Optimising the performance of the CMS Electromagnetic Calorimeter to measure Higgs properties during Phase I and Phase II of the LHC

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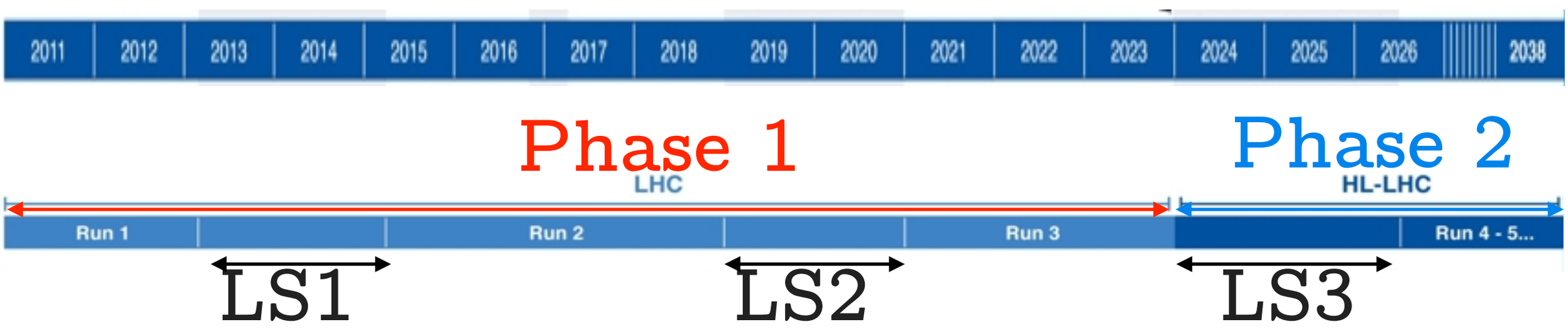
For the CMS Collaboration

Outline

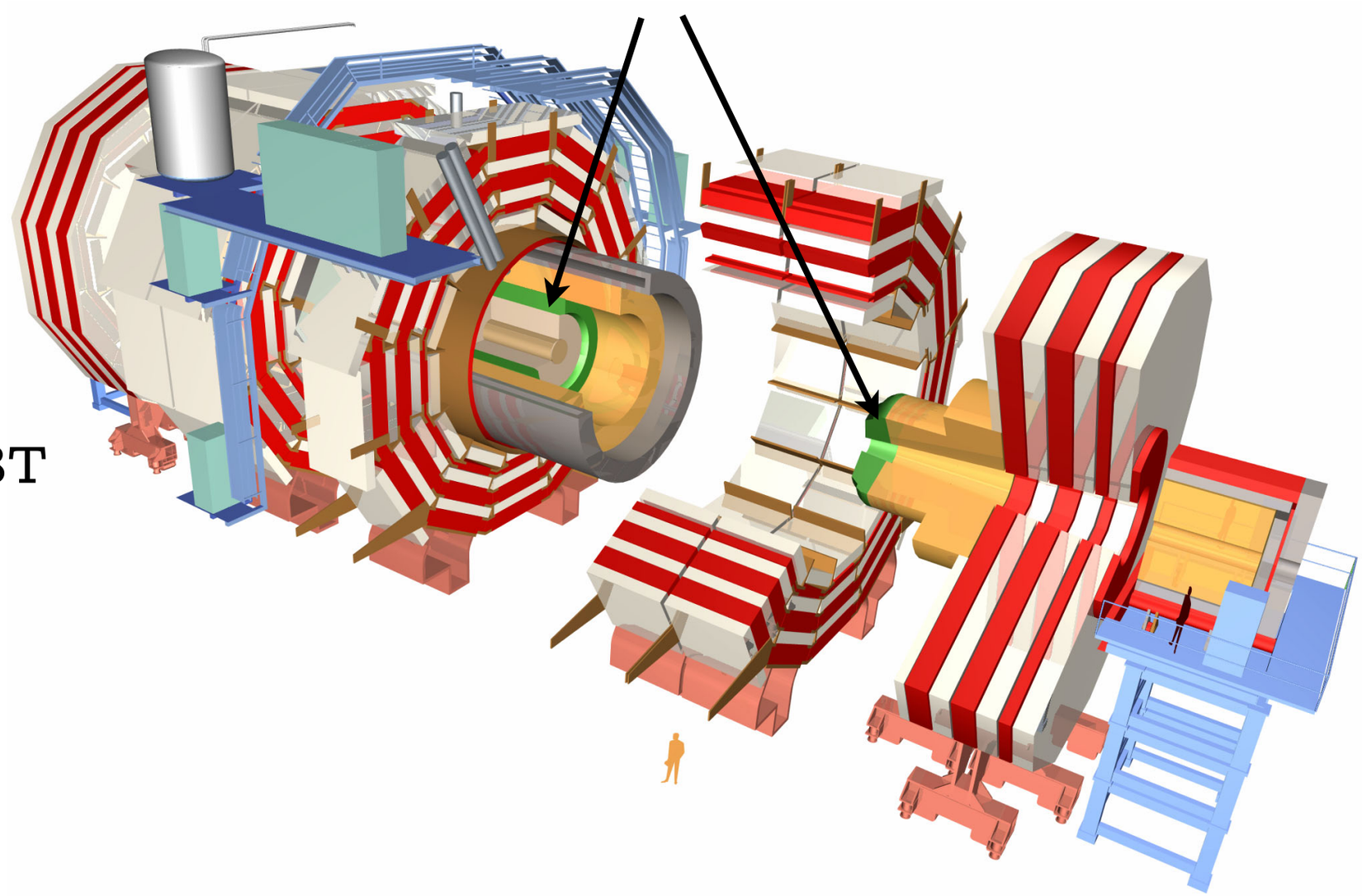
1. The current detector: description and performance during LHC Phase 1
2. The high luminosity LHC (HL-LHC)upgrade
3. ECAL Barrel upgrade and expected performance during LHC Phase 2 (HL-LHC)



Current Detector

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.

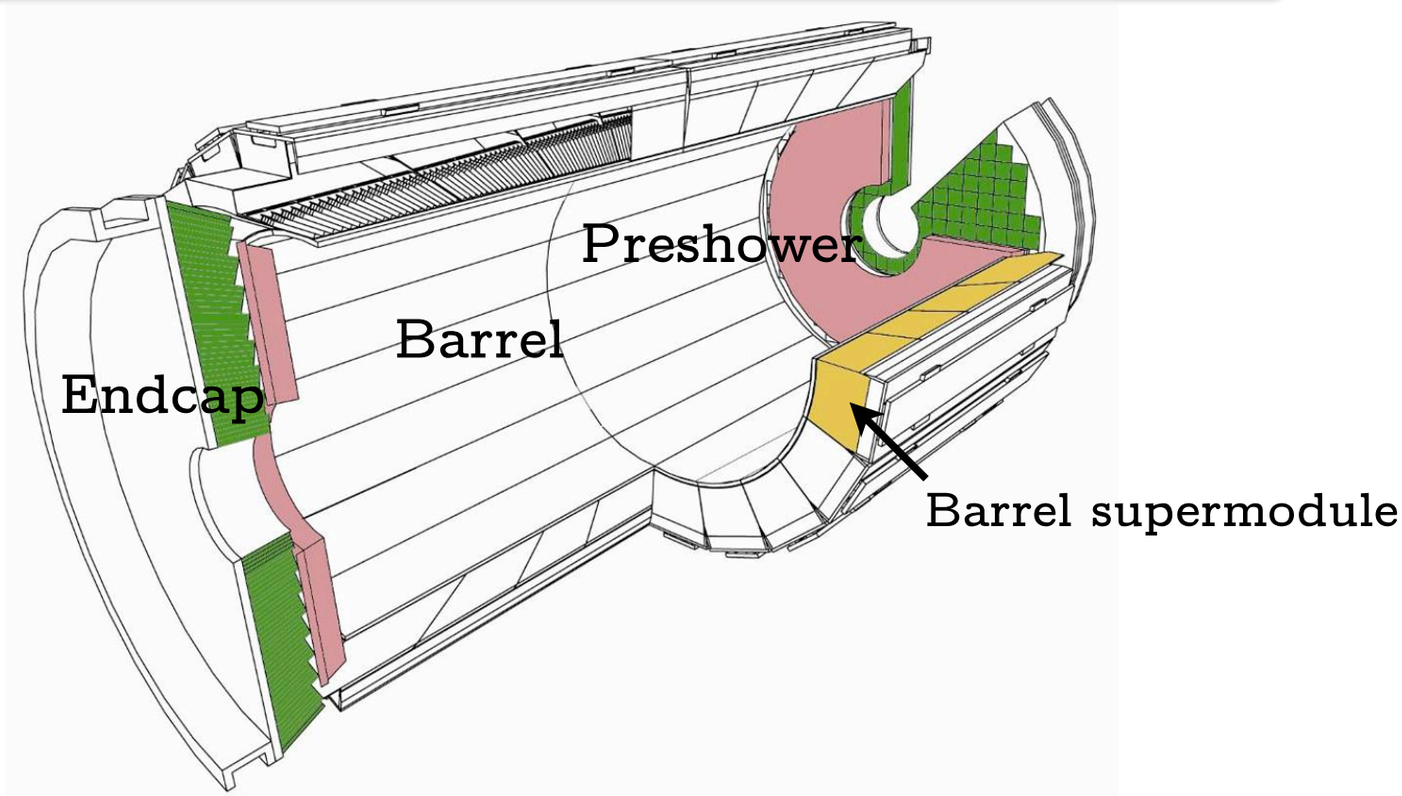
Goal: excellent diphoton mass resolution (~1%), needed for $H \rightarrow \gamma\gamma$ observation

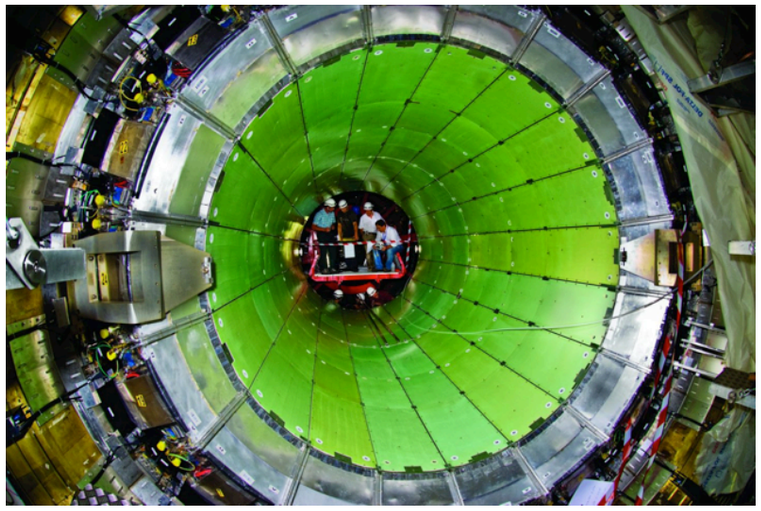
The CMS Electromagnetic Calorimeter

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

Two crystal producers:

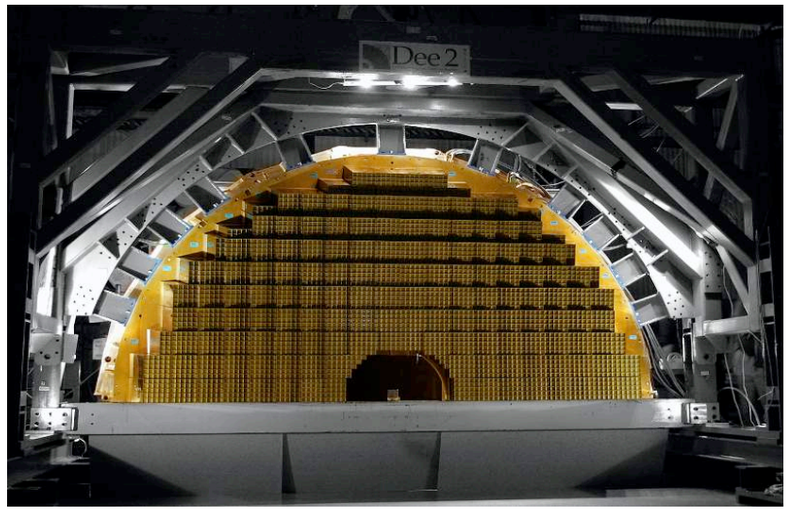
BTCP (Russia)
SIC (China)





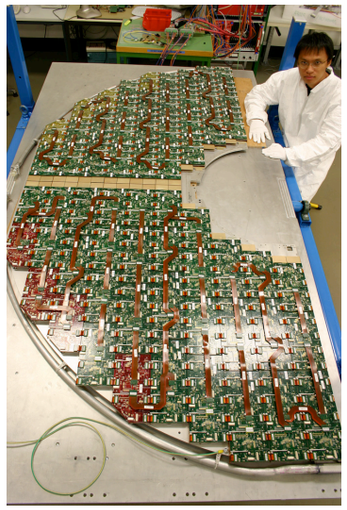
Barrel (EB)

36 supermodules (1700 crystals)
Total of 61200 $PbWO_4$ crystals
Avalanche PhotoDiode readout
coverage: $|\eta|<1.48$



Endcap (EE)

4 half-disks (3662 crystals)
Total of 14648 $PbWO_4$ crystals
Vacuum PhotoTriode readout
coverage: $1.48<|\eta|<3.0$

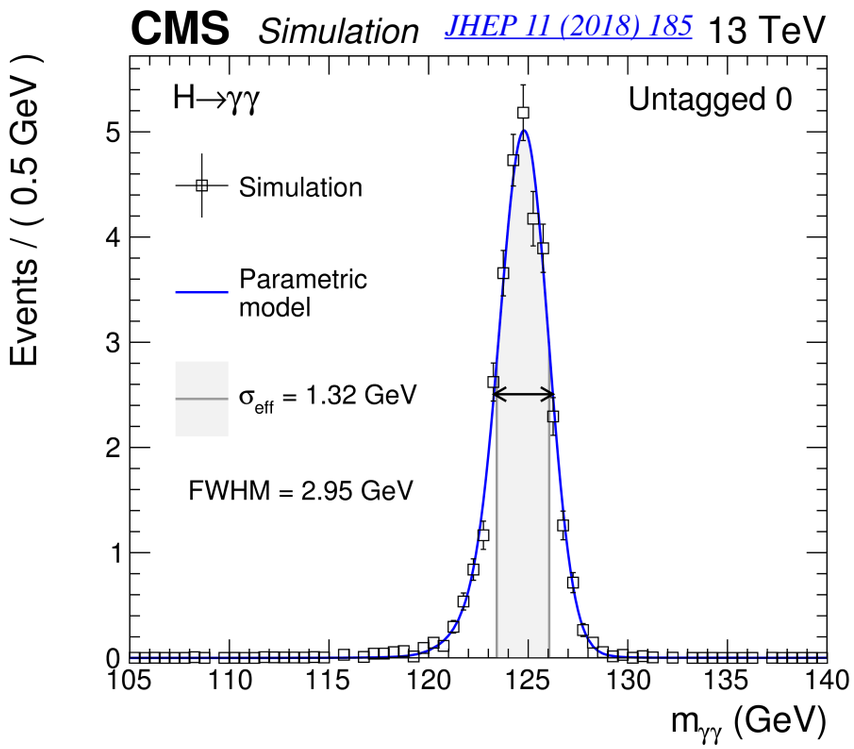


Preshower (ES)

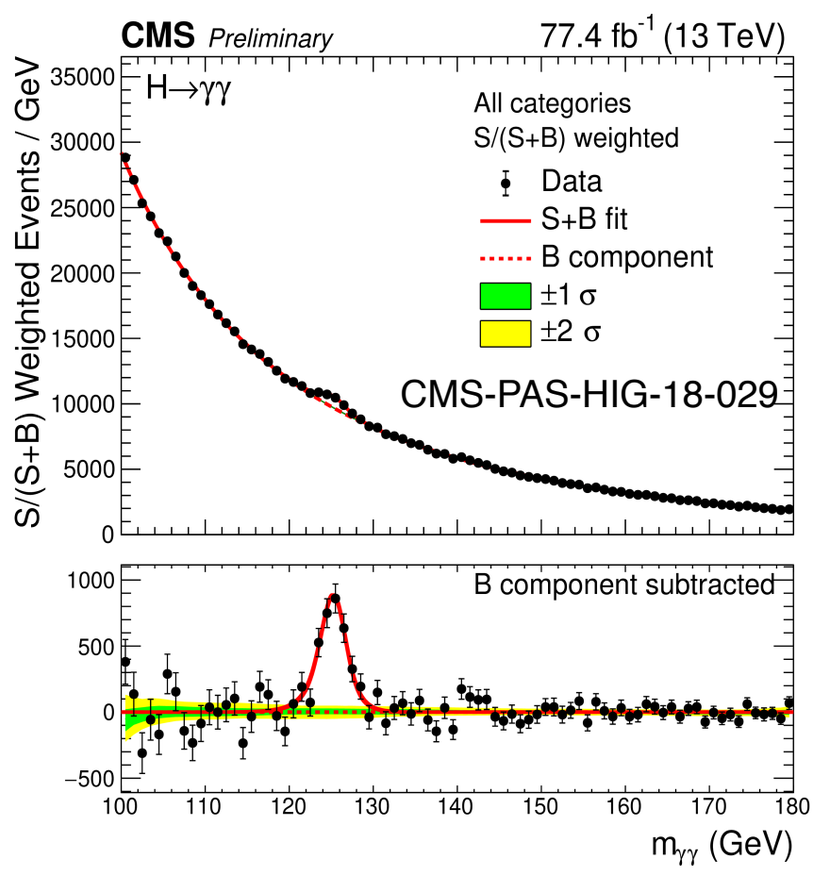
Two Lead/Si planes
137216 Si strips ($1.8 \times 61 mm^2$)
coverage: $1.65<|\eta|<2.6$

