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

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On behalf of the CMS collaboration

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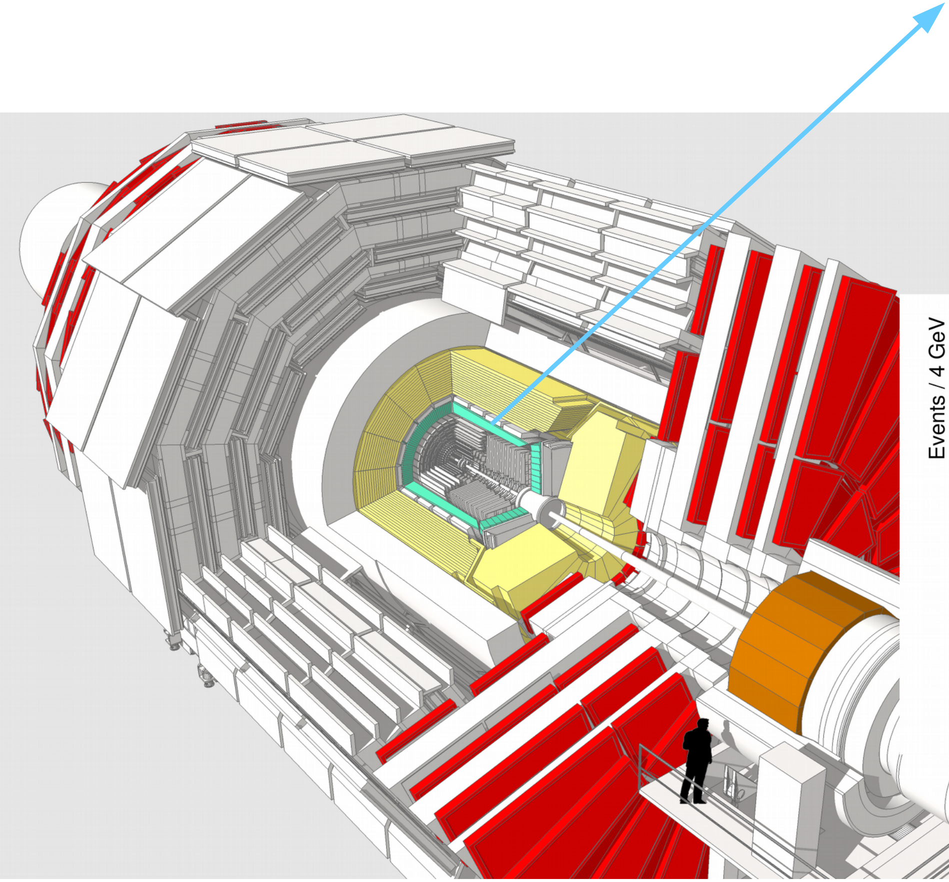
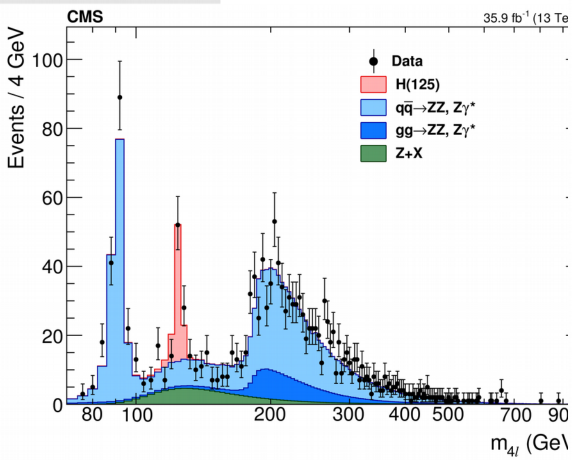
CMS Experiment

ECAL: Compact, homogeneous, hermetic and fine grain calorimeter

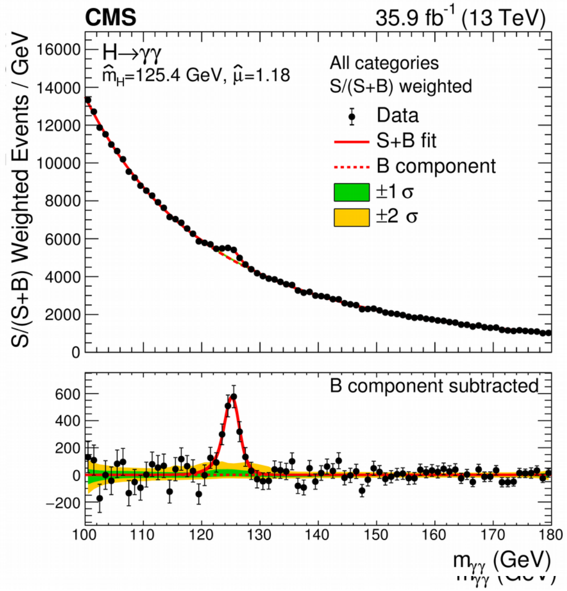
- Embedded in 4 T magnetic field
- 75848 lead-tungstate ($PbWO_4$) scintillating crystals
- Intrinsic light yield 100γ/MeV → 4p.e./MeV on the APDs
- Detector designed for excellent energy resolution for photons with 0.1 MeV-1.5 TeV



H→ZZ→4ℓ CERN-EP-2017-123



H→γγ CERN-EP-2018-060



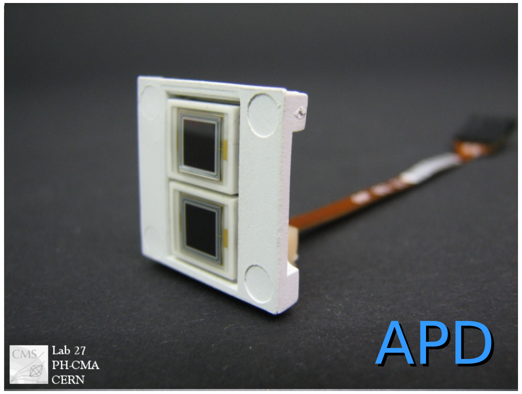
Excellent resolution and electron/photon ID of the CMS ECAL crucial for discovery and characterization of the 125 GeV Higgs Boson

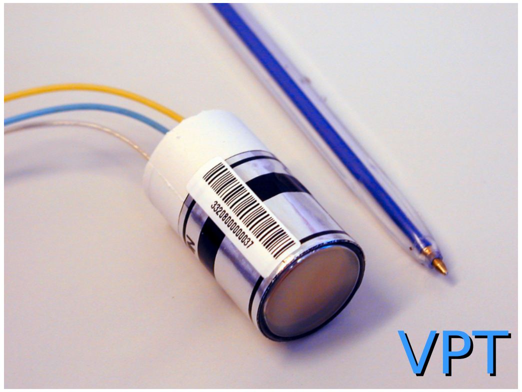
ECAL Detector

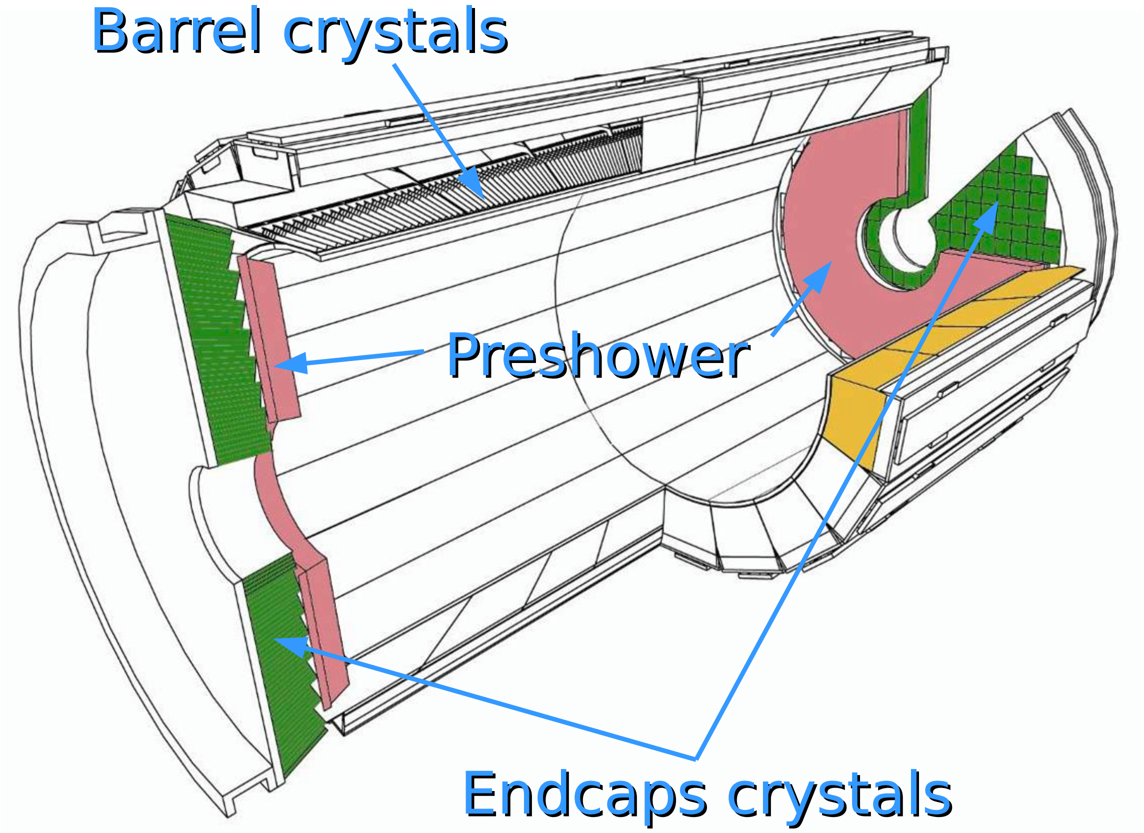
- **Barrel (EB):**
  - 36 supermodules (1700 channels)
  - Total of 61200 $PbWO_4$ crystals
  - Avalanche Photo-Diode readout (APD)
  - Coverage $|\eta| < 1.48$

