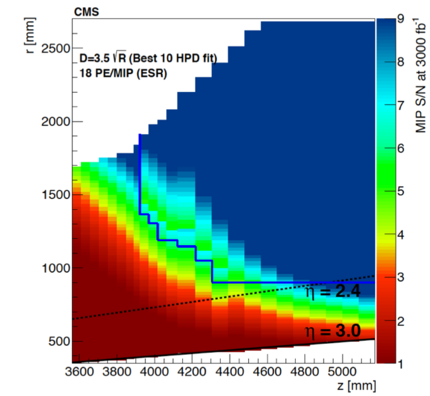
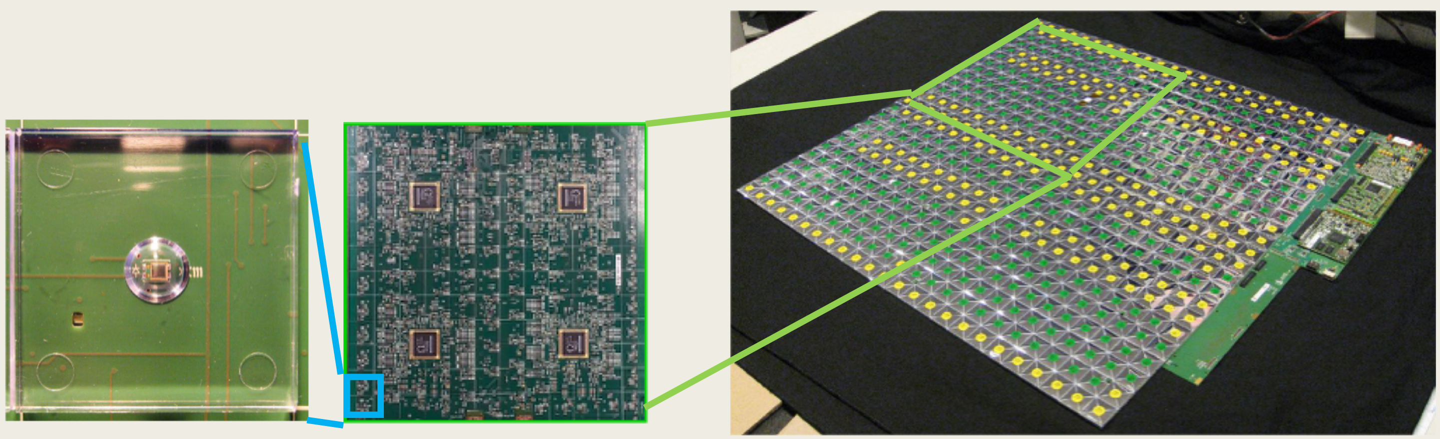
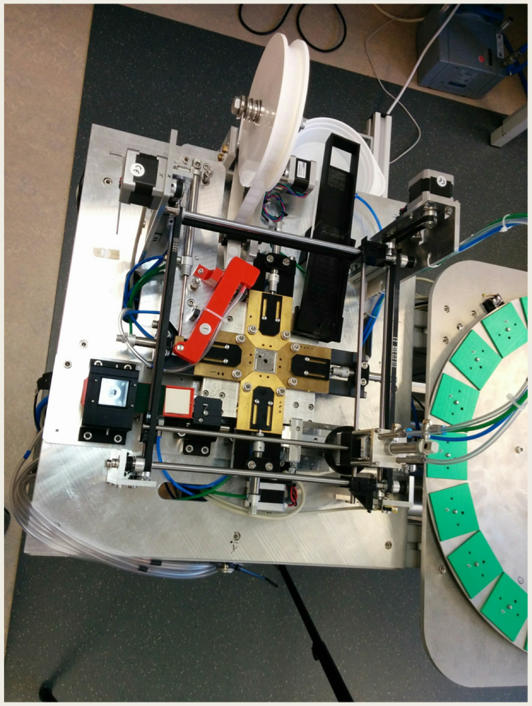


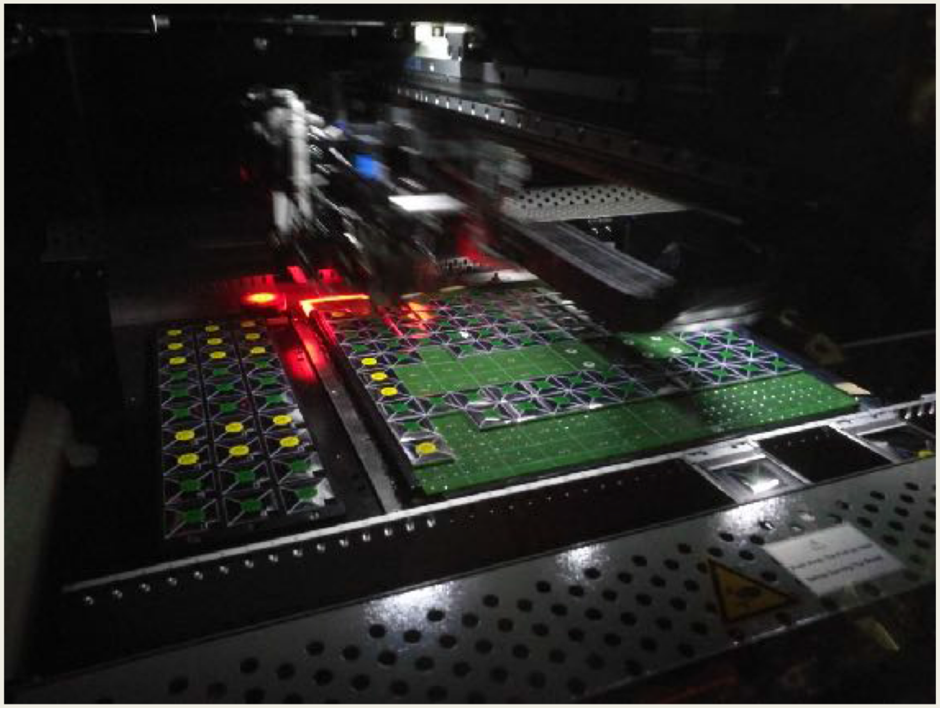
Figure 2.14: Signal-to-noise ratio for a MIP, after an integrated luminosity of 3000 fb^{-1}, shown as a two-dimensional map in r and z. The region, at larger z and r, in which SiPMs mounted on scintillator tiles can provide $S/N(\mathrm{MIP}) > 5$ after 3000 fb^{-1} is outlined.



