The CMS High Granularity Calorimeter for the High Luminosity LHC

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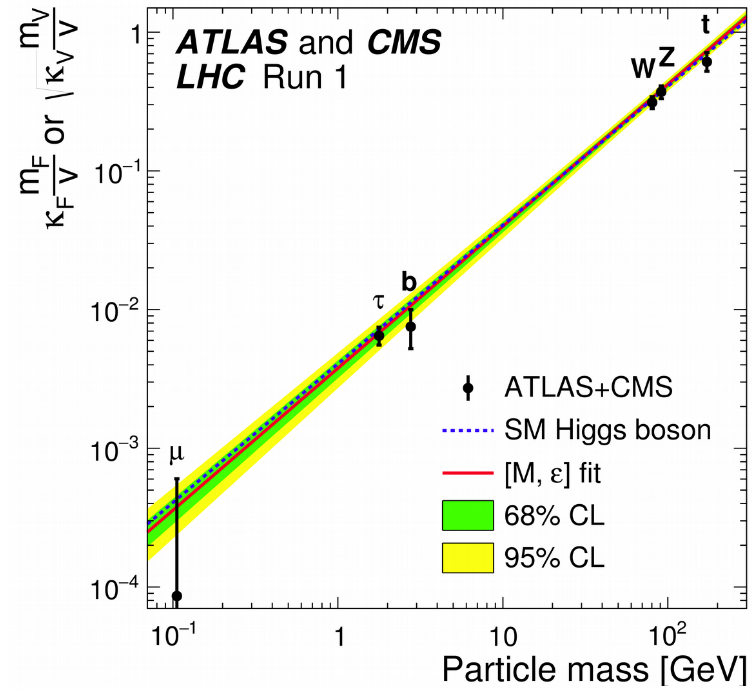
Projet emblématique HIGHTEC
P2IO Physique des 2 Infinis et des Origines

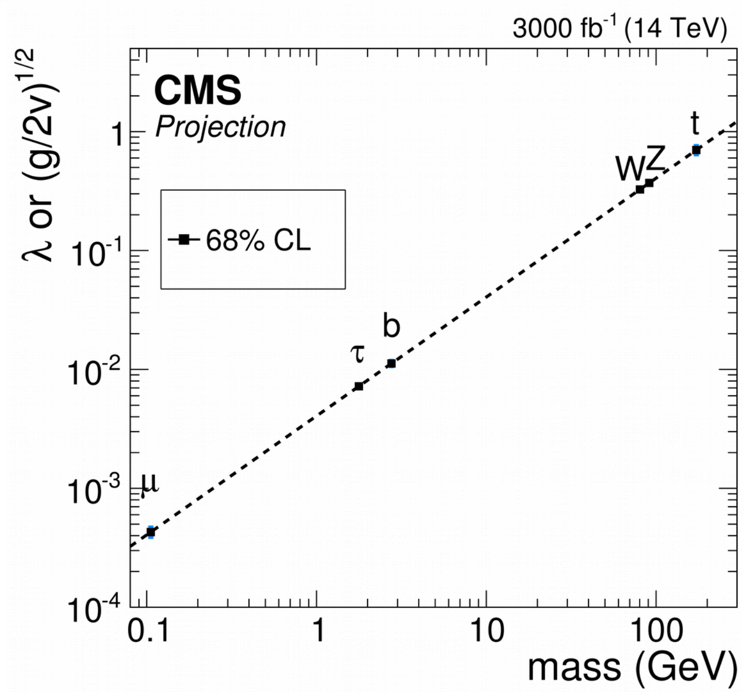
Why the HL-LHC?

The Higgs is the most tangible window to new physics so far
And the LHC is a Higgs factory

The detectors exist
The infrastructure exists
Fastest path to explore the electroweak landscape

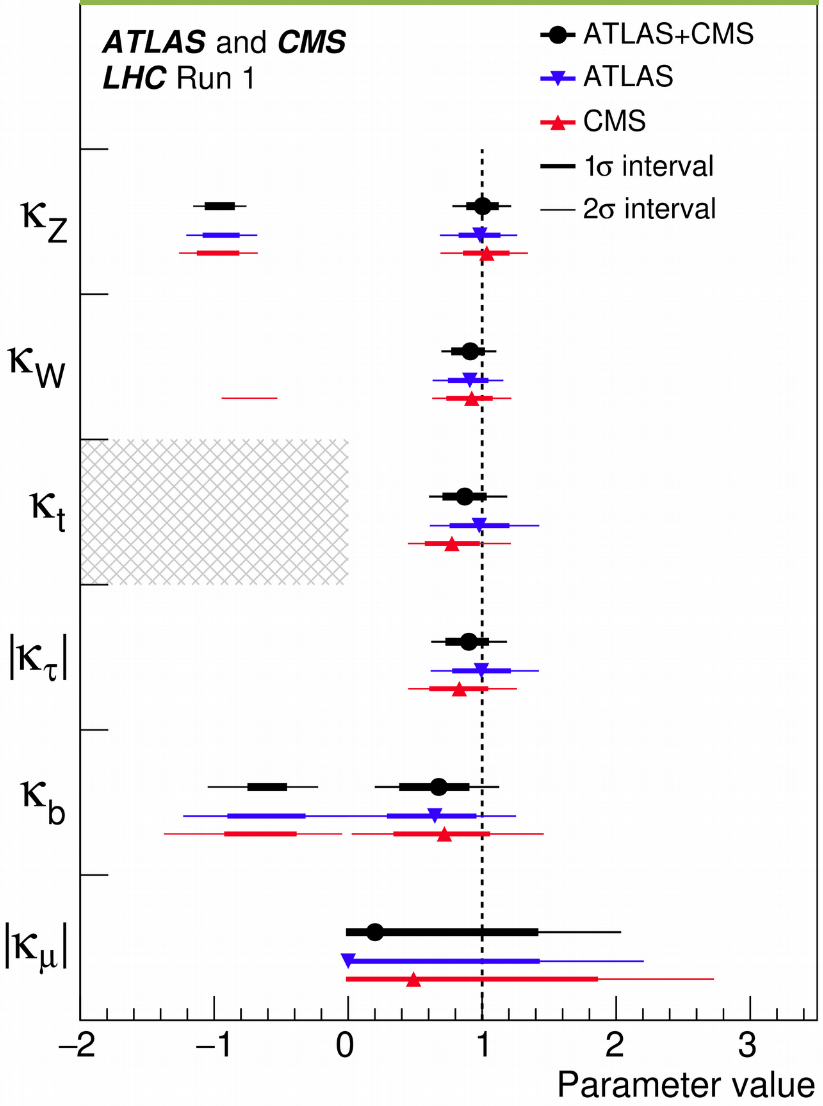
But we need luminosity
Higgs rare decays: H → μμ, H → Zγ, etc.
Vector boson scattering & unitarity tests
Double Higgs constraints & Higgs self-coupling





What else? Precision physics

Current picture

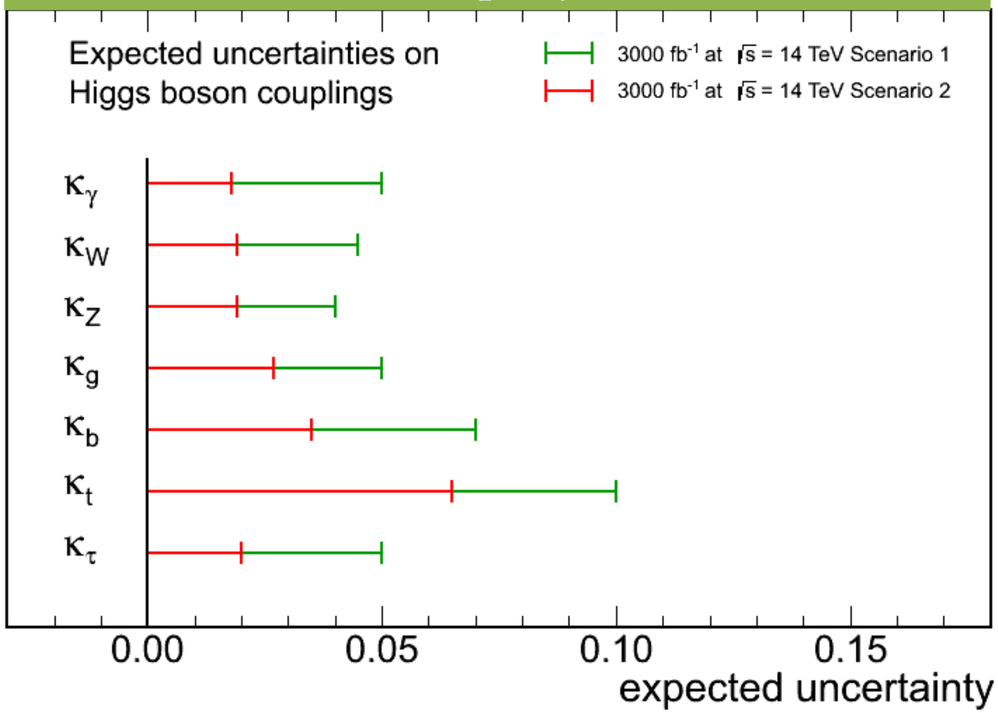


It will be a precision machine

Higgs coupling strengths

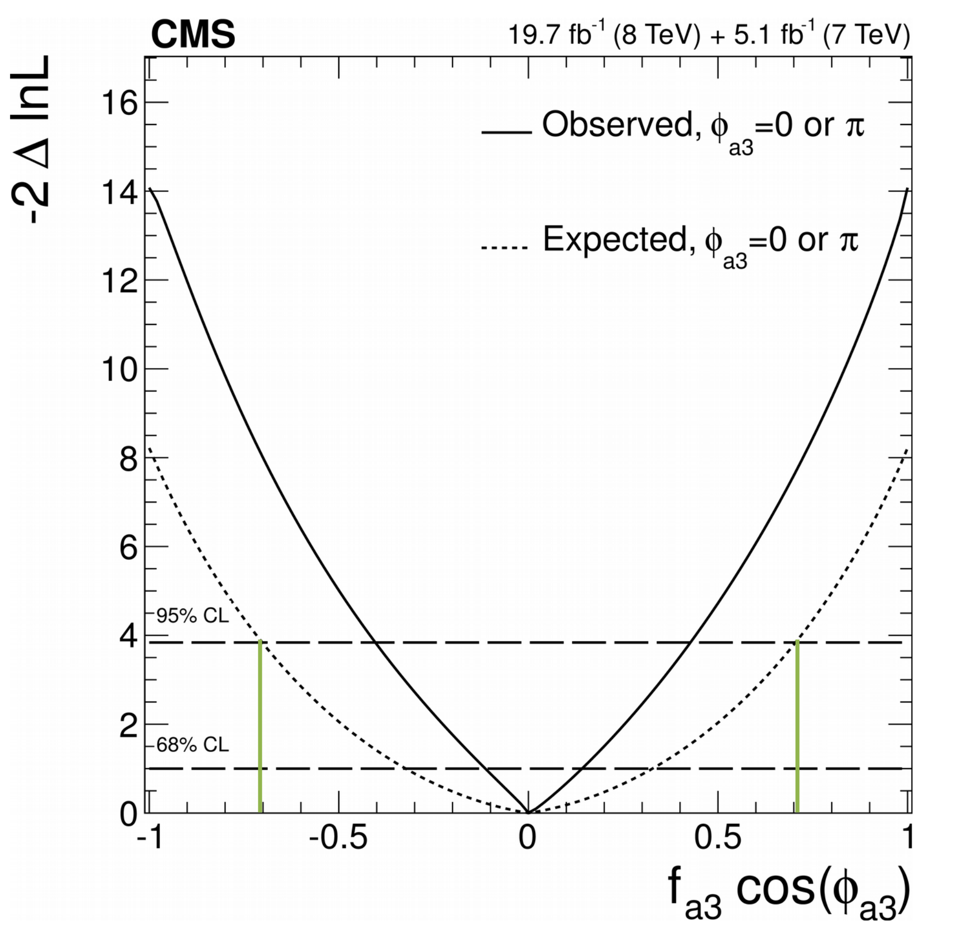
→ NP expected around few % to 10%

HL-LHC projection



What else? Precision physics

Current fa_3 measurement



It will be a precision machine

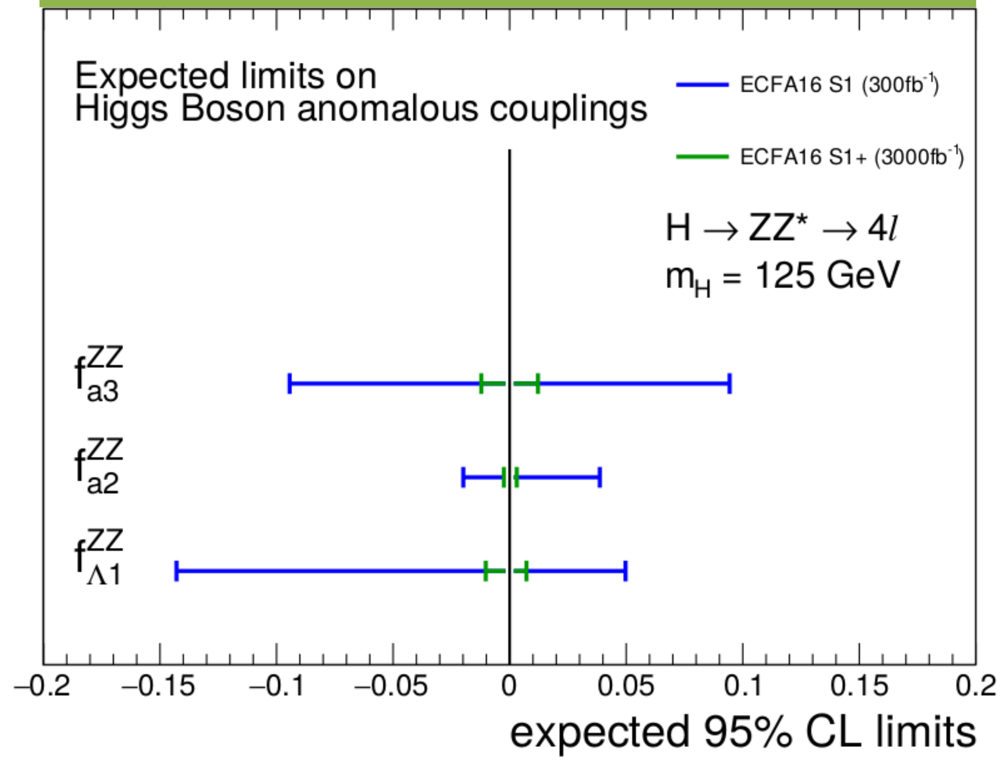
Higgs coupling strengths

→ NP expected around few % to 10%

Higgs coupling structure

→ Pseudoscalar, higher-order contrib.

HL-LHC projection



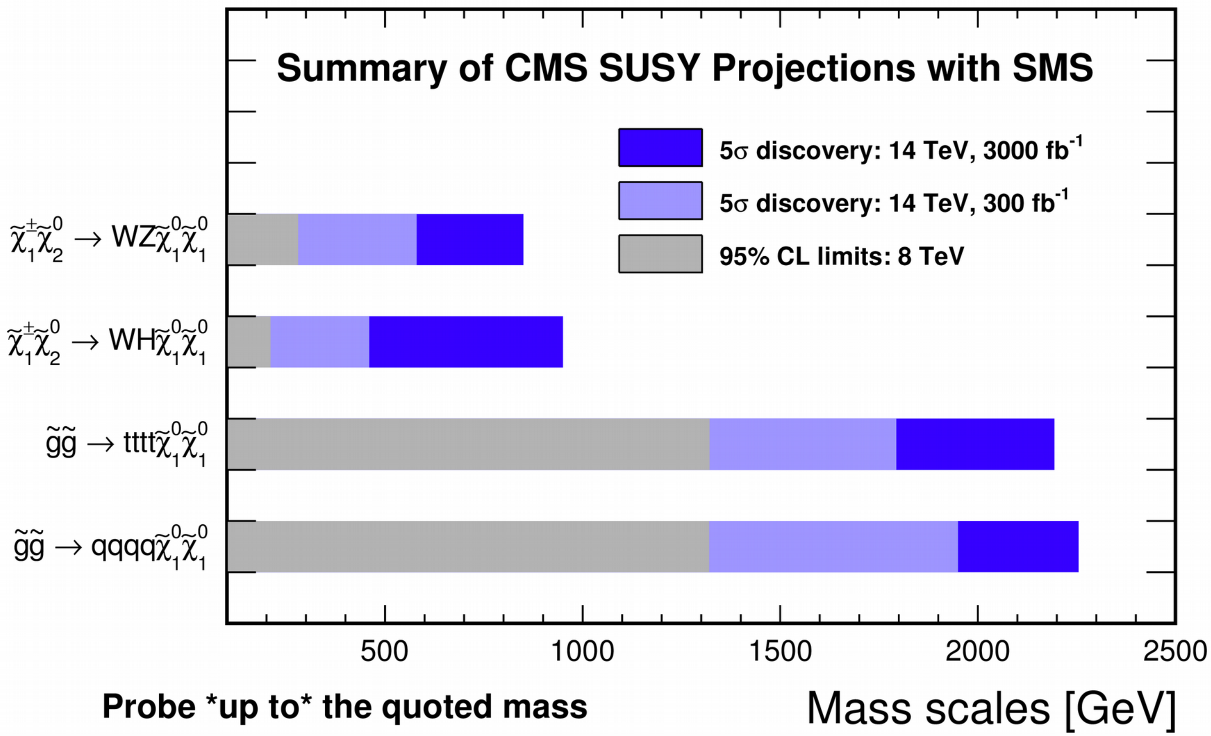
What else? High mass searches

It can extend high mass particle searches

Reaches lower cross-sections, higher masses

SUSY, dark matter, heavy gauge bosons

SUSY HL-LHC projection summary



Probe *up to* the quoted mass

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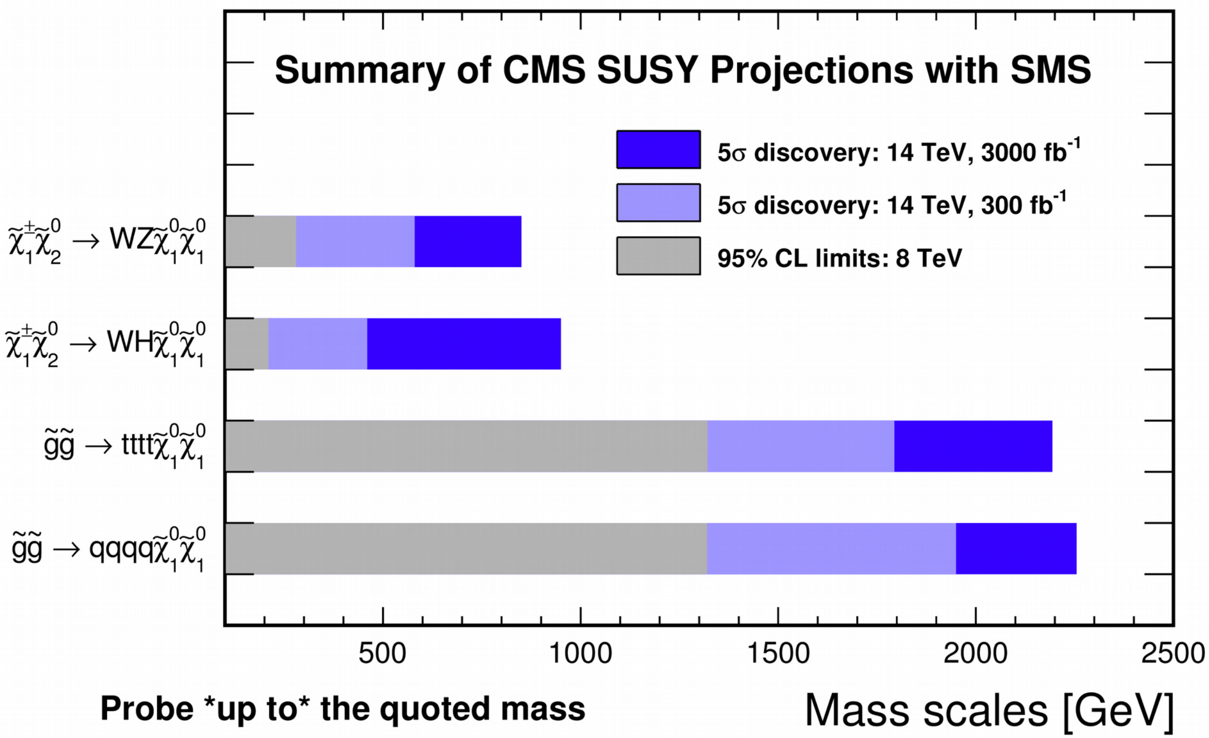


