The CMS High Granularity Calorimeter for the High Luminosity LHC

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LLR CNRS / École Polytechnique

CHEF2017 – 03/10/2017

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.

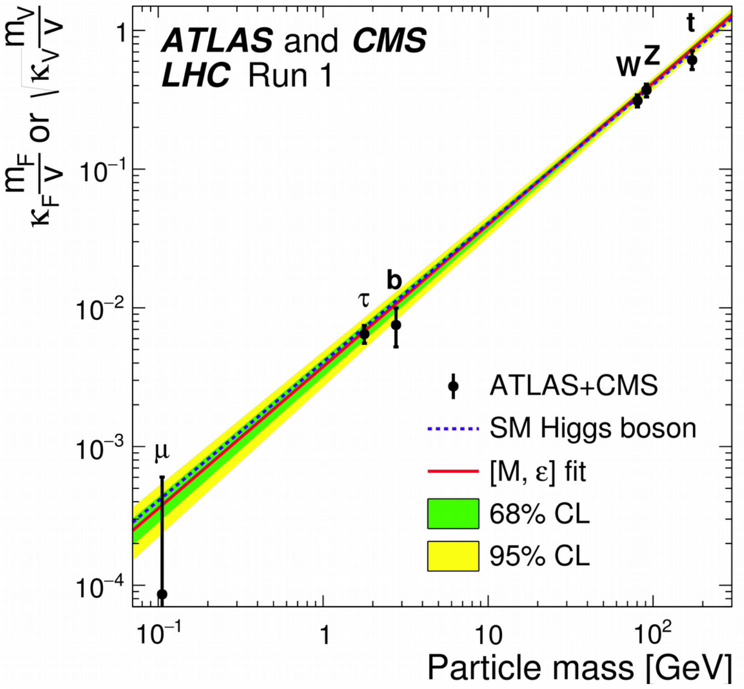
Vector boson scattering & unitarity tests

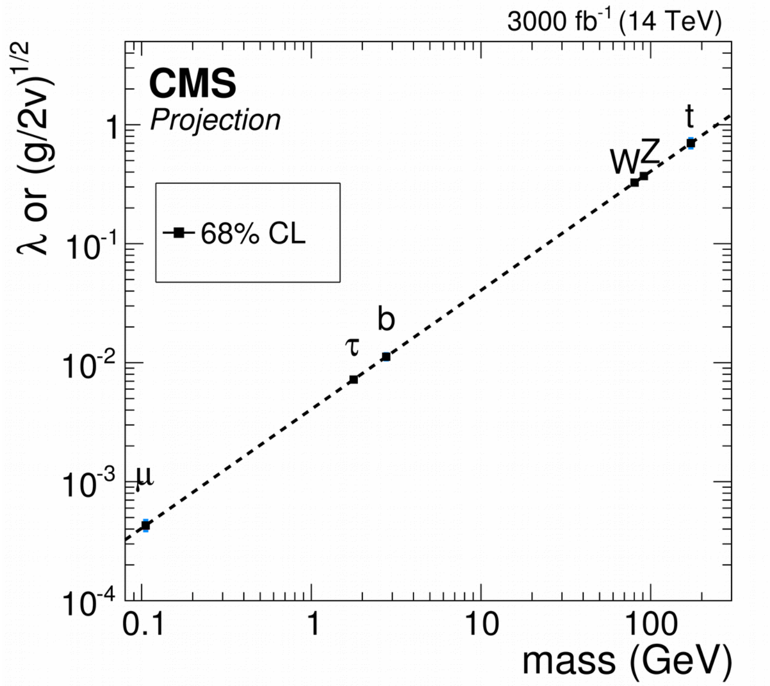
Double Higgs constraints & Higgs self-coupling

And also…

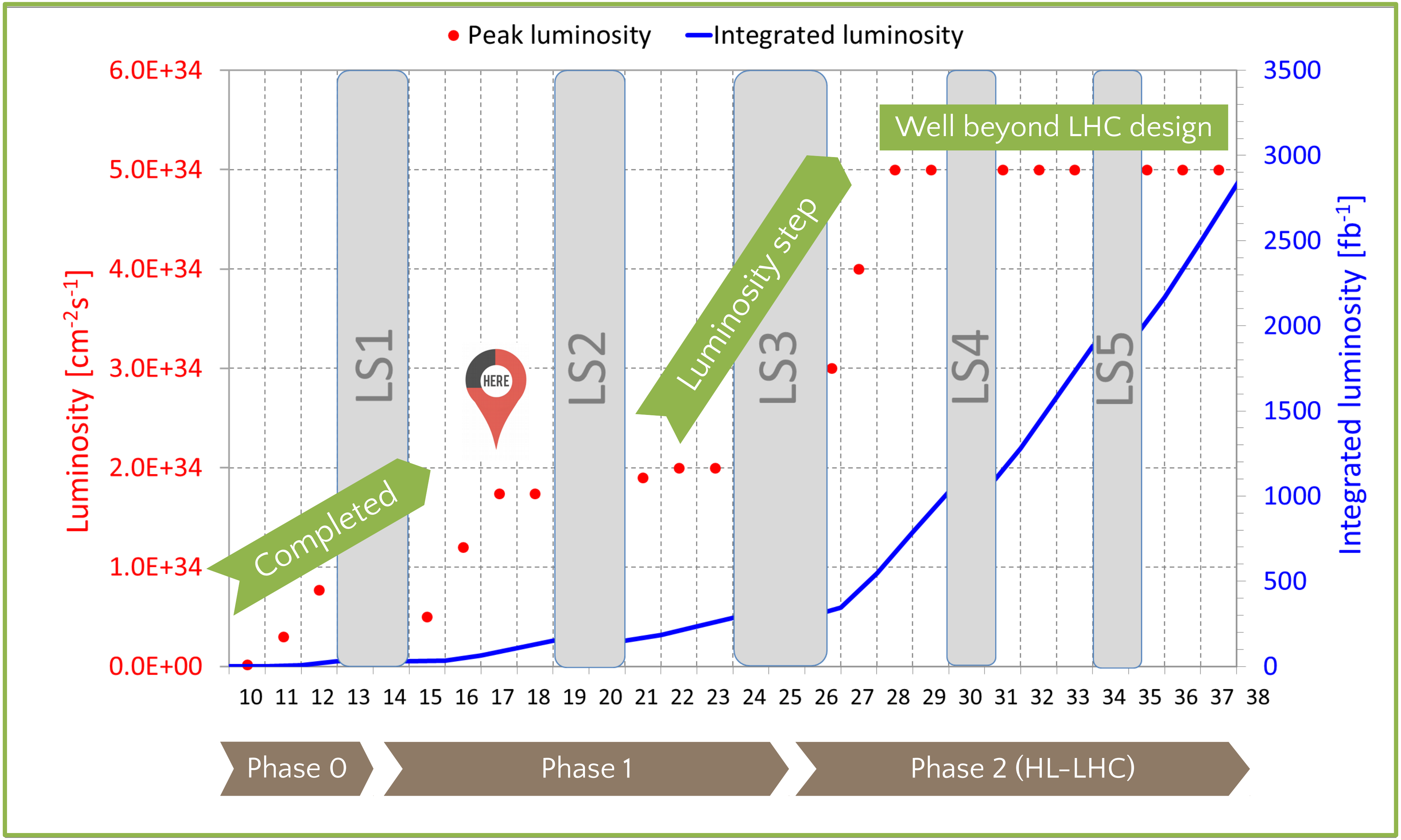
Higgs precision measurements

Extension of high mass particles searches





LHC and HL-LHC timeline



03/10/2017

Why upgrade the calorimeters?

