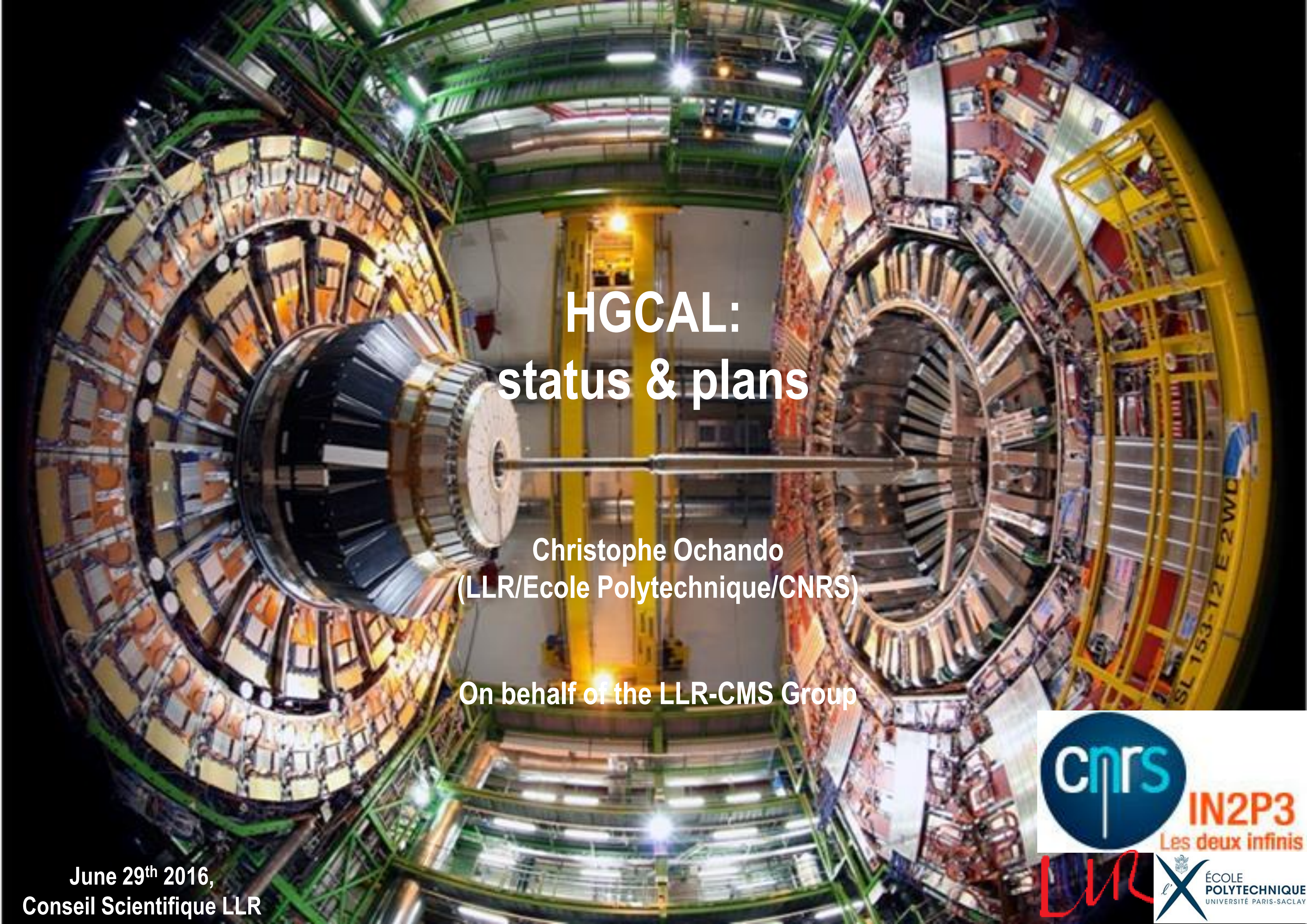


HGCAL: status & plans

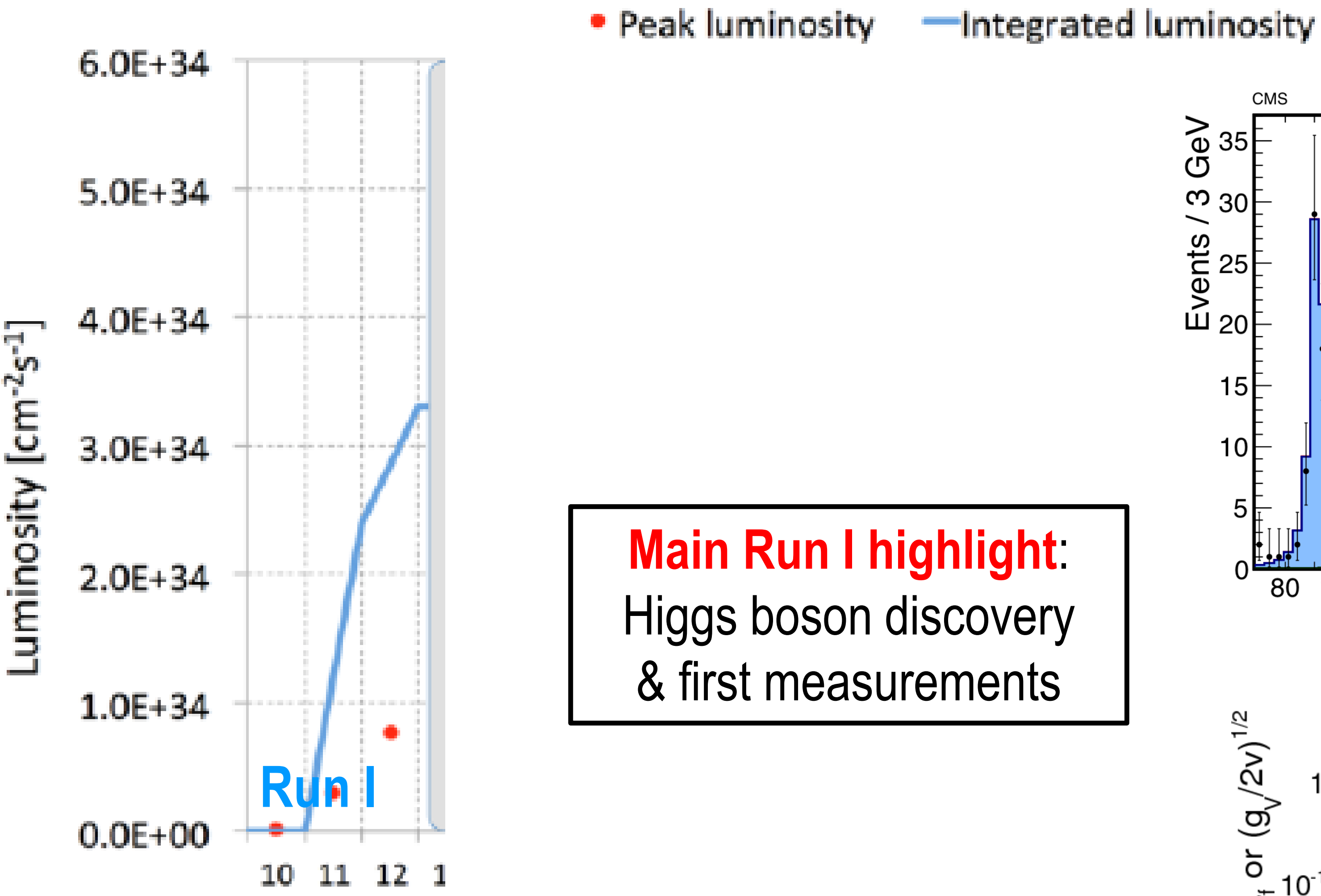
Christophe Ochando
(LLR/Ecole Polytechnique/CNRS)

On behalf of the LLR-CMS Group

June 29th 2016,
Conseil Scientifique LLR

cnrs IN2P3 Les deux infinis
LLR
l'X ÉCOLE POLYTECHNIQUE UNIVERSITÉ PARIS-SACLAY

LHC: from Run I to HL-LHC



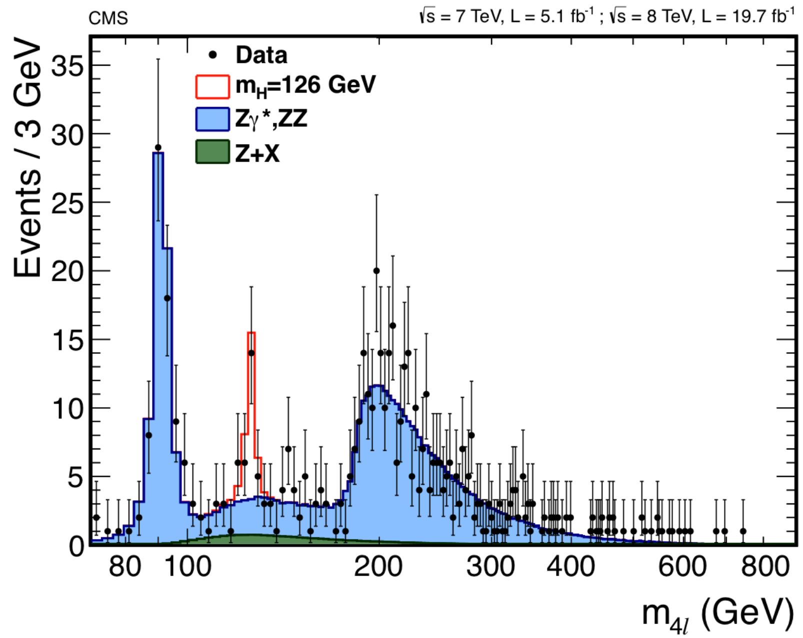
“Phase 0”,

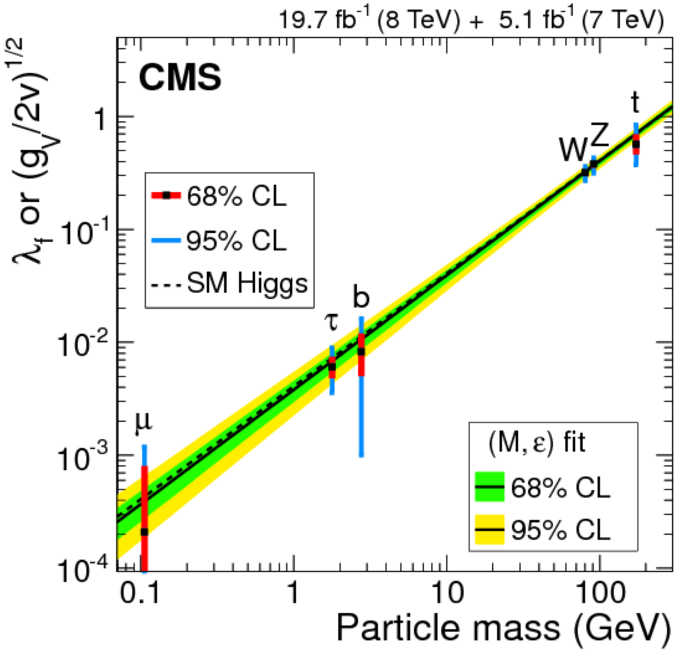
$\sqrt{s}$ = 7-8 TeV

$\int$ L dt = 25 fb^{-1}

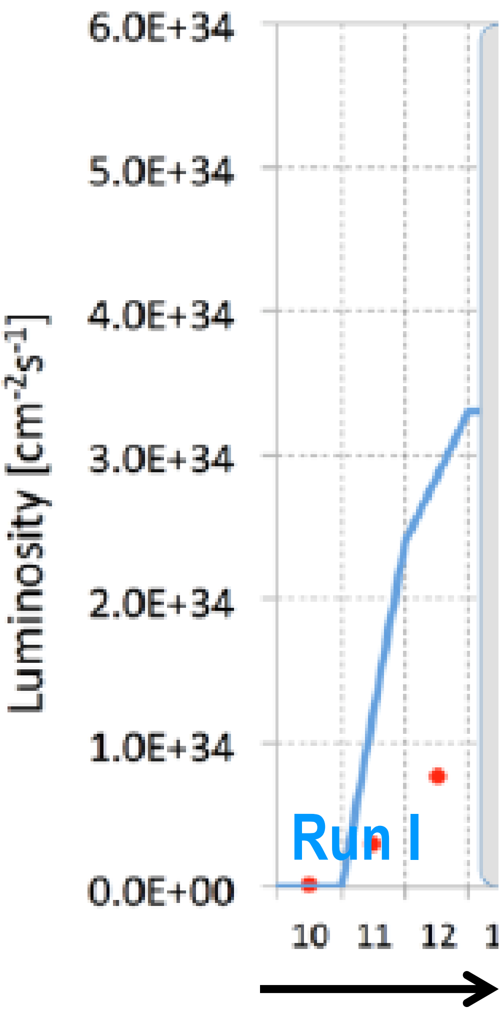
Higgs boson discovery

Main Run I highlight:
Higgs boson discovery
& first measurements





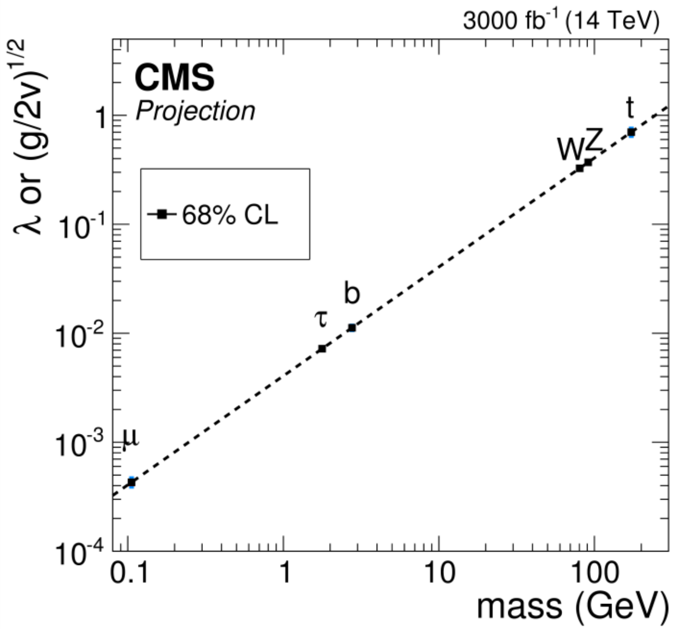
LHC: from Run I to HL-LHC



"Phase 0",

$\sqrt{s}$ = 7-8 TeV
$\int L\,dt$ = 25 fb^{-1}
Higgs boson discovery !

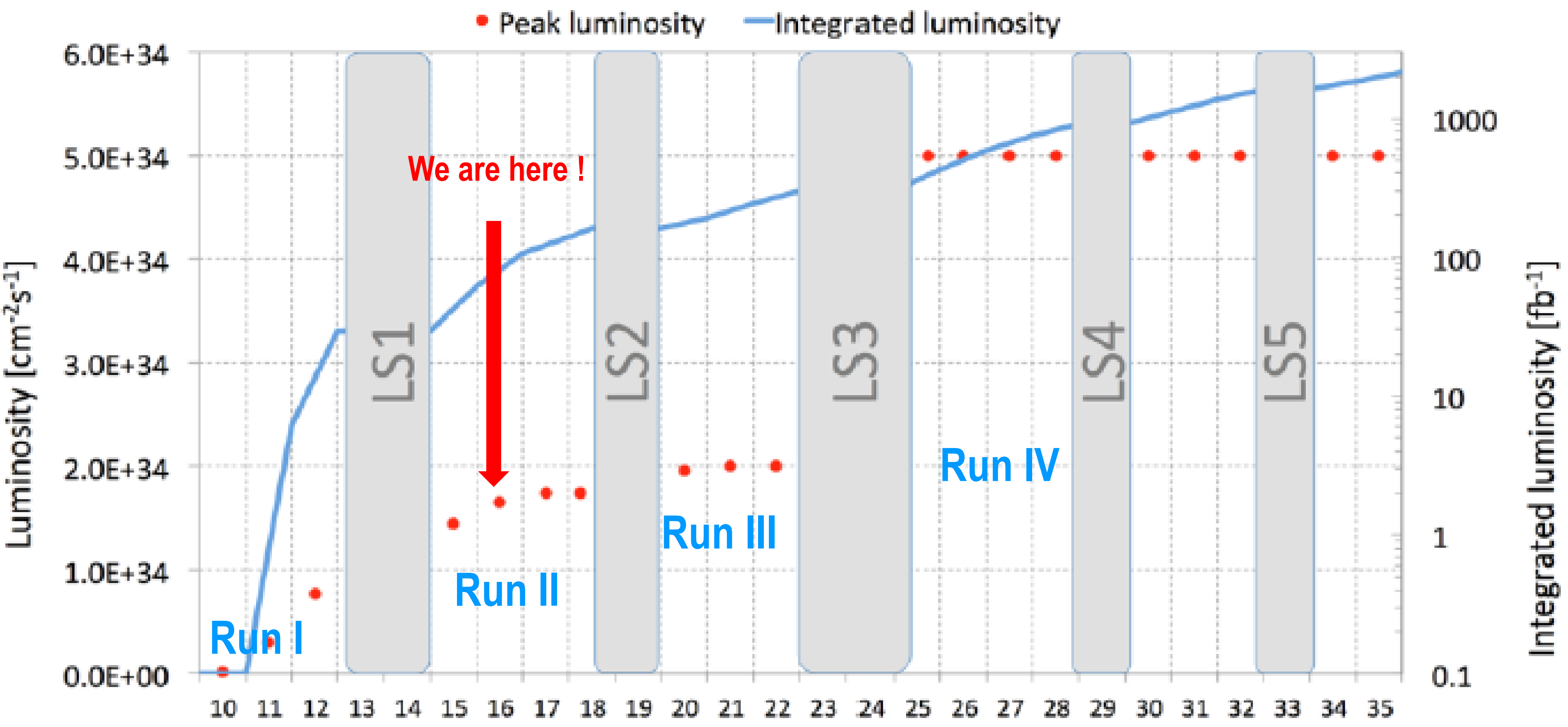
- **Unraveling the true nature of EWSB**
  - Precision measurement of the Higgs Sector
  - Observation of HH production, constraints on self-coupling λ
  - Rare ($\mu\mu$, $Z\gamma$…) or forbidden H_{125} decays ($\tau\mu$…)
  - Unitarity via Vector Boson Scattering



- **Search for new physics and/or measurements of BSM particles** (if found in $\geq$ Run II)
  - Extended Scalar Sector,
  - SUSY, Dark Matter, …

Powerful demand on **very high luminosity !**

LHC: from Run I to HL-LHC



"Phase 0",

$\sqrt{s}$ = 7-8 TeV
$\int L\,dt$ = 25 fb^{-1}
Higgs boson discovery !

Phase I

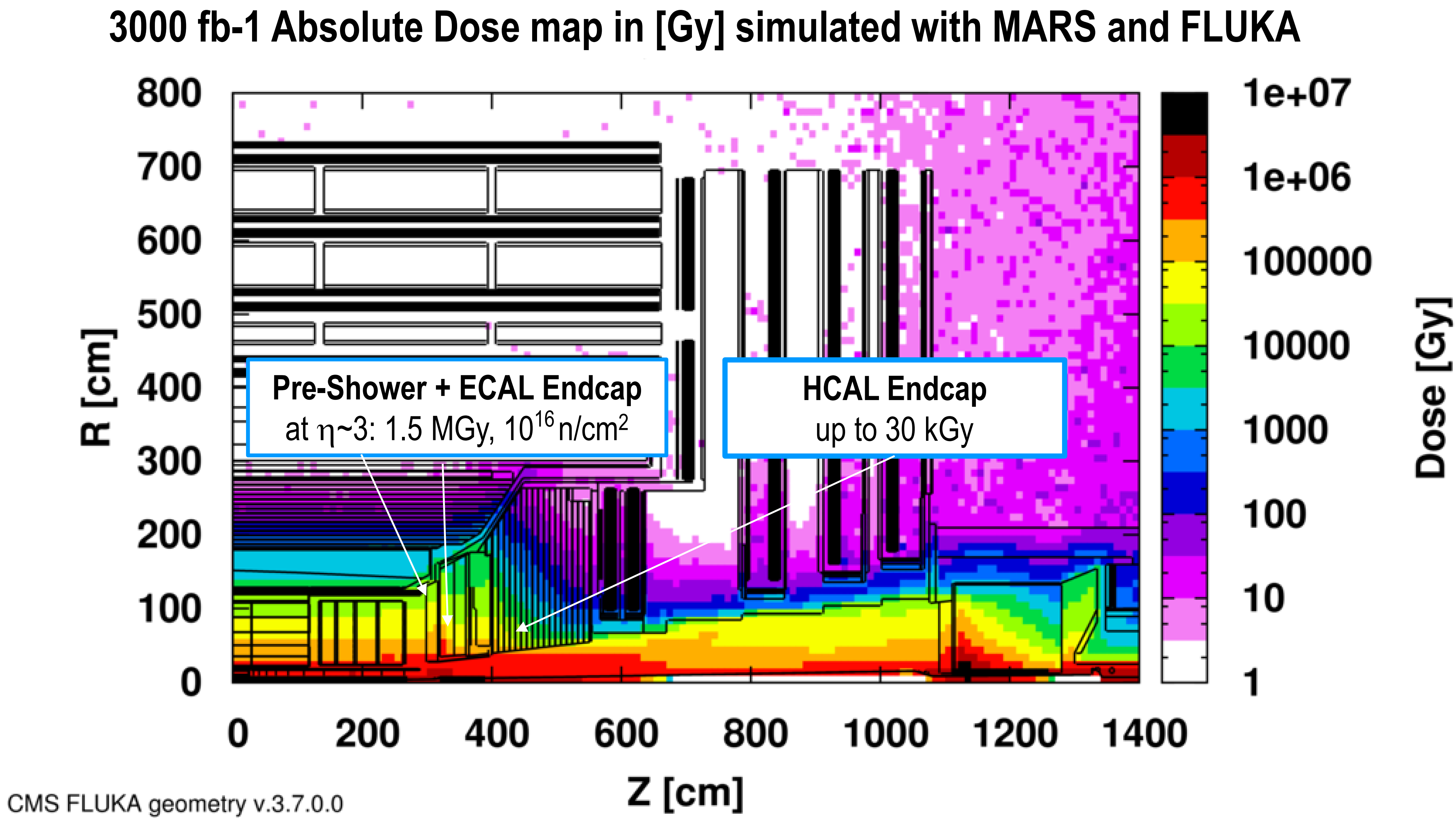
$\sqrt{s}$ = 13 TeV
Lumi inst. : up to 2.5x10^{34} cm^{-2}s^{-1},
$\int L\,dt$ = 300-500 fb^{-1}
<PU> : from ~25 to 60
X(750) ? SUSY ? ☺

Phase II (HL-LHC, >2025)

$\sqrt{s}$ = 13-14 TeV
Lumi inst. : >= 5x10^{34} cm^{-2}s^{-1},
$\int L\,dt$: 3000 fb^{-1}
<PU> : ~140-200

Well beyond design !

Challenges: Radiation damage



Aging studies shows that **Endcap Calorimetry (+Tracker) has to be replaced.**

Challenges: Pile-Up (PU)

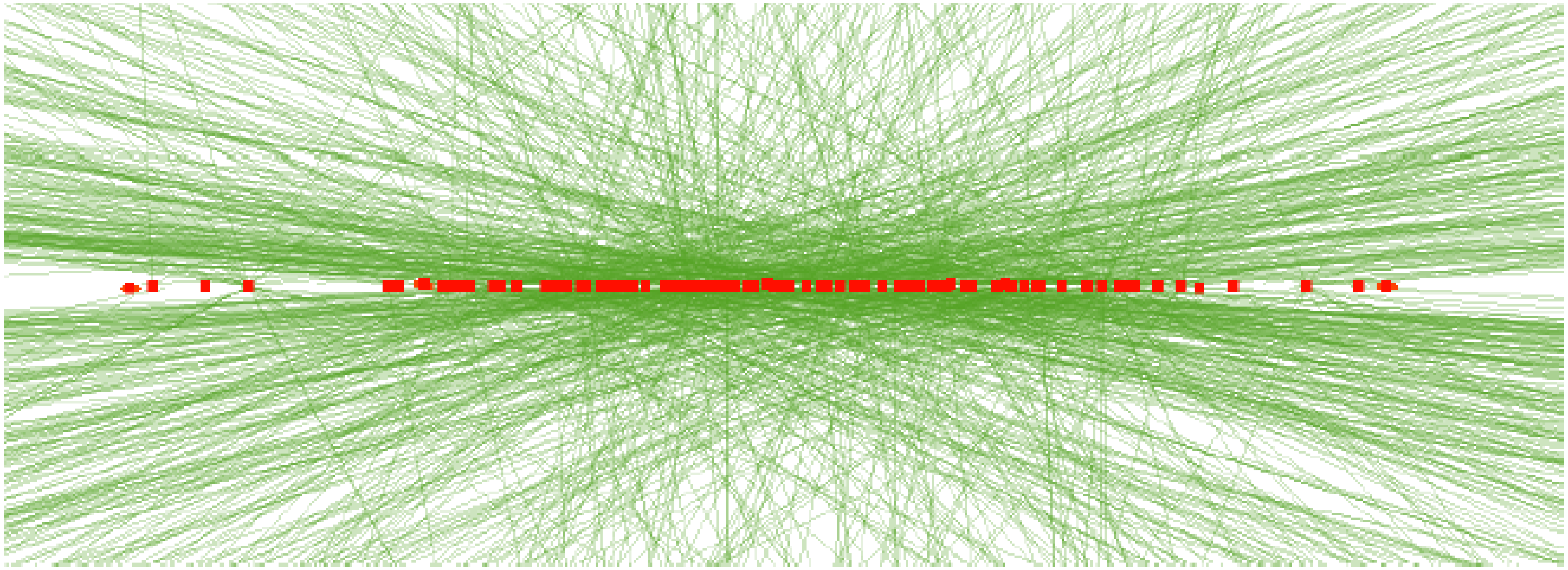


Figure 9.1: An event display showing reconstructed tracks and vertices of a simulated top-pair event with additional 140 interactions overlaid for the Phase-II detector.

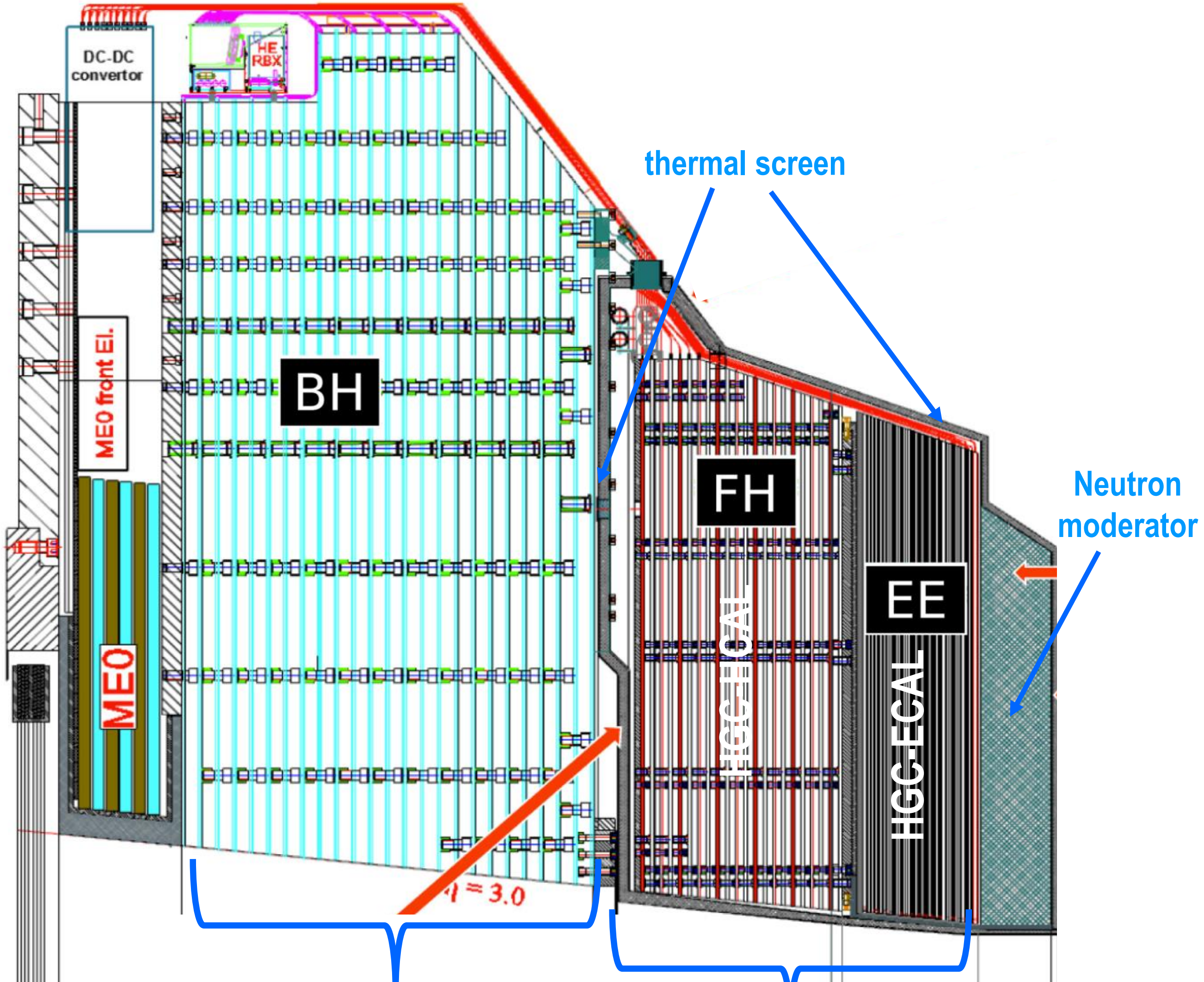
- HL-LHC Nominal Parameters:
  - 140 additional interactions per bunch crossing (every 25 ns) + out-of-time PU
    - Could go up to 200
  - Instantaneous Peak Luminosity: 5×10^{34} $cm^{-2}s^{-1}$,
- **Challenges for Triggers (especially Level 1 !) & offline reco + computing (30xLHC)**

Need to preserve "low" energy physics (125 GeV Higgs) and explore TeV scale (e.g. SUSY) in a very harsh environment !