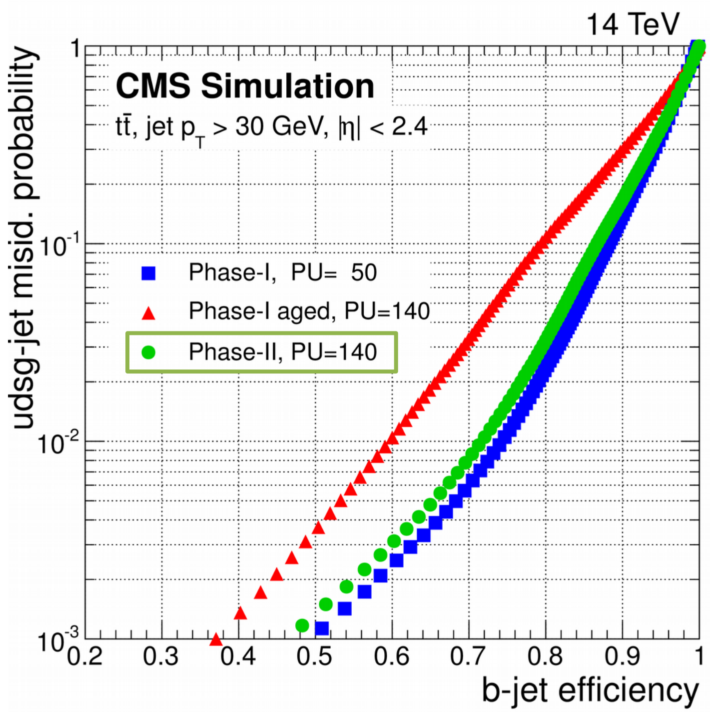
Probe *up to* the quoted mass

And of course new particles discovered during Phase 1 can be studied

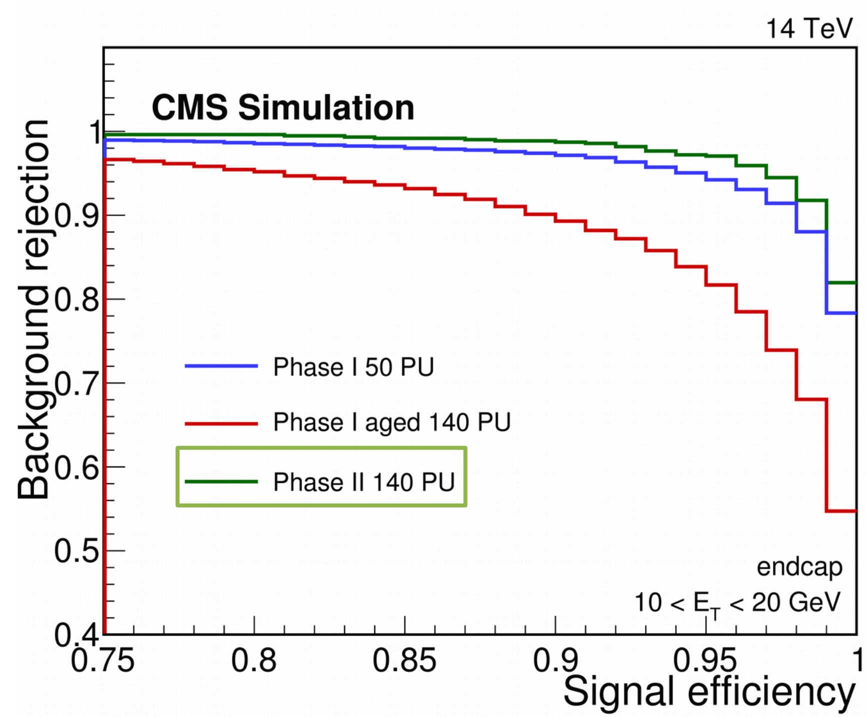
Good physics requires good detectors

Precise reconstruction of objects: electrons, muons, taus, b-jets, etc.
High efficiency and background rejection
Good MET resolution
Efficient forward-jet tagging for VBF, VBS

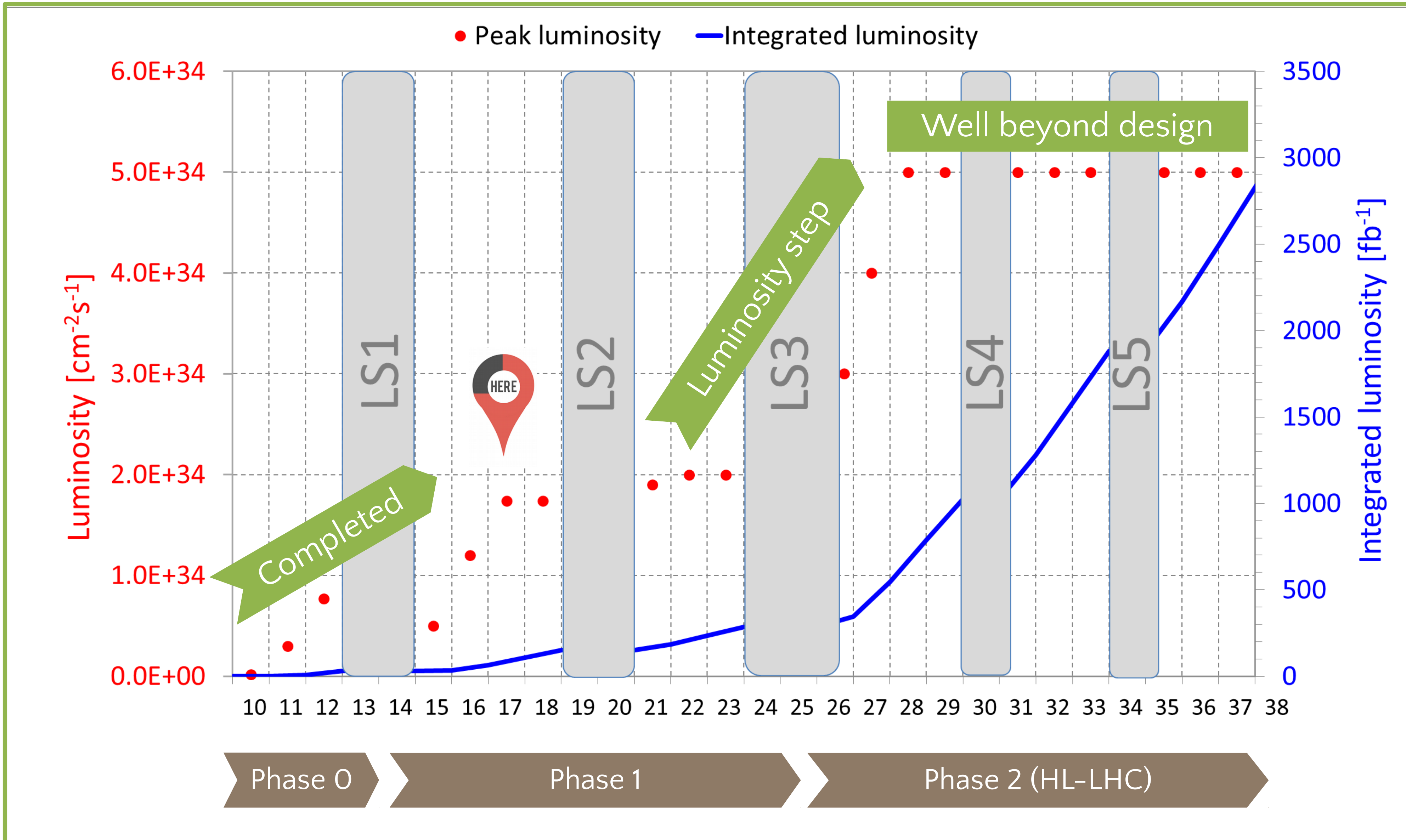
b-jets efficiency



electrons efficiency



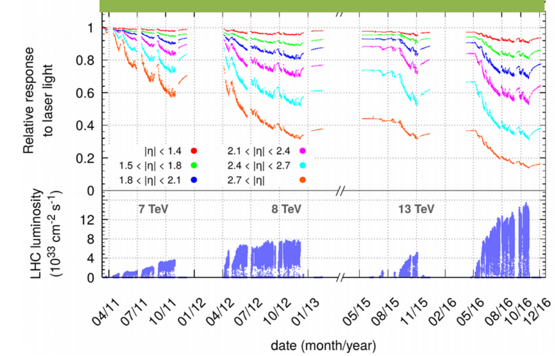
LHC and HL-LHC timeline



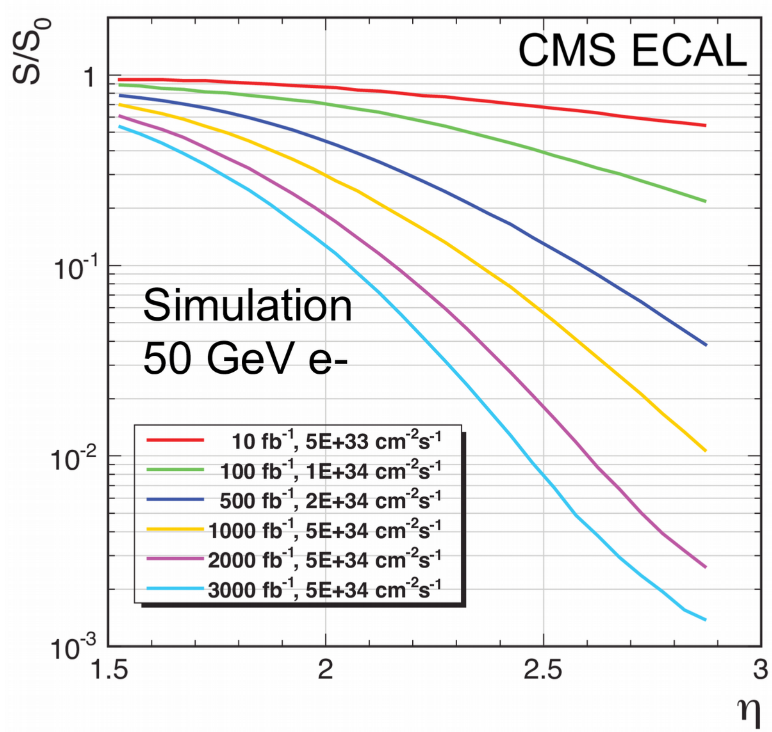
Why upgrading the calorimeters?

With the current technology
signal yield deteriorated by radiation-induced effects
Mitigated by laser monitoring, but only to a certain point
→ Impact on the energy resolution
→ Constant term: 10% at the end of HL-LHC

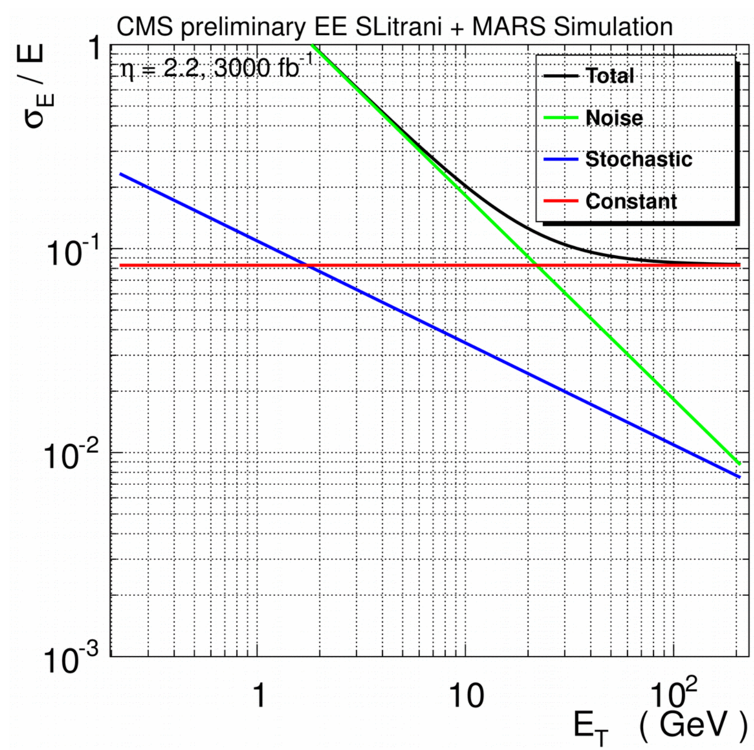
Laser monitoring



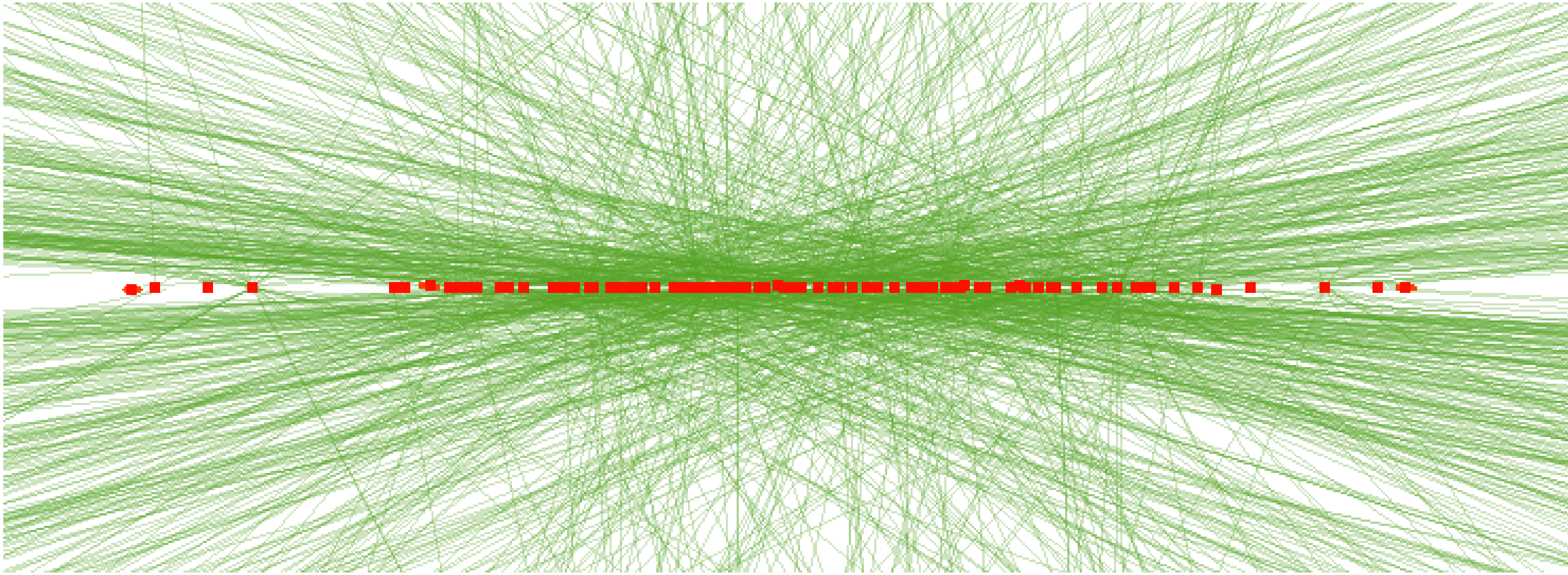
Relative response of the existing ECAL endcaps



Expected ECAL energy resolution after 3000 fb^{-1}



What is needed? High granularity



Top pair event + 140 additional low energy interactions
"Classical" spatial view of the vertices

140 – 200 simultaneous interactions
High granularity calorimeters and longitudinal segmentation to separate their contributions

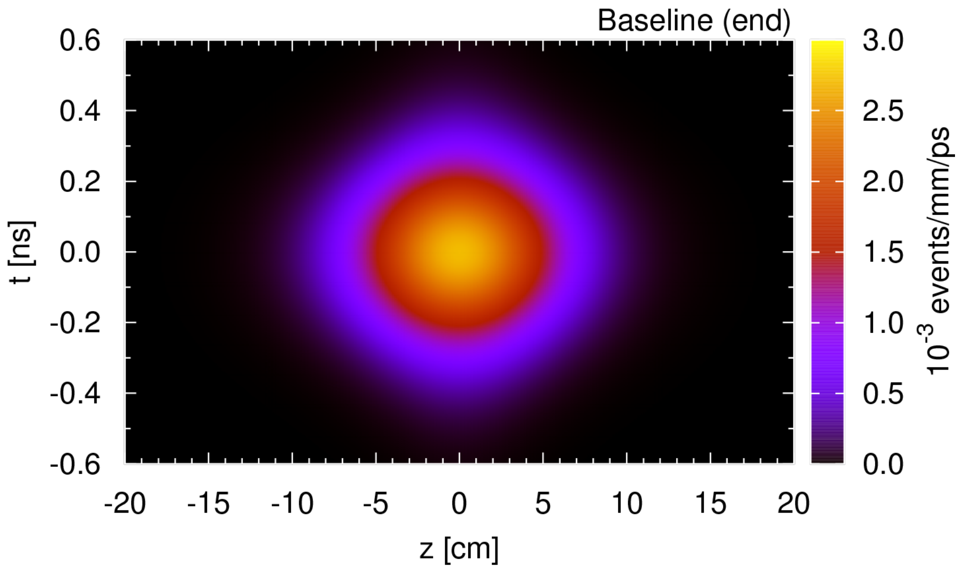
Vertices concentrated within a few centimeters
High granularity tracker to keep low occupancy

What is needed? Precision timing

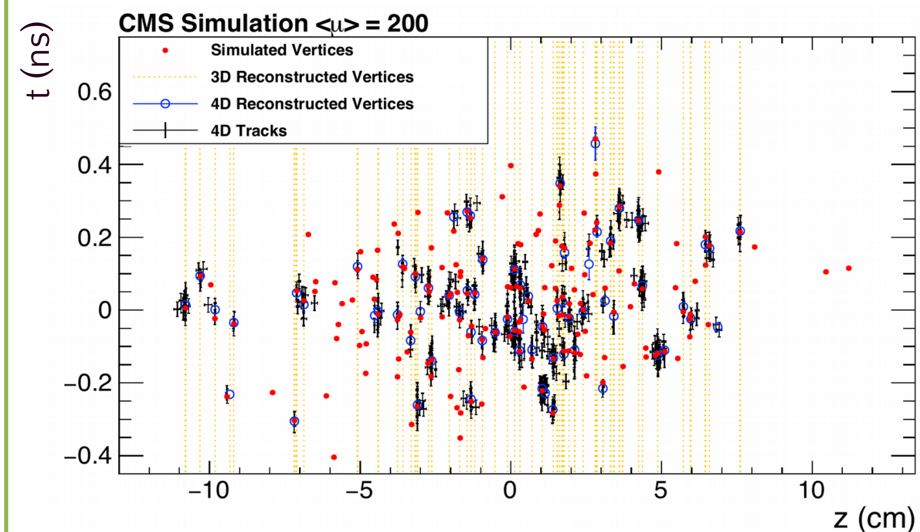
Interactions are spread over space and time
100 – 200 ps

