Picosecond timing with CMS ECAL lead tungstate crystals.

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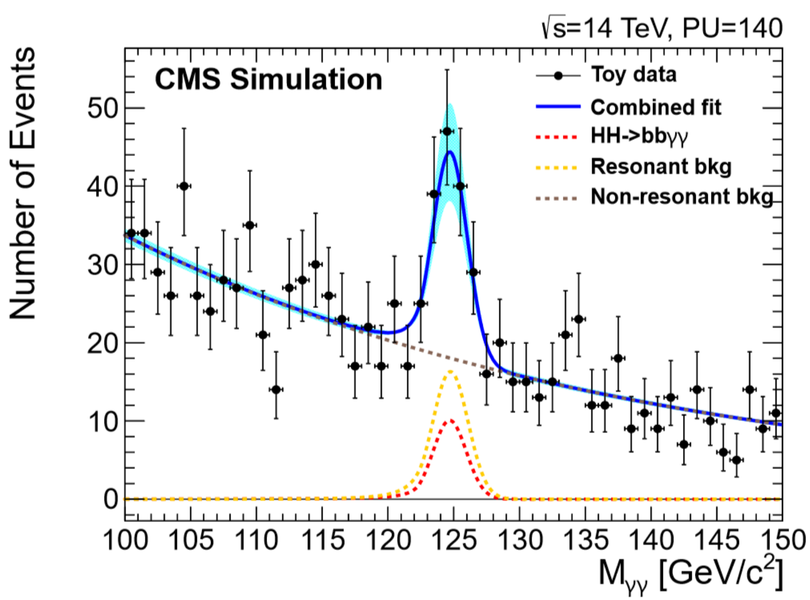
High Luminosity Large Hadron Collider (HL-LHC)

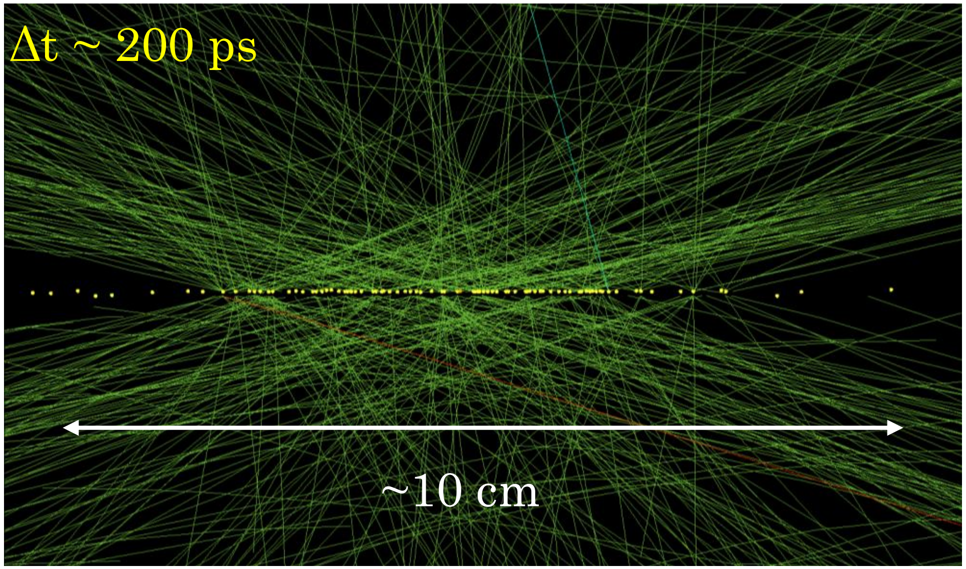
	LHC	HL-LHC
$\sqrt{s}$ (TeV)	7-14	14
Istantaneous luminosity ($cm^{-2}\ s^{-1}$)	$2.2 \cdot 10^{34}$ (2017)	5-7$\cdot 10^{34}$
Integrated luminosity (fb^{-1})	500 (end of 2023)	3000 (2025-2035)
pile-up	40-60	140-200

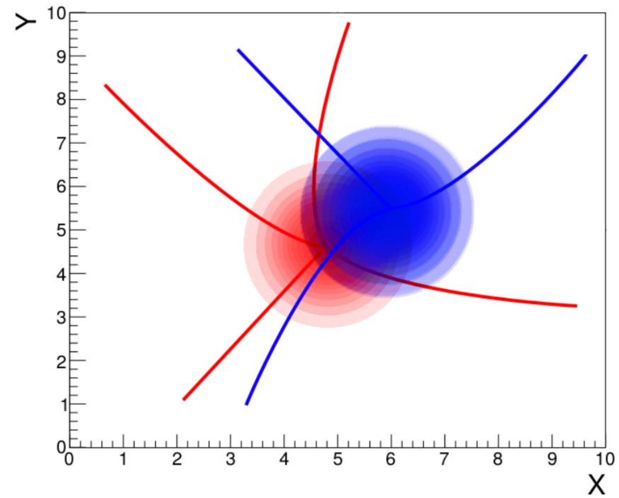
HL-LHC targets:

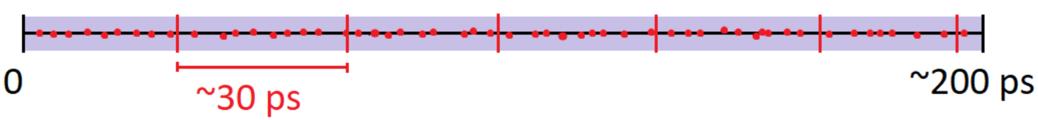
- Better measure of Higgs couplings (10^8 Higgs production)
- Rare processes observation ($HH \rightarrow bb\gamma\gamma$, first seen in 08/2018)
- High precision measurements of stantard model parameters (difference between theory and experiments can be signal of theories beyond standard model)

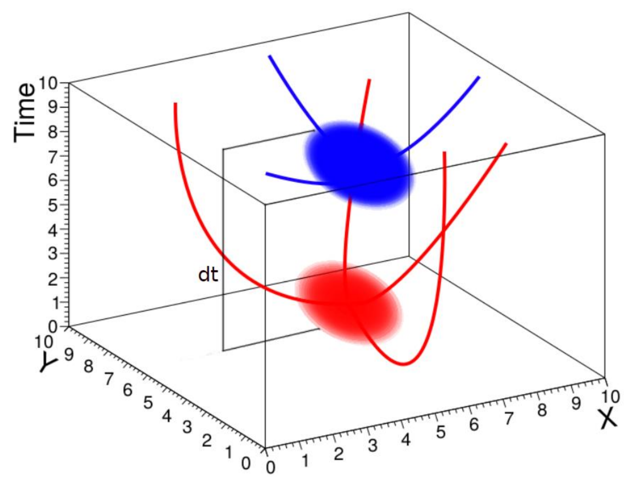


Increased pile-up









Design timing resolution:

$\sigma_t < 30\ ps$ for $E > 50\ GeV$ → photon pile-up reduction of a factor 6 (200÷30)

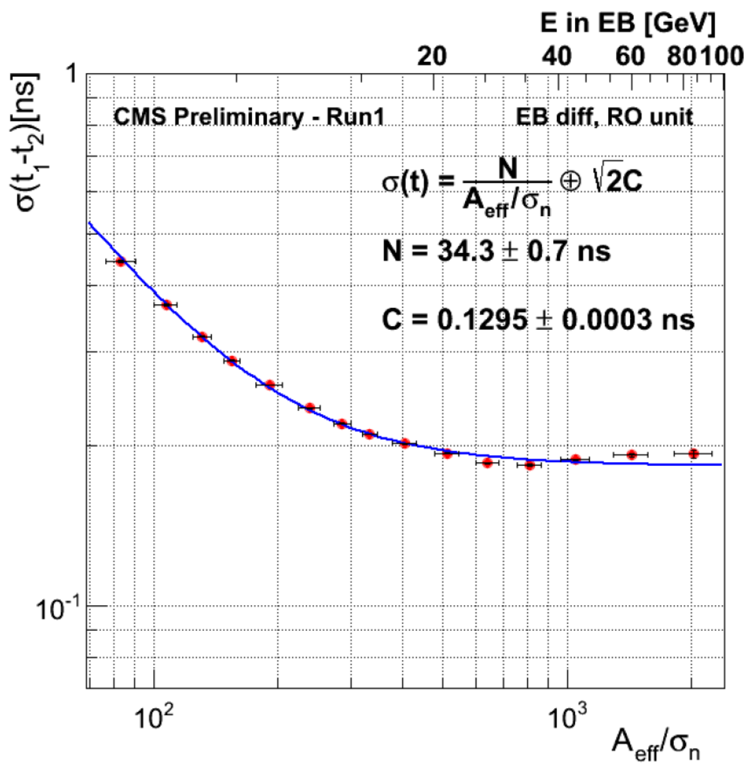
ECAL Timing nowadays

ECAL crystal time resolution:

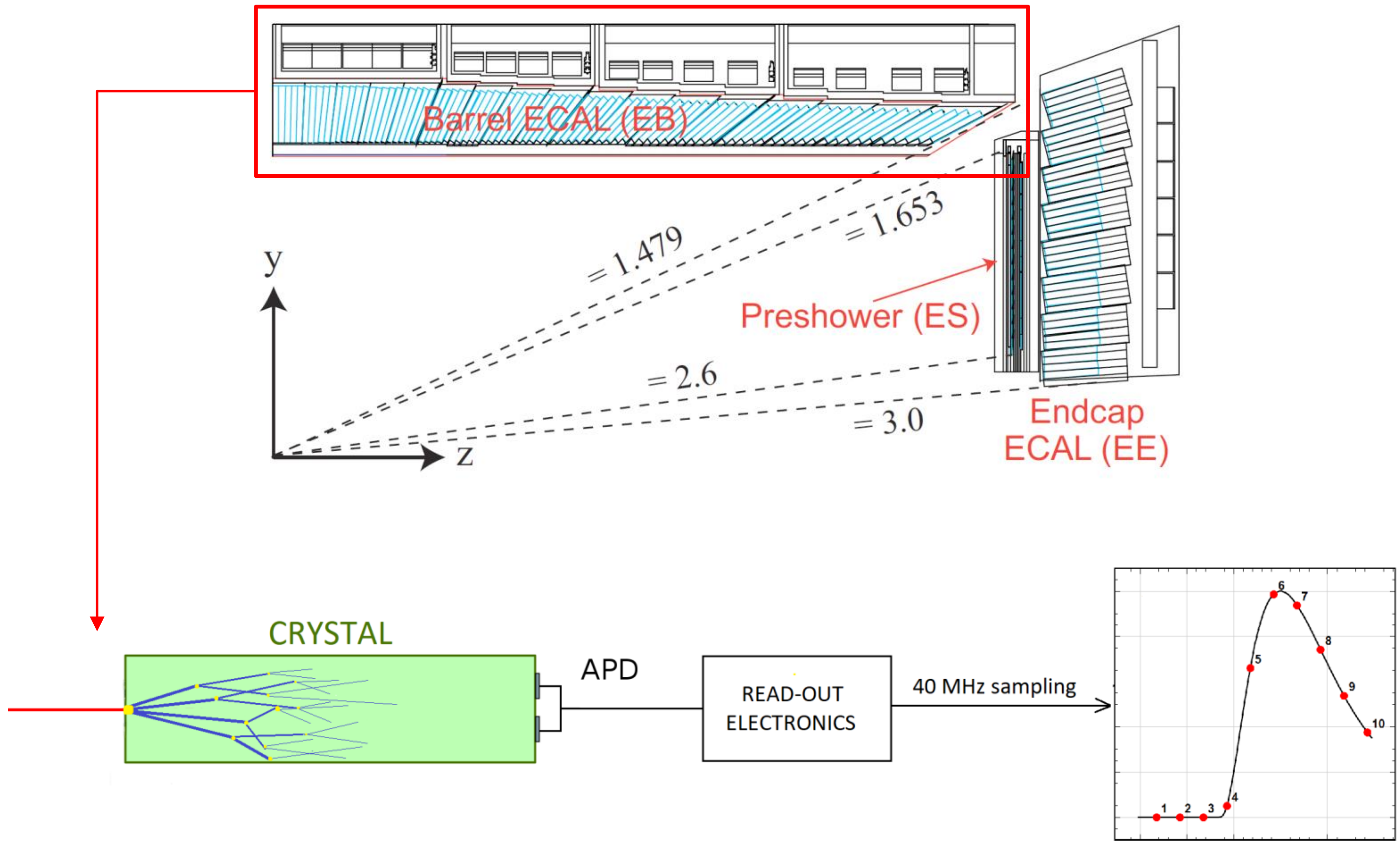
$$\sigma_{t_{Crystal}} = \frac{N}{A/\sigma_n} \oplus C$$