SiPM-on-Tile Modules

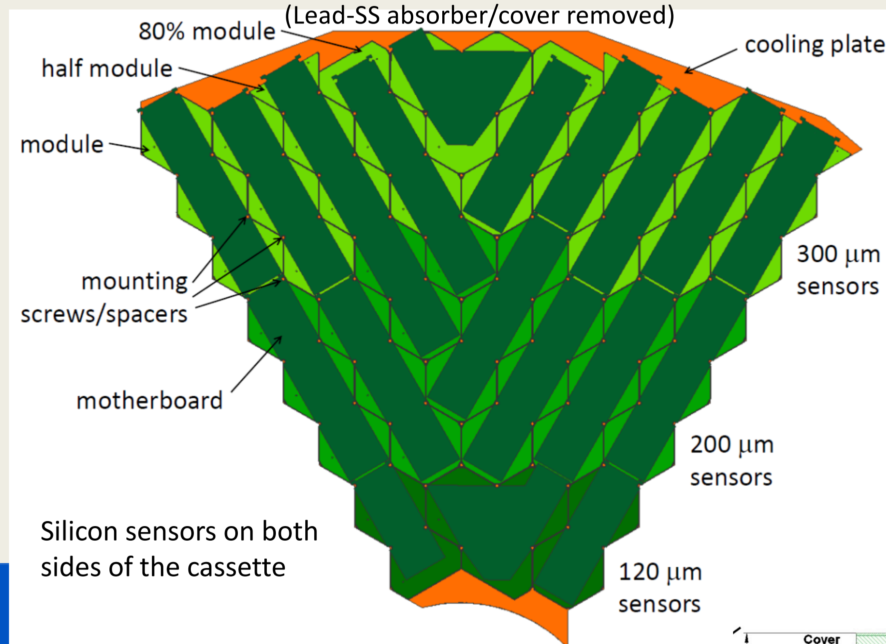
HL Milestones (2018-2019)
CE.SC.1 July 2019 Scintillator and tile board assembly technique selected

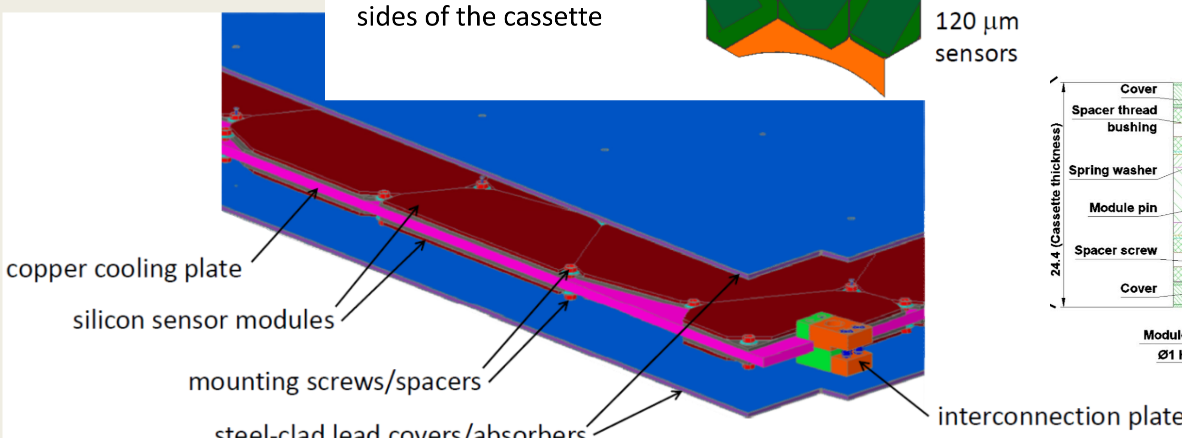


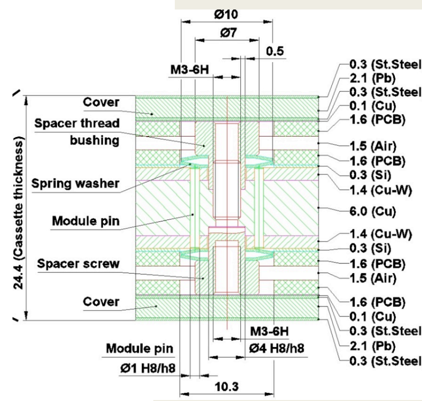


TACs: DESY (Lead Site), NIU/FNAL,
RDMS (Dubna or CERN?)

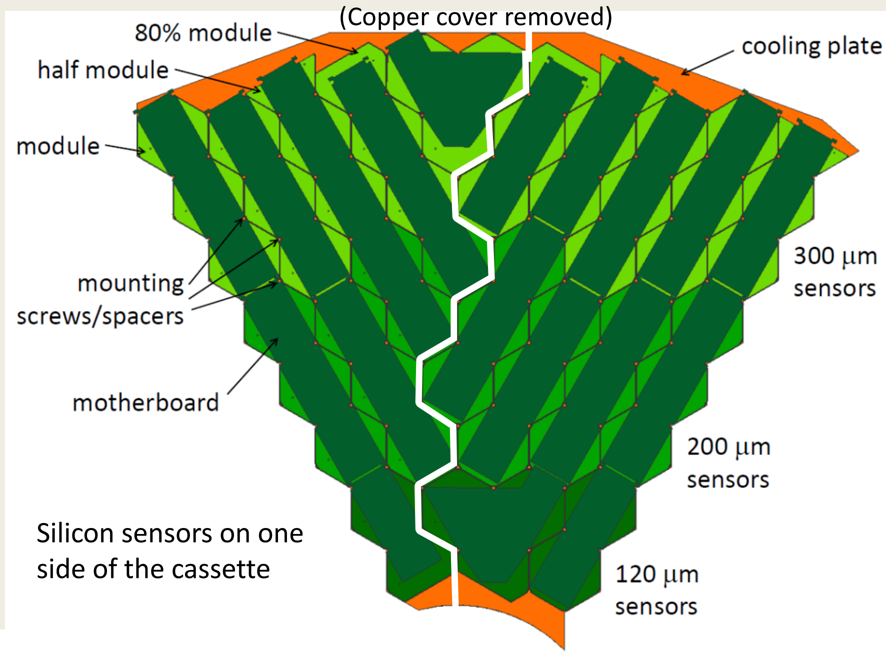
Silicon Sensor Cassettes (CE-E)

