CMS HL-LHC Endcap Calorimeter: A Child of CALICE

September 15, 2016

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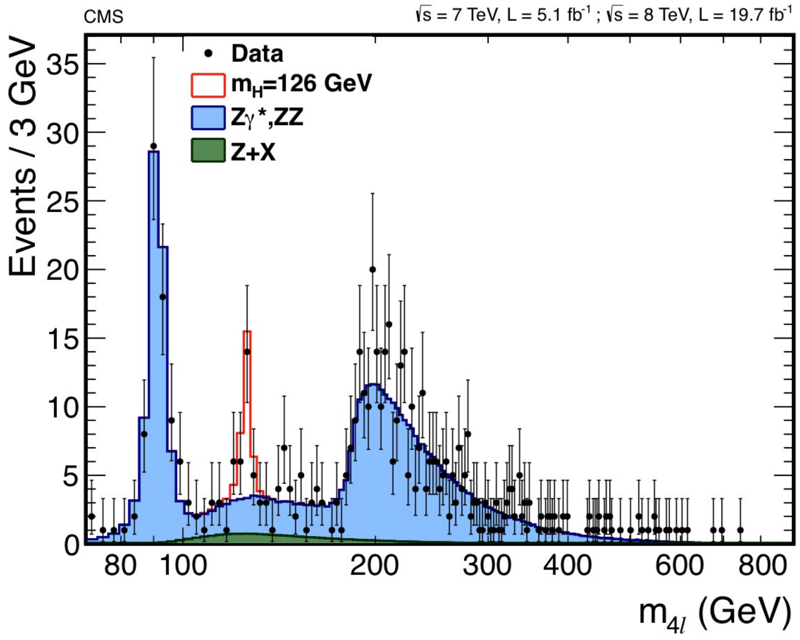
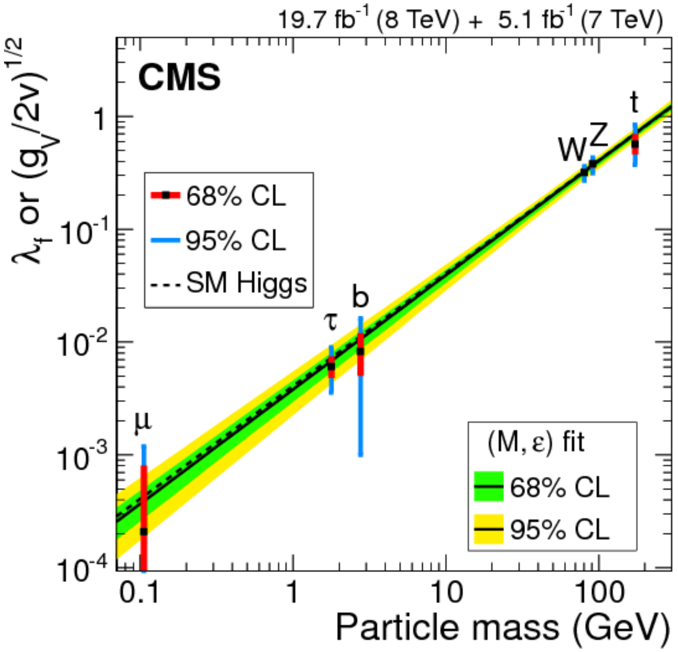
LHC → HL-LHC and the Higgs

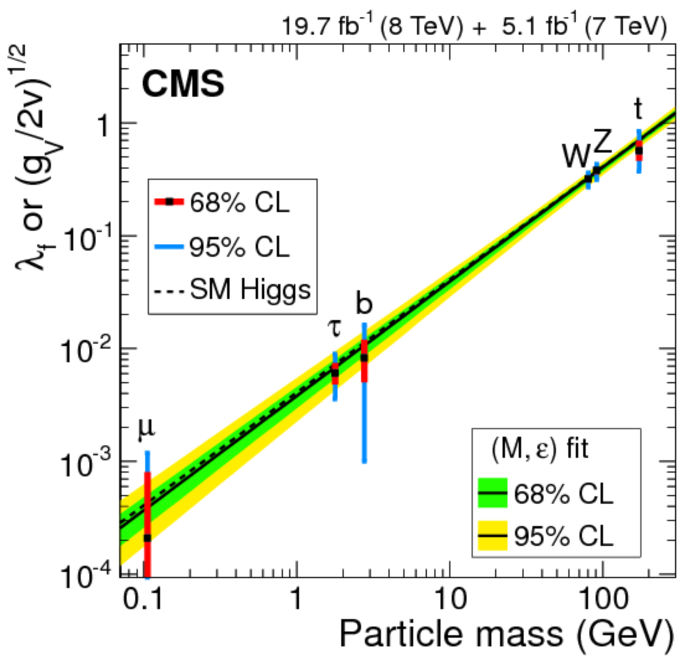


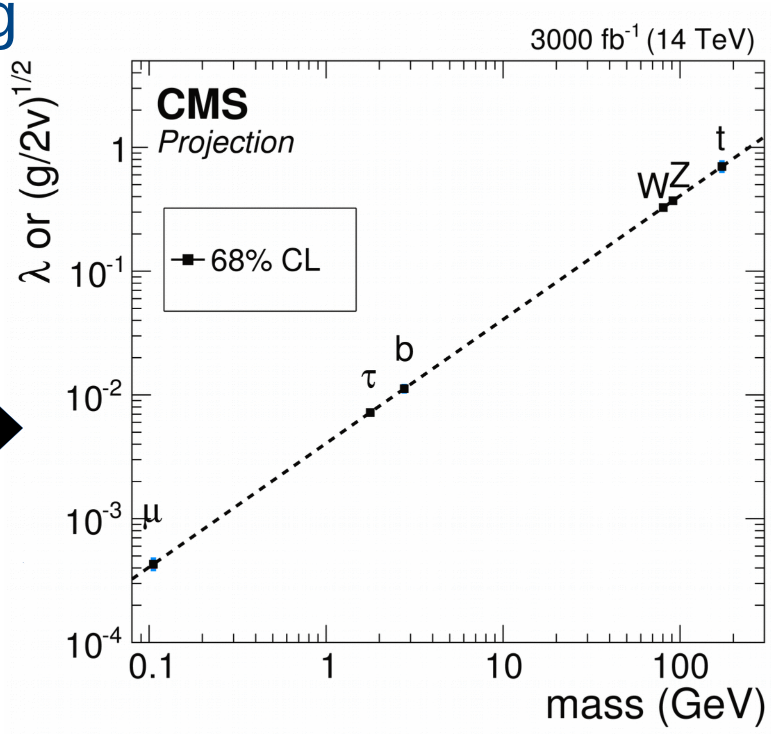


- Discovery of the Higgs was **the** exciting and defining event of LHC Run I
- Run I was pretty easy on the detectors
  - Peak luminosity of 0.7 x 10^{34} $cm^{-2}s^{-1}$, compared with design of 10^{34} $cm^{-2}s^{-1}$
  - Lower pileup cross-section and multiplicity due to lower center of mass energy
  - Bunches spaced by 50ns compared with 25ns

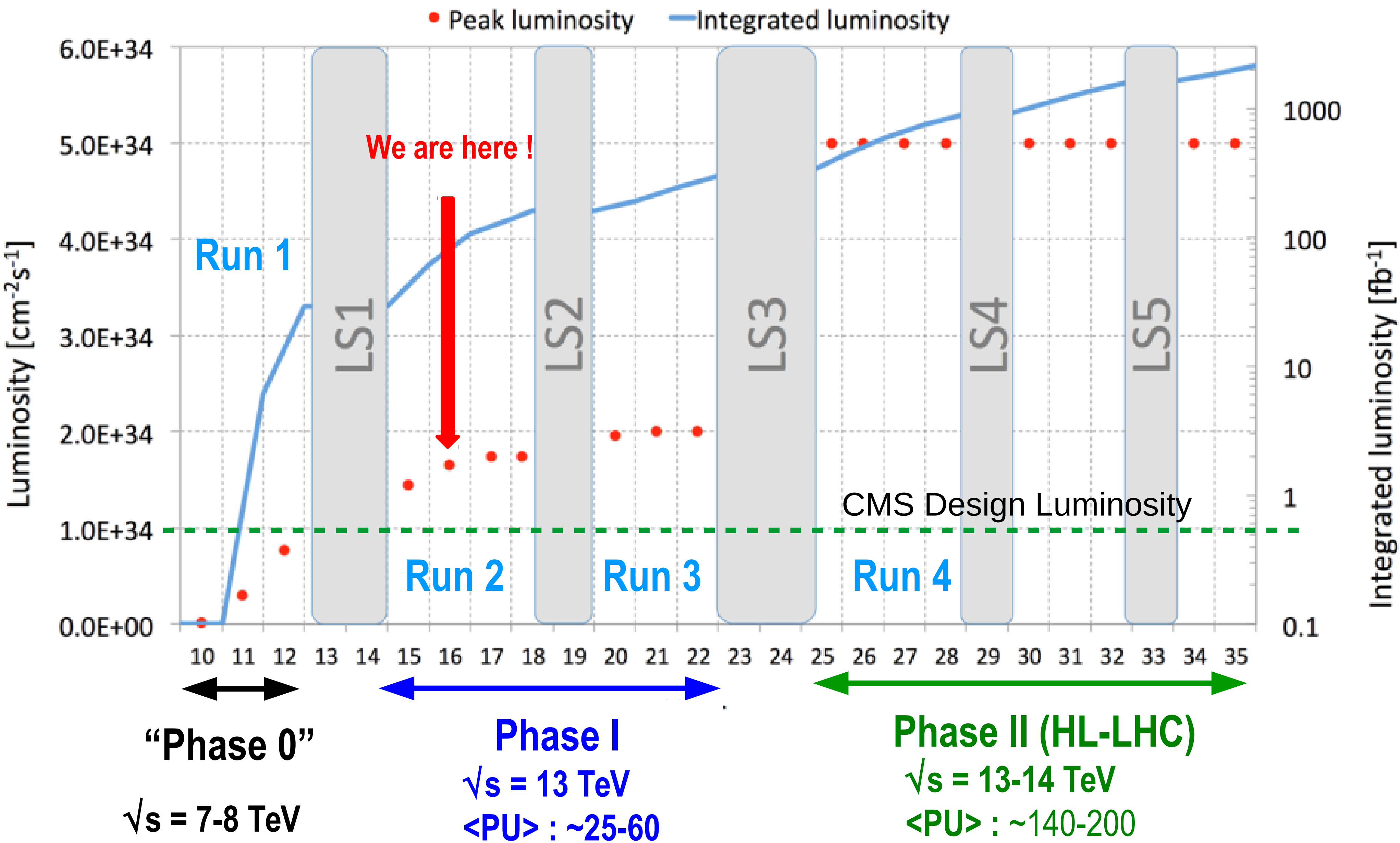
HL-LHC Physics goals in the Higgs sector

- Unraveling the true nature of EWSB
- Precision measurement of the Higgs Sector
- Observation of HH production, constraints on self-coupling
- Rare (μμ, Zγ…) or forbidden H_{125} decays (μτ…)
- Unitarity via Vector Boson Scattering