Contributions to crystal time resolution:

- electronic noise → Noise term (N);
- effects of e.m. shower fluctuations in time measurements → Constant term (C);
- errors coming from time reconstruction method → Constant term (C);
- Clock distribution errors→ Constant term (C).



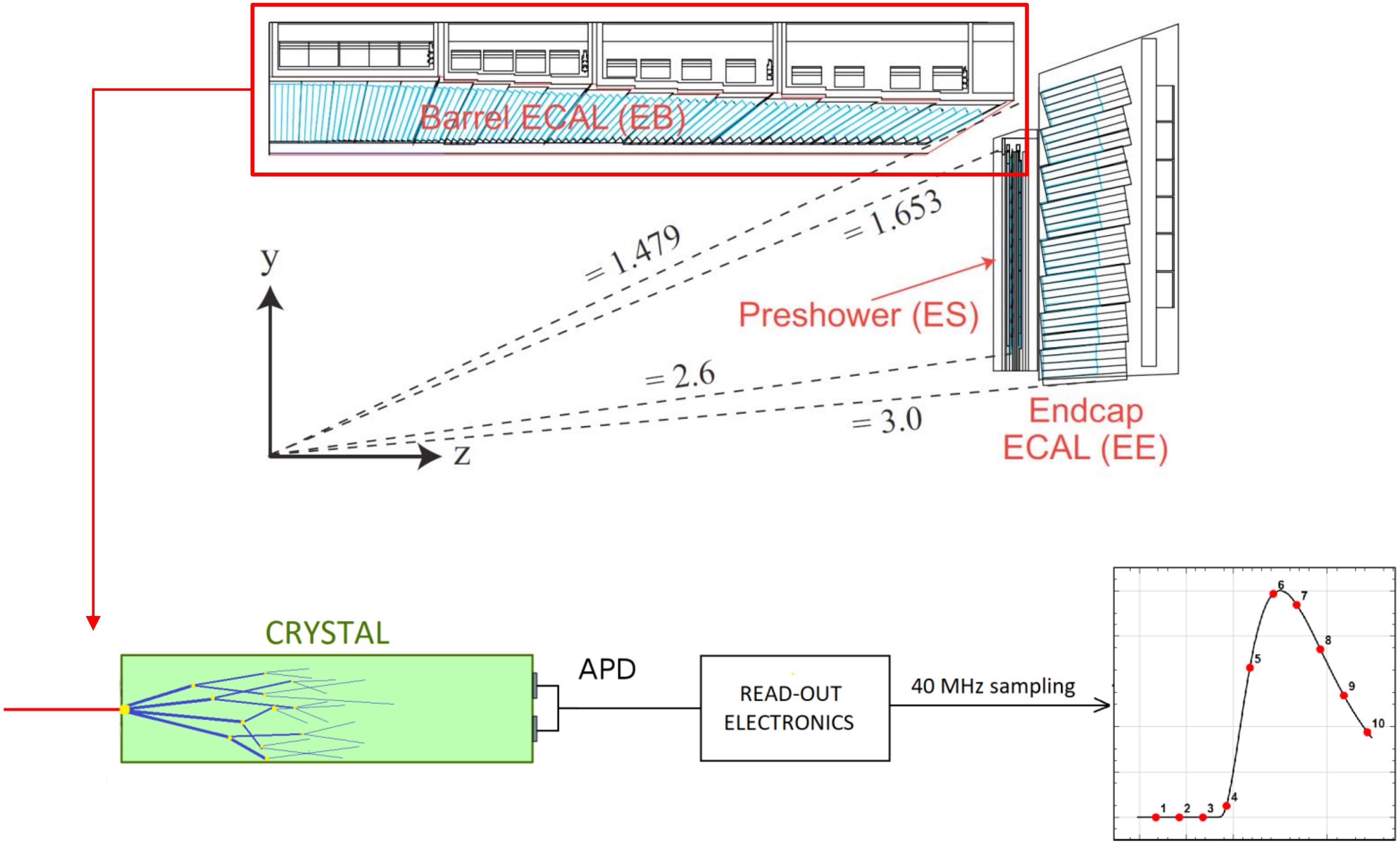
ECAL barrel upgrade



Lead tungstate ($PbWO_4$) crystals:
- Fast scintillation time
- Radiation resistant
- Light yeld: 100 γ/MeV

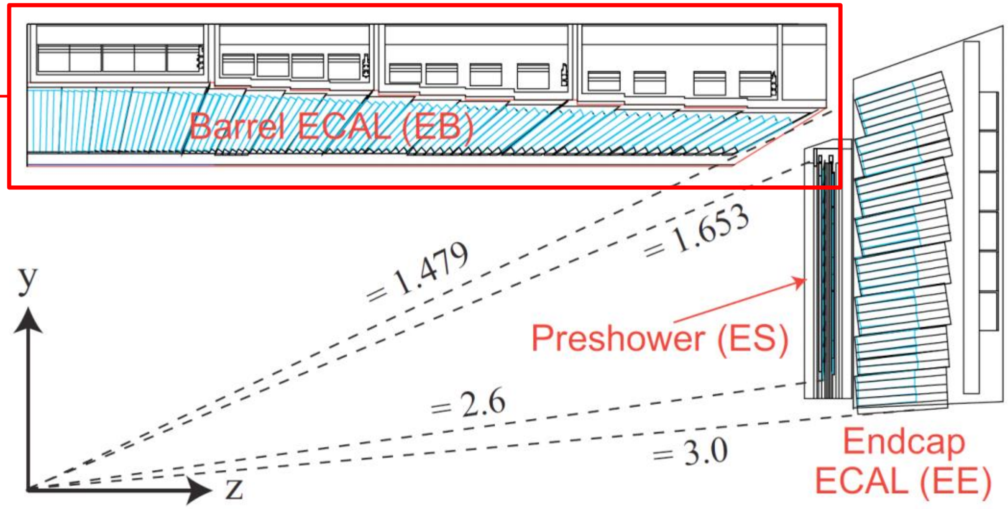
Avalanche Photo-Diode (**barrel**):
- Coupled photodetectors (2 x crystal)
- Radiation resistant

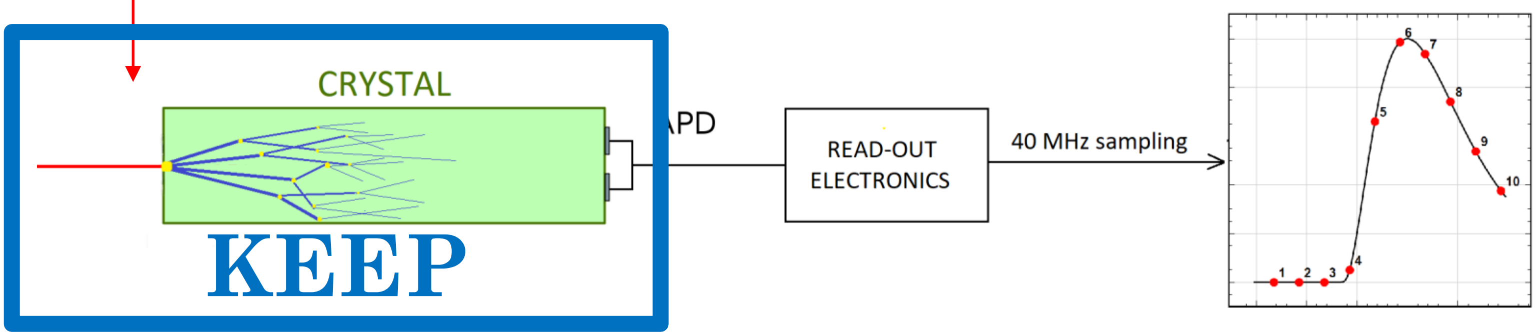
ECAL barrel upgrade



First level trigger latence: 3.2 $\mu s \rightarrow$ 12.5 μs
First level trigger rate: 100 $kHz \rightarrow$ 750 kHz