- **Endcaps (EE):**
  - Four half-disk Dees (3662 channels)
  - Total of 14648 $PbWO_4$ crystals
  - Vacuum Photo Triode readout
  - Coverage: $1.48 < |\eta| < 3.0$

- **Preshower**
  - Two Lead/Si planes
  - 137,216 Si strips (1.8 × 61 mm 2)
  - Coverage: $1.65 < |\eta| < 2.6$







Simulation of ECAL response

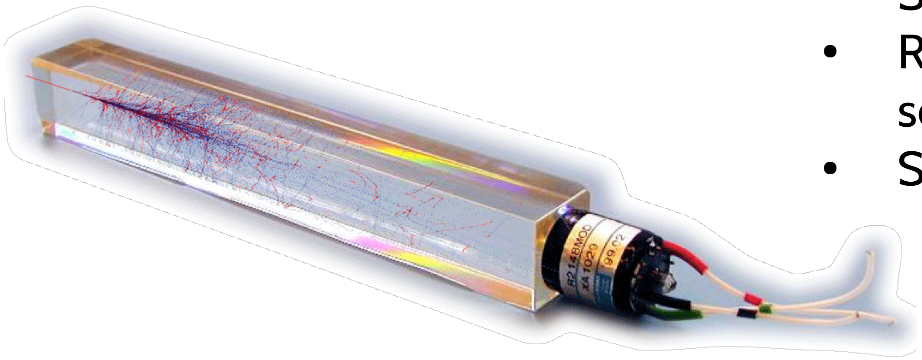
- **Simple strategy:**
  - Simulate energy depositions in crystal volume with GEANT4
  - Assume the response of ECAL channel is (almost) proportional to energy depositions

→ Full Simulation:

- Step1: Energy depositions with GEANT4
- Step2: Propagation of Scintillation/Cherenkov photons
- Step3: Pulse shape at front-end stage and digitization

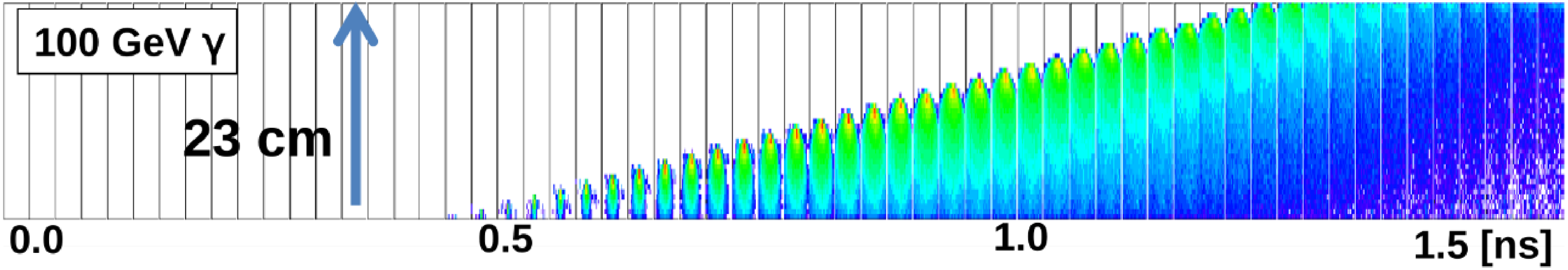
→ Time evolution of photo-detector noise and crystal response

Step1: Energy depositions with GEANT4



- Standard simulation of EM shower in crystal material
- Record energy depositions to be converted into scintillation light
- Simulate Cherenkov radiation

→ Record time of individual depositions to simulate time evolution of EM shower



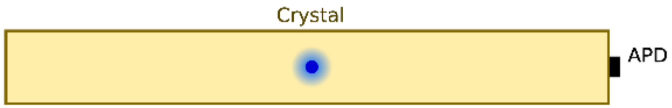
Step2: Propagation of Scintillation/Cherenkov photons

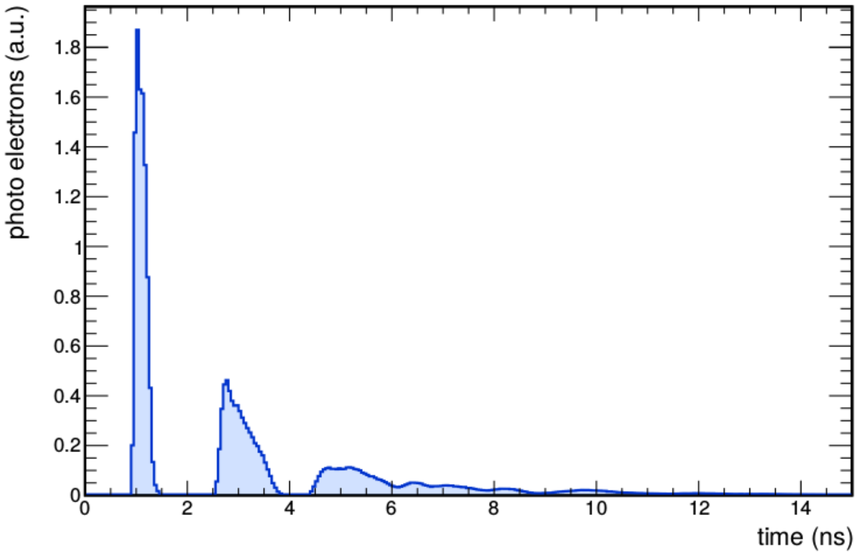
- **Transport of optical photons from emission point to photo-detector** (GEANT4 in full simulation, Litrani[1] for detailed studies)

- **Input information:**
  - Geometry of ECAL crystal (trapezoid)
  - Geometry of photo-detectors
  - Quality of surface polishing
  - Properties of wrappings
  - Decay times of $PbWO_4$ scintillation
  - Wavelength dependent parameters:
    → *Spectrum of emitted photons*
    → *Absorption of $PbWO_4$*
    → *Refractive index of crystal, glues, entrance windows*
    → *Photon-detection efficiency of APDs and VPTs*

[1] F. X. Gentit, "Litrani: a general purpose Monte-Carlo program simulating light propagation in isotropic or anisotropic media", NIM A 486 (2002) 35-39 https://doi.org/10.1016/S0168-9002(02)00671-X

