ATLAS and CMS upgrades on calorimetry and timing for the HL-LHC

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LLR CNRS / École Polytechnique

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Why the HL-LHC?

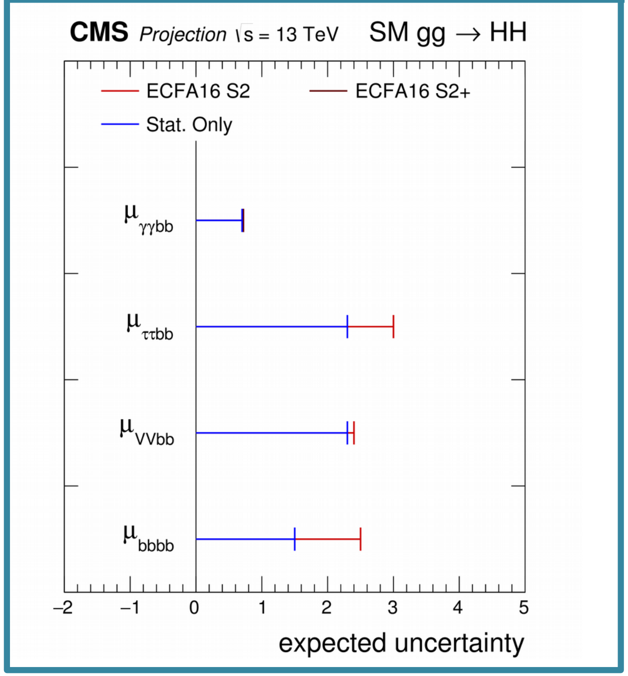
The Higgs is one of the most tangible window to new physics so far
And the LHC is a Higgs factory

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

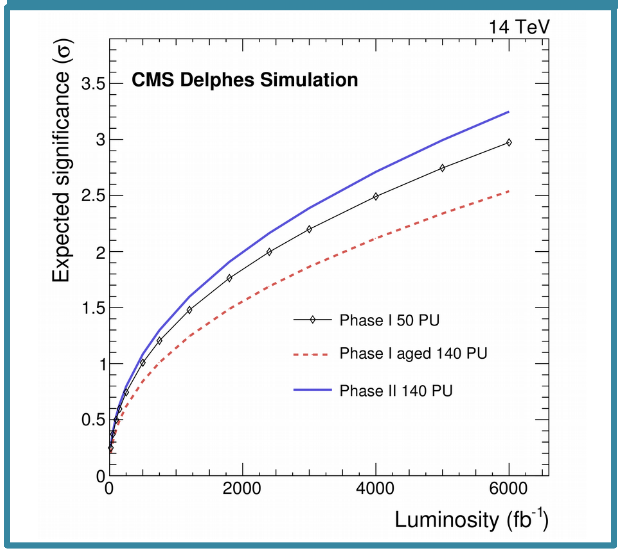
But we need luminosity
Higgs rare decays: H → μμ, H → Zγ, etc.
Double Higgs constraints & Higgs self-coupling
Vector boson scattering & unitarity tests

And also...
Higgs precision measurements
Extension of high mass particles searches

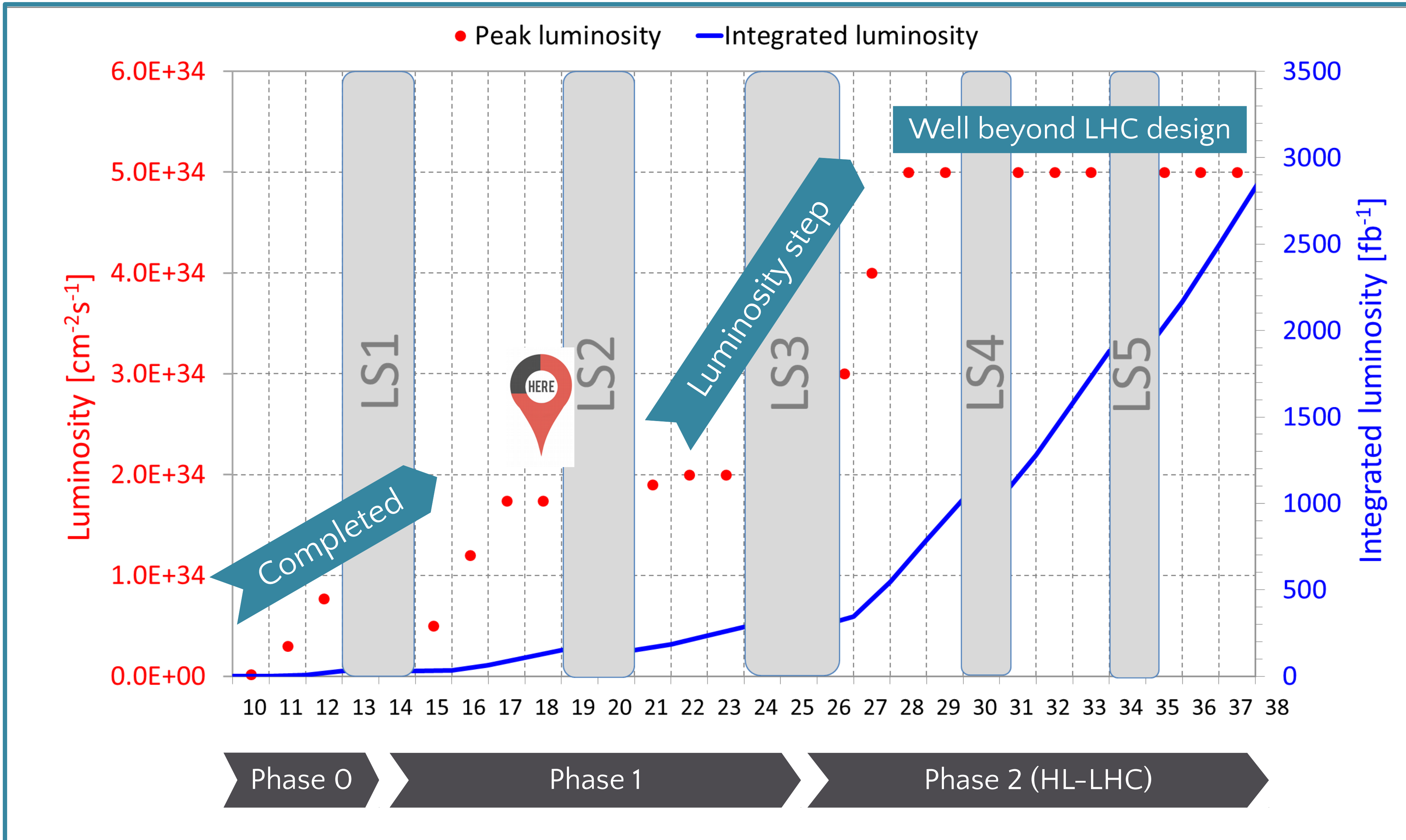
SM gg→HH projections



Longitudinal VBS significance

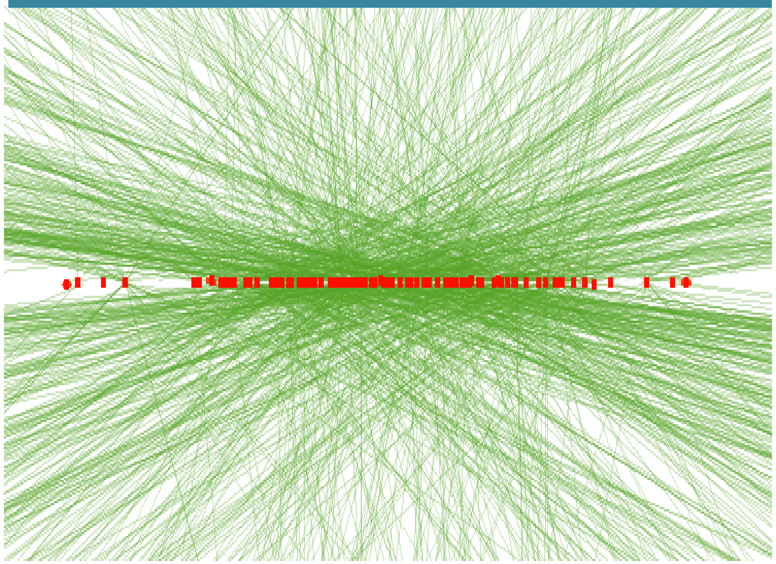


LHC and HL-LHC timeline

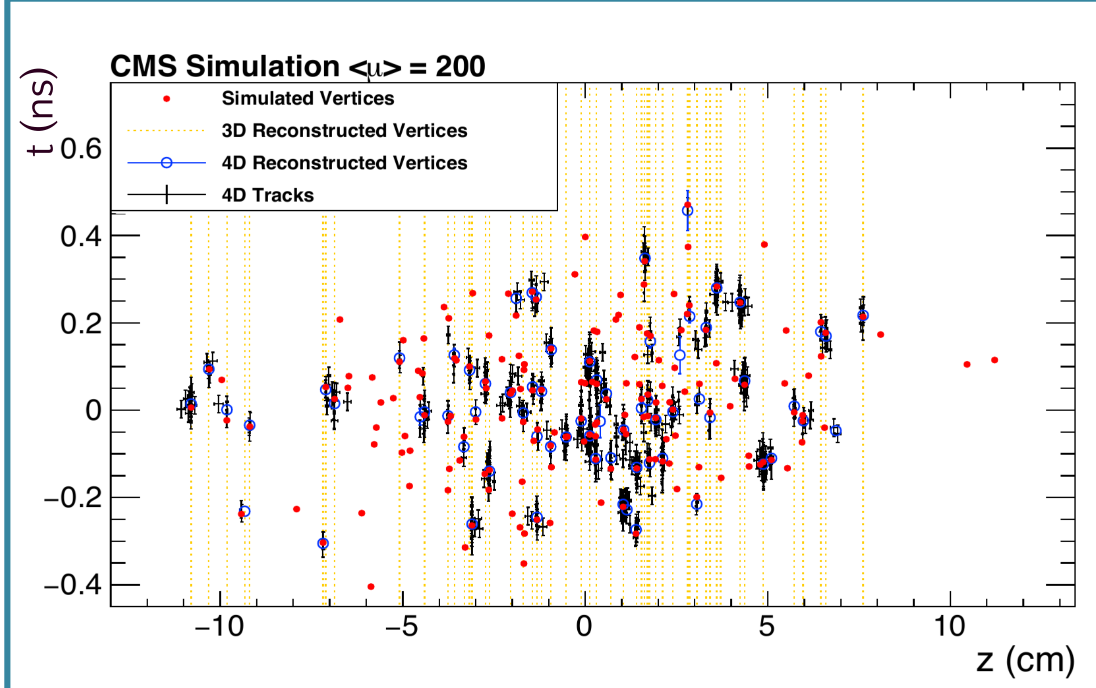


Higher granularity & Precision timing needed

Top pair event + 140 PU interactions in CMS
"Classical" spatial view of the vertices