ECAL barrel upgrade





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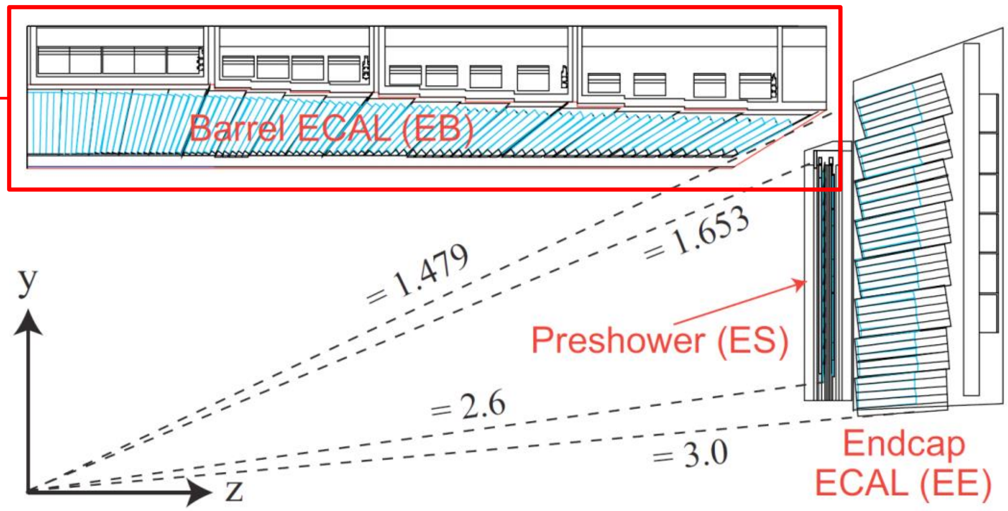
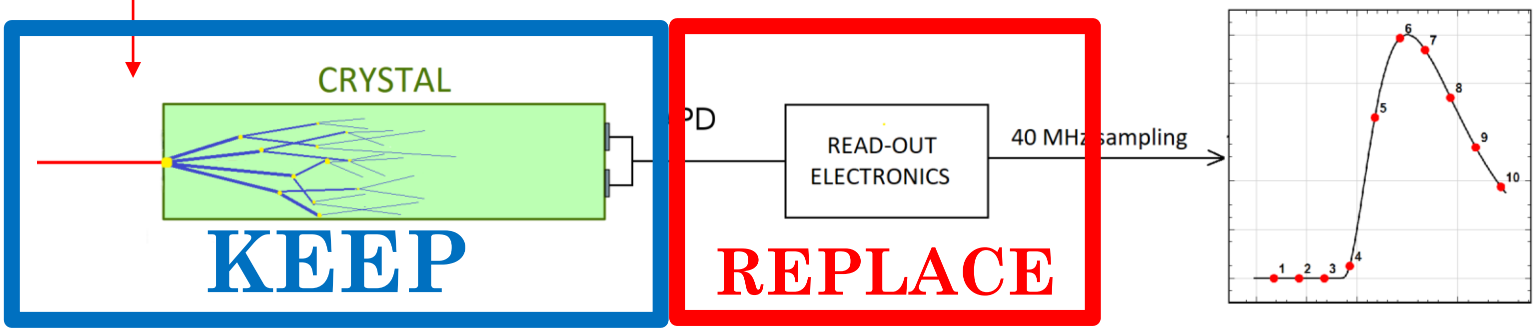
ECAL barrel upgrade





First level trigger latence: $3.2\ \mu s \rightarrow 12.5\ \mu s$
First level trigger rate: $100\ kHz \rightarrow 750\ kHz$

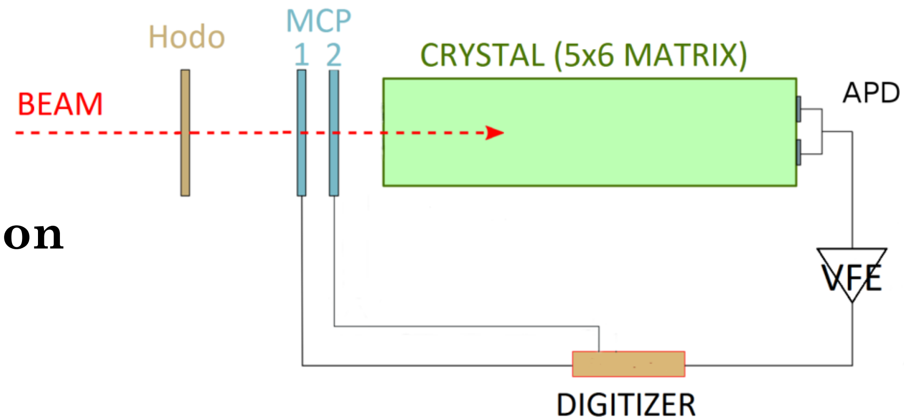
Testbeam setup

My thesis work:

Analysis of ECAL crystal time resolution with the new read-out electronics based on data from 2016 testbeams at the H4 test beam facility (CERN).

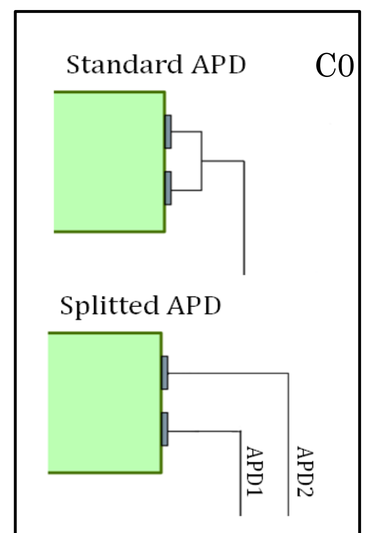
Thesis aim:

Estimation of lead tungstate intrinsic limit in time resolution



Setup:

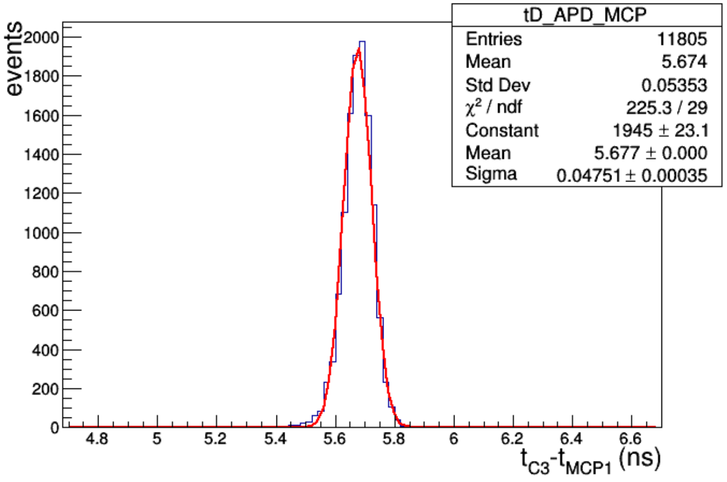
- electron beam: 20, 50, 100, 150, 200 GeV
- 30 crystal matrix read by APD
- 2 MCP ($\sigma_t \sim 20\ ps$)
- 1 crystal with a splitted APD
- VFE equipped with TIA pre-amplifier (Saclay University prototipe)
- external digitizer with 5 GS/s sampling frequency (CAEN V1472)

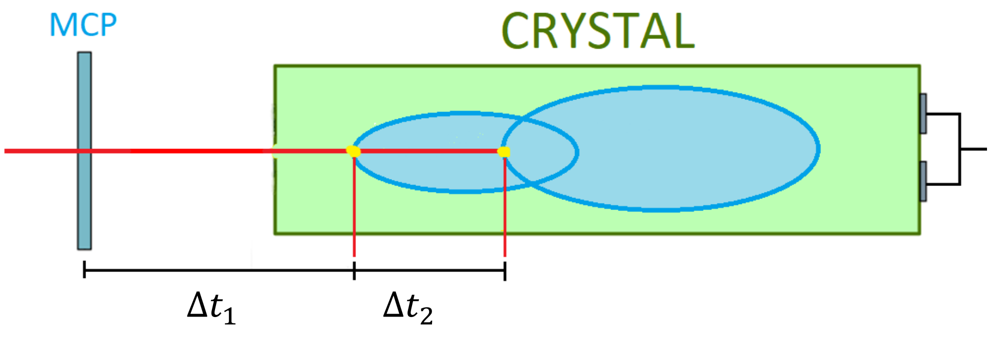


Time resolution of a crystal wrt external time reference

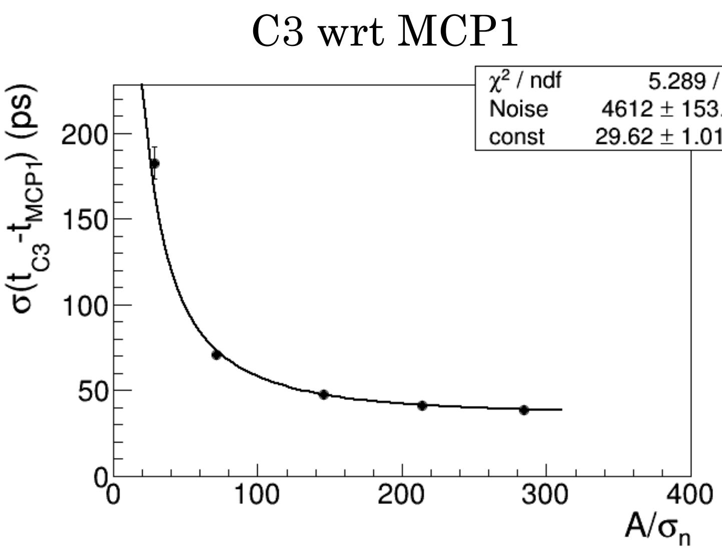
- Time measure sensitive to fluctuation in electromagnetic shower begin point
- Use of an external time reference (MCP) → contribution of the time resolution of the reference to the time resolution of the crystal
- 2 MCP → subtraction of the reference time resolution using a triangulation algorithm

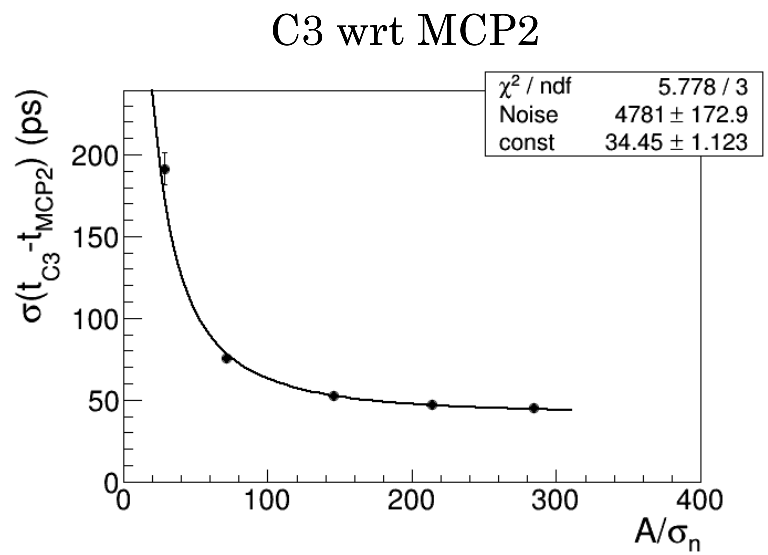
$t_{crystal} - t_{MCP}$ distribution

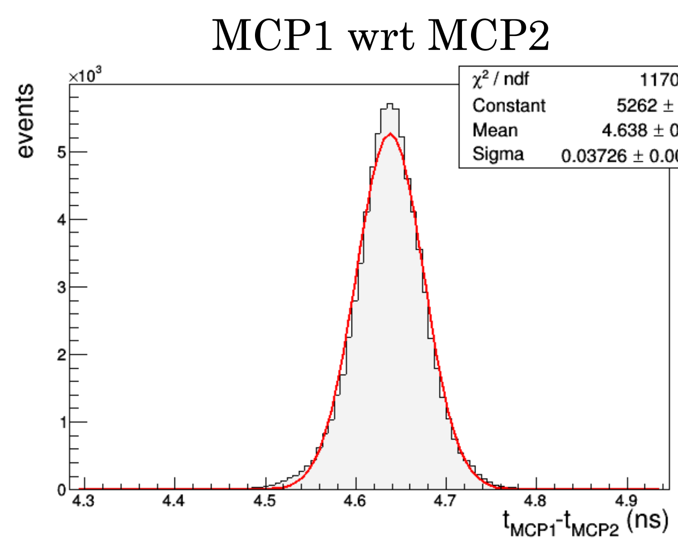




Crystal wrt external reference







Fit function:

$$\sigma(t_C - t_{MCP}) = \frac{N}{A/\sigma_n} \oplus C$$

Noise Term:

$$N \sim 4.5 - 5\, ns$$

Constant term (crystal+MCP):

$$\sigma_{t_{C3}-t_{MCP1}}\left(E \to \infty\right) = 29\ \pm 1\, ps$$

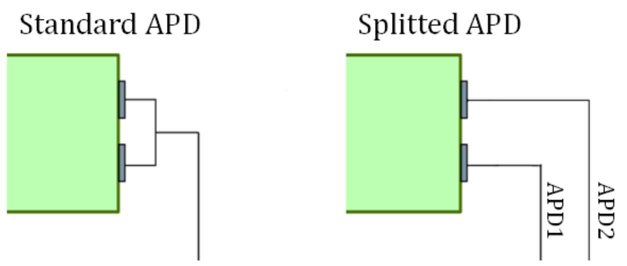
$$\sigma_{t_{C3}-t_{MCP2}}\left(E \to \infty\right) = 34\ \pm 1\, ps$$

De-coupled Resolutions at high energies

APD Gain	Crystal (C3) (ps)	MCP1 (ps)	MCP2 (ps)
50	17 ± 2	23 ± 2	30.1 ± 0.7
100	19 ± 2	23.3 ± 0.6	29.4 ± 0.7
Average	18 ± 1	23.3 ± 0.4	29.4 ± 0.3

Limit time resolution below 30 *ps*

Time resolution of two single APDs reading the same crystal



- Splitted APD (crystal C0)
- Direct comparation of time measured by the two single APDs
- NONE effects on time resolution coming from fluctuation in e.m. shower

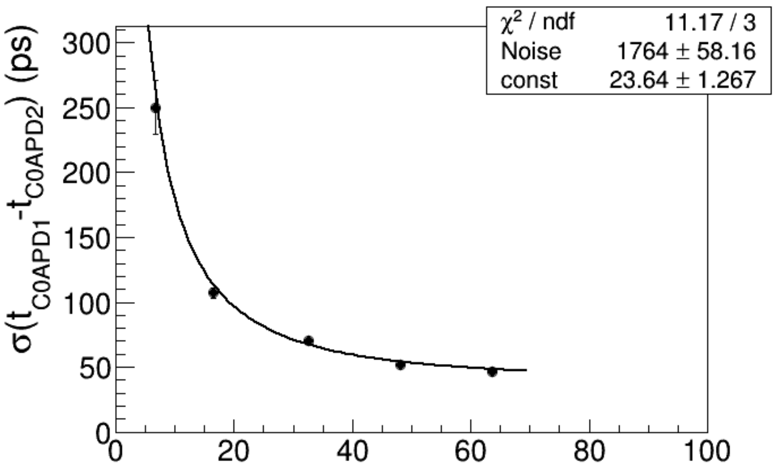
Combined resolution of two APD:

$$\sigma^2(t_{APD1} - t_{APD2}) = \left(\frac{N_1}{A_1/\sigma_1}\right)^2 + \left(\frac{N_2}{A_2/\sigma_2}\right)^2 + C_1^2 + C_2^2 = \left(\frac{N}{A_{eff}/\sigma}\right)^2 + 2C^2$$

Effective amplitude: $A_{eff} = \frac{A_1 A_2}{\sqrt{A_1^2 + A_2^2}}$; $\quad A_1 \simeq A_2 \rightarrow A_{eff} \simeq \frac{A}{\sqrt{2}}$

Time resolution of two APDs

C0APD1 wrt C0APD2



A_{eff}/σ_n

Fit function:

$$\sigma^2(t_{APD1} - t_{APD2}) = \left(\frac{N}{A_{eff}/\sigma}\right)^2 + 2C^2$$

Constant term (limit res.):

$$\sigma_{t_{C0APD}}(E\rightarrow\infty) = 24 \pm 1\, ps$$

Constant term (using MCP):

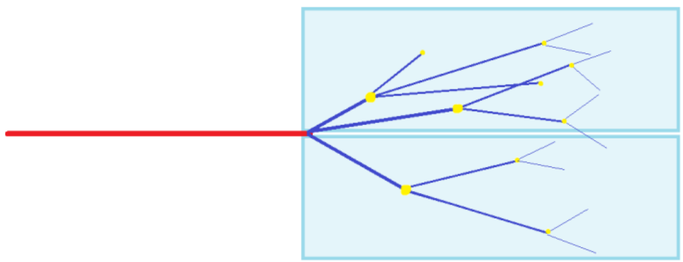
$$\sigma_{t_{C0APD}}(E\rightarrow\infty) = 24 \pm 1\, ps$$

Negligible effects on time resolution due to shower fluctuations

Time resolution: neighbour crystals

Comparison between APD time measurements from different crystals:

- Shared e.m. shower
- Wide spread in A_{eff}



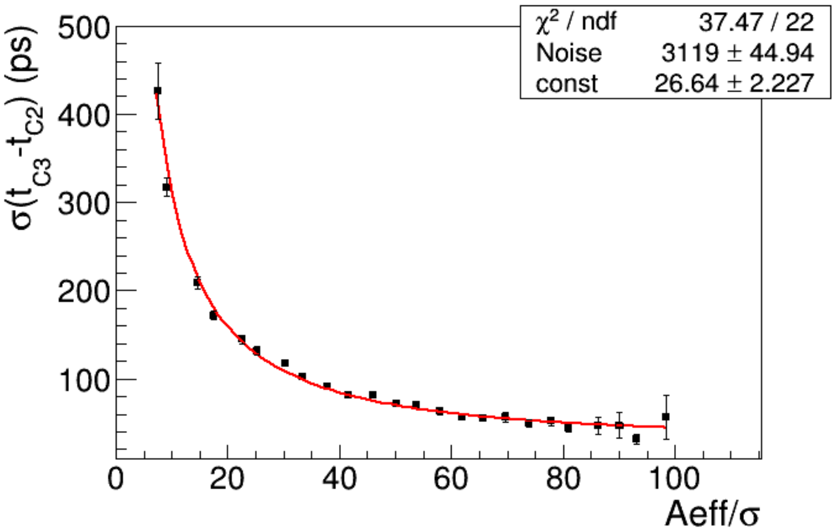
Fit function:

$$\sigma^2(t_{C3} - t_{C2}) = \left(\frac{N}{A_{eff}/\sigma}\right)^2 + 2C^2$$

Constant term:

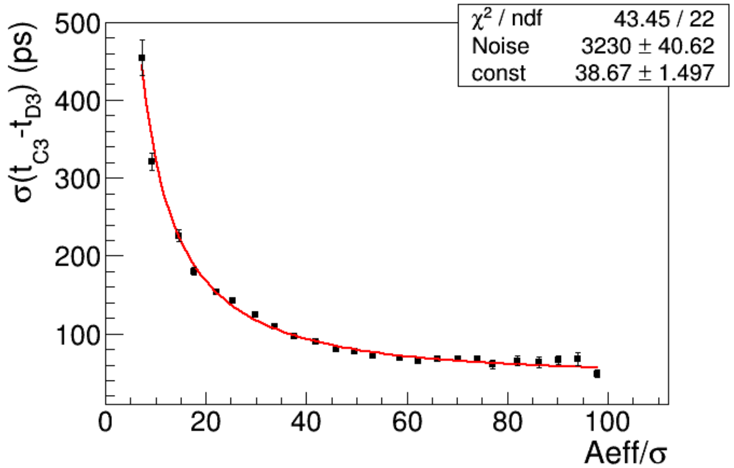
$$\sigma_{t_C}(E \to \infty) = 27 \pm 2\ ps$$

C2 vs C3



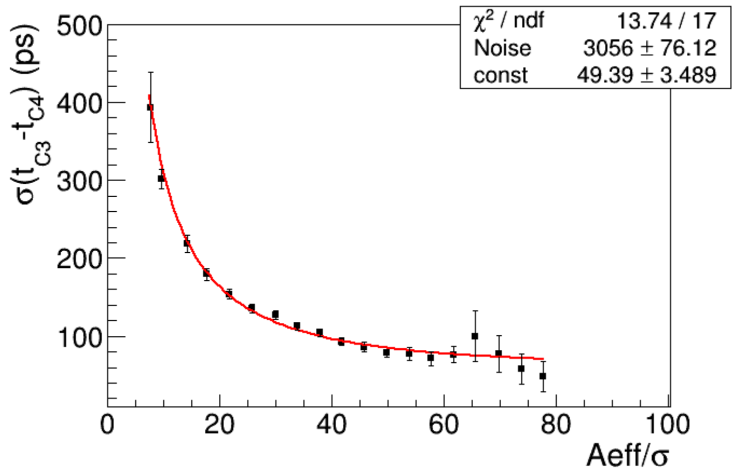
Time resolution: neighbour crystals

D3 vs C3



$$\sigma_{t_C}(E \to \infty) = 39 \pm 1\ ps$$

C4 vs C3



$$\sigma_{t_C}(E \to \infty) = 49 \pm 3\ ps$$

- Different C for different crystals→ different systematic errors in the template fit for different crystals
- C is larger than previous analysis on crystal C3

Conclusions

- Analysis performed on the time resolution of crystal C3 shows:
  - $N = 4.5 - 5\, ns$
  - $C = 18 \pm 1\, ps$
- Noise term with new VFE prototypes is 7 time smaller than actual one ($\sim 35\, ns$, 2015). Constant term is consistent with a target resoluation <30 ps for photons with energy of 50-60 GeV.
- Shower fluctuation effects on constant term are negligible
- Constant term is different between to be studied in future test beams with final VFE prototipes.