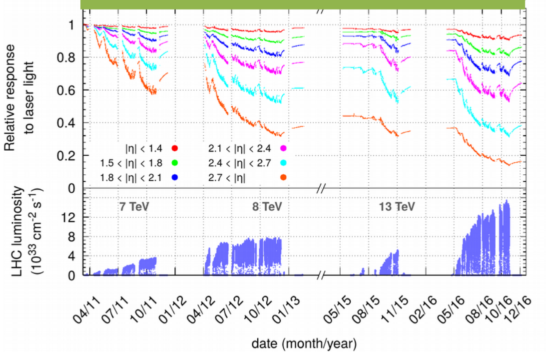
With the current technology
signal yield deteriorated by radiation-induced effects

Mitigated by laser monitoring, but only to a certain point

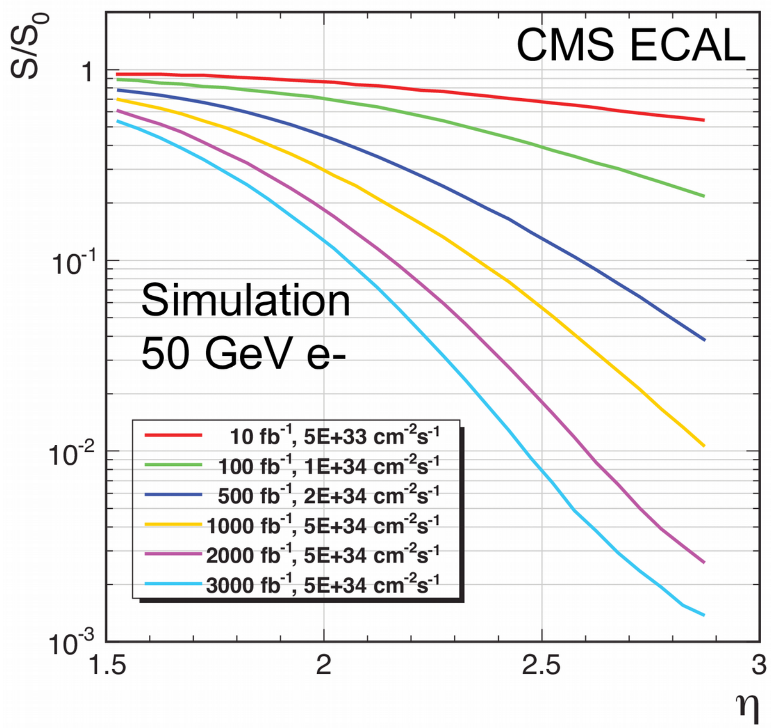
→ Impact on the energy resolution

→ Constant term: 10% at the end of HL-LHC

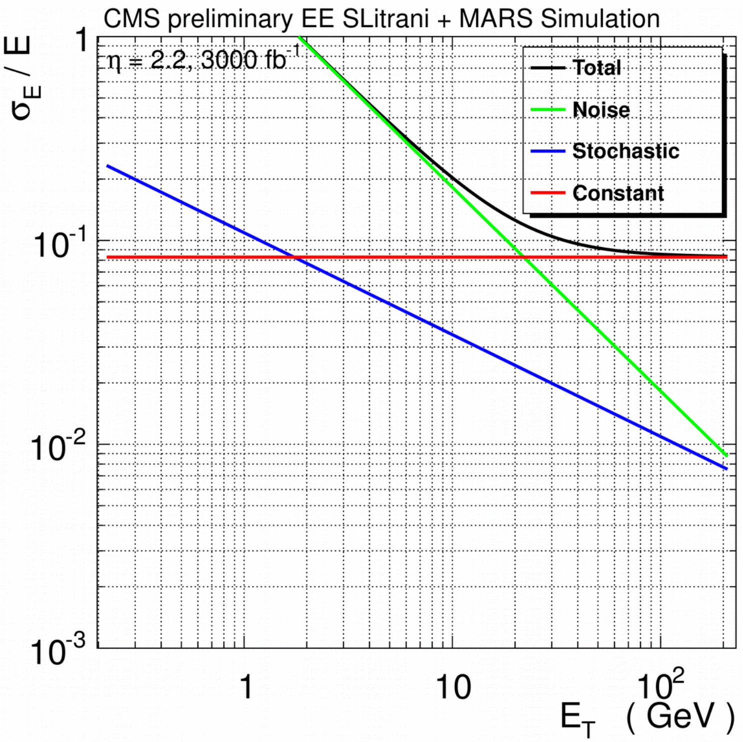
Laser monitoring



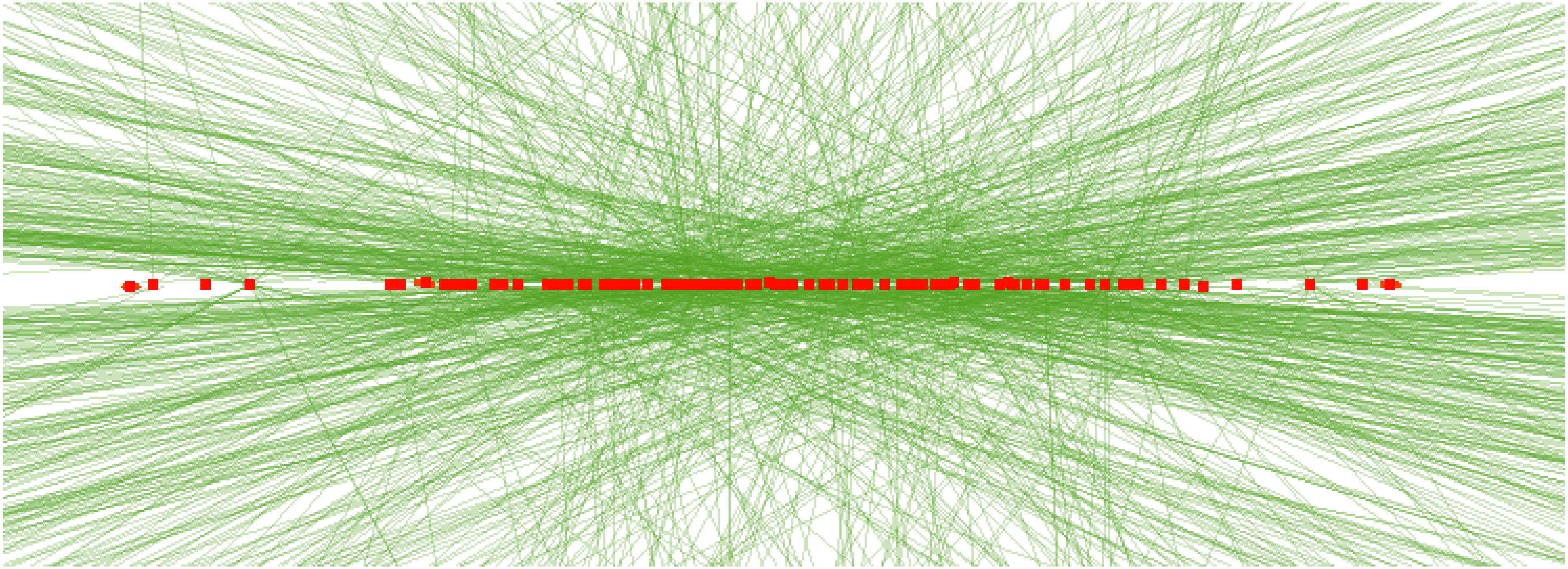
Relative response of the existing ECAL endcaps



