Photon detection with the CMS ECAL in the present and at the HL-LHC and its impact on Higgs boson measurements

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On behalf of the CMS collaboration

Photon2019:

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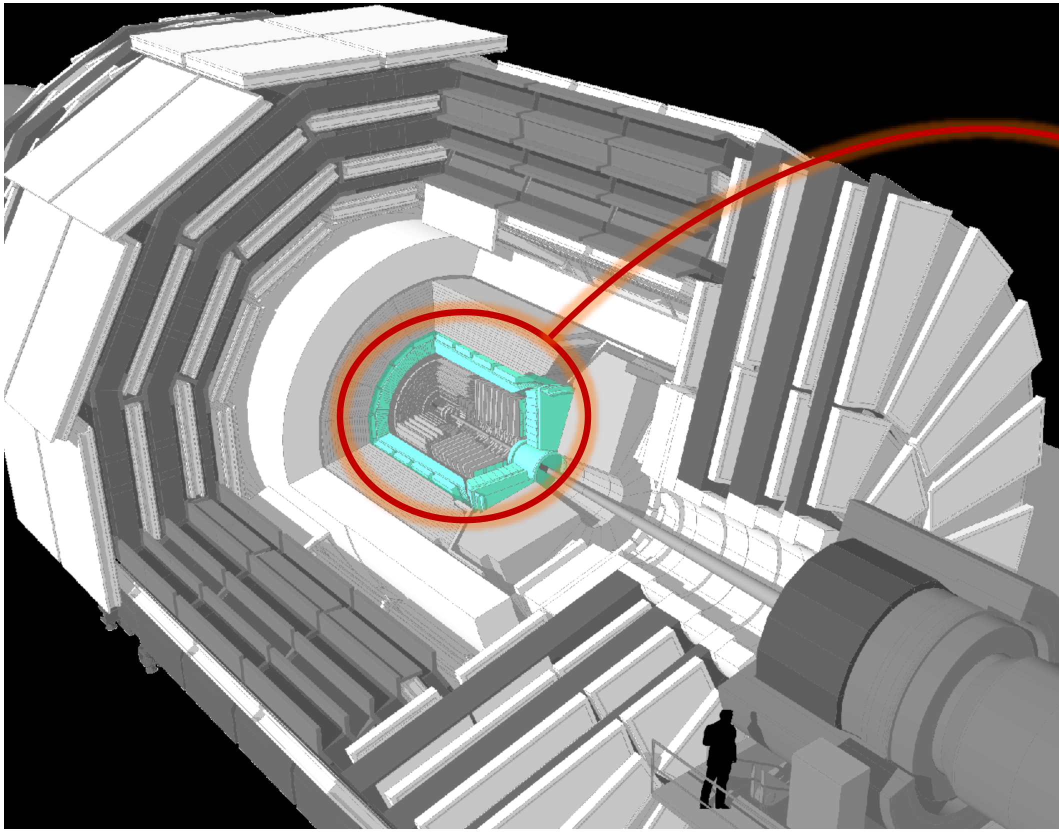
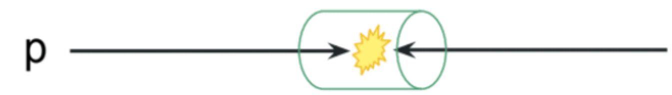
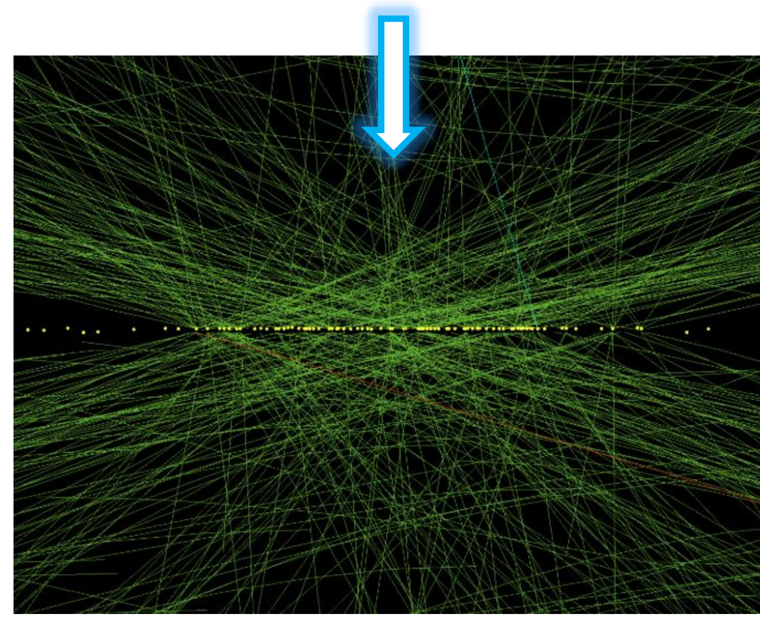
CMS detector at the LHC



Electromagnetic calorimeter (ECAL)





40 MHz bunch crossing (BX) rate (every 25 ns)

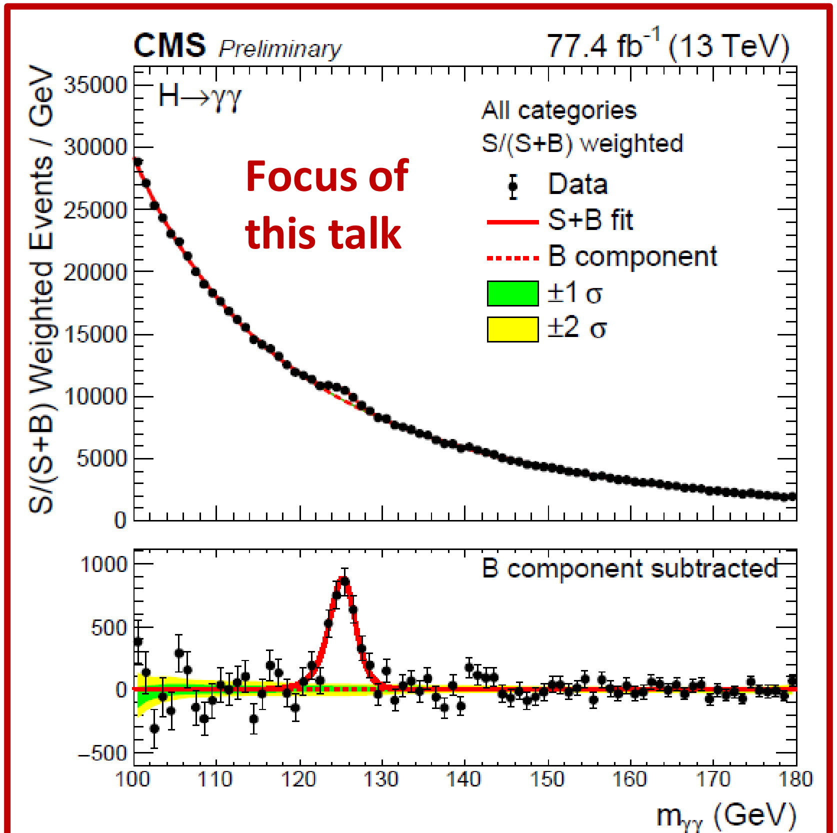
Multiple pp interactions per BX (pileup, PU)

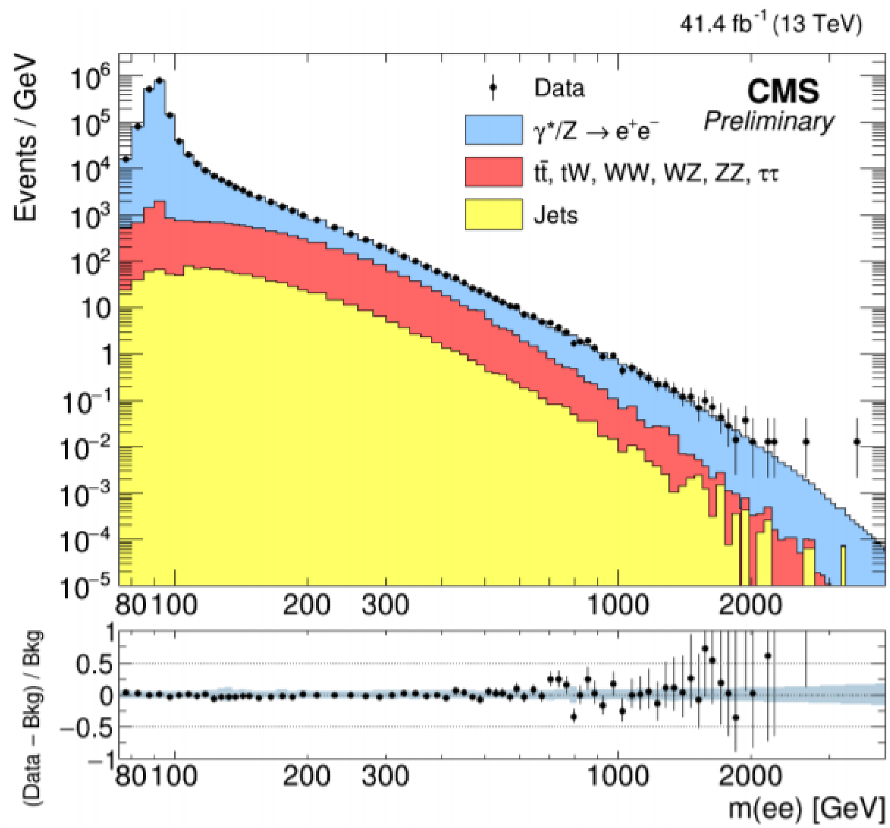
- $\langle PU \rangle \approx 40$ during Run 2 (in-time PU)
- overlap among consecutive BX (out-of-time PU)

Physics with photons and electrons

e/γ provide clean experimental signatures and good energy resolution

- suitable for Standard Model (SM) precision measurements: $H \to \gamma\gamma, H \to ZZ^* \to 4e$
- interesting channels for searches for new physics (NP): e.g. $Z' \to ee$

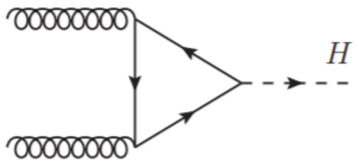




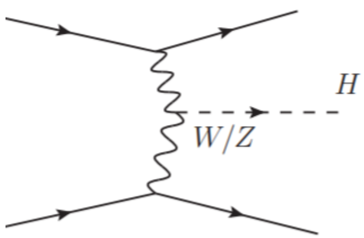
Higgs physics at the LHC

Production

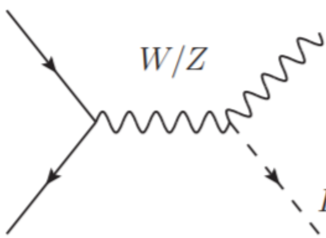
gluon-gluon fusion (ggH)
≈ 50 pb



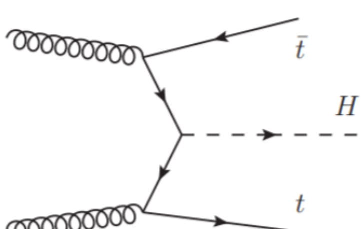
vector boson fusion (VBF)
≈ 4 pb



Higgs-strahlung (VH, V = Z,W)
≈ 2 pb



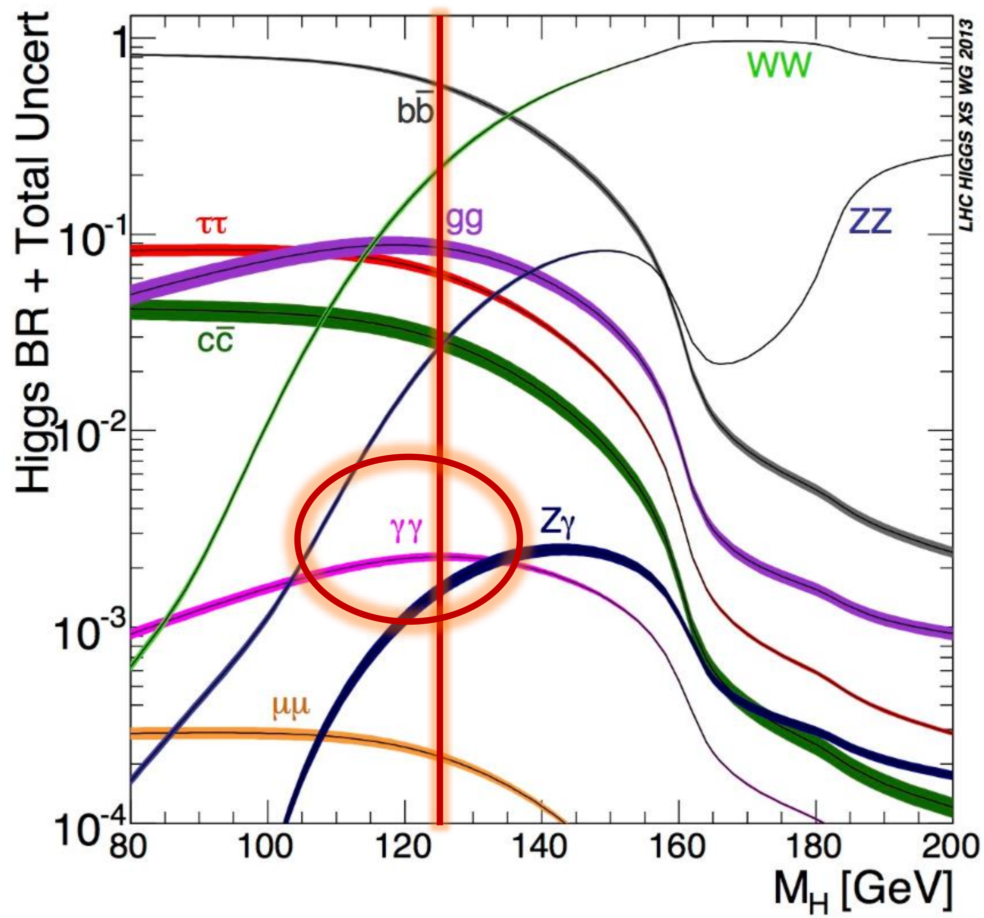
associated production with top quarks (ttH)
≈ 0.5 pb



pp inelastic cross section ≈ 80 mb

- signal xsec >= 9 orders of magnitude lower

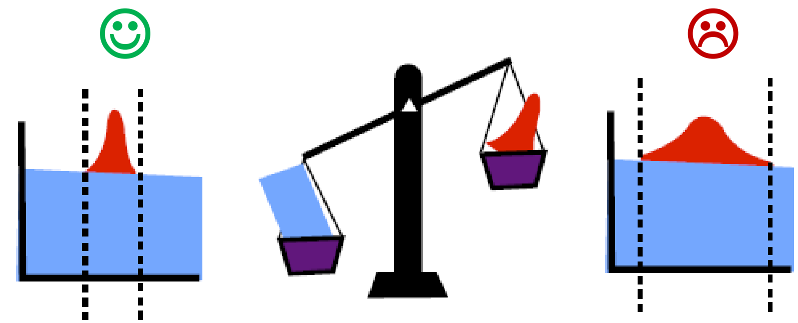
Decay



Experimental challenges for $H \rightarrow \gamma\gamma$

Peak in $\gamma\gamma$ invariant mass spectrum

- the narrower the better
- width dominated by experimental resolution

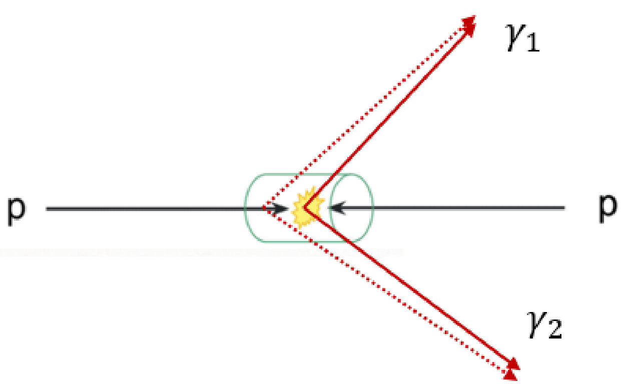


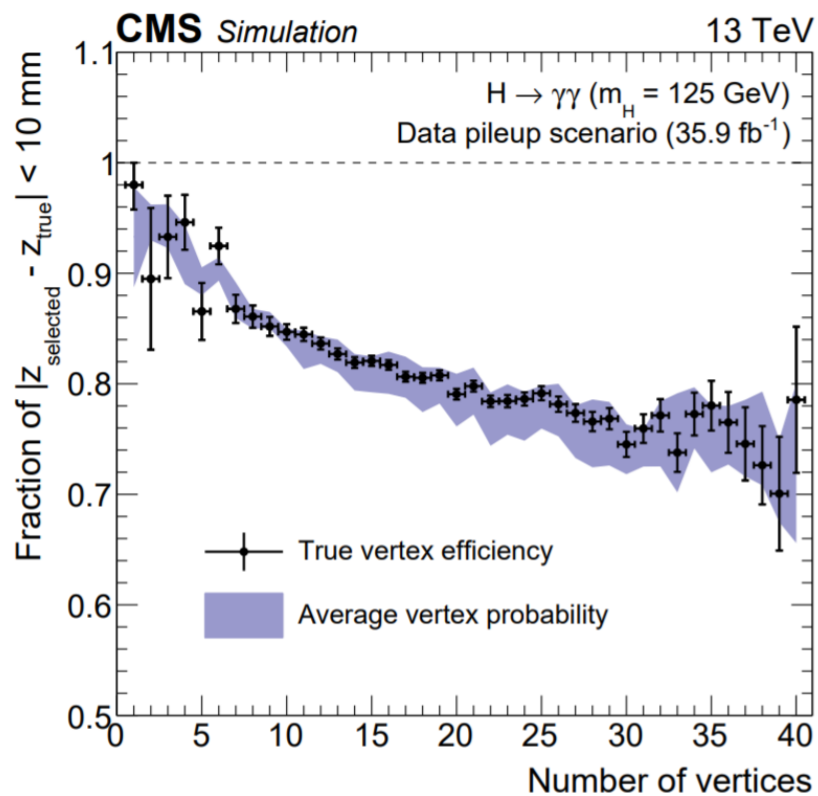
$$m_{\gamma\gamma} = \sqrt{E_1^2 + E_2^2 + 2E_1E_2(1 - cos\vartheta)}$$

$$\frac{\sigma_m}{m} \propto \frac{\sigma_E}{E} \oplus \frac{\sigma_\vartheta}{\tan \vartheta/2}$$

