The upgrade of the CMS Electromagnetic Calorimeter for HL-LHC

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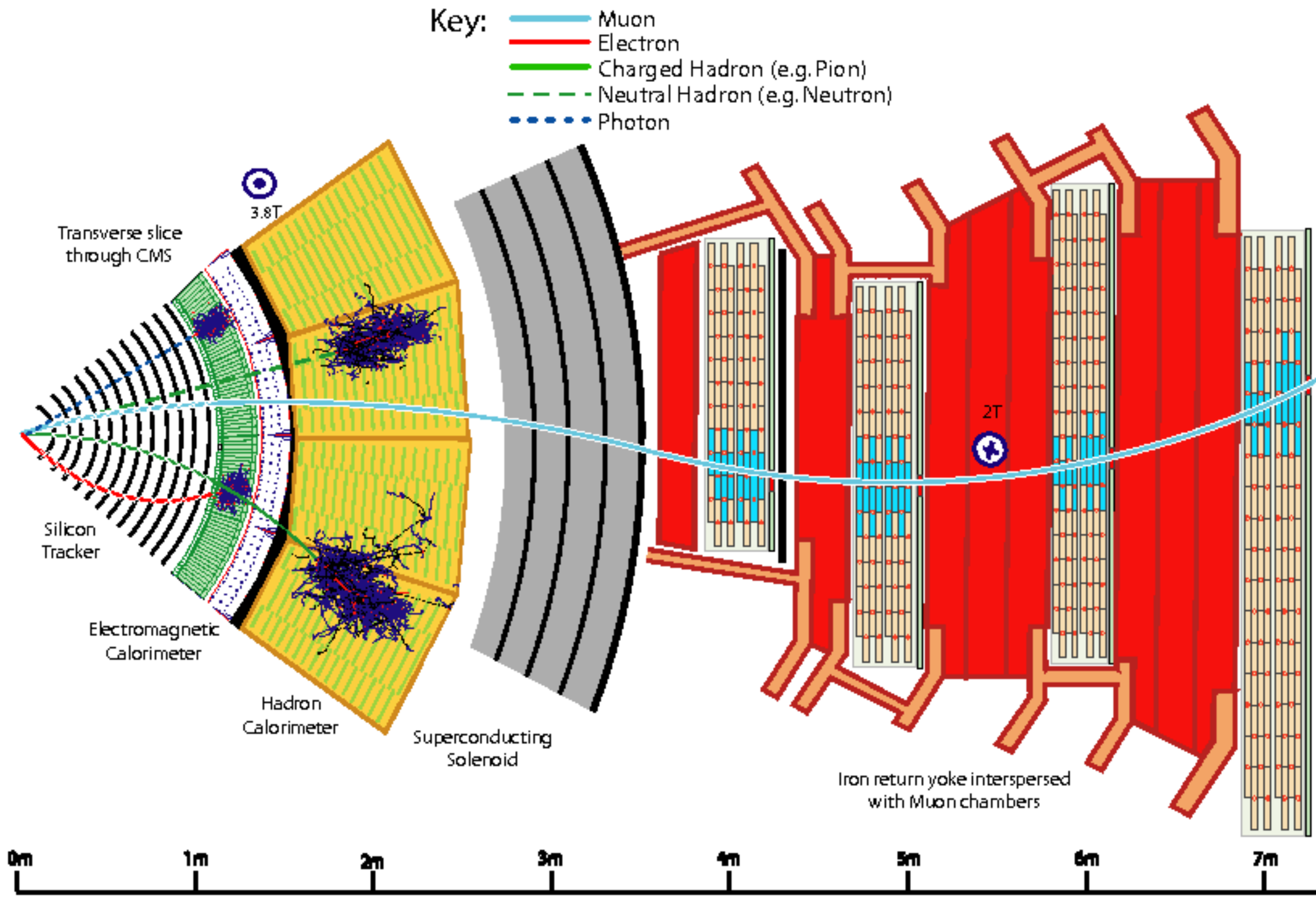
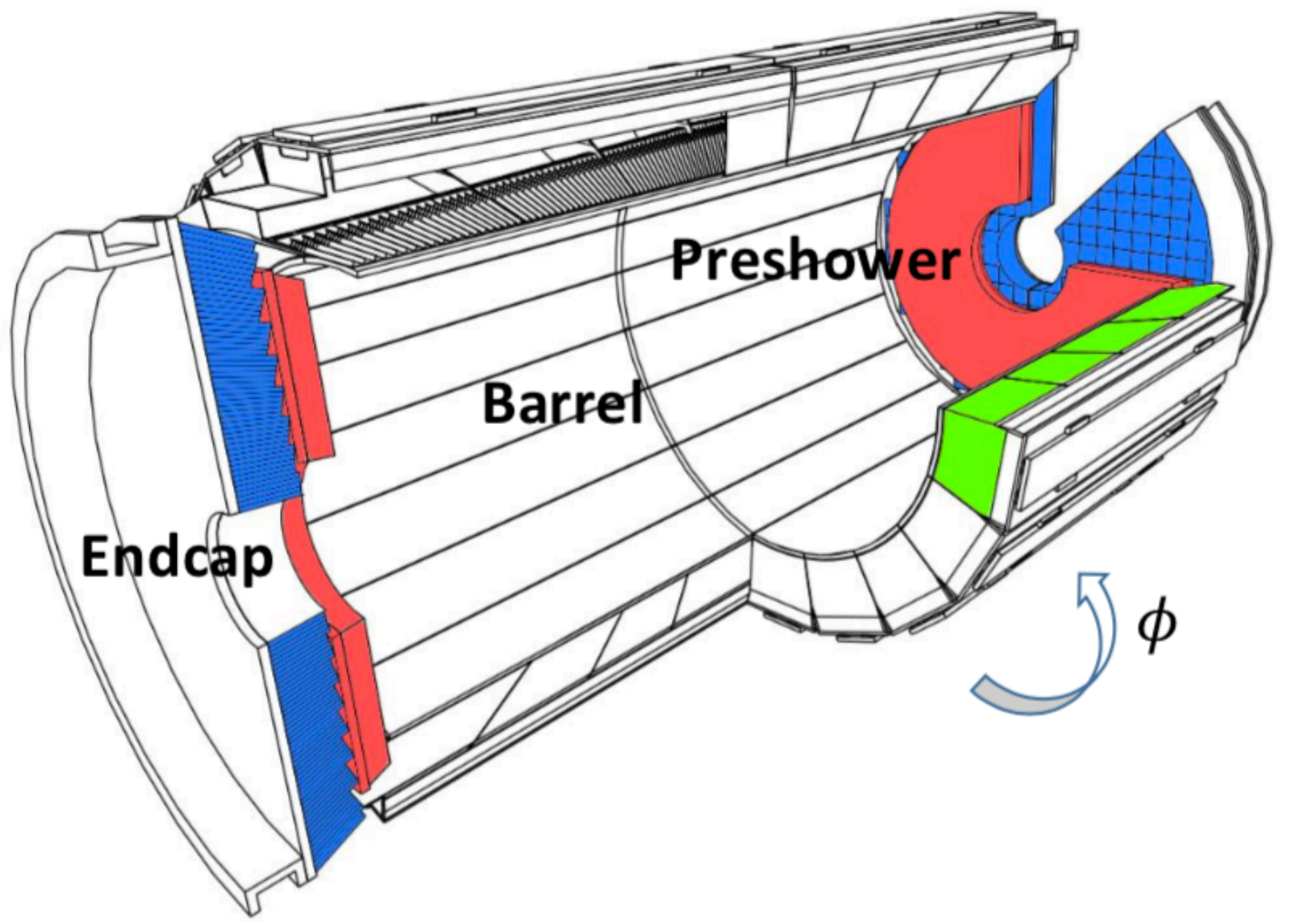
The CMS ECAL in a nutshell

- The Electromagnetic calorimeter (ECAL) of the CMS experiment:
  - **fine granularity**: 61200 crystals in the barrel, 14648 in the endcaps;
  - **lead tungstate $PbWO_4$**: fast decay scintillation light (25 ns), short radiation lenght (X_0 = 0.89 cm), small Moliere radius (2.2 cm);
  - Barrel is read by avalanche photo-diodes (APDs) sensors, vacuum phototriodes (VPTs) for the endcaps;
- Fundamental to detect *e*/γ: Marco Pieri's talk
  - **Good di-photon mass resolution for Higgs events**: ~1%
  - **Crucial role** for the discovery of the Higgs boson in the final states with two photons or four leptons.