HGCAL: General Layout

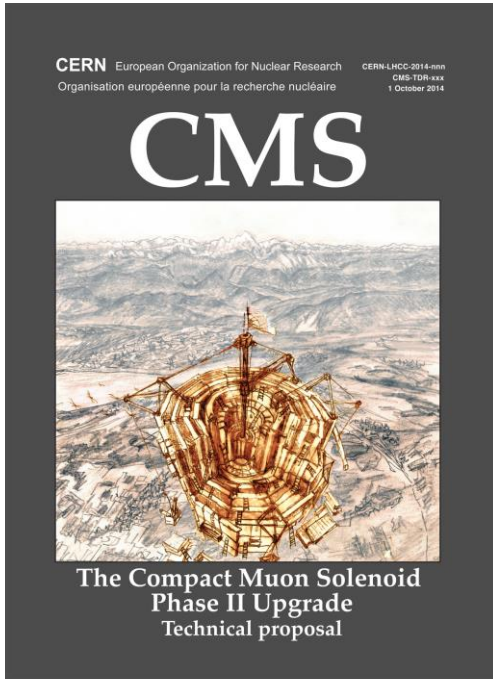
CMS choice: **High Granular Sampling Si-based Calorimeter [*]**
with 4D measurement of showers (energy, position)
(possibly 5D with timing) [**]

HGC+BH: covers η range up to 3



Back Hadron Calorimeter
(Brass or Steal + Scintillators)

HGC



Technical Proposal
CERN-LHCC-2015-010
(Juin 2015)

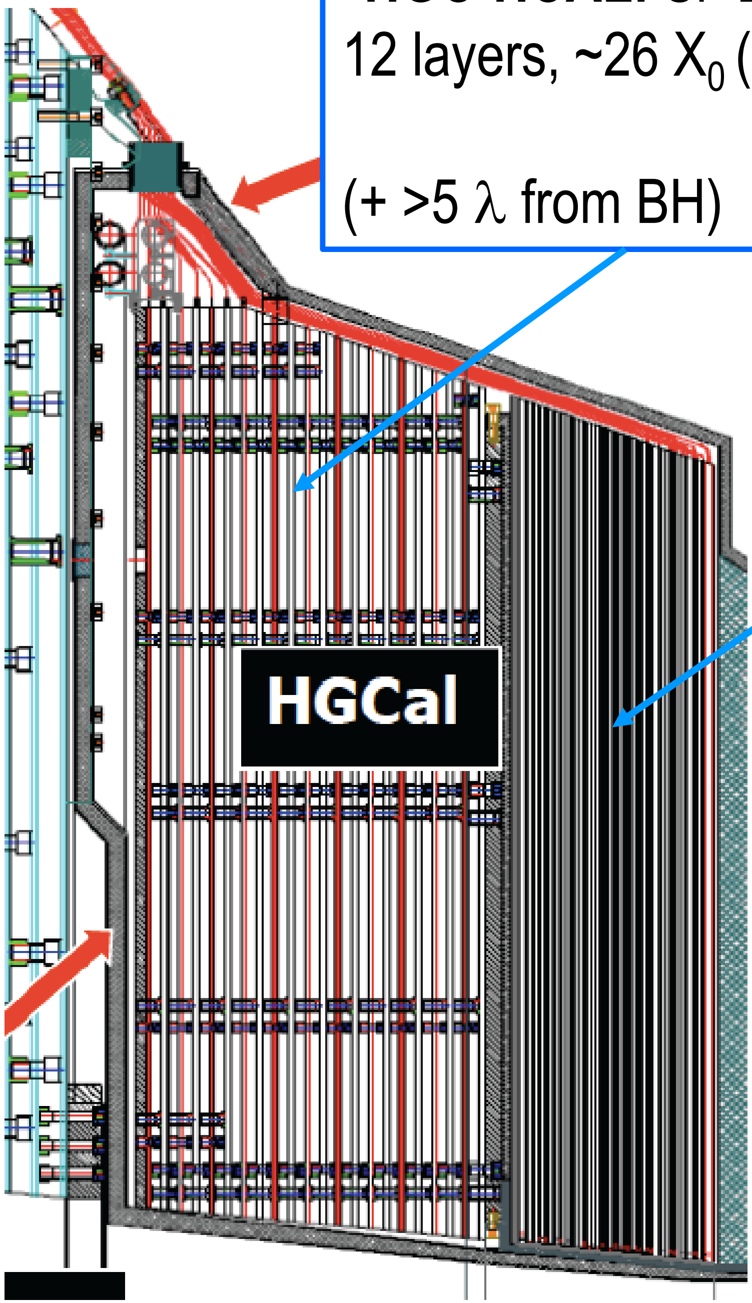
[*] thanks to CALICE developments,
progress on Si & data transmission

HGC Parameters

HGC-HCAL: Si+Brass or Steal
12 layers, ~26 X_0 (>3.5 λ)

(+ >5 λ from BH)

HGC-ECAL: Si+W/Cu
28 layers, ~26 X_0 (1.5 λ)
10 x 0.65 X_0 +
10 x 0.88 X_0 +
8 x 1.26 X_0



Operation at -30°C via CO_2 Cooling
(to mitigate Si leakage current)

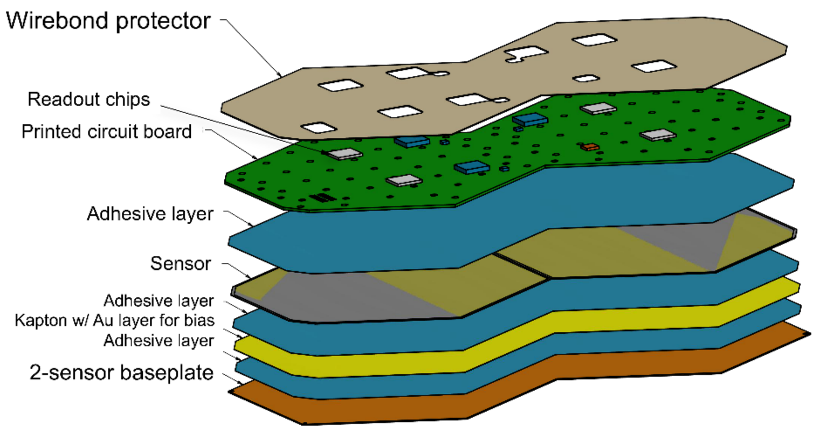
Table 3.2: Parameters of the EE and FH.

	EE	FH	Total
Area of silicon (m^2)	380	209	589(*)
Channels	4.3M	1.8M	6.1M
Detector modules	13.9k	7.6k	21.5k
Weight (one endcap) (tonnes)	16.2	36.5	52.7(**)
Number of Si planes	28	12	40

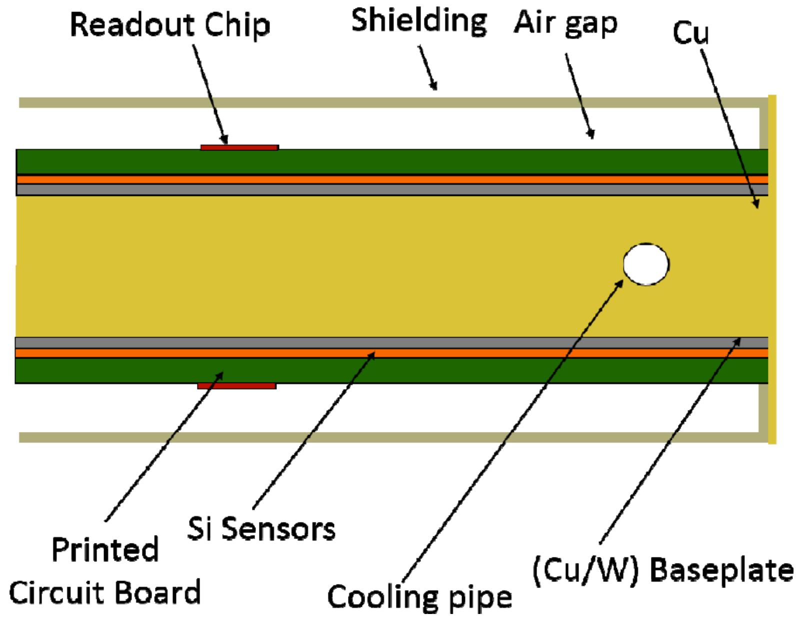
(*) 3x CMS tracker !   (**) one HGC+BH endcap: ~230 tonnes

Modules, Cassettes & Mechanics (Technical Proposal)

Modules
with 2x6 or 8” Hexagonal Si sensors,
PCB, FE chip, on W/Cu baseplate



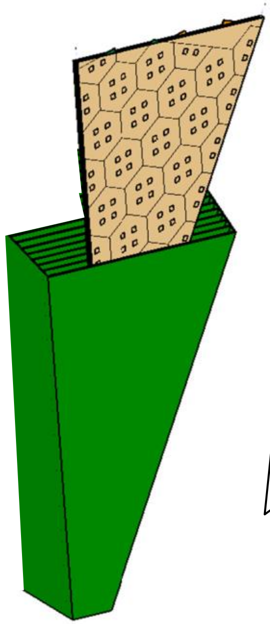
Modules mounted on
Cu Cooling plate with embedded pipes
== **Cassettes**



To cope the irradiation / PU:

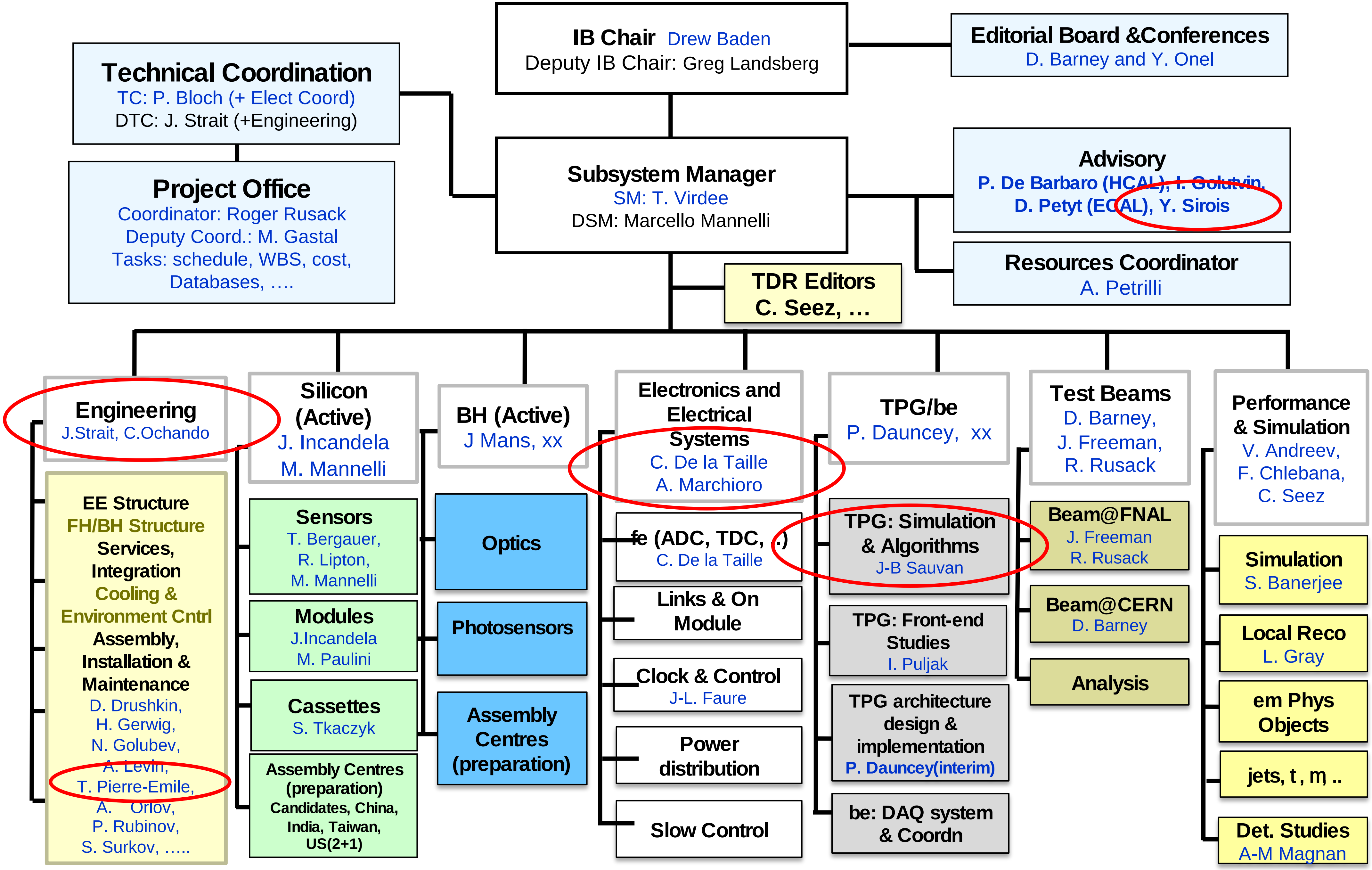
- η-dependent depletion of Si (100, 200 or 300μm)
- η-dependent cell size (0.5 cm² or 1 cm²)

Cassettes
inserted in **mechanical structure**
(containing absorber)

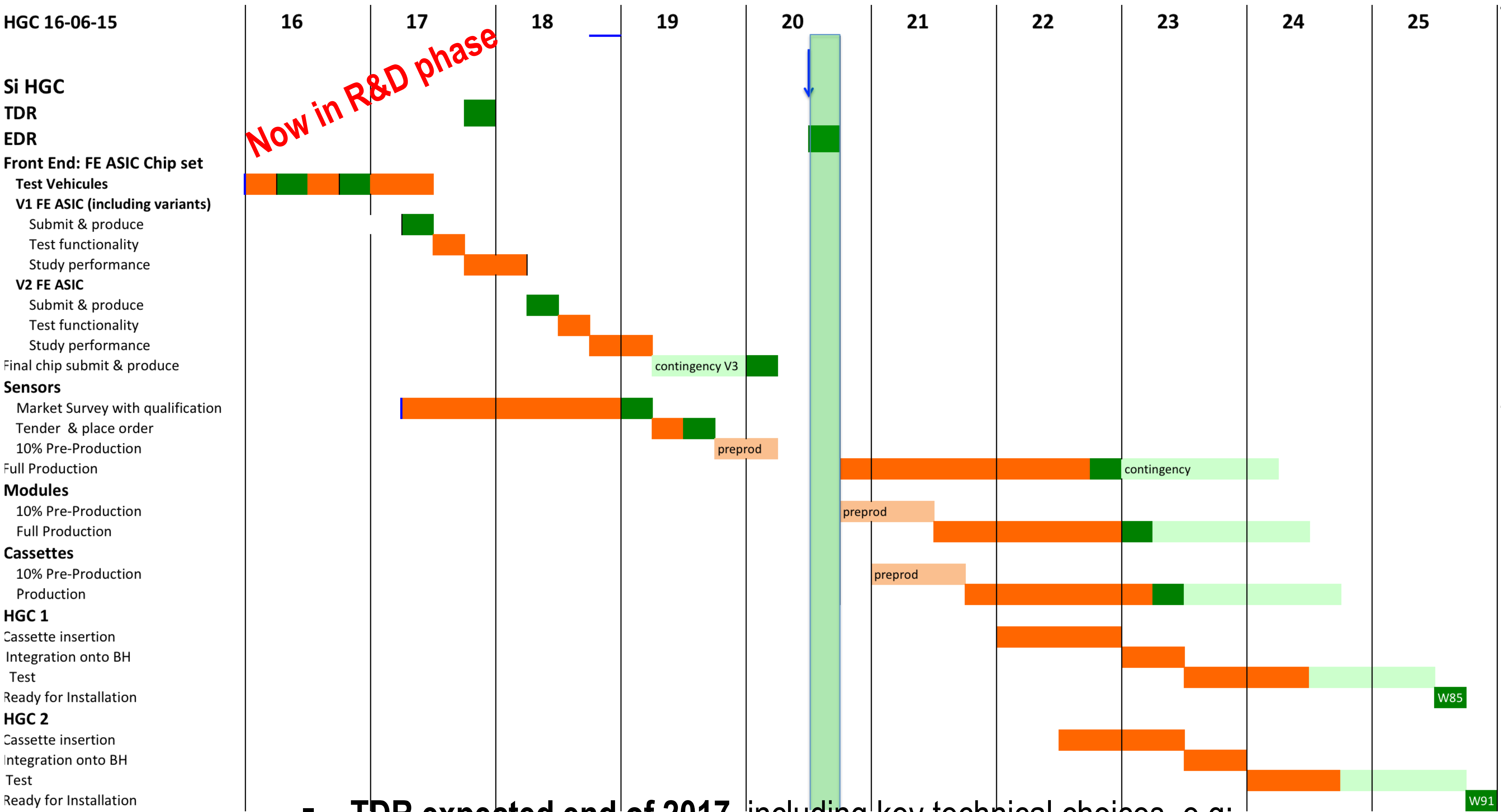


W/C-fiber EE alveolar structure

Endcap Calorimeter Project
Structure to Q1-17 (making Technical Choices, ..)



Timeline / Milestones



- **TDR expected end of 2017**, including key technical choices, e.g:
  - **EE structure (October 2016)**
  - All cold endcap or not (December 2016)
  - 6” or 8” Si Wafers (May 2017) …
- Construction starts in ~2020, Installation during LS3 (~2023)

Many hidden lines: other on detector components, mechanics, TPG/BE, Test Beams, software…

Hardware HGCAL pour CMS à l'X

Chapeau:
Ecole Polytechnique/IN2P3
HGCAL Finance Board and Institution Board: **Y. S.**

Economie du ticket d'entrée CMS pour le laboratoire Oméga; ∀ accès via CMS-LLR

Laboratoire **OMEGA**
X / **IN2P3**

Laboratoire **LLR**
X / **IN2P3**

FE chip
Ch de la Taille et al.

Back-End Electronics
J.B. Sauvan et al.

Mechanics
C. Ochando et al.

Omega (Fr.),
Timing: IC London (UK) ?
SPP Saclay (Fr.) ?

HGCAL FE chip
SKIROC-CMS
Test Vehicules

LLR (Fr.), CERN, FESB Split (Cr.), SPP Saclay (Fr.), IC London (UK), Minnesota (USA)

Trigger
J.B. Sauvan et al.
Architecture,
Trigger primitive generation***
Simulation & algorithms

LLR (Fr.), CERN, RDMS

ECAL
Design & structures
Simulations

- **Mechanics:** C.O, Th. Pierre-Emile, Y.S., (M. Frotin)
- **Trigger:** P.Busson, S. Baffioni, T. Romanteau + JB. Sauvan (CERN)
- **Perf.:** C. Charlot, R. Salerno, Y.S.
- *Tests pour FE/TPG*: Y. Gerebaert, JB. Sauvan (CERN), I. Puljak (FESB)

*** TPG FE studies: JB Sauvan (CERN), I. Puljak (FESB)

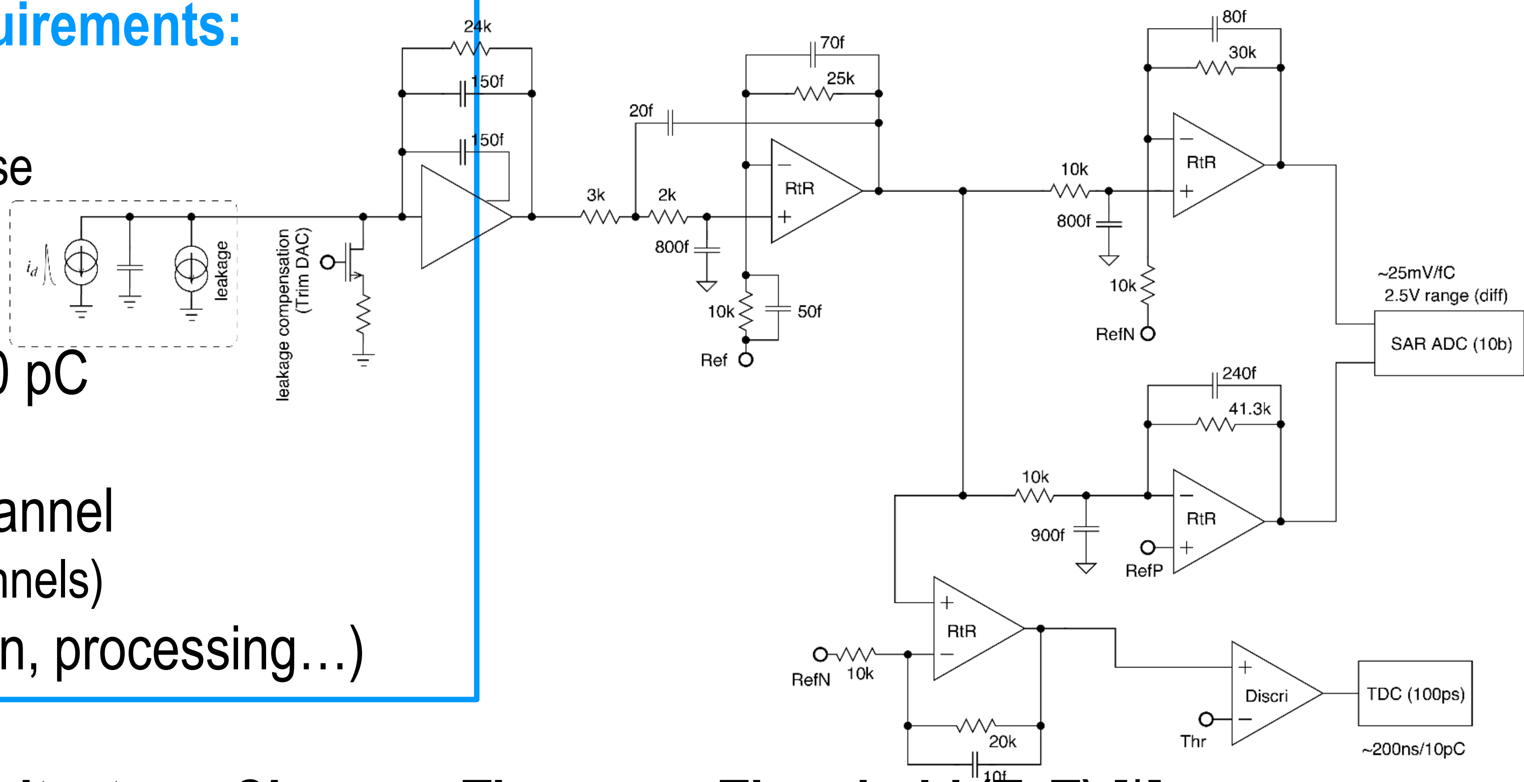
Front-End Electronics (1)

One of the most challenging aspect of the project !

Need to have large dynamic range @ low power + low noise

➢ **(stringent) Requirements:**

- **Low Noise**: ~ 2000 e-
  - including sensor I_{leak} noise
- Shaping Time: 10-20 ns
  - Pulse Shape is 1-2 ns
- Dynamic Range: up to ~10 pC
  - ~3000 MIP in 300μm Si
- **Low Power**: ~10 mW / channel
  - (Σ = 100 kW for 6M channels)
- System on chip (digitization, processing…)



➢ **Baseline architecture: Charge + Time-over-Threshold (ToT) [*]**

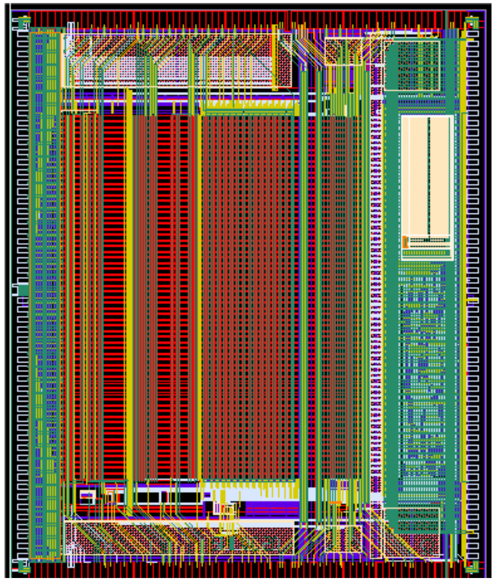
- Switch from charged readout to ToT at ~100 fC
- ADC (10 bits) and TDC (12 bits) with existing designs
- Potential for 50 ps timing per cell

[*] alternative: more classical readout (bi-gain) or switched feedback

Front-End Electronics (2)

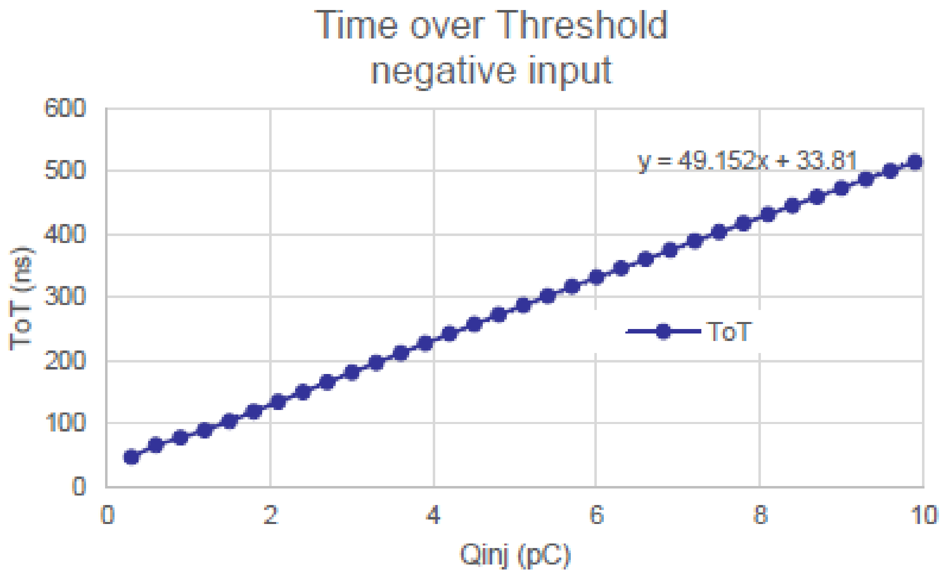
One of the most challenging aspect of the project !

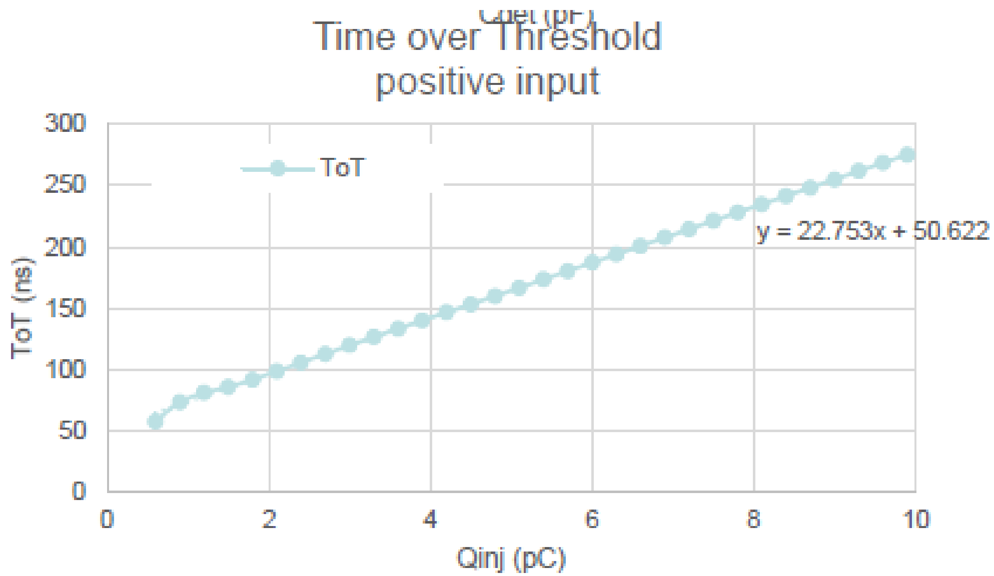
Need to have large dynamic range @ low power + low noise



➢ **SKIROC2_CMS** (not the final chip)**:**

- Includes some of the HGC features:
  - ~20ns shaping time and 40MHz sampling
  - ADC + TOA (~50ps) + TOT
  - P-on-N and N-on-P read-out options
- **Production launched in January, Received mid-June**
- **First tests on-going** (noise, stability, linearity, crosstalk, …)

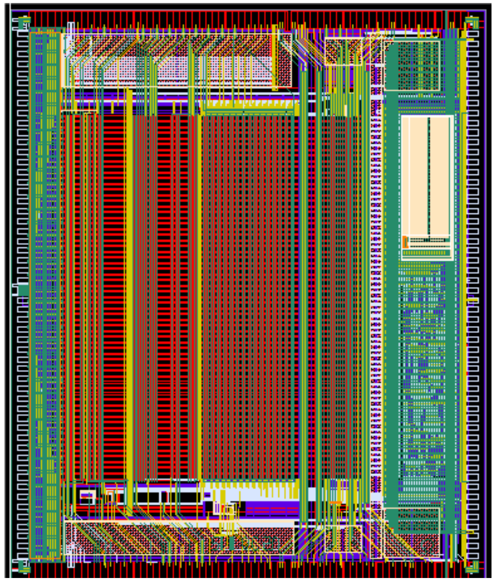




Front-End Electronics (3)

One of the most challenging aspect of the project !