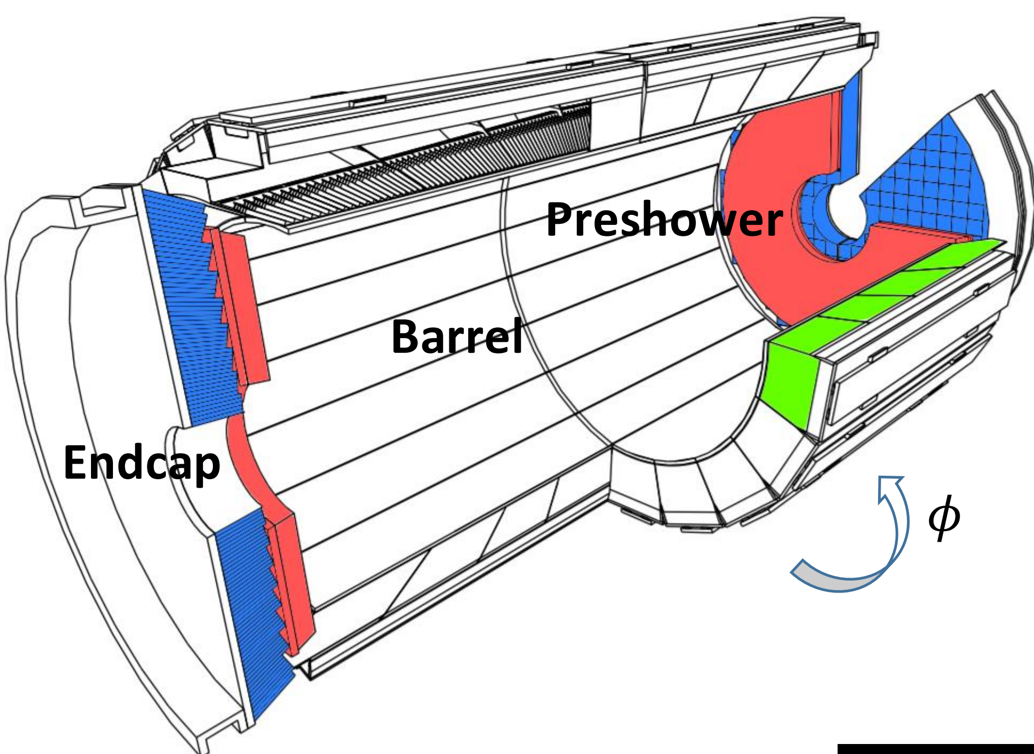
No tracks for γ → choose vertex with highest $\sum|p_T|$ of tracks recoiling against H

- negligible impact of σ_ϑ on $m_{\gamma\gamma}$ if $\Delta z < 1$ cm





CMS electromagnetic calorimeter (ECAL)



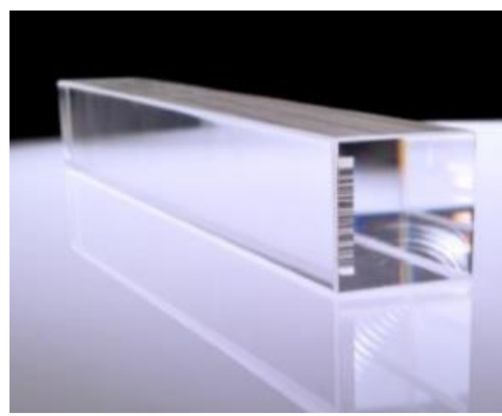
BARREL (EB): 61200 crystals
36 supermodules (SM), 4 modules each
$|\eta| < 1.48$
Avalanche PhotoDiodes (**APD**) readout

ENDCAP (EE): 14648 crystals
2 half disk Dees for each side
$1.48 < |\eta| < 3.0$
Vacuum PhotoTriodes (**VPT**) readout

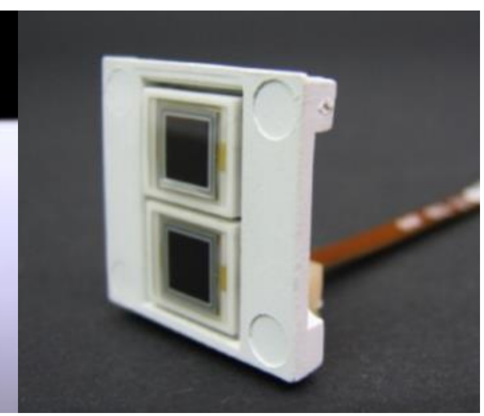
PRESHOWER (ES):
4 Dees made of 2 Pb/Si planes
$1.65 < |\eta| < 2.6$

Homogeneous, high-granularity hermetic $PbWO_4$ crystal calorimeter

- fast decay scintillation light (25 ns)
- short radiation lenght (X_0 = 0.89 cm)
- small Moliere radius (2.2 cm)



$PbWO_4$ crystal



APD

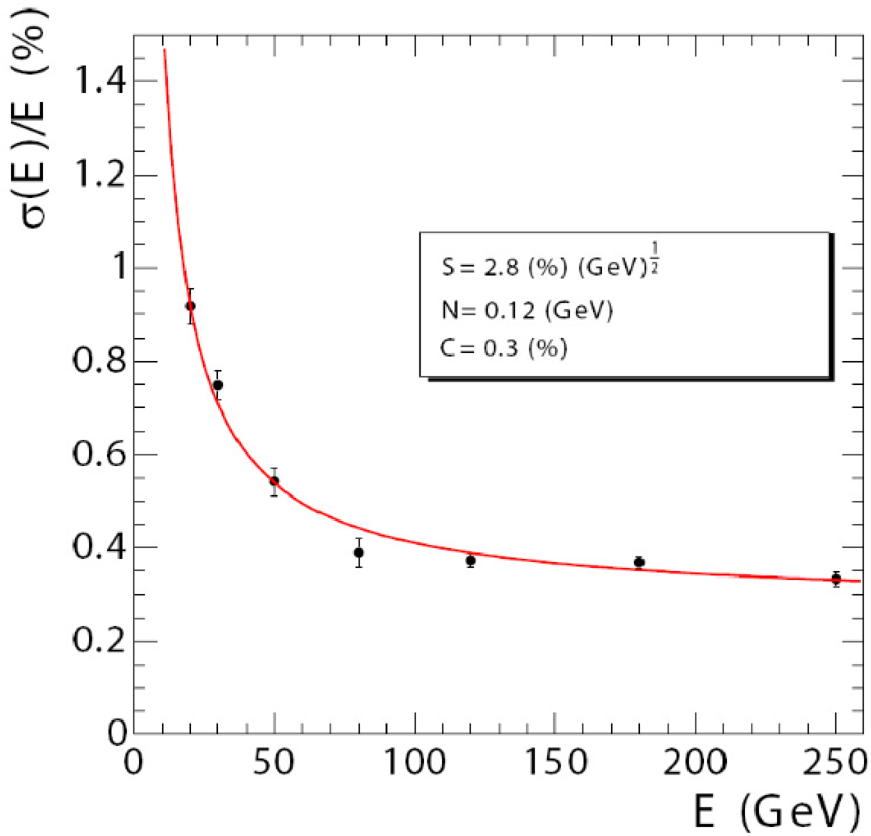
ECAL energy resolution

Measured in test beam in 3x3 crystals

- no magnetc field
- no materal upstream of ECAL
- no irradiation

$$\frac{\sigma(E)}{E} = \frac{2.8\%}{\sqrt{E}} \oplus \frac{0.128}{E(GeV)} \oplus 0.3\%$$

- channel uniformity and stability affect constant term: **required in situ $\lesssim$ 0.5%**



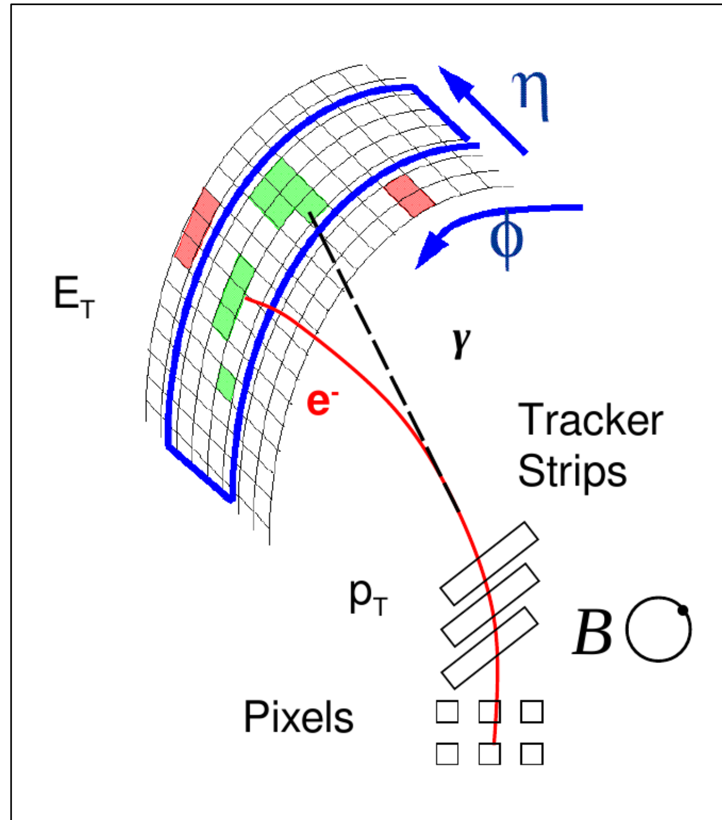
$\approx$ 1% energy resolution achieved for high energy electrons in EB during Run 1-2

Electron and photon energy reconstruction

Electromagnetic shower spread over several crystals

- further spread due to e bremsstrahlung, γ conversions

Dynamic clustering able to recover additional radiation



Energy measured using all crystals in shower

$$E_{e,\gamma} = F_{e,\gamma} \cdot G \cdot \sum_{i \in shower} S_i(t) \cdot C_i \cdot A_i$$

- $F_{e,\gamma}$ → cluster corrections
- G → global scale
- $S_i(t)$ → response (laser monitoring)
- C_i → intercalibration
- A_i → pulse amplitude

Pulse reconstruction

Multifit algorithm developed for Run 2 to cope with out-of time (OOT) PU

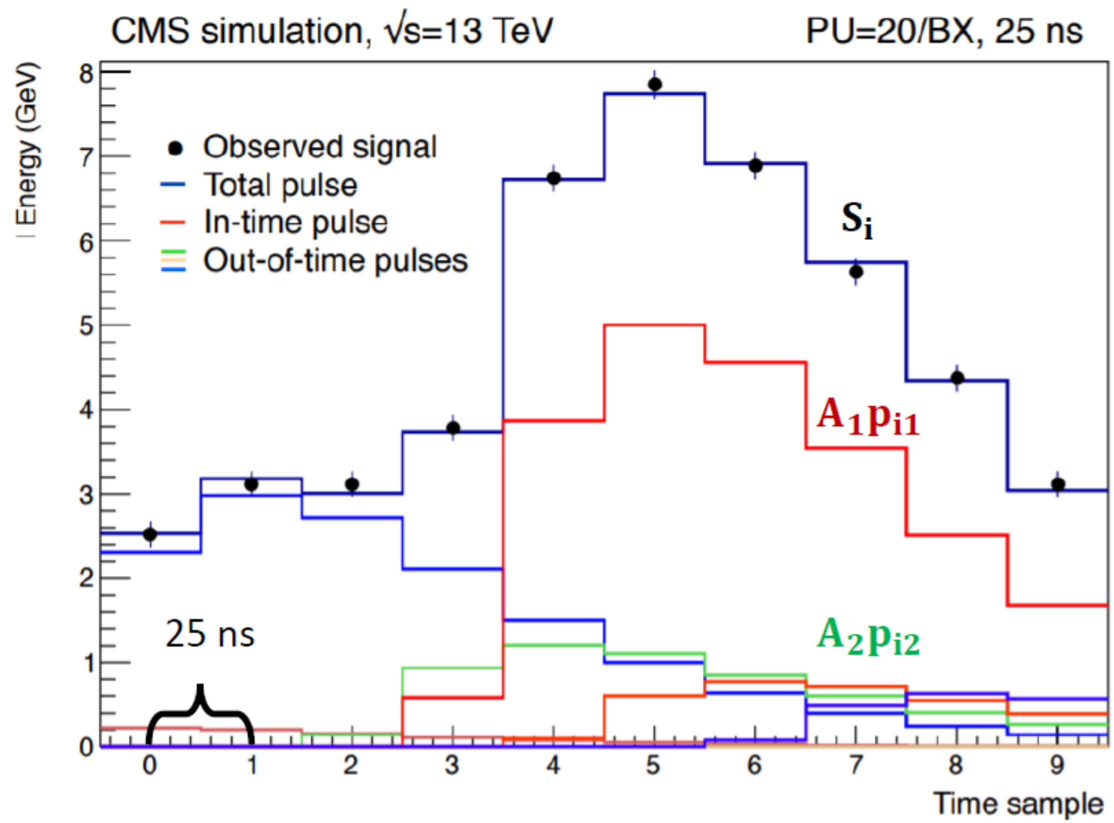
- pulse shape modeled as a sum of one in-time and up to 9 OOT pulses
- extract in-time pulse through χ^2 minimization
  - fast → used also at trigger level

time sample (every 25 ns)