Space-time view of the vertices



140 – 200 quasi simultaneous interactions

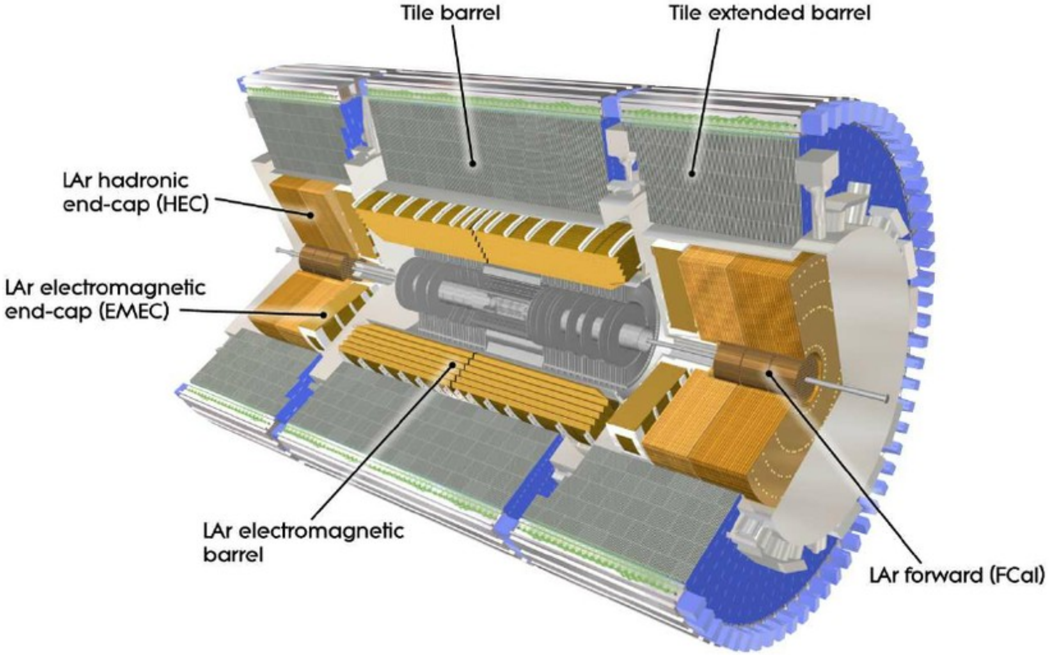
High granularity calorimeters and longitudinal segmentation to separate their contributions

Disentangle overlapping vertices with precise timing

Time spread: 100 – 200 ps
Key resolution: 10-30 ps

CMS and ATLAS calorimeter and timing upgrades

ATLAS



Endcaps Timing detector

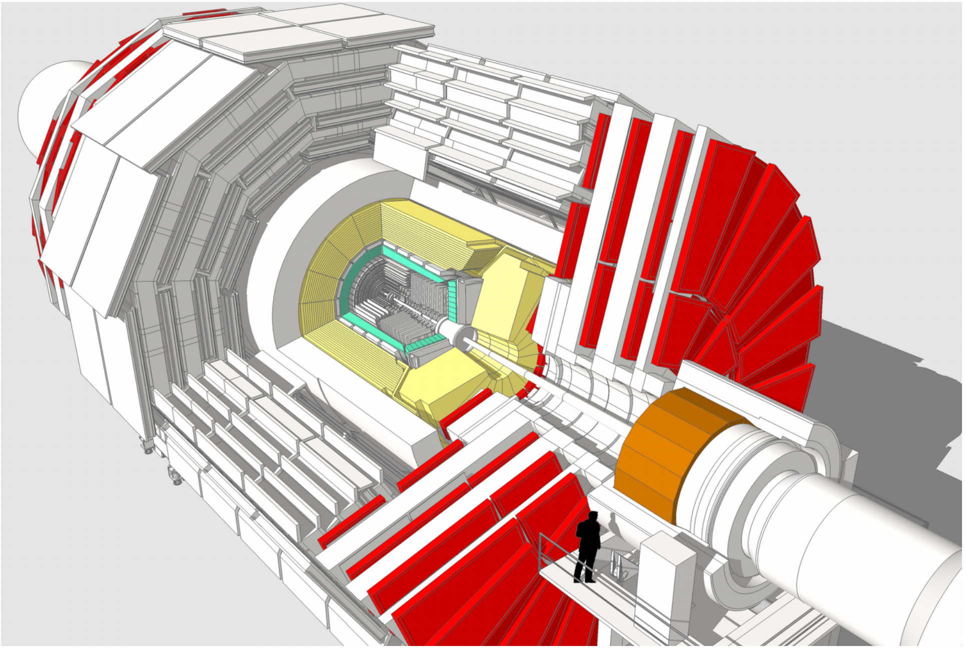
Calorimeter electronics upgrade
Replace FE/BE electronics
Full granularity at L1 (already Run 3)

CMS

New endcap calorimeters

Timing layer
Barrel & endcaps

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



ATLAS LAr electronics

Upgraded calorimeter trigger

Already during LS2 (2019-2020)

Demonstrators running since 2014

Finer granularity: trigger towers → super cells

Better energy resolution

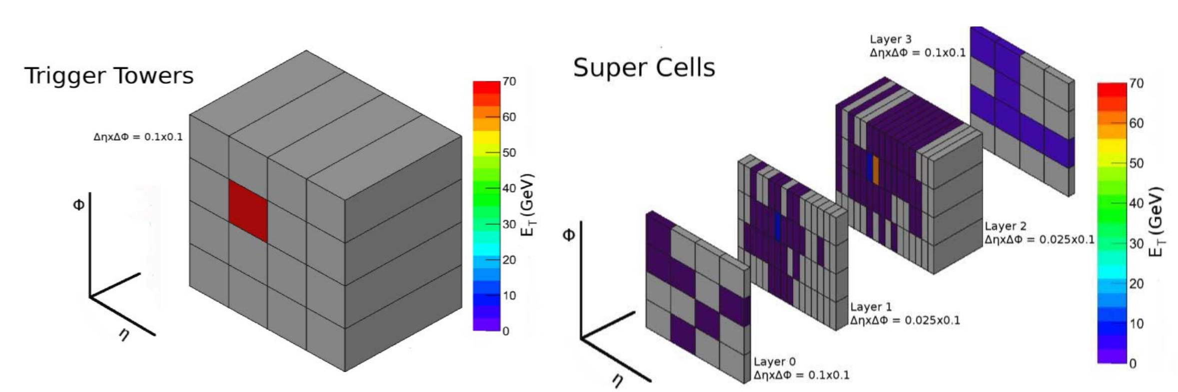
Better signal discrimination with shower shapes

Keeps the efficiency turn-on sharp

Keeps the e/γ trigger thresholds low

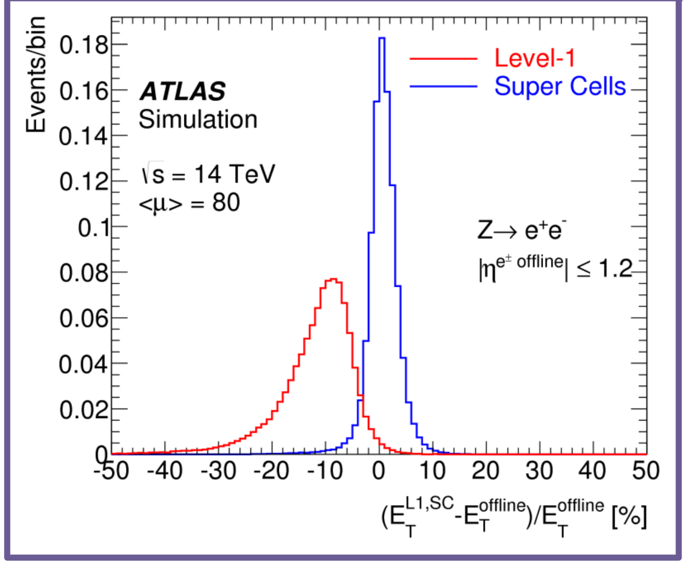
20-25 GeV for 80 PU

Increased granularity at trigger level

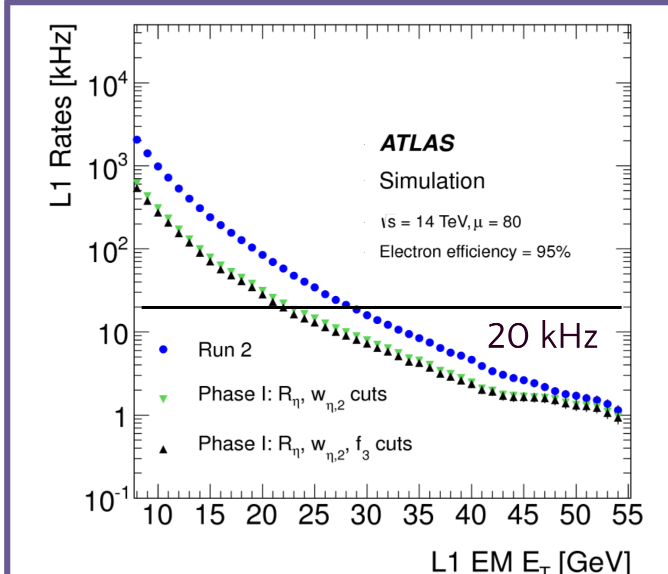


ATLAS LAr Phase-1 TDR [ATLAS-TDR-022]