Need to have large dynamic range @ low power + low noise



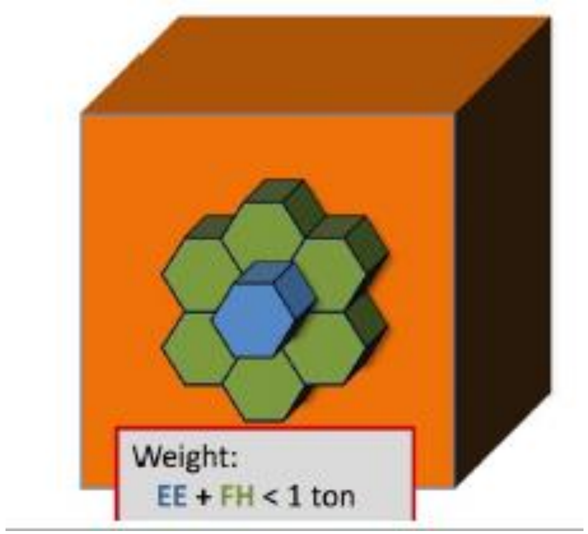
➢ **SKIROC2_CMS** (not the final chip)**:**

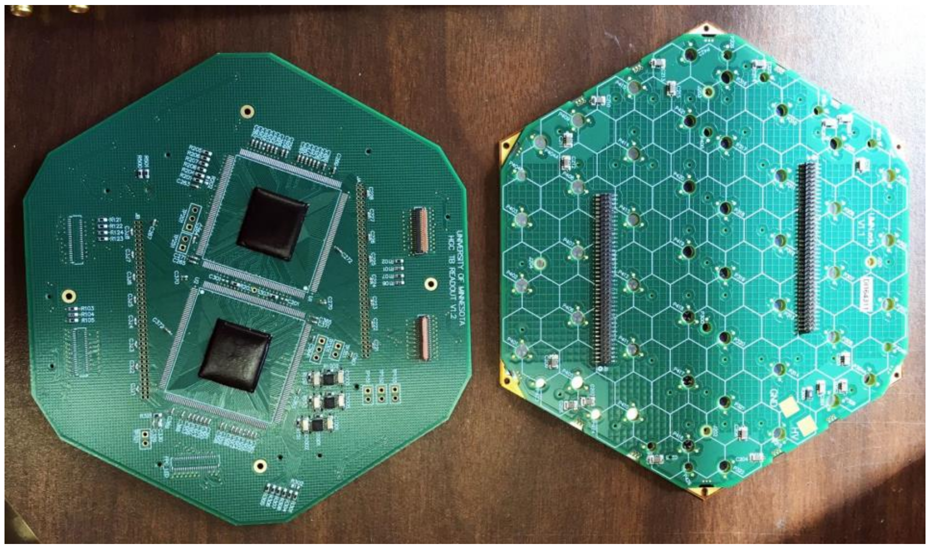
- Includes some of the HGC features:
  - ~20ns shaping time and 40MHz sampling
  - ADC + TOA (~50ps) + TOT
  - P-on-N and N-on-P read-out options
- **Production launched in January, Received mid-June**
- **First tests on-going** (noise, stability, linearity, crosstalk, …)
- Plan to use it for CERN test beams (Fall)

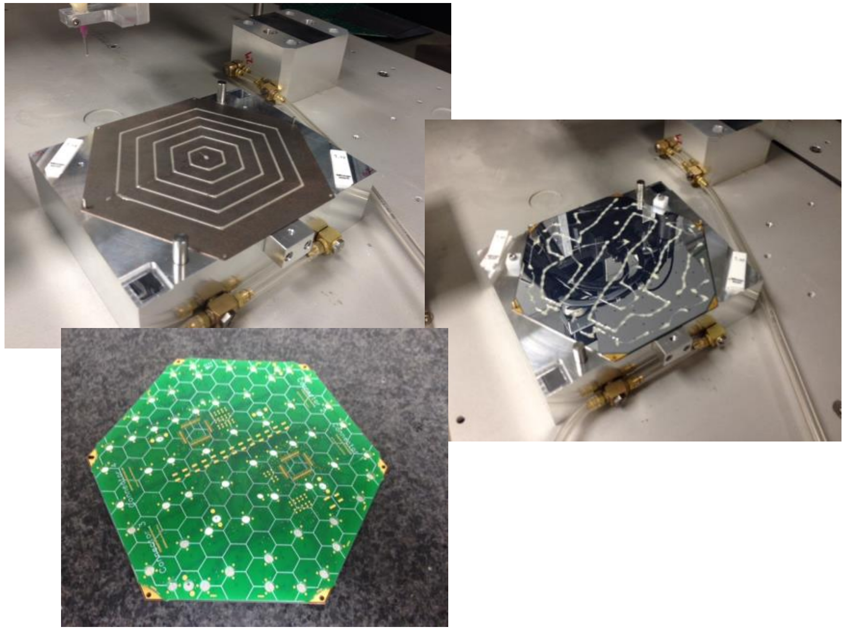
- Also: test vehicles on blocks launched
  - (TSMC 130nm, various preamps flavors, shapers, discriminators)
  - Second TV in September with one full channel (various flavors)
- **First iteration of full chip expected by Spring 2017.**
  - with feedback from test vehicles & SKIROC2_CMS

Recent Highlights: Test beams (1)

- **Test beams Goals:**
  - Proof of concept (modules, PCB-to-Si connections, …)
  - Use of SKIROC2_CMS (25 ns shaping, ToT, …)
  - Very fast timing
  - Calorimeter Performances
    (energy response, resolution,… simulation)
    - with setups from 1 layer (April 2016)
      to full HGC (28 EE layers + 12 FH layers, 2017 ?)





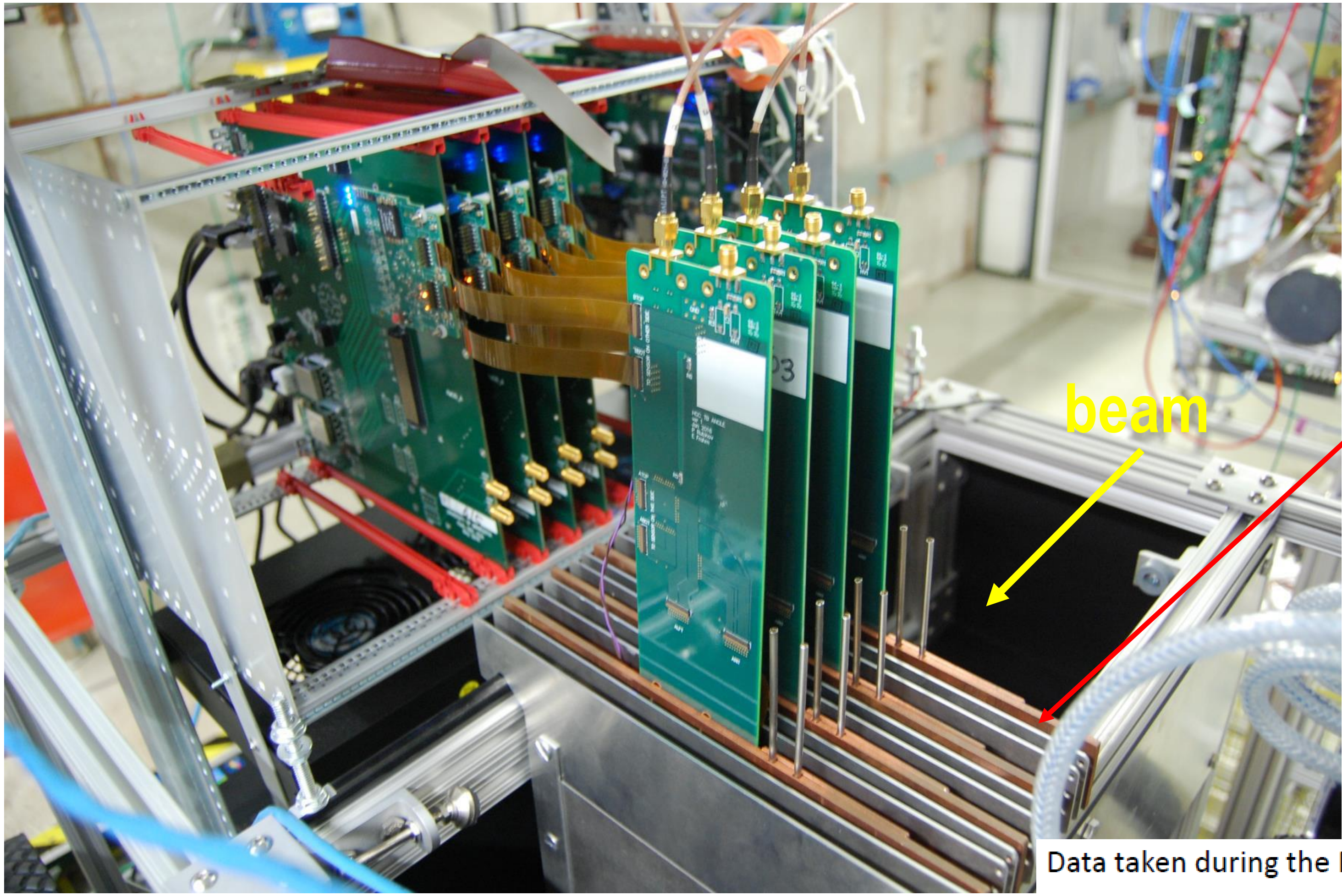


Module assembly (UCSB)

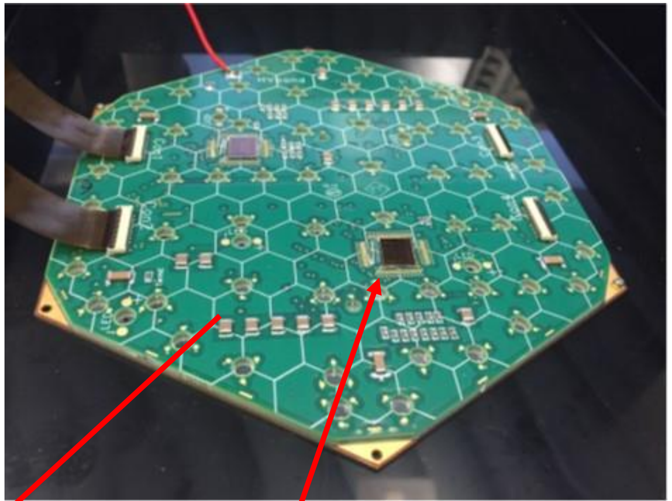
- **Tests at FNAL & CERN** (2015 - …)

Test beams (2)

➢ 4 layers setup at FNAL (June)



Module with 6” HPK 128 ch sensor



SKIROC2

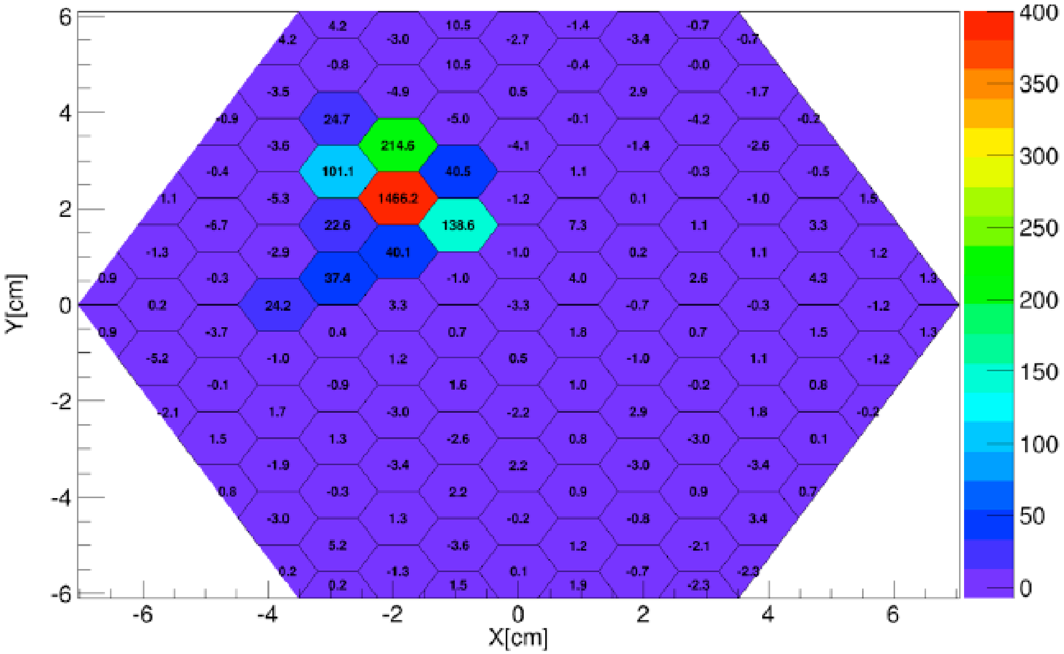
Data taken during the May/June run.

- 4 layers of sensors at 3, 6, 9 and 12 X_0.
- 200 μm sensors with W/Cu plates in stack with tungsten and copper cooling plates at room temperature.
- Beams: Electrons at 8, 16 and 32 GeV, Protons at 120 GeV.
- Čerenkov information not available.
- Gain 2.33 higher than March run.
- ADC gain set to 1 ADC count ~ 830 electrons.

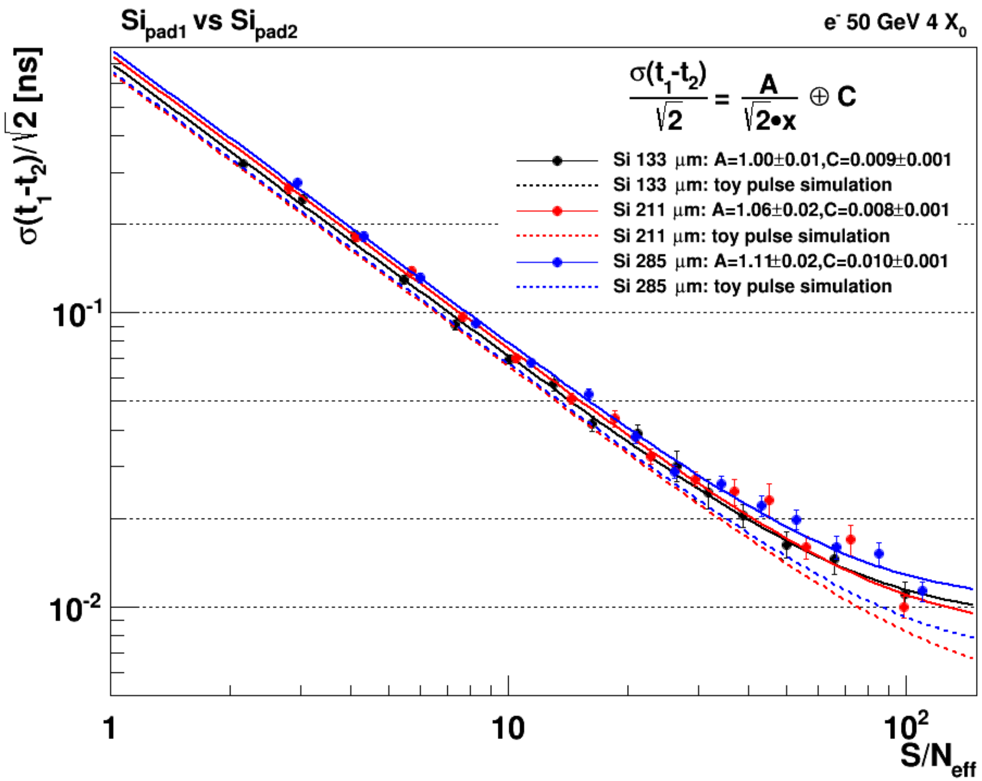
Recent Highlights: Test beams (3)

First results:

32 GeV electron after 6 X0



Size of cluster ~ 2 cm
Pedestals subtracted



Timing precision ~15ps for S/N>60 (~20 MIPs) for the 285mm thick diodes
~no change with irradiation

Next steps:

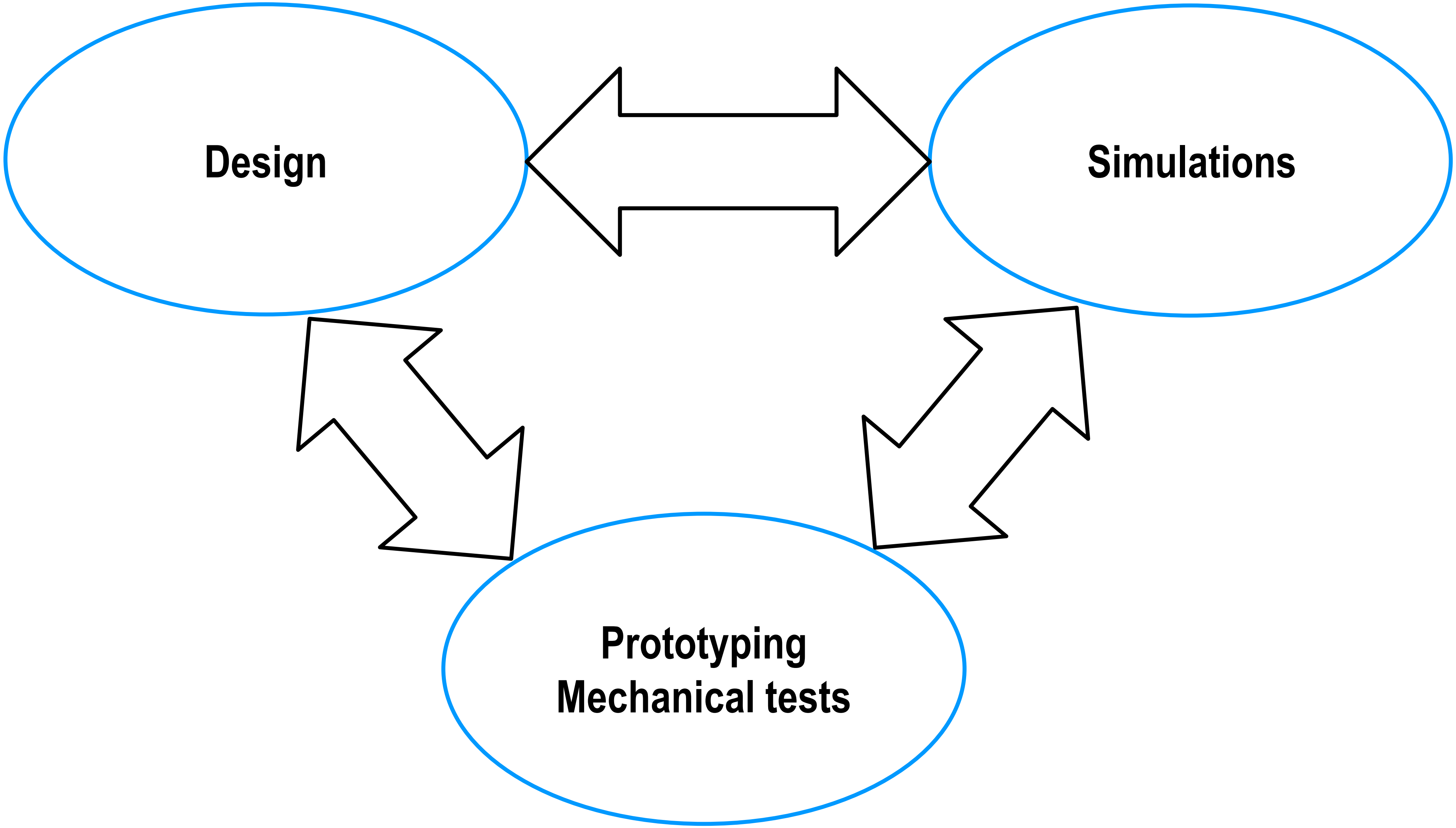
- **FNAL:** <= 28 layers for tests in June/July **[SKIROC2]**, + Fall 2016
- **CERN:**
  - short period in H2 (August/September, November) **[SKIROC2_CMS, if validated]** (+ timing dedicated tests)
  - **Periods in 2017** (2-3 weeks already foreseen beginning of year)

LLR will contribute here (shifts, analysis)
P2IO post-doc will help a lot ☺

Mechanics (1)

M. Anduze, M. Frotin, C. Ochando,
T. Pierre-Emile, Y. Sirois

Focus on EE mechanics: W/C-fiber alveolar structure:



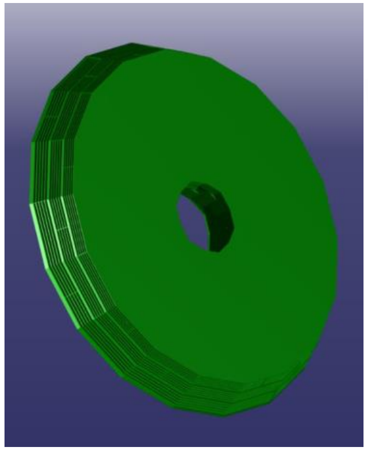
M. Anduze, M. Frotin, C. Ochando, T. Pierre-Emile, Y. Sirois

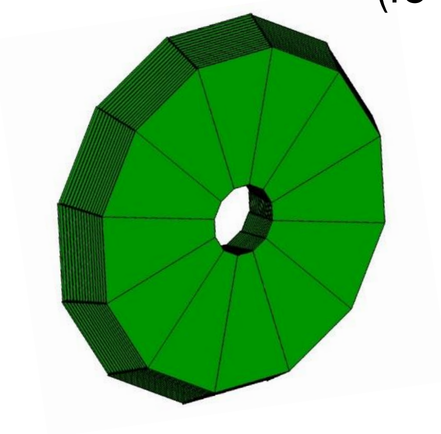
Focus on EE mechanics: W/C-fiber alveolar structure:

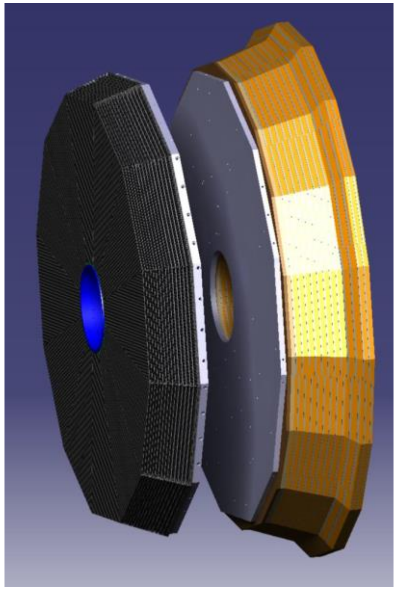
Design

Study of various geometries

Linked with G4 simulations (IC London)



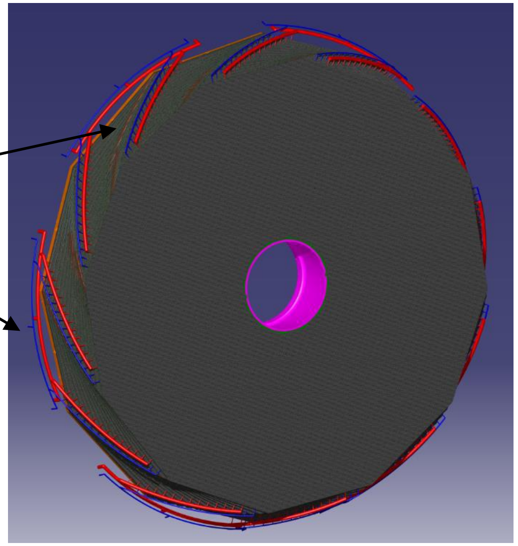


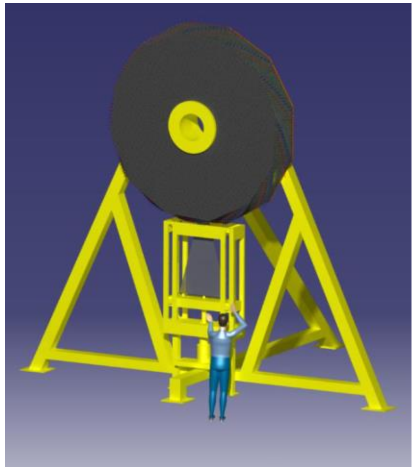


Study of EE/FH interface

Study of Services arrangement, Assembly, Integration (with CERN)

Cooling manifolds





Cassettes insertion

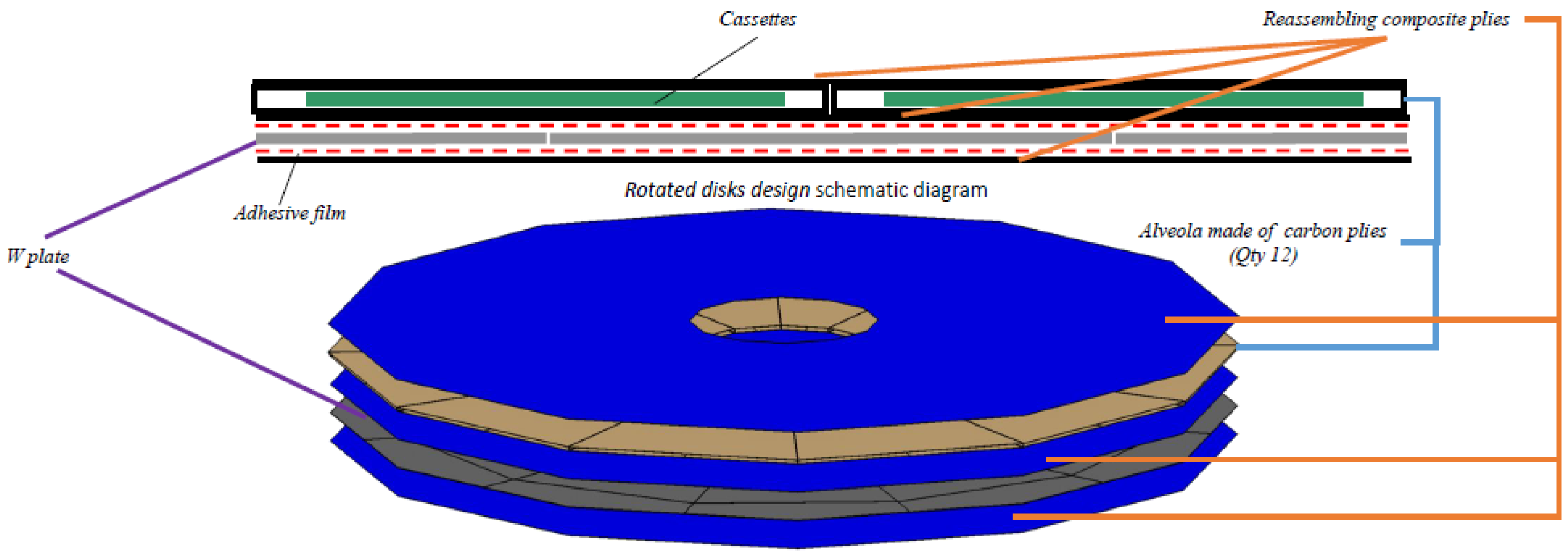
M. Anduze, M. Frotin, C. Ochando, T. Pierre-Emile, Y. Sirois

Focus on EE mechanics: W/C-fiber alveolar structure:

Design

Current design:

- Disks of alveoli
- Can be rotated one wrt each other
  - (continuous 2° rotation, staggered, …)
- Compromise to find between physics, services layout, assembly.



- Each disk is made of 12 alveola (in brown on the 3D view)
- Reassembling plies are put on both sides of each alveola to improve load distribution and avoid fiber discontinuity within the same plane (in blue on the 3D view).