Role of ECAL in Higgs Physics

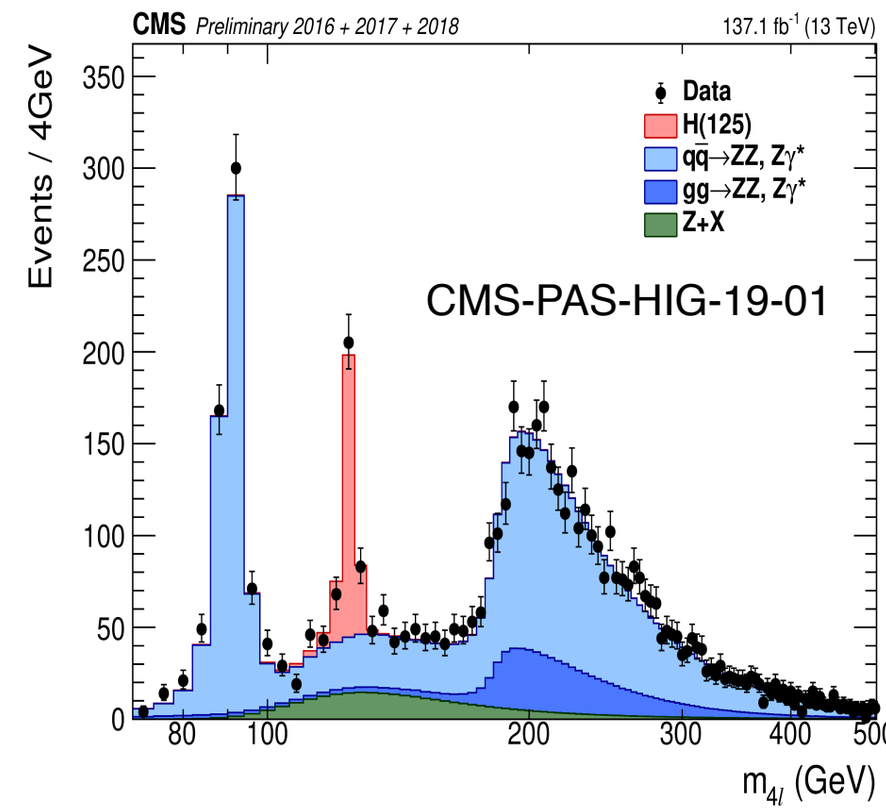
$H \rightarrow \gamma\gamma$



Mass resolution in best category ~1%



$H \rightarrow ZZ \rightarrow 4l$

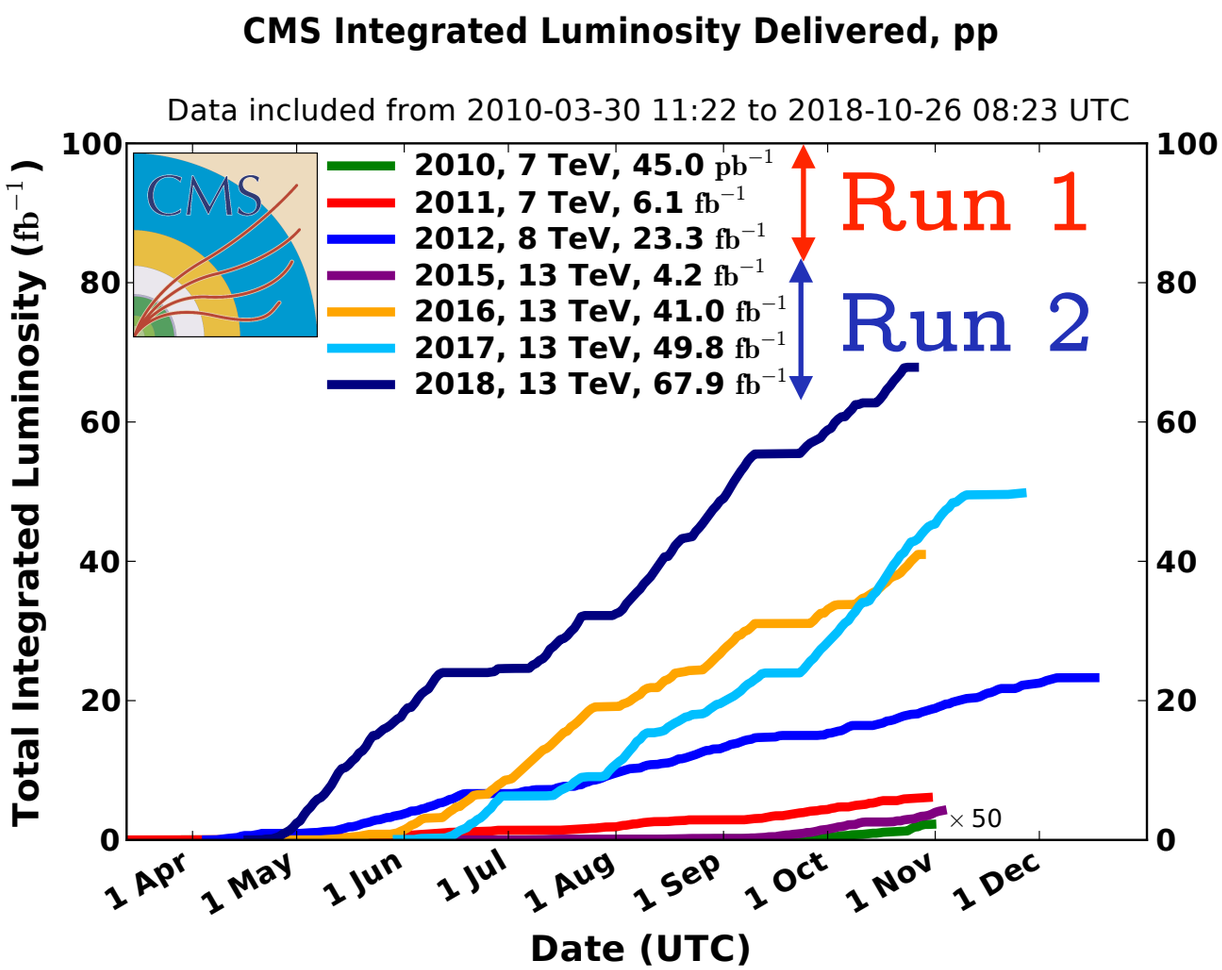


The excellent resolution and electron/photon ID of the CMS ECAL was crucial in the discovery and subsequent characterisation of the 125 GeV Higgs Boson

The continued excellent performance of ECAL in the entire pseudorapidity range is a key component of many searches for new Physics

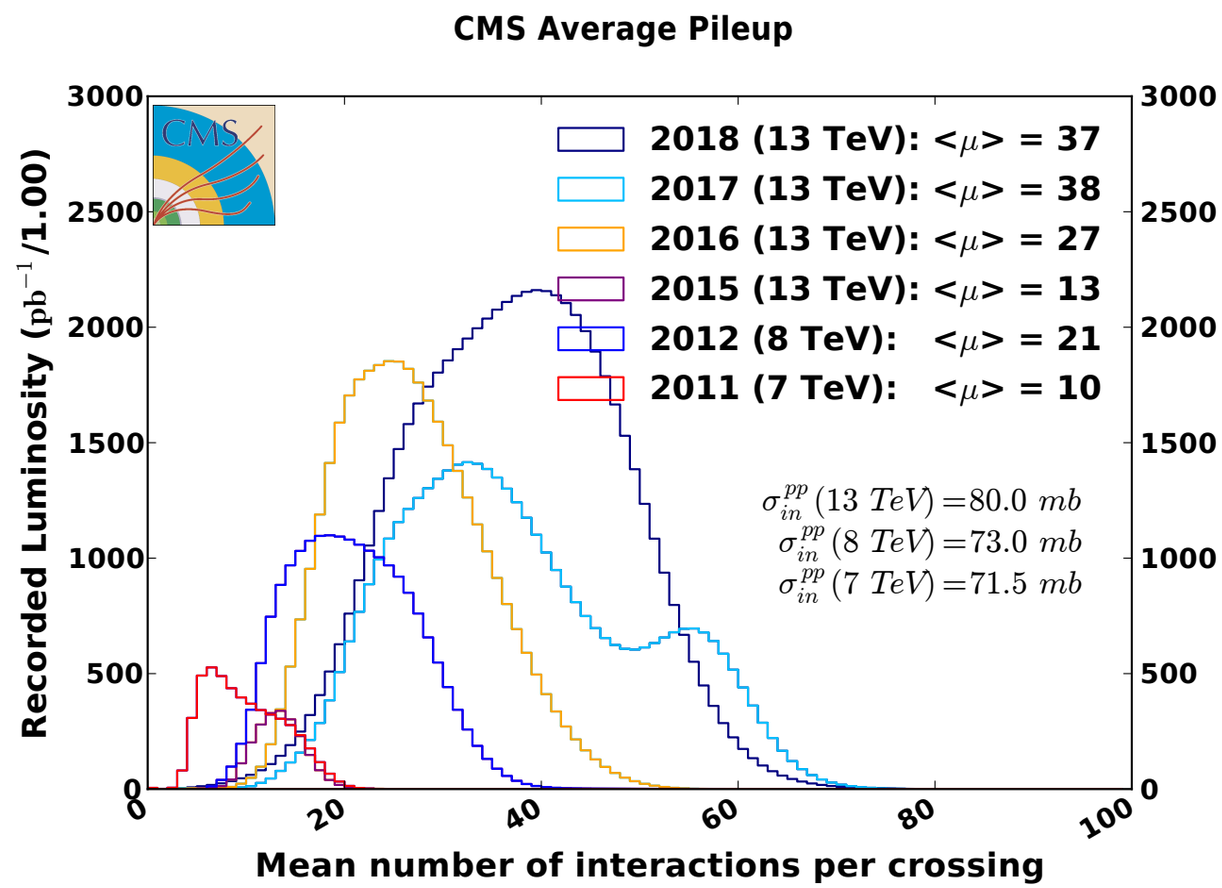
Challenges during Run 2 (2015-2018)

Higher integrated Luminosity



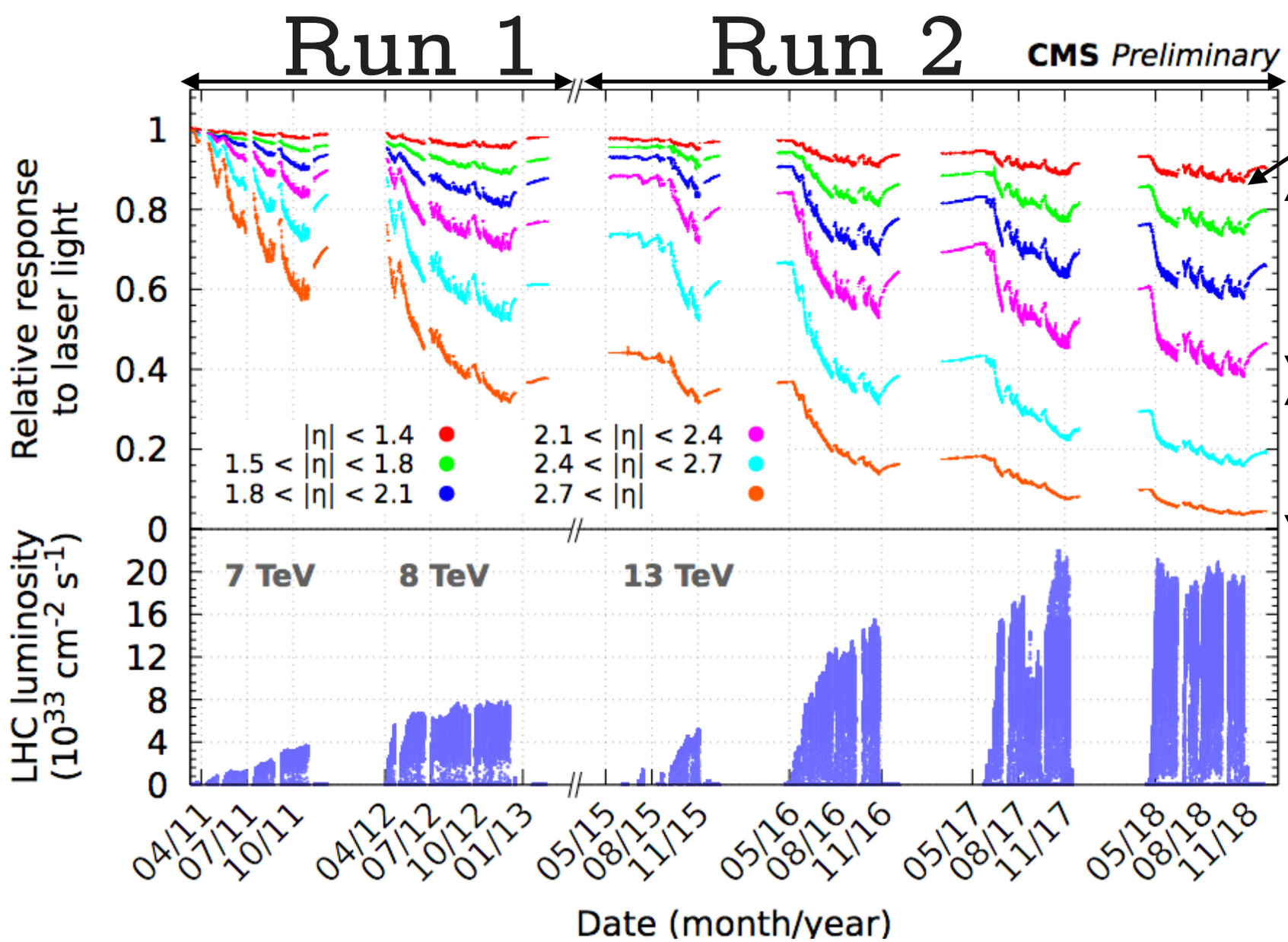
Larger radiation dose:
increase of loss of light of crystals (transparency degradation), and of radiation induced ageing of photodetectors and on detector readout

Higher average number of interactions per crossing:



Larger 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 Run 1 and Run 2



Barrel (13%)

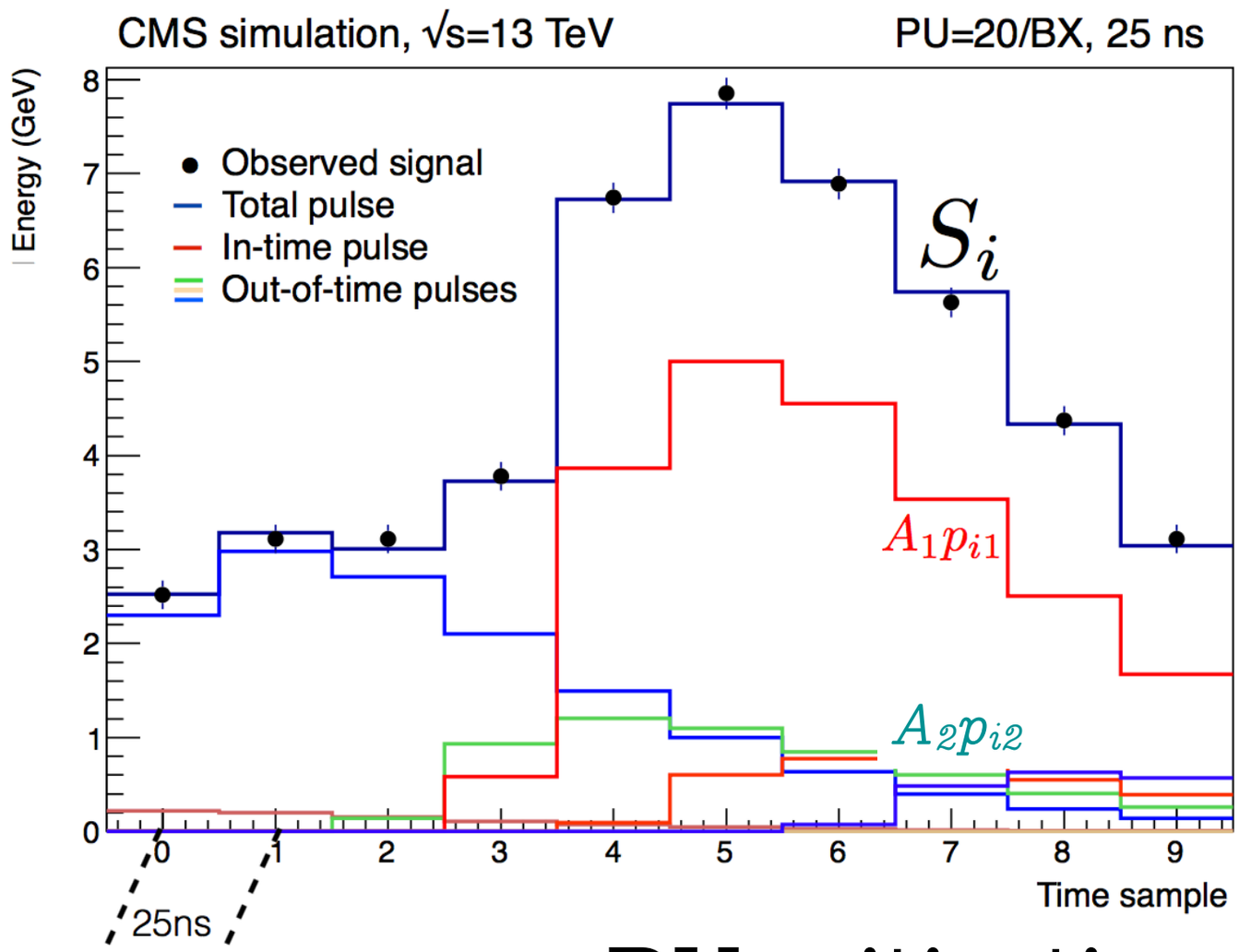
Endcap region covered by CMS tracker (62%)

Endcap region relevant for forward jets: low response (max: 96% loss) due to ageing induces amplification of the noise: Noise mitigation is performed with optimized energy clustering

Significant response changes (crystal+photodetector) due to LHC irradiation
Monitoring of each channel via a dedicated laser system, is performed every 40 minutes and corrections are provided within 48 hours.