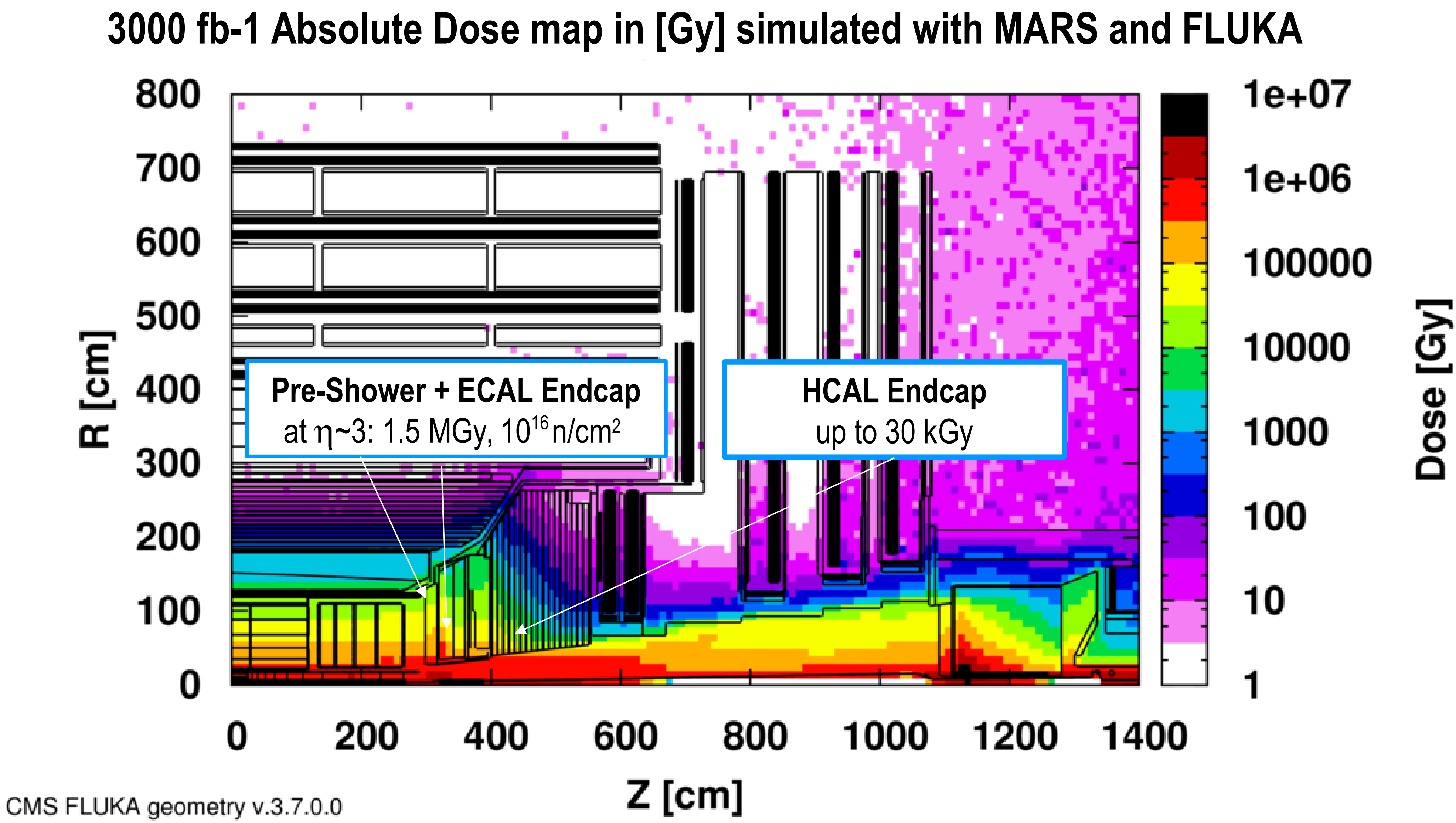




LHC Luminosity Evolution



Challenge: Radiation Tolerance



Challenge: Pileup

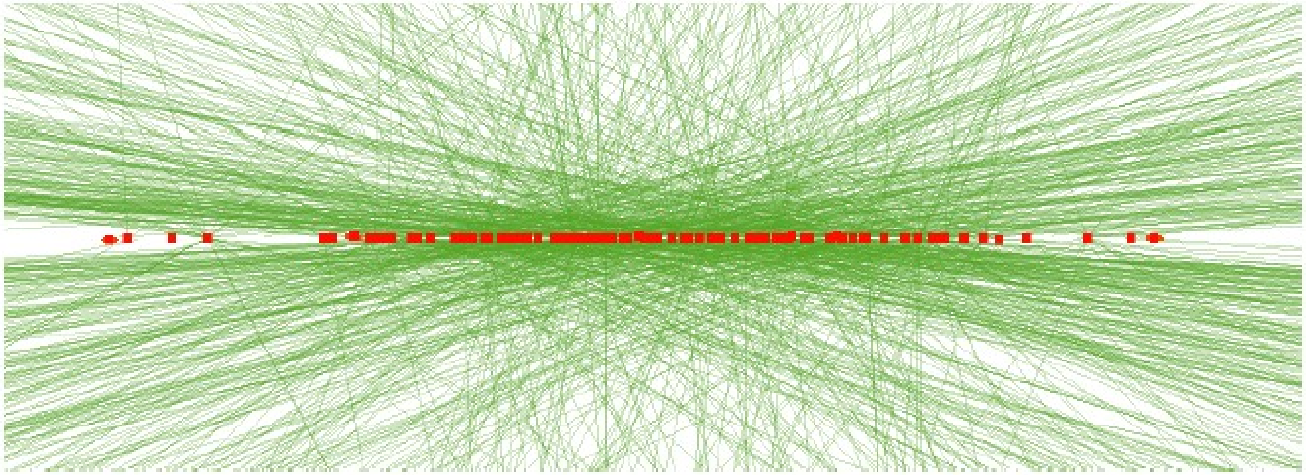


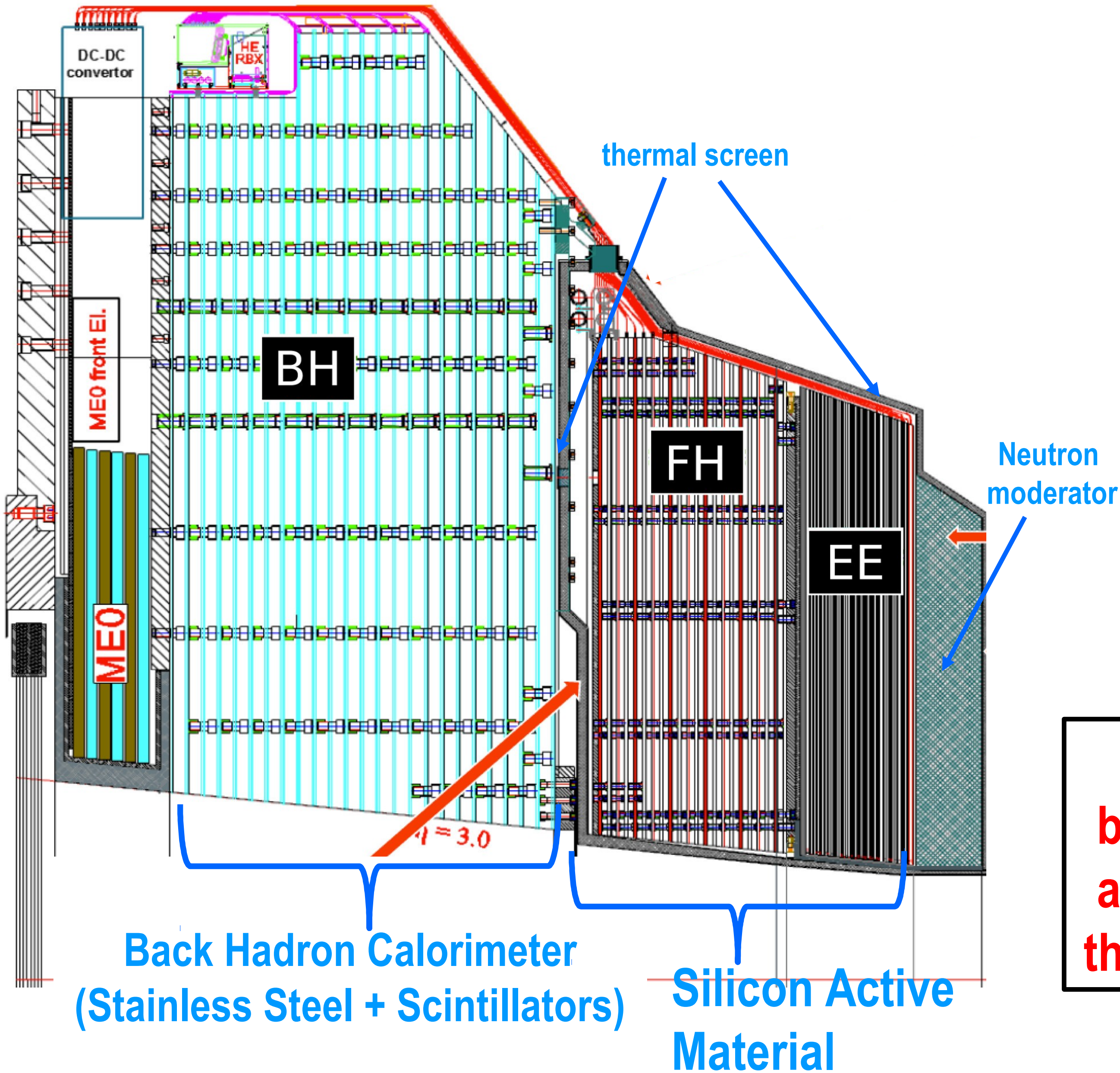
Figure 9.1: An event display showing reconstructed tracks and vertices of a simulated top-pair event with additional 140 interactions overlaid for the Phase-II detector.

- HL-LHC Nominal Parameters
  - 140 additional interactions per bunch crossing (every 25 ns) + out-of-time PU
    - Could go up to 200
  - Luminosity levelled – detector must operate for hours at peak conditions
- Challenges for Triggers (especially Level 1 !) & offline reco + computing

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

Child of CALICE in the Endcap

covers η range ~1.4 to 3



Technical Proposal
CERN-LHCC-2015-010

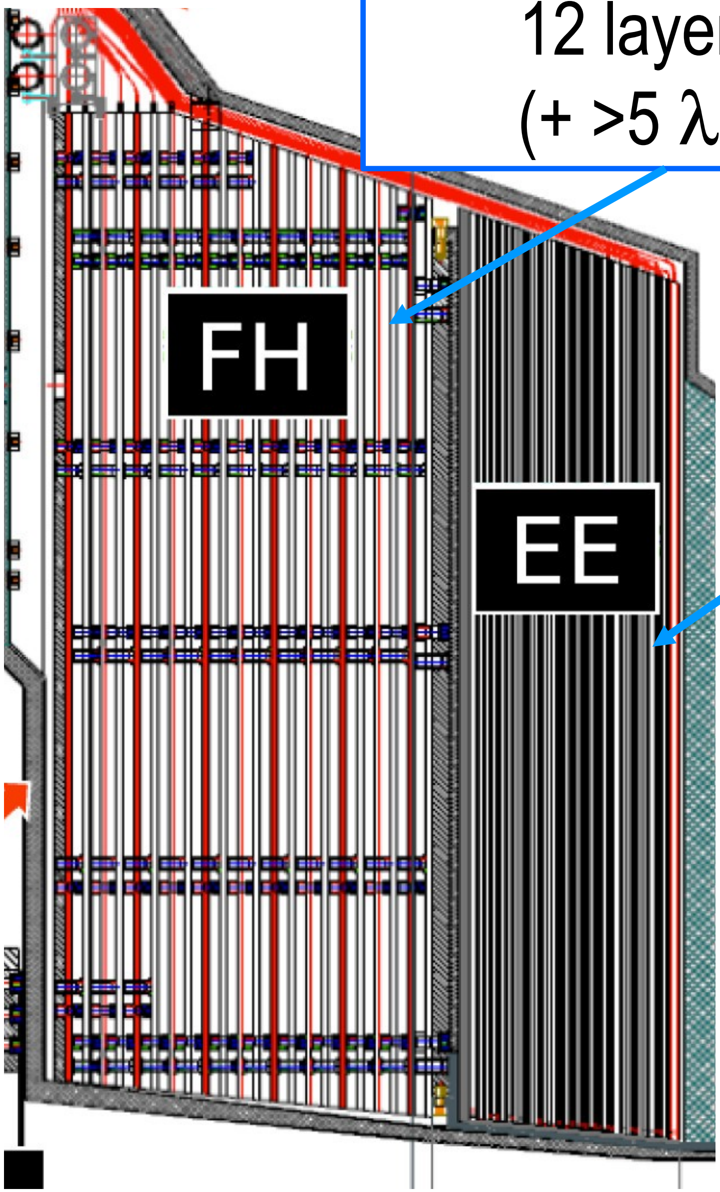
Concept is heavily based on the simulation and testbeam studies of the CALICE collaboration

ILC/LHC Contrasts

- Continuous-mode operation required for CMS
  - Many-hour fills in a circular collider with 25 ns bunch spacing, compared with more-widely spaced bunches and lower frequency pulses of ILC
  - Implication: power and cooling are much more important for CMS than for CALICE
    - CMS: 125 kW cooling requirement
- Collision environment
  - Silicon technology motivated in CMS initially by radiation tolerance, secondarily by performance potential
  - Managing pileup is a critical physics task to pick out true low p_T jets (weak-scale) from fakes produced by pileup fluctuations

EE/FH Design Details

Silicon Detector Parameters



FH: Si+(Steel + Cu)
12 layers, >3.5 λ
(+ >5 λ from BH)

EE: 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

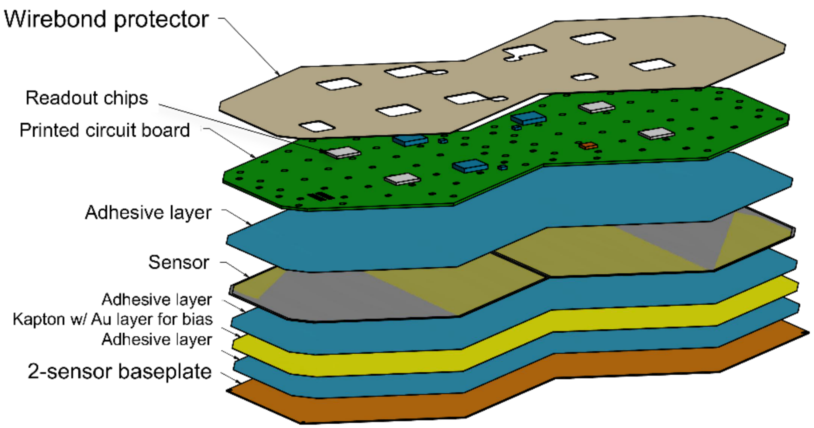
Operation at -30°C via CO_2 Cooling
(to mitigate Si leakage current)

Table 3.2: Parameters of the EE and FH.

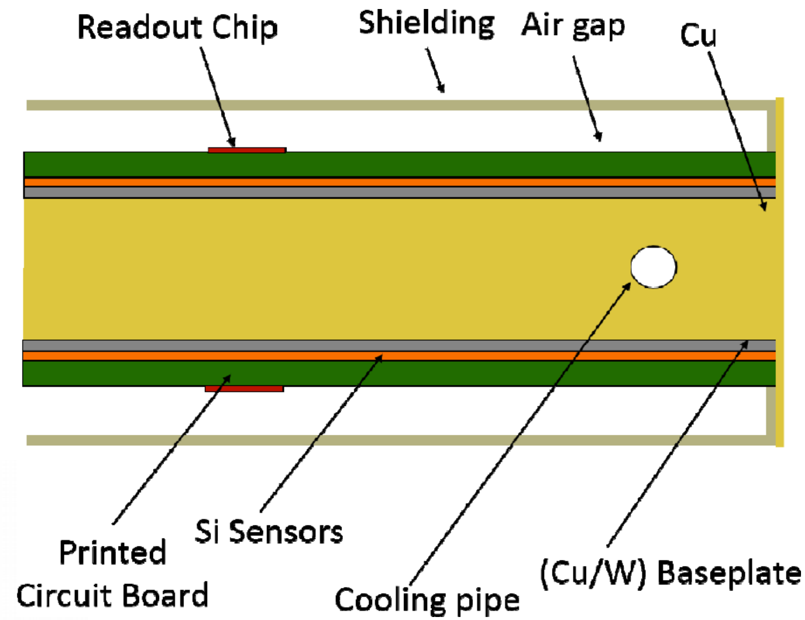
	EE	FH	Total
Area of silicon (m^2)	380	209	589
Channels	4.3M	1.8M	6.1M
Detector modules	13.9k	7.6k	21.5k
Weight (one endcap) (tonnes)	16.2	36.5	52.7
Number of Si planes	28	12	40

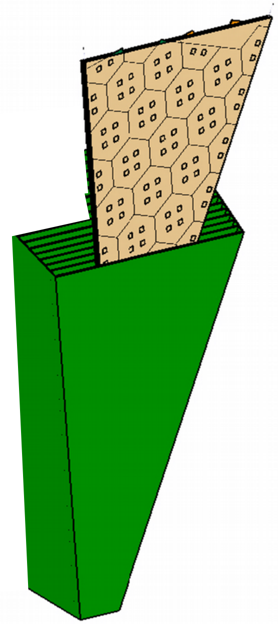
Building up the EE

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



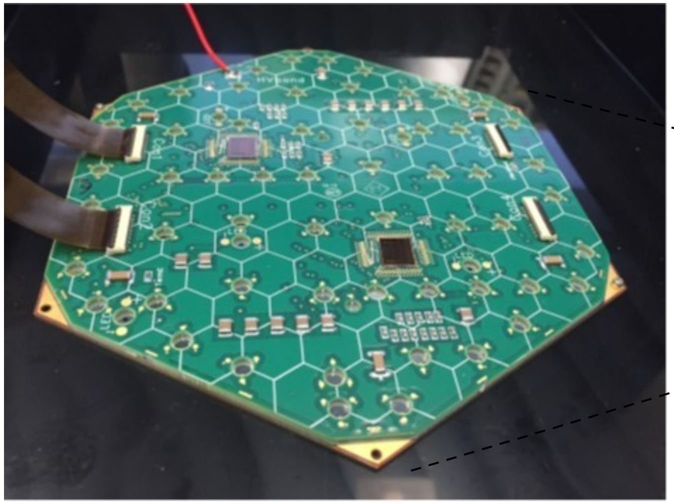
Modules mounted on **Cu Cooling plate** with embedded pipes == **Cassettes**