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

σ_{S_i}: noise covariance matrix, measured from pedestal runs

p_{ij}: pulse templates, with same shapes but 25 ns time shift

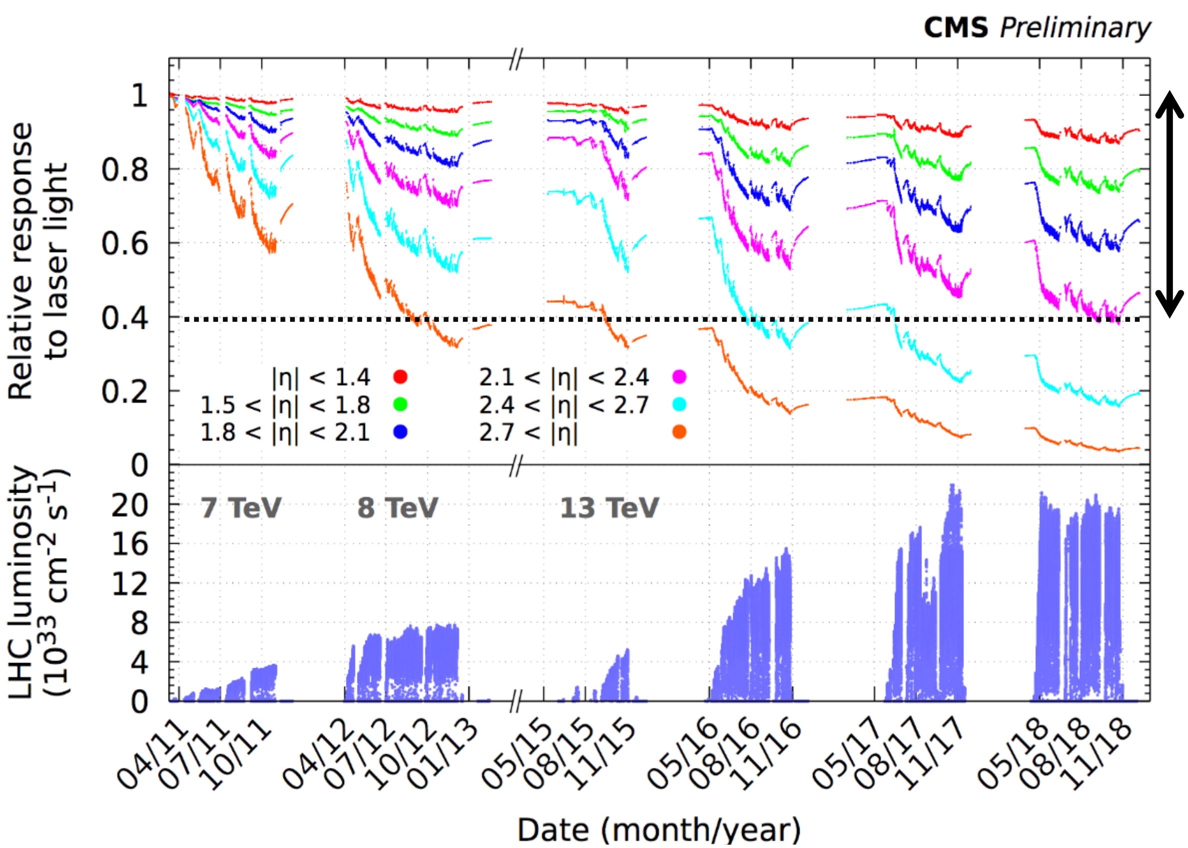


Response monitoring

Continuous crystal transparency change due to radiation damage

- energy response drift assessed with dedicated laser system and corrected
- energy scale stability monitored using physics signals: $\pi^0 \rightarrow \gamma\gamma$, electrons from W/Z

e/γ precision physics up to $|\eta| \leq 2.4$ (tracker coverage), jet physics beyond



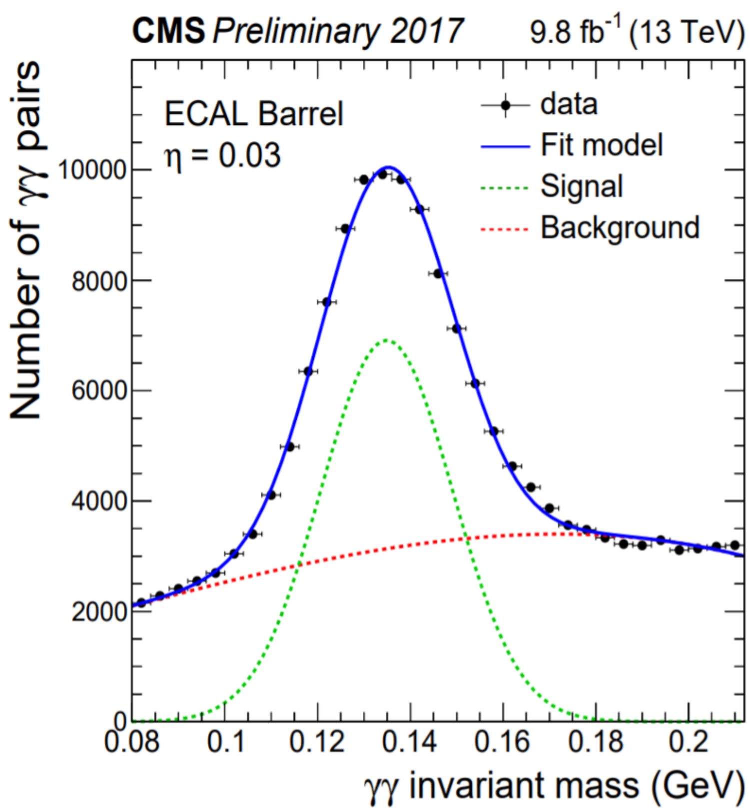
Impossibile visualizzare l'immagine.

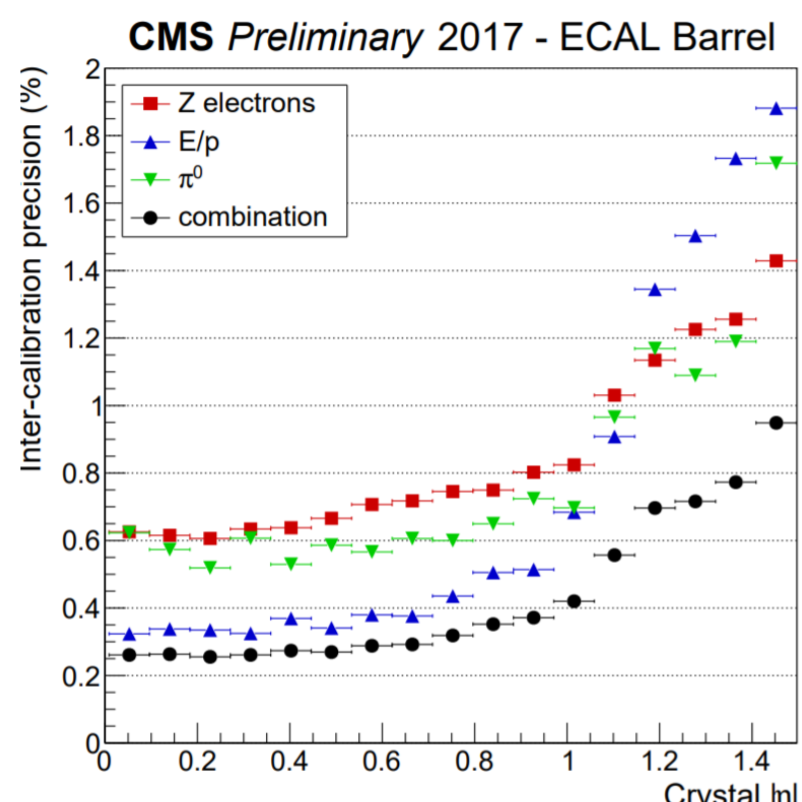
each point is a fit to $\approx 10^5$ $\pi^0 \rightarrow \gamma\gamma$, collected by special triggers in 5 minutes

Intercalibration (IC)

Goal: equalize energy response variations among different ECAL crystals

- Several methods based on physics processes (different stat. and syst. uncertainties)
  - $\boldsymbol{\pi^0/\eta^0 \rightarrow \gamma\gamma}$: position of invariant mass peak
  - $\boldsymbol{Z \rightarrow ee}$: position of invariant mass peak
  - **E/p**: compare electron energy E with its momentum p in $Z \rightarrow ee$ and $W \rightarrow e\nu$ events





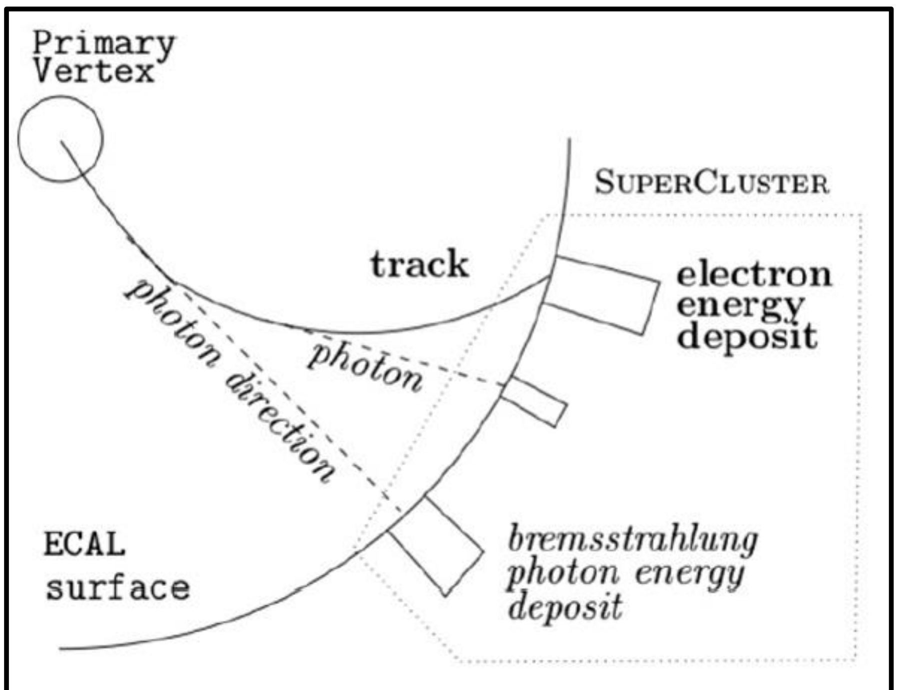
Clustering and corrections

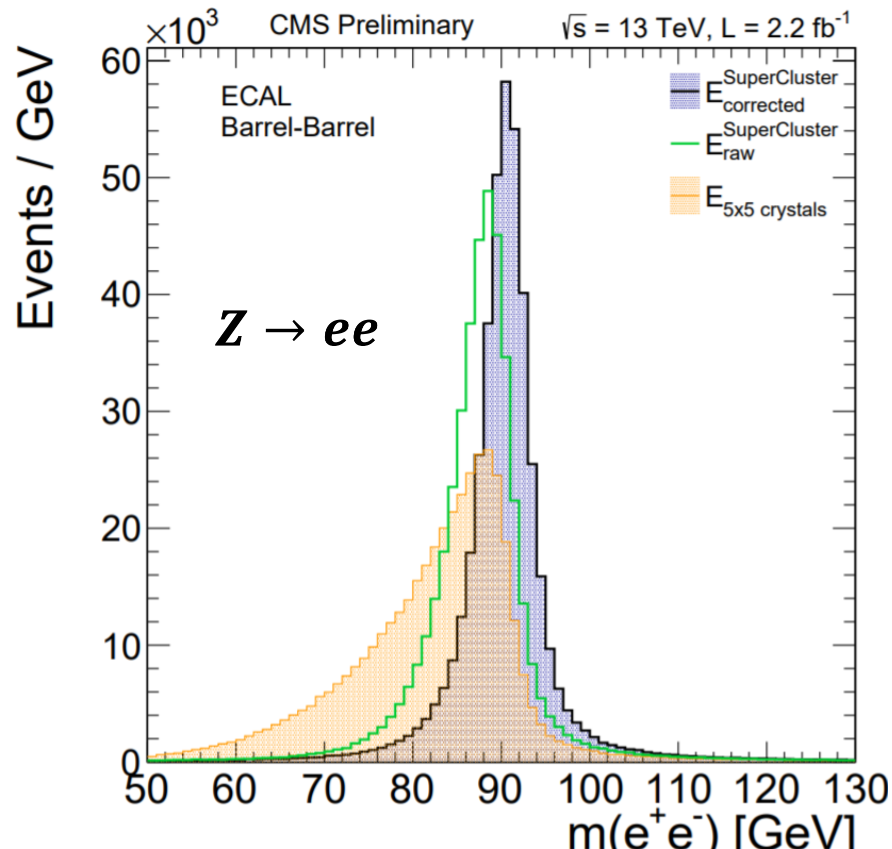
e/γ clusters in ECAL extended along ϕ to form superclusters (SC)

- e clusters matched to tracks (γ if none)

SC energy corrected with multivariate (MVA) regression trained on MC

- account for energy containment effects, energy loss in material upstream of ECAL, PU

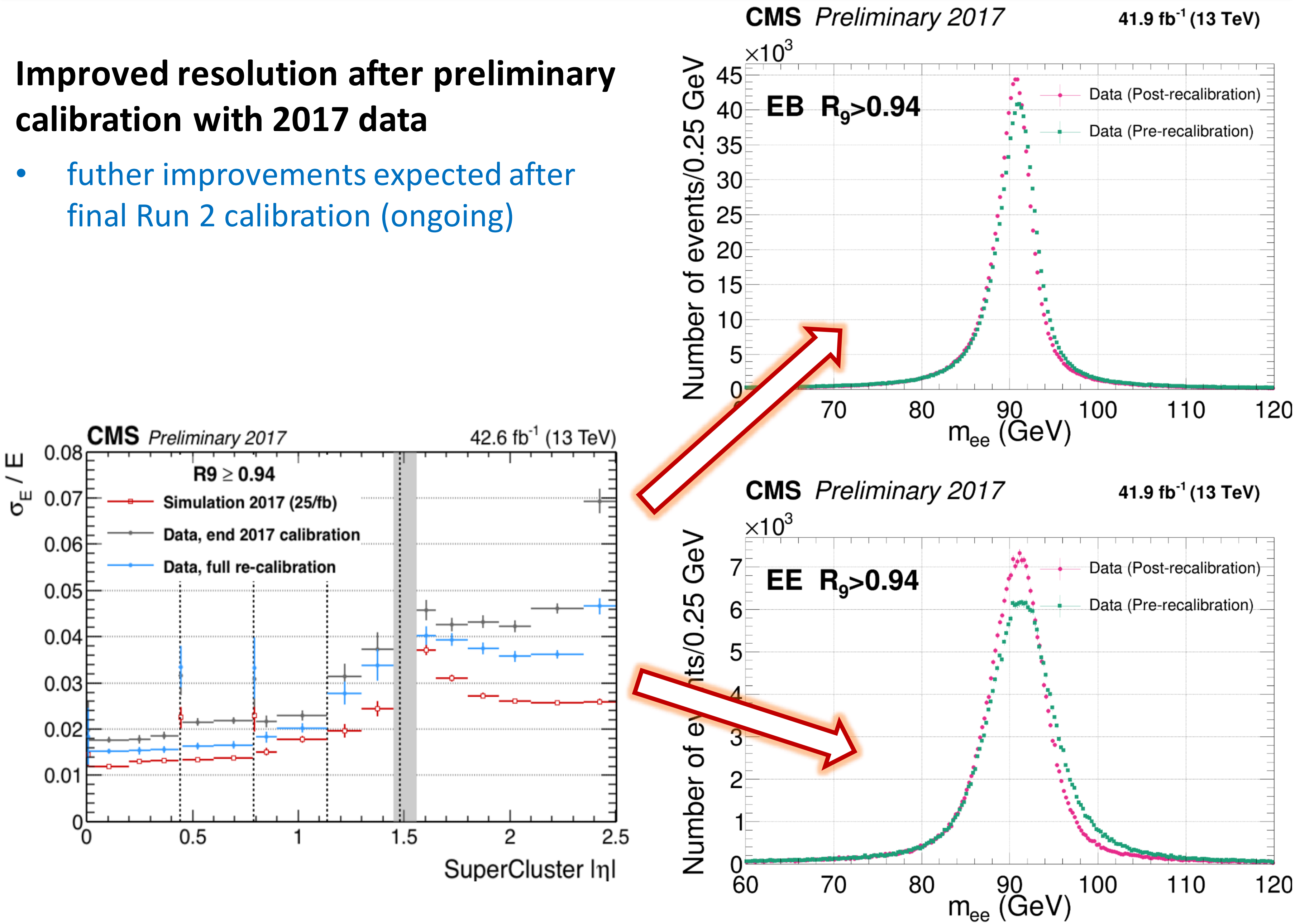




Energy resolution in Run2

Improved resolution after preliminary calibration with 2017 data

- futher improvements expected after final Run 2 calibration (ongoing)

