HGCAL:
A High-Granularity Calorimeter for the Endcaps of CMS at HL-LHC

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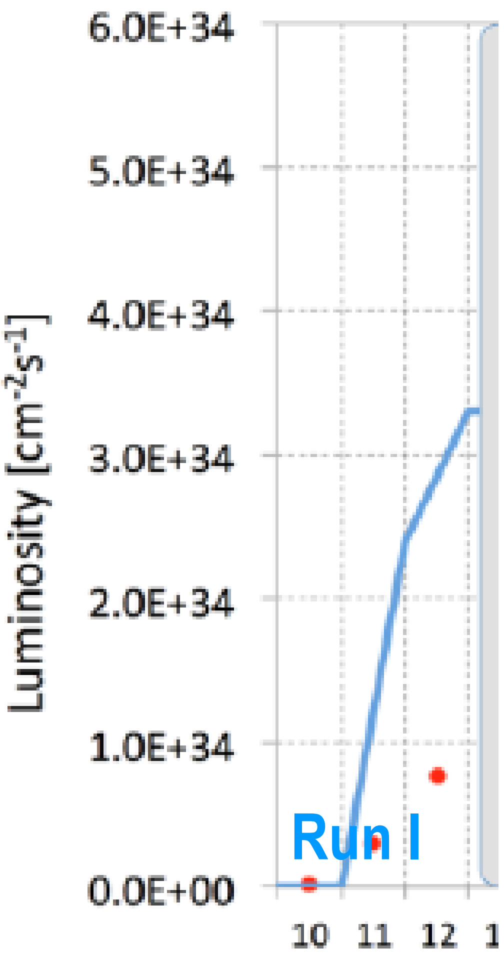
On behalf of the CMS Collaboration

May 18th 2016,
CALOR, Daegu

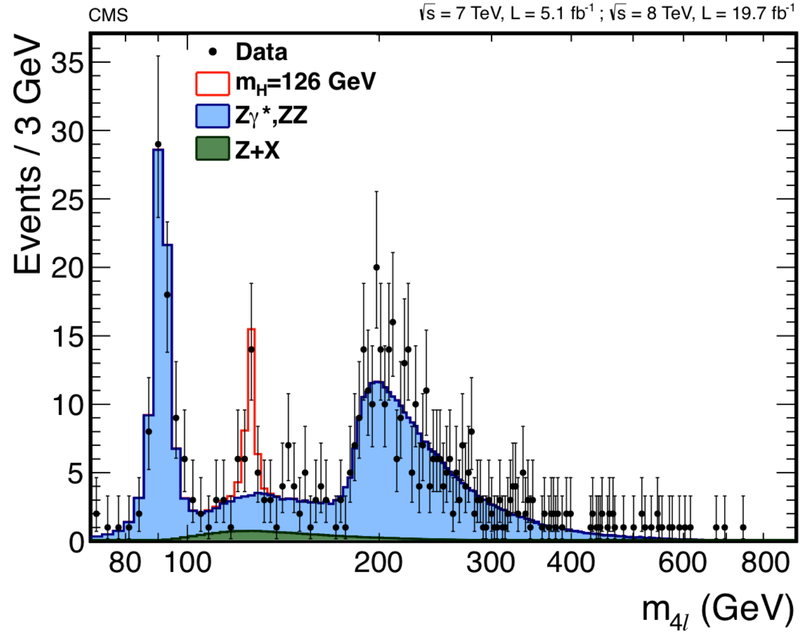
LHC: from Run I to HL-LHC

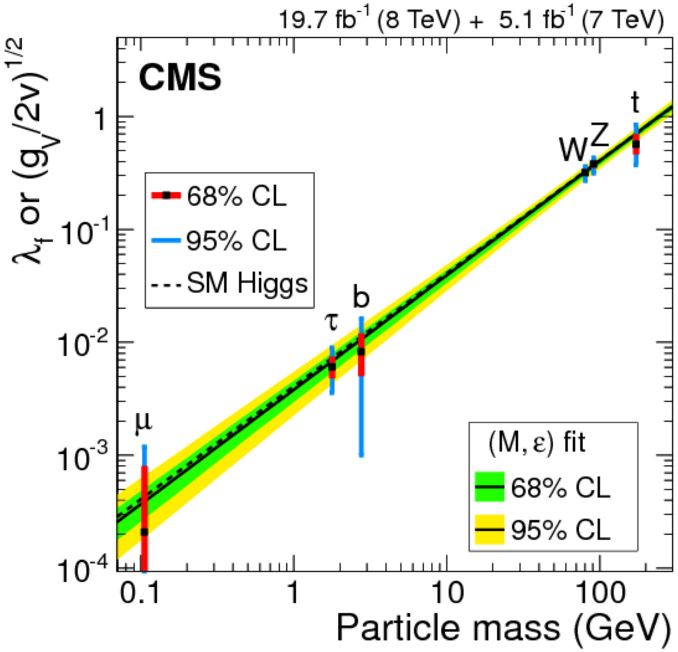


"Phase 0",

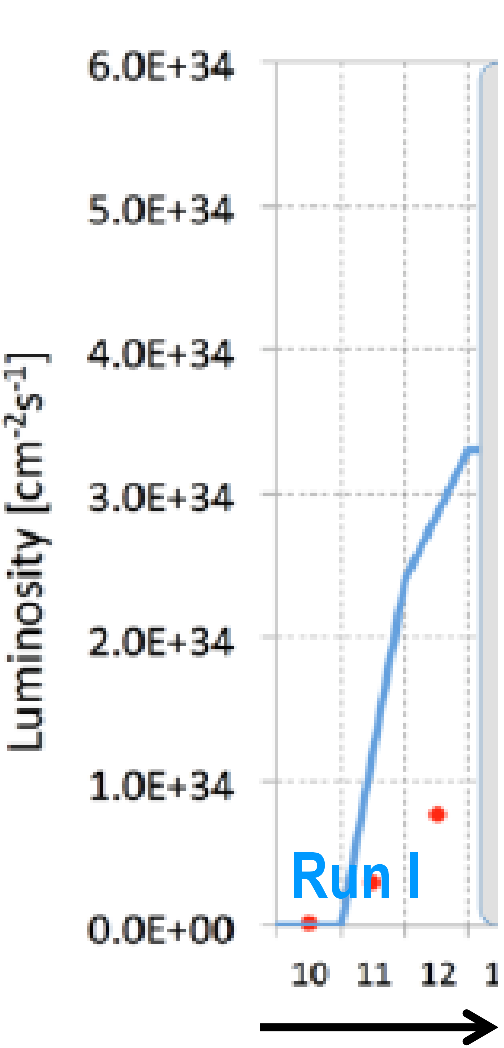
$\sqrt{s}$ = 7-8 TeV
$\int$ L dt = 25 fb^{-1}
Higgs boson discovery

Main Run I highlight:
Higgs boson discovery
& first measurements





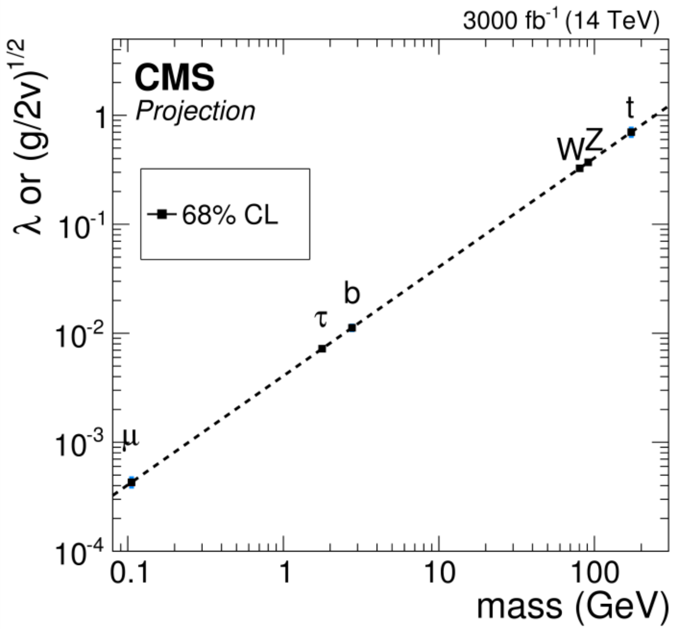
LHC: from Run I to HL-LHC



"Phase 0",

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

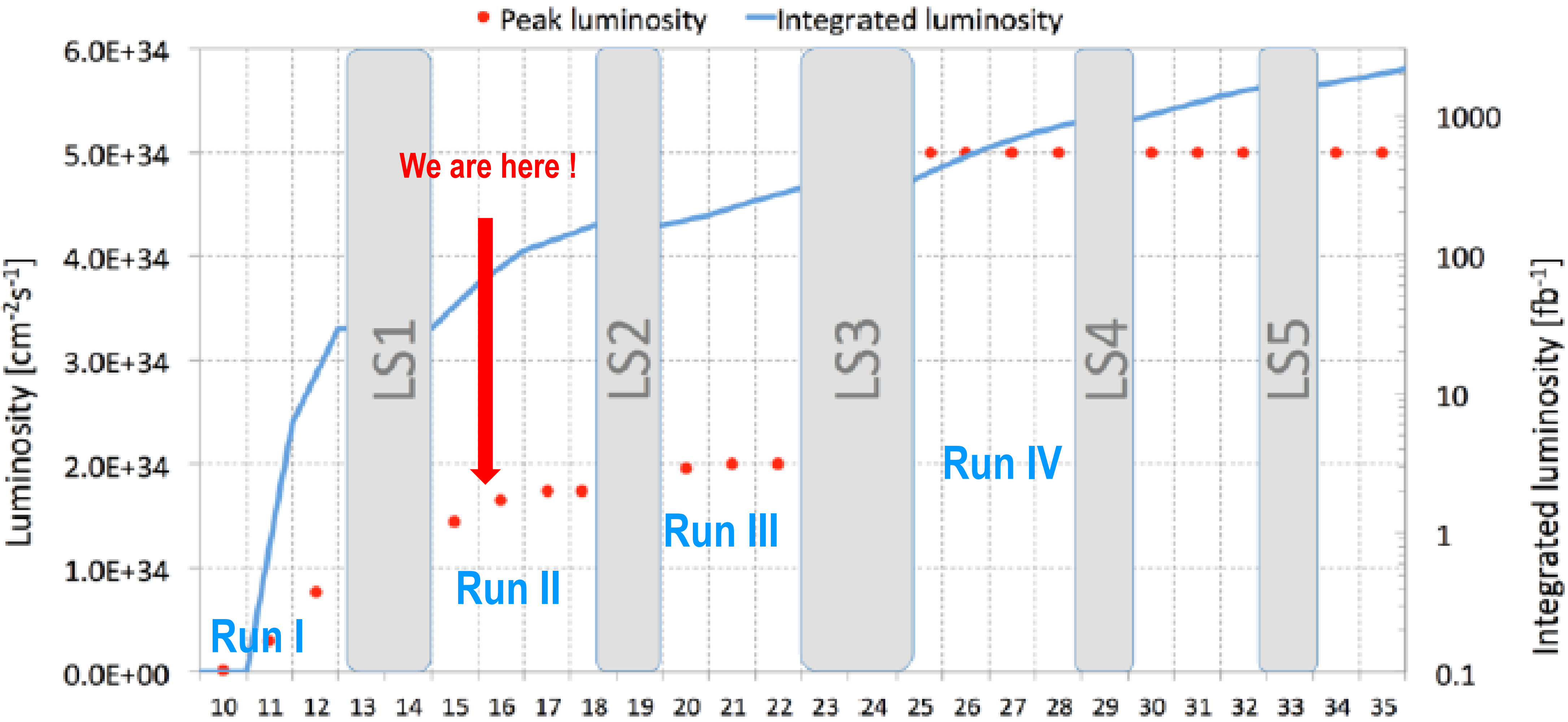
- **Unraveling the true nature of EWSB**
  - Precision measurement of the Higgs Sector
  - Observation of HH production, constraints on self-coupling λ
  - Rare ($\mu\mu$, $Z\gamma$…) or forbidden H_{125} decays ($\tau\mu$…)
  - Unitarity via Vector Boson Scattering



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

Powerful demand on **very high luminosity !**

LHC: from Run I to HL-LHC



"Phase 0",

Phase I

Phase II (HL-LHC, >2025)

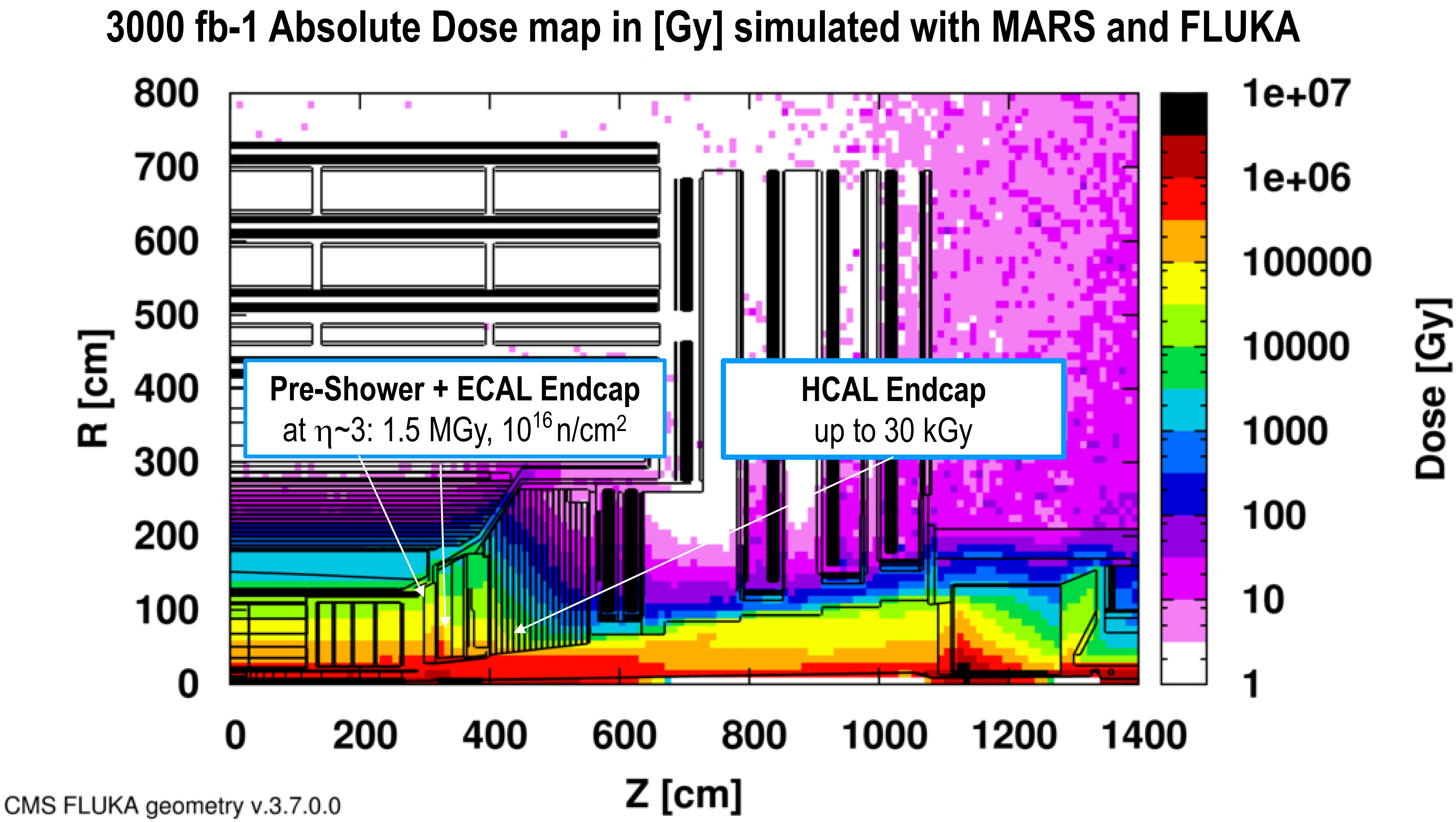
$\sqrt{s}$ = 7-8 TeV
$\int L\,dt$ = 25 fb^{-1}
Higgs boson discovery !

