Prospects for a precision timing upgrade of the CMS PbWO crystal electromagnetic calorimeter for the HL-LHC

5th October 2017

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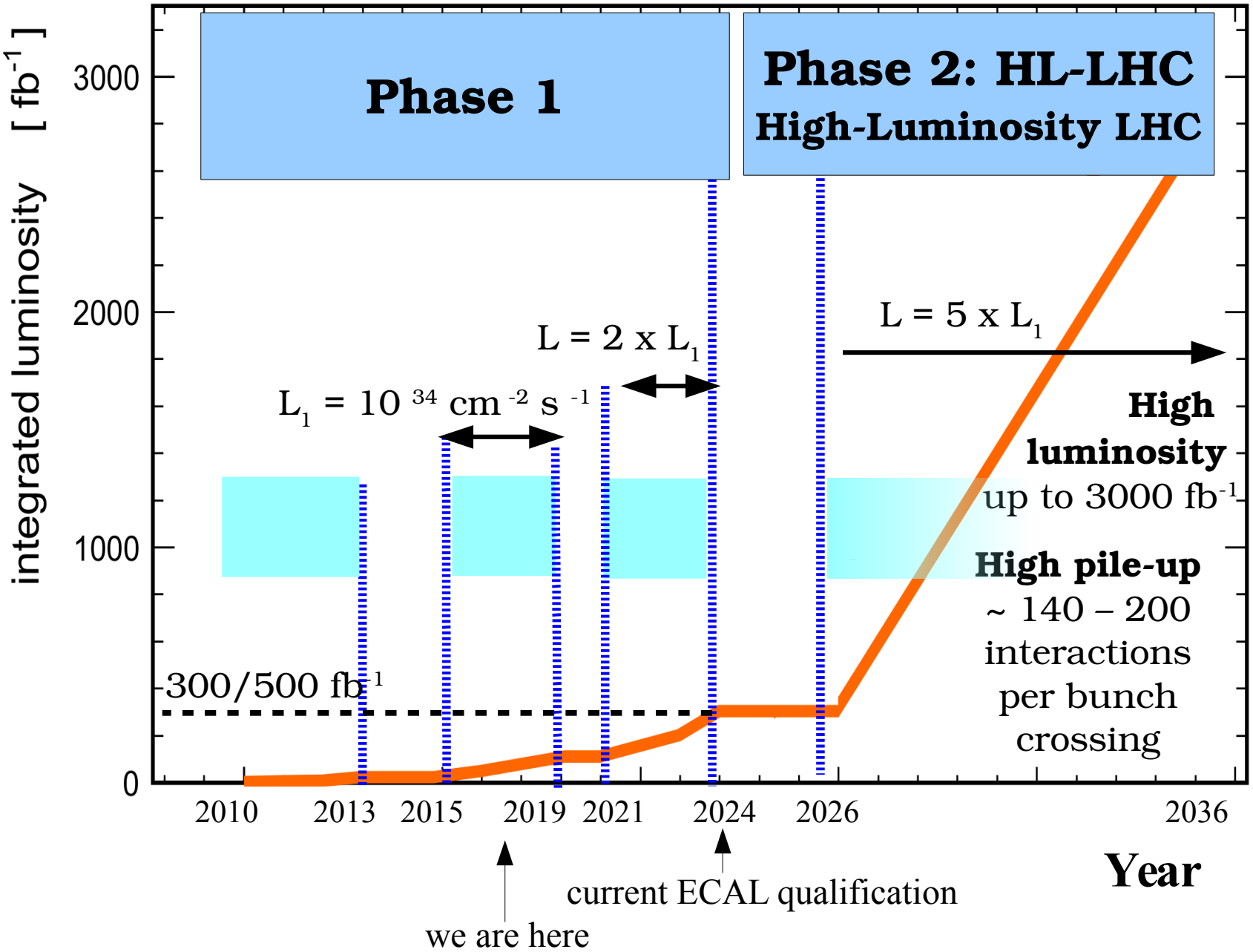
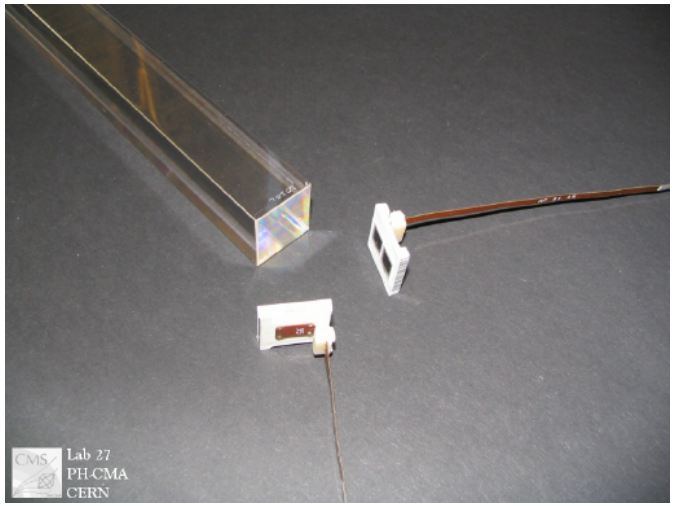
(Northeastern University)
on behalf of the CMS collaboration

The High-Luminosity LHC: HL-LHC



Present ECAL in a glance



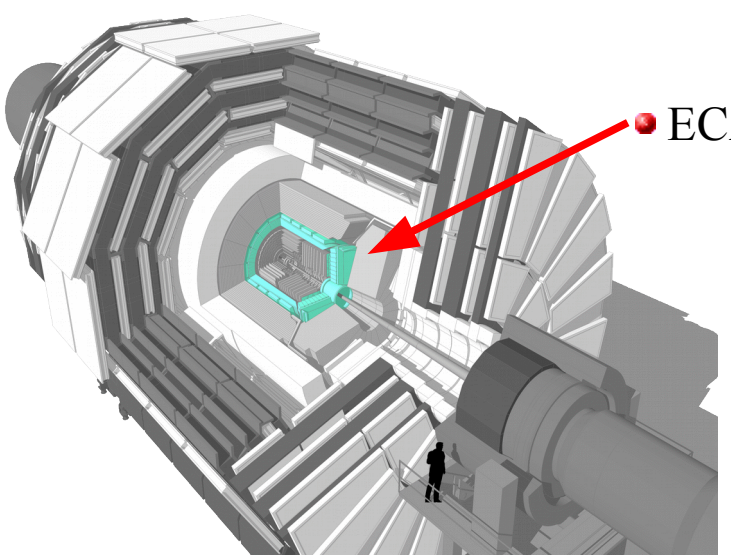
- The **Electromagnetic Calorimeter** of CMS (ECAL)
  - Homogeneous, compact, hermetic, fine grain $PbWO_4$ crystal calorimeter
  - Goal is excellent energy resolution

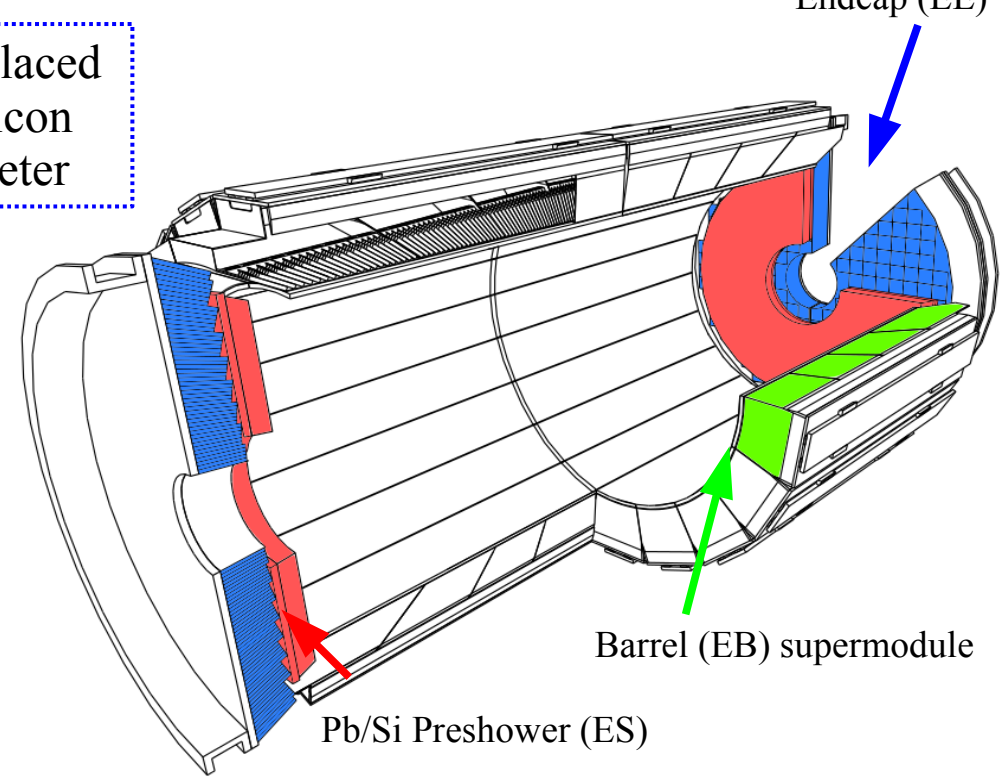
Performance of the CMS precision electromagnetic calorimeter at the LHC Run II and prospects for high-luminosity LHC by Zhicai Zhang

Electronics to be replaced

- **Barrel**: $|\eta| < 1.48$, **APD** readout, **61200** crystals
- **Endcap**: $1.48 < |\eta| < 3.0$, VPT readout
- **Preshower**: $1.65 < |\eta| < 2.6$

To be replaced with silicon calorimeter





ECAL Barrel Upgrade @ HL-LHC

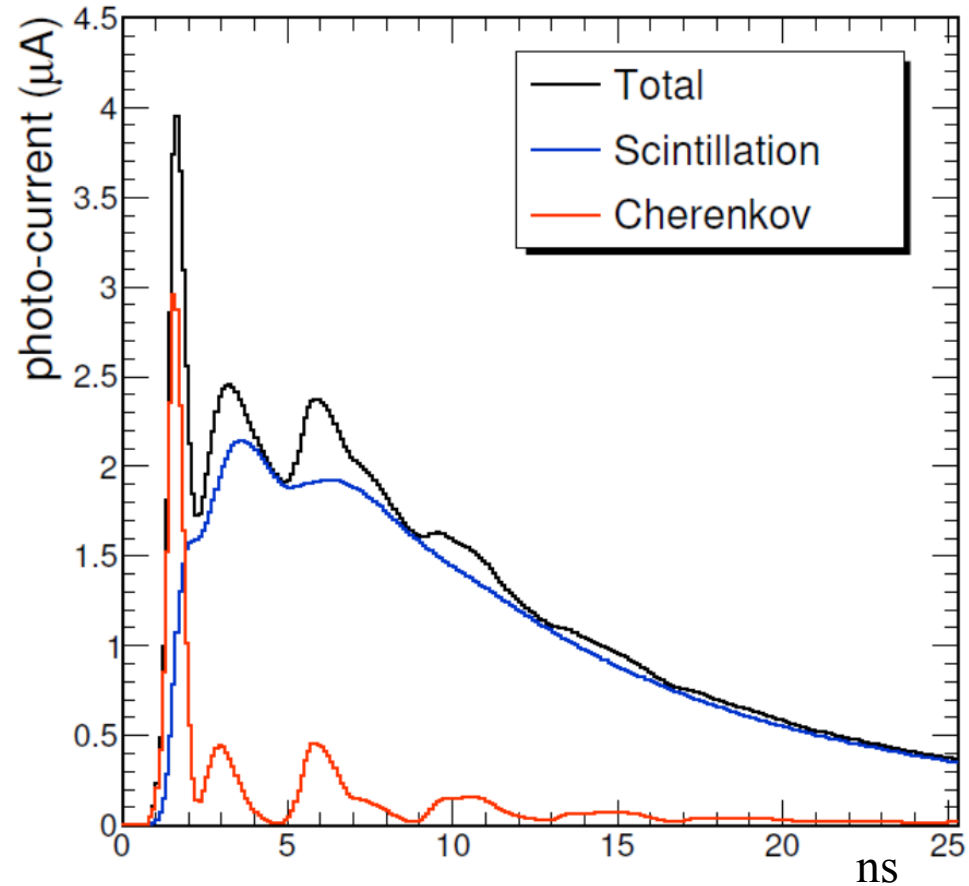
- **Trigger**
  - Accommodate HL-LHC **trigger** requirements
  - Provide **1x1 crystal info** to **trigger** instead of present 5x5. Better isolation and also better spike rejection