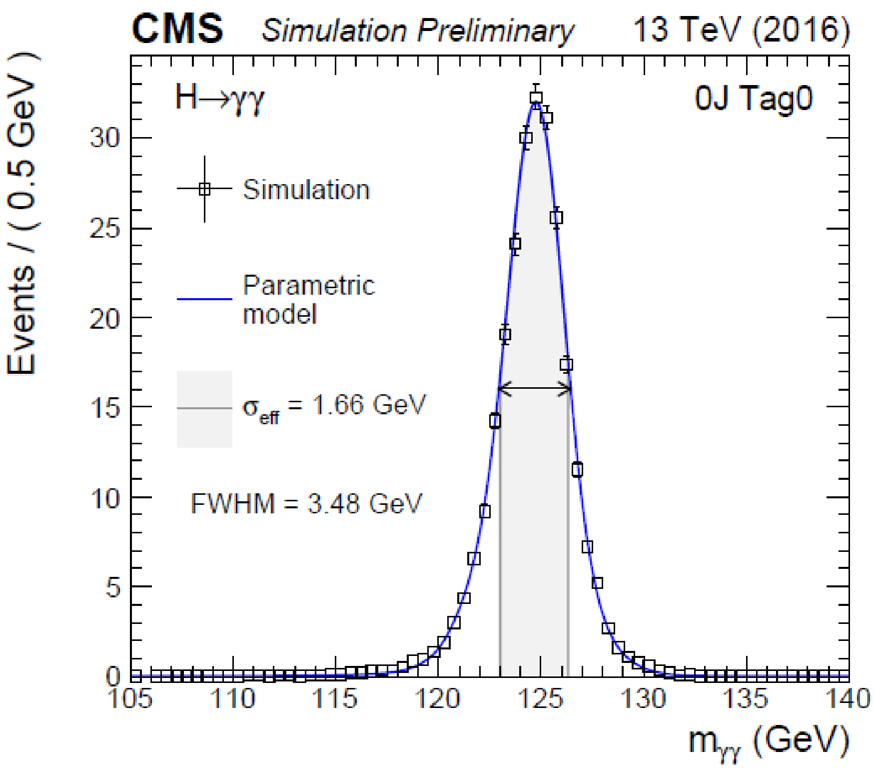


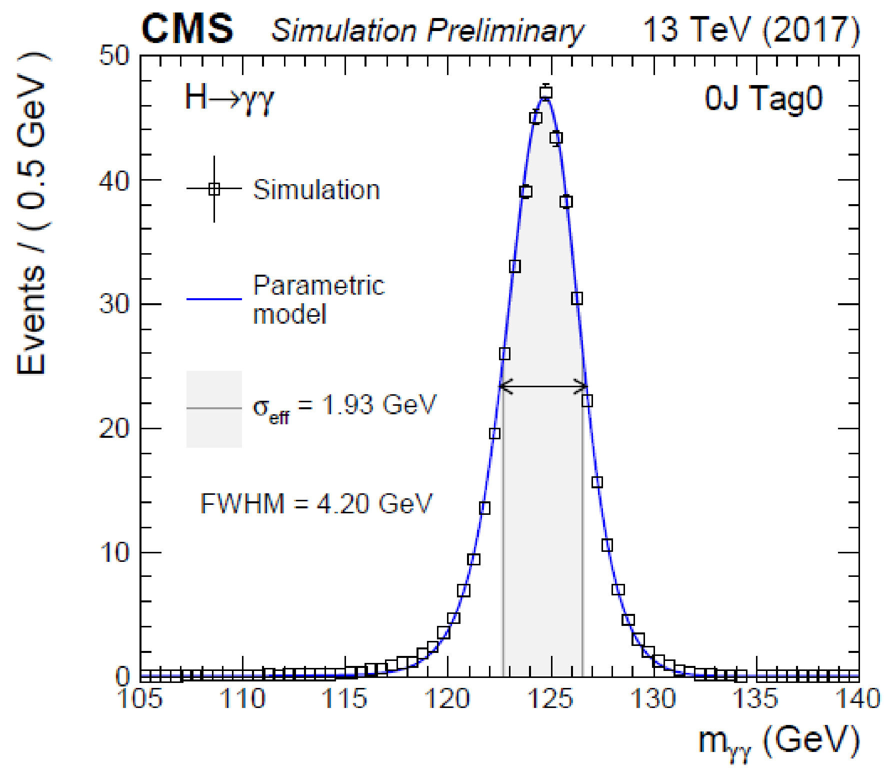
Impact on $H \to \gamma\gamma$

Calibration performed and assessed using $Z \to ee$ events

- lack of high energy standard candles decaying into photons
- need $e \to \gamma$ extrapolation → systematic uncertainty on $m_{H\to\gamma\gamma}$ measurement

≈ 1% $m_{\gamma\gamma}$ resolution achieved in best category after preliminary calibration



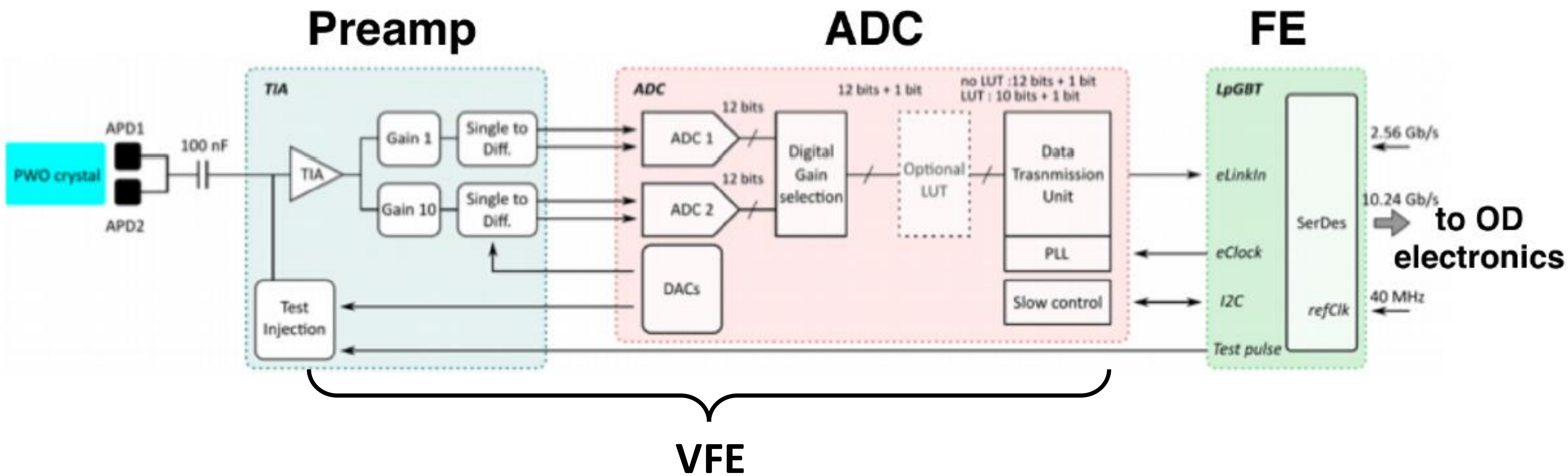


High-Luminosity (HL) LHC

Giant leap in instantaneous luminosity during HL-LHC → $\langle \mathrm{PU} \rangle \approx 200$

- particle reconstruction and correct assignment to primary interaction vertices will be a serious challenge for detectors → upgrade needed to maintain current performance

ECAL Barrel upgrade



Larger L1 trigger rate (750 kHz) and latency (12.5 μs) at HL-LHC

- 100 kHz and 4.2 μs up to Run 2
- need new faster (very-)front-end electronics → Trans-Impedance Preamplifiers (TIA)

Key point for upgraded VFE is reduction of signal shaping time

- mitigate OOT PU
- improve signal arrival time
- better discrimination of scintillation from anomalous signals in APD (spikes)

ECAL Barrel upgrade

Level-1 trigger data read in streaming towards off-detector electronics (FPGA processors)

- single-crystal granularity available at L1 (x25)

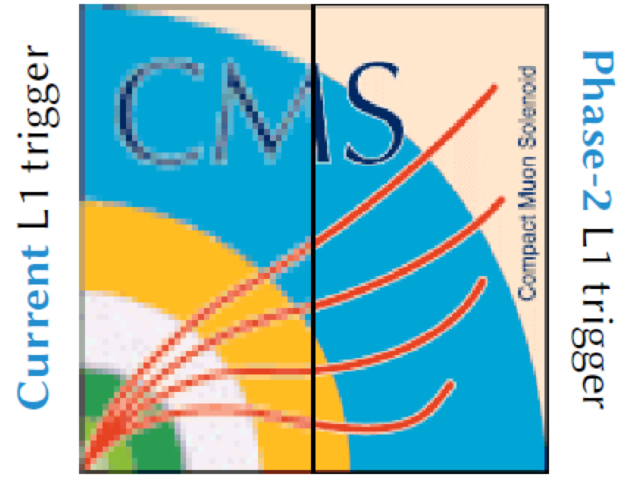
Sampling frequency at 160 MHz (was 40), pulse modeled with 20 samples (was 10)

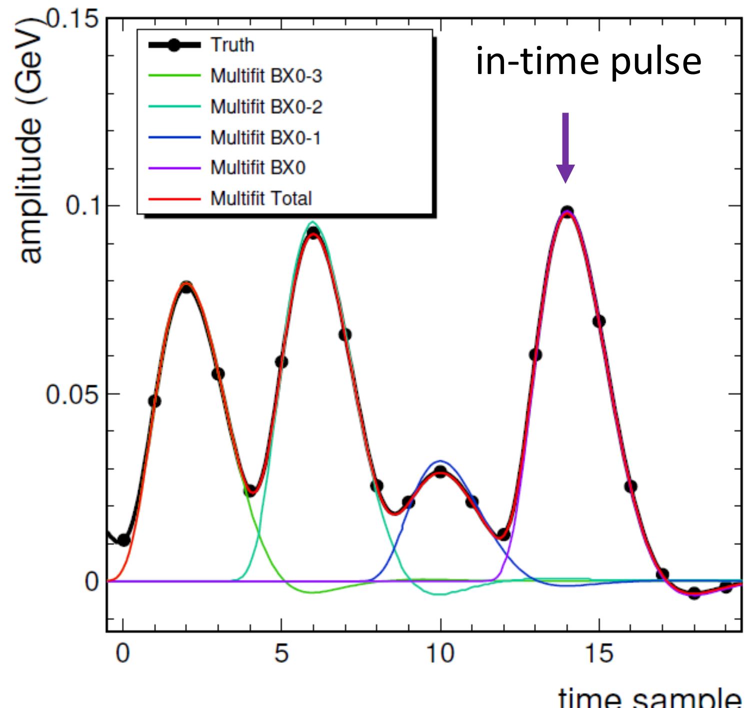
- mitigate OOT PU

Operate detector at 9° C (was 18° C) to limit radiation-induced APD noise

- also enhance light yield by 20%

Will preserve Run 2 energy resolution





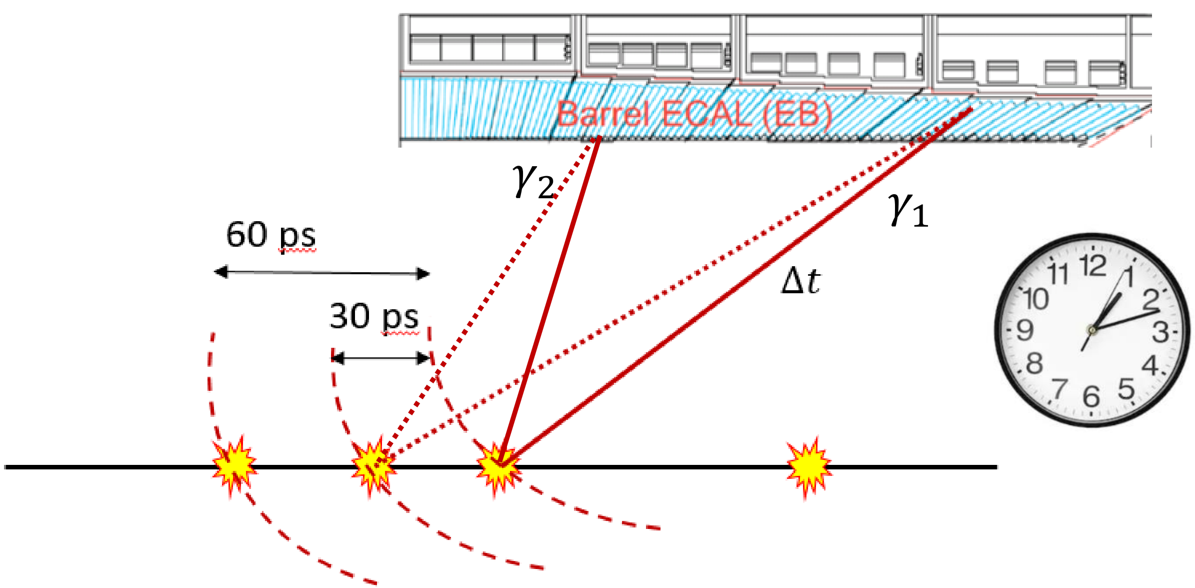
Timing and prospects for Higgs physics

$H \rightarrow \gamma\gamma$ vertex assignment relies on MVA techniques using tracks information

- 80% signal efficiency with $\langle PU \rangle \lesssim 40$, down to 30% with $\langle PU \rangle \approx 200$

Improved time tagging planned for EB during HL-LHC

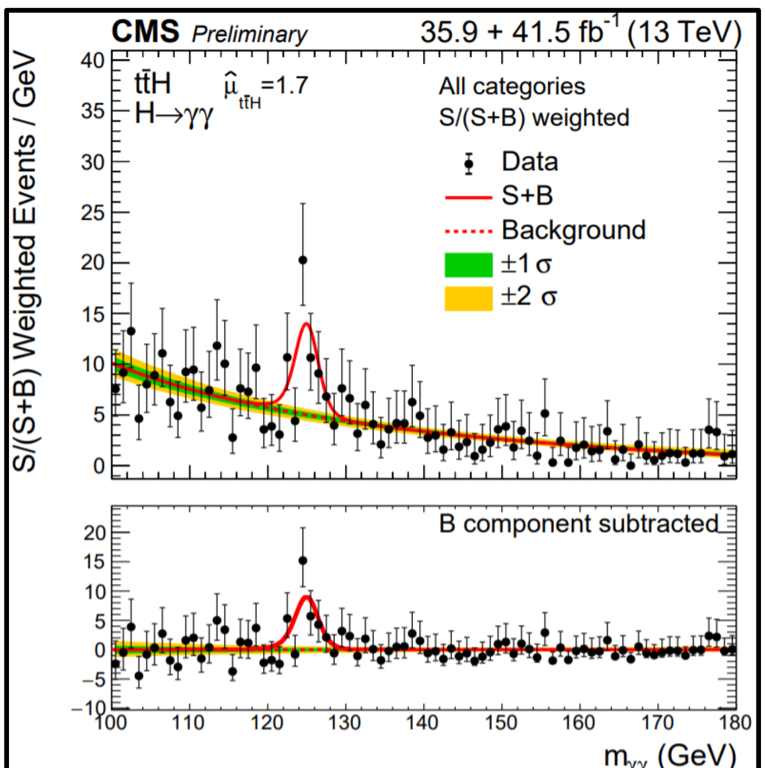
- lead to same effective PU as in Run 2
- 30 ps resolution can help identify correct vertex within 1 cm through triangulation
    - 10% improvement on $m_{\gamma\gamma}$ resolution compared to no timing



Exploring rare processes

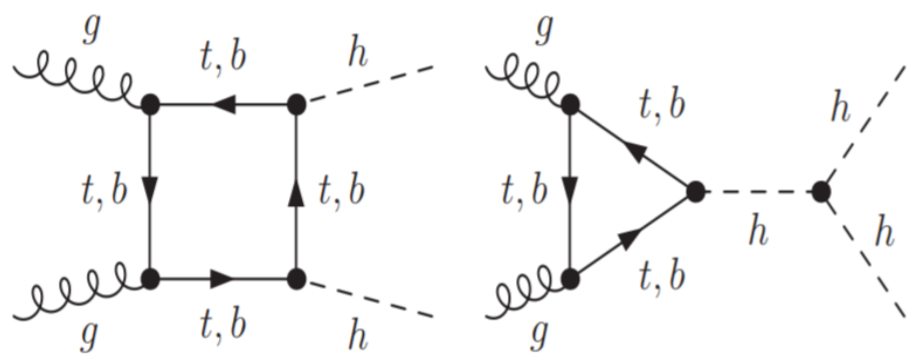
Many milestone results on the Higgs sector during Run 2

- observation of ttH production: https://arxiv.org/abs/1804.02610



About 3000 fb^{-1} expected at HL-LHC

- perform differential measurements
- enhanced sensitivity to rare processes: **Higgs pair production and self-coupling**



Tag through $HH \rightarrow b\bar{b}\gamma\gamma$ decay

- $\gamma\gamma$ → clean invariant mass peak
- $b\bar{b}$ → vertex tagging and highest BR

Summary

ECAL has shown excellent performance in photon reconstruction during Run 2

- fundamental for Higgs physics programme based on $H \rightarrow \gamma\gamma$ decays
- **recalibration of Run2 data ongoing**

HL-LHC will provide pp collisions with unprecedented intensity

- harsher data-taking conditions and several experimental challenges to deal with
- **ECAL upgrade necessary** to maintain same performance as in Run 1 and Run 2

Huge amount of data will be collected at HL-LHC

- perform differential measurements
- target rare processes: **Higgs pair production and self-coupling**
- quite interesting times ahead of us!