$\sqrt{s}$ = 13 TeV
Lumi inst. : up to 2.5×10^{34} $cm^{-2}s^{-1}$,
$\int L\,dt$ = 300-500 fb^{-1}
<PU> : from ~25 to 60
X(750) ? SUSY ? ☺

$\sqrt{s}$ = 13-14 TeV
Lumi inst. : >= 5×10^{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)

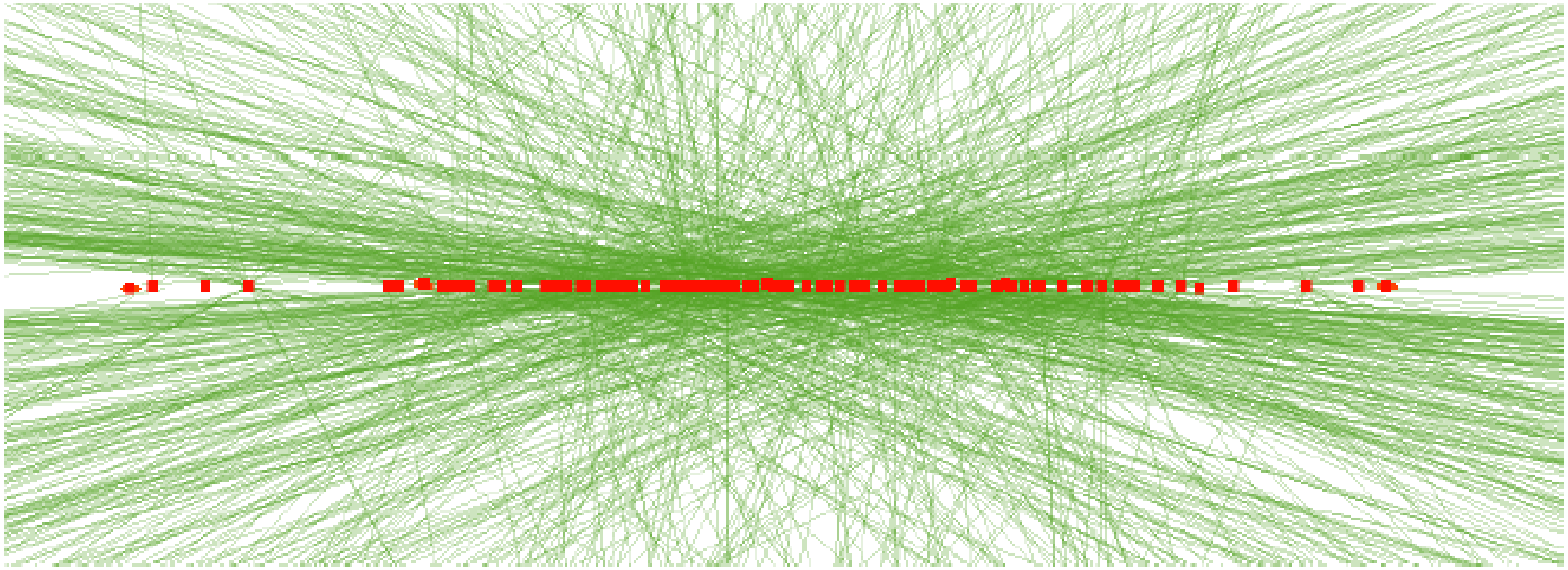


Figure 9.1: An event display showing reconstructed tracks and vertices of a simulated top-pair event with additional 140 interactions overlaid for the Phase-II detector.

- 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} $cm^{-2}s^{-1}$,

See talks by JB. Sauvan (L1) and F. Chlebana (Pflow)

- **Challenges for Triggers (especially Level 1 !) & offline reco + computing (30xLHC)**

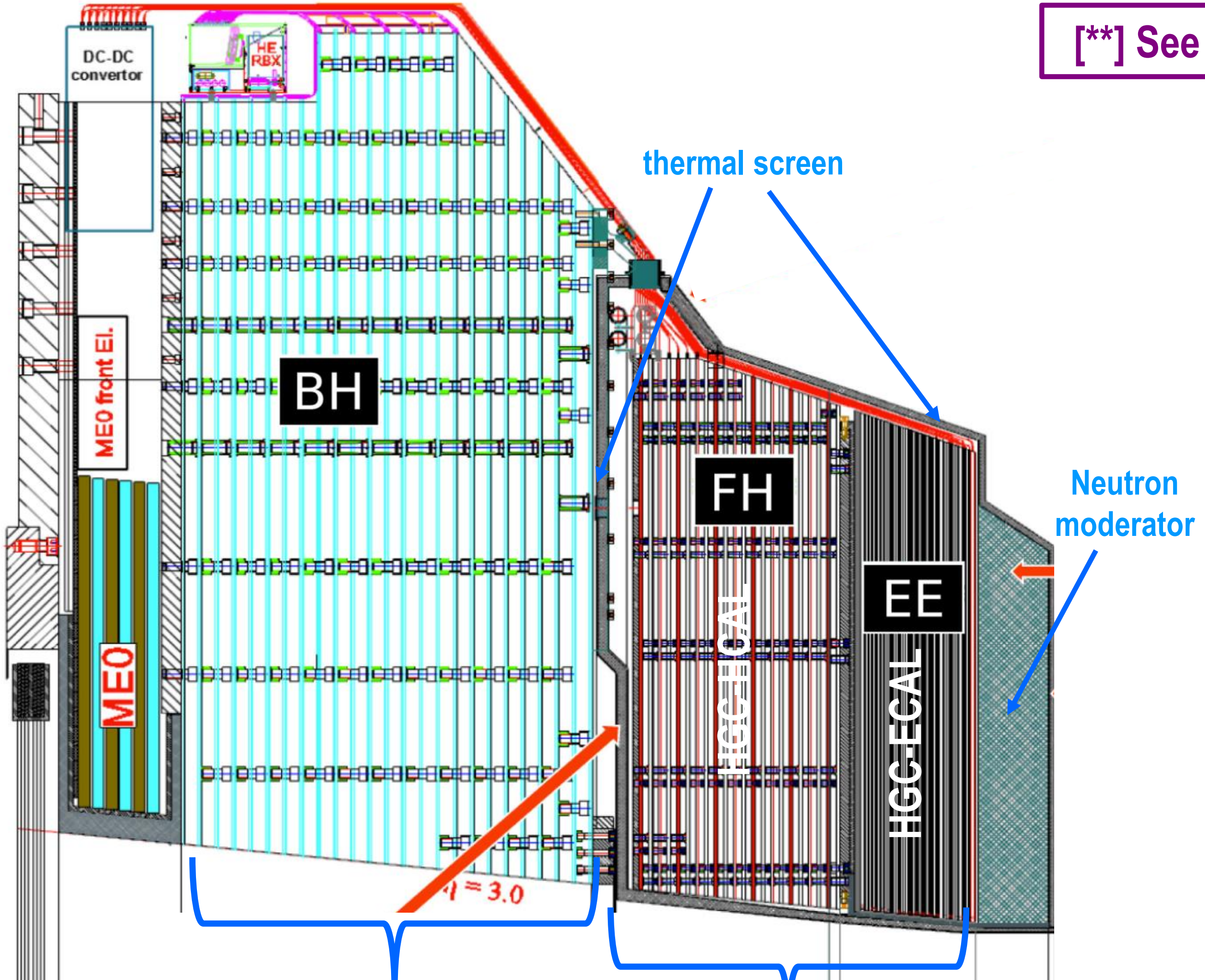
Need to preserve "low" energy physics (125 GeV Higgs) and explore TeV scale (e.g. SUSY) in a very harsh environment !

HGCAL: General Layout

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

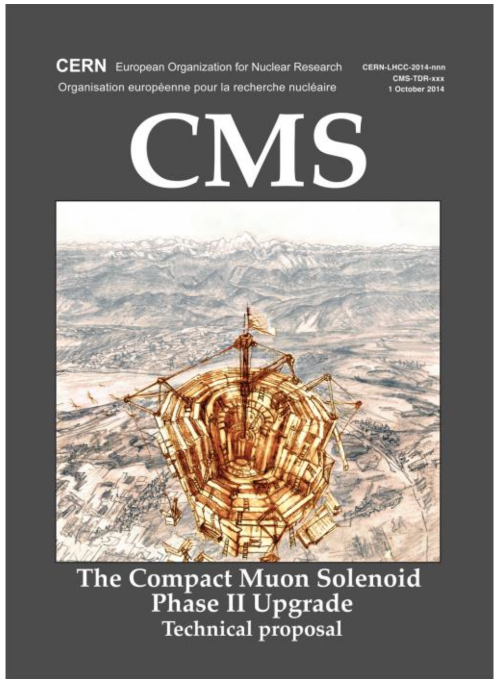
[**] See talk by N. Akchurin

HGC+BH: covers η range up to 3



Back Hadron Calorimeter
(Brass or Steal + Scintillators)

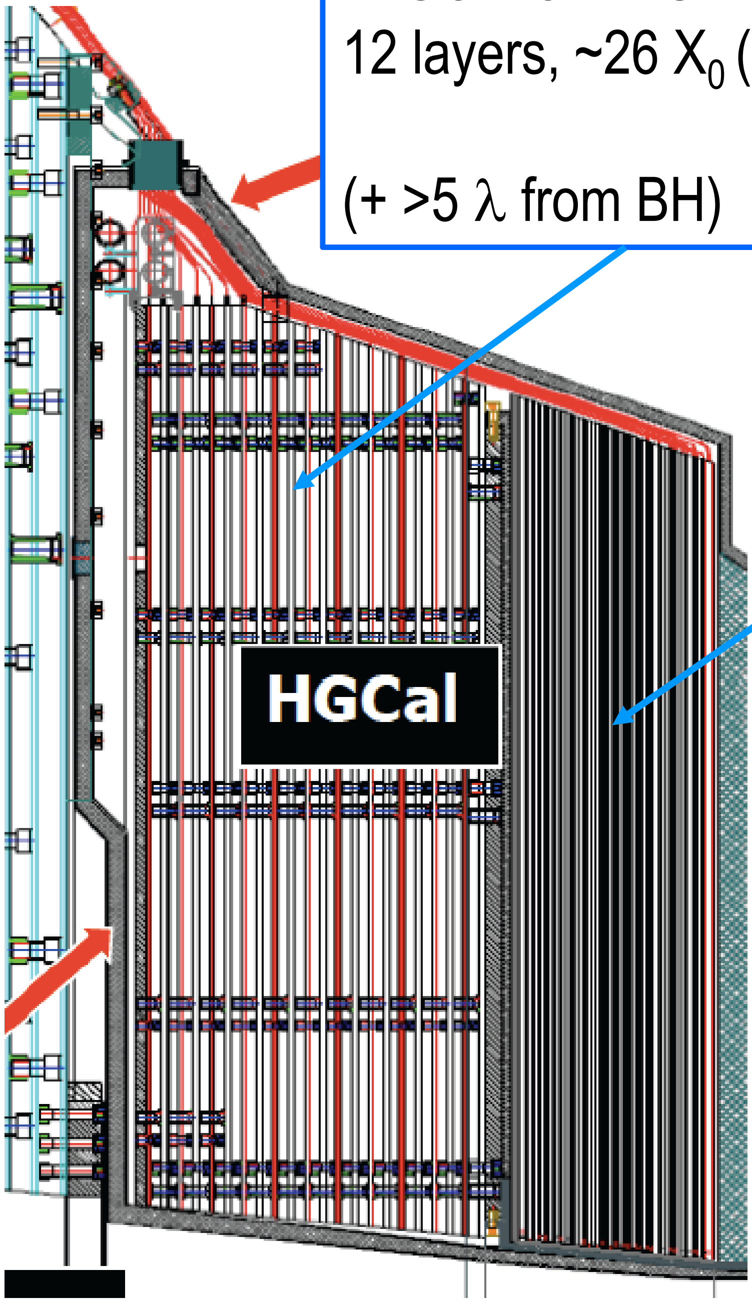
HGC



Technical Proposal
CERN-LHCC-2015-010

[*] 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)

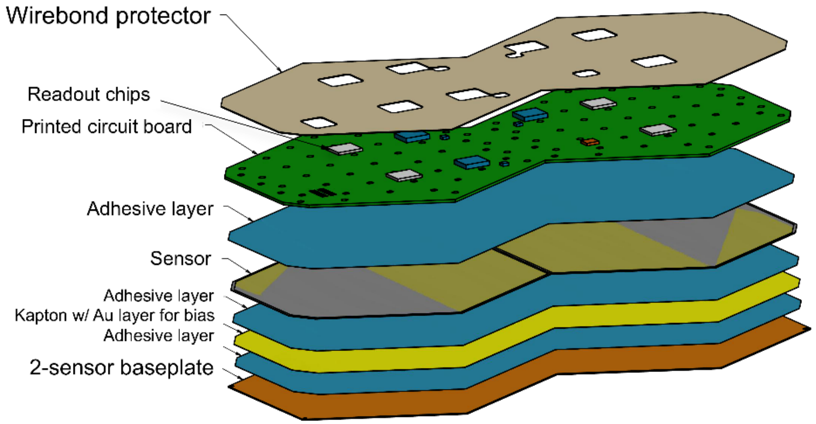
Table 3.2: Parameters of the EE and FH.

	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

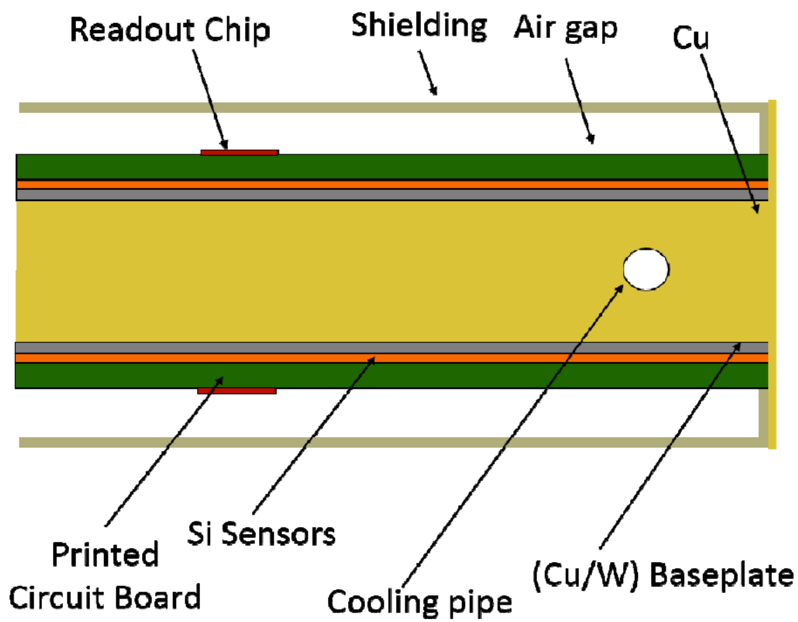
(*) 3x CMS tracker ! (**) one HGC+BH endcap: ~230 tonnes

Modules, Cassettes & Mechanics (Technical Proposal)

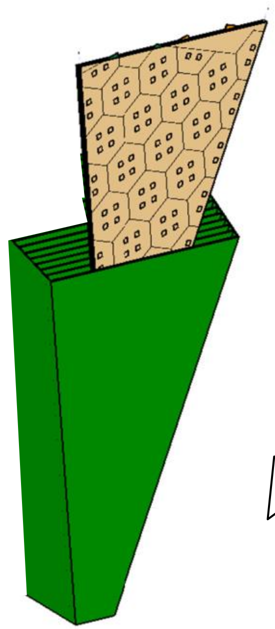
Modules
with 2x6 or 8” Hexagonal Si sensors,
PCB, FE chip, on W/Cu baseplate