The challenge of High Lumi

- **ECAL must maintain its performances during 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 (APD leakage current) + crystal transparency loss
  - Higher rate of anomalous signals induced by hadrons interacting directly with the APD core ("spikes")
  - trigger latency moves from 3.8 us of phase 1 to 12.5 us of phase 2.
- **Actions:**
  - Replacement of the Endcap part of ECAL with a new High Granularity calorimeter. Clemens Lange's talk
  - Reduction of the ECAL operating temperature from 18° to 9° C to mitigate the APD dark current
  - **Upgrade of the Ecal Barrel Electronics to have: precise timing + spike rejection + single crystal information available @ L1**

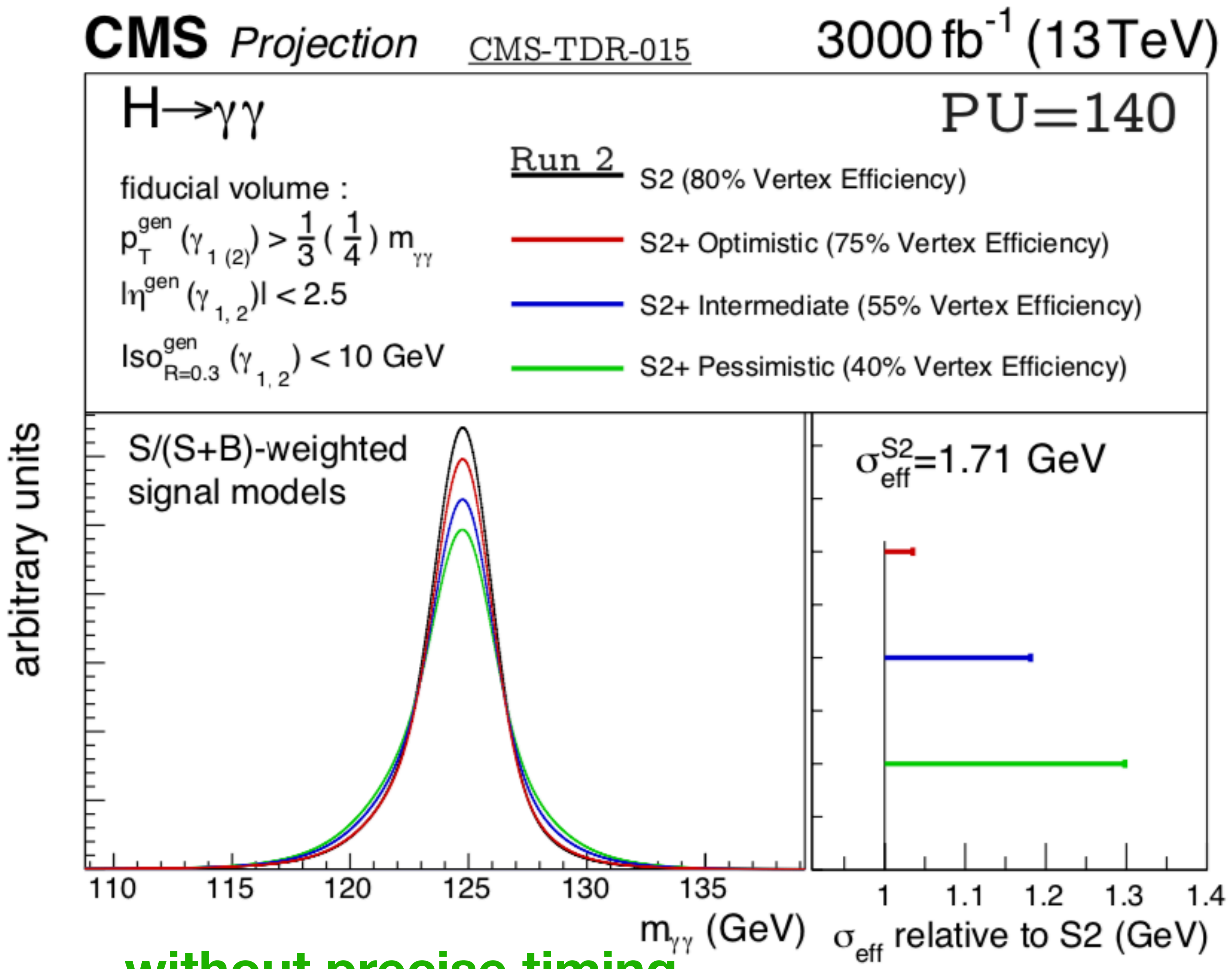
Precise timing in Phase 2

- 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 $H \to \gamma\gamma$ decays

The fiducial cross-section sensitivity and $H \to \gamma\gamma$ mass resolution can be almost completely recovered exploiting the ECAL timing information together with the new timing layer;