References

CMS experiment

- CMS Collaboration, "The CMS experiment at the CERN LHC", JINST 3, S08004 (2008)

CMS ECAL

- CMS Collaboration, "CMS: The electromagnetic calorimeter. Technical design report", CERN-LHCC-97-33, CMS-TDR-4

ECAL Detector performance plots

- CMS twiki: https://twiki.cern.ch/twiki/bin/view/CMSPublic/EcalDPGResults

The Phase-2 Upgrade of the CMS Barrel Calorimeters

- https://cds.cern.ch/record/2283187/files/CMS-TDR-015.pdf

Higgs physics public results from CMS

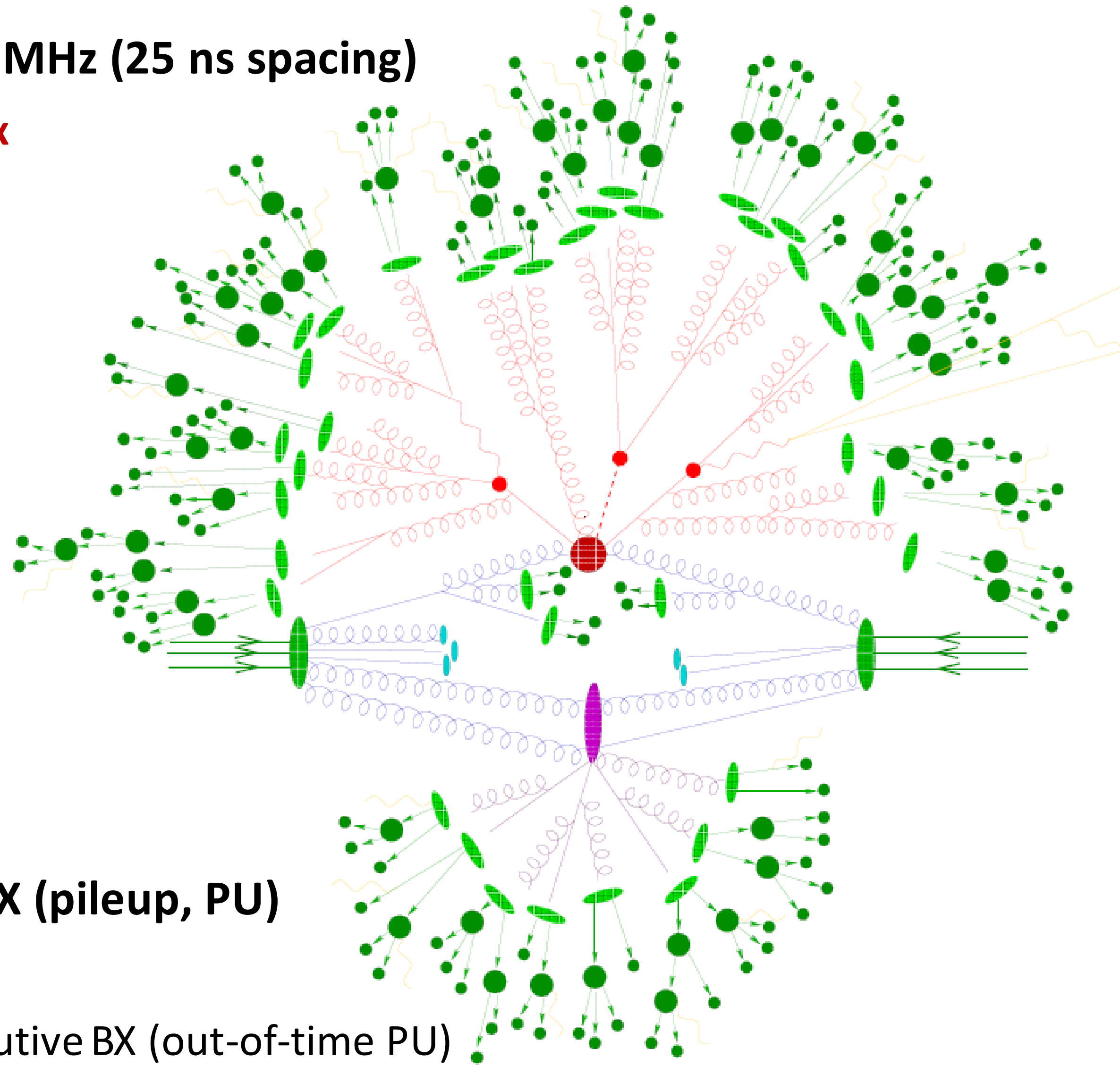
- preliminary
- published

BACKUP

Proton-proton collisions at the LHC

Bunch crossing (BX) rate of 40 MHz (25 ns spacing)

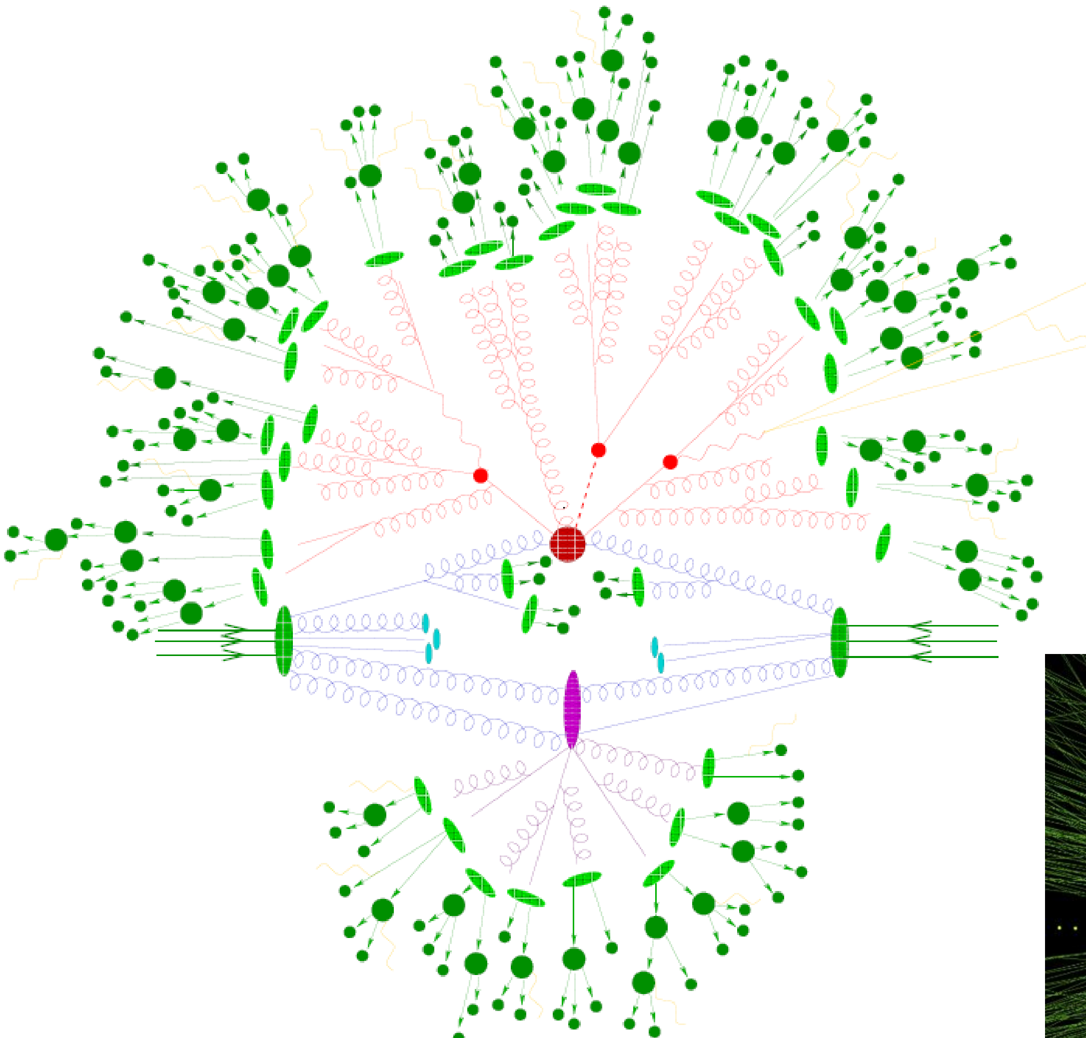
- primary hard scattering vertex
- second hard scattering vertex
- guark/gluon hadronization
- hadron decays
- beam remnants



Multiple pp interactions per BX (pileup, PU)

- $\langle PU \rangle \approx 40$ during Run 2
- energy overlap among consecutive BX (out-of-time PU)
- high detector granularity and good space-time resolution are paramount

Proton-proton collisions at the LHC



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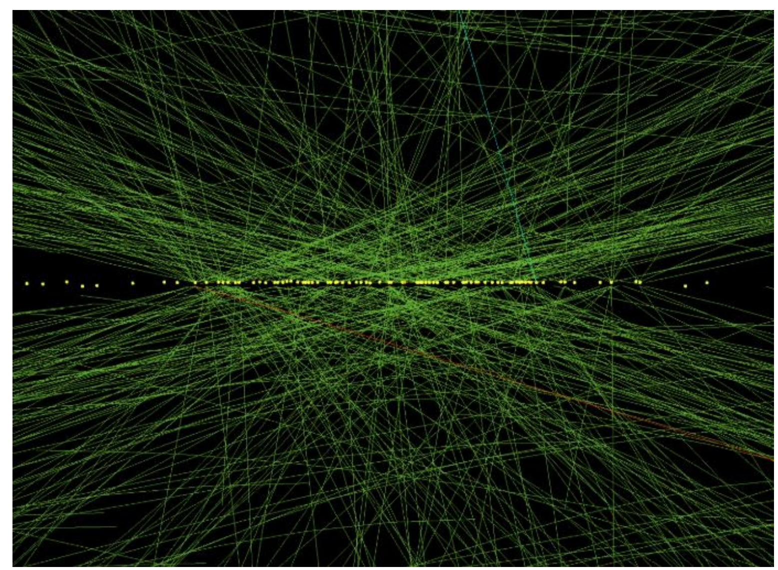
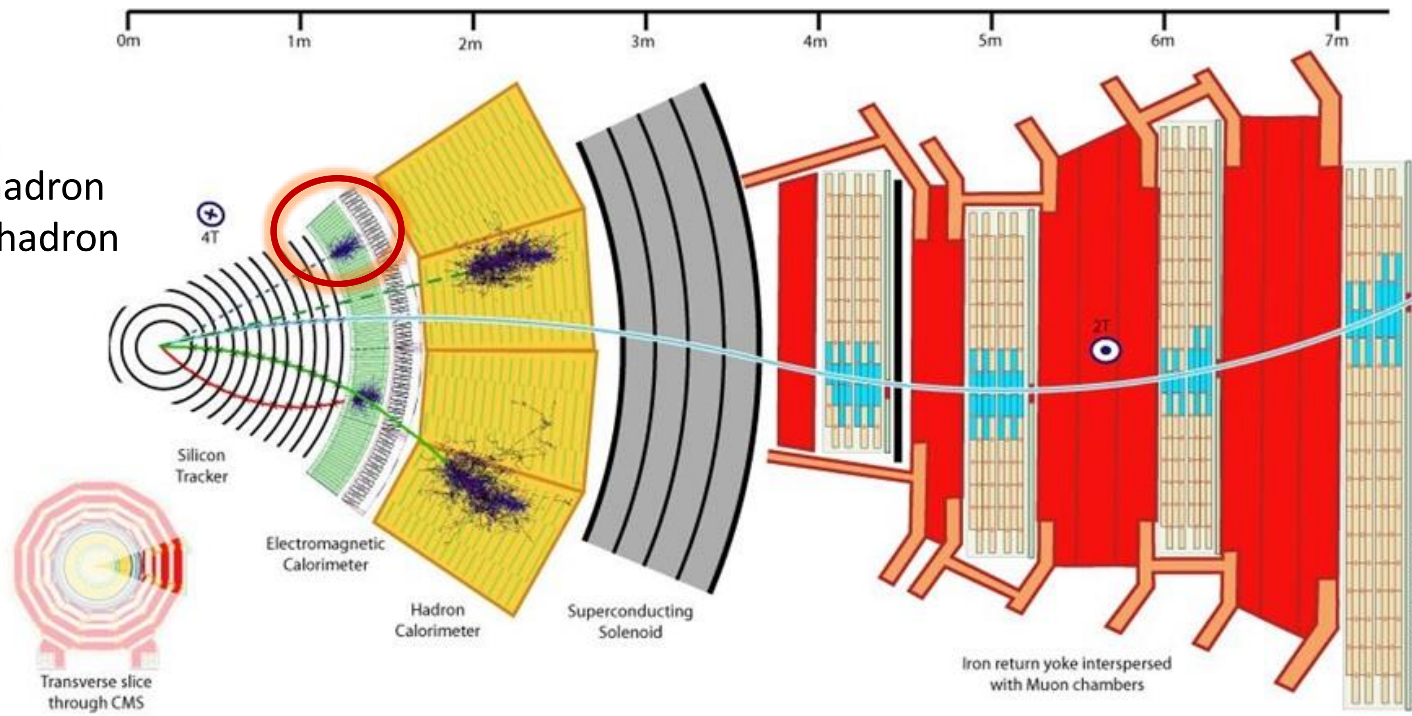


Particle reconstruction in CMS

- muon
- electron
- **photon**
- neutral hadron
- charged hadron

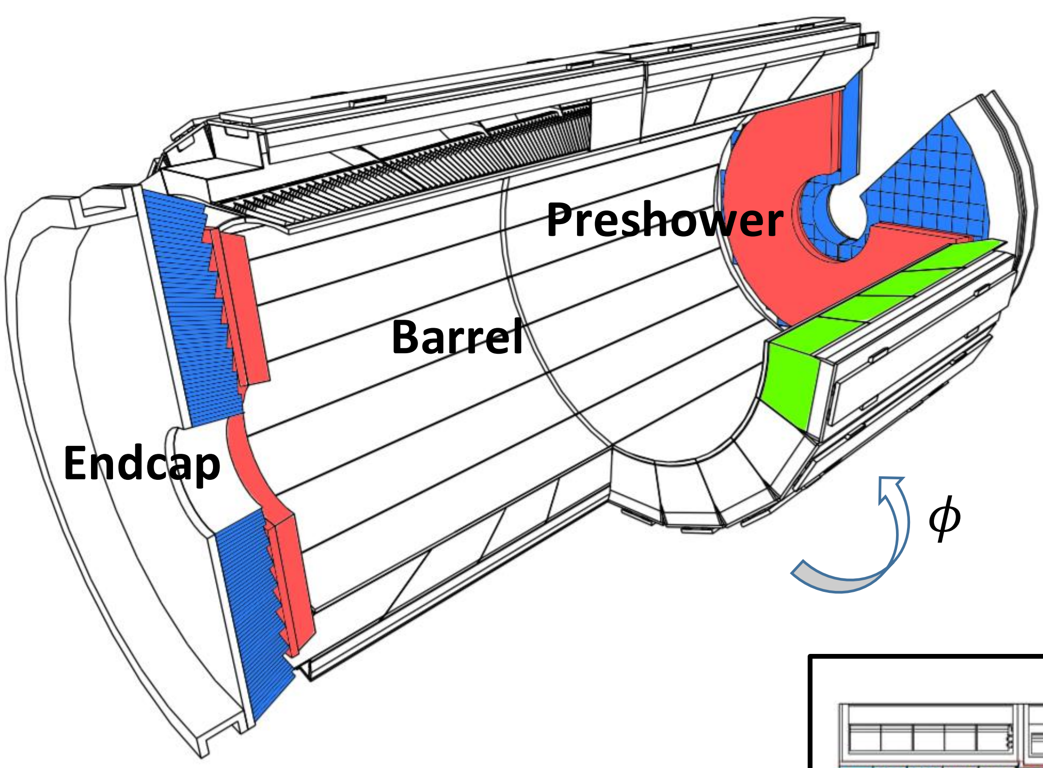


transverse plane:
⊥ to beam axis

Particle Flow (PF) algorithm for particles' identification

1. low-level information from all detectors (e.g. hits in tracker, deposits in calorimeters)
2. assemble into high-level detector objects (e.g. tracks, clusters)
3. combine to form physics objects: electrons, photons, muons