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



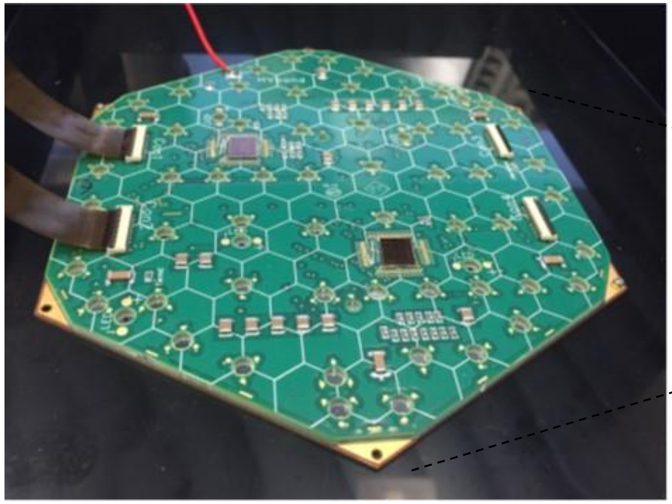
Cassettes
inserted in **mechanical structure**
(containing absorber)

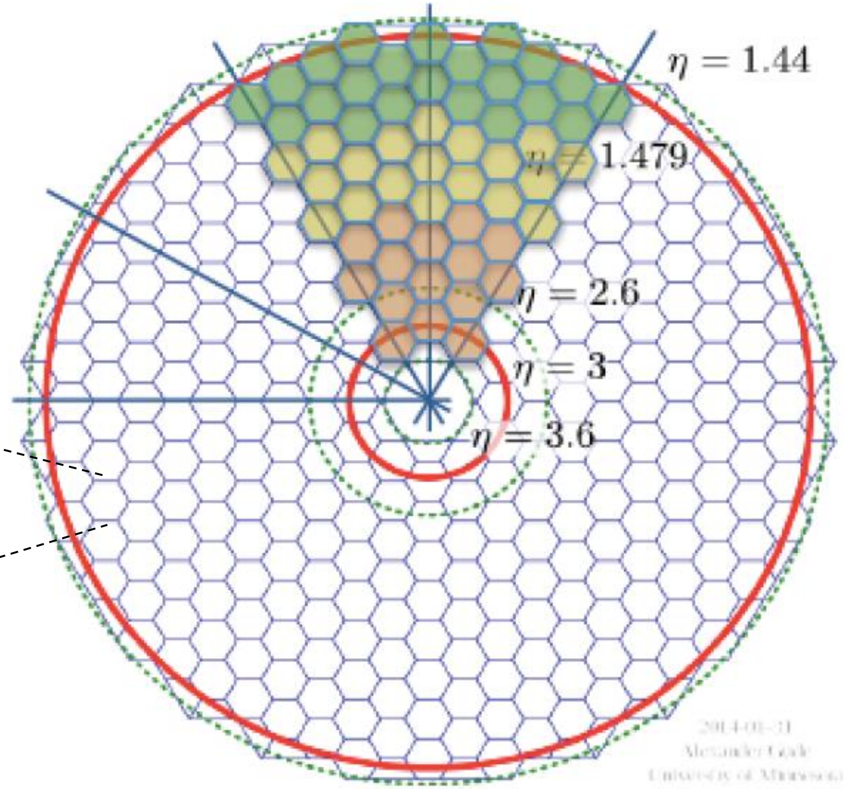


W/C-fiber EE alveolar structure

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

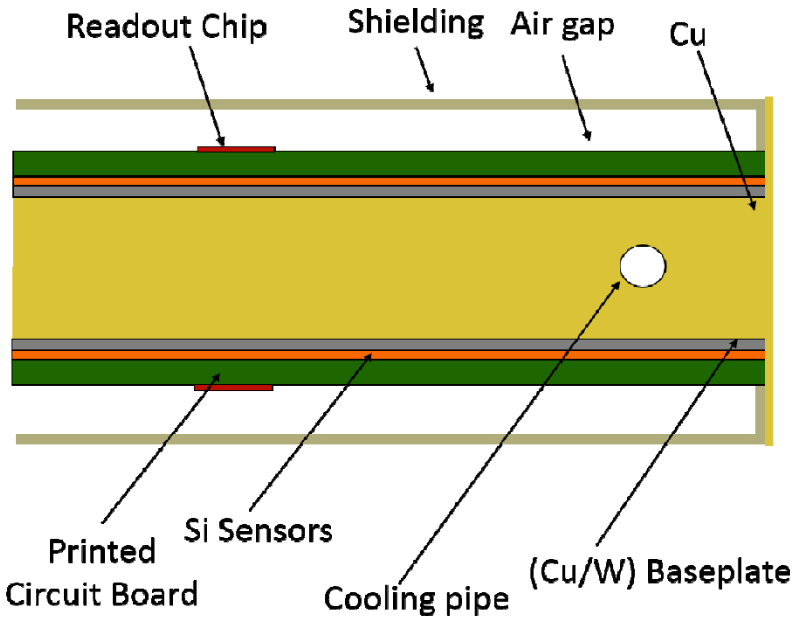
Thickness	300 μm	200 μm	100 μm
Maximum dose (Mrad)	3	20	100
Maximum n fluence (cm^{-2})	6×10^{14}	2.5×10^{15}	1×10^{16}
EE region	$R > 120$ cm	$120 > R > 75$ cm	$R < 75$ cm
FH region	$R > 100$ cm	$100 > R > 60$ cm	$R < 60$ cm
Si wafer area (m^2)	290	203	96
Cell size (cm^2)	1.05	1.05	0.53
Cell capacitance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

Modules, Cassettes & Mechanics (Cassettes)

"dummy" cassette for thermal tests

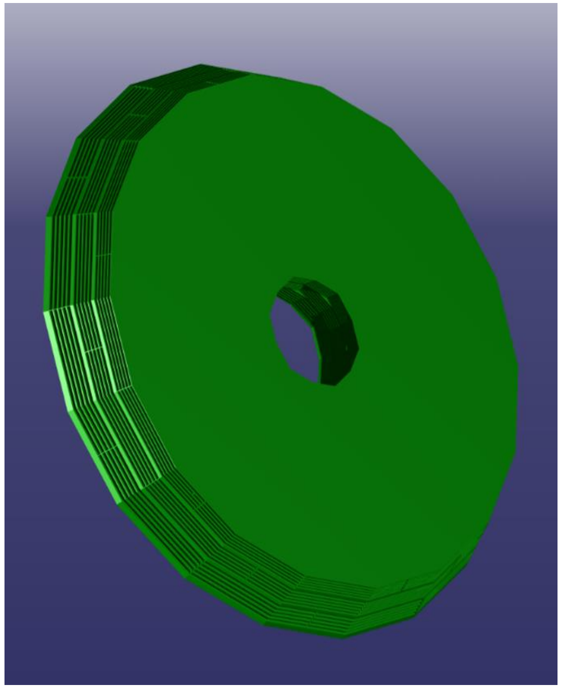
CO_2 cooling plant at FNAL

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

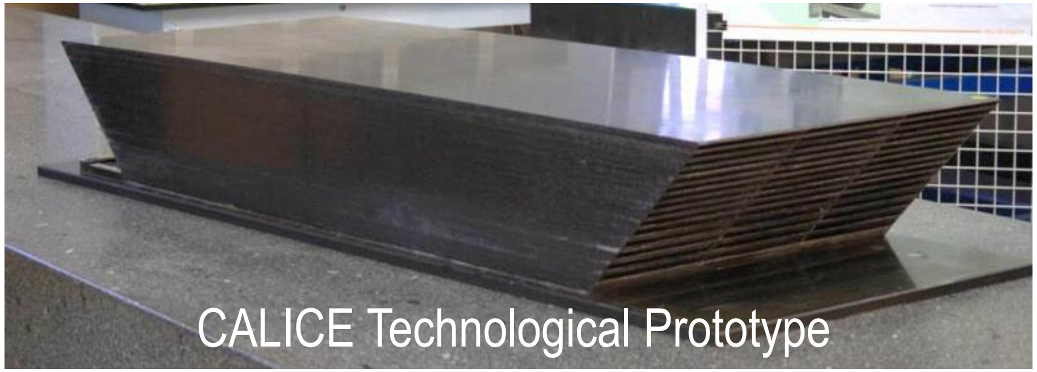


Modules, Cassettes & Mechanics (Structures)

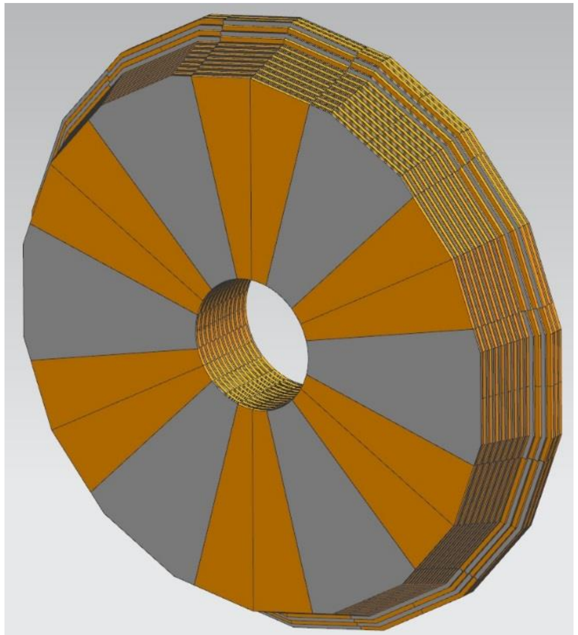
HGC-EE: C-fiber Alveolar structure with embedded W plates



Inspired from CALICE Si/W

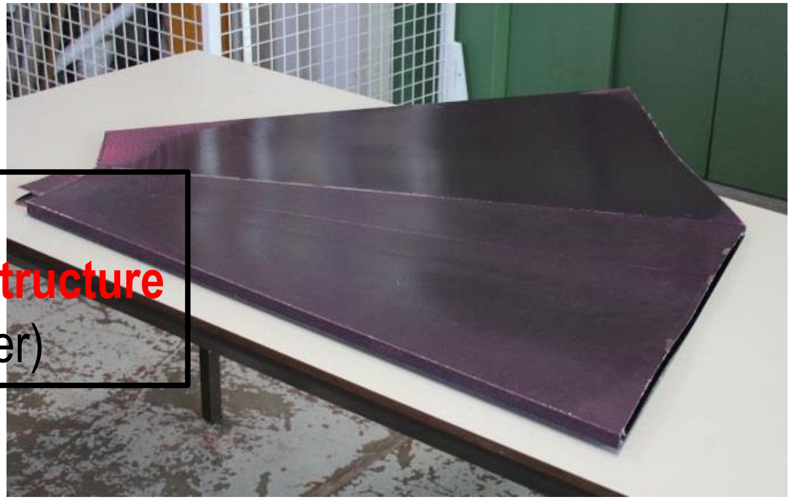


HGC-HCAL Structure (similar to current HE)



Will evolve if absorber=steel to minimize machining

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



C-fiber “petal” alveolar prototypes

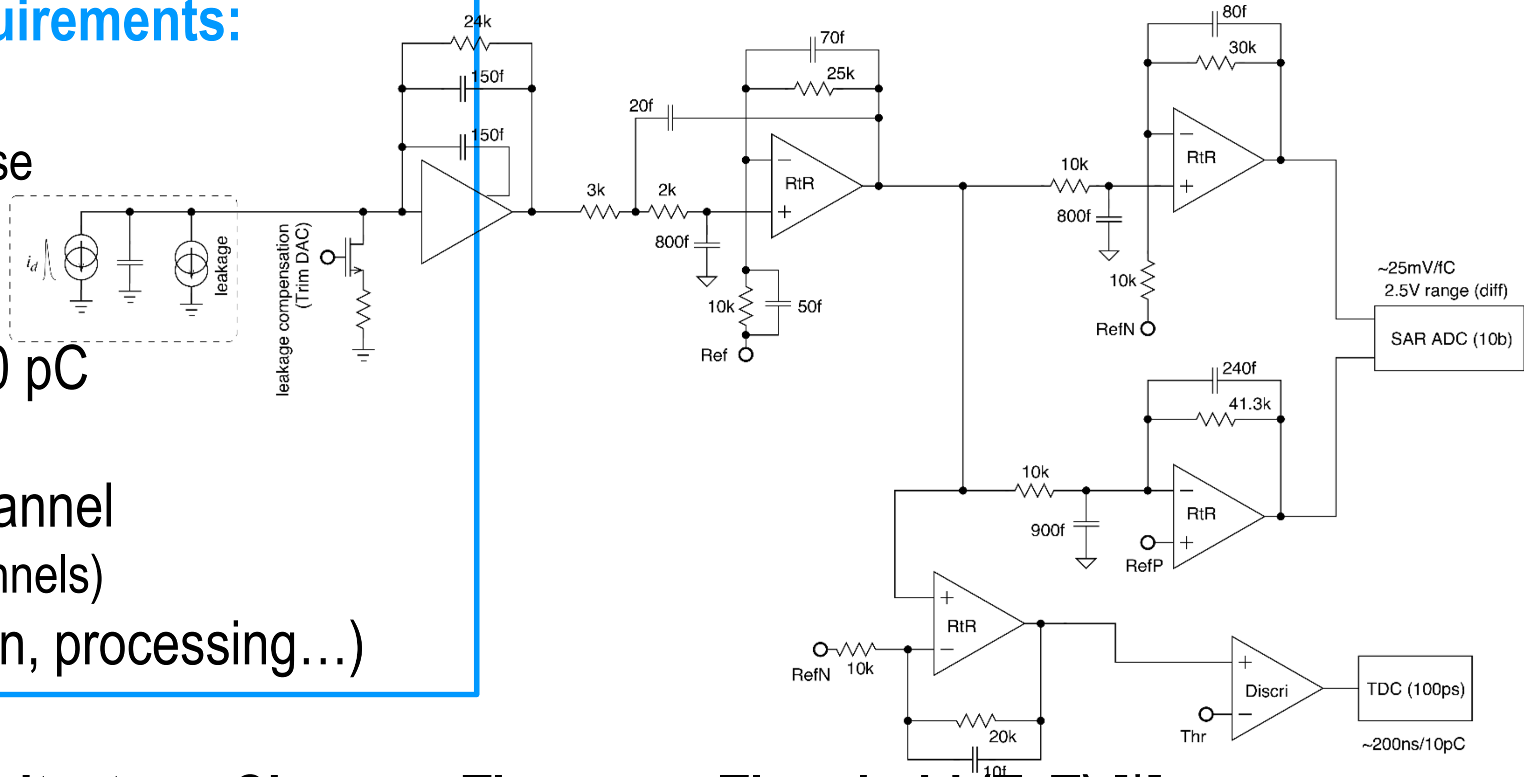
Front-End Electronics (1)

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) [*]**

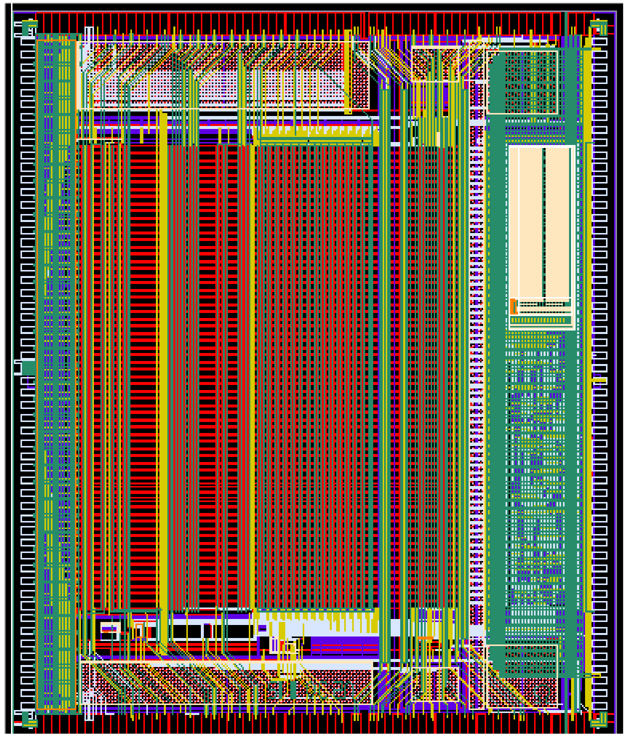
- Switch from charged readout to ToT at ~100 fC
- ADC (10 bits) and TDC (12 bits) with existing designs
- Potential for 50 ps timing per cell