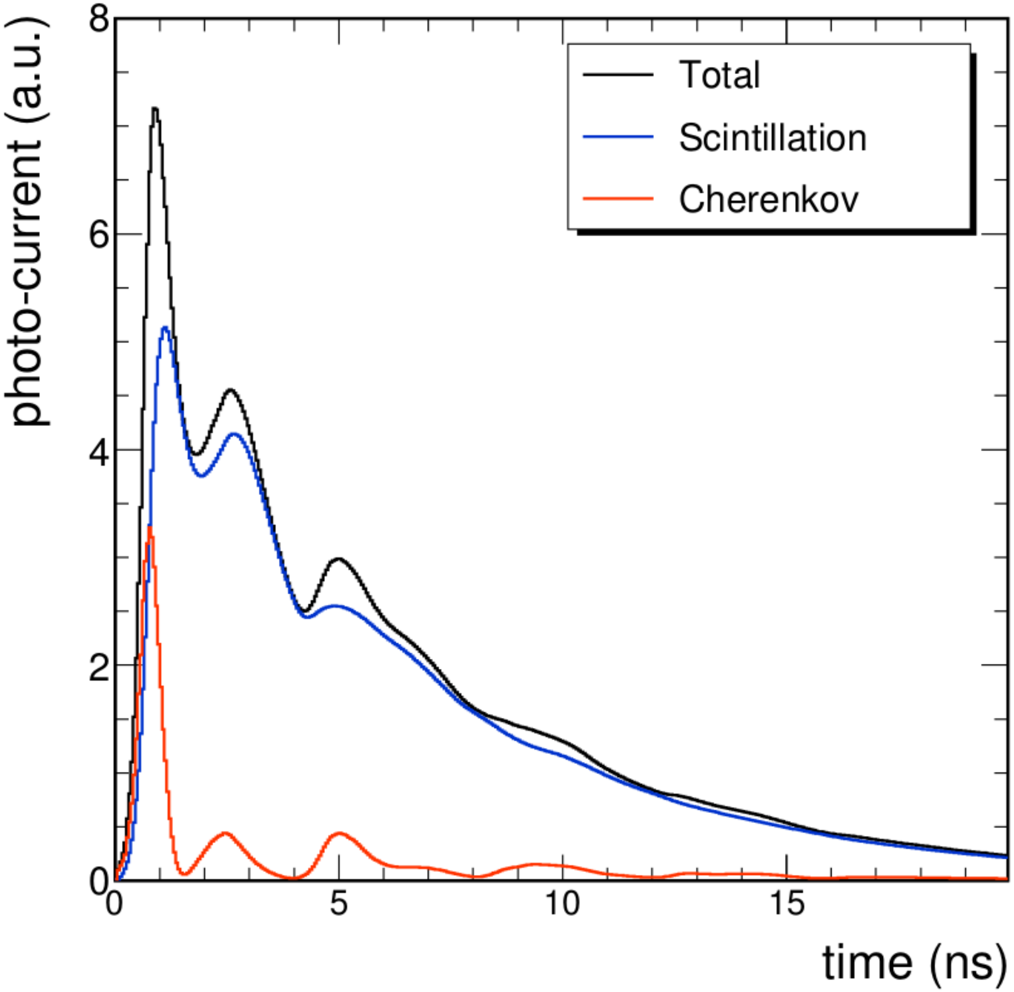
Step2: Propagation of Scintillation/Cherenkov photons





- **Time distribution of detected photons:**
  → Emitted isotropically from the center of a crystal at t=0
  → Depends on emission point of scintillation
- **Discrete structure** due to photons in forward and backward directions
- **Width of the peaks** due to dispersion and finite size of the photo-detector
- **90% of light yield collected within 25 ns**

Average pulse shape of photo-current from EM shower



Step3: Pulse shape at digitization

- **Pulse shape at digitization step:** photo-current pulse convoluted with single pulse response (SPR) function of the front-end

- **SPR:**
  → Include internal capacitance of APDs, inductance and capacitance of cables
  → Measured with short laser pulses and nucleon interaction with APDs

- **Two front-end electronics:** legacy Phase-1 and upgrade prototype for HL-LHC

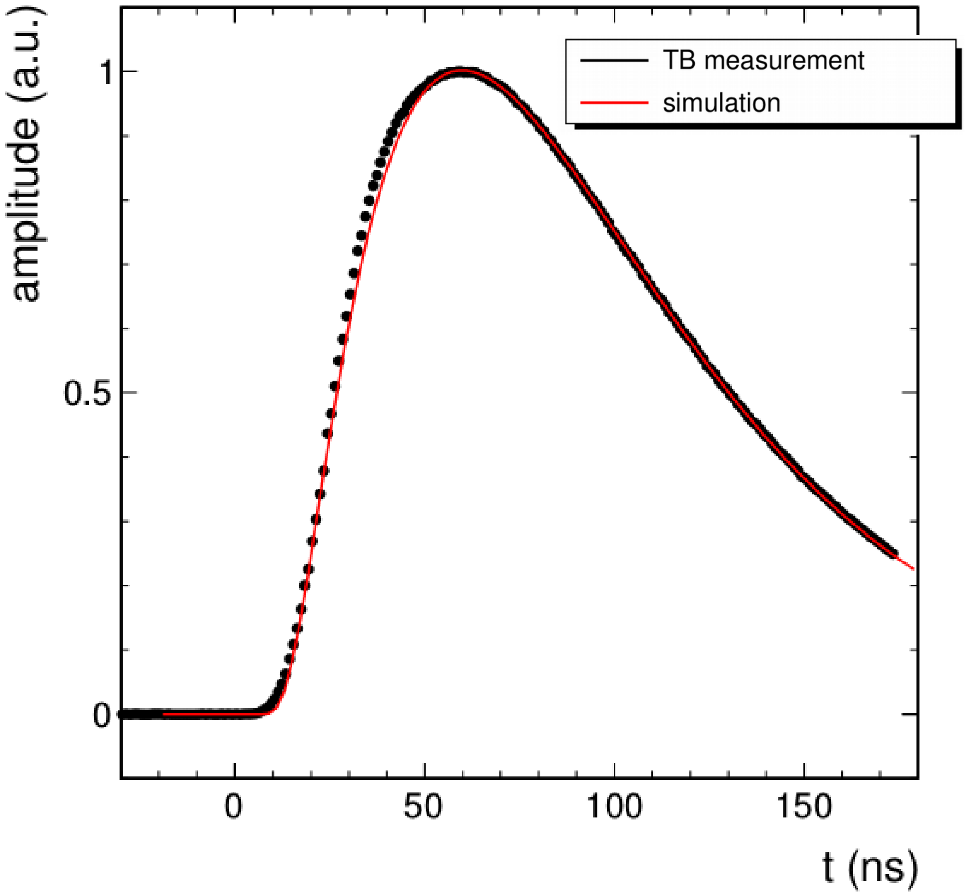
Legacy Phase-1:

→ CR-RC shaping
→ τ = 43 ns
→ Average EM shower pulse shape measured at test beam

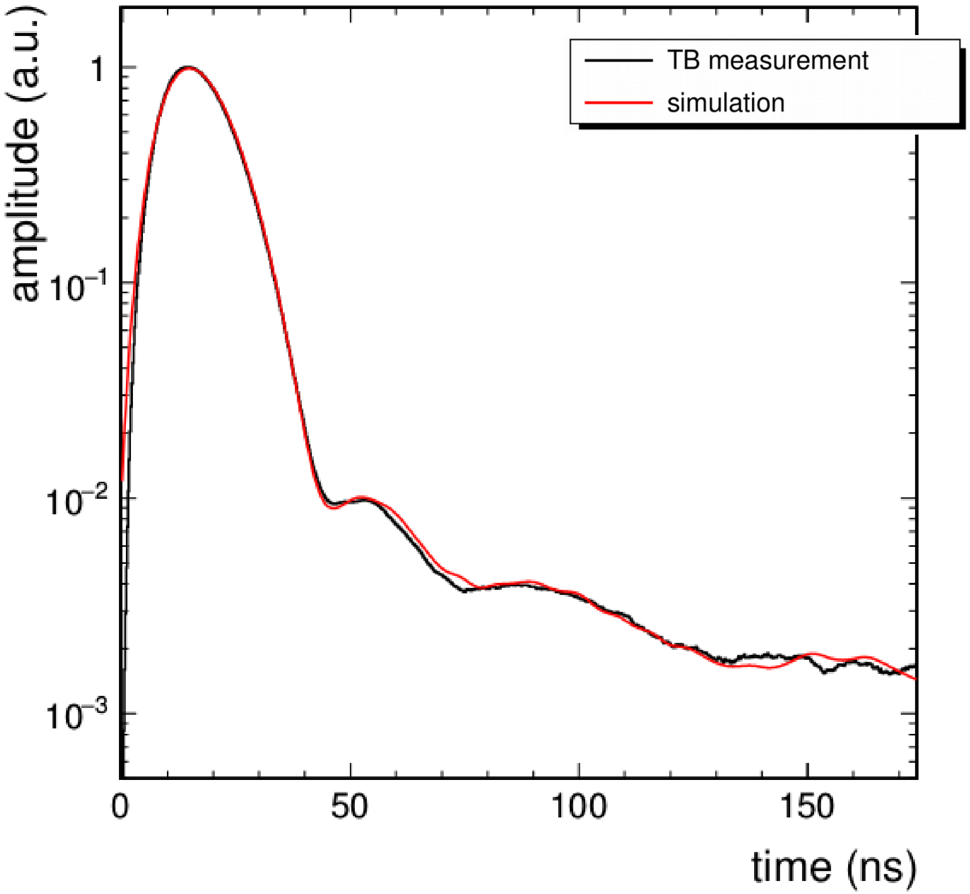
Upgrade prototype for HL-LHC:

→ Trans-Impedance Amplifier (TIA) architecture
→ Minimal pulse shaping
→ Average EM shower pulse shape measured at test beam

Step3: Pulse shape at digitization

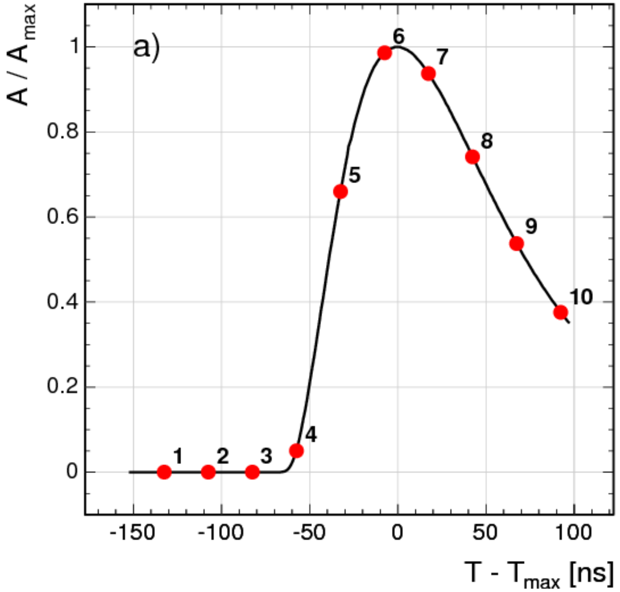


Legacy Phase-1:
43 ns shaping time and sampling ADC at 40 MHz



HL-LHC prototype:
minimal shaping time and sampling at 160 MHz

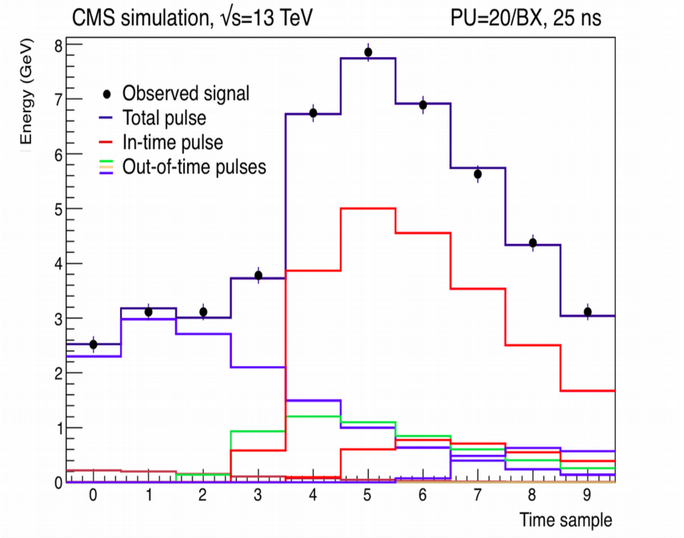
Readout data frame and reconstruction: Legacy Phase-1



- **Pile-up simulation:**
  → in-time and out-of-time PU from -12 to +3 bunch-crossing (every 25 ns)
  → Simulate both in time and out-of-time PU

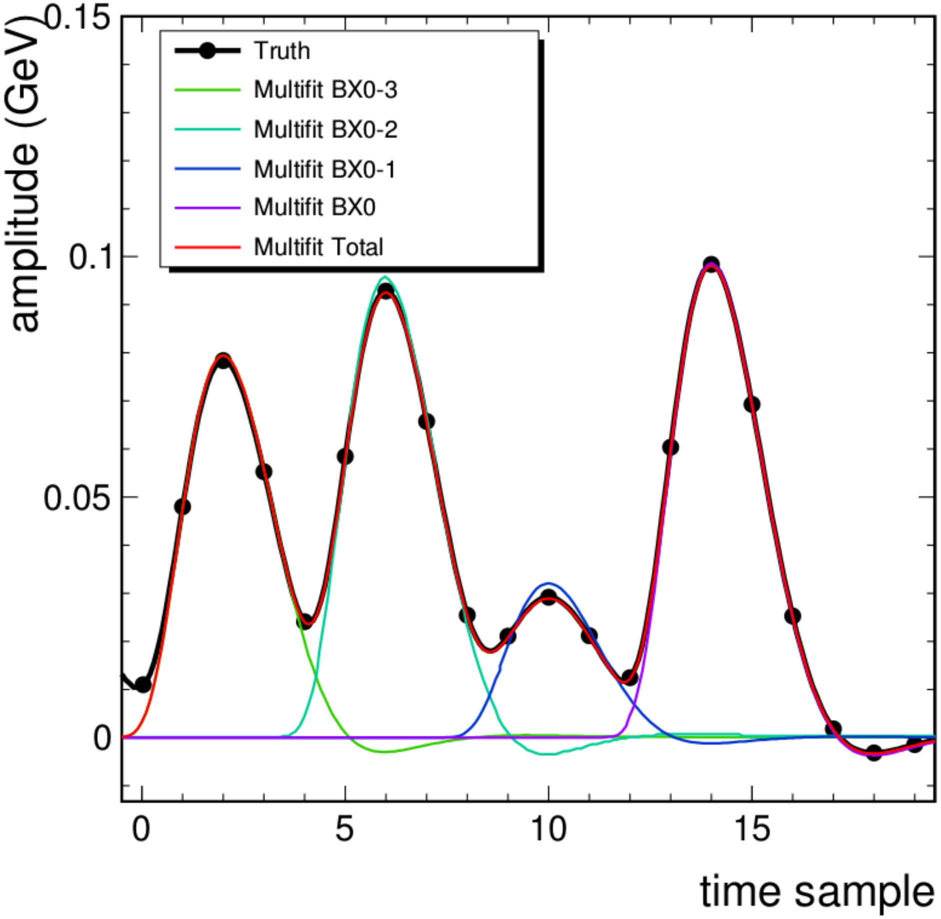
- **Pulse-shaping and digitization:**
  → 43 ns shaping time and sampling ADC at 40 MHz
  → Storing 10 samples from each bunch-crossing

- **Energy reconstruction:**
  → Multifit:
  Estimates the in-time signal amplitude and up to 9 out of time amplitudes



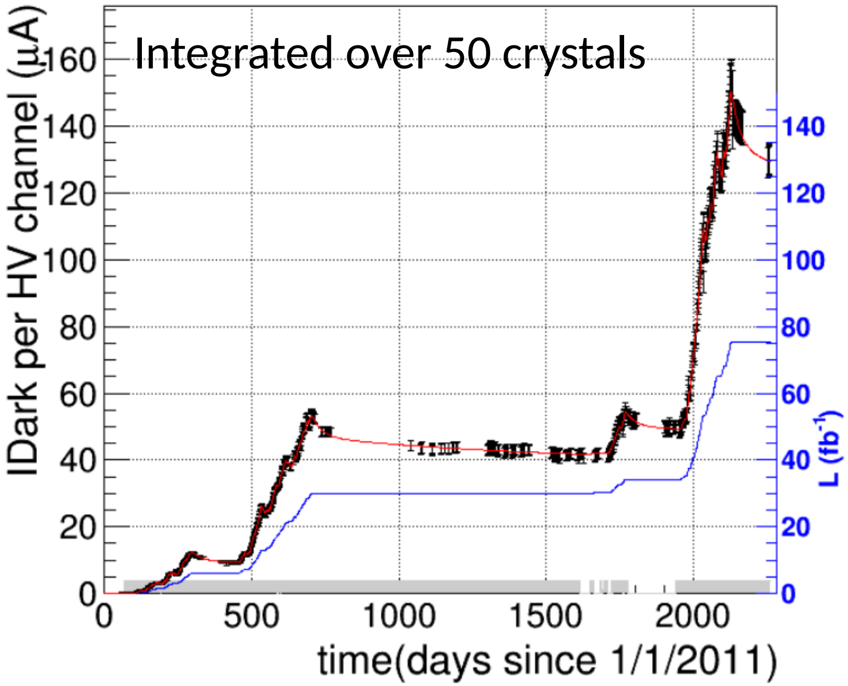
Readout data frame and reconstruction: HL-LHC Prototype