CMS electromagnetic calorimeter (ECAL)



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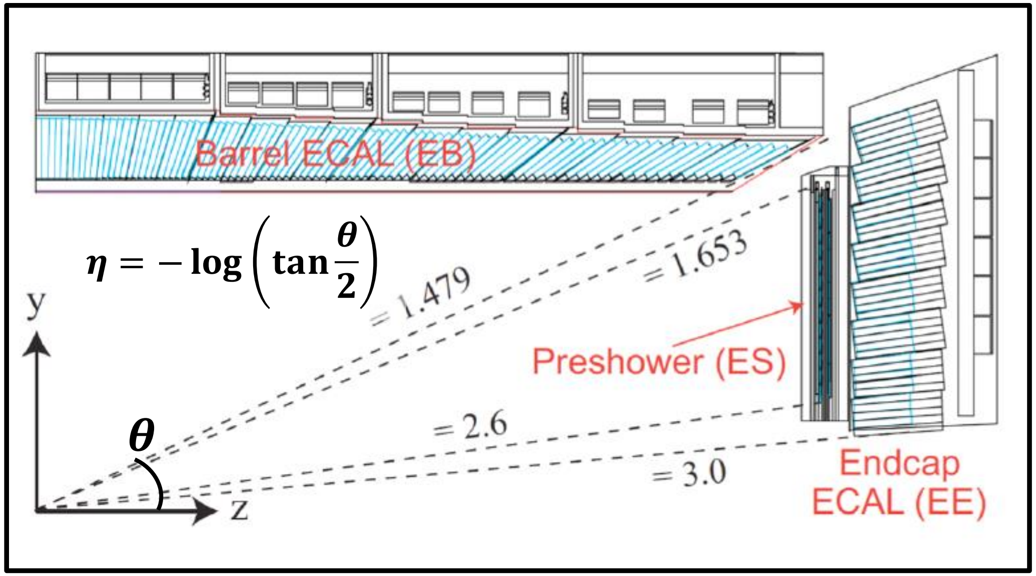
36 supermodules (SM), 4 modules each
$|\eta| < 1.48$

ENDCAP (EE): 14648 crystals
4 half disk Dees, 2 for each Endcap
$1.48 < |\eta| < 3.0$

PRESHOWER (ES):
4 Dees made of 2 Pb/Si planes
$1.65 < |\eta| < 2.6$

Tracker coverage: up to $|\eta|$ = 2.4

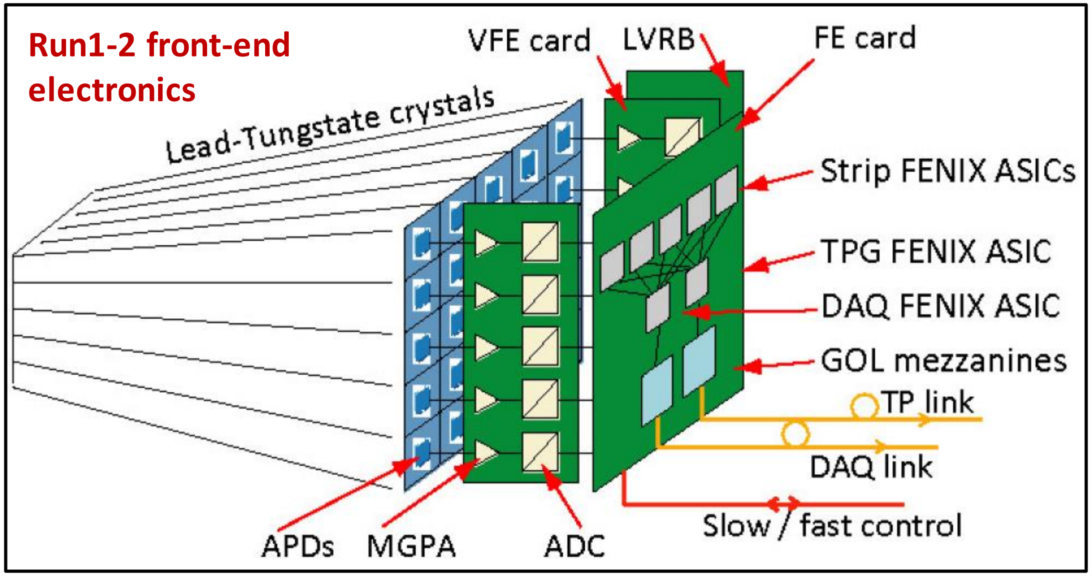
- $|\eta| < 2.4$: e/γ precision physics
- $|\eta| > 2.4$: jet physics



ECAL EB front-end electronics in Run2

Crystal light in EB collected by Avalanche Photodiodes (APD)

- very-front-end (VFE) card provides pulse amplification, shaping, and digitization
- 40 MHz sampling frequency



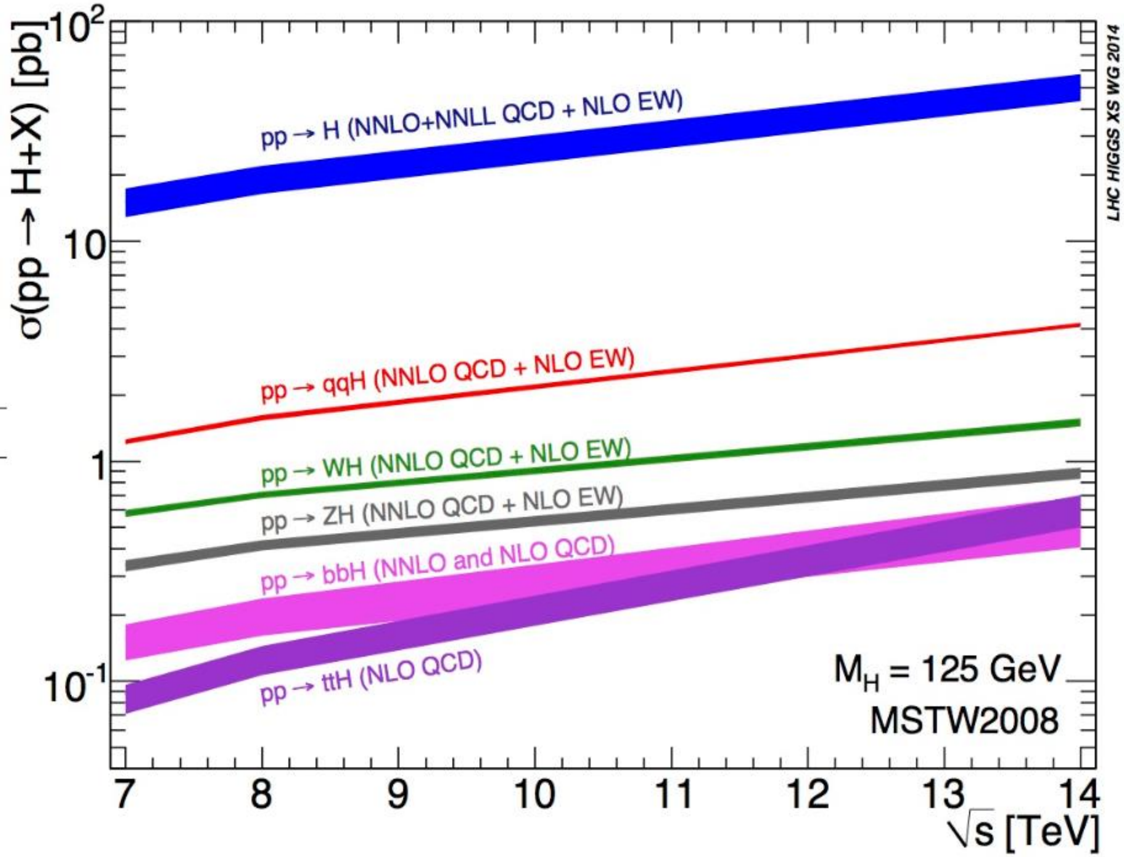
First trigger stage (Level-1) in Run1-2 made of on-detector hardware processors

- reduce rate from 40 MHz to 100 kHz with 4.2 μs latency
- trigger towers (TT) made of 5x5 crystals, managed by the same FE card

No by-crystal information available at L1

- anomalous signals from APD direct ionization (spikes) would saturate L1 rate at HL-LHC

Higgs production cross section



Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.28×10^{-3}	$^{+5.0\%}_{-4.9\%}$
$H \to ZZ$	2.64×10^{-2}	$^{+4.3\%}_{-4.1\%}$
$H \to W^+W^-$	2.15×10^{-1}	$^{+4.3\%}_{-4.2\%}$
$H \to \tau^+\tau^-$	6.32×10^{-2}	$^{+5.7\%}_{-5.7\%}$
$H \to b\bar{b}$	5.77×10^{-1}	$^{+3.2\%}_{-3.3\%}$
$H \to Z\gamma$	1.54×10^{-3}	$^{+9.0\%}_{-8.9\%}$
$H \to \mu^+\mu^-$	2.19×10^{-4}	$^{+6.0\%}_{-5.9\%}$

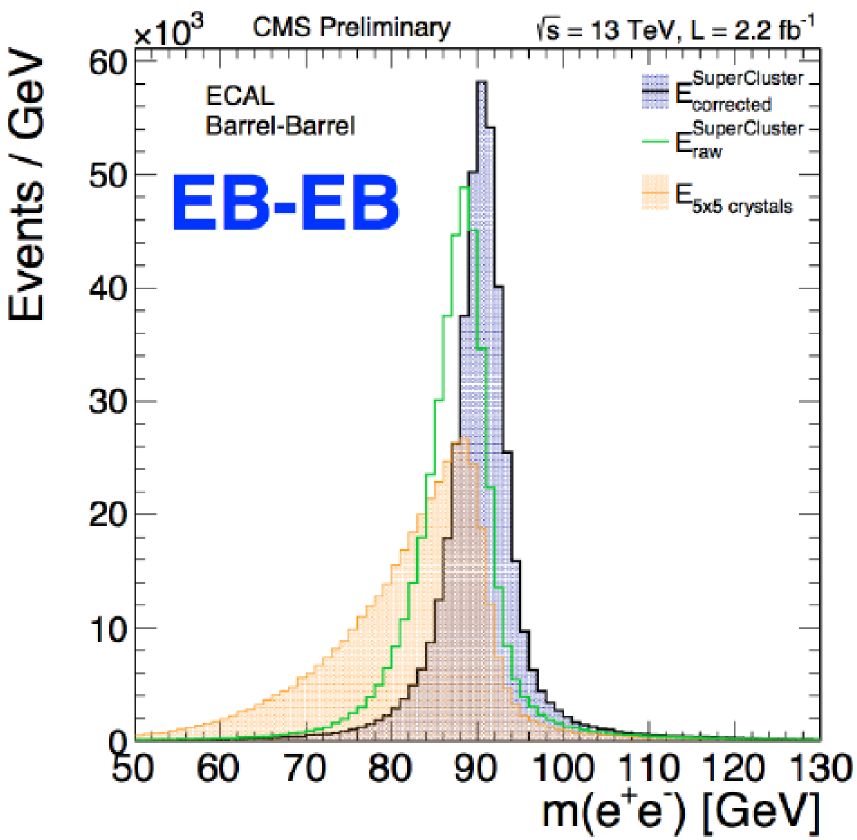
Very low cross section compared to other processes at the LHC

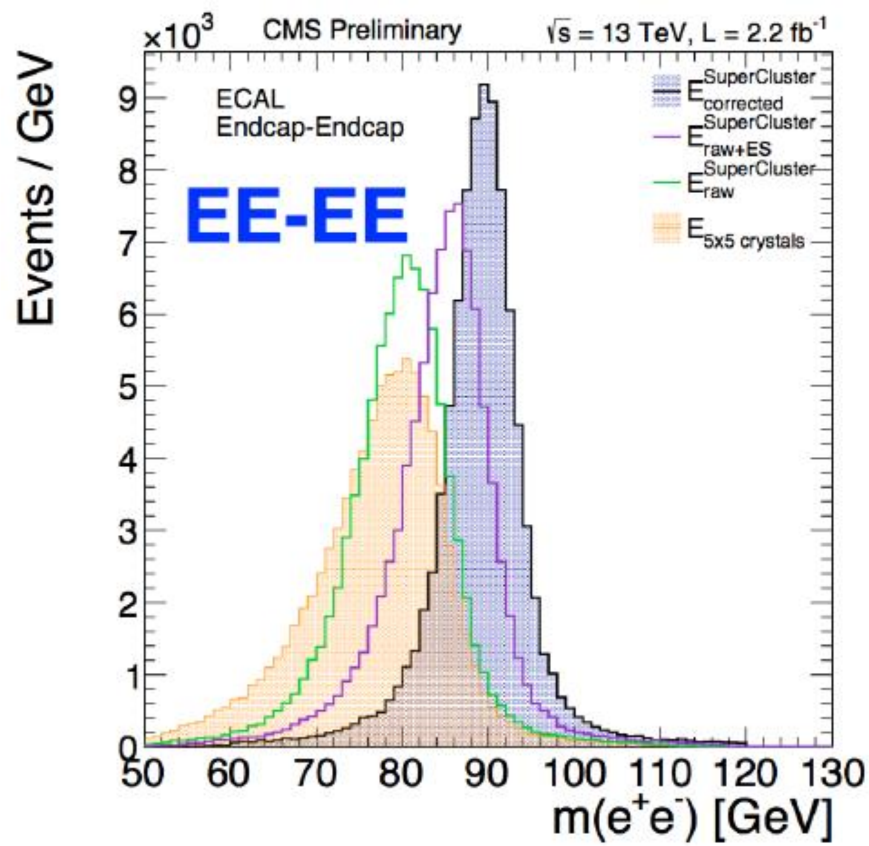
- need a huge amount of data and high signal efficiency and background rejection