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

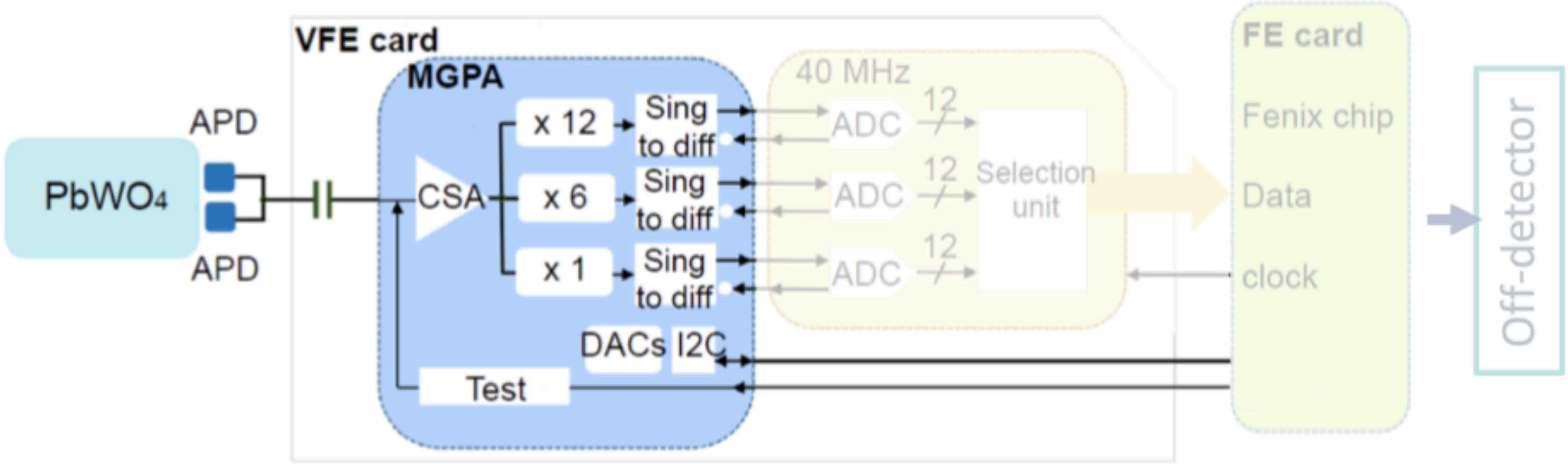


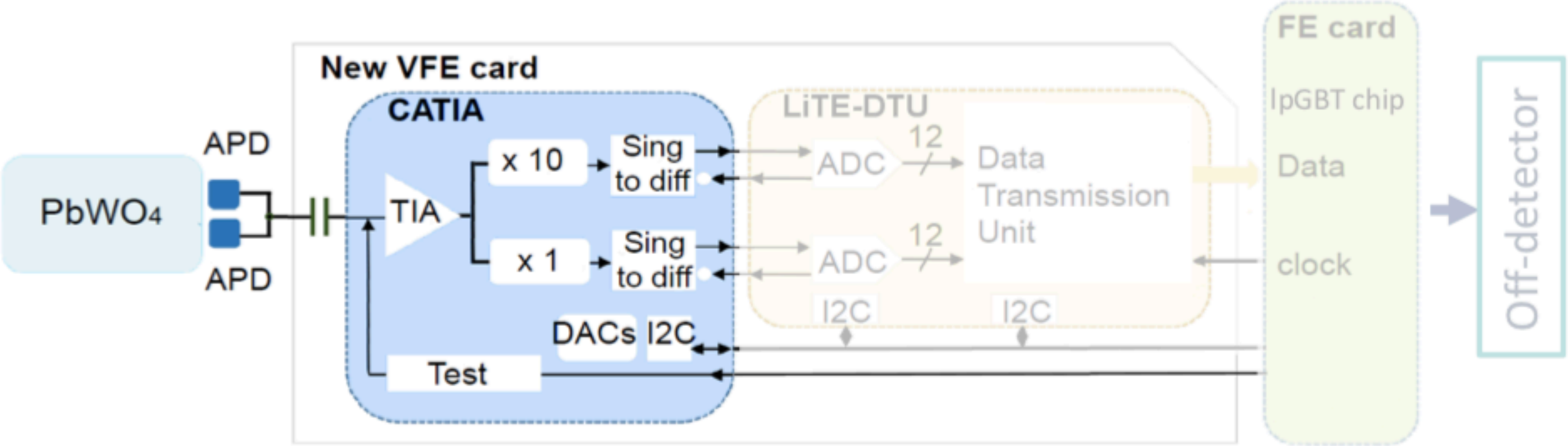
without precise timing

with precise timing (30ps) in calorimeter

Adding the timing layer to precisely tag MIPs

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 / gain value
- 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**

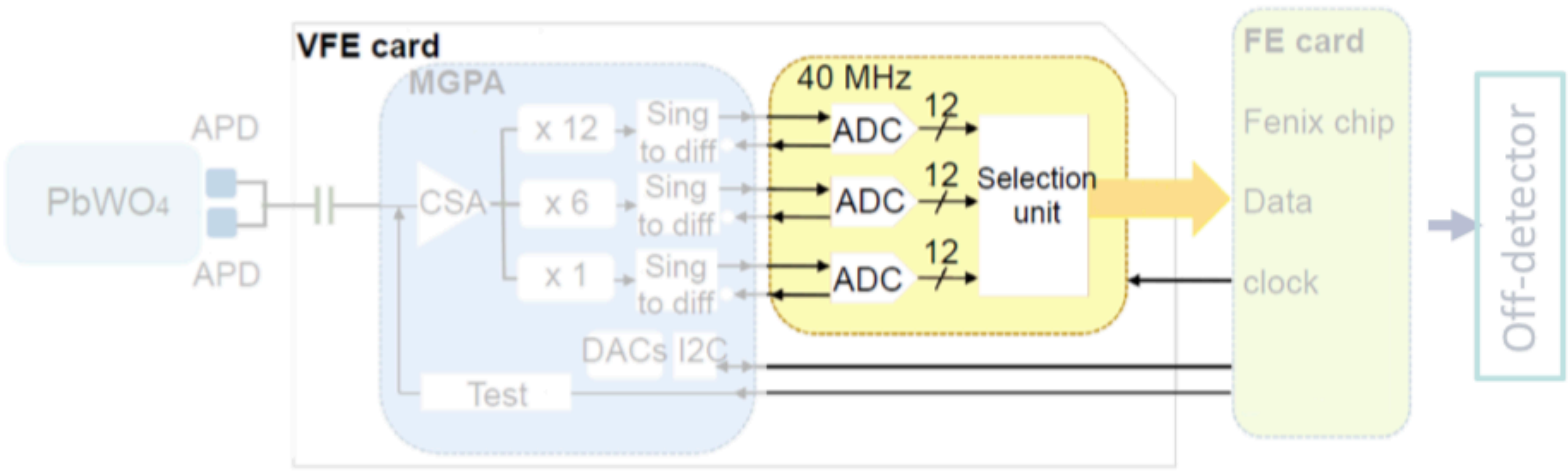
Lite-DTU ASIC:

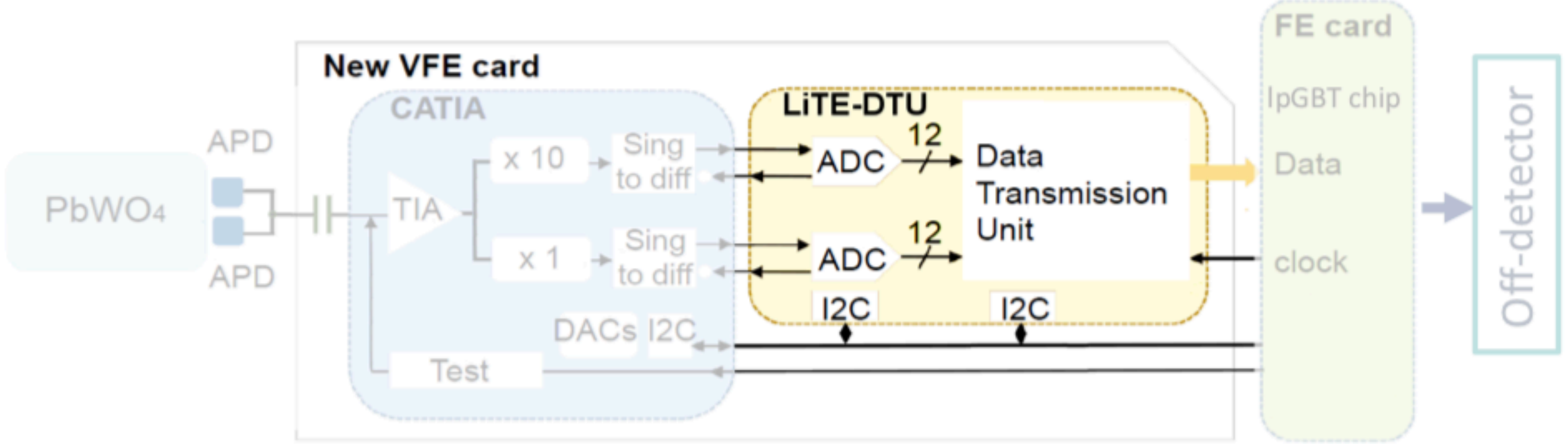
- ADC resolution: 12 bit / gain value
- ADC sampling frequency: 160 MS/s
- Selection and **compression** unit

New Front-End Card:

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

Legacy vs upgraded on-detector readout





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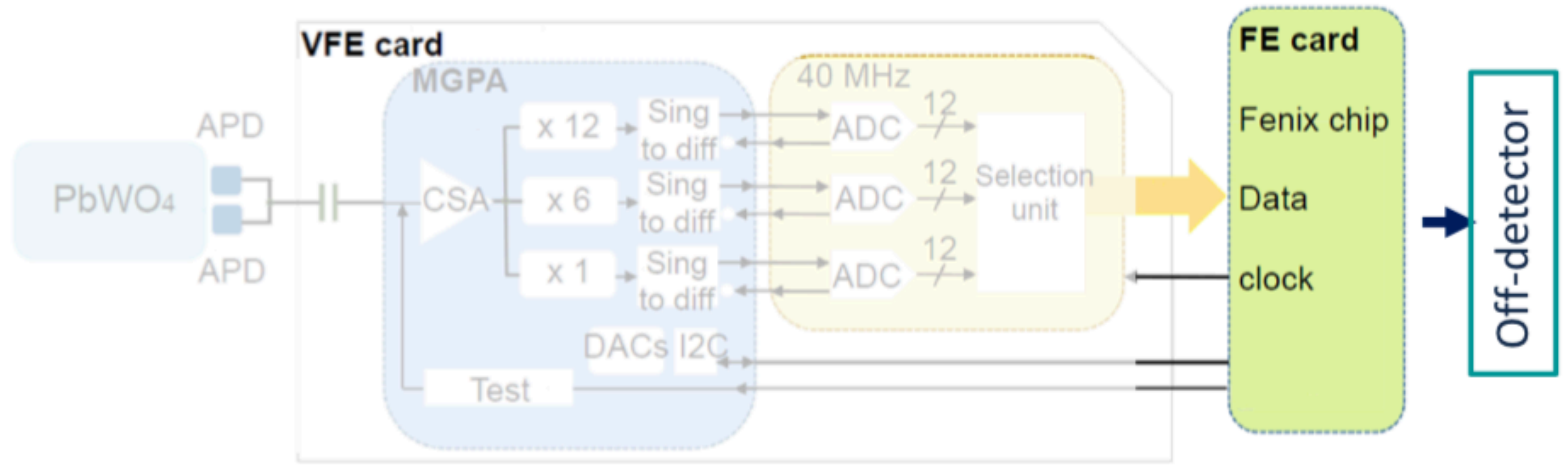