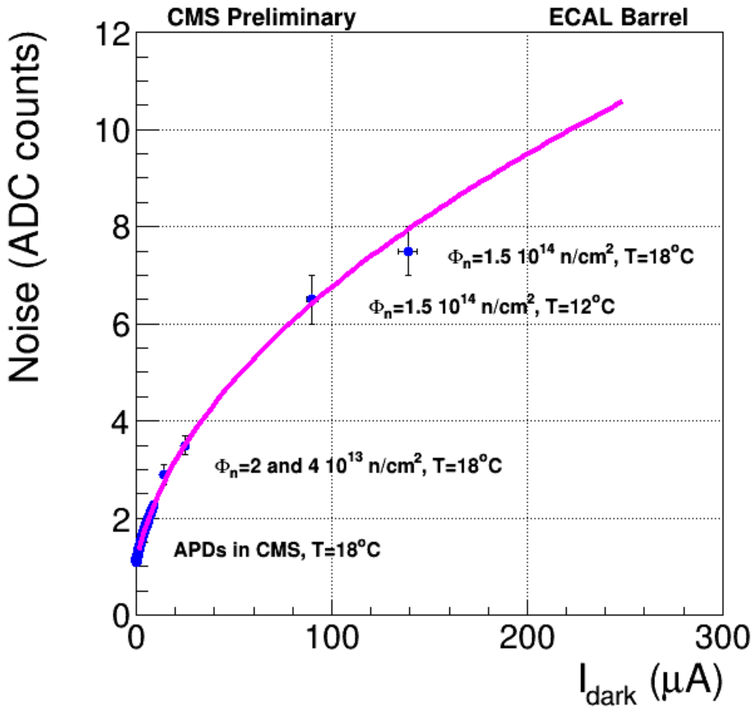
- **Pulse-shaping and digitization:**
  → minimal shaping time with TIA architecture
  → ADC sampling at 160 MHz
- **Energy reconstruction:**
  → Multifit: same strategy as Phase-1



Noise evolution of photo-detectors

- **VPT noise not affected by radiation** → noise constant in time (≈2ADC)
- **APDs noise evolution:**
  → Noise increases due to the radiation-induced increase of the APD leakage current
  → Dark current evolution fitted with 3 exponentials and one permanent damage term
  → Measurement of the dark current–Noise dependence


Integrated over 50 crystals


CMS Preliminary

ECAL Barrel

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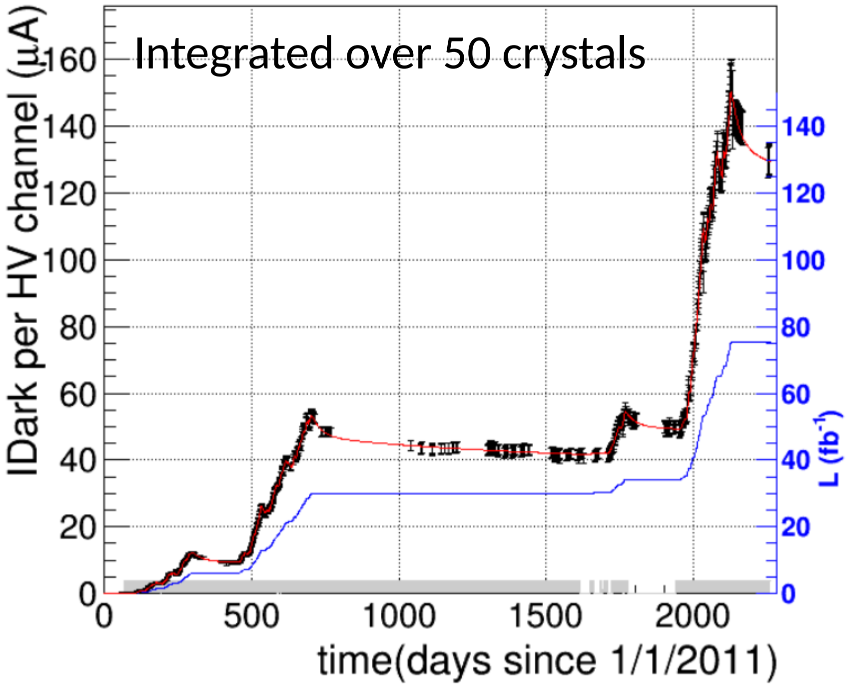
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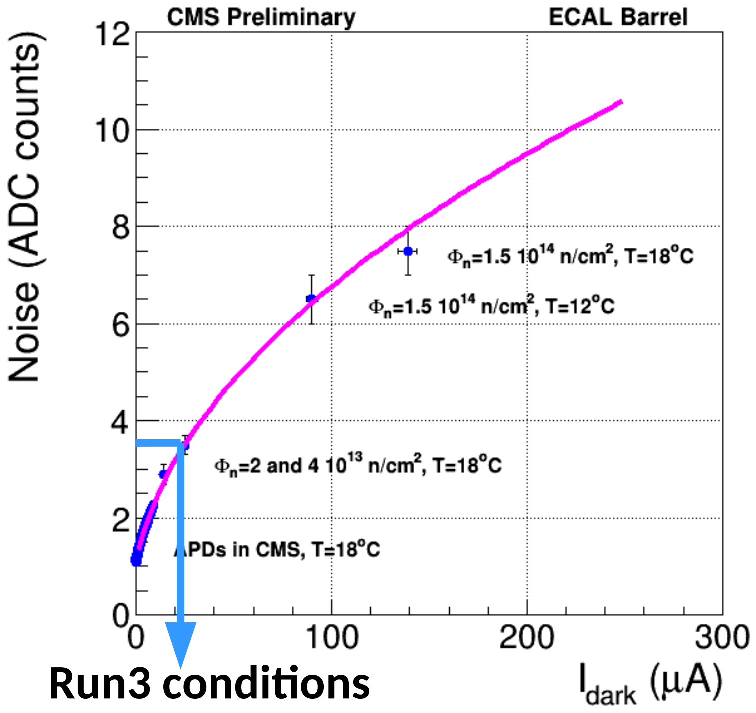