Improved energy resolution

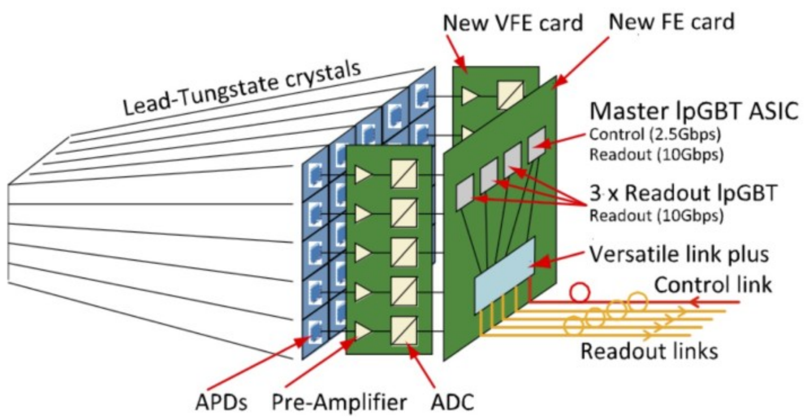


L1 e/γ rate reduction



CMS ECAL barrel

New FE electronics architecture



CMS ECAL Barrel TDR [CMS-TDR-015]

Upgraded VFE and FE electronics

Shaping time reduction

Full crystal granularity sent to back-end

Faster shaping

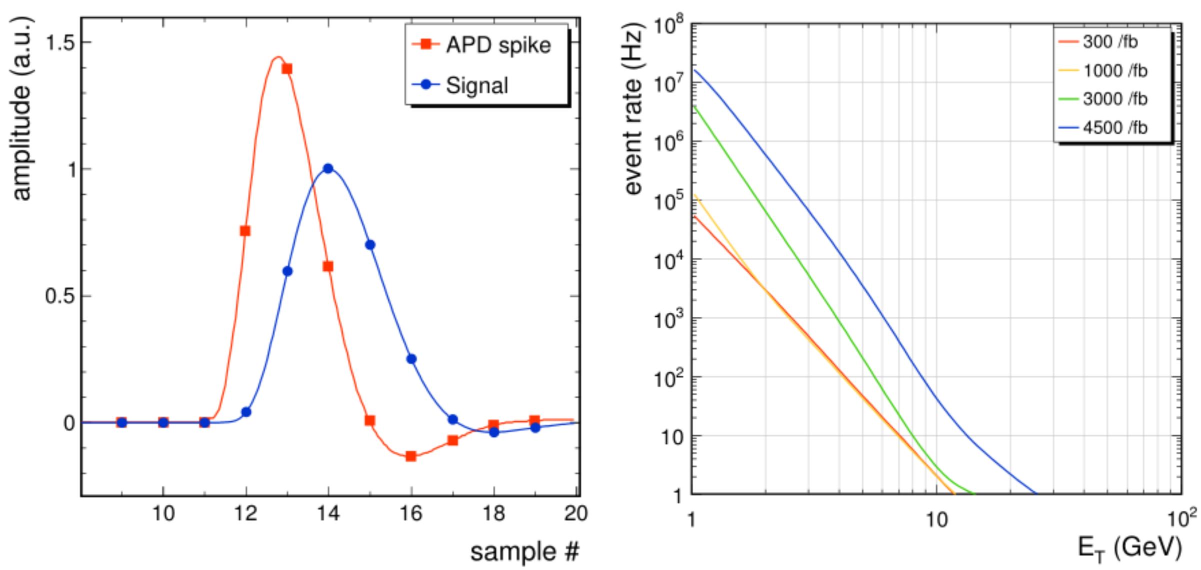
Reduced out-of-time pile-up

Better discrimination scintillation vs spikes

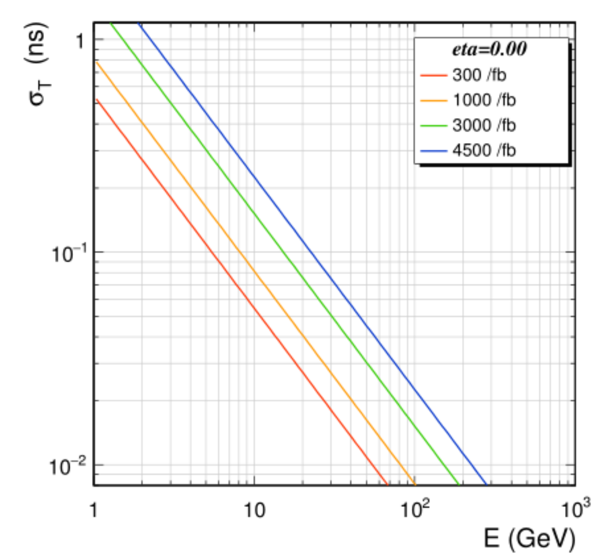
Faster rise time

30 ps timing resolution

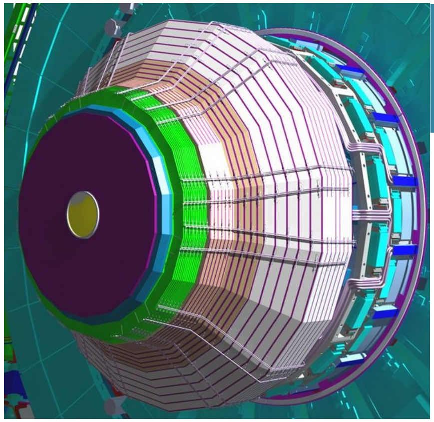
APD spike tagging and rate



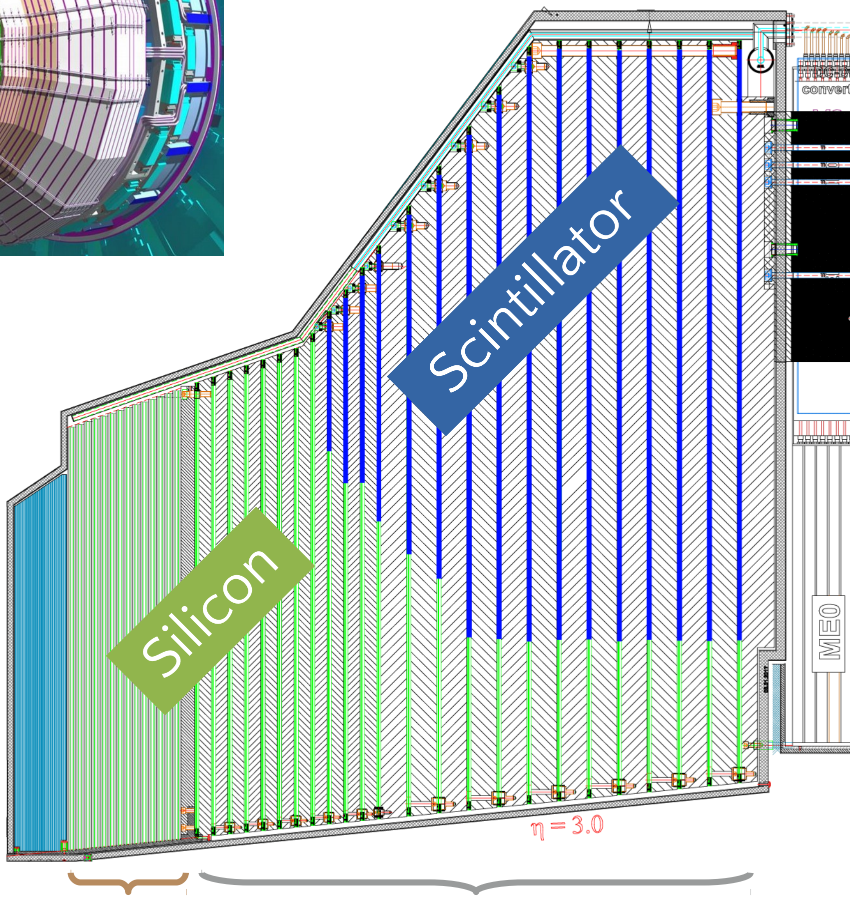
Timing resolution



CMS HGCal design overview



CMS HGCAL
[CMS-TDR-019]



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

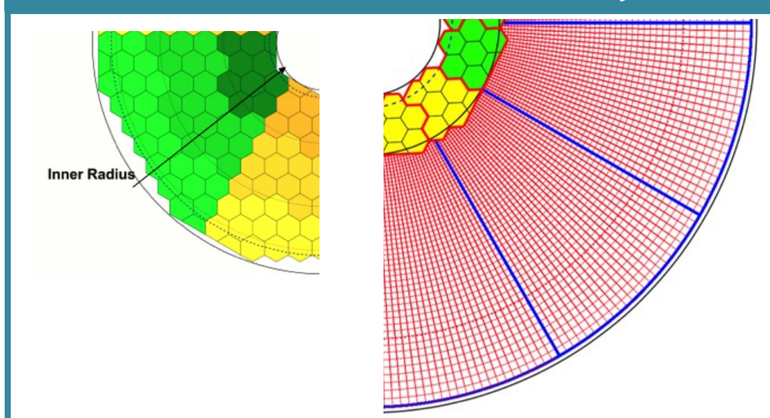
HCAL (CE-H)
Silicon/Scintillator + Steel
24 layers
9 λ

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

Full Silicon and mixed layers



See Ed Scott talk for more details (link)