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

Crucial to mitigate out-of-time pileup



$$\chi^2 = \sum_{i=1}^{10} \frac{(\sum_{j=1}^{M} A_j \times p_{ij} - S_i)^2}{\sigma_{S_i}^2}$$

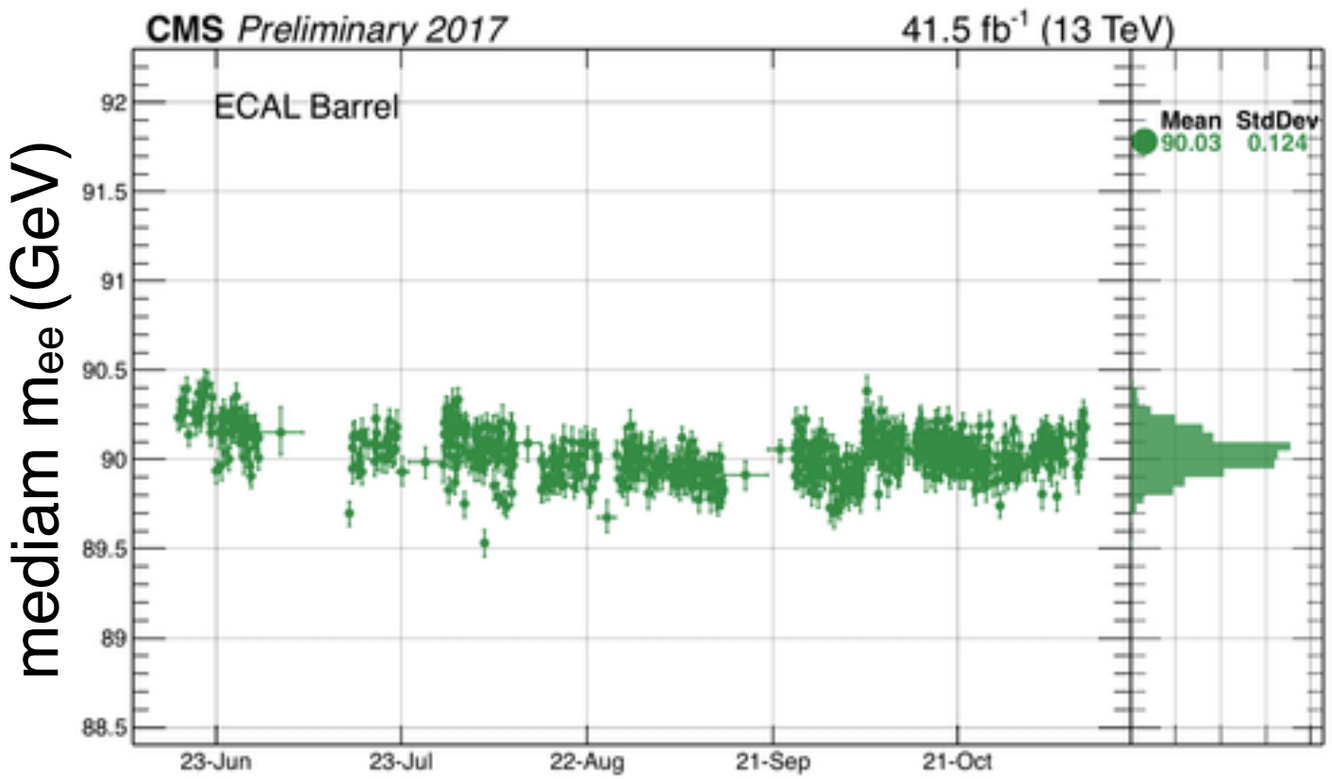
1. Multifit: pulse shape is modeled as in-time pulse plus several OOT pulses (up to 9)
2. Minimizing χ^2 to get best estimate of in-time pulse amplitude
3. Contamination from out-of-time (OOT) pulses effectively removed

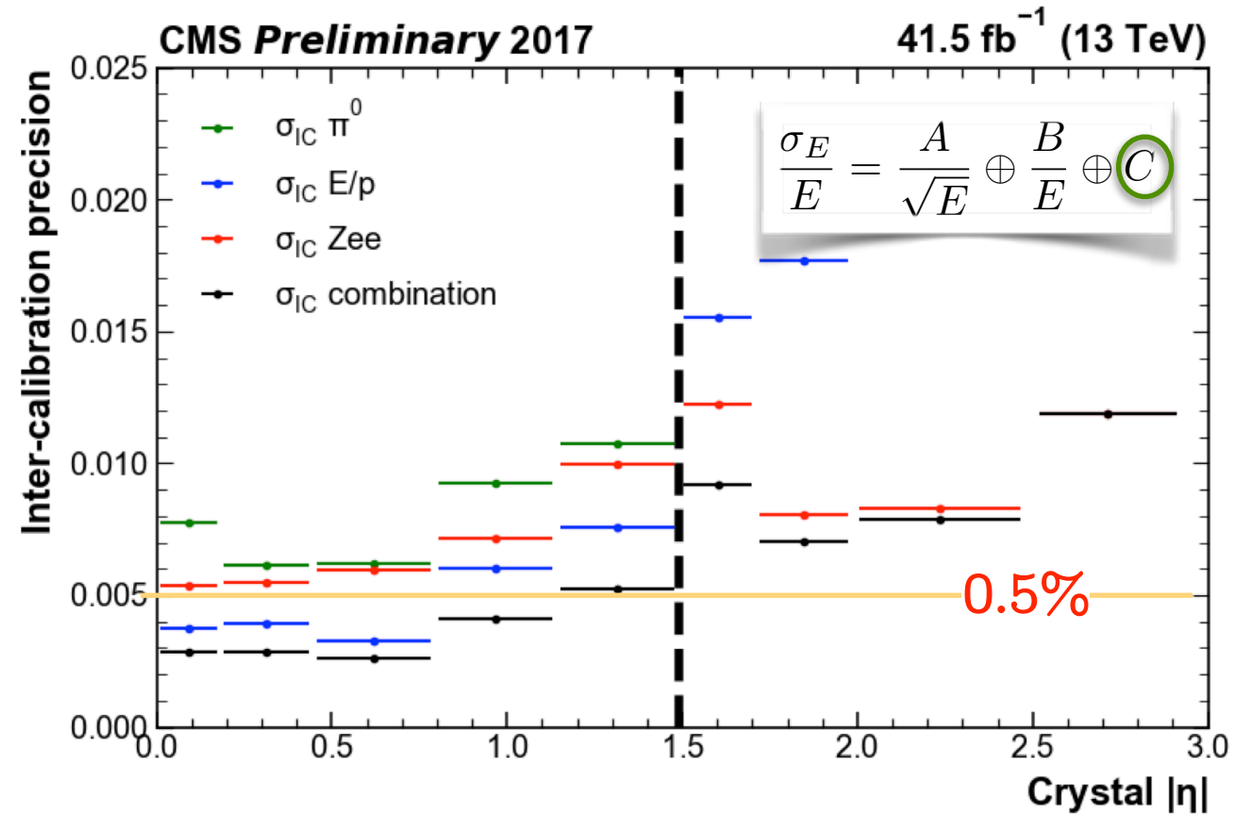
PU mitigation improved

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

Crucial to maintain optimum resolution





Regular recalibrations

using W and Z electrons

achieve the time stability of the di-electron invariant mass distribution

Regular recalibrations

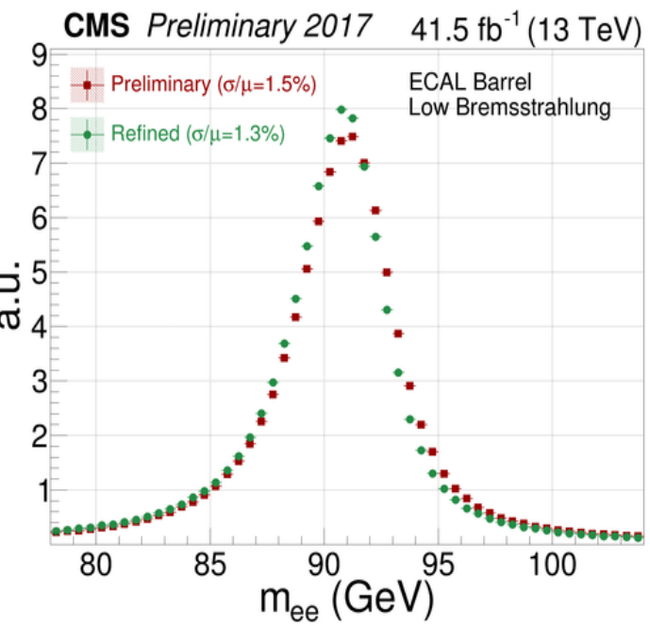
using several in-situ methods

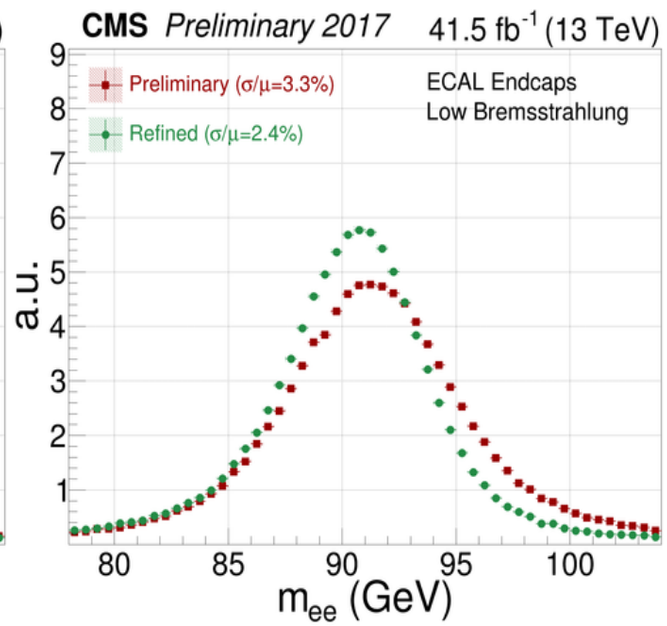
Equalise response of all channels to physics signals

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

Excellent energy resolution maintained during run 2

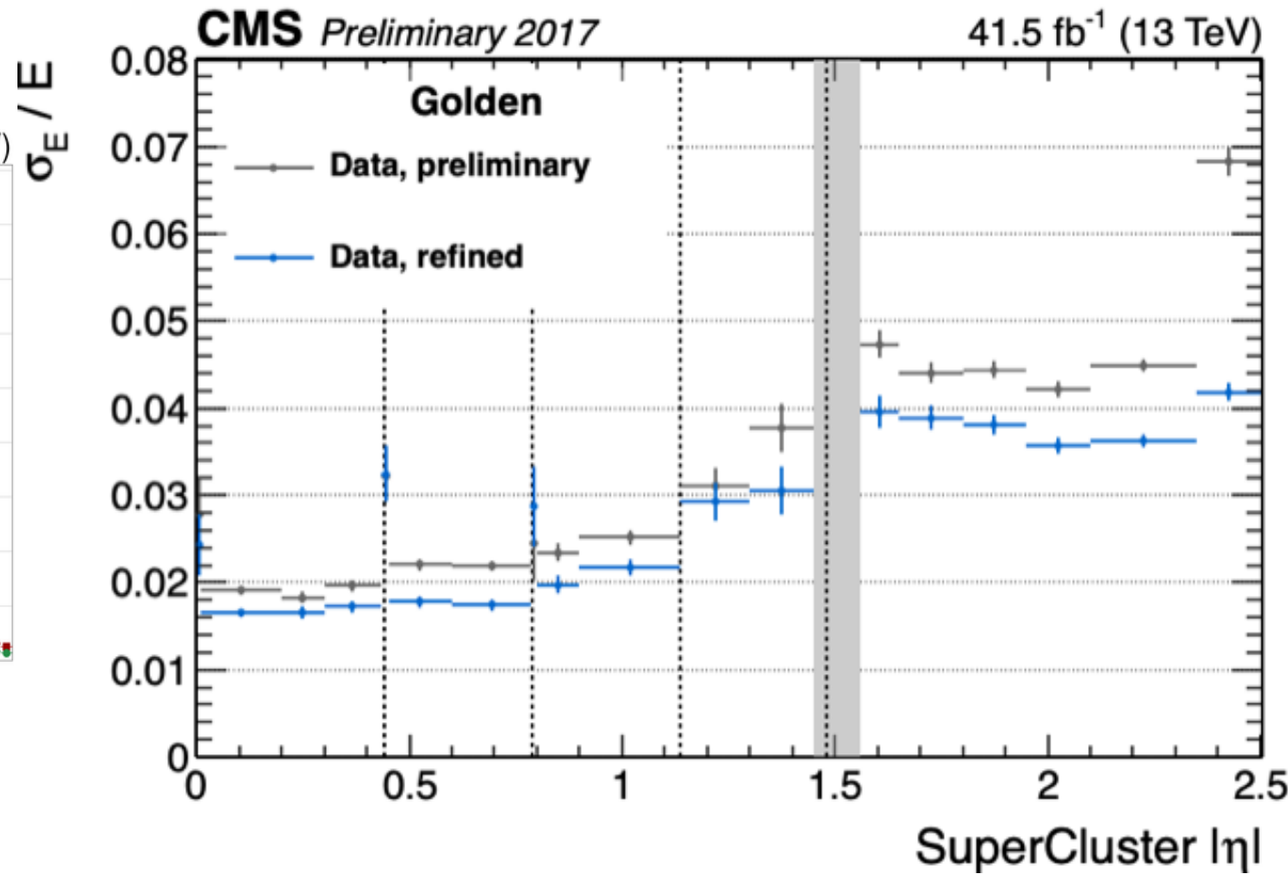
as a result of improved energy reconstruction and regular recalibration





Di-electron invariant mass distribution using Z→ee low-bremsstrahlung electrons

recalibrated data (green) shows improved performance



Unfolded single electron fractional resolution vs |η|, 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

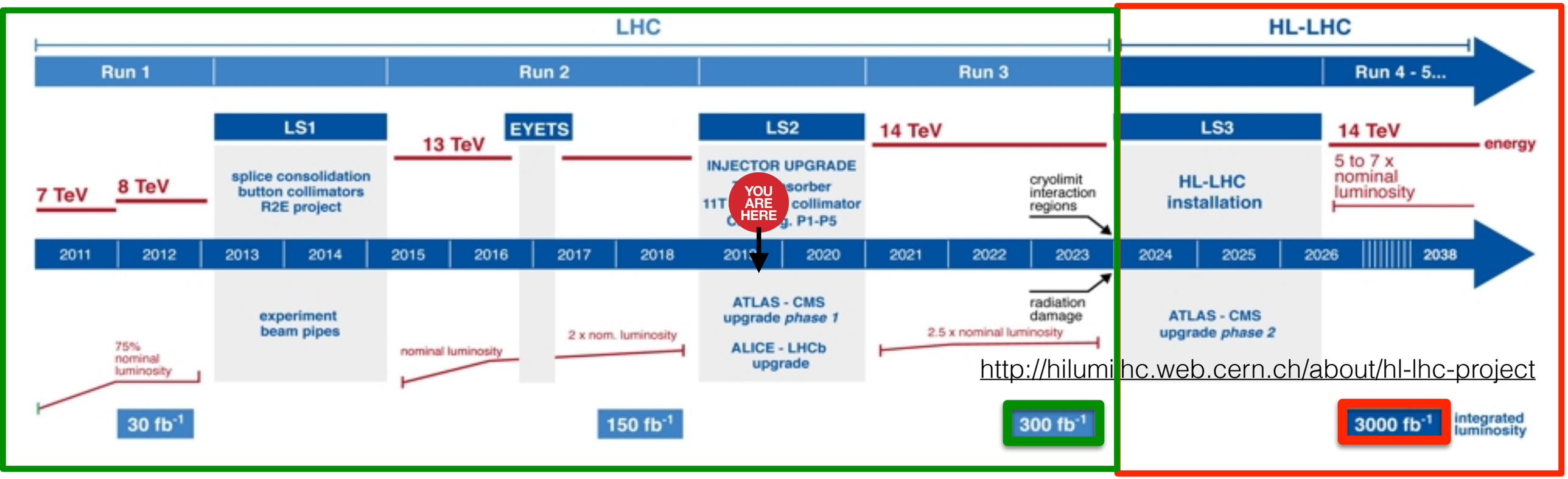
despite significantly larger pileup and larger radiation-induced detector ageing