Run3 conditions

Noise evolution of photo-detectors

- **VPT noise not affected by radiation** → noise constant in time (≈2ADC)
- **APDs noise evolution:**
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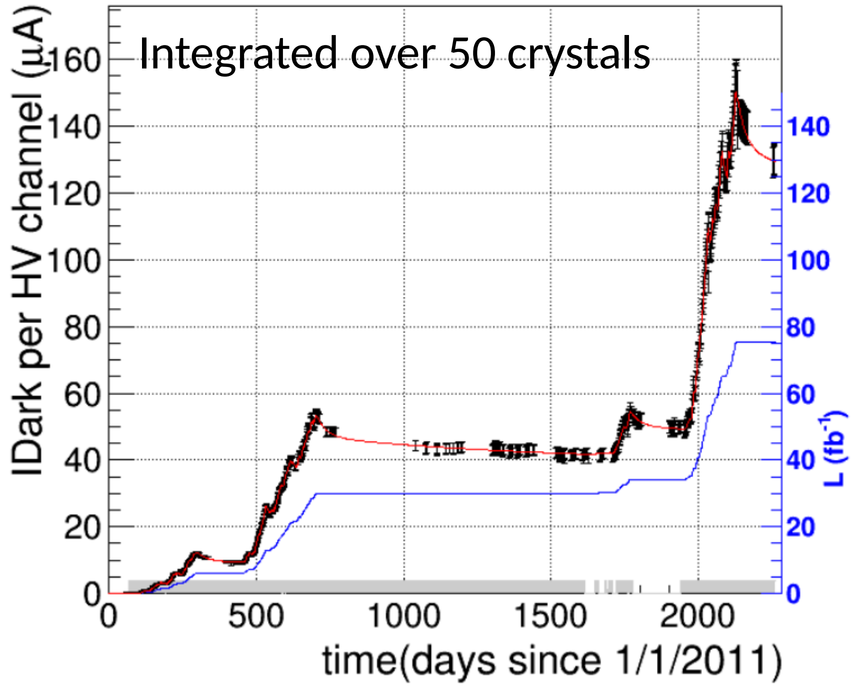
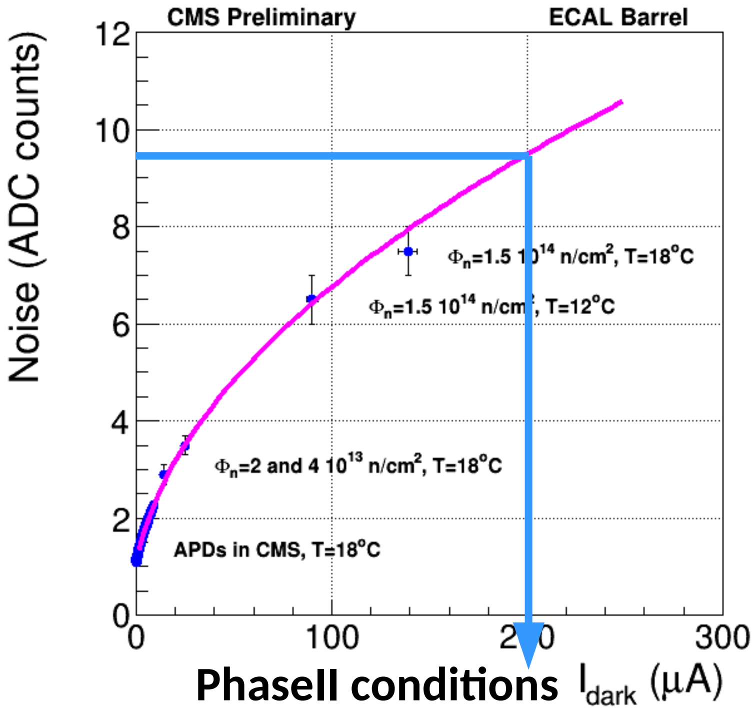
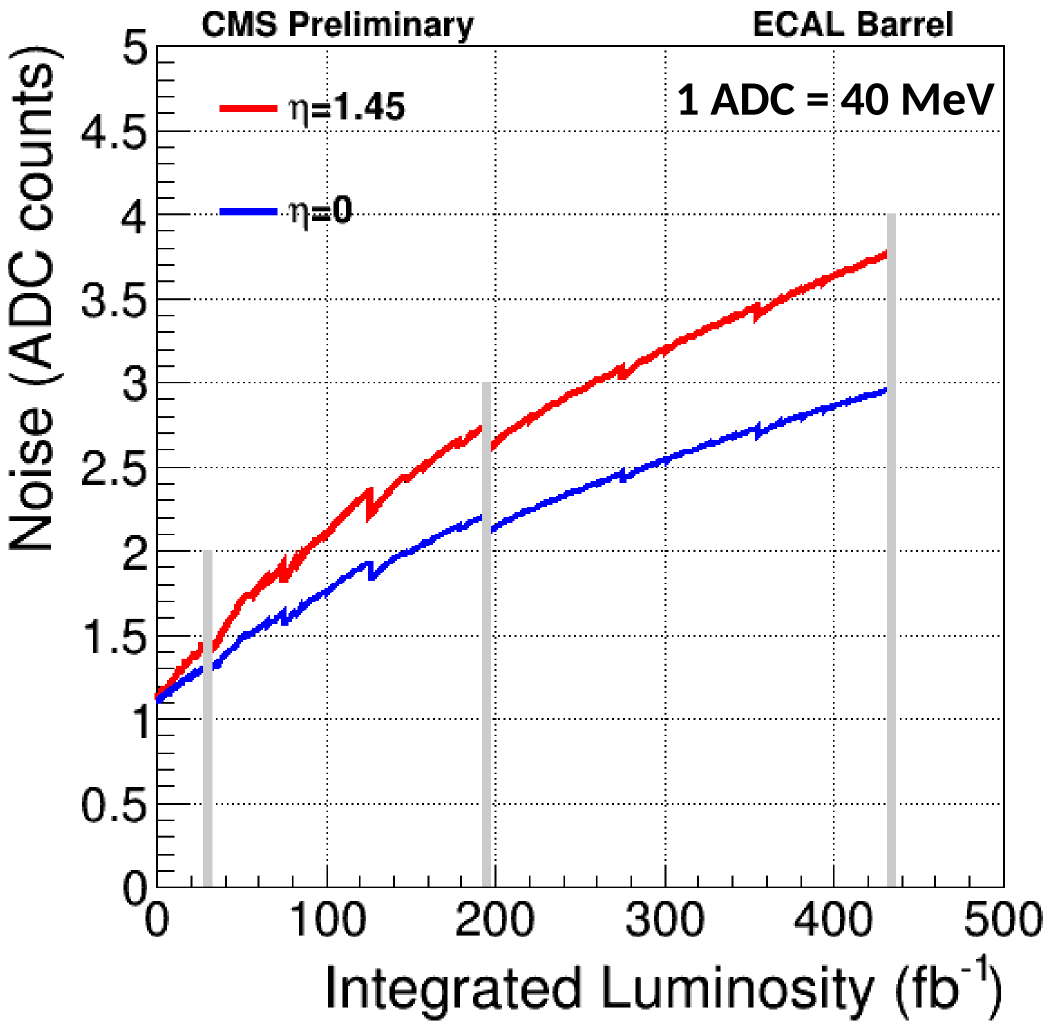
  → Measurement of the dark current–Noise dependence





PhaseII conditions

Prediction of noise evolution

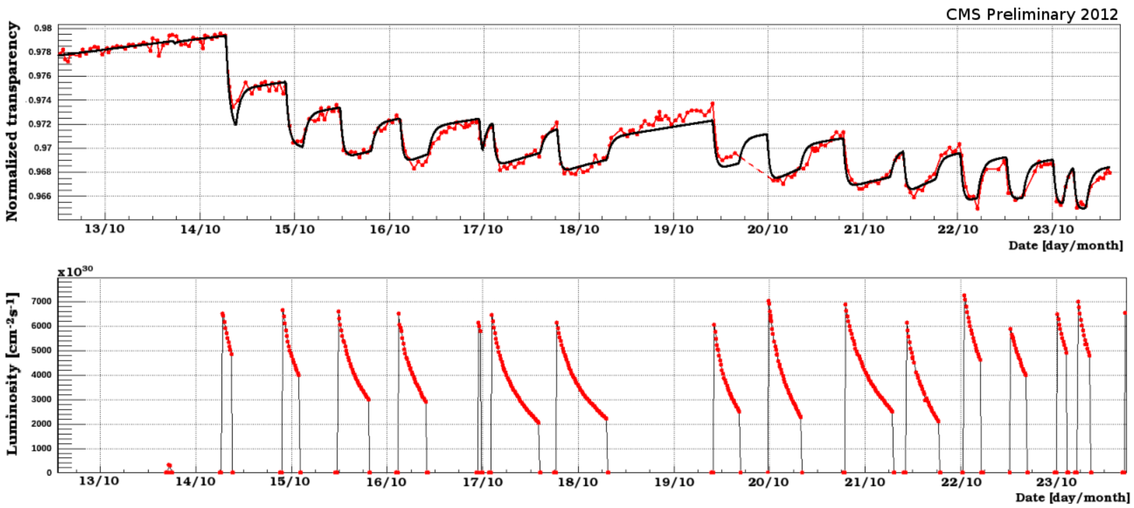


Simulation of crystal response

- **Radiation damage** results in development of absorption and scattering centers
  → **loss of transparency in crystals**

- **Radiation damage changes pulse shapes:**
  → Loss in amplitude
  → Non-linearity of response

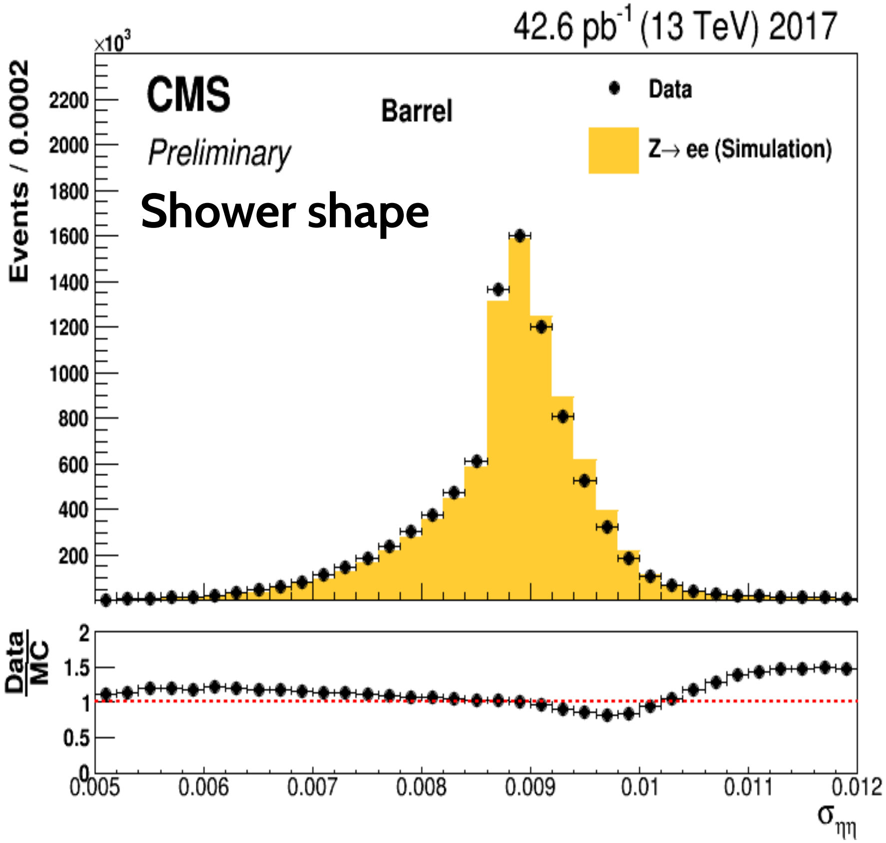
- **Worsening of energy resolution**
  → Deterioration of the stochastic term
  → Noise increase
  → Deterioration of light collection uniformity