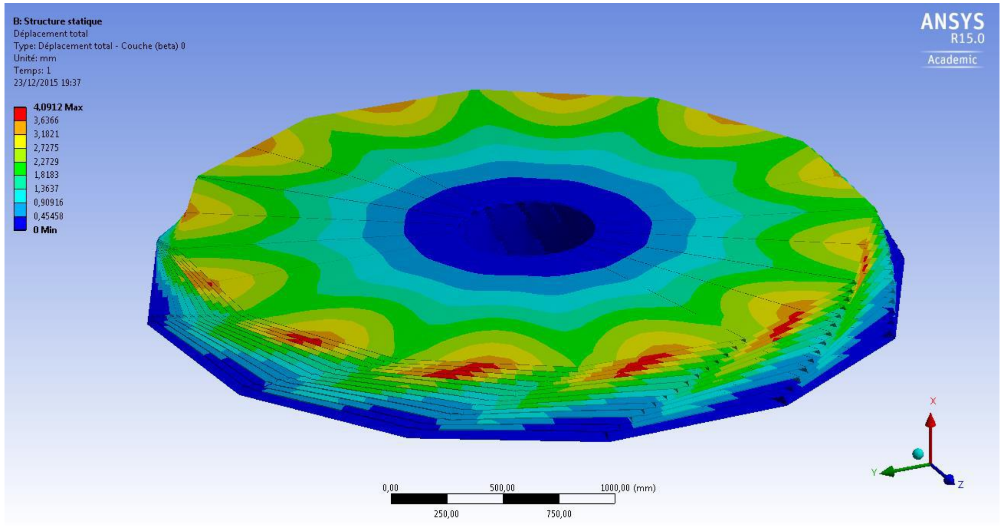
M. Anduze, M. Frotin, C. Ochando,
T. Pierre-Emile, Y. Sirois

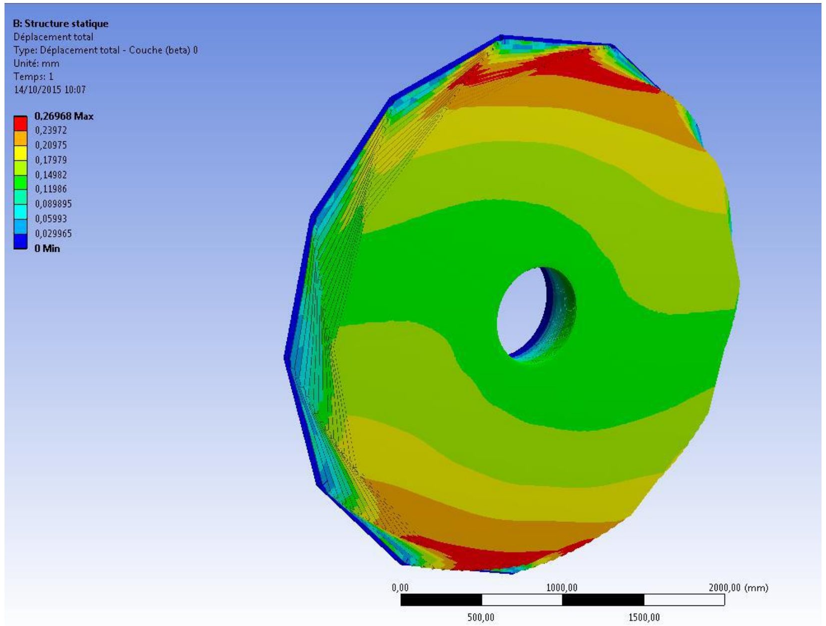
Focus on EE mechanics: W/C-fiber alveolar structure:

Assess Mechanical behavior via FEA simulations:

- in various positions,
- for various material properties,
- stresses from T° cycling
- …

Simulations





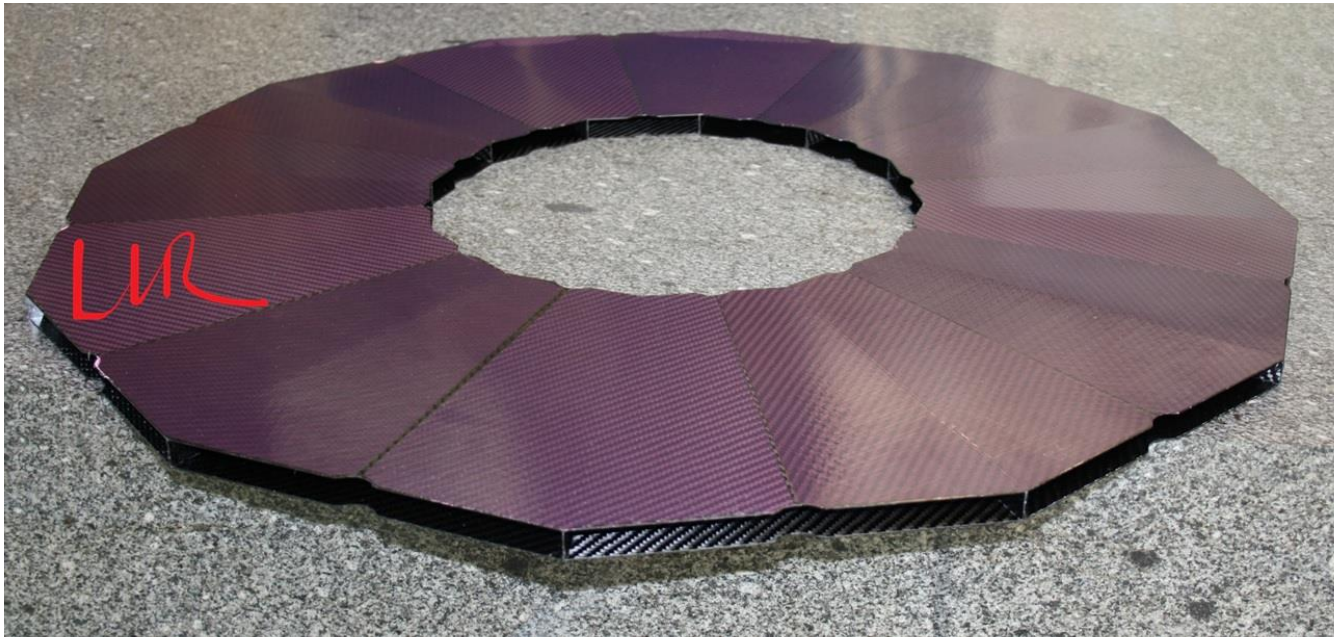
Mechanics (5)

M. Anduze, M. Frotin, C. Ochando, T. Pierre-Emile, Y. Sirois

Focus on EE mechanics: W/C-fiber alveolar structure:

Mechanical tests on small samples
Before/After irradiation, T° cycling,…

Producing small prototypes
Note: Autoclave not big enough for real size production….



small disk of alveoli proto (~1/3 size)

Prototyping / Mechanical tests

Mechanics (6)

M. Anduze, M. Frotin, C. Ochando,
T. Pierre-Emile, Y. Sirois

Focus on EE mechanics: W/C-fiber alveolar structure:

Mechanical tests on small samples
Before/After irradiation, T° cycling,…

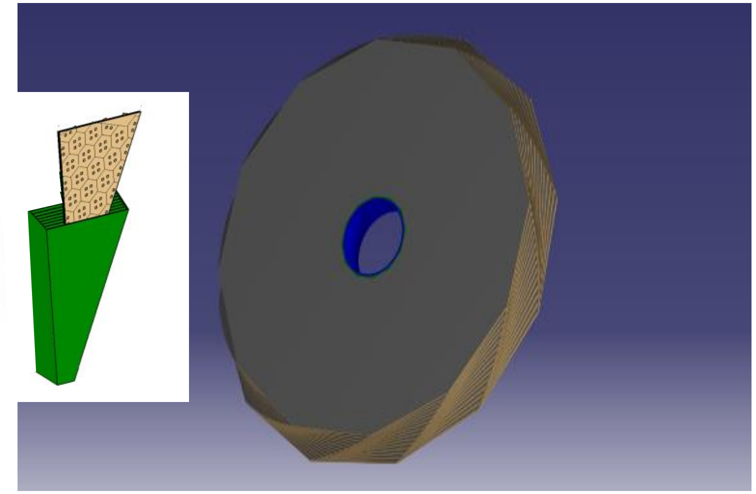
- **Suffers from Mickael's departure…**
- Not so easy to find neutron sources with sufficient fluence, room to install setup, …
- Possible sites: Ljubljana, Louvain?, ILL ?
- **Mandatory to complete the design !!!**
    - NIM papers can be written on these topics…

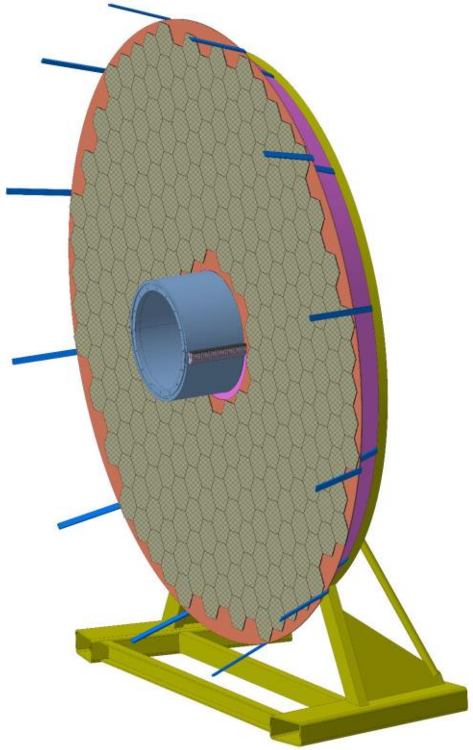
Prototyping / Mechanical tests

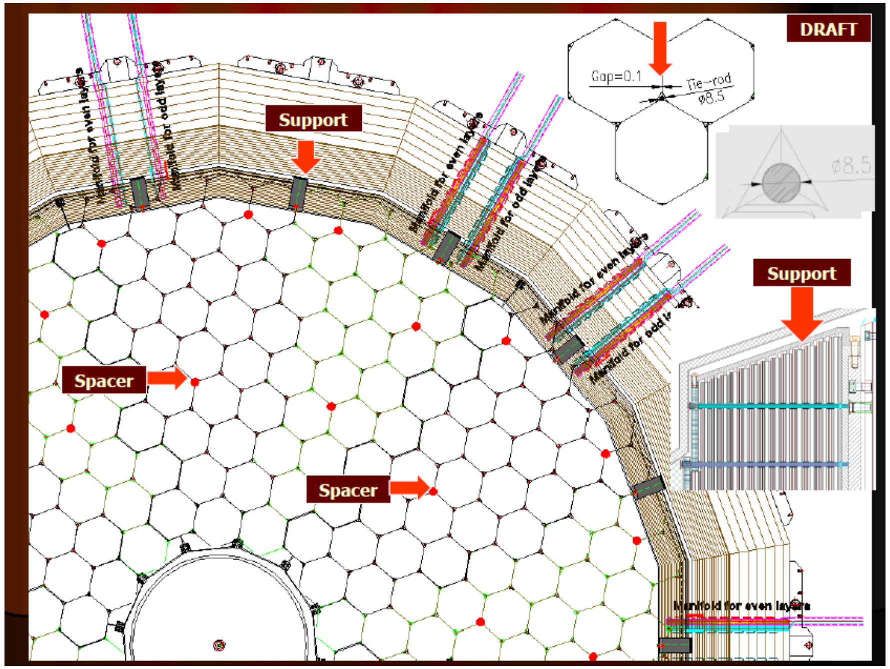
Mechanics in HGCAL: EE mechanical structure options (1)

3 different designs under study (**with different level of maturity**)

Decision: October 2016







(A) W/C-fiber Alveolar Structure

- phi-sector Disks,
- WITH INSERTABLE cassettes

(B) Full Disk

- Inspired from PreShower experience
- Full disk of Cu & absorber, stacked in vertical position
- NO cassettes
- Services decoupled from Cooling

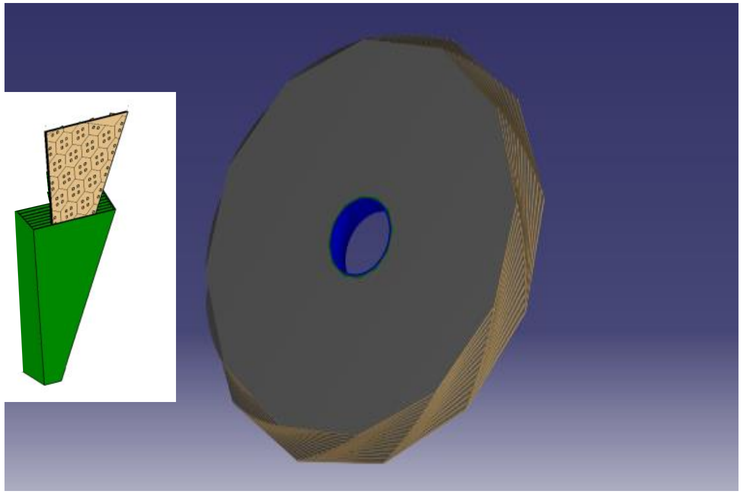
(C) "Disk & Spacer" design

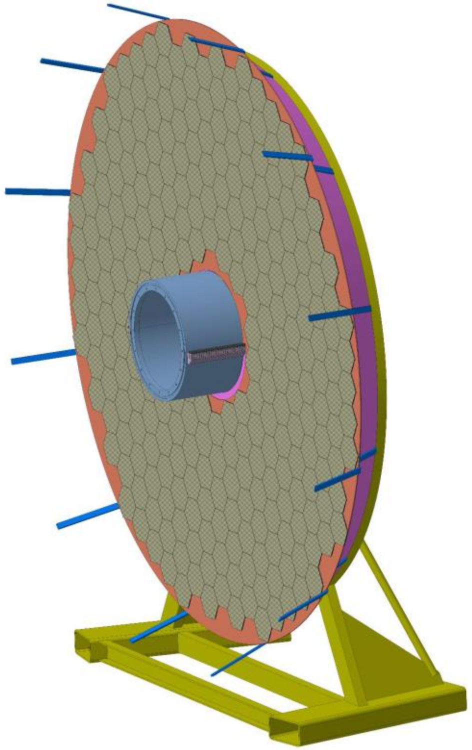
- Variant of "full disk"
- Made from 30° cassettes, connected in inner/outer periphery + spacers + …
- Horizontal assembly

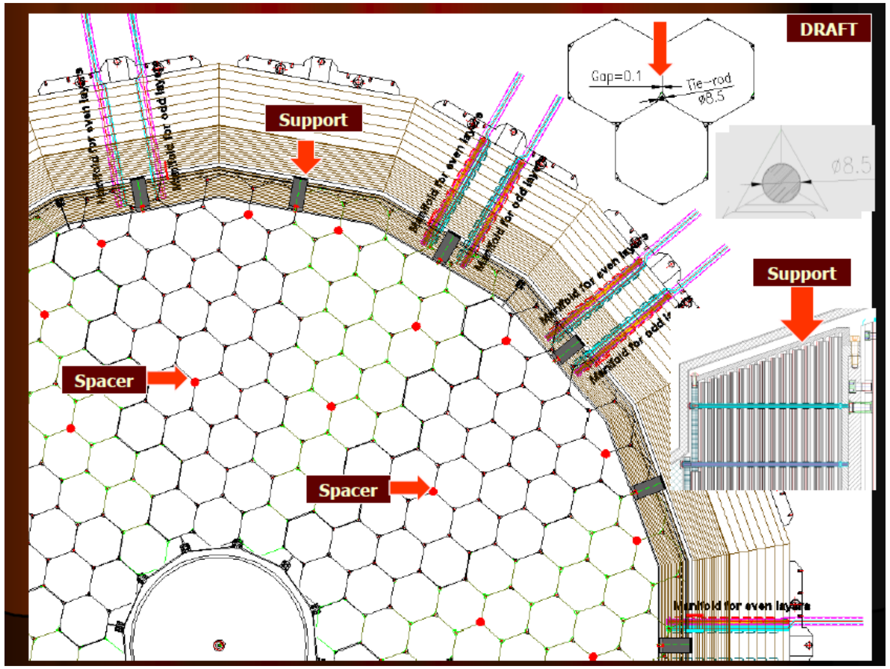
Mechanics in HGCAL: EE mechanical structure options (2)

3 different designs under study (**with different level of maturity**)

Decision: October 2016



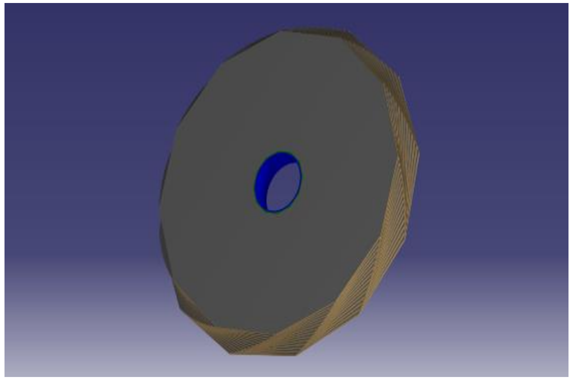




General Points to address (to be completed)

- **Physics:** cracks (what is tolerable?), total thickness ?
- **Cassettes:** insertable or not.
- **Mechanical behavior:** under various positions, under T° cycling, under events (magnet quench, earthquakes,…)
- **Assembly/Installation/Services:** strategy for cabling, vertical or horizontal, …

Mechanics in HGCAL: EE mechanical structure options (3)

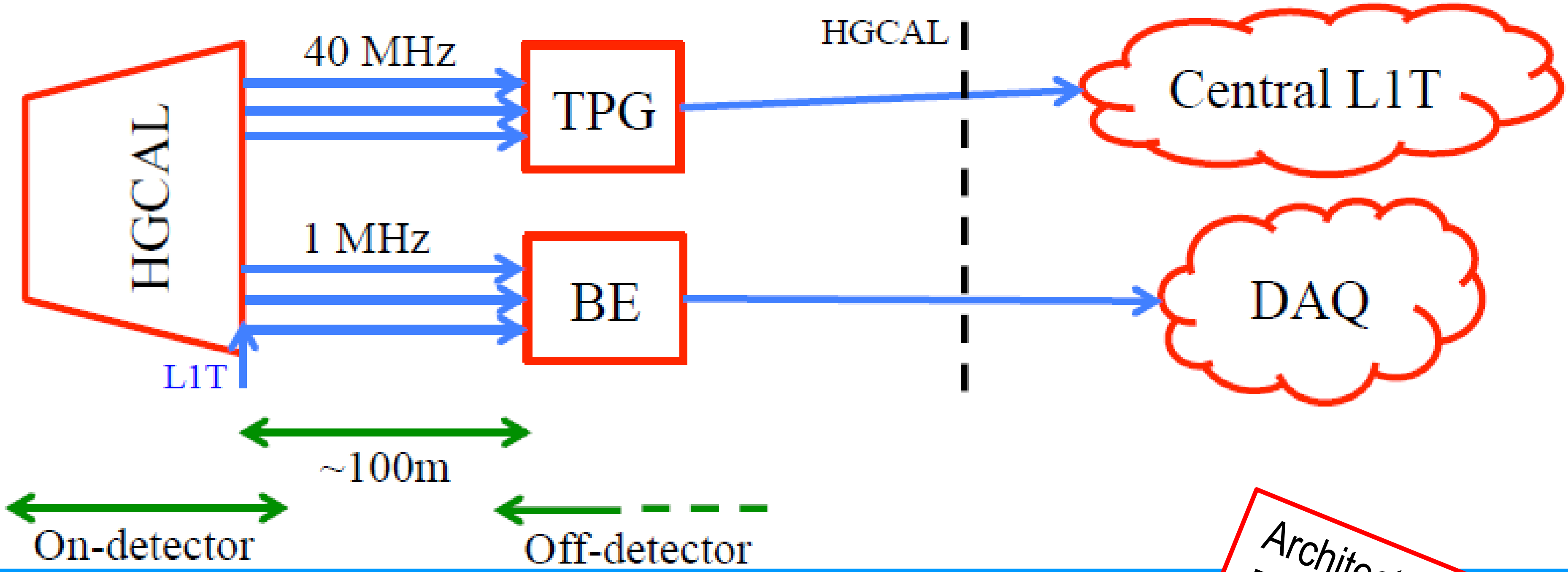


LLR design:

- **Physics:** ~ok (not perfect but may not be decisive now)
- **Mechanical behavior:** ~ok (still need T° cycling + radiation)
- **Assembly/Installation** (from assembly of structure, cassette insertion, cabling, mounting of the rest of HGC…)
  - To be developed (including idea of tooling) **with HIGH priority.**
  - Some temporary help (mechanics, electronics?) needed !
- **But:**
  - **Cassettes:** needed or not ?
    - HGC buried under cables/pipes + radiation: prevents to replace cassettes
  - use of **more sensors geometries** than full disk due to cassettes (dedicated PCB/readout, more cables, …)
  - **Flexible enough ?** (need to know exactly the cassette thickness before launching production)

L1 Trigger & Back-end Electronics

Ph. Busson, Th. Romanteau,
S. Baffioni, JB. Sauvan, I. Puljak, …

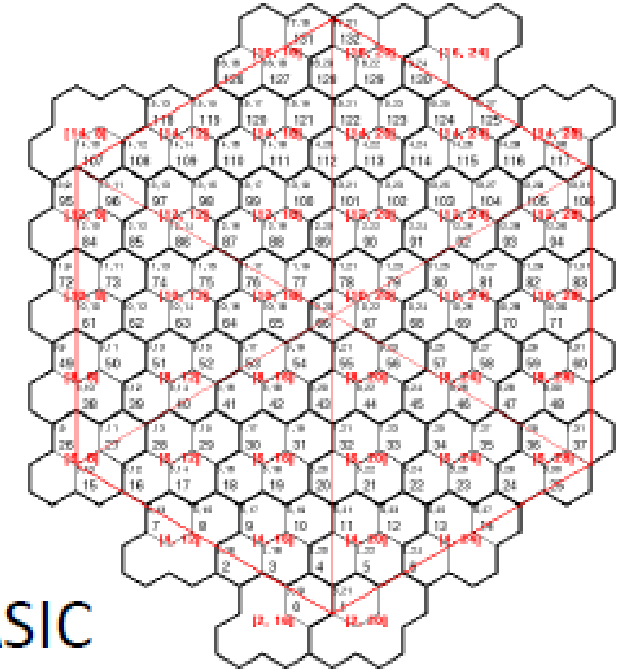


- All data sent off-detector on radiation tolerant links. **Challenges:**
  - Data volume: 1 Pb/s ! To be reduced by at least a factor 20…
  - Data volume -> Number of link (~8k for trigger) -> cost !
  - Huge Pile-Up: reduction of info <=> reduction of rejection power… Trade-off/Optimization to found.

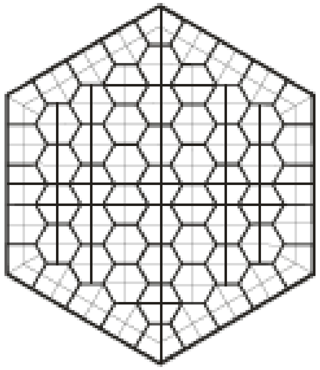
- **The LLR has been one of the main drivers of the HGCal L1 trigger project**, together with the University of Split (Croatia)…
  - Significant parts of the studies done for the Technical Proposal, feasibility studies
  - Software developments, firmware developments
  - Coordination activities
- **… and wants to remain a main actor !**

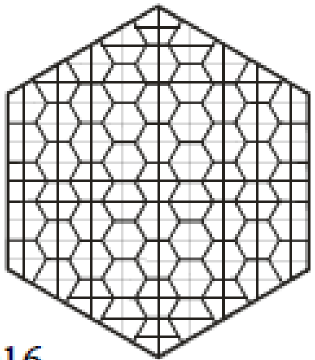
Ph. Busson, Th. Romanteau,
S. Baffioni, JB. Sauvan, I. Puljak, …

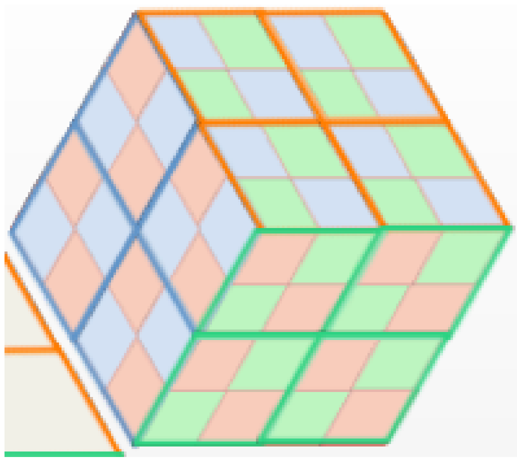
Sensor cell geometries



- Hex cell geometry makes trigger sums quite non-uniform
  - A lot of messy edge effects around wafer
  - Often have less cells than four in the sum; means more trigger channels
  - Or more than four in sum; complicates FE ASIC







- Other sensor cell geometries may be preferable
  - Systematic study of possible alternatives being done
  - Including starting with trigger cells and then subdividing

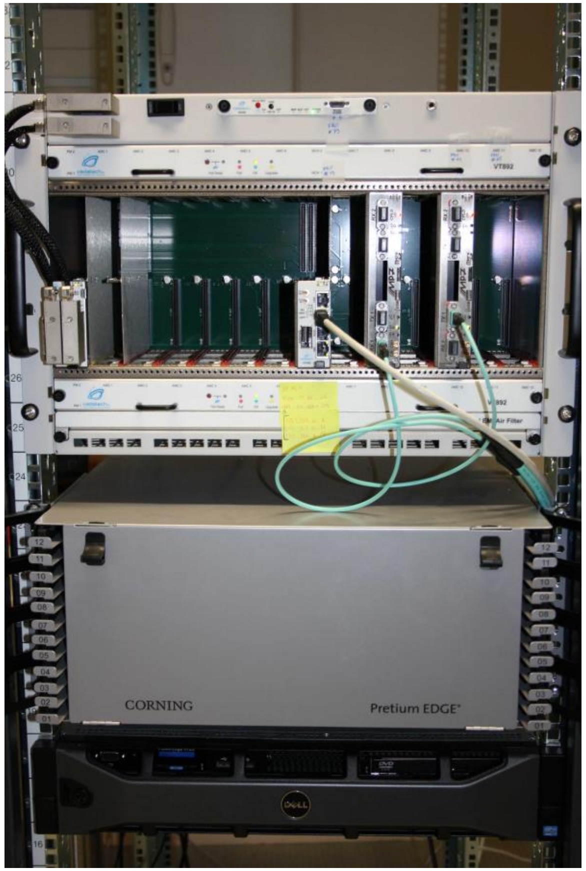
L1 Trigger & Back-end Electronics: LLR+friends** plans (1)

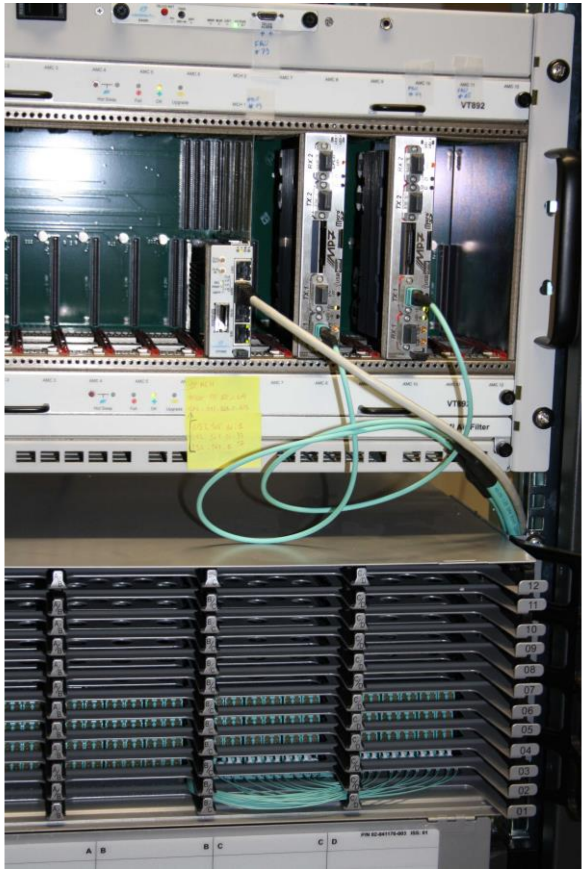
Ph. Busson, Th. Romanteau,
S. Baffioni, JB. Sauvan, I. Puljak, …

- Development of the trigger system, driven by algorithms
  - Development of the best possible algorithms
  - Dimension the system according to these algorithms

- Need continuous monitoring of algorithms resource and latency needs
  - Test platform for algorithm evaluation based on currently available hardware
  - Test platform available at LLR, with many free slots for more µTCA boards

µTCA crate + optic patch panel + server @ LLR





** friends = Split, CERN, …

Ph. Busson, Th. Romanteau,
S. Baffioni, JB. Sauvan, I. Puljak, …

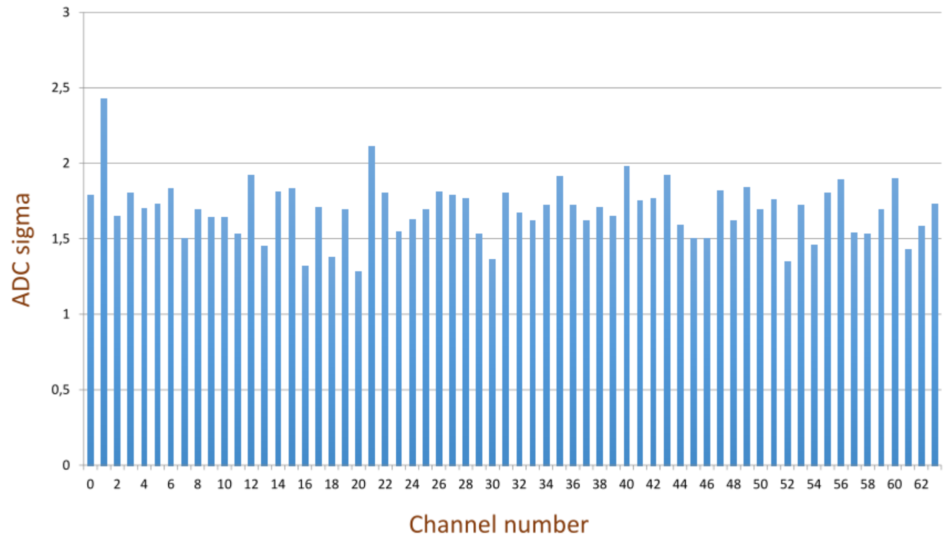
- Participation to the front-end ASIC tests and test beams
  - SKIROC2, test vehicles and future HGCROC chips
  - Benefits from the close contact with Omega

- Part of the trigger processing will be done in the front-end ASICs and the off -detector electronics will be interfaced to these chips
  - It is important to follow very closely, test and control that the front-end ASIC is compatible with the trigger needs

- Test of the SKIROC2 chip already started by the LLR+Split team
  - Measurements of pedestal, linearity, crosstalk, noise, etc.