Disentangle overlapping vertices with precise timing
Key resolution: 10-30 ps

Beam spot space-time profile

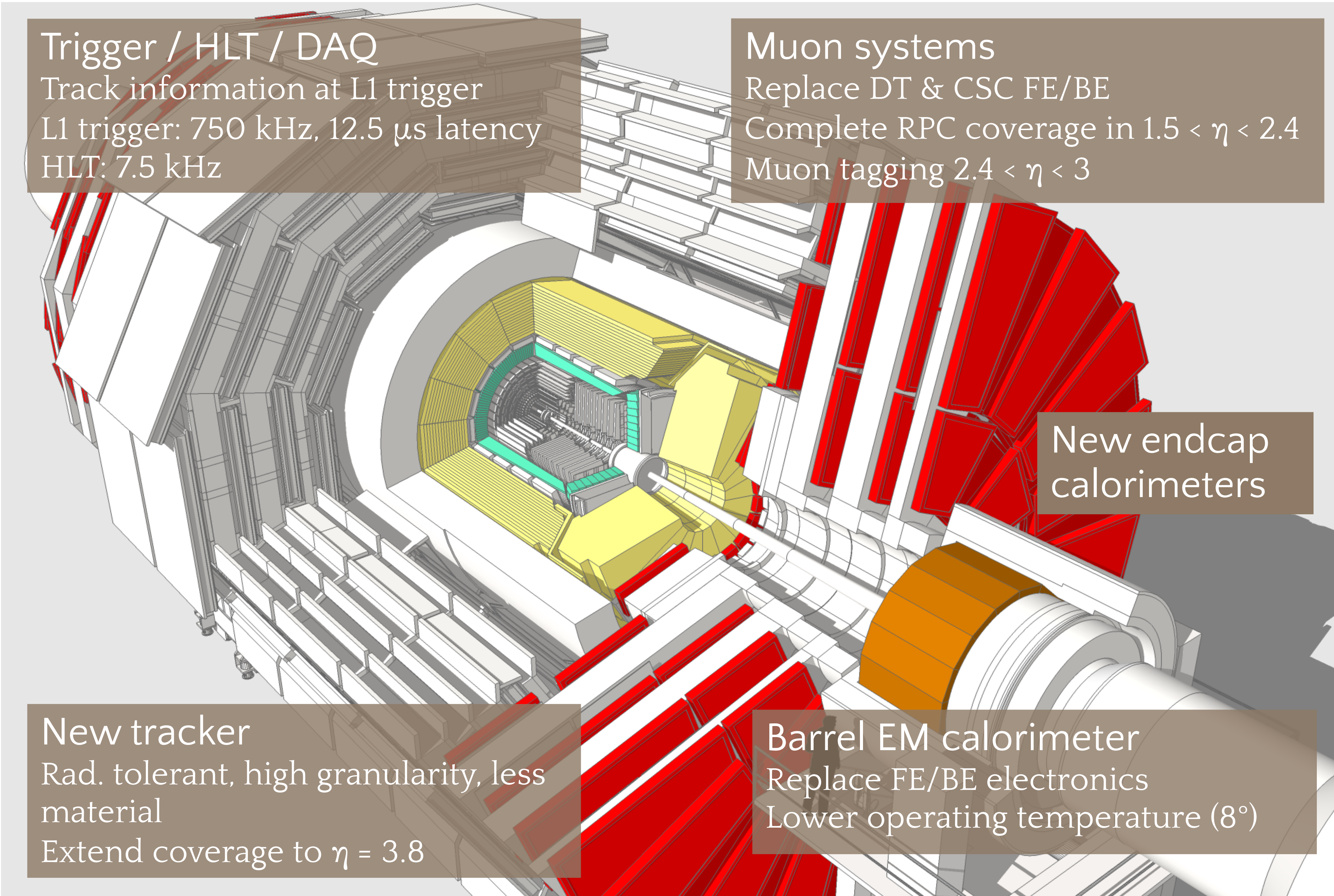


Space-time view of the vertices



Collisions every 25 ns → "out-of-time pile-up"
Fast detector response and fast shaping

CMS Upgrade overview



Trigger / HLT / DAQ
Track information at L1 trigger
L1 trigger: 750 kHz, 12.5 μs latency
HLT: 7.5 kHz

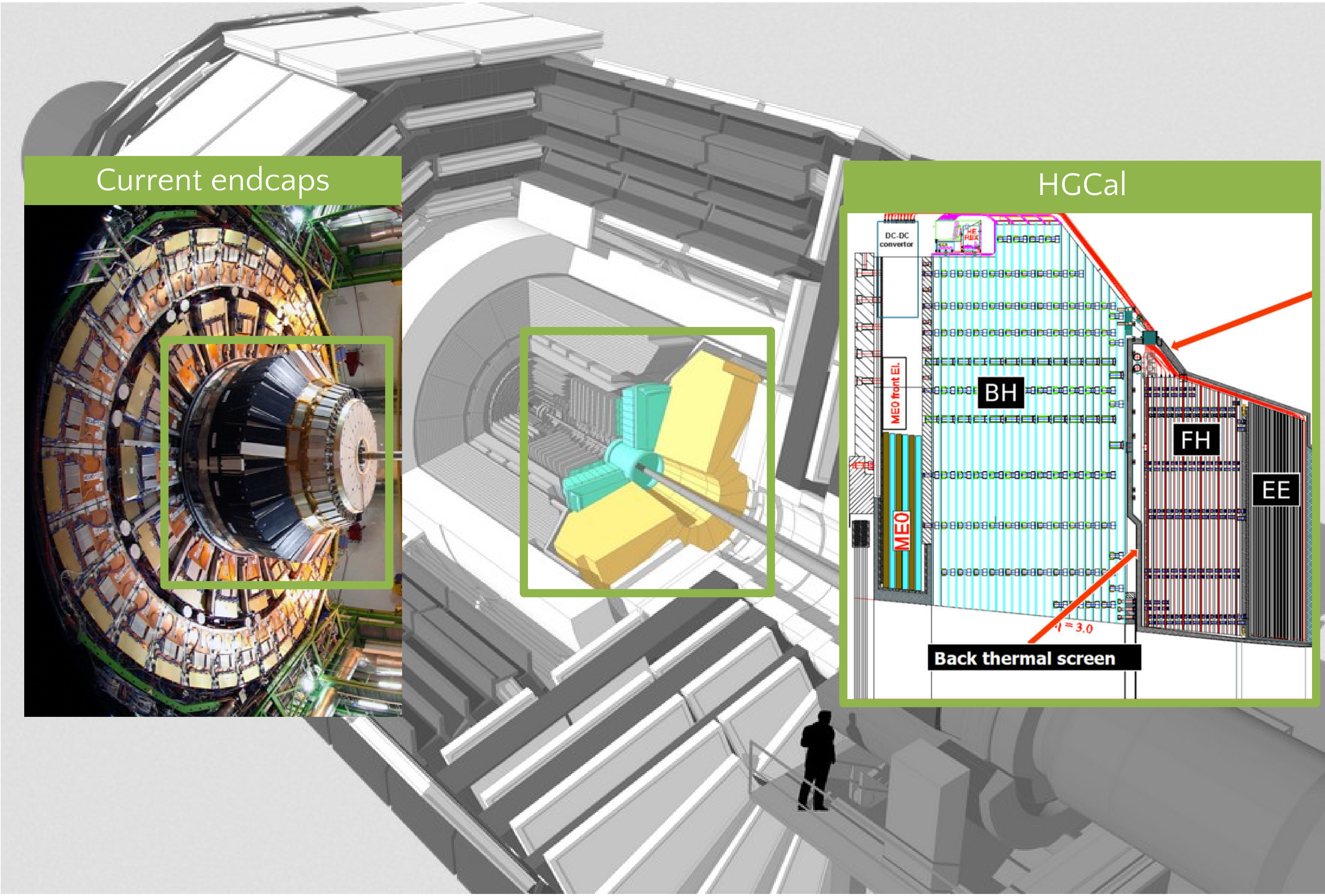
Muon systems
Replace DT & CSC FE/BE
Complete RPC coverage in $1.5 < \eta < 2.4$
Muon tagging $2.4 < \eta < 3$

New endcap calorimeters

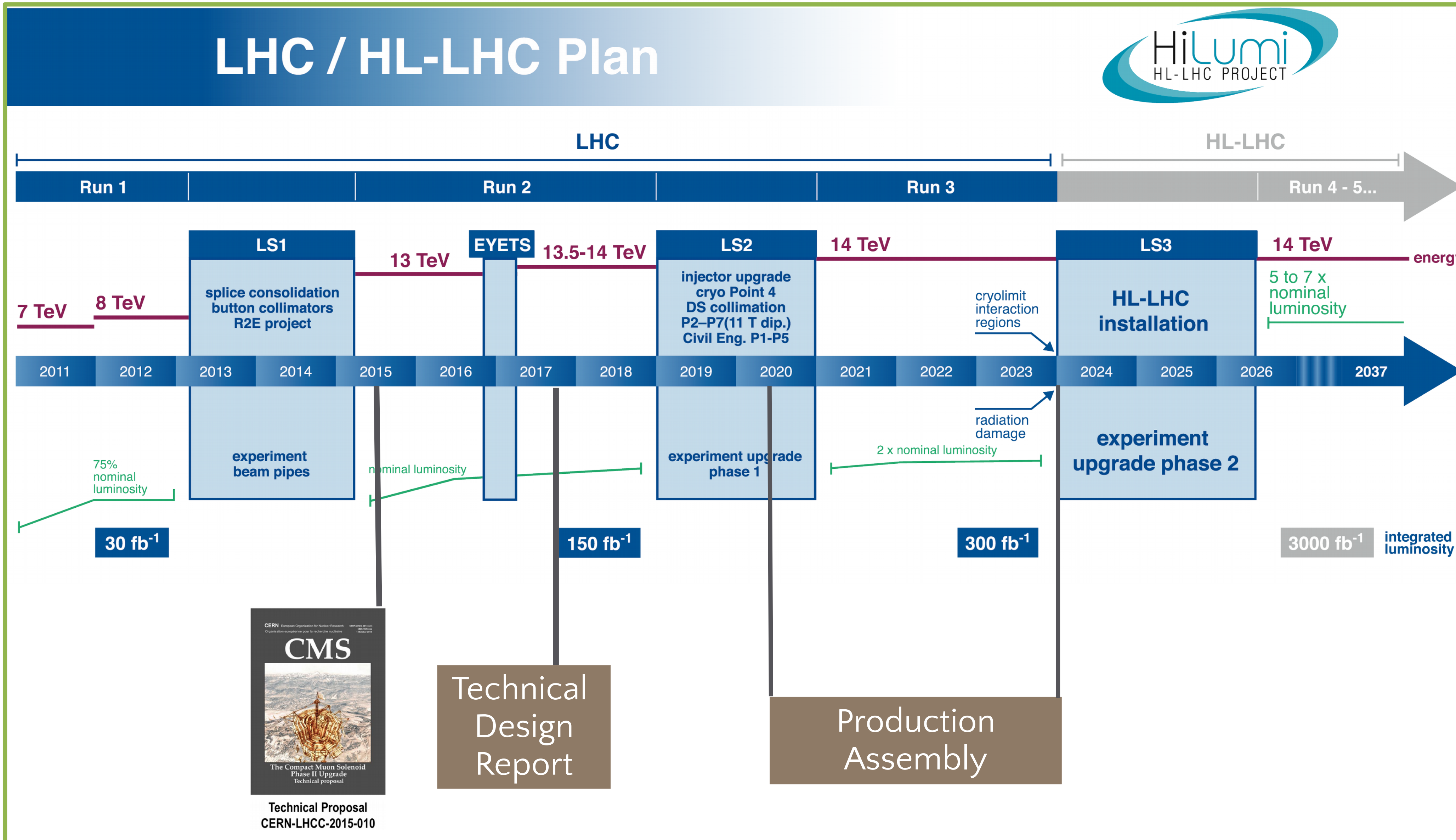
New tracker
Rad. tolerant, high granularity, less material
Extend coverage to $\eta = 3.8$

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

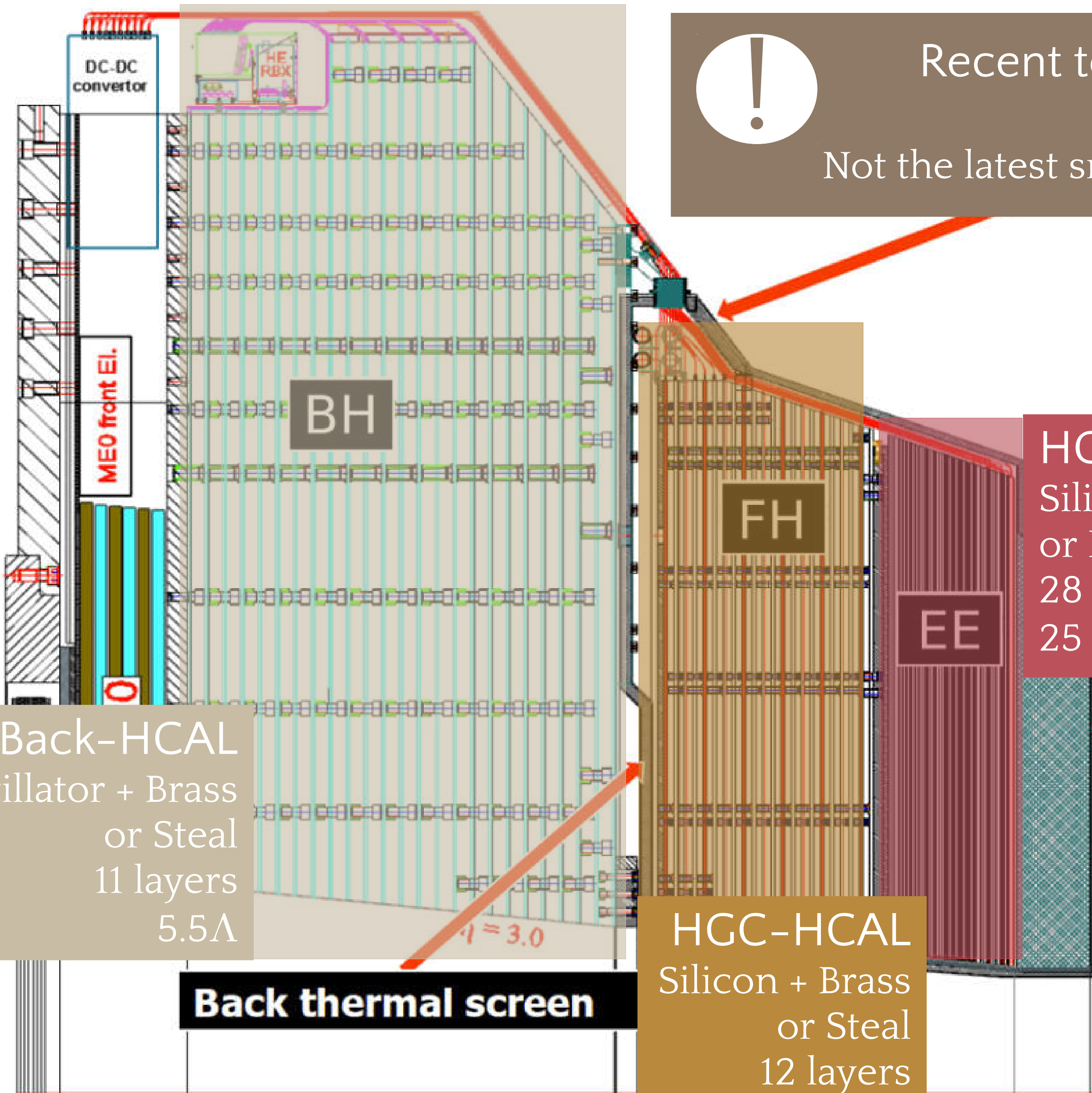
CMS endcap calorimeters



HGCal timeline



HGCal design overview



Recent technical choices are not all public
Not the latest snapshot presented here

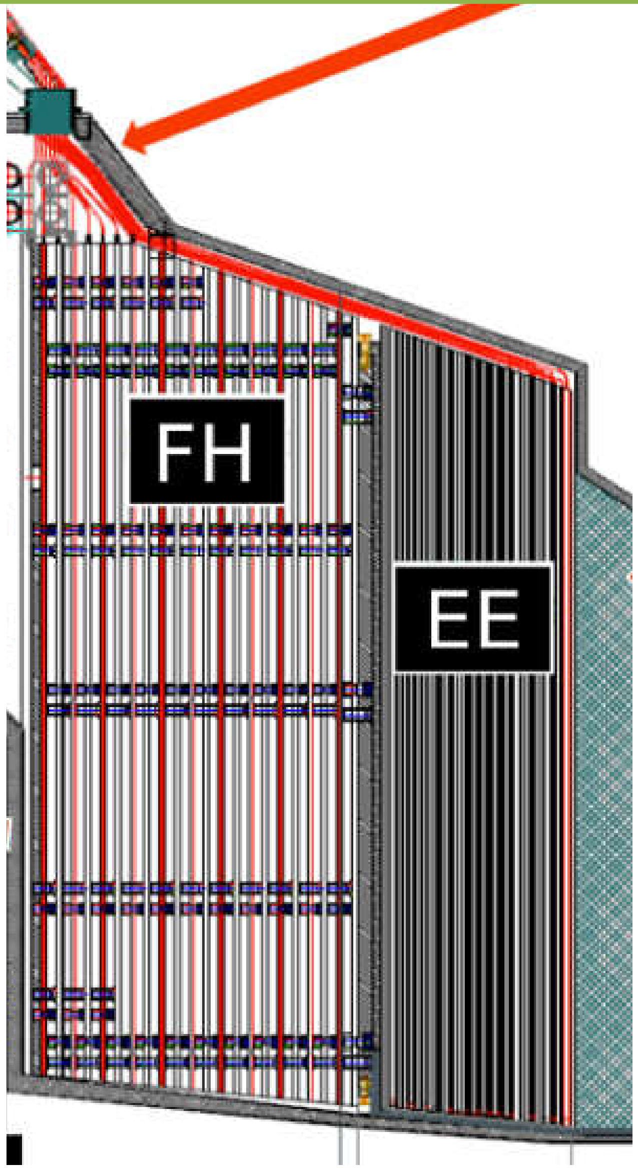
HGC-ECAL
Silicon + Copper/Tungsten or Lead/Steal
28 layers
25 X_0, 1.3Λ

Back-HCAL
Scintillator + Brass or Steal
11 layers
5.5Λ

HGC-HCAL
Silicon + Brass or Steal
12 layers
3.5Λ

HGCal design overview (Silicon part)

Focusing on the Silicon parts
And mainly on the ECAL



Detector key numbers

	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

6 millions channels
3× area silicon in tracker
0.5 and 1 cm^2 cell sizes

Operation at –30°C: CO_2 cooling
Mitigate leakage current
Back HCAL also at -30°C?

Modules

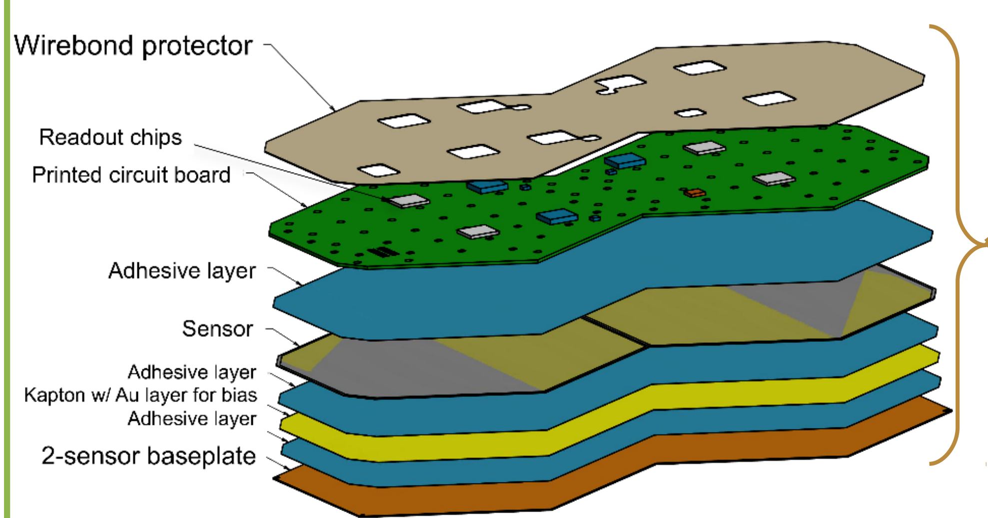
Hexagonal silicon sensors built into modules

6" wafers: 2 sensors per module
Or 8" wafers: 1 sensor per module
21660 modules

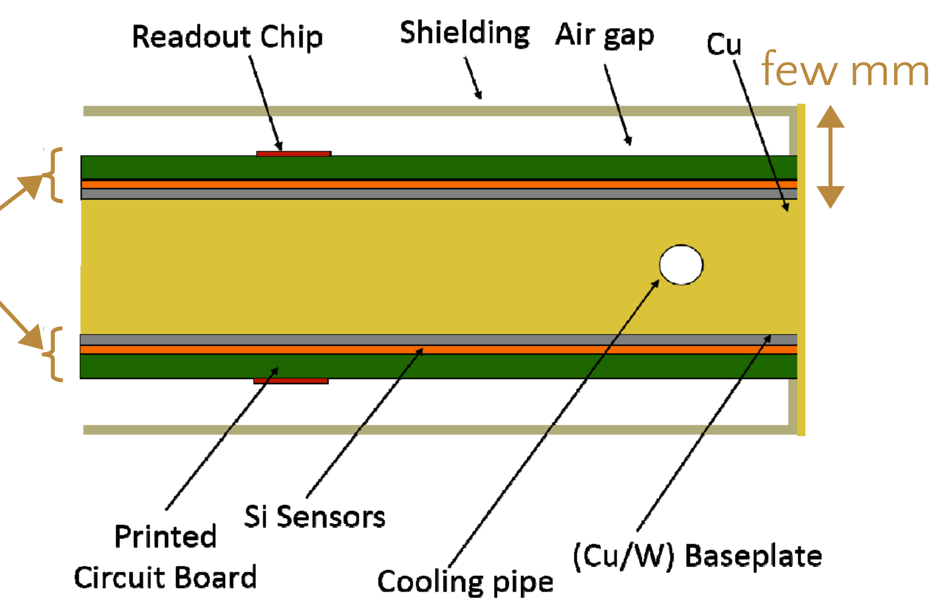
Modules mounted on copper cooling plates