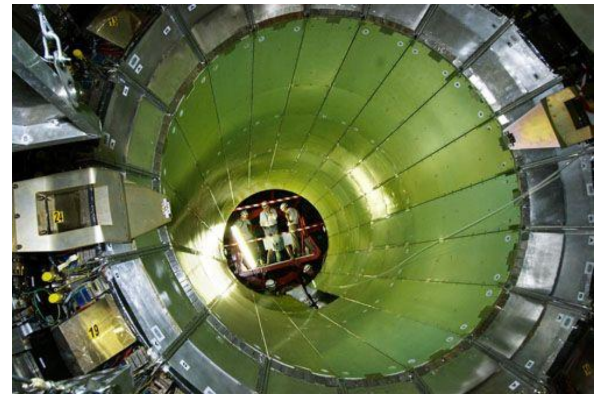
Thanks for the attention

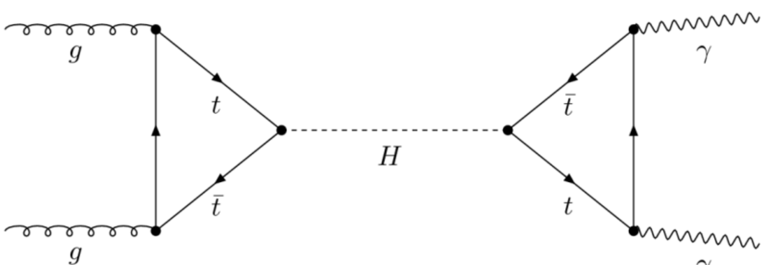
backup

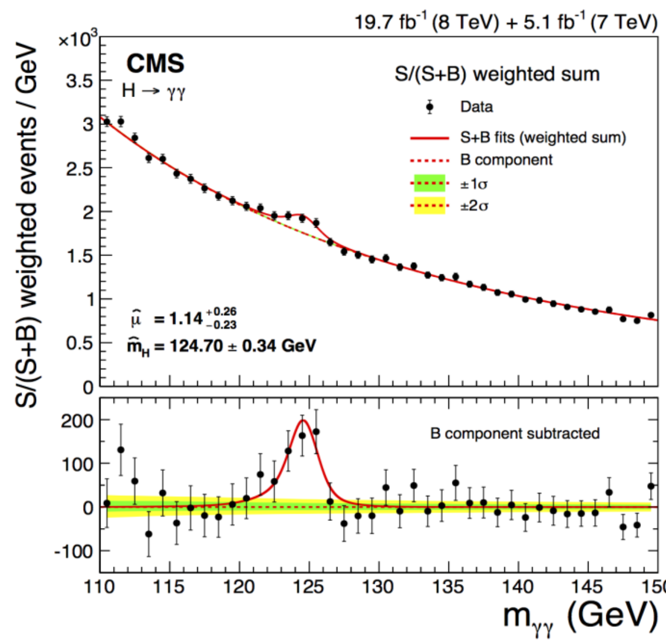
ECAL
(CMS Electromagnetic CALorimeter)

- High granularity homogeneous calorimeter. It measures the energy of photons, electrons and positrons.

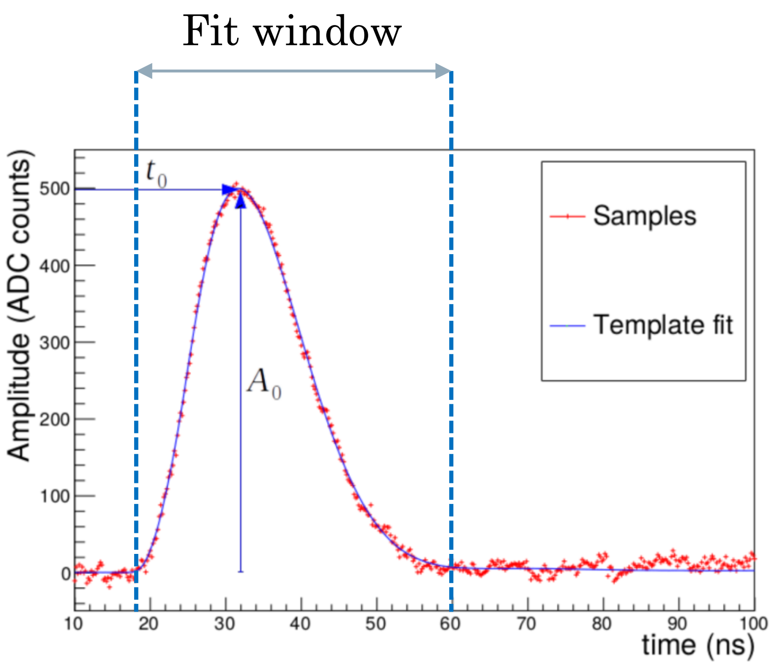
- Fundamental for the reconstruction of the Higgs boson in the $H \rightarrow \gamma\gamma$ decay (2012, discovery channel) and for studies on many processes with photons and electrons in the finale state.







Signal reconstruction
(template fit)



$$\chi^2 = \sum_i \frac{\left[A_{sample}[t_i] - A_0 \cdot F_{template}(t_i - t_0)\right]^2}{\sigma_n^2}$$

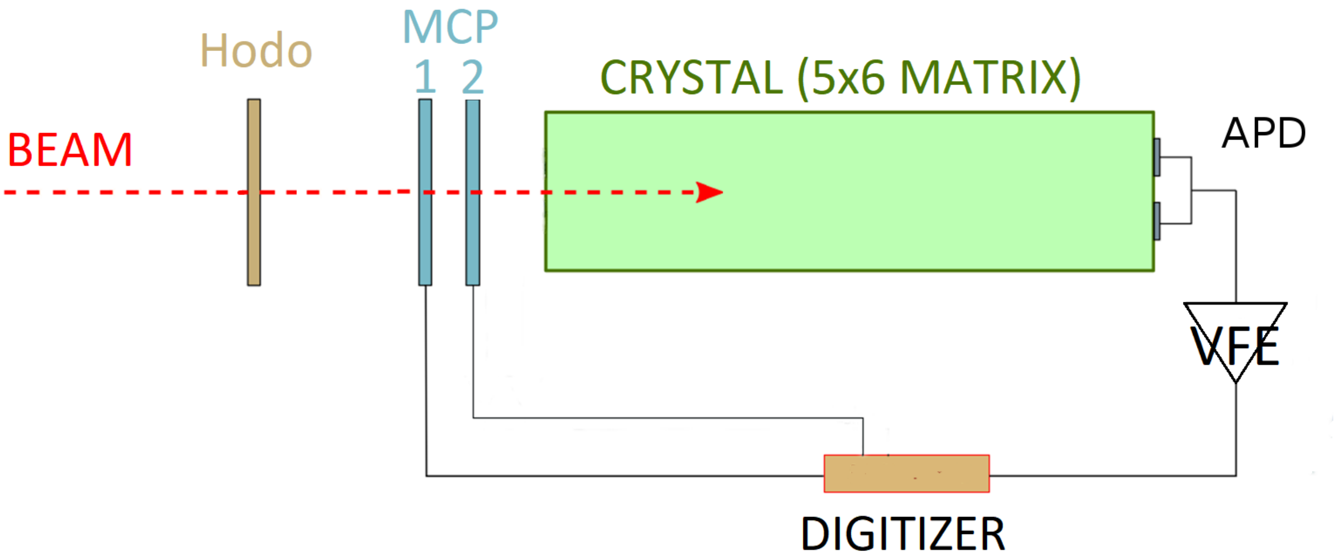
Signal reconstruction

- $F_{template}$: mean signal pulse-shape normalized to 1 (mean over a large sample of selected events)
- Pulse shape used as a template to fit data:
  - Shif parameter (t_0)
  - Scale factor (A_0)
  - χ^2 minimization
- Fit window: ~40 *ns* around peak (optimized to obtain the best time resolution)

Testbeam 2016

Setup:

- electron beam: 20, 50, 100, 150, 200 GeV
- 30 crystal matrix read by APD
- 2 MCP (Micro-Channel Plates) ($\sigma_t \sim 20\ ps$)
- New VFE prototypes (made by discrete components)
- external digitizer with 5 GS/s sampling frequency (CAEN V1472)

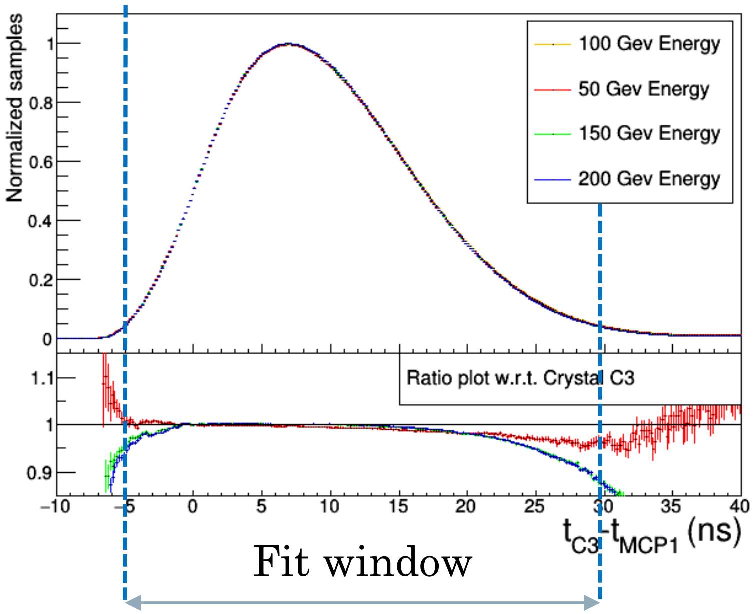


Study of ECAL cristal time resolution in barrel configuration (APD):

- using an external time reference (MCP)
- using a splitted APD (two APD reading the same crystal)
- using neighbour crystals

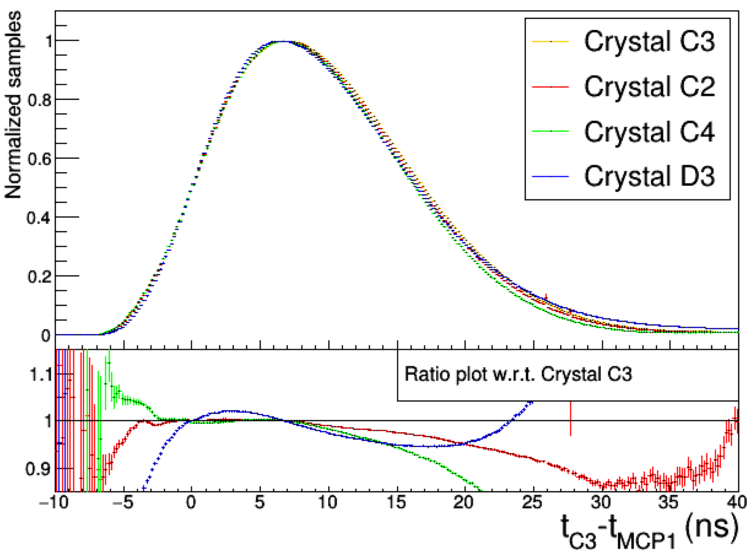
Pulse-shape stability study

Different energy of incoming particle



Less than 10% pulse-shape variation inside fit window at different energies

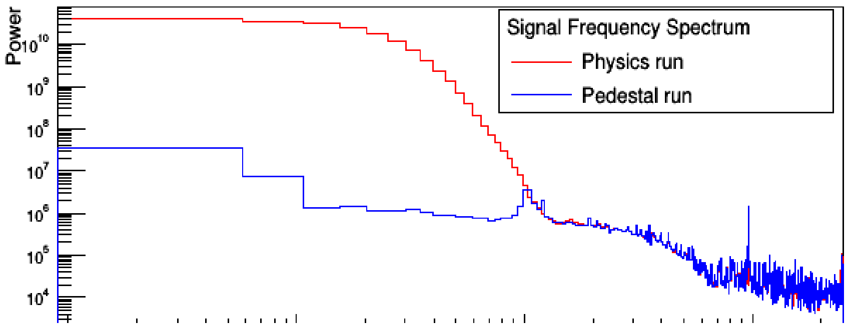
Different crystals



Different pulse-shapes for different channels → use of a specific pulse-shape as template for each channel