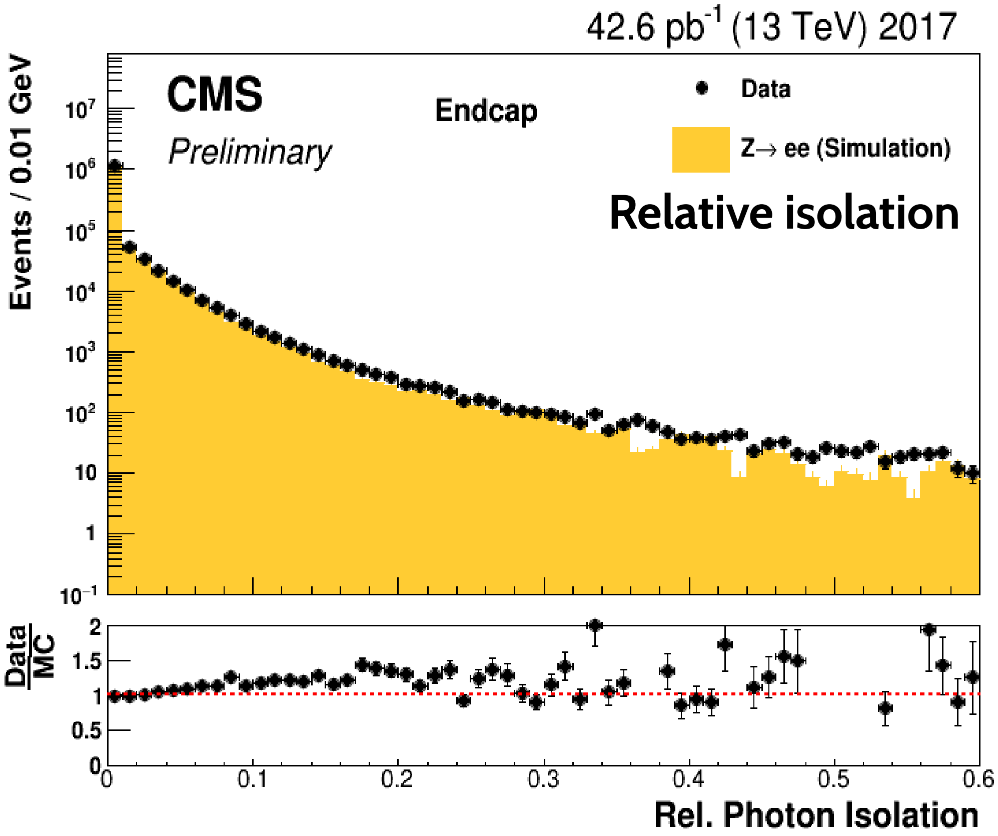


→ Fit to the data transparency loss used for short term prediction of the aging

Data and simulation agreement

- Aging models used for predicting conditions on short term for the on-going data taking
- At the end of the year conditions taken from data to re-generate latest simulations
- Additional improvement: use evolving conditions in the simulation taken from the data (CERN-PH-EP-2015-006,CERN-PH-EP-2015-004)

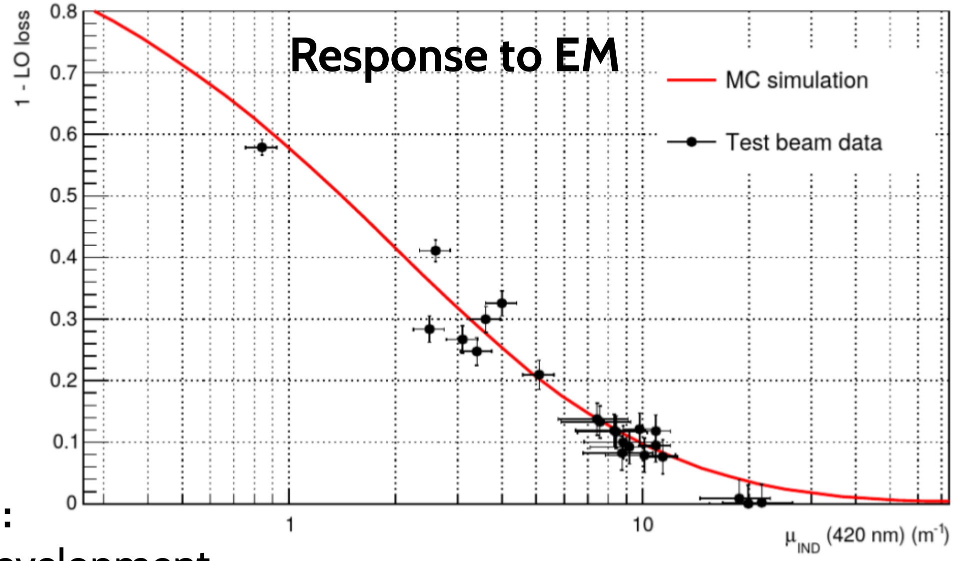




Simulation of crystal response: PhaseII predictions

- **Parametrized with induced absorption: $\mu_{ind}(x,\lambda)$:**
  → Effective loss of light on a path of length L
  → Affecting propagation of optical photons from emission point towards photo-detector

$$LY/LY_0 = \exp(-\mu_{ind}(x,\lambda)\, L)$$



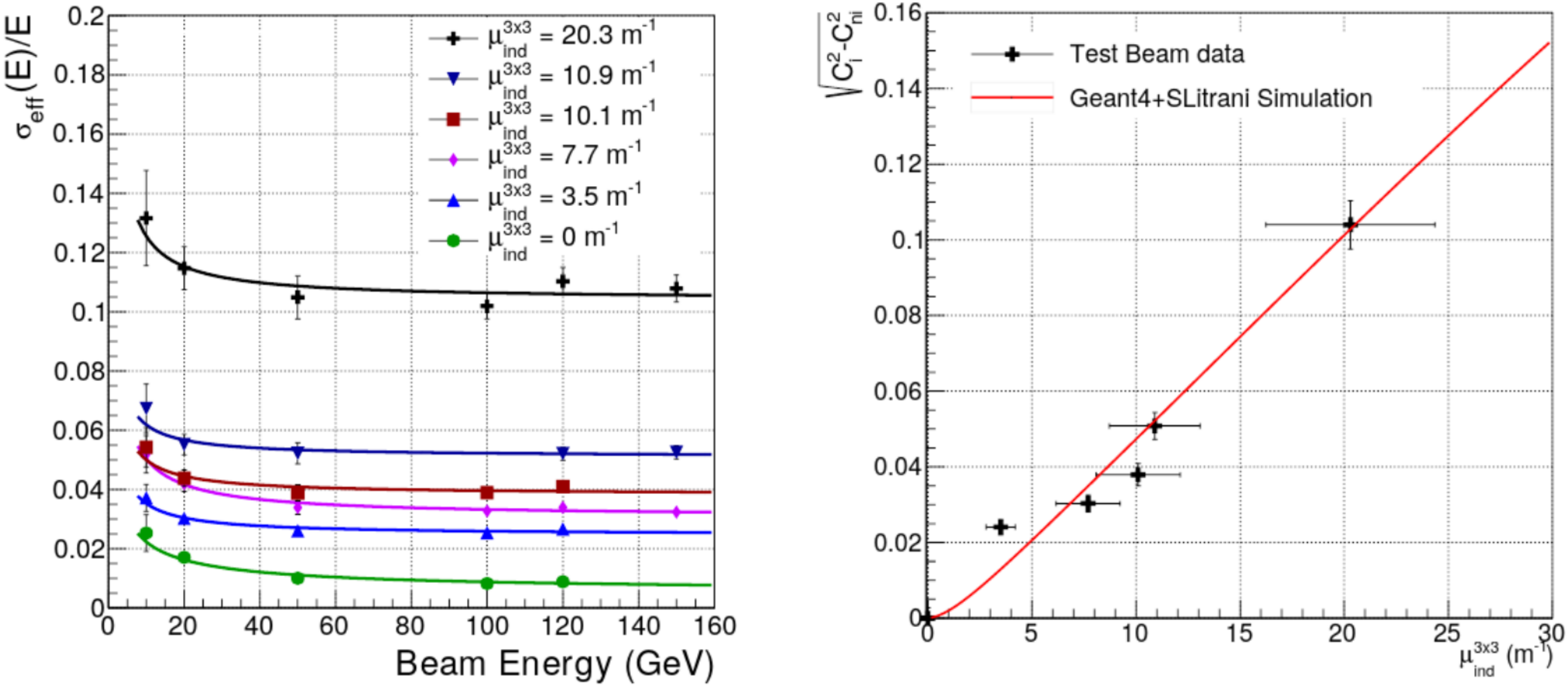
CMS: JINST 11 P04012 (2016):
→ Light output loss as a function of the induced absorption coefficient
→ 2012 Test beam data
→ MC simulation with GEANT4+SLitrani