Embedded pipes
30° sectors = "cassettes"

Module stack



Double layer cross section



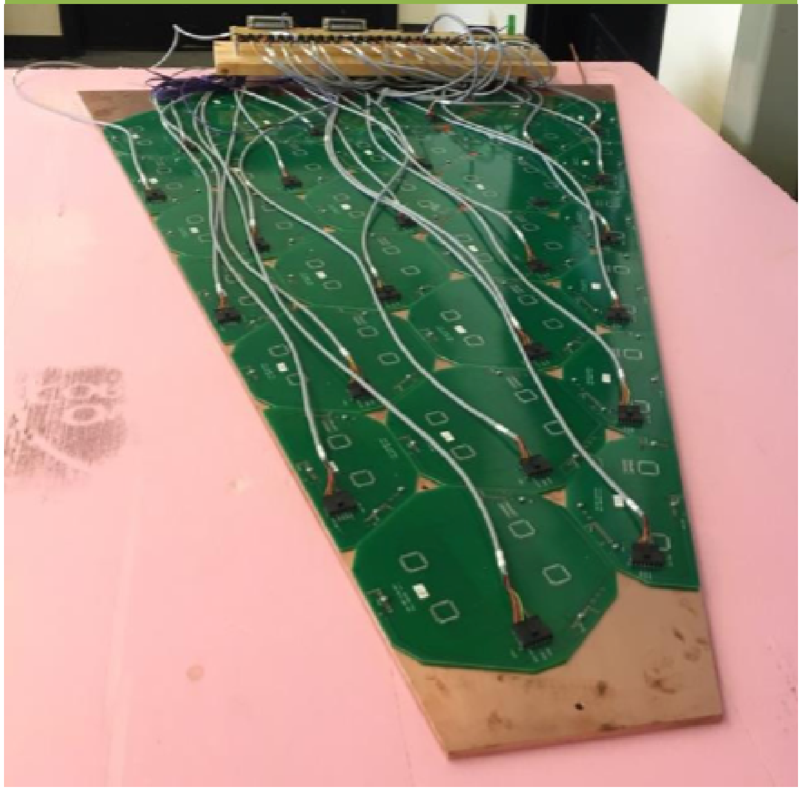
Cassettes cooling

Goal: ΔT = 1–2° around –30°C

Mockup with uniform heat load

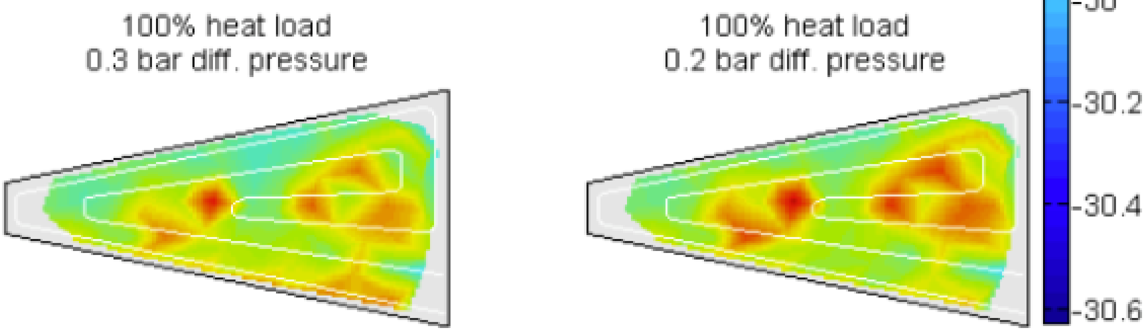
Results: ΔT = 1.1 – 1.2°

Mockup with heaters and CO_2 cooling



Measured temperatures

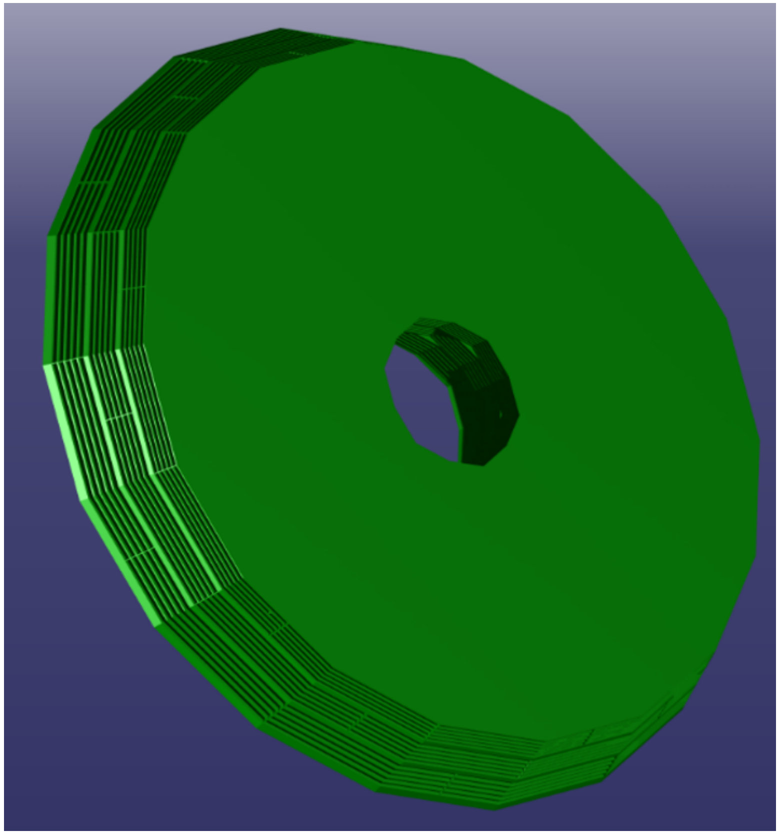
Results Summary (post-calibration)	Full heat load, 0.3 bar	Full heat load, 0.2 bar
Min. temp. (°C)	-30.3	-30.2
Max. temp. (°C)	-29.2	-29.0
Temp. spread (°C)	1.1	1.2
Mean (°C)	-29.8	-29.7
Standard dev. (°C)	0.225	0.226



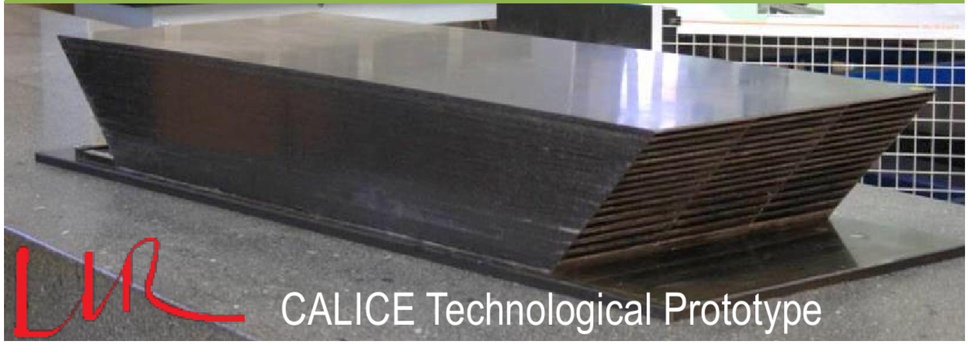
ECAL mechanical structure (Technical Proposal)

ECAL part inspired by the CALICE design
Carbon fiber + Tungsten structure
Insertable cassettes

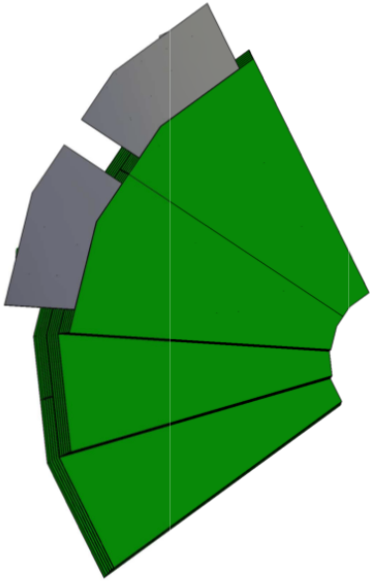
HGCal mechanical structure



CALICE prototype



30° cassettes

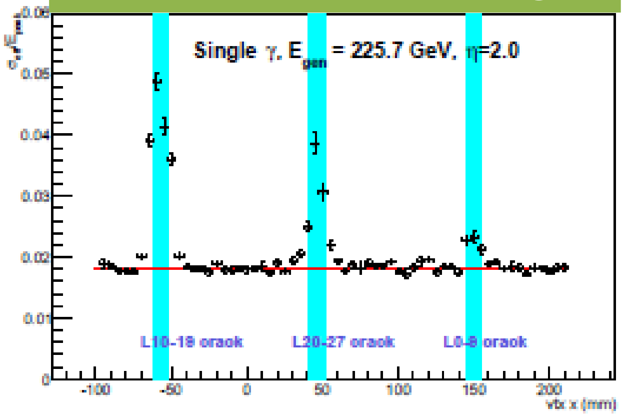


Petals instead of rectangular structure
3 staggered groups of layers
Limit the impact of projective cracks

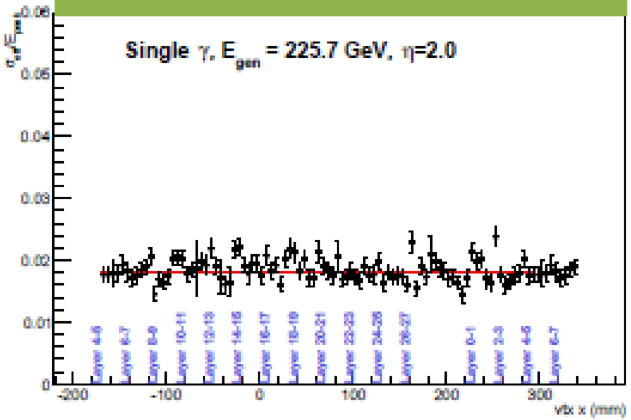
Evolution from the TP design

Limit crack impact further
Rotation of each individual layers

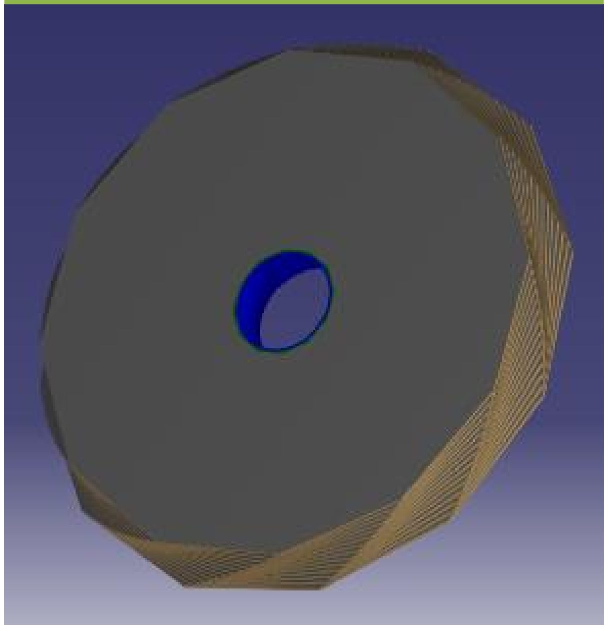
Resolution (initial design)



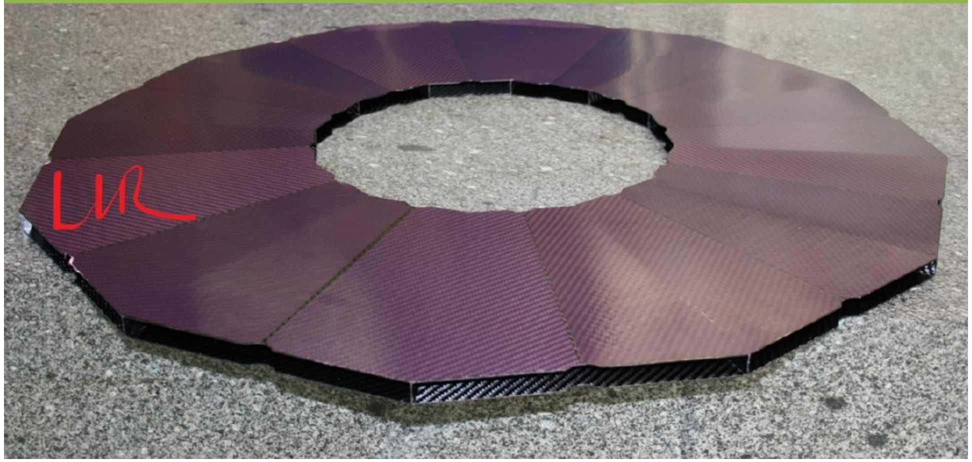
Resolution (layer rotation)



Layer rotation



Single layer structure mockup

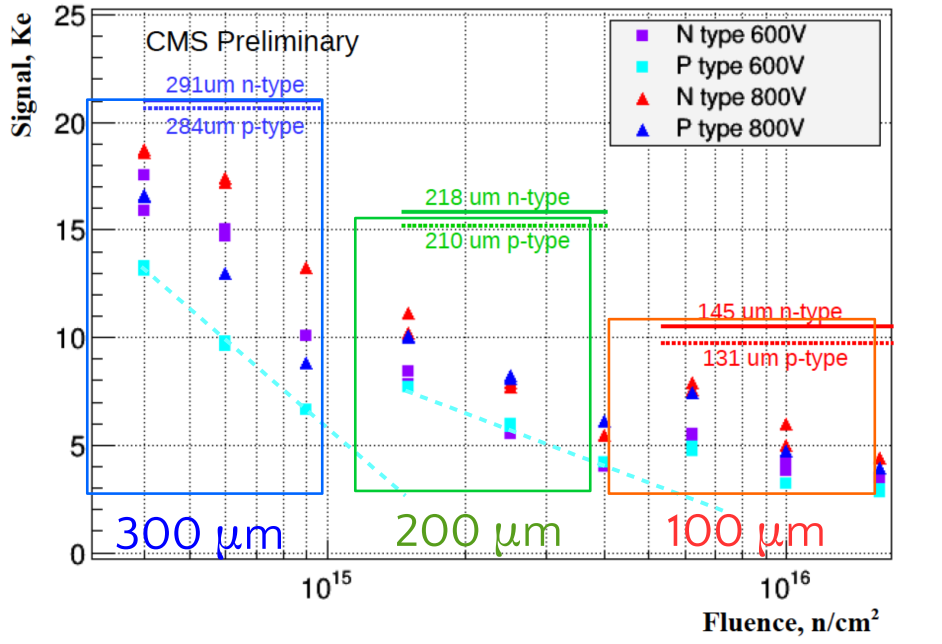


Cassettes can also be part of the structure
Stack of cassettes and absorber plates with spacers
Compressed by front and back planes

Radiation tolerance

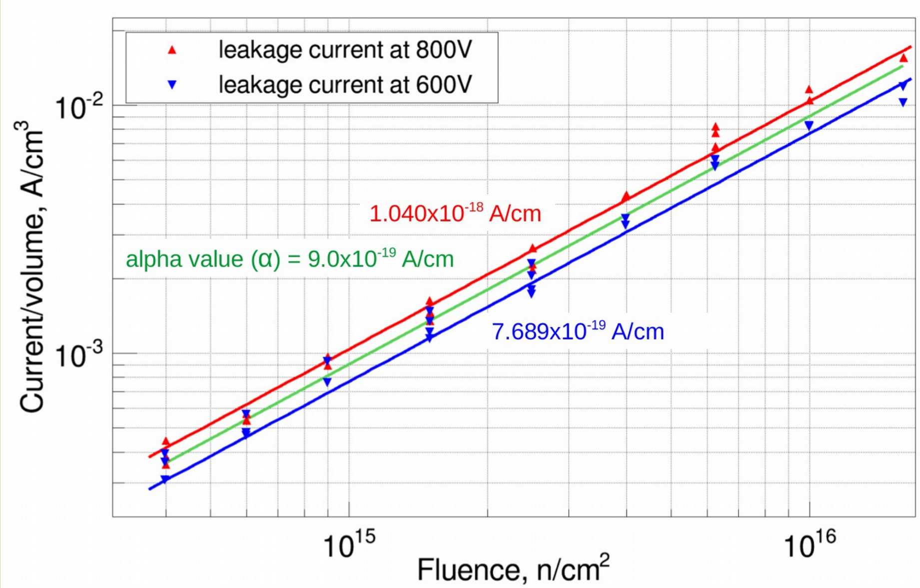
High fluence
Better charge collection of thiner sensors

Collected signal

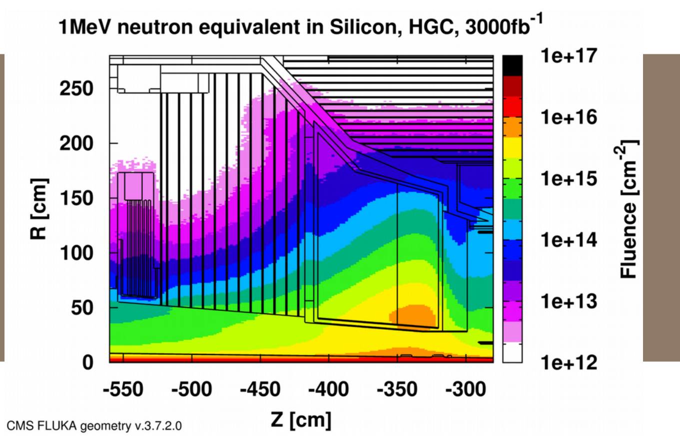


Leakage current increases linearly with fluence and volume
Heating ∝ I_{leak} and Noise ∝ $\sqrt{I_{leak}}$

Leakage current per volume unit vs fluence



Reduce cell thickness for high fluence regions



Silicon sensors

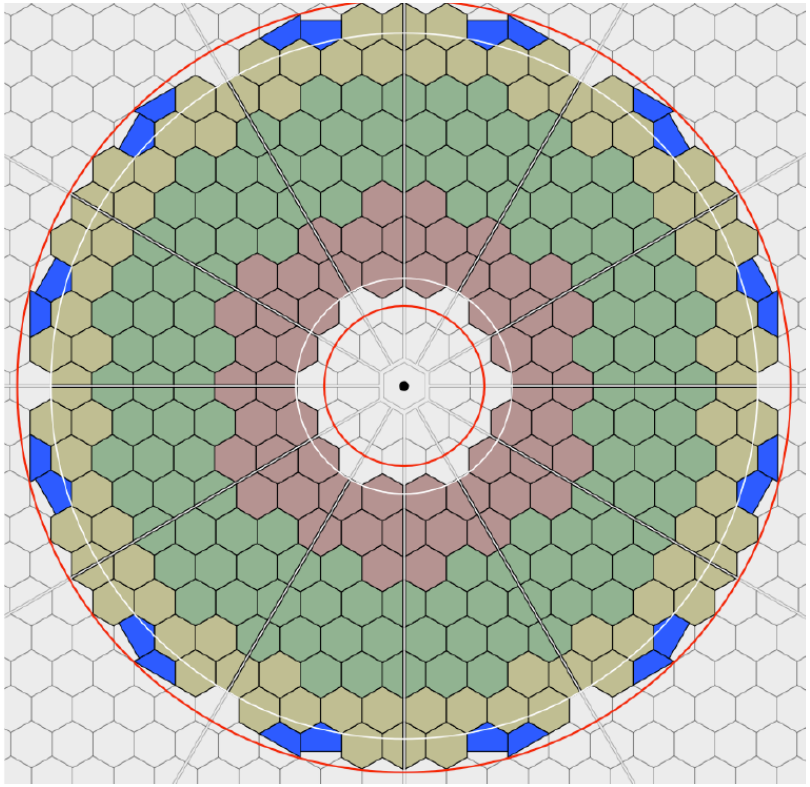
Three sensor thicknesses

Low pseudorapidity → thicker sensors
High pseudorapidity → thiner sensors

Sensor parameters

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

Thickness partition



Cell capacitances increases for thiner sensors

Meaning higher noise
Smaller cell sizes for 100 μm sensors → reduces also the cell occupancy

Front-end readout chip

Critical part of the system
Analogue + digital (large buffers, trigger data reduction), high-speed readout