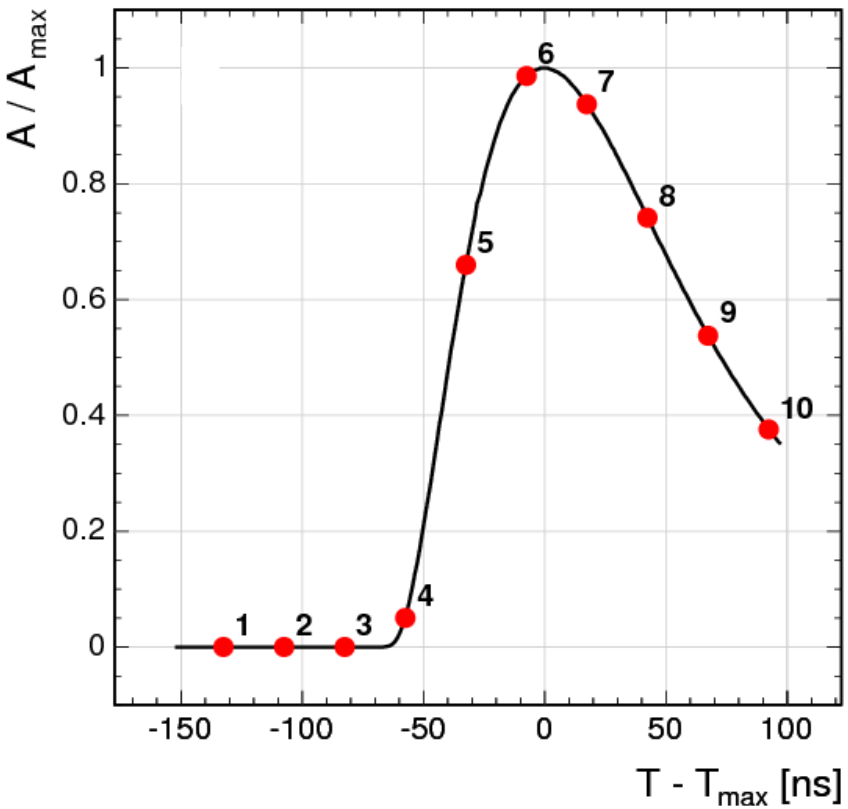
	Max Level 1 Accept Rate	Max Latency
ECAL Phase 1	100 kHz	6.4 μs
Trigger Phase 2	750 kHz	12.5 μs

- **Energy resolution**
  - **Cool photodetectors** and **crystals** (18→ 9° C) to reduce increase noise in APD due to radiation damage
- **Time resolution**
  - Change **pre-amp** for more optimal noise filter and 30 ps timing @50 GeV to suppress spikes and pileup and improve physics performances

The crystals and the present readout

- Original design requirements on ECAL timing to ensure good **energy resolution**: 0.1% energy stability in reconstruction for **1 ns**
- $PbWO_4$ is a **fast** scintillator
  - 90% of light within **25 ns**
  - **~10%** contribution from **Cherenkov**

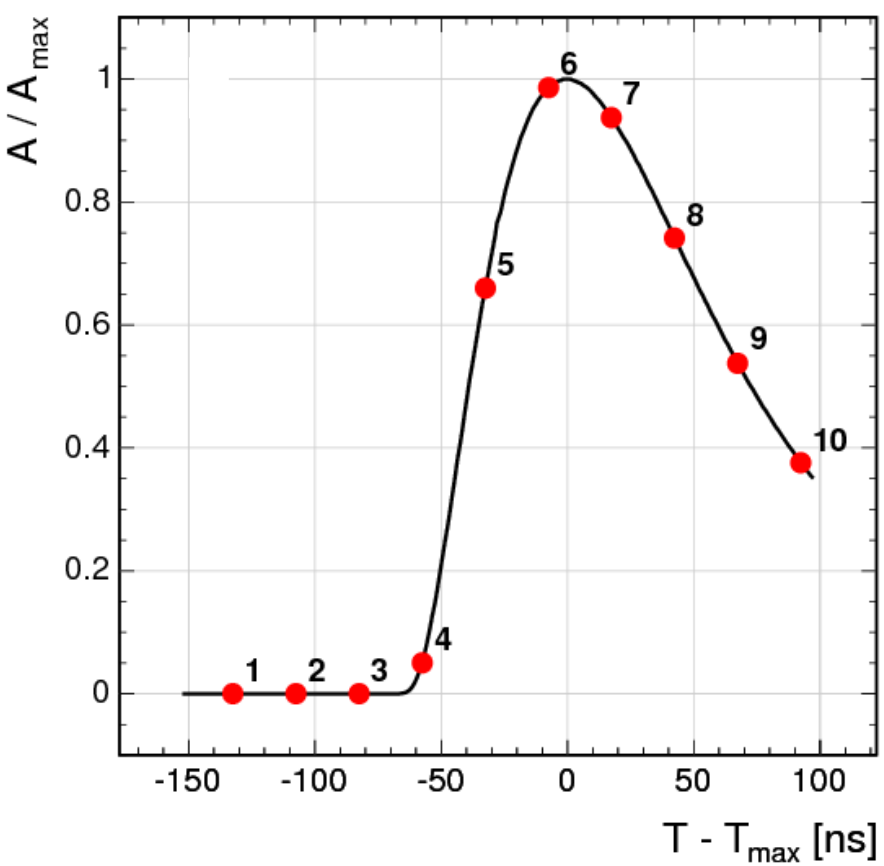


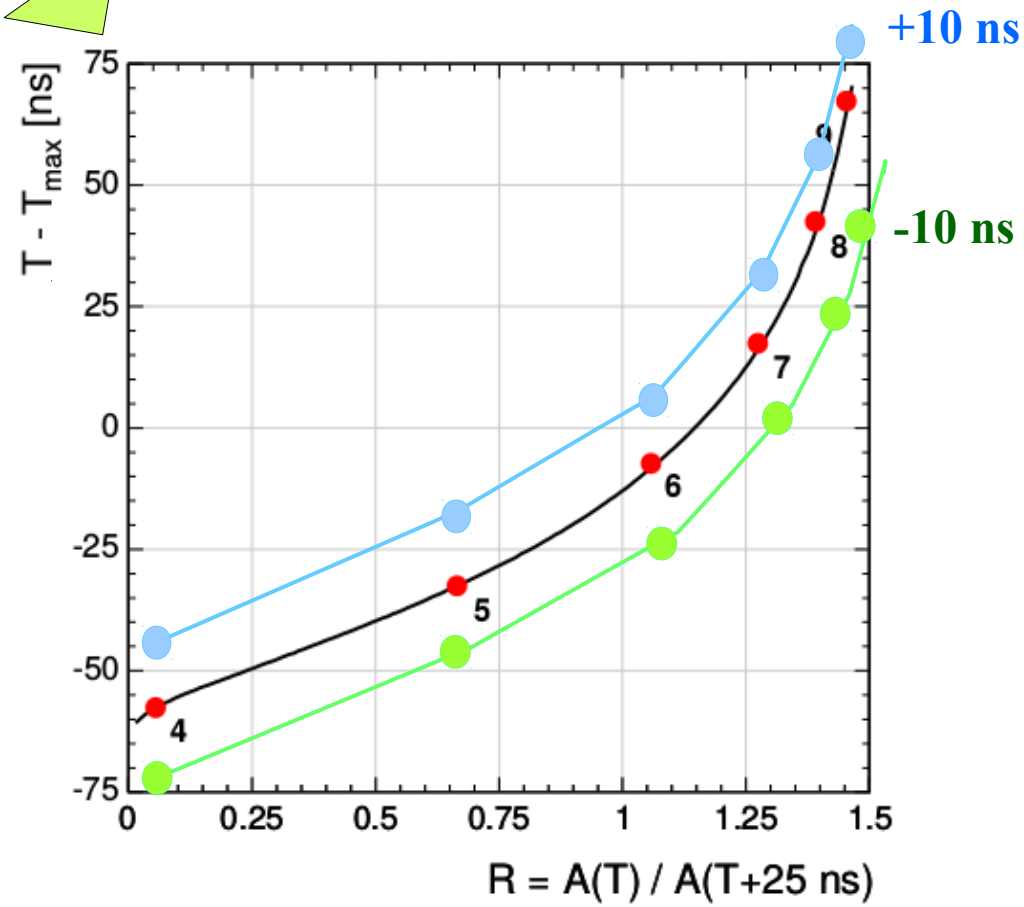


- Current pulse: optimized for LHC, different conditions for HL-LHC
  - 43 ns electronics CR-RC shaping time
  - sampling at 40 MHz → one sample every 25 ns
- Using assumption about **pulse shape** to derive time information

What time is it?

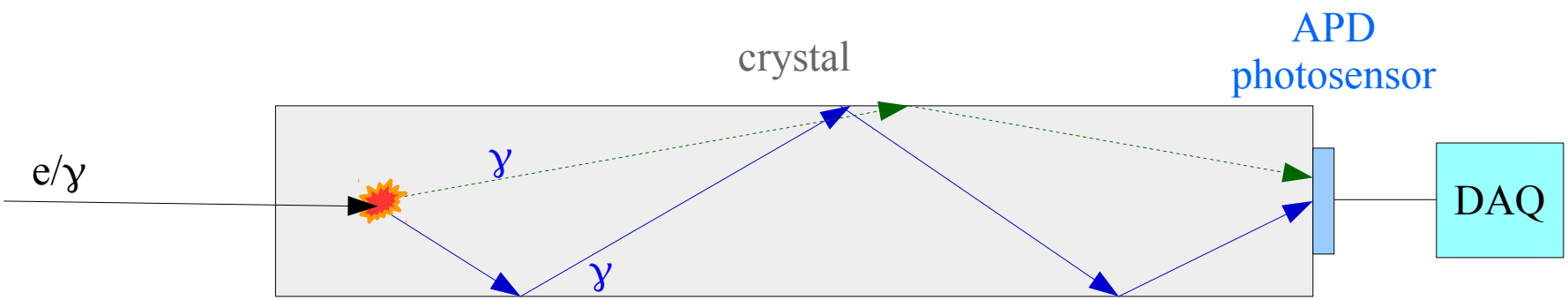
- Time information extracted exploiting the **universal character of the pulse shape**
- Time from **ratios** of **consecutive samples**





ECAL time resolution

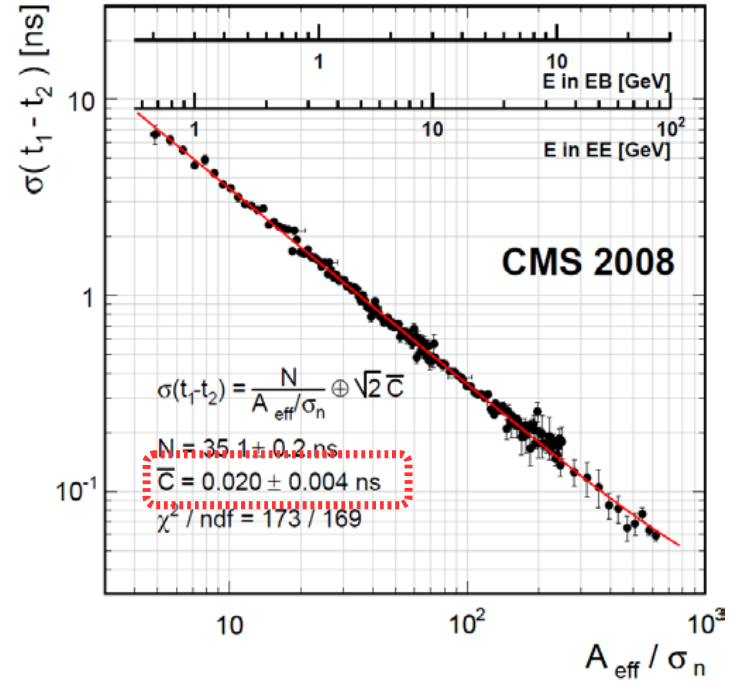
- Several ingredients determine the time resolution of an electromagnetic shower in a homogeneous crystal calorimeter
  - **Intrinsic EM shower fluctuations**
    - longitudinal shower fluctuations
    - optical transit time spread: scintillation rise/decay time, light propagation
  - **Photodetector + electronics**
    - photodetector: rise time, transit time
    - noise: dark current, electronic noise
  - **DAQ**
    - clock distribution

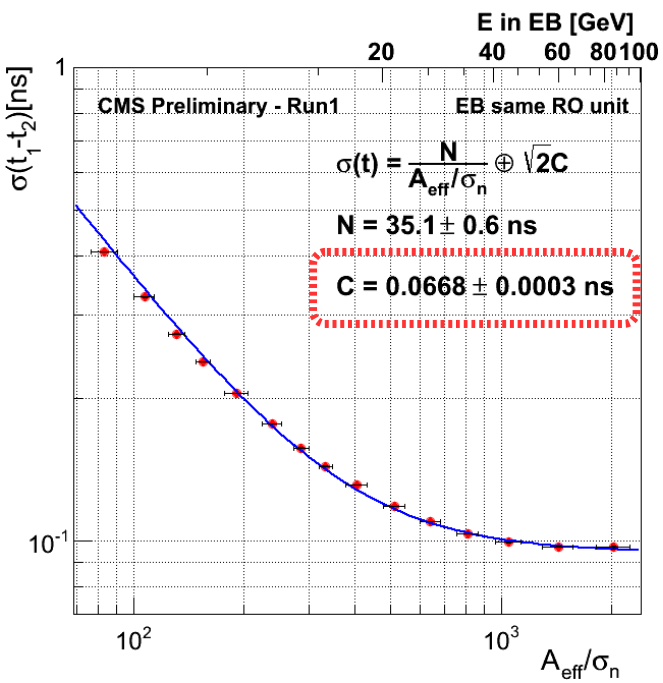


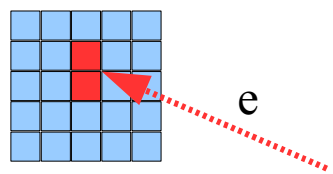
Simulation of the CMS electromagnetic calorimeter response at the energy and intensity frontier
By Alexander Ledovskoy

Current time resolution

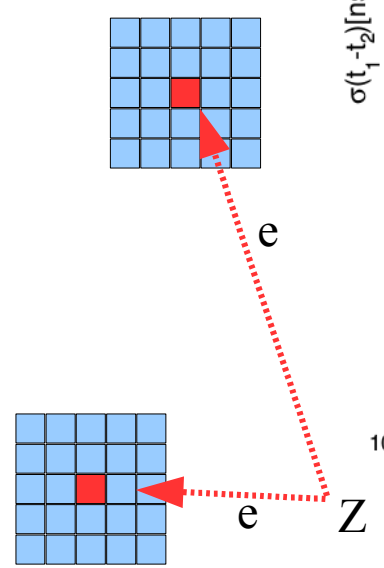
- Results from test beams and pp collision data at LHC :
  - A_{eff} effective amplitude, σ_n = noise
  - $A_{eff} = A_1 A_2 / \sqrt{A_1^2 + A_2^2}$, A_1 and A_2 crystals amplitudes
  - Constant term of resolution:
    - ~**20 ps** in test beam
    - ~**70 ps** in situ, Z→ee, same clock (close-by crystals)
    - ~**150 ps** in situ, Z→ee, different regions of clock distribution