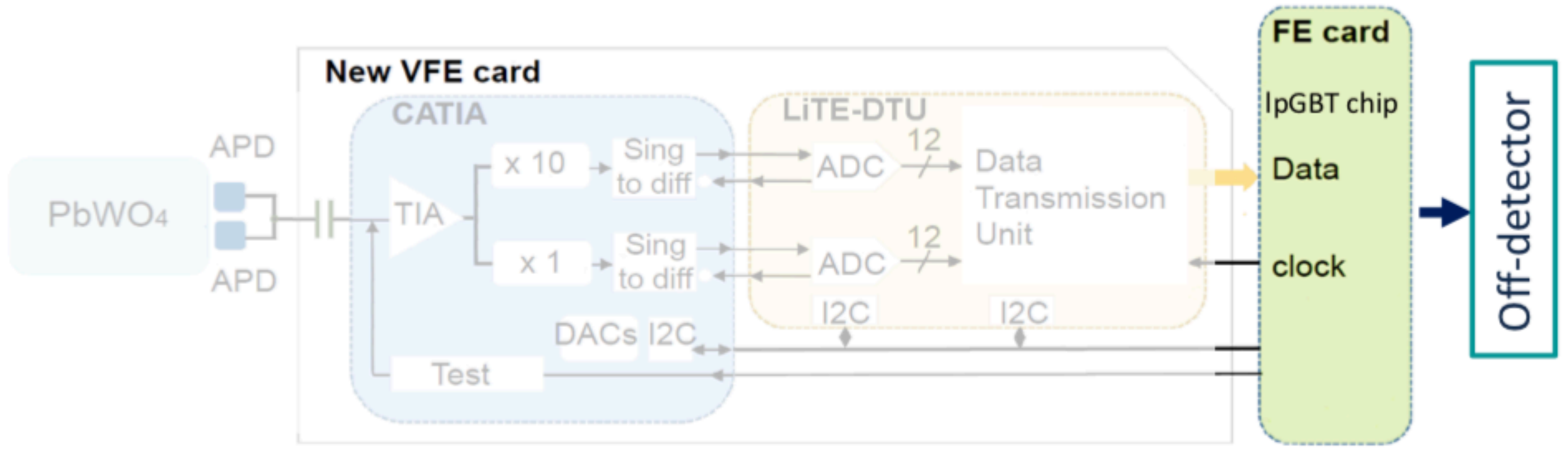

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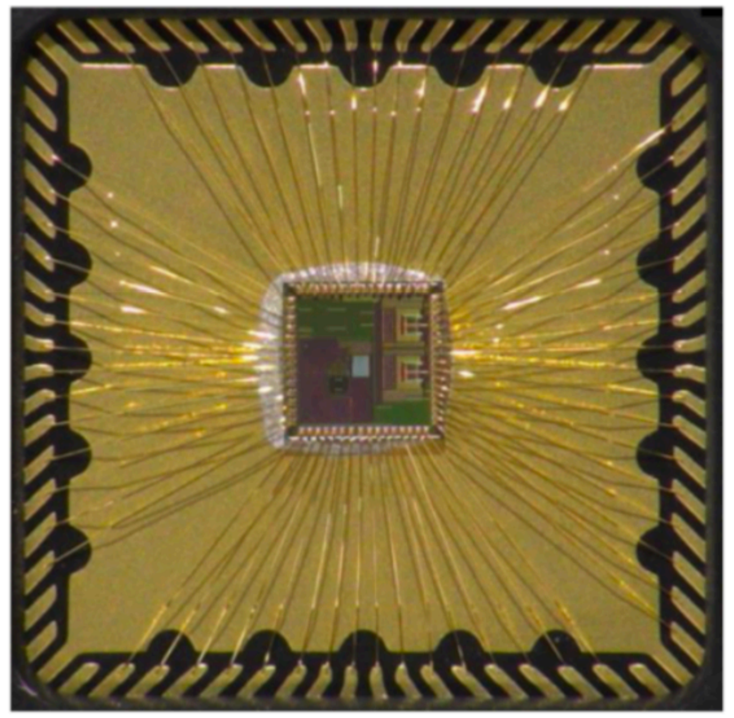
The LiTE DTU Chip

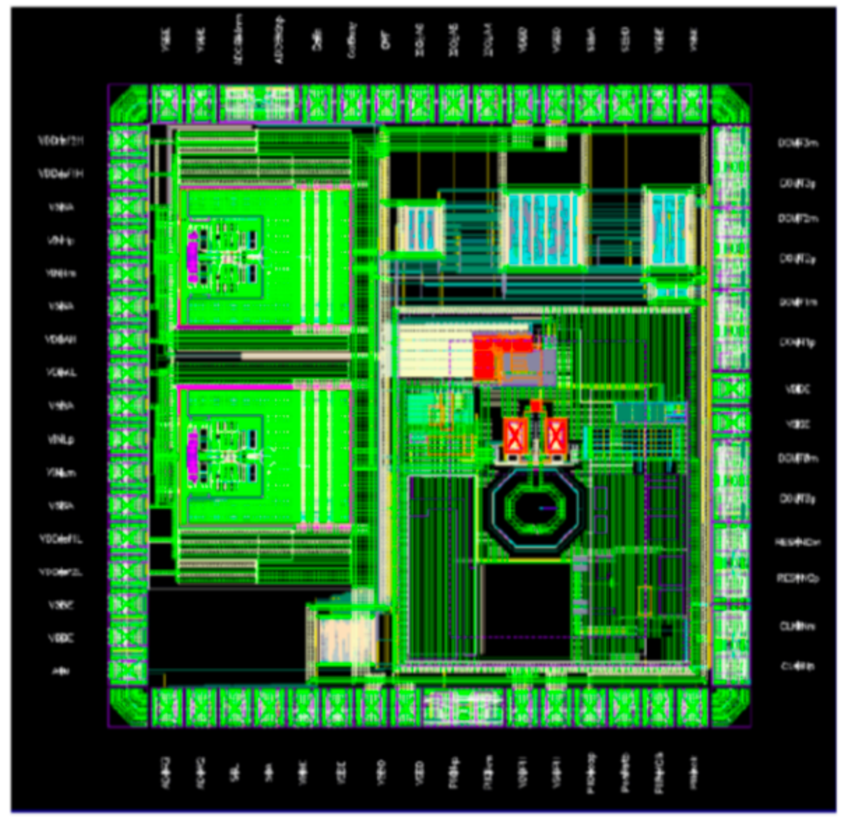
Two 12-bits ADCs, 160 MS/s data conversion:
ENOB @ 50MHz = 10.2 bit

