Precision calorimetry at high luminosity: the CMS electromagnetic calorimeter from the LHC Run 2 to the HL-LHC

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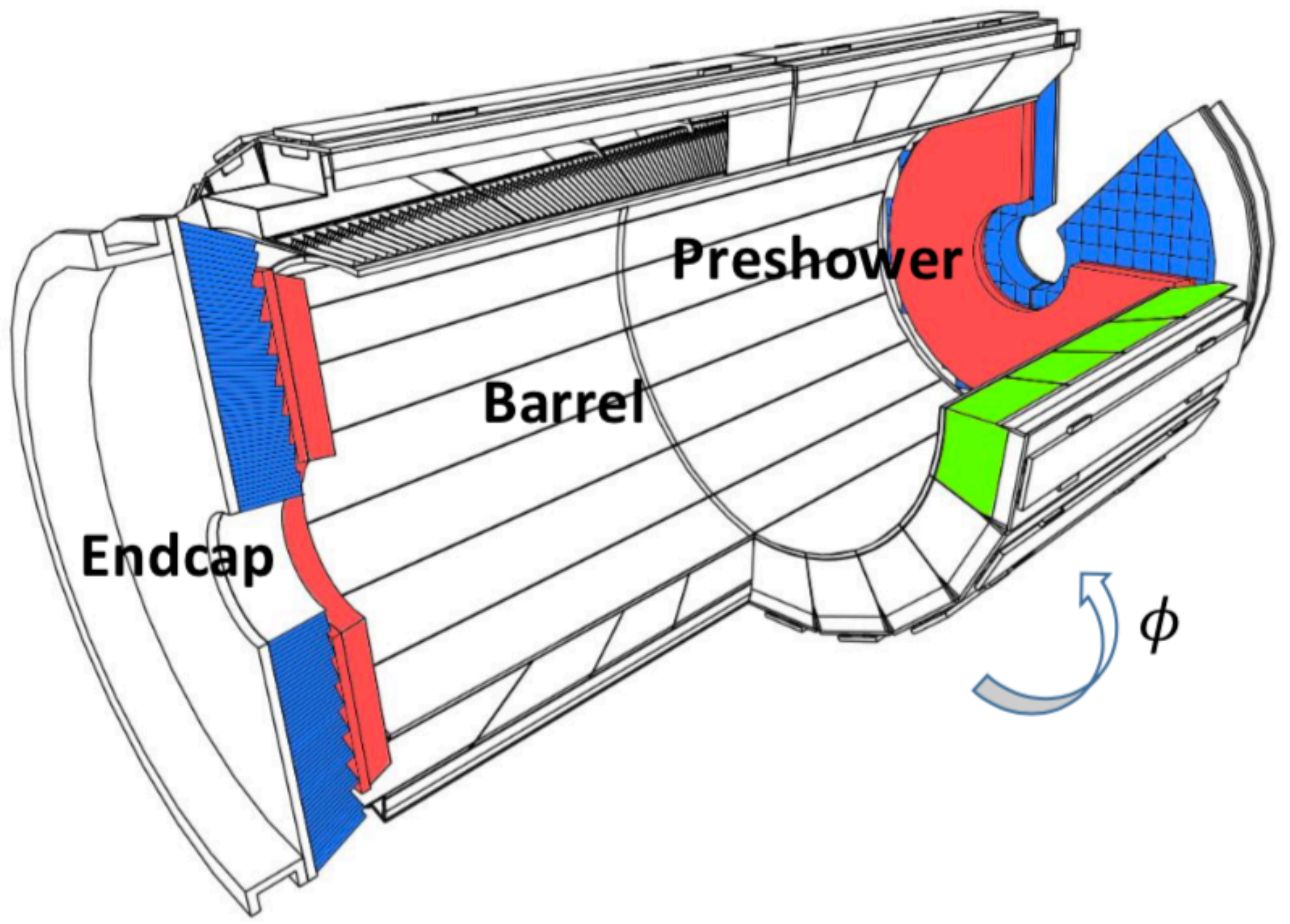
INFN TORINO

CMS

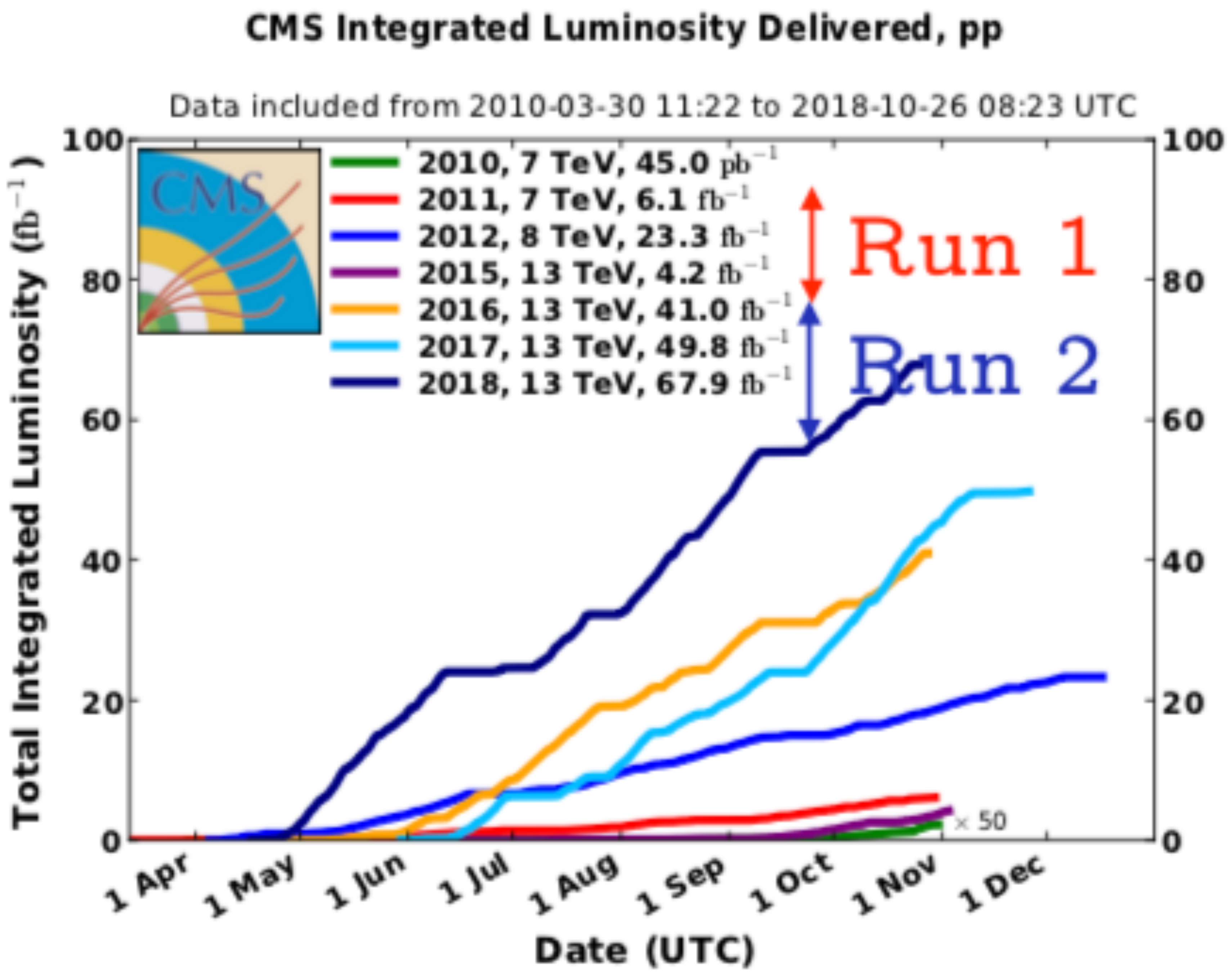
The CMS ECAL Calorimeter in a nutshell

- The Electromagnetic calorimeter (ECAL) of the CMS experiment:
    - **high granularity**: (75848) crystals
    - **lead tungstate $PbWO_4$**: fast decay scintillation light (25 ns), short radiation lenght (X_0 = 0.89 cm), small Moliere radius (2.2 cm)
    - avalanche photo-diodes (APDs) sensors
- Fundamental to detect high energy *e*/γ
    - **Good di-photon mass resolution**: ~1%
- **Crucial role** for the discovery of the Higgs boson in the final states with two photons or four leptons.