Low noise
Large dynamic range
0.4 fC – 10 pC

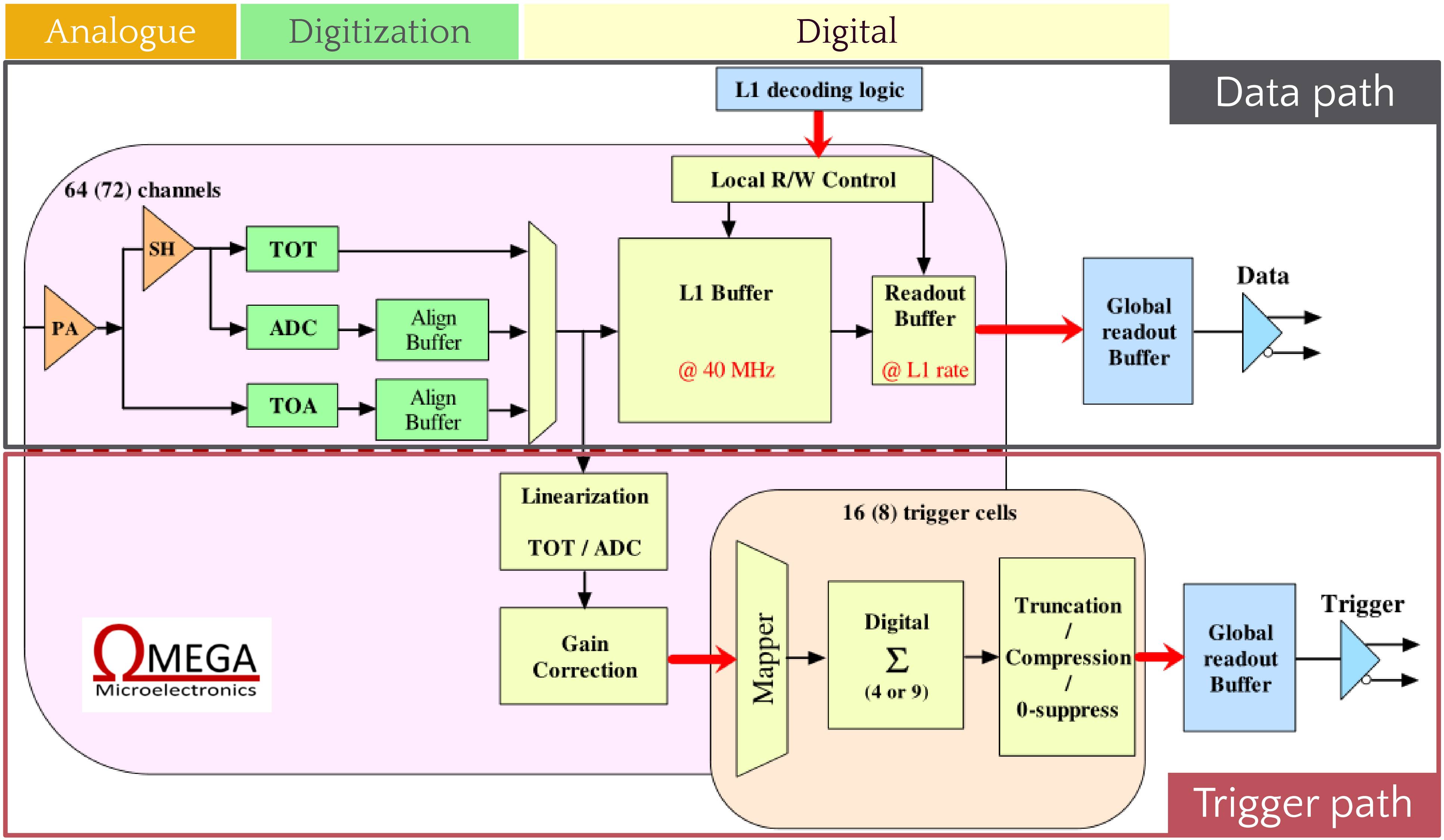
Low power budget
< 10 mW / channel

Timing information
50 ps accuracy

High radiation resistance

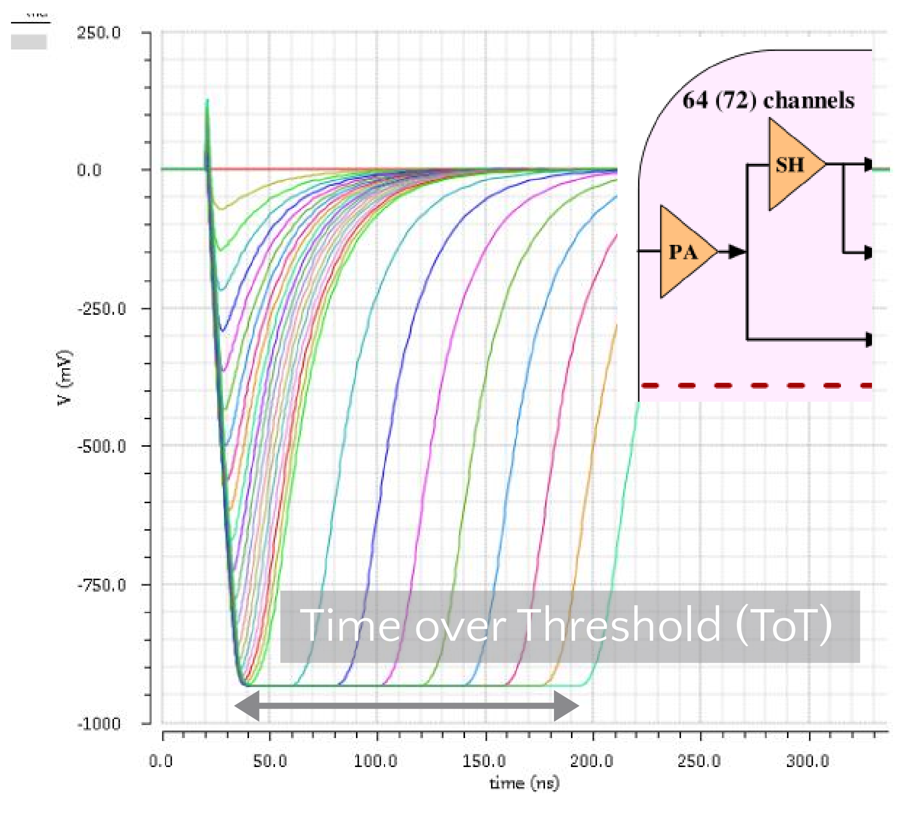
Baseline
130 nm technology – known radiation hardness
Charge + time-over-threshold (ToT)
Variants with bi-gain also studied

Front-end readout components

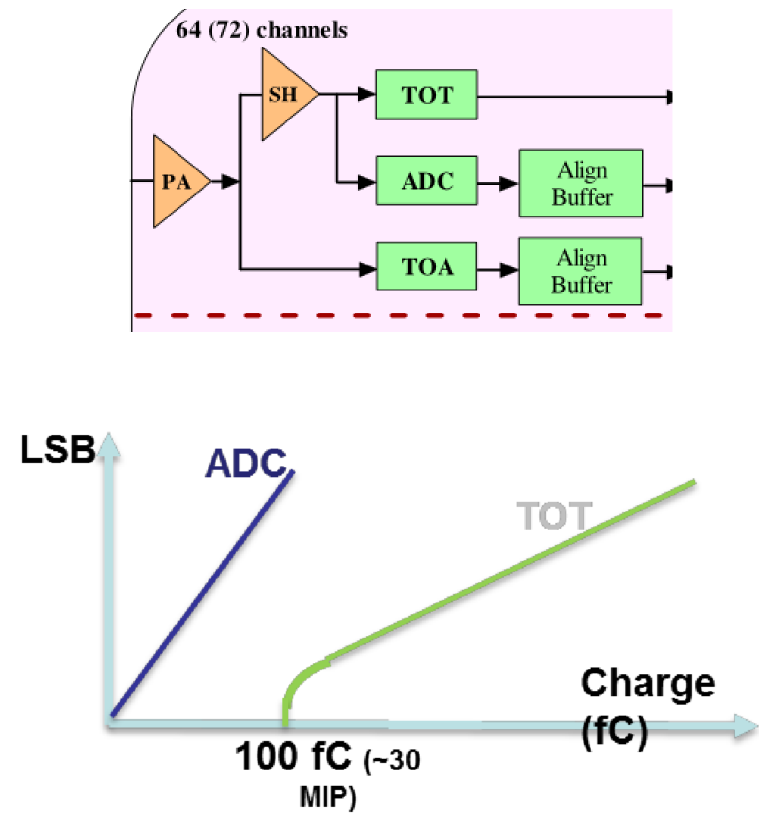


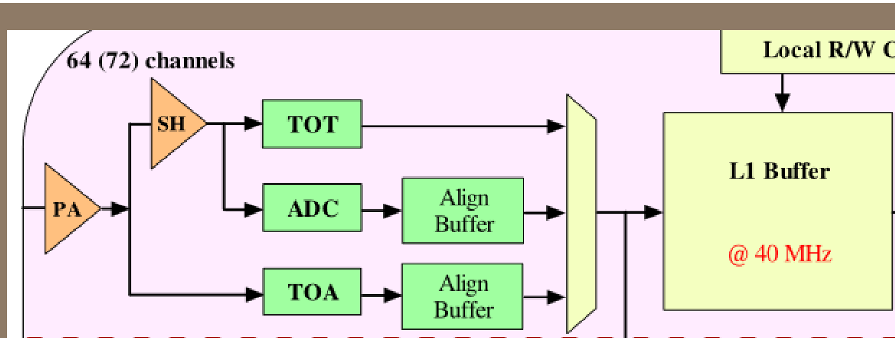
Data path

Signal after shaper



ADC – ToT





Buffer waiting L1 trigger accept

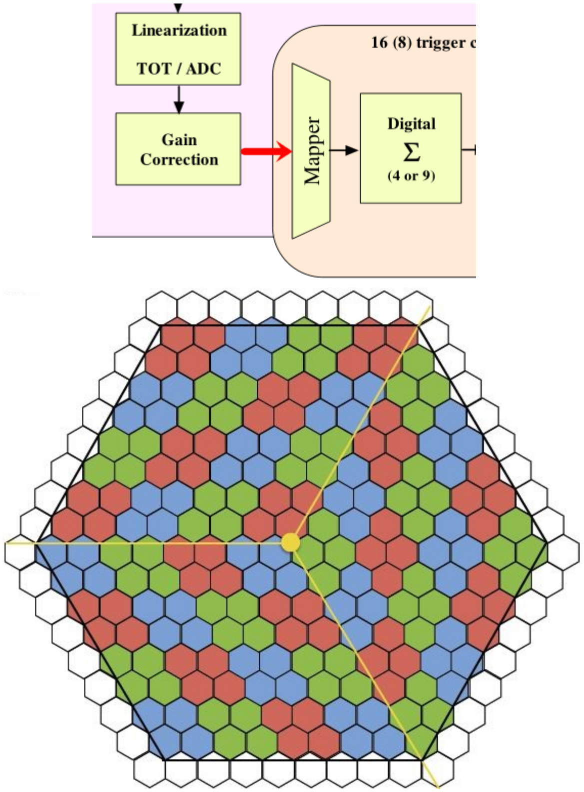
12.5 µs latency

512 events × 32 bits = 16.4 kb / channel

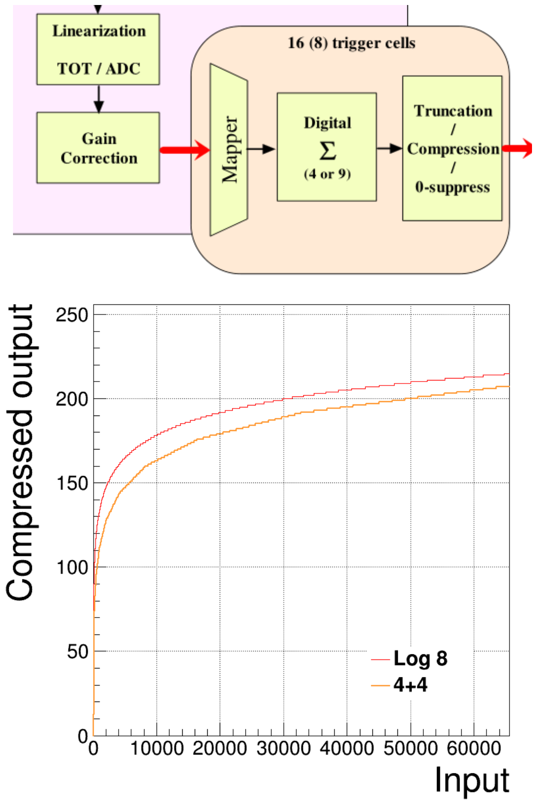
Power consumption: 2 mW / channel

Trigger path

Reducing granularity



Reducing energy resolution



Trigger cell sums
Possible alternative cell geometry

Energy compression
8 bits, log or floating point coding

Output at 40 MHz
~300 Tb/s in total

VFE chip development strategy

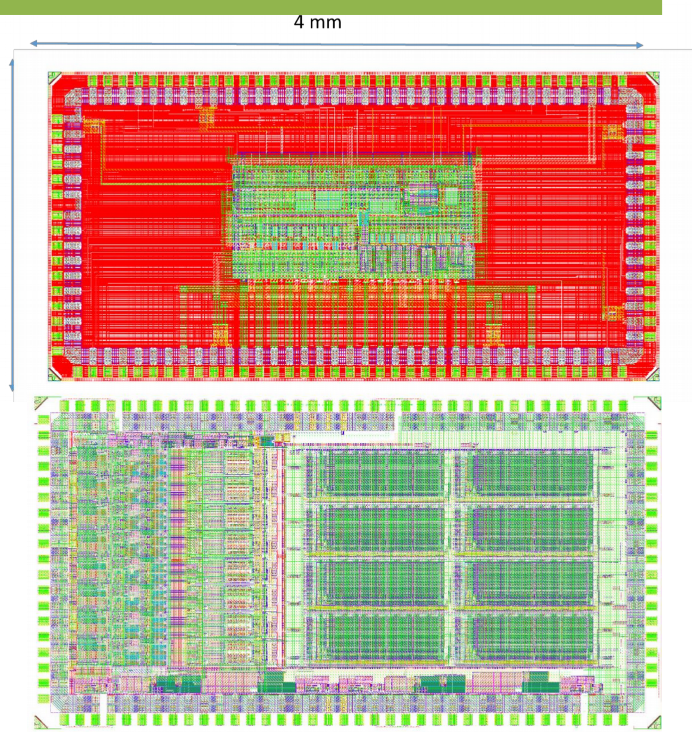
Modify existing SKIROC2 chip
Add functionalities like ToT, fast timing
Faster shaper: 25 ns instead of 200 ns
Used for 2017 test beams

Submit several “Test vehicles”
Test building blocks, baseline + variants

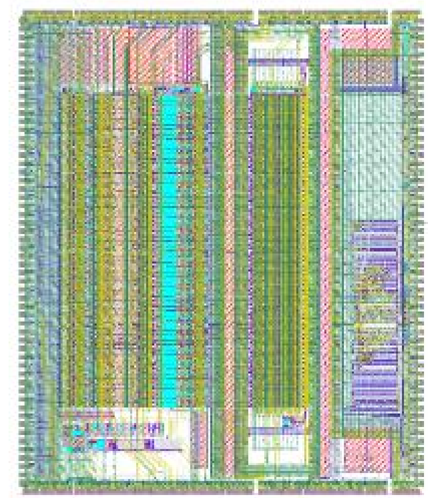
Test Vehicles 1 & 2

TV1
Test analogue architecture

TV2
8 channels
Test ADC + ToT
Buffers



SKIROC2_CMS



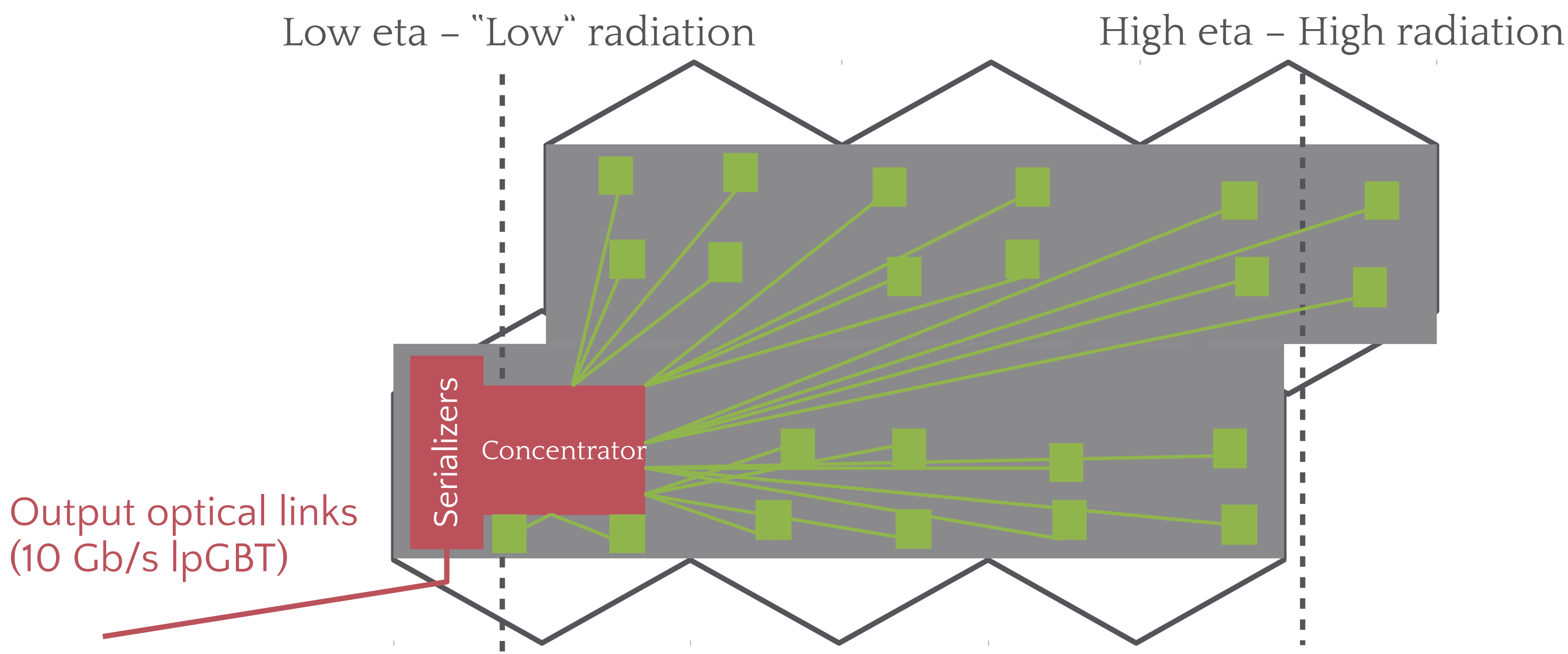
First “HGROC” ASIC
Submission mid-2017
2 more iterations foreseen

Data concentration

Motherboard PCB covering several modules

Separate noise sensitive VFE from concentration / transmission digital activity

Motherboard and data concentration schematic



Data transmission in lower radiation region

Use 10 Gb/s optical fibers

Concentrator aggregating data from several modules

Better trigger data reduction

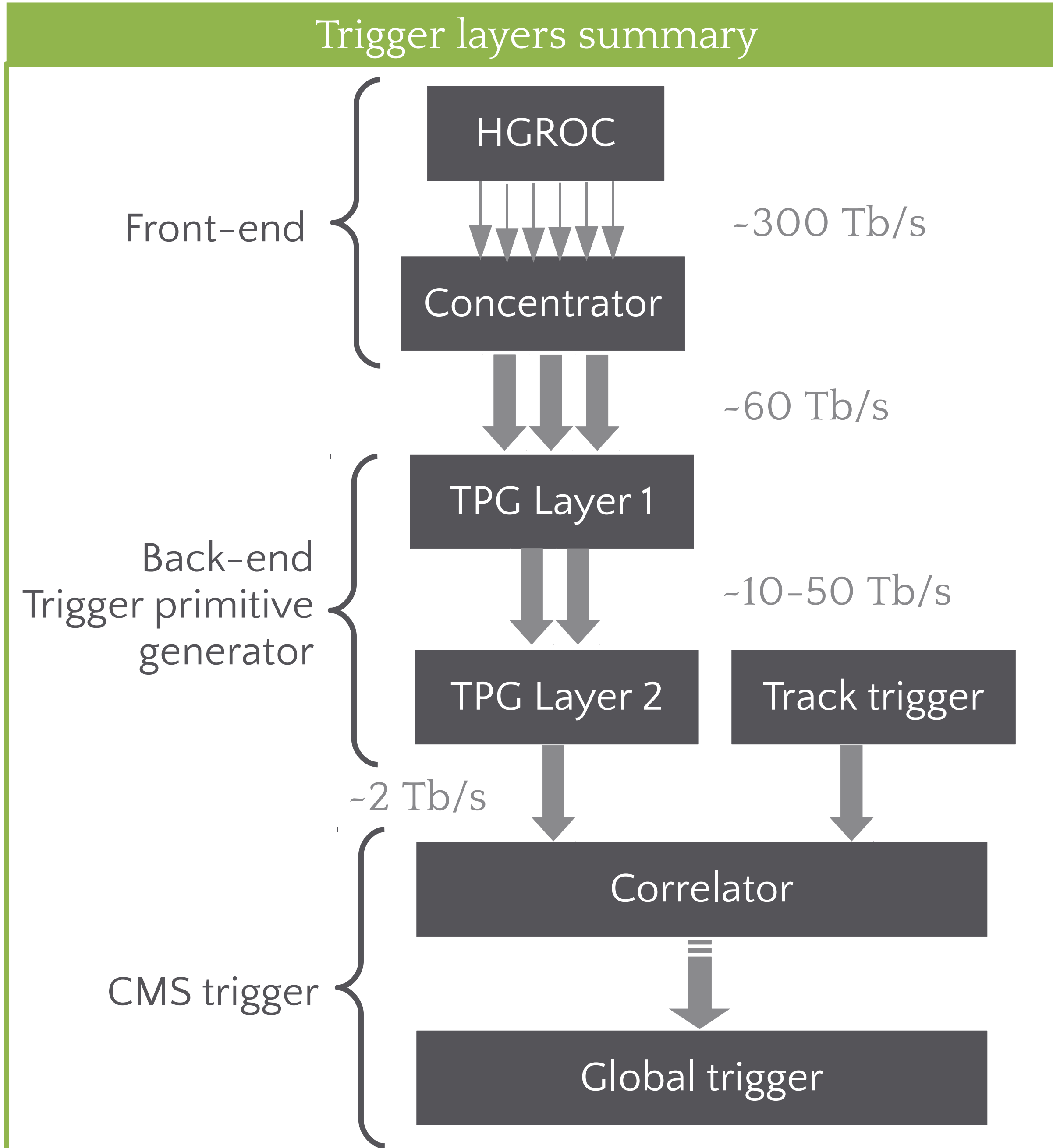
Trigger: from the front-end to the back-end