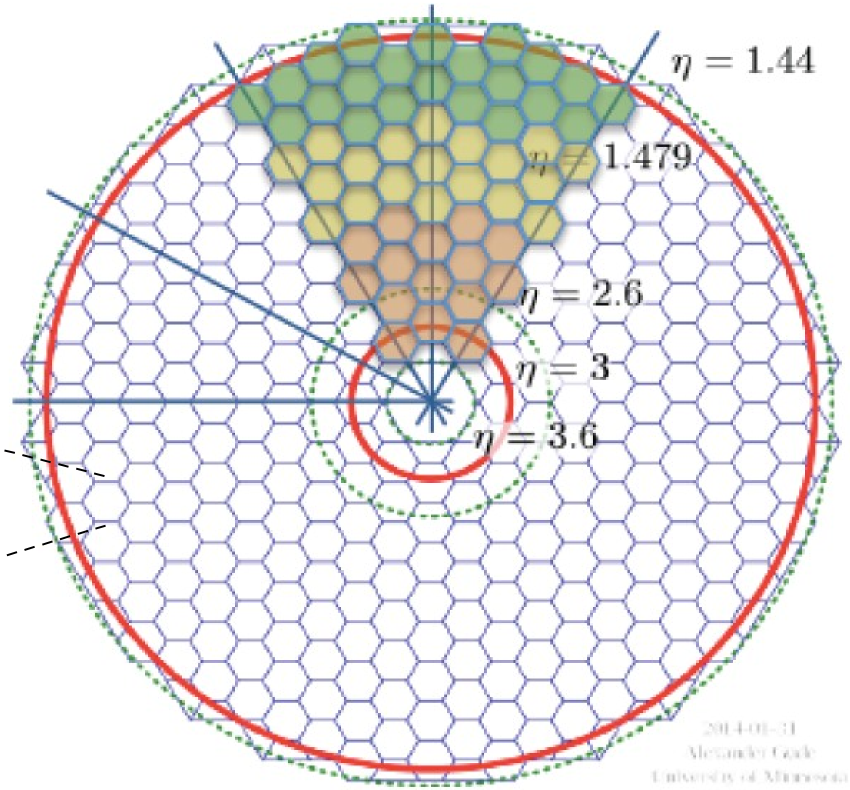




Cassettes
inserted in **mechanical structure**
(containing absorber)

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

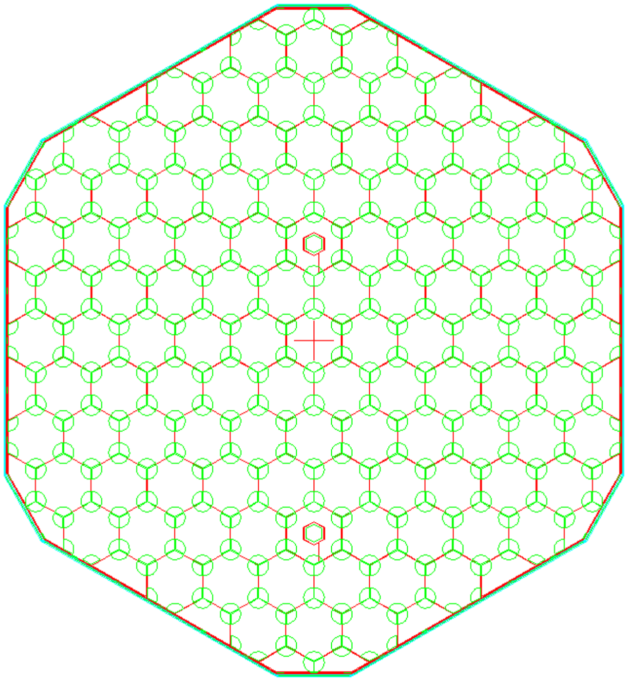


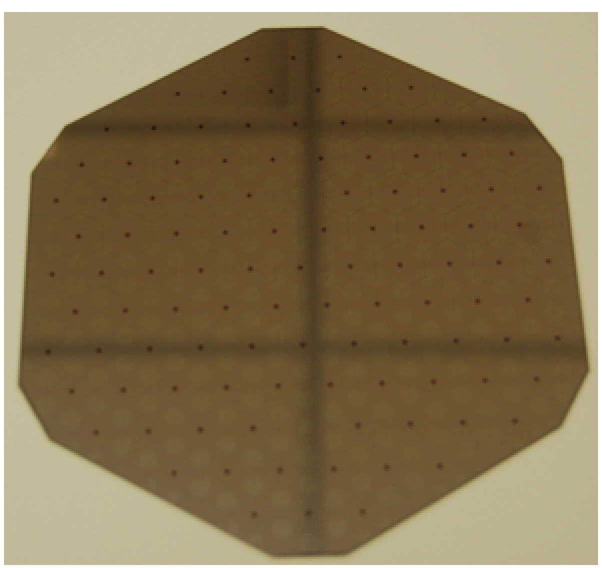


Thickness	300 μm	200 μm	100 μm
Maximum dose (Mrad)	3	20	100
Maximum n fluence (cm^{-2})	6×10^{14}	2.5×10^{15}	1×10^{16}
EE region	$R > 120$ cm	$120 > R > 75$ cm	$R < 75$ cm
FH region	$R > 100$ cm	$100 > R > 60$ cm	$R < 60$ cm
Si wafer area (m^2)	290	203	96
Cell size (cm^2)	1.05	1.05	0.53
Cell capacitance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

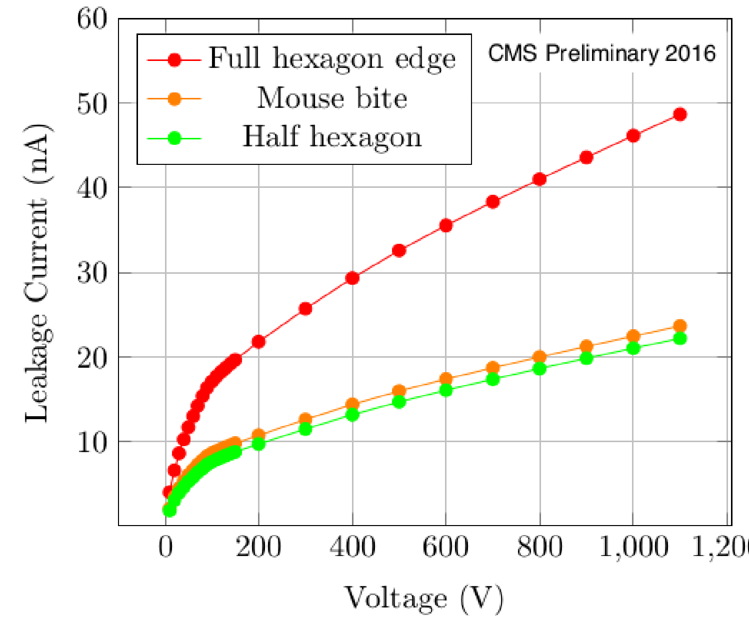
To cope with the irradiation / PU:

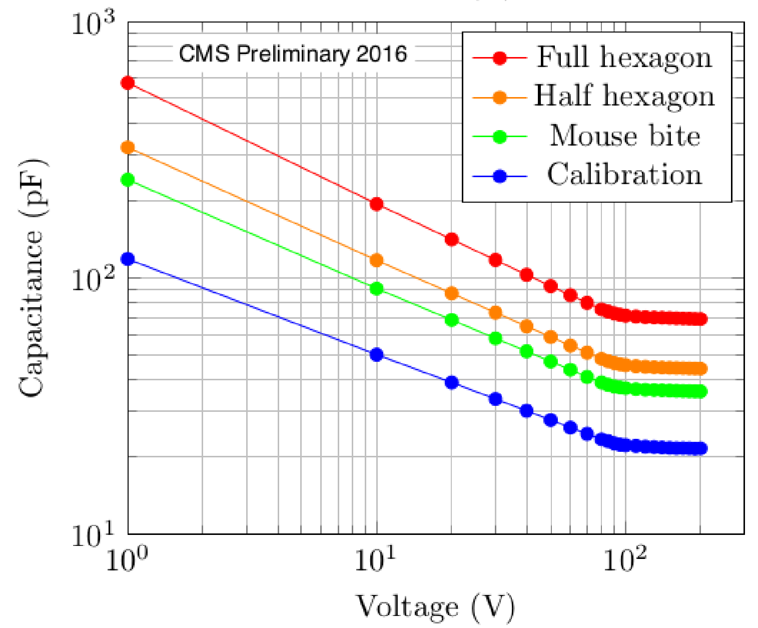
- η-dependent depletion of Si
- η-dependent cell size

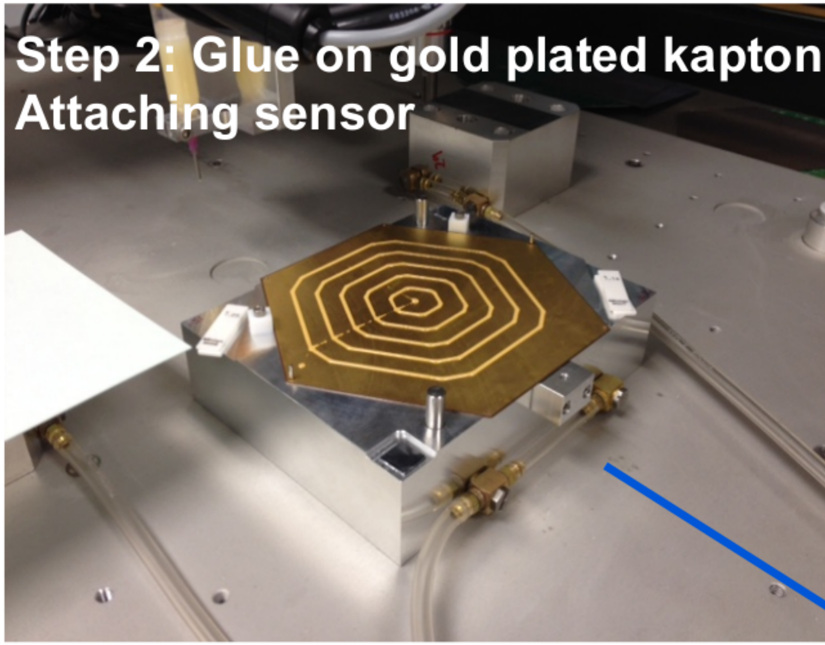


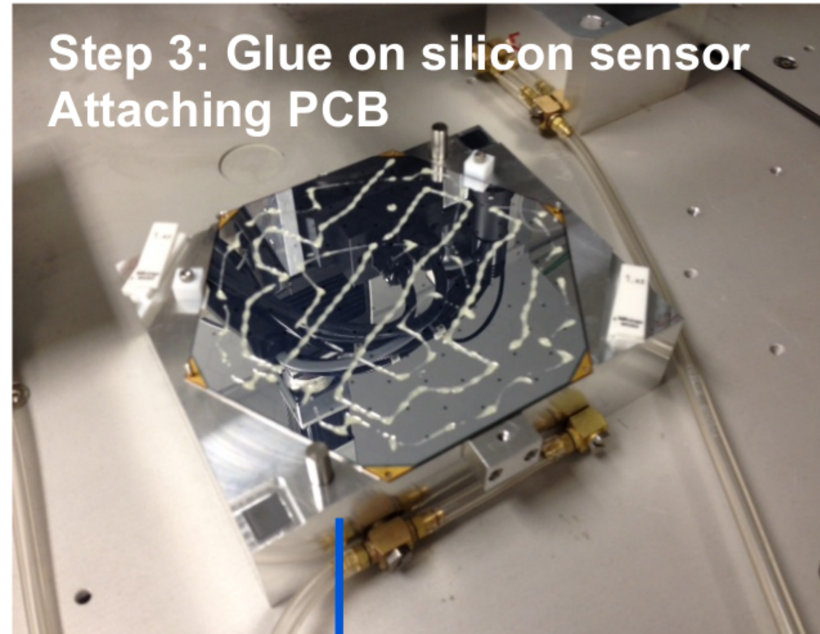


- Prototype 6" sensors obtained from Hamamatsu for all three active thicknesses
- Testbeam modules initially instrumented with 200um active thickness
- Excellent results observed in sensor tests at FNAL