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

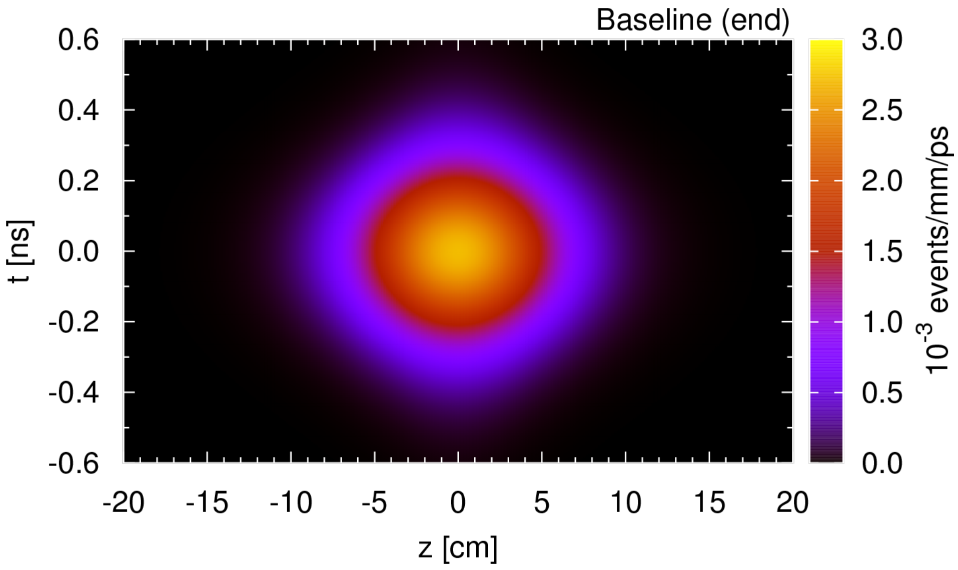
Interactions are spread over space and time

100 – 200 ps

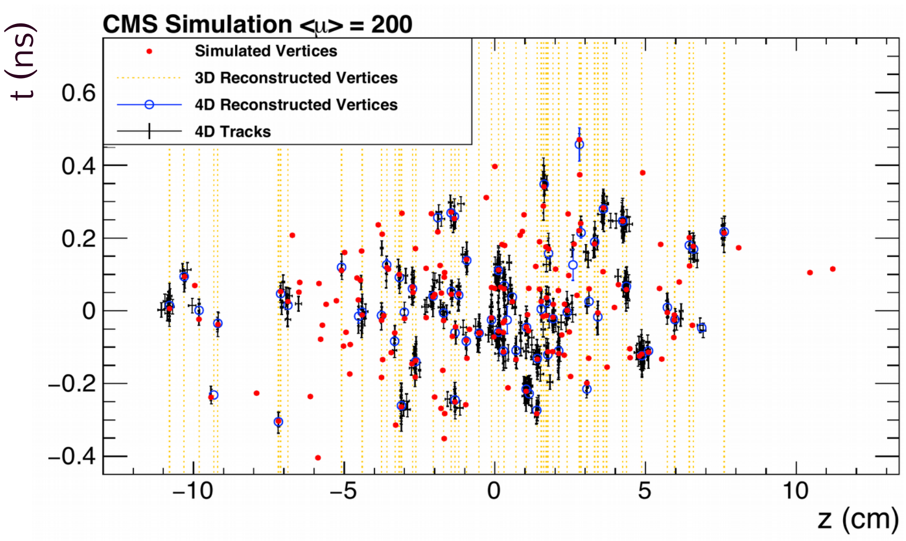
Disentangle overlapping vertices with precise timing