[*] 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



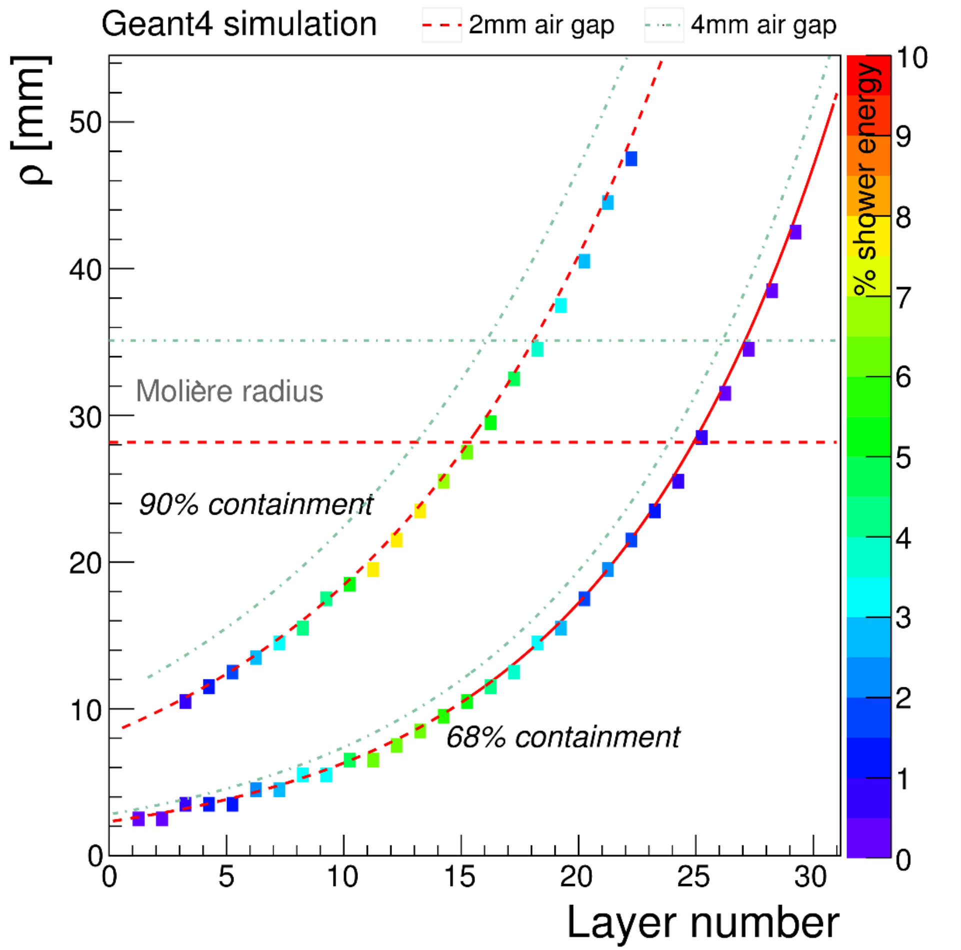
➢ **SKIROC2_CMS** (not the final chip)**:**

- 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, Available in ~June**
- Plan to use it for CERN test beams (Fall)
  - after tests on board (noise, stability, linearity, crosstalk, …)

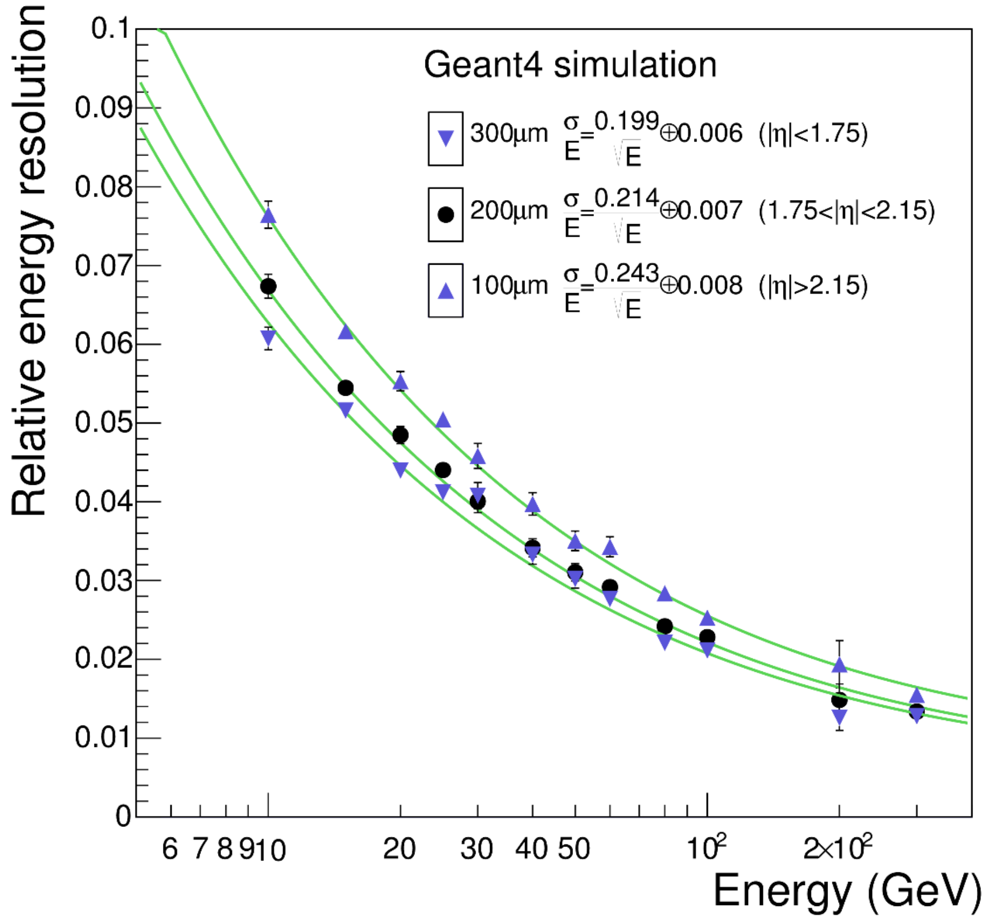
- Also: test vehicles on blocks launched (TSMC 130nm)
- **First iteration of full chip expected by Spring 2017.**
  - with feedback from test vehicles & SKIROC2_CMS

HGC Performance (1)

EM shower energy containment



Electron energy resolution vs Si thickness



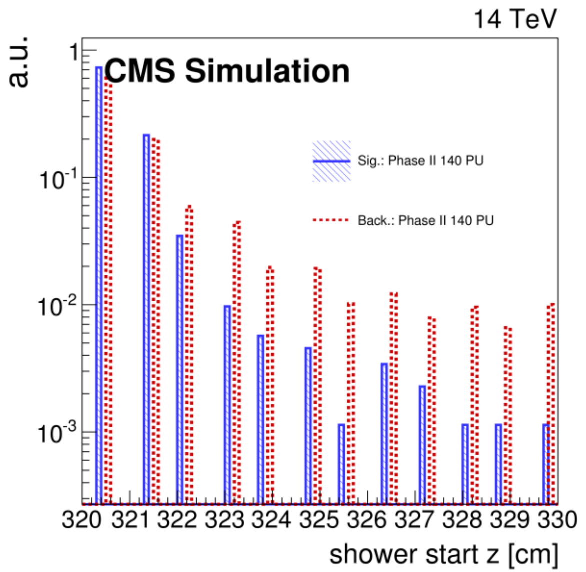
Shower radius quite small in first layers.
Can use longitudinal segmentation for PU rejection, …

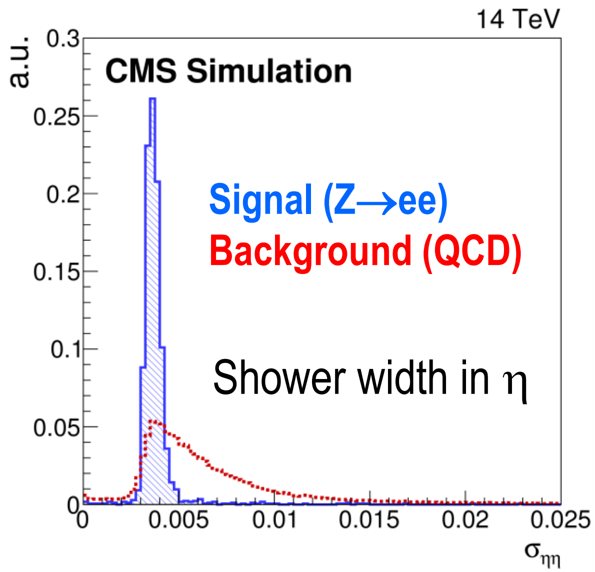
Stochastic term: ~20%
but **low constant term** (target: 1%)

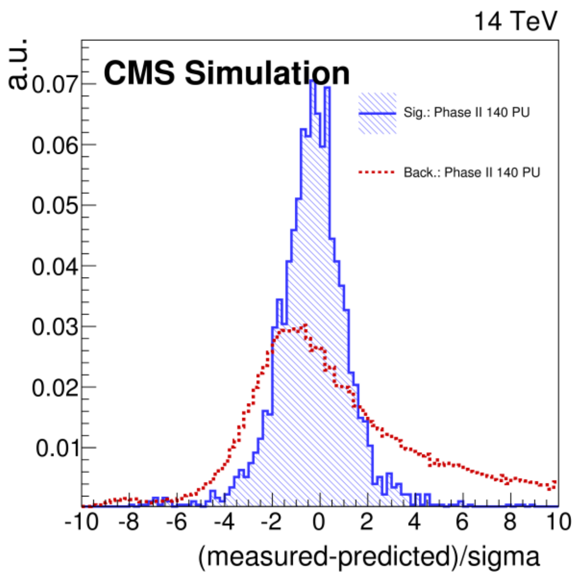
Obtained with standalone G4 simulation. Benchmarked againt CALICE test-beam results

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…

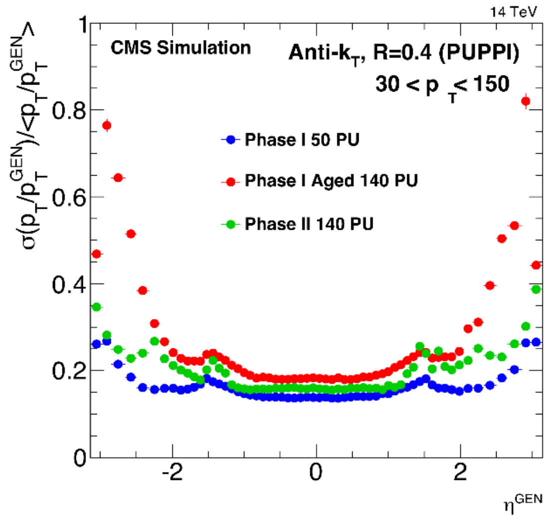




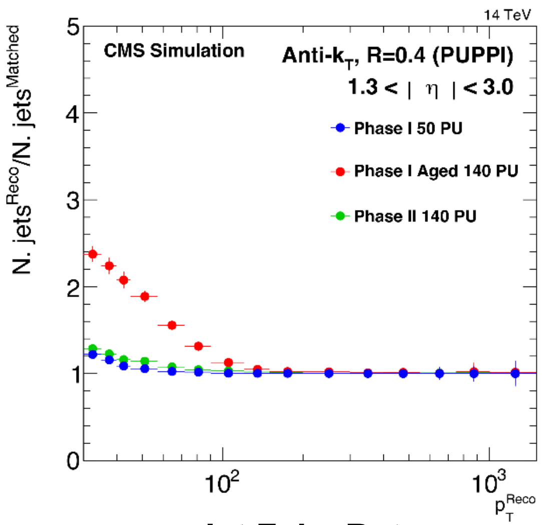


With 1x1 cm² squared cells

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



Jet Energy Resolution vs η



Jet Fake Rate

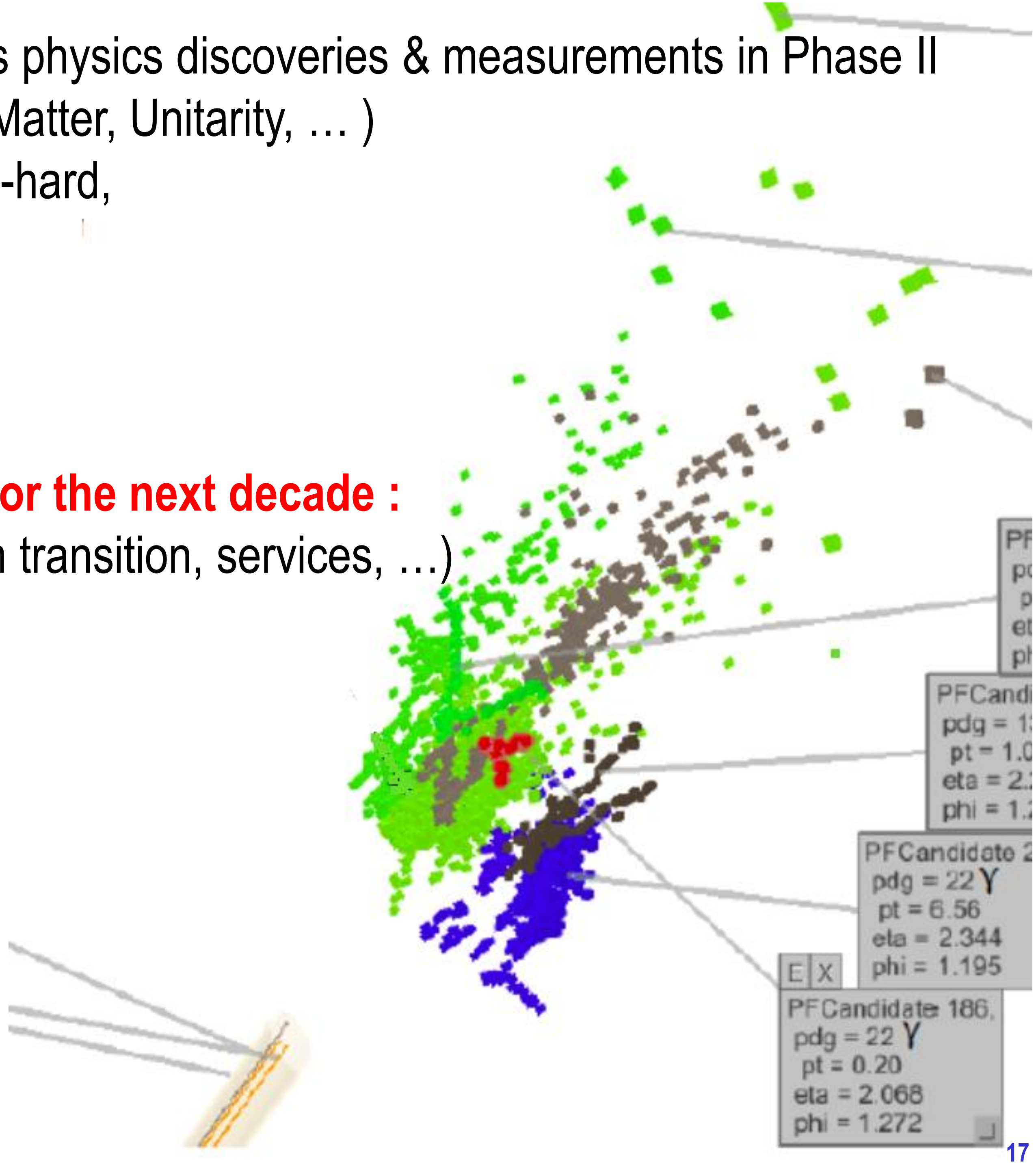
- **~Recover Phase I 50 PU performance !**