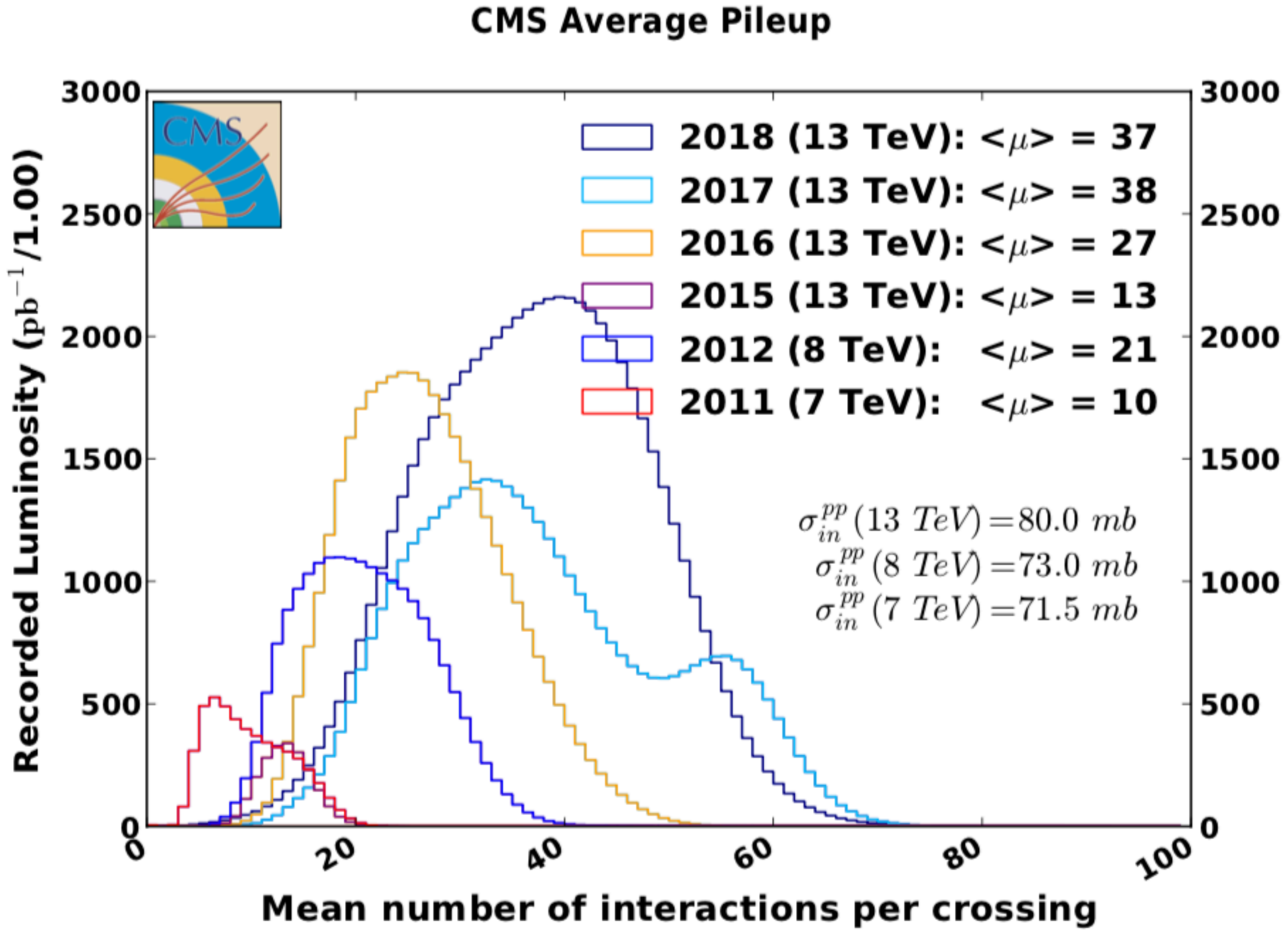


The Run 2 Conditions

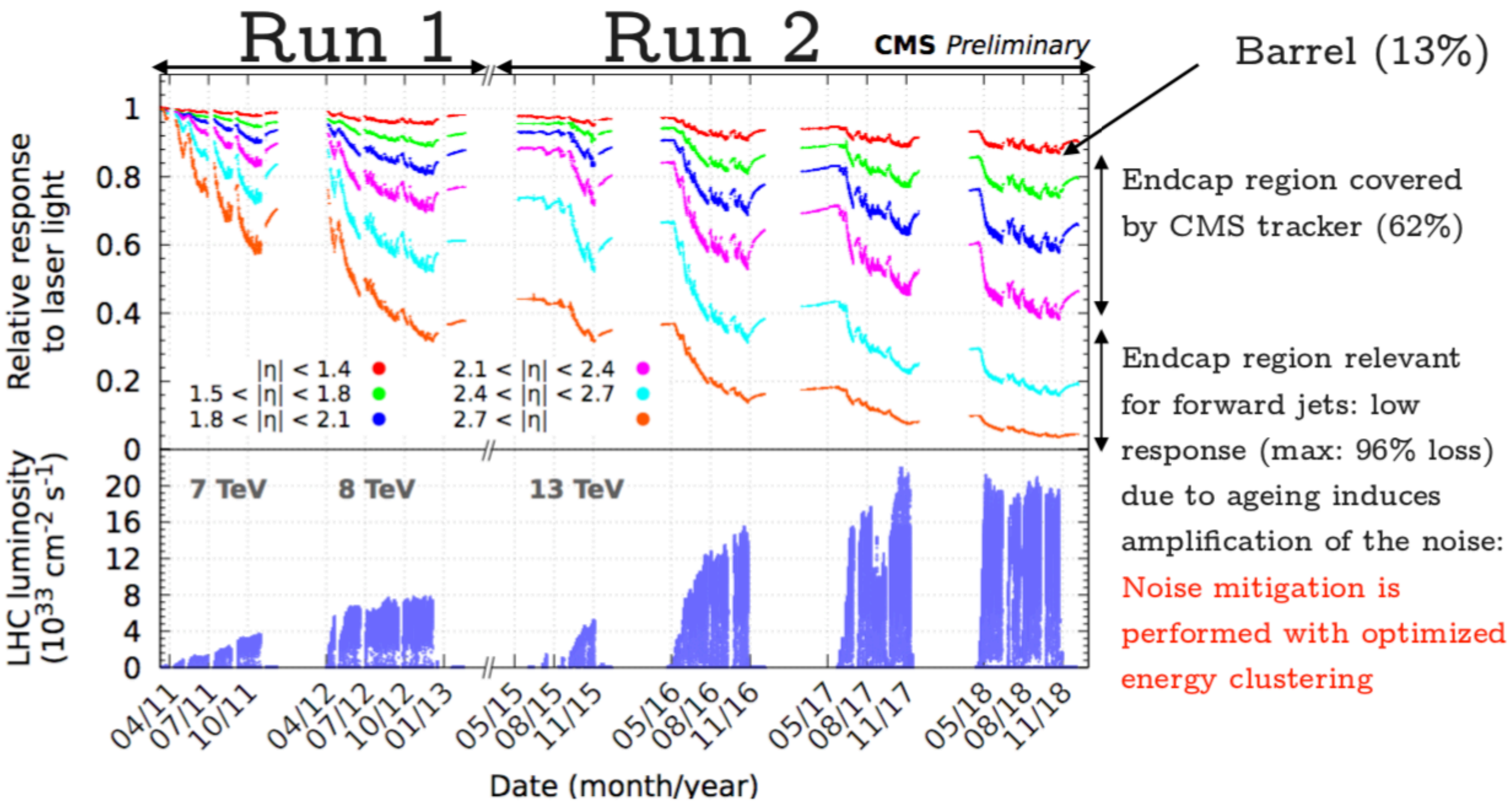
- **Higher integrated Luminosity wrt Run 1:**
  - Larger irradiation dose
  - increase of loss of light of crystals (transparency degradation), and of radiation-induced ageing of photodetectors and of detector readout

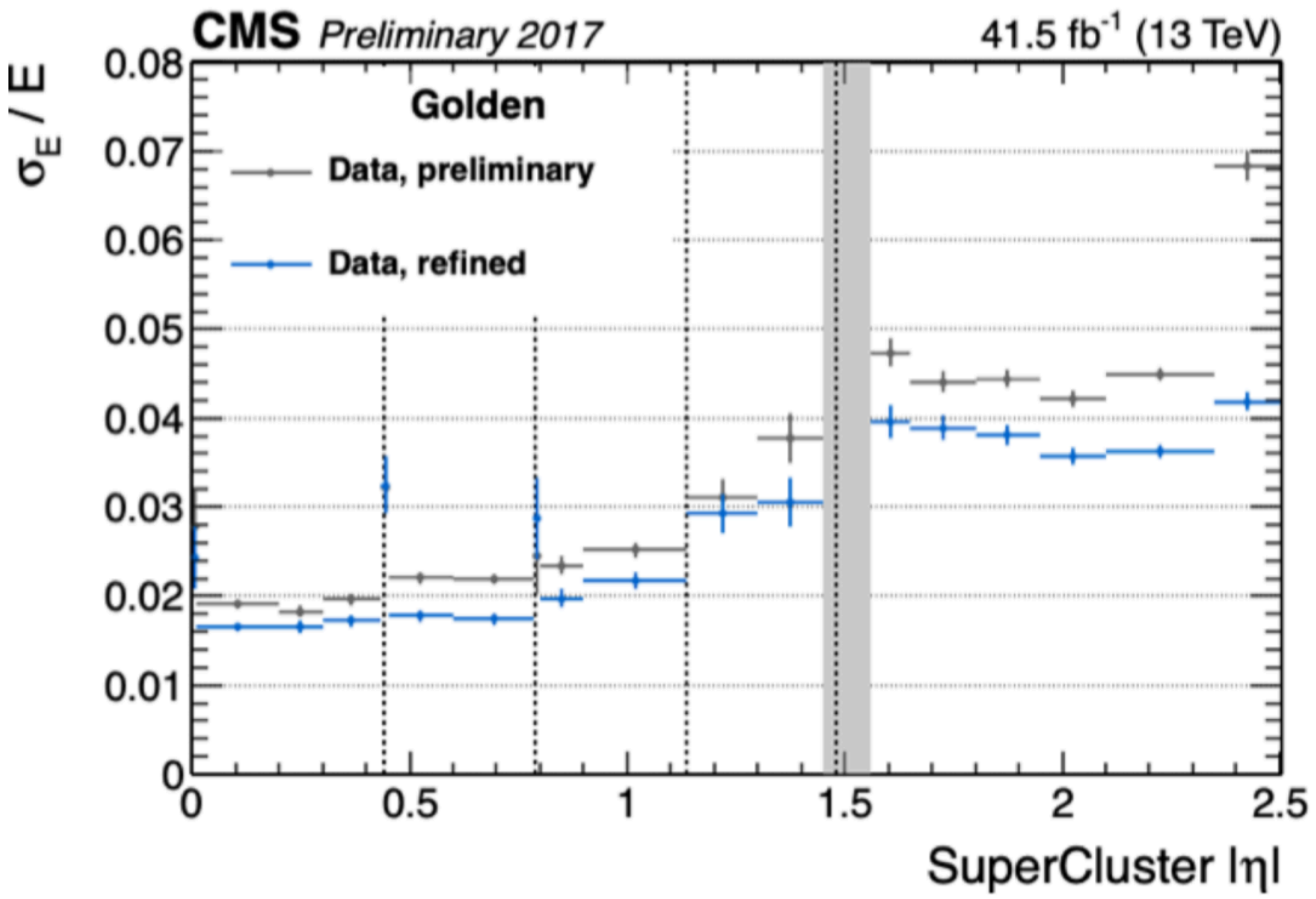


- **Larger pileup (PU) wrt Run 1:**
  - from higher bunch intensities, and from 25 ns bunch spacing (larger out-of-time PU) → impact on ECAL pulse reconstruction



How to maintain performances at best in Run 2





- We monitor each channel with dedicate laser system performed every 40 minutes: corrections provided every 48 hours.
- Regular calibrations allow to maintain an excellent energy resolution and a good stability over the time
- Multi-fit algorithm considering out-of-time pulse effects to mitigate the PU at the reconstruction level

More infos in Dmitri Konstantinov's poster

The challenge of High Lumi

ECAL must maintain the same performances during the Phase 2, when the pile up will be 5-7 times larger.

At luminosity of $5{\cdot}10^{34}\ cm^{2}s^{-1}$ we get 1 fb^{-1} in 5.5 hours

Phase 2 implies:

- Higher trigger rate (from 100 kHz to 750 kHz)
- Higher data bandwidth
- Higher radiation → higher noise
- higher anomalous high energy (≥ 100 GeV) signals induced by hadrons interacting directly with the APD core (“spikes”)

Actions:

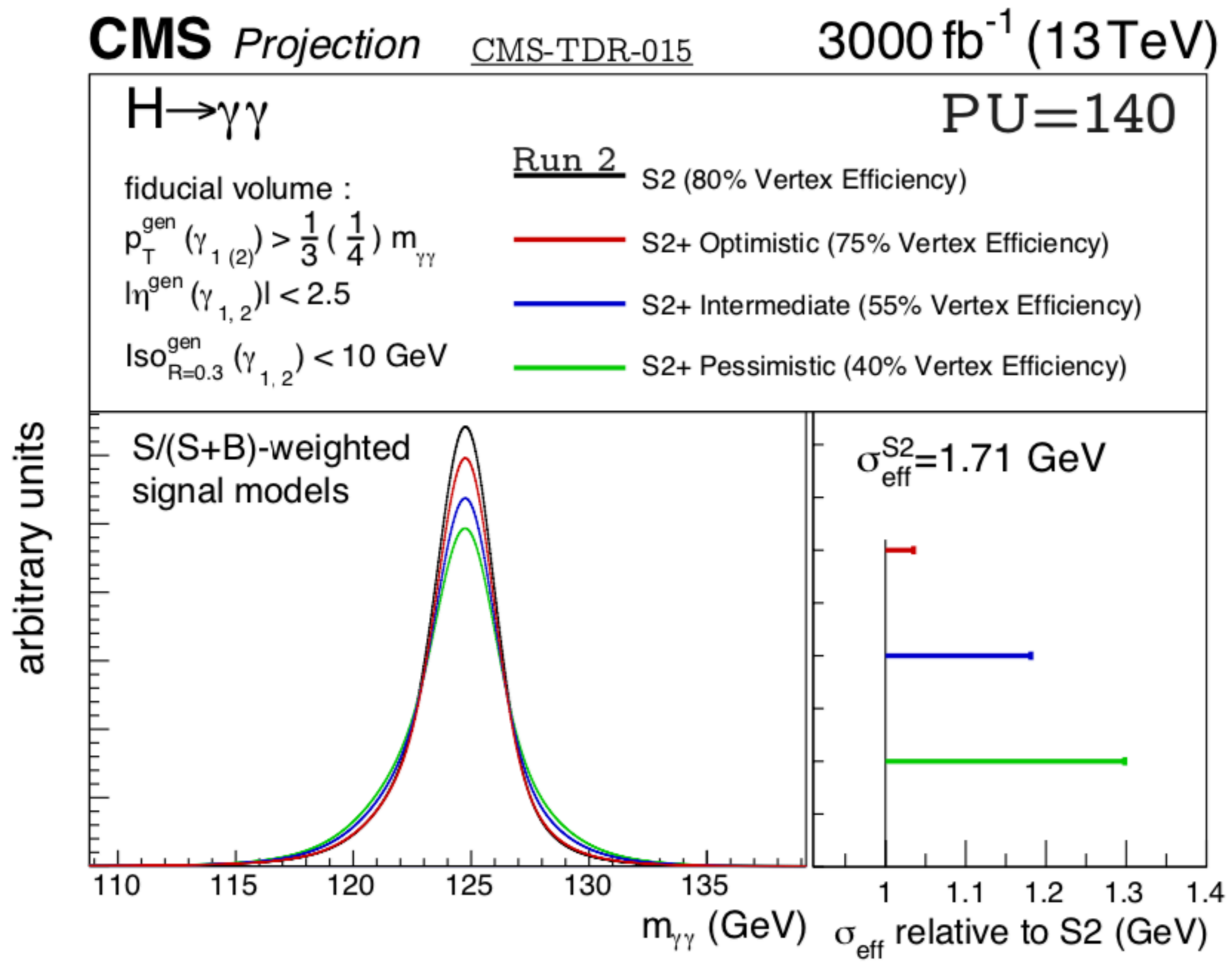
- Substitution of the Endcap part of ECAL with a new High Granularity calorimeter.
- Reduction of the temperature from 18° to 9° Celsius degrees to mitigate the APD dark current
- **Upgrade of the Ecal Barrel Electronics to have: precise timing + spike rejection + full detector read-out @ L1**

Precise timing in Phase 2

- To maintain the reconstruction performance at 140-200 pileup: precise timing in calorimeter is needed

- At 200 pileup the primary vertex reconstruction efficiency is reduced to 30% 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



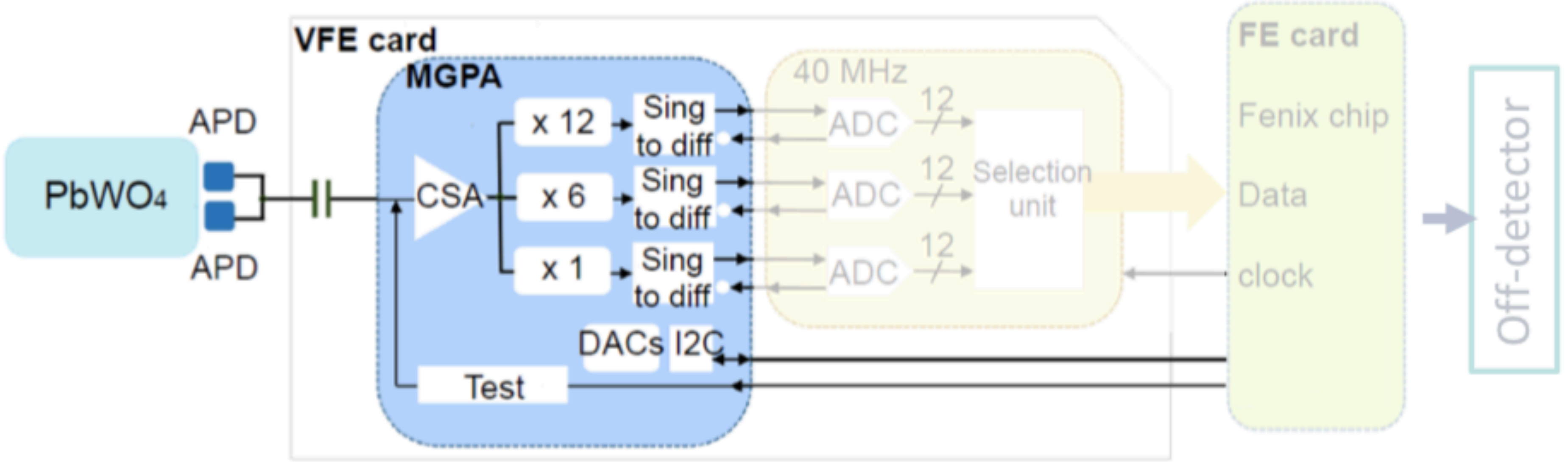
without precise timing

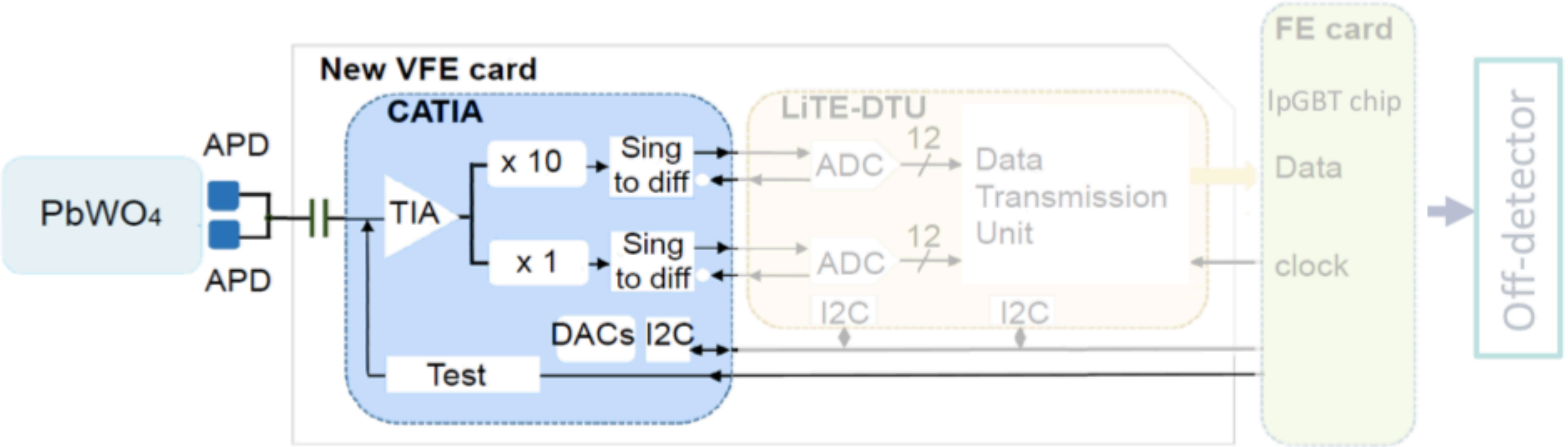
with precise timing (30ps) in calorimeter

Adding the timing layer to precisely tag MIPs (see Nan Lu presentation on Tuesday)

The new readout chain is specified to deliver the desired time resolution of 30ps for energies > 50 GeV

Legacy vs upgraded on-detector readout





Multi-gain pre-amplifier (MPGA):

- Charge sensitive amplifier
- 3 outputs, gain values: **x1, x6 and x12**

Multi-channel ADC:

- ADC resolution: 12 bit
- ADC sampling frequency: 40 MS/s

Front-End Card:

- Data pipeline
- Trigger primitives generation
- Trigger data granularity: 5x5 crystals

CATIA ASIC:

- Trans-impedance Amplifier (TIA) architecture
- 2 outputs, gain values: **x1** and **x10**

Lite-DTU ASIC:

- ADC resolution: 12 bit
- ADC sampling frequency: 160 MS/s
- Selection and **compression** unit

New Front-End Card:

- Fast rad-hard optical links to stream crystal data off-detector through CERN lpGBT/VL
- Trigger data granularity: crystal level

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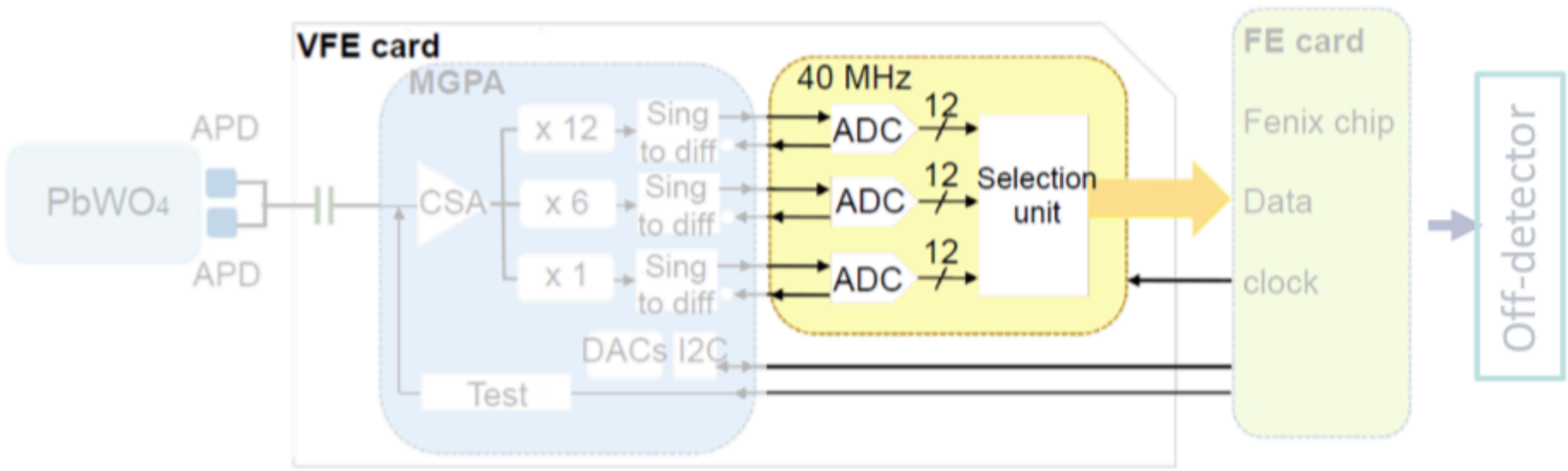