Key resolution: 10-30 ps

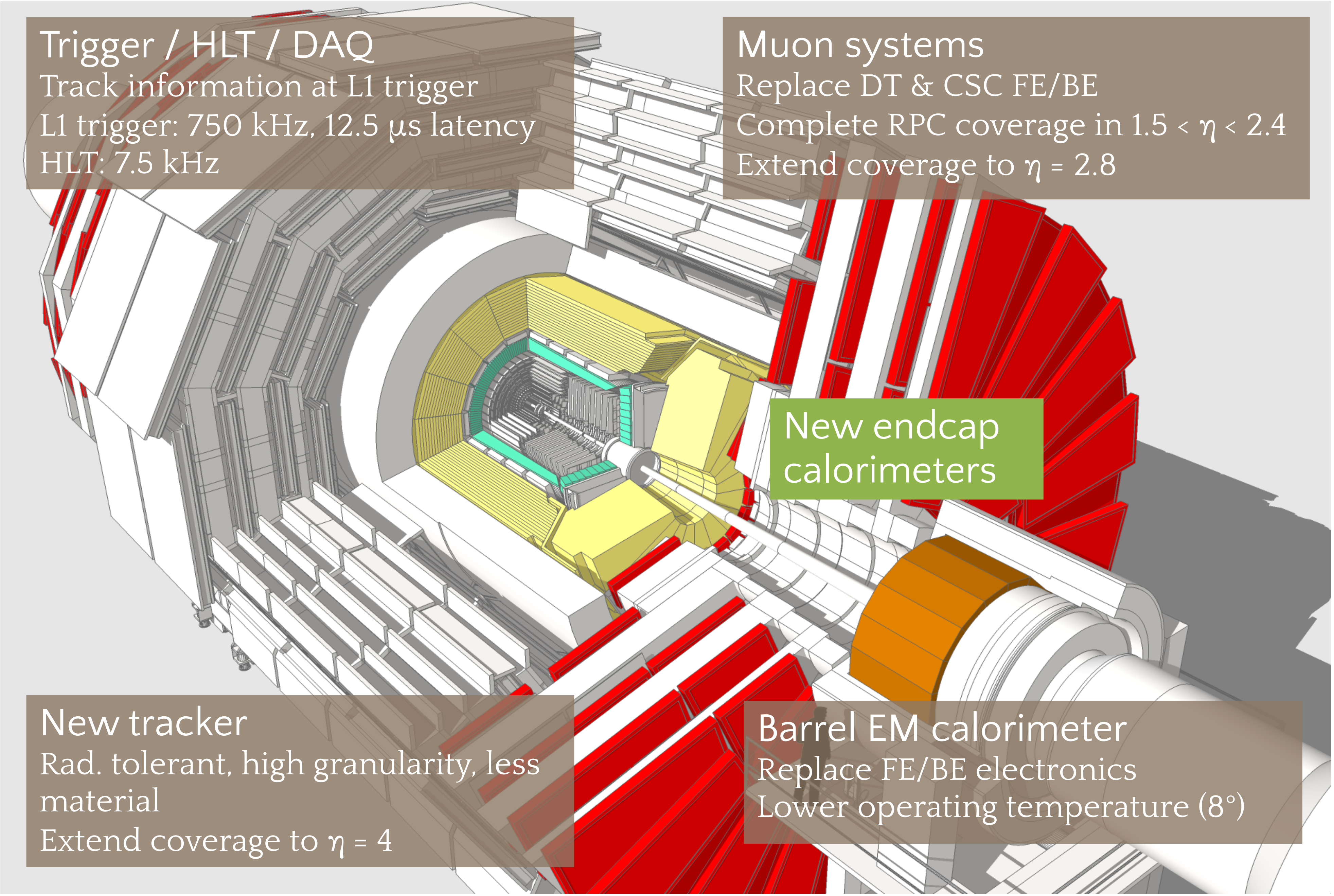
Beam spot space-time profile



Space-time view of the vertices



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 $1.5 < \eta < 2.4$

Extend coverage to $\eta = 2.8$

New endcap calorimeters

New tracker

Rad. tolerant, high granularity, less material

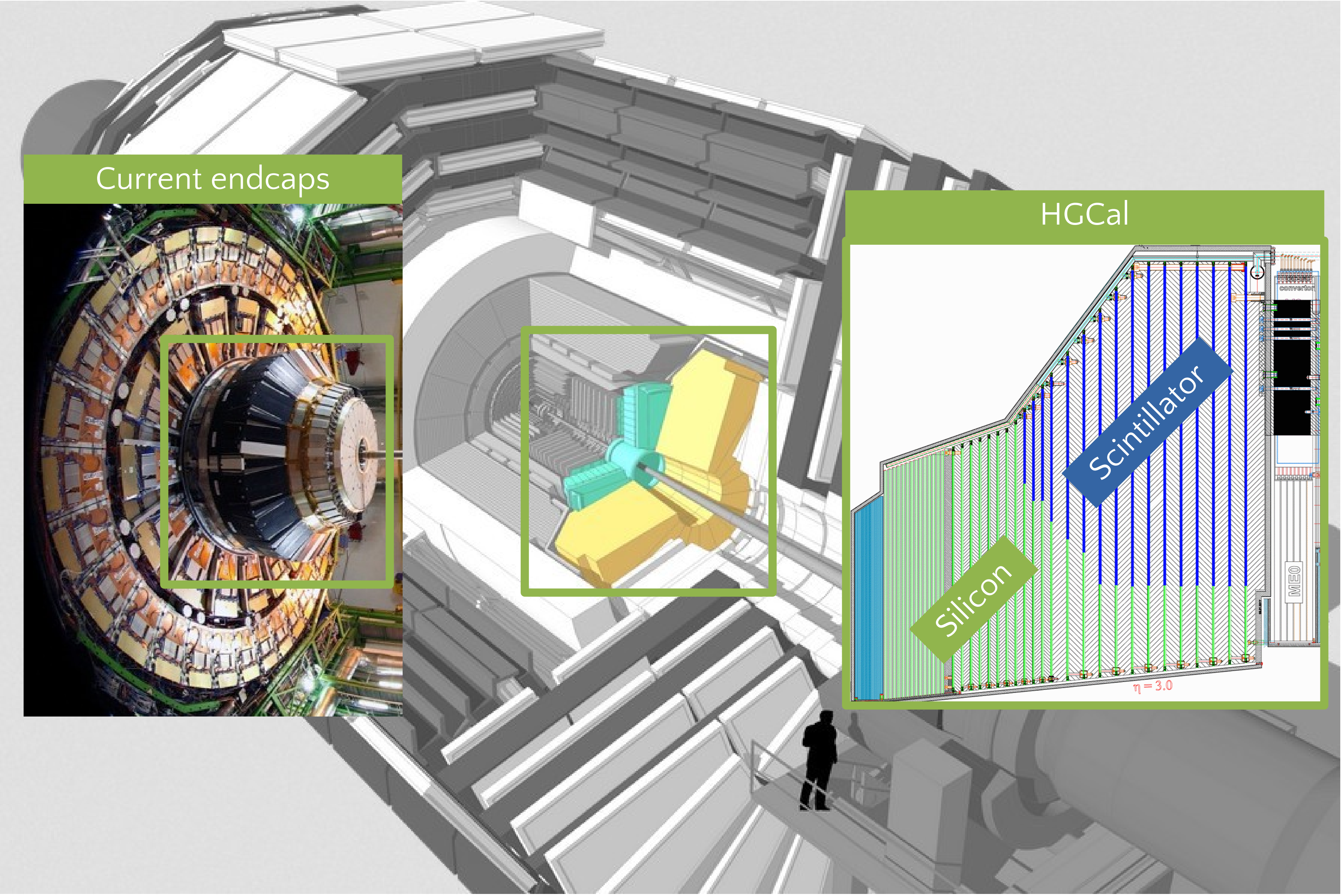
Extend coverage to $\eta = 4$

Barrel EM calorimeter

Replace FE/BE electronics

Lower operating temperature (8°)

CMS endcap calorimeters



HGCal design overview

TDR not released yet – Here: recent technical choices but older prelim. performance results

ECAL (CE-E)
Silicon + Lead/Steel
28 layers
26 X_0, 1.7 λ

HCAL (CE-H)
Silicon/Scintillator + Steel
24 layers
9 λ

6 million Silicon channels
≈ 600 m^2 ≈ 3× CMS Tracker
0.5 and 1 cm^2 cell sizes

Mixed layers in hadronic part
≈ 500 m^2 Plastic scintillator
On-tile SiPM

Operation at -30°C
With CO$_2$ cooling
Mitigate Si leakage current

Sensors, modules and cassettes

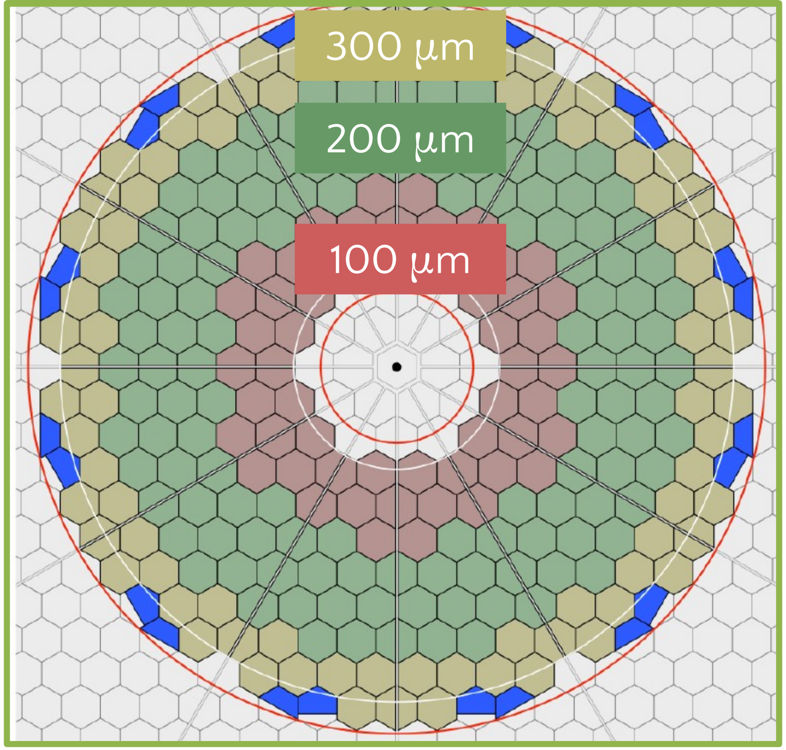
Hexagonal Silicon sensors
6" or 8" wafers (baseline 8")

