Optimising the performance of the CMS ECAL to measure Higgs properties during Phase 1 and Phase 2 of the LHC

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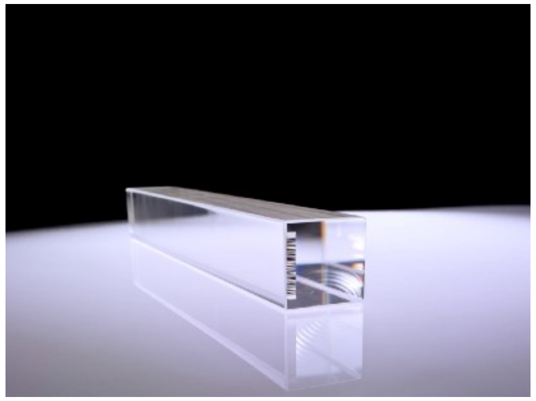
1. Current Detector

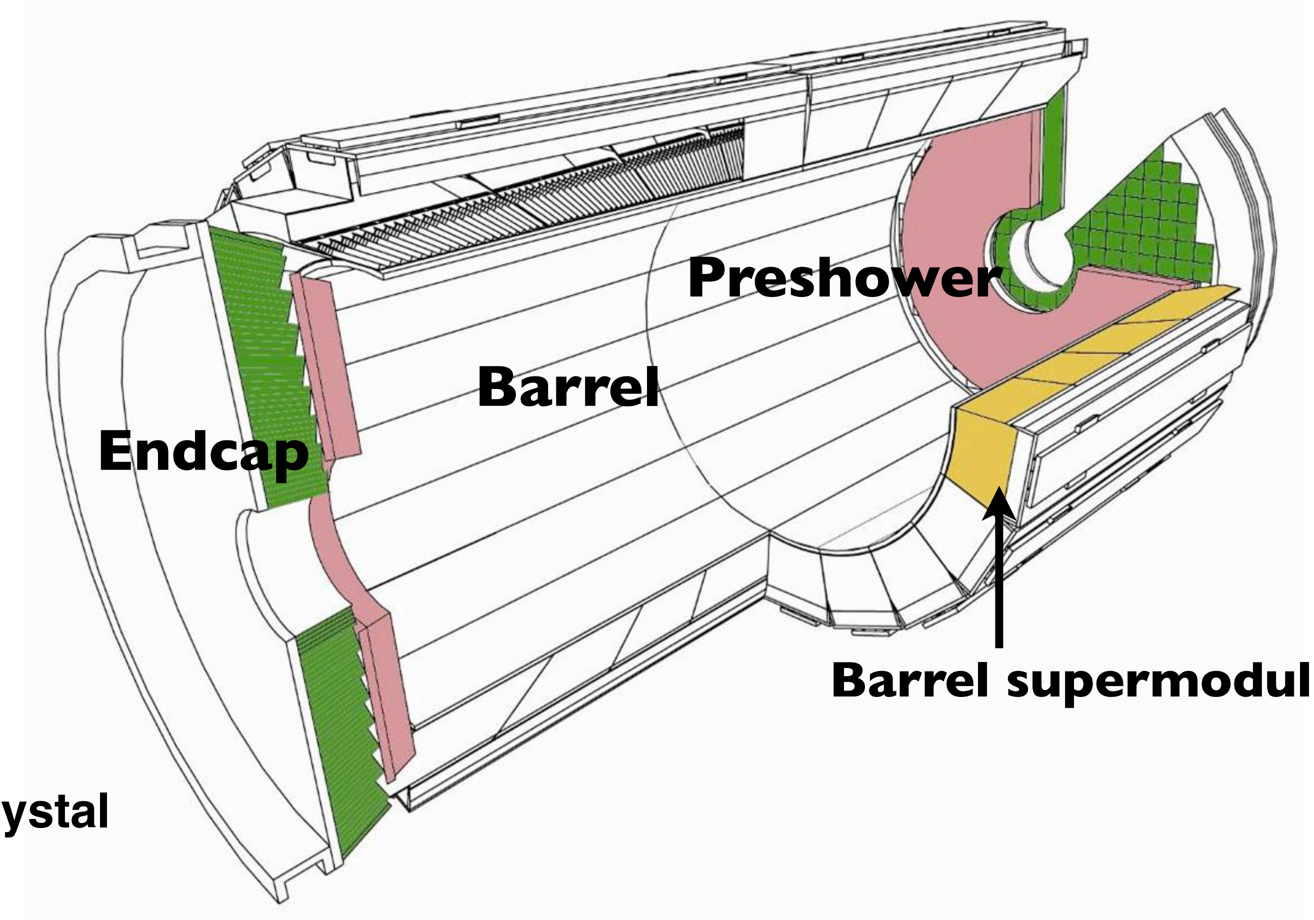
The ECAL in CMS
Physics Output Involving ECAL
Optimisations during LHC Run 2

The CMS Electromagnetic Calorimeter

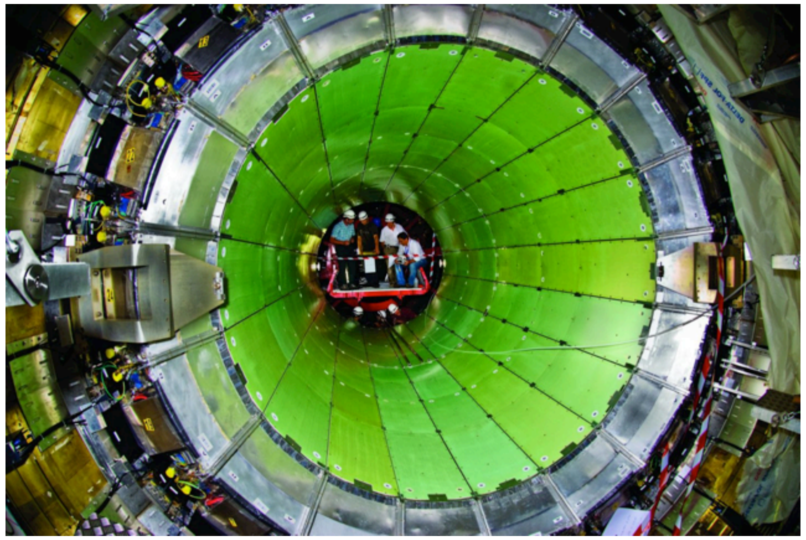
Crystal **Barrel** & **Endcaps** (75848 $PbWO_4$ crystals) + Lead/Si Preshower



Lead Tungstate ($PbWO_4$) crystal

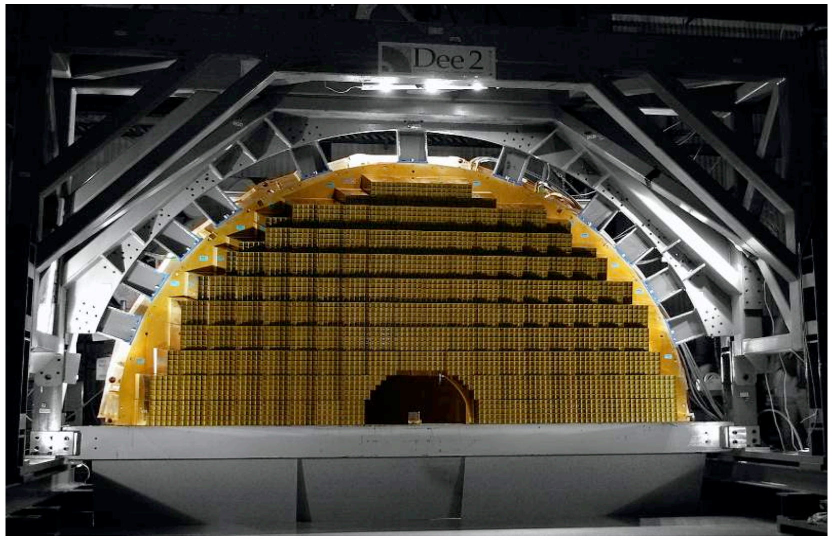


- **Excellent energy resolution** in the harsh LHC radiation environment
  - Goal: **achieve 1% mass resolution** for low-mass H→γγ decays



Barrel (EB)

36 supermodules
Avalanche PhotoDiode readout
coverage: $|\eta|<1.48$

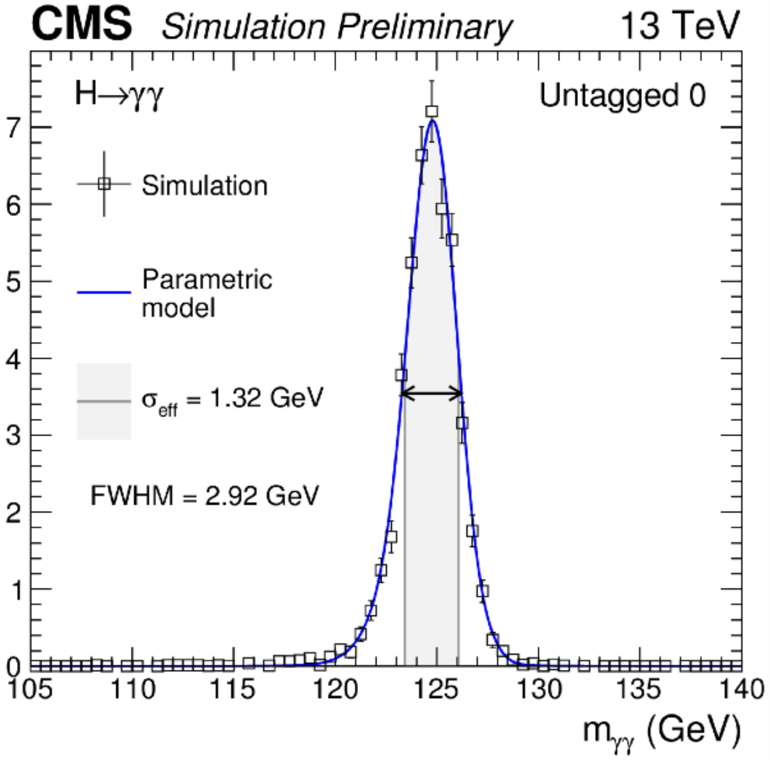


Endcaps (EE)

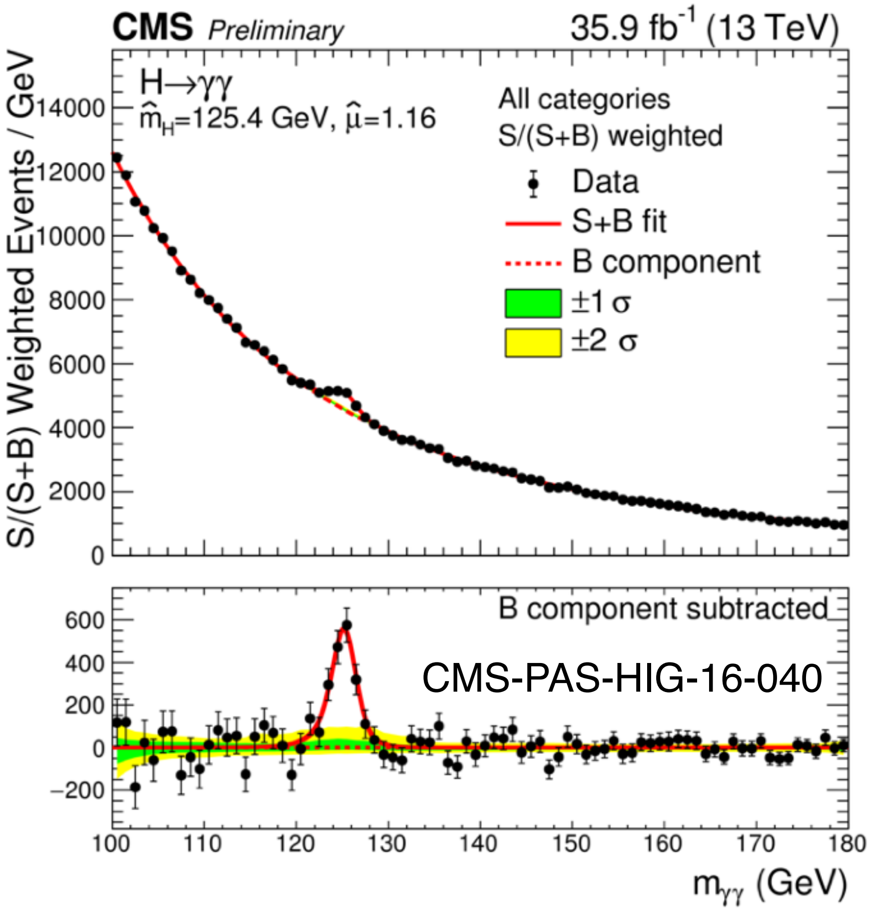
4 half-disk Dees
Vacuum PhotoTriode readout
coverage: $1.48<|\eta|<3.0$

Role of ECAL in Higgs Physics

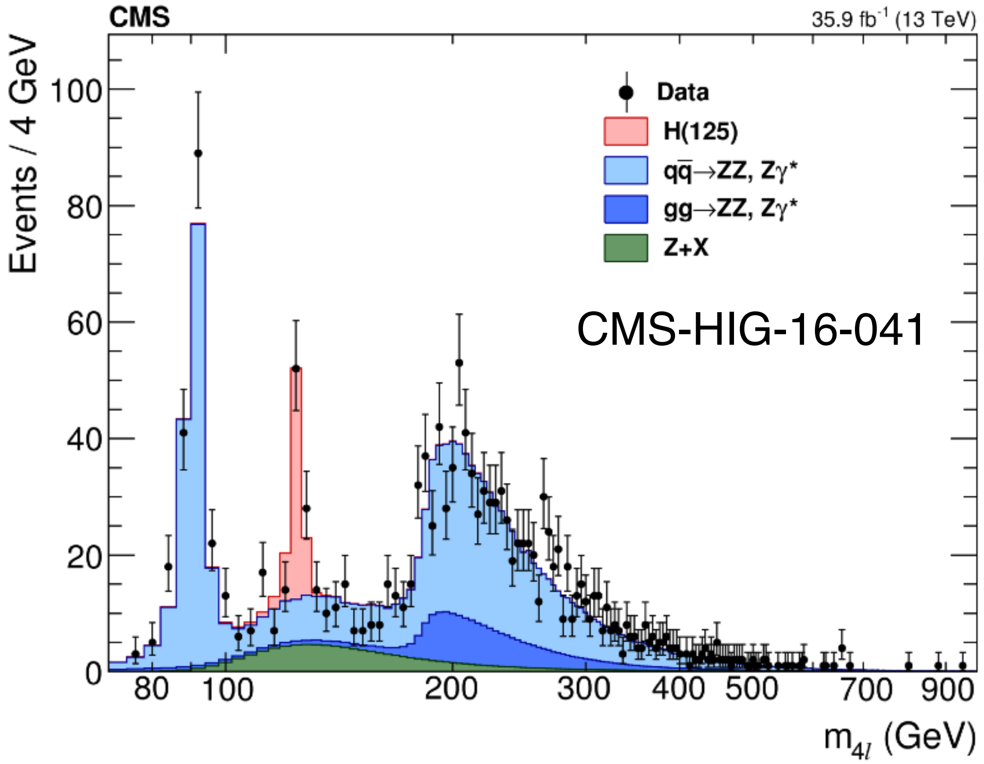
H→γγ



Mass resolution in best category ~1%



H→ZZ→4l

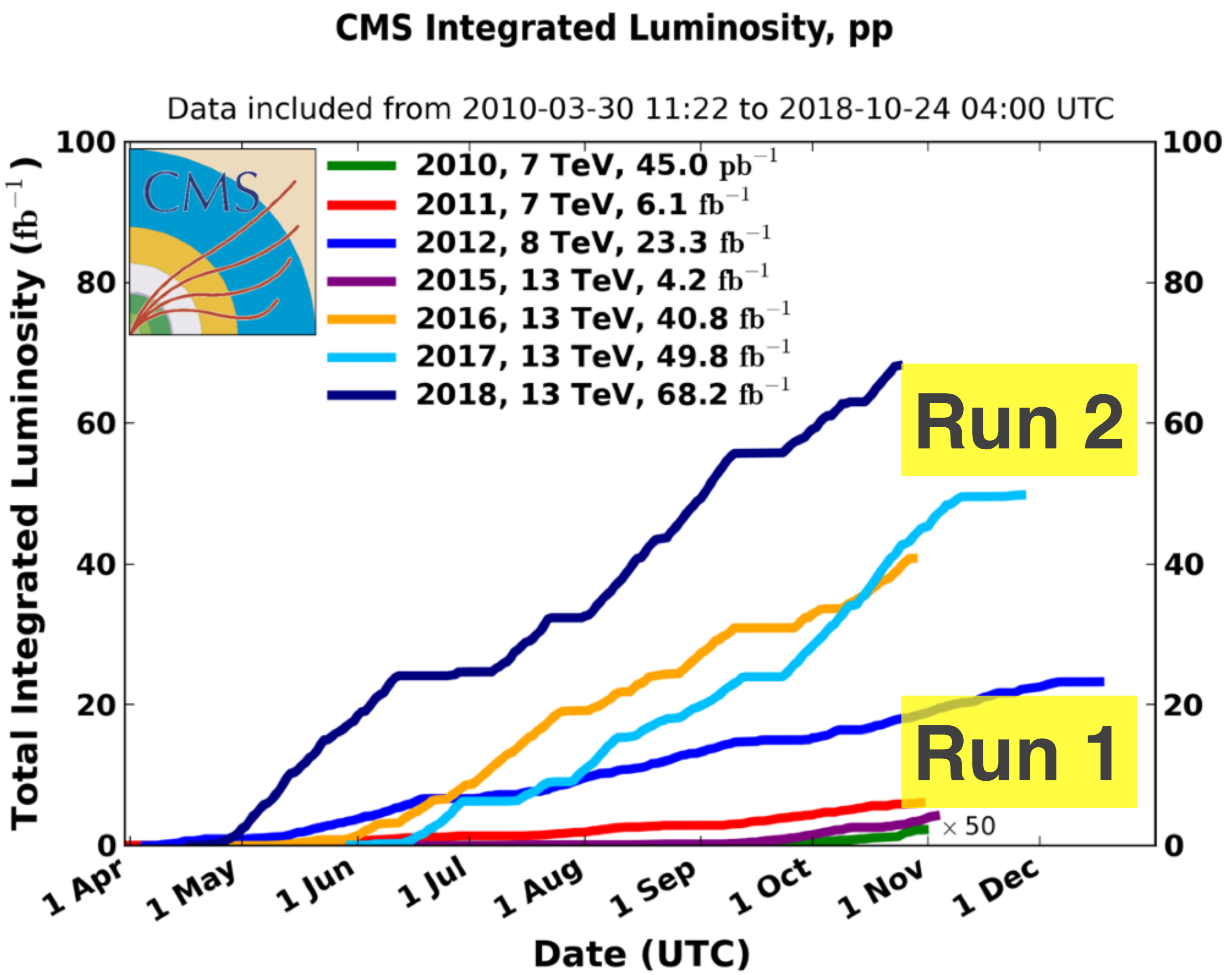


The **excellent resolution and electron/photon ID** of the CMS ECAL were crucial in the discovery and subsequent characterisation of the **125 GeV Higgs Boson**

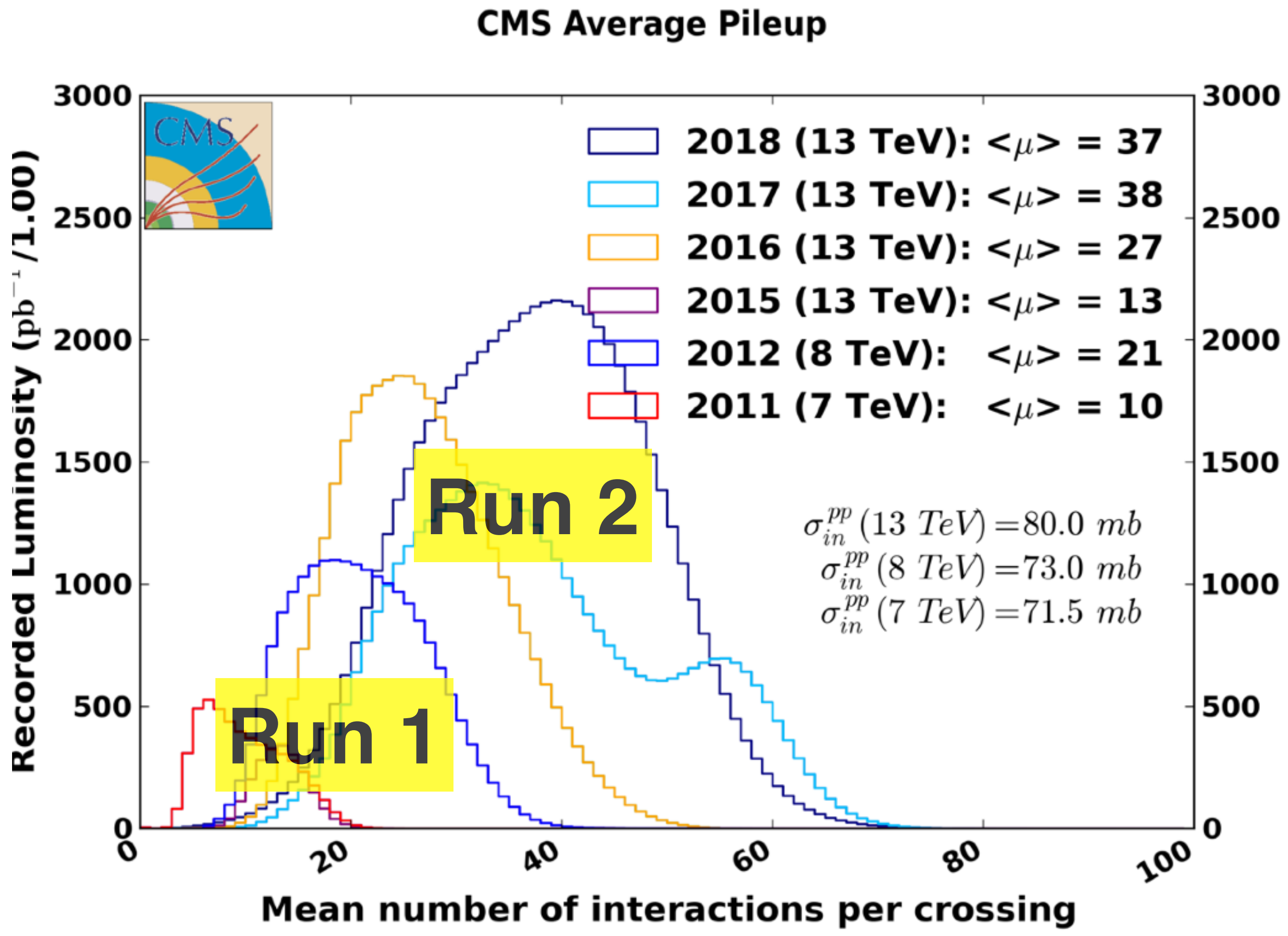
The **continued excellent performance** of ECAL in the **entire pseudorapidity range** is a key component of **Higgs Boson precision measurements** and **searches for new Physics**

Challenges during Run 2

Higher Integrated luminosity



Larger Average pileup

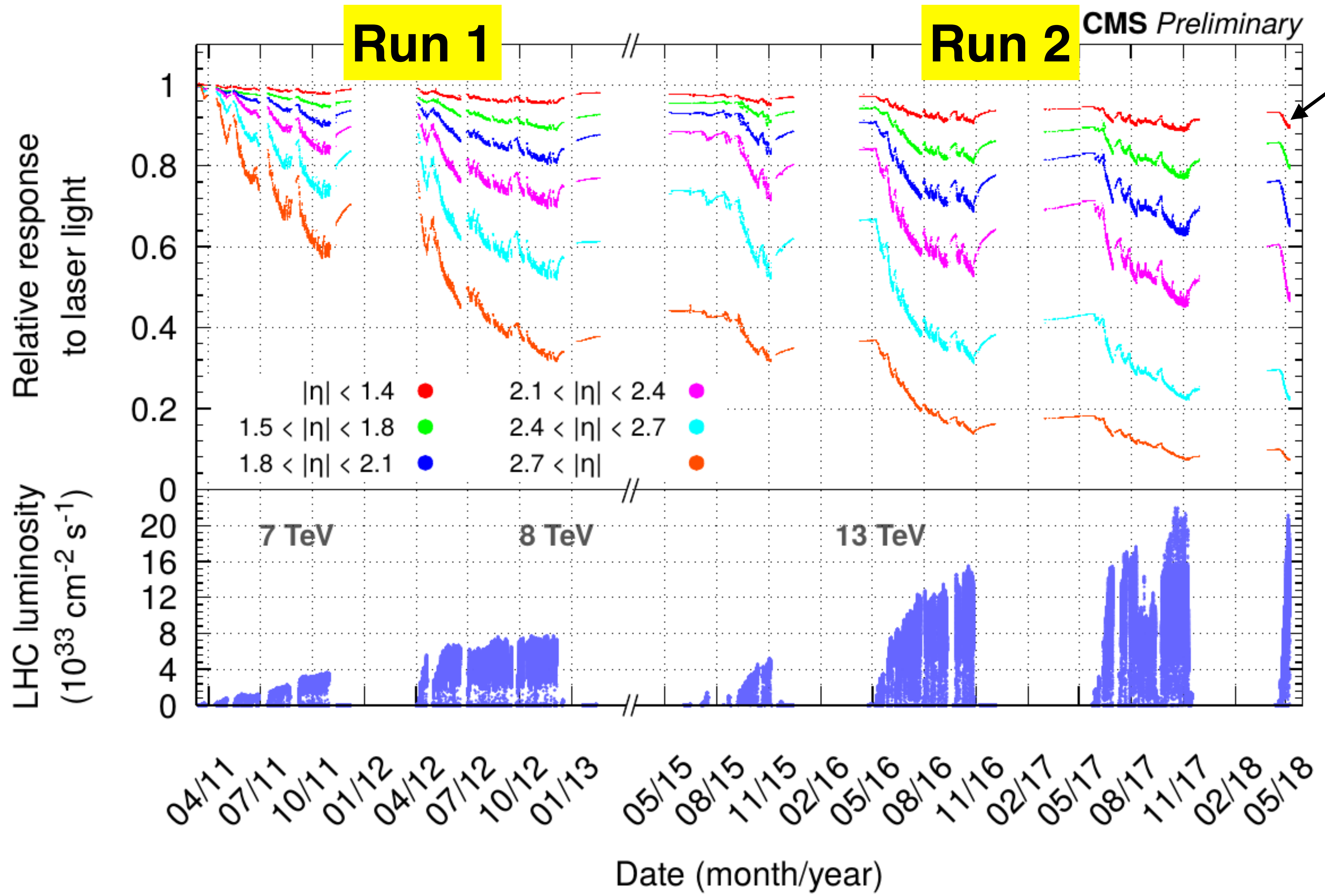


Run 2 challenges:

1) Larger radiation dose: increased radiation induced ageing to crystals, photodetectors, on-detector readout

2) Large increases in pileup (PU): from higher bunch intensities, and from 25ns bunch spacing (larger out-of-time PU) → impact on ECAL pulse reconstruction

ECAL response changes over 8 years



Barrel

endcap region covered by CMS tracker

endcap region relevant for forward jets

Significant response changes (crystal + photodetector) due to LHC irradiation

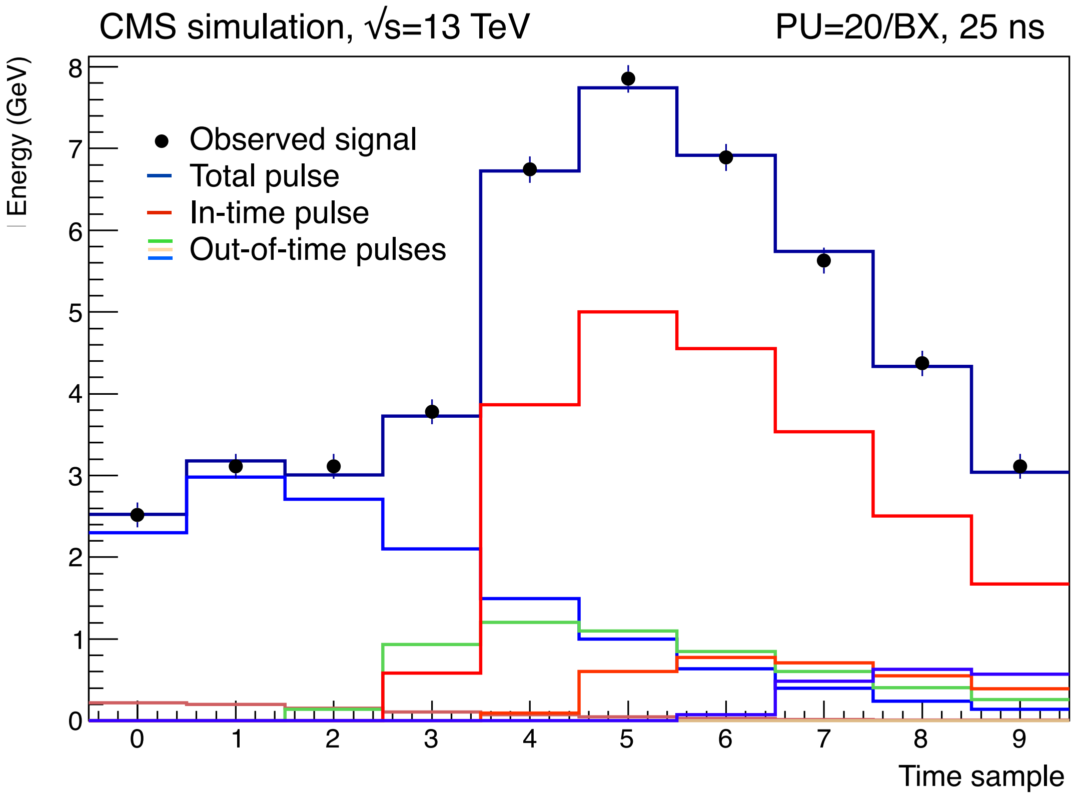
Corrections are provided within 48h via dedicated laser monitoring system

These are crucial to maintain stable ECAL energy scale and resolution over time

Energy reconstruction and calibration updates

crucial to mitigate out-of-time pileup and maintain optimum resolution

ECAL energy reconstruction



allows up to 9 out-of-time pulses

PU mitigation improved

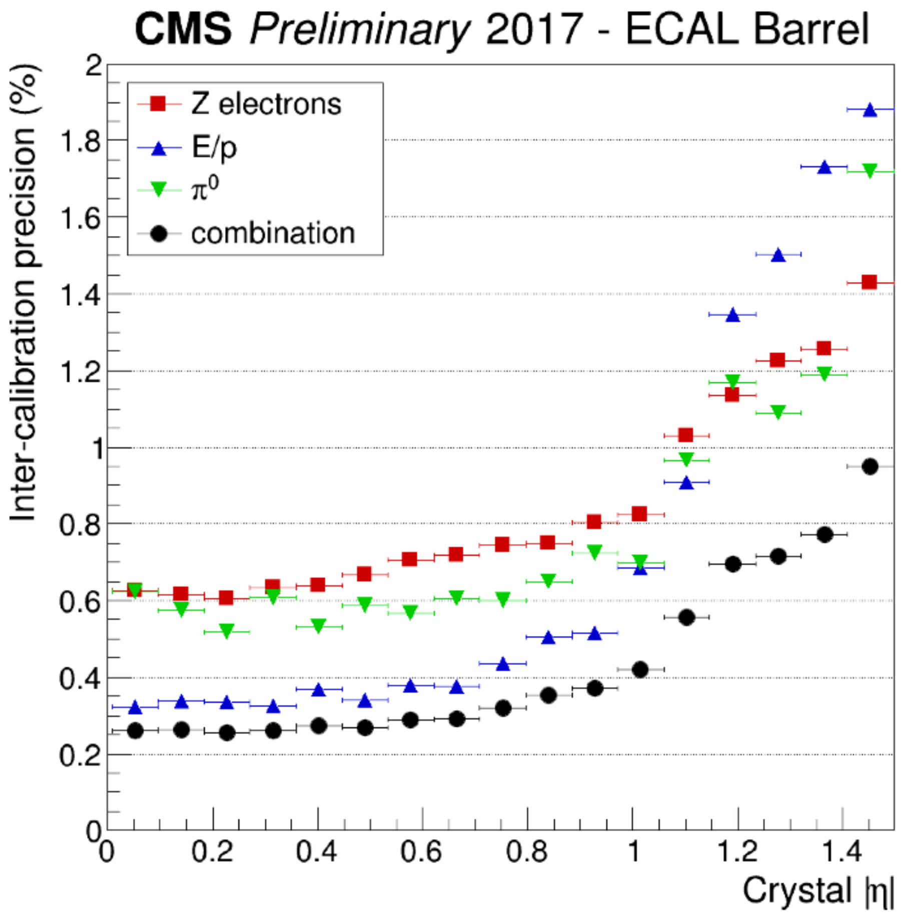
template fit -> subtracts out-of-time pulses

Large improvements in low energy e/γ and jet response are obtained

Regular updates of pulse templates and baseline pedestals are performed

to mitigate ageing effects on crystals and on-detector readout

ECAL energy calibration



Regular recalibrations

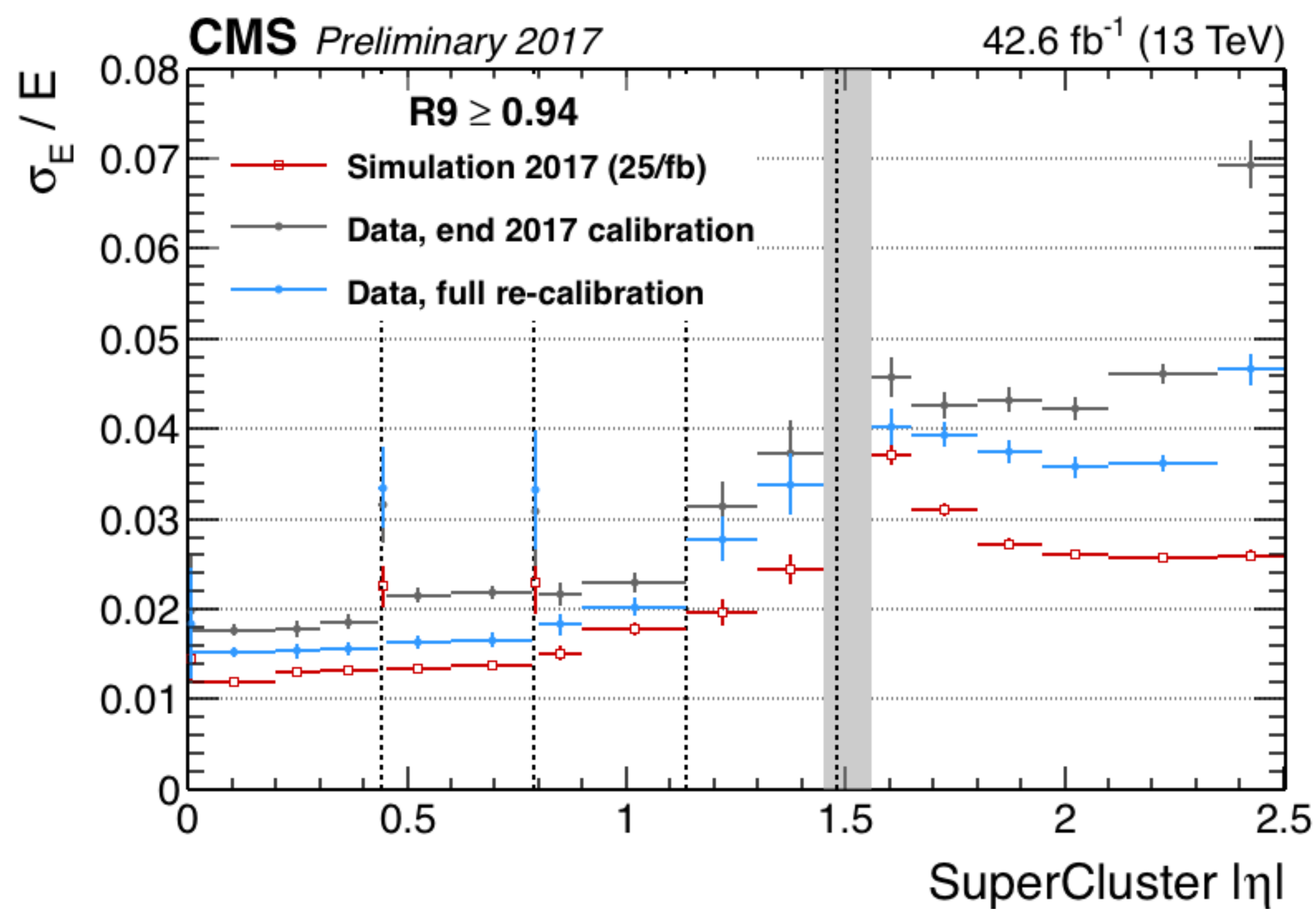
using several in-situ methods

Equalise response of all channels to physics signals

Precision of better than 0.5% obtained in central barrel (|η|<1)

Excellent energy resolution maintained in Run 2

as a result of improved energy reconstruction and regular recalibrations



Unfolded single electron fractional resolution vs eta, from Z→ee events

recalibrated data (blue) shows improved performance

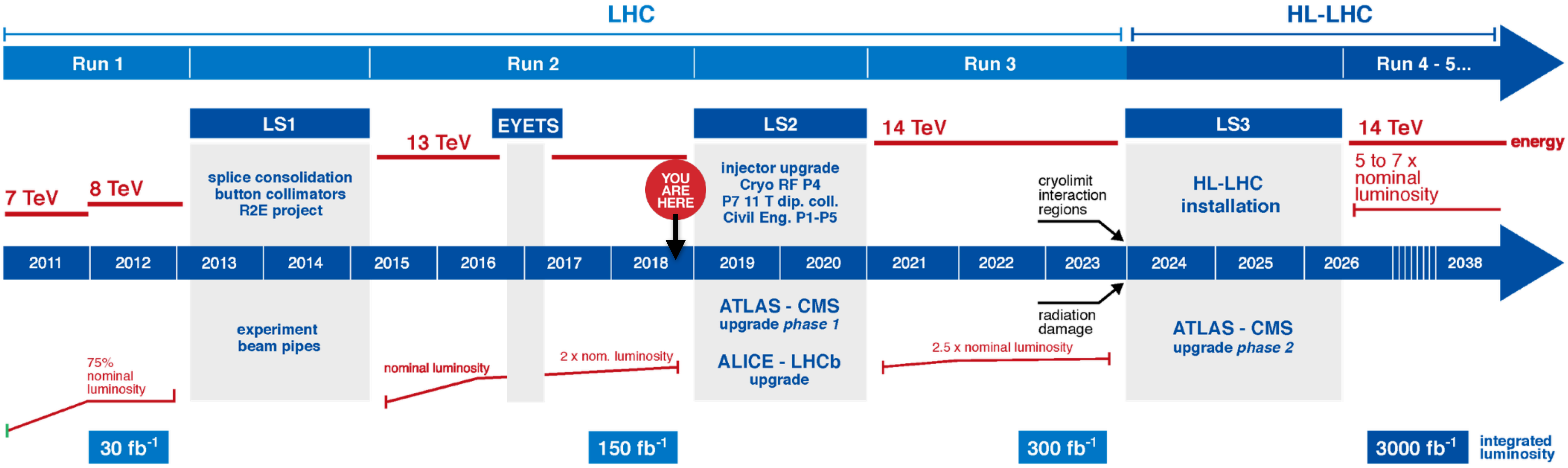
Excellent Run 1 ECAL energy scale stability and resolution has been maintained in Run 2

despite significantly larger pileup and larger radiation-induced detector ageing

2. The High Luminosity LHC upgrade (HL-LHC)

Detector Requirements for HL-LHC
The ECAL Barrel Upgrade
Physics projections for LHC Phase 2

HL-LHC upgrade plan (LHC Phase 2)



http://hilumilhc.web.cern.ch/about/hl-lhc-project

HL-LHC: accelerator upgrade in LS3 to provide **x10 larger dataset** for physics

focus on new physics searches, Higgs coupling and precision SM measurements

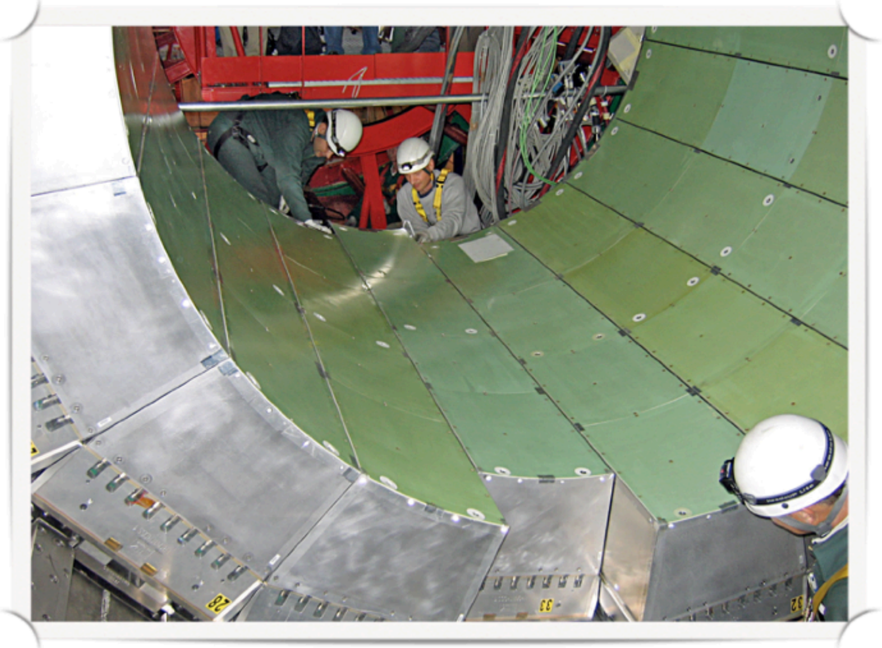
Detector must cope with large increases in peak lumi, integrated dose relative to LHC:

	Inst. lumi (cm^{-2}s^{-1})	peak pileup	integ. lumi (fb^{-1}/yr)
today (2018)	2.0x10^{34}	50	60
HL-LHC (baseline)	5x10^{34}	140	250
HL-LHC (stretch goal)	7.5x10^{34}	200	320

R. Tomas presentation at Chamonix 2017

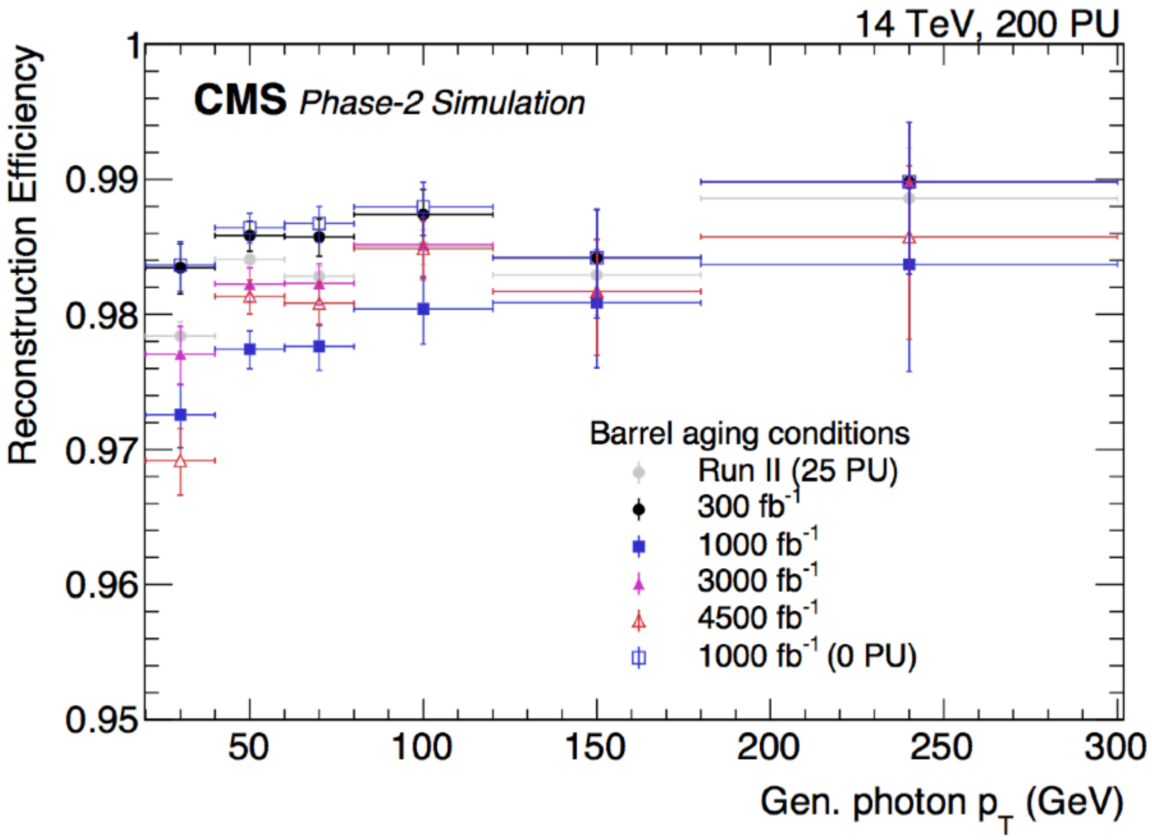
ECAL Phase 2 Upgrade scope

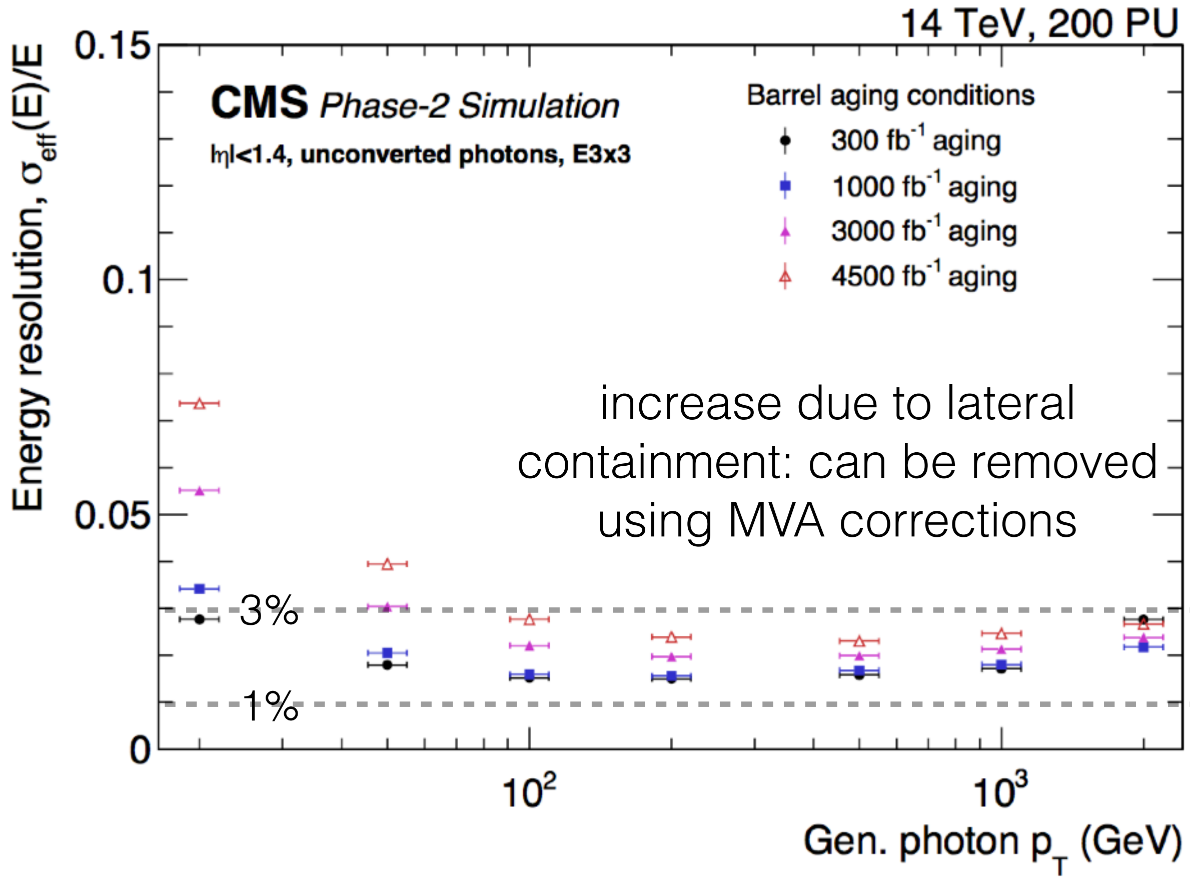
- **Barrel supermodules will be refurbished during LS3**
  - **Crystals and APDs will maintain performance throughout Phase 2**
  - **New on-detector readout**
    - **to be compatible with increased CMS Phase II trigger requirements**
    - to **maintain performance** in **more challenging HL-LHC conditions**
    - higher granularity of output data for **precise timing measurements** (**~30 ps**) of high energy photons and **improved trigger algorithms**
  - **Run colder** to mitigate increase in radiation induced APD noise (minimise impact on resolution)
- **Endcaps will be replaced during LS3**
  - **due to much larger response losses**