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,…

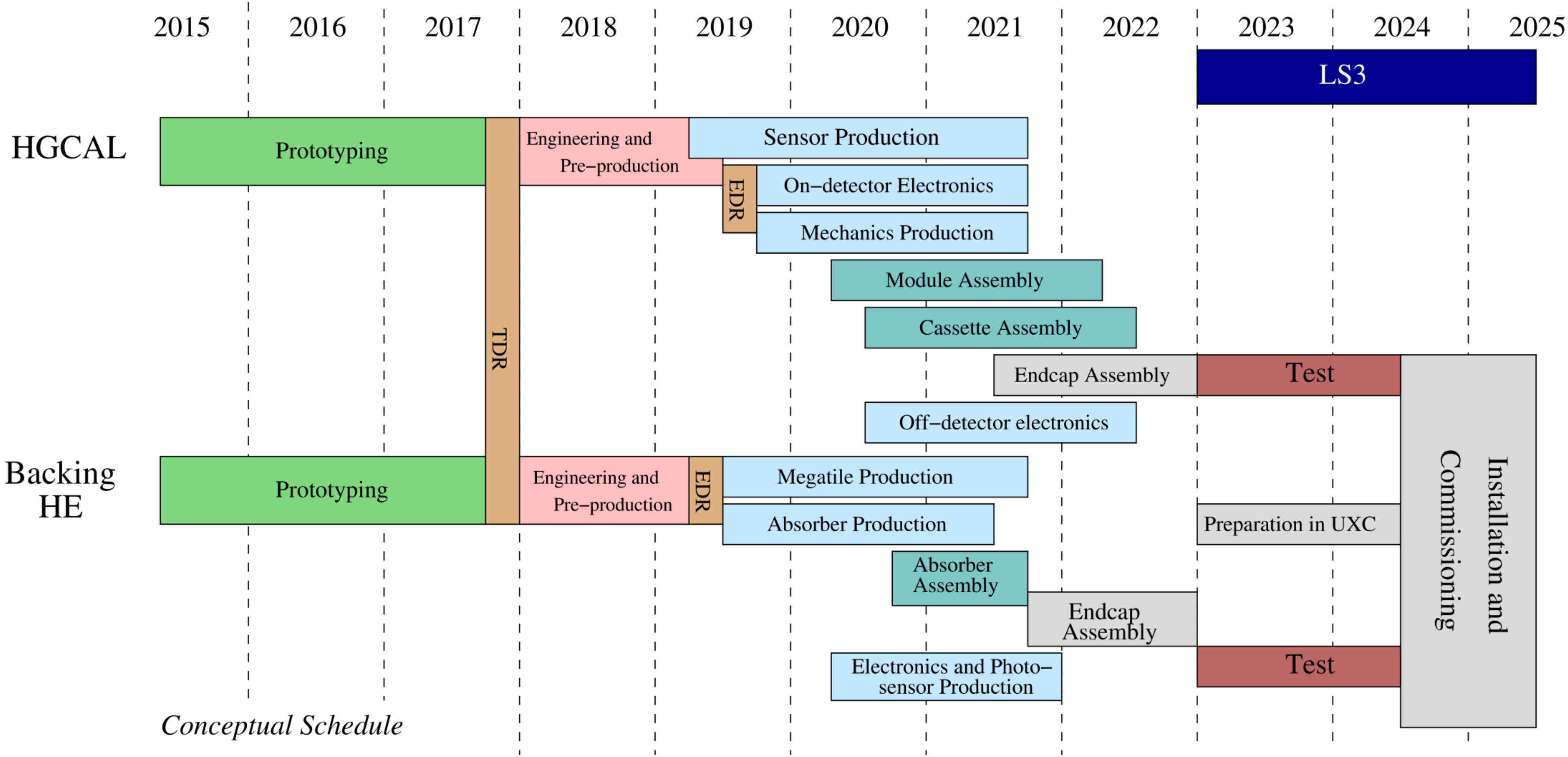
- **Many major & excited challenges for the next decade :**
  - Engineering (includes cold/warm transition, services, …)
  - FE electronics & L1 Trigger
  - Software, computing
  - …



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)

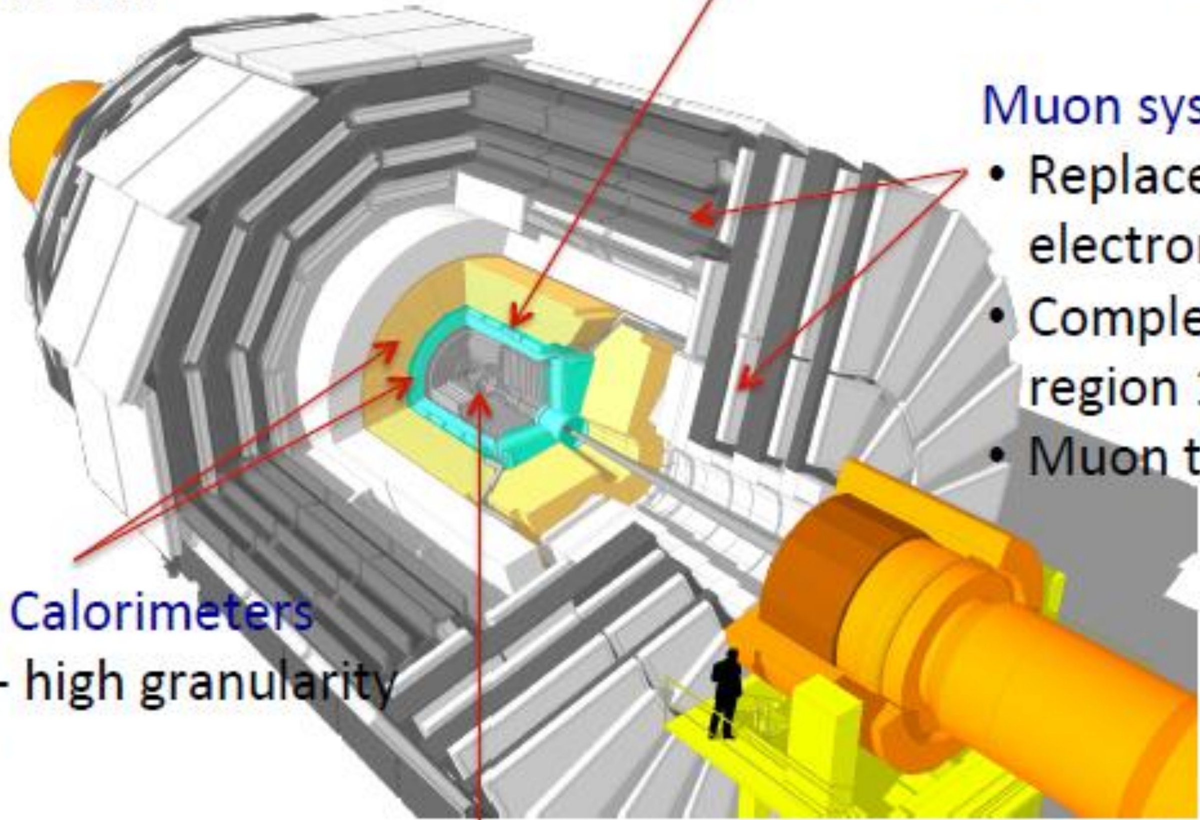


BACK UP SLIDES

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 $2.4 < \eta < 3$

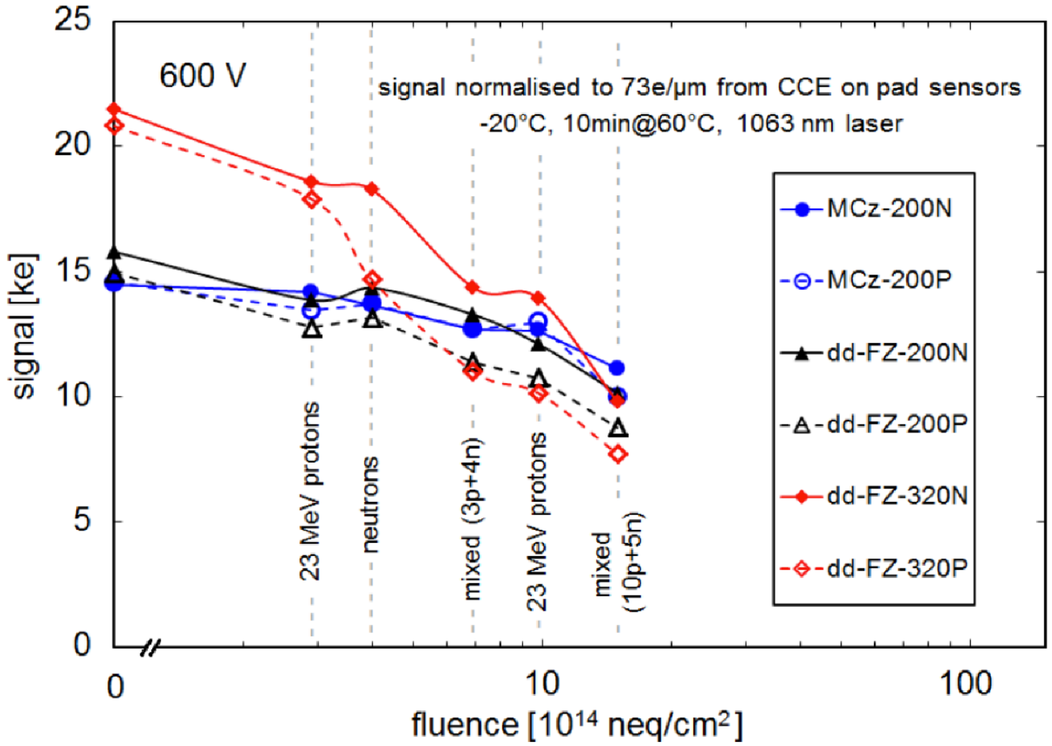
Replace Endcap Calorimeters
- Rad. tolerant - high granularity
- 3D capability

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 $\eta = 3.8$

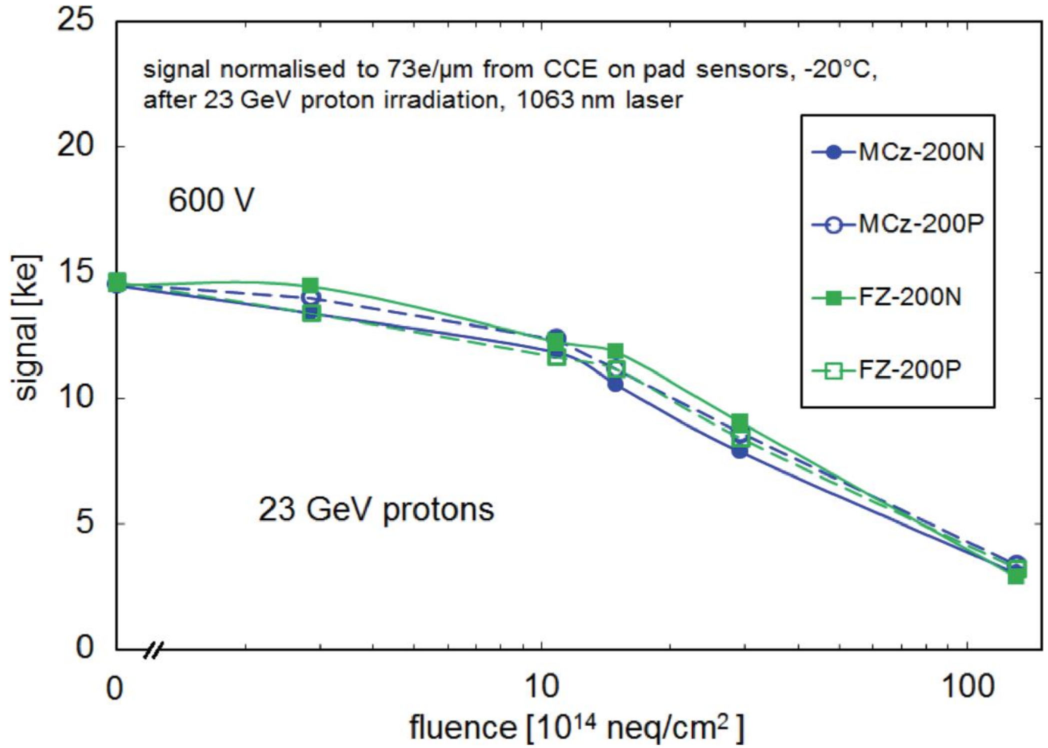
Radiation Tolerance (1)

Charge collection vs neutron fluence

300 & 200 μm active thickness

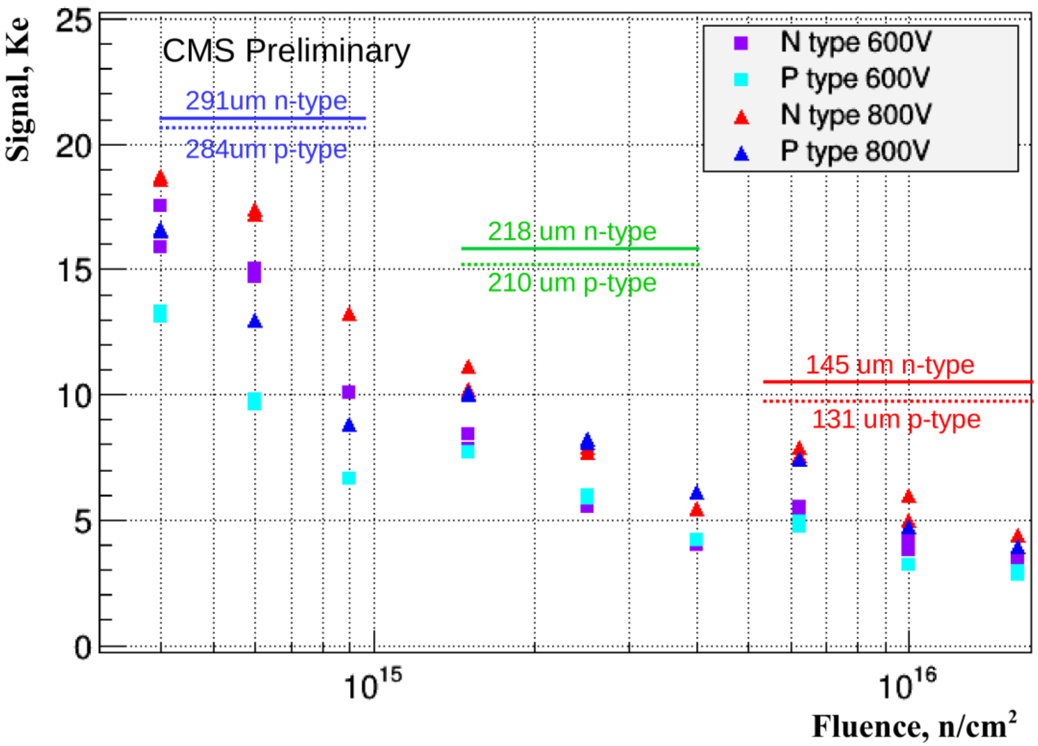


200 μm active thickness, p-in-n vs n-in-p

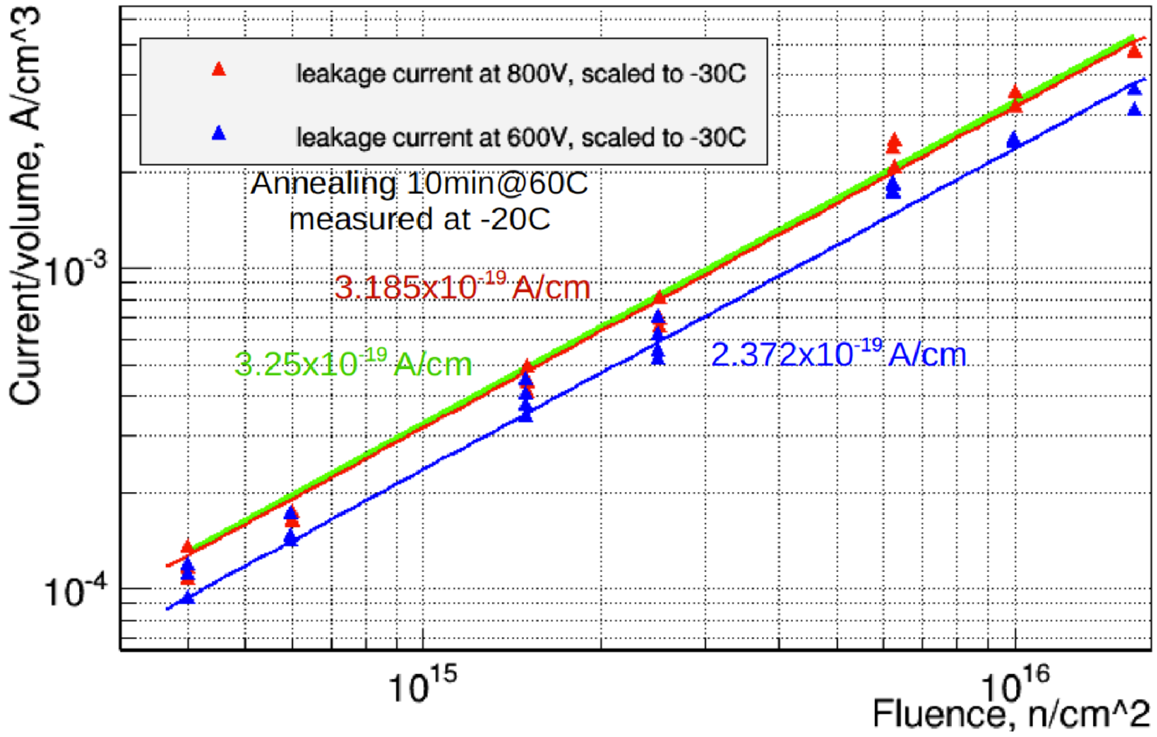


Radiation tolerance (2)