Three Silicon sensor thicknesses
Higher pseudorapidity → thiner sensors

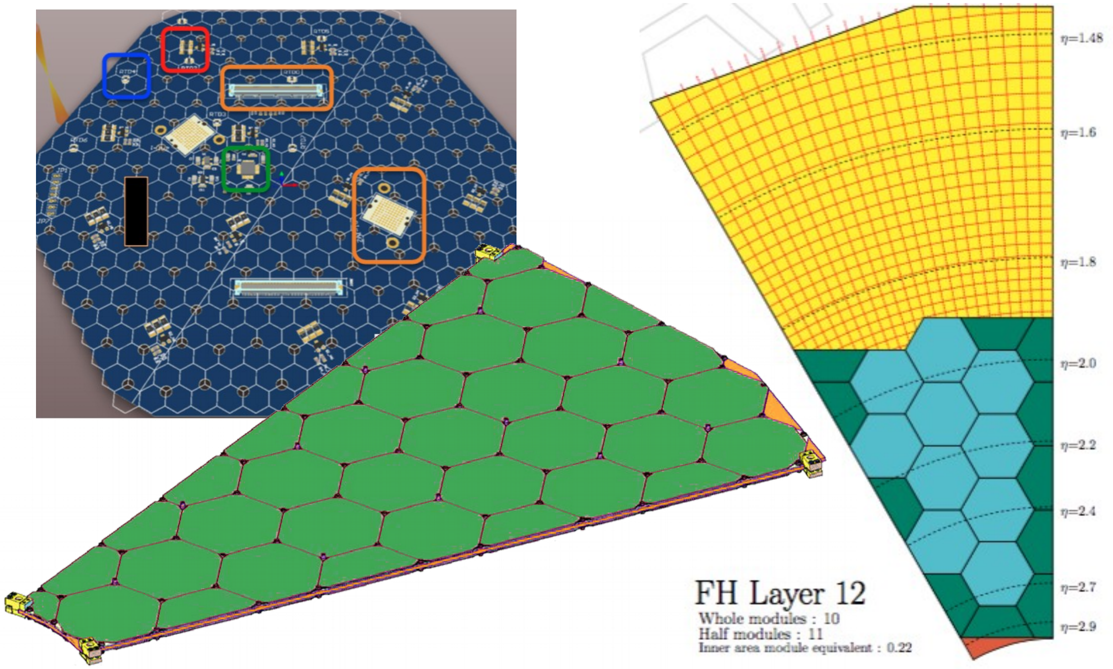
Modules assembled on cassettes
30° or 60° sectors

Scintillating tiles in the low-radiation region
Mixed Silicon-Scintillator cassettes

Full Silicon layer



Modules and cassettes



Details on Silicon sensors in the presentation of Elias Pree
Scintillator performance studies in the presentation of Francesca Ricci-Tam

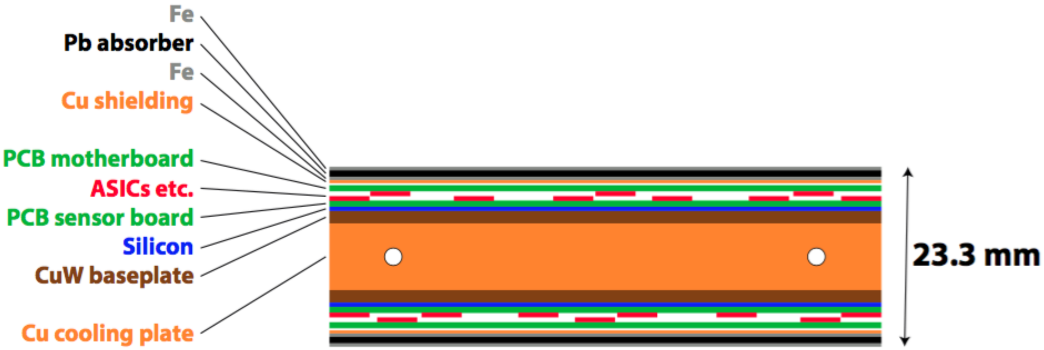
Mechanical structure

Silicon sensors mounted on copper cooling plates

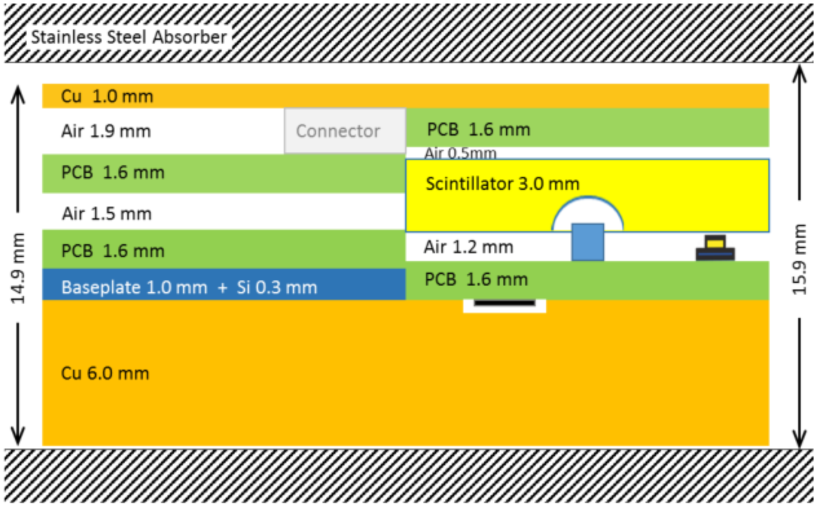
Two PCBs for each sensor layer

1 module PCB (wired-bonded to Si sensors) + 1 multi-module PCB (for communication)

Silicon double layer cross section



Mixed layer cross section



Stack of cassettes and absorber plates

ECAL: Lead absorber integrated into cassettes

HCAL: Cassettes inserted between full disks of Stainless Steel absorber

Front-end readout chip

Critical part of the system

Analogue + digital (large buffers, trigger data reduction), high-speed readout
Aim to be used for both the Silicon and the Scintillator parts

Low noise
Large dynamic range

~0.2 fC – 10 pC

Low power budget

Analog: < 10 mW / channel
Digital: < 5 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

Details on the front-end chip in the presentation of Artur Lobanov
(as well as on data concentration and trigger system)

Energy calibration

Calibration chain

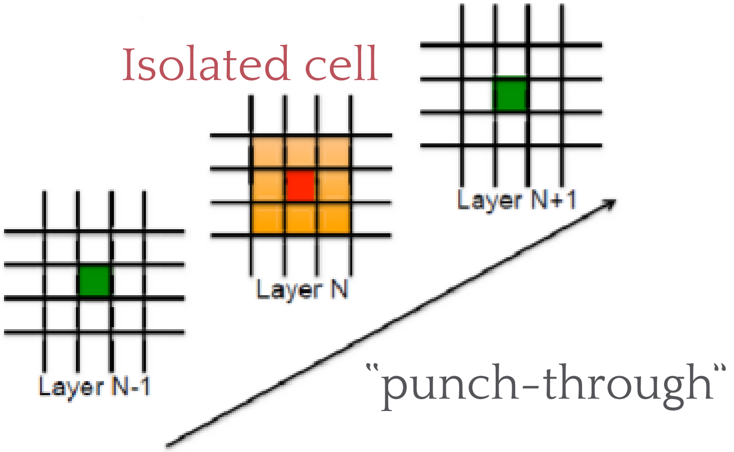
Equalization of the cell-to-cell response: inter-calibration