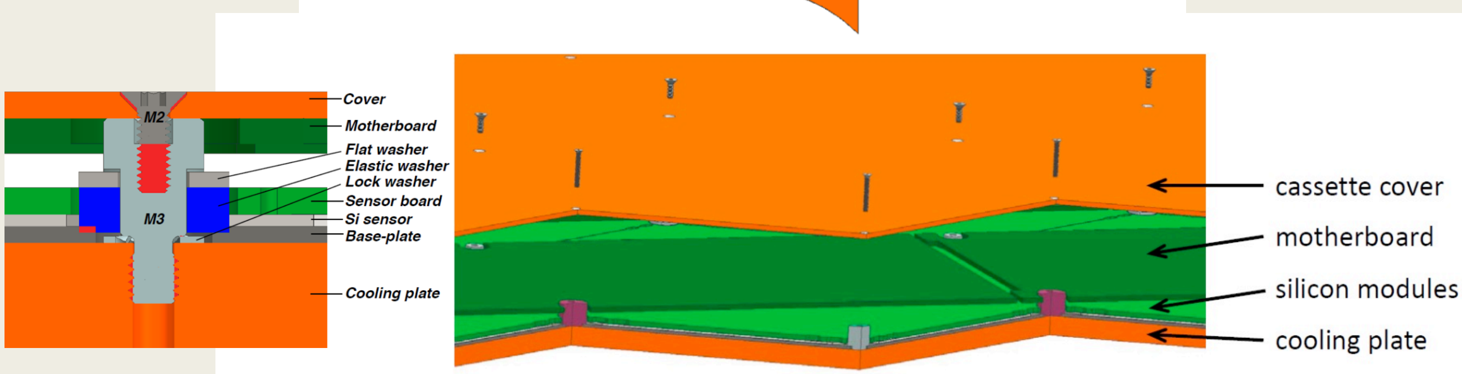




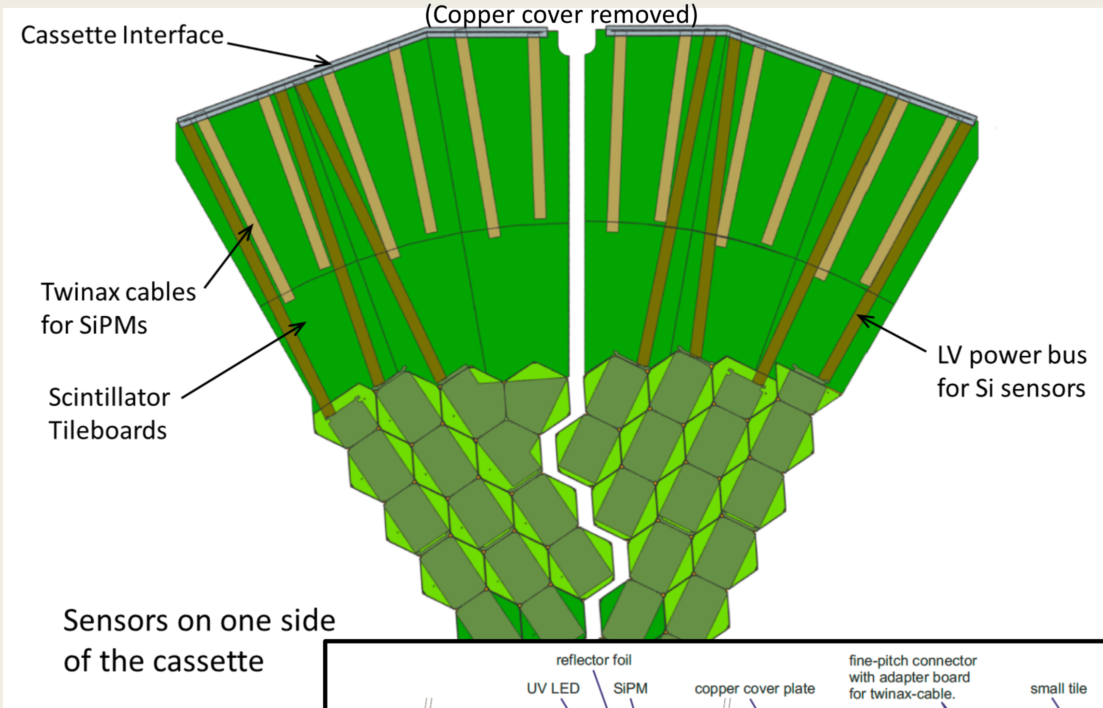


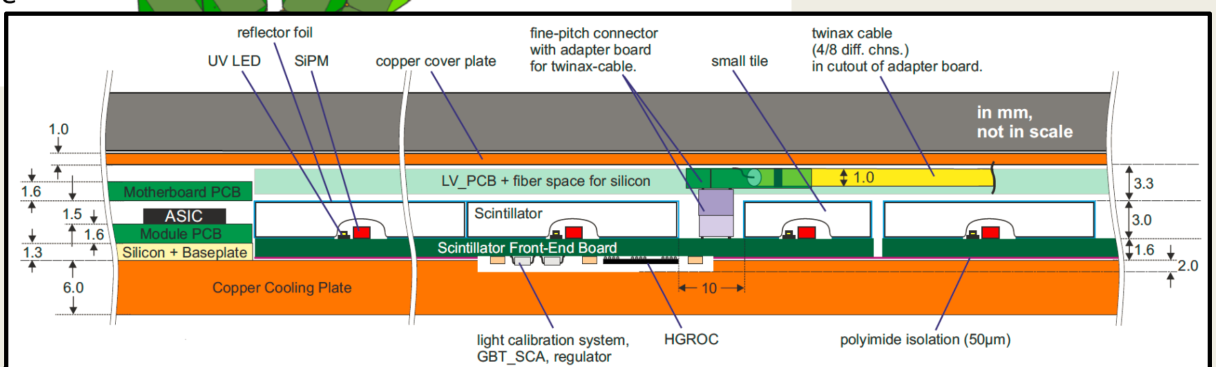
Silicon Sensor Cassettes (CE-H)