Cluster energy reconstruction

Recostruction based on SC performs bettern than using simple 5x5 matrices

- MVA regression further improves energy scale and resolution

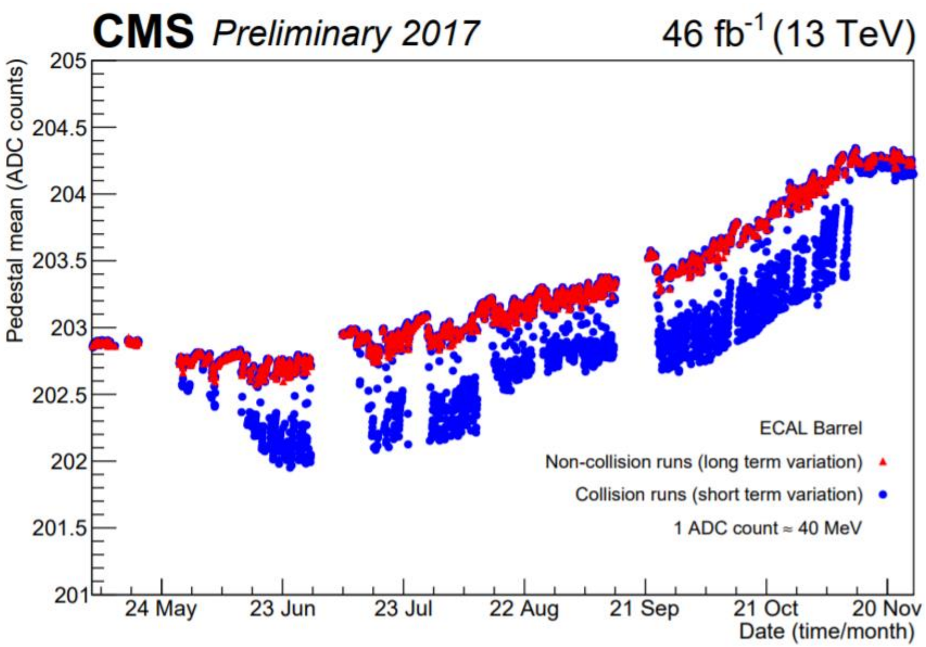


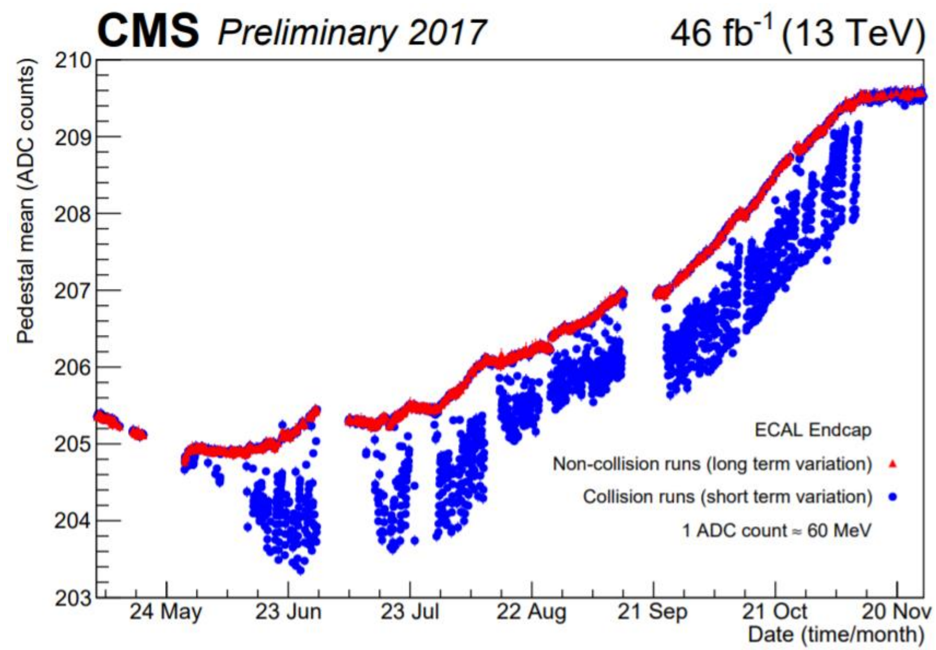


Pedestals versus time

ECAL signal is readout with a multi gain ADC (gain 12, 6, and 1). Energy deposits up to about 150 GeV are read with gain 12.
Gain 12 pedestals mean history in EB (left) and EE (right) for 2017 is shown below

A long-term, monotonic drift upwards is visible. In the short term (in-fill) luminosity related effects are visible. Short term variations are smaller when the LHC luminosity is lower (e.g. in August with respect to July). In November, when LHC produced heavy-ions collisions at low luminosity, in-fill effects almost vanish. Long term drift depends on integrated luminosity, short term effects depend on instantaneous luminosity.





ECA energy resolution in Run 2

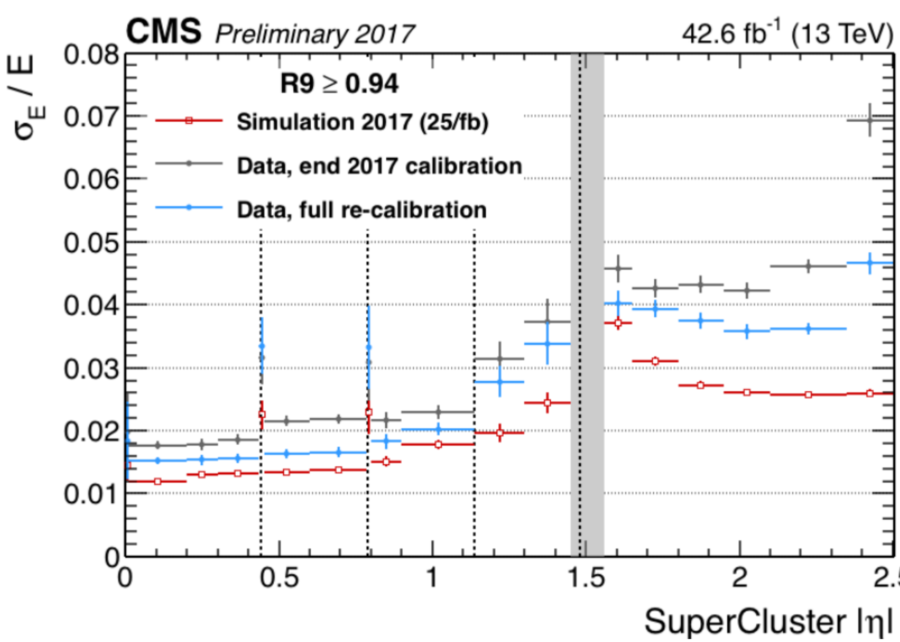
Resolution derived for both showering (low R_9) and non-showering electrons (high R_9)

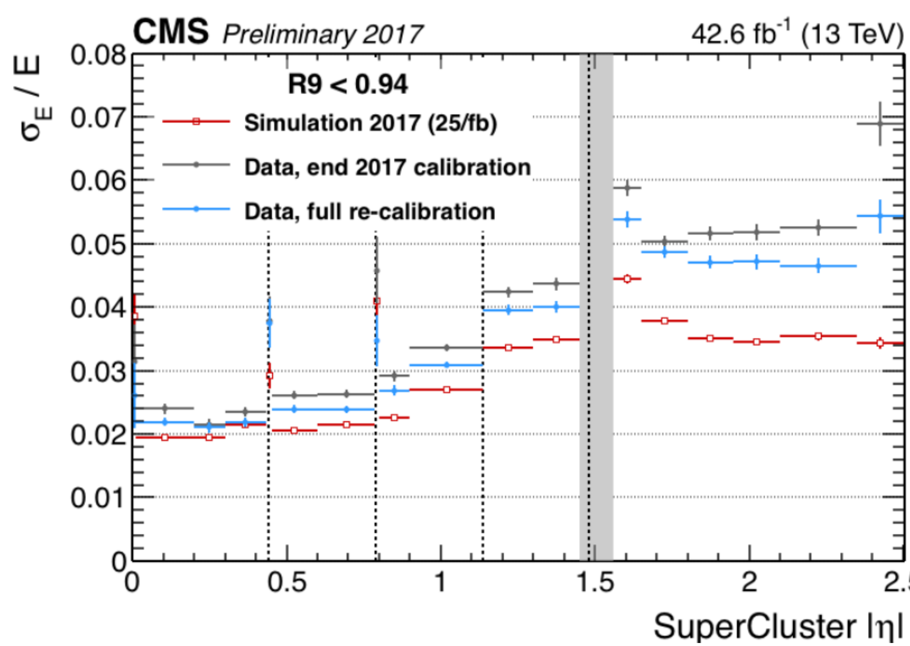
$\mathbf{R_9 = E_{3x3}/E_{SC}}$ **shower shape variable**

$\mathbf{E_{SC}}$: energy of the supercluster (SC)

$\mathbf{E_{3x3}}$: energy in matrix of 3x3 crystals around the most energetic one in the SC

If electrons do not emit bremsstrahlung photons, most of energy reconstructed inside 3x3 crystals

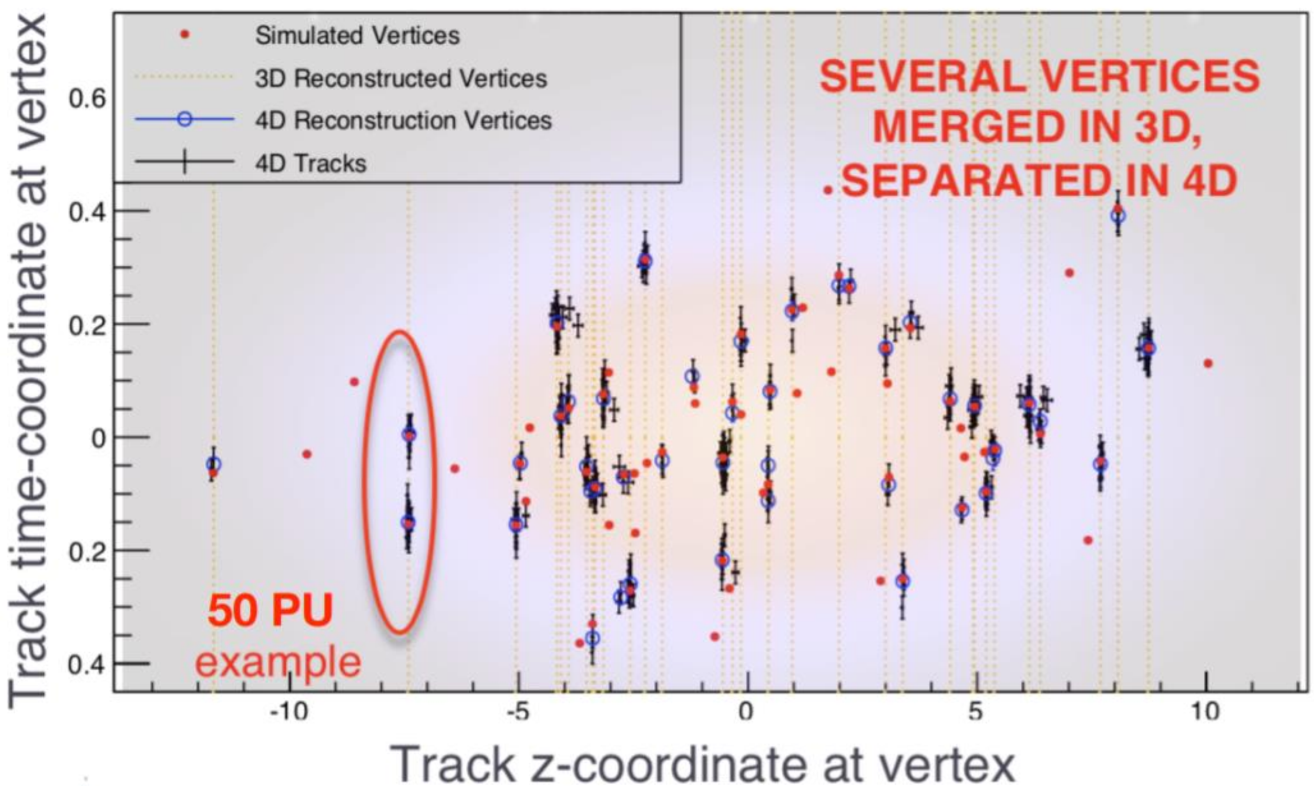




ECAL upgrade for HL-LHC

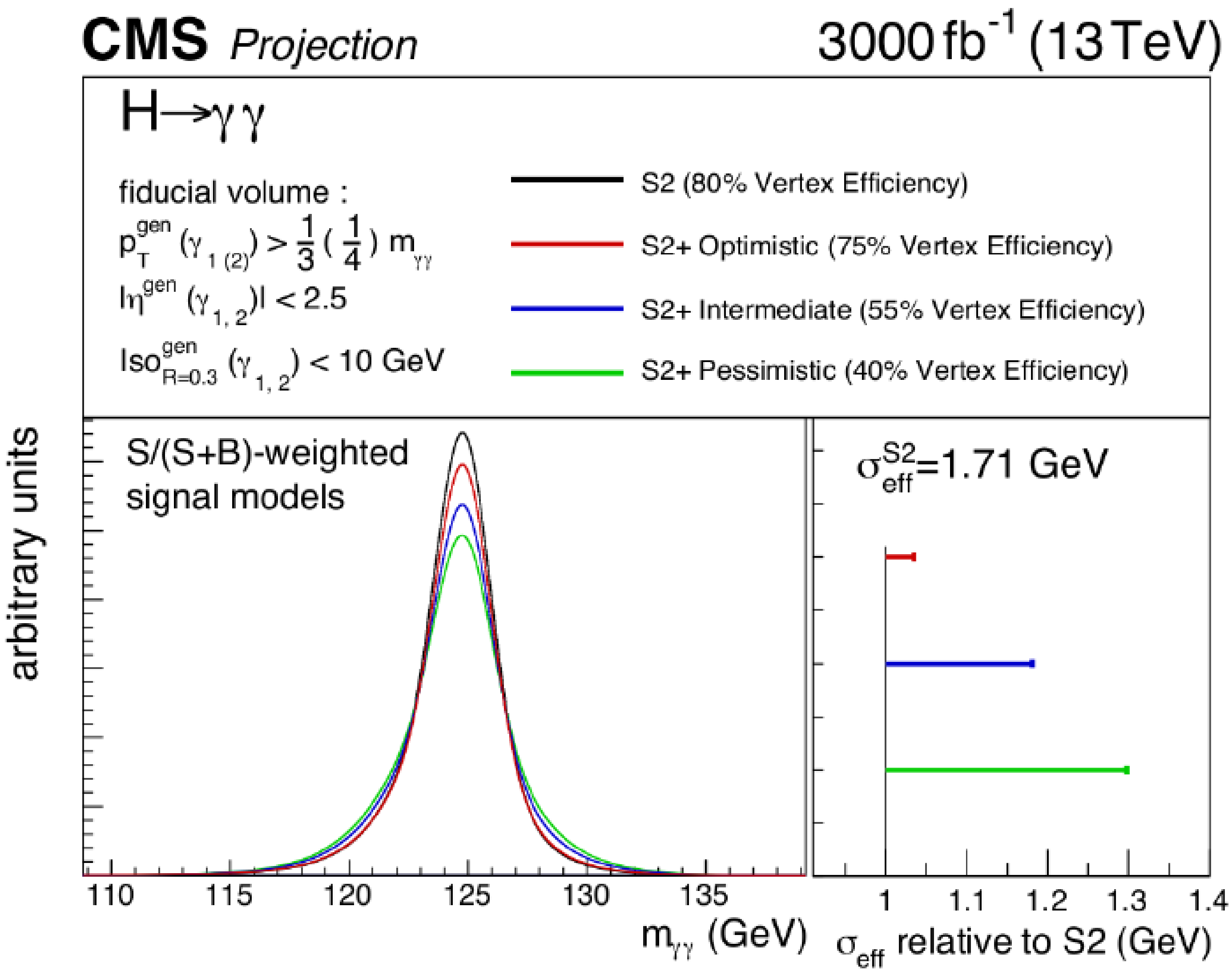
Two major ECAL upgrades planned during HL-LHC (not covered in this talk)

- EE replaced with brand-new High-Granularity Calorimeter (HGCAL)
- new MIP timing detector with 30 ps resolution installed in front of EB
    - time tagging of minimum ionizing particles (MIP) provides further discrimination of interaction vertices in same 25 ns bunch crossing beyond spatial tracking algorithms
    - hold promise to recover a track purity of vertices similar to current LHC conditions



Impact of timing on $H \to \gamma\gamma$

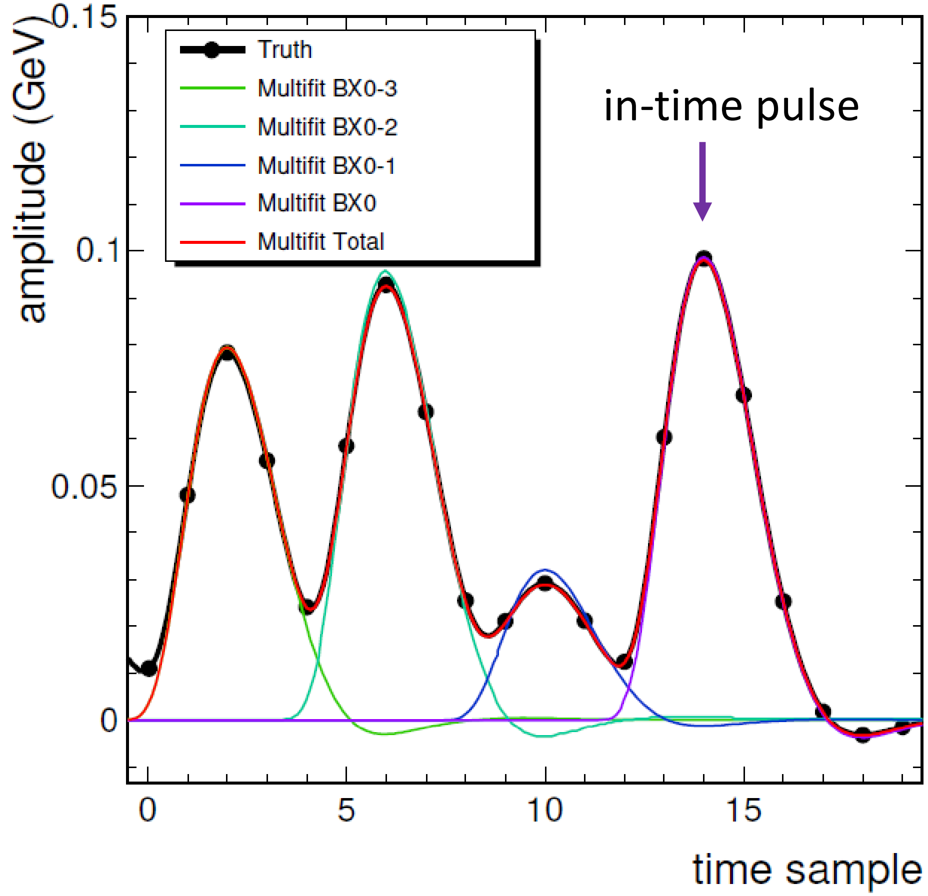
Run 2 baseline | no timing | precise timing in ECAL | precise timing for MIP (dedicated detector)