Cell weights taking into account absorber and active material

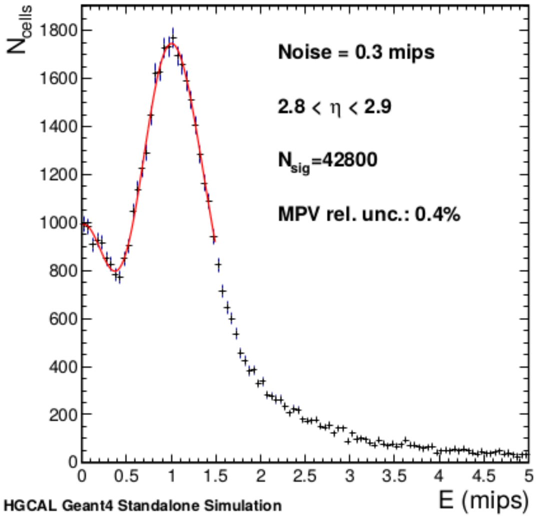
Absolute energy scale corrections (e.g. with standard candles like Z → ee)

(Standard techniques very similar to what is used in current detectors)

Inter-calibration with punch-through



MIP peak fit example



Inter-calibration

Require isolated cell

Track MIP signal in layers ±1

< 1% constant term requires 3% precision

1.5M minimum bias events needed

Noise of 0.4 mips → 3% precision

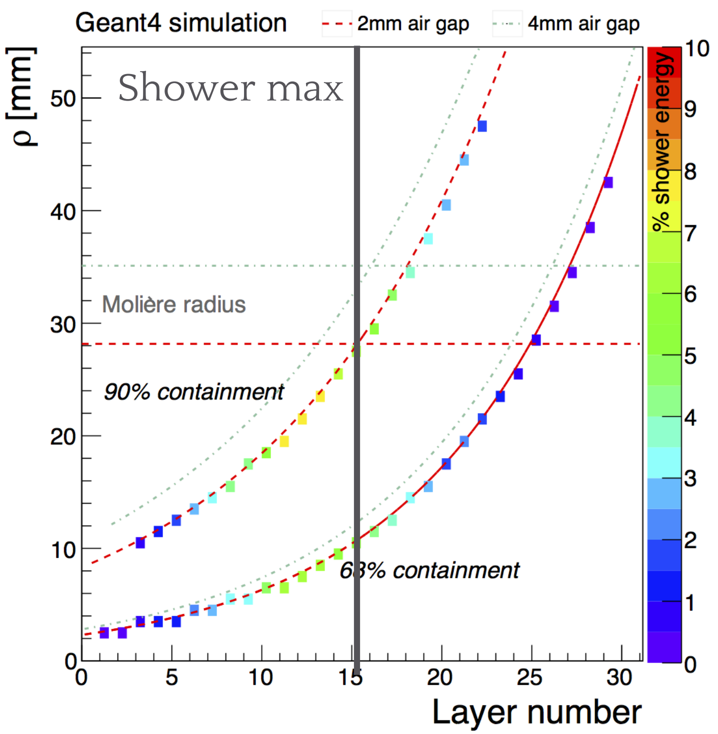
Events available daily

Can be done at the HLT with L1 rate

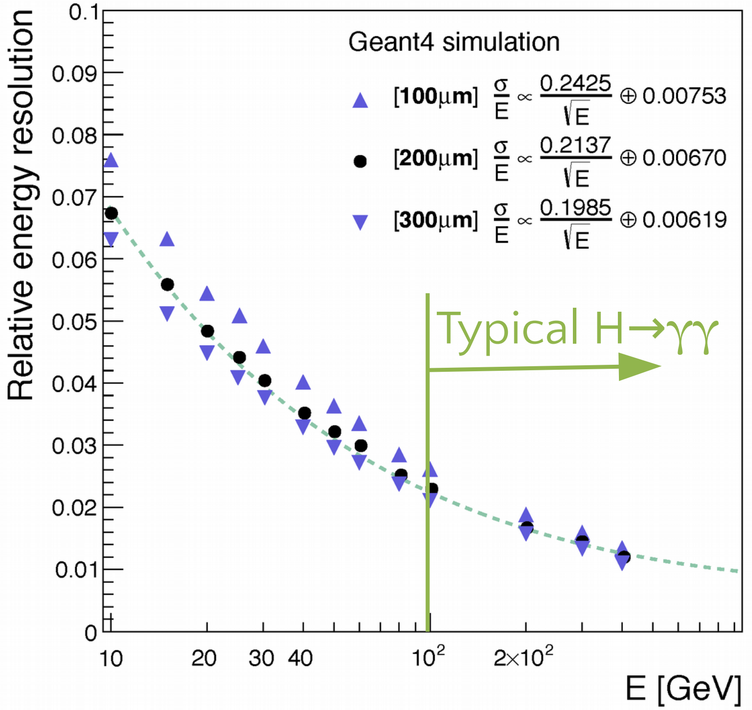
Overview of calibration techniques at HL-LHC in the presentation of Martin Aleksa

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 – 25 %
Constant term: target 1%
Forward: moderate p_T = high energy

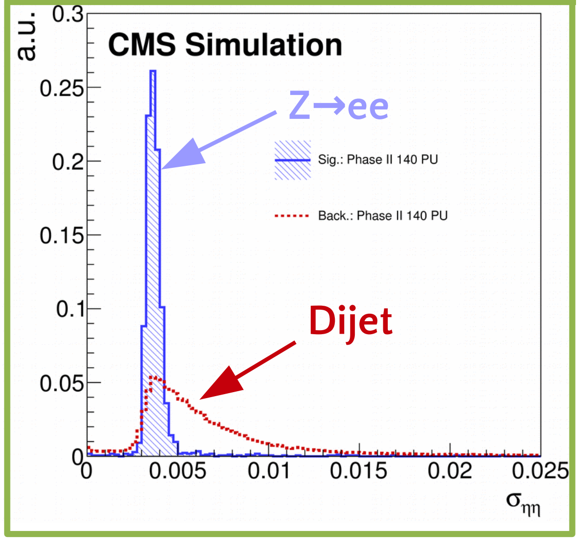
Results from the Technical Proposal (CMS-TDR-15-02)