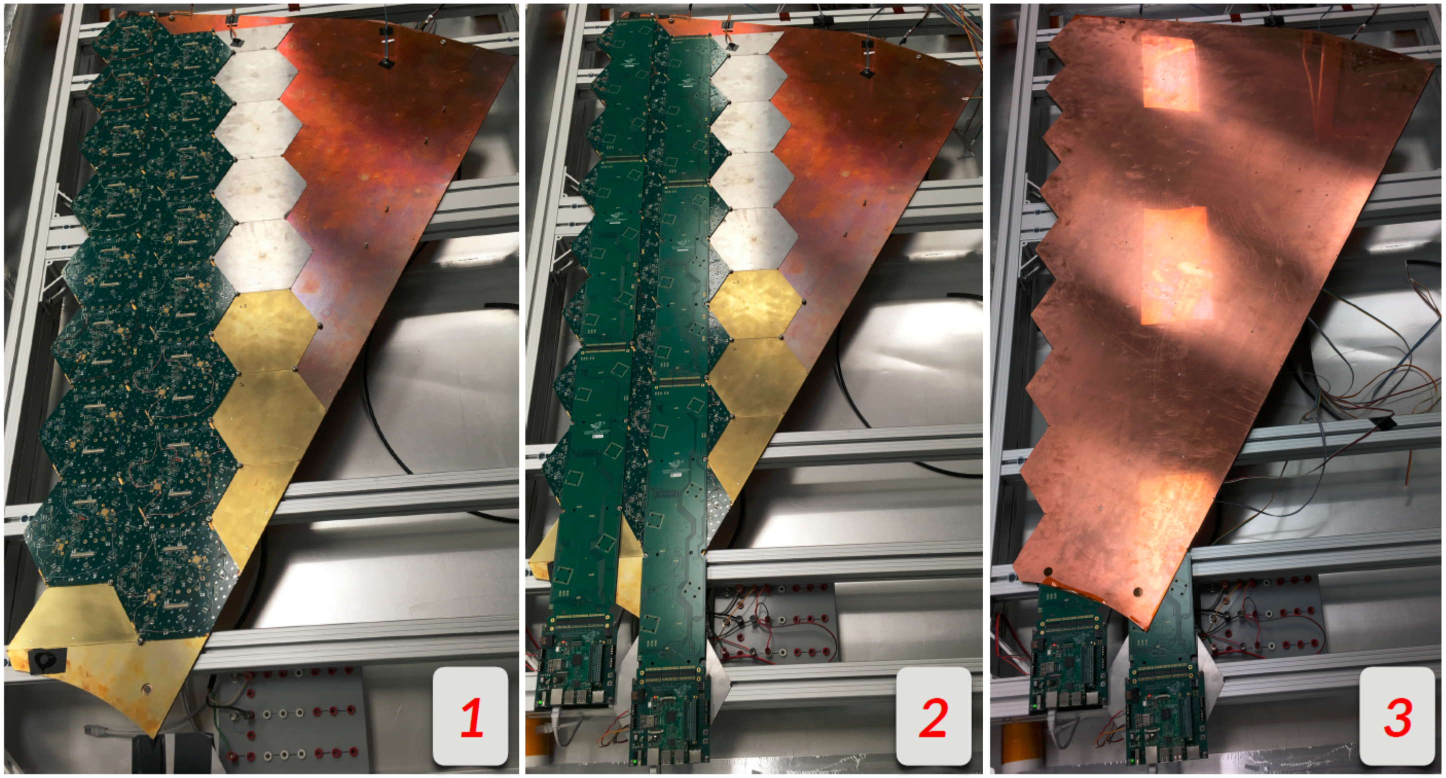
Mixed Silicon/Scintillator Cassettes (CE-H)



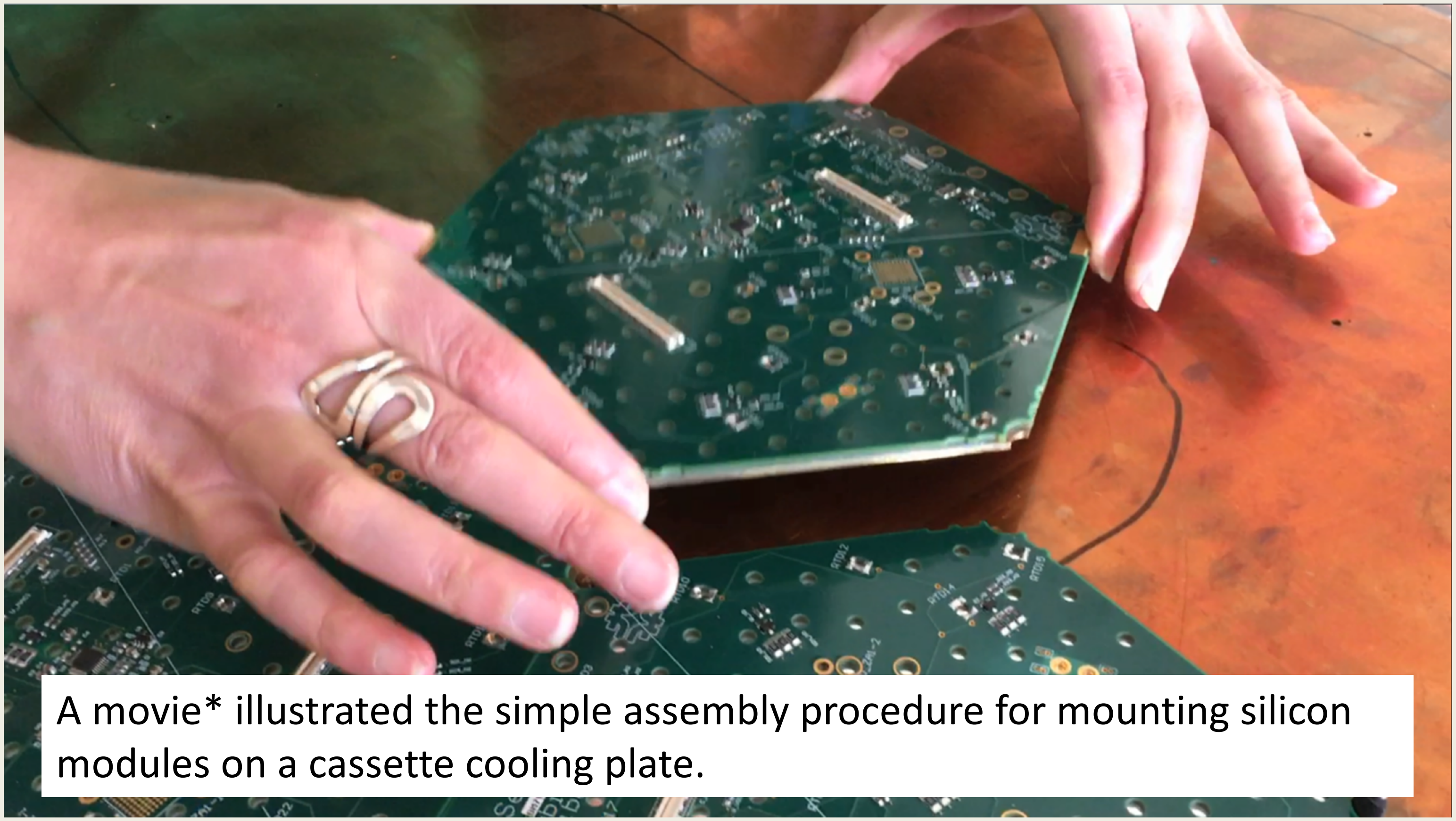


Assembled the Mock-up Cassette

- The mockup cassette has been fabricated, assembled and cold tested
  - 16 full modules and 6 motherboards



Assembling a Cassette



A movie* illustrated the simple assembly procedure for mounting silicon modules on a cassette cooling plate.