HGROC
Granularity reduction
Energy resolution reduction

Concentrator
Selection of a fraction of trigger cells

HGCal back-end
Clustering of energies
2D clustering
3D cluster linking

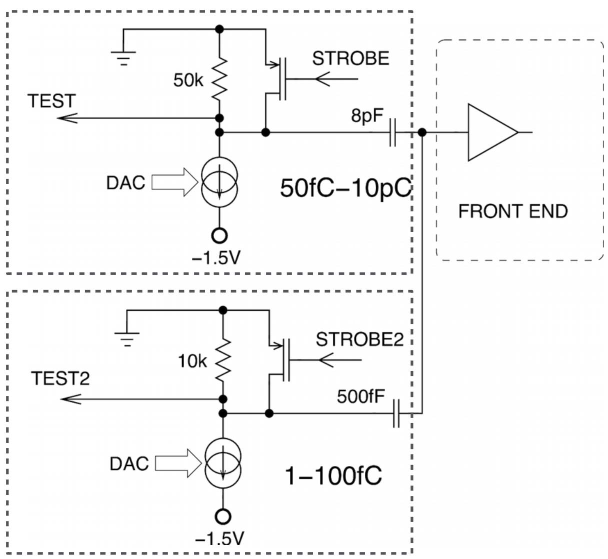
CMS back-end
Combination with other sub-detectors
L1 trigger decision



Energy calibration

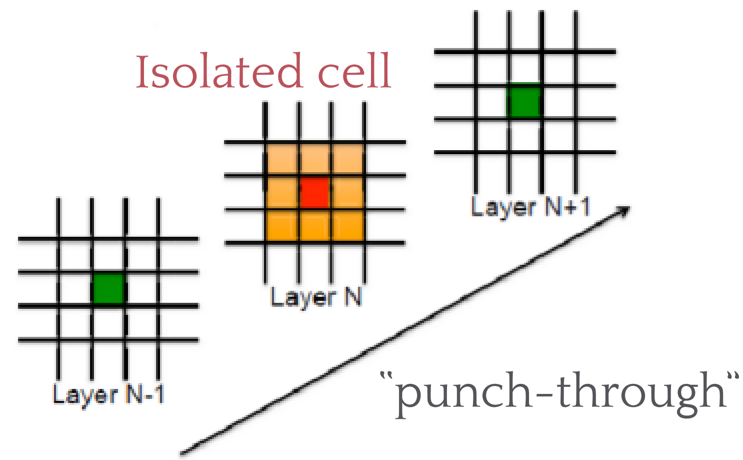
Calibration chain
Equalization of the cell-to-cell response: inter-calibration
Cell weights taking into account absorber and silicon thicknesses
Absolute energy scale using standard candles like Z → ee
Extrapolation to high energy electrons / photons

Electronics monitoring



Charge injection circuit
2 overlapping ranges
1 fC – 10 pC

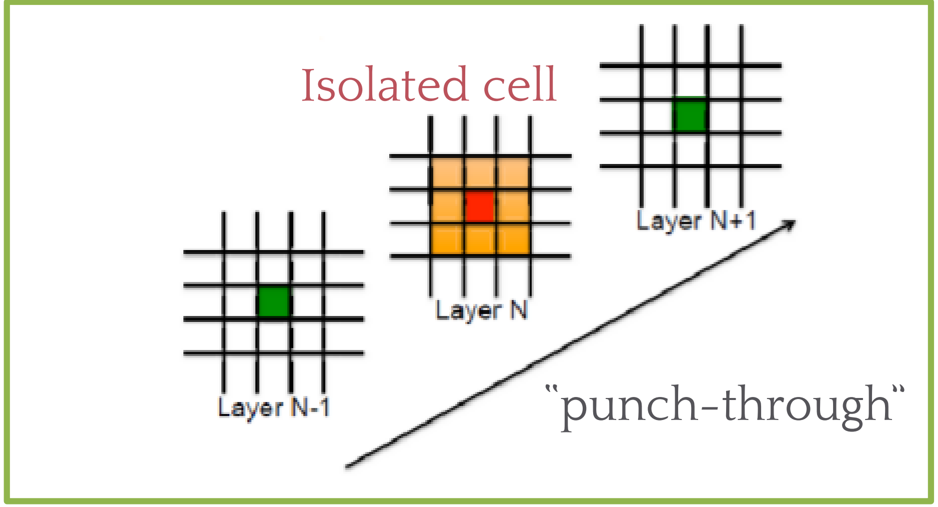
Inter-calibration with punch-through



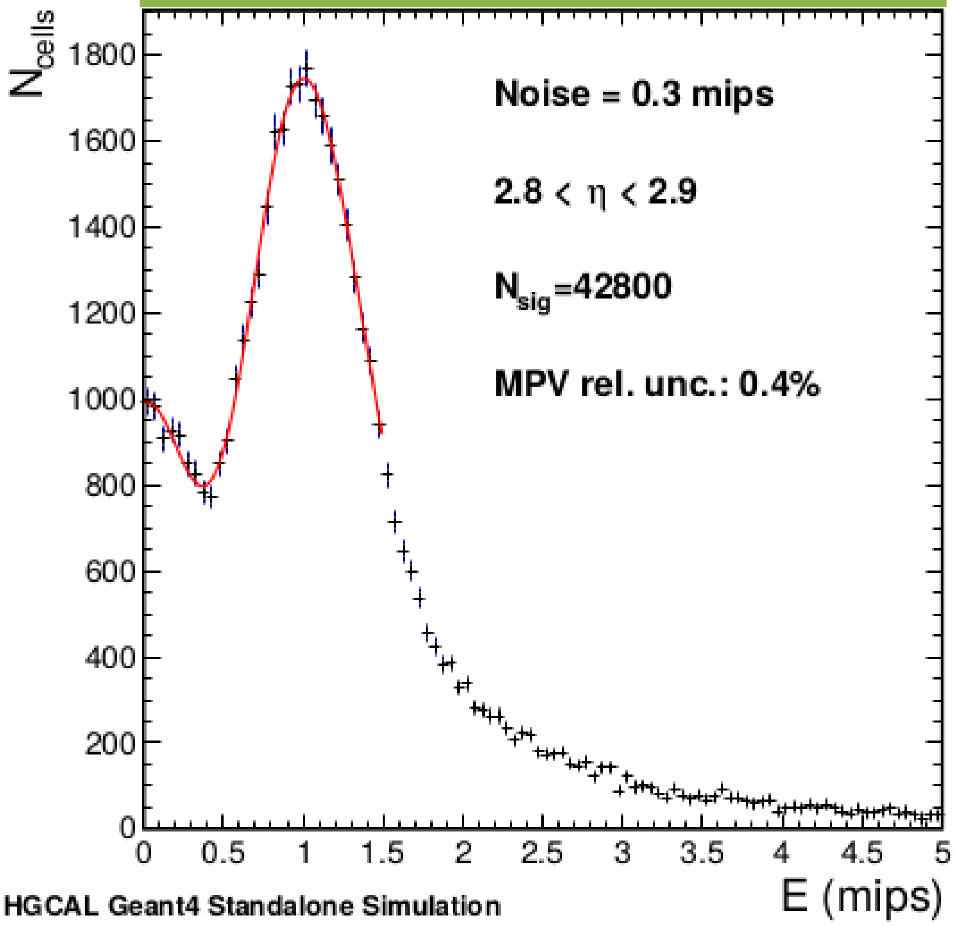
Inter-calibration
Require isolated cell
Track MIP signal in layers ±1
< 1% constant term requires 3% precision

Inter-calibration with "MIP" tracking

Inter-calibration with punch-through



MIP peak fit example

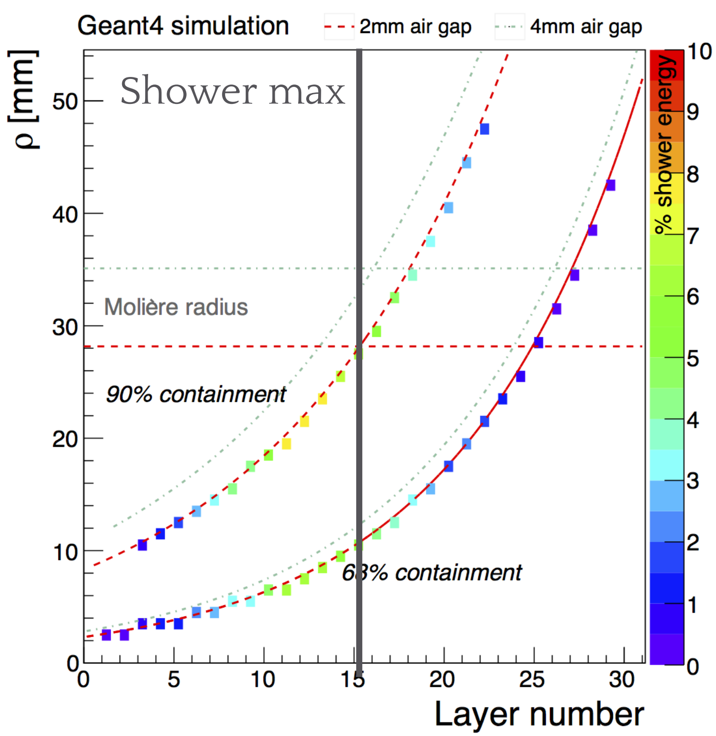


1.5M minimum bias events needed

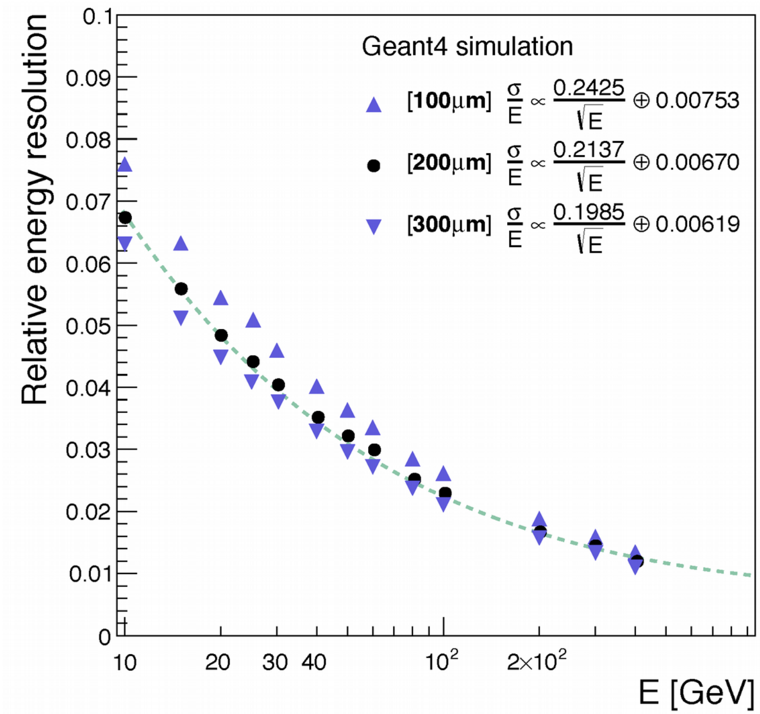
Noise of 0.4 mips → 3% precision
Events available daily
Can be done at the HLT with L1 rate

ECAL simulated intrinsic performance

Transverse size vs depth



Energy resolution (3 thicknesses)



Electromagnetic shower size

Very narrow in the first layers
Pile-up rejection, particle separation
Moliere radius around 3 cm

Energy resolution

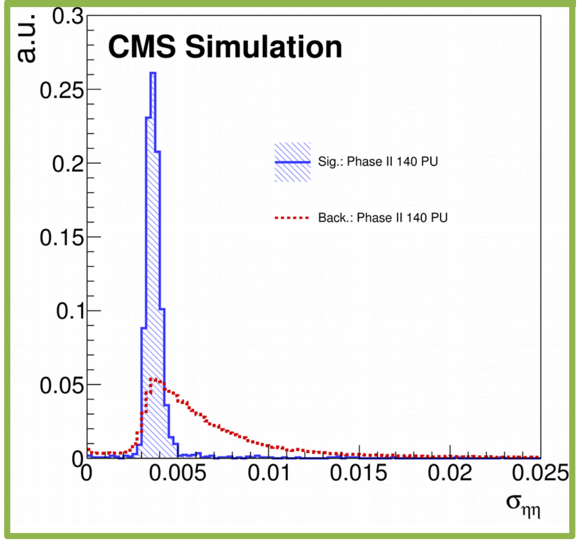
Stochastic term: ~ 20%
Constant term: target 1%
Forward: moderate p_T = high energy

Electromagnetic object identification

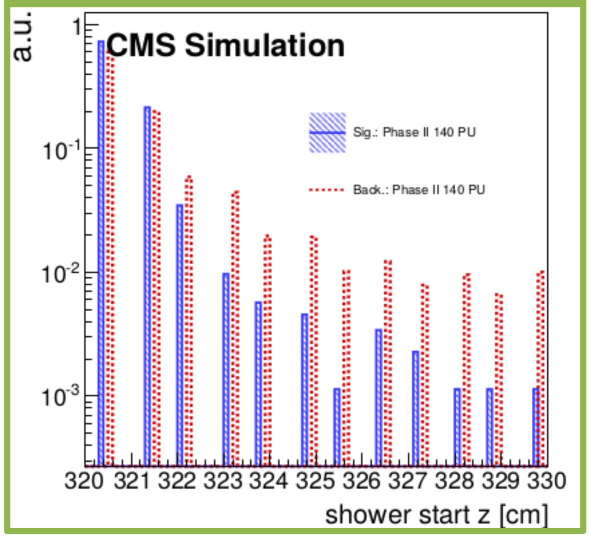
Improved particle identification

Thanks to the high granularity and the longitudinal segmentation

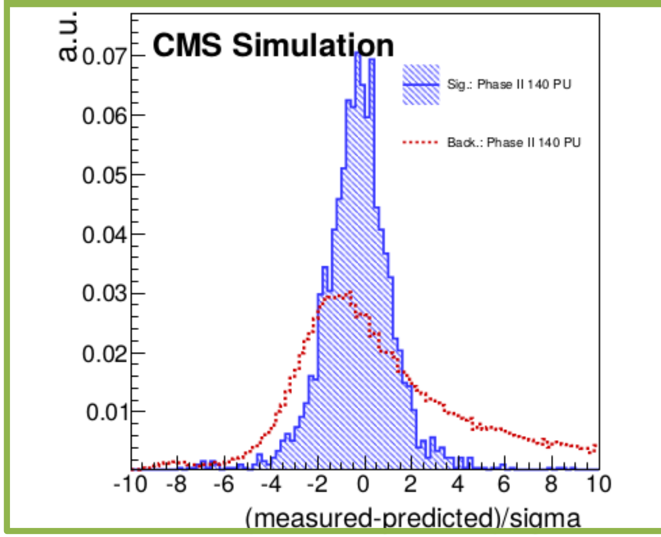
Shower width



Shower start position



Compatibility with expected EM shower length



Reconstruction of the shower axis

Improved shower width variables

Even without mechanical projectivity

Shower start

Separation charged pions vs EM objects

Shower length

Easily parametrized

Logarithmic E dependence

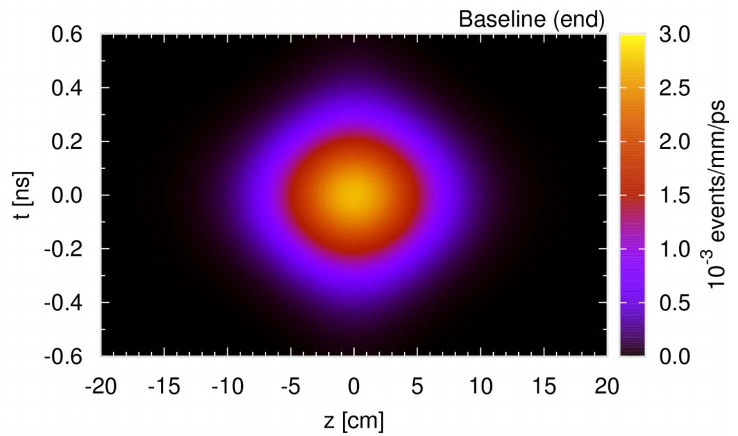
Powerful ID variable

Timing

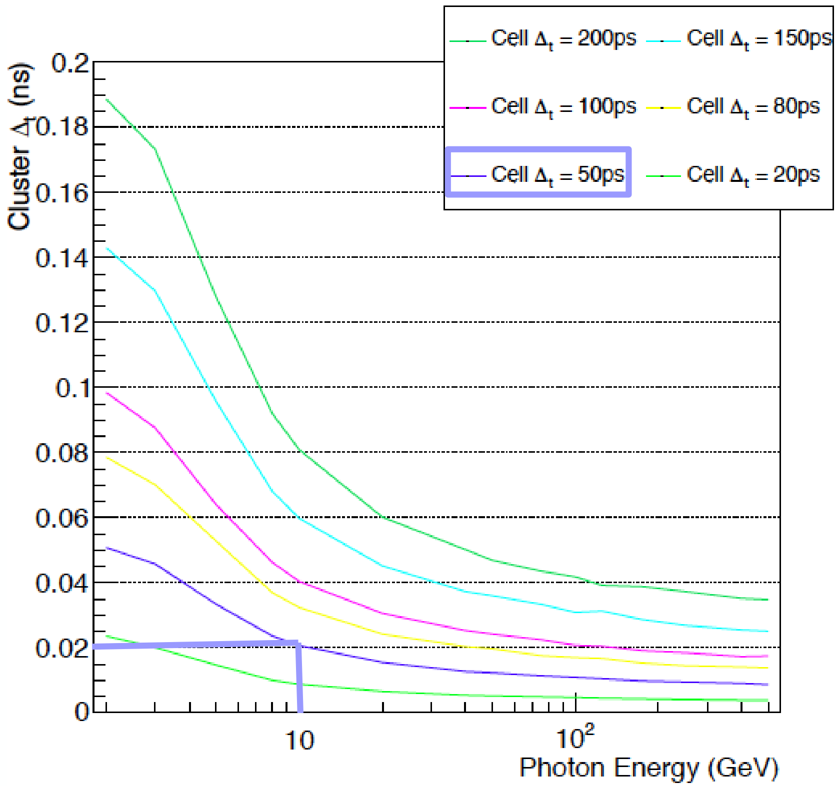
Per cell Δt = 50 ps

Cluster resolution: < 20 ps
For energy > 10 GeV

HL-LHC: 160 ps wide crossing



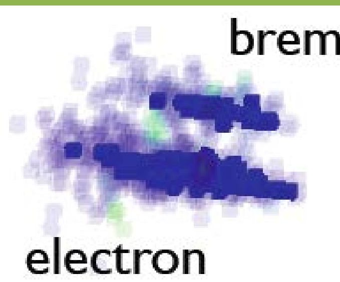
Cluster timing resolution vs energy



Can collect energy deposits within a 30 ps window

Electron: Seed and brem photons
Jets: reject PU particles

Electron with bremstrahlung

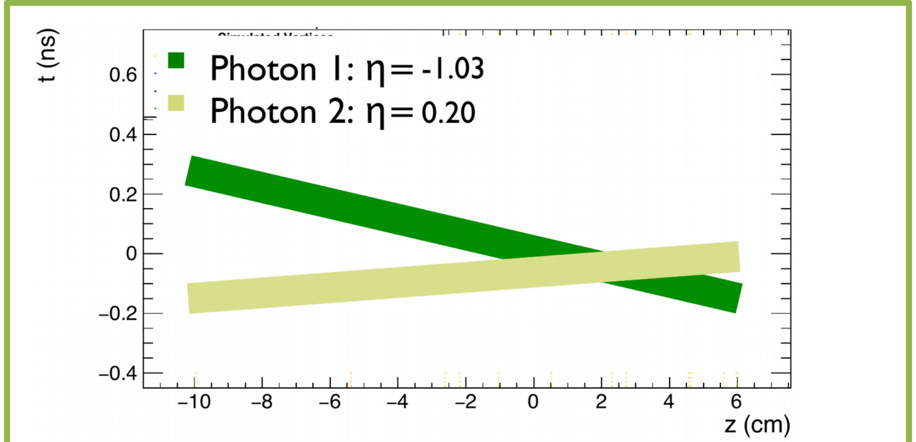


Timing and vertex triangulation

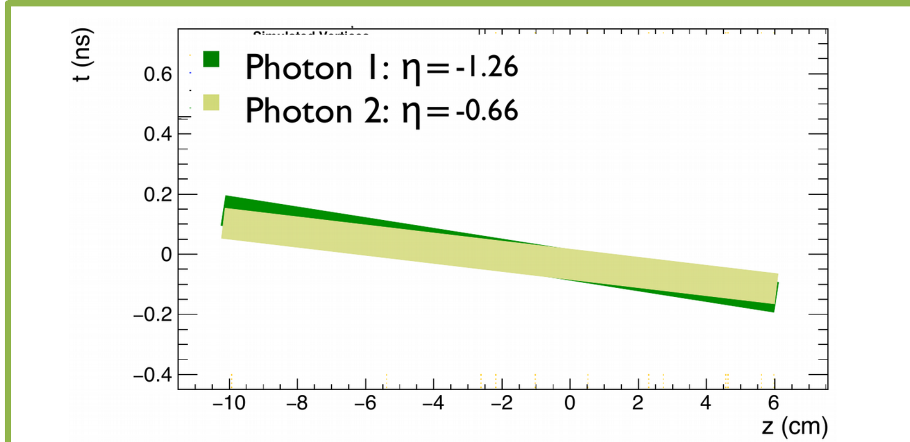
Reconstruction of vertex space-time from object timing