Electromagnetic object identification

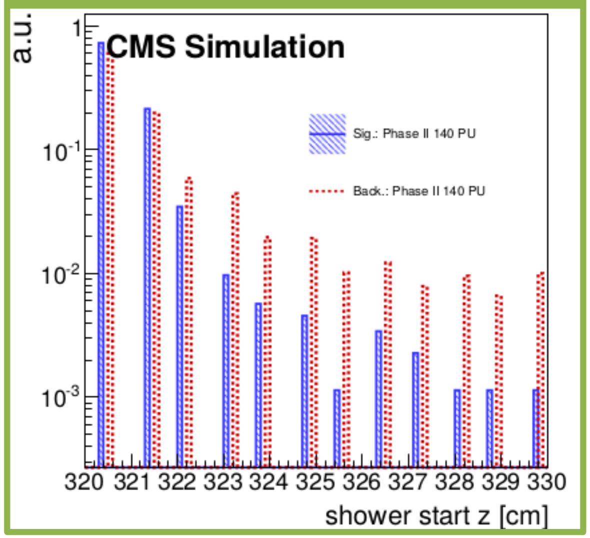
Improved particle identification

Thanks to the high granularity and the longitudinal segmentation

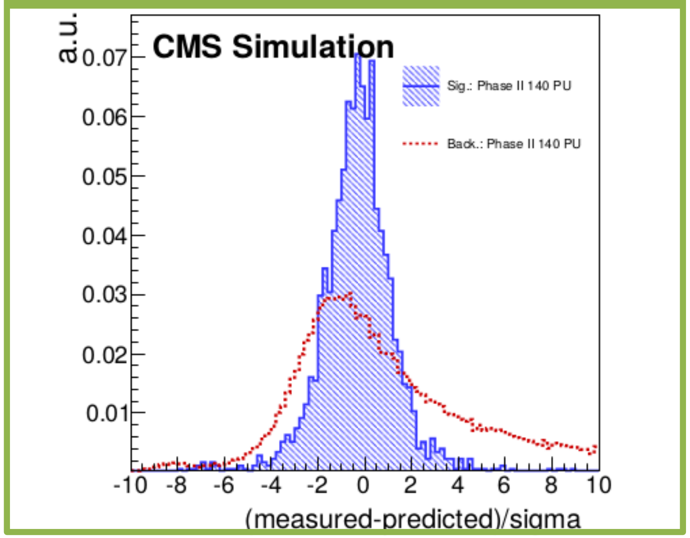
Shower width



Shower start position



Compatibility with expected EM shower length



Reconstruction of the shower axis

More precise shower width variables

Even without mechanical projectivity

Shower start

Separation charged pions vs EM objects

Shower length

Easily parametrized

Logarithmic E dependence

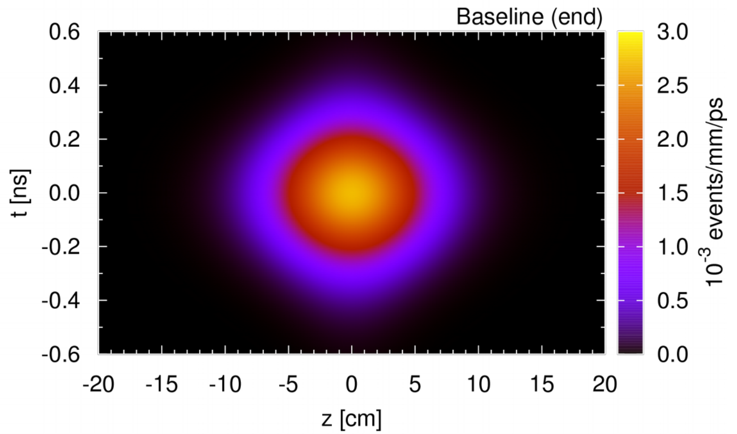
Powerful ID variable

Results from the Technical Proposal (CMS-TDR-15-02)

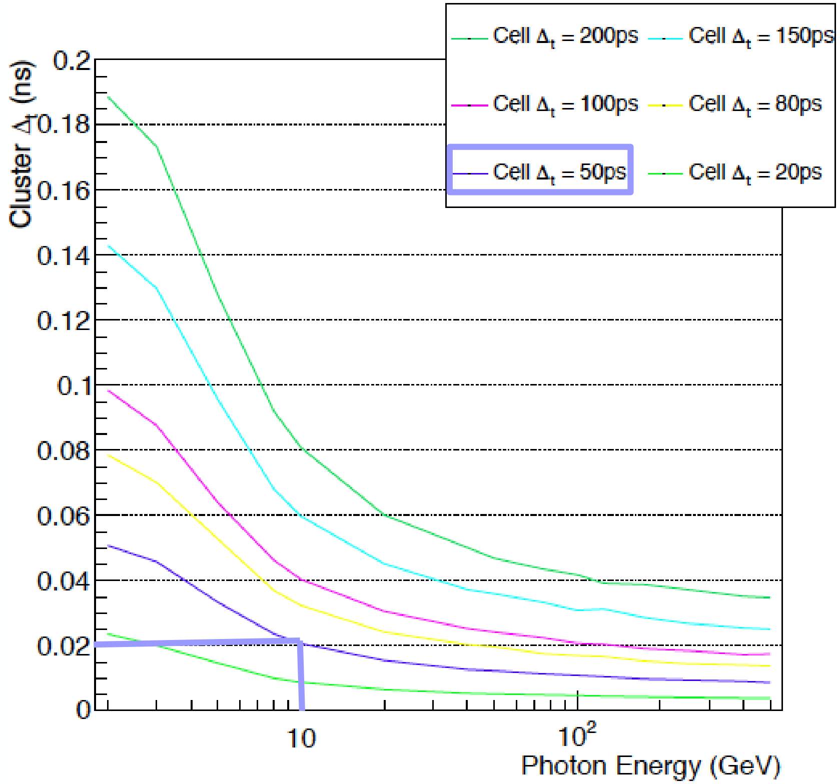
Timing

Per cell Δt = 50 ps
Cluster resolution: < 20 ps
For energy > 10 GeV

HL-LHC: 160 ps wide crossing

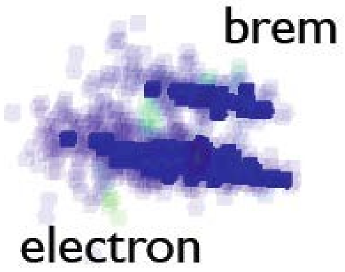


Cluster timing resolution vs energy



Can collect energy deposits within a 30 ps window
Electron: Seed and brem photons
Jets: reject PU particles

Electron with bremsstrahlung



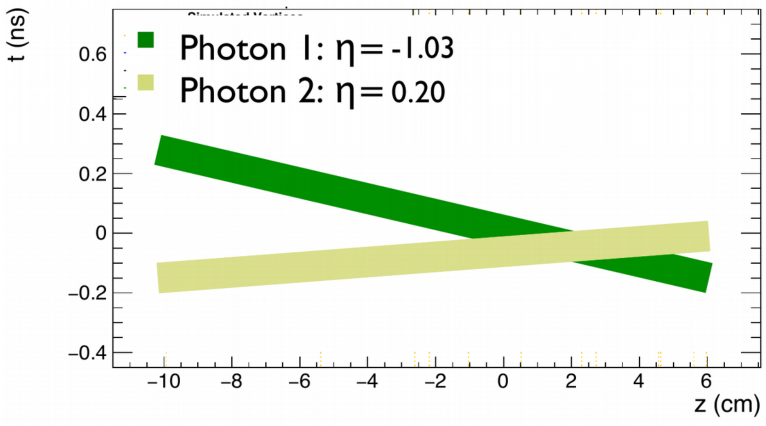
Timing and vertex triangulation

Reconstruction of vertex space-time from object timing

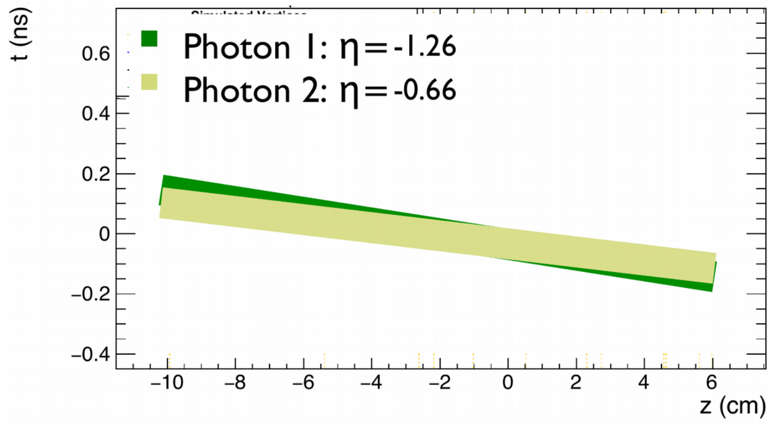
2 objects needed: e.g. 2 photons

30 ps resolution assumed below (study in the barrel but works for endcaps as well)