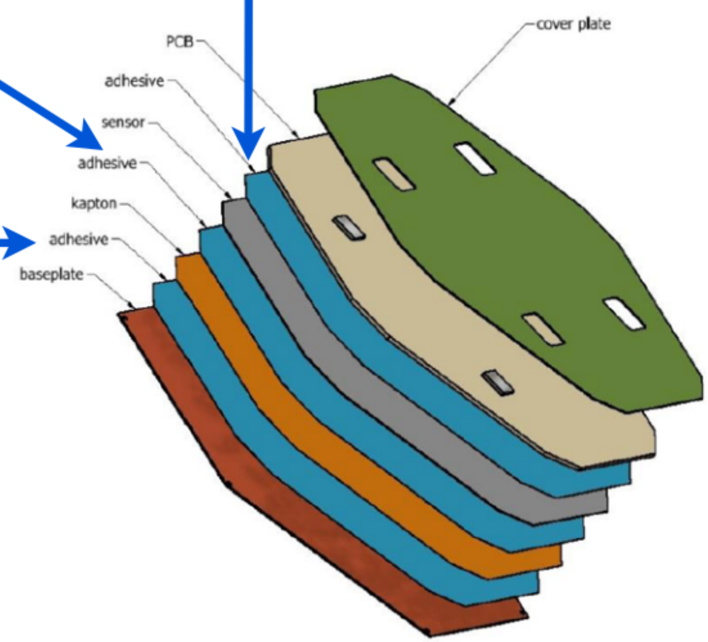




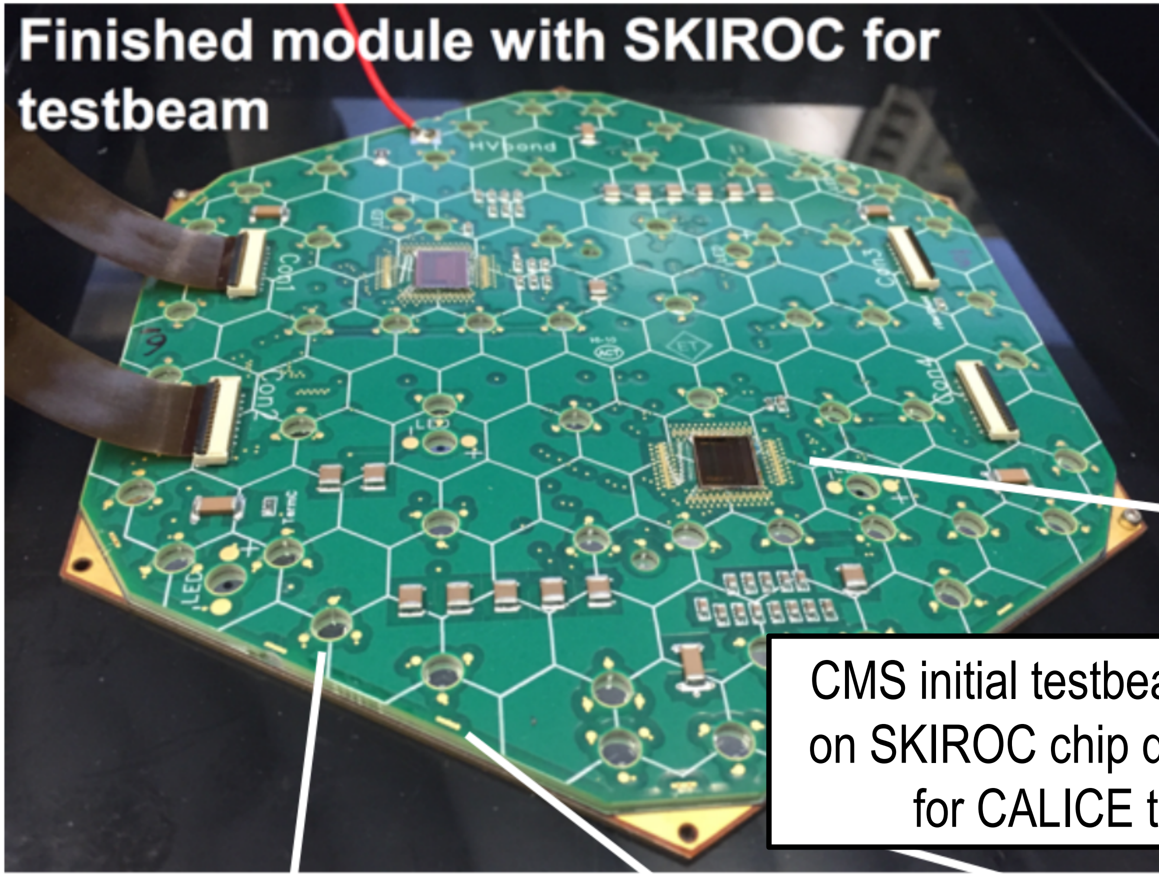

Step 2: Glue on gold plated kapton
Attaching sensor


Step 3: Glue on silicon sensor
Attaching PCB

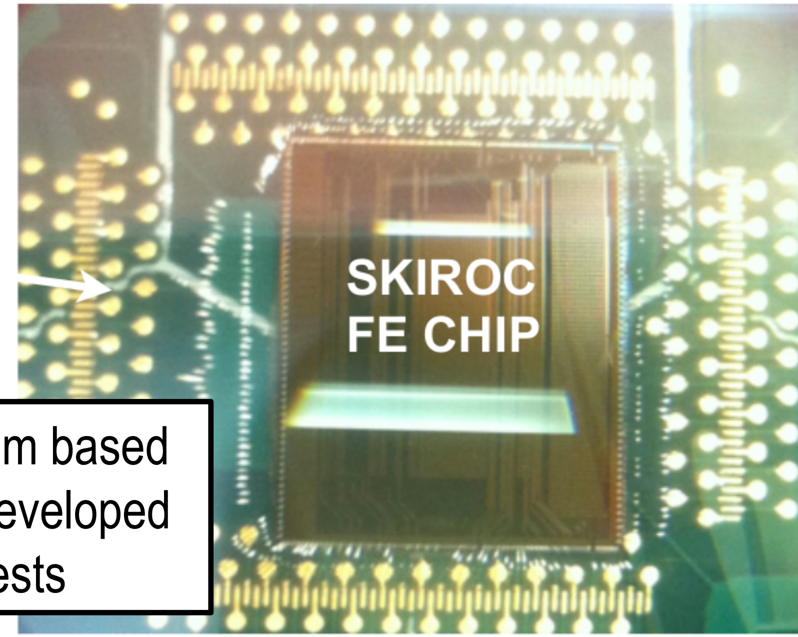

Step 1: Glue on W/Cu baseplate
Attaching kapton


cover plate
PCB
adhesive
sensor
adhesive
kapton
adhesive
baseplate

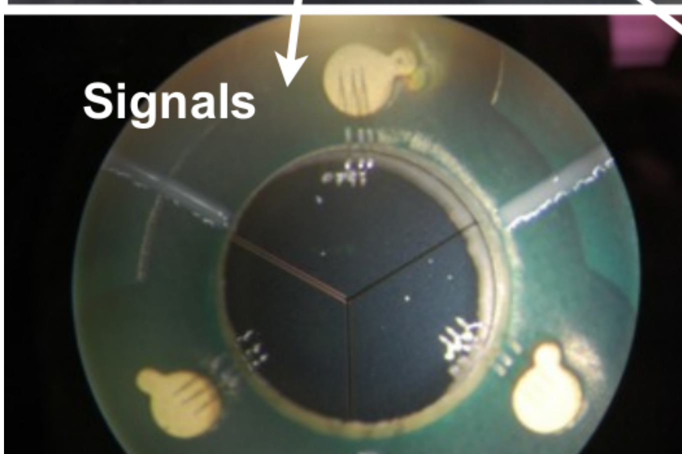
Wire bonding the module

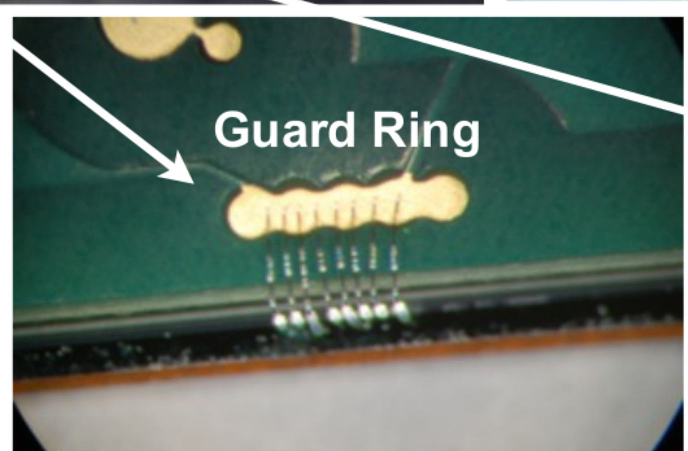


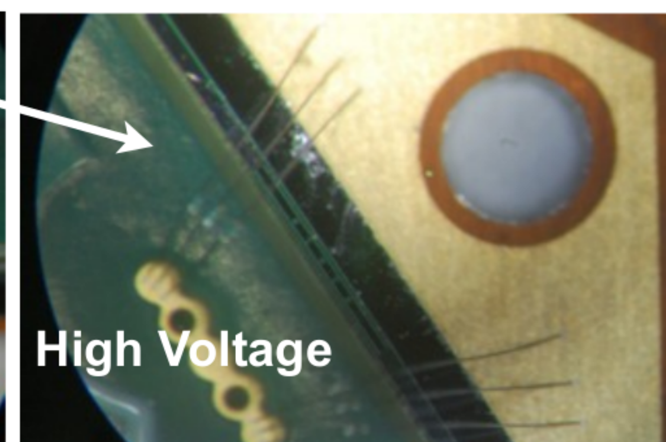
- ~ 700 wire bonds on a single module!



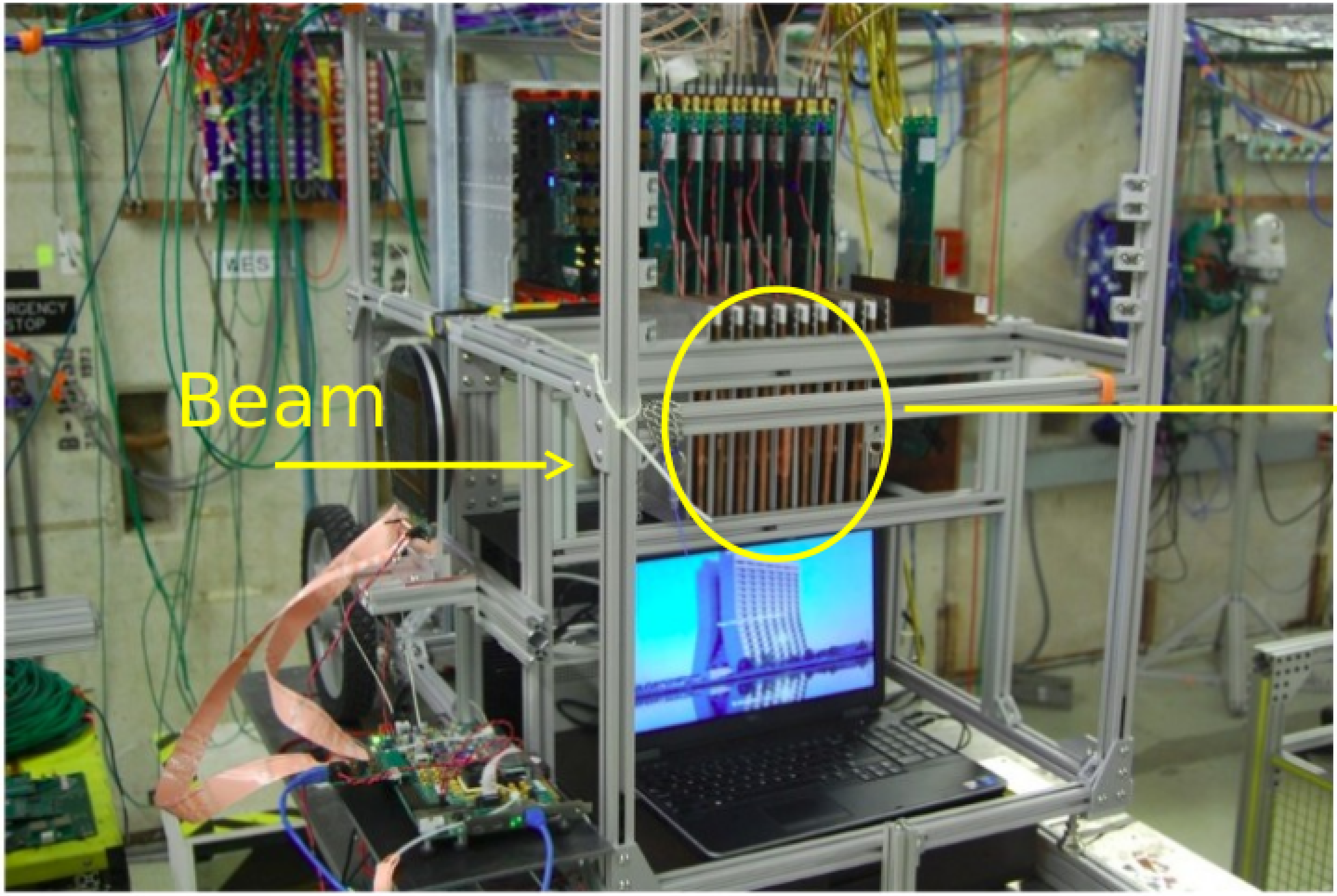
CMS initial testbeam based on SKIROC chip developed for CALICE tests