For Run 3 (2021-2023) regular recalibration and optimized energy clustering are planned in order to mitigate the same effects (PU and ageing) and retain the excellent ECAL performance

The High Luminosity LHC upgrade (HL-LHC)

A. Zghiche
IN2P2-CNRS/LLR-Polytechnique

HL-LHC upgrade plan



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

HL-LHC: accelerator upgrade in Long Shutdown 3 (LS3) to provide x10 larger dataset for physics focus on new physics searches, Higgs coupling and precision SM measurements

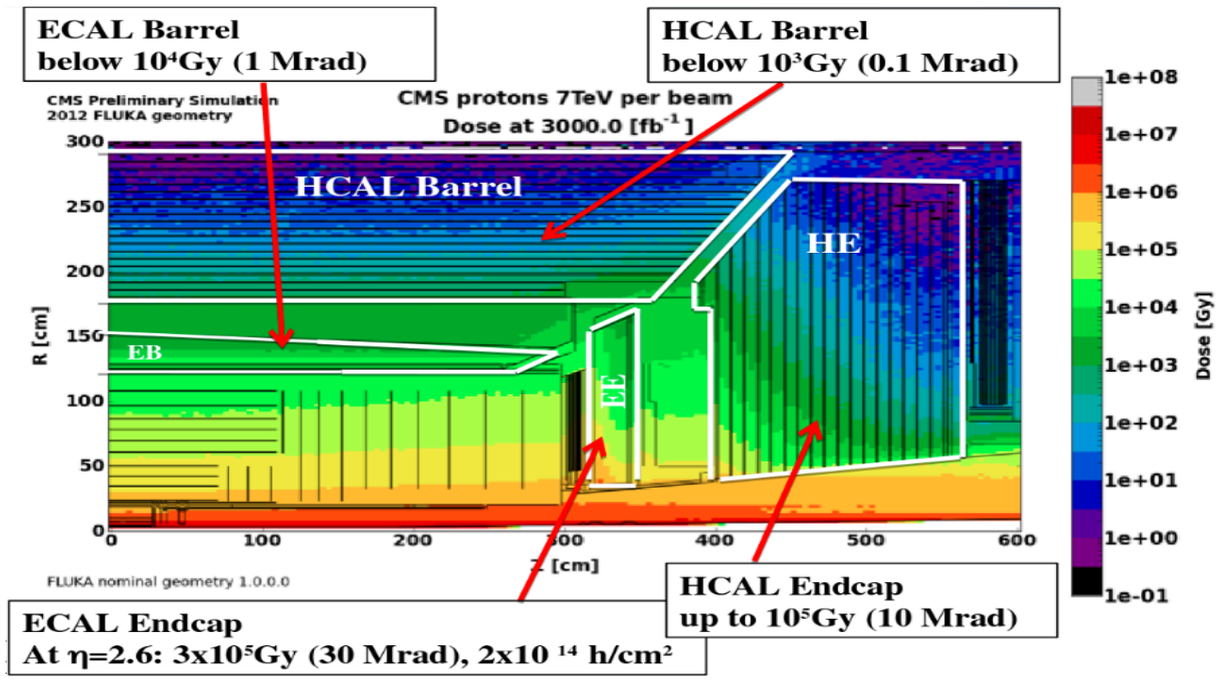
Large increases in peak lumi, integrated dose relative to LHC:

	Inst. lumi ($cm^{-2}s^{-1}$)	peak pileup	integ. lumi (fb^{-1}/yr)
Run 2 (2018)	2.0×10^{34}	50	60
Run 3 (2021-2023)	2.0×10^{34}	53	100
HL-LHC (baseline)	5×10^{34}	140	250
HL-LHC (stretch)	7.5×10^{34}	200	320

R. Tomas presentation at Chamonix 2017

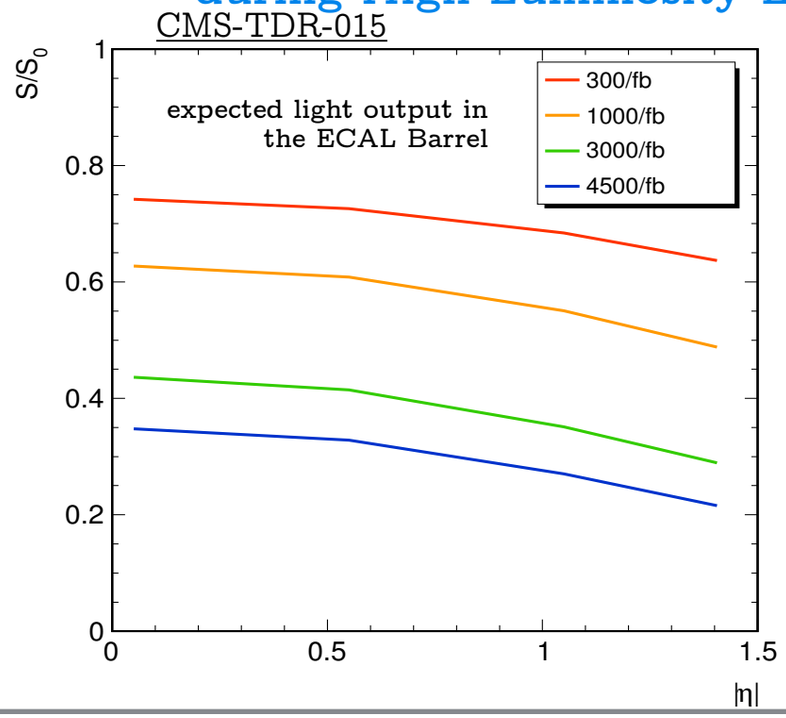
ECAL expected Energy resolution at HL-LHC

γ dose and hadron fluences are higher closer to the beam pipe (Endcaps)-Caveat: this is the current geometry

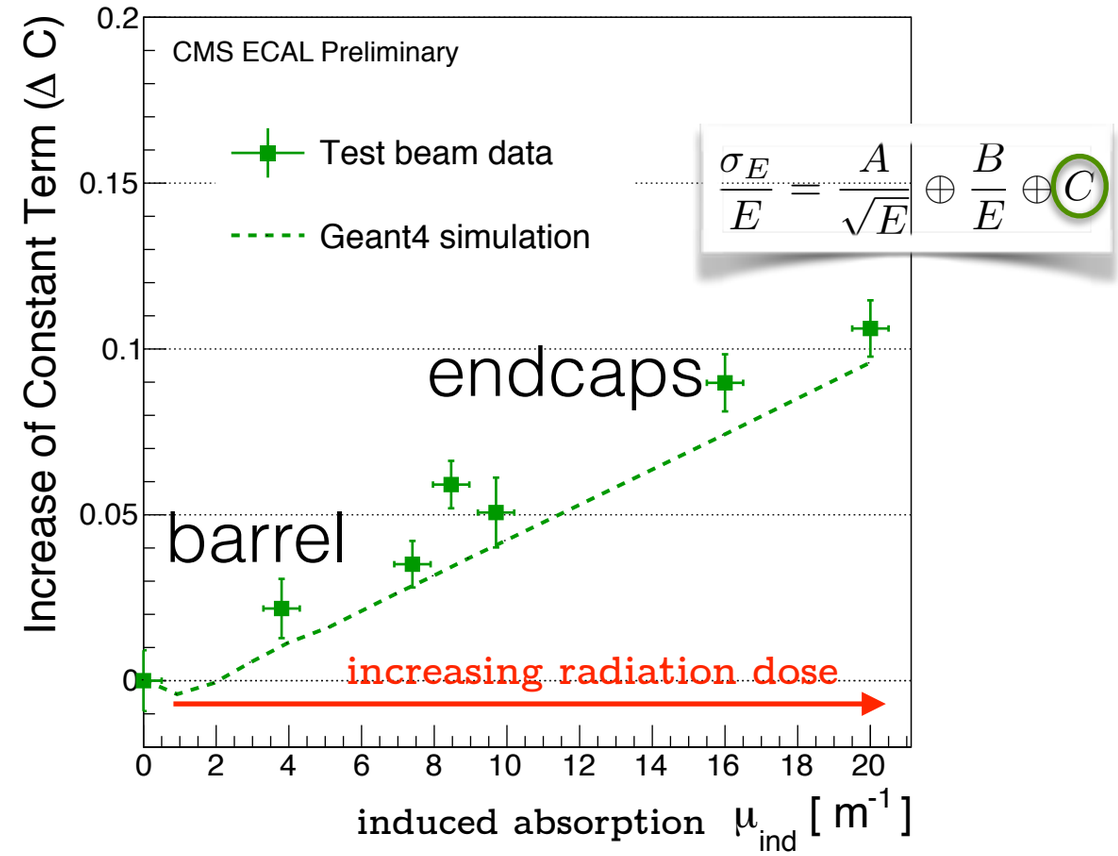


Expected up to ~ 6 times higher hadron fluence level during High Luminosity LHC (HL-LHC)

CMS-TDR-015



Degradation of energy resolution



Barrel crystals will perform well during HL-LHC: will retain ~40% of light after 3000fb^{-1}(end of HL-LHC)

with limited degradation of energy resolution

Endcaps will suffer large light output losses and a large degradation of the resolution

For HL-LHC, ECAL Endcaps will be replaced with High Granularity Calorimeter (HGCal)

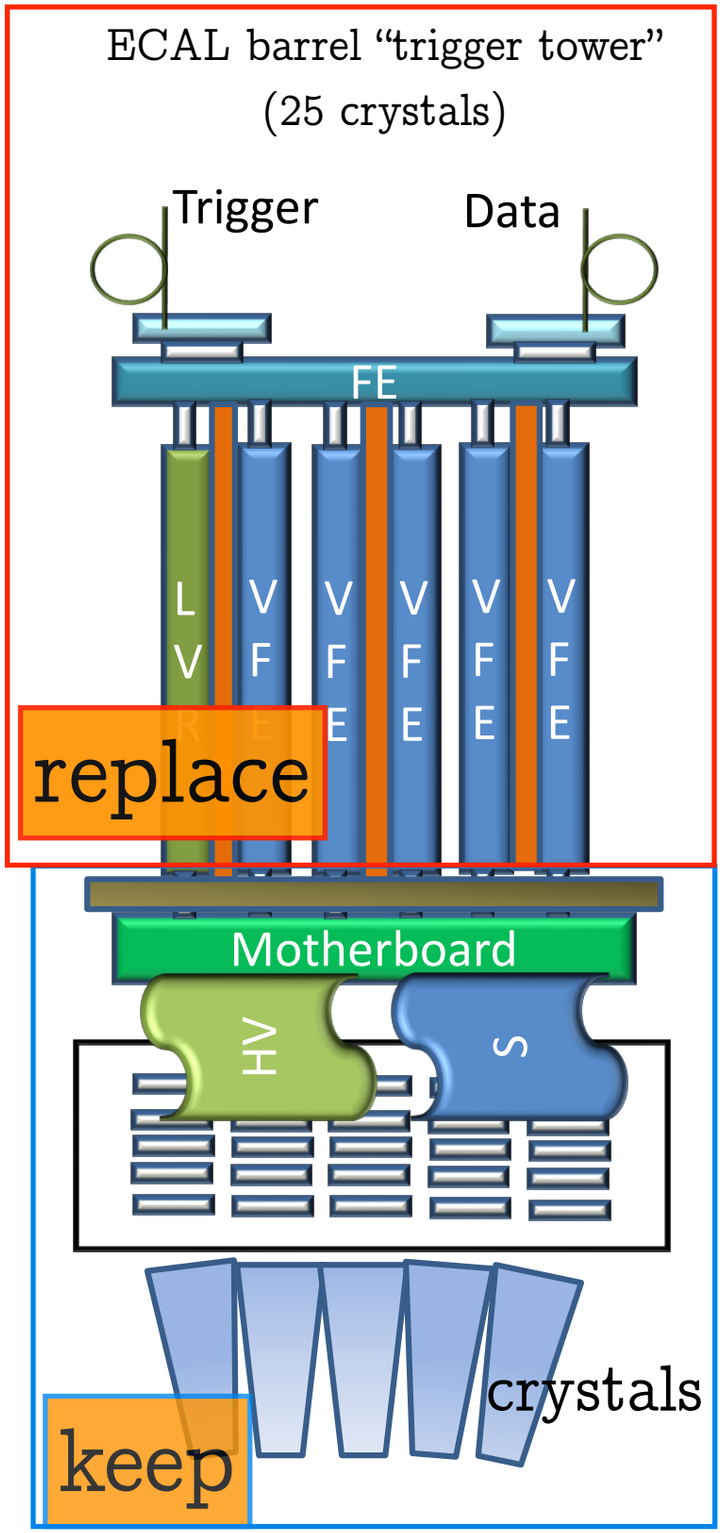
ECAL Barrel Upgrade and performance

A. Zghiche
IN2P2-CNRS/LLR-Polytechnique

ECAL Barrel Phase 2 upgrade scope

Plan to Refurbish ECAL Barrel Supermodules during LS3:2024-2026

1. Crystals + APDs will be kept and are expected to maintain performance throughout Phase 2
2. Replace Front-End (FE) and Very-Front-End (VFE) readout to
   1. Maintain performance in more challenging HL-LHC conditions (noise(x10), pileup(200/currently 60), APD spikes).
   2. Achieve precise (~30ps) timing measurements for high energy photons.
3. New off-detector (OD) readout to be compatible with increased CMS Phase 2 trigger requirements: higher output bandwidth(rate:750/currently100kHz; latency: 12.5/currently 4μs)
4. Operate at lower temperature 9°C (now 18°C) to mitigate the increase in noise due to radiation induced APD dark current and minimize its impact on resolution

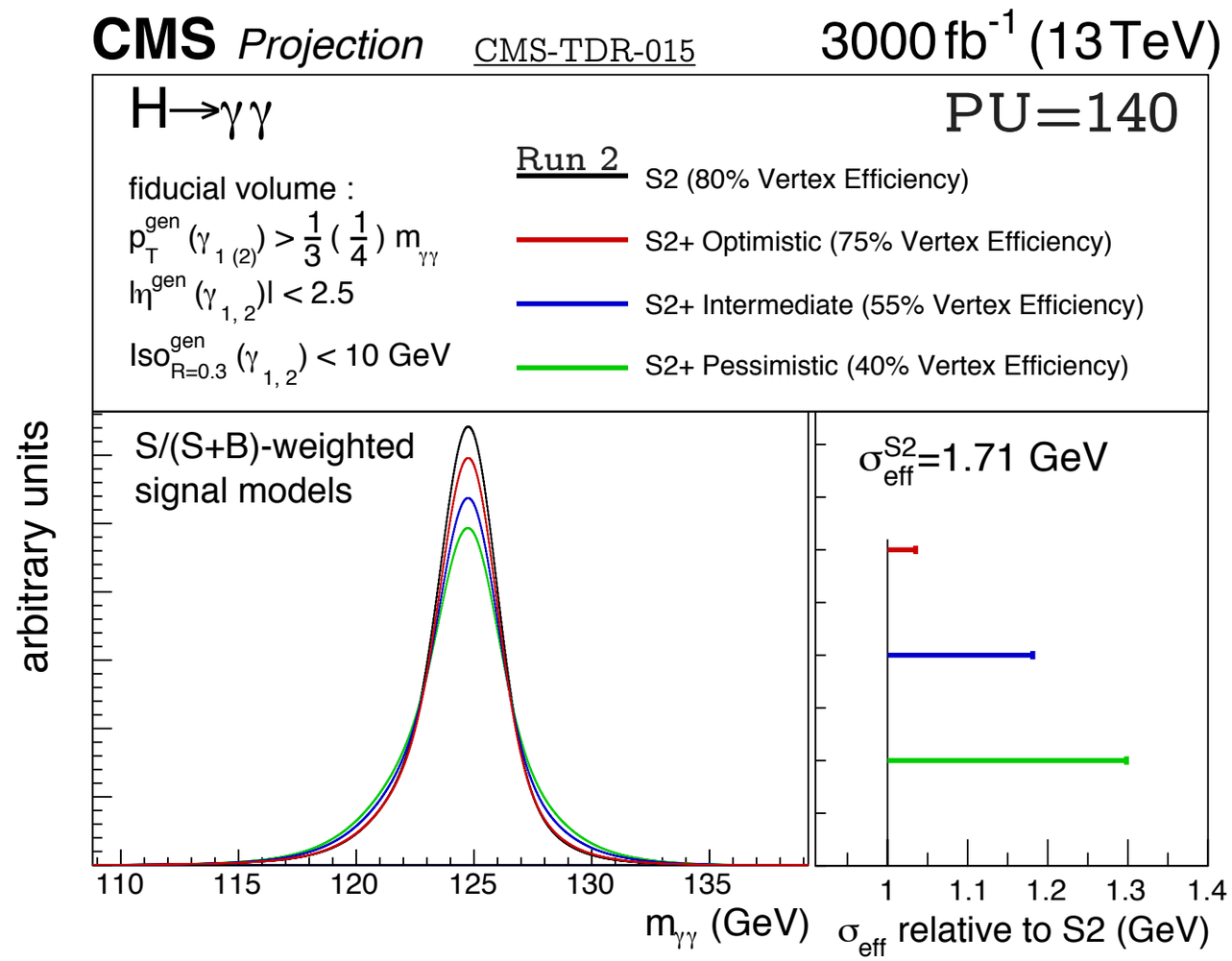


Precise timing in Phase 2

needed to maintain the reconstruction performance at 140-200 pileup

-at 140-200 pileup **the primary vertex efficiency is reduced** (from 80% to 40% (at PU=140) and to 30% at PU=200) for H→γγ decays