Phase Locked Loop
1.28 GHz clock for the ADC and the data transmission

Lossless data compression

ID tolerance up to 20 kGy
SEU-protected control logic





Lossless data compression

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**

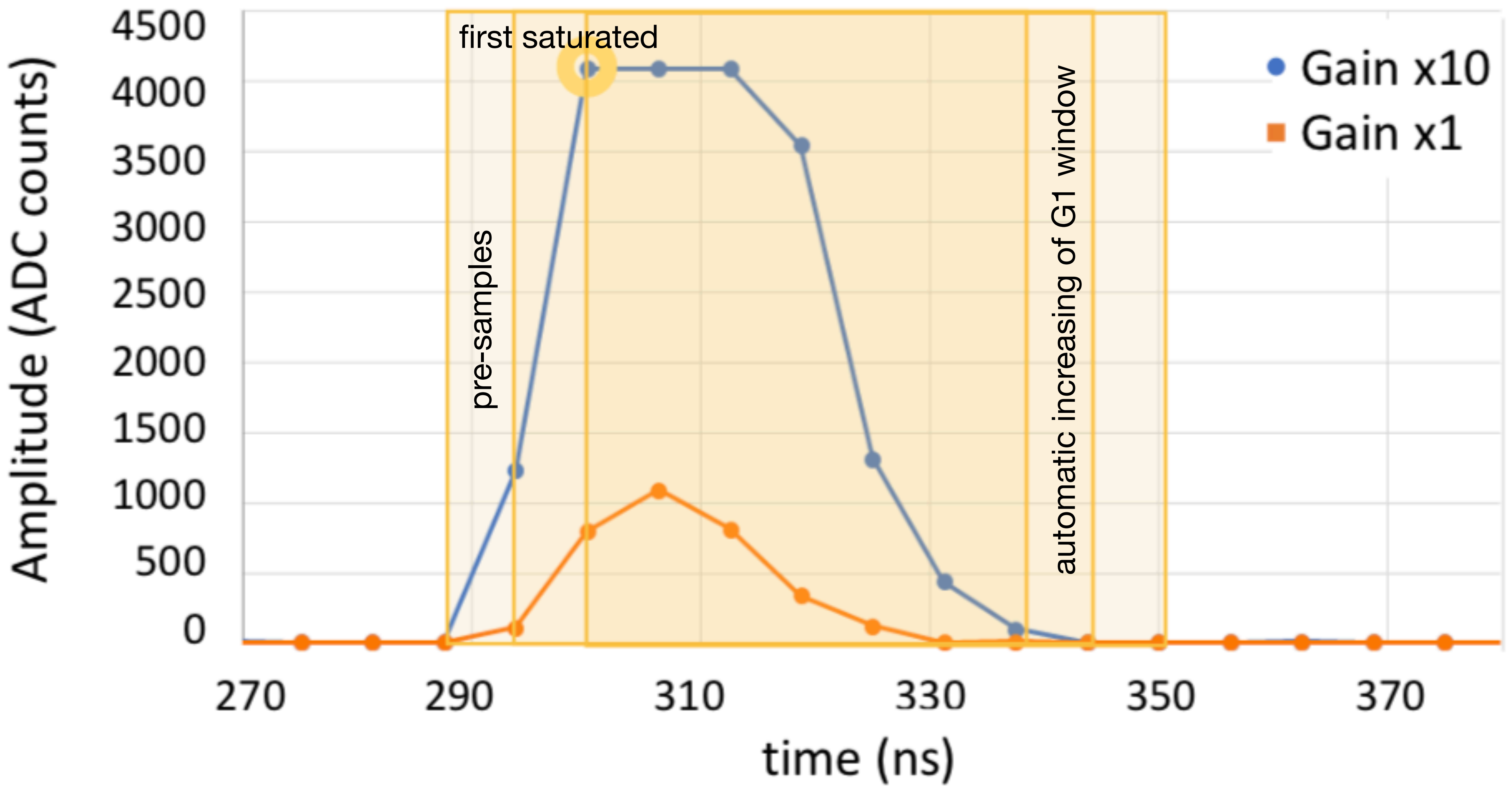
Gain sample	Significant non-zero bits	Sample Classification[a]	Output (Nbits)
x10	$\leq$ 6 bits	"Baseline" sample	6 bits
x10	$>$ 6 bits	"Signal" sample	13 bits (MSB = 0)
x1	any value	"Signal" sample	13 bits (MSB = 1)

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

The data compression assumes that data in the crystals are usually at low energy: the LiteDTU usually delivers baseline signals.

Other LiTE-DTU features

- **Look-ahead algorithm:** sample saturation check prevents the mixing of samples from different gains in the same APD signal timeframe.
- Two gain1 dynamic windows: 8 or 16 samples
  - If there are N saturated samples at g10, the gain1 is automatically enlarged up to 8 + (N-1) or 16 + (N-1).

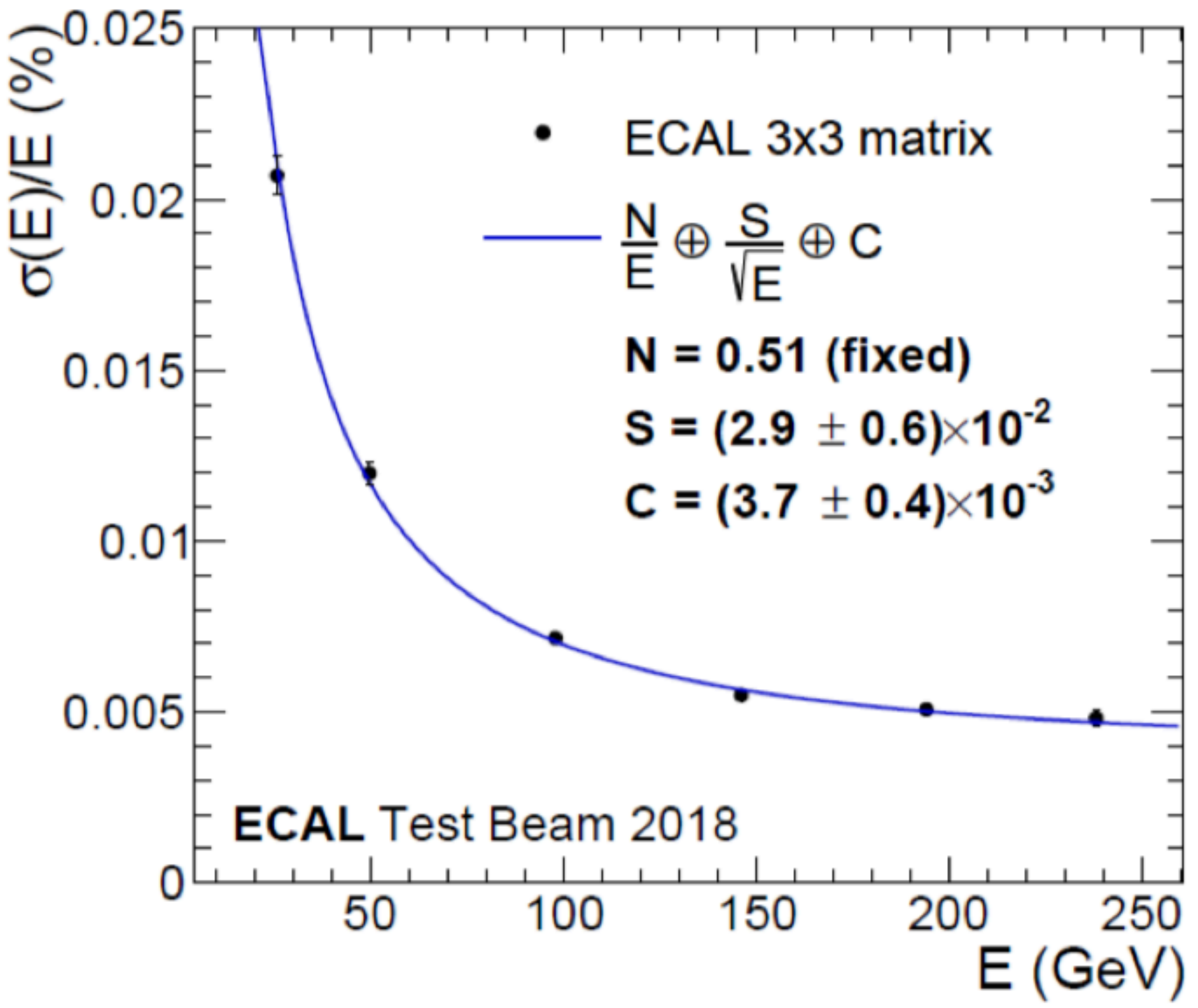


- **ADC test mode:** to send the ADC output without any gain selection or compression;
- **Forcing gain selection:** to transmit data using always the same gain;
- **Downgrade the sampling frequency:** to read data at 80MHz;
- **Baseline subtraction:** to subtract a fixed value to all the samples to reduce the probability of being above the baseline threshold;
- **Shift of the ADC values:** to divide the ADC values of a factor 2 or 4: for cases of very noisy channels in which the average baseline is low but its oscillation is large, going above the baseline threshold.