Neutron irradiation



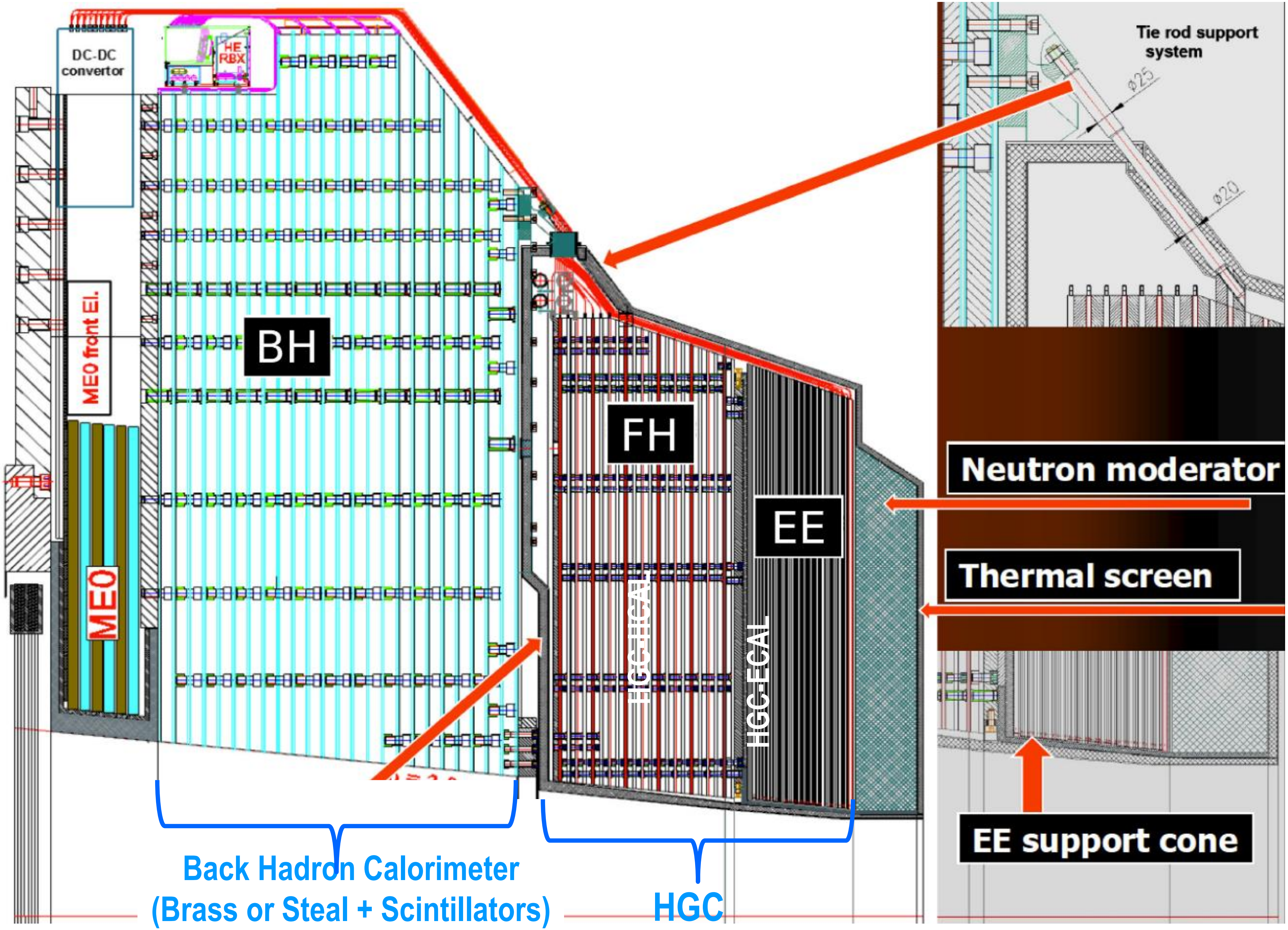
Charge collection efficiency



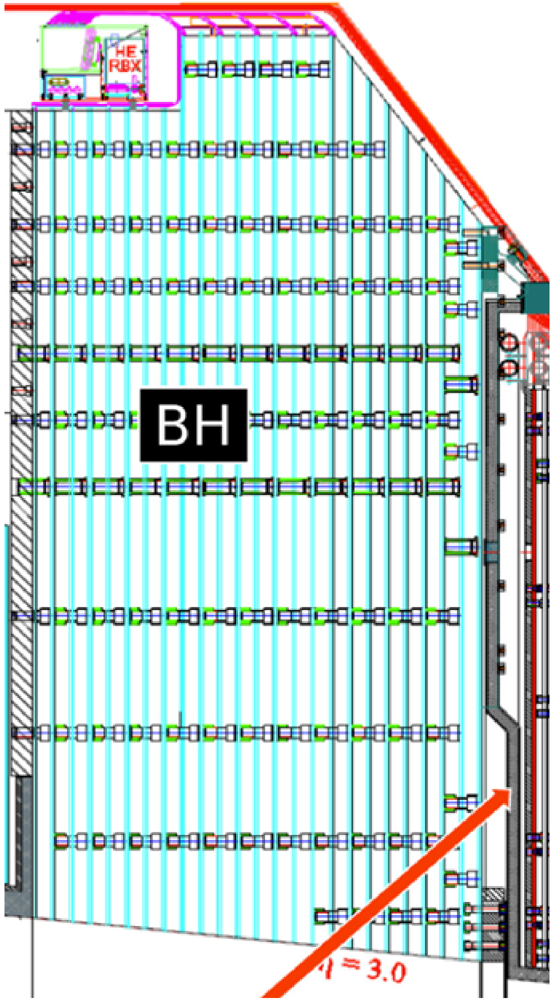
Leakage current vs fluence at -20°
(extrapolated to -30°)

Draft paper in preparation

HGCAL: General Layout



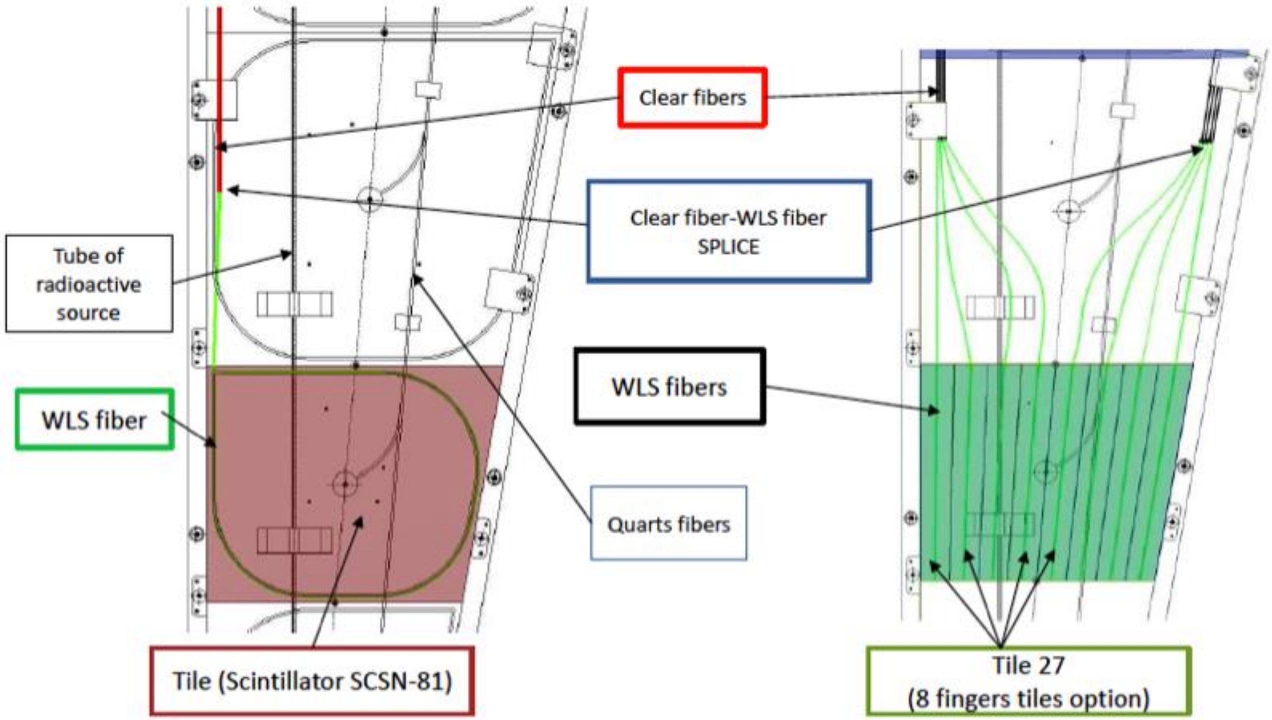
Back-Hadron Calorimeter



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

- **<u>Calibration requires:</u>**
  - 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)

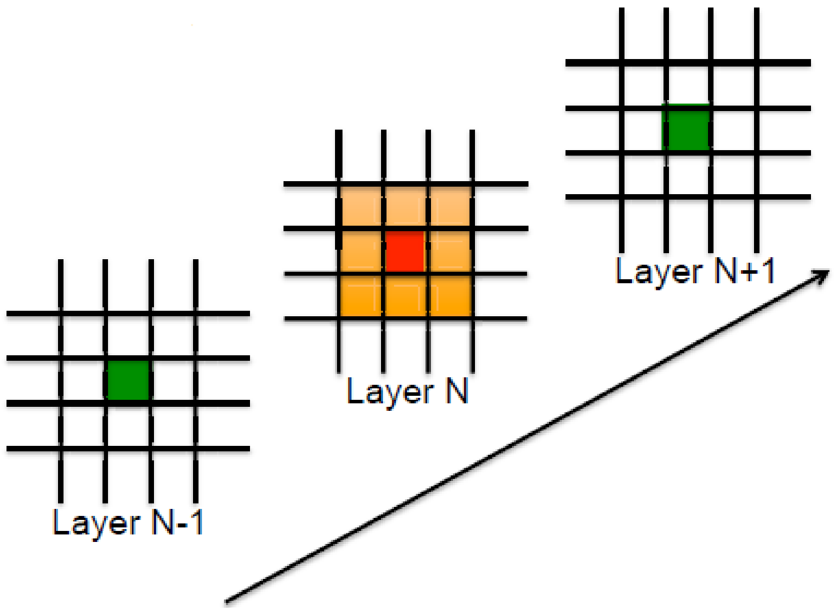
  - Cells weights taking into account absorber thickness
    - W plates: thickness contained within +/- 40 μm
    - W/Cu plates: thickness contained within +/- 50 μm
    - Si wafer: thickness contained within +/- 5 μm
    - Diffusion depth of all pads (within a wafer):
      +/- 3 μm of the average of the wafer

  - Response Linearity, Monitoring → **Charge injection**

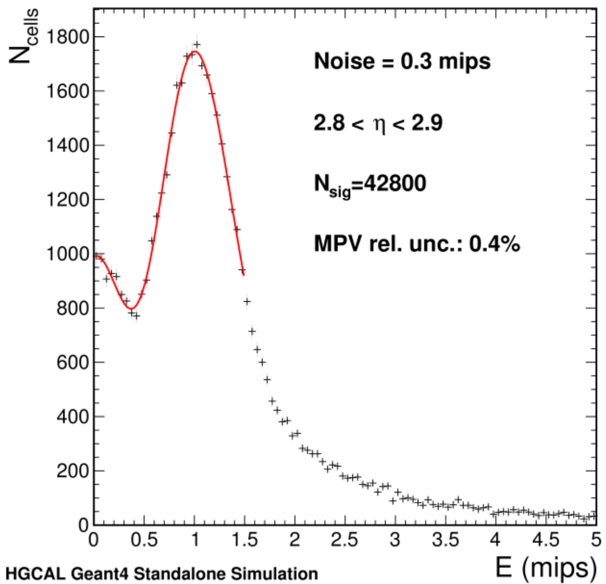
  - Absolute scale with standard candles

HGC calibration: inter-calibration with MIP tracking

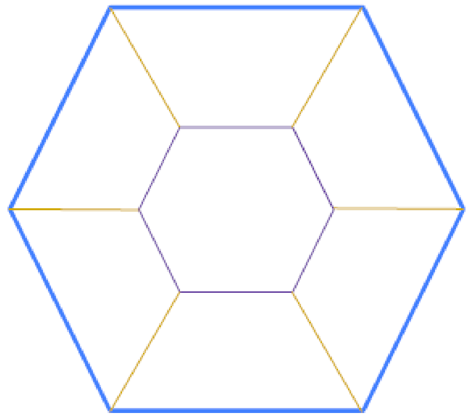
- **"MIP" Tracking ("punch through")**
  - Require signal in layer before/after + isolation
  - Can be done on any readout (L1, offline)



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

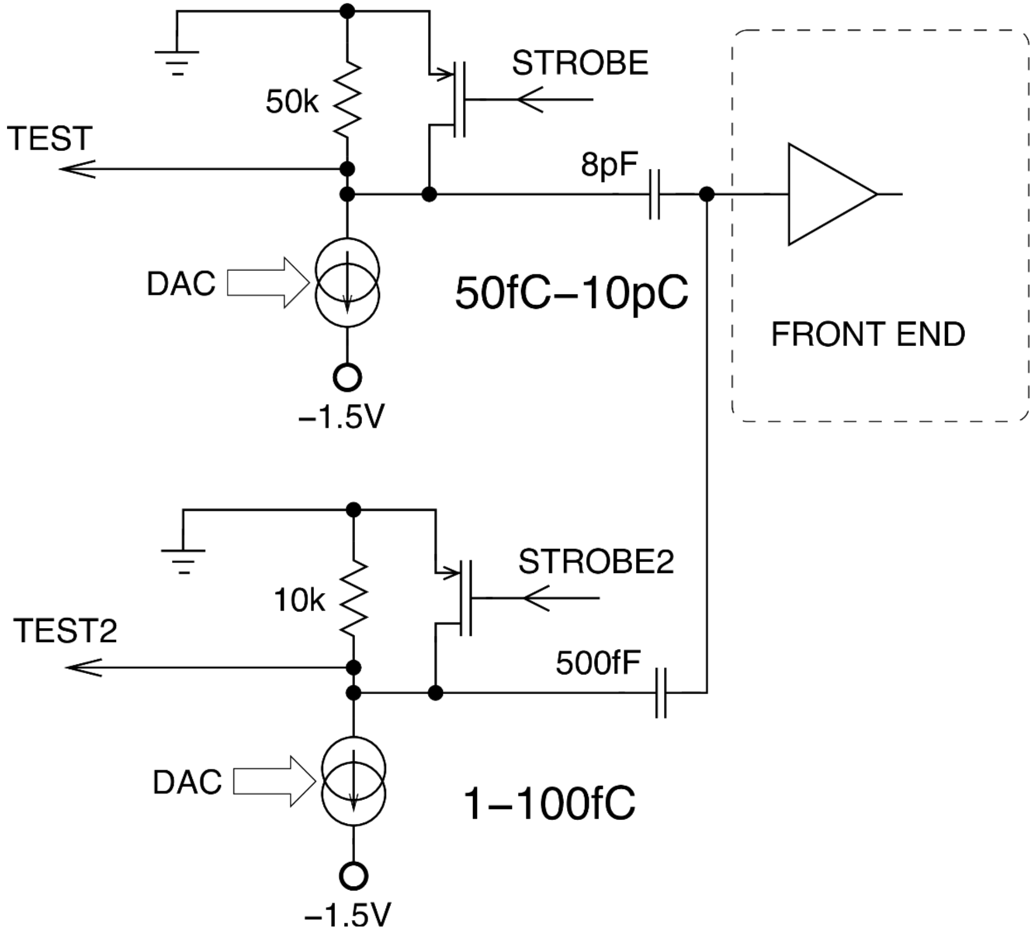


- **In addition, for redundancy:**
  - Low-capacitance/low-noise cell included in each wafer for calibration:
  - 7 sub-cells subscribed inside a standard hexagonal cell (large S/N)