Sensors, modules and cassettes

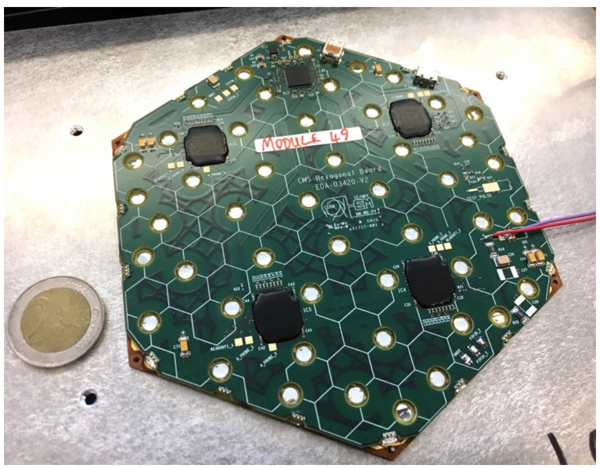
Hexagonal Silicon sensors
8" wafers

Modules assembled on cassettes
30° or 60° sectors

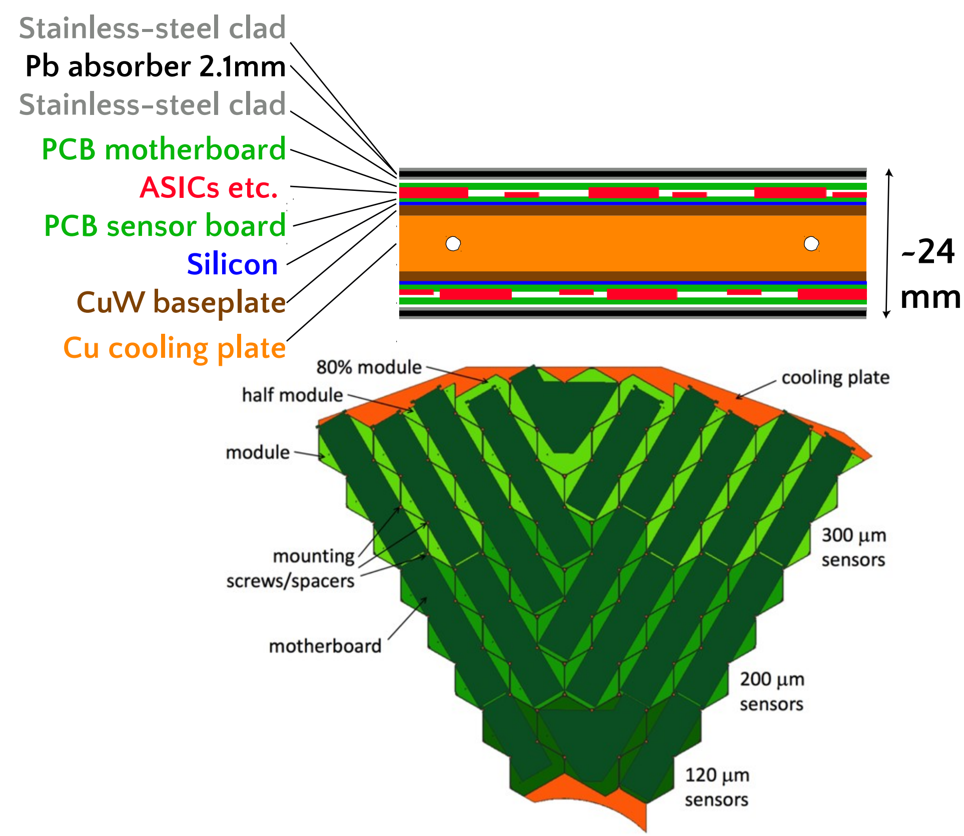
Two-PCBs architecture
Sensor PCB and motherboard

Sandwich of several elements
Cu+CuW plates, Silicon, PCBs. absorber

Modules and motherboard



Cassette (ECAL section)

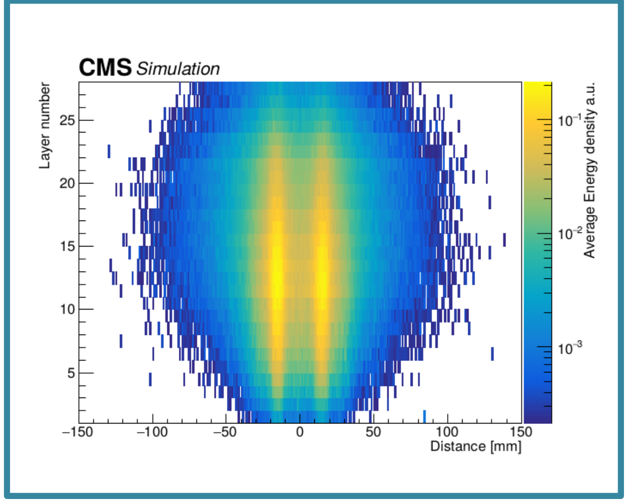


Electromagnetic shower properties

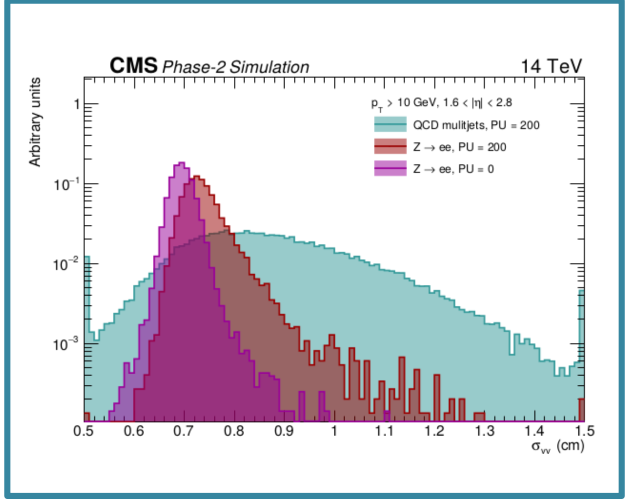
Electromagnetic shower size
Very narrow in the first layers
Particle separation, pile-up rejection
Moliere radius: 3 cm

Energy resolution
Stochastic term: 20 – 25 %
Constant term: target 1%
Forward: moderate p_T = high energy

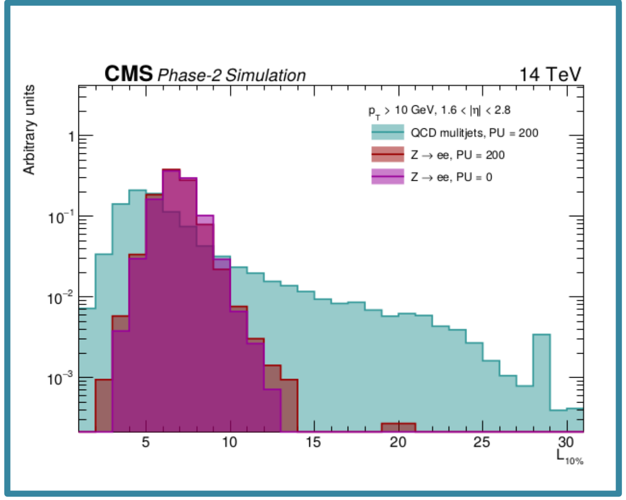
Profile of 2 close-by photons



Shower width



Depth integrating 10% of the shower energy



Reconstruction of the shower axis
More precise shower width variables
Better matching with tracks for electrons
Even without mechanical projectivity

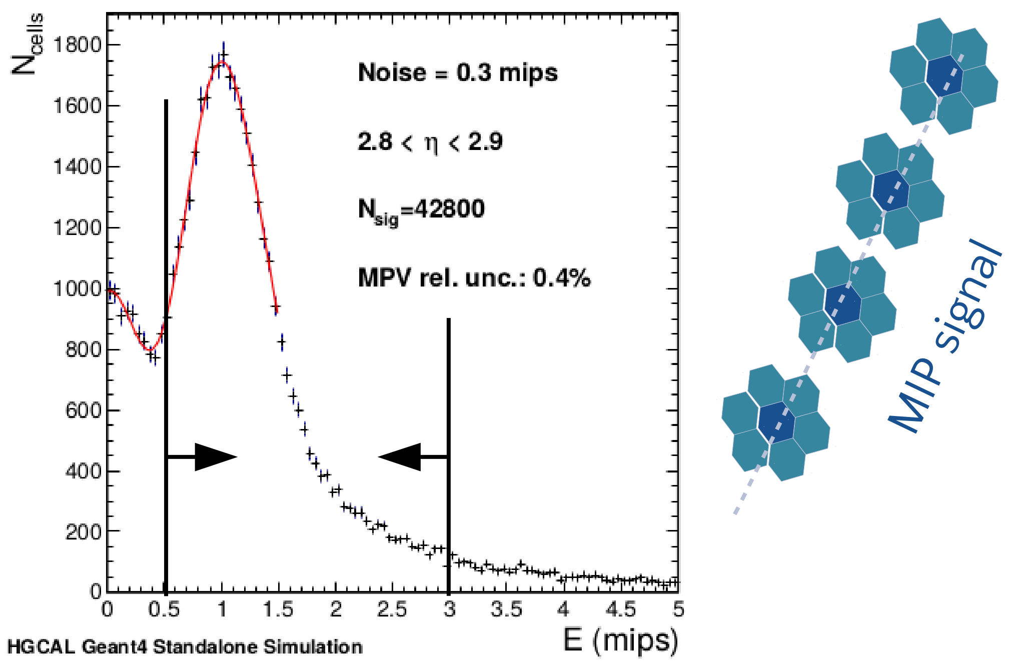
Shower depth information
Powerful ID variables
Robust to pile-up
Easily parametrized

Muon tagging

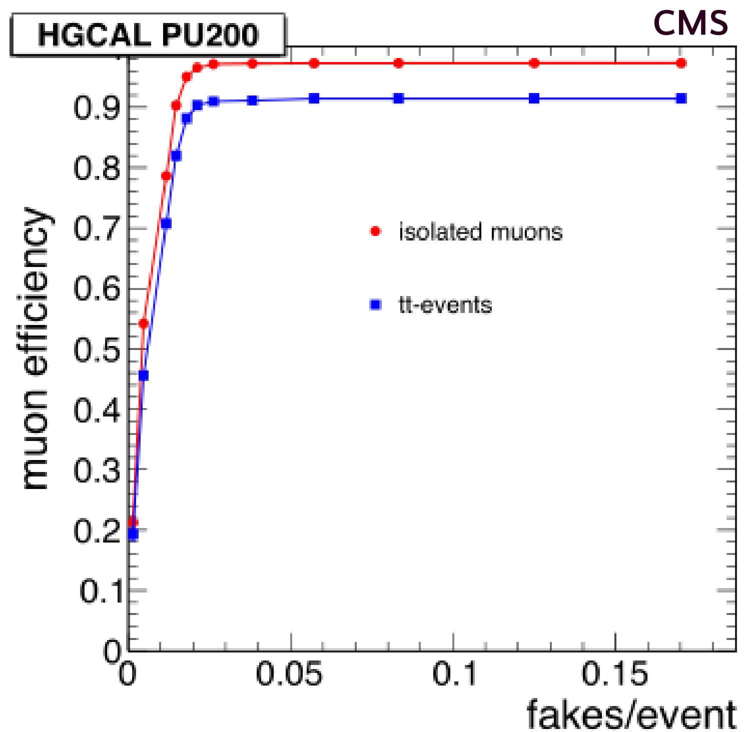
MIP signal around extrapolated tracks
Back of the HCAL part (reduced PU background)
Count number of layers containing a MIP signal

Complementary to muon chambers (ME1/1 and ME0)
In particular for η > 2
Full Silicon for η > 2.4

MIP "tracking"