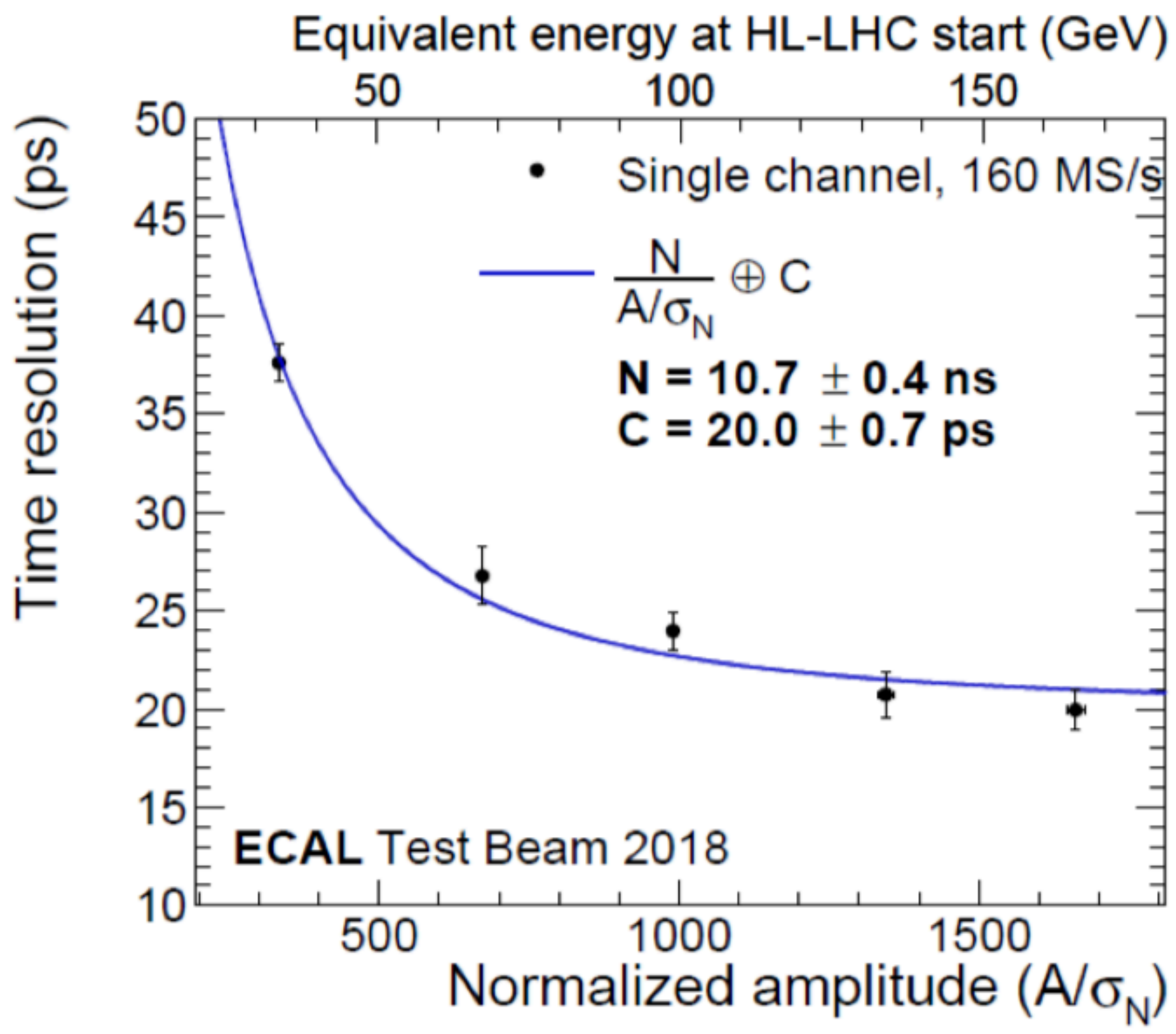
CATIA ASIC Performance from Test Beam

- One ECAL tower (25 channels) equipped with CATIA chip connected with **160 MHz commercial ADC;**
- Electron beam, energy range: 25 - 250 GeV;
- The timing and energy resolutions match the requirements;