Phase 2 object reconstruction

- **The aim of the upgraded detector is to preserve the current performance in the challenging HL-LHC conditions**





increase due to lateral containment: can be removed using MVA corrections

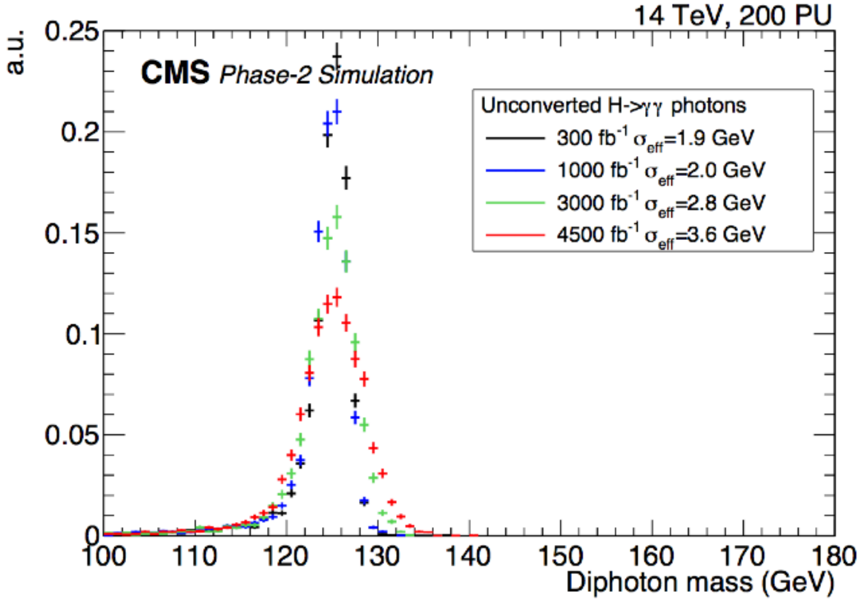
Photon reconstruction

small impact of ageing

Photon energy resolution

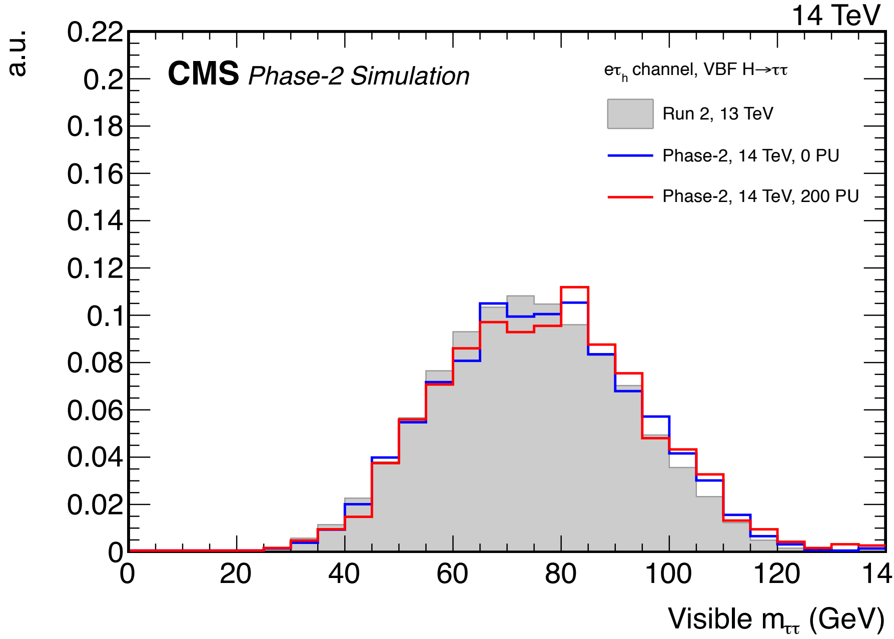
2.5 to 4% resolution for E_T=50 GeV

Higgs Physics in Phase 2



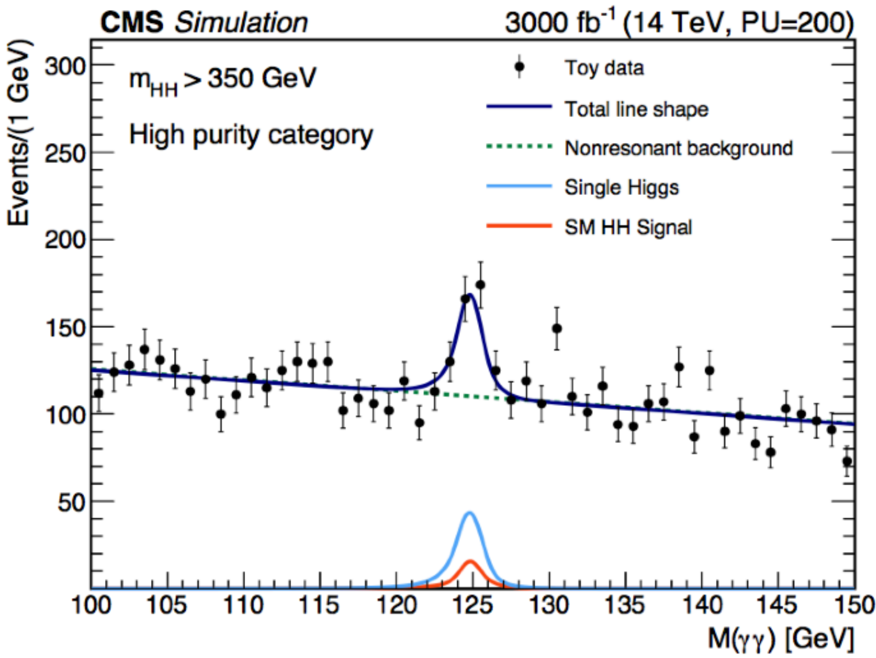
H→γγ resolution

slow degradation with ageing



H→ττ mass resolution

same performance as Run 2



HH→bbγγ signal

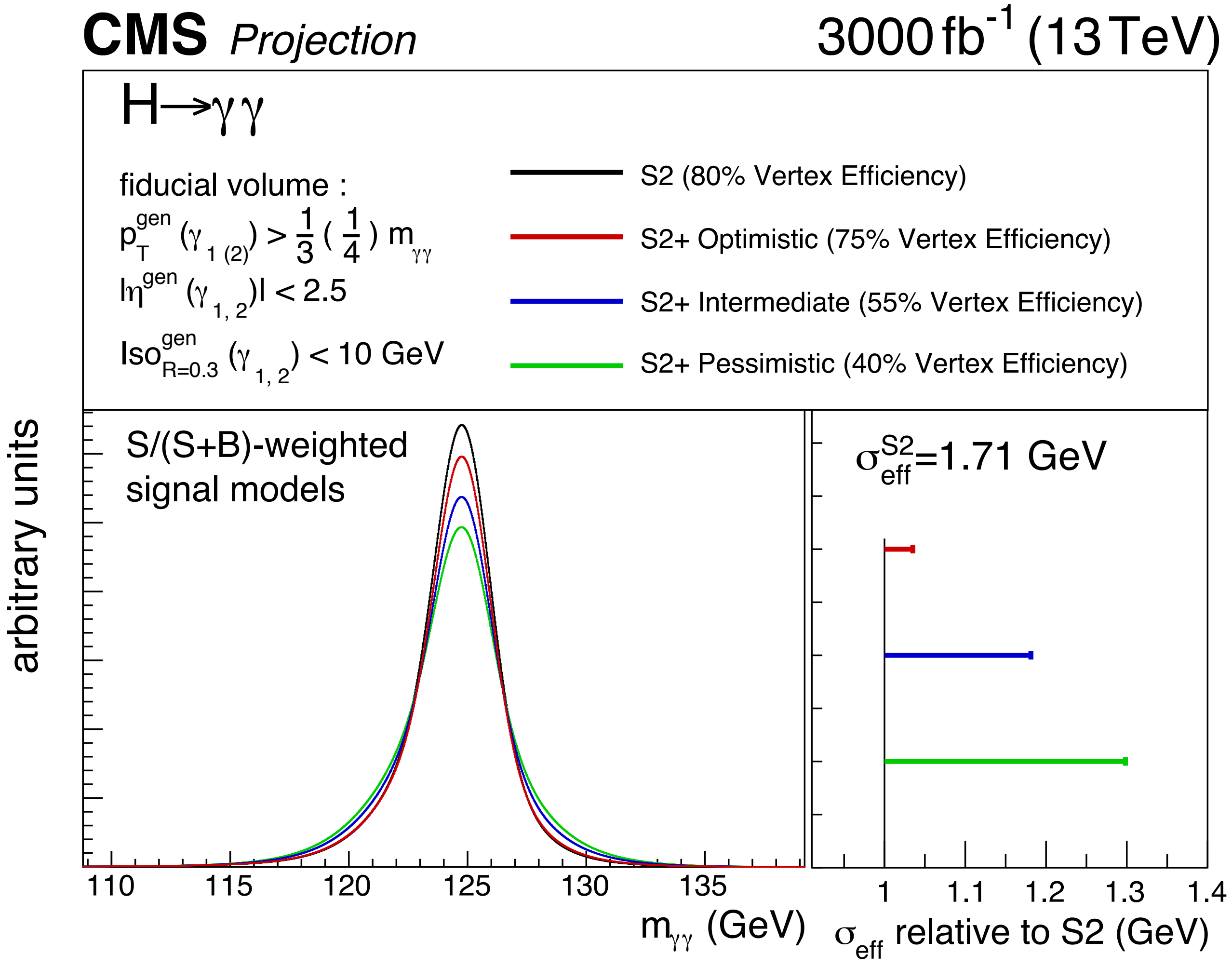
with Phase 2 photon resolution

- **With full optimisation (MVA corrections), we expect to achieve similar H→γγ resolutions for Phase-2, 1000fb^{-1} as was obtained in Run 2**

Full details in Barrel Calorimeter Phase II TDR and upcoming HL-LHC Yellow Report

Benefits of precise timing in Phase 2

- **Challenging to maintain reconstruction performance at 140-200 pileup**
  - reduced primary vertex efficiency (75%->30%) from H→γγ decays
- **Improved vertex localisation possible with precise (~30ps) timing capabilities**
  - **sensitivity gain (ECFA 2016): ~10%** on H→γγ resolution and fiducial cross-section relative to no precise timing case at **PU=140**
- **30ps timing resolution has already been achieved in test beam evaluations of Phase II ECAL prototype electronics**



H→γγ mass resolution with different assumptions on vertex efficiency:

no precise timing

+ precise timing in calorimeter

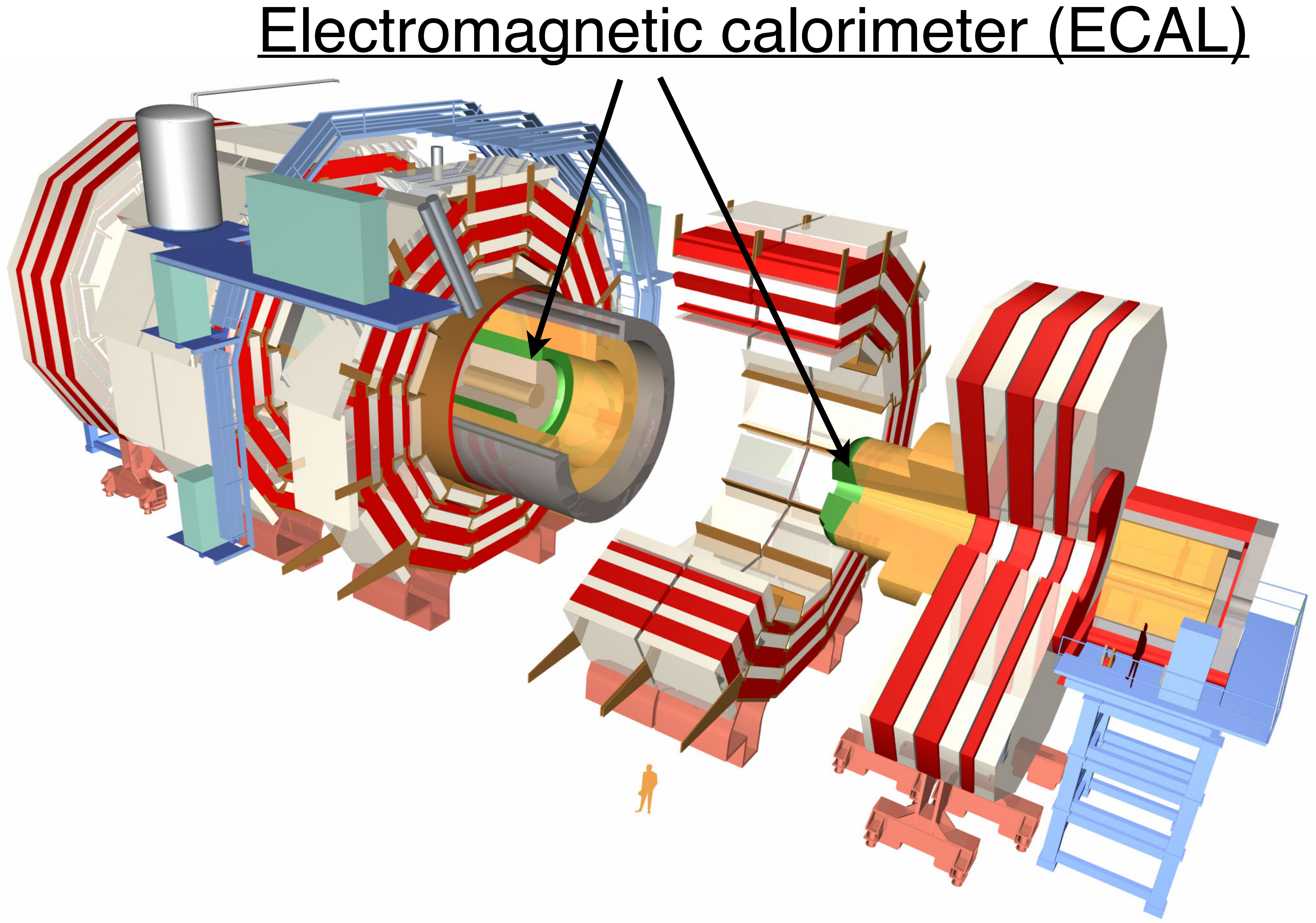
+ precise MIP timing (timing layer)

Summary

- **Excellent ECAL energy resolution maintained during Run 2**
  - **as a result of significant improvements to energy reconstruction and regular recalibrations of channel response**
  - **H→γγ mass resolution remains ~1% in the best analysis category**
- **Upgrade of ECAL barrel supermodules planned for LS3**
  - **to be compatible with increased CMS Phase II trigger requirements and to maintain performance in more challenging HL-LHC conditions**
  - Targeting **precise timing measurements** (**~30 ps**) for high energy photons and electrons.
    - **we are now producing and testing prototype chips and readout boards**
- **With these upgrades we will provide a detector that retains excellent photon/electron/jet performance for Higgs Physics, and meets the challenges of HL-LHC**

Backup slides

The CMS Detector and the ECAL



Electromagnetic calorimeter (ECAL)

CMS:

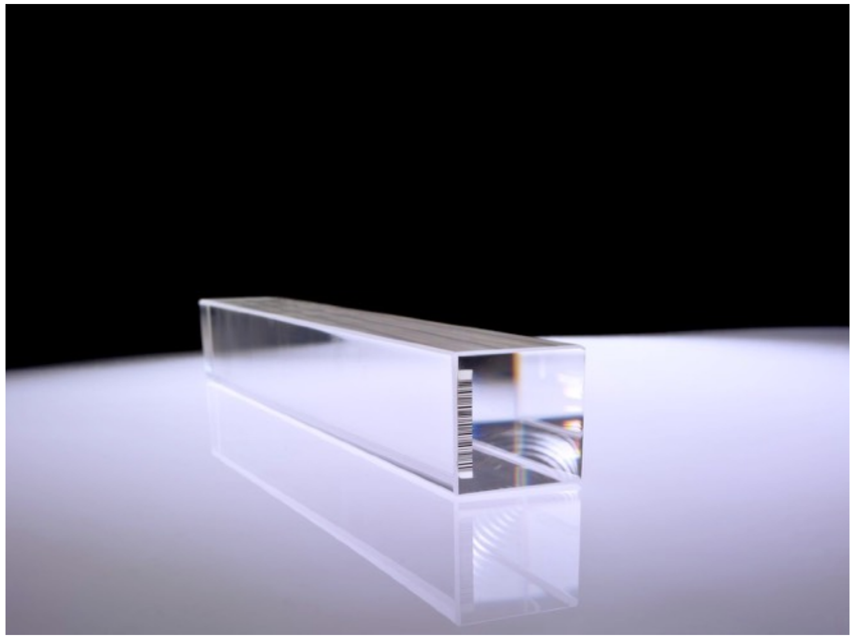
Length: 21.5m
Diameter: 15m
Weight: 14kT
Magnetic field: 3.8T

ECAL: the main component of CMS to **detect and precisely measure** the energies of **electrons and photons**.

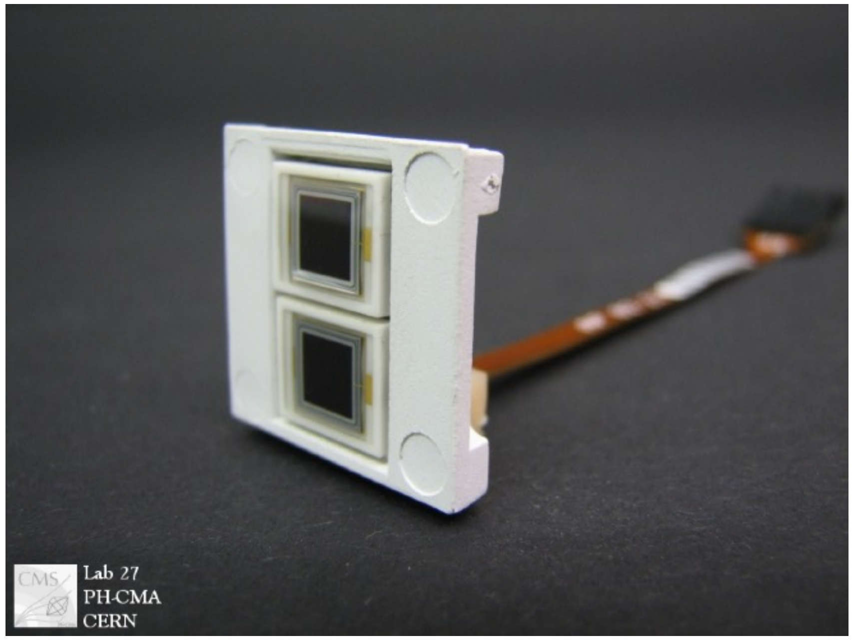
Goal: **excellent diphoton mass resolution** (~1%), needed for H→γγ observation

CMS ECAL design criteria

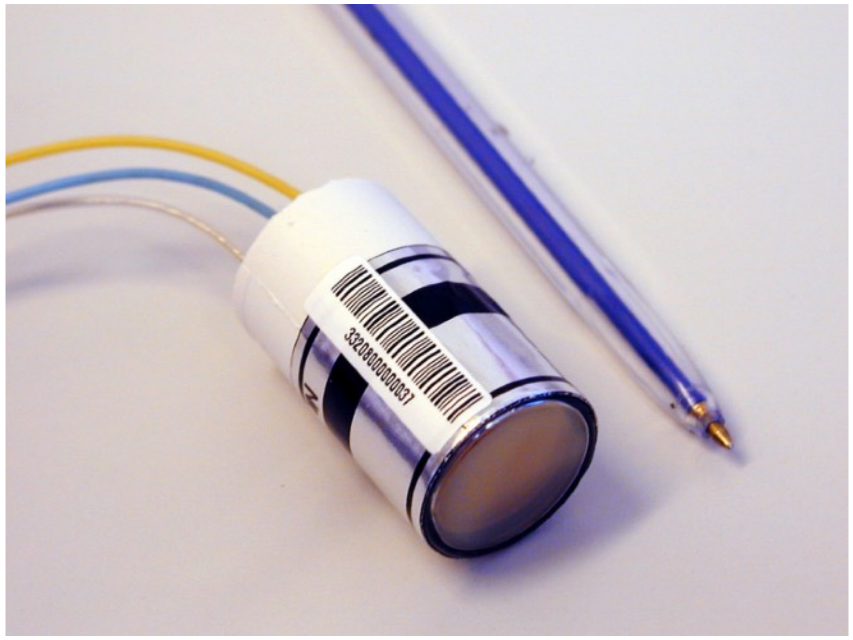
- **The CMS ECAL was designed with challenging goals in mind:**
  - **Extreme energy resolution** in the harsh LHC radiation environment
    - **achieve 1% mass resolution** for low-mass Higgs in the $\gamma\gamma$ decay channel
  - **Hermetic and compact detector** with coverage up to $|\eta| = 3.0$
- **Solutions were obtained through intense R&D campaigns**
  - Lead tungstate (**PbWO$_4$**) **crystal calorimeter**
    - compact, fast, radiation tolerant
  - Radiation and magnetic-field tolerant **APD and VPT photodetectors**



Lead Tungstate (PbWO$_4$) crystal



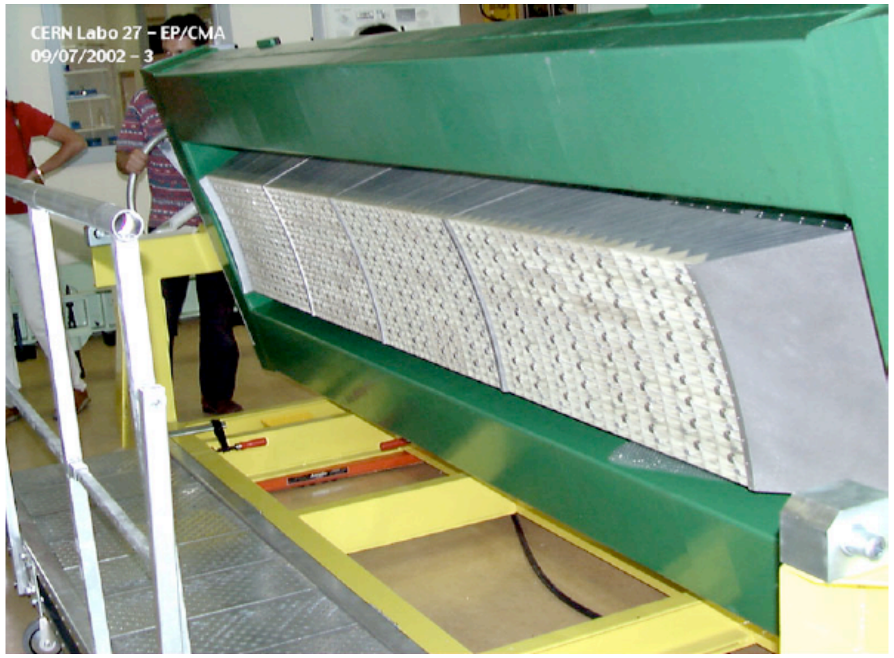
Avalanche PhotoDiode (APD)



Vacuum PhotoTriode (VPT)

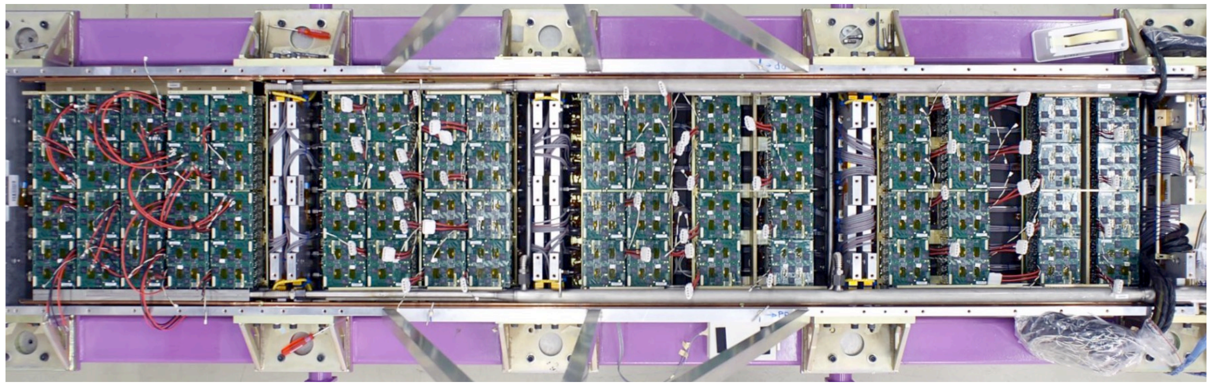
Elements of the ECAL Barrel

36 Supermodules



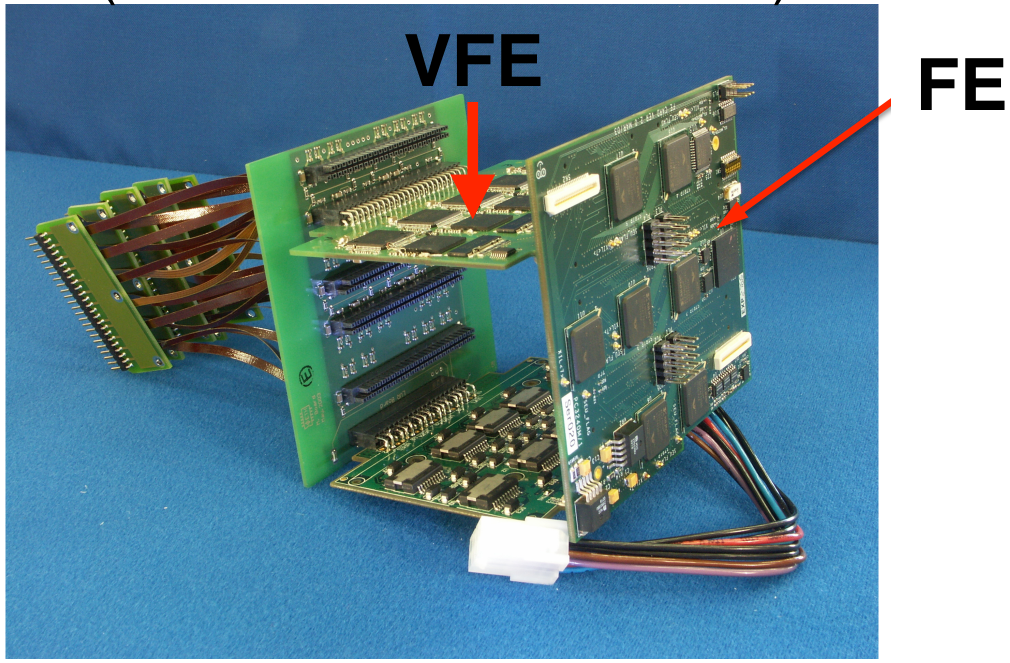
61200 Lead Tungstate crystals
61200 APD pairs

Supermodule in the process of electronics installation



2448 Trigger towers

(readout of 5x5 channels)