- the vertex localisation efficiency can be improved with precise (30ps) timing: 10% improvement in the fiducial cross-section sensitivity and H→γγ resolution compared to no precise timing case



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

no precise timing

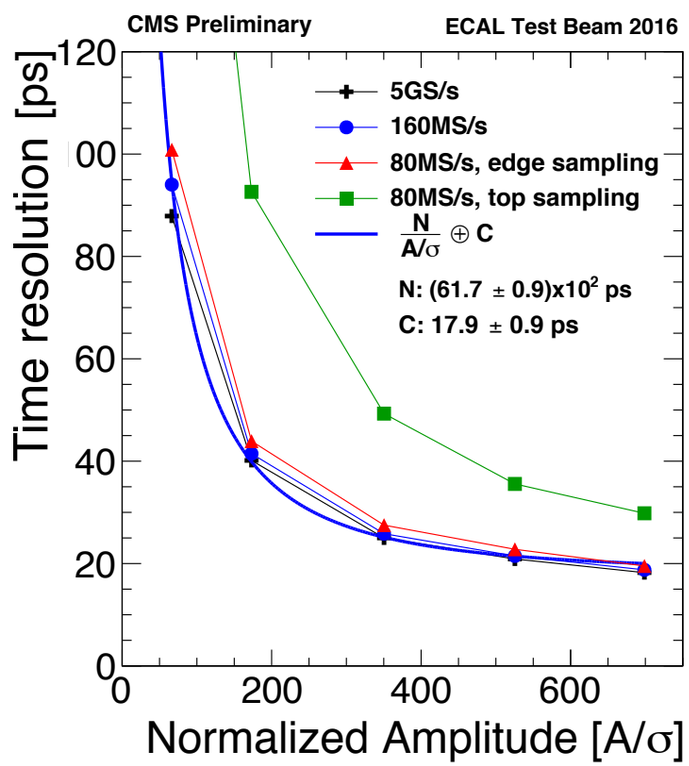
adding precise timing in calorimeter

adding precise MIP timing (timing layer(see N. Minafra talk in this conference))

VFE prototype tests results

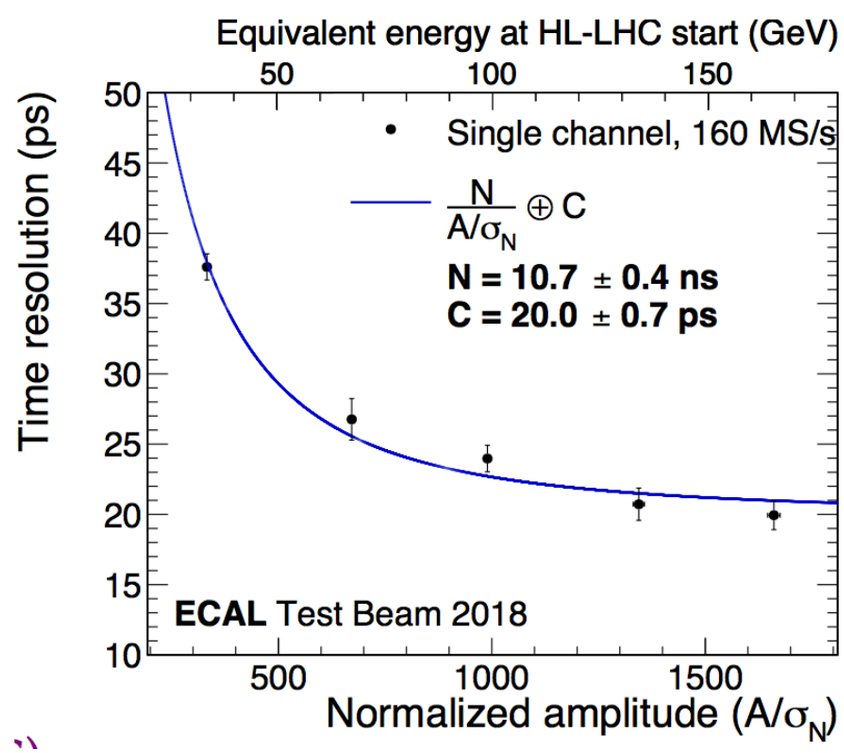
-30ps timing resolution has been achieved in test beam evaluations of Phase 2 ECAL prototype electronics

2016: Trans Impedance Amplifier (TIA) discrete components @5GHz (5GS/s))

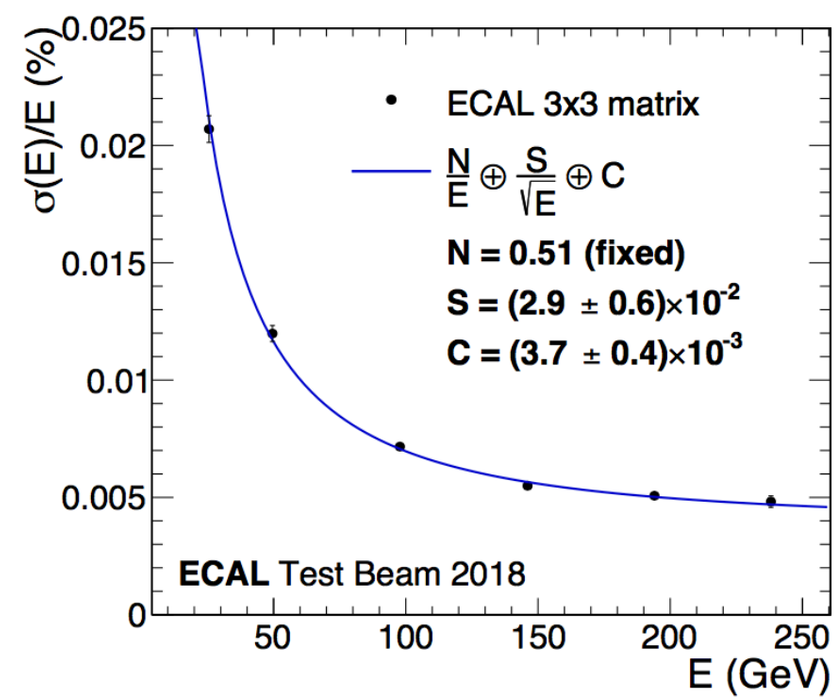


The emulated sampling at 160MS/s shows a time resolution similar to that of 5GS/s

2018: first prototype ASIC TIA chip + commercial ADC @ 160MHz



Test results with ADC sampling at 160MS/s show a time resolution that matches the 30ps target



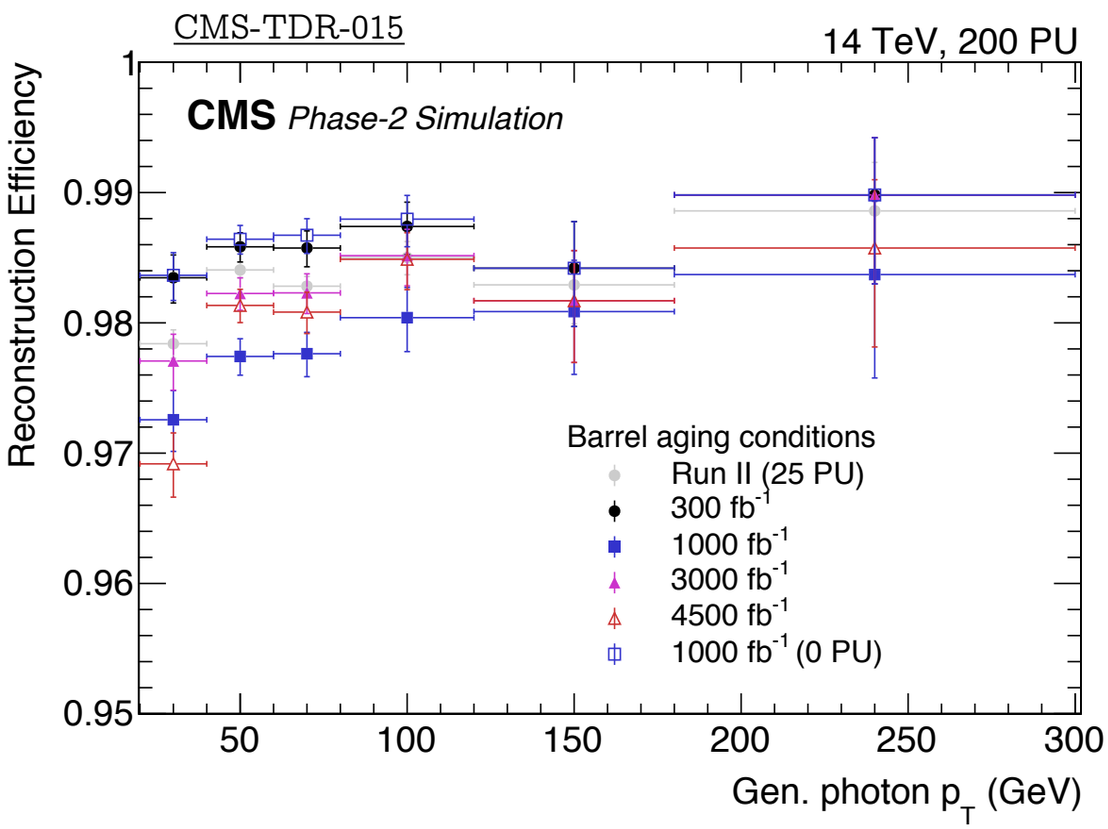
Excellent Phase 1 Energy resolution retained

run2 performance: https://cds.cern.ch/record/2682203/files/DP2019_021.pdf

Phase 2 object reconstruction

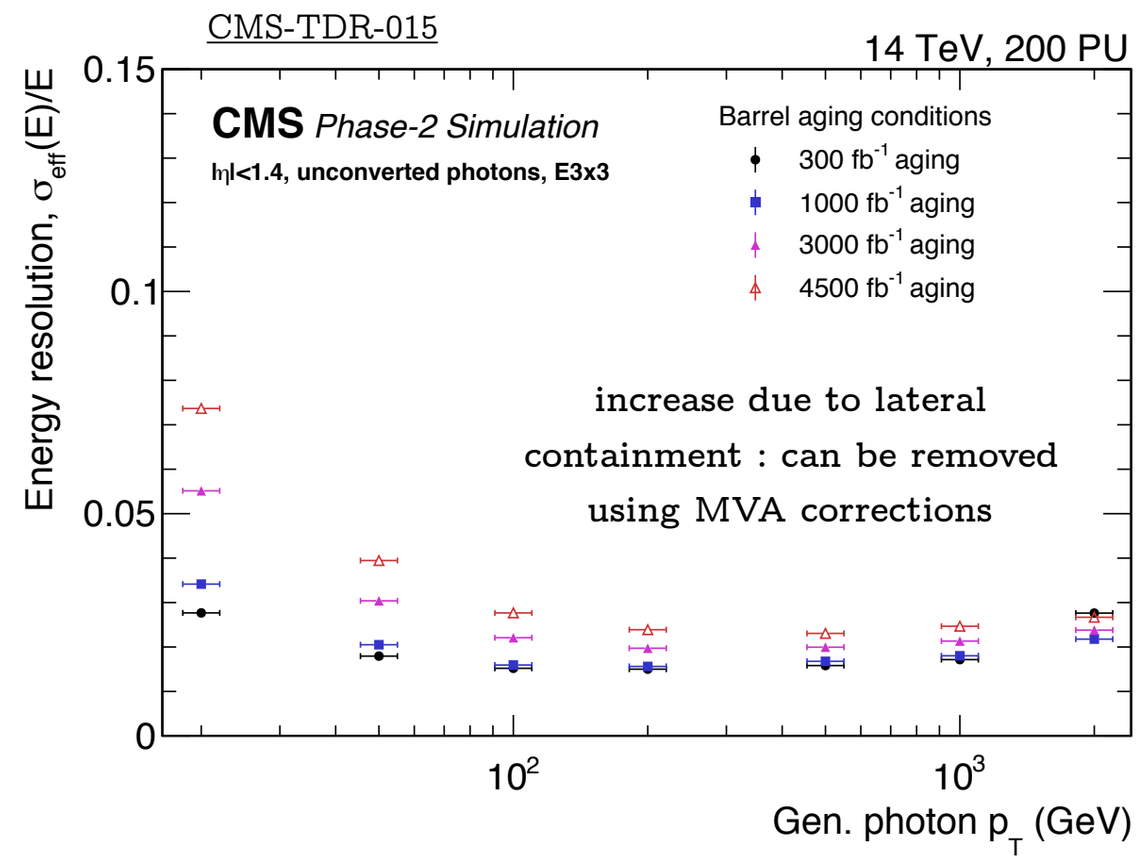
Aim for the upgraded ECAL to preserve the current performance in the challenging HL-LHC conditions