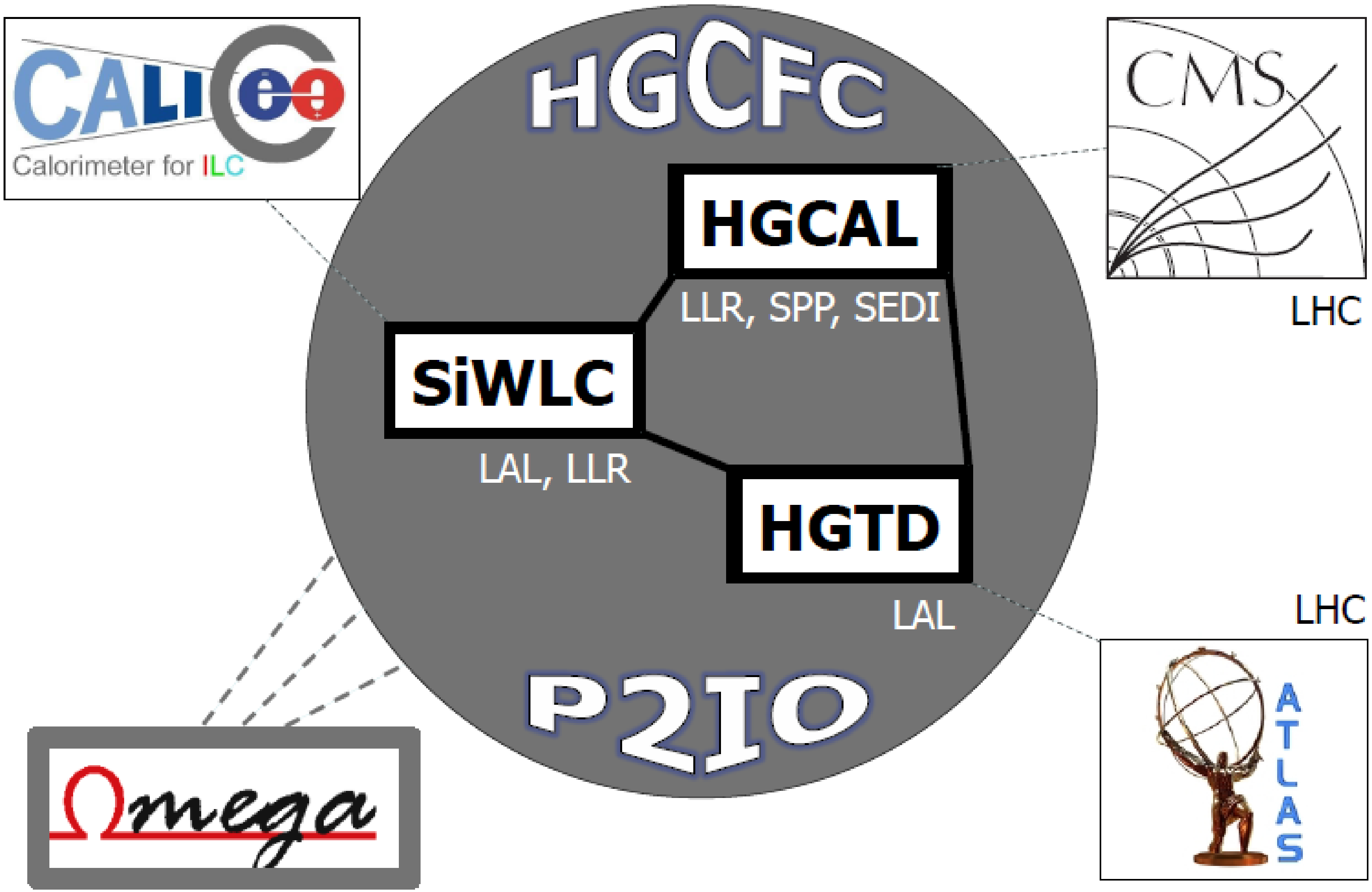
Test board from Omega

Noise measurement



P2IO “Projet Emblématique”

The HIGHTEC Project at P2IO



LLR Palaiseau CNRS, LAL Orsay CNRS, SPP + SEDI Saclay CEA

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P2IO "Projet Emblématique"

900 keuros asked.
765 keuros received (-15 %)

- Includes post-doc at LLR for HGCAL (+ILC test beam) from X+IN2P3
- 45% SiWLC, 46.2% HGCAL, 8.7% HGTD
- ~57% hardware / 43% manpower + travel funds
- Cut on hardware + post-doc

Will help a lot in test beams + synergy CMS/CALICE !

> **P2IO & LLR-CMS:**
> - Mechanics: fund to help R&D, prototypes, tests
> - L1 Trigger: fund to help test bench
> - Test beams, Performances, Detector design/optimization: post-doc

Conclusion

HGCAL Project is very ambitious, challenging… and thus exciting !

- **So far, so good, we are on track and on time:**
  - Si wafer design & Module mounting
  - Test beams underway (FNAL, CERN)
  - Front-End electronics: SKIROC2_CMS being tested, test vehicles launched, on time for first iteration of full chip in 2017, …

- **At LLR:**
  - Mechanics: **major decision in October on EE structure**
    - LLR has the most studied & complete design.
    - But does not mean it is the "best" or will be chosen…
    - (temporary) help needed for the rush…

  - L1 Trigger:
    - Project would highly benefit from an additional firmware engineer (development of algo firmware to be tested on our test platform)
    - Will also need more processing boards

- **P2IO:**

Although reduced budget will impact us, it will provide valuable support on R&D and test beams/performance

BACK UP SLIDES

L1 Trigger at LLR&friends (1)

N'oublie pas de couvrir un peu FE / BE electronics (i.e. quelque slides avec les responsabilitésde Polytechnique + mention des liens avec Split (BE) et arrivé de JBS (trigger) + 1 post-doc
(test-beam analysis)

(major) Changes wrt TP

The TP chose schemes that could be built using currently available technologies. Now studying many options that may lead to cost or performance benefits.

Absorber for FH and BH: non-magnetic stainless steel

Under consideration: enclosing the whole endcap calorimeter in the cold volume

EE and FH: tiling the full face of the disks with hexagons or keeping the phi-wedges. A module comprises one 8" sensor or two 6" sensors.

We can use FEC5 protocol LpGBT links that can transmit 9.0 Gb/s instead of the assumed 6.4 Gb/s

The numbers of links "10 Gb/s" optical links has increased: Data 3761 -> 5415 and Trigger 6428 -> 7572.

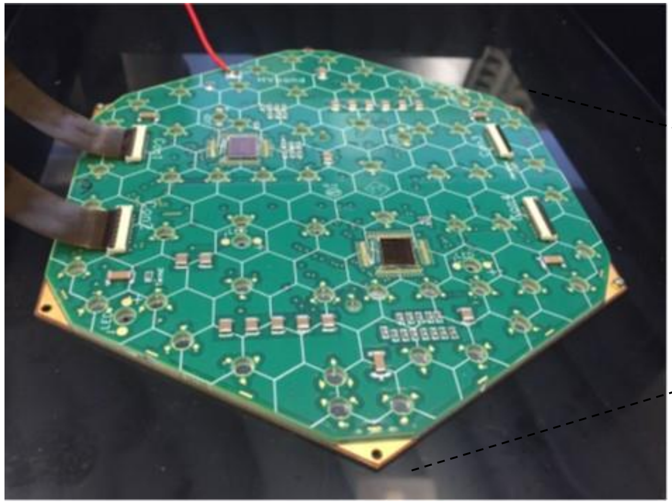
The trigger scheme and granularity is being reassessed

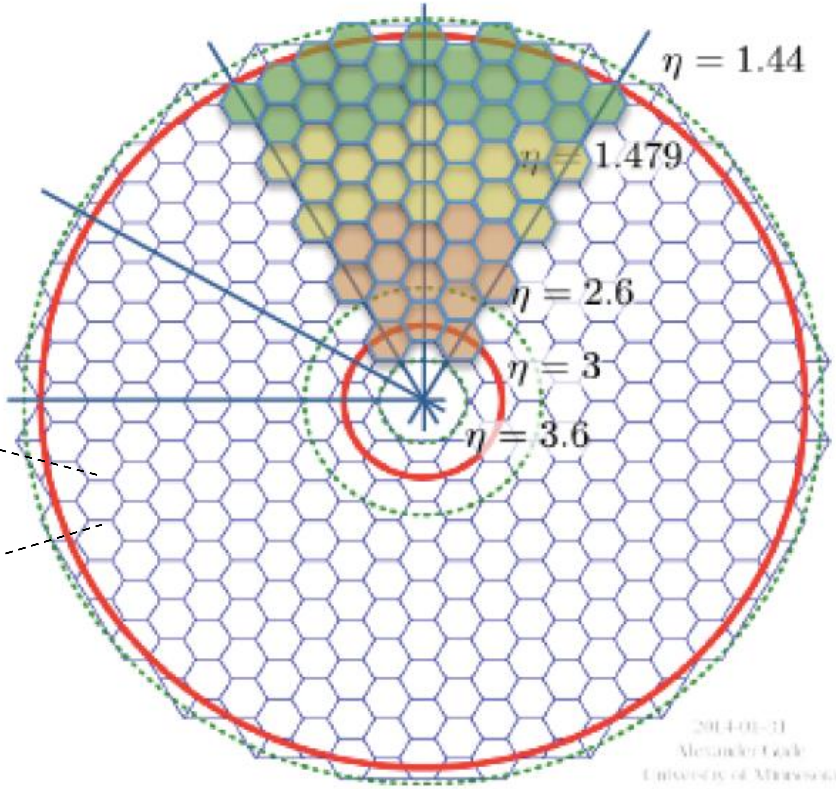
Hexagonal cells have been introduced in the simulation geometry

The milestones are being updated

Modules, Cassettes & Mechanics (Si & modules)

Modules
with 2x6 or 8” Hexagonal Si sensors, PCB, FE chip, on W/Cu baseplate





See talk by Z. Gecse (test beam)

To cope the irradiation / PU:

- η-dependent depletion of Si
- η-dependent cell size

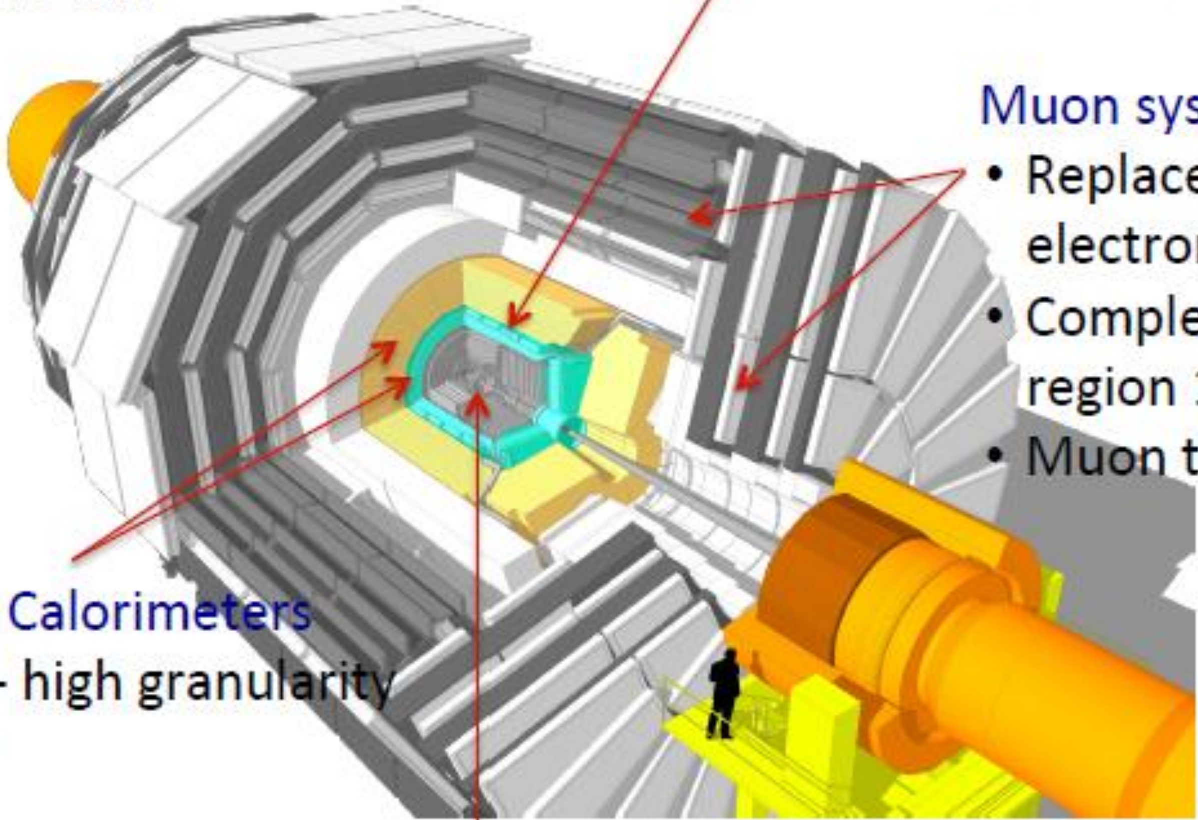
Thickness	300 μm	200 μm	100 μm
Maximum dose (Mrad)	3	20	100
Maximum n fluence (cm^{-2})	6×10^{14}	2.5×10^{15}	1×10^{16}
EE region	$R > 120$ cm	$120 > R > 75$ cm	$R < 75$ cm
FH region	$R > 100$ cm	$100 > R > 60$ cm	$R < 60$ cm
Si wafer area (m^2)	290	203	96
Cell size (cm^2)	1.05	1.05	0.53
Cell capacitance (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

Summary of the CMS upgrades for Phase-II

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

Barrel EM calorimeter
- Replace FE/BE electronics
- Lower operating temperature (8°)

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



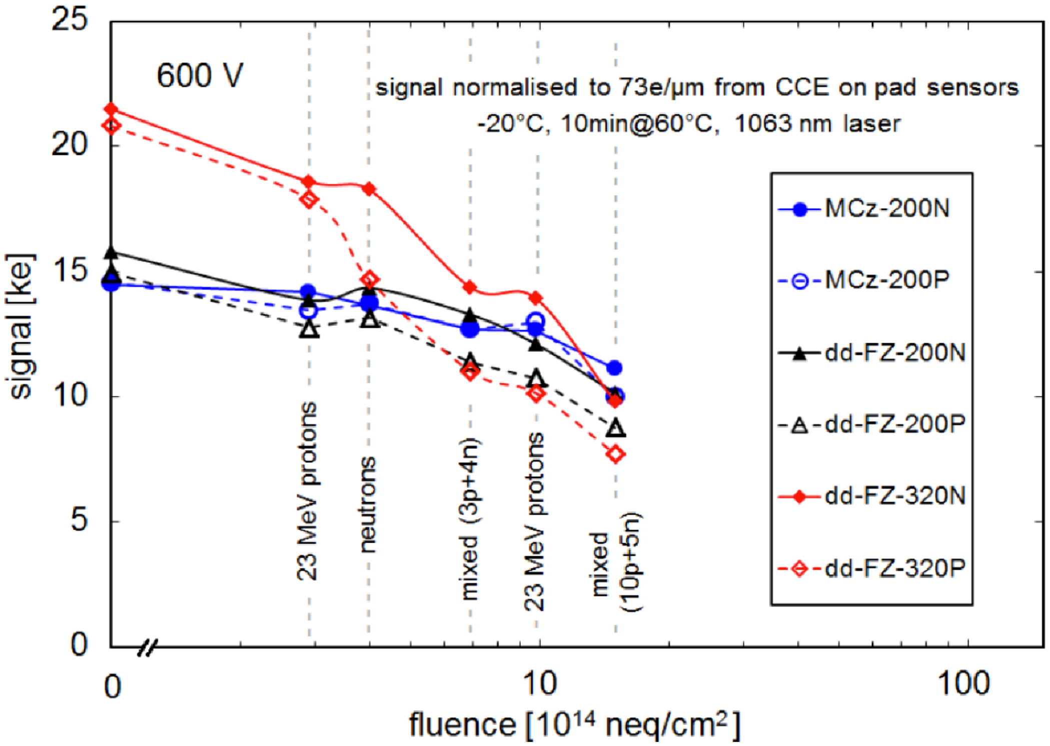
Replace Endcap Calorimeters
- Rad. tolerant - high granularity
- 3D capability

Replace Tracker
- Rad. tolerant - high granularity - significantly less material
- 40 MHz selective readout (Pt≥2 GeV) in Outer Tracker for L1-Trigger
- Extend coverage to $\eta = 3.8$

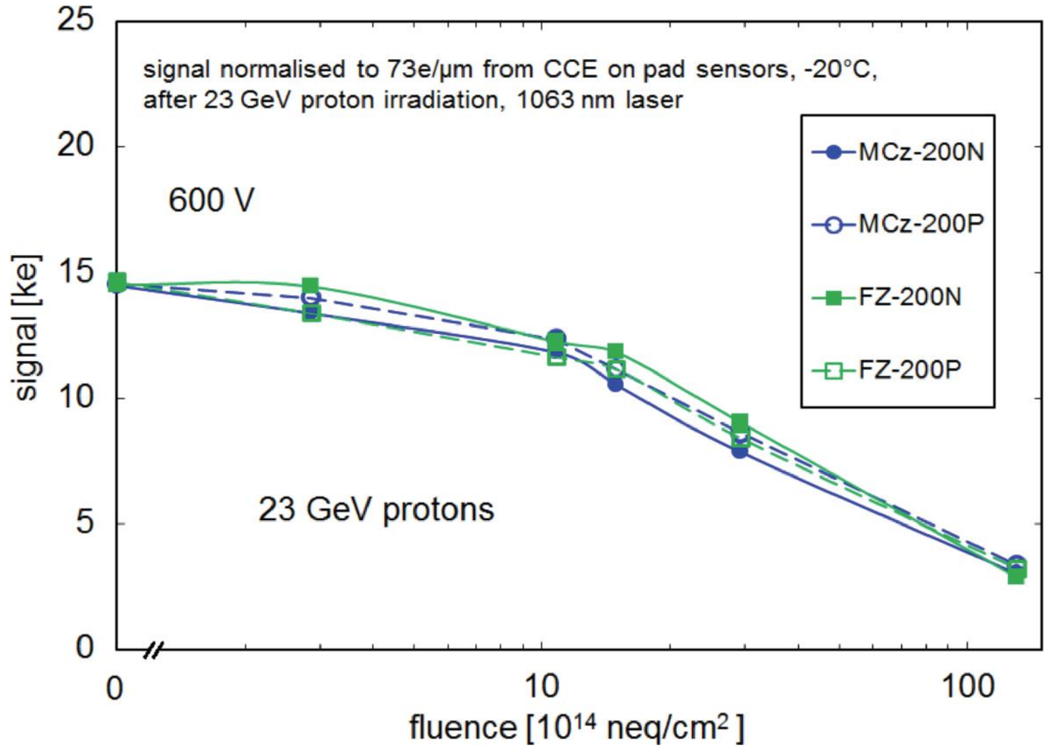
Radiation Tolerance (1)

Charge collection vs neutron fluence

300 & 200 μm active thickness

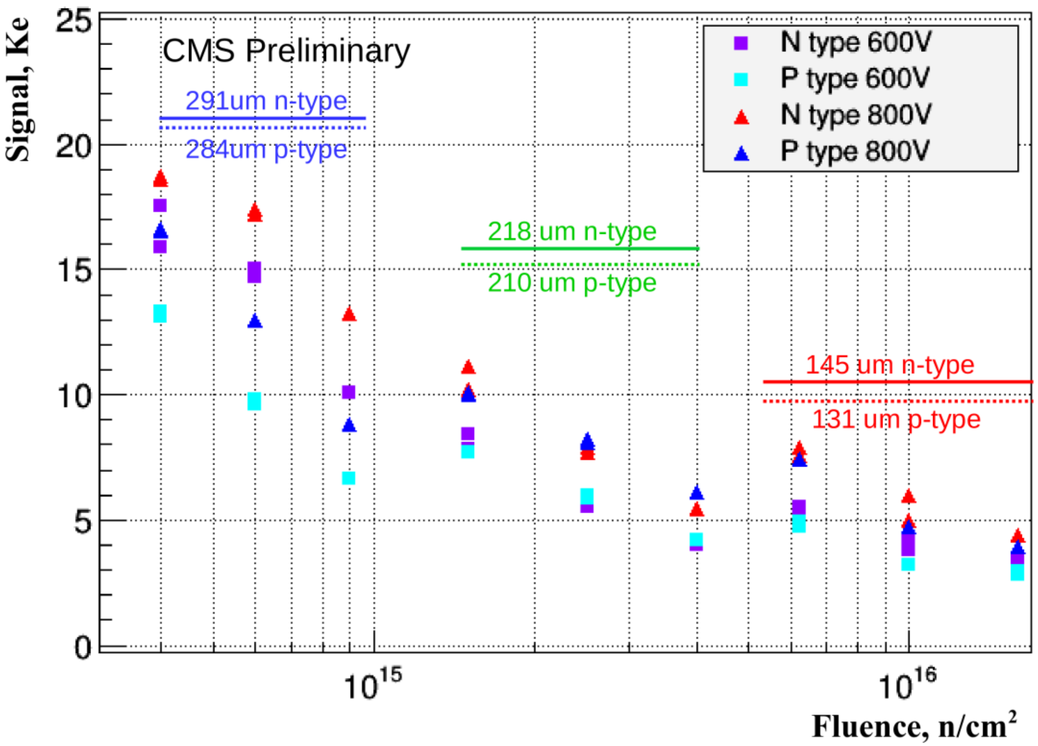


200 μm active thickness, p-in-n vs n-in-p

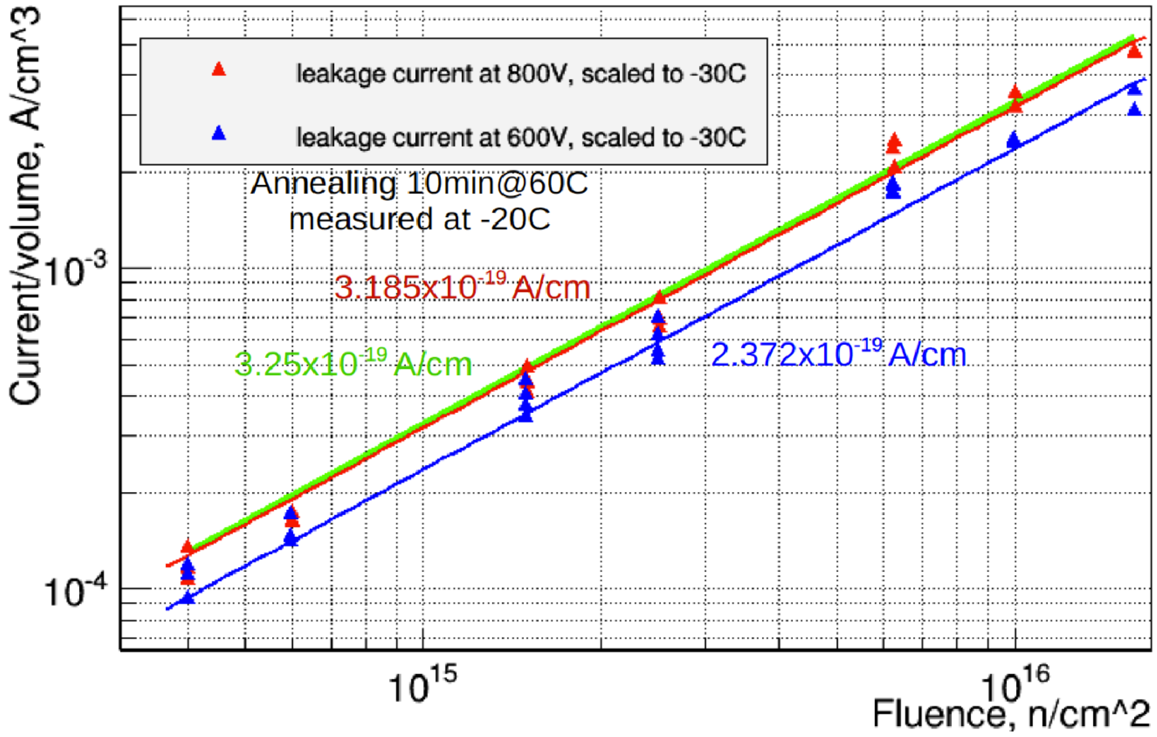


Radiation tolerance (2)

Neutron irradiation



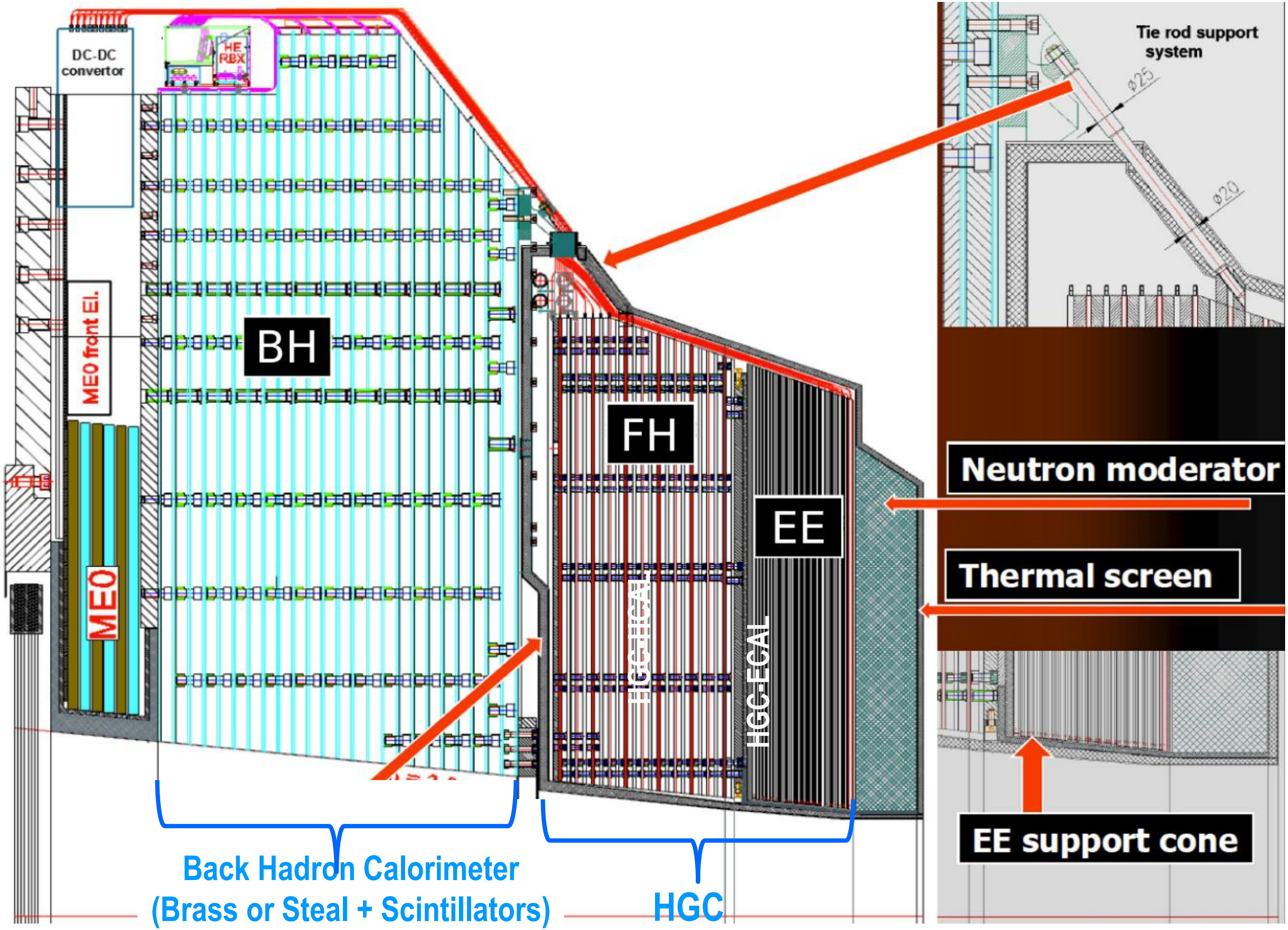
Charge collection efficiency



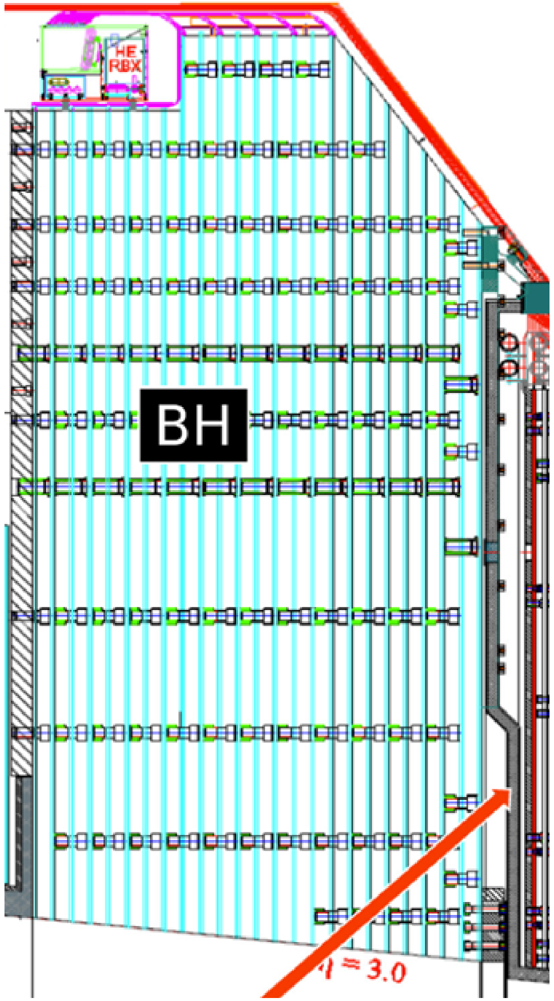
Leakage current vs fluence at -20° (extrapolated to -30°)