Time resolution: filter application

Noise analysis:
- 5 GS/s sampling → high frequency noise
- Fourier analysis signal and pedestal;



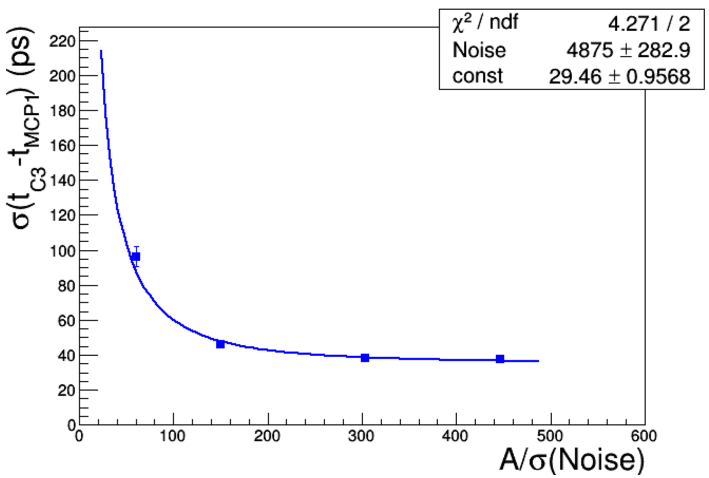
Butterworth low pass filter:

$$|T(j\omega)| = \frac{1}{\sqrt{1+\left(\omega/\omega_0\right)^{2n}}};$$

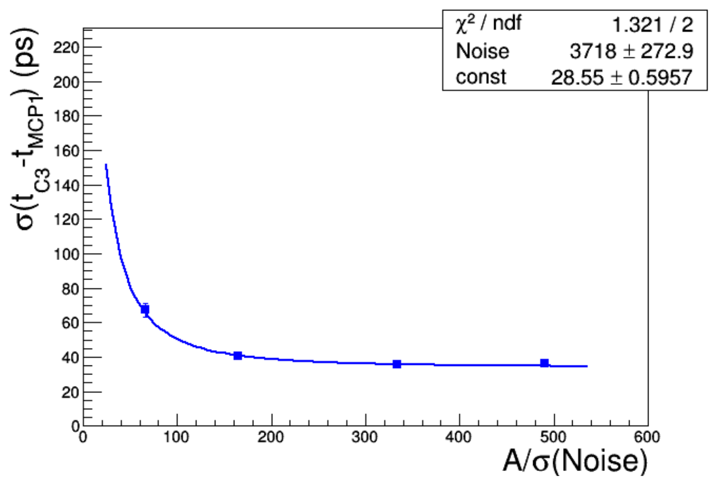
$$n = 2;$$

$$\omega_0 = 200\ MHz;$$

No filter

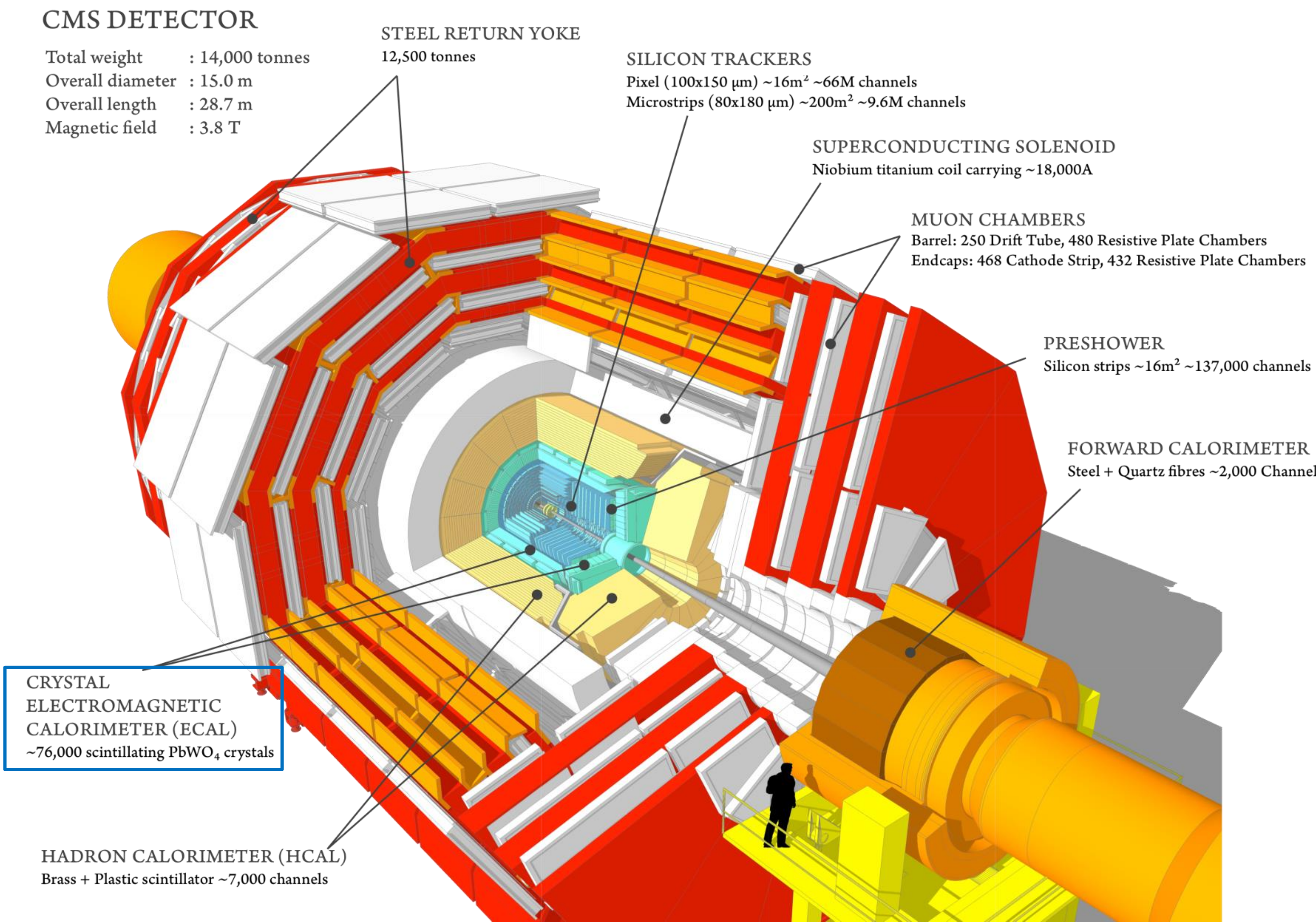


With filter

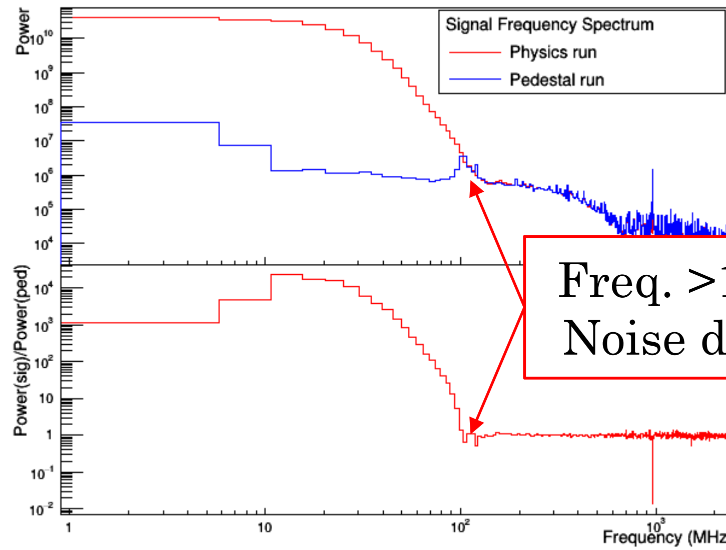


- 25% noise term reduction
- 10% increase of A/σ_n (at same energy)

Compact Muon Solenoid (CMS)



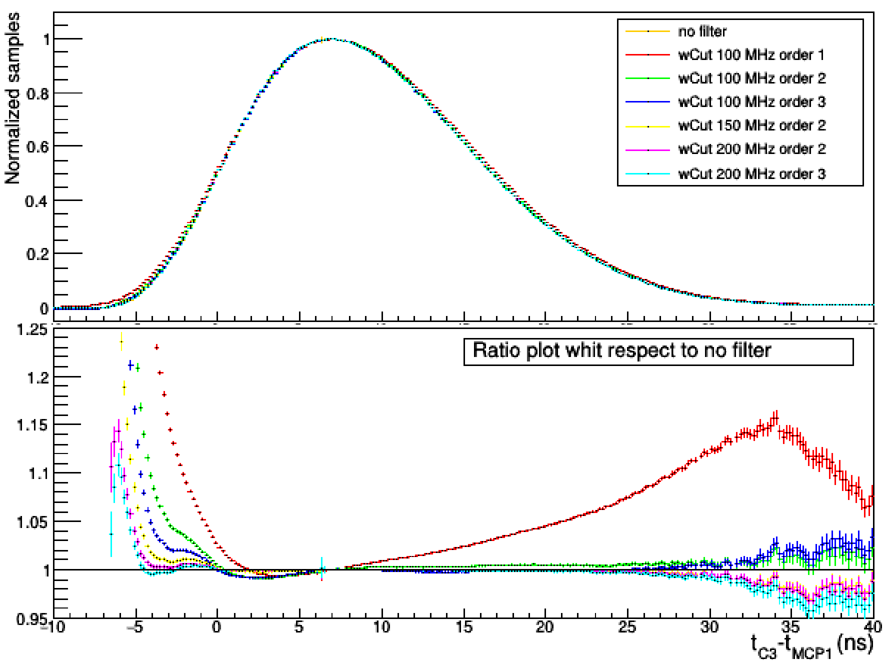
Signal filtering



Freq. >100 MHz
Noise dominant

Noise analysis:

- 5 GS/s sampling → high frequency noise
- Fourier analysis of signal and pedestal