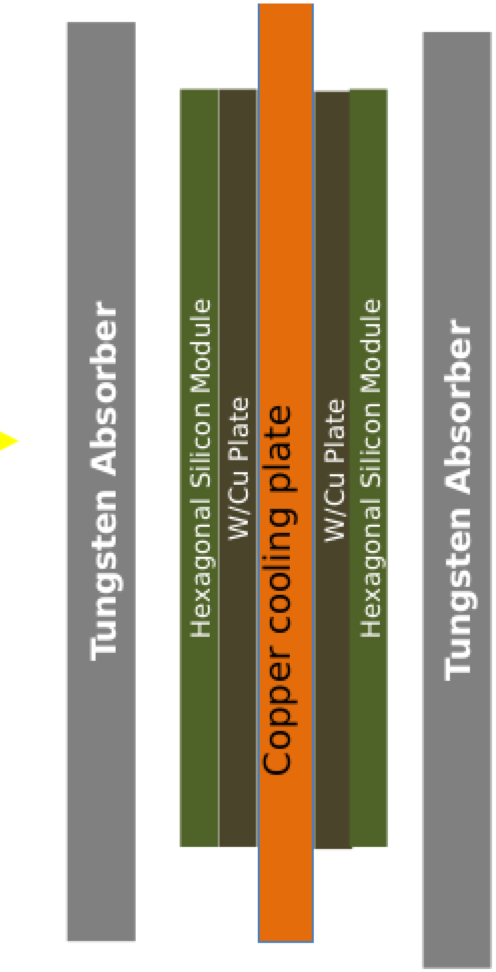






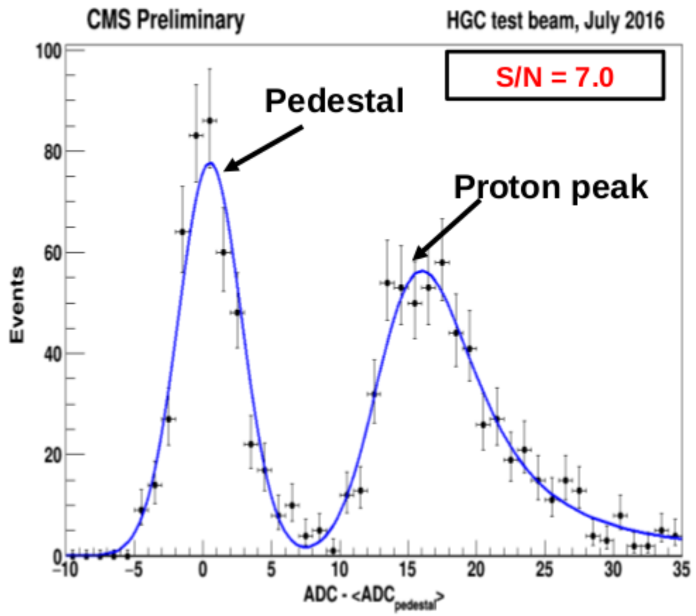
Testbeam stack at FNAL

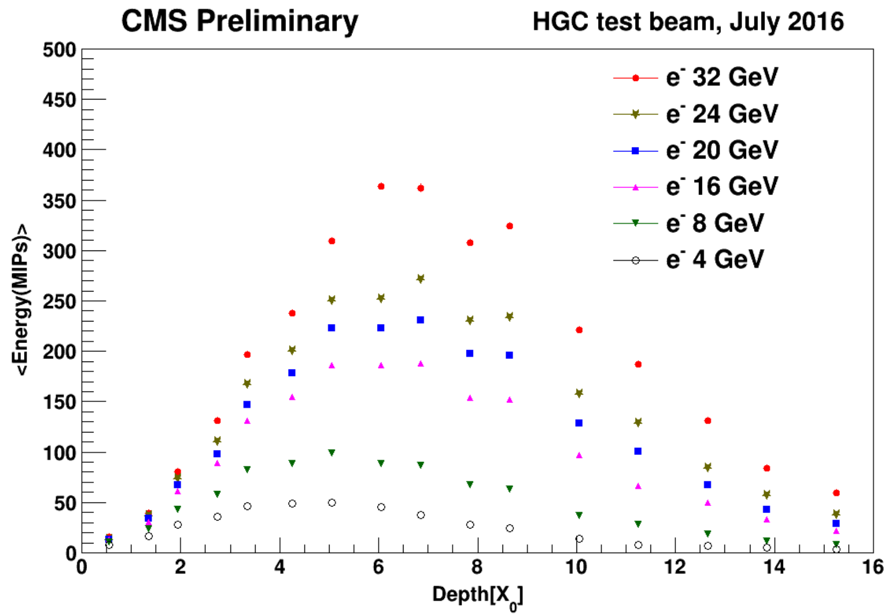


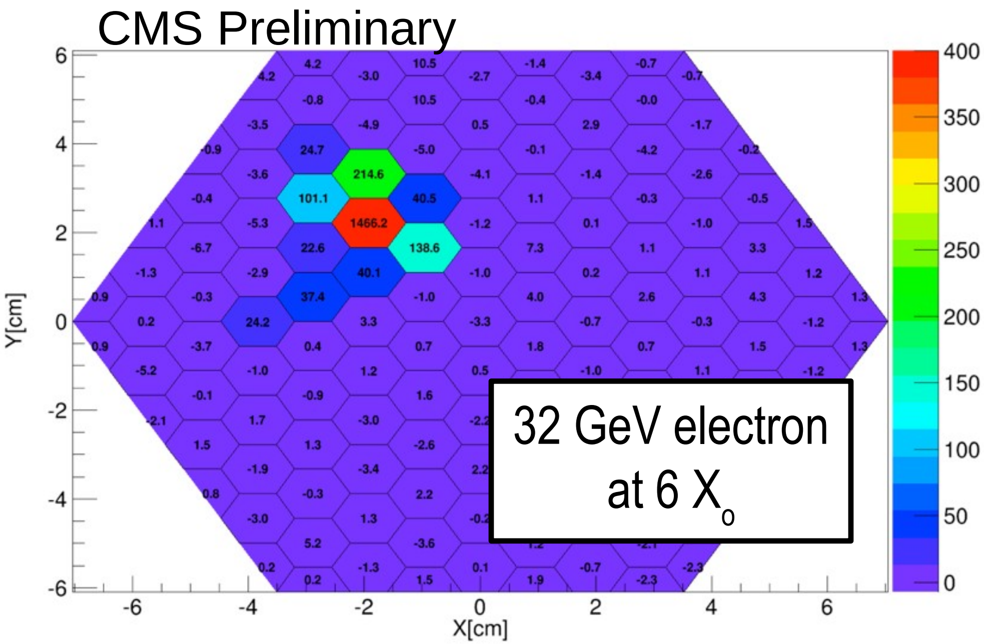


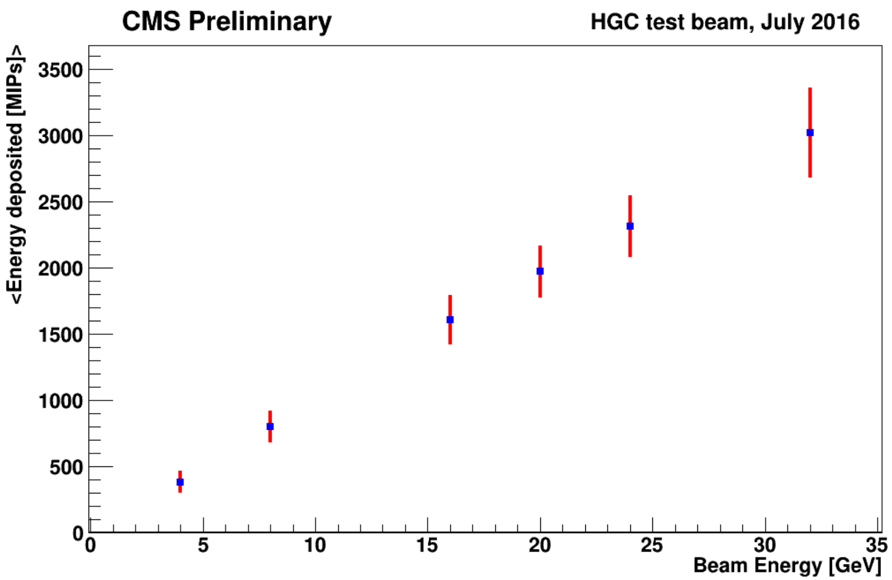
- The 16 detector modules are at depths of: 0.6, 1.4, 2.0, 2.8, 3.4, 4.3, 5.1, 6.1, 6.9, 7.9, 8.7, 10.1, 11.3, 12.7, 13.9 and 15.3 X_o respectively.
- The mechanics consists of a hanging file structure for flexibility:
  - Enables easy insertion of detector modules as well as absorbers of different thicknesses.
  - It is easy to have different distances between the layers.

Results from Testbeam







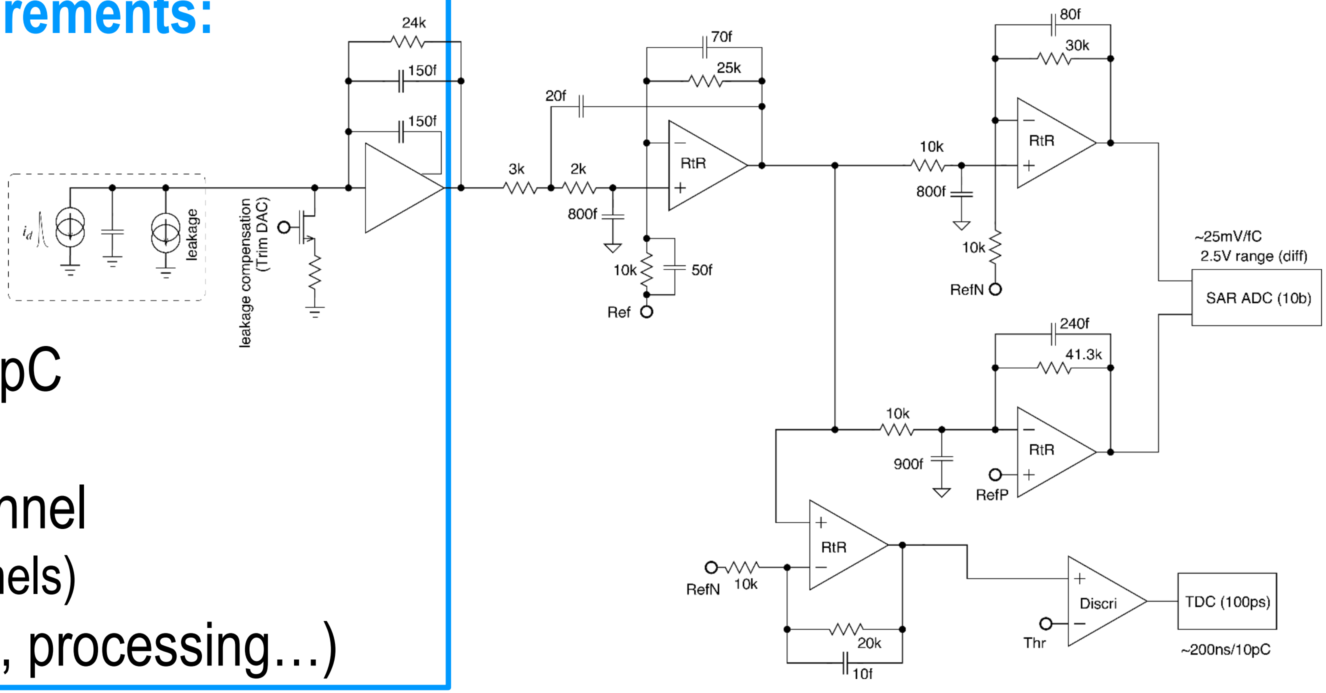


Electronics

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…)



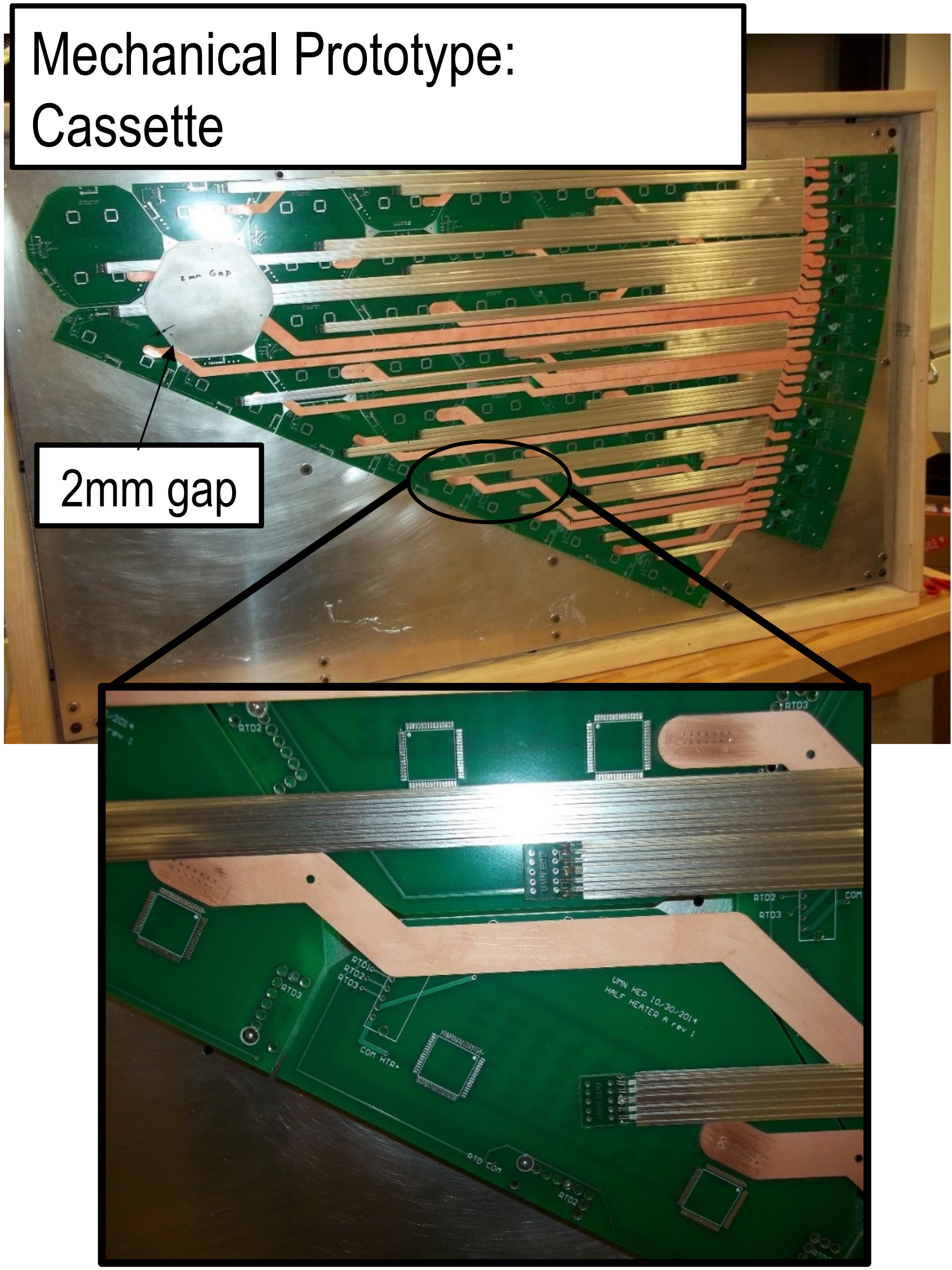
➢ **Baseline architecture: Charge + Time-over-Threshold (ToT) [*]**

- 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

Cassettes

"dummy" cassette for thermal tests

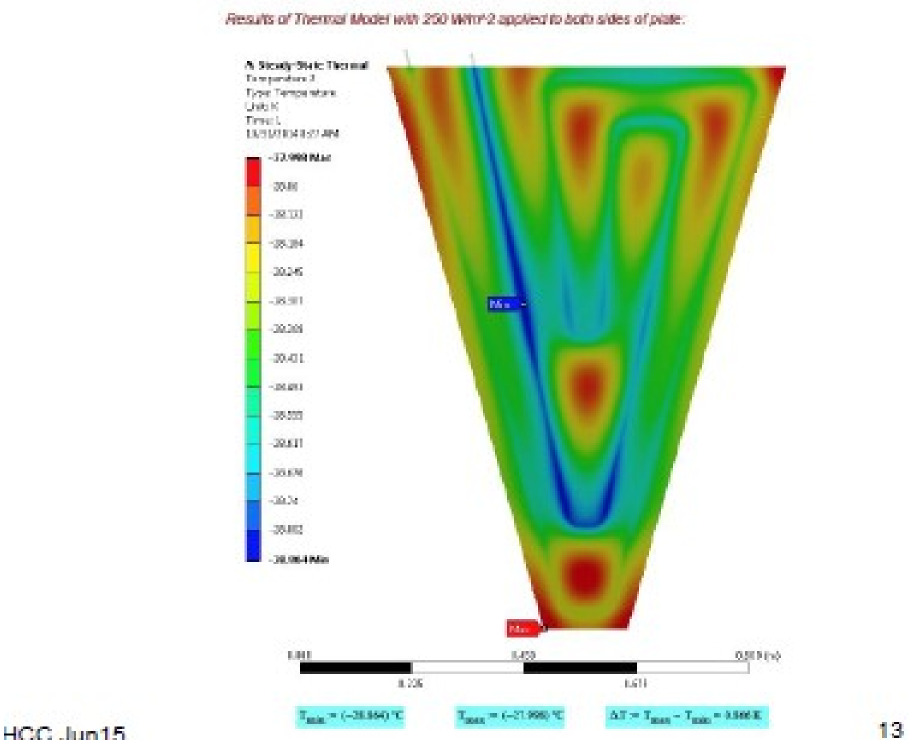


CO_2 Cooling

Cassettes FEA

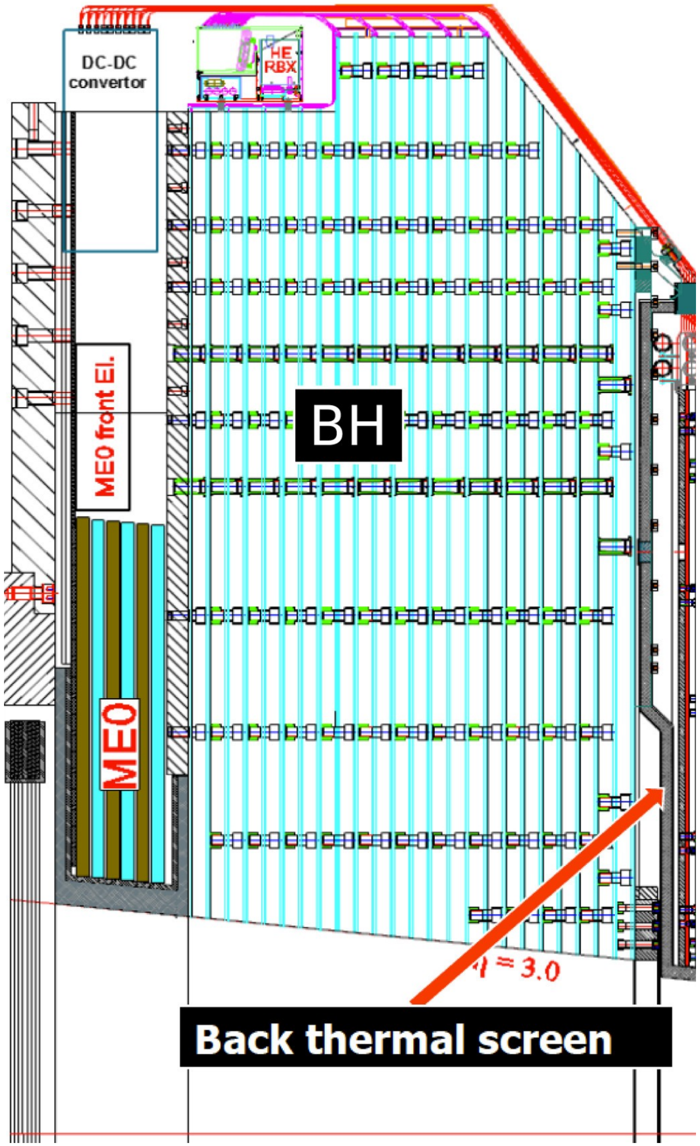
Goal: ΔT ~ 1-2 K
6mm Cu plate 1 pipe – uniform heat load
ΔT ~ 0.9K (over the cassette)
Cooling Tube: OD-4.8mm, ID-3.2mm,
Length - 5.9 m, mass flow: 2.0 gm/sec,
T_{max} -28.00C, T_{min} -28-86C.