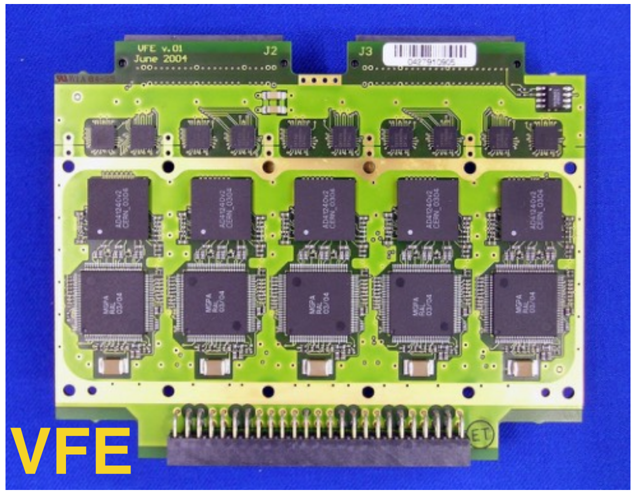


12240 Very Front End cards

pulse amplification, shaping, digitization

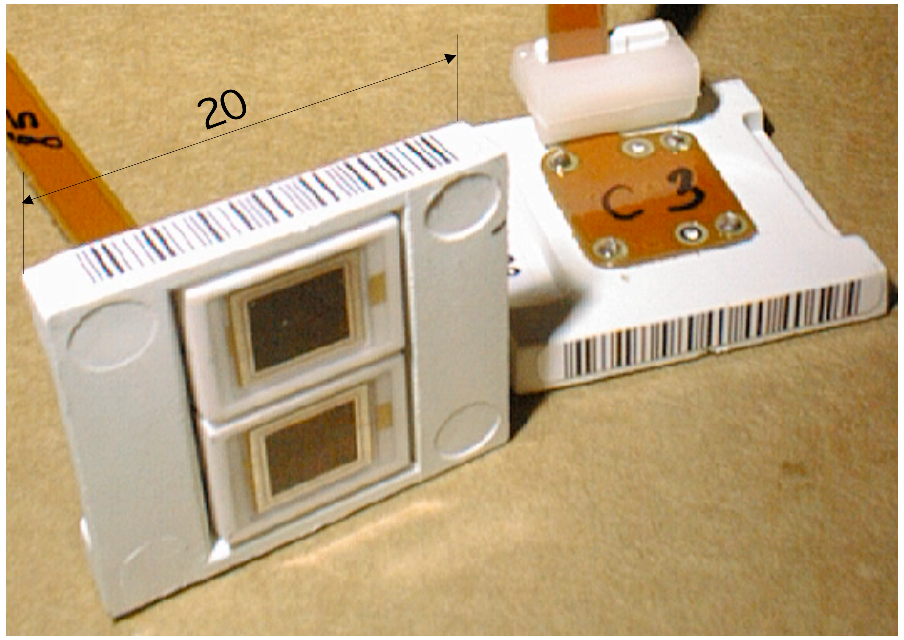
2448 Front End cards

data pipeline and transmission, TP formation, clock/control



ECAL photodetectors

Barrel: Avalanche PhotoDiodes (APD)



Hamamatsu S1848 APDs

two 5x5mm^2 sensors

glued to back of PbWO$_4$ xtal

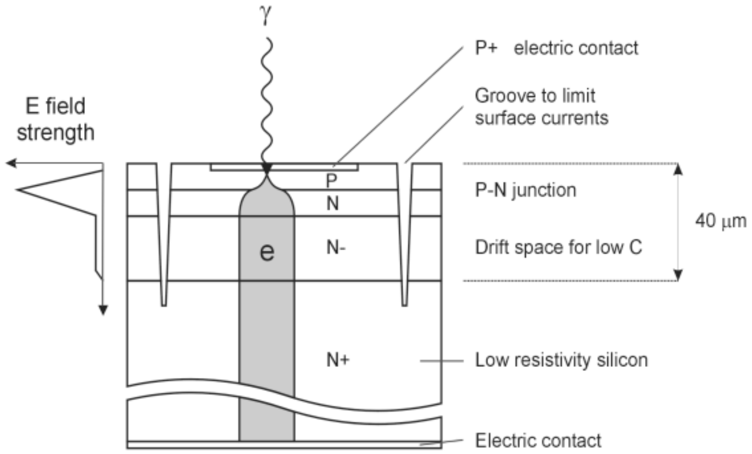
high QE: ~75%

operate at gain 50

operating voltage 340-440 V

Temperature sensitivity

-2.4%/°C



Endcaps: Vacuum PhotoTriodes (VPT)

NRIE (St Petersburg) PMT188 VPT

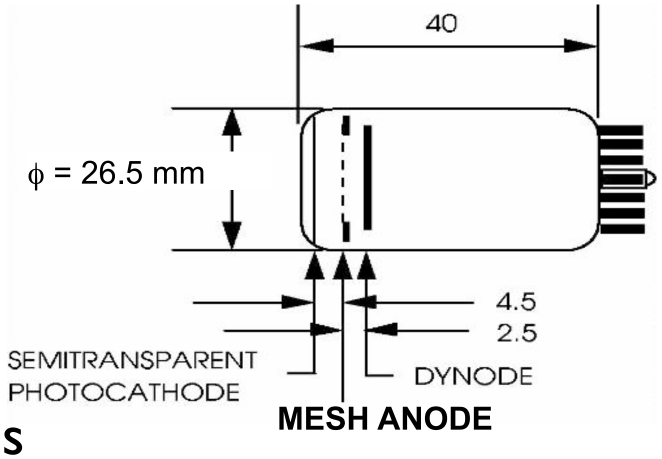
280mm^2 sensor area

glued to back of PbWO$_4$ xtal

QE: ~20% (420nm)

operate at gains 8-10 (4T)

anode/dynode voltage 800/600 V



More radiation tolerant than Si diodes

UV glass window

~4.5 photoelectrons/MeV @18°C in both APDs and VPTs

Energy Reconstruction

For electron/photon object:

Pulse Amplitude

intercalibration

cluster corrections

$$E_{e,\gamma} = \sum_i [A_i \times S_i(t) \times c_i] \times G(\eta) \times F_{e,\gamma}$$

time-dependent response corrections:
laser monitoring system

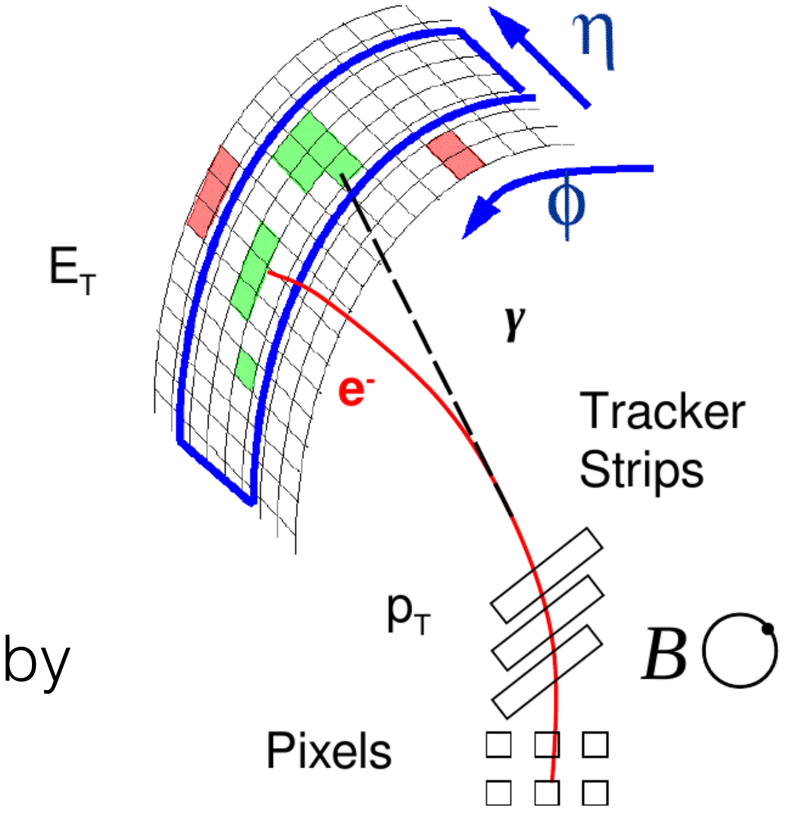
Global scale

intercalibration takes into account differing response of crystals and photodetectors

Clustering:

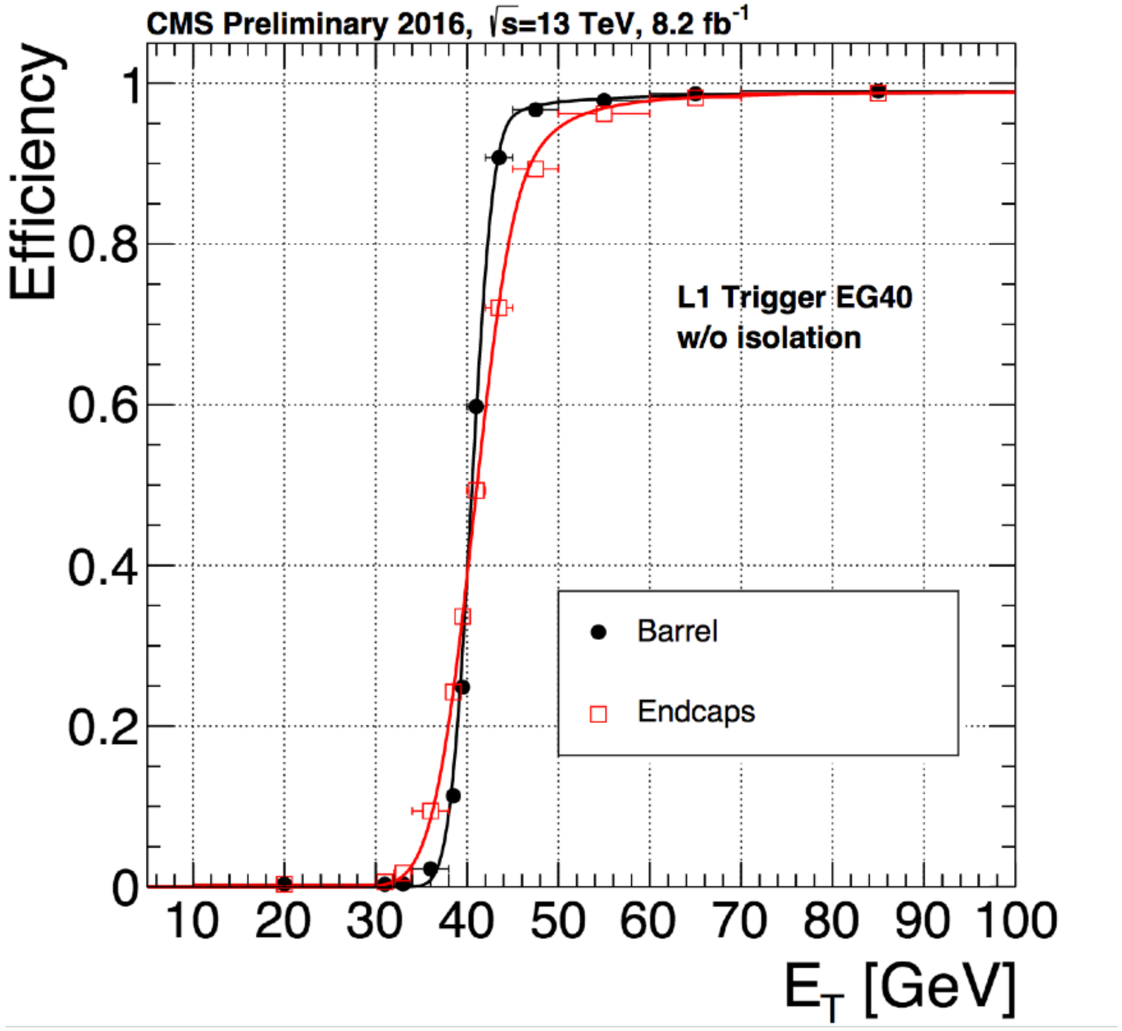
Superclusters: dynamic sized clusters to gather energy radiated in phi (field bending direction)
(add preshower energy in EE)

MVA **cluster corrections:** improve energy determination by optimally employing event information (i.e. showering/non-showering, proximity to dead regions/cracks)

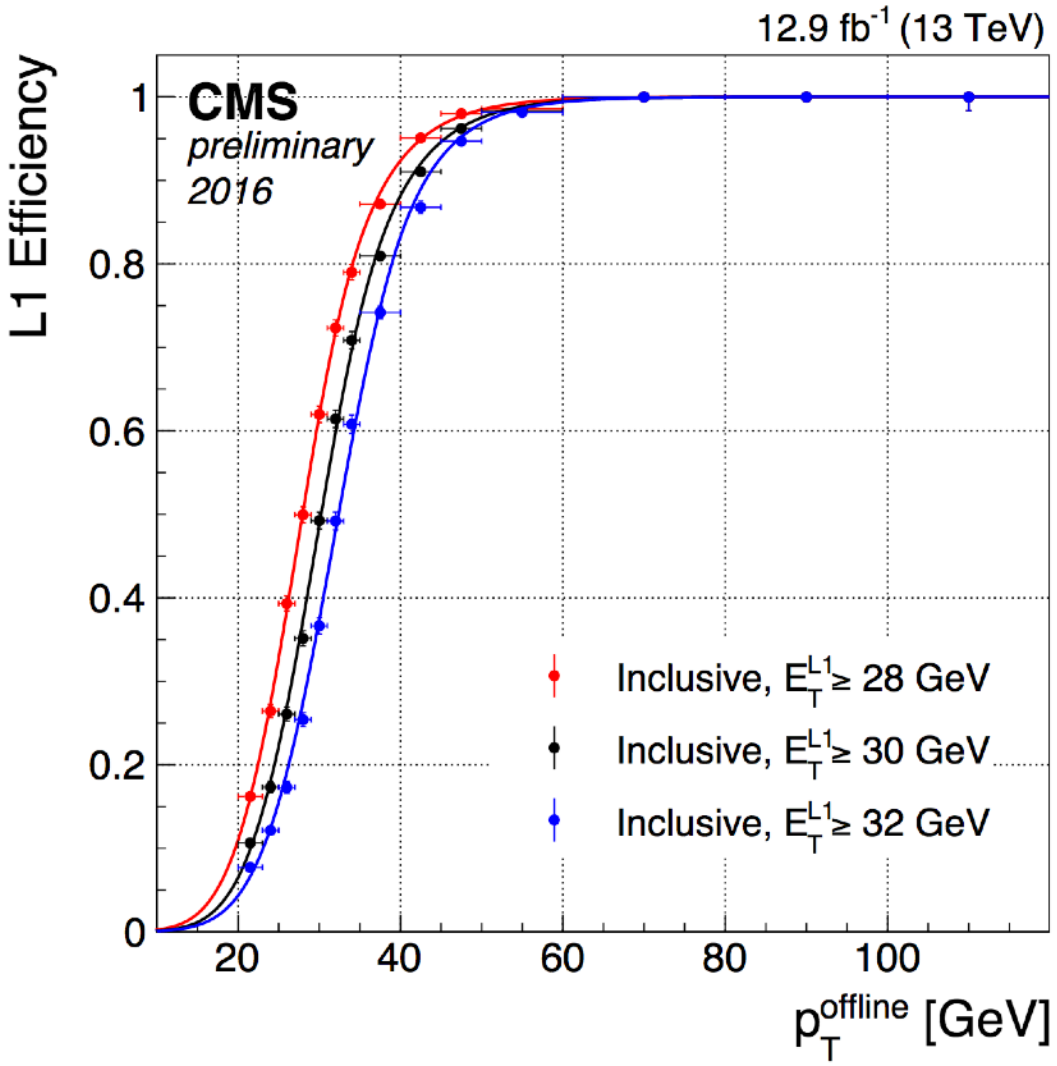


Triggering

Single electron



Tau



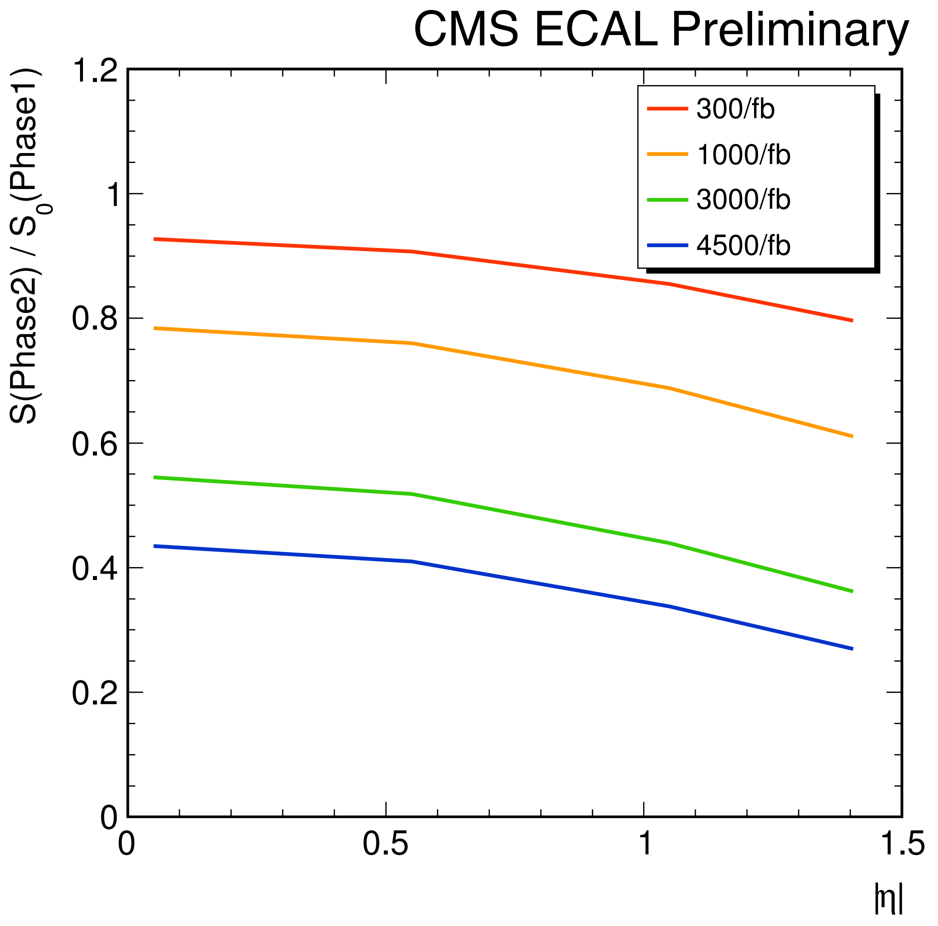
Improved L1 trigger algorithms in 2016 following Phase I upgrade

full trigger tower granularity available at Level 1

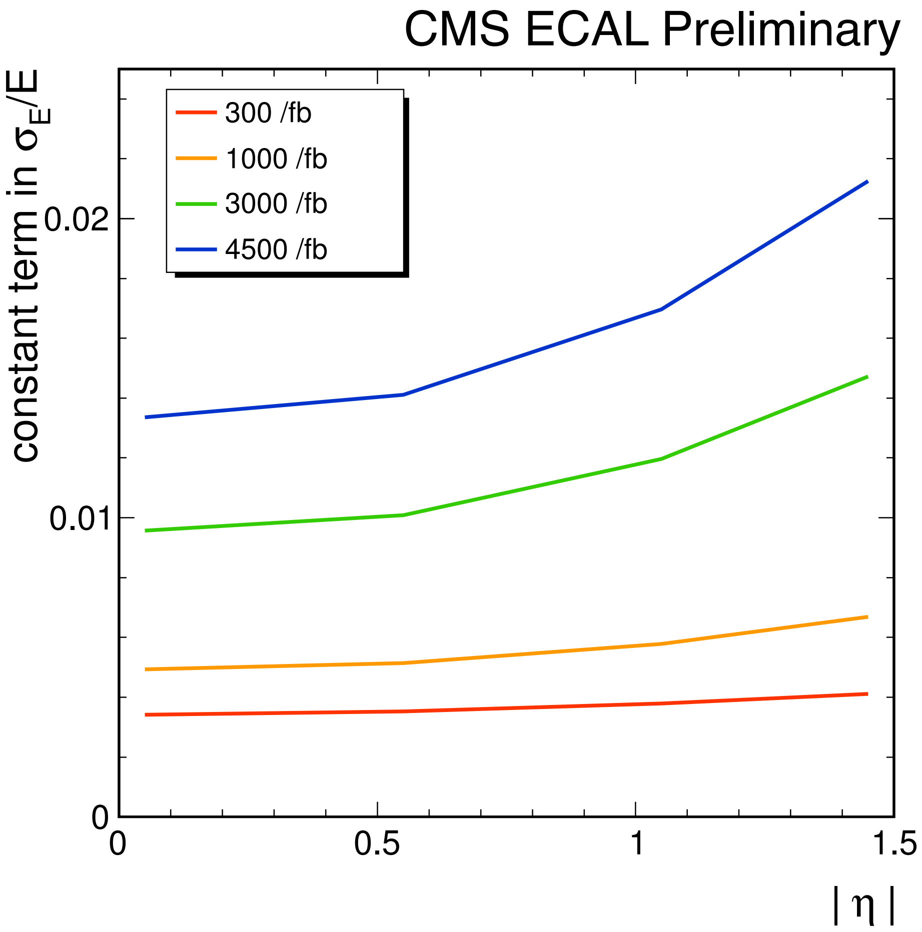
significant improvements in spatial and energy resolution, PU resilience and selection efficiency (especially for tau triggers)

Barrel crystals will be retained for HL-LHC

HL-LHC predictions from Geant 4 simulation



Will retain significant fraction of original light output



Modest evolution of constant term of energy resolution

(due to non-uniformity of light collection)

Barrel crystals will perform well during HL-LHC:

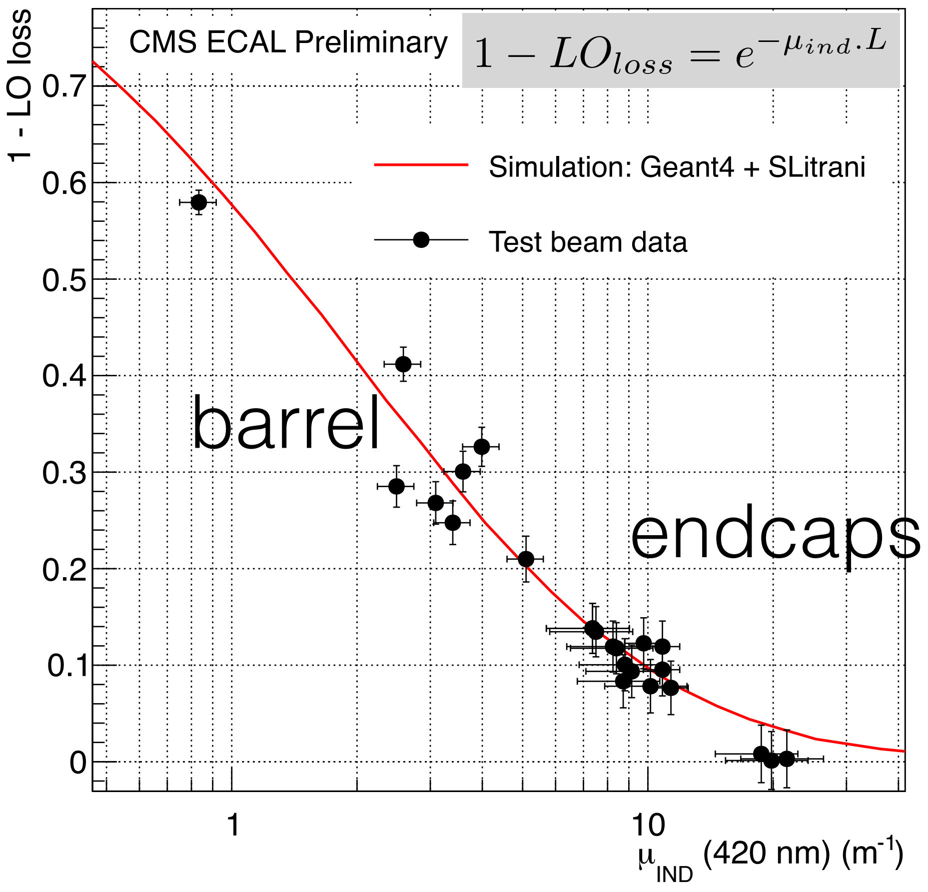
small degradation of energy resolution during lifetime of detector