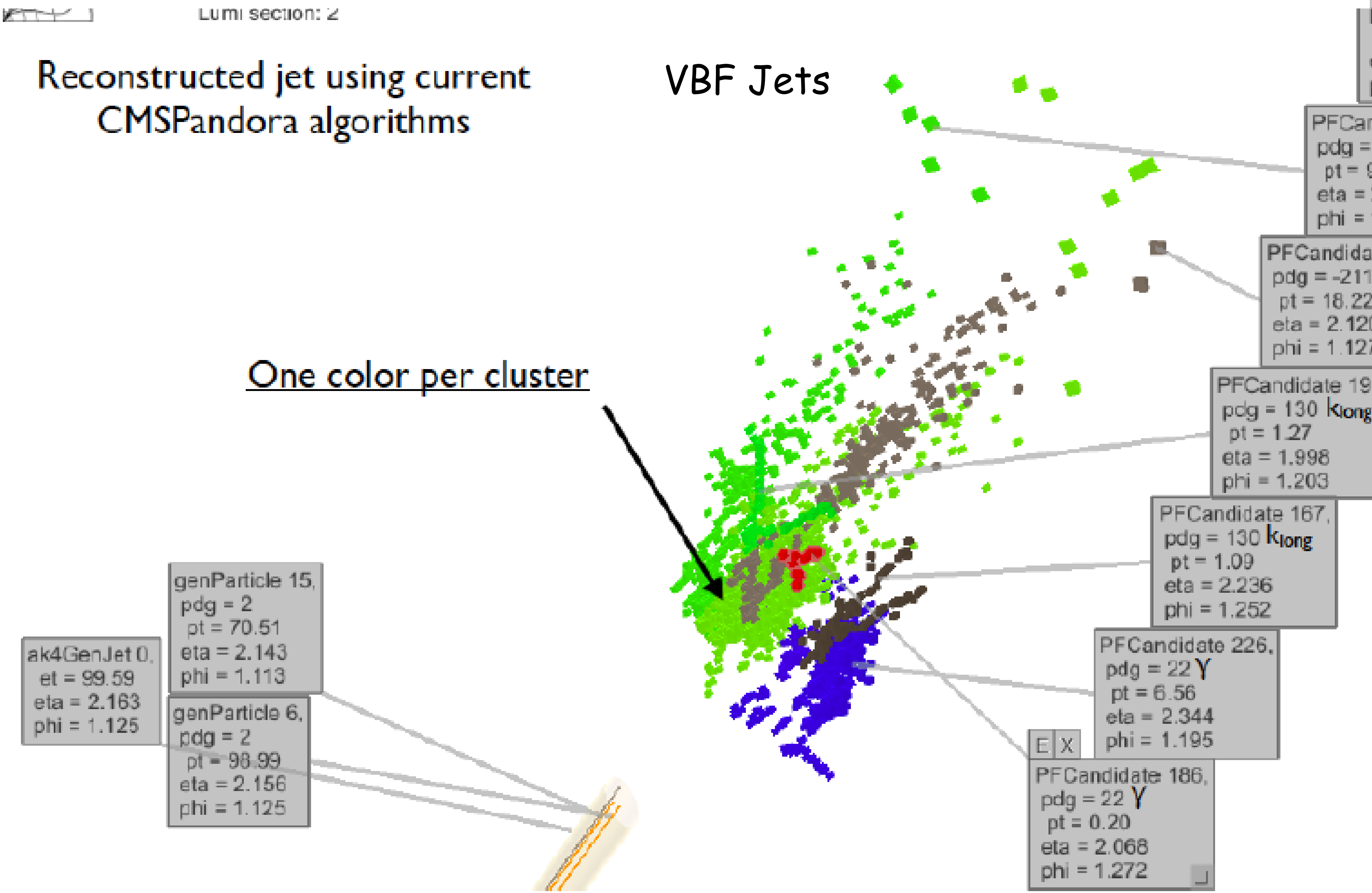
HGC Calibration: linearity, monitoring

- 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)

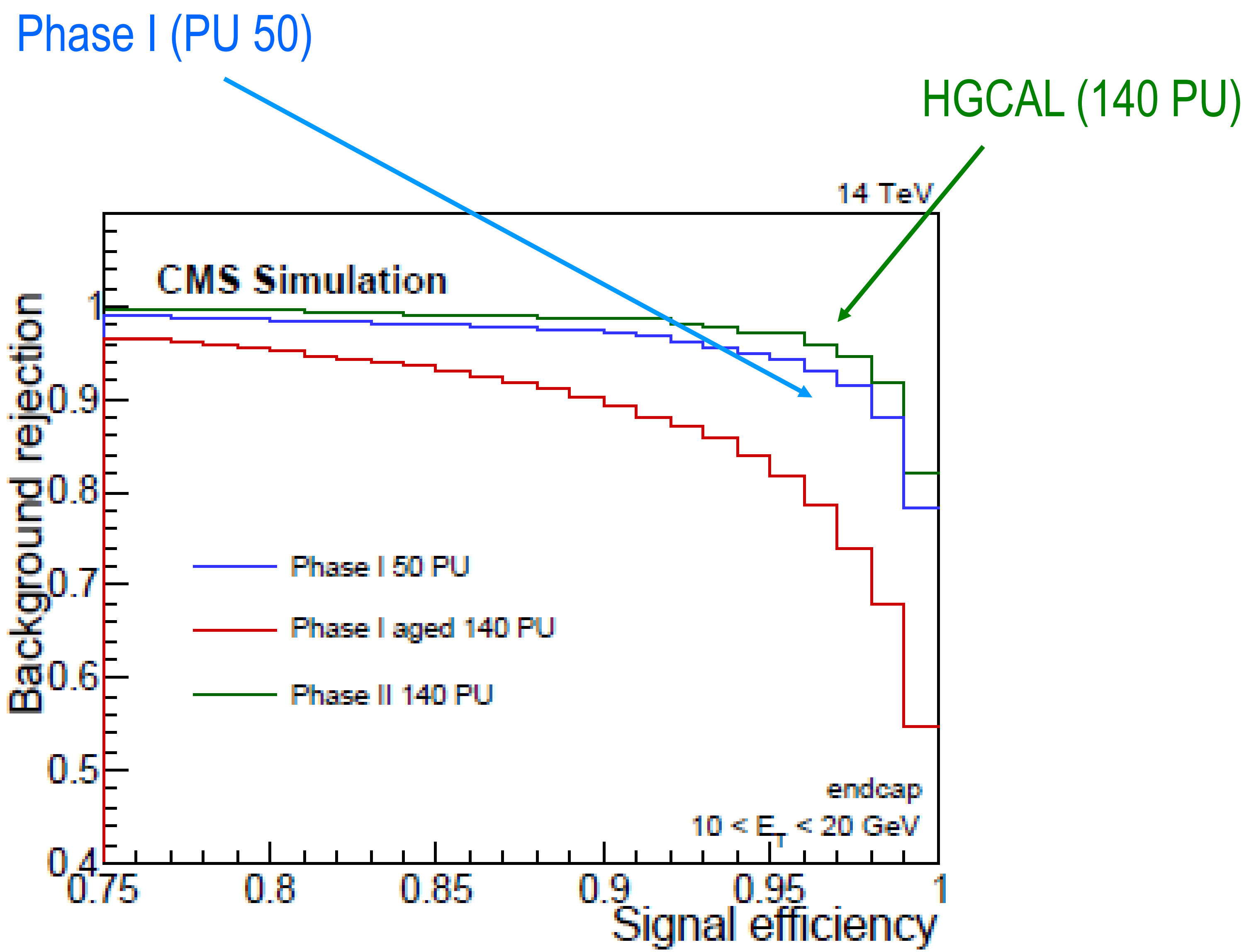
HGCAL Performances



e/g Performances (2)

BDT Electron ID performances

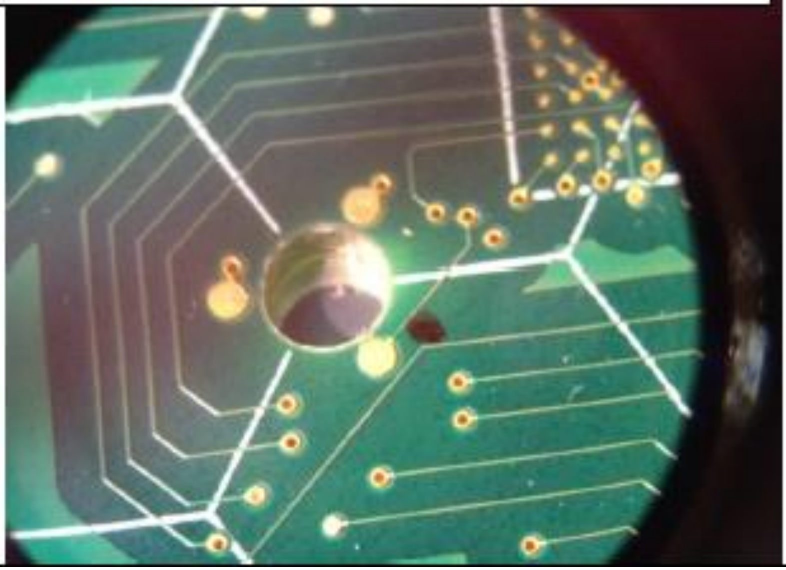
(low ET, critical for multi-leptons topologies: H→ZZ→4 leptons, …)



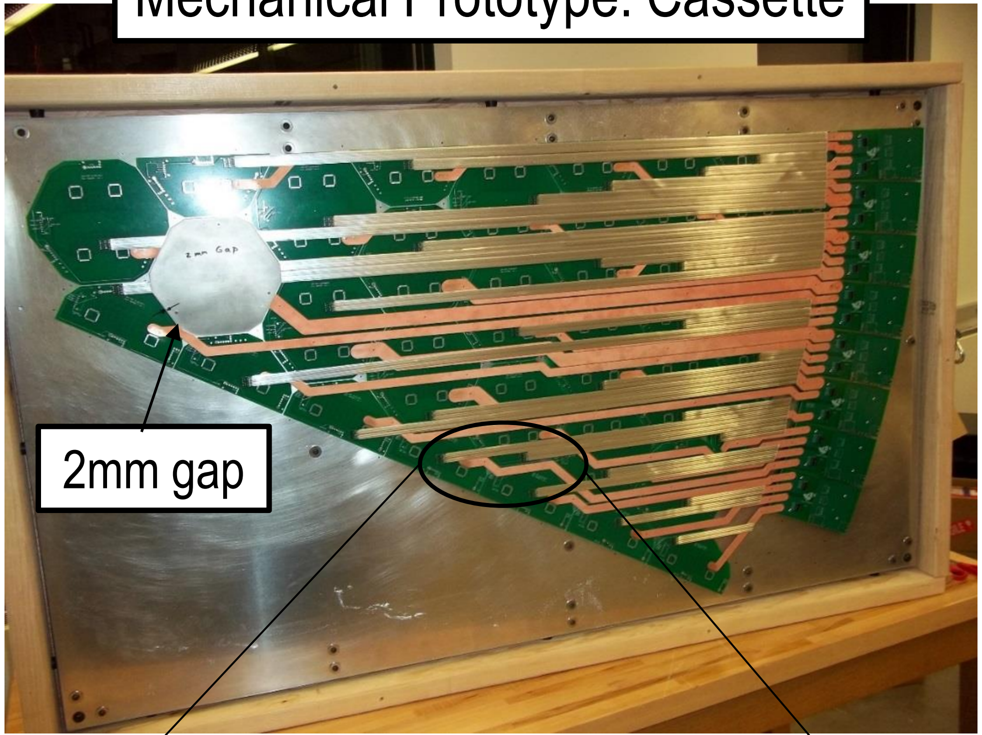
First Prototypes/Mock-up

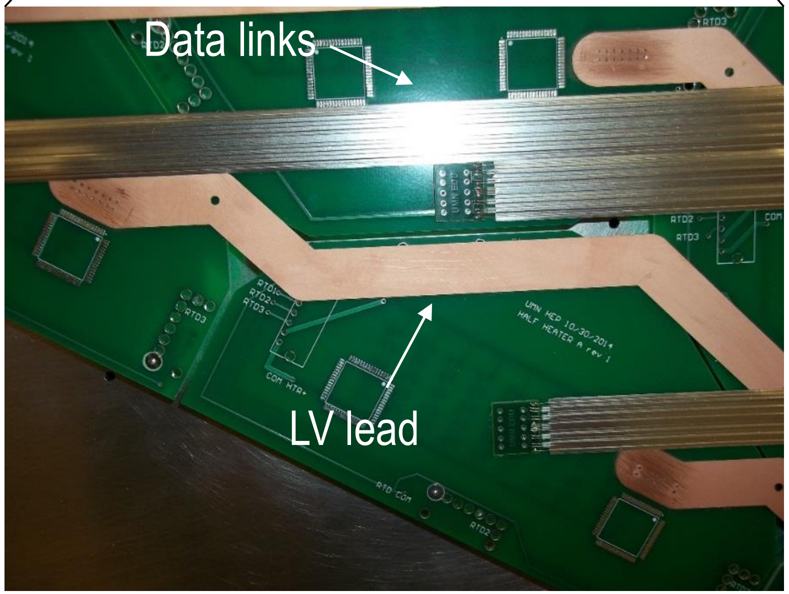
Mechanical Prototype: Modules for Cooling Tests