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



Backing Calorimeter

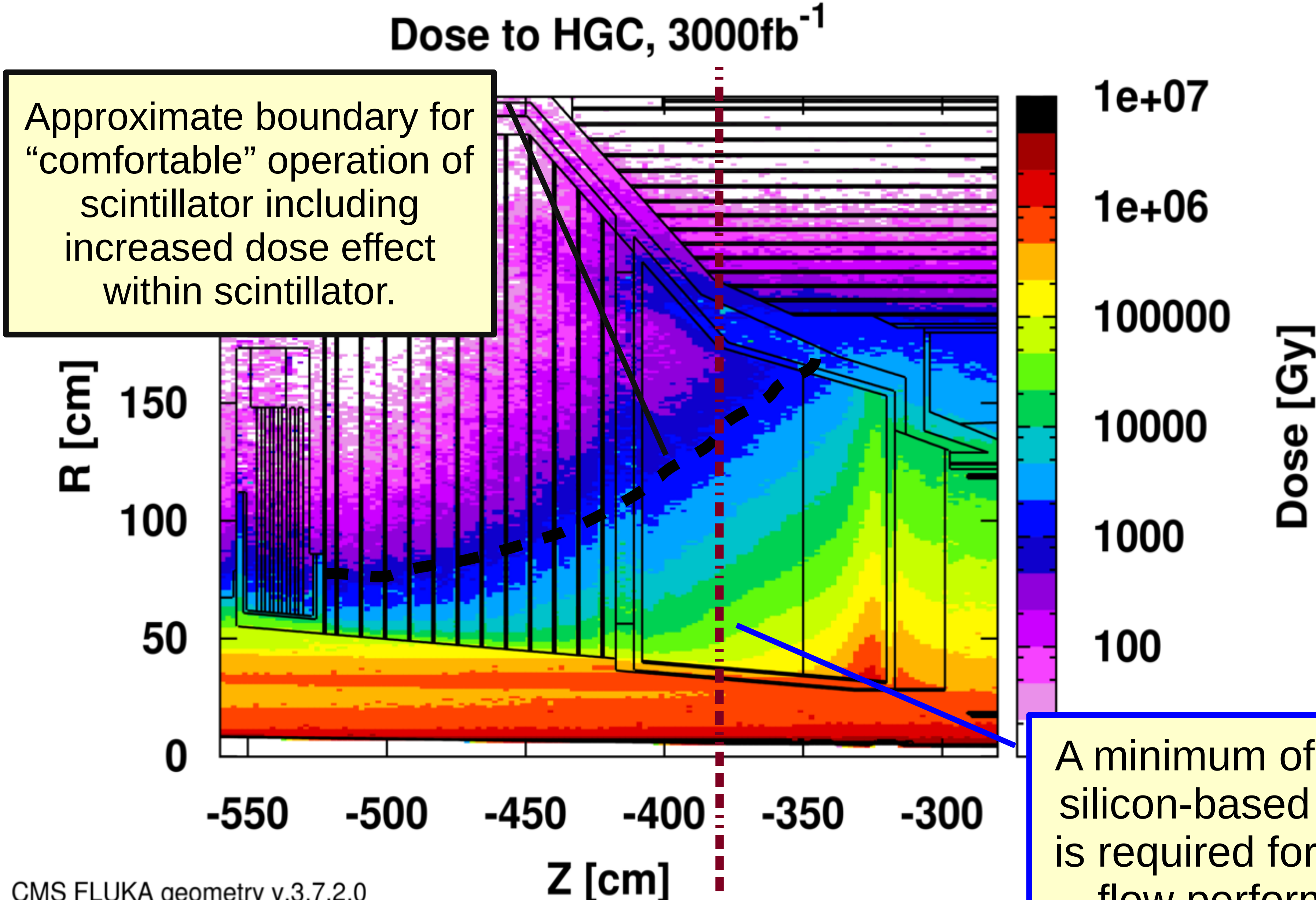
BH Detector Parameters



BH: Scintillator + Steel
12 layers, >5 λ
~450 m^2 of scintillator

- Technical Proposal Concept
  - WLS fiber readout with SiPM phototransducers ~identical to Phase 1 upgrade
  - Specialized materials potentially needed in highest radiation zones
- Current R&D
  - Enclose full detector in thermal screen
  - Allows use of silicon modules in high-radiation zones and allows possible adoption of SiPM-on-tile technology

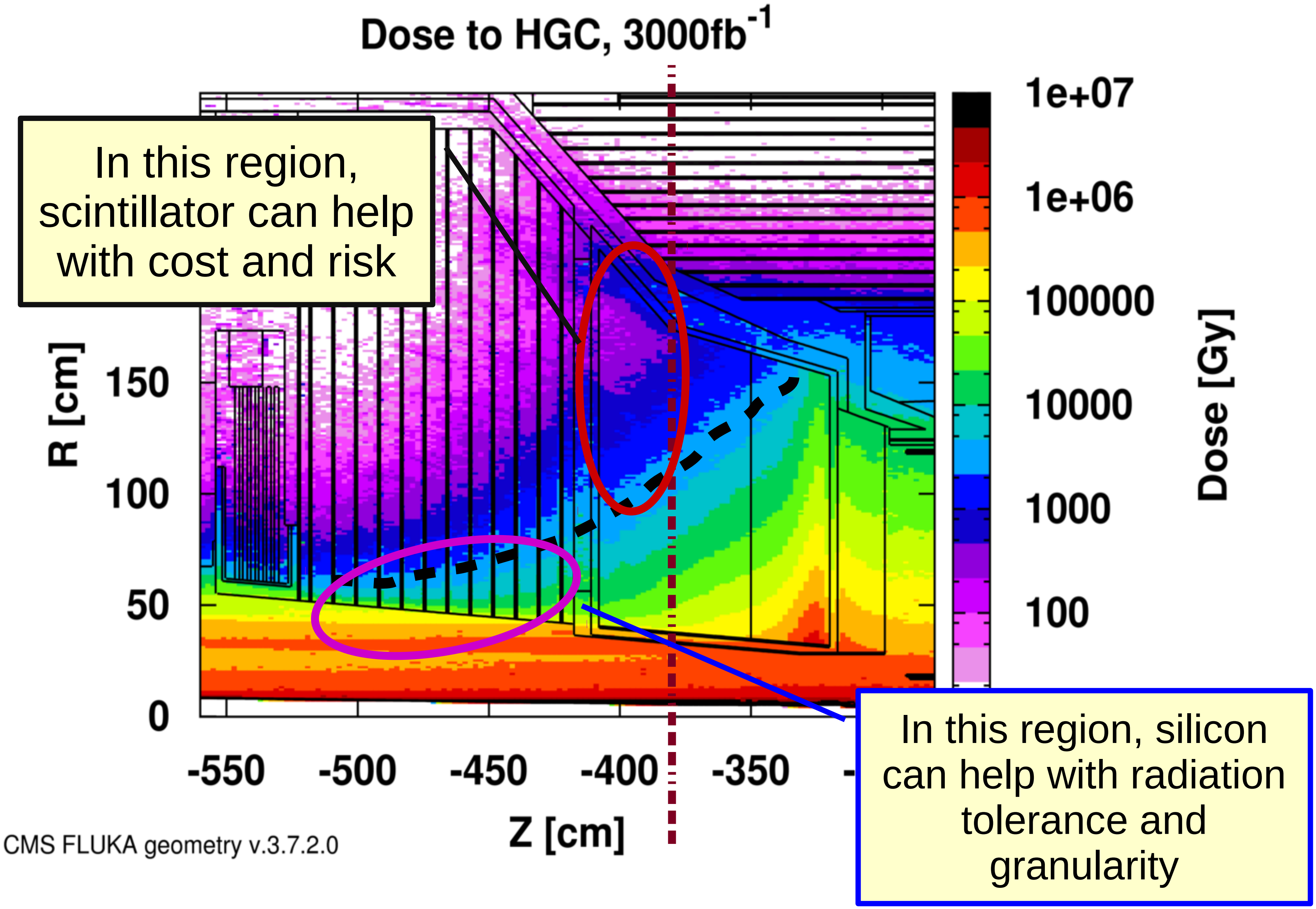
Radiation Dose



Approximate boundary for "comfortable" operation of scintillator including increased dose effect within scintillator.

A minimum of O(3λ) of silicon-based detector is required for particle-flow performance.

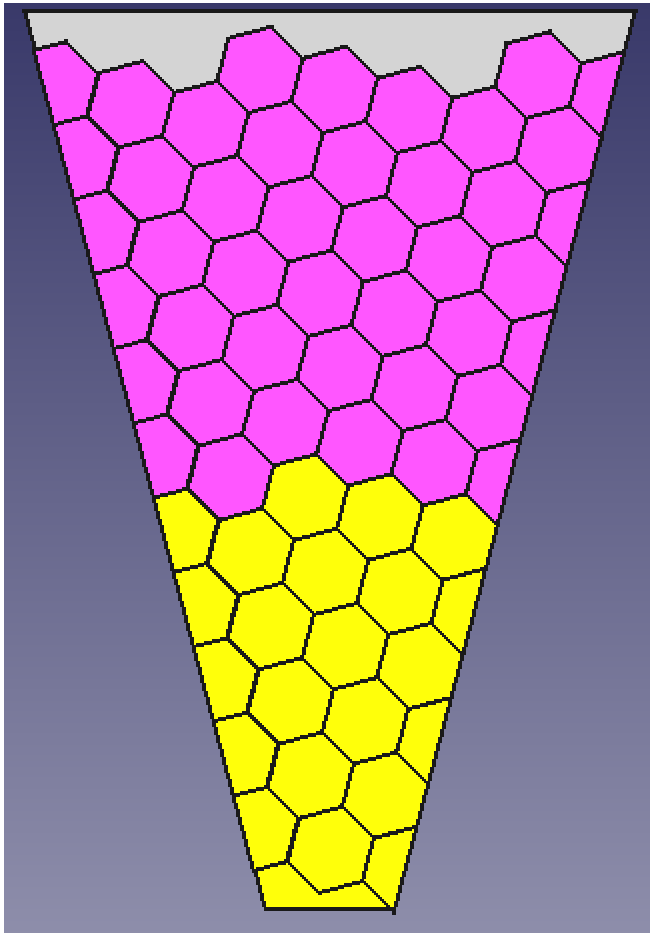
Tradeoffs



Dose to HGC, 3000fb^{-1}
In this region, scintillator can help with cost and risk
In this region, silicon can help with radiation tolerance and granularity
R [cm]
150
100
50
0
-550
-500
-450
-400
-350
Z [cm]
1e+07
1e+06
100000
10000
1000
100
Dose [Gy]
CMS FLUKA geometry v.3.7.2.0

Flexible Concept

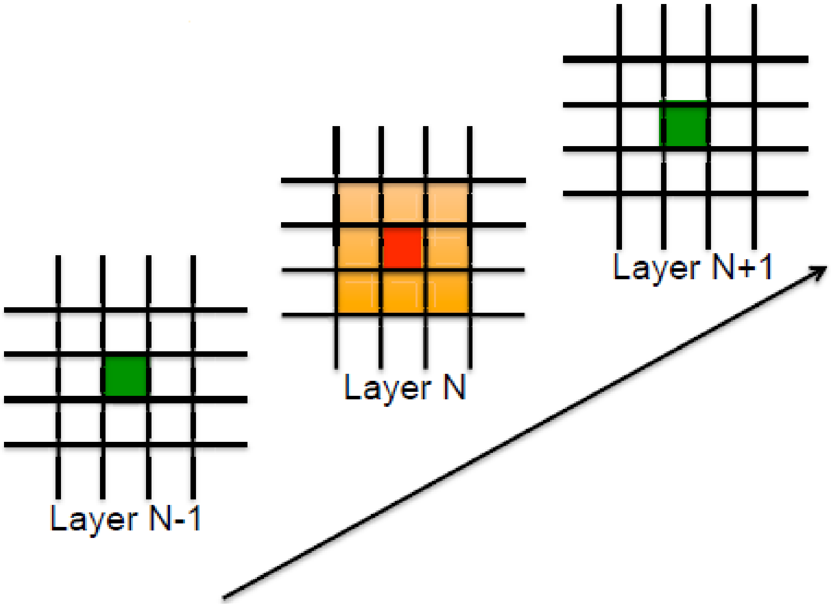
- If the whole endcap runs at -30C, the boundary between silicon and scintillator can be flexible
  - “Mixed” cassettes with silicon and scintillator sections – or megatiles with silicon sections!
- Since SiPMs are inside the cold volume, can consider use of SiPM-on-tile technology as in CALICE A-HCAL
  - Very appealing for muon-id performance and system uniformity if read out by variant of silicon readout chip
- Depends on understanding plastic scintillator radiation tolerance at low temperature – under study now

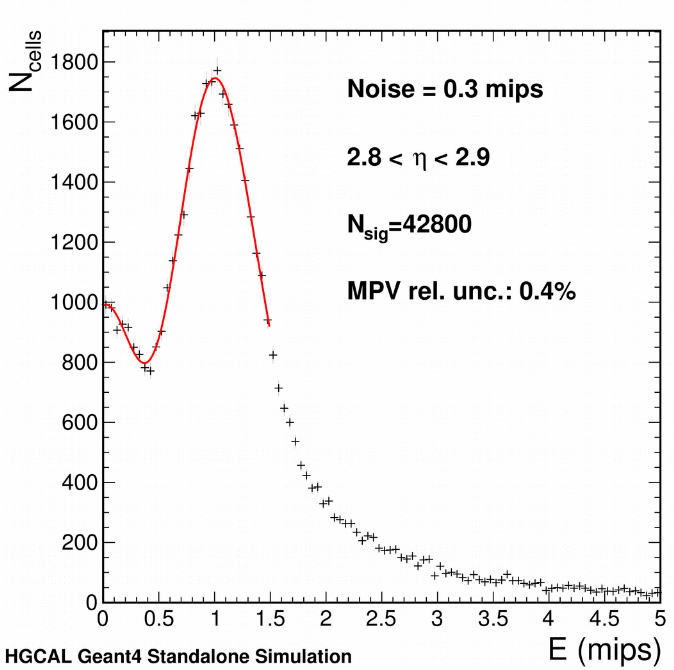


Calibration and Performance

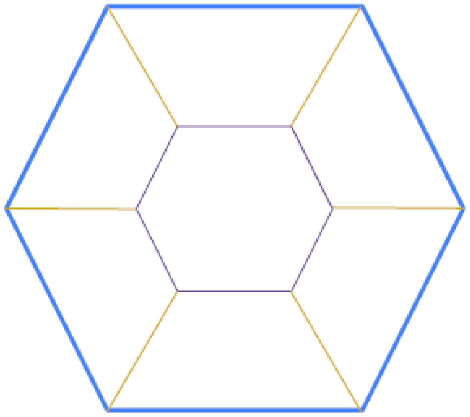
Calibration by MIPs

- **"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)