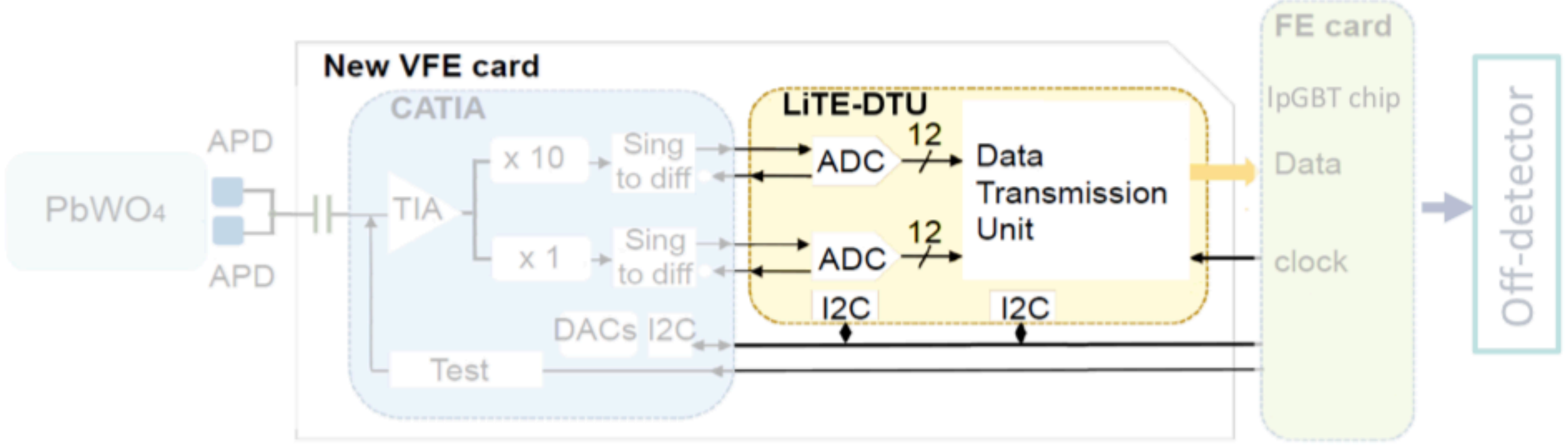

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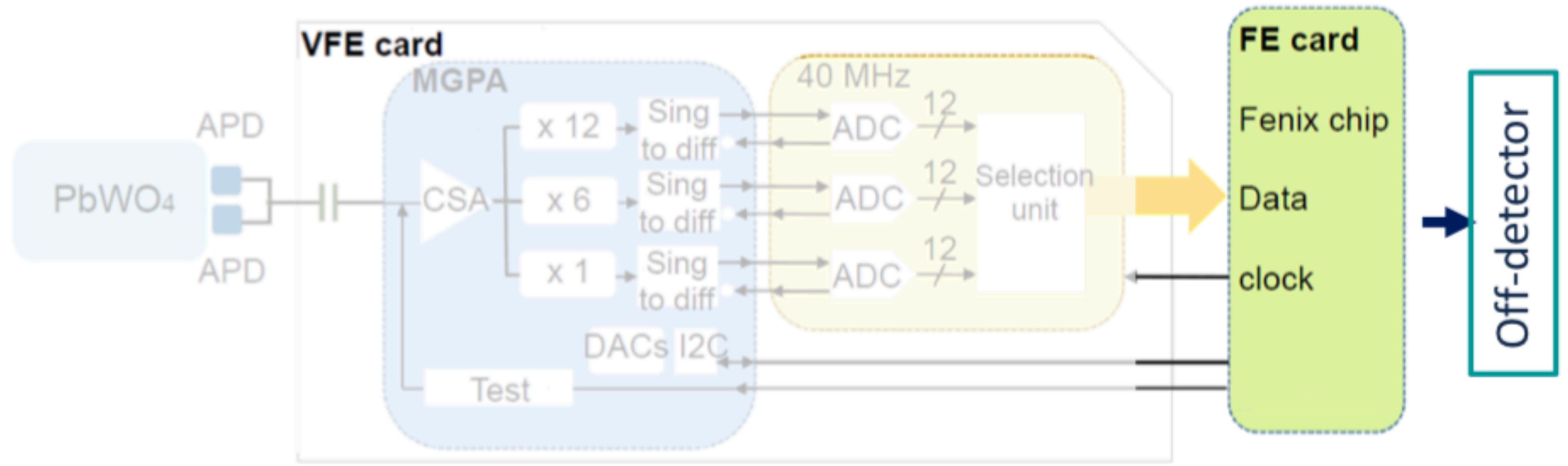

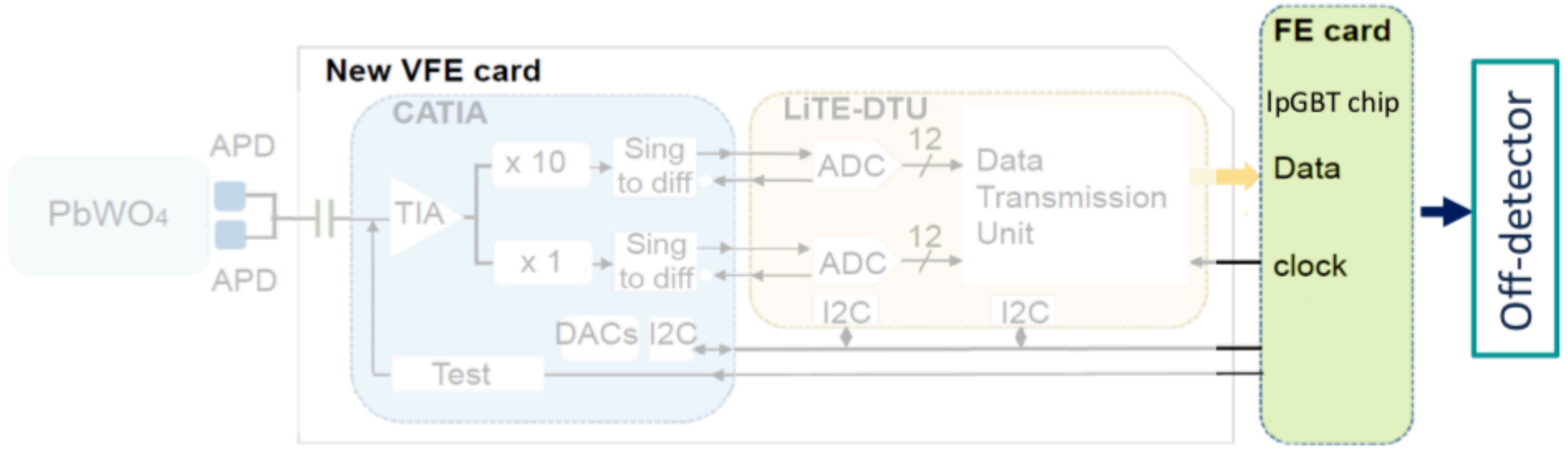

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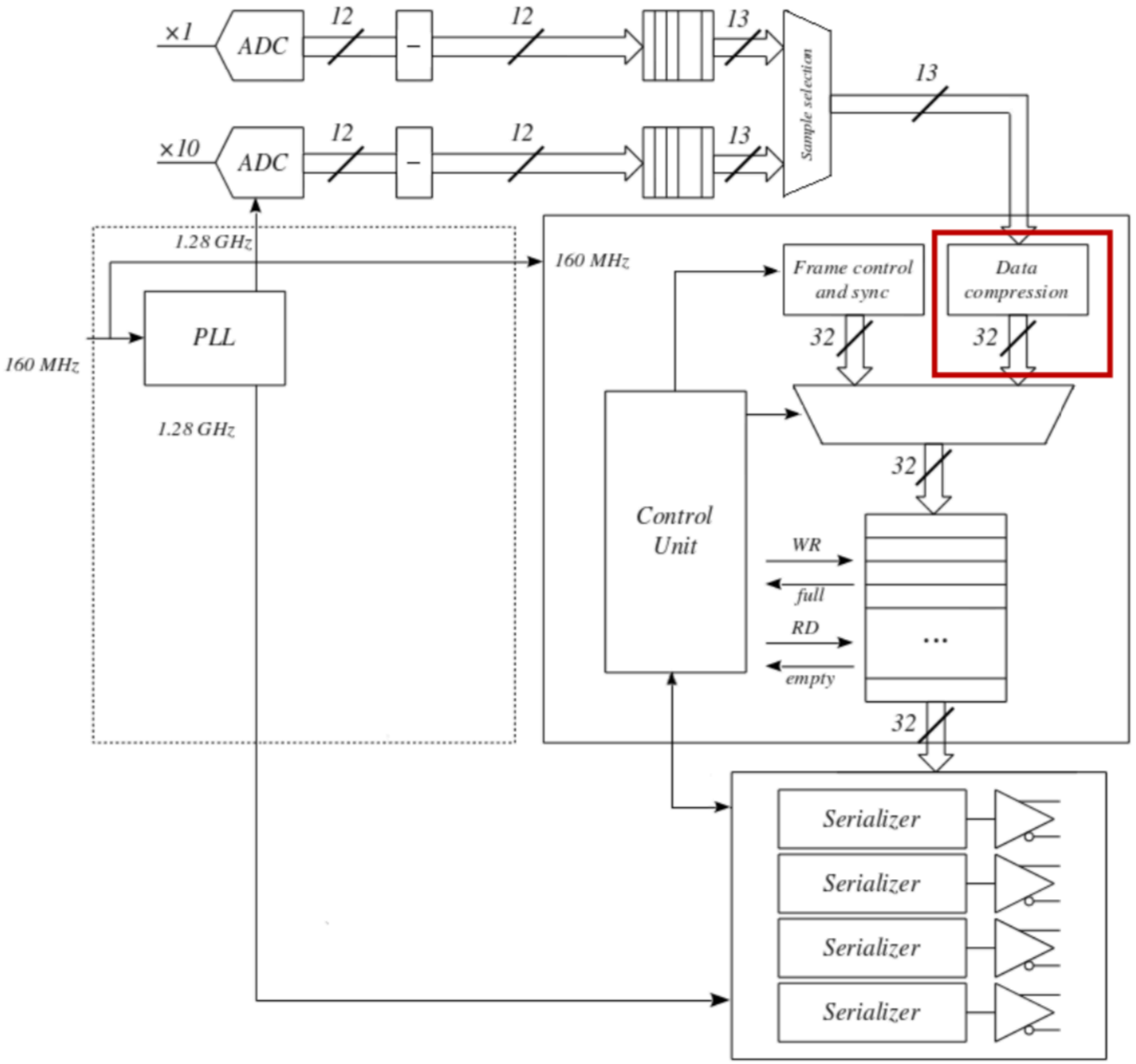
Compression, how to



Direct connections between LiTE-DTU and lpGBT e-links

- LiTE-DTU rate: 13-bit words @ 160 MHz → **2.08 Gb/s**
- lpGBT e-link rate: **1.28 Gb/s**
- LiTE-DTU rate after compression → **1.08 Gb/s**

Simplified Huffman Code

Gain sample	Significant non-zero bits	Sample Classification[a]	Output (Nbits)
x10	$\leq$ 6 bits	"Baseline" sample	6 bits
x10	$>$ 6 bits	"Signal" sample	13 bits (MSB = 0)
x1	any value	"Signal" sample	13 bits (MSB = 1)

- 6 bits corresponds to ~2.4 GeV
- Probability to have > 2.4 GeV:
- 7.3×10^{-5}, 1.6×10^{-4}, 5.8×10^{-4} @ $\eta = 0,\ 0.8,\ 1.4$