Muon tagging efficiency vs fake rate

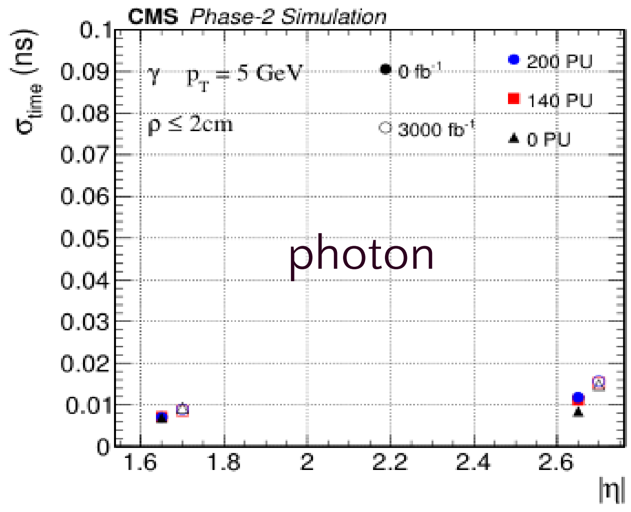


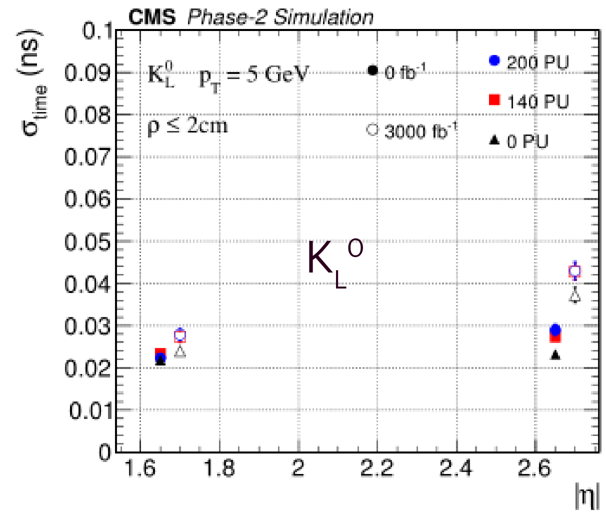
Cell and cluster timing

Timing above 12 fC
Cell resolution 20-150 ps
p_T=5 GeV photon → 10-15 ps
p_T=5 GeV K_L^0 → 30 ps

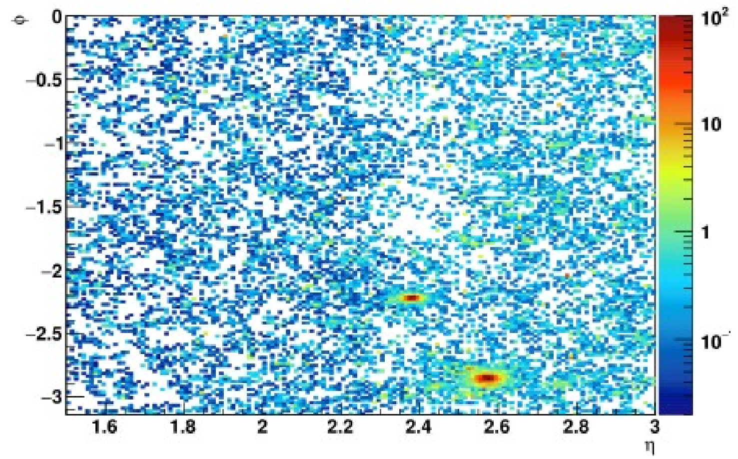
Reject PU clusters
Clean PU cells in clusters