Draft paper in preparation

HGCAL: General Layout



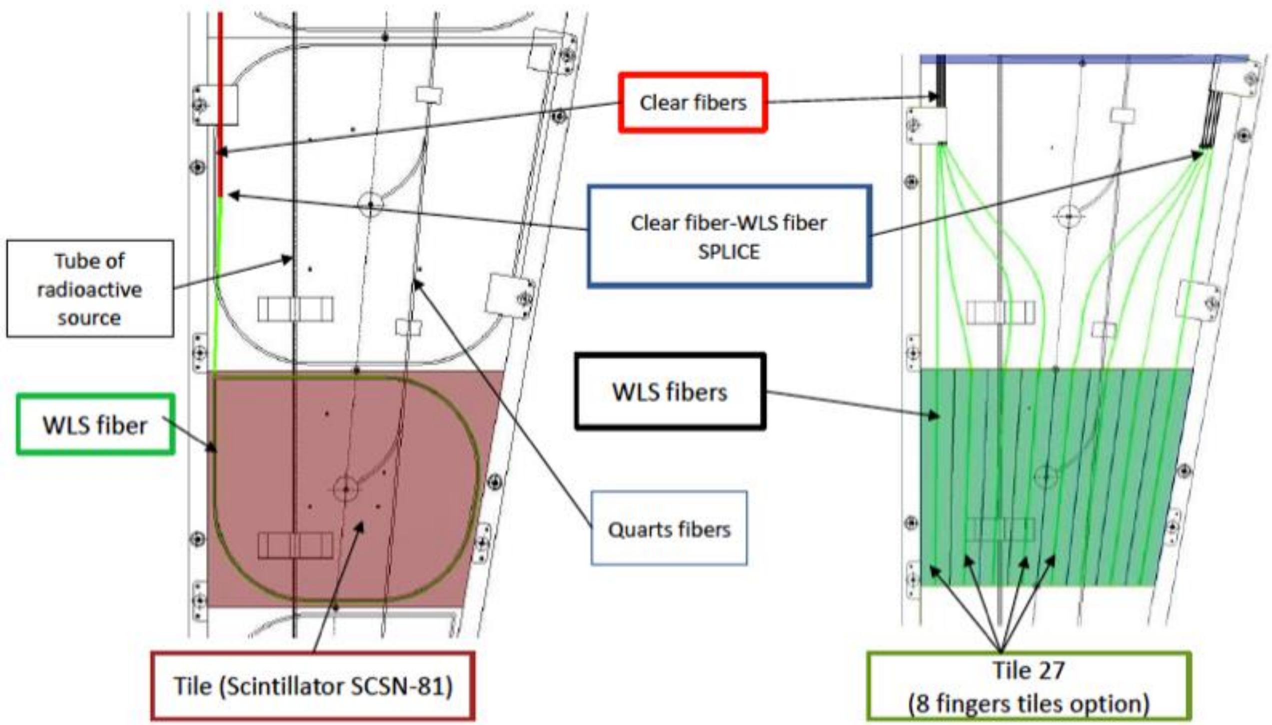
Back-Hadron Calorimeter



BH	number
Scintillator	428 m^2
WLS fibers	12 km
Clear fibers	73 km
SiPMs	5184
Optical fibres (data)	1152

- Improvement of current HE tiles for ~ 5 Mrad tolerance, with increased granularity (~ x2 in ϕ, x1.3 in η):
  - doubly-doped plastic scintillator x 2 light after irradiation
  - Finger tile design: shorter light path

HCAL Endcap Megatiles Upgrade



- Also thinking of usage of Si at high eta.
  - Would require to cool down the full endcap calo…

HGC Calibration

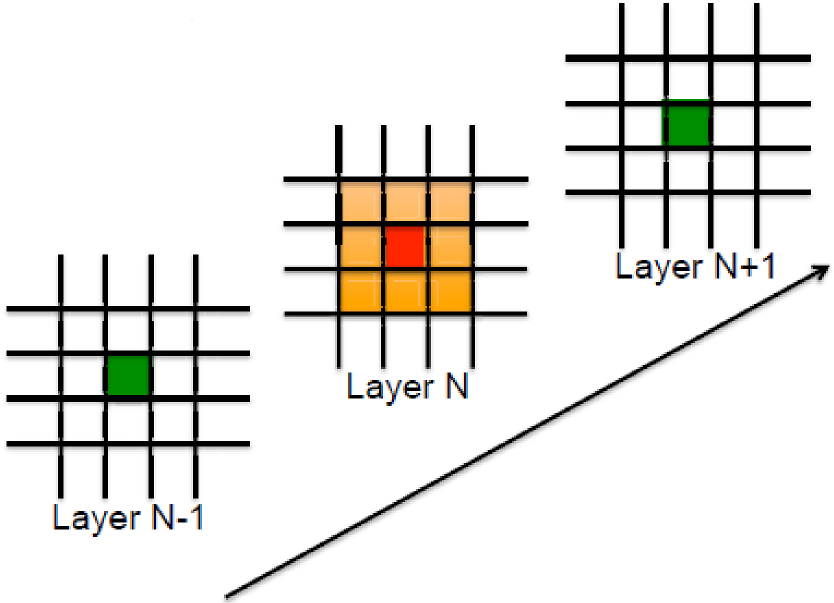
- **Calibration requires:**
  - Inter-calibration (cell-by-cell response equalization) → **With MIPs + specialized cells**
    - Objective: Constant term smaller than 1%

      ⇔ 3% precision for IC (results in <0.5% constant term)
  - Cells weights taking into account absorber thickness
    - W plates: thickness contained within +/- 40 μm
    - W/Cu plates: thickness contained within +/- 50 μm
    - Si wafer: thickness contained within +/- 5 μm
    - Diffusion depth of all pads (within a wafer):

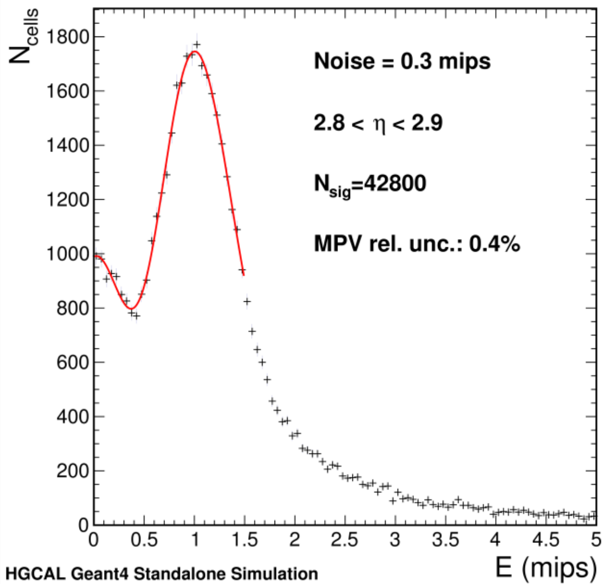
      +/- 3 μm of the average of the wafer
  - Response Linearity, Monitoring → **Charge injection**
  - Absolute scale with standard candles

HGC calibration: inter-calibration with MIP tracking

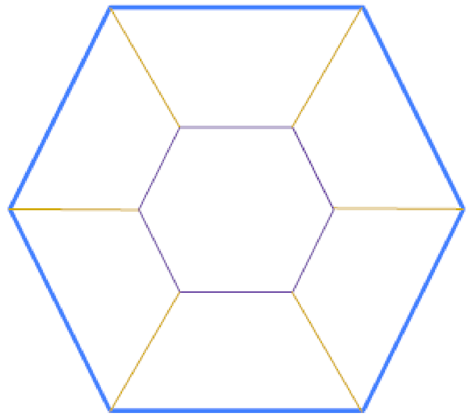
- **"MIP" Tracking ("punch through")**
  - Require signal in layer before/after + isolation
  - Can be done on any readout (L1, offline)



- Tested in MC minimum-biased sample with $<N_{PU}>=140$
- Need 1.5M events to reach 3% precision (takes ~ 1 day)

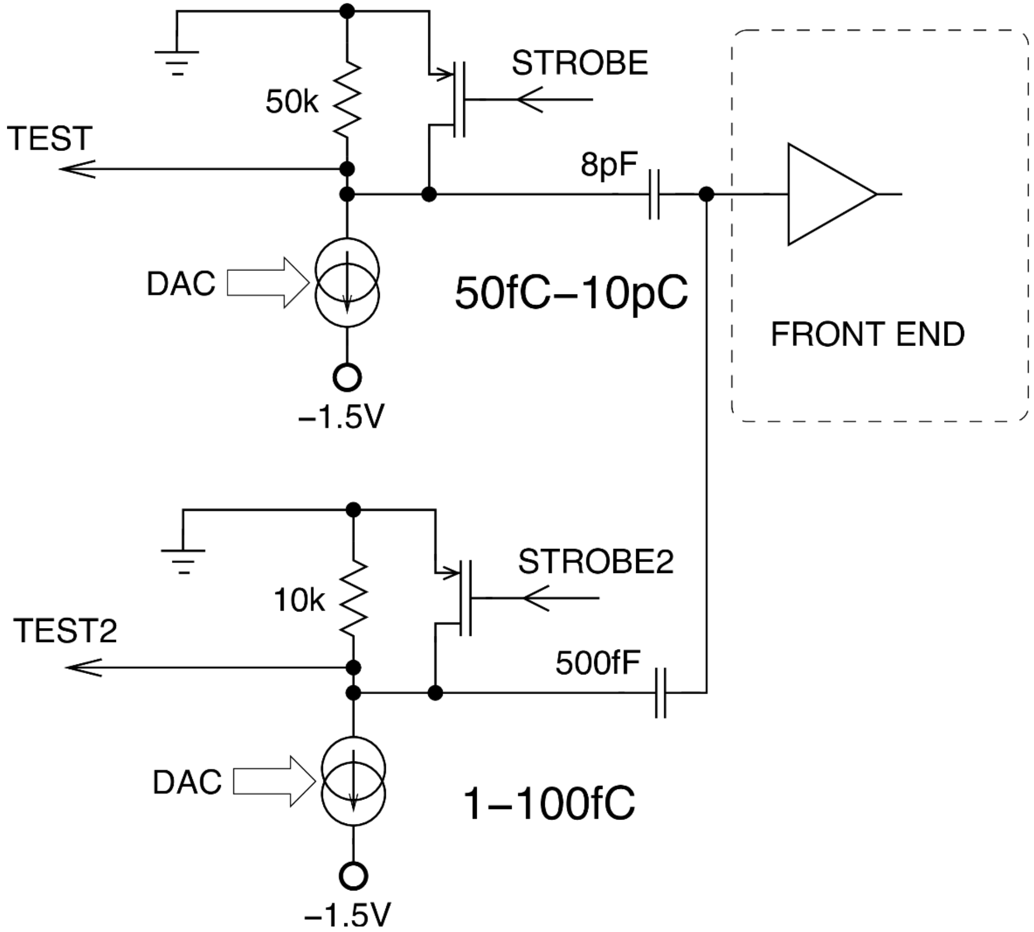


- **In addition, for redundancy:**
  - Low-capacitance/low-noise cell included in each wafer for calibration:
  - 7 sub-cells subscribed inside a standard hexagonal cell (large S/N)



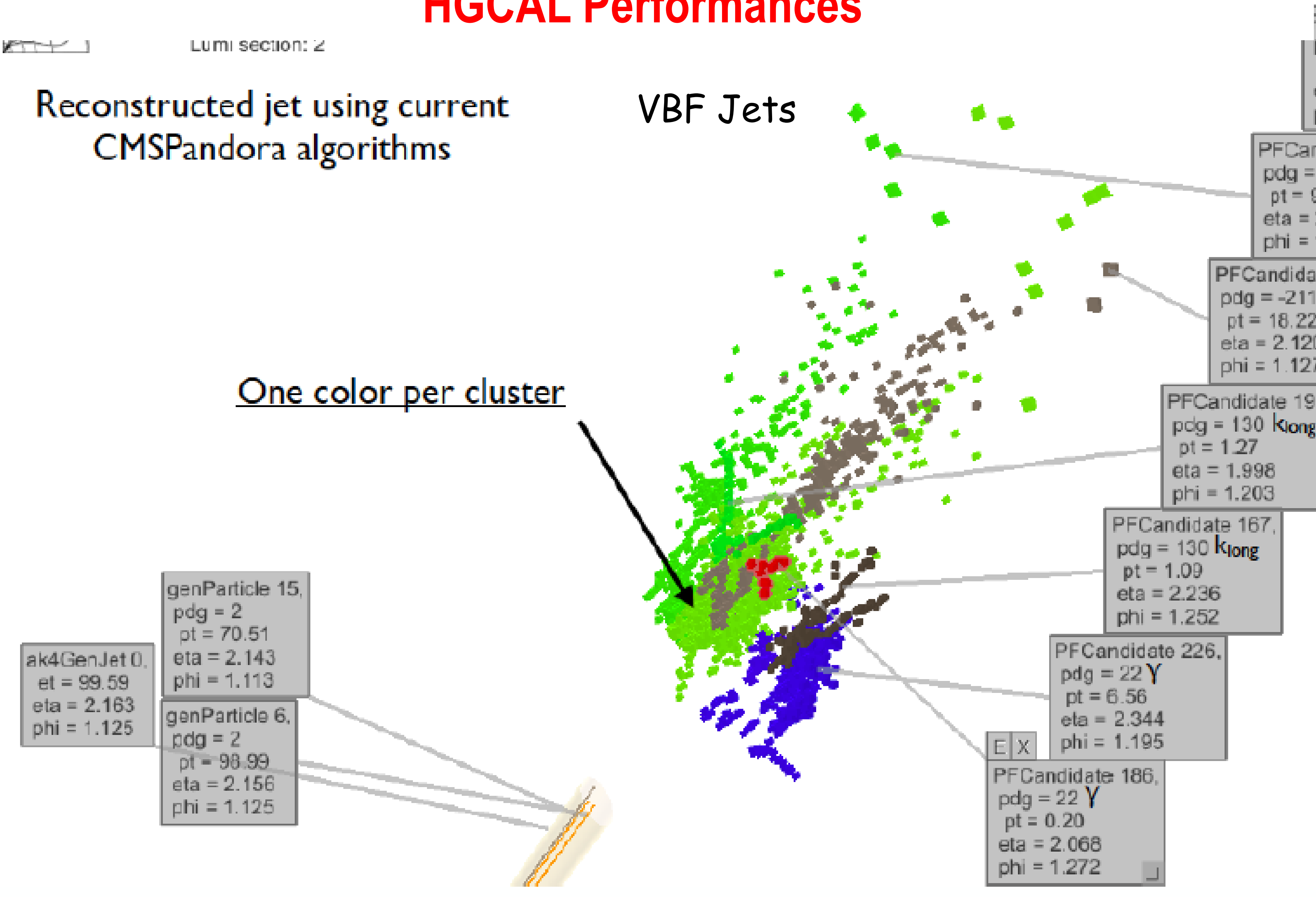
HGC Calibration: linearity, monitoring

- Electronic chain of each channel:
  - linearized, monitored with charge injection system (chopper circuit, fixed calibration capacitances connected to FE)



Electronics calibration circuit.
Two sections with overlapping ranges (one for small, 1-100 fC, one for large signals)

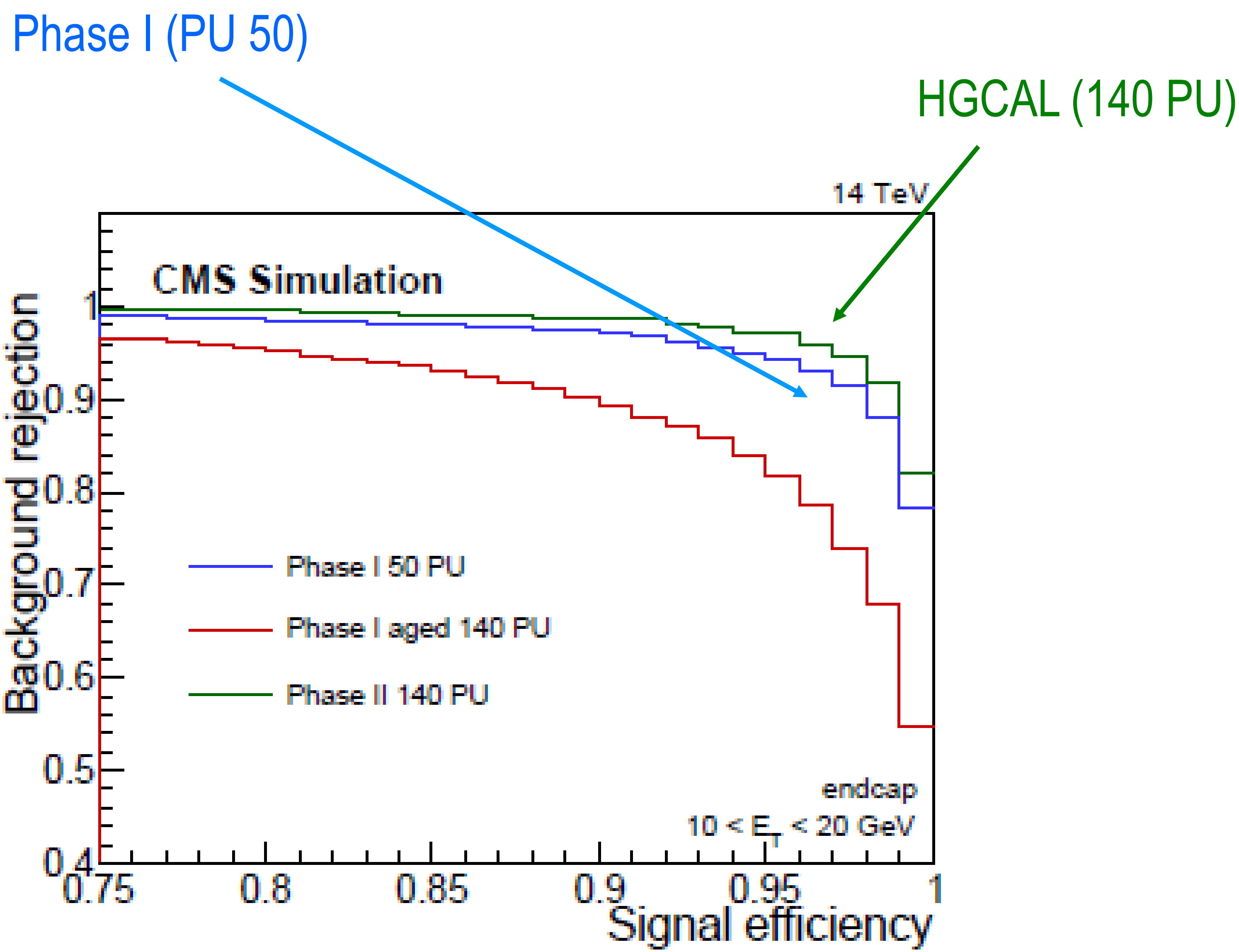
HGCAL Performances



e/g Performances (2)

BDT Electron ID performances

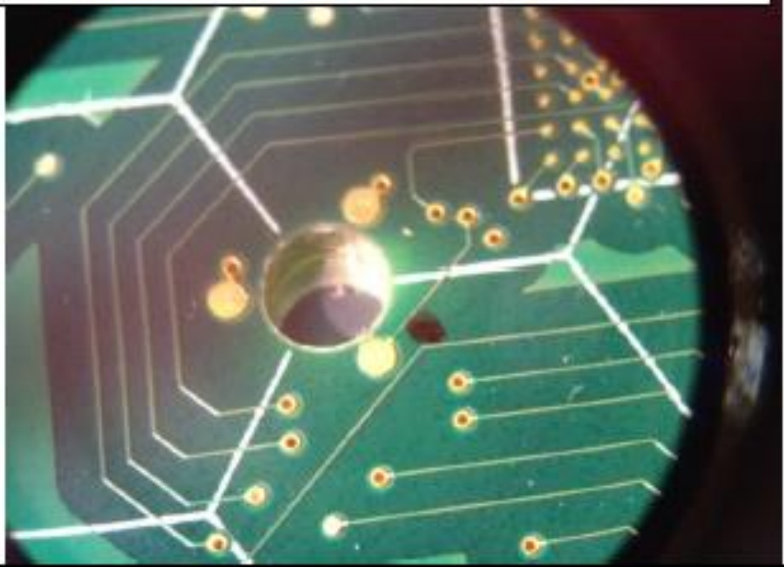
(low ET, critical for multi-leptons topologies: H→ZZ→4 leptons, …)



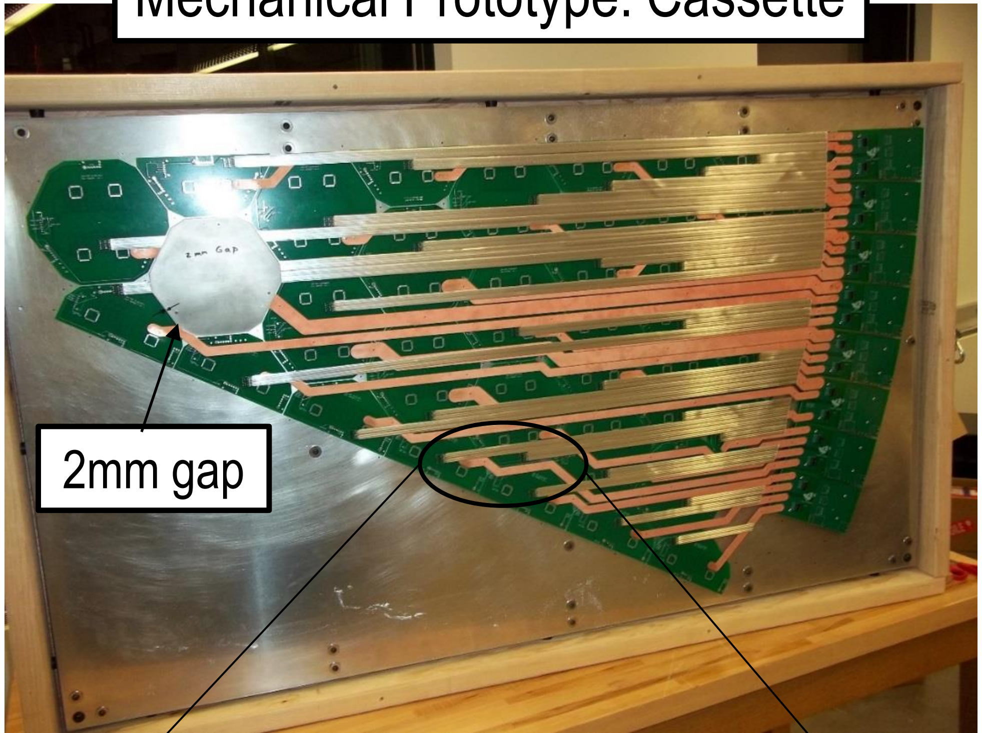
First Prototypes/Mock-up

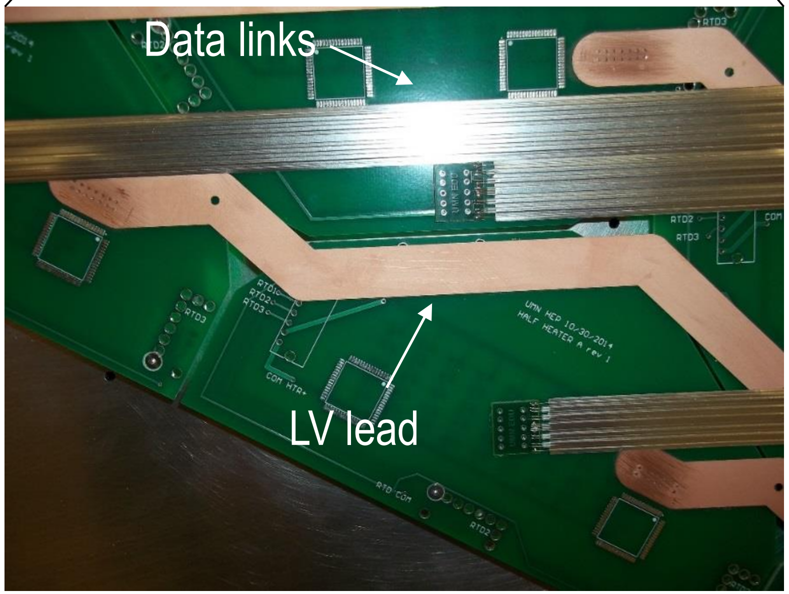
Mechanical Prototype: Modules for Cooling Tests

Automated Bonding Tests



Mechanical Prototype: Cassette



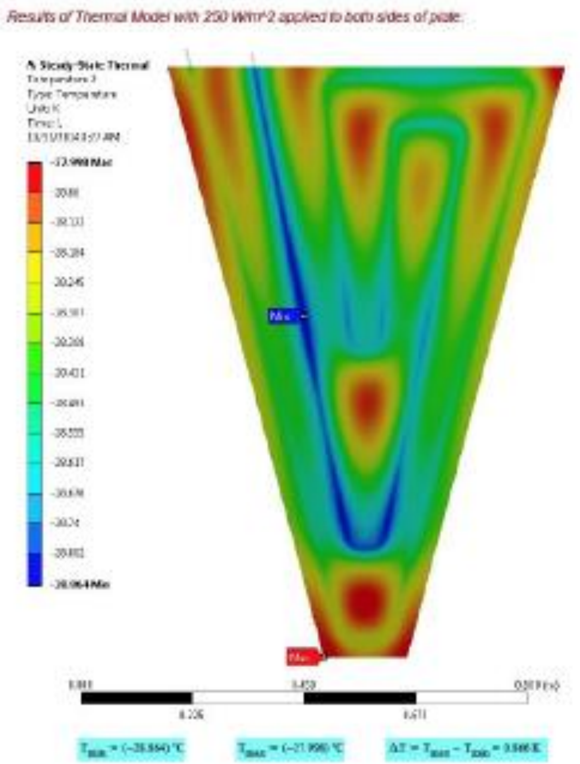


CO_2 Cooling

CMS internal

Cassettes FEA

Goal: $\Delta T \sim$ 1-2 K
6mm Cu plate 1 pipe – uniform heat load
$\Delta T \sim$ 0.9K (over the cassette)
Cooling Tube: OD-4.8mm, ID-3.2mm,
Length - 5.9 m, mass flow: 2.0 gm/sec,
T_{max} -28.00C, T_{min} -28-86C.