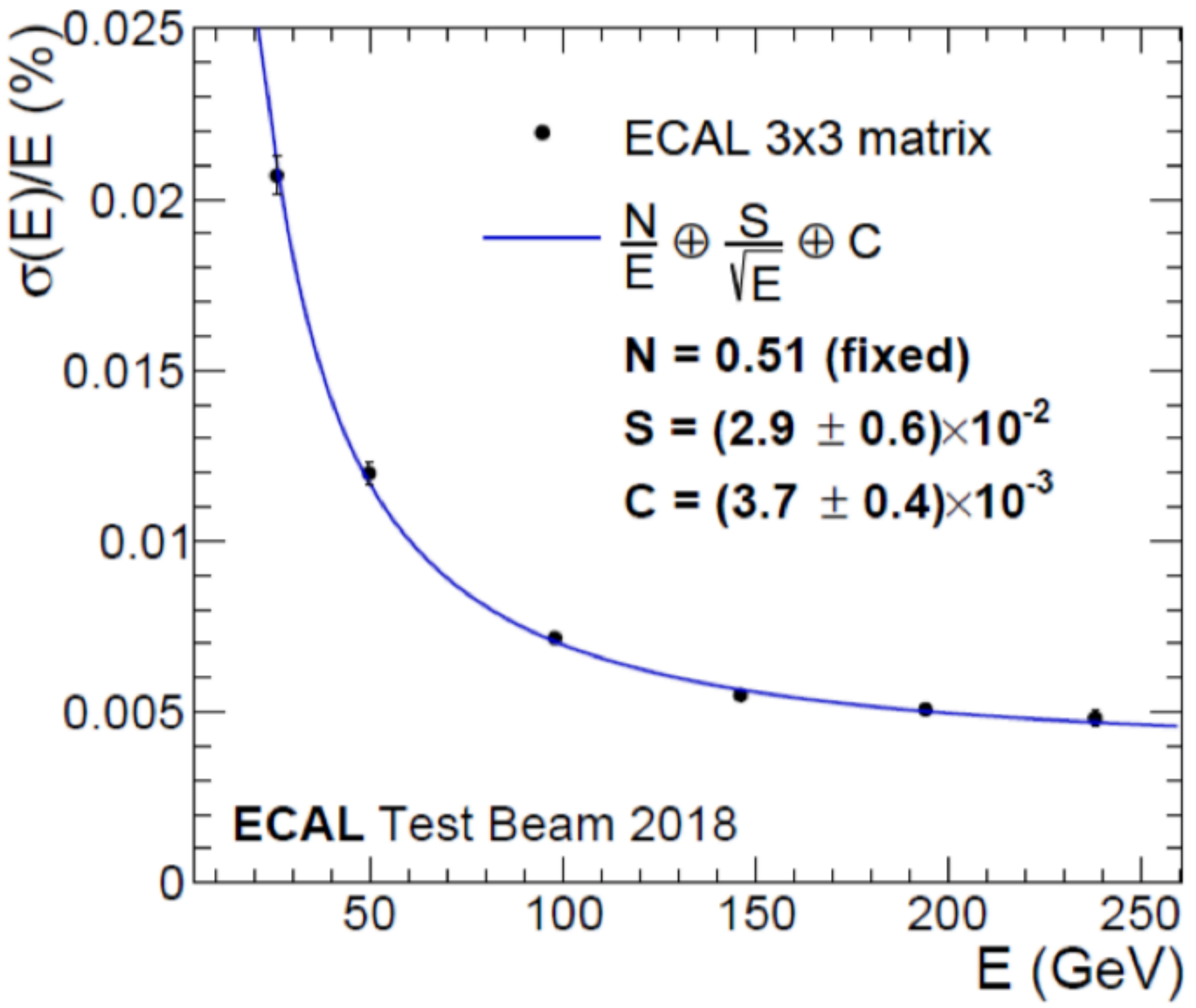
CATIA ASIC Performances from Test Beam

One ECAL tower (25 channels) equipped with CATIA chip connected with **160 MHz commercial ADC**

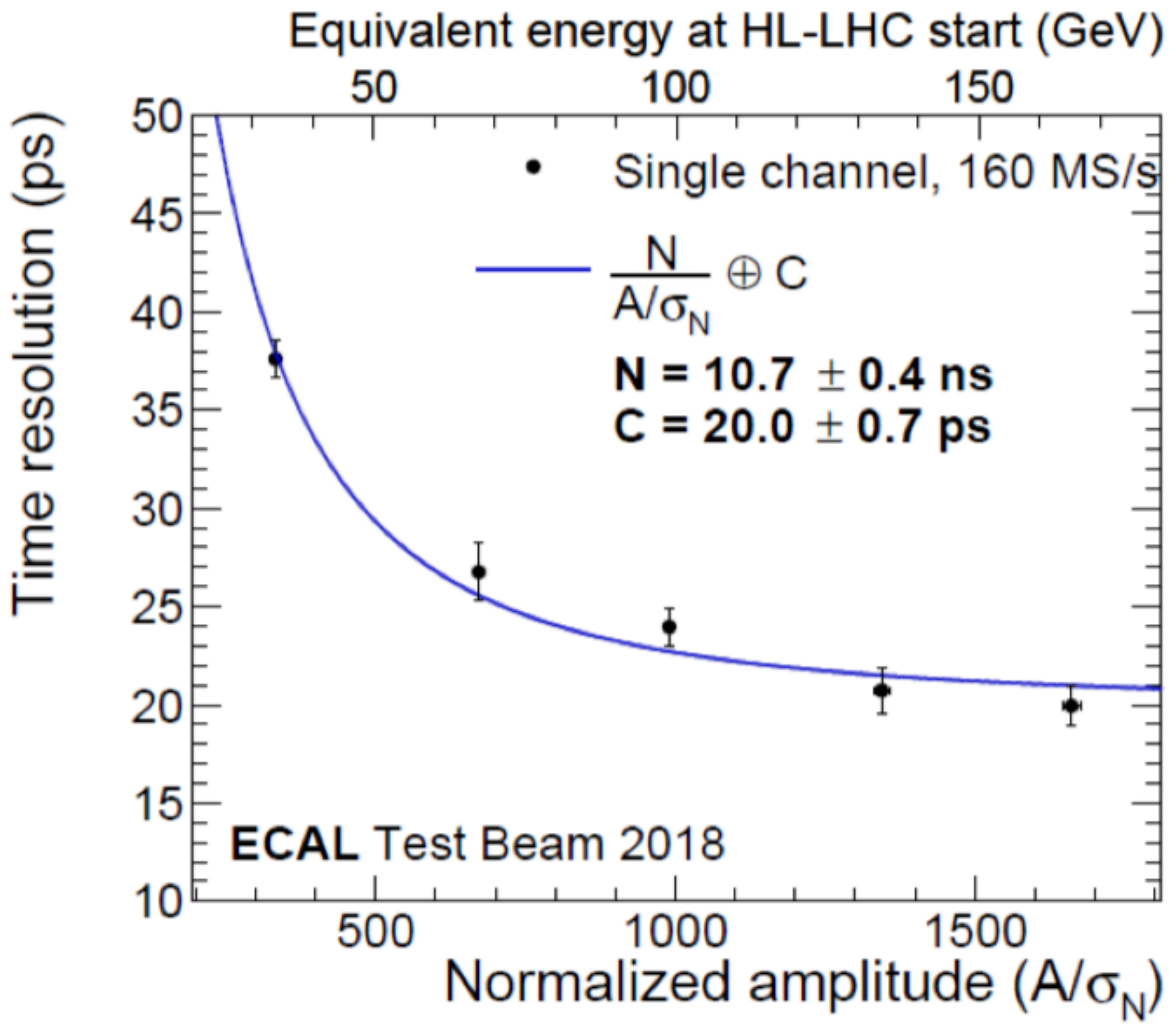
Electron beam, energy range: 25 - 250 GeV

Setup kept at 18 °C (current ECAL operating temperature)