Automated Bonding Tests



Mechanical Prototype: Cassette



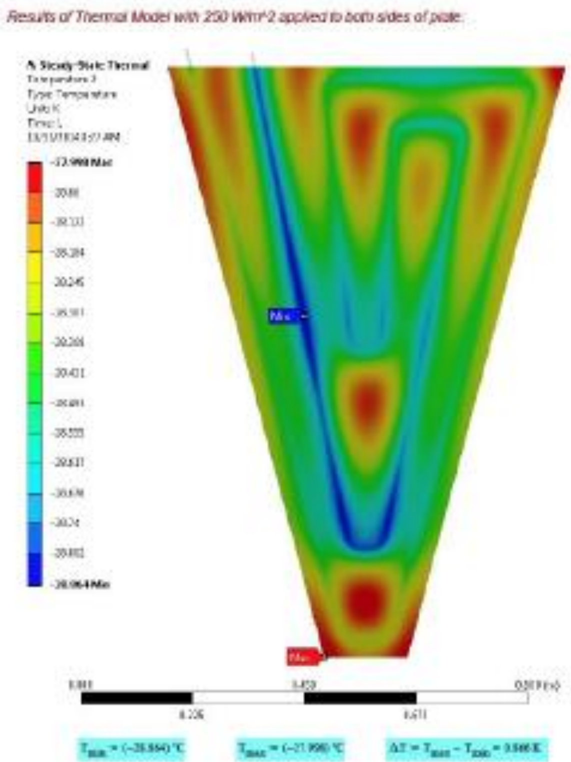


CO_2 Cooling

CMS internal

Cassettes FEA

Goal: ΔT ~ 1-2 K
6mm Cu plate 1 pipe – uniform heat load
ΔT ~ 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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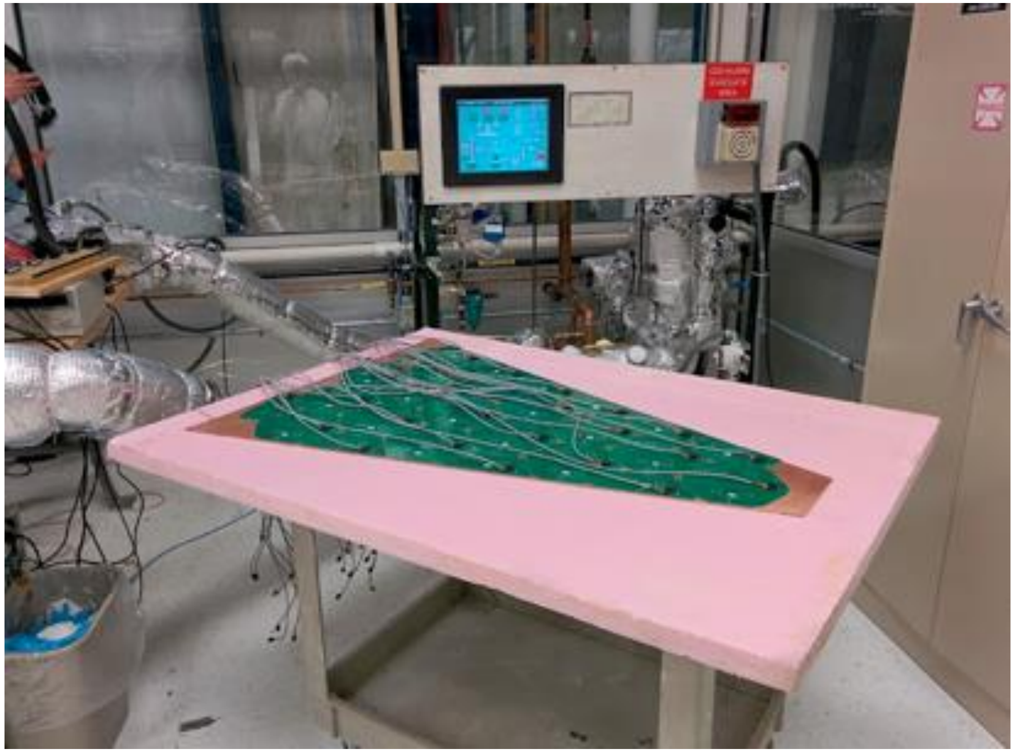
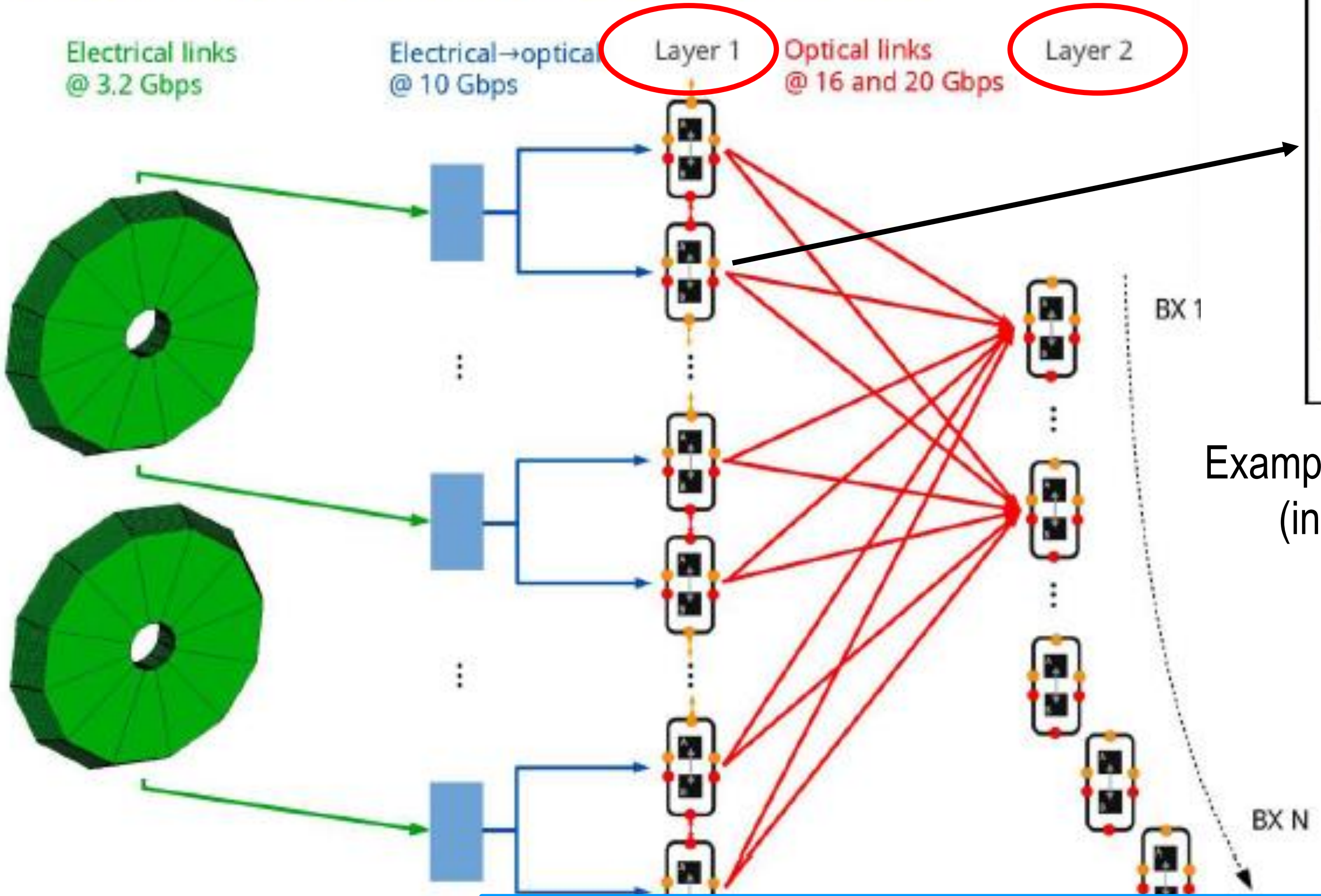
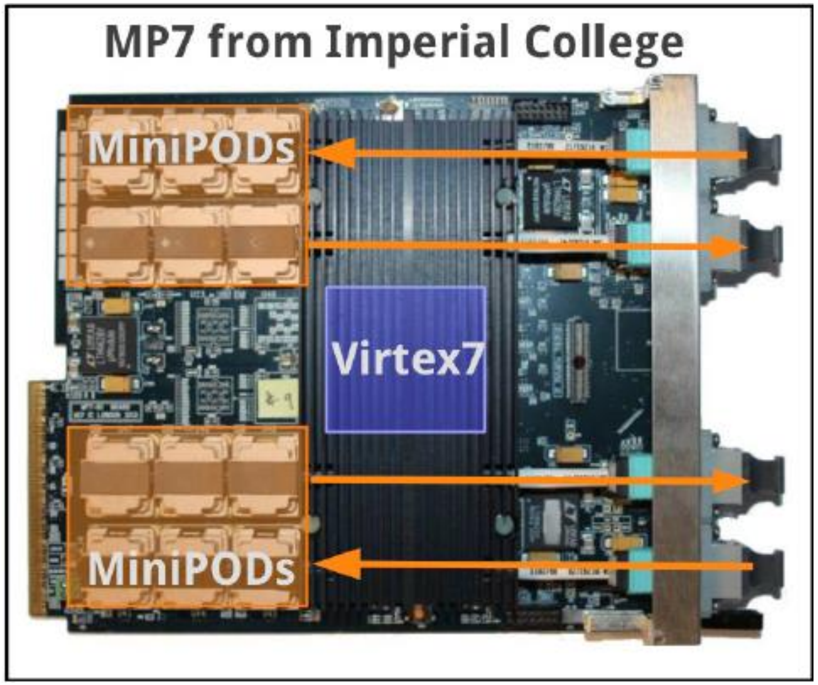
Thermal Mock-up with tests (CO_2 Cooling stations at FNAL, IPNL)



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



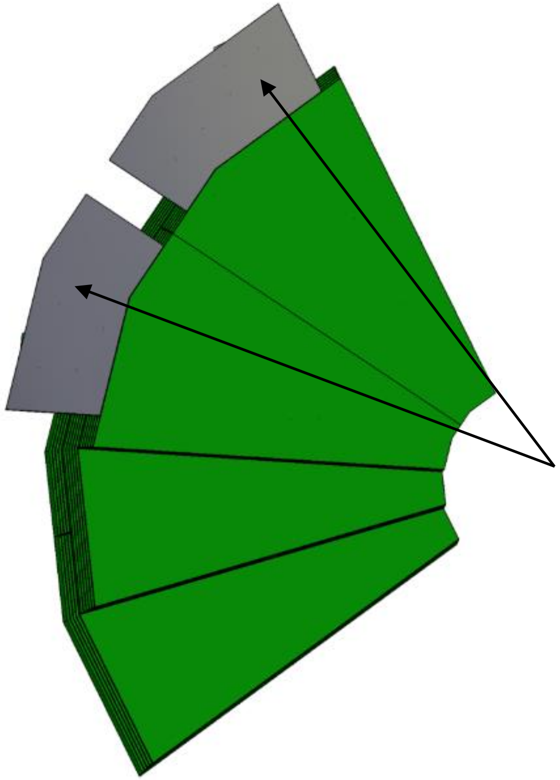


Example of HGC-Trigger module, with modern FPGA (inspired from MP7, used in Phase I Trigger)

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

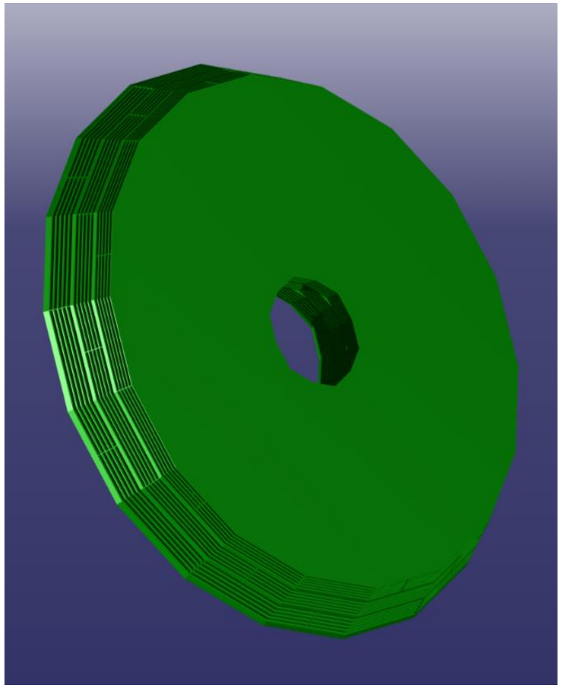
Mechanics: HGC-EE

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

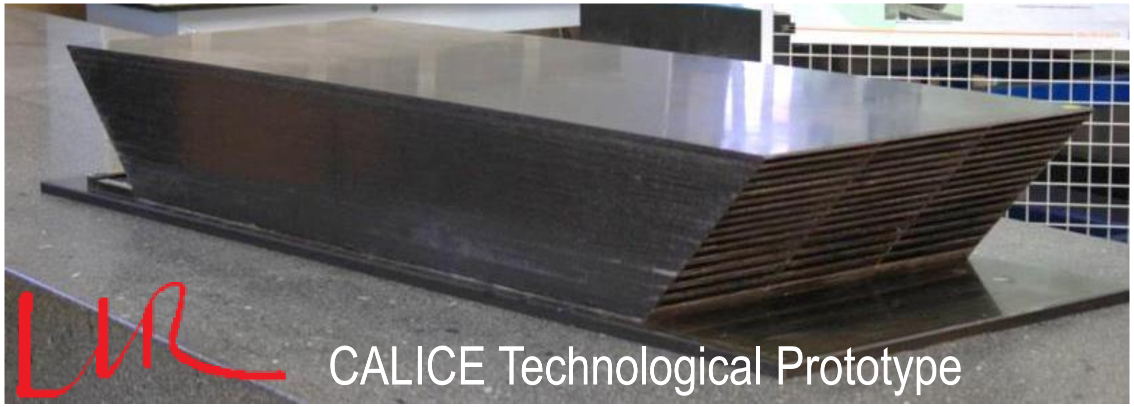


Cassettes (with active element) inserted in alveoli.

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



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

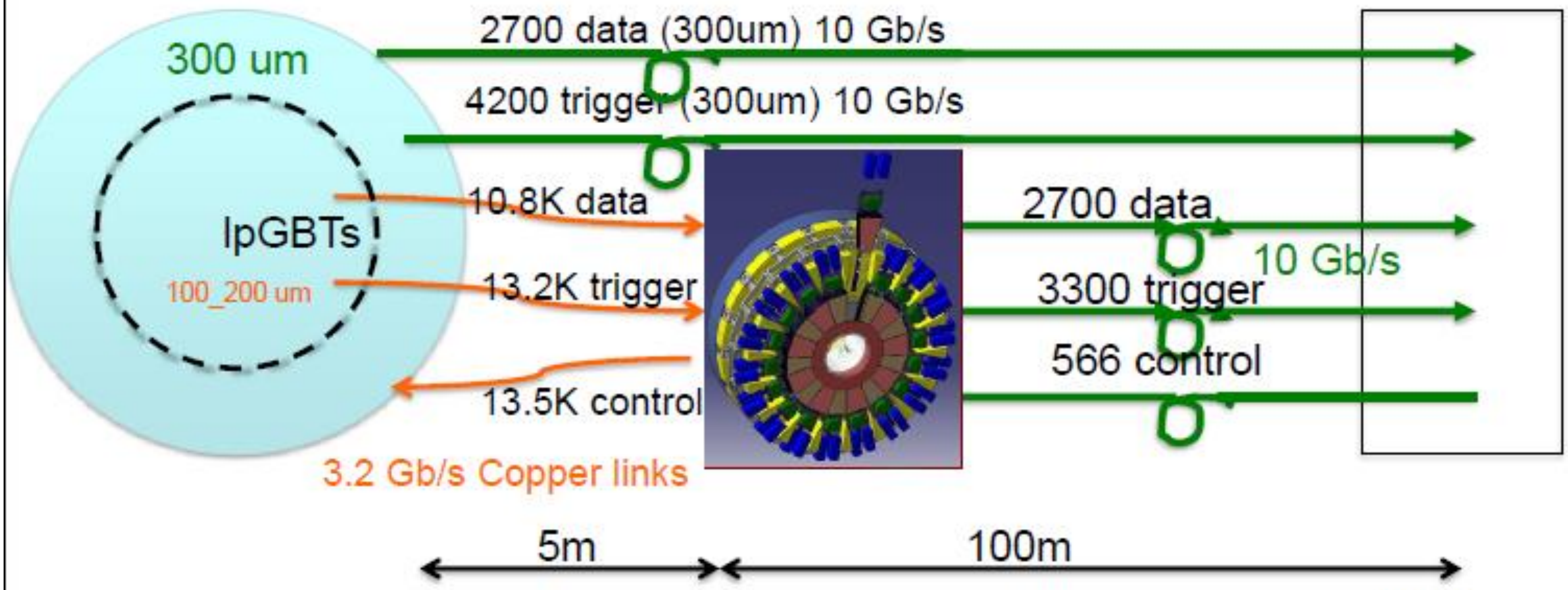


Why CO2 Cooling ?

From N. Lumb (IPNL)

- Current Endcap uses monophase (liquid) cooling
  - Coolant heat capacity (C6F14): 1.05 kJ/kg/oC
  - Kinematic viscosity: 0.4 cSt
  - Density: 1.68 g/ml
- CO2 based systems are 2-phase
  - Latent heat of vapourisation CO2: 574 kJ/kg
  - Kinematic viscosity: 0.1 cSt
  - Density: 1.0 g/ml
- **Consequently, CO2 based systems remove same amount of heat with much lower mass flow (factor ~100 depending on allowed monophase ΔT)**
  - 150W removed by ~1g/s CO2!
  - **Can use pipes with smaller cross-section**
  - Reduction in mass of pipes and the liquid contained within them
- Also in favour of CO2:
  - High heat transfer coefficient
  - Radiation hard
  - Environmentally friendly: Global warming potential = 1 (vs several 1000s for C6F14)

TP description : sketch [P. Bloch]



USC
Trigger + Data
Back End

Cold detector

TPG generation on detector

RBX region on the back of BH

- DCDC converters
- Data concentrators for copper links

~ 14K optical links
~ 36K copper links

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

17

CdLT HGCAL electronics CERN