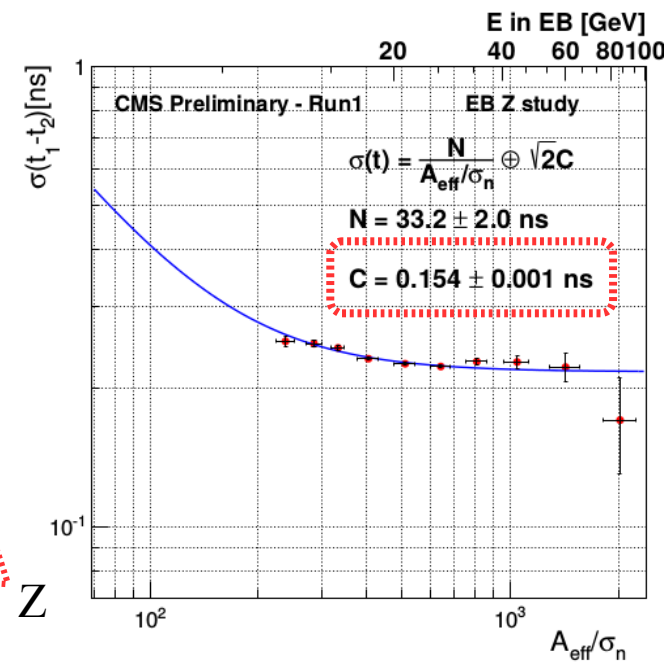






close-by crystals

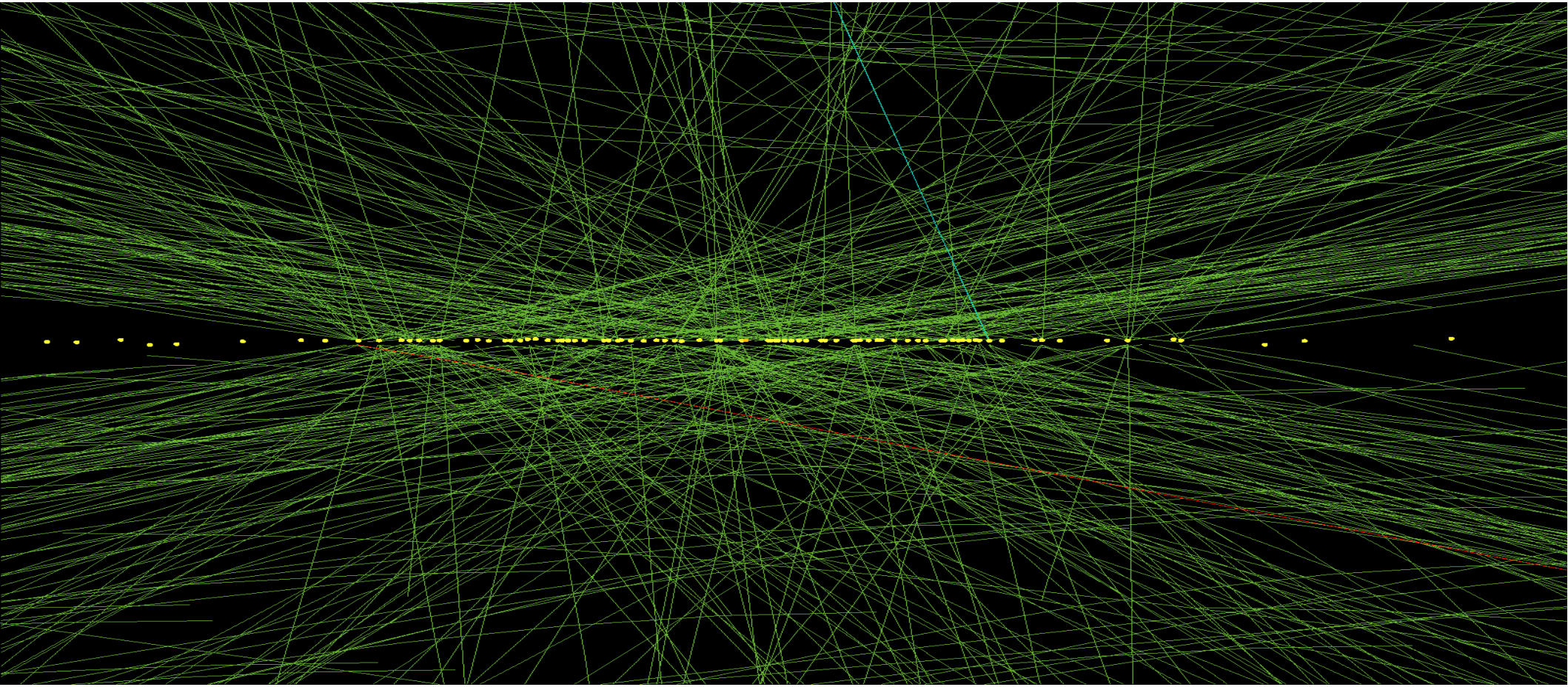




Pile-up

LHC

High pile-up run
78 vertices

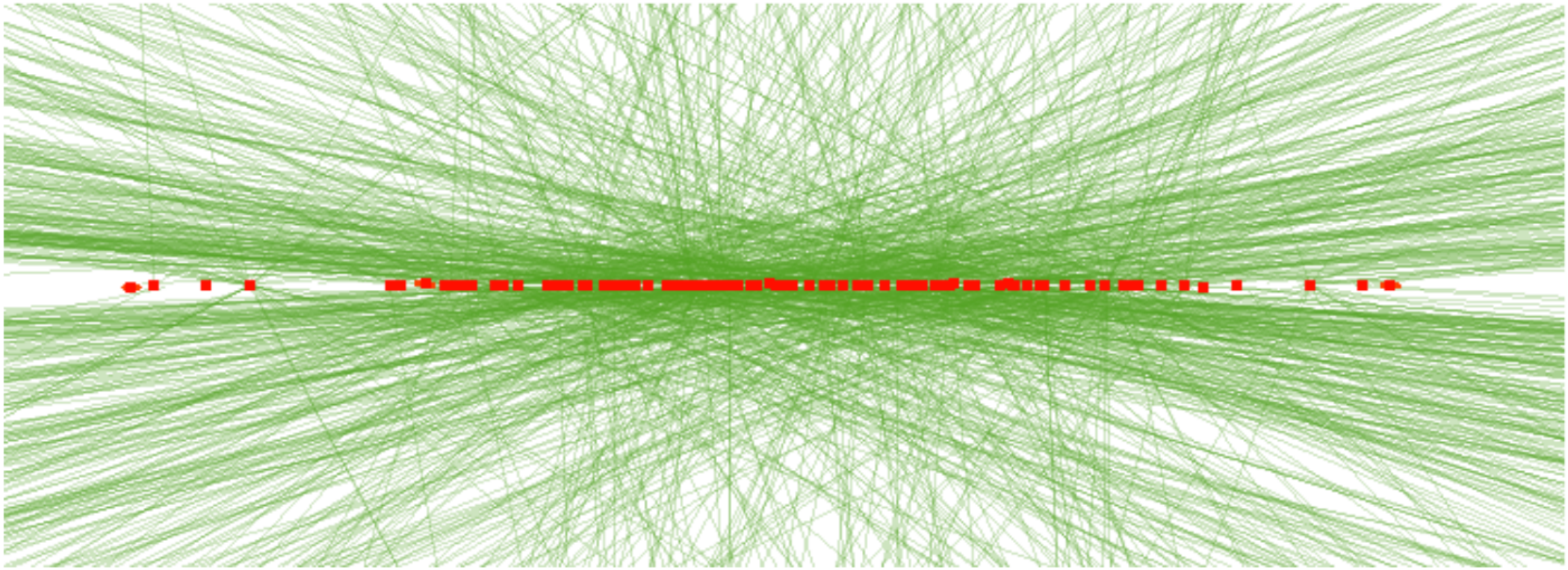


Benefits of precision timing

- **Timing as mitigation of pile-up**
  - Subtraction of **neutral energy from pile-up** in electron and photon clusters
  - Identification of **pile-up jets**
  - **Vertex** assignment in high **pile-up** environment

HL-LHC

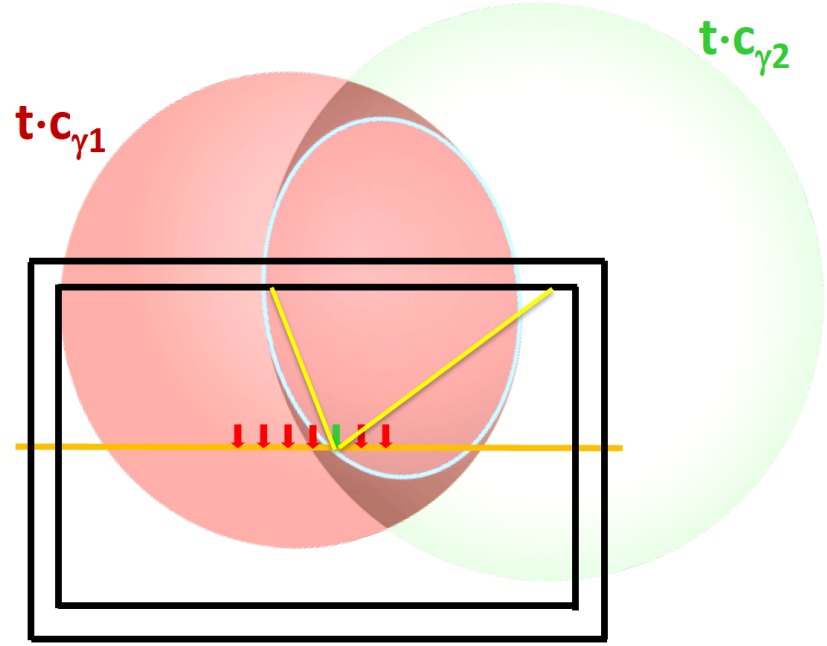
Simulated event: 140 interactions

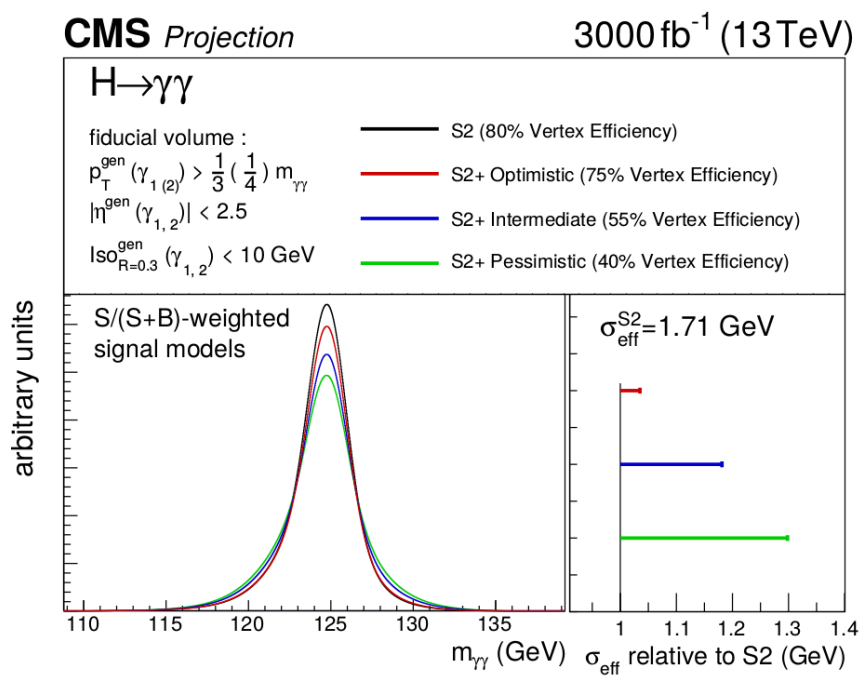


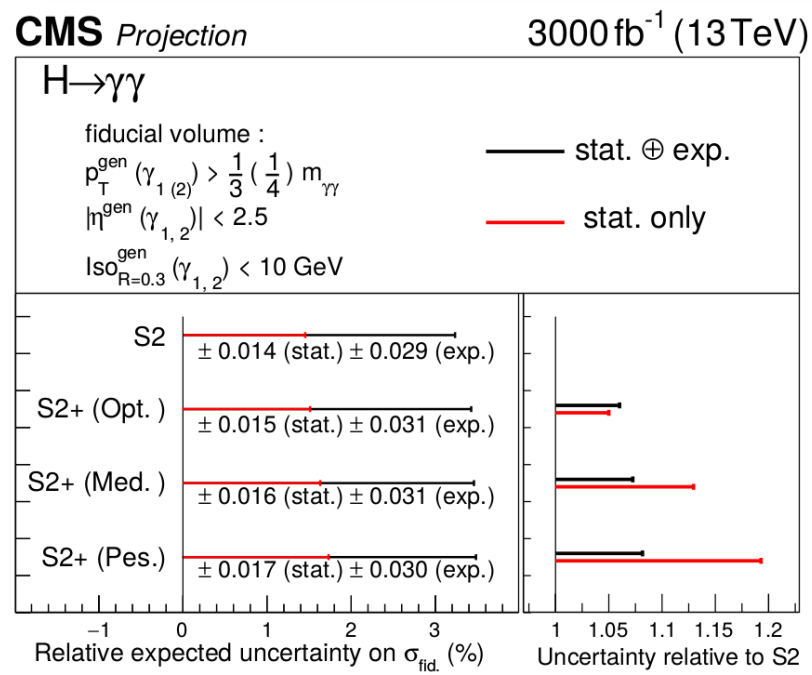
Time precision and vertexes

- Time used to triangulate the vertex
  - **Vertex** assignment in high pile-up environment
  - H → γγ: correctly assign vertex → **$m_{\gamma\gamma}$ peak resolution**
    - ECAL has no longitudinal segmentation, no pointing
    - Vertexes spread 5 cm along beam axis
    - ~**20/30 ps** → ~ 1 cm resolution on vertex

$$\frac{\Delta m_{\gamma\gamma}}{m_{\gamma\gamma}} = \frac{1}{2}\left[\frac{\Delta E_{\gamma 1}}{E_{\gamma 1}} \oplus \frac{\Delta E_{\gamma 2}}{E_{\gamma 2}} \oplus \frac{\Delta\theta_{\gamma\gamma}}{\tan(\theta_{\gamma\gamma}/2)}\right]$$