2 objects needed: e.g. 2 photons
30 ps resolution assumed below

Large rapidity gap



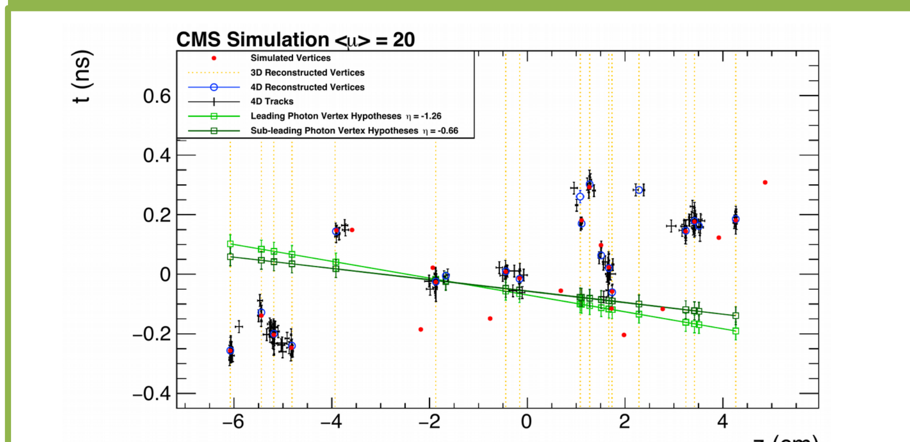
Small rapidity gap



Small rapidity gap: triangulation breaks down

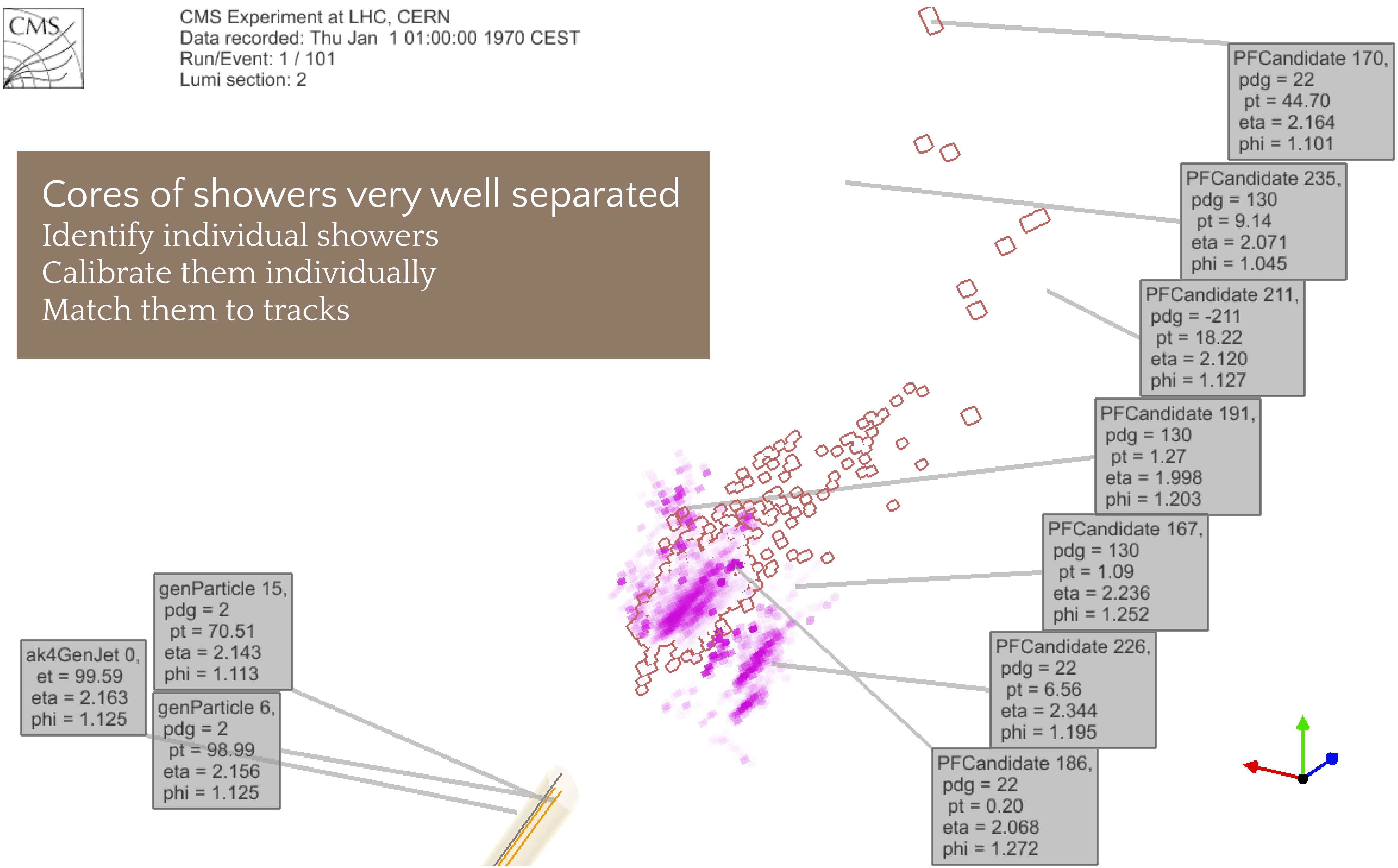
But can combine information with 4D reconstructed vertices

Space-time vertices



Cores of showers very well separated

Identify individual showers
Calibrate them individually
Match them to tracks

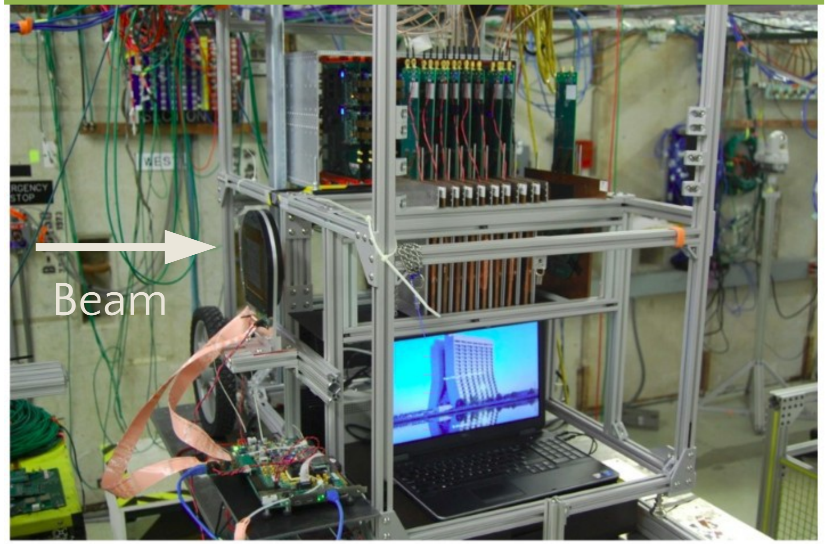


Test beams

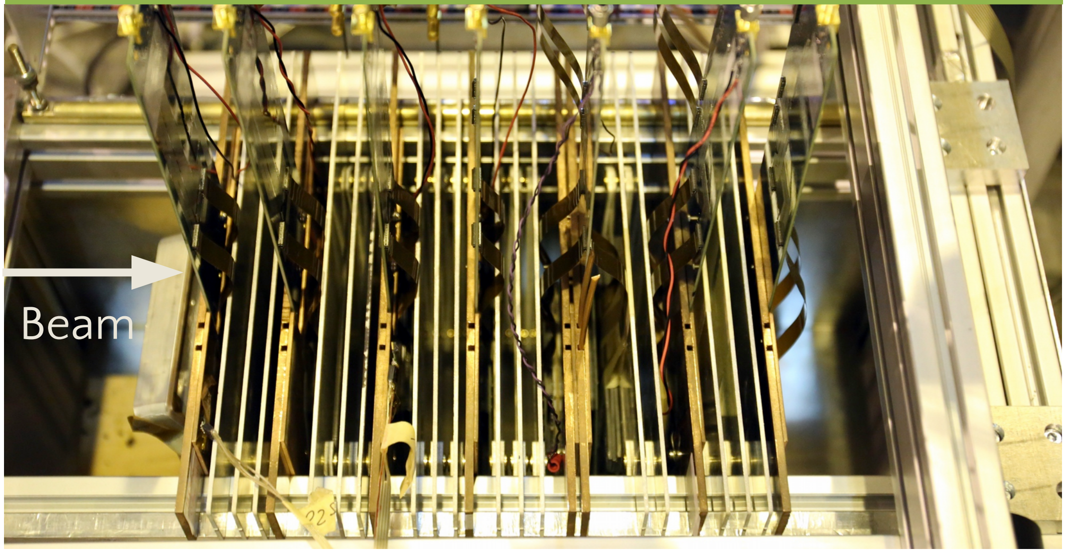
Purpose: test stacked modules
Calibration with MIPs, S/N measurements
Energy responses, energy and position resolutions
Comparisons with simulations

Where? @ FNAL & CERN

Setup at FNAL



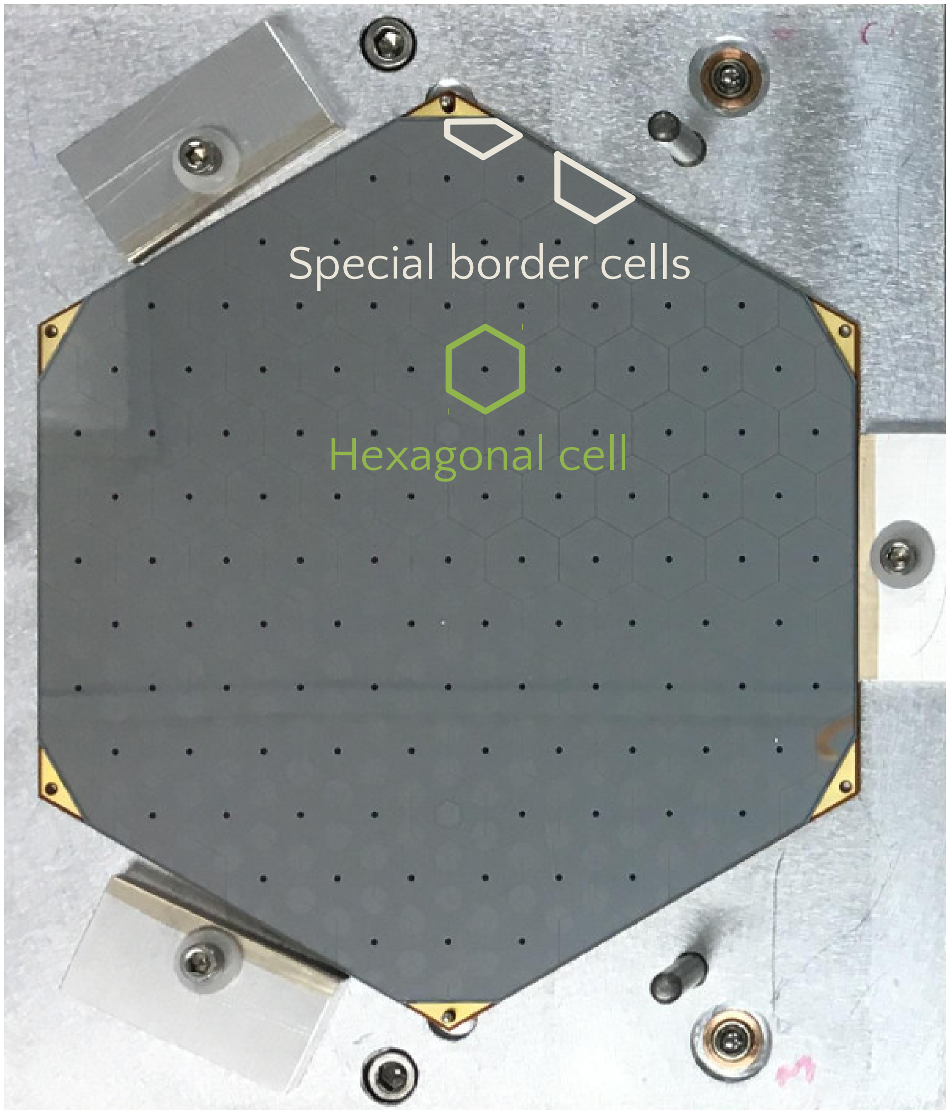
Setup at CERN



FNAL
Up to 16 layers, about 15 X_0
Electrons up to 32 GeV
Protons at 120 GeV

CERN
Up to 8 layers, up to 27 X_0
Electrons up to 250 GeV
Pions at 125 GeV, muons from pions

What has been tested?



14 cm

12.5 cm

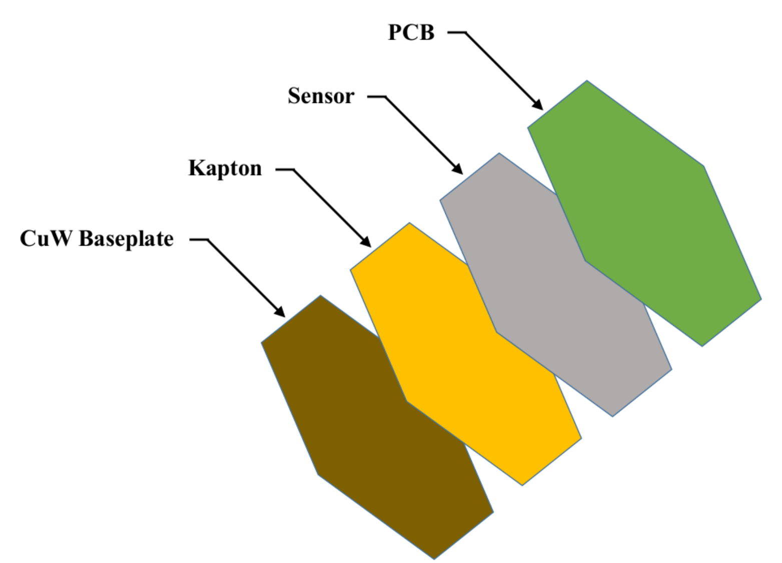
Hexagonal sensors

6" wafers

200 μm thickness

128 channels, 1.1 cm^2 cell size

Glued stack of baseplace, Kapton™, sensor and PCB



Readout and layer configuration at CERN

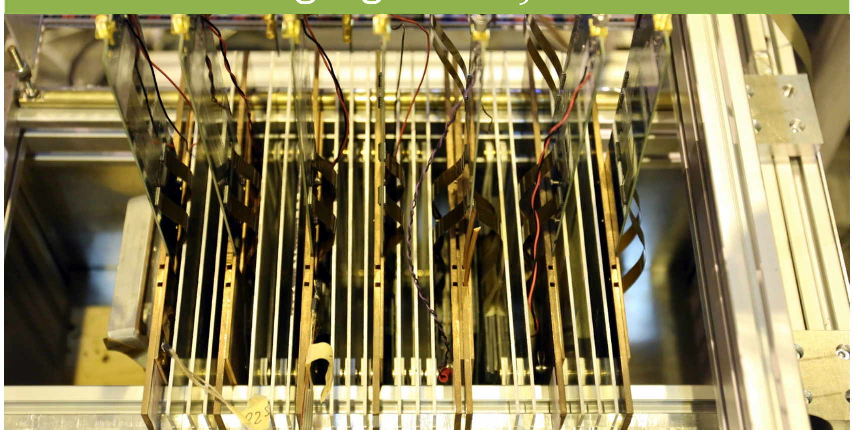
Module with 2 PCBs

Double PCB design
Flexibility
Easily change the top part with different chips

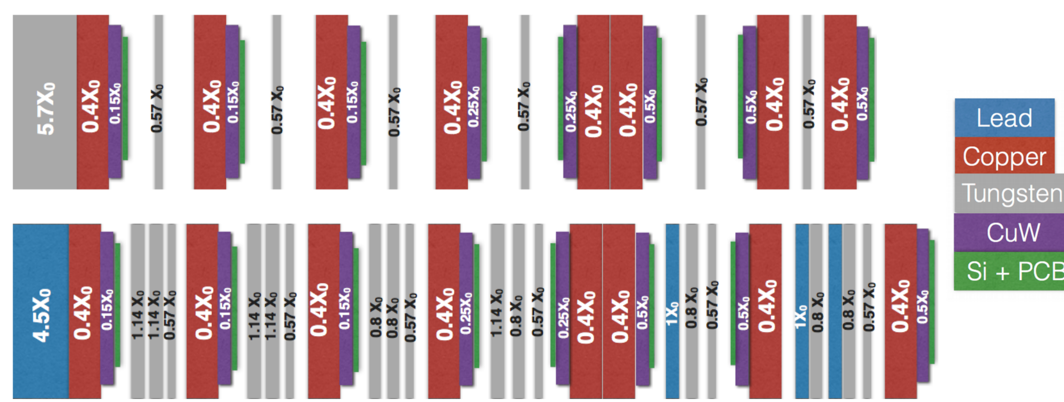
2 SKIROC2 ASICs
Developed by Omega for CALICE