Large rapidity gap



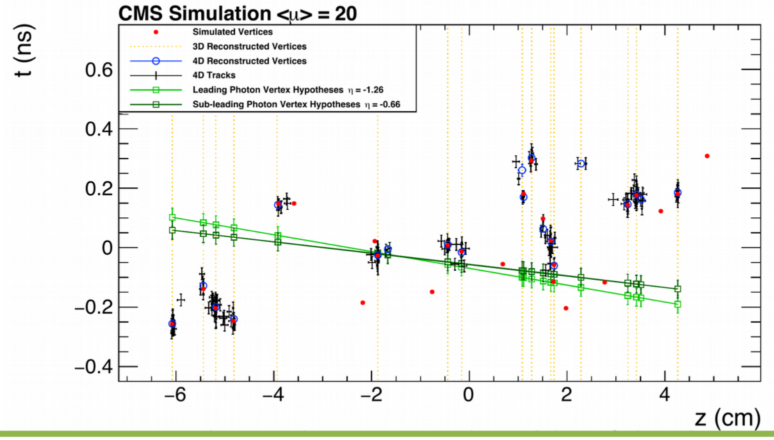
Small rapidity gap



Small rapidity gap: triangulation breaks down

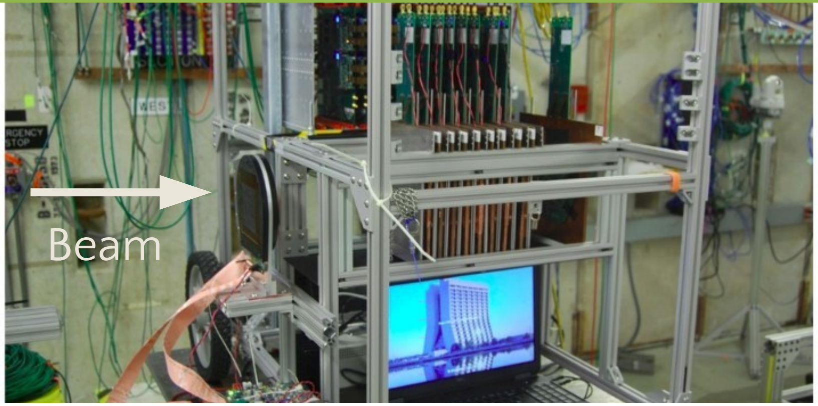
But can combine information with 4D reconstructed vertices

Space-time vertices

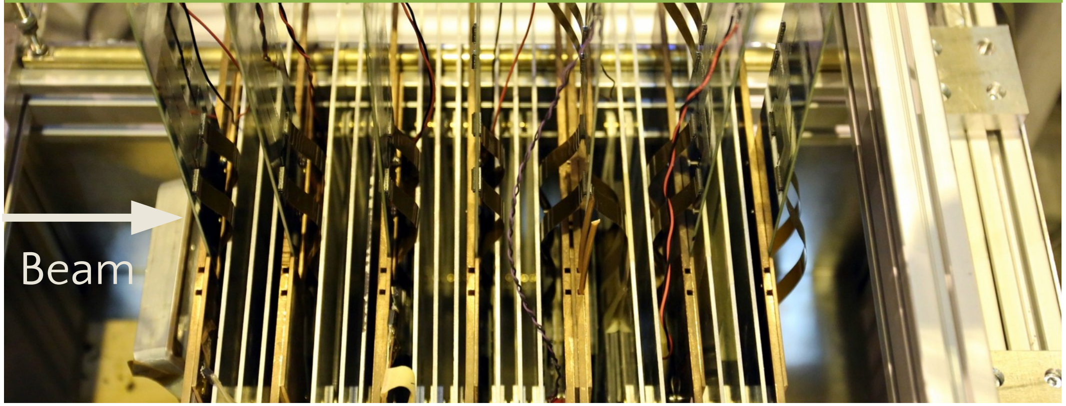


Test beams

Setup at FNAL

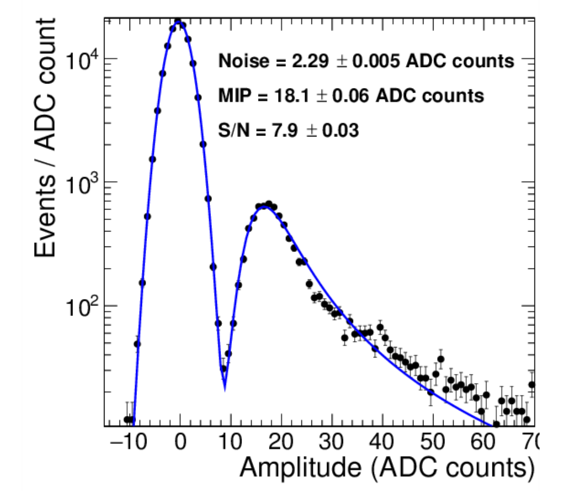


Setup at CERN

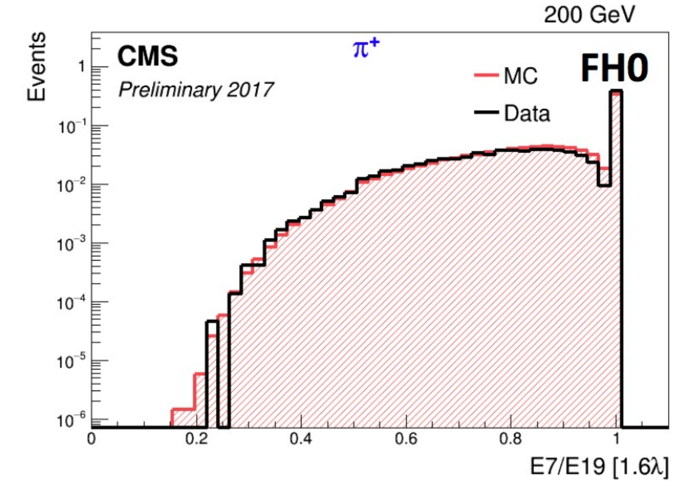


Validation of overall concept
Good agreement between data and simulation

MIP peak fit



Shower size – Data vs Sim



Covered in the presentation of Thorben Quast

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 being developed

To provide the best possible performance

The project is progressing at full speed on every aspect

TDR at the end of the year

On schedule for an operation with the first HL-LHC collisions