Photon reconstruction efficiency



Small impact of ageing

Photon energy resolution



2.5-4% resolution for E_T=50GeV

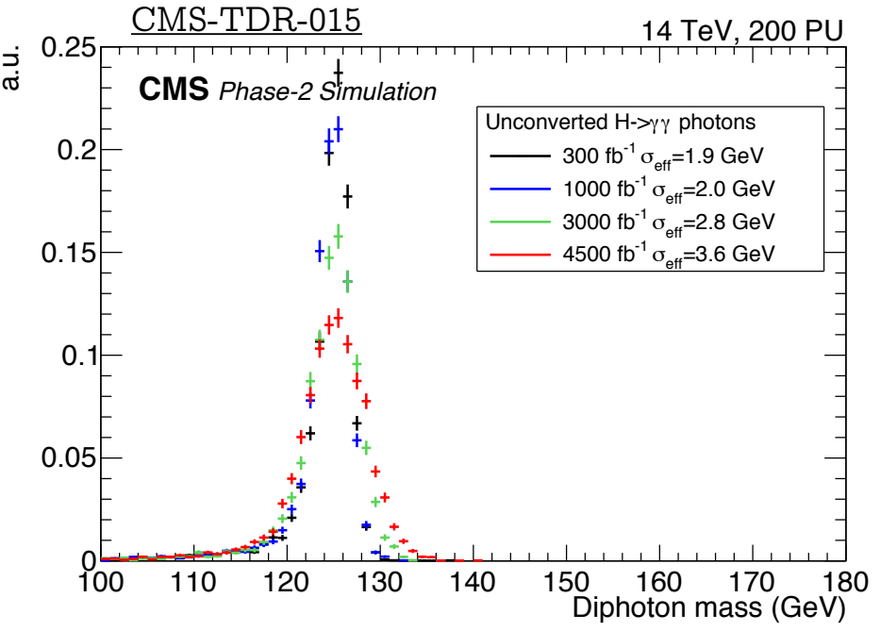
Higgs Physics in Phase 2 with ECAL

Full details in Barrel Calorimeter Phase 2 TDR and the Physics at HL-LHC Report

HL-LHC will provide x10 larger dataset for physics

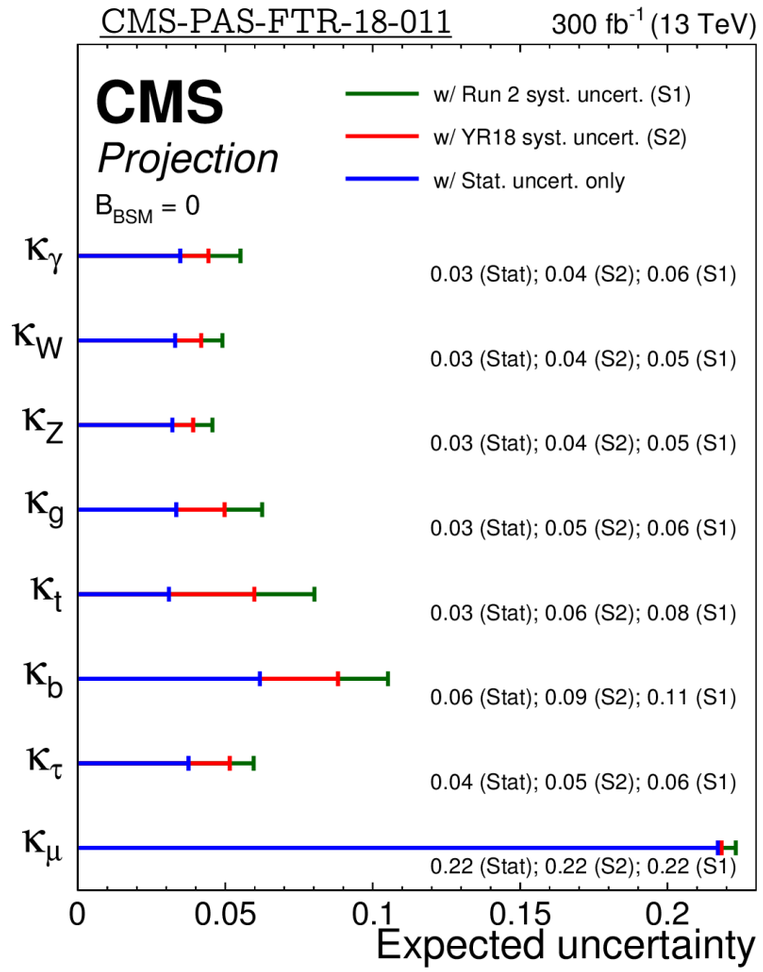
H→γγ resolution

CMS-TDR-015

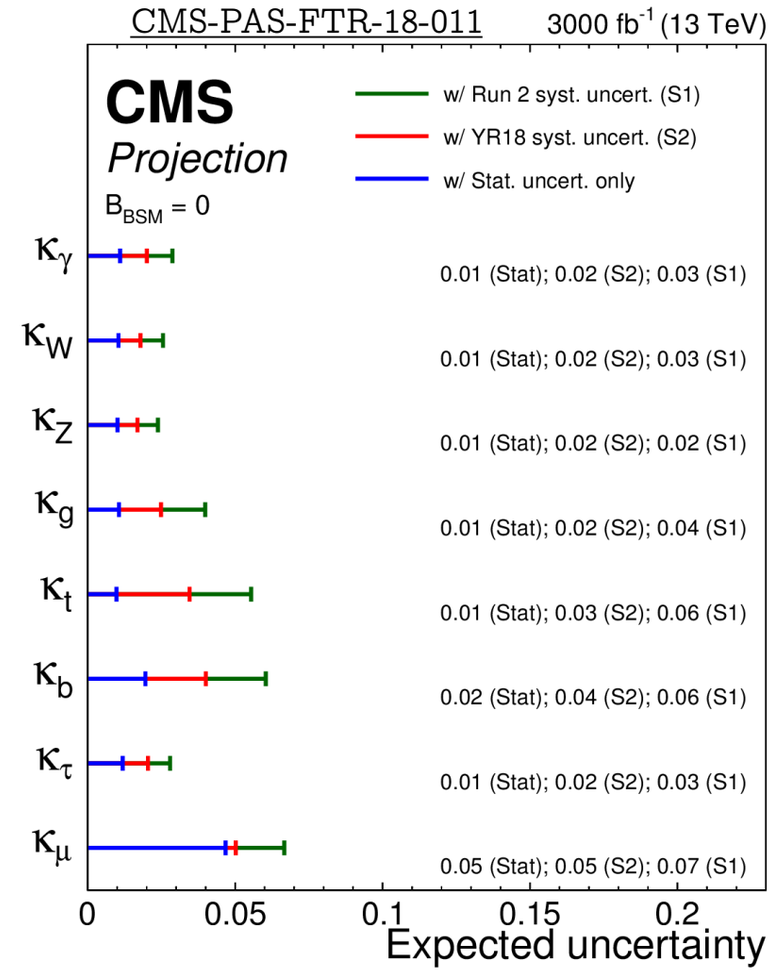


Slow degradation with ageing

CMS-PAS-FTR-18-011



CMS-PAS-FTR-18-011



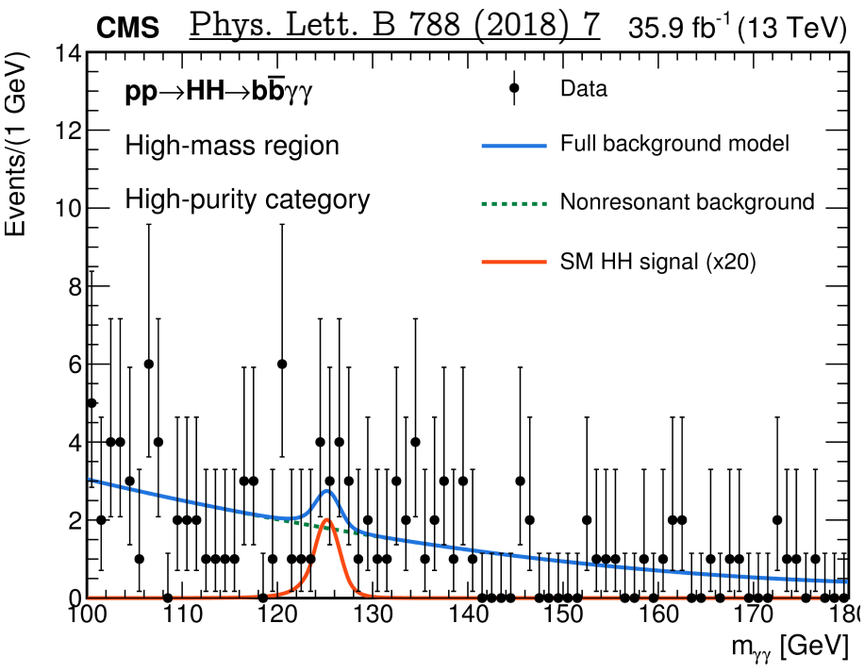
-With full optimisation, H→γγ resolutions expected to be achieved for Phase 2, up to 1000/fb are similar to run 2 and a slow degradation is expected beyond

-Couplings are expected to be determined with less than 5% uncertainties

Higgs Physics in Phase 2 with ECAL

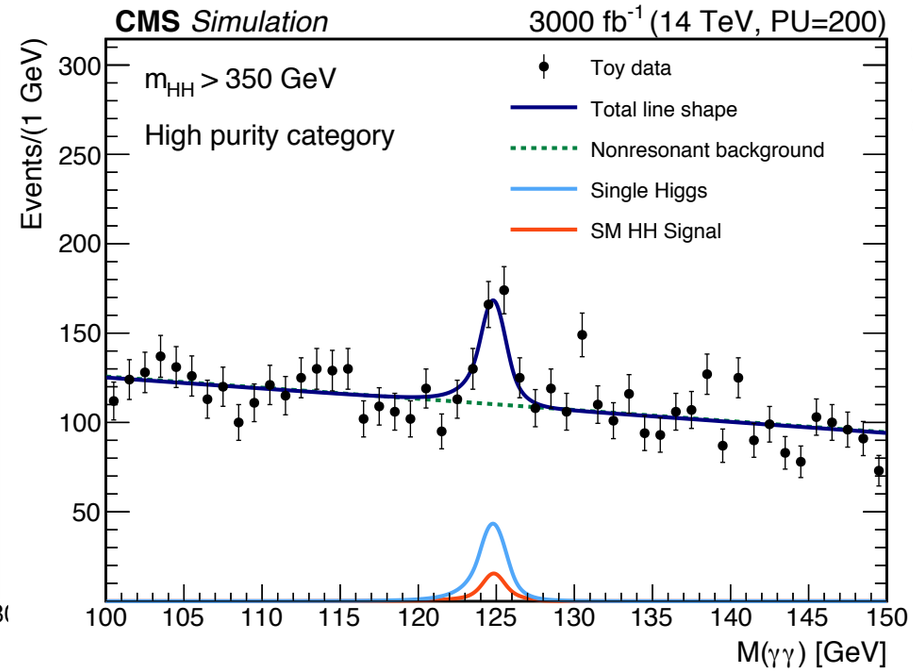
Full details in Barrel Calorimeter Phase 2 TDR and upcoming HL-LHC Yellow Report

$HH \to b\bar{b}\gamma\gamma$ signal



Performance in Run 2

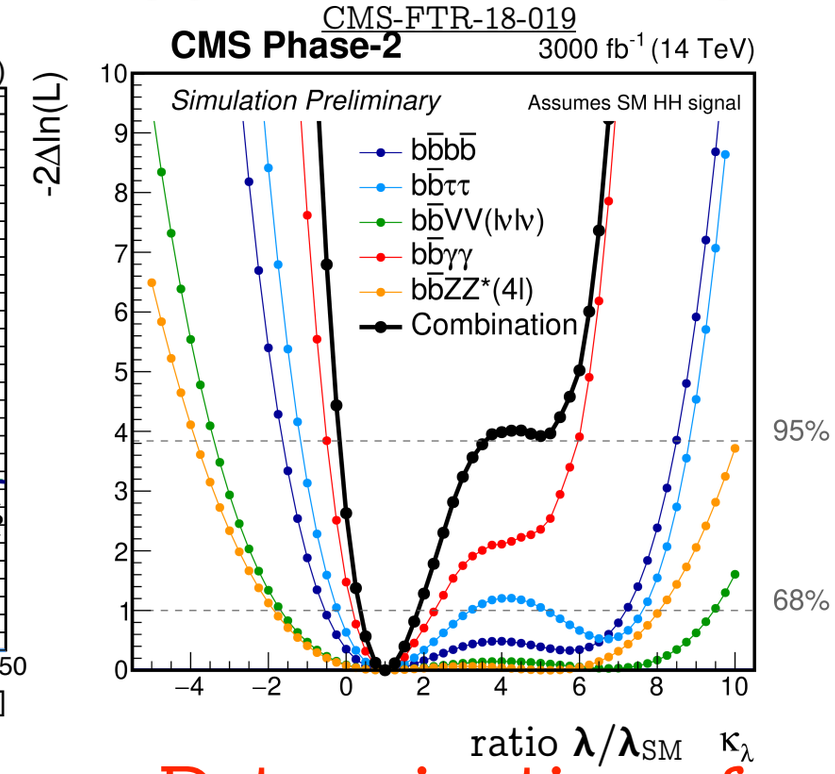
CMS-TDR-015



signal with Phase 2 photon resolution

Higgs self-coupling λ

CMS-FTR-18-019



Determination of the Higgs self-coupling

-Combined HH signal significance of 2.6σ (with $HH \to b\bar{b}\gamma\gamma$ as the best sensitivity channel)

-The Higgs self-coupling λ is expected to be in the interval [0.35,1.9]*λ_{SM} at the 68% CL and in [−0.18,3.6]*λ_{SM} at the 95% CL

Summary

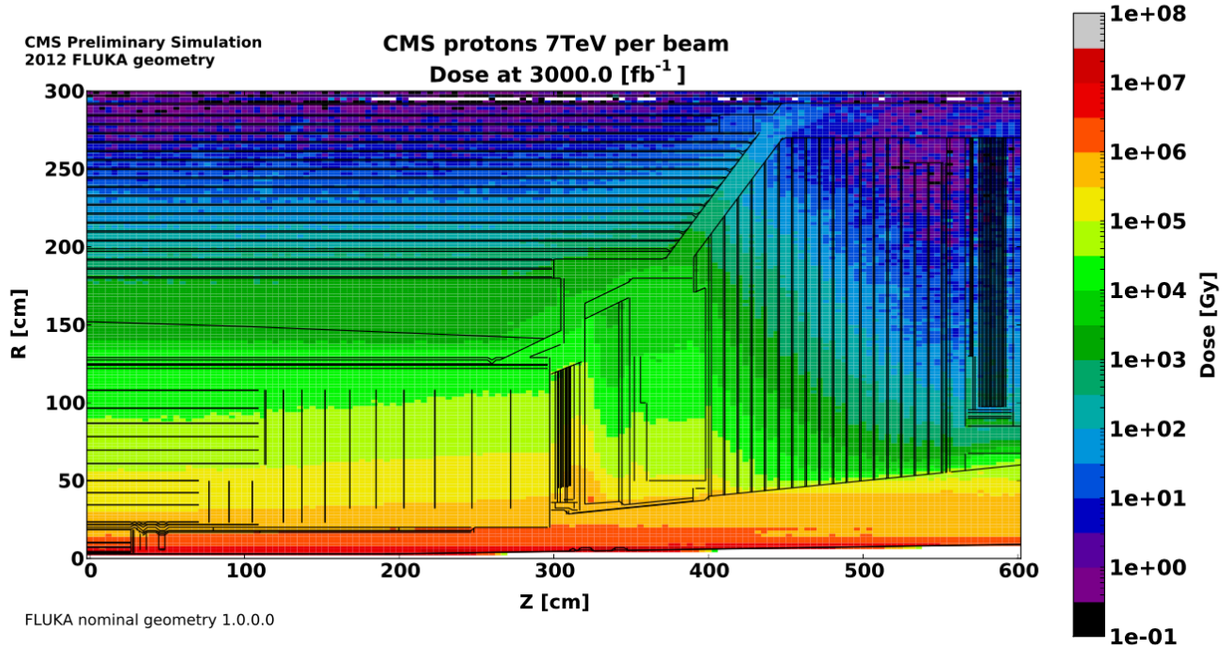
- Run 2: Excellent ECAL energy resolution maintained
- Run 3: ECAL performance is also expected to be maintained with improved PU and ageing effects mitigation and optimised energy clustering
- Phase 2: Upgrade of ECAL barrel supermodules planned for LS3
- With Phase 2 upgrades CMS ECAL will continue to provide excellent photon/electron/jet performance for Higgs Physics, and meet the challenges of HL-LHC

Backup slides

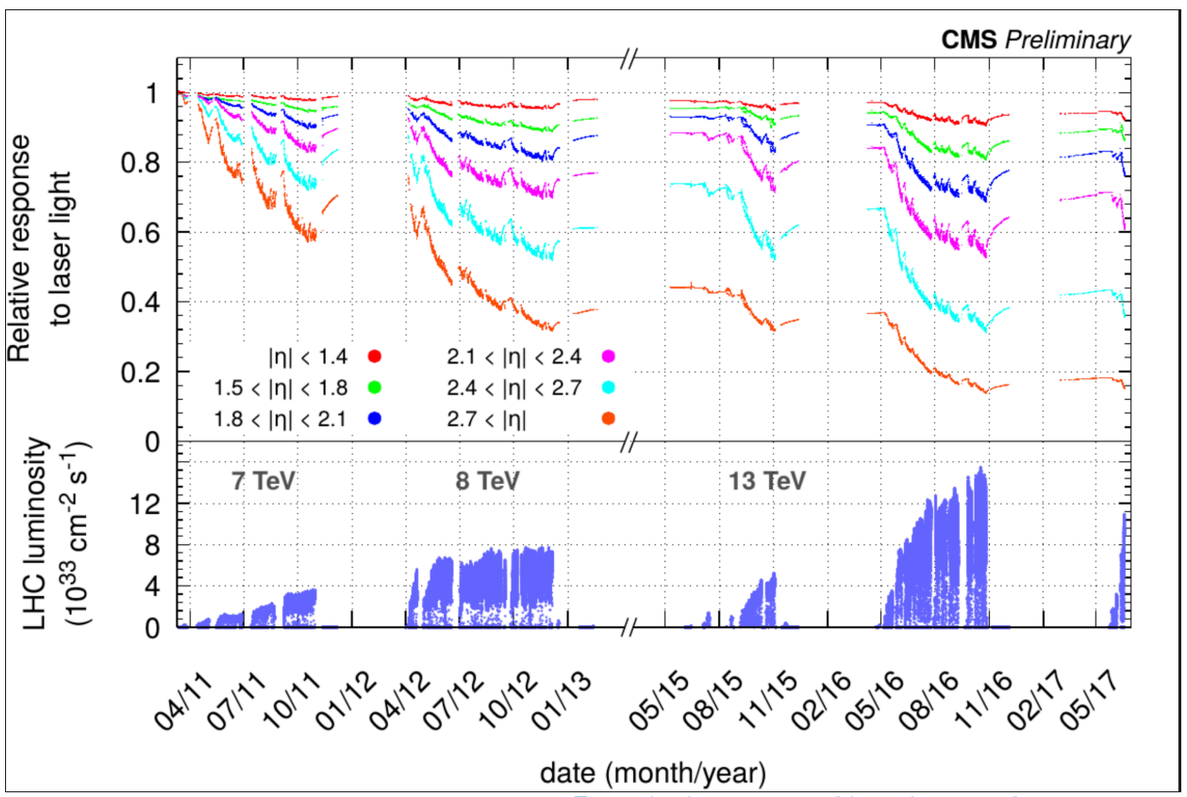
ECAL Longevity

	LHC design	HL-LHC prediction
Luminosity [$cm^{-2}s^{-1}$]	1×10^{34}	5×10^{34}
Int. Luminosity [fb^{-1}]	500	3000
γ **dose rate** (EB $\lvert\eta\rvert = 1.0$)	0.2	1.0
[Gy/h] (EE $\lvert\eta\rvert = 2.6$)	6	30
hadron fluence (EB $\lvert\eta\rvert = 1.0$)	12×10^{11}	7.6×10^{12}
[cm^{-2}] (EE $\lvert\eta\rvert = 2.6$)	3×10^{13}	2.0×10^{14}