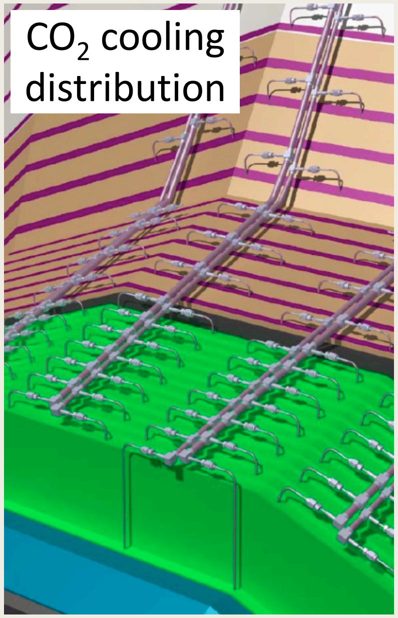
*https://indico.cern.ch/event/689924/contributions/2833142/attachments/1581219/2498774/MockupCassette.MOV

Cooling of the HGCAL

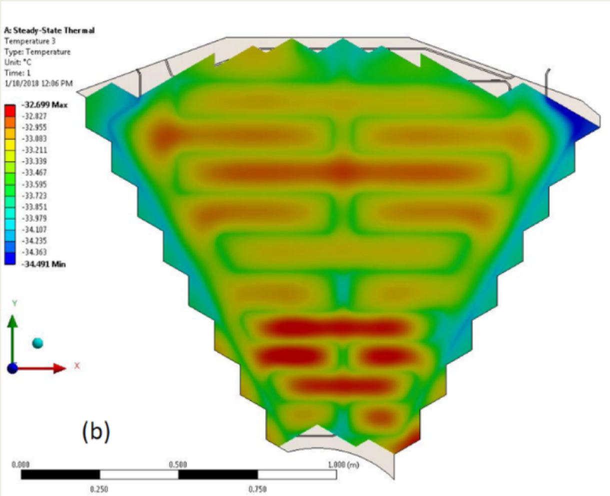
CO_2 cooling is distributed throughout the HGCAL via tubes embedded in cooling plates in each cassette.

- Covers the full radial extent of each layer
- Heat is dominated by electronics; removed as close to the source as possible.
- Large-area contact => low thermal impedance between silicon sensors and cooling plate.
- SiPMs well anchored thermally to the cooling plate.

CO_2 cooling distribution

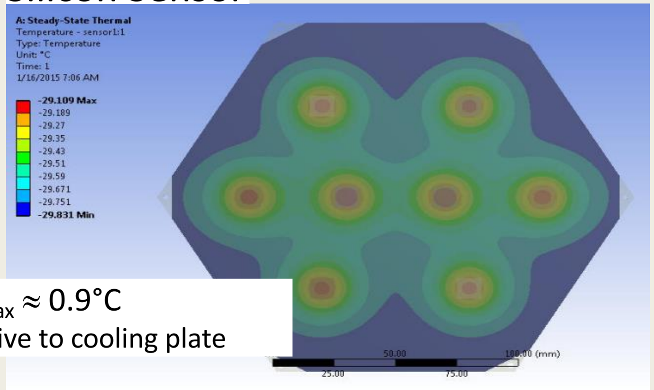


Cooling Plate



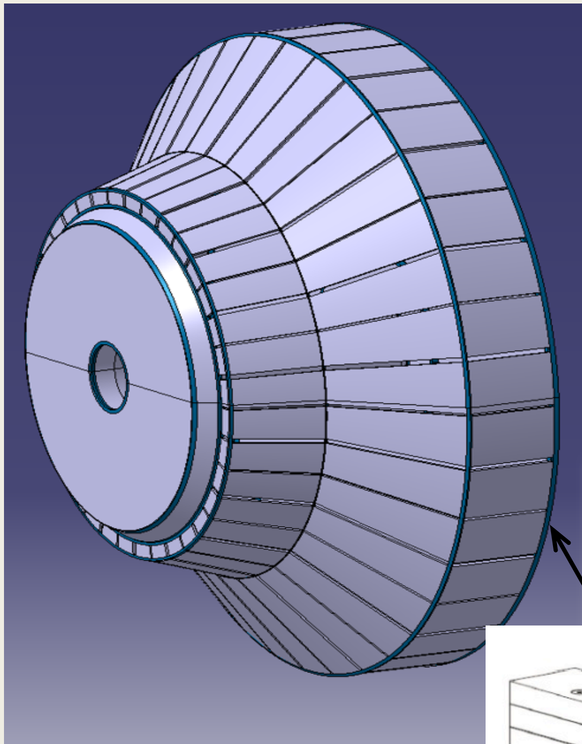
$\Delta T_{max} < 1.8°C$
highest power cassette

Silicon Sensor

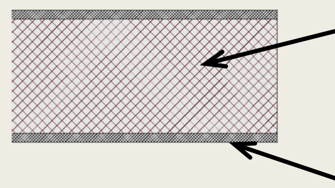


$\Delta T_{max} \approx 0.9°C$
relative to cooling plate

Thermal Screen and Feedthrough (TDR)

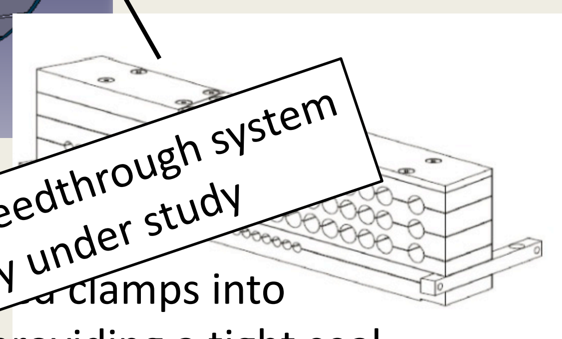


Thermal screen built from 20° wide panels,
15 – 32 mm thick depending available space



Insulating material:
Spaceloft Subsea
0.0145 W/(m·K)