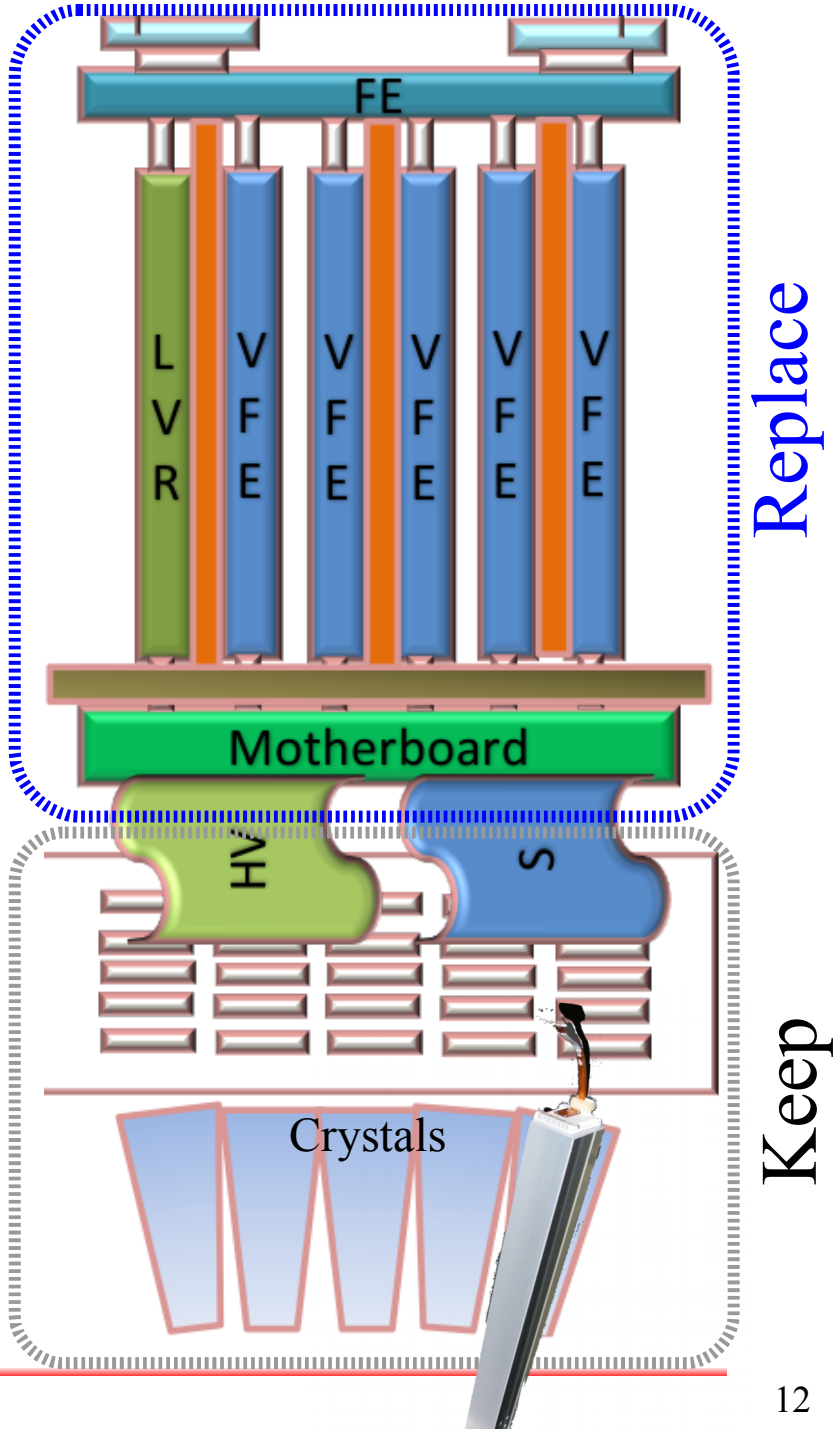




Time precision upgrade

- **Intrinsic EM shower fluctuations**
  - longitudinal shower fluctuations
  - optical transit time spread: scintillation rise/decay time, light propagation
- **Photodetector + electronics**
  - photodetector: rise time, transit time
  - noise: dark current, electronic noise
- **DAQ**
  - clock distribution

Where we can work to improve the time precision



- Upgrade Very Front End (VFE) based on dual gain

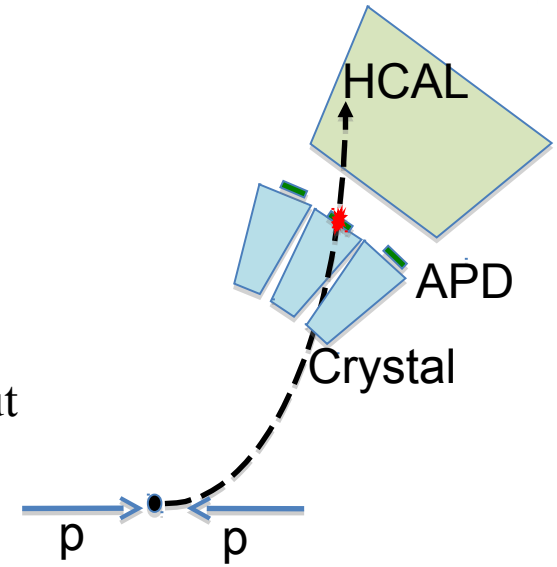
  Trans Impedence Amplifier (**TIA**)

  - **Preserve a fast signal to optimize time resolution**
- ADC sampling rate increased @ **160 MHz**
- **Clock distribution** has a crucial role: need to ensure clock stability <10 ps on a large distributed system

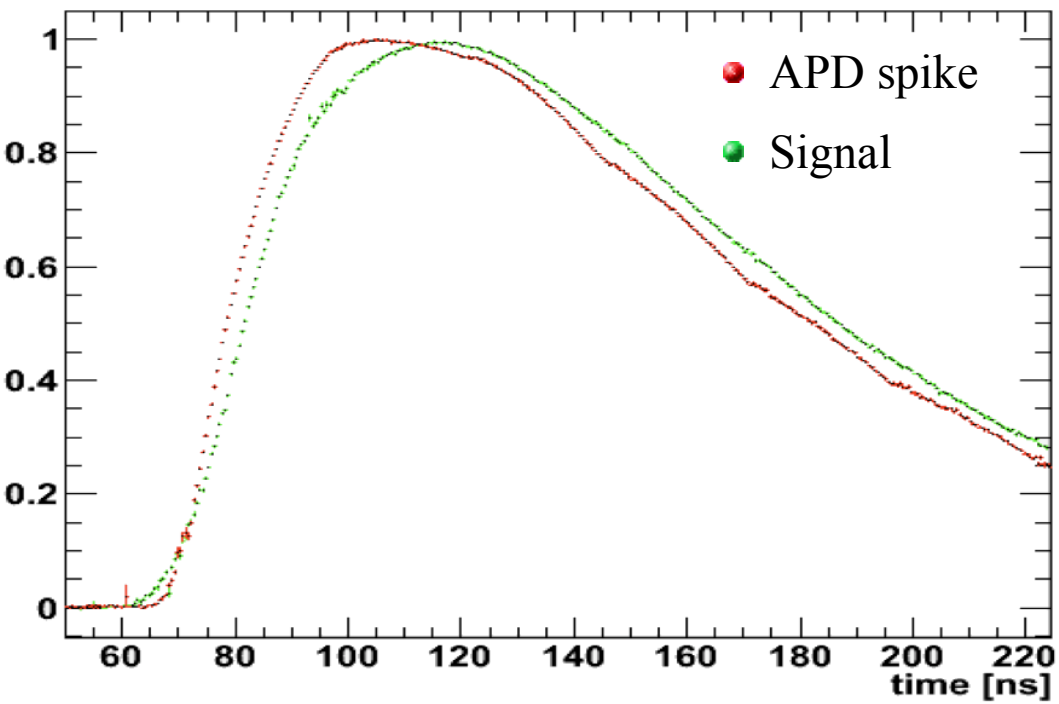
The front-end data conversion and readout electronics for the CMS ECAL upgrade
by Gianni Mazza

Spikes mitigation

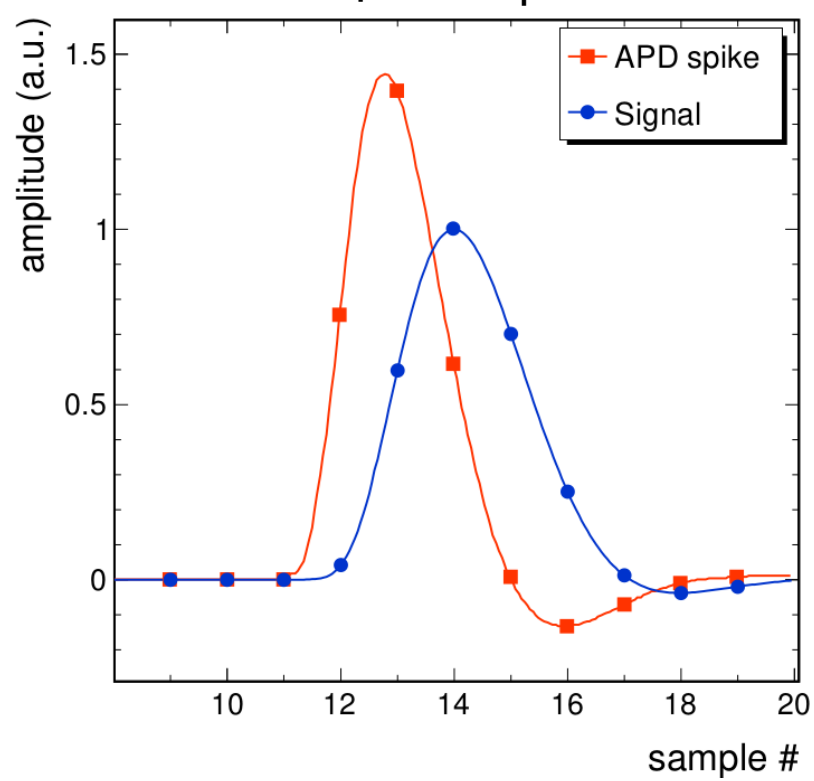
- Discrimination between scintillation and signals generated by hadron interactions in the APD, **spike**
  - Spike → more prompt pulse
  - Time information to distinguish