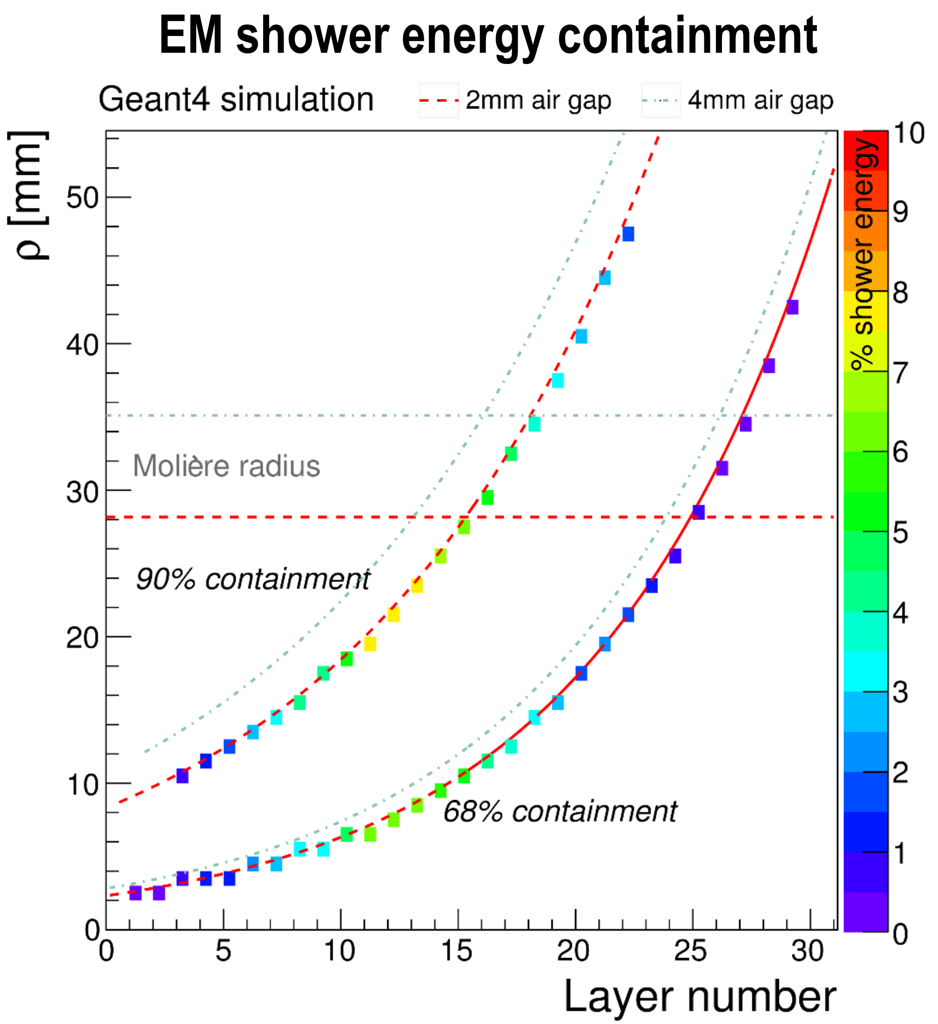


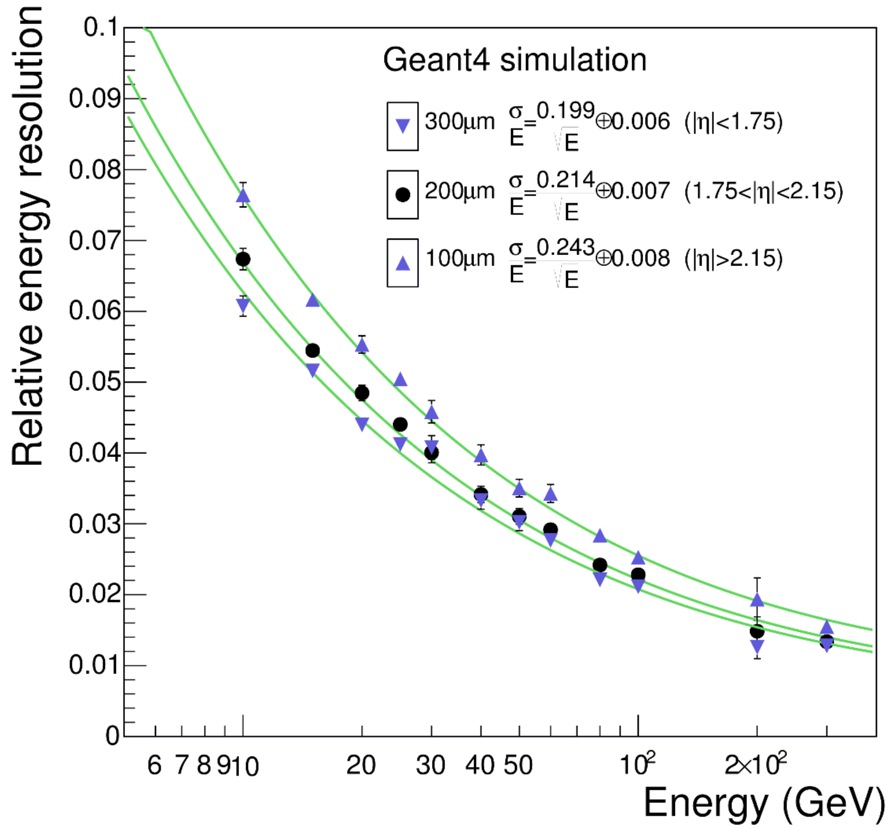


- **In addition, for redundancy:**
  - Low-capacitance/low-noise cell included in each wafer for calibration



Electromagnetic Performance



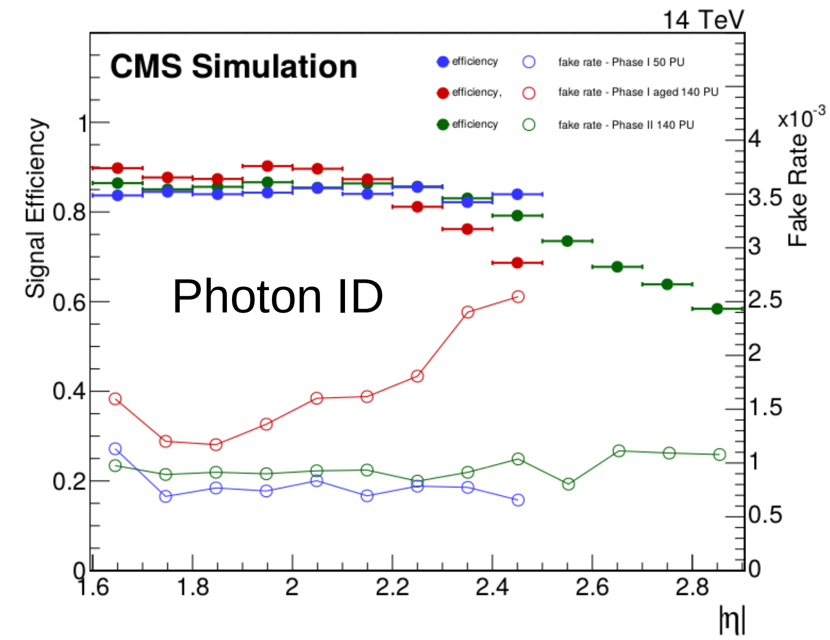


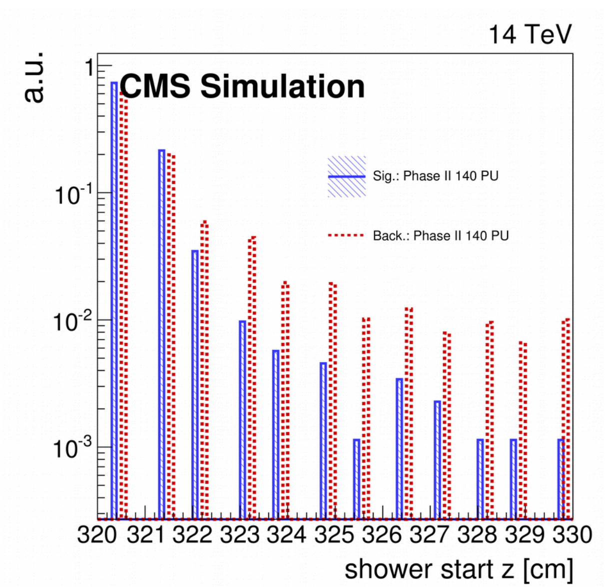
Shower radius quite small in first layers.
Can use longitudinal segmentation for PU rejection, …

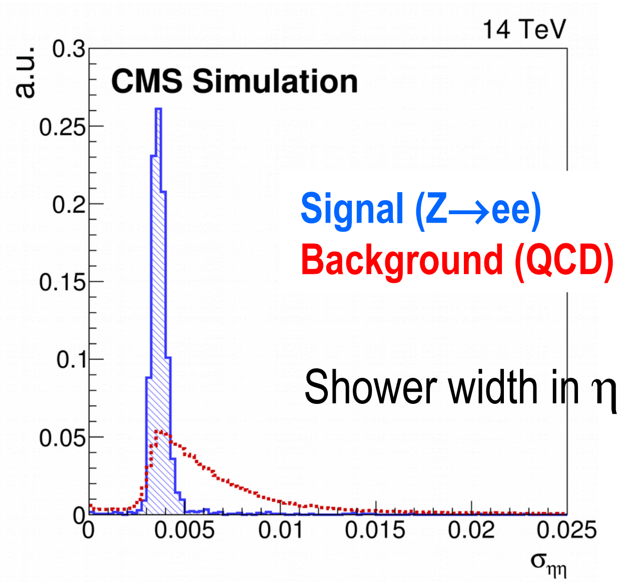
Stochastic term: ~20%
but **low constant term** (target: 1%)
Endcap calorimeter – E/E_T factor between 2 and 10