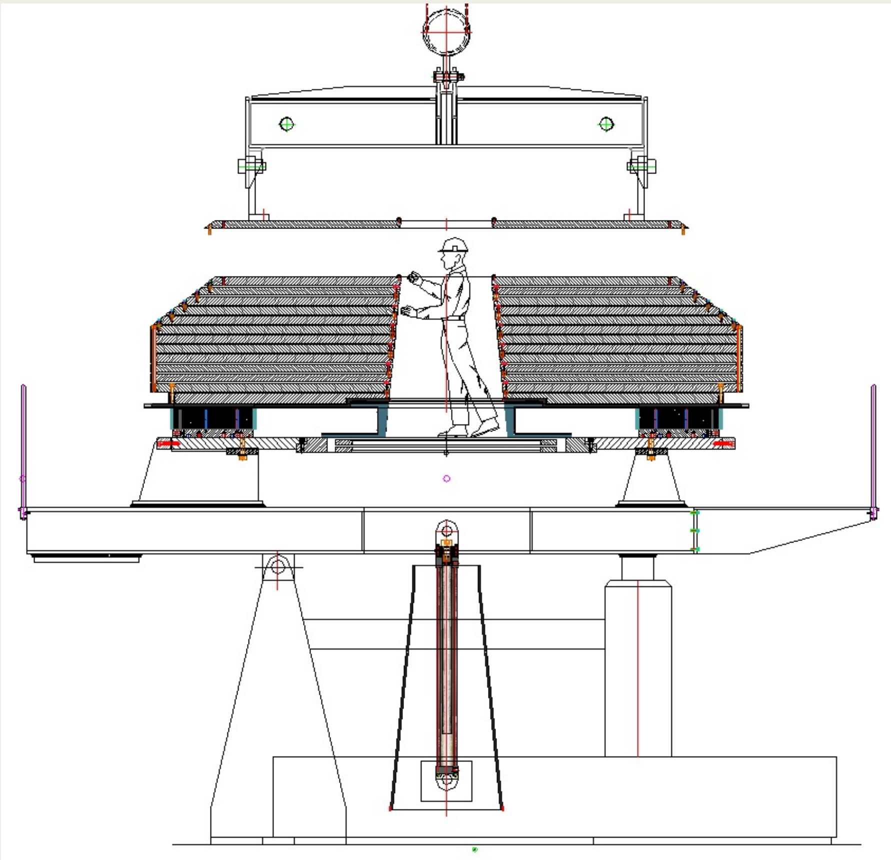
Skin material:
Permaglas ME771
0.35W/(m·K)



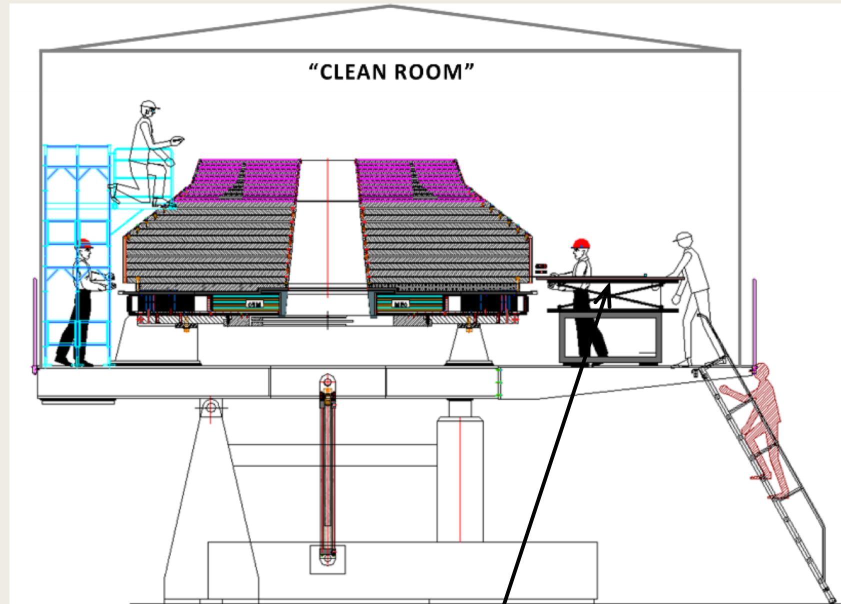
Warm-cold feedthrough
based on desig…
and pixels: cu… clamps into
which cables a… potted providing a tight seal

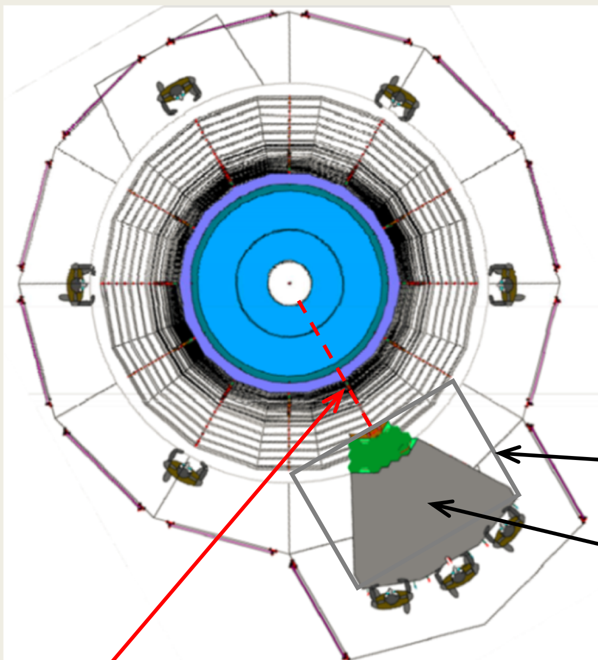
Design of feedthrough system
is currently under study