Cluster timing resolution for photons and K_L^0

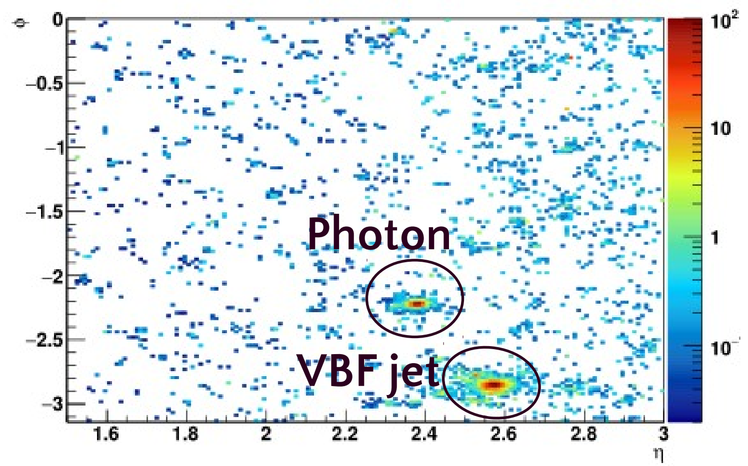




Pile-up cell cleaning

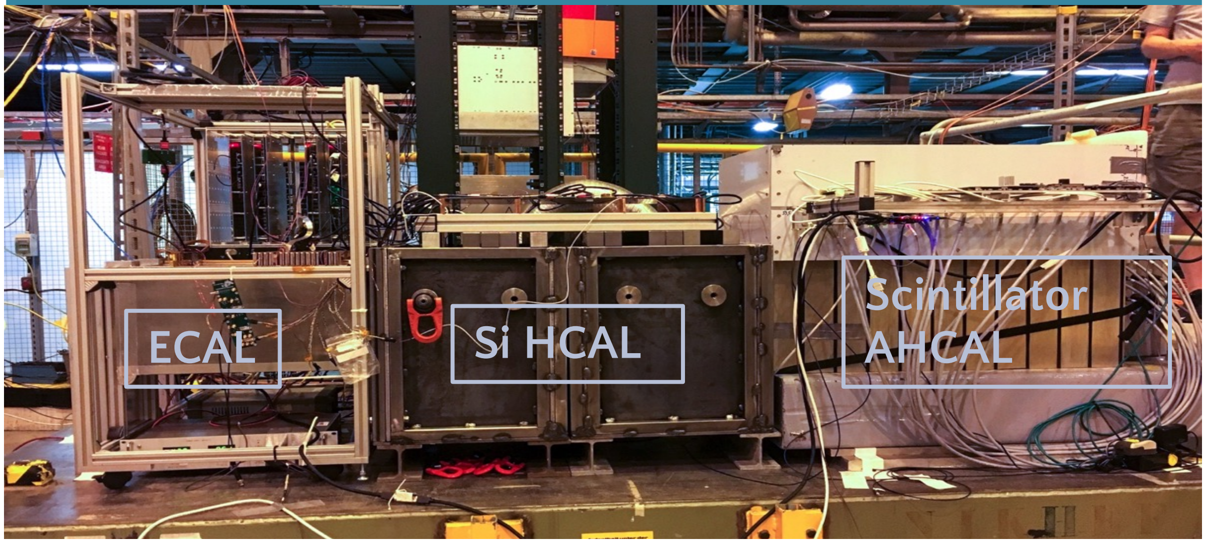


ΔT < 90ps

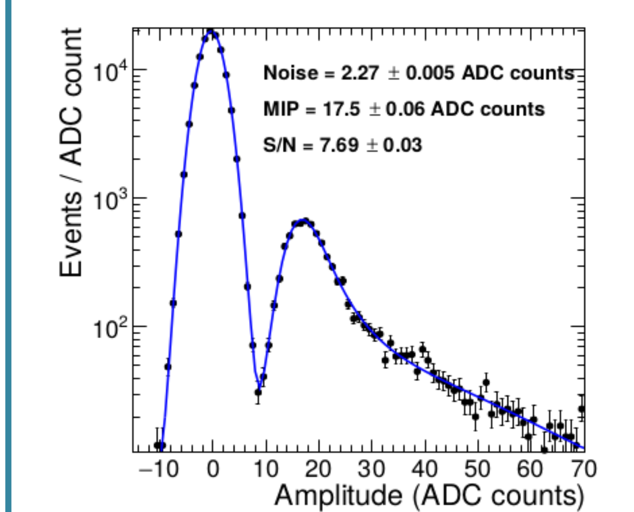


Test beams

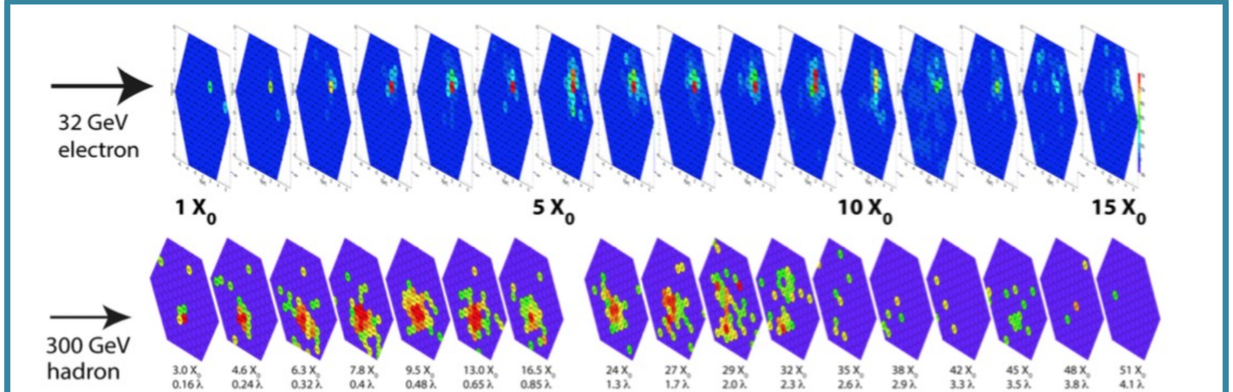
2017-2018 setup at CERN



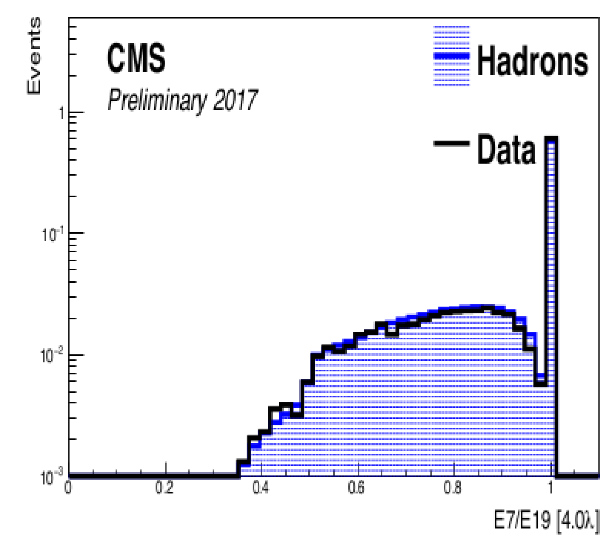
MIP peak fit



EM & HAD shower displays



Shower size – Data vs Sim



Validation of overall concept
Good agreement between data and simulation

ATLAS and CMS timing detectors

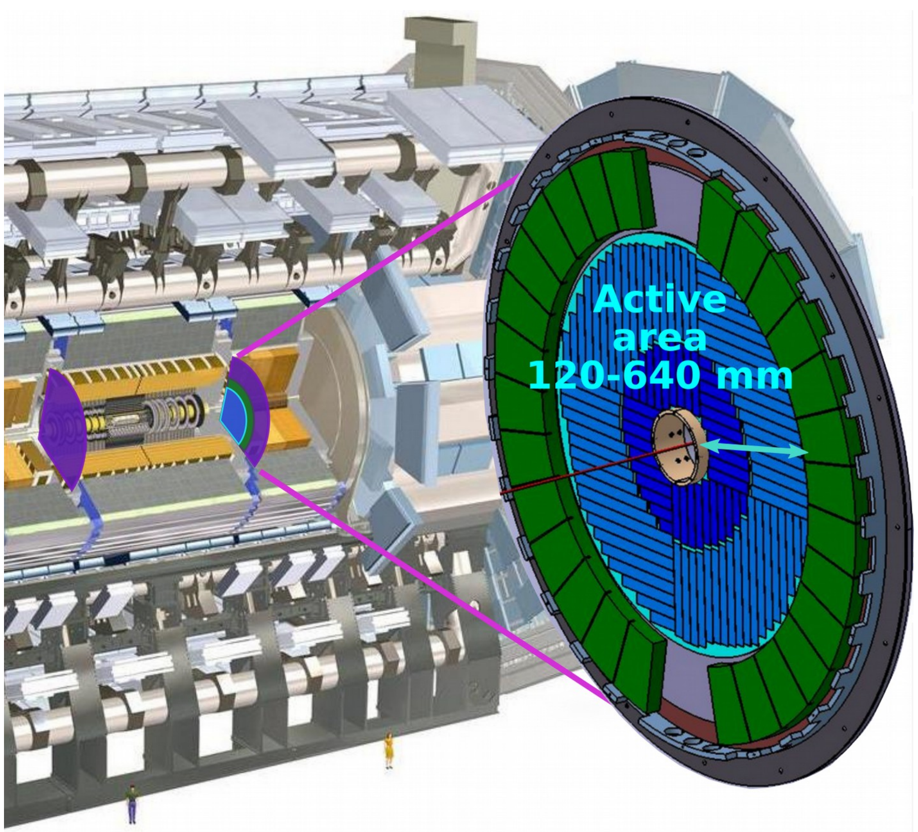
ATLAS HGTD

Coverage 2.4 < η < 4
75 mm thickness between tracker & calo
2 layers of Silicon sensors (LGAD)
30 ps resolution per charged track

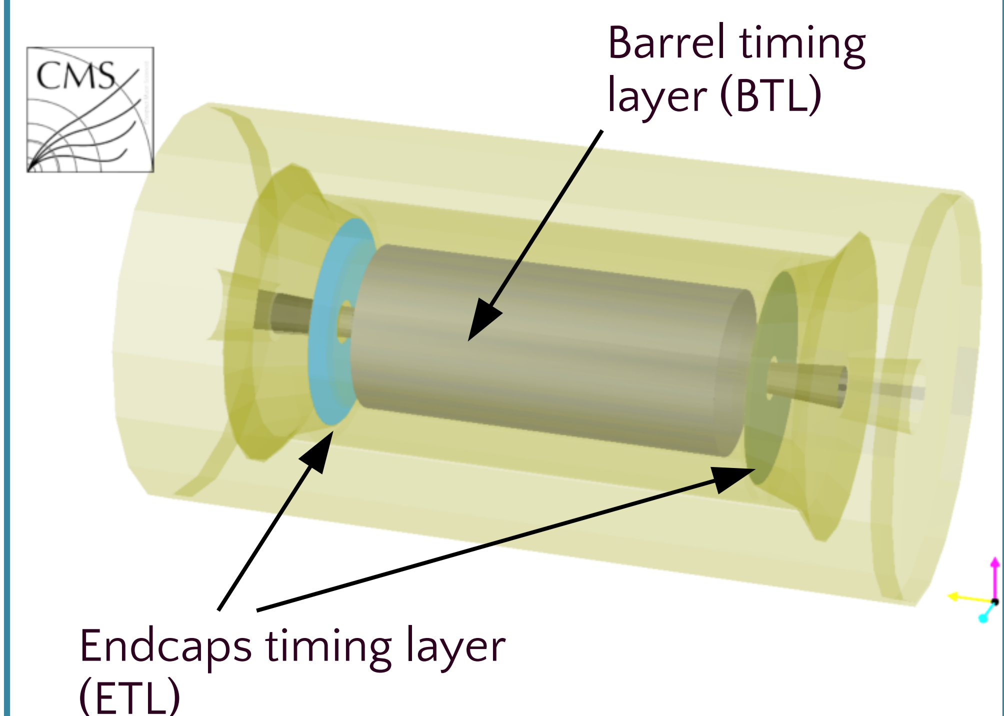
CMS MTD

Coverage η < 3
Barrel: 1 layer LYSO:Ce crystals + SiPMs
Endcaps: 1 layer Silicon sensors (LGAD)
30-40 ps resolution per charged track

ATLAS High-Granularity Timing Detector



CMS MIP Timing Detector



CMS MTD TP [LHCC-P-009]

See Christian Ohm talk for more details (link)

Detectors layouts

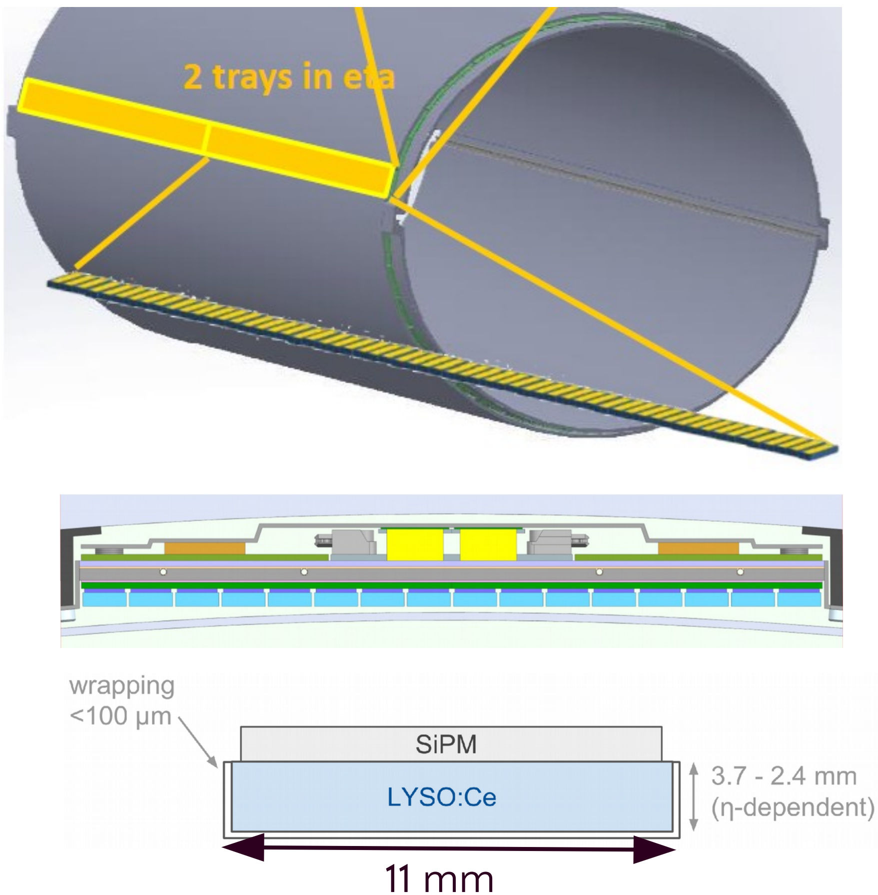
CMS barrel timing layer

$11 \times 11\ mm^2$ tiles (250k channels)
Variable thickness
→ material budget and S/N uniformity

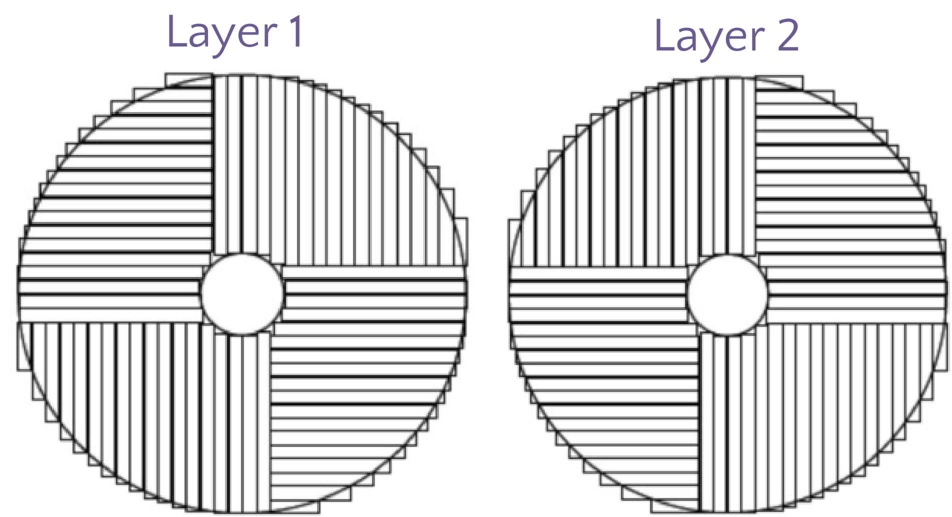
Endcaps timing layers

CMS: $1 \times 3\ mm^2$ pixels (1.8 M channels)
ATLAS: $1.3 \times 1.3\ mm^2$ pixels (3.54 M channels)