Energy resolution matches legacy electronics

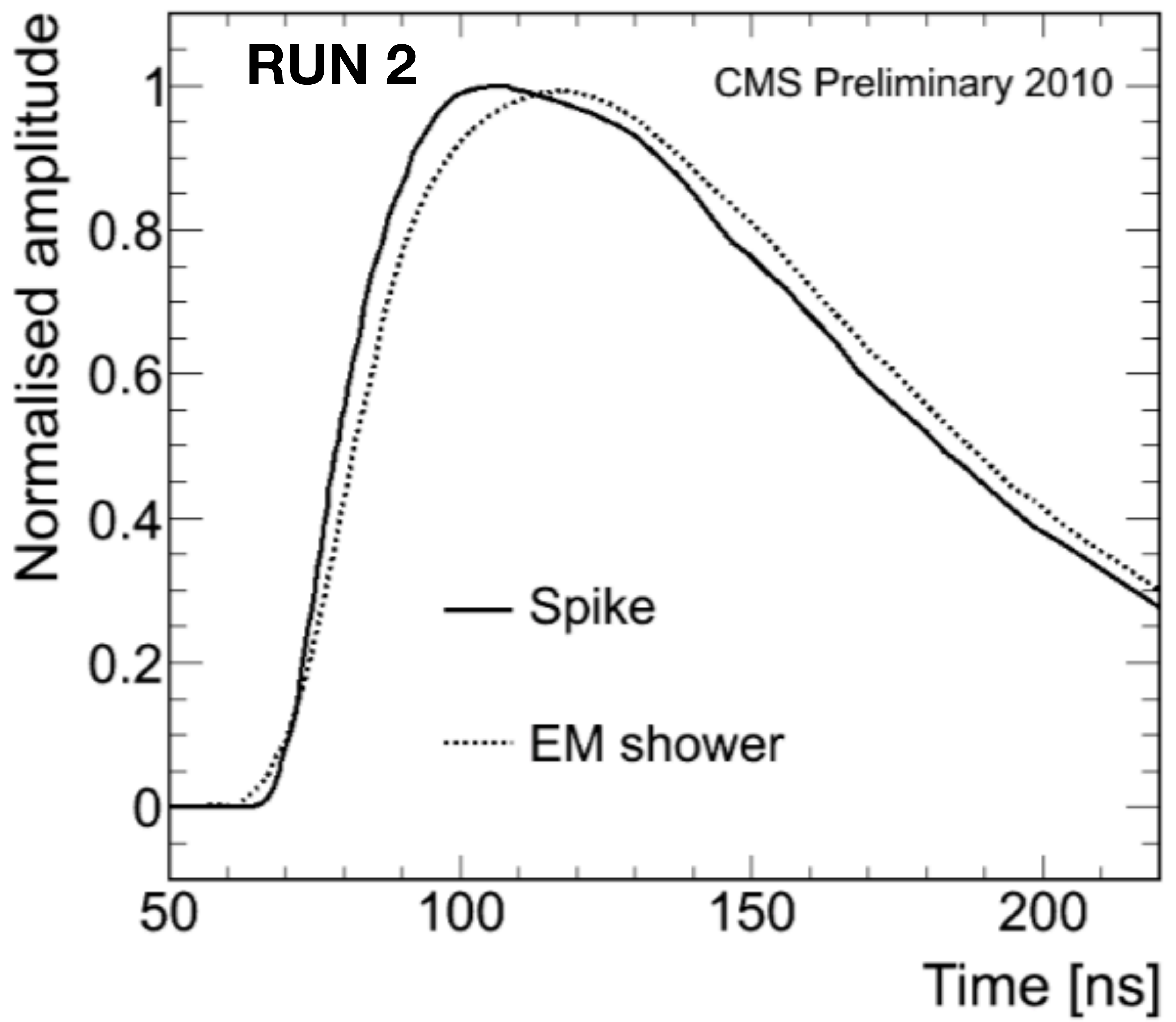


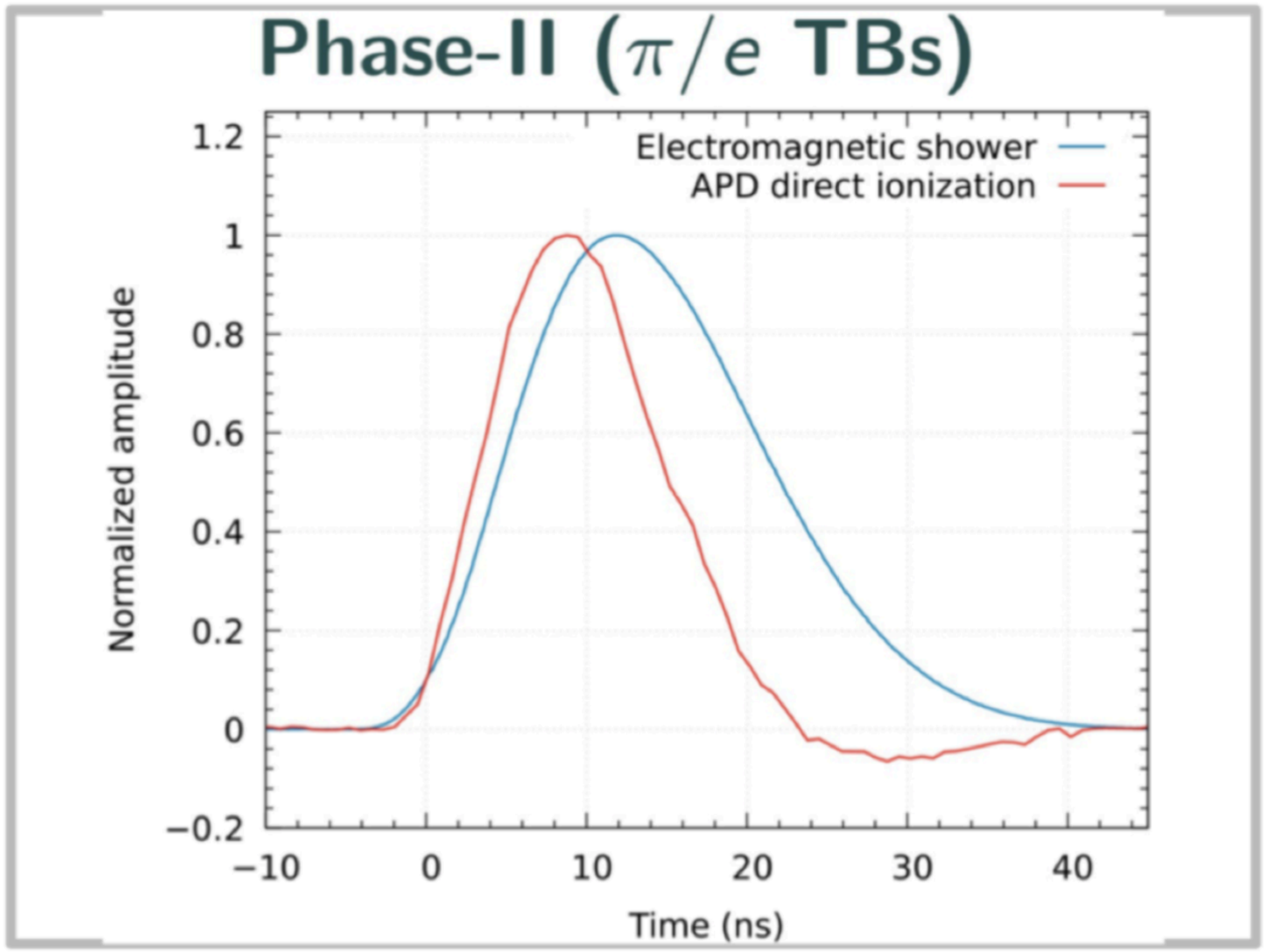
Time resolution matches targets



CATIA ASIC Performances

- Much improved **rejection of spikes** in the EB photodetectors.
- obtained with the new shorter pulse shaping

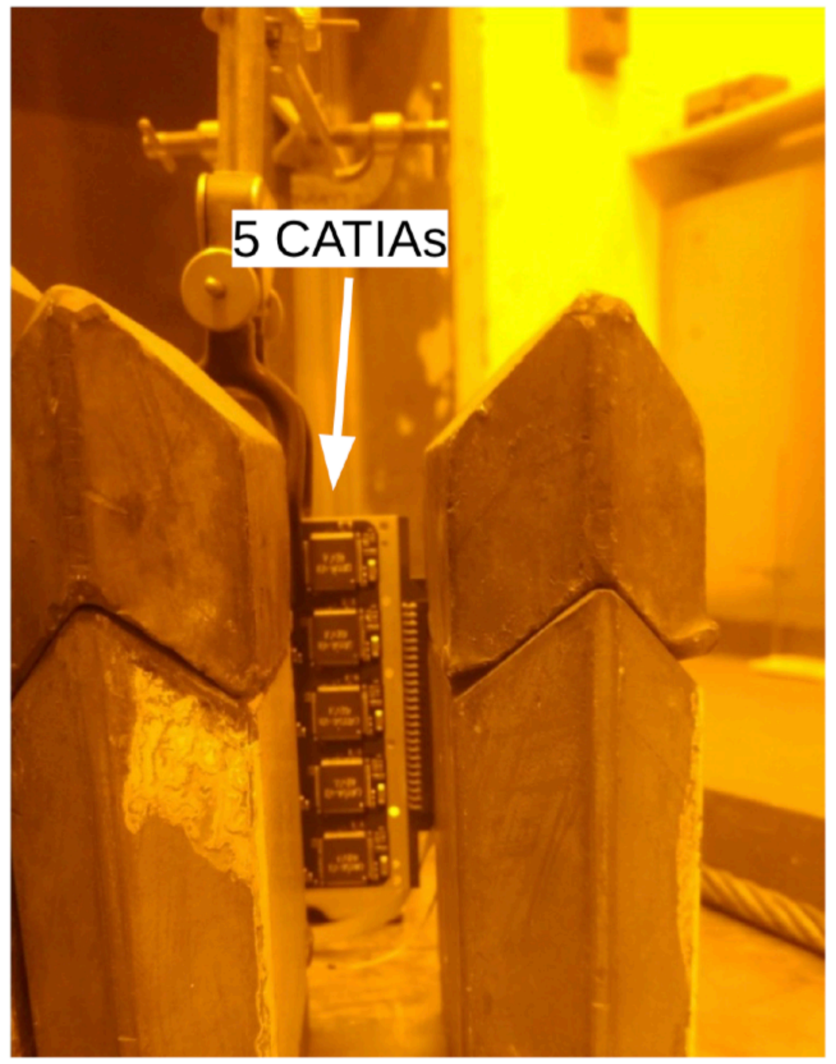


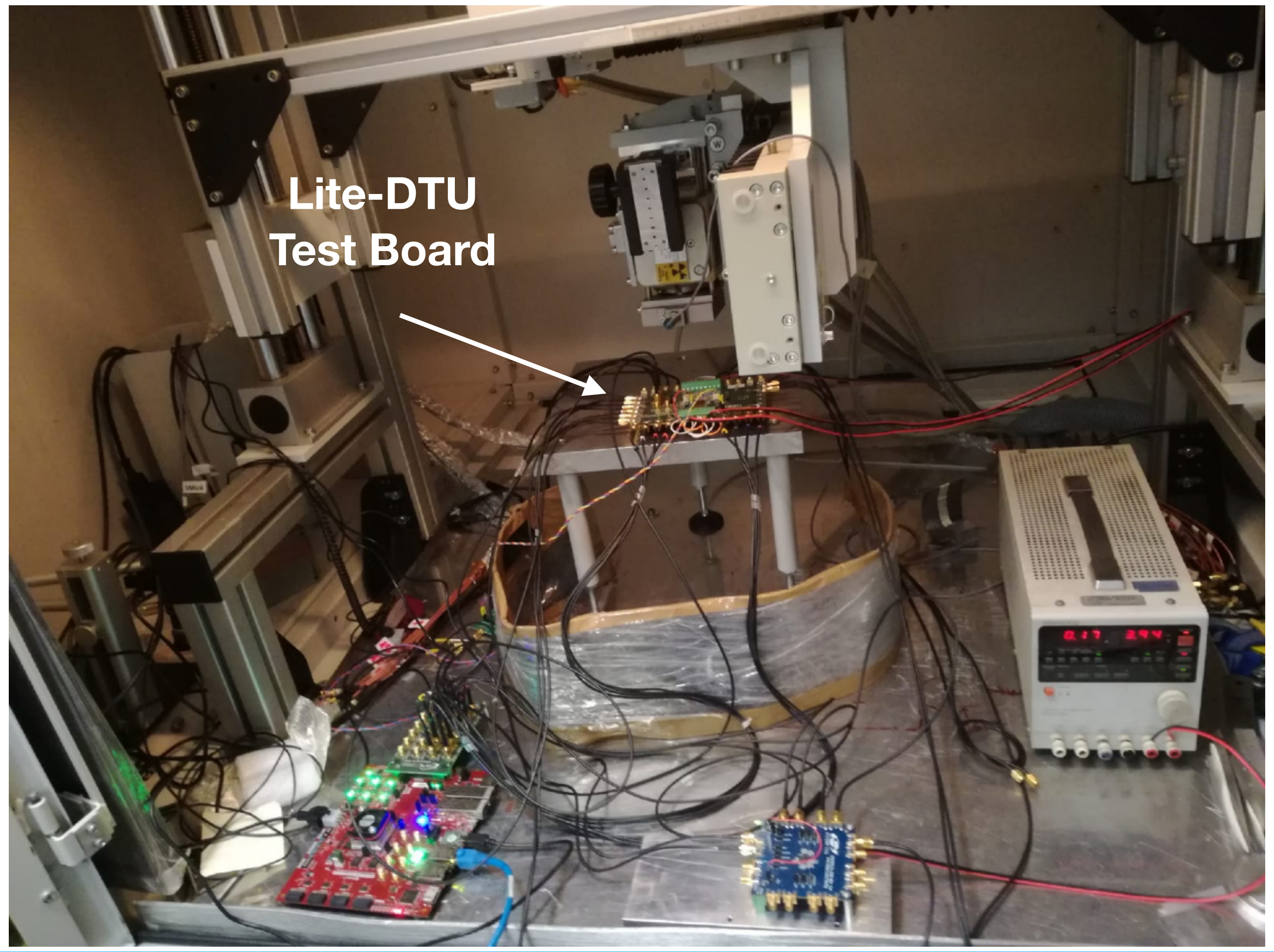


Further ongoing tests

Several tests are ongoing to characterise the full electronics chain

- Radiation Hardness of the devices
- Characterisation of CATIA (gain, noise)
- Characterisation of the Lite-DTU ADC
  - Effective Number of Bits, INL, DNL, Calibration…
- Connection between CATIA and Lite-DTU





Conclusions

The transition from the Run 2 conditions to the High-Luminosity for the CMS ECAL calorimeter has been presented