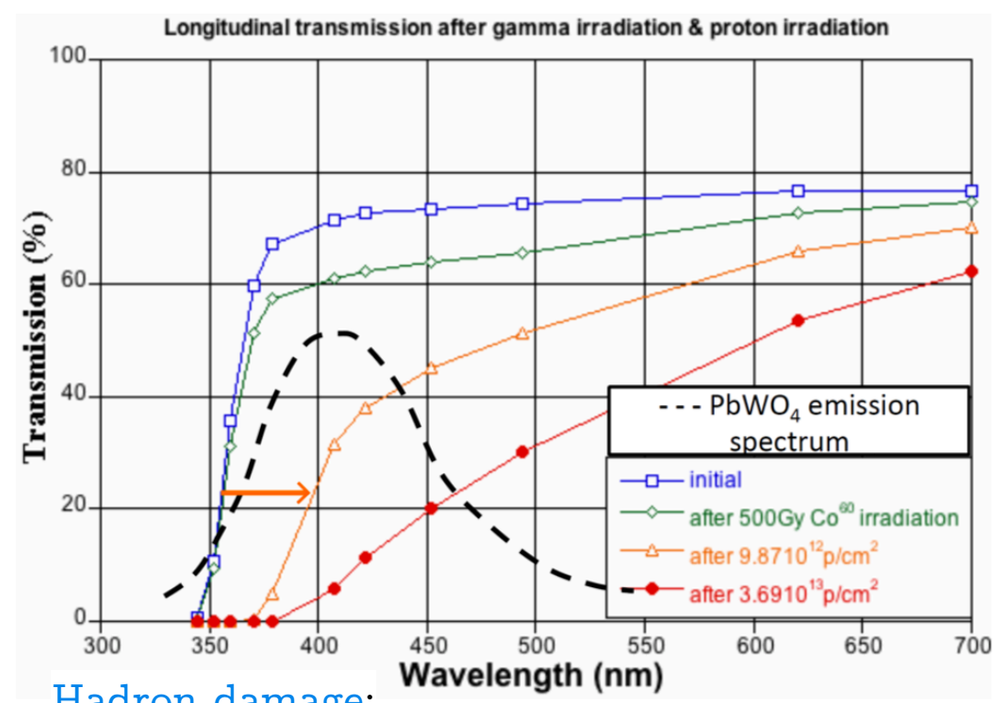
Expected up to ~ 6 times higher radia



Radiation is higher closer to the beam pipe (Endcaps)-Caveat: this is the current geometry



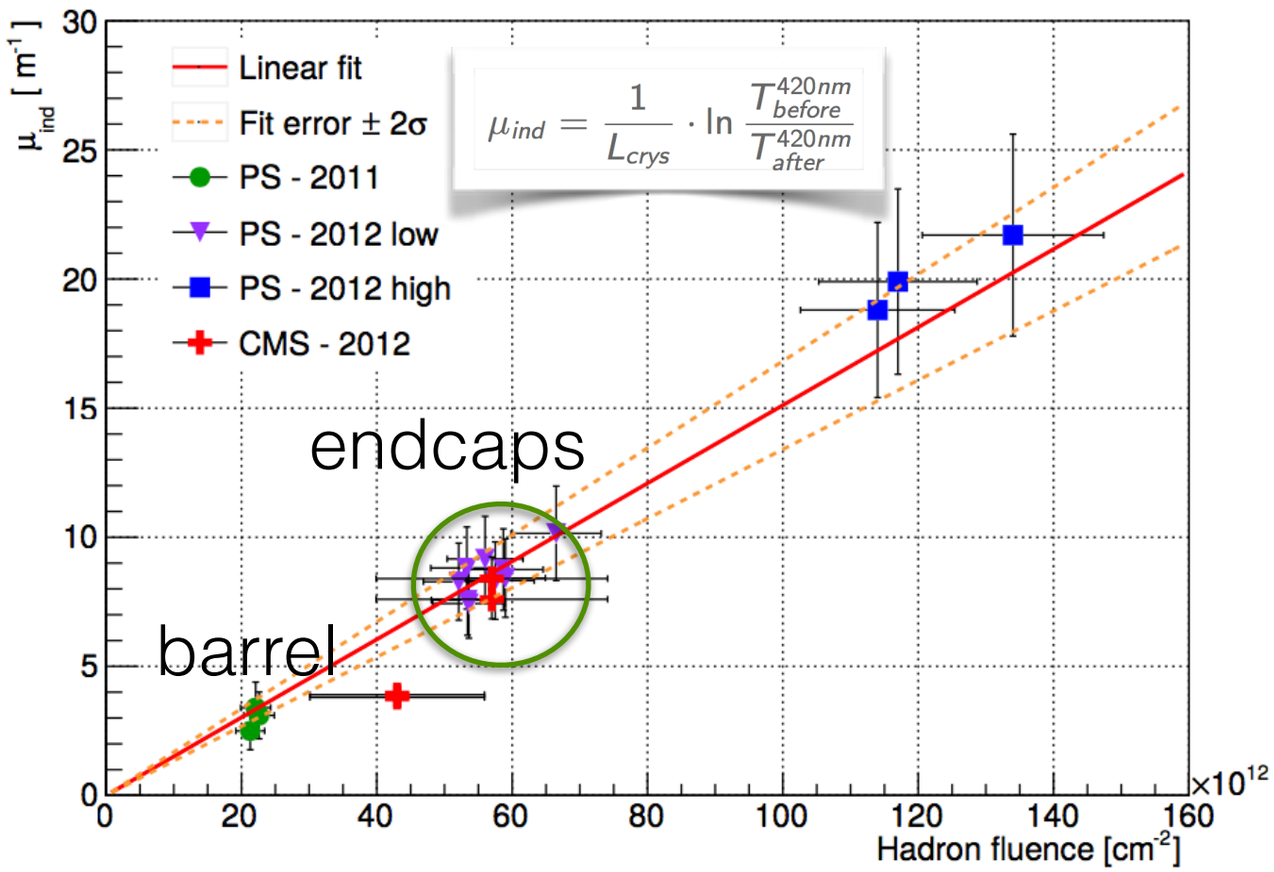
Ionizing radiation damage:
It recovers at room temperature
Light transmission of crystals is constantly monitored in ECAL using laser light
Evolution of the response is in agreement with expectations



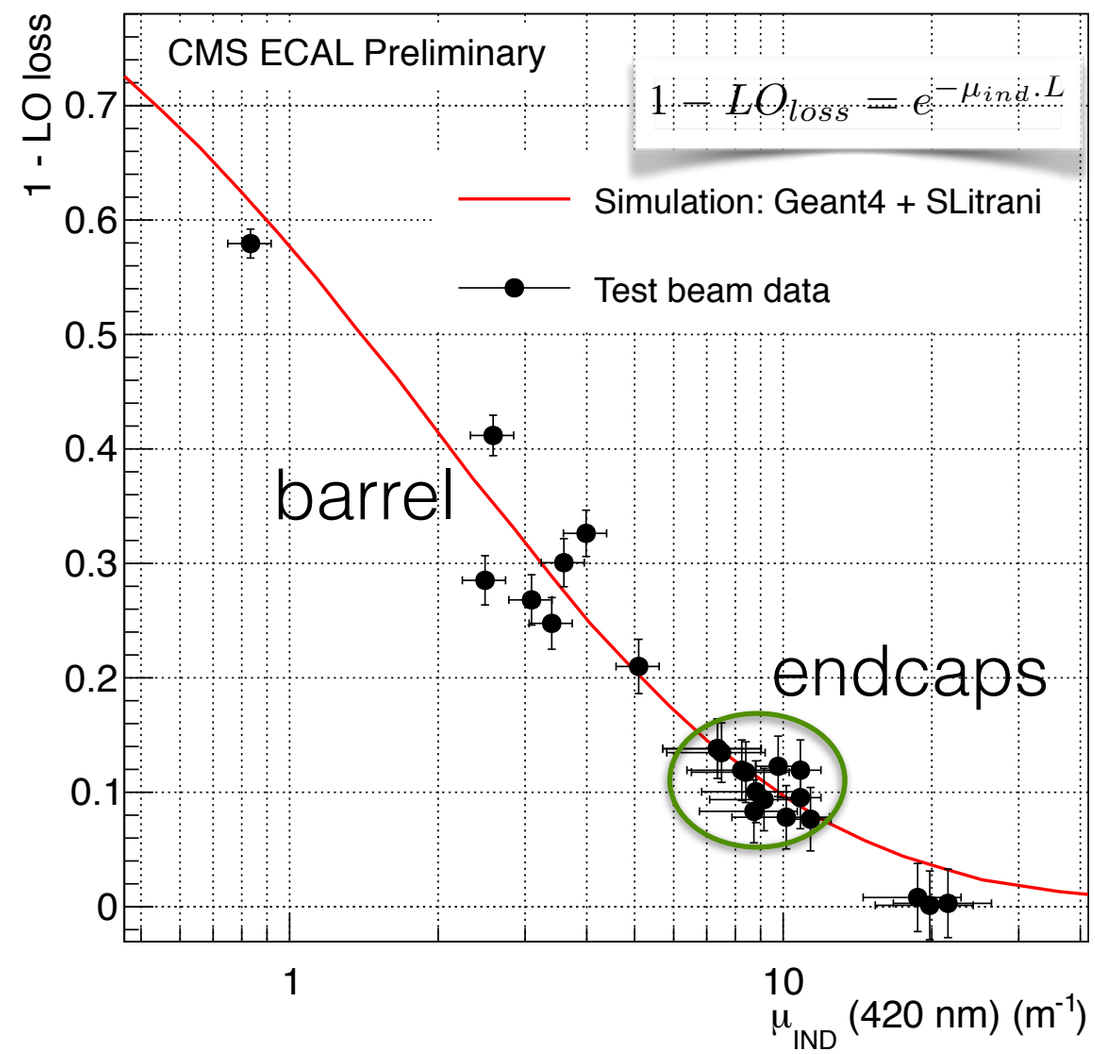
Hadron damage:
No recovery at room temperature
Shift of transmission band edge
Dominant losses at HL-LHC

ECAL lead tungstate crystal performance

Induced absorption coefficient



Loss of light output

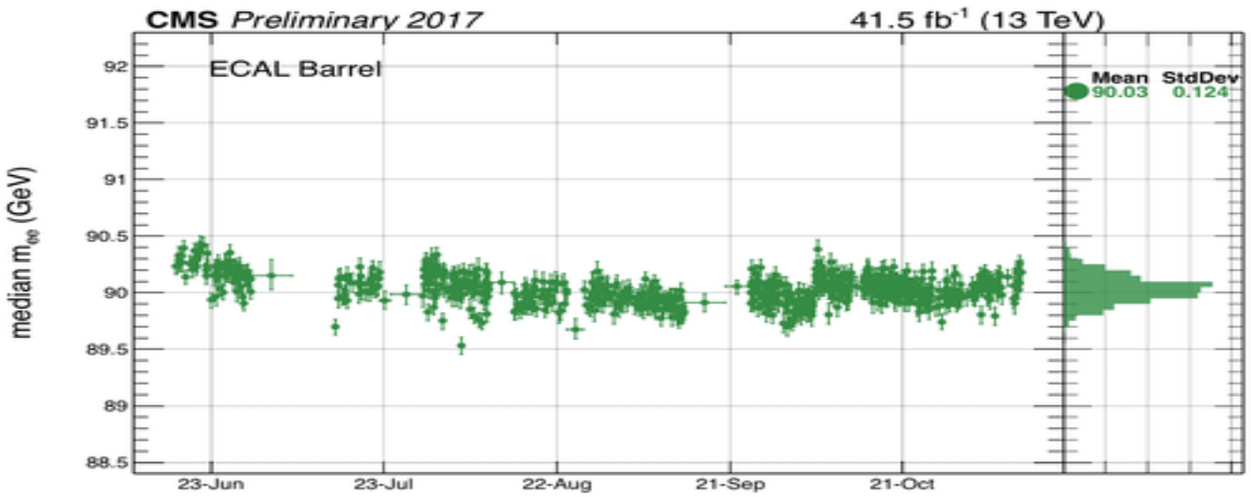


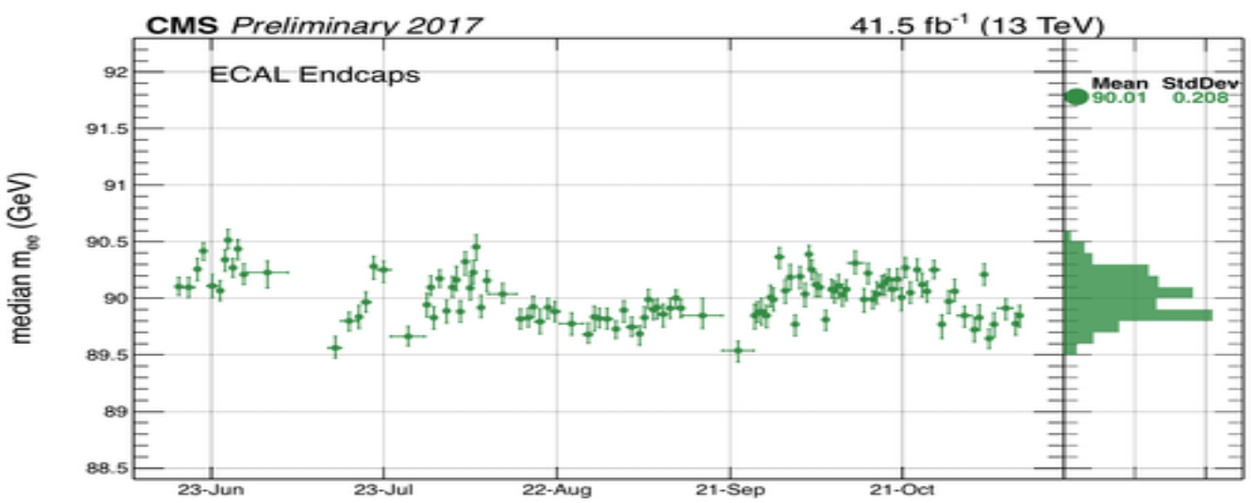
-Measured correlation between the hadron fluence to which the crystals were exposed and the corresponding induced absorption coefficient.

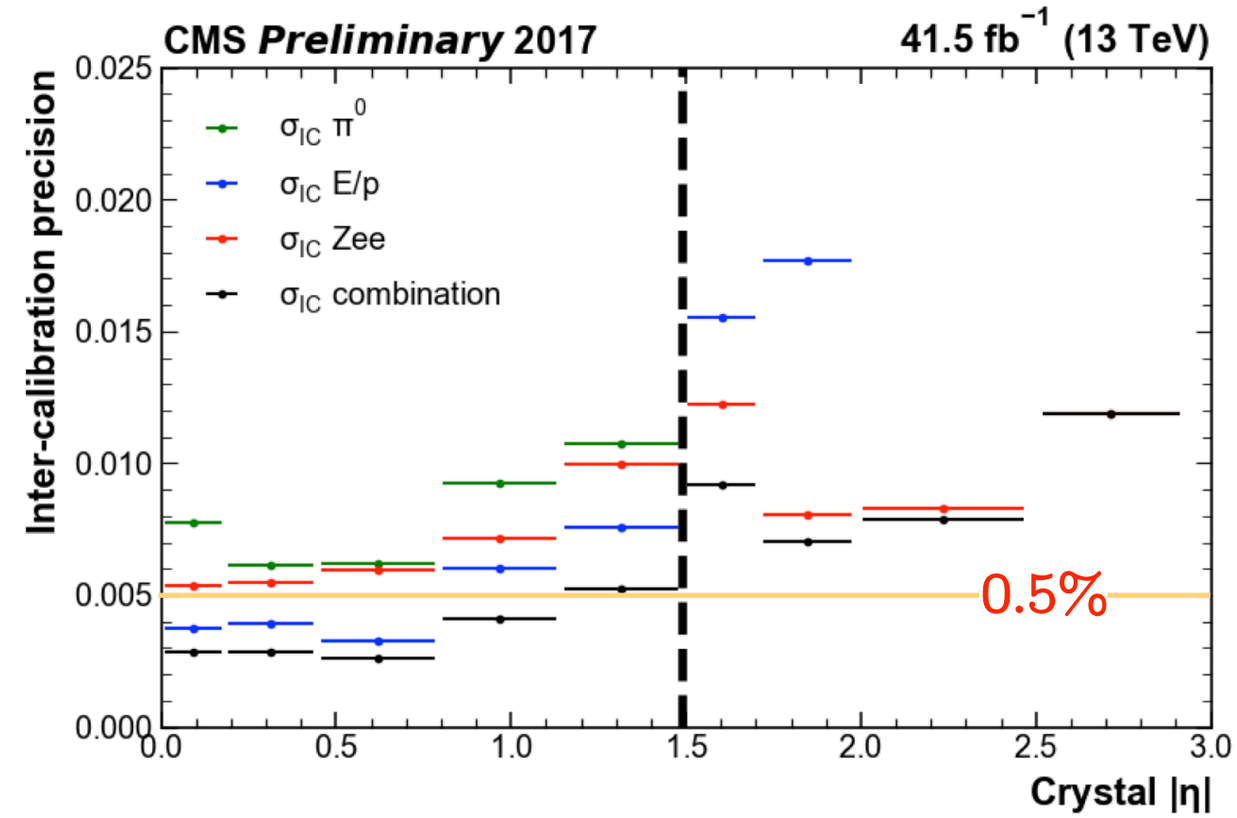
- Measured loss of light output of proton-irradiated $PbWO_4$ crystals as a function of induced absorption, compared with simulation predictions