- Current readout

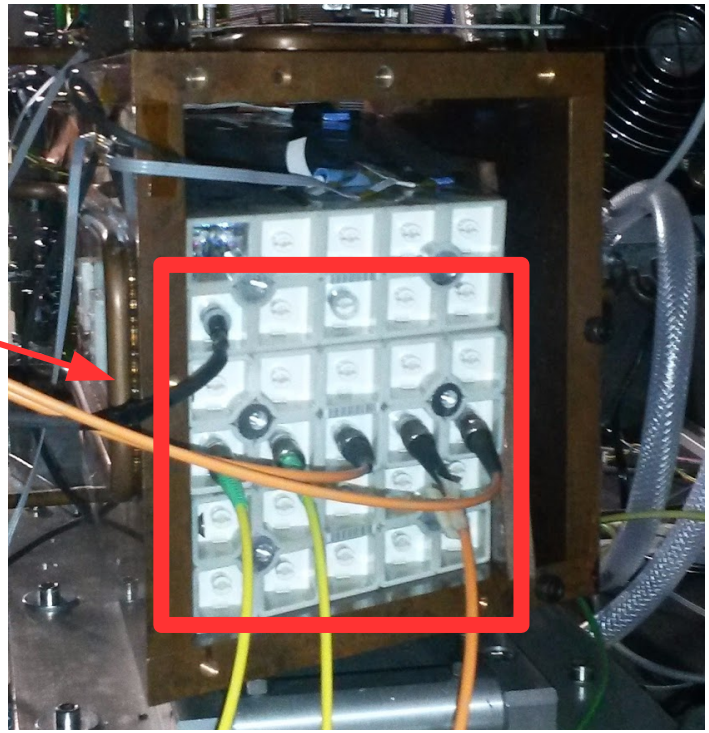


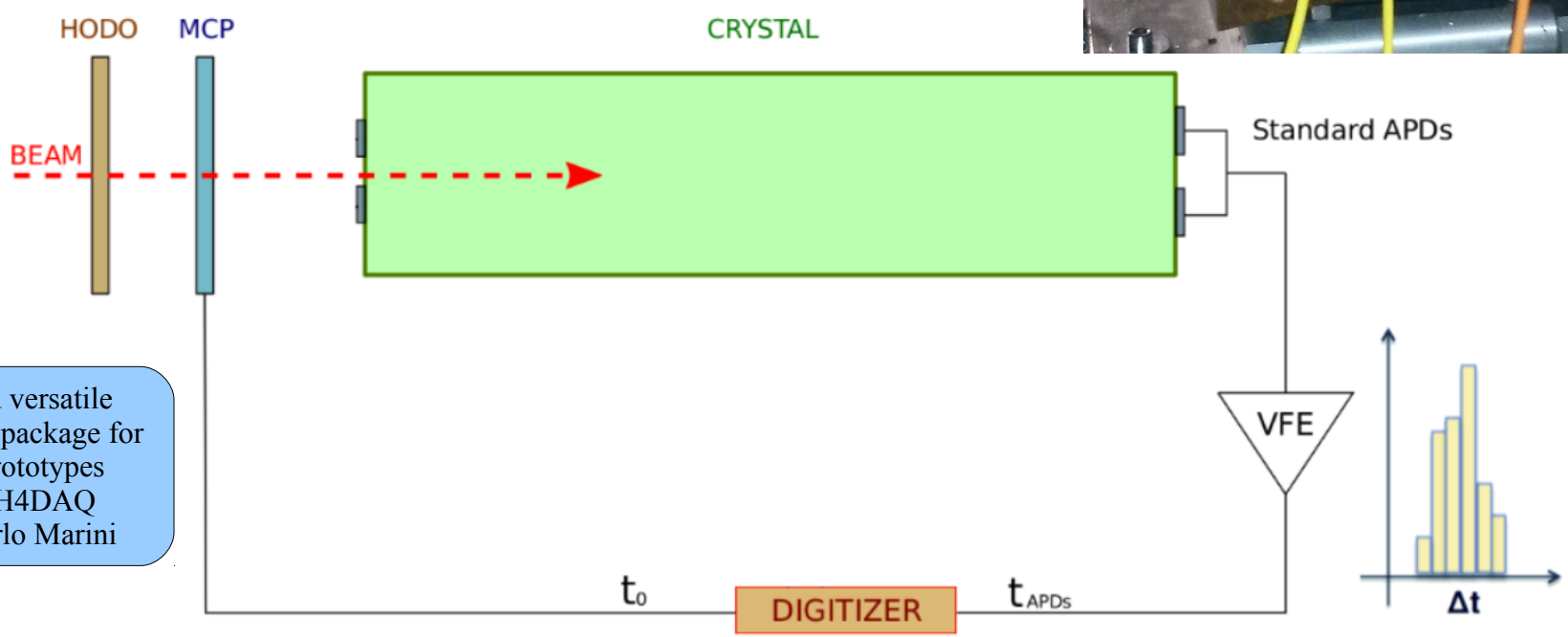
- New TIA readout



Test beam results

- Test beams performed in 2015, 2016 and 2017 @ **CERN SPS H4** to study **intrinsic $PbWO_4$ timing** capabilities and **new electronics**
  - 5x5 matrix of ECAL barrel crystals + APDs
  - Different VFE electronics configuration
  - Signals readout by a fast digitizer (CAEN V1742, 5 GHz)
  - Time extracted from a fit to the pulse shape
  - Micro-Channel Plate (MCP) detectors used as time reference (σ_t ~20 ps)

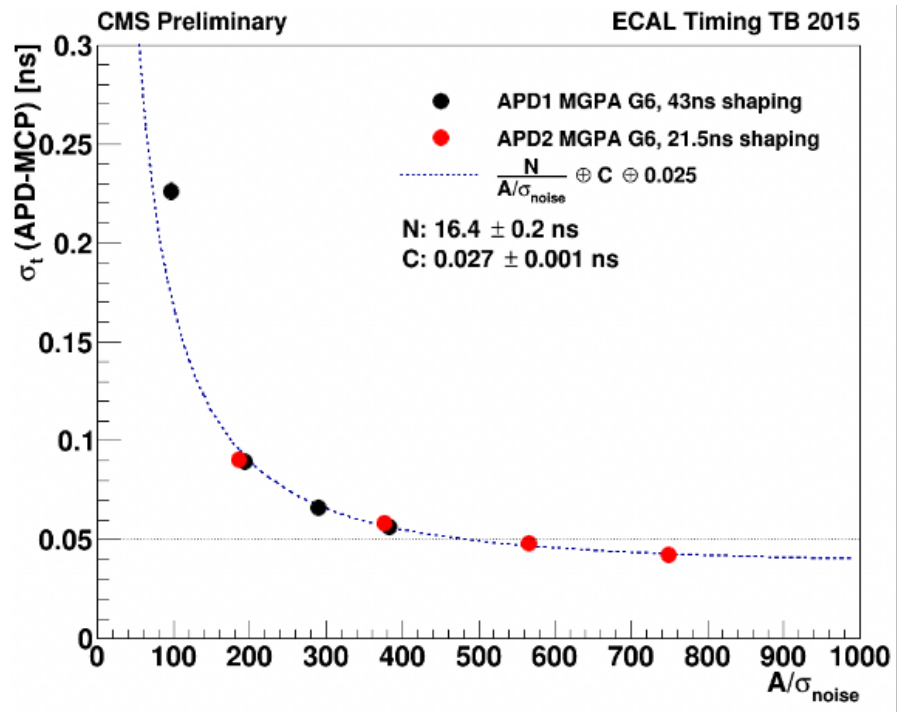


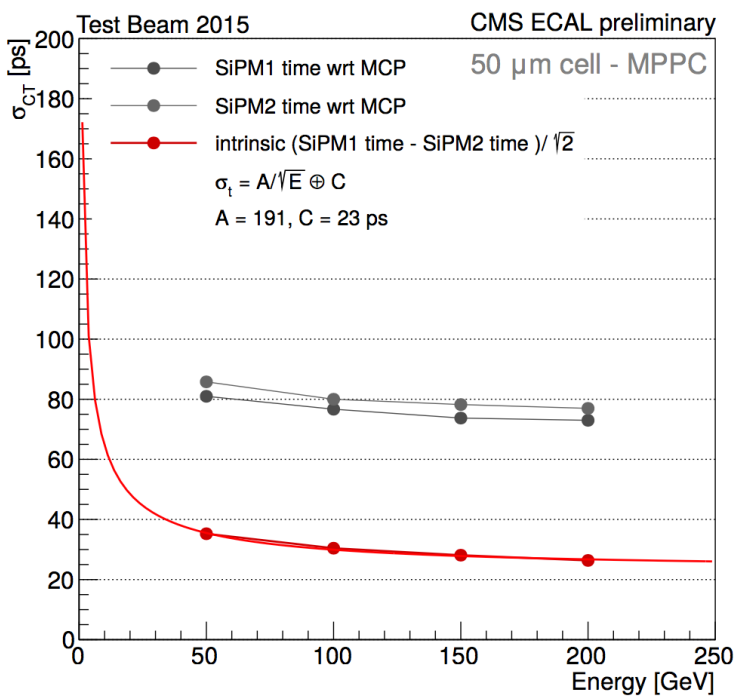


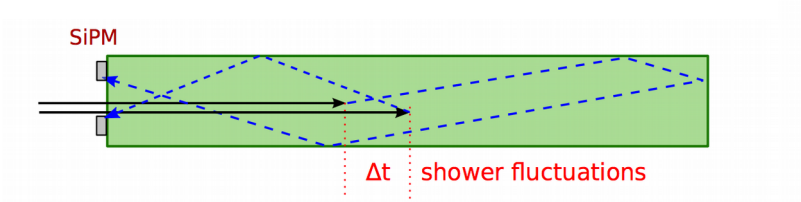
A modern and versatile data-acquisition package for calorimeter prototypes test-beams: H4DAQ by Andrea Carlo Marini

Test beam 2015

- APD + VFE electronics with standard (43 ns) and **reduced** (21.5 ns) **shaping time**
  - 21.5 ns shaping time almost x2 A/σ noise
- Additional noise from test beam custom electronics
  - in CMS: A/σ noise ~800 for a 50 GeV shower



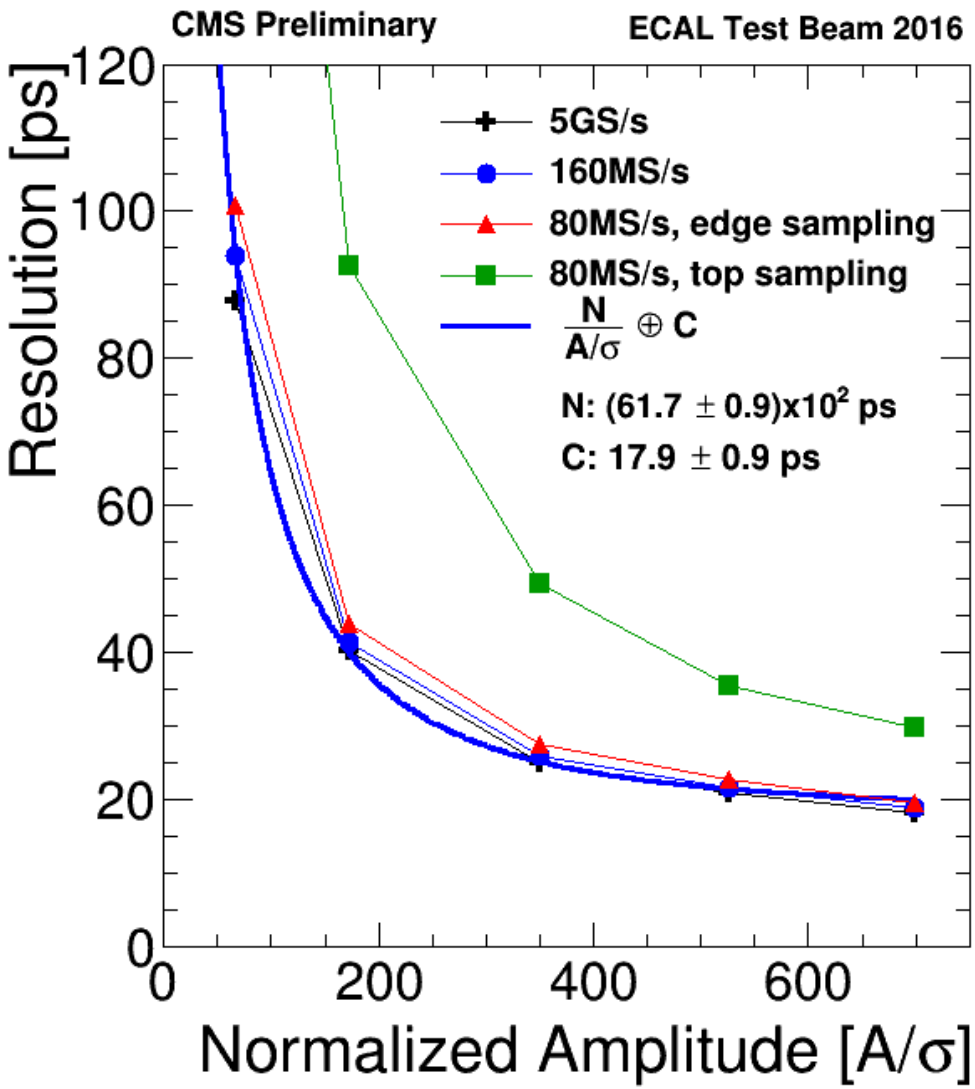


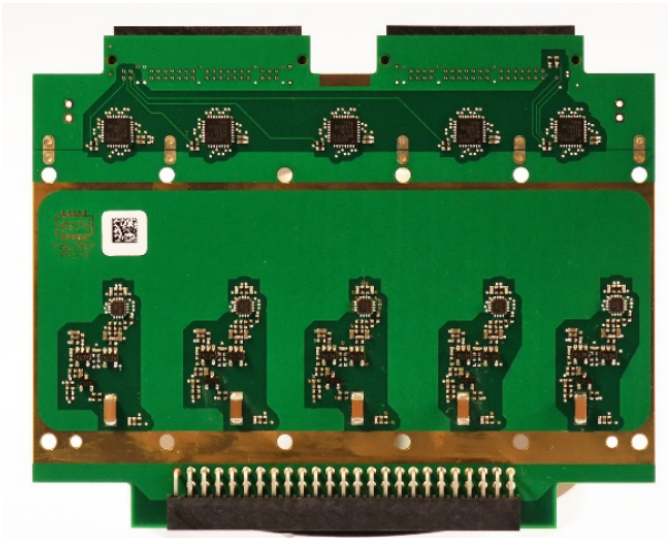


- Readout using 2 **SiPMs** from the front face
- Resolution with different readout dominated by longitudinal shower fluctuations (~80 ps constant term)

Test beam 2016

- Prototype **VFE with TIA** implemented using **discrete components**
- 30 ps resolution for A/σ = 250
  - 25 GeV @ HL-LHC start (100 MeV noise)
  - 60 GeV @ HL-LHC end (240 MeV noise)
- Signals readout by a fast digitizer 5 GHz
- Optimal performance already with 160 MHz sampling
- Test beam with advanced prototype **TIA ASIC + integrated ADC** in June 2017