Software Butterworth filter:

- Transfer function:

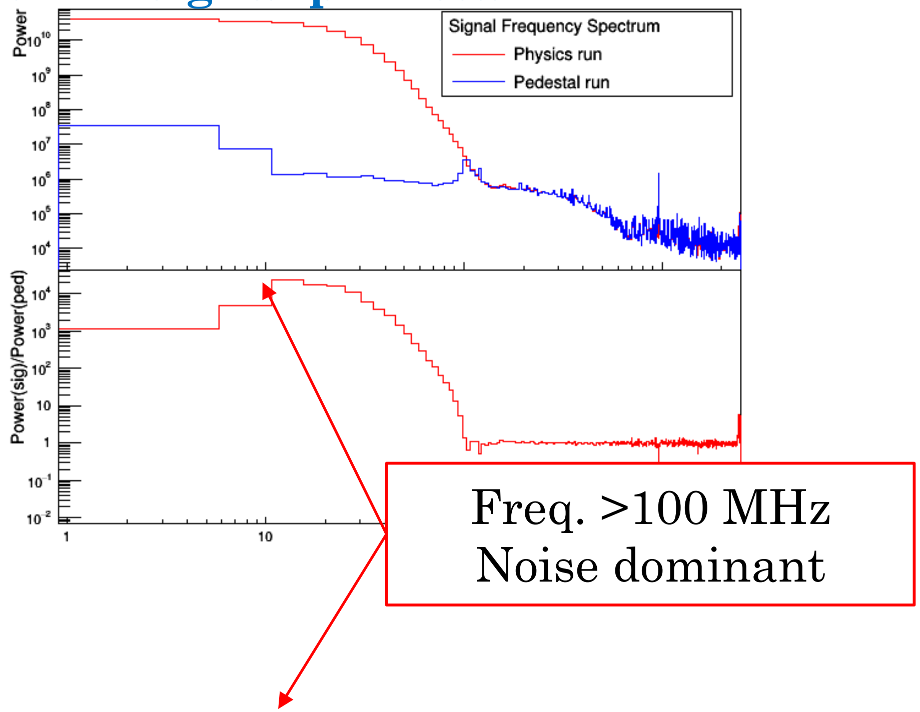
$$|T(j\omega)| = \frac{1}{\sqrt{1+\left(\omega/\omega_0\right)^{2n}}}$$

- Order: $n = 2$
- Cut frequency: $\omega_0 = 200\ MHz$

Noise Analysis

- 5 GS/s sampling → high frequency noise
- Greater noise term (wrt 160 MS/s)
- Fourier analysis of signal and pedestal

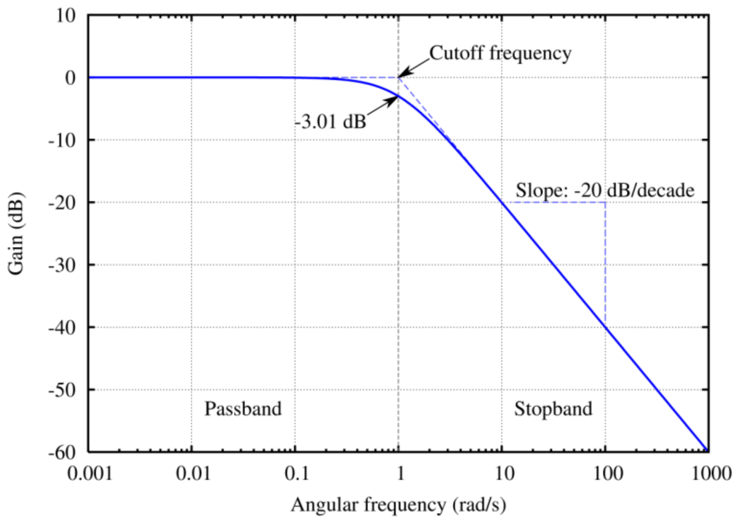
Power spectrum signal/pedestal

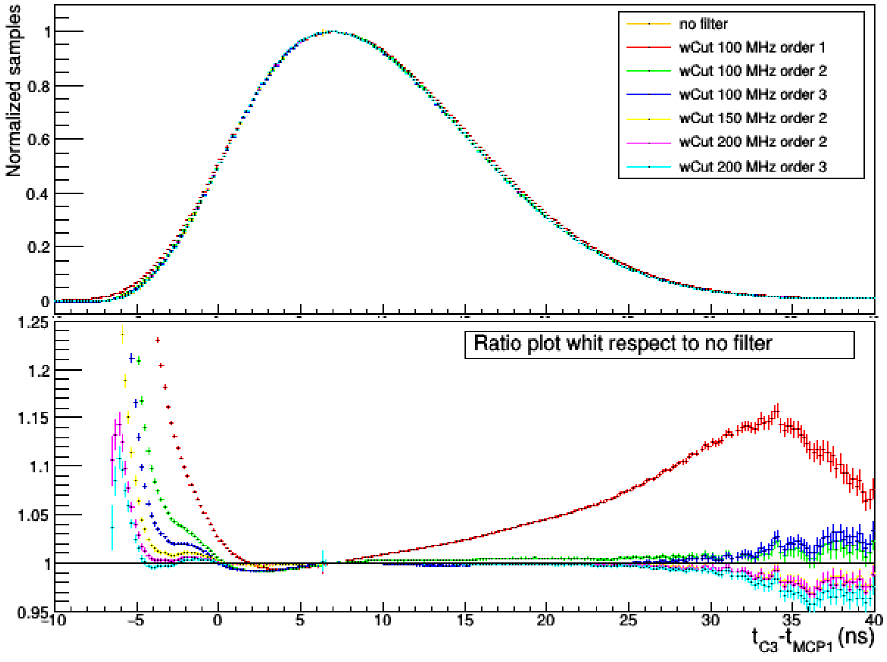


Butterworth filter (low pass)

Software Butterworth filter.
Transfer function:

$$|T(j\omega)| = \frac{1}{\sqrt{1 + \left(\omega/\omega_0\right)^{2n}}}$$





Parameters optimization (keep same *pulse-shape* after filter):

- Order: $n = 2$
- Cut frequency:

$$\omega_0 = 200\ MHz$$

Lo scenario:

- Large Hadron Collider (LHC): collisore adronico più potente al mondo
- 4 maggiori esperimenti: ATLAS, CMS, ALICE, LHCb
- High Luminosity LHC (2025): maggiore luminosità → maggiore quantità di dati raccolti → condizioni operative più difficili
- Necessarie migliorie degli attuali rivelatori

Argomento della tesi:

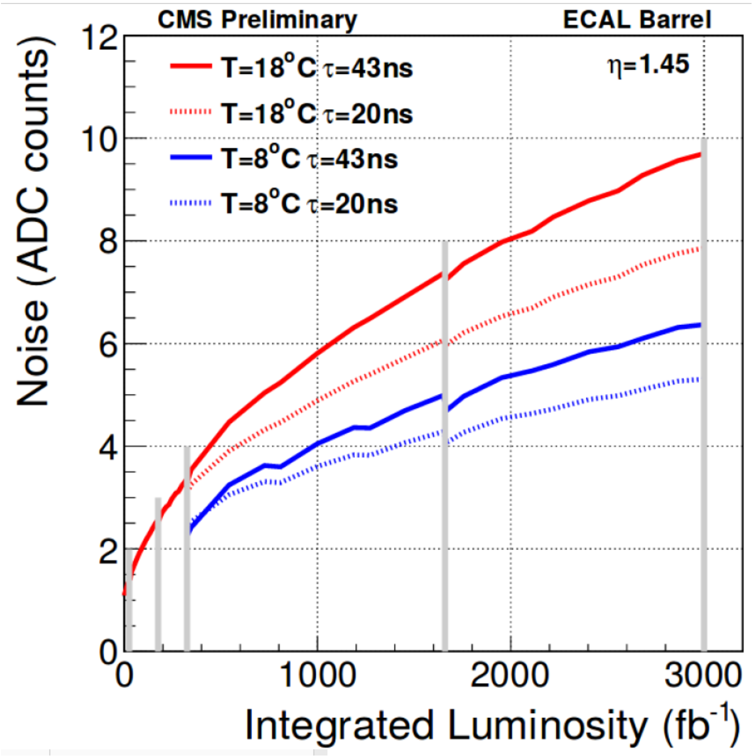
- Miglioramento della risoluzione temporale del calorimetro elettromagnetico di CMS (ECAL) al fine di mantenere la qualità dei dati raccolti
- Studio della risoluzione temporale di ECAL con la nuova elettronica di lettura

Upgrade del barrel di ECAL

Danno da radiazione: aumento del rumore elettronico degli APD → diminuzione temperatura da 18°C a 9°C e sostituzione elettronica di front-end

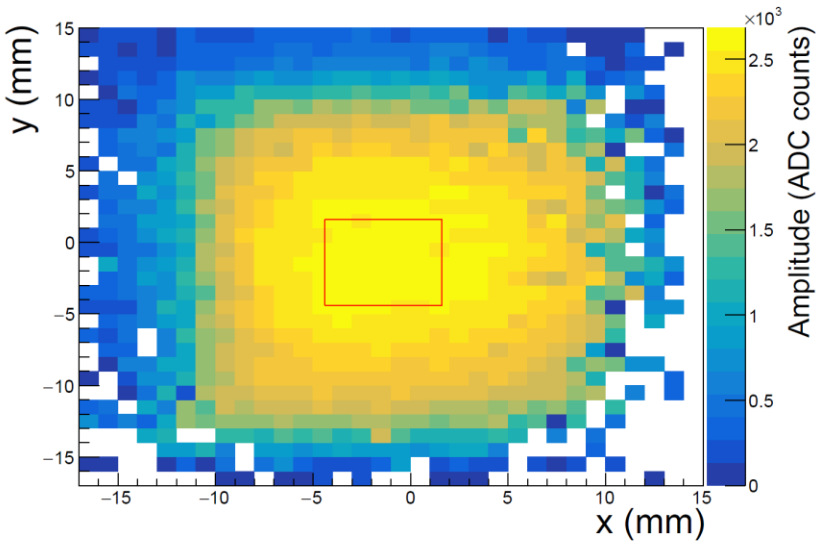
Aumento rate di trigger ($100\ kHz \rightarrow 750\ kHz$) e latenza ($3.2\ \mu s \rightarrow 12.5\ \mu s$) → sostituzione elettronica di acquisizione e trigger

