Status of the CMS ECAL phase 2 upgrade for high precision timing and energy measurements

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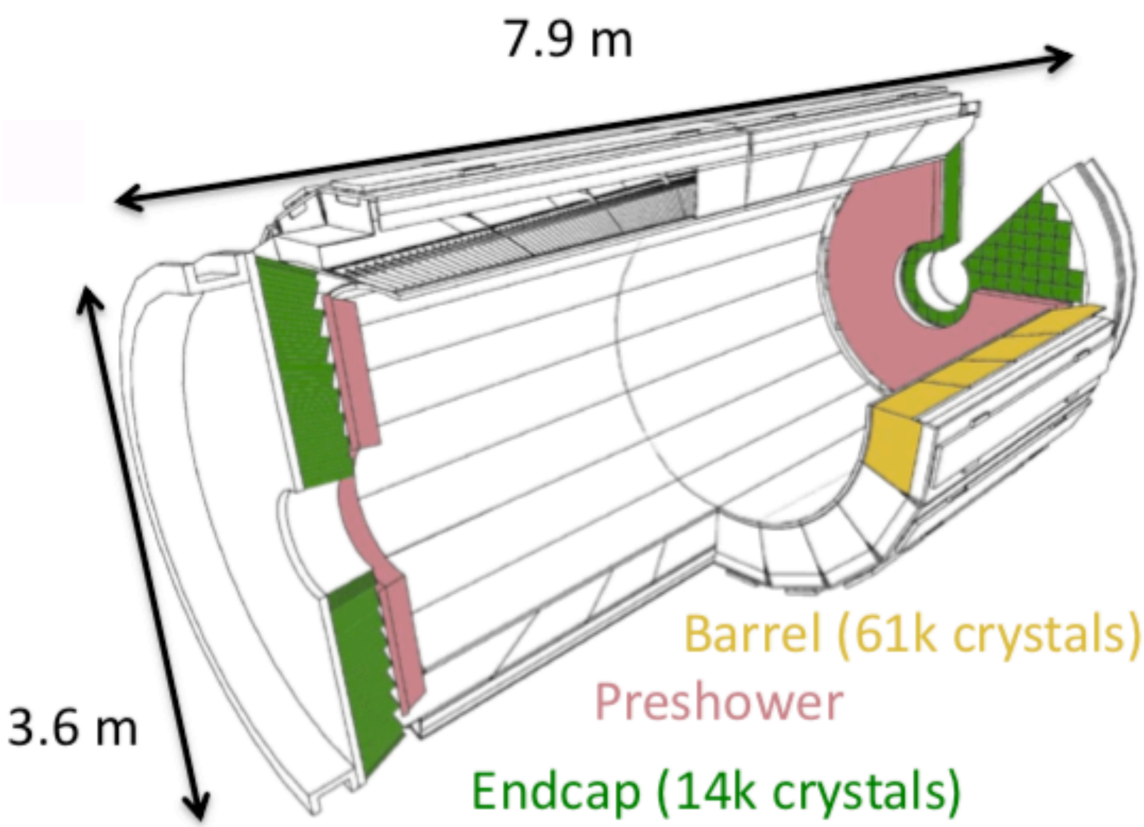
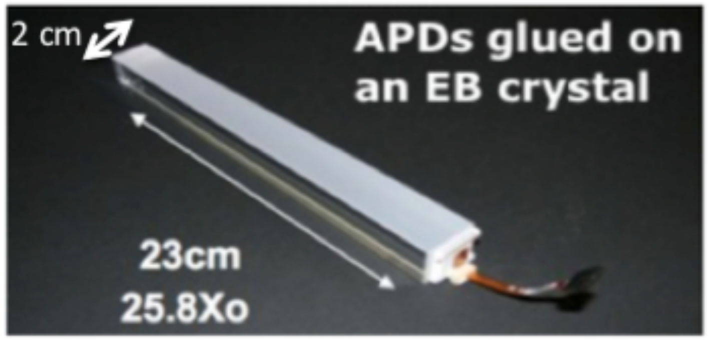
CMS ECAL TODAY