- **Model to predict response of crystals during Phase II:**
  → Full model with simulation of the GEANT shower development
  → Ray tracing inside the crystals
  → Ageing of crystals and photodectors as a function of wavelength
  → Dose and fluence from FLUKA[2] simulation

- **Many test beam measurements to verify and refine the models**

[2] C. Battistoni, et al., "The FLUKA code: description and benchmarking", https://doi.org/10.1063/1.2720455

Energy resolution degradation

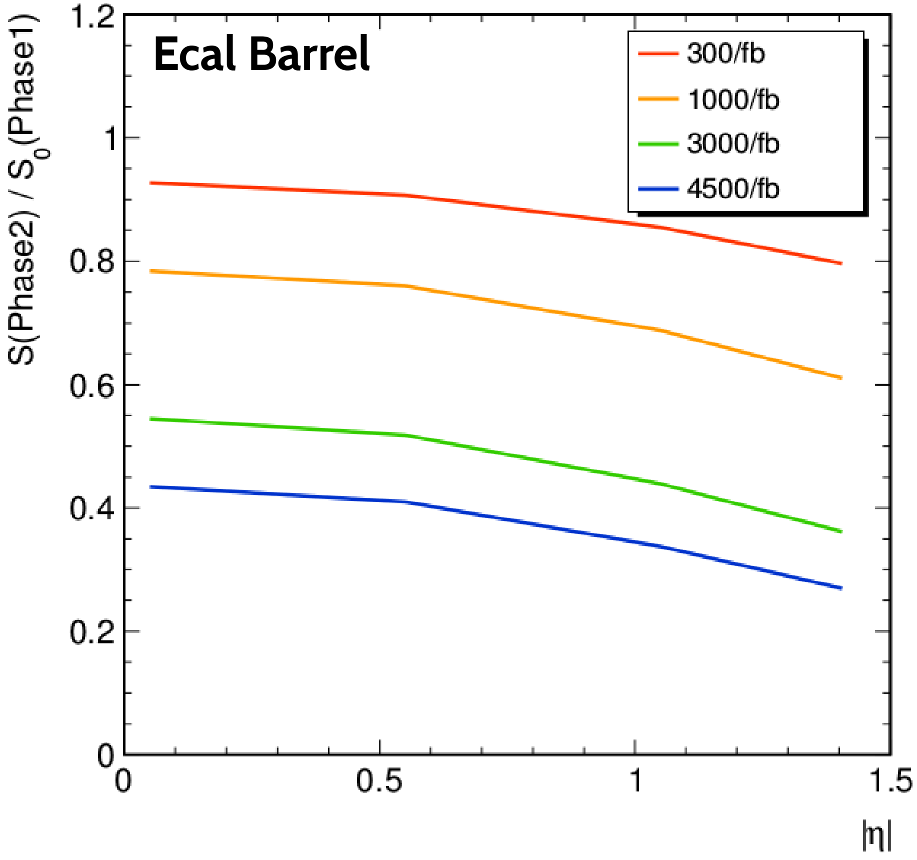


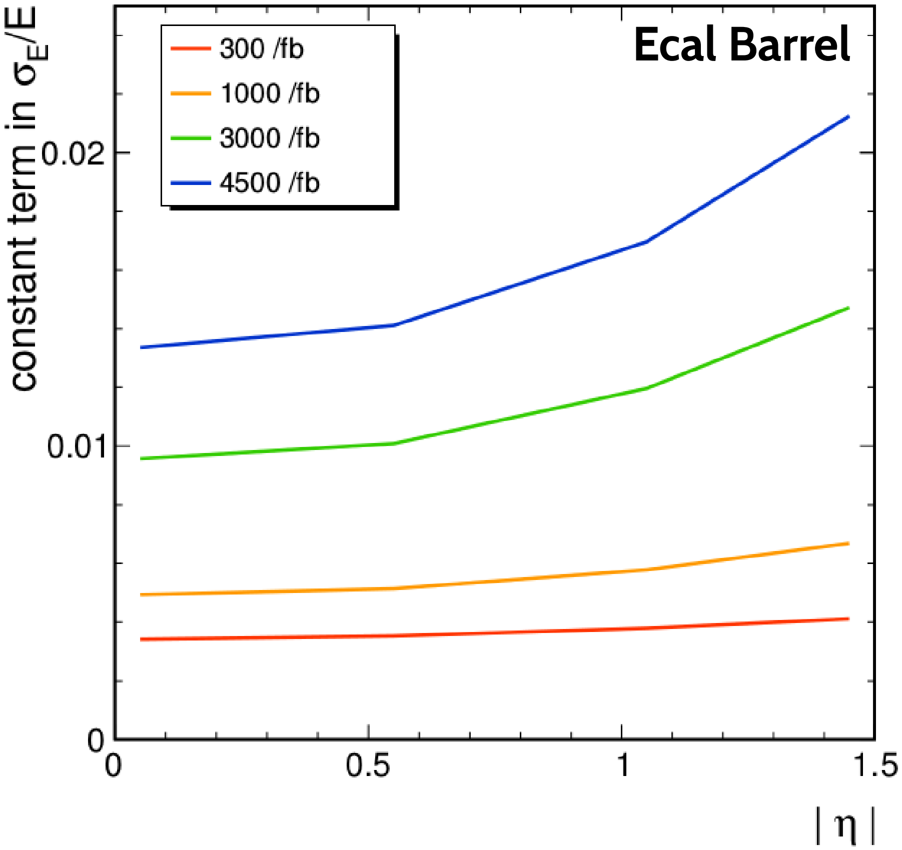
→ CMS: JINST 11 P04012 (2016):

Left: resolution degradation for different induced absorption coefficients

Right: increase of resolution constant term as a function of induced absorption coefficient, comparison of the TB with the model

Prediction of crystal response loss: PhaseII predictions





Summary

- **CMS ECAL detector designed for excellent energy resolution for photons with 0.1 MeV-1.5 TeV:**
  → 75848 lead-tungstate ($PbWO_4$) scintillating crystals
  → Signal read by APDs (in EB) and VPTs (in EE)

- **Full Simulation:**
  - **Step1:** Energy depositions with GEANT4
  - **Step2:** Propagation of Scintillation/Cherenkov photons
    → Simulate both the propagation of scintillation and Cherenkov light
  - **Step3:** Pulse shape at front-end stage and digitization
    → Legacy Phase-1: τ = 43 ns shaping time, 40 MHz sampling
    → HL-LHC Prototype: minimal shaping time, 160 MHz sampling

- **Time evolution of photo-detector noise and crystal response for PhaseI and PhaseII:**
  - APD noise evolution predicted using CMS collected data
  - Crystal response evolution predicted using both data (short term) and simulations from GEANT and Fluka (PhaseII)

- **Good agreement between data and simulation!**

Back-up Slides

Upgrade for HL-LHC

- **Reduce the shaping time**, using the TIA architecture
- Test beam measurements reach σ≃ **20 ps, using a 160 MHz sampling**
- **Simulation of individual pulses:**
  → EM shower fluctuations result in <20 ps contribution to timing resolution