Assembling the CE-H: Stacking Absorbers



Assembling the CE-H: Inserting Cassettes





cassette insertion table

Two 30° cassettes joined
into 60° unit for insertion

cassette guiding system

Integration of CE-E with CE-H

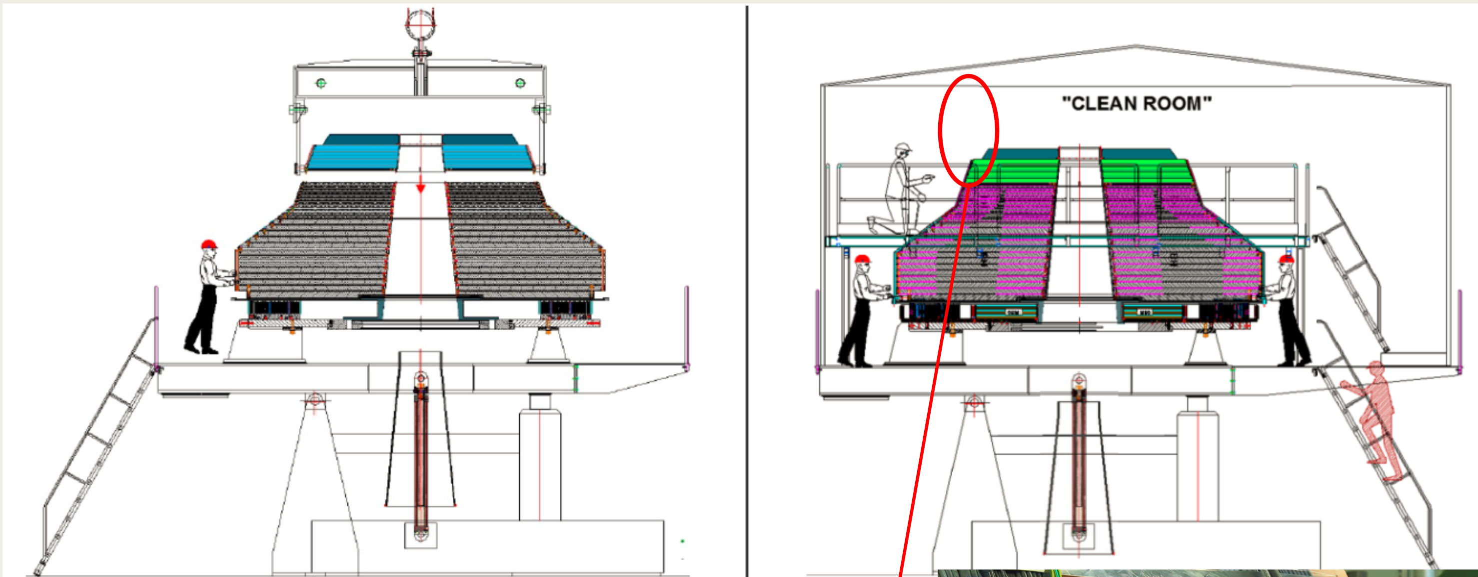
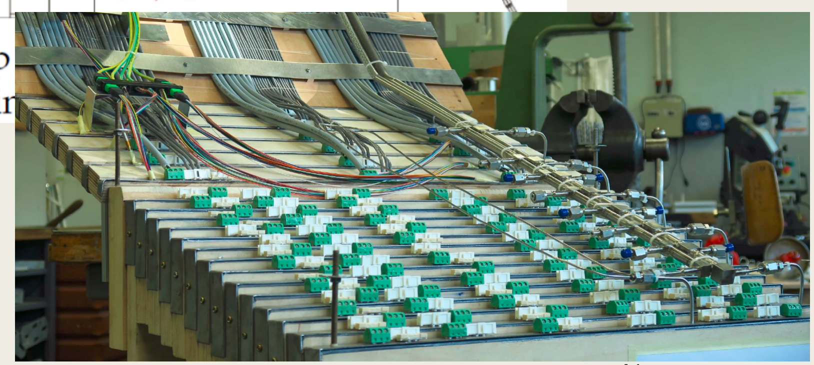
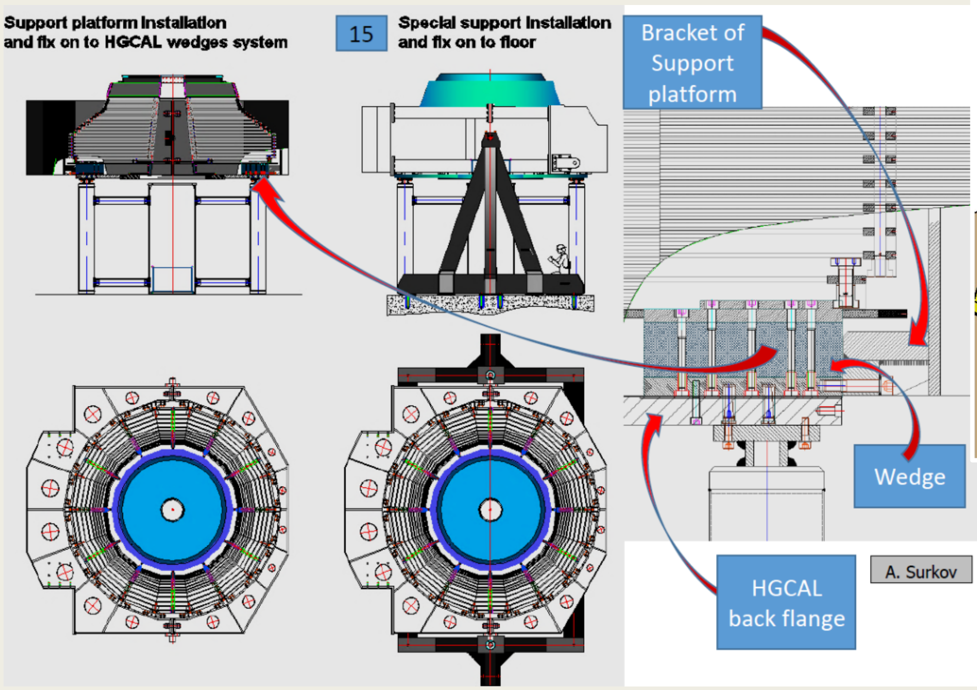


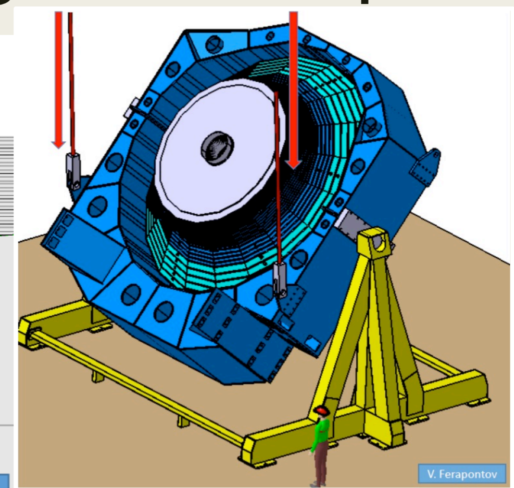
Figure 9.35: Left: Installation of the completed CE-E on top
CE-E electrical and optical services and installation of coolir

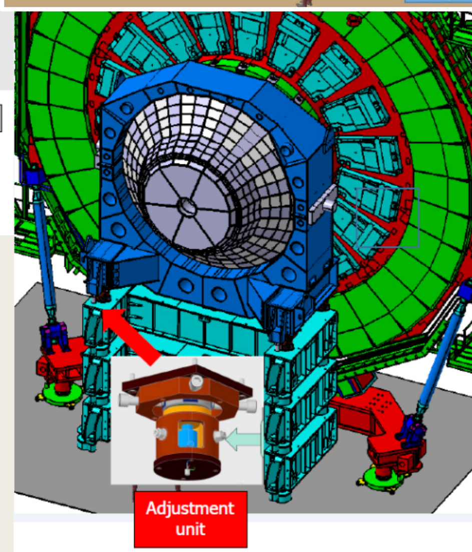


K.Rapacz

Installation Tooling Design Development







A. Surkov, V. Ferapontov

Engineering Summary

- The CE-H structure is a conventional design:
  - *Steel absorber disks with slots to insert active elements.*
- The CE-E structure is a different design:
  - *Lead absorbers are integral part of the cassettes*
  - *Cassettes are directly stacked against each other*
- Cassettes are key detector integration units
  - *Support active elements and integrate FE electronics*
  - *Provide robust cooling that removes most heat at the source*
  - *Part of CE-E structure; independent of CE-H structure*
- Assembly and installation tooling and procedures are under active development