Energy resolution matches legacy electronics

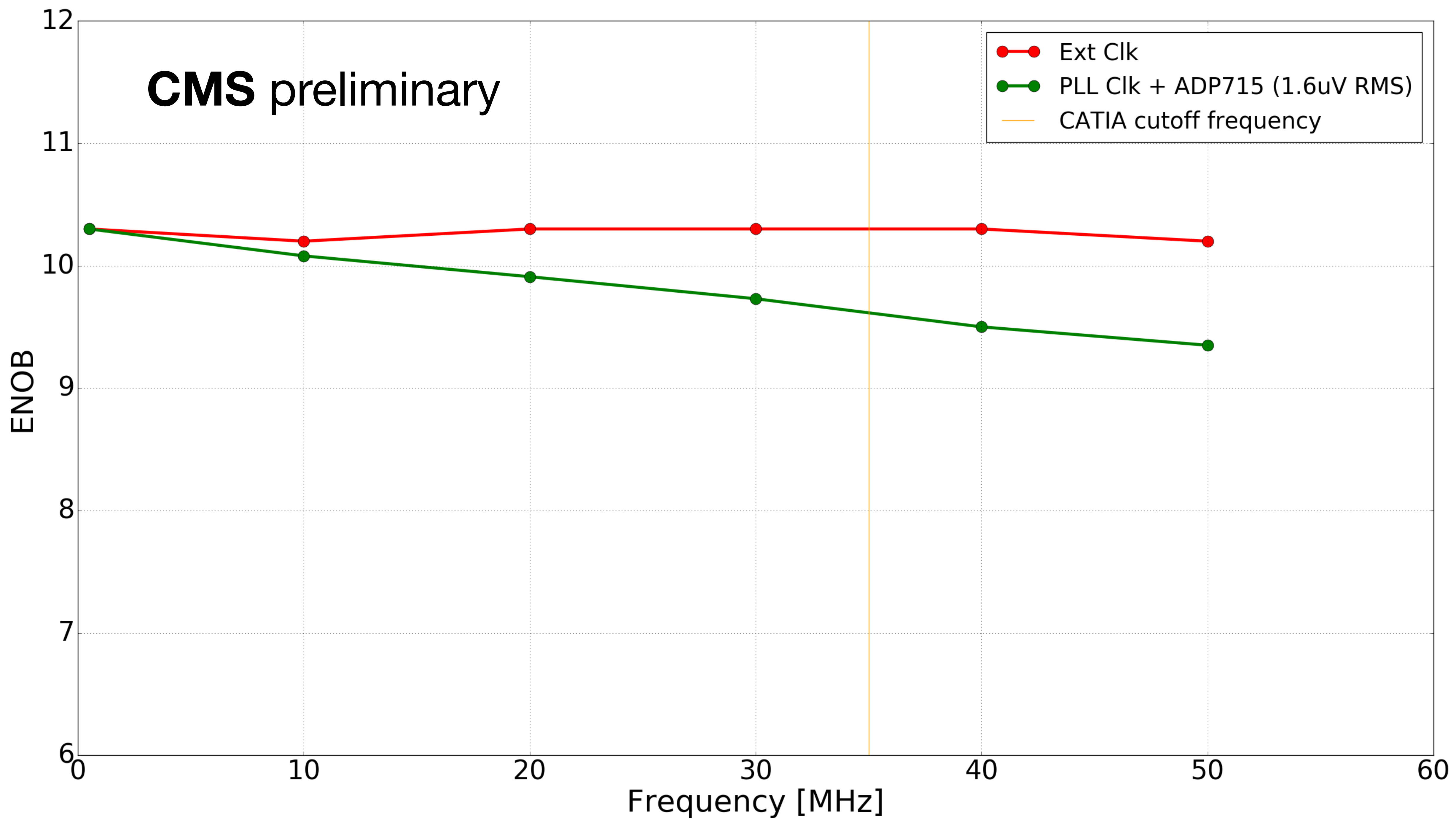


Time resolution matches targets



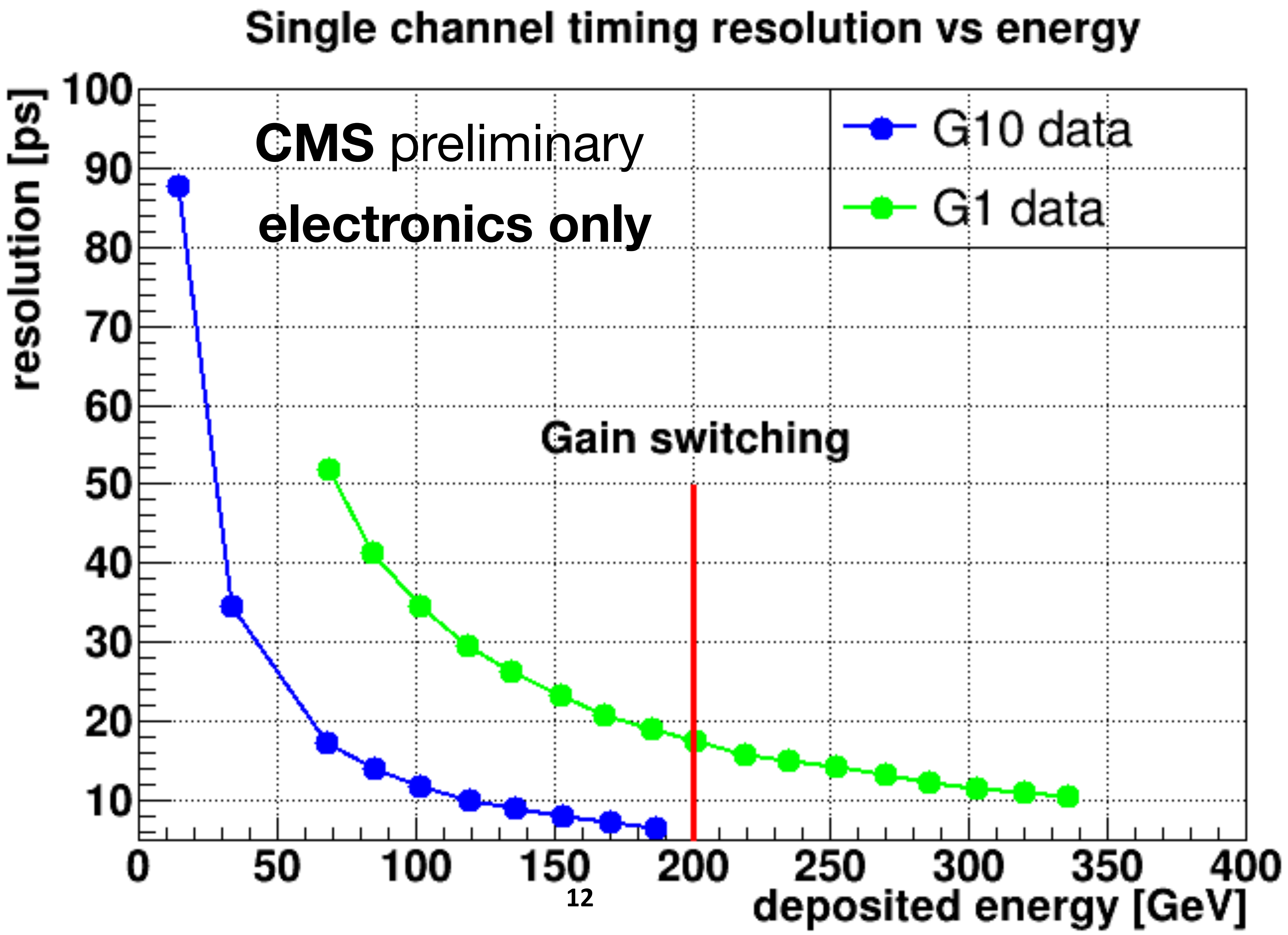
LiTE-DTU laboratory tests

- **Check the ADC performance:**
  - ENOB scan as a function of the frequency;
  - Test performed with **external clock generator** (jitter < 3 ps) gives an ENOB which fits the expected performance;
  - Results with the **PLL v0** are already promising;
  - We submitted a new LiTE-DTU chip, implementing a new version of PLL, with a reduced jitter;



Integration of CATIA + LiTE DTU

- The first version of the DTU chips have been assembled with the CATIAs on the new Very Front End boards;
- Results from the timing resolution obtained considering only the electronics (no Crystals, no APDs, no shower fluctuations…) match the requirements;
- A test beam with the integrated system as been performed last week - results soon;



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Conclusions

The High-Luminosity upgrades needed for the CMS ECAL calorimeter has been presented:

- Brand new electronics have been designed for the ECAL Barrel:
  - will provide a time resolution of ~30 ps to mitigate the PU effects;
  - will provide a new shaping electronics to reject spikes already at the read-out level or L1 trigger
  - single crystal granularity for L1 trigger
- Replace the Endcap with the High Granularity calorimeter;
- Reduced temperature in the Barrel;

First results of CATIA + commercial ADC from the test beam and of the electronic chain CATIA + LiTE-DTU from laboratory tests meet requirements

Last week the first test beam with the CATIA + LiTE-DTU system has been performed: results will come soon