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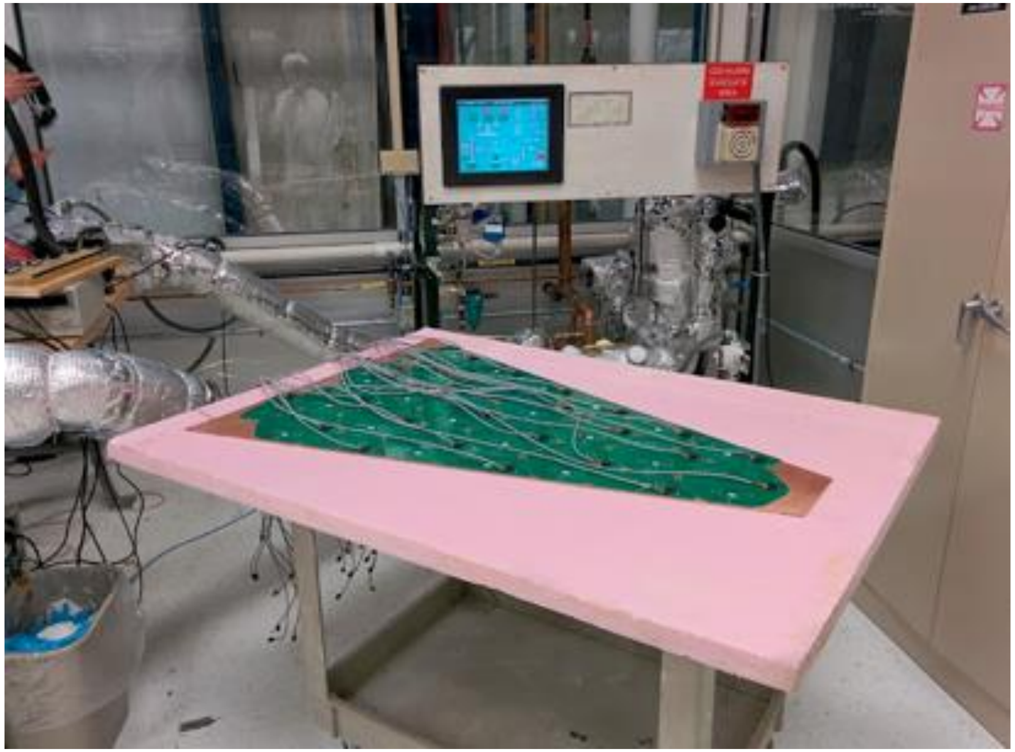
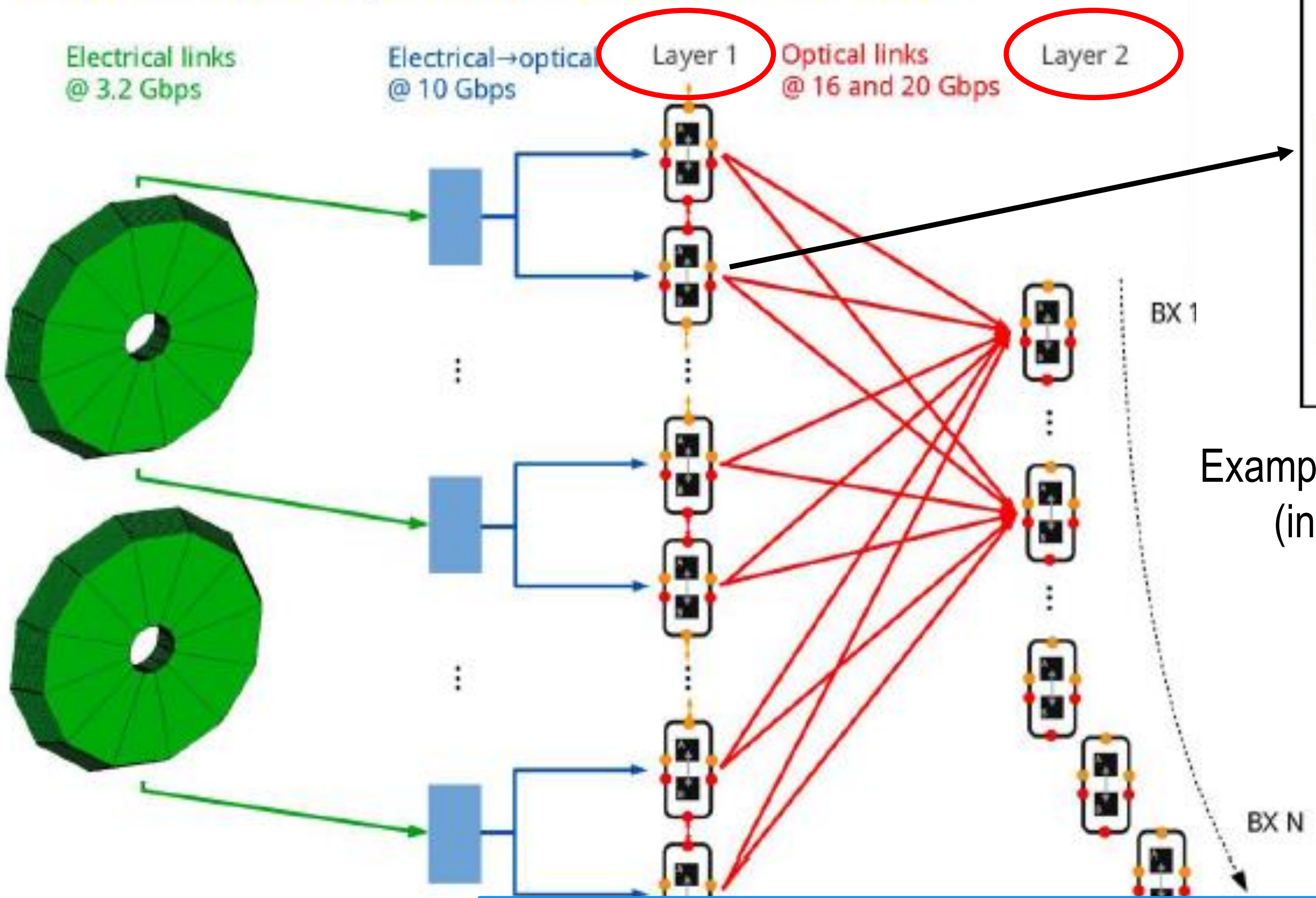
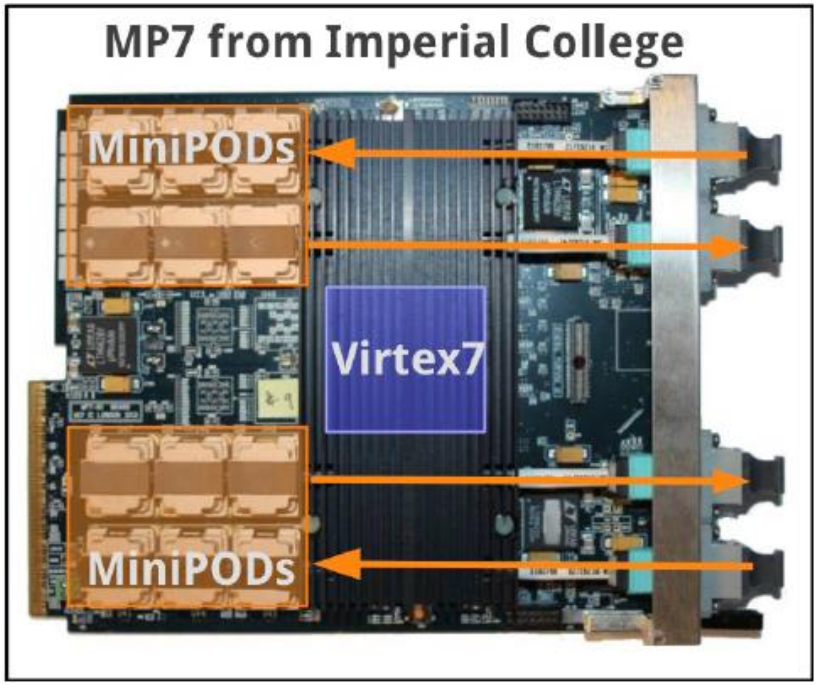
Thermal Mock-up with tests
(CO_2 Cooling stations at FNAL, IPNL)



Level 1 Trigger (1)

Group 4 cells to get a trigger cell
Simple data compression
Full resolution data
Each module produces up to 6 Gb/s





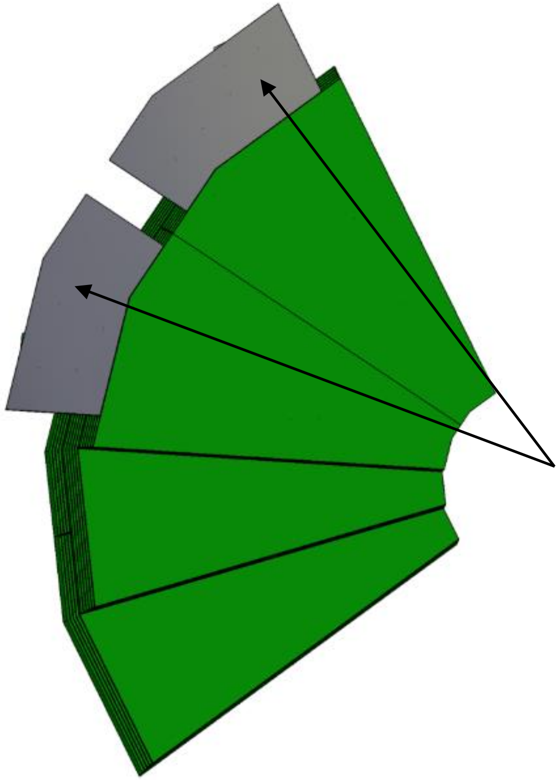
Example of HGC-Trigger module, with modern FPGA (inspired from MP7, used in Phase I Trigger)

- 2-Phase Architecture similar to Phase 1 CMS Trigger (regional Layer 1, global Layer 2, etc…)
- Based on (near-)existing technology (FPGAs, links, …)

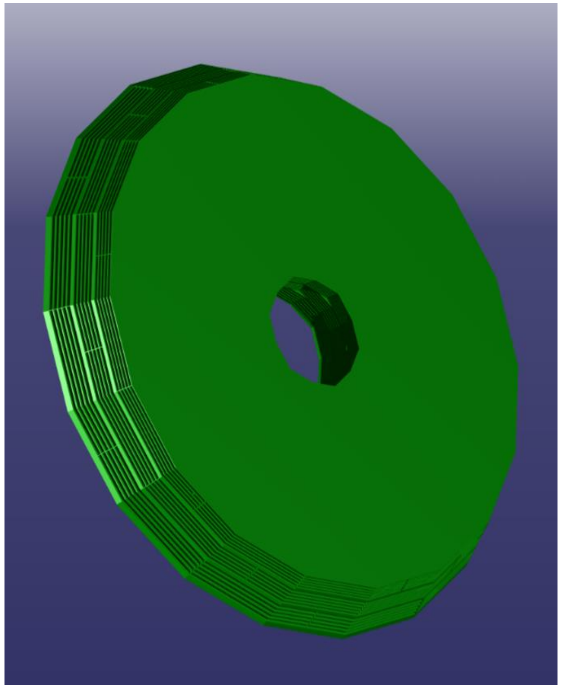
Mechanics: HGC-EE

W/C-fiber Alveolar 30° "petals"/"wedges"
(8-9 layers each)

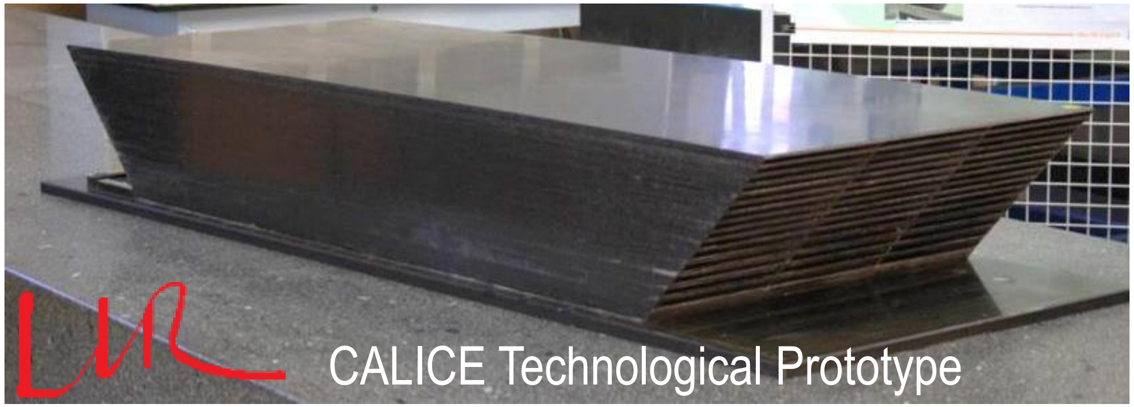
Petals assembled together as 3 wheels, glued together
(each wheel is rotated by (up to) 10°)



Cassettes (with active element) inserted in alveoli.



Design & Building technique inspired by the CALICE Si/W ECAL mechanical structure

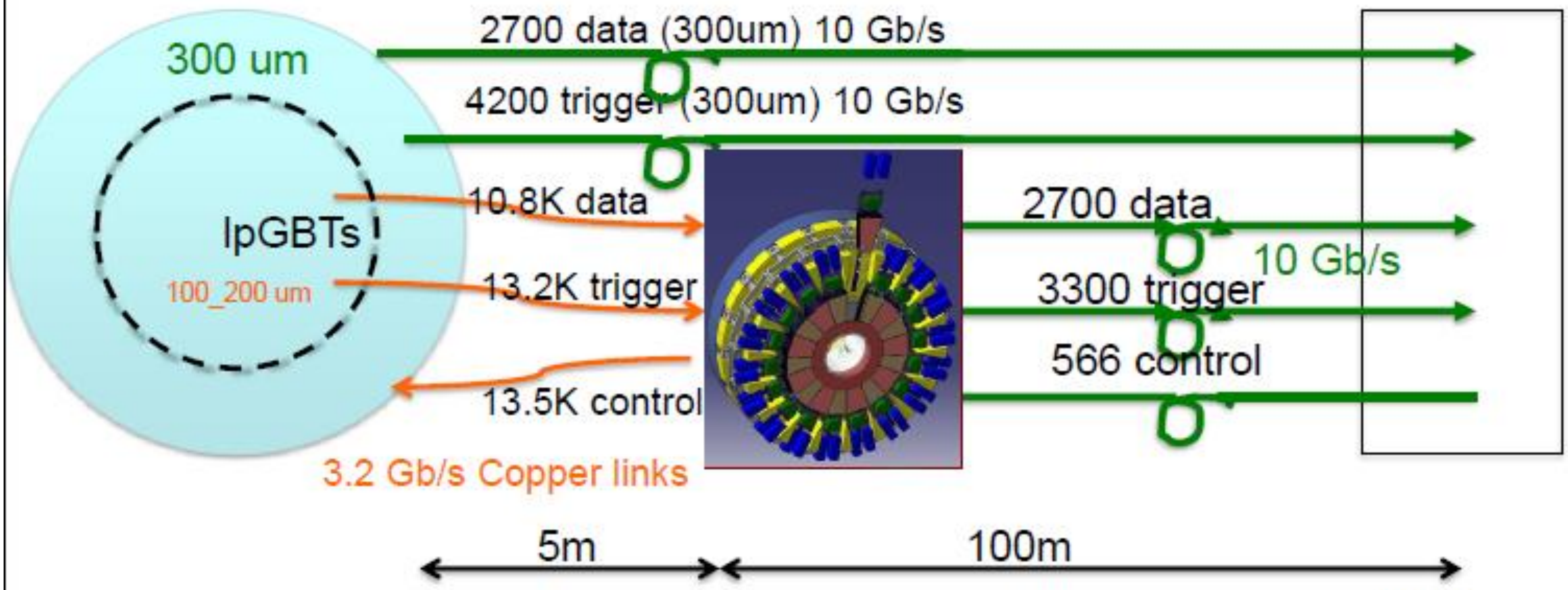


Why CO_2 Cooling ?

From N. Lumb (IPNL)

- Current Endcap uses monophase (liquid) cooling
  - Coolant heat capacity (C_6F_{14}): 1.05 kJ/kg/oC
  - Kinematic viscosity: 0.4 cSt
  - Density: 1.68 g/ml
- CO_2 based systems are 2-phase
  - Latent heat of vapourisation CO_2: 574 kJ/kg
  - Kinematic viscosity: 0.1 cSt
  - Density: 1.0 g/ml
- **Consequently, CO_2 based systems remove same amount of heat with much lower mass flow (factor ~100 depending on allowed monophase ΔT)**
  - 150W removed by ~1g/s CO_2!
  - **Can use pipes with smaller cross-section**
  - Reduction in mass of pipes and the liquid contained within them
- Also in favour of CO_2:
  - High heat transfer coefficient
  - Radiation hard
  - Environmentally friendly: Global warming potential = 1 (vs several 1000s for C_6F_{14})

TP description : sketch [P. Bloch]



Cold detector

TPG generation on detector

RBX region on the back of BH

- DCDC converters
- Data concentrators for copper links

USC
Trigger + Data
Back End

~ 14K optical links
~ 36K copper links

4** copper links -> 1 optical one
** assumes further data compression by 30-40%

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Timeline / Milestones

- **27-28 June 2016: First CMS Comprehensive Review,**
  - including external reviewers: L.Serin (ATLAS), Frank Simon (CALICE)

- **End of 2017: Technical Design Report**
  - including key technical choices:

Examples of Milestones for 2016

Subject	Item	Process/Criteria	Internal Milestone	LHCC Milestone
FH & BH Absorber	Brass or SS	Activation and Cost	Jun-16	Q2 2016
EE Mechanical Design	Full disk or phi sectors	Simulation / Performance& Design pros & cons	Oct-16	Q4 2016
FE electronics	Confirm 130 or 65 nm	Irradiation & Test vehicles	Oct-16	Q4 2016
DC-DC converters	Location: local or remote	Irradiation & Prototyping / System implications	Dec-16	Q4 2016
Electrical/optical links	Location: local or remote	Irradiation / System implications	Dec-16	
BH Active Material	Scintillator Type, Megatile Structure	Radiation hardness, ability to operate cold	*Dec-16*	Q4 2016
Cold Volume	Si only or full HGCAL	Integration studies / Performance & System Implications	Dec-16	Q4 2016
Si Sensors	p-in-n or n-in-p	Irradiation / Performance & System	Mar-17	Q1 2017
Si Sensors	6"or 8"	Dialogue with vendors	Mar-17	

Engineering
Silicon (Active)
BH (Active)
Electronics & Elect. Systems

- **End of 2019: Construction starts…**

R&D is NOW !

Recent Highlights: Front End

Ch. De La Taille et al., (Omega)
Test FE pour TPG: Y. Geerebaert

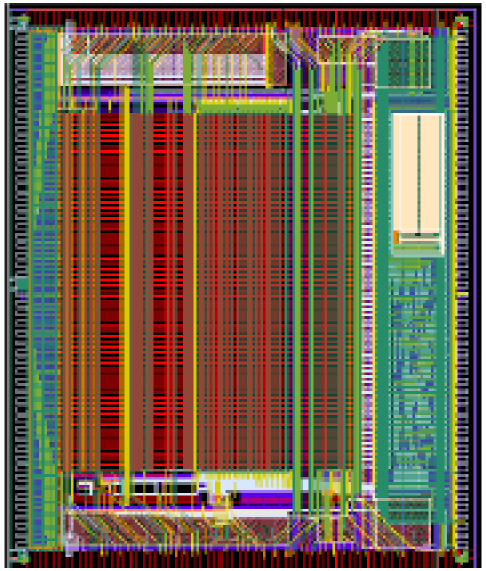
Stringent requirements for Front-End Electronics

- Low power (few mW), low noise (<2000 e-)
- High radiation (200 Mrad, $10^{E}16$ N)
- System on chip (digitization, processing…)
- High speed readout (5-10 Gb/s)
- Timing information to 50ps accuracy

- SKIROC2_CMS expected in June.
- 4-5 boards will be equipped for tests (can start with SKIROC2)

Milestones

15-Feb-16	Submit v0 fe chip (SKIROC-CMS)	⇒ end january
31-Mar-16	Submit f.e. test vehicles in TSMC130 nm technology	⇒ end april
1-Jun-16	**1st Comprehensive Review**	⇒ 26-27 june
30-Sep-16	1st results from f.e test vehicles	⇒ 2nd test vehicles : full one channel
31-Oct-16	Confirm choice of front-end electronics (130 nm) ?? Under study	
15-Dec-16	Define architecture & specs for LV/HV supply, links and on-module components	
15-Dec-16	Define location of DC-DC converters	
15-Dec-16	Define location of electrical/optical links	? Testbeam results of TOT architecture
31-Mar-17	Submit V1 ASIC	⇒ First 32/64 ch ASIC with full functionnality
31-Mar-17	Choice of Si sensors type: all n-on-p or mixed (i.e. n-on-p and p-on-n)	
1-Jun-17	**2nd Comprehensive Review**	
30-Sep-17	1st results from tests of V1 ASIC	
1-Nov-17	**Submit TDR**	
30-Jun-18	Submit V2 ASIC	

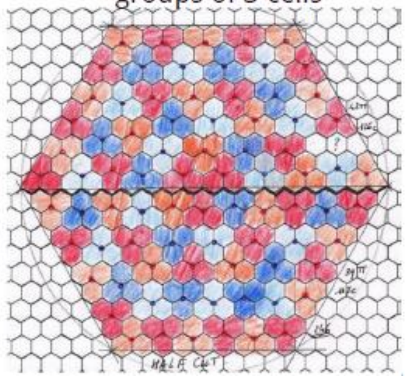


P. Busson, S. Baffioni, *T. Romanteau*, J-B. Sauvan

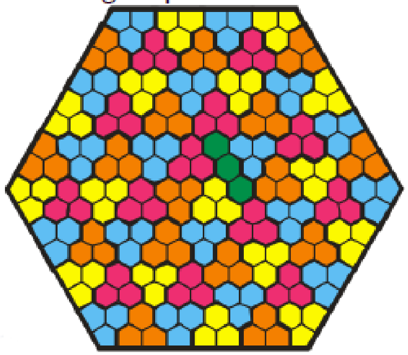
- **LLR among the main drivers of the HGCAL L1 Trigger project**
  - **Now in strong collaboration with Split & CERN**

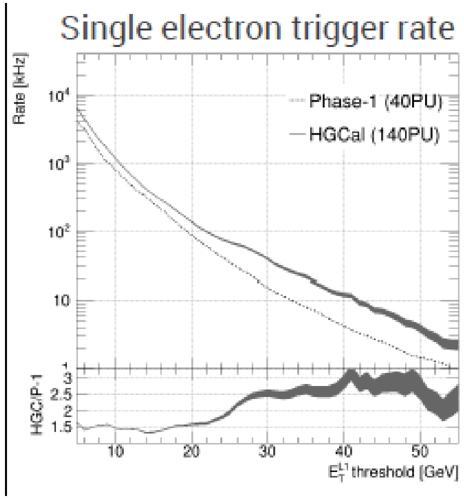
Architecture	Front-End Studies	Simulation & Algorithms
Define baseline architecture for TP	Work on trigger "raw data" (Data reduction, trigger cell geometry, …)	Development of emulator, + standalone tools (digitization, ..)

252 cells with groups of 3 cells



192 cells with groups of 3 cells



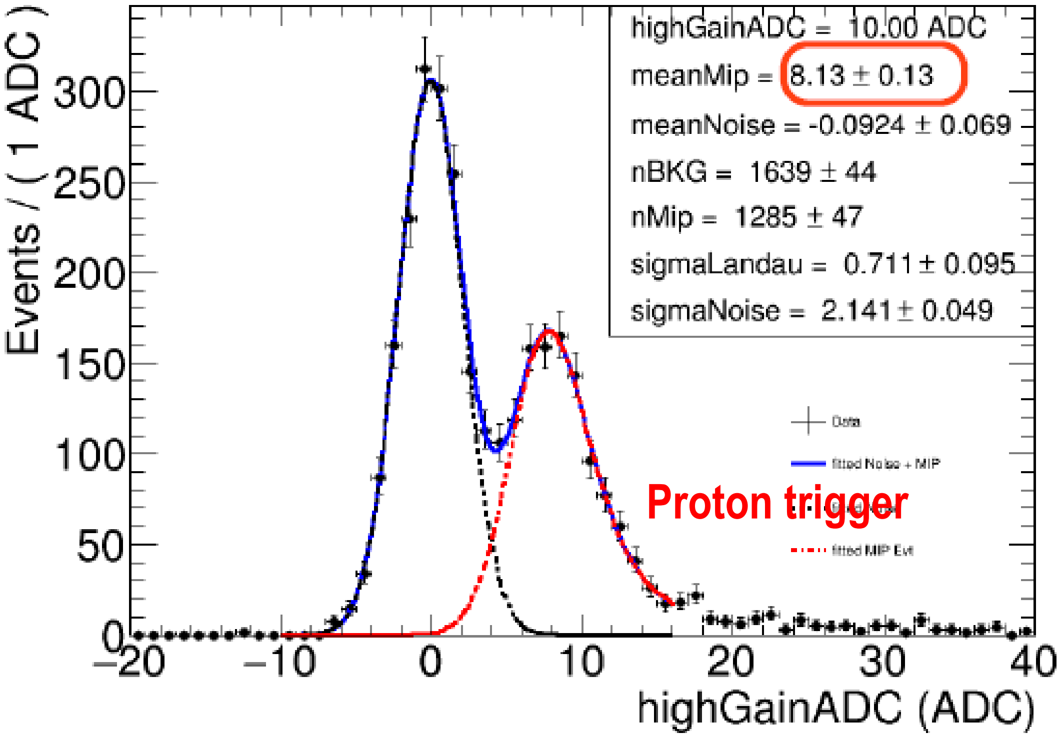


Besoin urgent d'un Test Bench SKIROC-CMS au LLR pour rester dans le jeu côté interface trigger avec le chip de FE

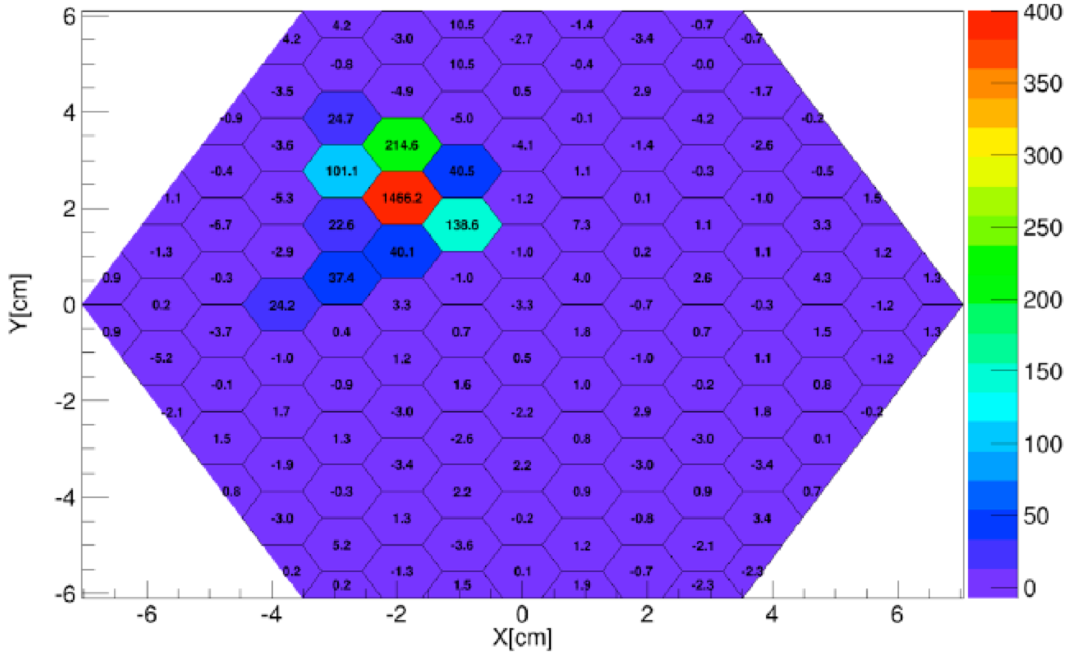
Recent Highlights: Test beams (3)

➢ **First results:**

120 GeV protons as a proxy for MIP and calibration



32 GeV electron after 6 X0



Size of cluster ~ 2 cm
Pedestals subtracted

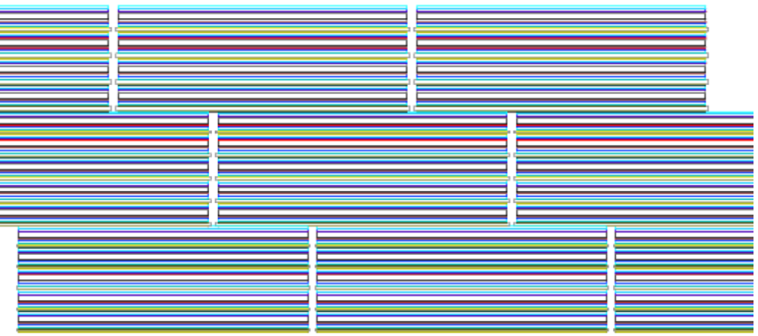
➢ **Next steps:**

- <= 28 layers for tests in May **[SKIROC2]**
- First tests at CERN in August/May (preceded by CALICE tests), then in November **[SKIROC2 or SKIROC2_CMS if validated].**