Hanging file system
Ability to change layer configurations

Hanging files system

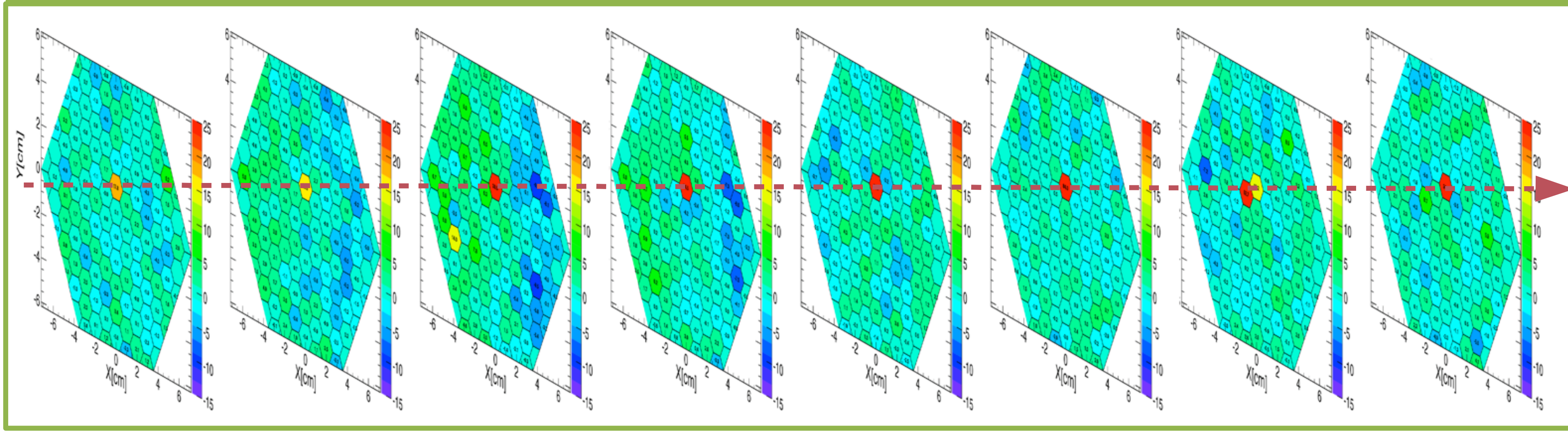


Layer configurations



Response to muons and pions

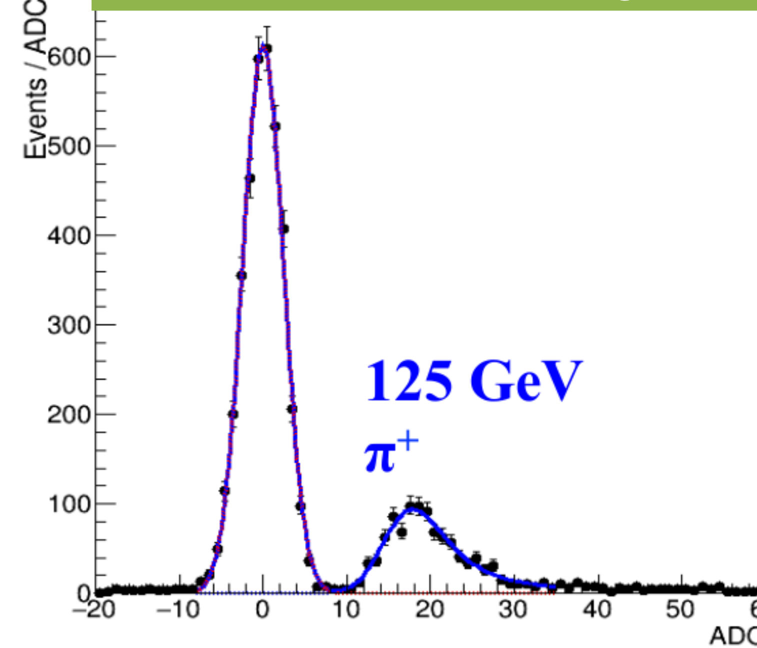
125 GeV charged pion passing through 8 layers



Nice MIP signal
Muons and pions
Noise = 2.4 ADC
S/N = 7.4

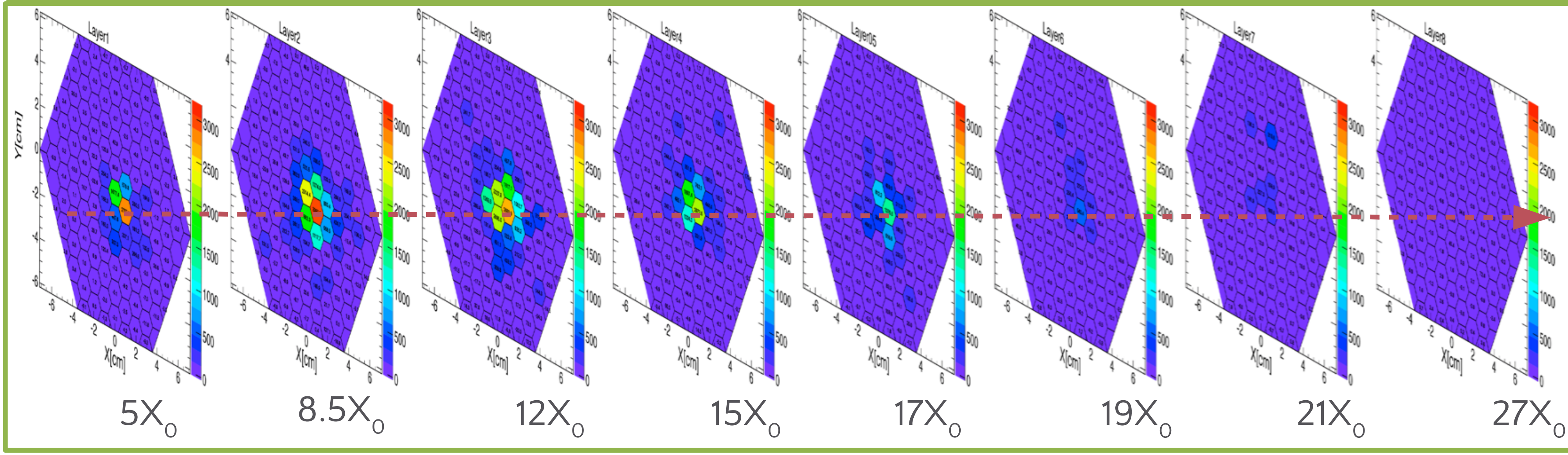
Used for calibration

Reconstructed MIP signal

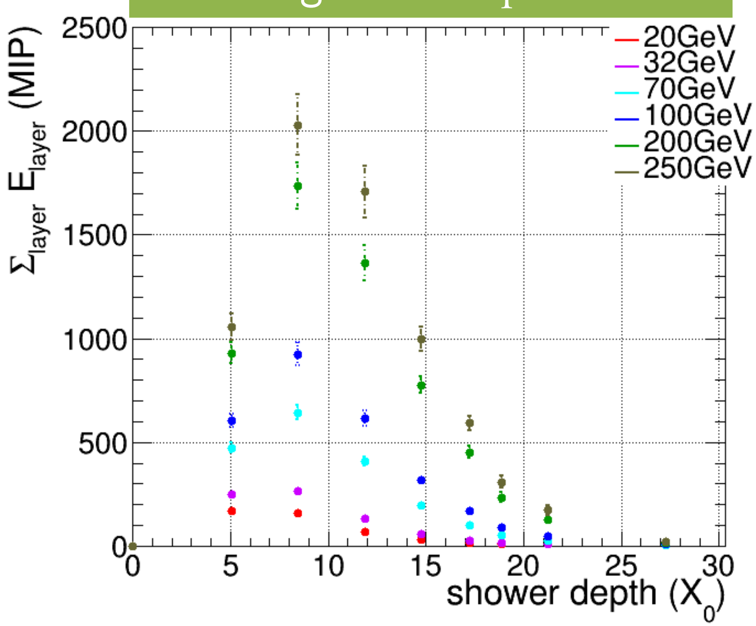


Electrons at 250 GeV

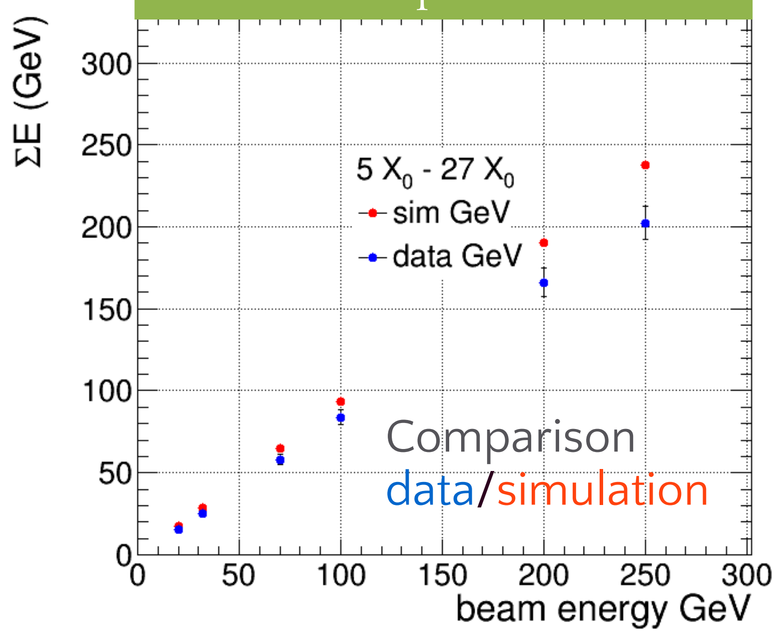
250 GeV electron passing through 8 layers – 27 X_0



Longitudinal profile



Response



Electron energy resolution

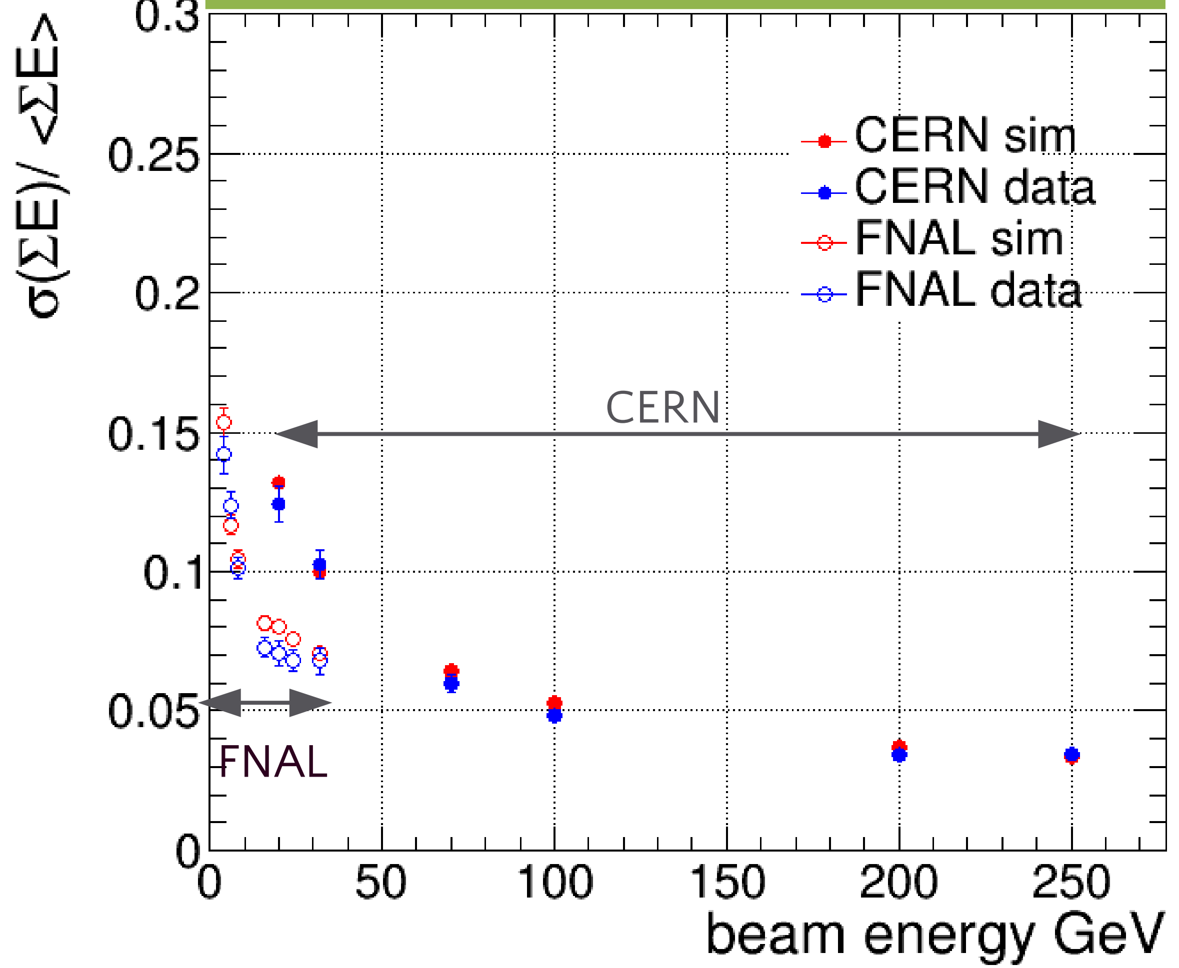
Energy resolution vs beam energy

Low energy points from FNAL
High energy points from CERN
Overlap between the two

Data / simulation

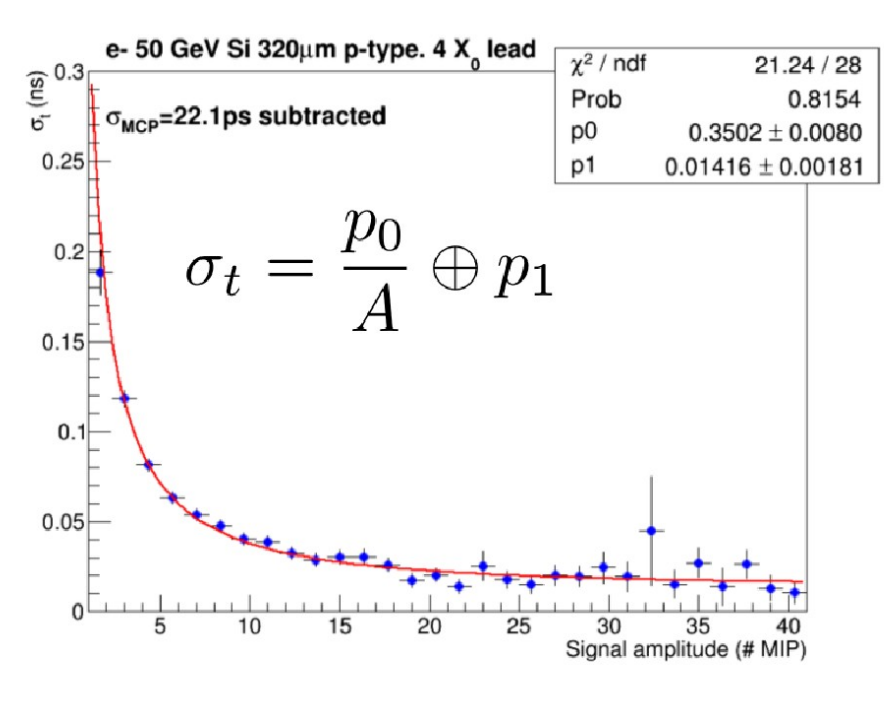
Good agreement

Energy resolution – 2 configurations



Timing tests

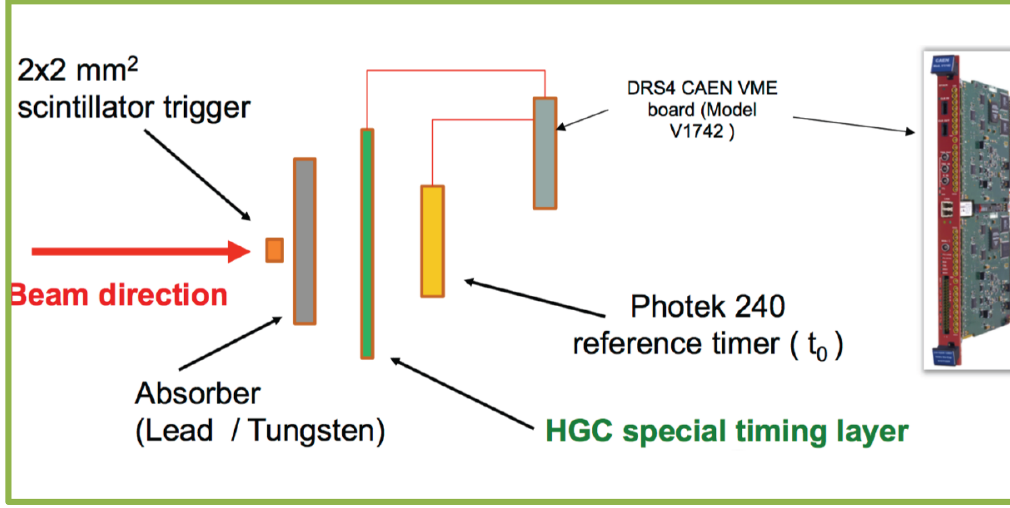
Timing resolution vs amplitude



Time resolution improves with S/N

Constant term: 14 ps, for S > 20 mips

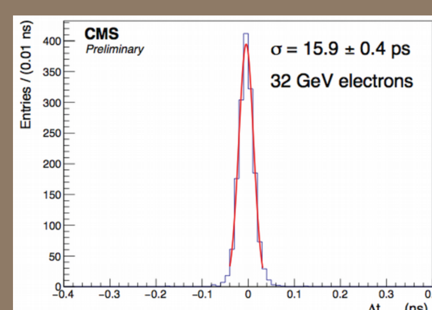
Timing test with special fast readout



Timing test with 300 μm layer

Fast readout

16 ps for 32 GeV electrons



CERN beam tests in November 2016

Up to 250 GeV electrons

Analysis ongoing

Short term perspectives

Many more results this year

Complete analysis of 2016 test beam data
CERN test beams between May and July

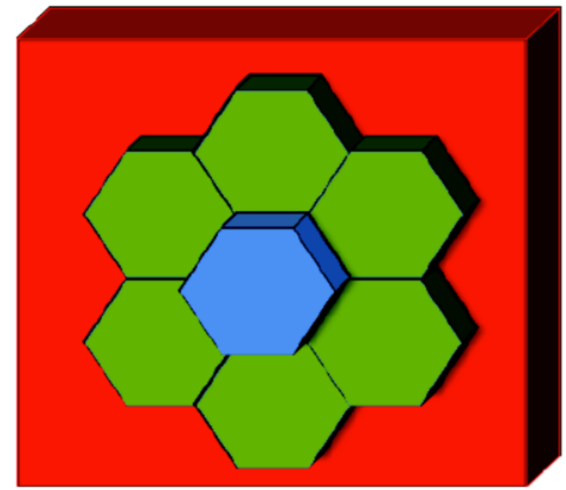
2017 beam tests

28 EE layers + 12 FH layers + modified AHCAL prototype
Updated readout chip: SKIROC2 _CMS
Full system performance and timing of hadron showers

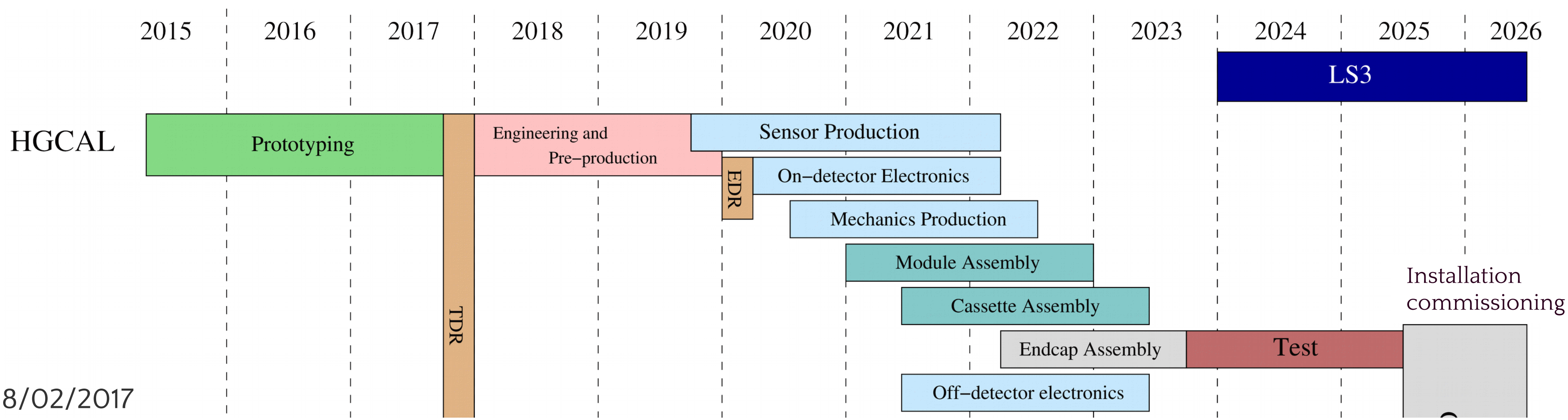
TDR at the end of the year

Refined engineering studies and choices
Refined simulation and reconstruction

Detector structure for 2017 test beams



ECAL
Silicon HCAL
AHCAL



Summary and conclusion

Very ambitious project of a High Granularity Calorimeter for the HL-LHC
Adapted to the extremely harsh environment: pile-up, radiation

The HGCal provides multiple measurements in one place
Energy, tracking, timing

Innovative mechanical, electronics and reconstruction solutions are developed
To provide the best possible performance

The project is progressing at full speed on every aspects
On schedule for an operation with the first HL-LHC collisions