Amplitude reconstruction at HL-LHC

The readout of an ECAL channel is a set of amplitude samples

- 10 samples during Run 2 (40 MHz sampling frequency)
- pulse reconstruction at HL-LHC through multifit algorithm, just as in Run2



Larger OOT PU mitigated with increased sampling frequency

- e.g. using 20 samples
- also help suppress anomalous signals (spikes), which are only slightly earlier than physics signals

Spikes rejection at HL-LHC

Spikes are anomalous signals from hadrons ionizing in the APDs

- would saturate L1 trigger bandwidth at HL-LHC

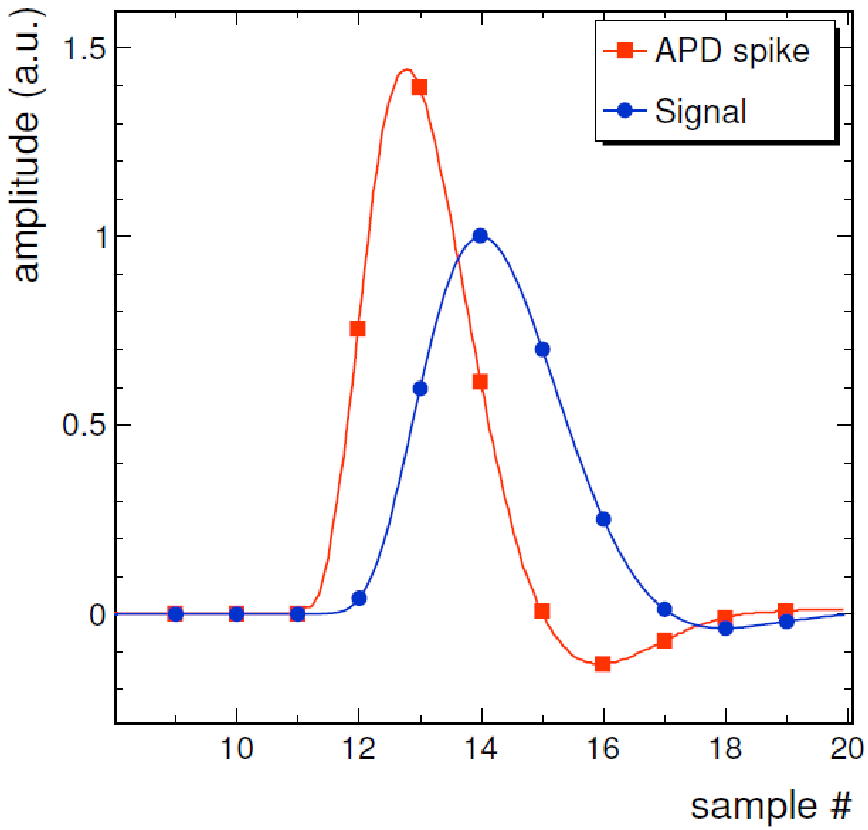
Spikes produce slightly earlier signals

- no light collection → faster rise time

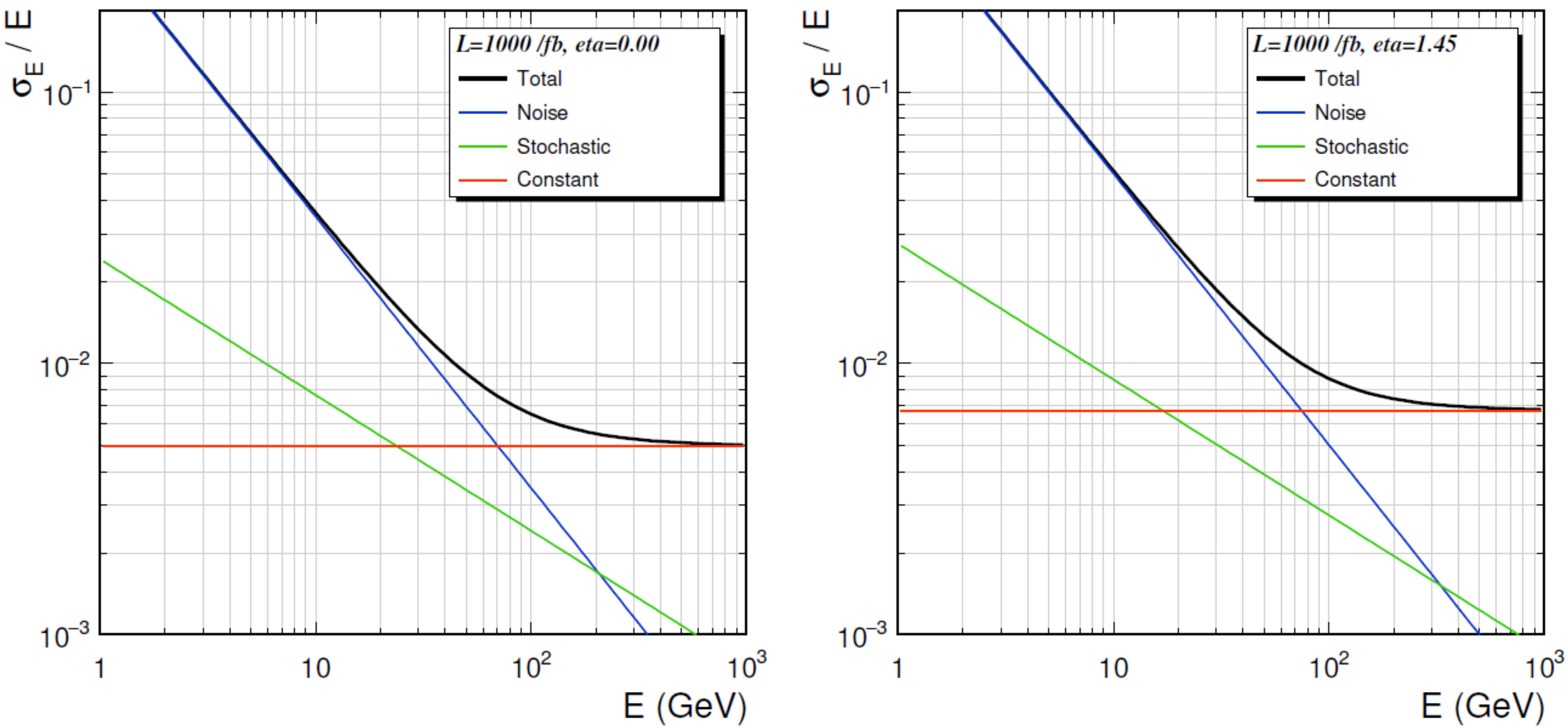
Can be better identified with increased sampling frequency

At HL-LHC, L1 trigger data processed by faster off-detector electronics

- exploit x25 granularity for better spike indentification and rejection



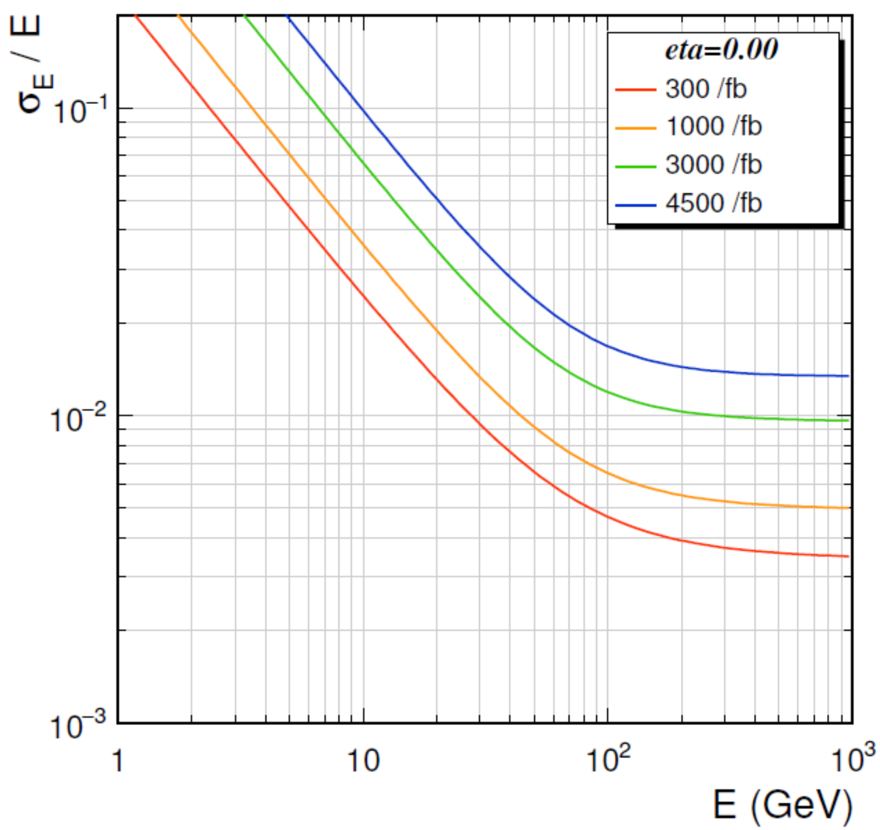
Energy resolution at HL-LHC

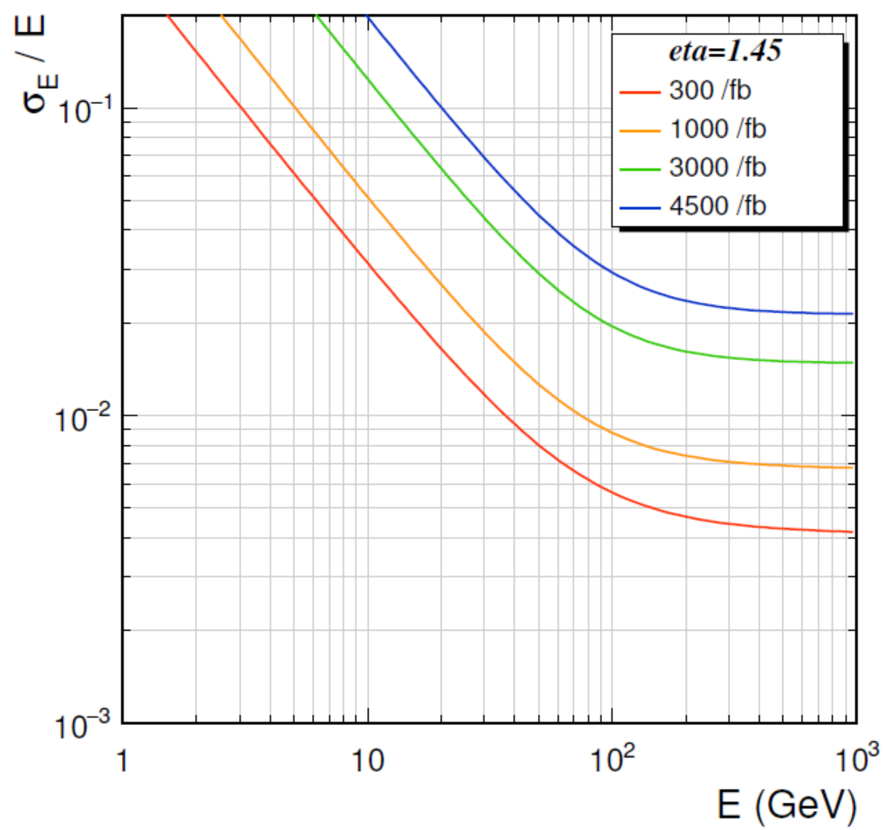


Assuming electromagnetic shower contained in 3x3 matrix of ECAL crystals

- showing contribution of each term of energy resolution

Evolution of energy resolution at HL-LHC





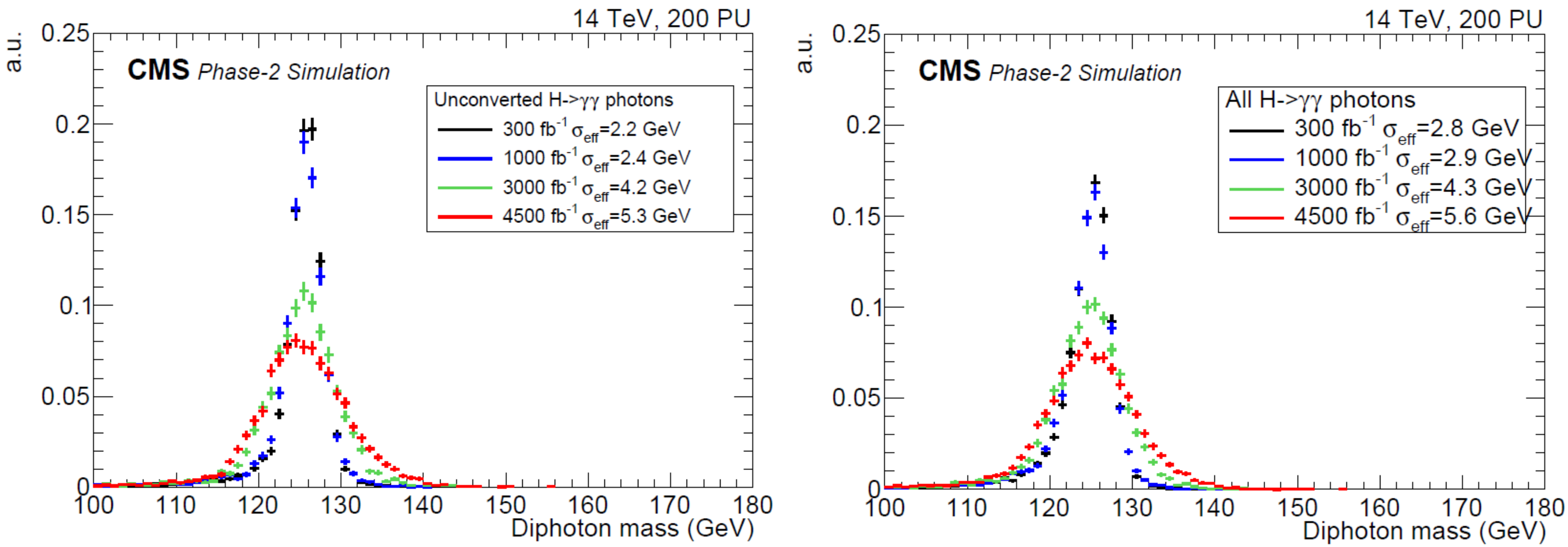
Assuming electromagnetic shower contained in 3x3 matrix of ECAL crystals

- showing resolution for different integrated luminosity scenarios

$H \to \gamma\gamma$ resolution at HL-LHC

Resolution expected to degrade with time due to detector radiation damage

- (partially) compensated with calibration and improved reconstruction algorithm
- better performance for unconverted photons



photon energy shown here calculated as sum of energy in 15 highest energy ECAL crystals in standard photon object

- better performance expected with proper reconstruction and detector upgrade

HH at HL-LHC

Search for HH performed in Run 2

- $HH \rightarrow b\bar{b}\gamma\gamma$ most sensitive channel
- no signal observed (CMS-HIG-17-030)
- need full HL-LHC statistics