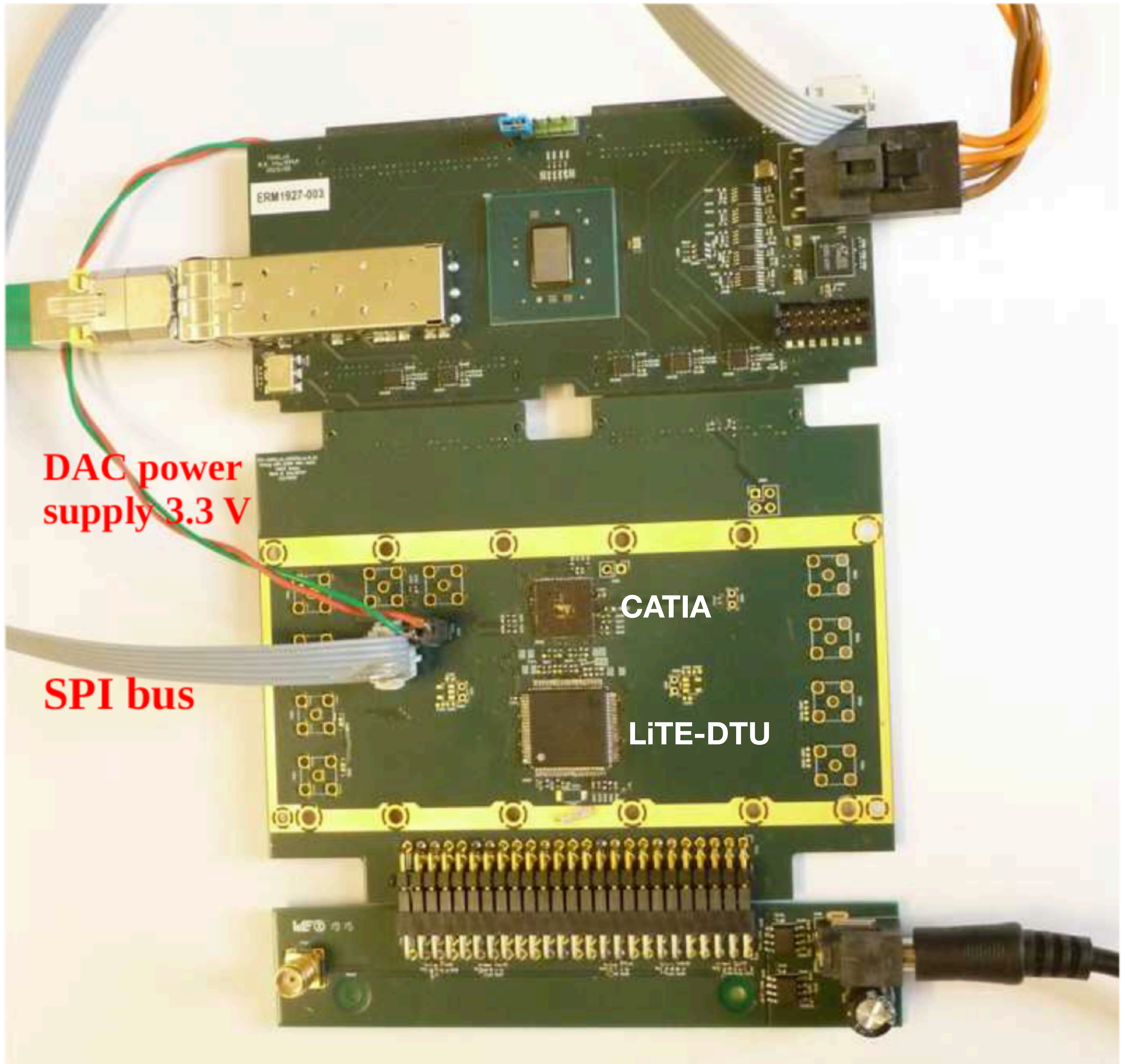
- In Run 2 the increased Pile-Up and radiation required to constantly monitor and calibrate the detector;
- The system maintained an excellent energy resolution together with a good stability over the time
- Nevertheless, for Phase 2, further interventions are needed:
  - The Endcap substitution
  - Reduced temperature in the Barrel
  - A brand new electronics has been redesigned for the ECAL Barrel:
    - it will provide a time resolution of ~30 ps to mitigate the PU effects;
    - it will provide a new shaping electronics to reject spikes already at the read-out level
    - reading each single channel it will provide a full detector read-out for the trigger

Preliminary results from the test bench have shown promising results with only CATIA + Commercial ADC.

- Tests with the Lite-DTU block are ongoing.

THANK YOU FOR YOUR ATTENTION

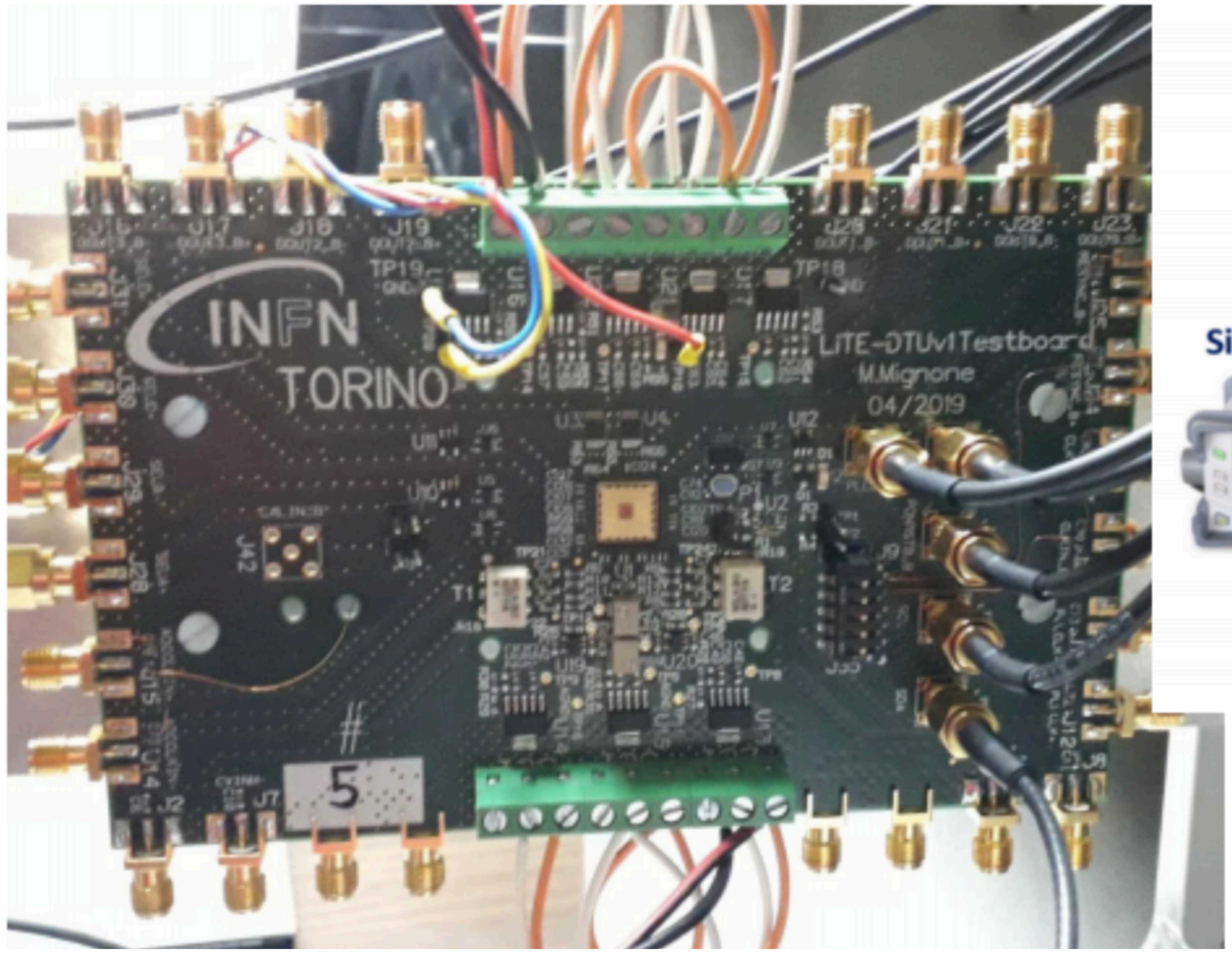
Integration of CATIA and Lite-DTU

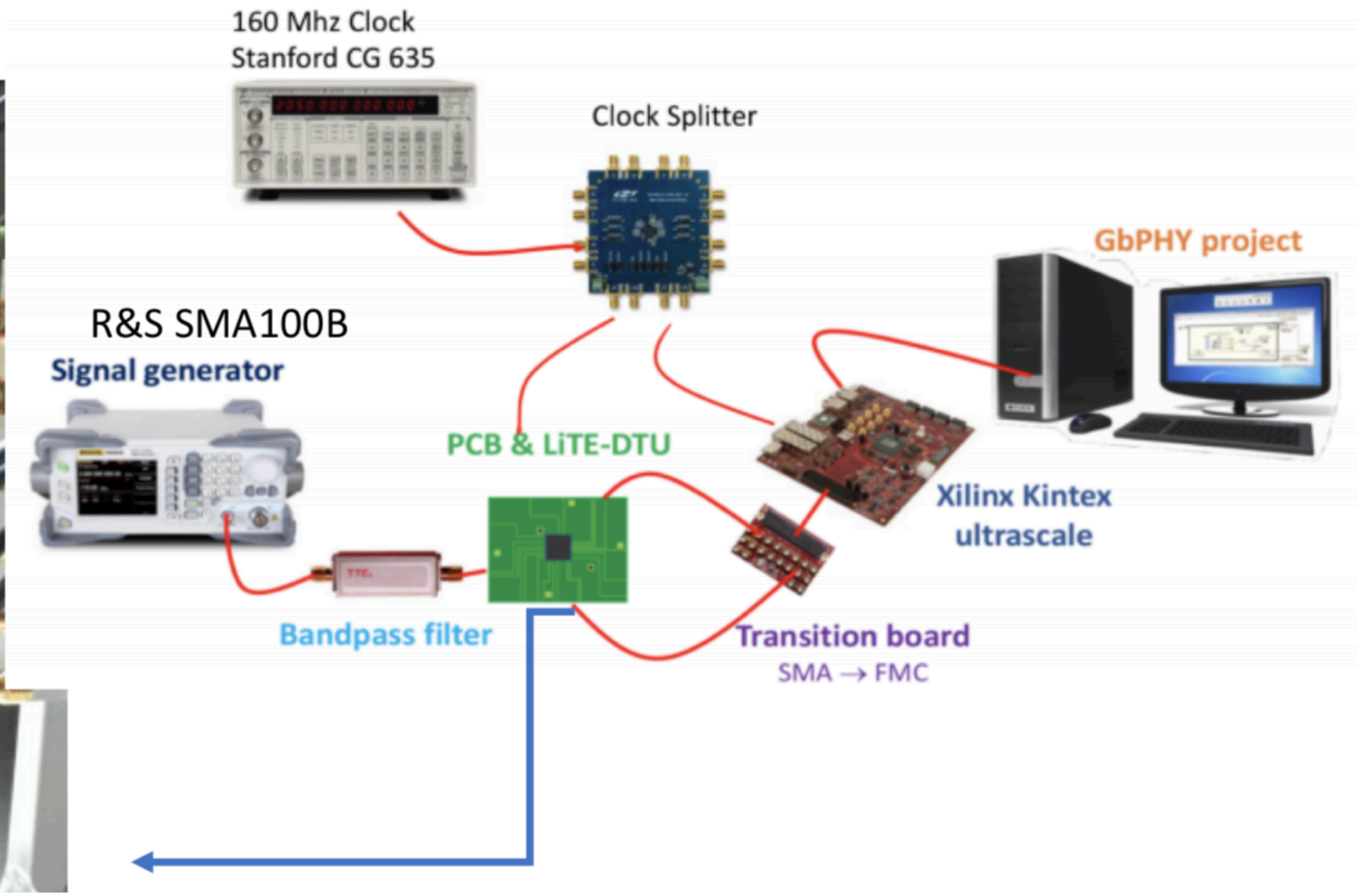


- Single channel board
  - CATIA+LiTE-DTU
  - Equipped with 16-bit DAC
  - Analog switch
    - Mux CATIA and DAC/DC signals