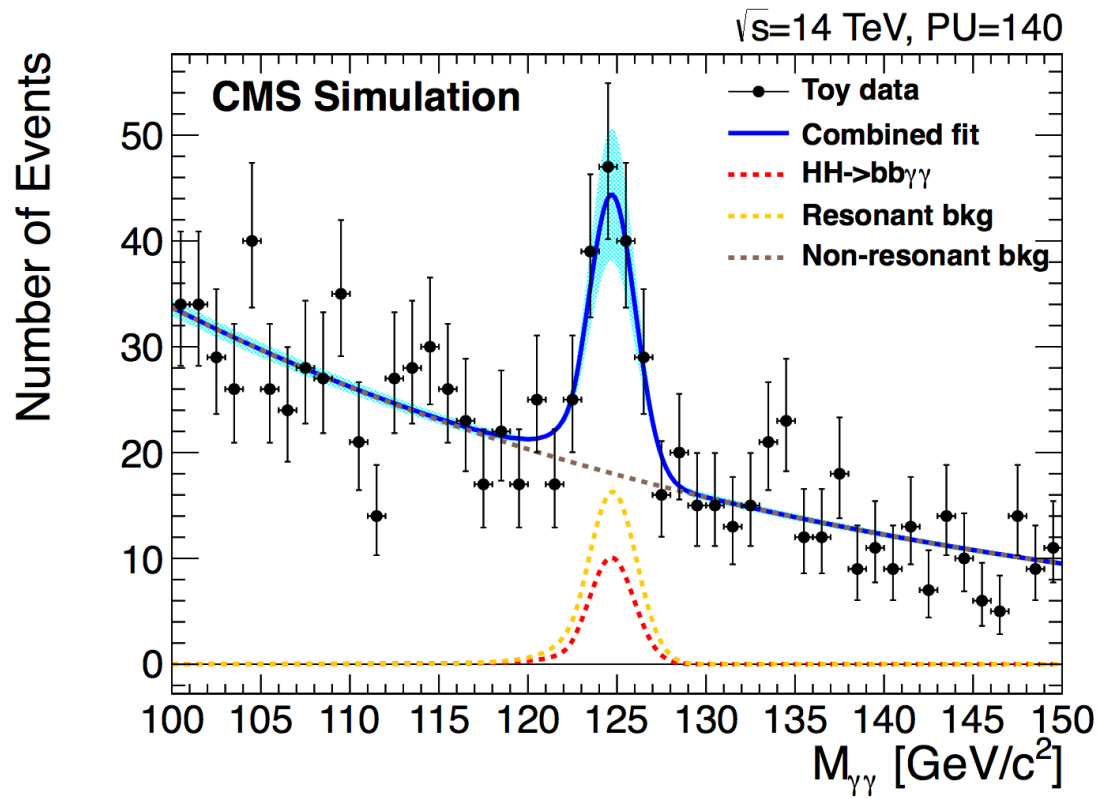


Conclusions

- ECAL Barrel upgrade: timing resolution of ~ **30 ps** for high energy photons and electrons
- Needed to maintain and improve performances for **precision physics**: exploit 3 ab^{-1} at **HL-LHC**
- New **readout electronics for ECAL Barrel Phase II**
  - Trans Impedence Amplifier (**TIA**) → high **energy** and **time precision**
  - Improved **spike** rejection

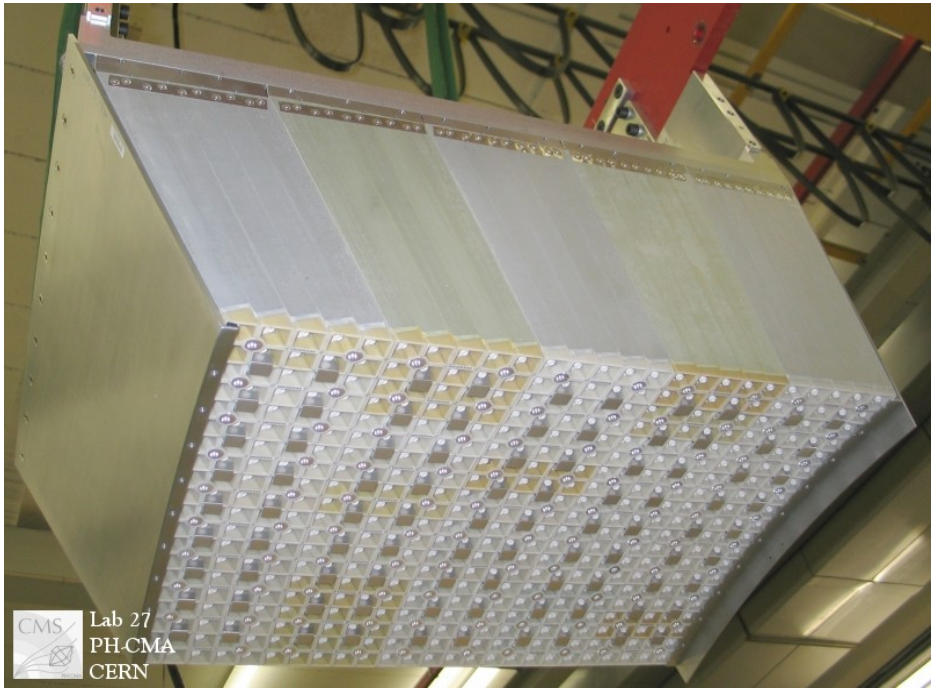
- Test beams for characterization:
  - Intrinsic crystal time resolution
  - Crystals + new electronics

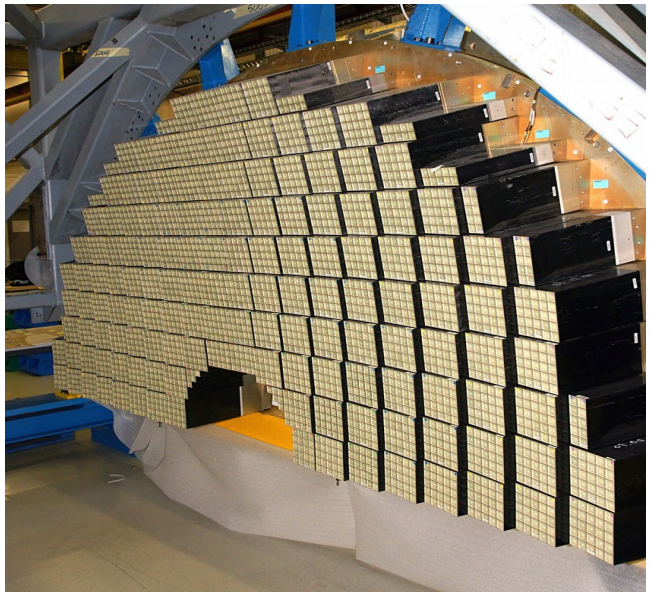
- **New and undiscovered physics** is waiting for us to be found!

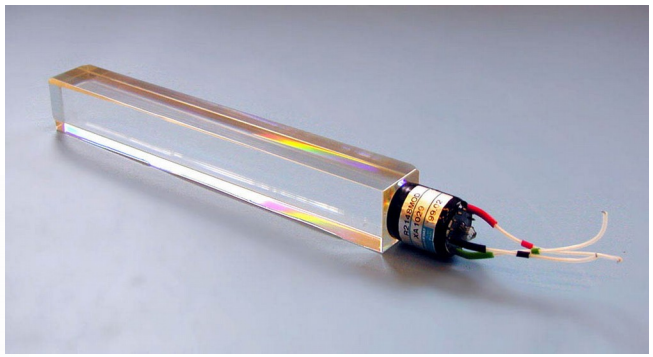


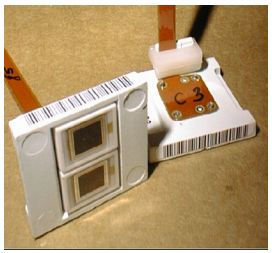
backup

ECAL structure

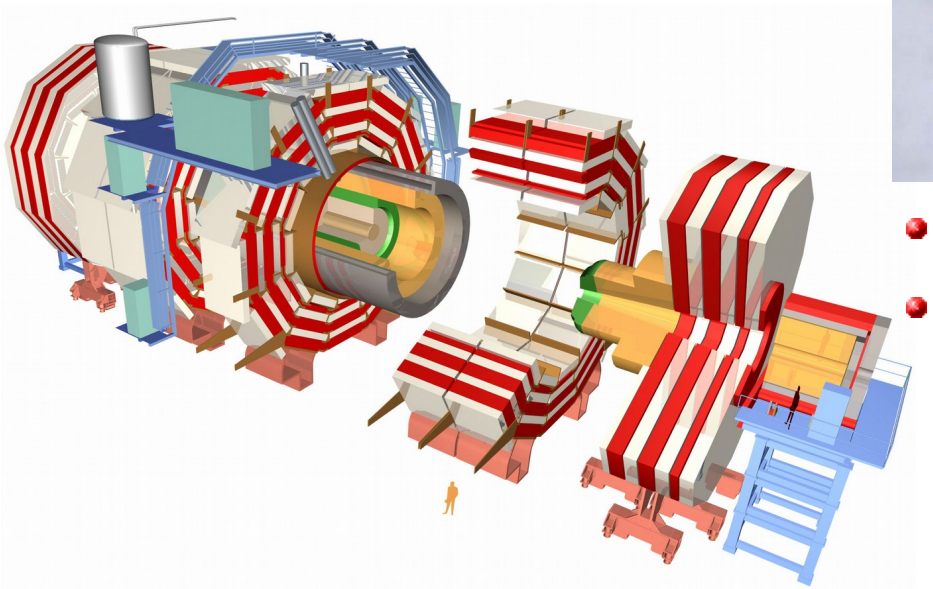








- Barrel
- APD



- Endcap
- VPT

Clock distribution

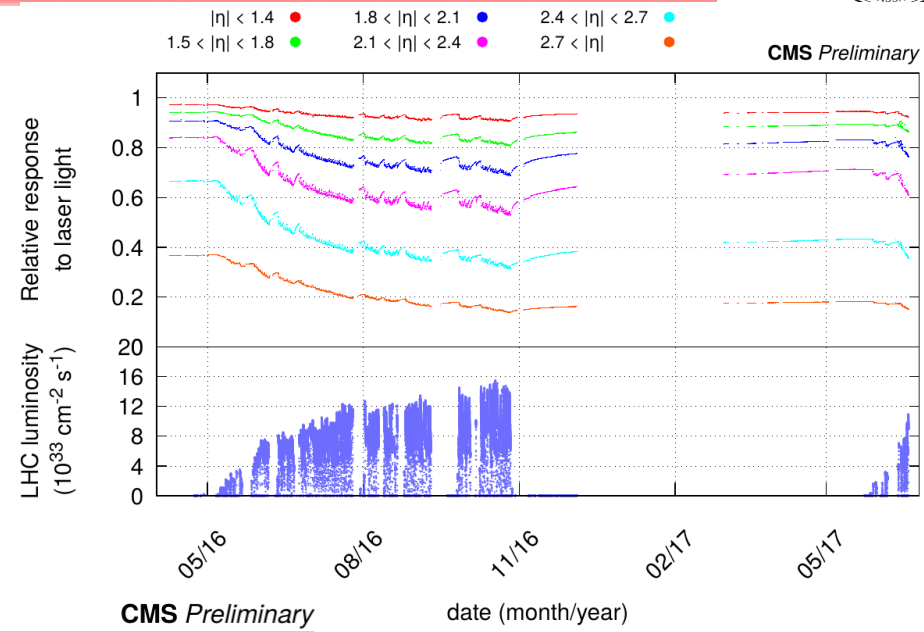
- The target performance for the EB upgrade is a clock distribution system with a stability better than 10 ps.
- The jitter and phase stability (skew) must be maintained below 10 ps during transmission across the detector and over long LHC running periods

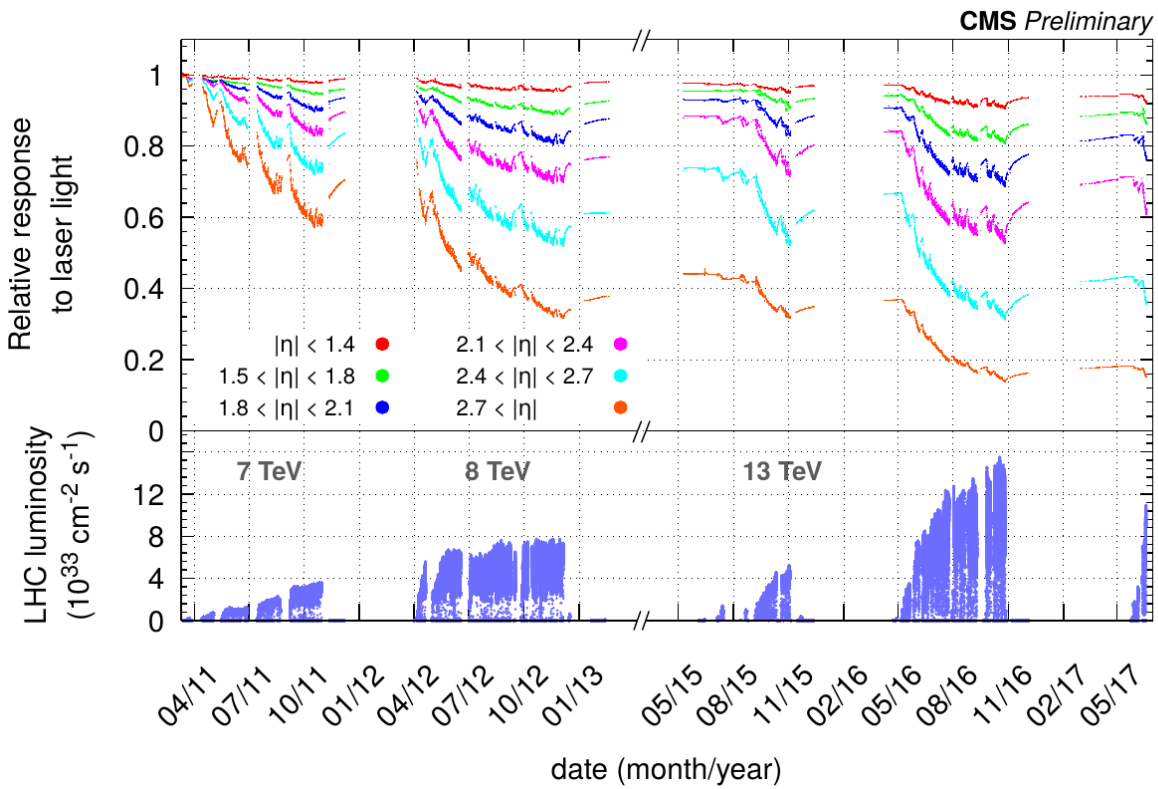
Laser and response monitoring

- Crystal **transparency loss** and **VPT** (endcap readout) **conditioning** under **irradiation**

  corrected by **laser system**

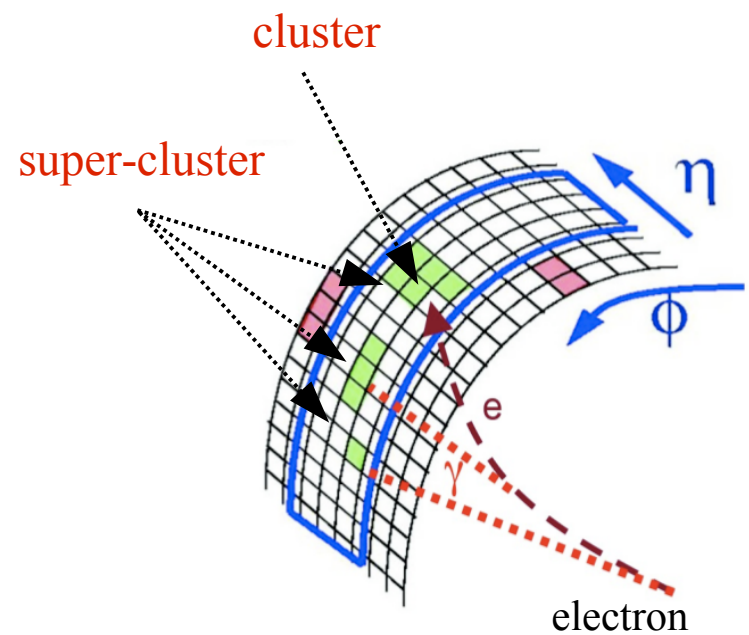
  - Monitor with laser light at 447 nm (close to max of scintillation spectrum)
  - During no irradiation periods transparency partially recovers