THANK YOU FOR YOUR ATTENTION

Backup

Features for debugging and resilience implemented in the LiTE-DTU

- **ADC test mode:** the output of the ADC is sent out without any gain selection or compression; Possibility to study the ADC performances, validate the output data, etc.;
- **Forcing gain selection:** possibility to transmits data using always the same gain;
- **Downgrade the sampling frequency:** gives the possibility to read data at 80MHz;
- **Baseline subtraction:** possibility to subtract a fixed value to all the samples to reduce the probability of being above the baseline threshold;
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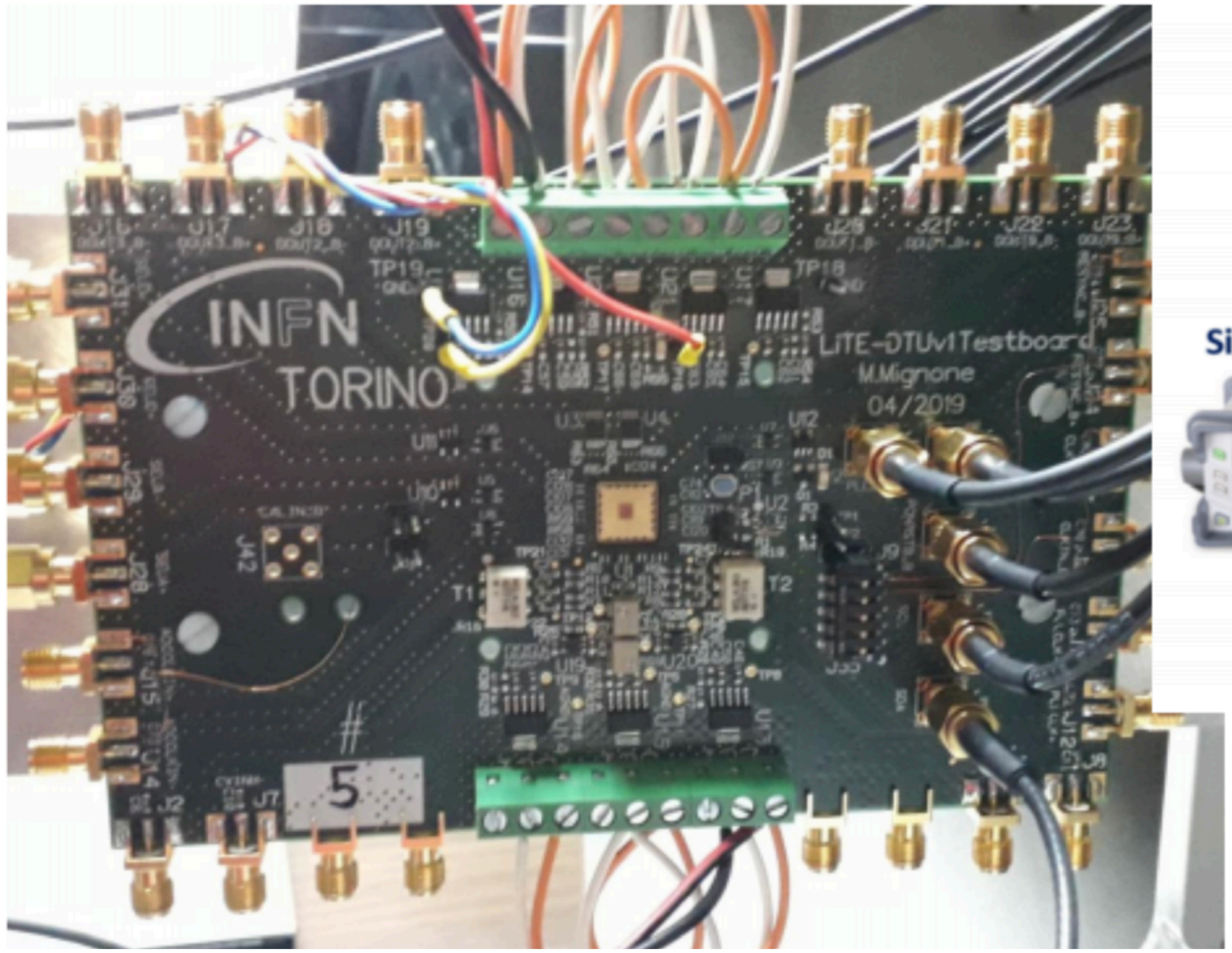
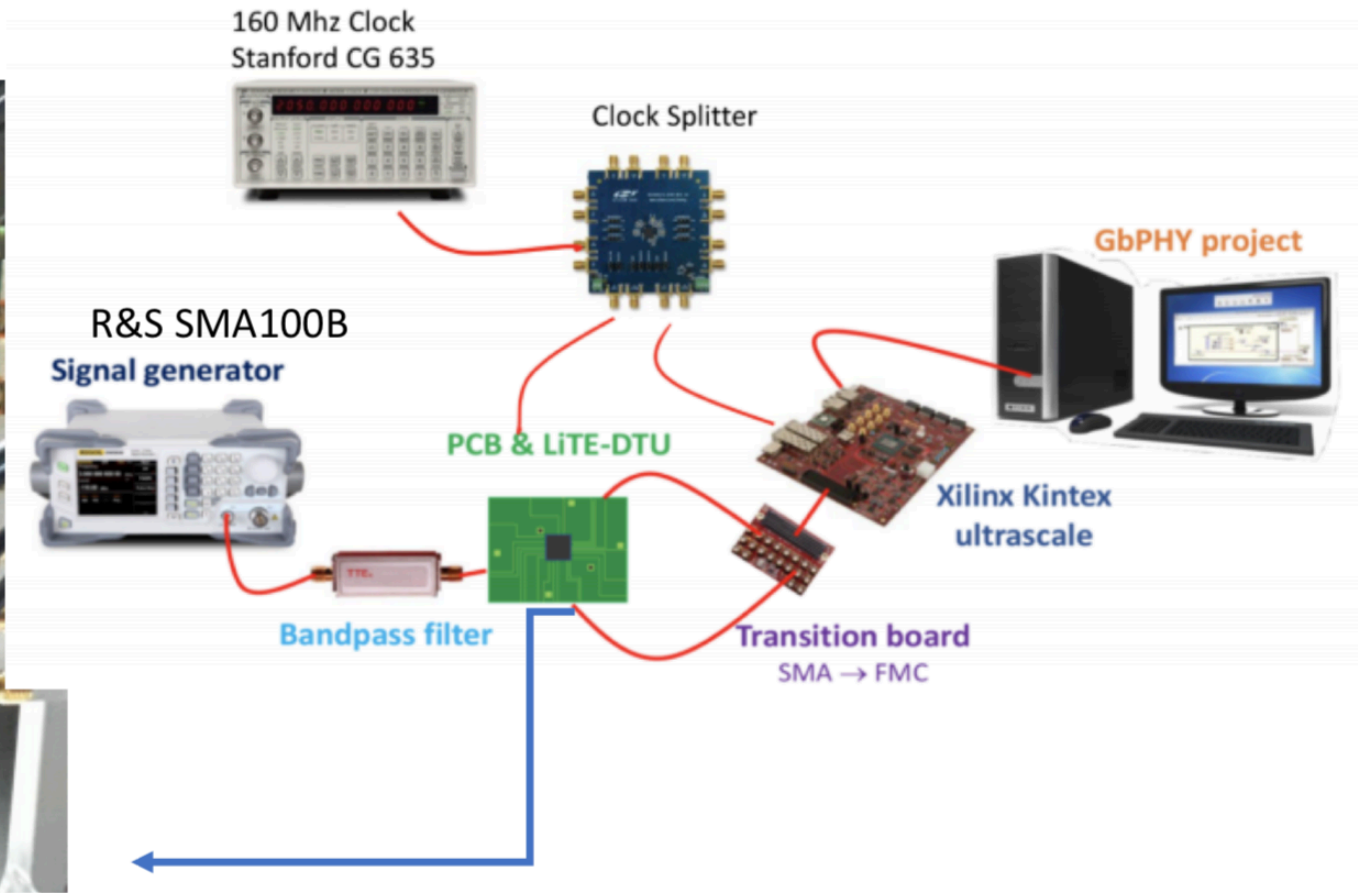
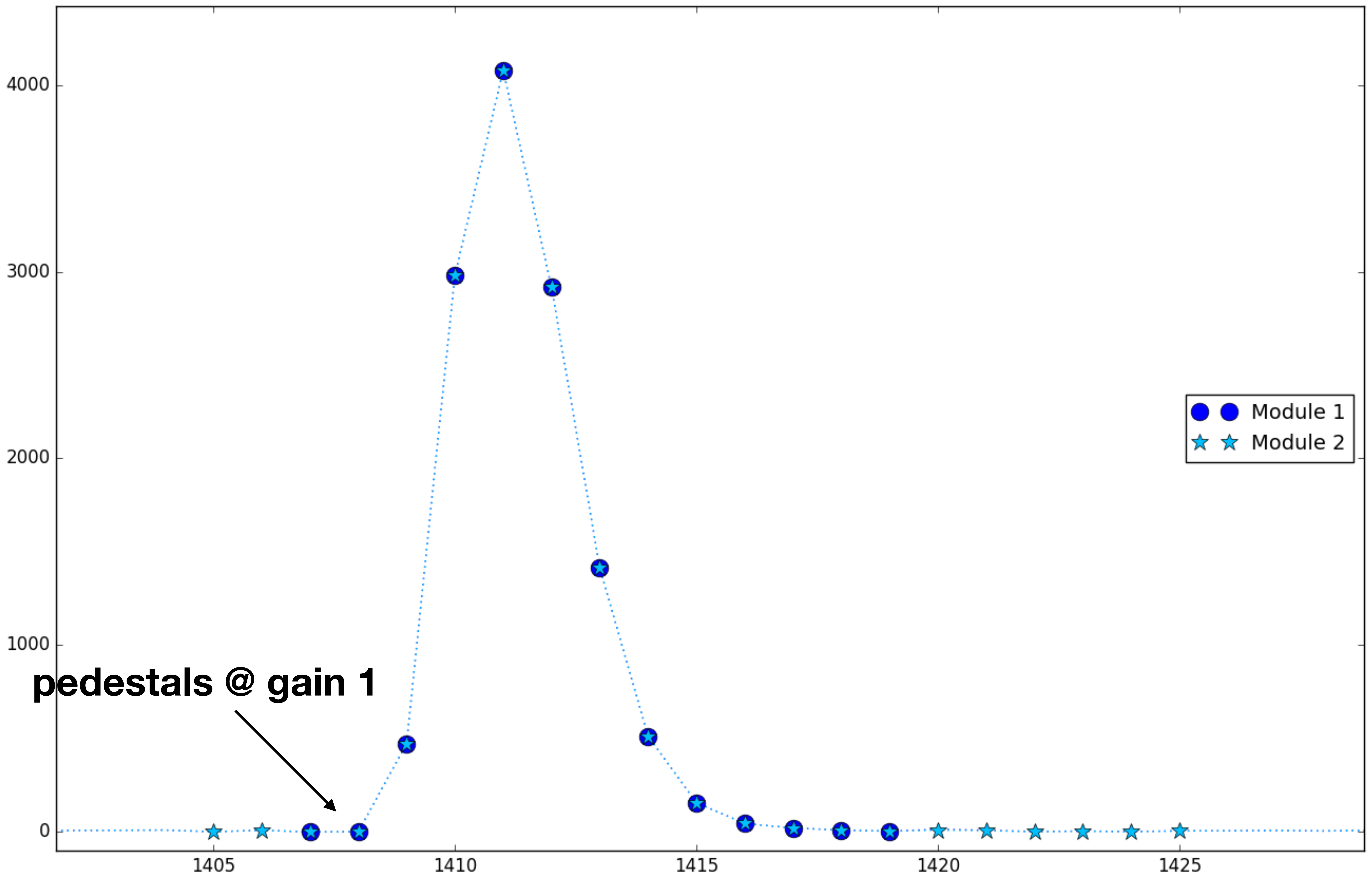
Test Setup In Torino





Test Setup In Torino

Example



4000
3000
2000
1000
0
1405
1410
1415
1420
1425
Module 1
Module 2
pedestals @ gain 1