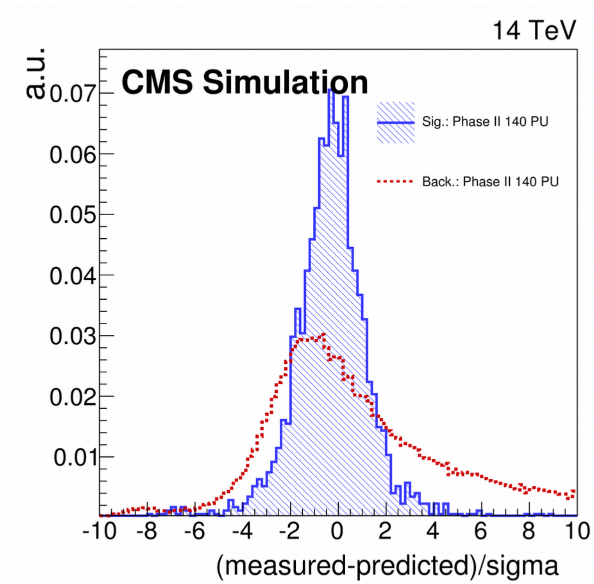
EM Id Performance

- **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…

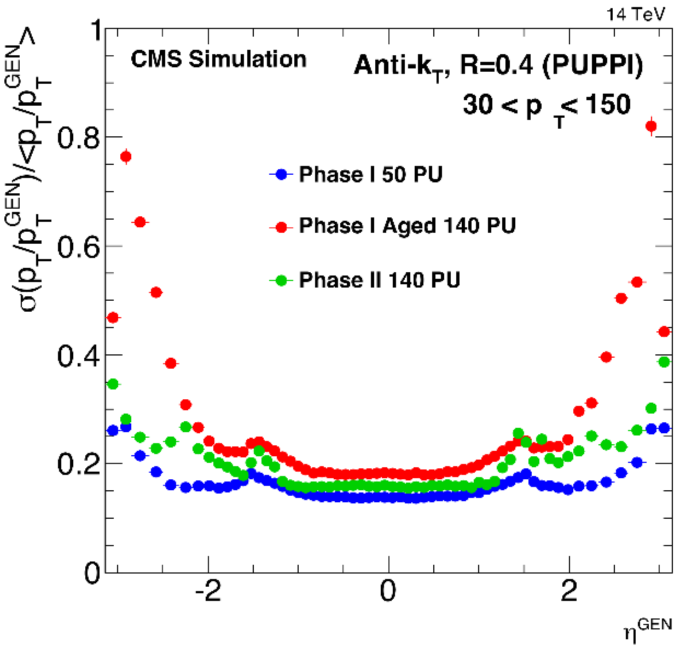




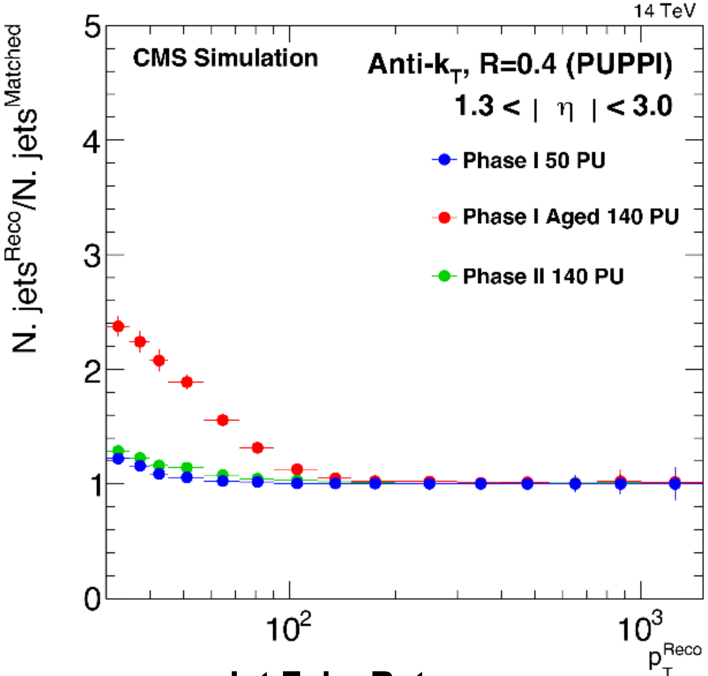




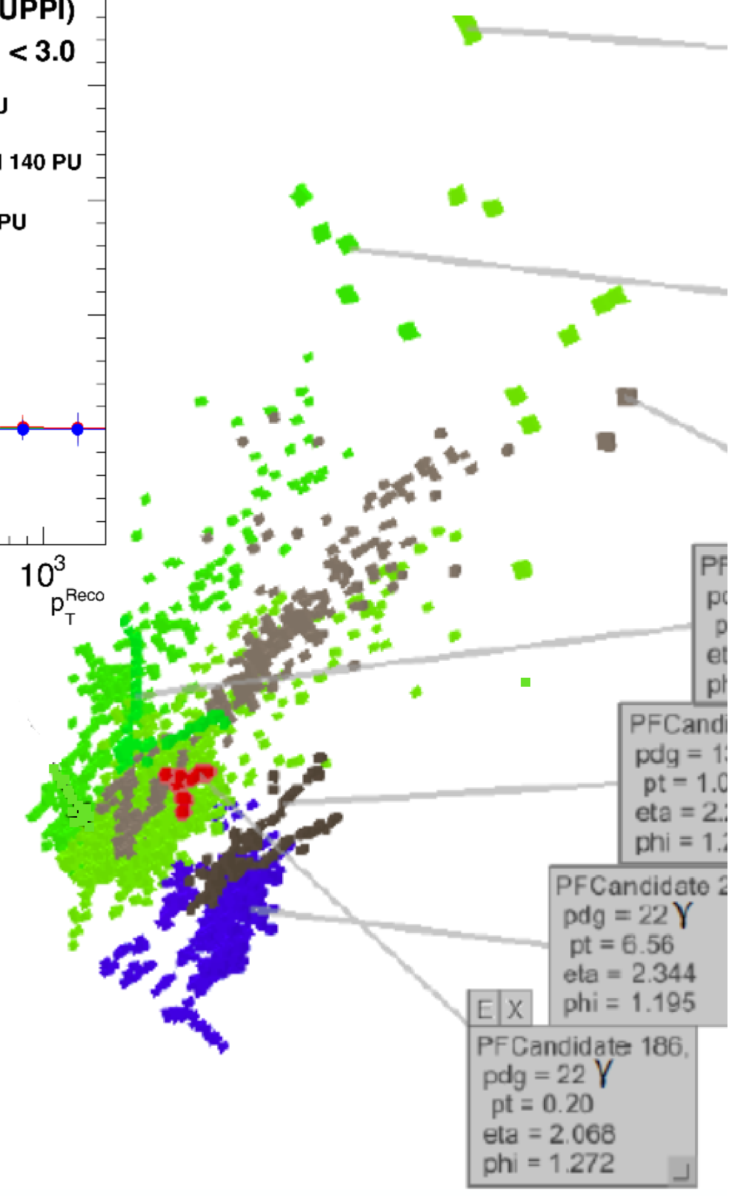
Jet Reconstruction



Jet Energy Resolution vs η

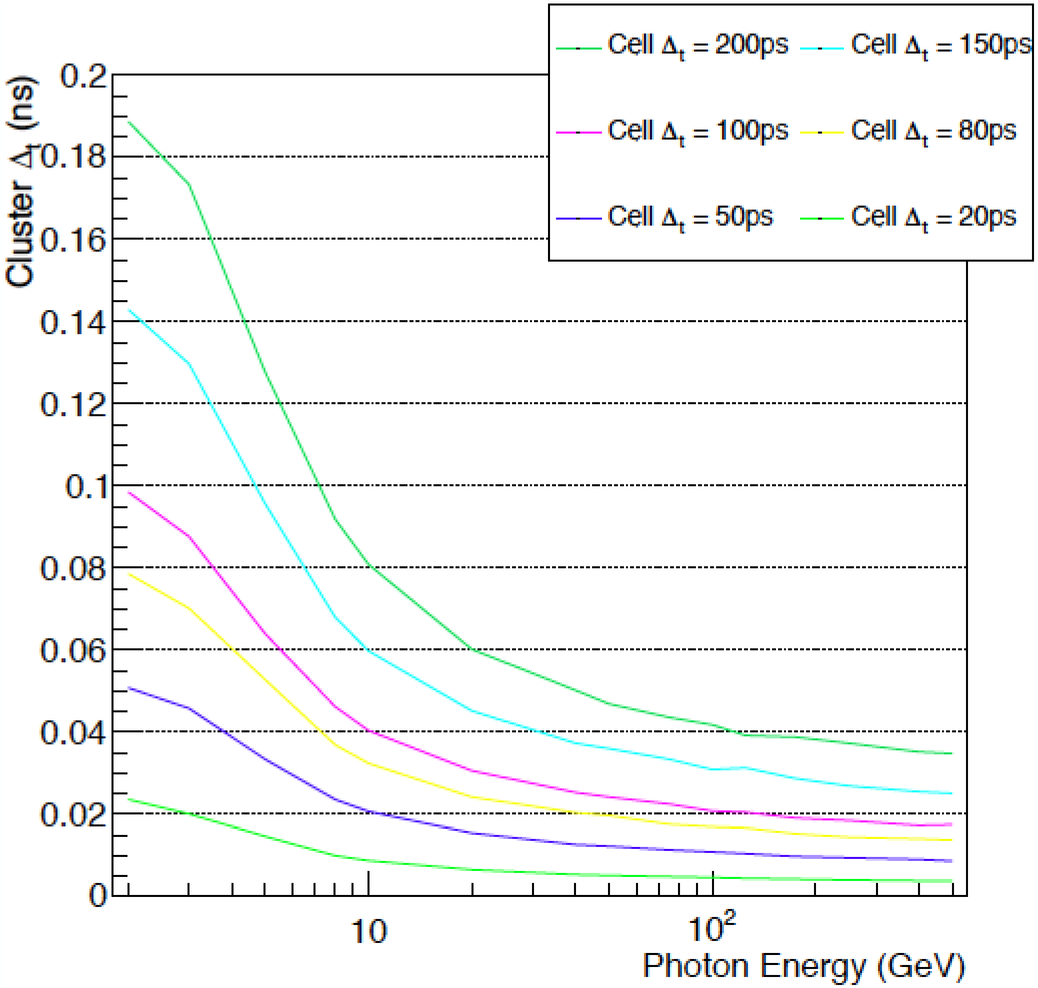


Jet Fake Rate



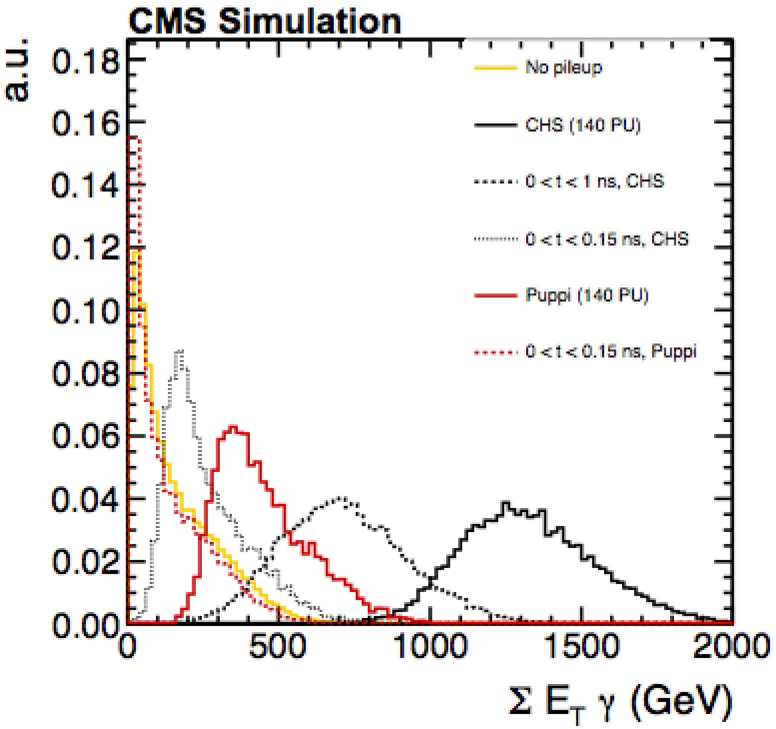
- Reconstruction of E_T ~30 GeV jets is important for vector-boson-scattering measurements
- Jet performance at 140 PU is already quite comparable to the original detector at 50 PU
  - Particle flow reconstruction is not fully optimized yet

Timing Potential



Δ_t is 68% effective RMS

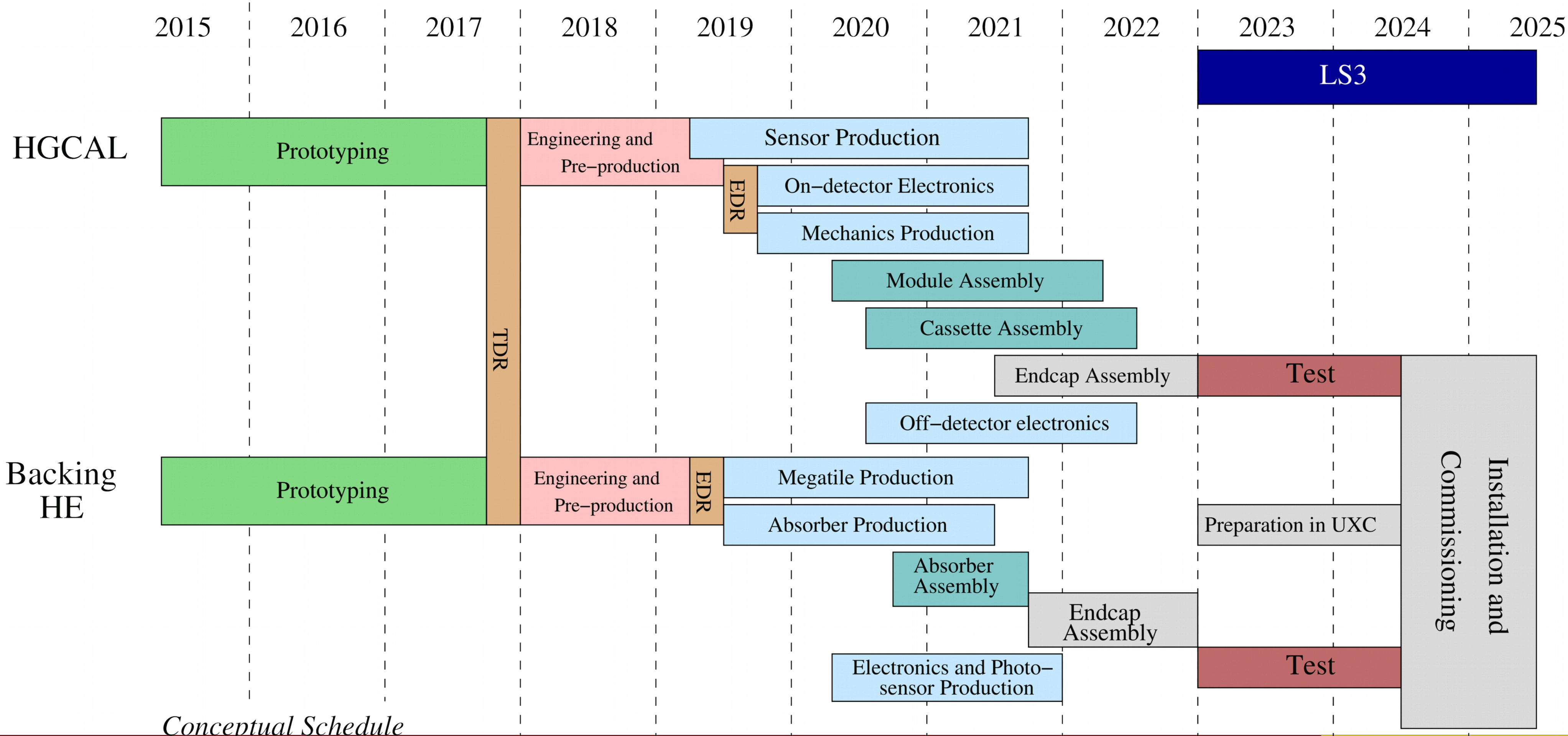
20ps * c = 6mm



- TDC capability of the proposed electronics brings the possibility of using timing information to improve pileup rejection and help drive appropriate reconstruction

Project Timeline

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

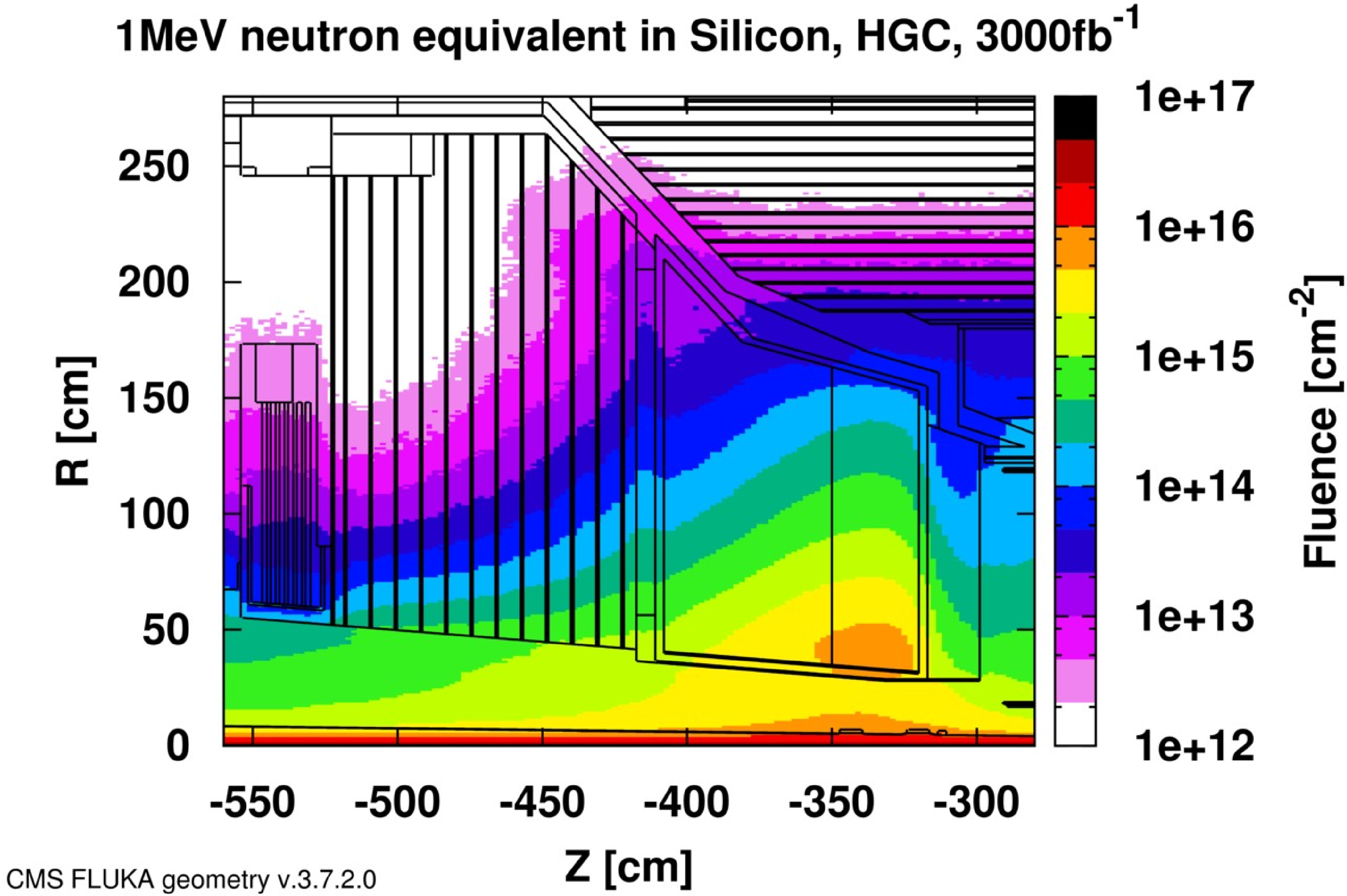


Summary

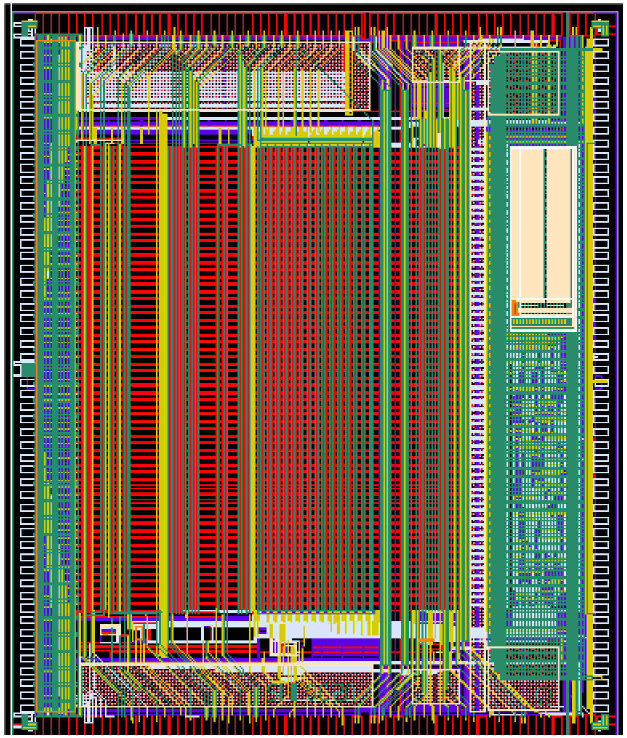
- CMS has decided to respond to the severe challenges of the HL-LHC by adopting technologies pioneered by the CALICE group to create a new endcap calorimeter
  - Silicon/tungsten electromagnetic calorimeter, silicon-based front hadronic calorimeter
  - Potentially an SiPM-on-tile backing calorimeter
- The CMS HL-LHC EC project has exciting physics potential and poses many interesting technical challenges
  - The time scale is aggressive and the project hopes for continued collaboration with CALICE groups

Additional Material

Neutron Fluence



SKIROC2-CMS



➢ **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