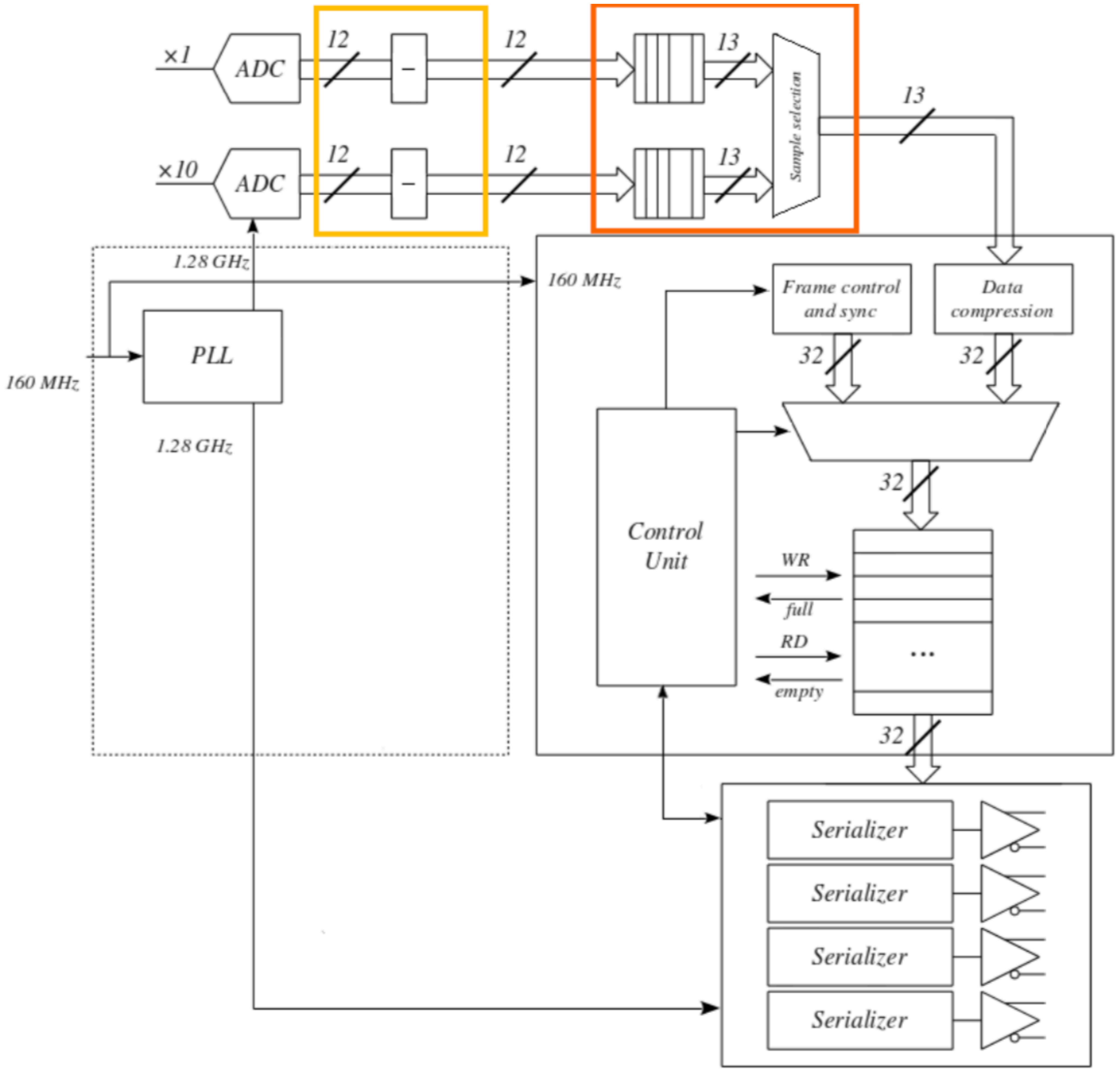
- **Allows to:**
  - Investigate calibration procedure
  - Study LiTE-DTU DC performances
  - Study CATIA/LiTE-DTU interface

Test Setup In Torino

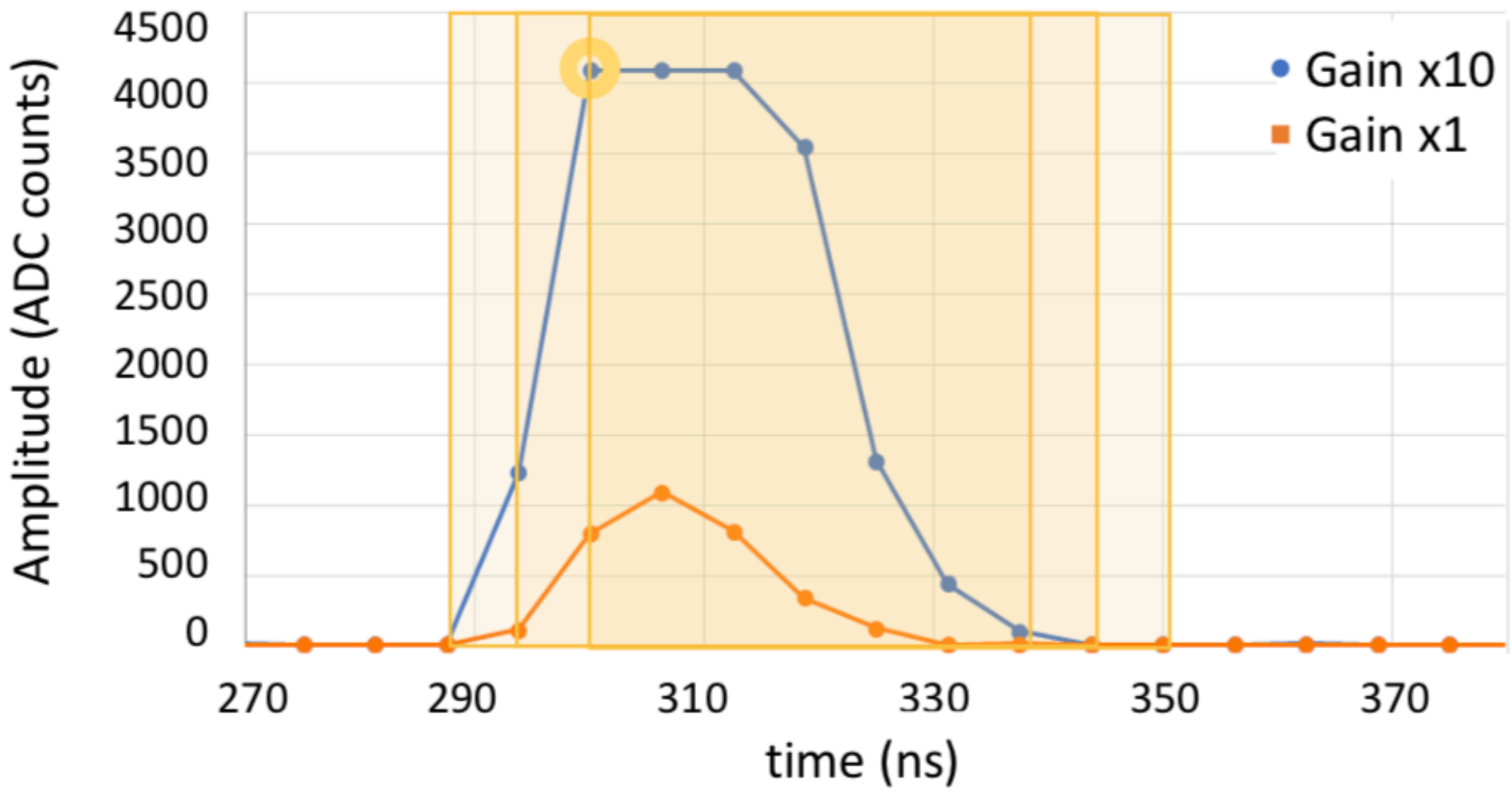




Data Compression Unit



- Sample selection unit:
  - **Look-ahead algorithm**: sample saturation check prevents the mixing of samples from different gains in the same APD signal timeframe.



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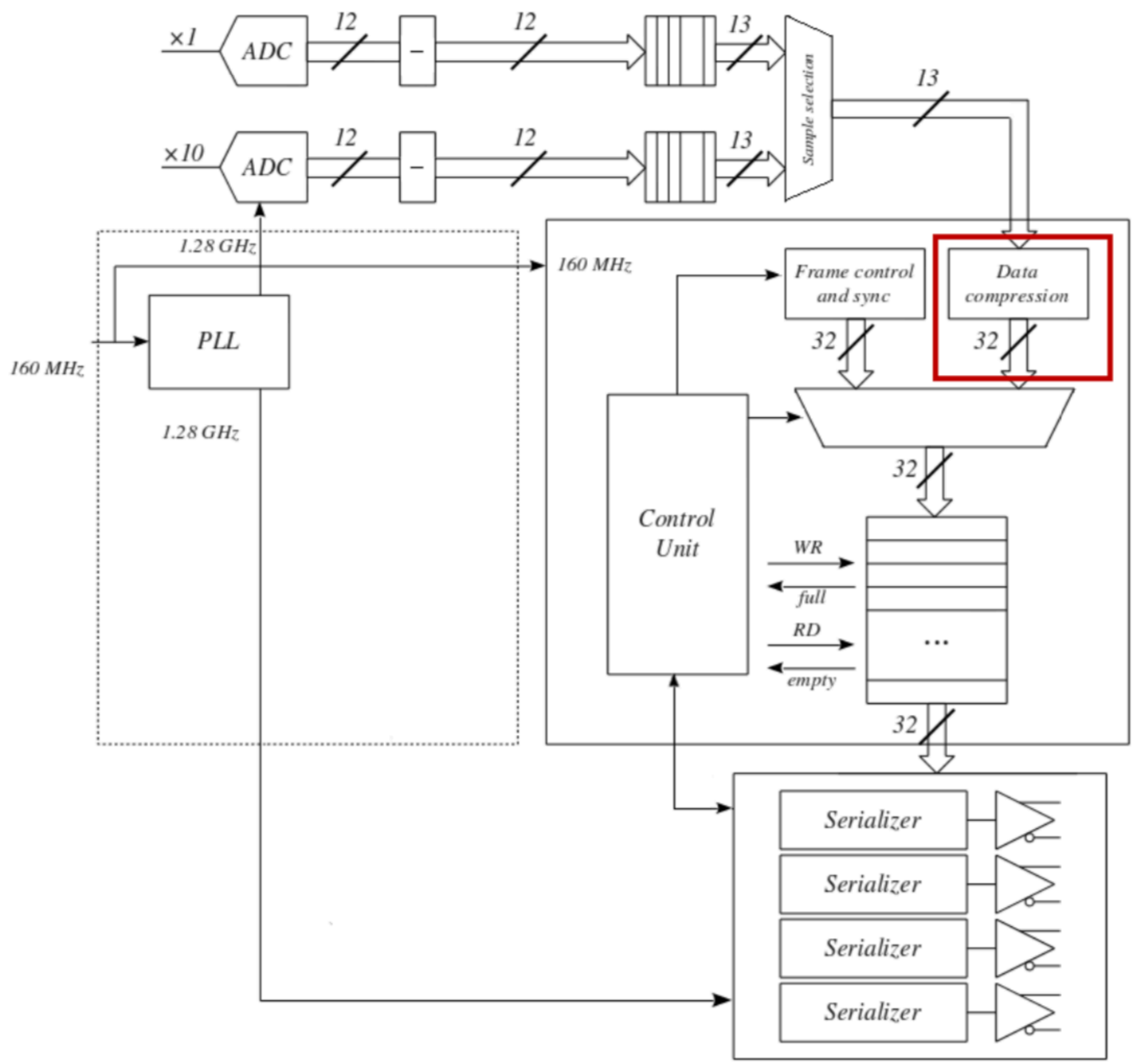

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Temperature effect on the APD dark current

The ECAL Barrel crystal light is read-out with Avalanche Photodiodes (APD).

- The APDs are Si photodiodes with internal amplification.

- The leakage current increases with the hadron fluence.

- The APD leakage current is measured at the HV crates.