Endcaps will suffer much larger losses and will be replaced in LS3

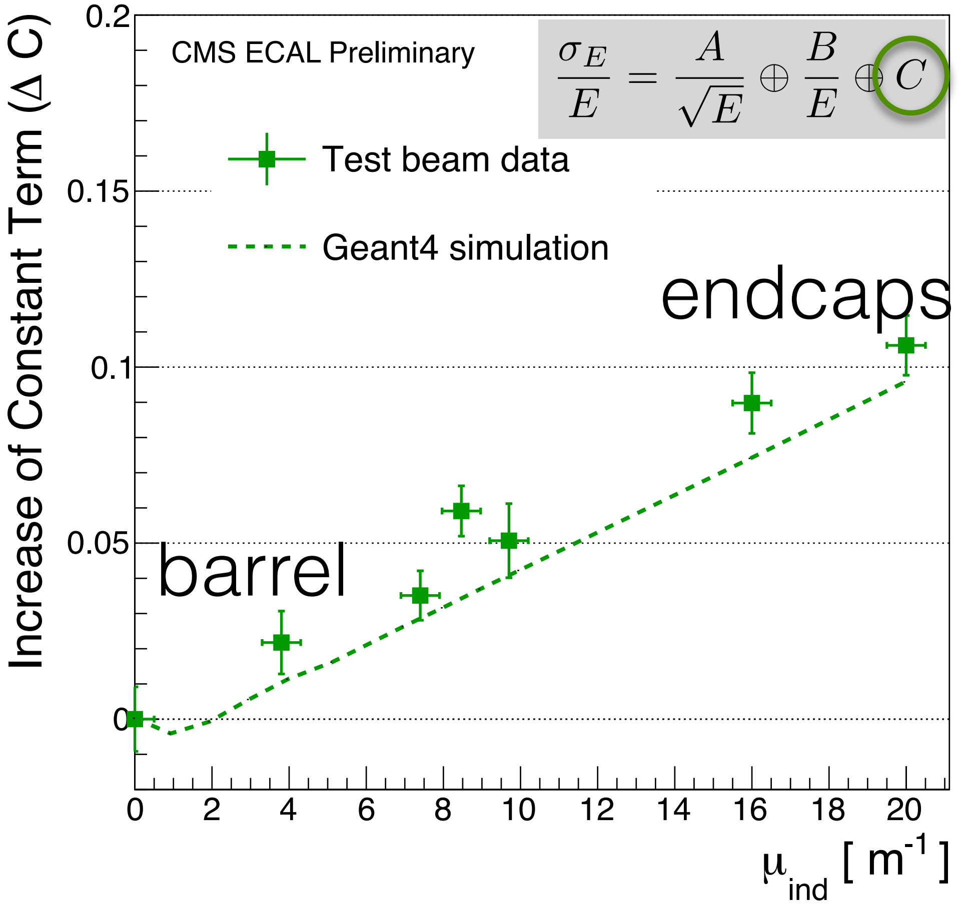
ECAL lead tungstate crystal performance

Main effect at HL-LHC due to hadron irradiation

Loss of light output



Degradation of energy resolution



Barrel crystals will perform well during HL-LHC:

will retain ~50% of light after 3000 fb^{-1}

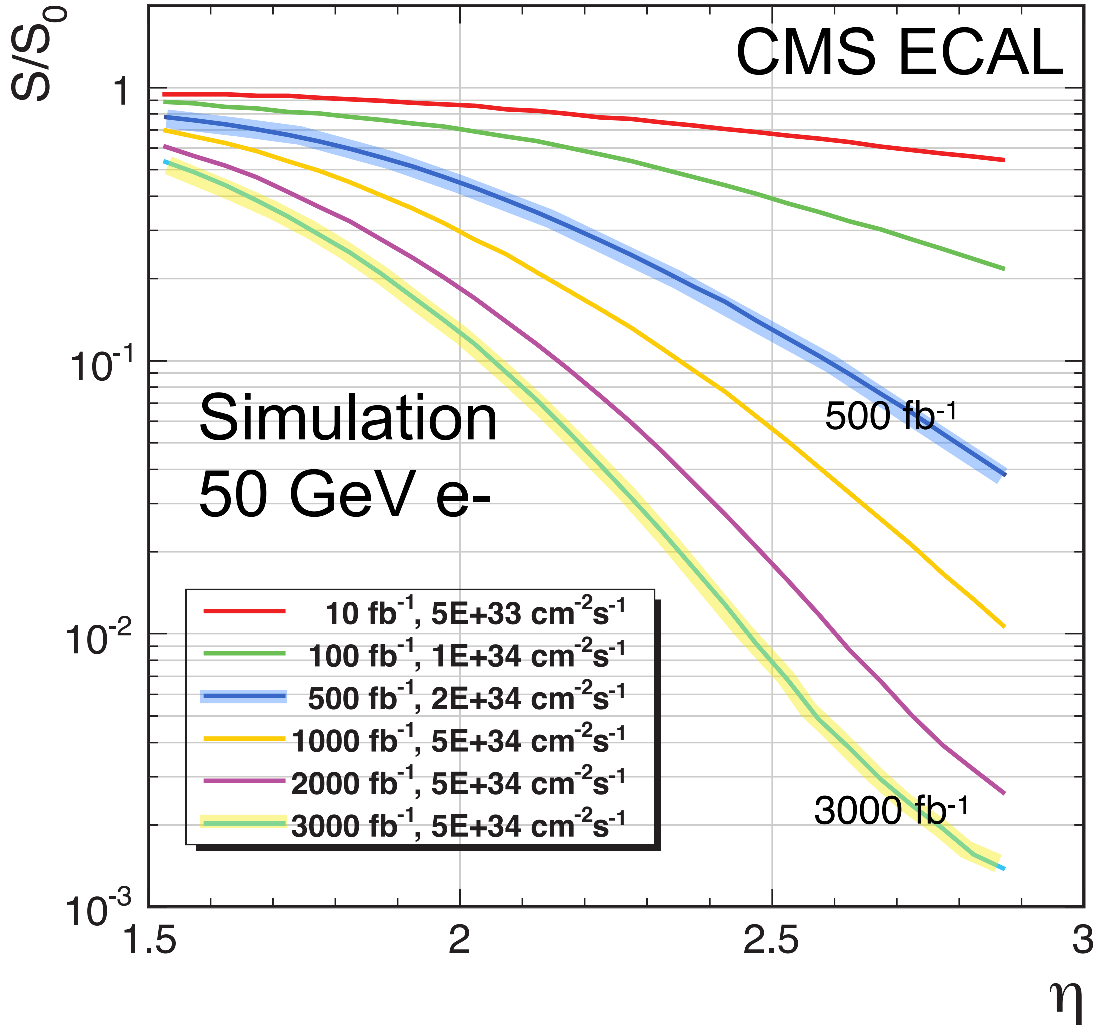
small degradation of energy resolution

Endcaps will suffer large light output losses

will be replaced by High granularity calorimeter for HL-LHC

EE longevity

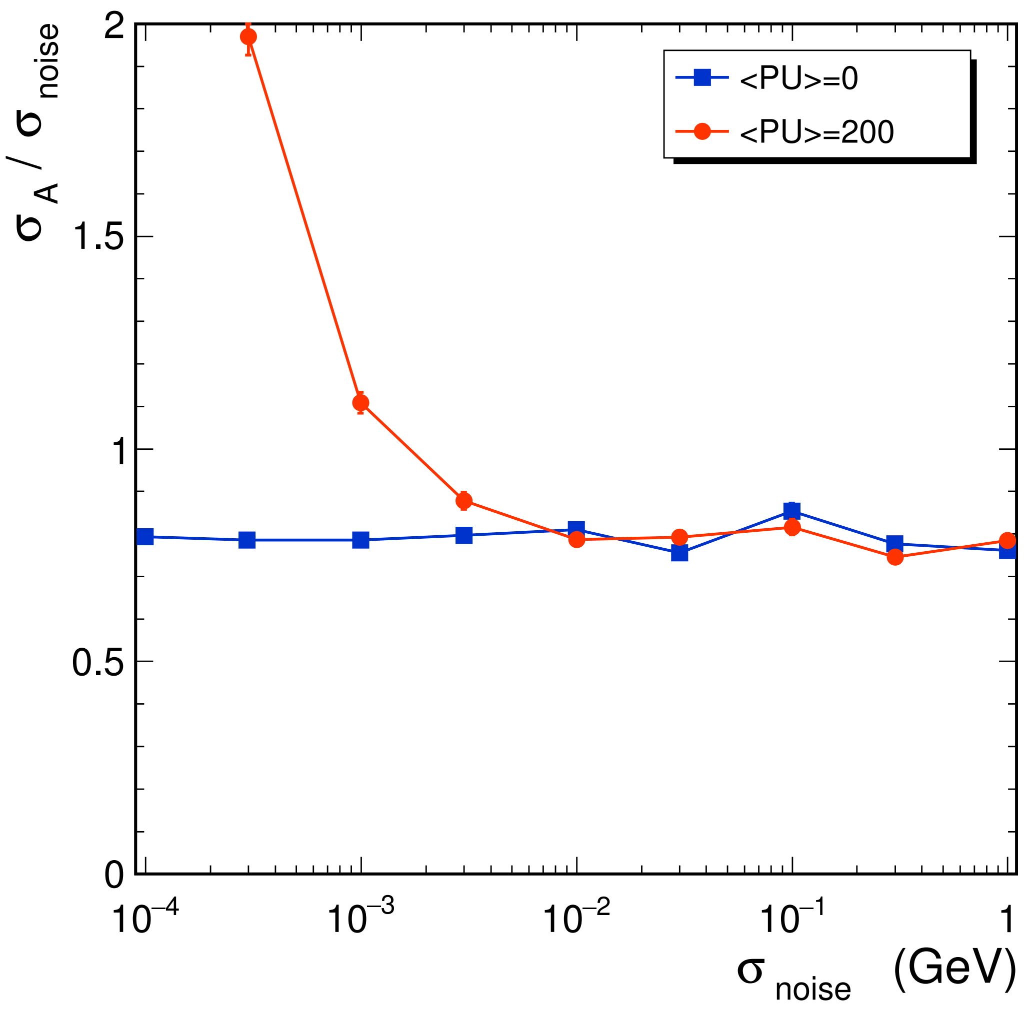
- ECAL endcaps (|η|>1.48) will suffer significant radiation damage after 500fb^{-1} and will need to be replaced during LS3
  - **cause:** loss of light transmission in $PbWO_4$ crystals caused by hadron irradiation. Cumulative, no recovery at room temperature.



Predicted ECAL Endcap signal response versus integrated luminosity and η

ECAL local reconstruction

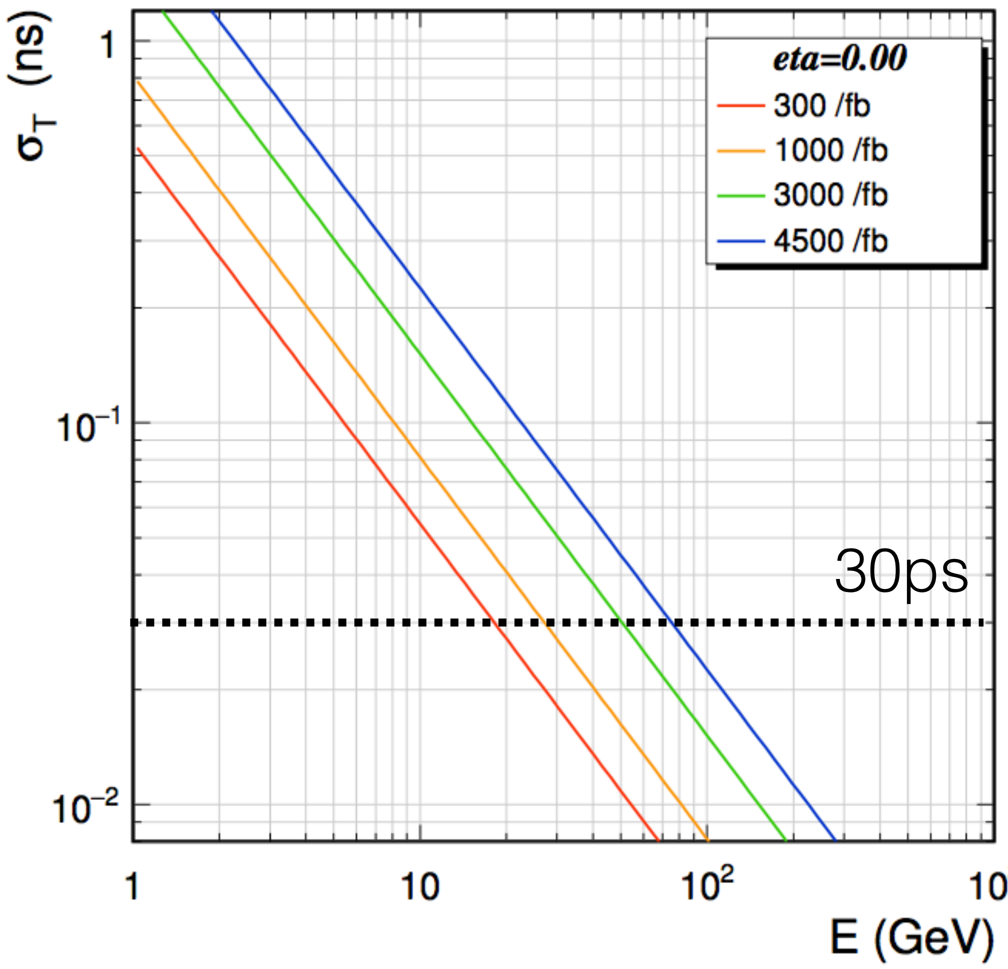
- **The aim of the upgraded detector is to preserve the current performance in the challenging HL-LHC conditions**



Amplitude reconstruction

subtracts out-of-time PU to negligible level

using Run II "multifit" algorithm



Timing resolution

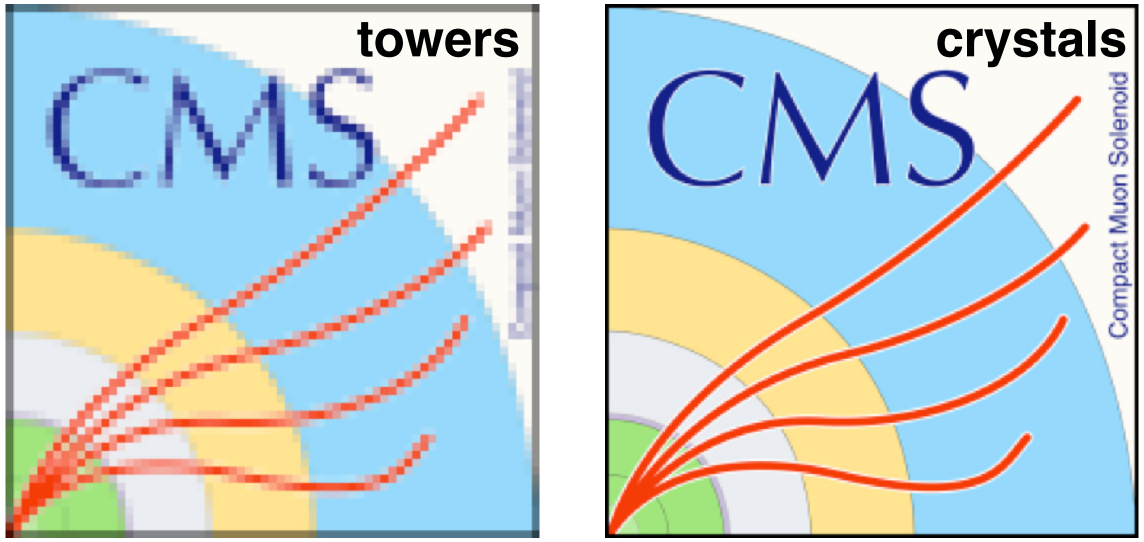
target of 30ps can be achieved

for 20-30 (50-90) GeV photons at the start (end) of HL-LHC

ECAL trigger upgrade

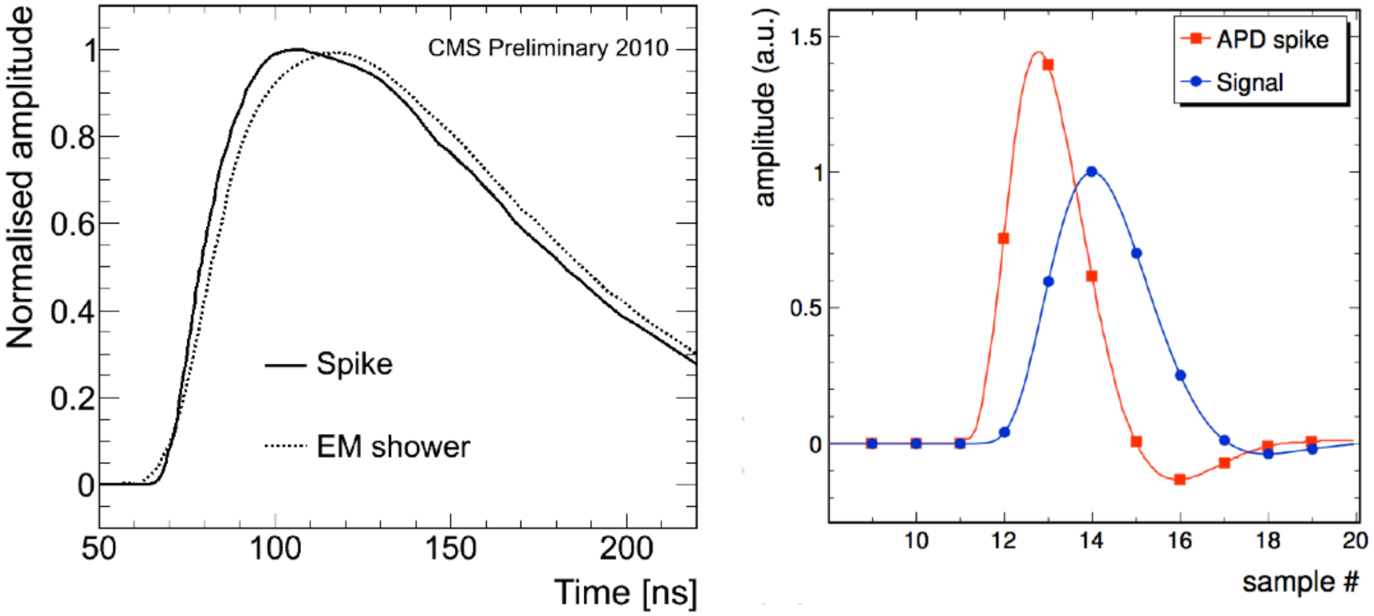
- **<u>ECAL upgrade will replace on-detector and off-detector electronics</u>**
- **<u>This will provide improved information to the Level-1 trigger</u>**
  - **Full ECAL granularity** available to L1 trigger (**improved by factor of 25)**
    - **Advanced clustering algorithms possible** in new off-detector electronics
      - with matching to Level-1 tracks— <u>implement particle flow algorithms at L1</u>
  - **Much improved rejection of spikes** in the EB photodetectors
    - due to new on-detector electronics with shorter pulse shaping

<u>Current</u> **<u>Upgrade</u>**



25x better trigger granularity

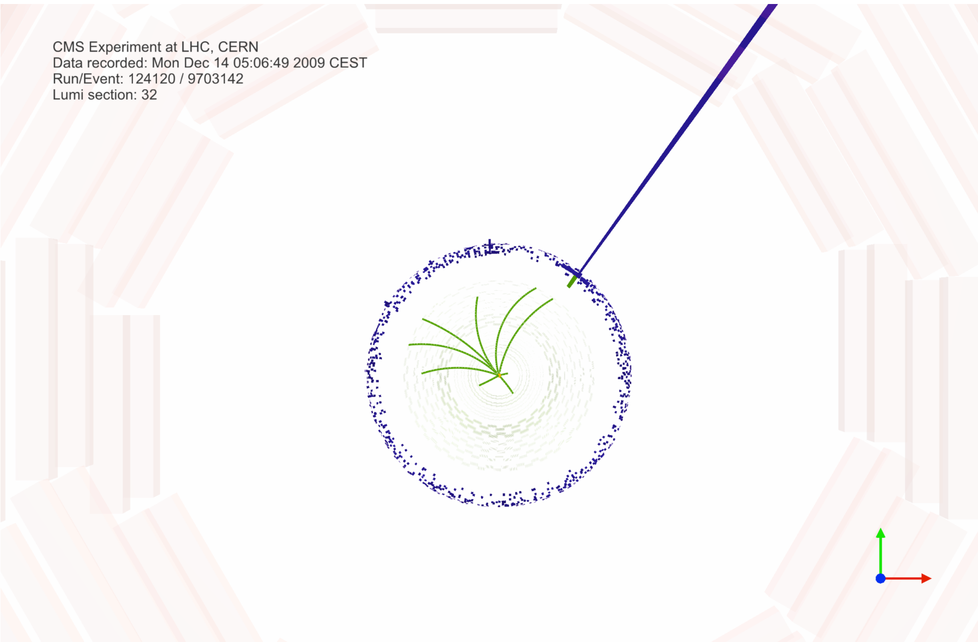
<u>Current</u> **<u>Upgrade</u>**



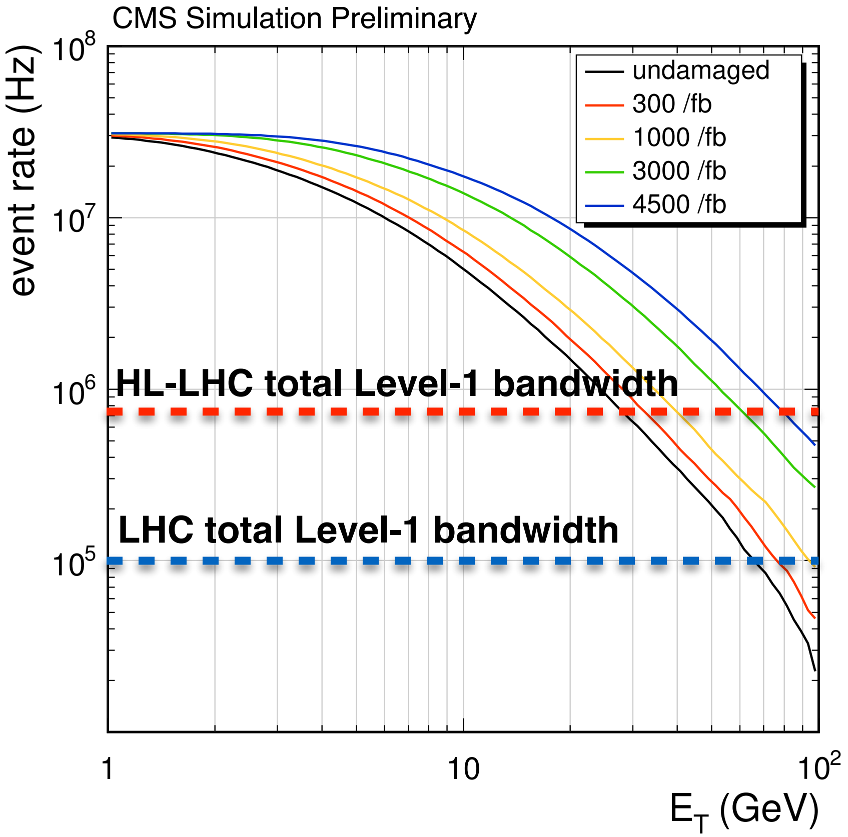
Much better “spike” rejection

ECAL triggering

- **Improved Level-1 trigger capabilities needed at HL-LHC**
  - larger trigger **rates** and trigger **latencies mandatory** to exploit larger luminosity and implement Level-1 track-trigger
  - **requires replacement of ECAL front-end and off-detector electronics**
- **Improved rejection of ECAL APD anomalous signals required**
  - “**spike**”: large isolated signal due to hadron interactions within APD volume
  - will **dominate** L1 trigger rate at HL-LHC if unsuppressed
  - **improved spike rejection needed in re-designed on-detector electronics**



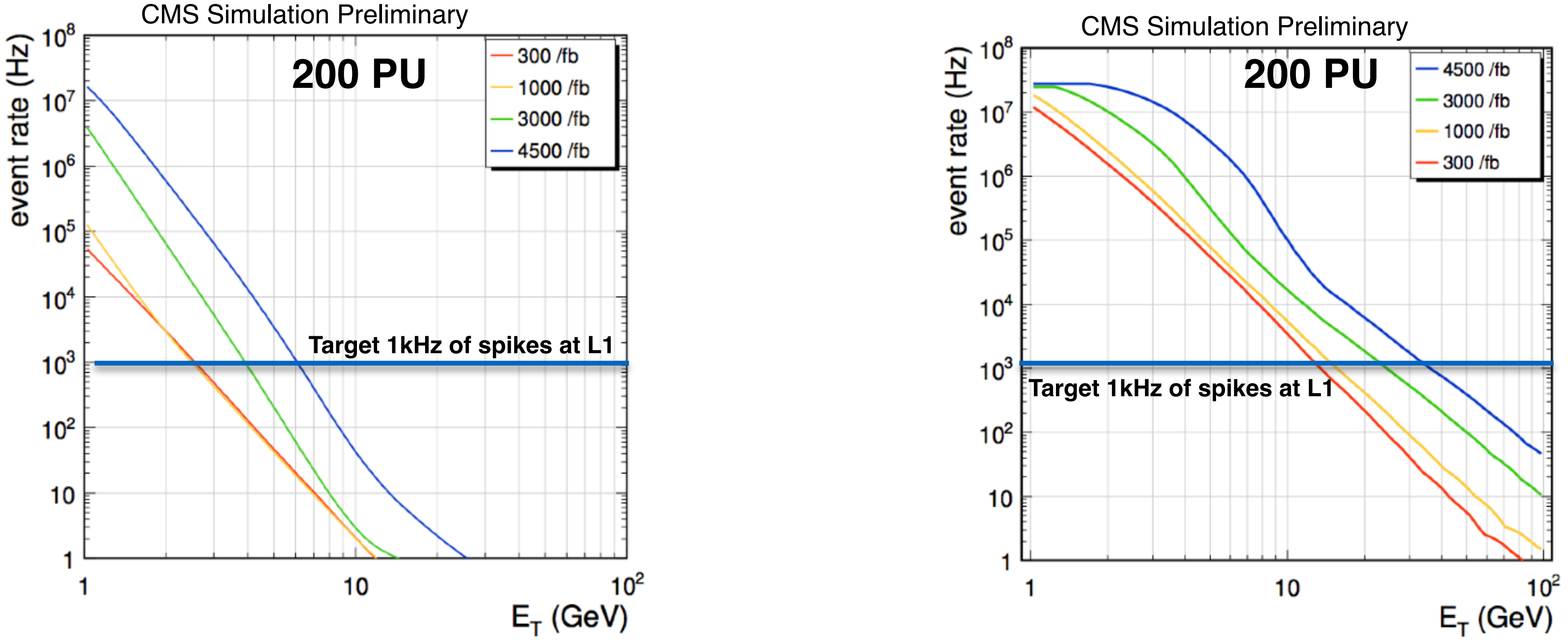
APD spike in CMS



Spike rate vs E_T threshold at HL-LHC

APD spike rejection at HL-LHC

- **Studying performance of two new spike killing algorithms**
  - **pulse shape** discriminant based on different signal shapes
  - **event topology** discriminant based on different spike/EM shower shapes
  - both can be implemented in off-detector readout