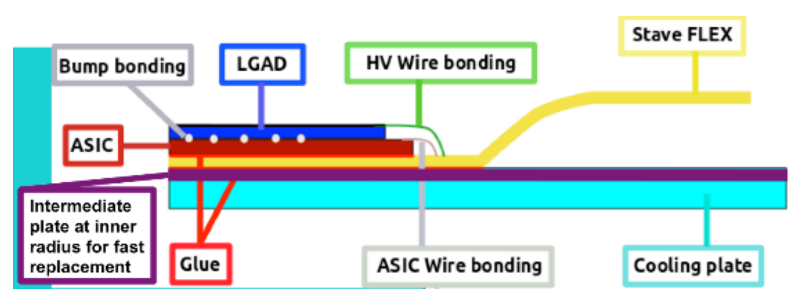
CMS BTL structure



ATLAS HGTD staves



ATLAS HGTD layer assembly

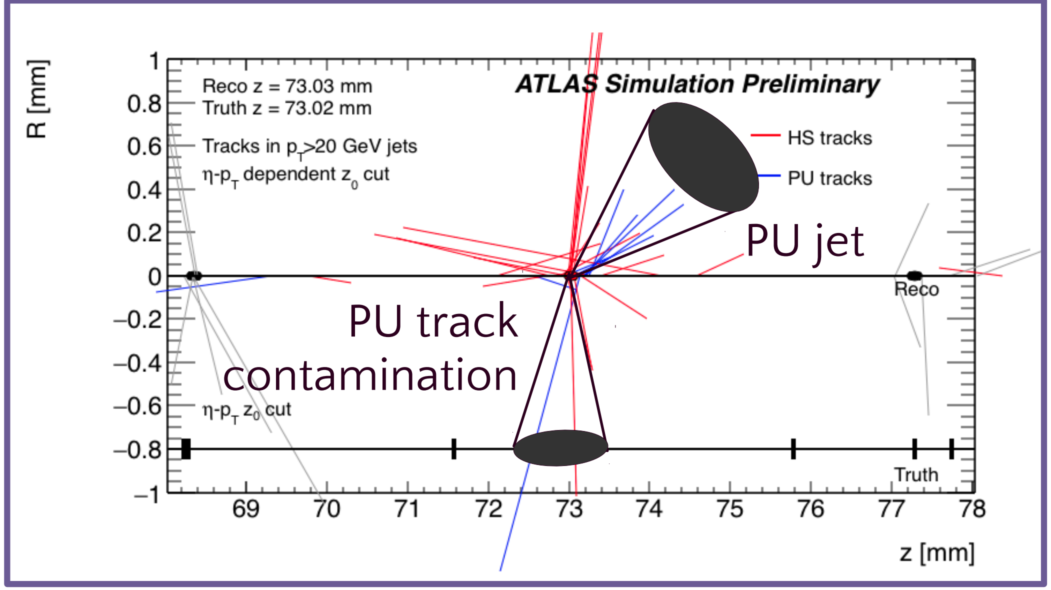


Pile-up jet cleaning

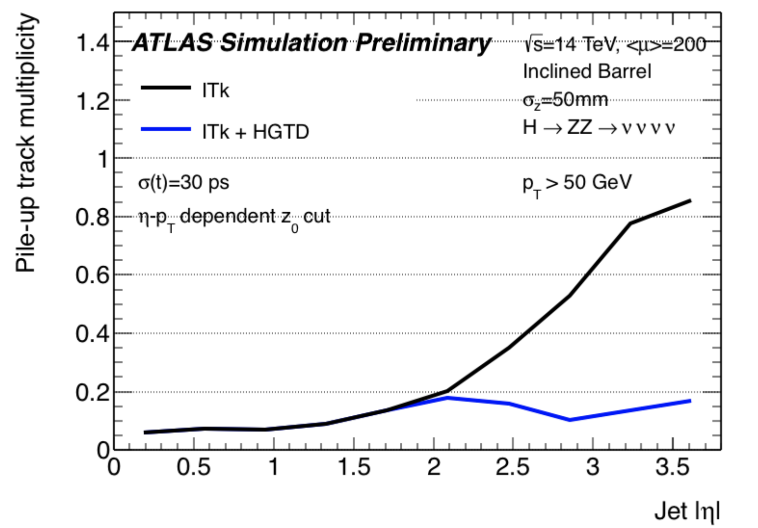
High vertex density
PU tracks associated to hard-scatter vertex

Timing information reduces the degeneracy
Improves PU track cleaning inside jets
Reduces the rate of PU jets

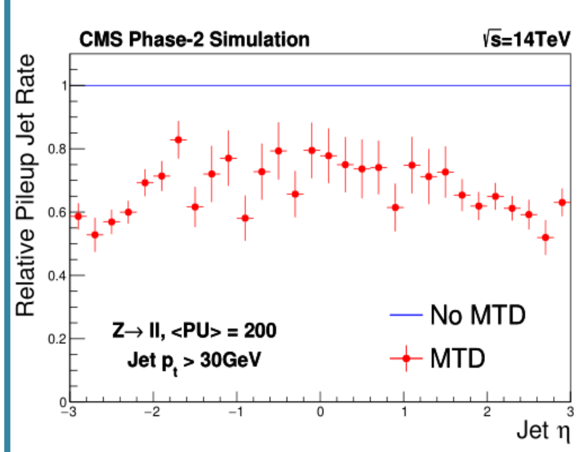
Hard-scatter and PU tracks in jets

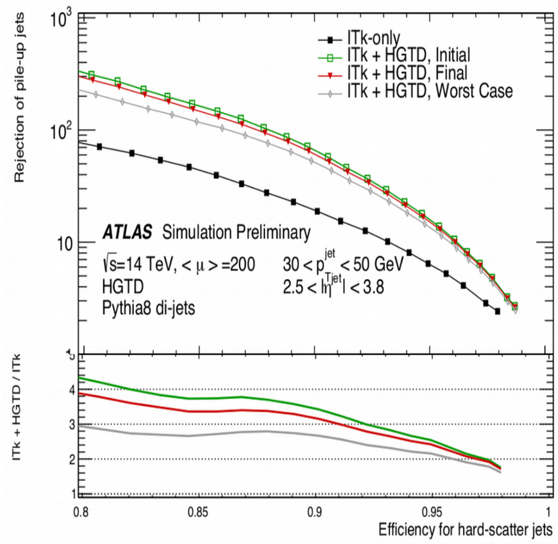


PU contamination in jets

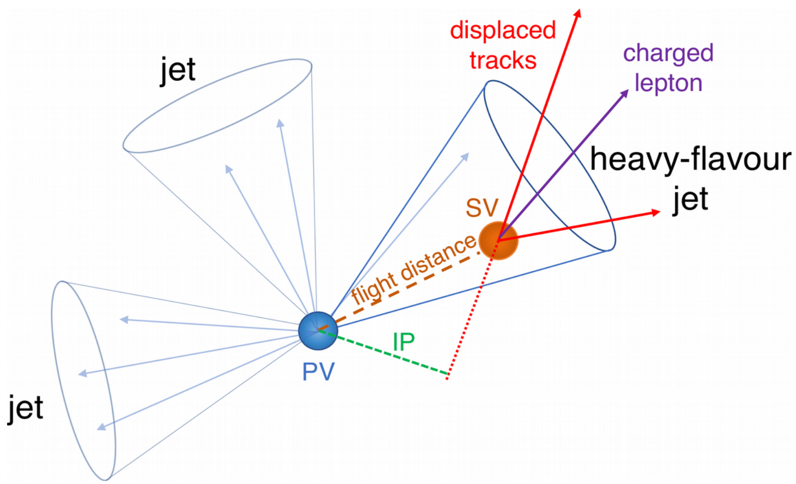


PU jet rate reduction

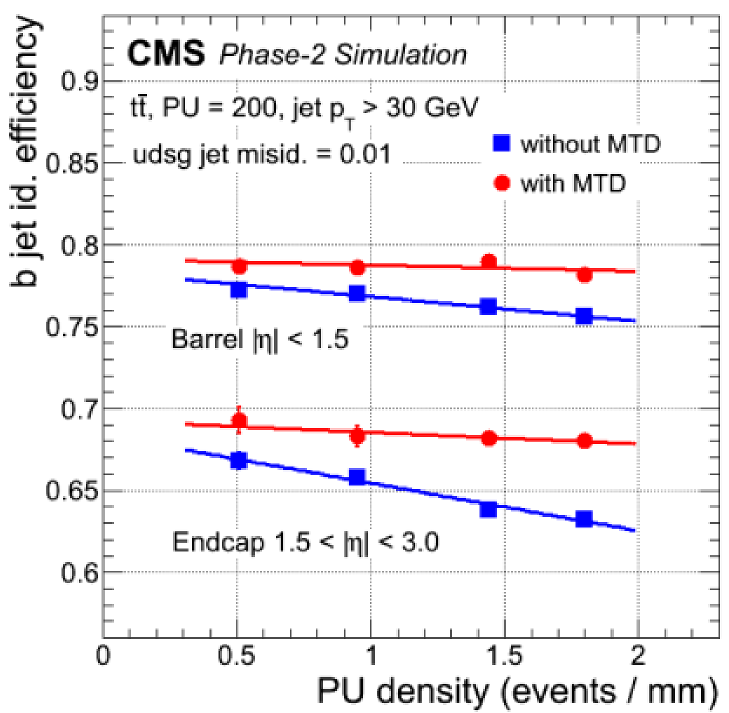




b-tagging



b-jet efficiency



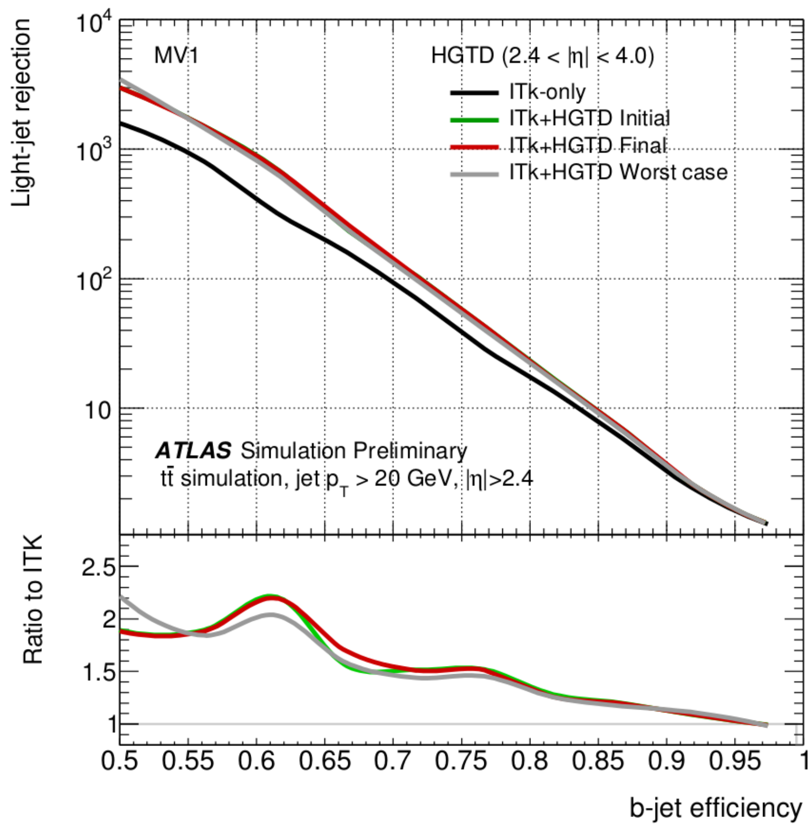
Spurious secondary vertices

Mitigated with timing

Reduce PU dependency

Impact acceptance-sensitive analyses ($HH \rightarrow bbbb$, $HH \rightarrow bb\gamma\gamma$)