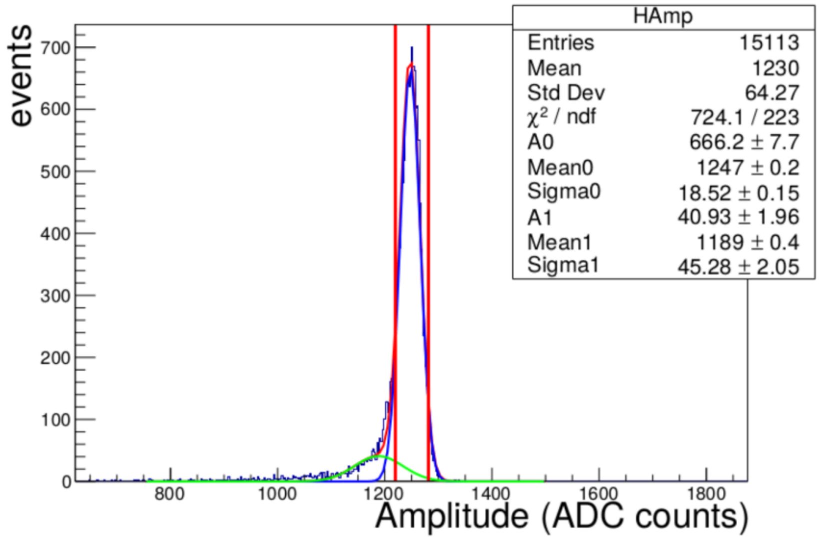
Ottenere una migliore risoluzione temporale → nuovo design elettronica di lettura, schede di VFE (Very Front-End)



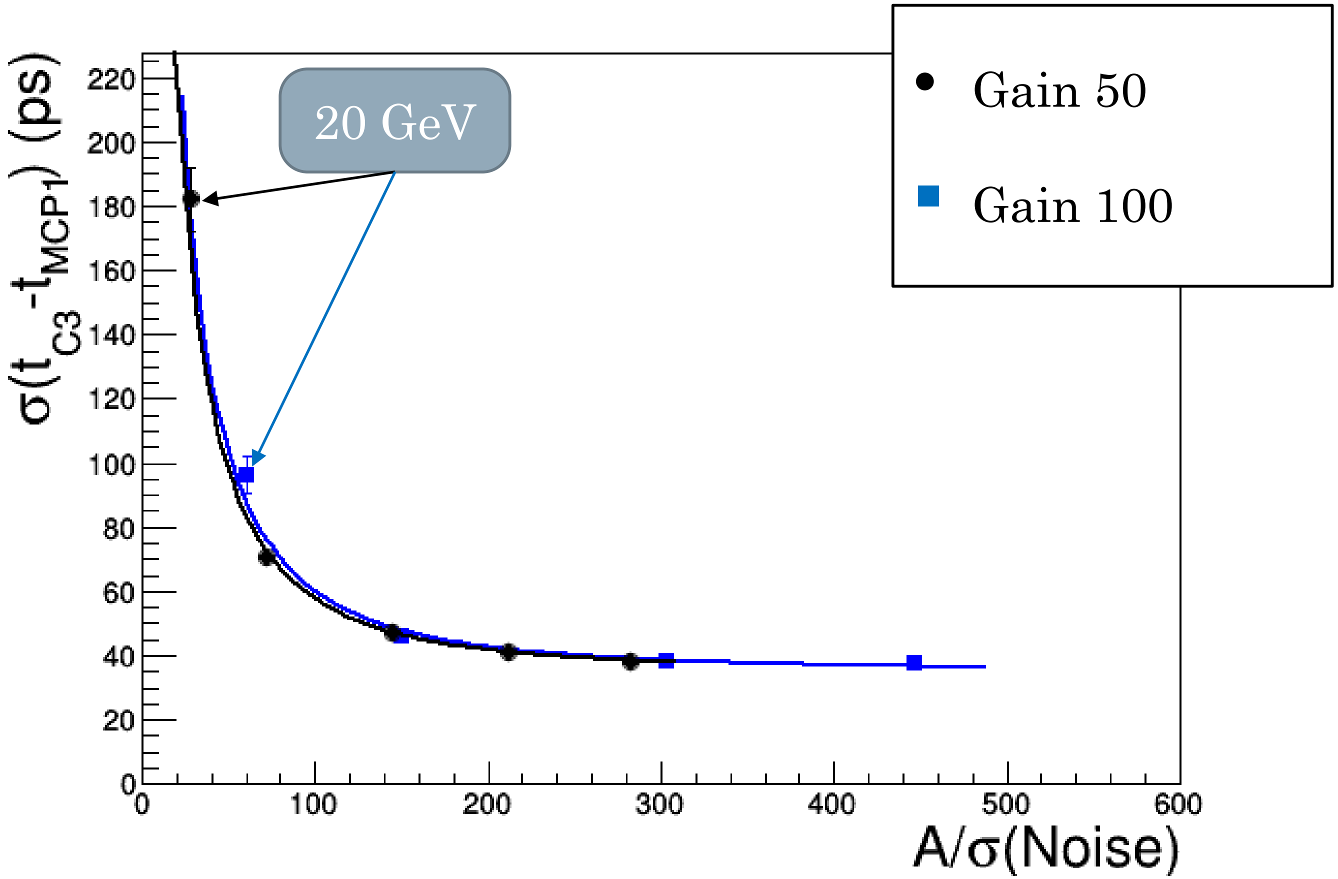
Event selection

- Impact point of the particle near crystal centre ($6 \times 6\ mm^2 \sim$ centre)
- Most of the shower inside the crystal → Signal amplitude $A \sim$ mean amplitude $\bar{A}$: $|A - \bar{A}| < 1\sigma_A$





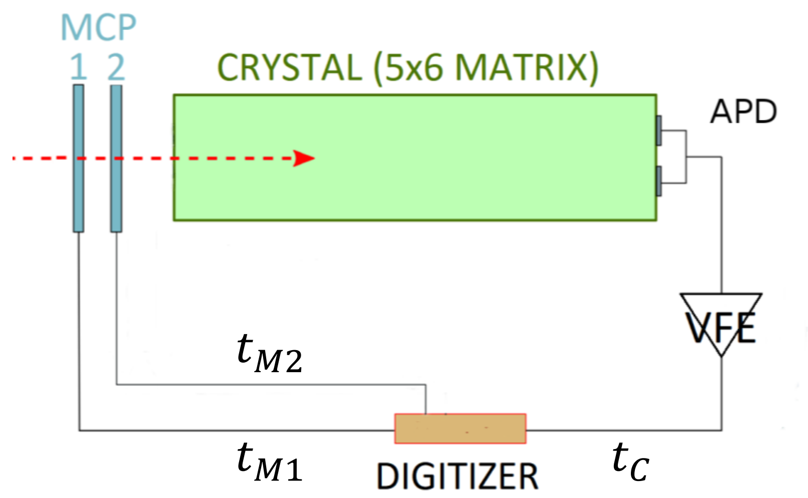
Time resolution with different APD gain



Same Energy → higher A/σ_n for higher gain → better time resolution

Time resolutions triangulation

$$\begin{cases} \sigma^2_{t_C - t_{M1}} = \sigma^2_{t_C} + \sigma^2_{t_{M1}} \\ \sigma^2_{t_C - t_{M2}} = \sigma^2_{t_C} + \sigma^2_{t_{M2}} \\ \sigma^2_{t_{M1} - t_{M2}} = \sigma^2_{t_{M1}} + \sigma^2_{t_{M2}} \end{cases}$$

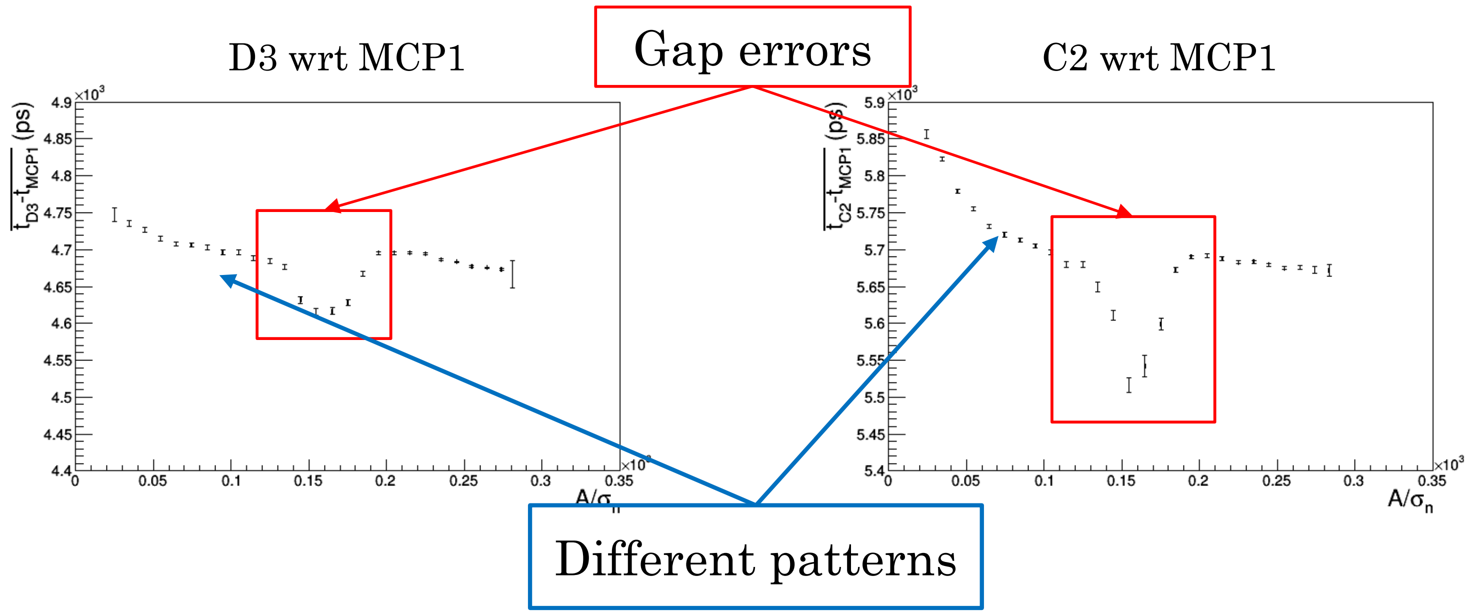


$$\begin{cases} \sigma^2_{t_C} = \dfrac{\sigma^2_{t_C - t_{M1}} + \sigma^2_{t_C - t_{M2}} - \sigma^2_{t_{M1} - t_{M2}}}{2} \\ \sigma^2_{t_{M1}} = \dfrac{\sigma^2_{t_C - t_{M1}} + \sigma^2_{t_{M1} - t_{M2}} - \sigma^2_{t_C - t_{M2}}}{2} \\ \sigma^2_{t_{M2}} = \dfrac{\sigma^2_{t_C - t_{M2}} + \sigma^2_{t_{M1} - t_{M2}} - \sigma^2_{t_C - t_{M1}}}{2} \end{cases}$$

Template fit sistematic error

Analysis of crystal mean time measurements → source sistematic errors in the template fit:

- Gap between crystals (removed using an event selection)
- Sistematic errors dependent on the pulse shape (different trend for different crystals)



Systematic errors combination in time resolution of two neighbour crystals → larger constant term