ECAL energy reconstruction

- Energy of **electrons/photons**
  - A_i = amplitude response
  - $S_i(t)$ = time-dependent corrections
  - C_i = inter-calibration among crystals
  - G = ADC to GeV
  - E_{ES} = preshower energy
  - $F_{e,\gamma}$ = cluster corrections



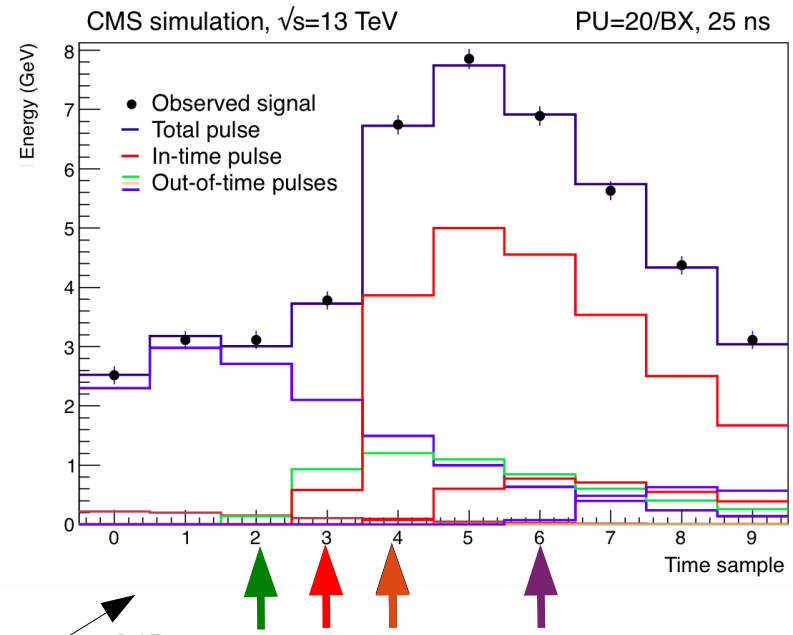
$$E_{e,\gamma} = F_{e,\gamma}\left[G \times \sum_{i=crystals} \left(C_i \times S_i\left(t\right) \times A_i\right) + E_{ES}\right]$$

Run II pulse reconstruction: Multi-Fit

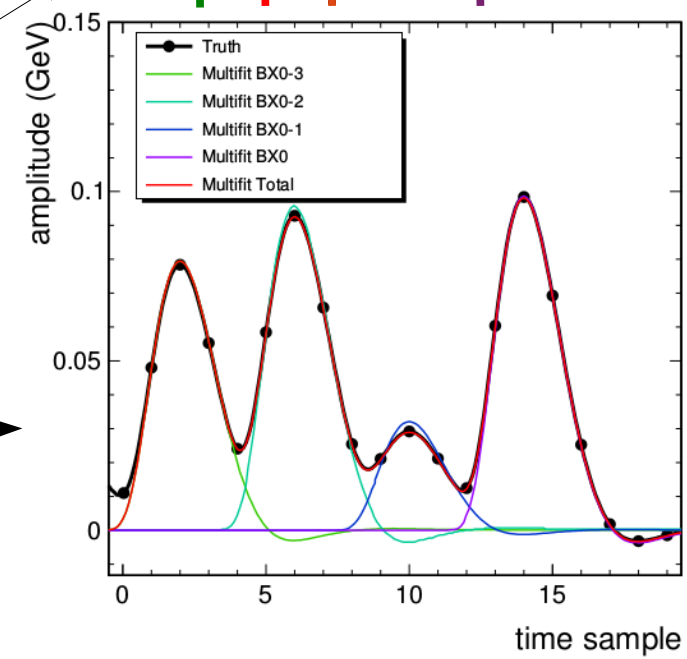
- Estimates the in-time signal amplitude and up to 9 out of time amplitudes by means of a minimization of χ^2

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

- S_i : digitized amplitudes
- A_j (≥ 0): amplitudes from pulse at bunch cross j
- p_{ij} : the pulses. All *identical and shifted* by j x 25ns
- σ_{Si} : noise covariance matrix



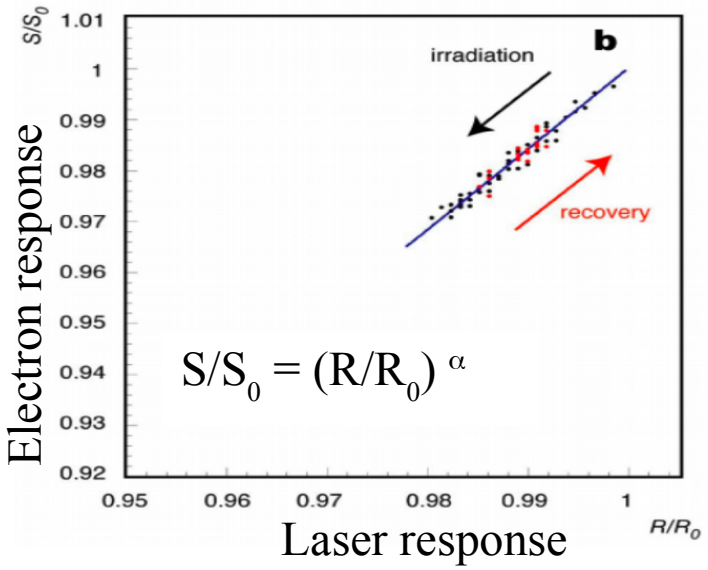
- Current ECAL
- New TIA readout electronics

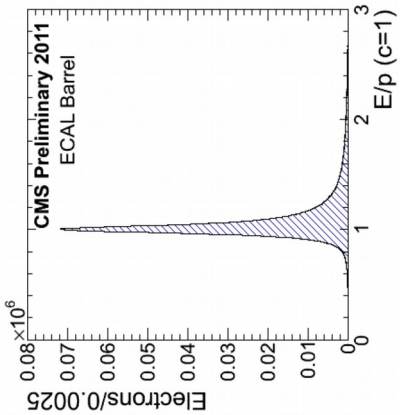


Laser and transparency loss: monitor

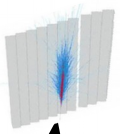
- **Laser** response vs "**electrons**" response
  - $S/S_0 = (R/R_0)^{\alpha}$
  - Check with electron response:

    energy from ECAL / momentum from tracker

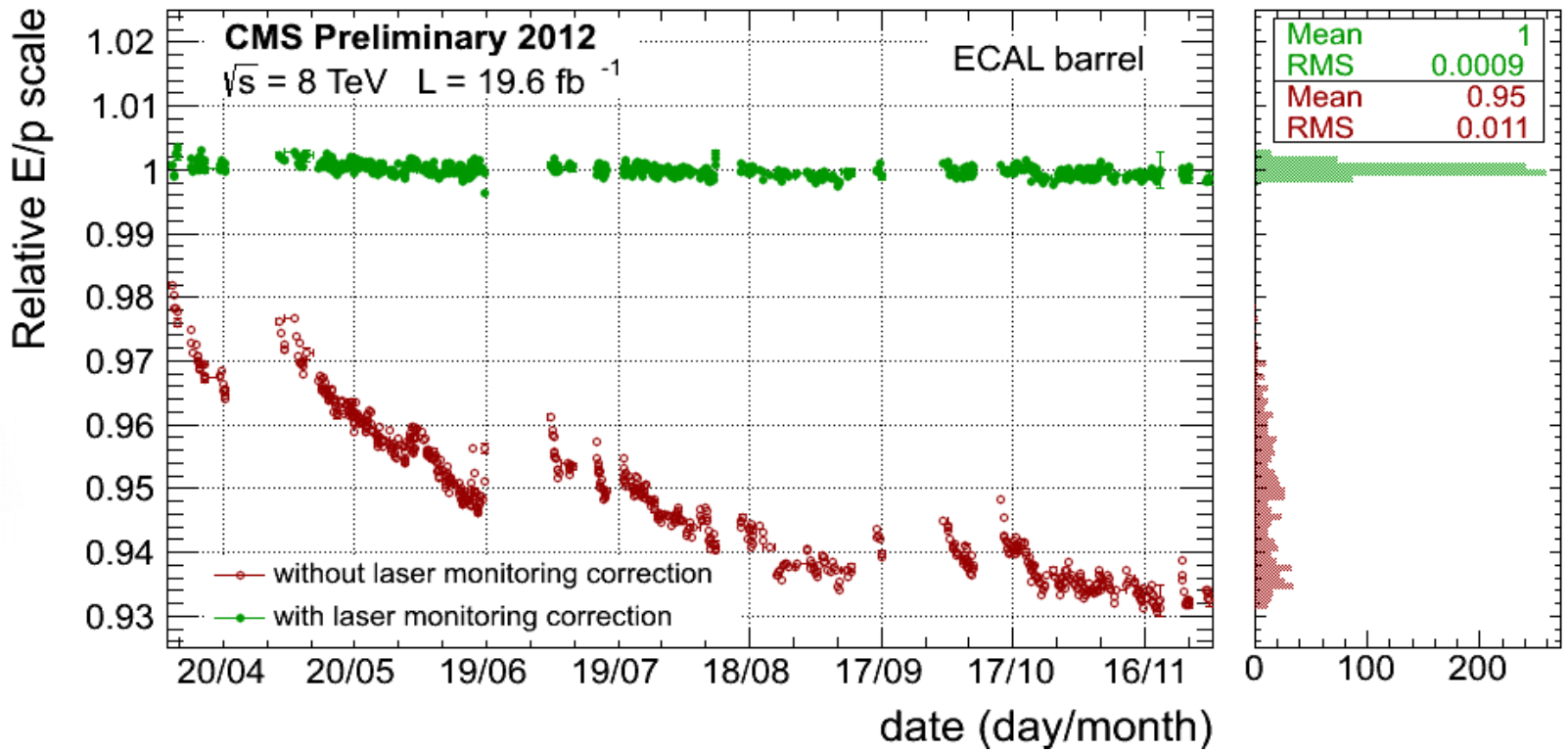




E by ECAL

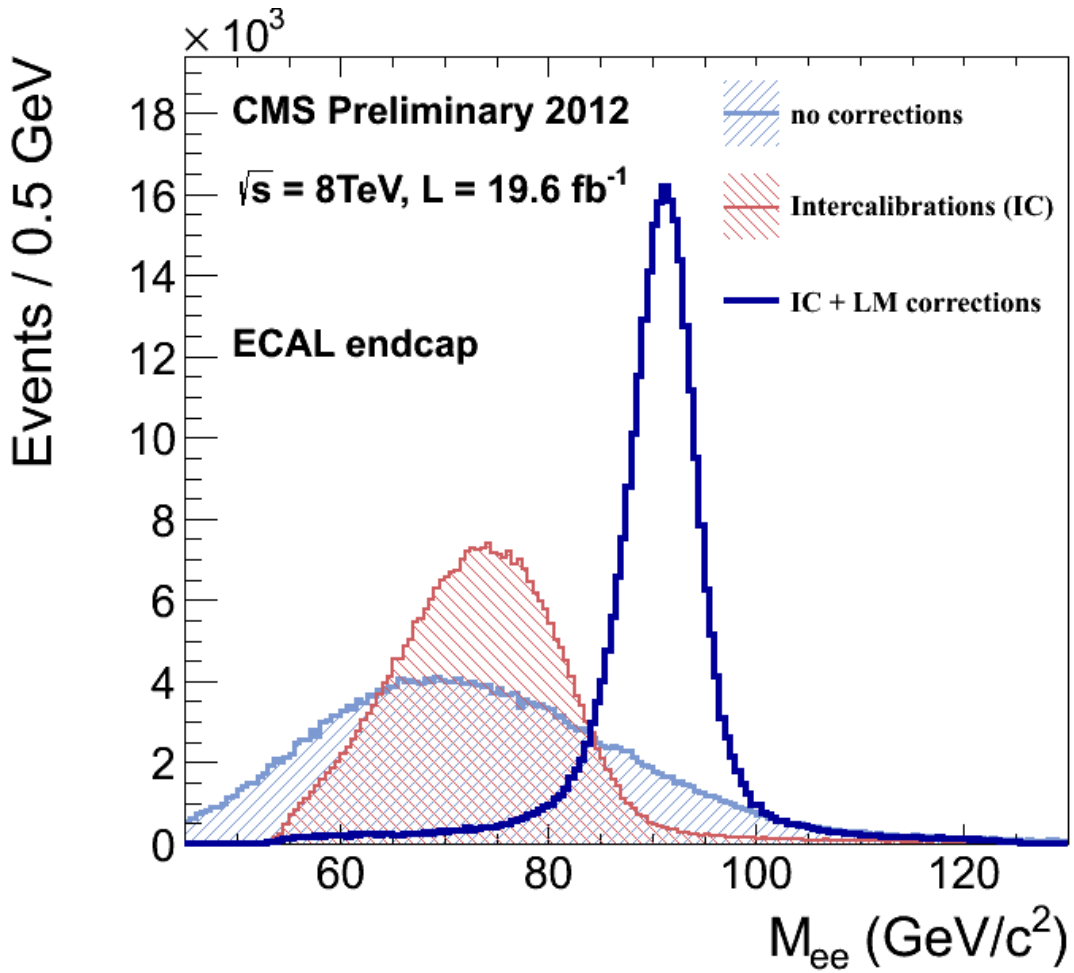


p by tracker



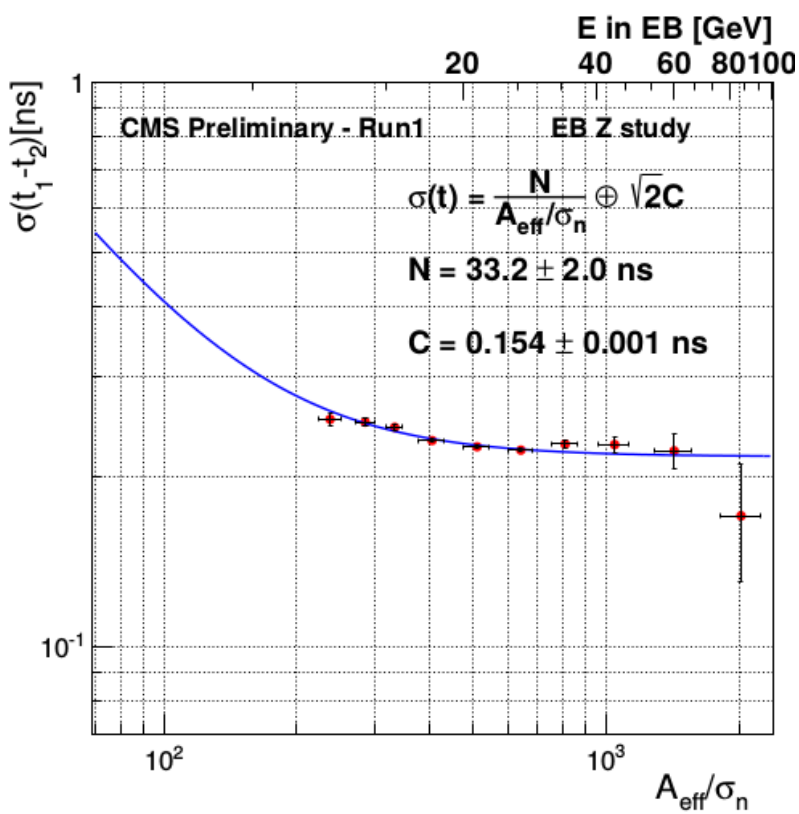
Inter-calibration and transparency corrections

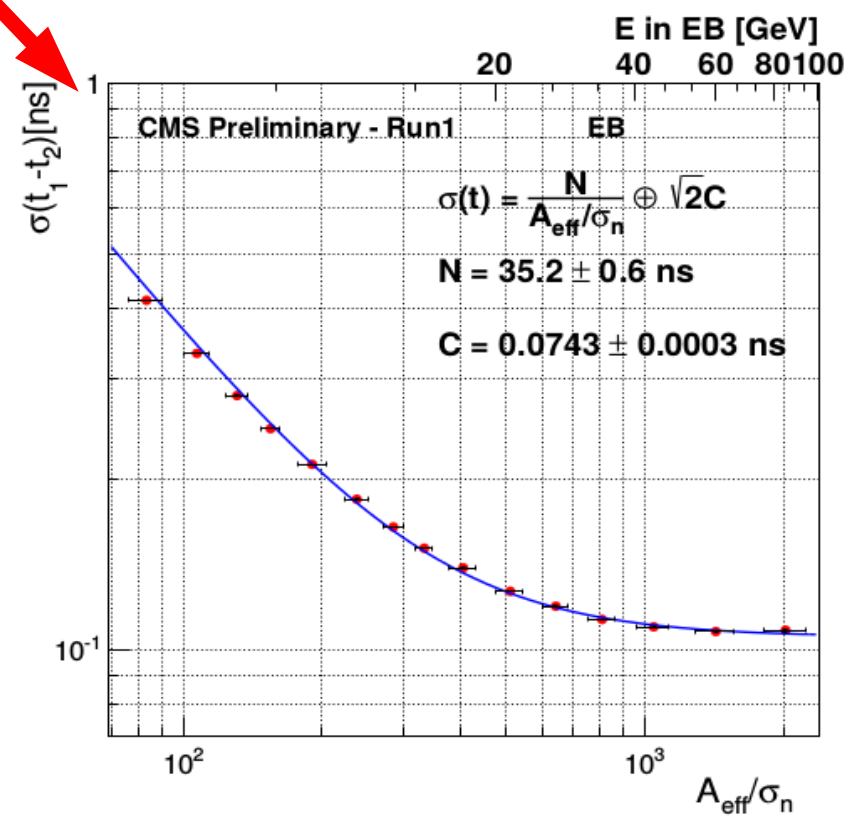
- Impact on the $Z \rightarrow e^+e^-$ of energy scale and resolution
- Inter-calibrations: energy scale corrections to account for the intrinsic spread in crystal and photo-detector response
- LM (laser monitoring): time-dependent corrections to compensate for channel response loss



ECAL timing

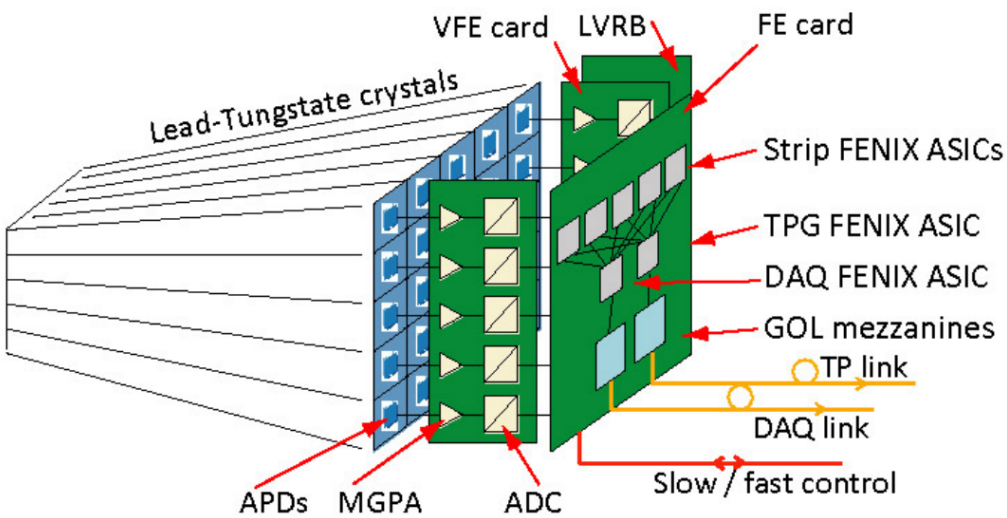
- ECAL sensitive to **time** of energy deposit
- Time resolution ~ **100 ps** for energies > 10 GeV
- Time information extracted exploiting the **reproducibility of the pulse shape**
- Time resolution measured in data
  - Comparing in **Z → ee** events the time from energy deposit from the **two leptons**
  - Comparing the time differences between **two neighbor crystals** in a photon cluster

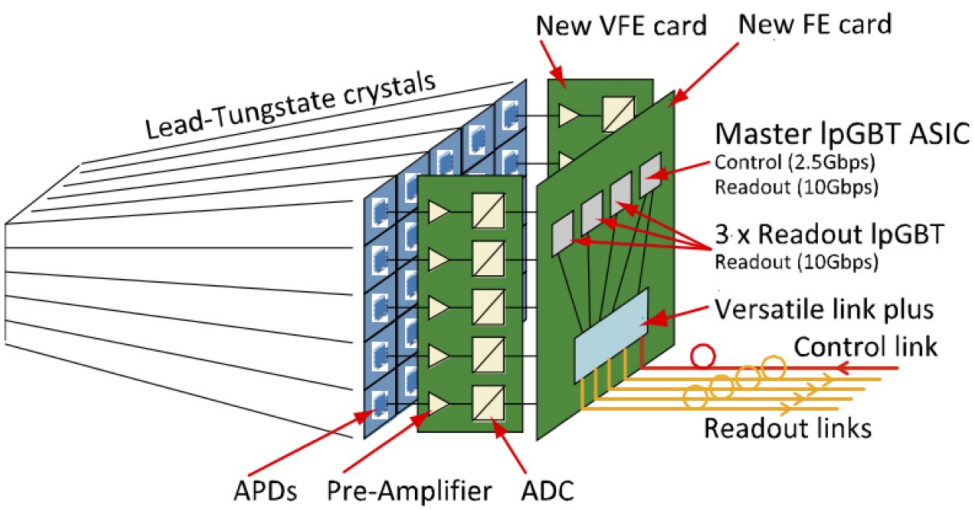




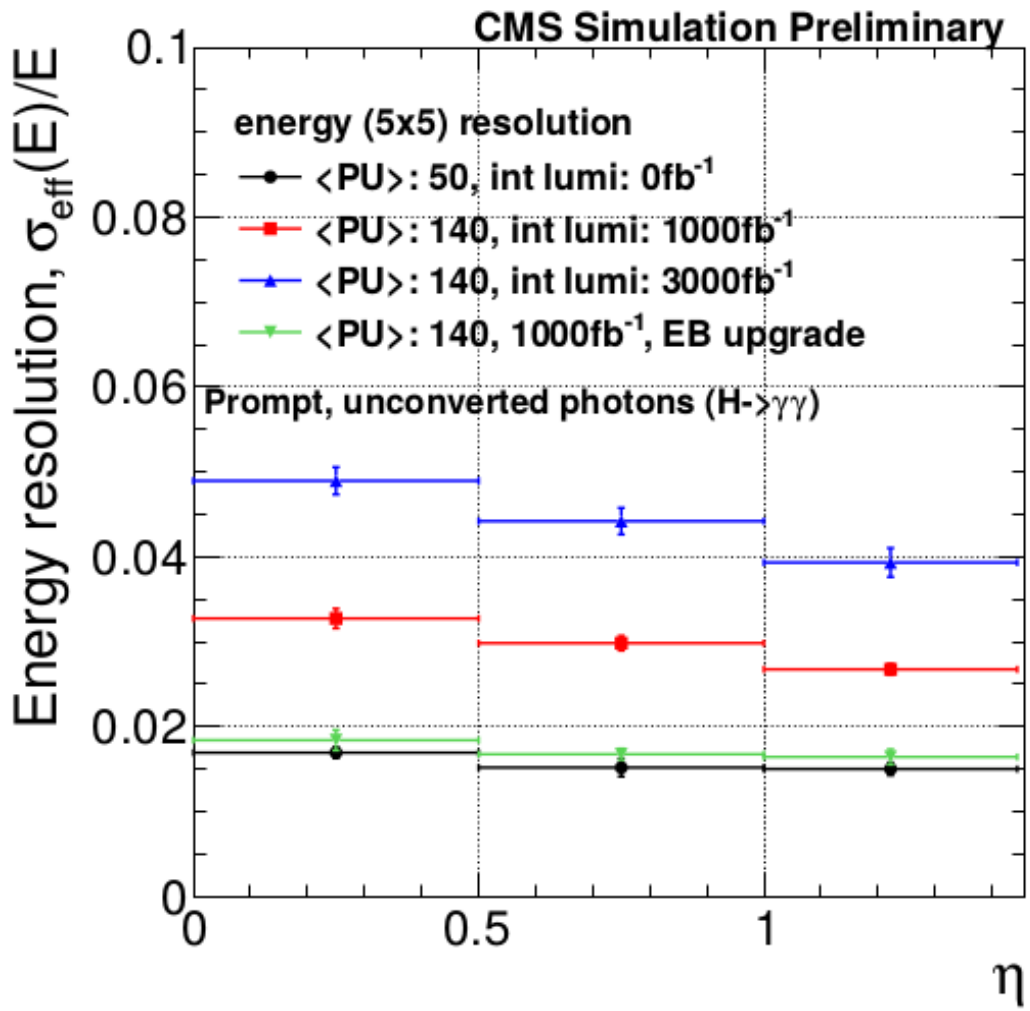
EB VFE and FE

- **New electronics: VFE and FE**
  - Avalanche Photodiode (**APD**): from light to electric pulse
  - Very Front End (**VFE**): pre-amplifier and ADC
  - Front End (**FE**): data for trigger and data for full event reconstruction





EB upgrade and energy resolution



ECAL Endcap upgrade

- Complete replacement of current ECAL Endcap
- **HGC**: High Granularity Calorimeter
  - 10 layers: 0.65 X_0 thickness absorber followed by a plane of silicon
  - 10 layers: 0.88 X_0 thickness absorber followed by a plane of silicon
  - 8 layers: 1.26 X_0 thickness absorber followed by a plane of silicon