ECAL energy calibration updates

Crucial to maintain optimum resolution







Regular recalibrations

using W and Z electrons

achieve the time stability of the di-electron invariant mass distribution

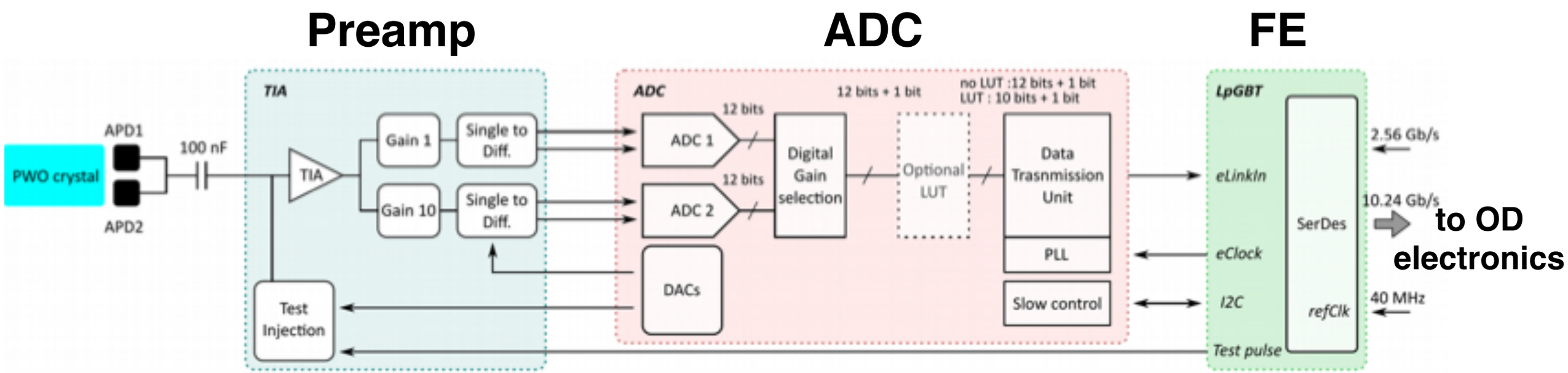
Regular recalibrations

using several in-situ methods

Equalise response of all channels to physics signals

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

EB Phase II architecture

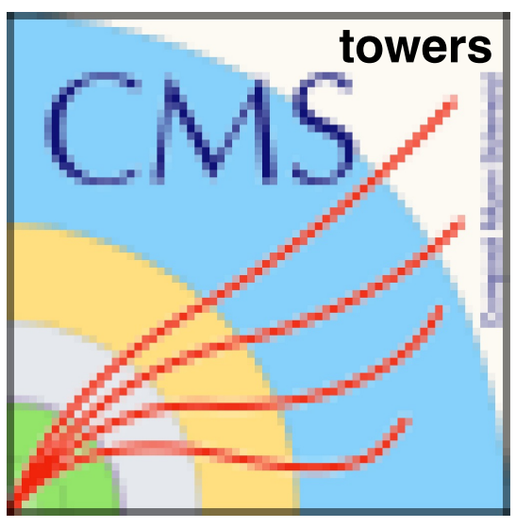


1. TIA (Trans Impedance Amplifier)preamp:
   1. Two gain ranges (G1,G10). 2 TeV dynamic range with 50 MeV LSB(=Least Significant Bit)
2. ADC
   1. 12 bit, 160 MHz sampling, dual channel with gain selection logic
   2. Data Transmission Unit (DTU) implements data compression before FE
3. FE
   1. lpGBT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

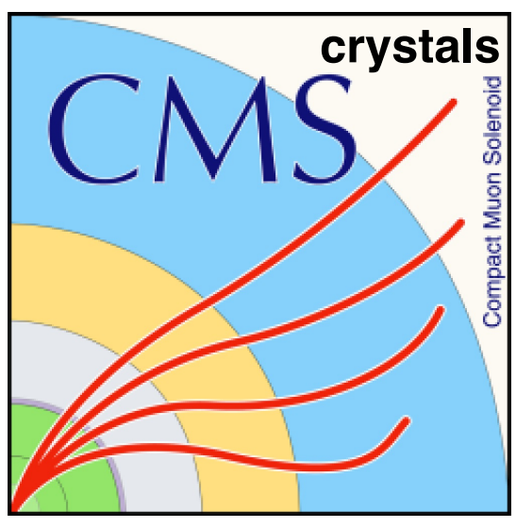
ECAL trigger upgrade

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

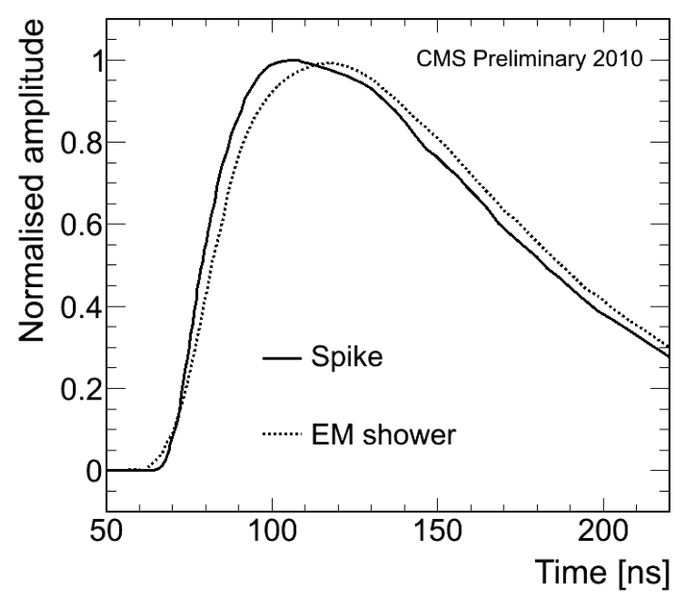
Current



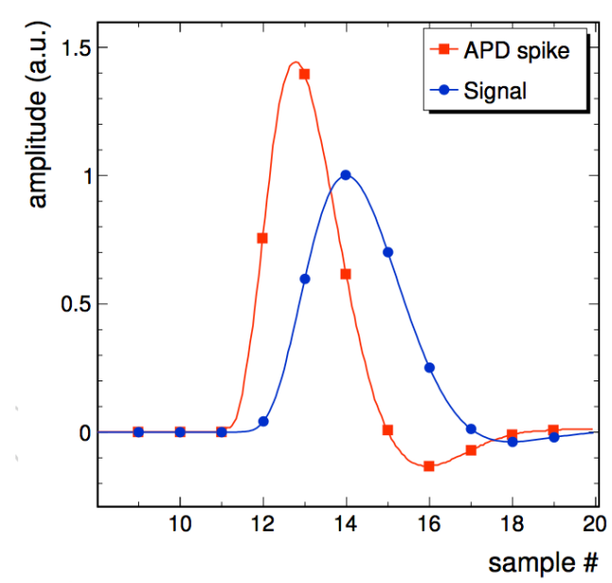
Upgrade



Current



Upgrade

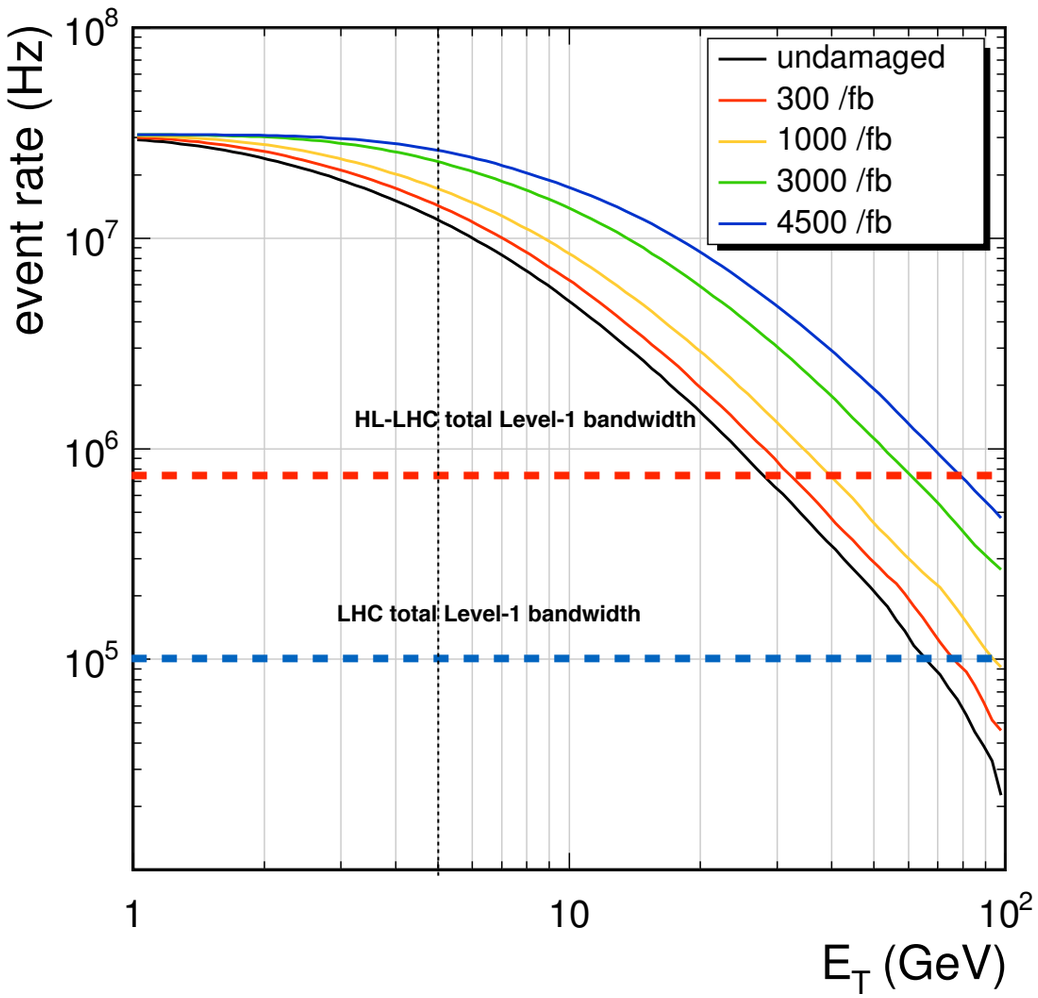


25x better trigger granularity

Much better "spike" rejection

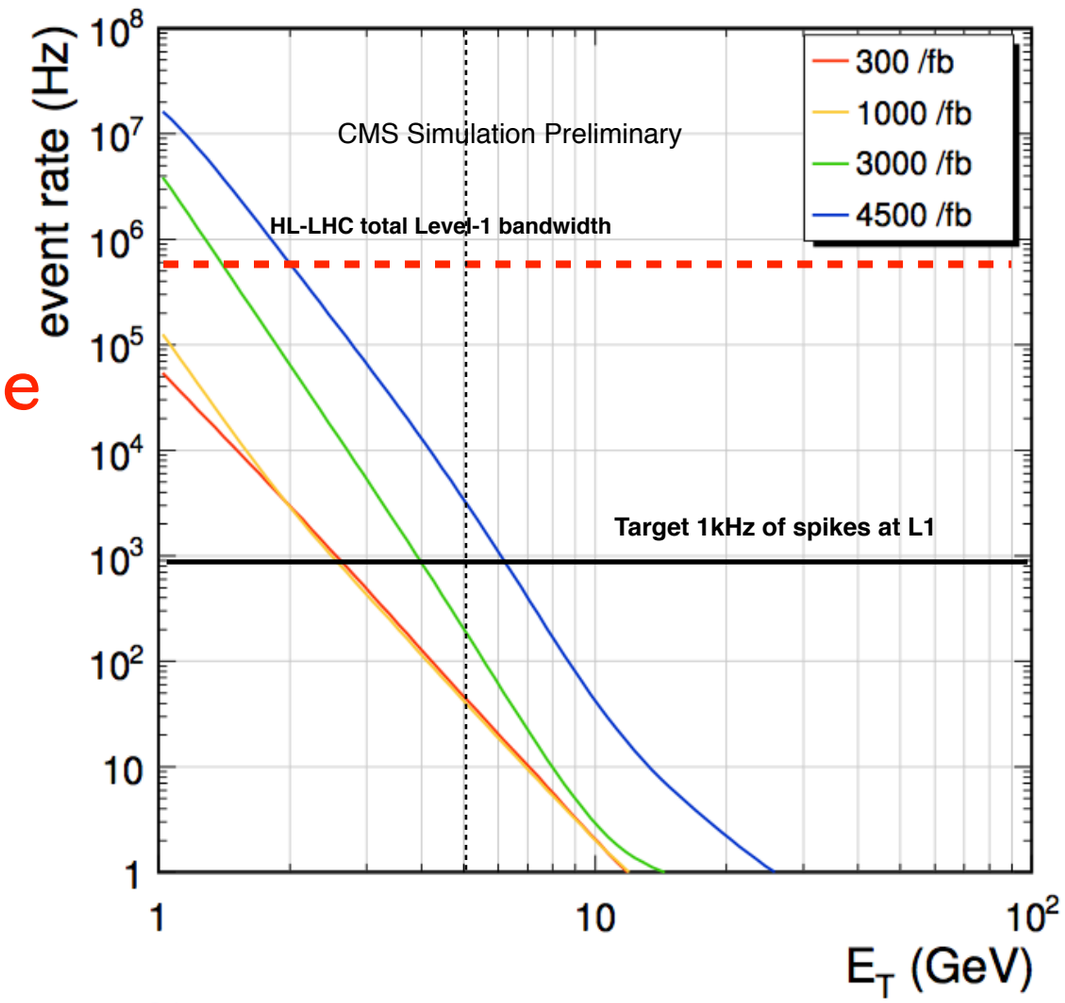
Prediction of the ECAL Barrel Spike mitigation

Spike rate vs E_T threshold at HL-LHC



upgrade

Pulse shape discriminant

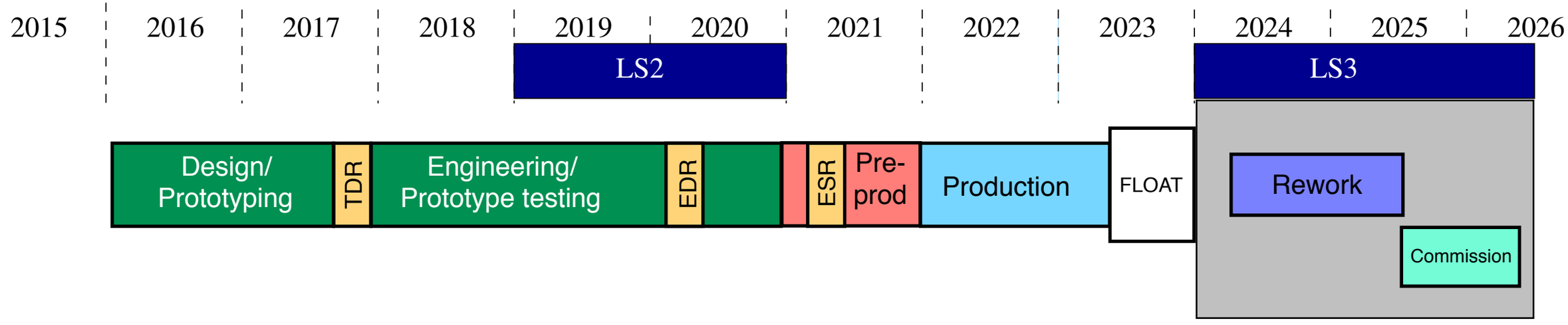


Shorter pulse shape

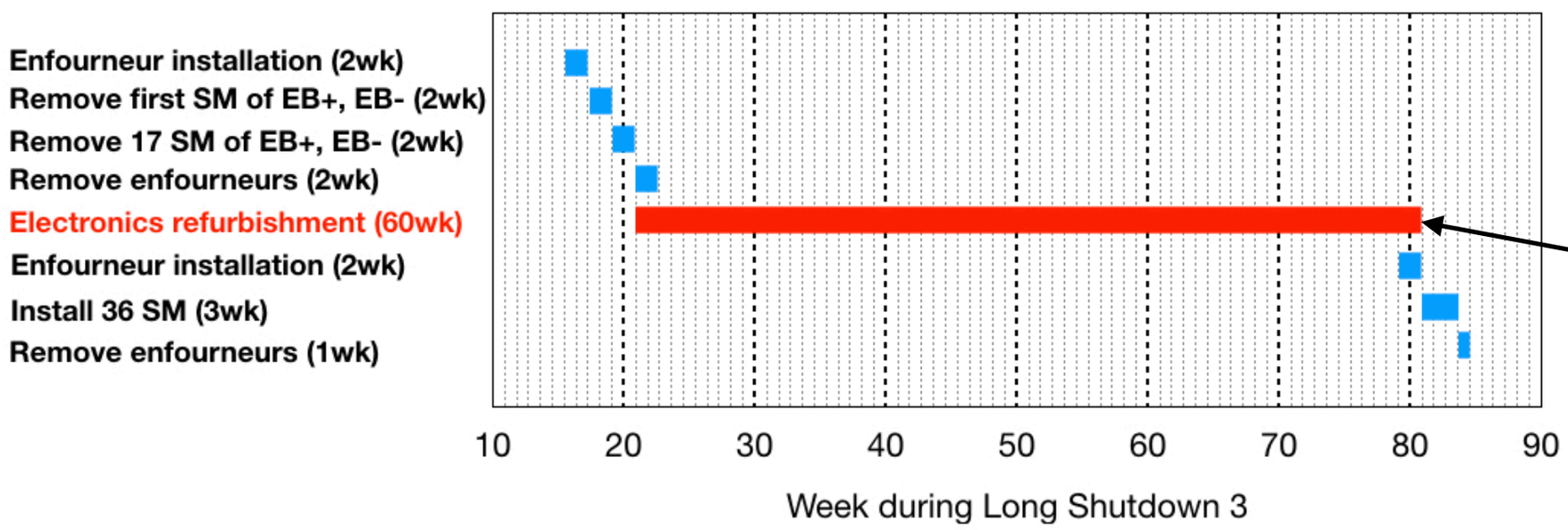
These upgrades are necessary to maintain good spike mitigation during HL-LHC running

Schedule and planning

Overall schedule



Supermodule refurbishment in LS3



TDR submitted to LHCC this month