Pulse shape discriminant

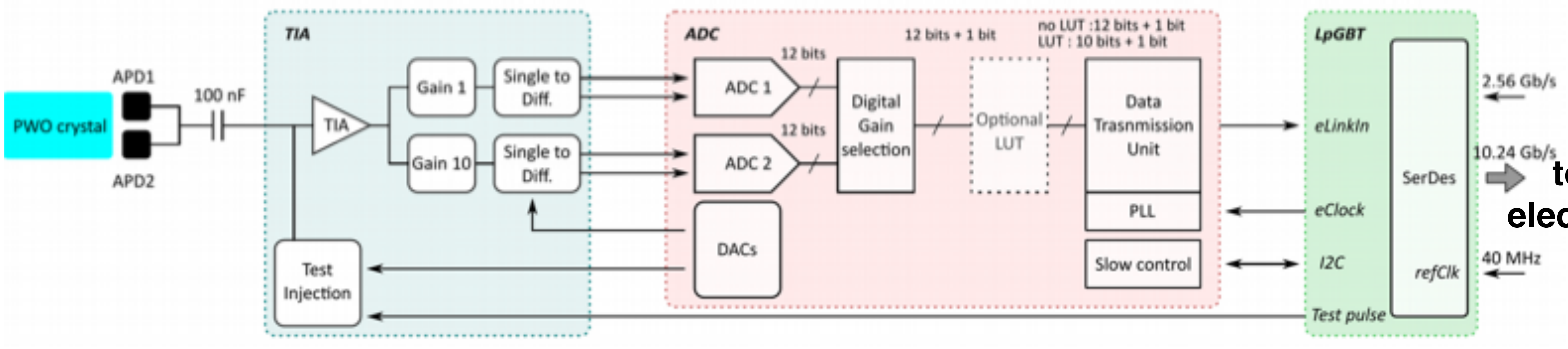
Event topology discriminant

Rate of spikes triggering Level-1 vs E_T for two Phase II spike killing algorithms

- **Pulse shape discriminant performs well at all HL-LHC luminosities:**
  - **<1kHz of residual spikes** triggering Level-1 for signals with E_T>5 GeV
  - Event topology more sensitive to noise and PU, but can be used as a backup

EB Phase II architecture

Preamp **ADC** **FE**



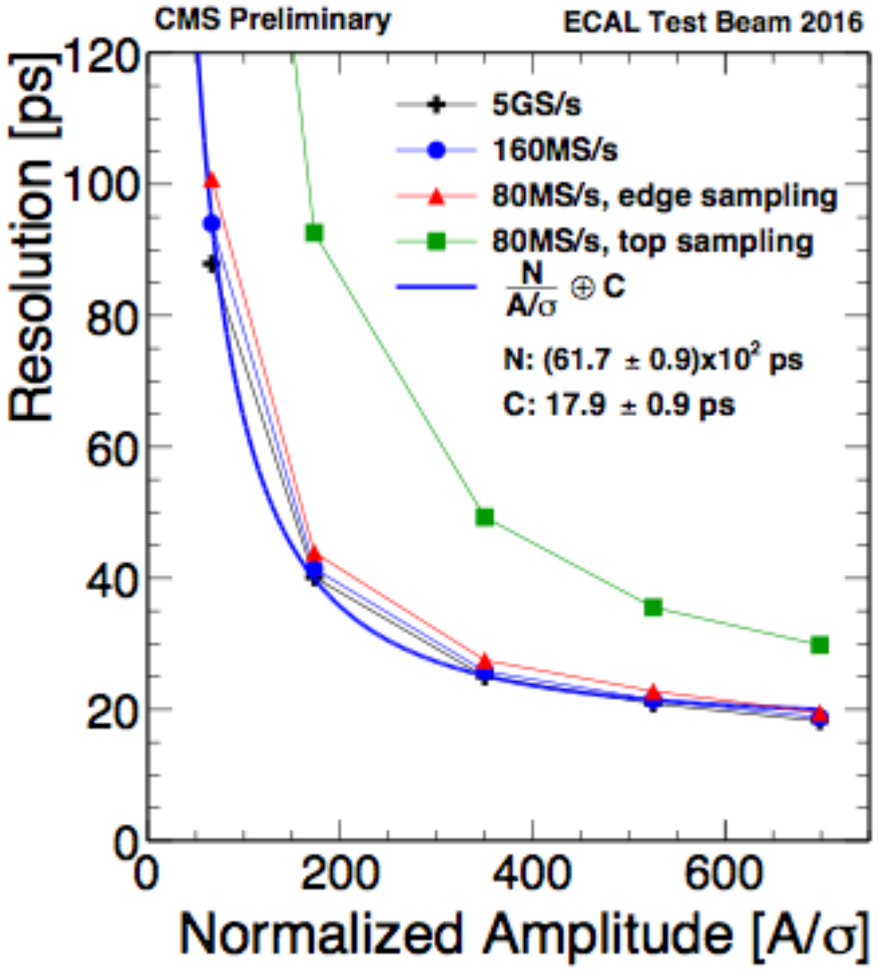
to OD electronics

- **TIA preamp:**
  - Two gain ranges (G1,G10). 2 TeV dynamic range with 50 MeV LSB
- **ADC**
  - 12 bit, 160 MHz sampling, dual channel with gain selection logic
  - Data Transmission Unit (DTU) implements data compression before FE
- **FE**
  - lpGBT (4x10.24 Gb/s data links, 1x2.56 Gb/s control link)
  - eLink serial interface to ADC, clock and i2C interface
- **Low voltage regulator (LVR):**
  - needed voltages (1.2, 2.5V) supplied by point-of-load FEAST DC/DC converters

Preamplifier ASIC R&D progress

Timing resolution of discrete component TIA

in H4 test beam



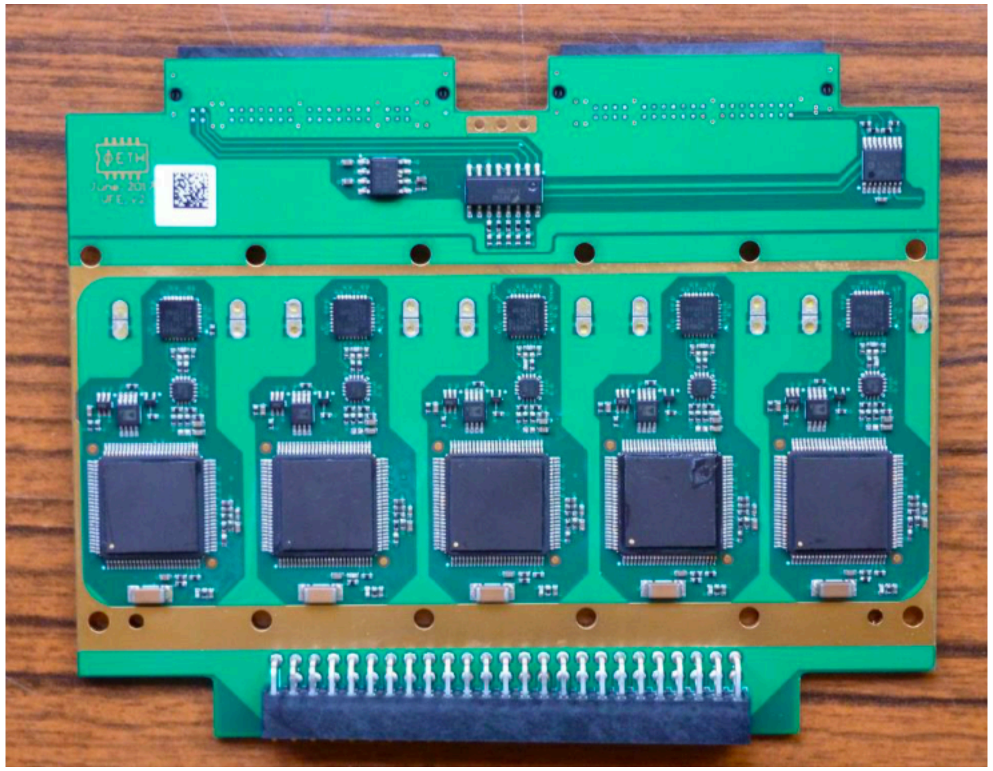
30 ps resolution achieved

Needs 160 MHz sampling

30 ps resolution reached at:

25 GeV **(HL-LHC start)**
60 GeV **(HL-LHC end)**

First tests of TIA ASIC: CATIA (CAlorimeter TIA)



Prototype CATIA mounted on VFE with commercial 160 MHz ADC

First ASIC produced and tested

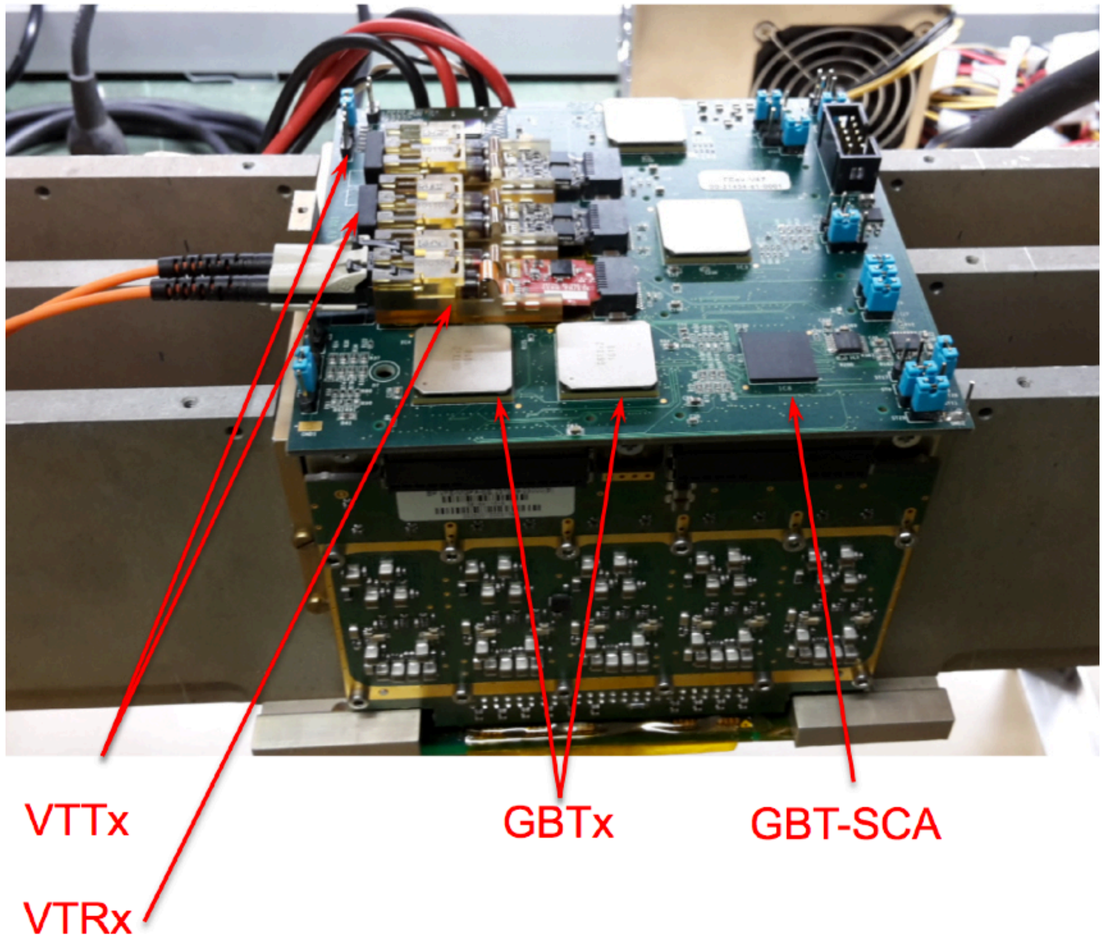
very promising performance

noise, amplitude and timing resolution verified in test beams

Front End card design

- **"streaming" FE**
  - **all crystal data transferred from VFE to off-detector electronics.**
  - **Trigger primitive formation in off-detector FPGA. No latency buffer/pipeline.**
- **Data rates:**
  - **~30 GB/s per 25 channels (with data compression)**
  - **fits in four 10 Gb/s lpGBT links**
- **FE demonstrator with GBT chipset being tested**
  - **with legacy VFE, using Phase I trigger board for DAQ**

FE demonstrator

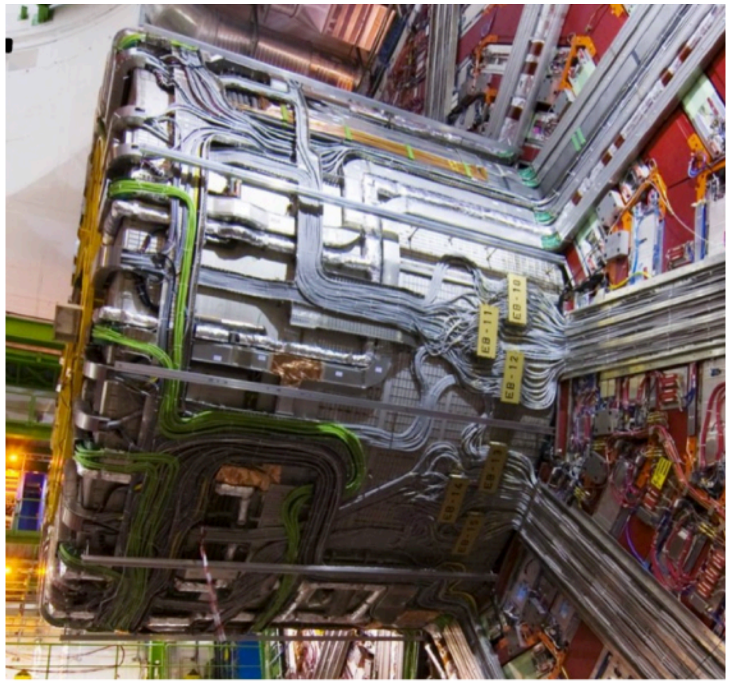


will be exercised in test beams with prototype upgrade VFE

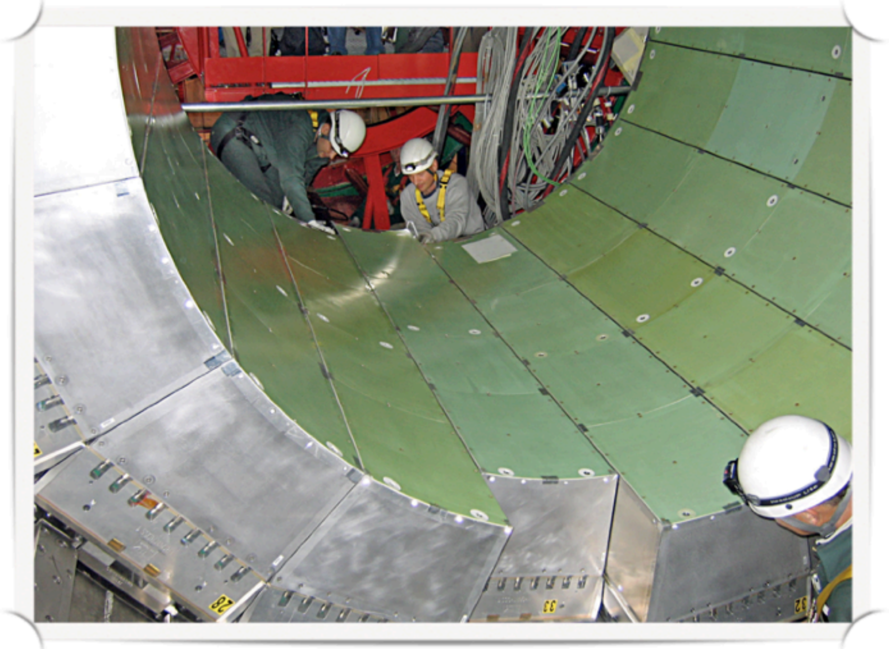
GBT: GigaBit Transceiver
http://cds.cern.ch/record/1235836

Detector cooling, refurbishment

- **<u>All supermodule services to be replaced during LS3</u>**
  - Low/High voltage, cooling pipes, readout fibres
  - Improved insulation of water cooling pipes + new cooling system (chilled water)
    - to operate at 9°C instead of current 18°C
- **<u>Supermodules to be removed/ refurbished/reinstalled during LS3</u>**
  - using specially prepared rework area at point 5 surface building



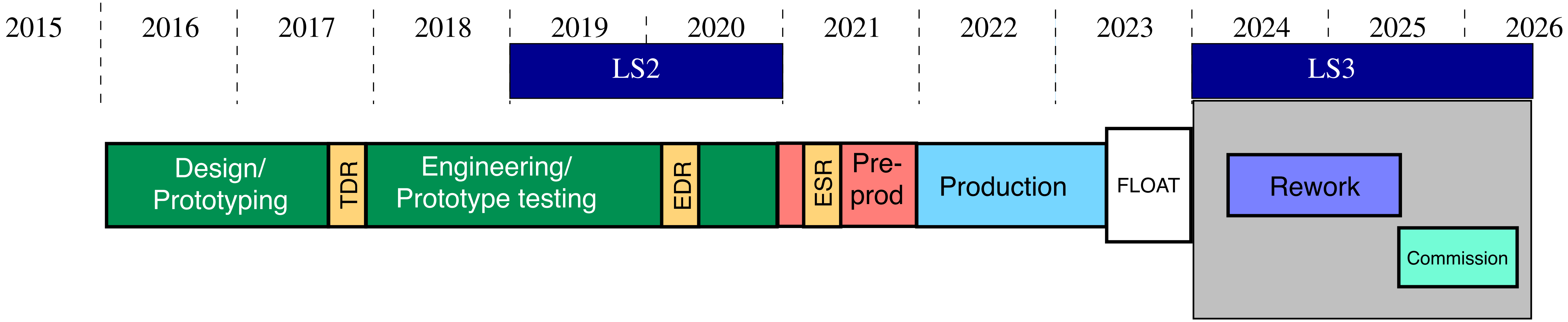
current supermodule services



supermodule insertion

Schedule and planning

Overall schedule



2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026

LS2

LS3

Design/ Prototyping

TDR

Engineering/ Prototype testing

EDR

ESR

Pre-prod

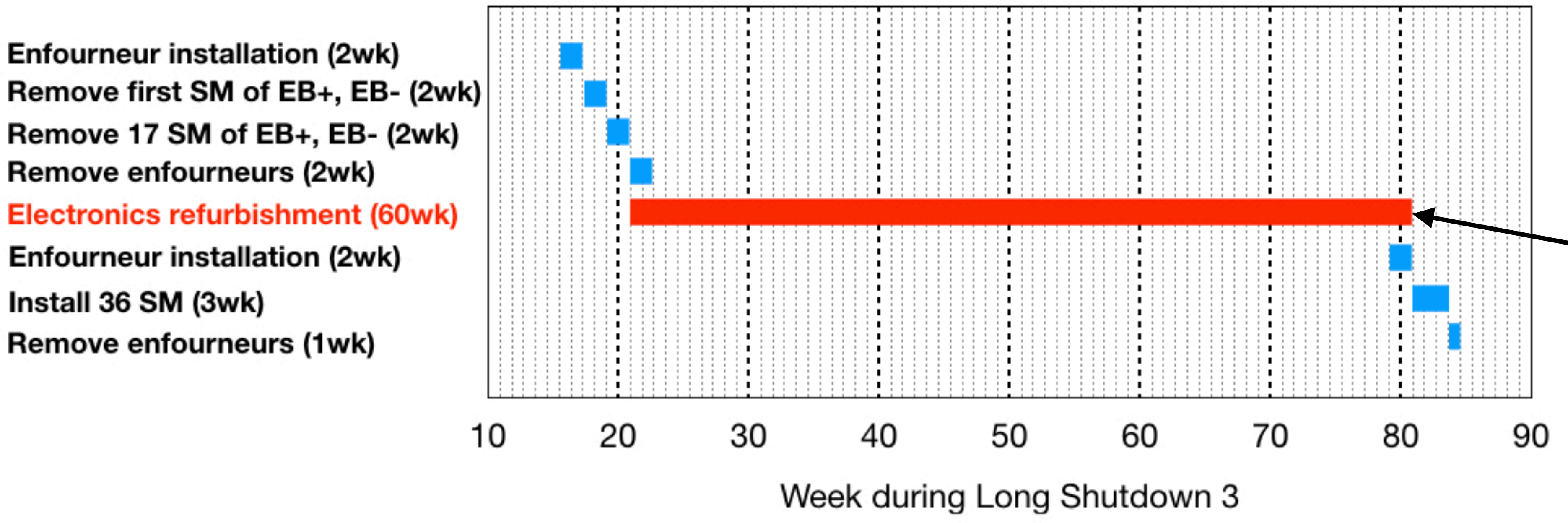
Production

FLOAT

Rework

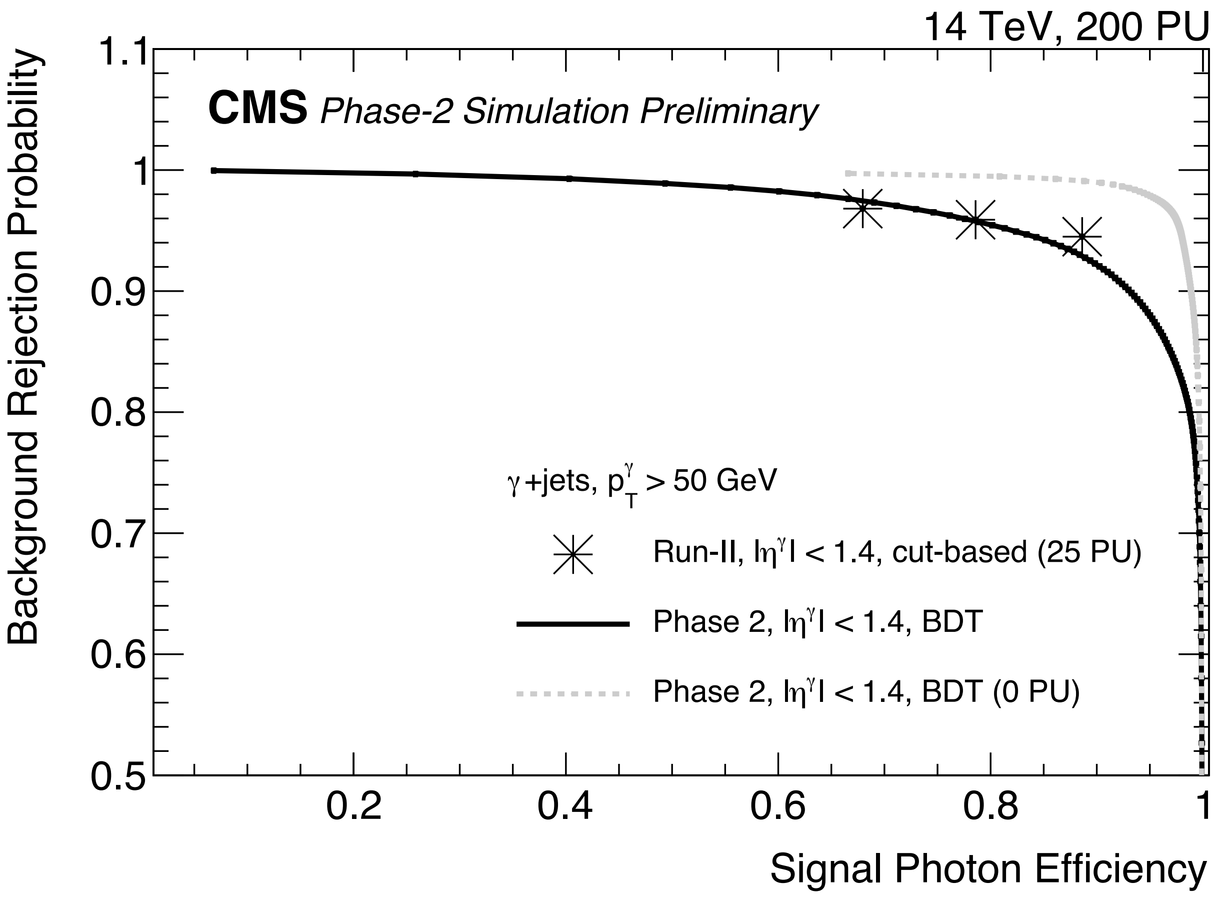
Commission

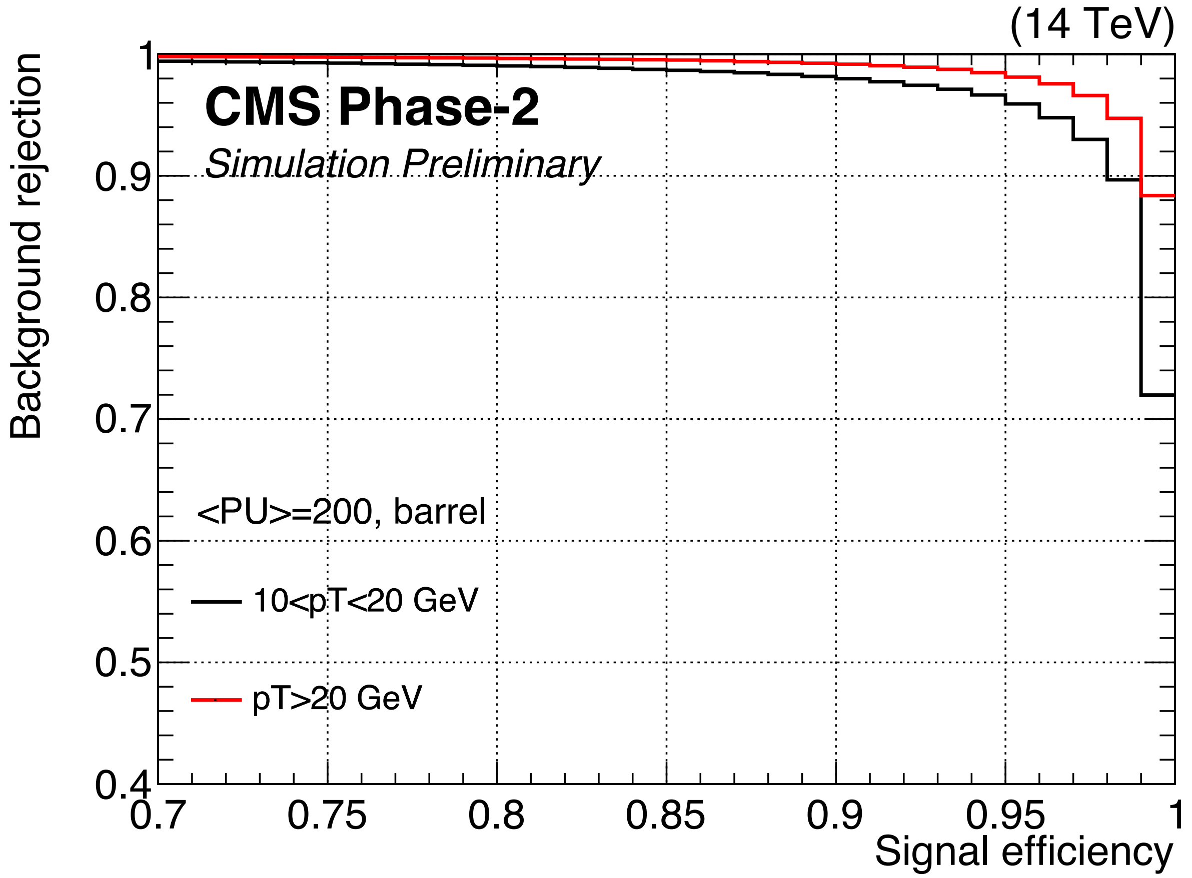
Supermodule refurbishment in LS3



Object identification

- **The aim of the upgraded detector is to preserve the current performance in the challenging HL-LHC conditions**