Light-jet rejection vs b-jet efficiency



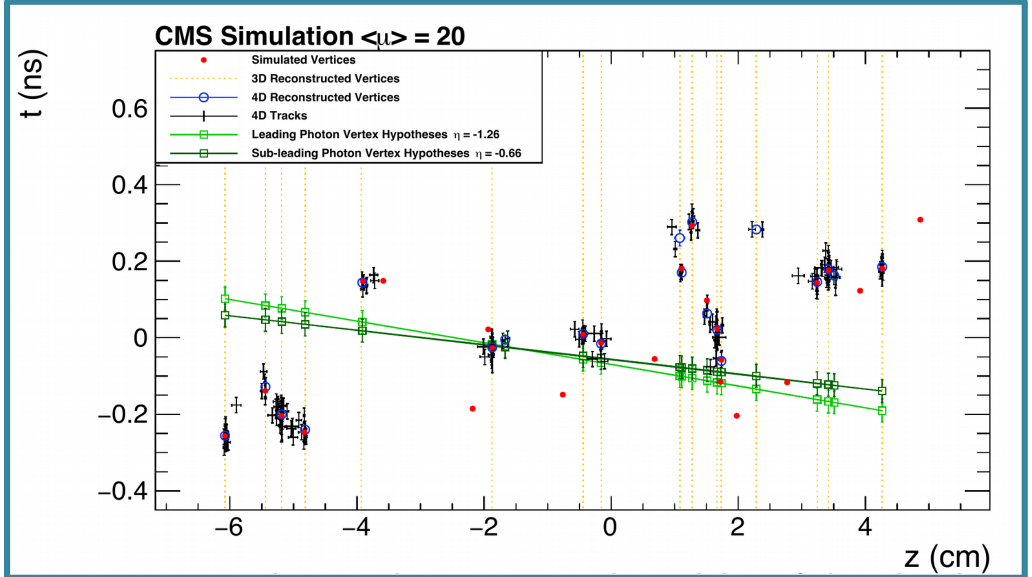
Di-photon vertex triangulation

Reconstruction of vertex space-time from photon timing (calorimeter)
Triangulation with 2 objects
Works even without pointing calorimeters

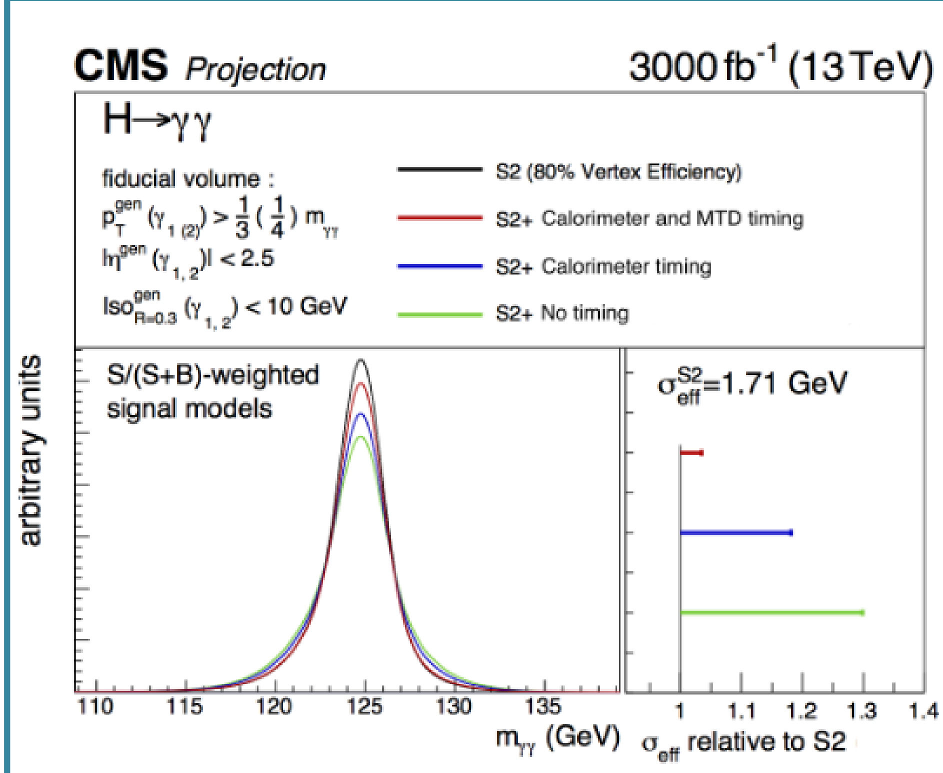
Small rapidity gap: triangulation breaks down
But can combine information with 4D reconstructed vertices from MIP timing

Run-2 performance nearly recovered

Space-time vertices and triangulation



Impact on H→γγ lineshape

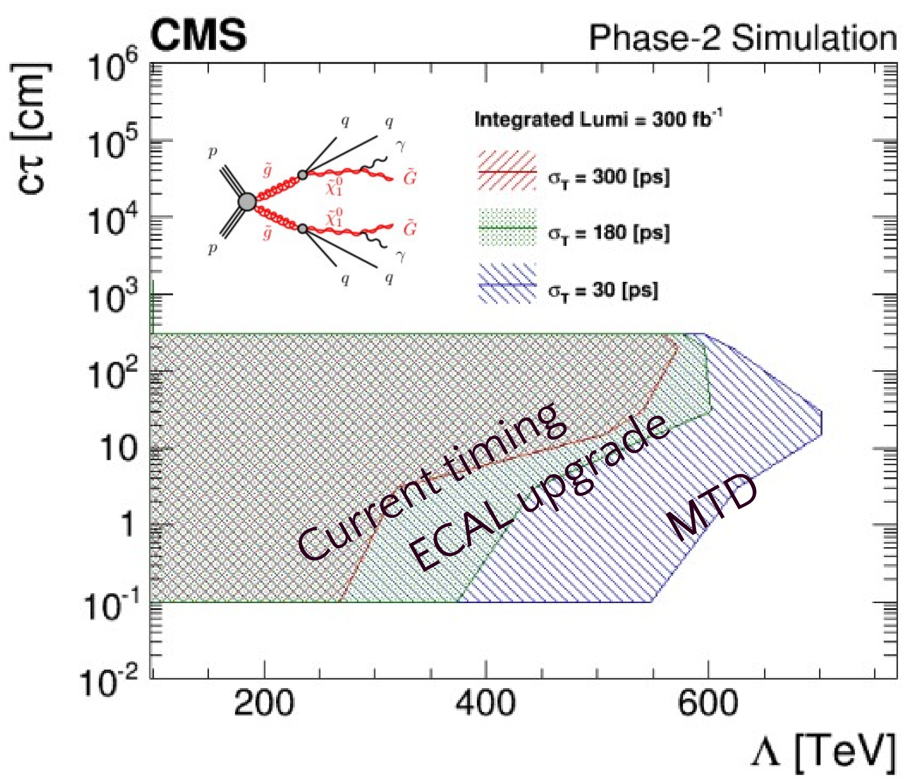


Impact of timing on physics

Long-lived particles

Velocity between primary → secondary vertices
Reconstruction of peaking mass variables
Large increase in search reach

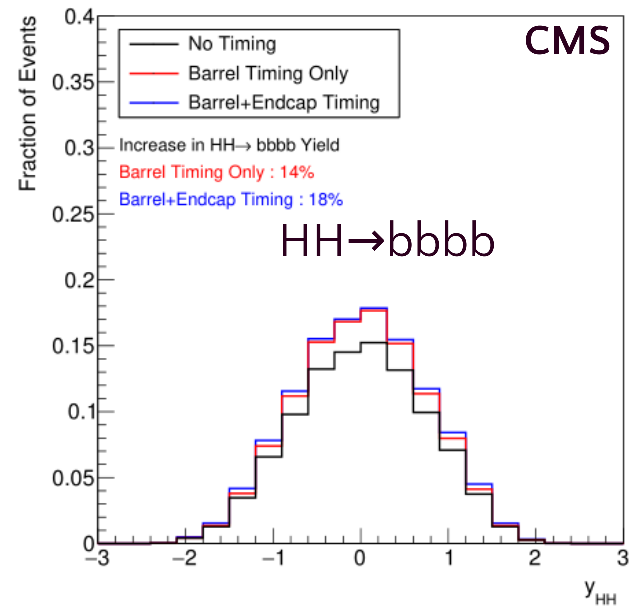
Long-lived particles search



Higgs & di-Higgs

18-26% increase in effective luminosity
Central decays: large impact from the barrel

Impact on some (di-)Higgs channels



Channel	Signal increase (%) BTL	BTL+ETL
$HH \to b\bar{b}\gamma\gamma$	17	22
$HH \to b\bar{b}b\bar{b}$	14	18
$H \to ZZ \to 4l$	19	26

Conclusions

Very ambitious projects of calorimeters with higher granularity
and improved timing measurements
Together with new MIP timing detectors
Adapted to the extremely harsh environment: pile-up, radiation

They provide additional measurement capabilities
Combined energy+tracking+timing, space-time track & vertex reconstruction

Performance evaluation with test beam campaigns
Results in line with expectations

Projects progressing at full speed for operations with the first HL-LHC collisions (or already for the Run 3 for the ATLAS LAr trigger)

ATLAS LAr Phase-1 TDR: ATLAS-TDR-022
CMS ECAL Barrel TDR: CMS-TDR-015
CMS HGCAL TDR: CMS-TDR-019
CMS MTD TP: LHCC-P-009 – TDR end of 2018
ATLAS HGTD TP public mid June – TDR beginning of 2019