Synoptic View of the HGCAL Schedule

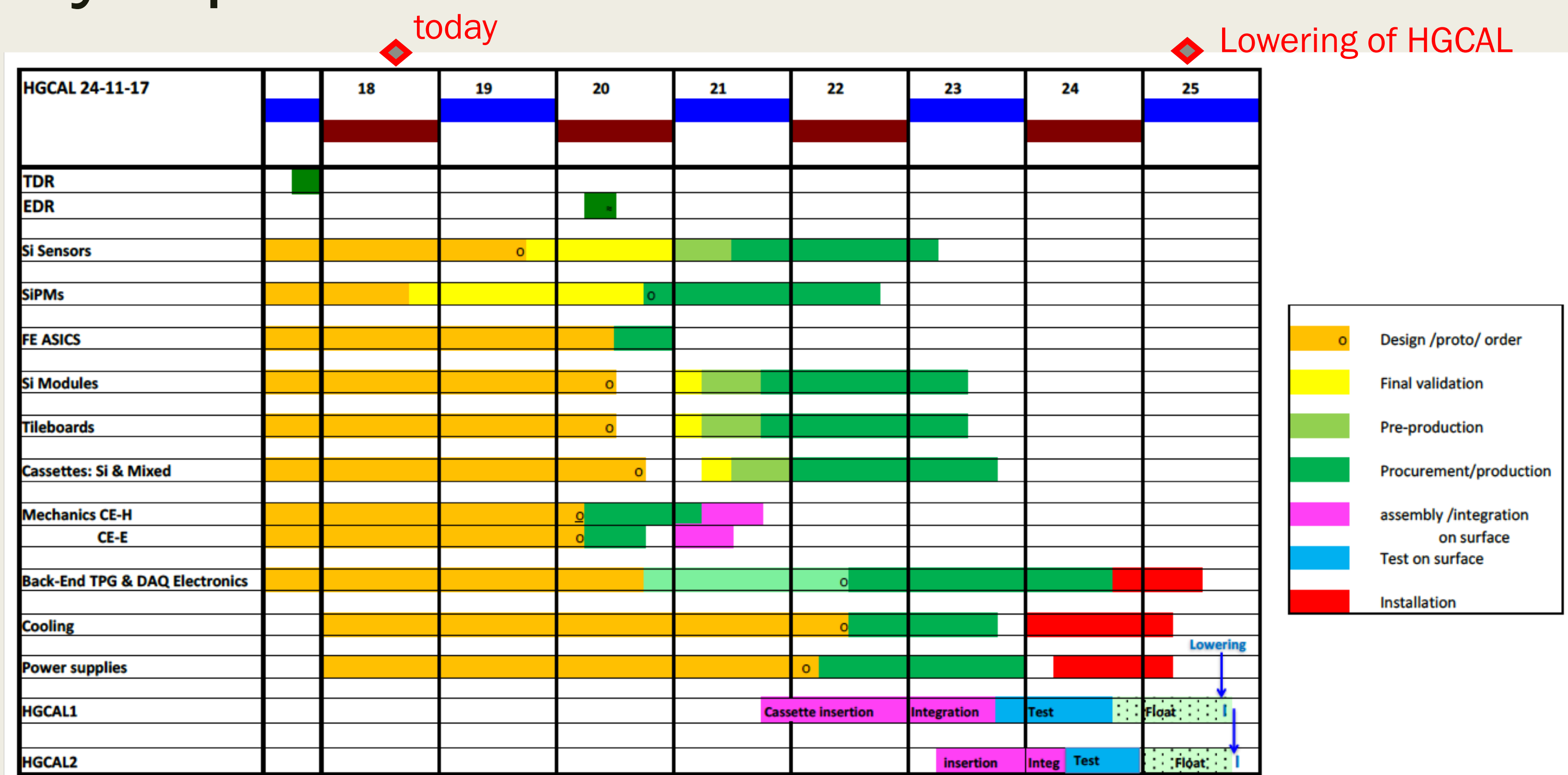


Figure 6.2: Simplified view of project timeline.

Participation of Minsk group in CMS Phase1 upgrade

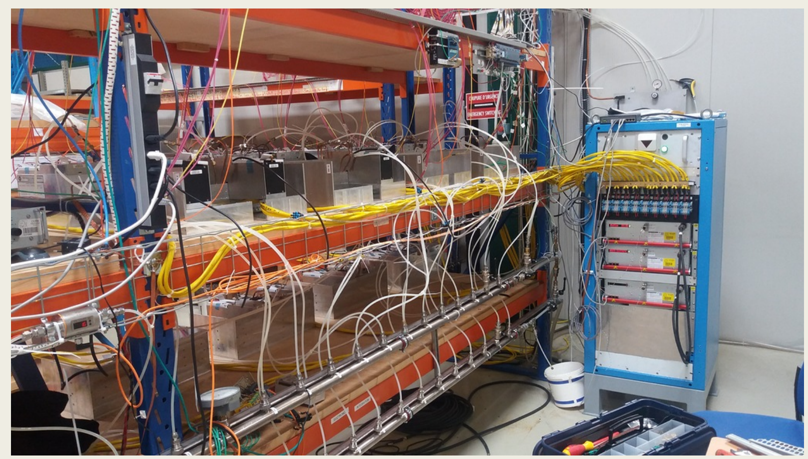
production of elements for HE and HB Front-End electronics

- Work performed in 2016-2017 by the joint CERN/Dubna/Minsk working group:

  1. Inspection of mechanical elements of HE Readout Modules according to the technical documentation.
  2. Test mechanical compatibility of the Readout Modules.
  3. Installation of HE Readout Boxes (RBXs) in the HE burn-in station, building b904 at CERN.
  4. Cooling test for the first HE RBX in the building b904.

  Participants:

- P. de Barbaro (CERN), P. Bunin (JINR Dubna) A. Litomin (INP Minsk), S. Savitsky ("Artmash" Minsk)



Participation of Belarus groups in the construction of CMS HGCAL

Number of particular projects for participation of Belarus groups in the construction of CMS HGCAL were suggested during recent visit of CMS management to Dubna and Protvino, with participation of Minsk group (A. Litomin, V. Tchehovsky):

- Design, procurement and manufacturing of CE-H Copper cooling plates
- Possible contribution in the Electronics sector
  - Front-End electronics Low Voltage powering:
    - Modules for housing of the DC-DC converters
  - Participation in R&D for PCB design
    - Preproduction, Production, testing and delivery to CERN

Summary

With the approval of the HGCAL TDR we enter the phase of finishing prototyping and the launch of construction of new CMS Endcap detector.

CMS is happy to have groups from Russia, Dubna and its Member States participate in the HGCAL Project in a mutually beneficial way.

In particular, CMS is looking forward to major contributions of Belarus groups to the construction of HGCAL detector.