Photon ID

comparable to Run 2 performance

bold line - Phase-2 performance at 200PU

stars (*) - Run 2 cut-based working points

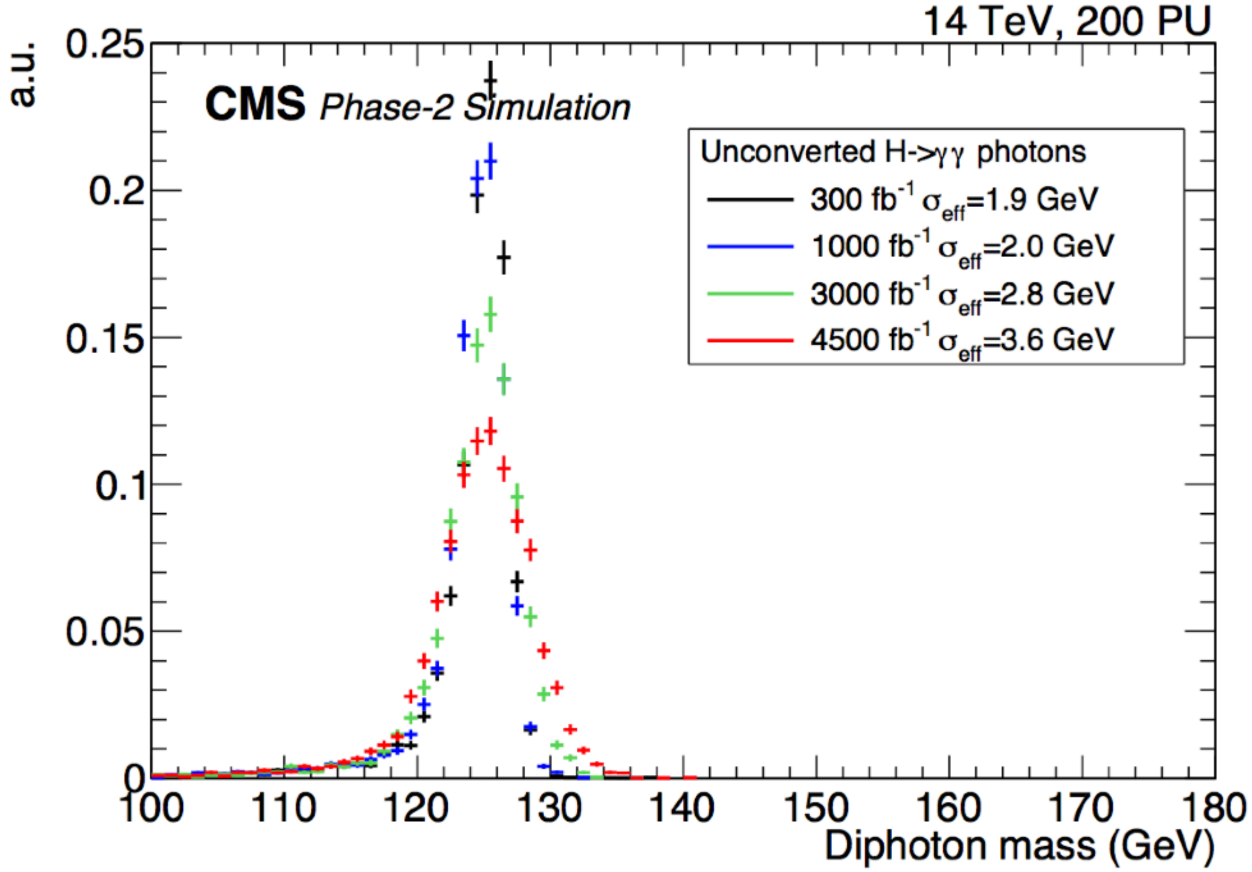
Electron ID

good performance at 200 PU

~95% efficiency, 2% fake rate for p_T>20 GeV

Physics: H→γγ

- **Benchmark analysis for performance:**
  - Excellent efficiency and energy resolution are required
- **Analysis details:**
  - Computed di-photon invariant mass comparing different ageing scenarios:
    - photon Pt>20,15 GeV, matched to a generator-level photon
  - Effect of multivariate photon regression has not been taken into account:
    - Observed significant improvements in Run2 using this technique:
      - **2.0 to 1.0 GeV for tight photons**
      - **3.0 GeV to 1.4 GeV for inclusive photons**
  - **With full optimisation, we expect similar resolution for Phase-2, 1000fb^{-1} as was obtained in Run 2**



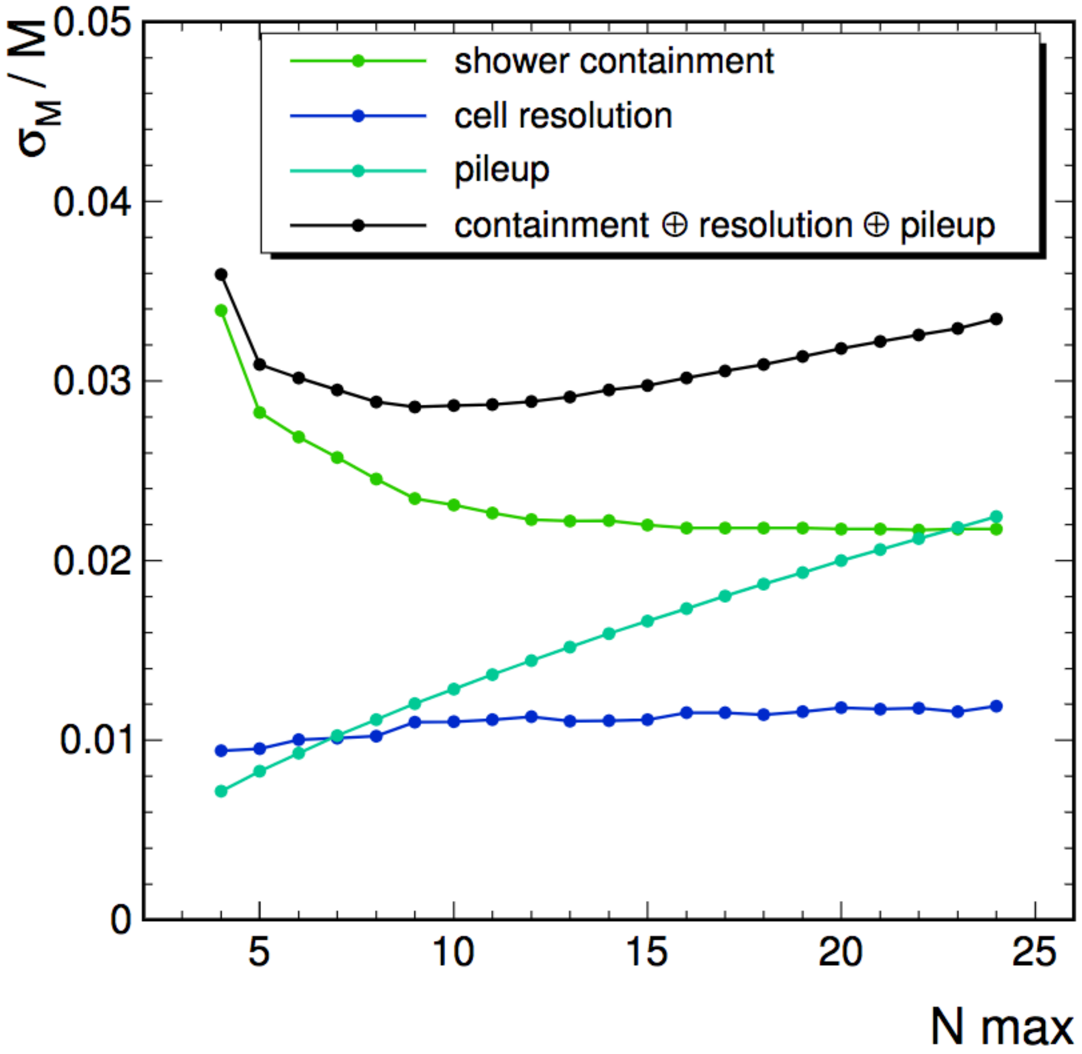
H→γγ resolution

slow degradation with ageing

unconverted photons, 3x3 cluster energy

Comments on H→γγ resolution

- **Ultimate energy resolution will require retuning of algorithms**
  - **current TDR clustering based on simple 3x3 crystal sums or the sum of the N "highest energy" hits**
- **Multivariate methods not yet applied**
  - **proved effective for Phase-1 analyses.**
  - **Should reduce "shower containment" component significantly**
    - **will allow resolutions close to Run-1 performance to be achieved for L=3000fb^{-1}**



Predicted contributions to H->gg resolution

for PU=200 and L=3000 fb^{-1}

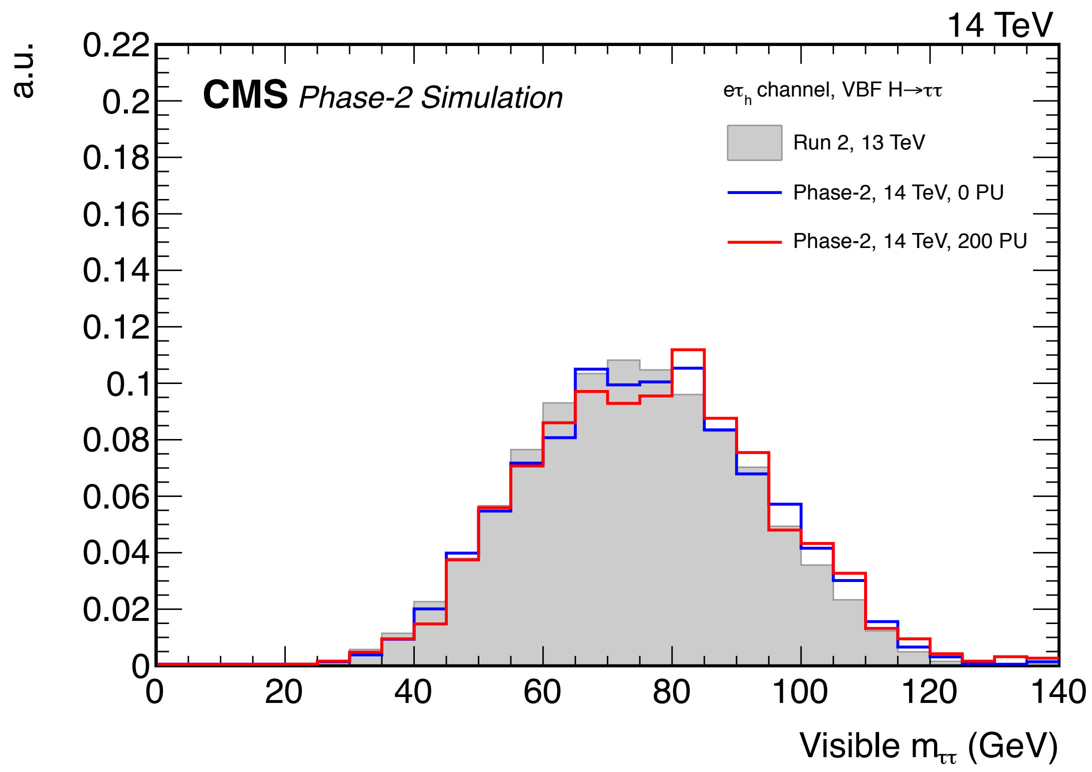
shower containment - *signal fluctuations*

cell resolution - *noise+constant term*

pileup - *in-time PU, mis-measured OOT PU*

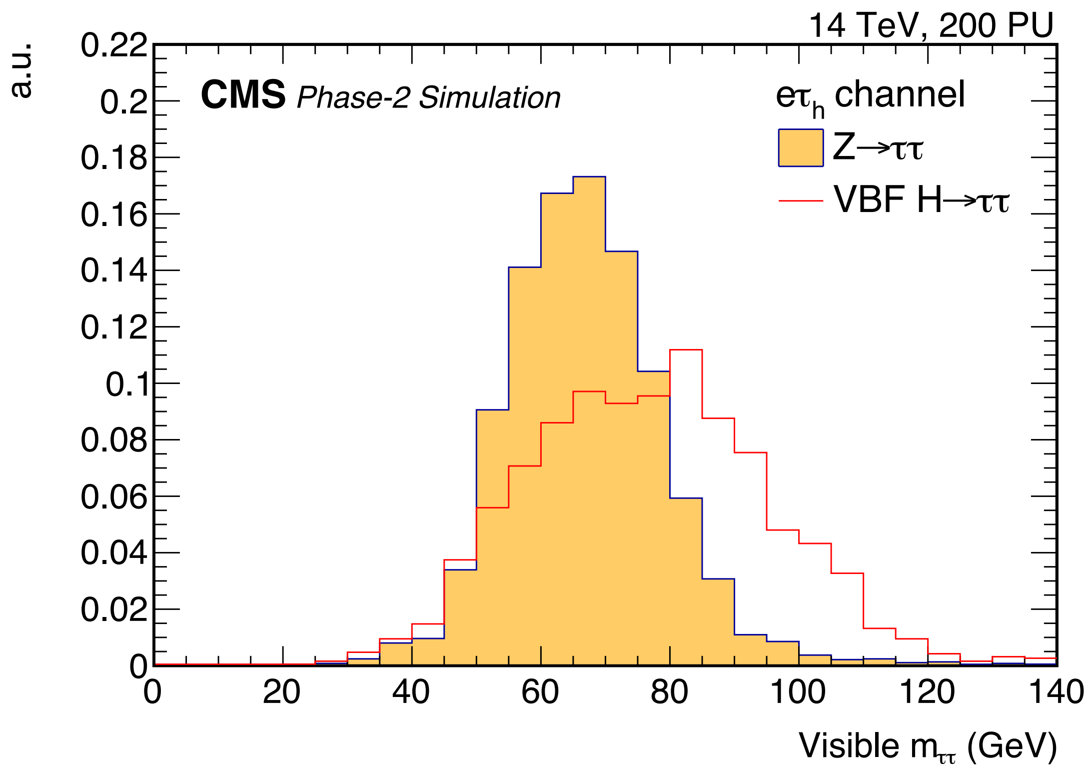
Physics: VBF $H\to\tau\tau$

- **Extrapolated precision reachable at HL-LHC on the modification of Higgs coupling to tau is estimated to be 2-5%**
- **Analysis details**
  - Studied of the e-τ_{had} final state of the di-τ pair
  - Comparing the visible mass distribution shows that **we can expect the same performance as in Run 2 for 200 PU**
  - Good separation of signal and Z->di-τ background is observed



$H\to\tau\tau$ mass resolution

same performance as Run 2

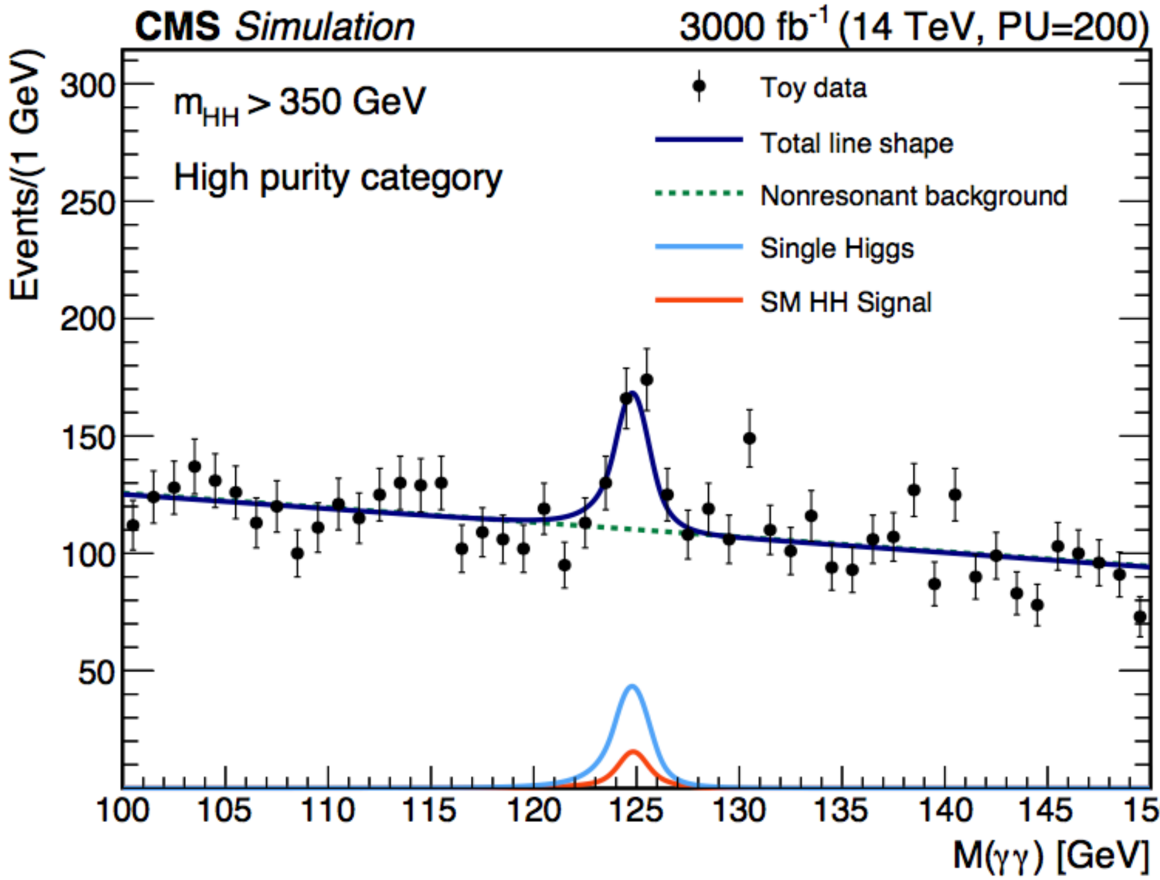


Signal/background separation

good separation with $Z\to\tau\tau$ background

Physics: HH→bbγγ

- **Analysis details:**
  - Sensitivity estimated for L=3000fb^{-1}, using detector resolution estimated for ageing corresponding to 1000fb^{-1}
    - improvements in photon resolution expected from application of regression techniques are applied
    - 1% uncertainty on jet energy scale assumed
    - improvements in b-tagging efficiency from upgraded tracker are applied
- **Projected sensitivity: 1.9σ**
    - further improvements (reduction of combinatorial backgrounds from fake photons) from the **use of precision timing information** are anticipated



HH→bbγγ signal

with Phase 2 photon resolution and L=3000fb^{-1}

Physics: HH→bbγγ

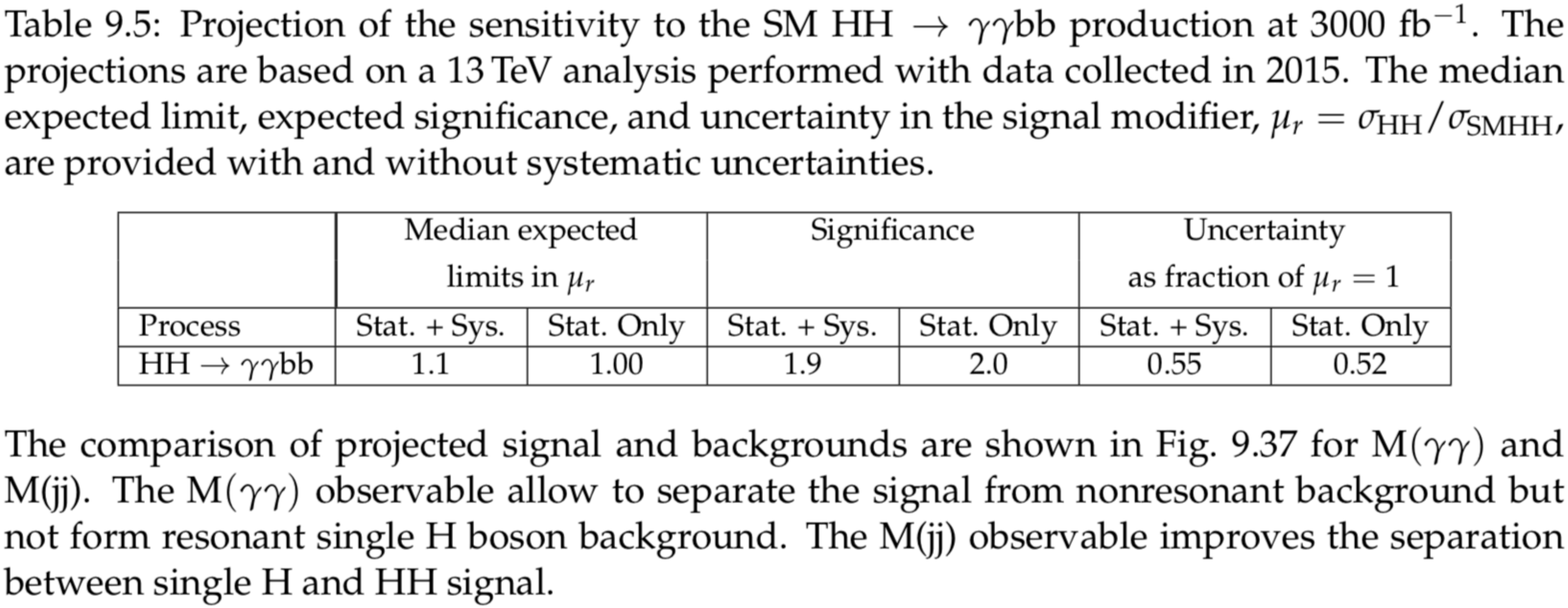


Table 9.5: Projection of the sensitivity to the SM HH $\rightarrow \gamma\gamma$bb production at 3000 fb^{-1}. The projections are based on a 13 TeV analysis performed with data collected in 2015. The median expected limit, expected significance, and uncertainty in the signal modifier, $\mu_r = \sigma_{\mathrm{HH}} / \sigma_{\mathrm{SMHH}}$, are provided with and without systematic uncertainties.

	Median expected limits in μ_r		Significance		Uncertainty as fraction of $\mu_r = 1$	
Process	Stat. + Sys.	Stat. Only	Stat. + Sys.	Stat. Only	Stat. + Sys.	Stat. Only
HH $\rightarrow \gamma\gamma$bb	1.1	1.00	1.9	2.0	0.55	0.52

The comparison of projected signal and backgrounds are shown in Fig. 9.37 for M($\gamma\gamma$) and M(jj). The M($\gamma\gamma$) observable allow to separate the signal from nonresonant background but not form resonant single H boson background. The M(jj) observable improves the separation between single H and HH signal.

Physics: HH→bbγγ

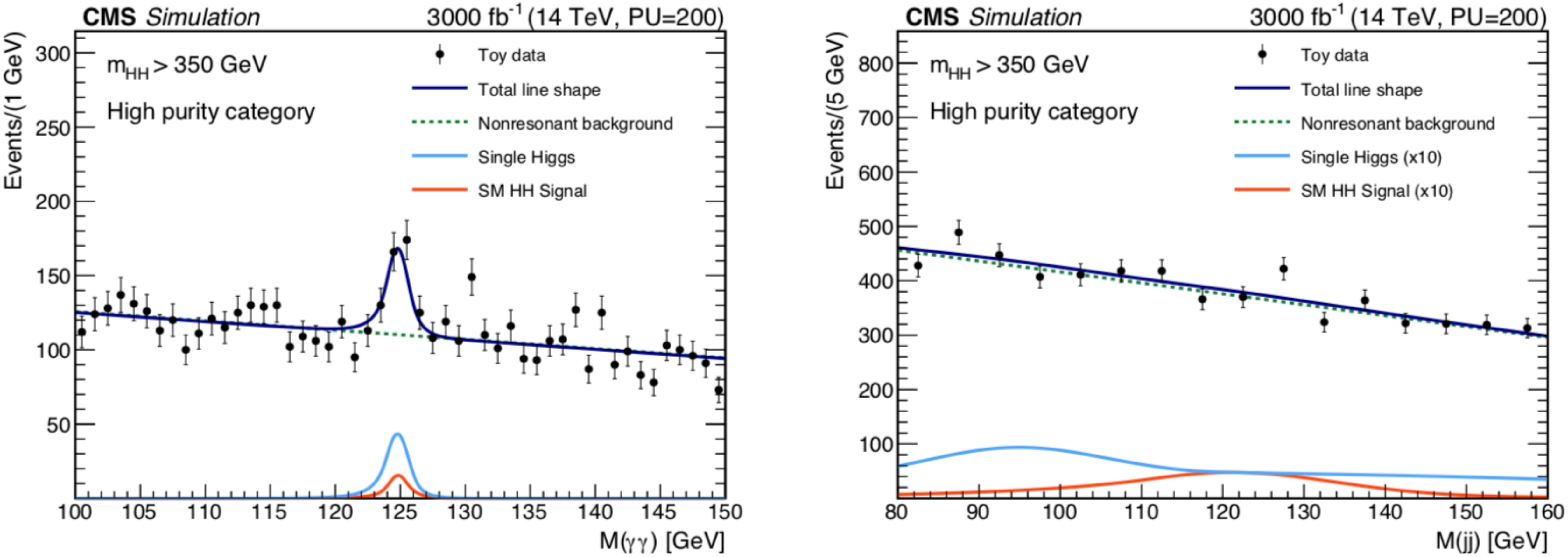


Figure 9.37: The M($\gamma\gamma$) (left) and M(jj) (right) distributions for ECAL ageing after 1000 fb^{-1} for an integrated luminosity of 3000 fb^{-1}. Note that some contributions are magnified by a factor of 10 in order to be visible on the m_{jetjet} distribution).