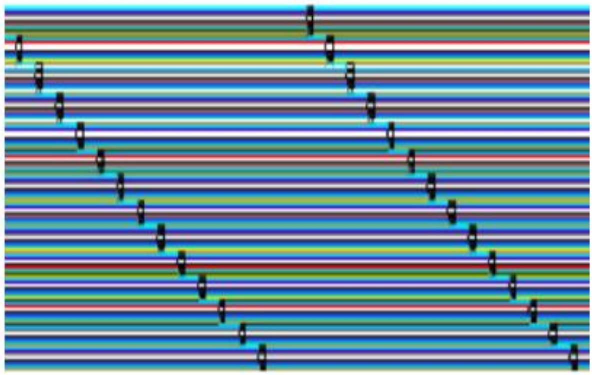
➢ (A) Phi-sector Disks

- Various configurations simulated

(1) "TP design"
3 blocks (8-10) layers rotated
by 10°



(2) Disks rotated every 2°
layer by layer
(or every 2 layers==1 cassette)

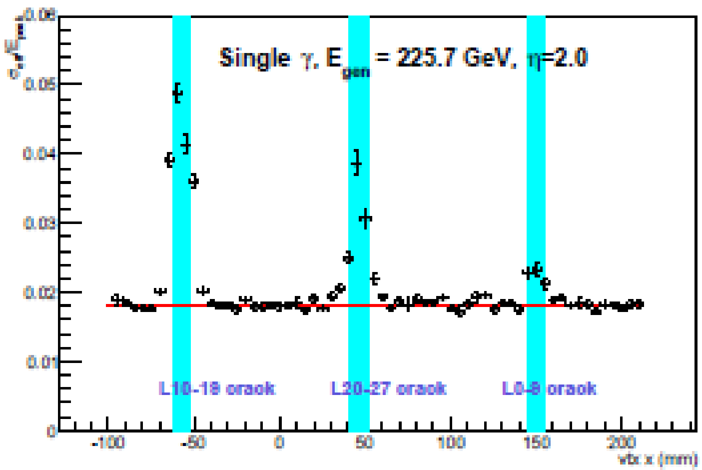


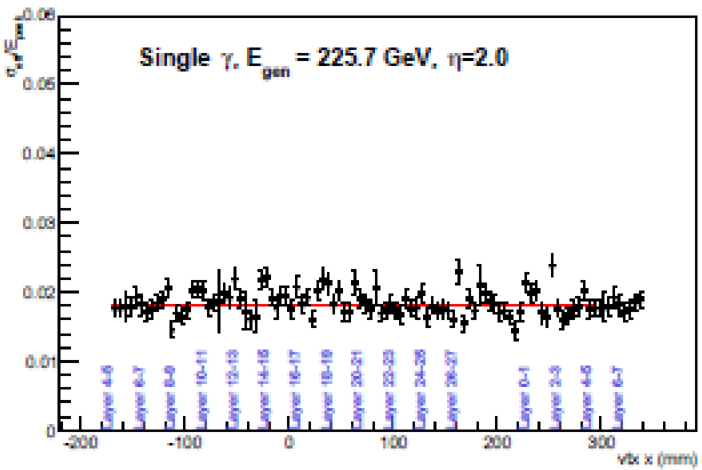
Continuous W

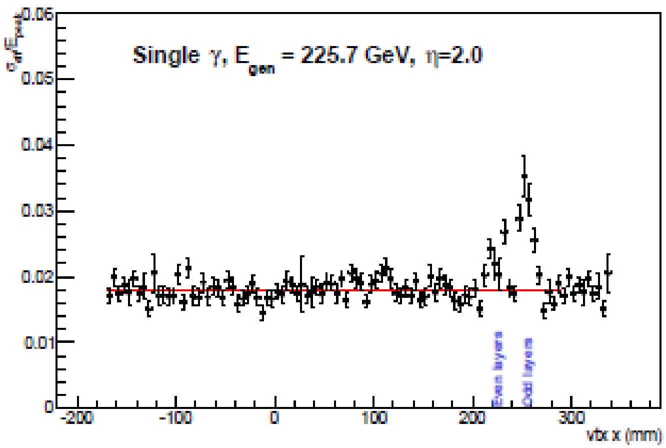
(3) Disks with staggered layers
(ever 2nd or 3rd)

Continuous W

➢ Active-to-active gap: mainly created by C-fiber alveoli (+ Si guard ring, mechanical tolerance): 0.5 – <1cm

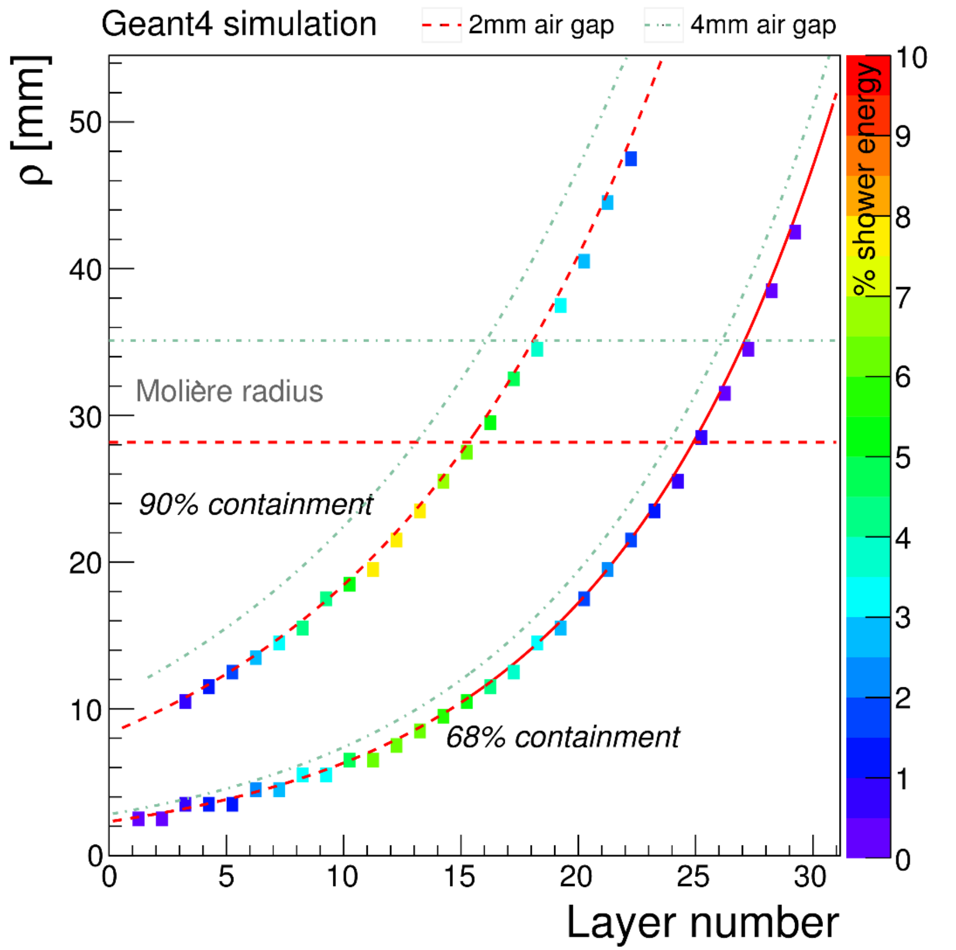




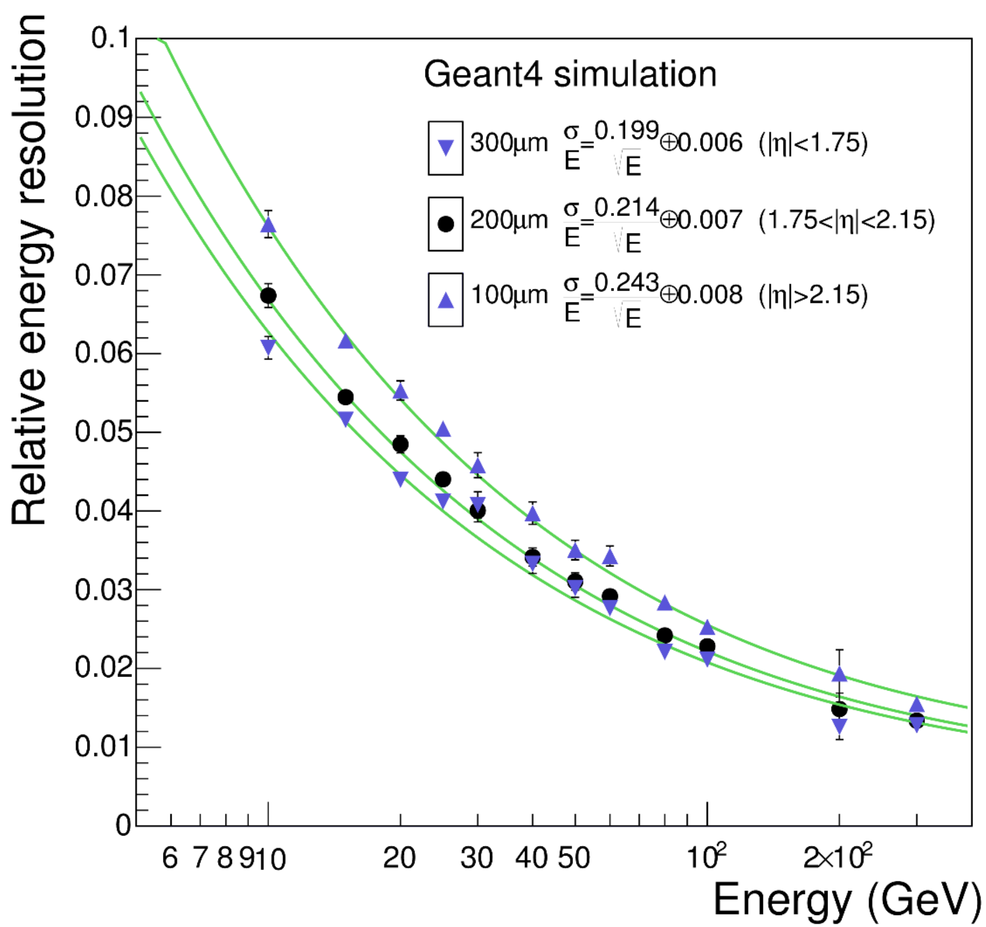


HGC Performance (1)

EM shower energy containment



Electron energy resolution vs Si thickness



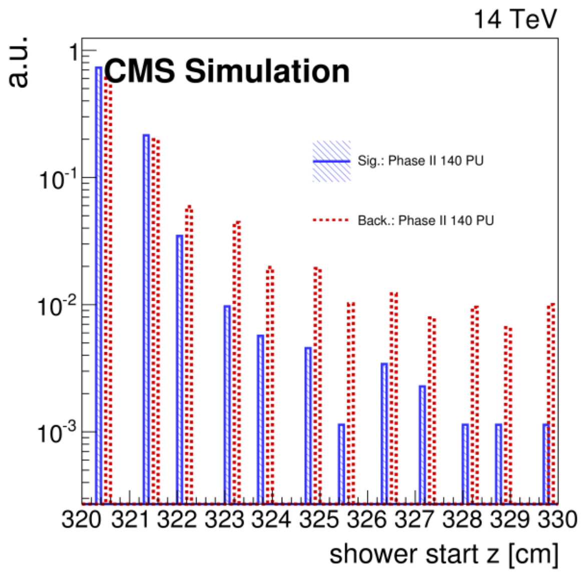
Shower radius quite small in first layers.
Can use longitudinal segmentation for PU rejection, …

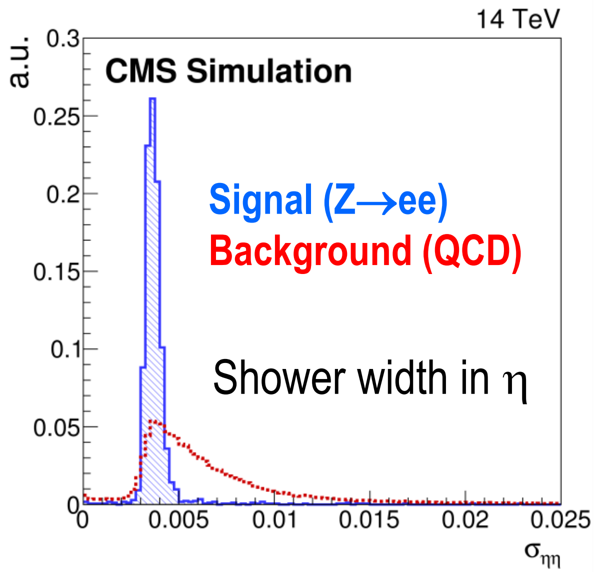
Stochastic term: ~20%
but **low constant term** (target: 1%)

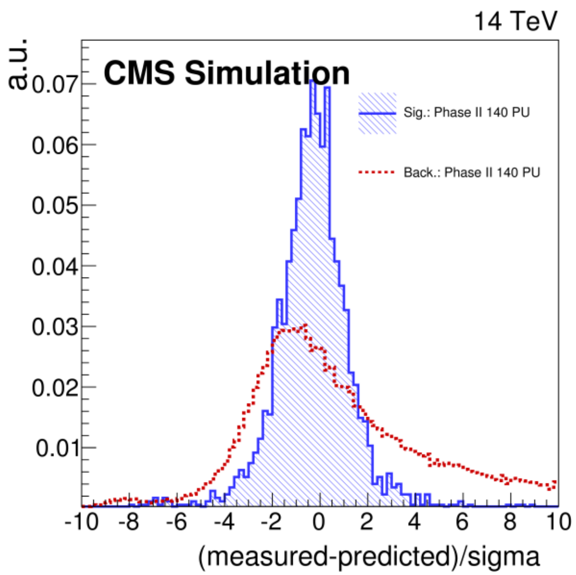
Obtained with standalone G4 simulation. Benchmarked againt CALICE test-beam results

HGC Performance (2)

- **High Granularity + longitudinal segmentation gives additional powerful handles for particle ID:**
  - shower start, shower length compatibility, restoration of projectivity, 3D shower profile fits, layer-by-layer PU subtraction, etc…

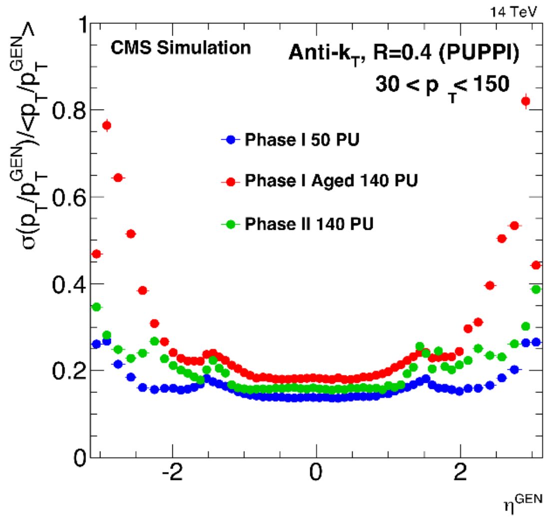




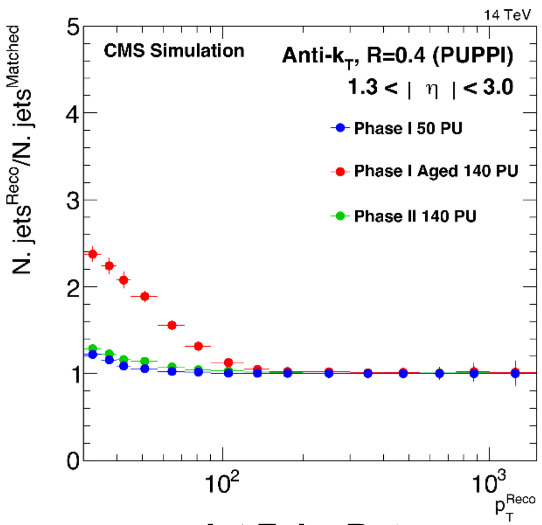


With 1x1 cm² squared cells

- Combination of HGC and Tracker (with far from optimal PFlow algo)



Jet Energy Resolution vs η



Jet Fake Rate

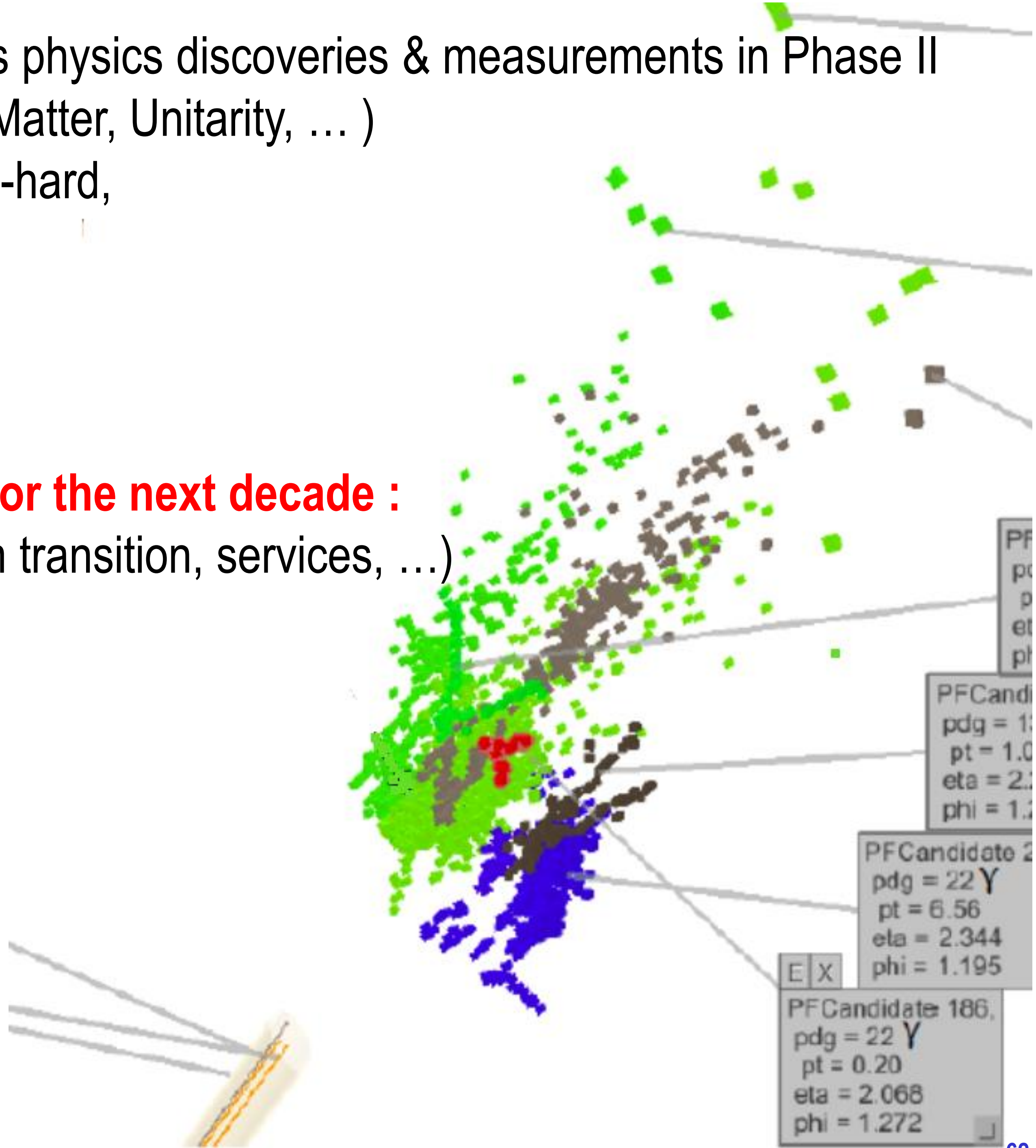
- **~Recover Phase I 50 PU performance !**

More in talk by F. Chlebana (PFlow)

Conclusion & Perspectives (1)

- HGCAL is on the critical path towards physics discoveries & measurements in Phase II (HH, VBF jets for Higgs/SUSY/Dark Matter, Unitarity, …)
  and has all ingredients for being rad-hard,
  mitigate PU,
  deal with high rates,…

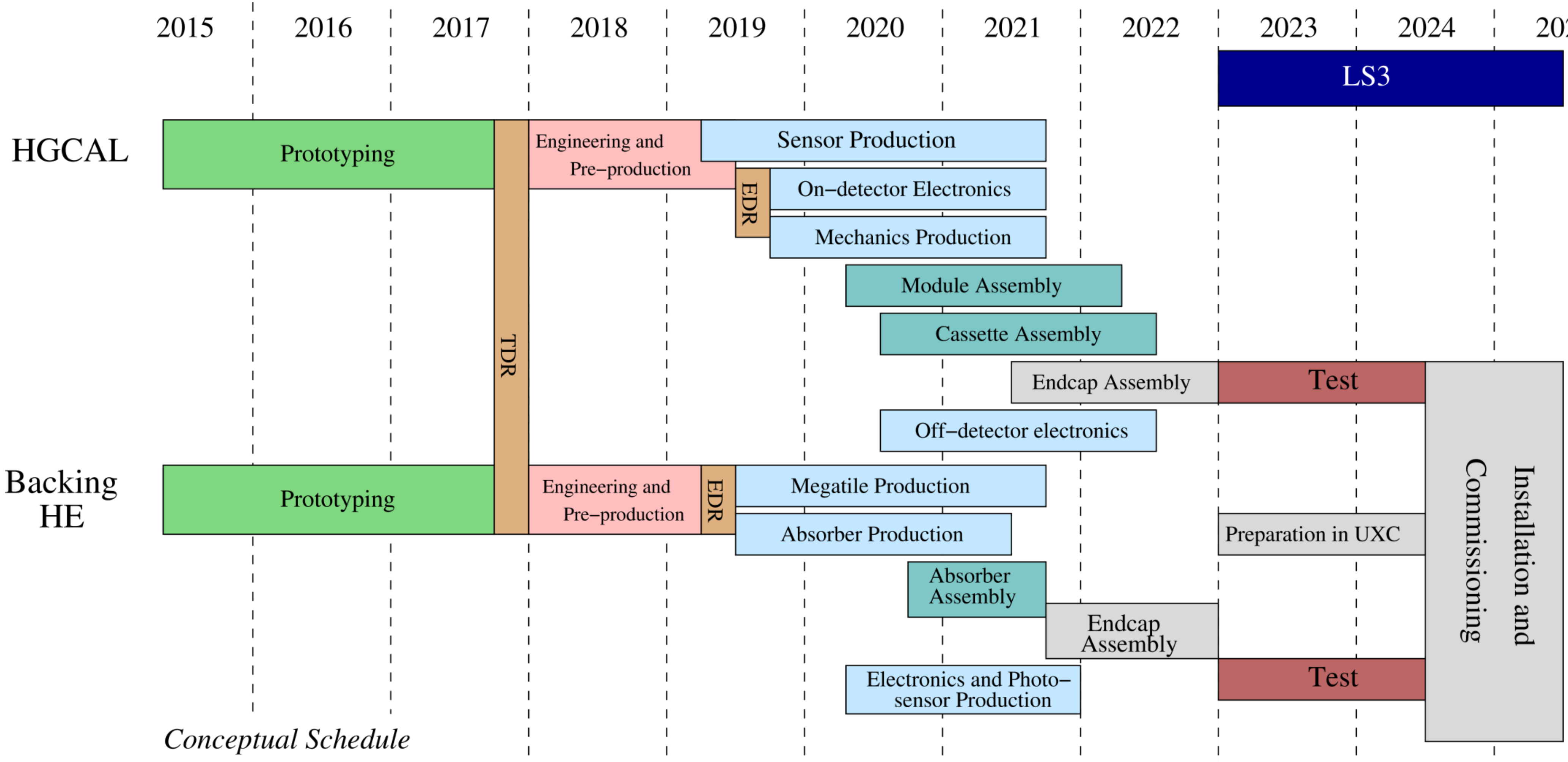
- **Many major & excited challenges for the next decade :**
  - Engineering (includes cold/warm transition, services, …)
  - FE electronics & L1 Trigger
  - Software, computing
  - …



Conclusion & Perspectives (2)

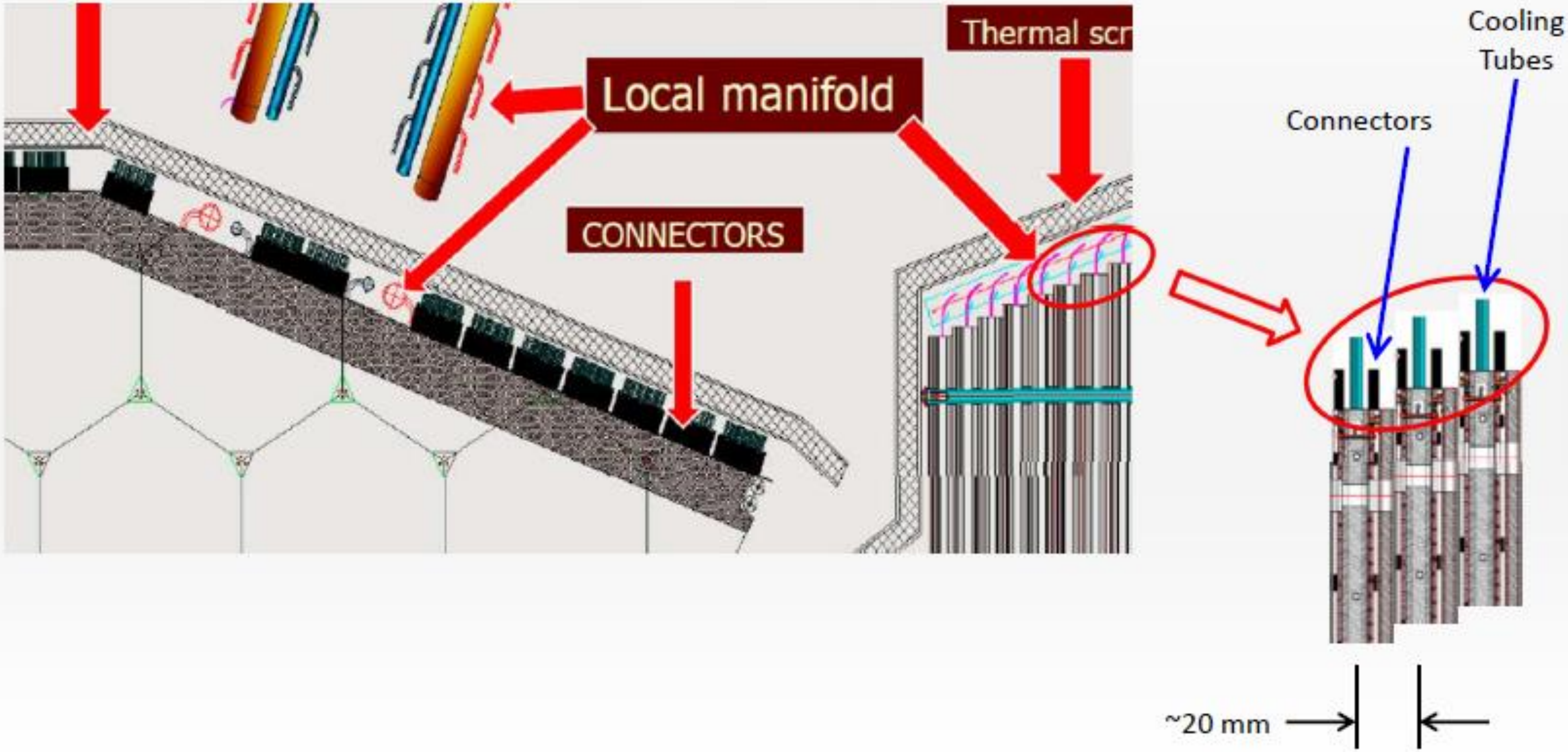
- **Now in R&D phase**
  - Fast progress since Technical Proposal (mechanics, sensors & modules, FE, …)
  - Several **test beams session scheduled this year** (FNAL, CERN)
  - **TDR expected end of 2017**, including key technical choices
  - Construction starts in ~2019

See talk by Z. Gecse (test beam)



Services: Turning the Corner at the Cassette Edge

- Very high density of services at the cassette edge: Electrical, Optical, Cooling
- Serious, integrated design effort is required … only barely begun



HIGHTEC© Synergies @ P2IO

An optimisation of ressources

- The R&D developments needed for SiWLC, HGCAL, and HGTD have a lot in common and will greatly profit from this common HGCFC P2IO project
- This interest for a common effort and sharing of knowledge and know-how between physicist and engineers in this HGCFC project applies to each of the four main areas:

Mechanical Design: SiWLC, HGCAL, HGTD use similar C-Fibre techniques and engineering expertise for their reference designs

FE & BE electronics: SiWLC, HGCAL, HGTD each rely on variants of the Omega "SKIROC" type of FE chips
Also, digital electronics and data flow is a similar and major challenge

Clocks and Timing: Clock distribution and the study of the impact of timing for pile-up mitigation are common issues of HGCAL and HGTD

Performances & TB: Similar PFlow algorithms and clusterisation adapted to high granularity are major developments from same post-docs
Common beam tests are foreseen at CERN*

* A first SiWLC beam test at CERN organized with CMS HGCAL has occurred already in November 2014 at the initiative of P2IO groups !