Physics: b-tagging efficiency

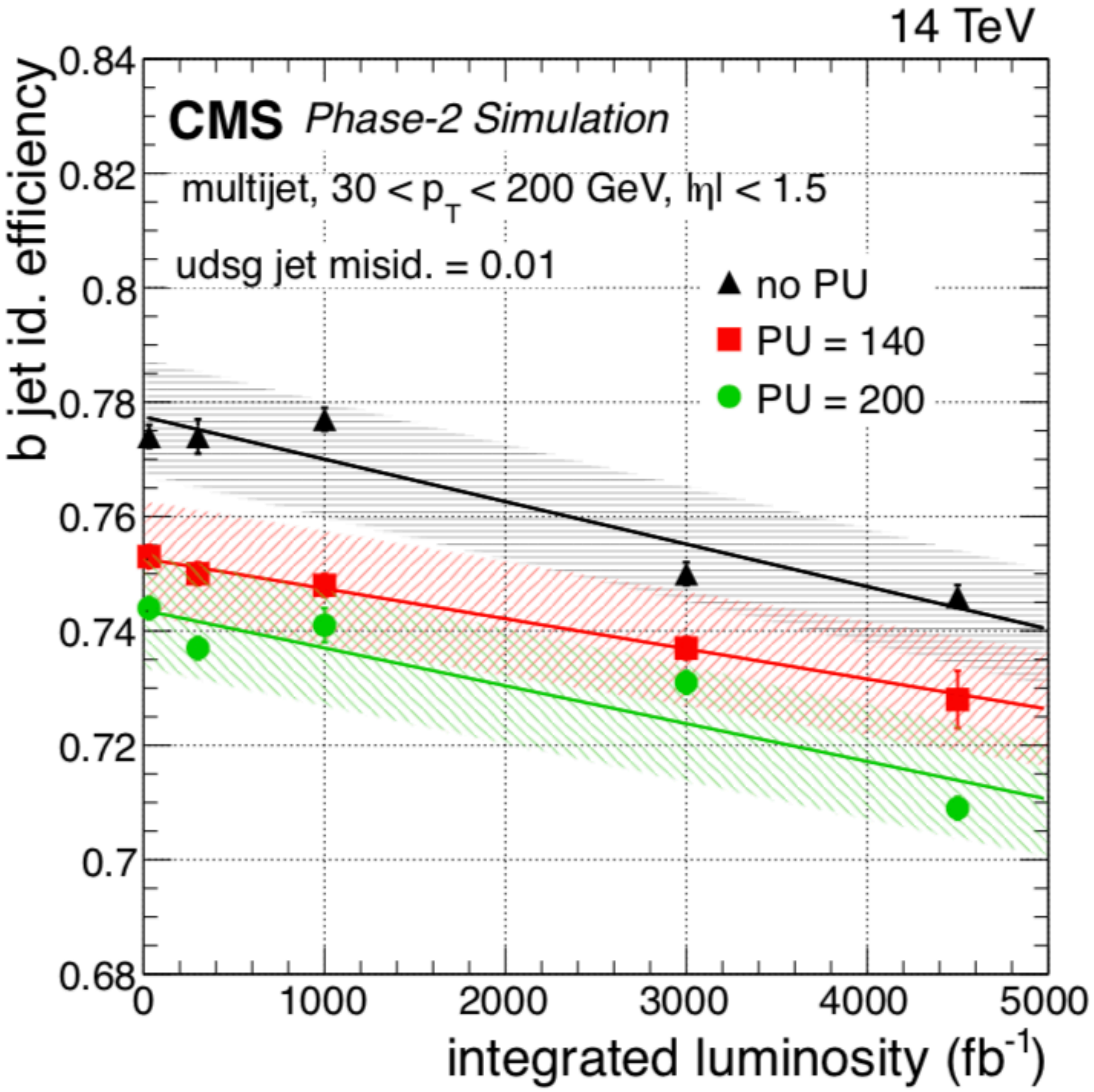
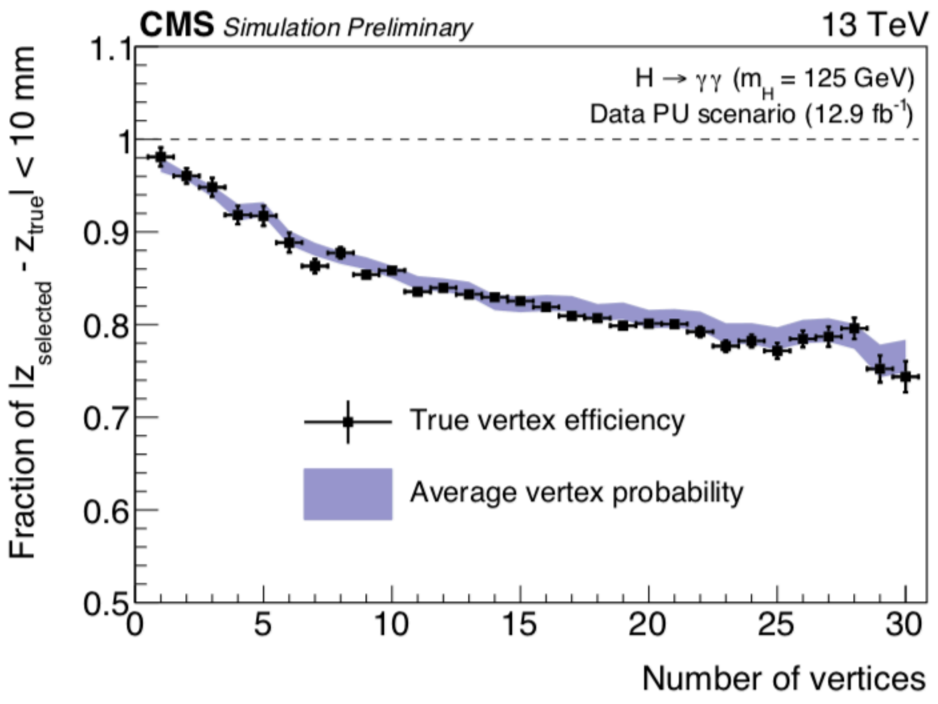
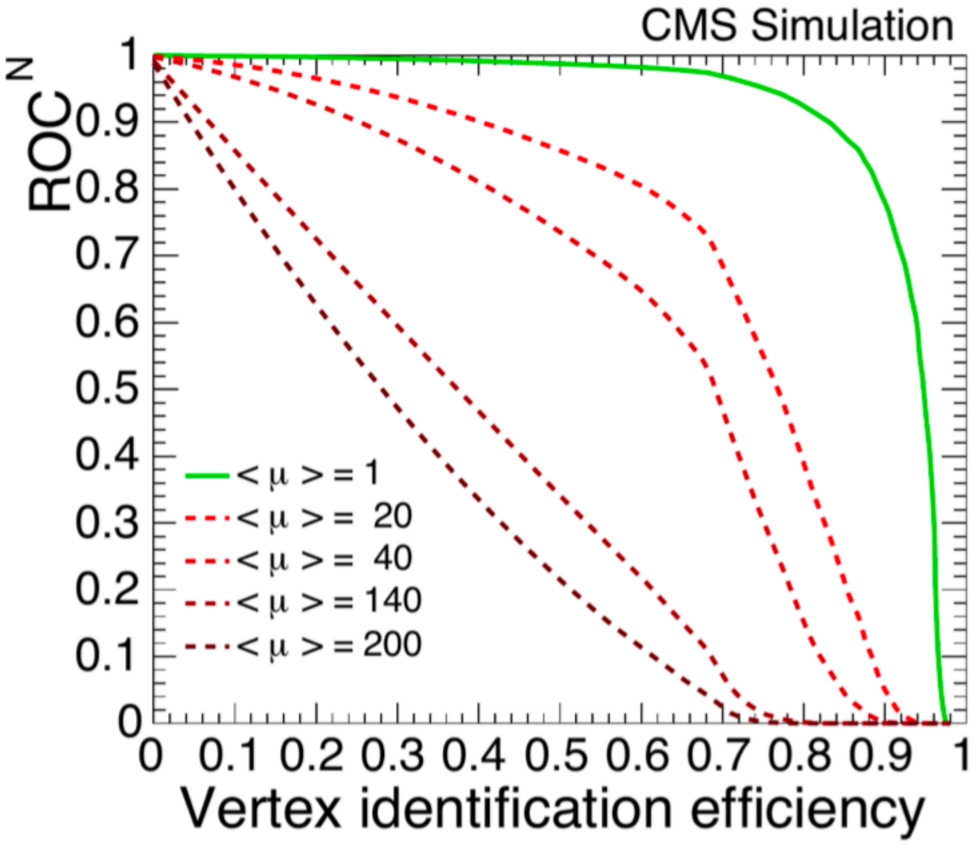


Figure 9.29: Efficiency of b tagging (with the cMVAv2 tagger) in simulated multi-jet events as a function of the integrated luminosity. Jets are required to satisfy $|\eta| < 1.5$ and have a p_T value in the 30–200 GeV range.

Primary vertex identification in $H \to \gamma\gamma$

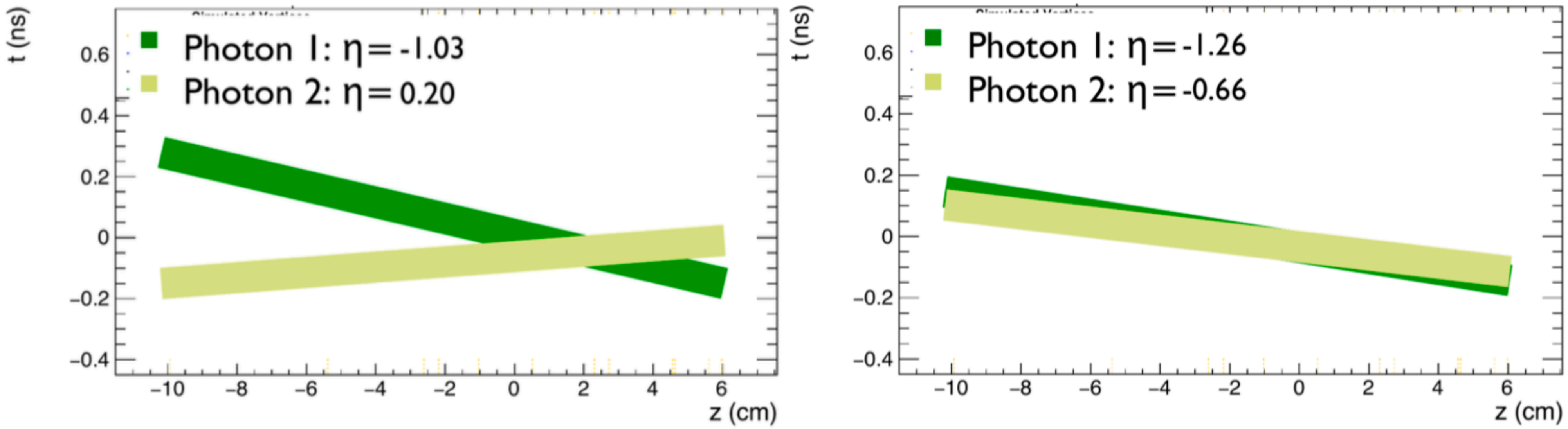
- No pointing information from ECal→ CMS relies on hadronic recoil balancing and conversion pointing to locate primary vertex in $H \to \gamma\gamma$ events
- Becomes increasingly difficult to locate the primary vertex at very high pileup
- Vertex selection efficiency drops from ∼80% in current conditions to ∼30% at 200 PU



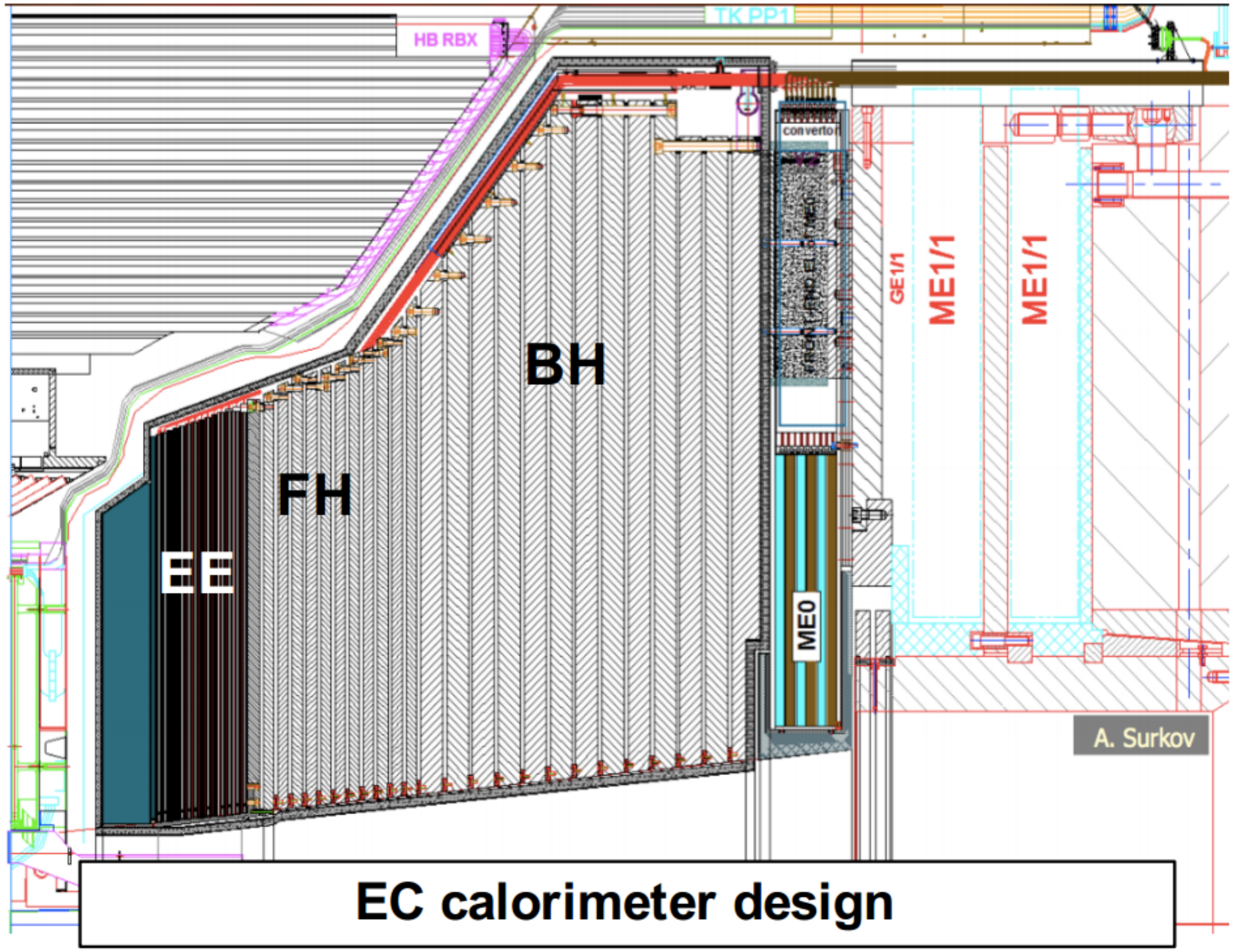


Precision timing for High Energy Photons - $H \to \gamma\gamma$

- Precision timing measurements for the high energy photons allows triangulation back to the primary vertex (30 ps resolution assumed here)
- Triangulation breaks down for small rapidity gap. In the absence of a known t_0 for the hard interaction, triangulation is ambiguous



Endcap Calorimeter layout



A. Surkov

EC calorimeter design

Construction:

- Hexagonal Si-sensors built into modules.
- Modules with a W/Cu backing plate and PCB readout board.
- Modules mounted on copper cooling plates to make wedge-shaped cassettes.
- Cassettes integrated into absorber structures at integration site (CERN)

Key parameters:

- 593 m^2 of silicon
- 6M ch, 0.5 or 1 cm^2 cell-size
- 21,660 modules (8” or 2x6” sensors)
- 92,000 front-end ASICS.
- Power at end of life 115 kW.

Complete replacement for EE and HE in LS3

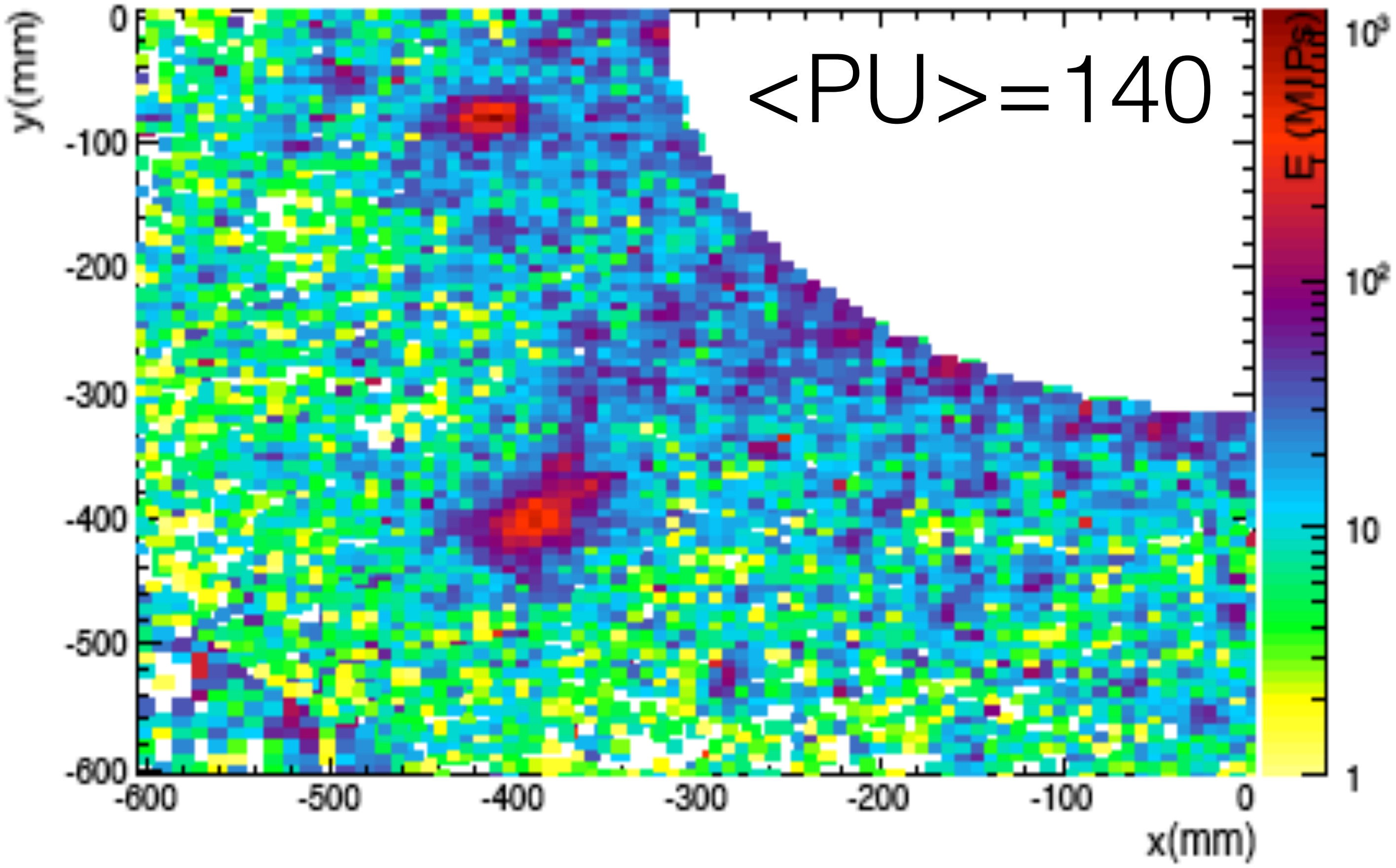
Sampling calorimeter with fine transverse granularity

silicon sensors in EE+FH and inner BH region: intrinsically rad-hard

must operate at -30 degC to limit Si leakage current

Challenges for calorimetry at HL-LHC

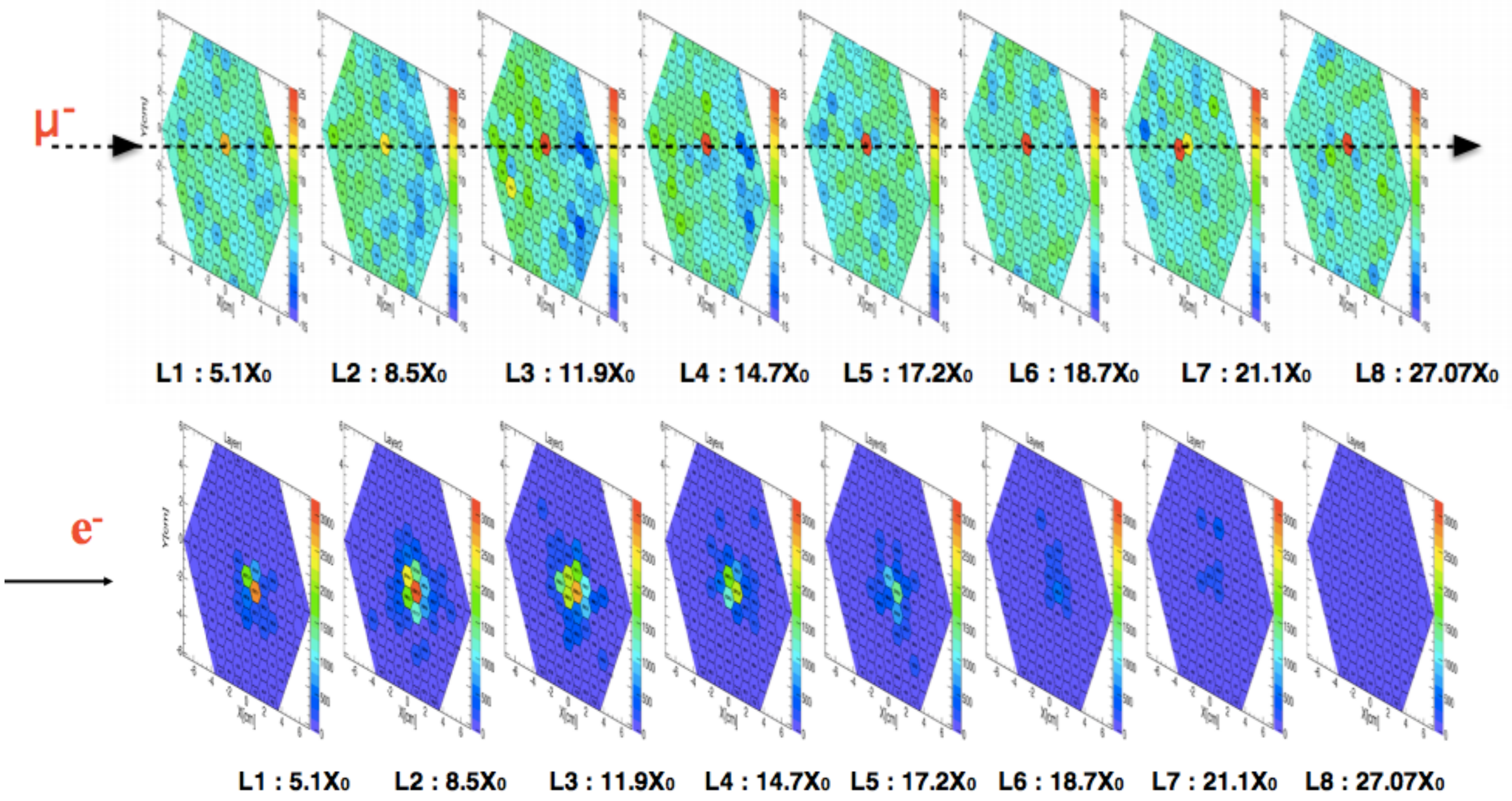
- **Expect LHC to deliver very high luminosity beams: <pileup> ~ 200**
- **Disentangling event properties at such high particle densities requires good transverse and longitudinal segmentation, and advanced reconstruction methods**
- **Endcap calorimeter is a highly granular rad-hard detector designed to meet the challenges of high beam intensity and event pileup**



Event display of VBF jets (H->gg)

EC concept being realised in test beams

- **Small-scale devices with prototype sensors and readout**
  - tested at CERN and FNAL test beams



- **Used to qualify devices, measure performance and develop hardware and software algorithms**