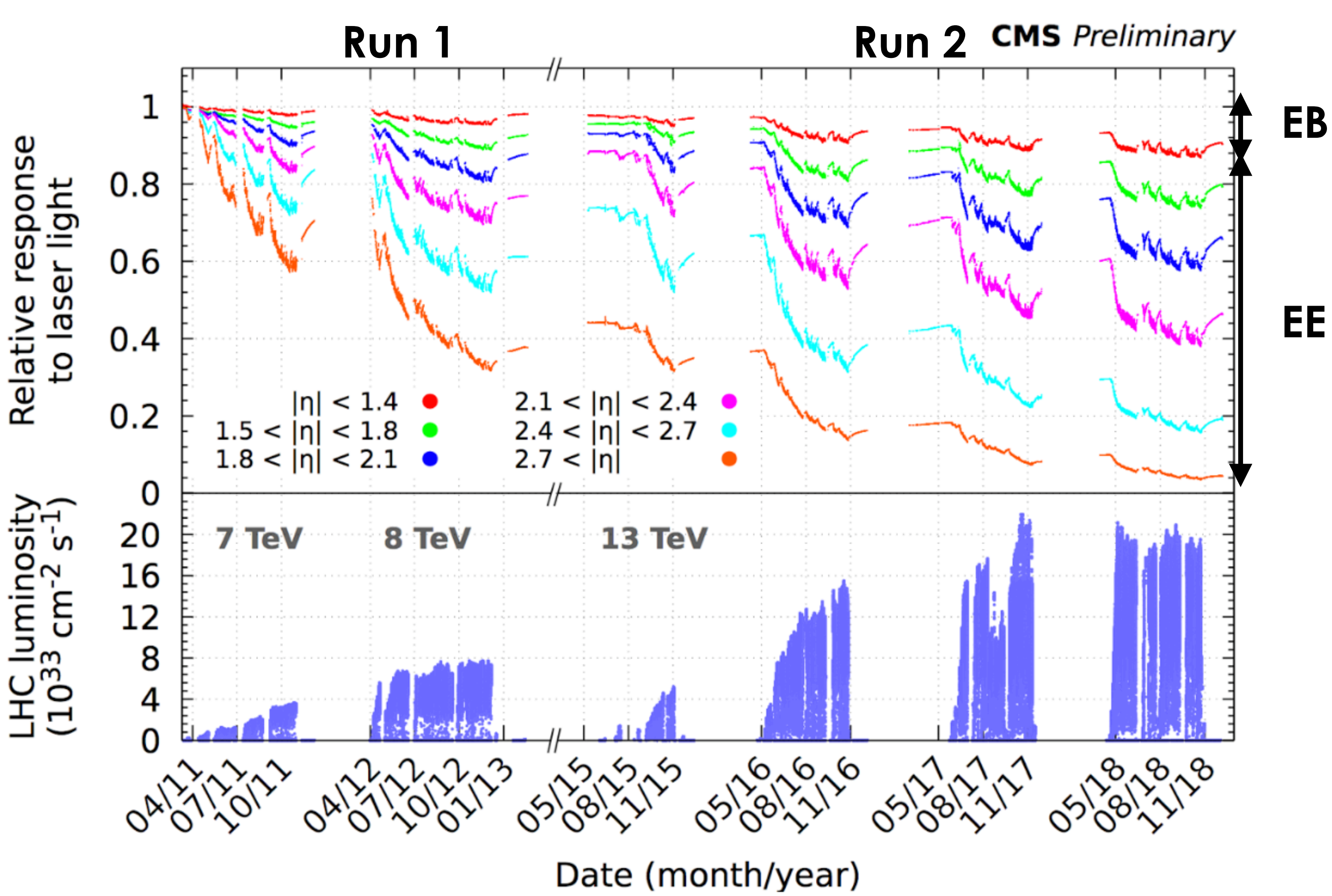


Total ~75k $PbWO_4$ crystals (r_M=2.19 cm, X_0=0.89 cm)

Photosensors:
- Barrel (EB): Avalanche Photo Diode (APD)
- Endcap (EE): Vacuum Photo Triode (VPT)

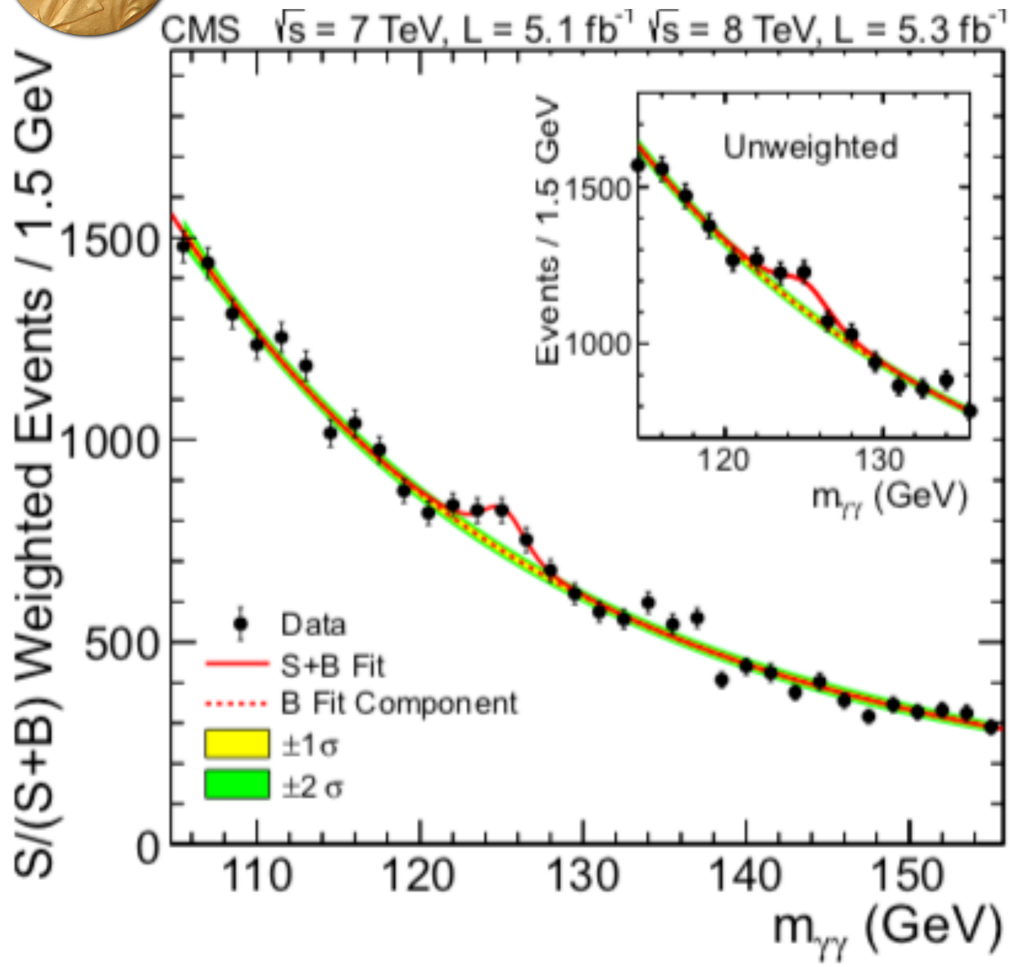


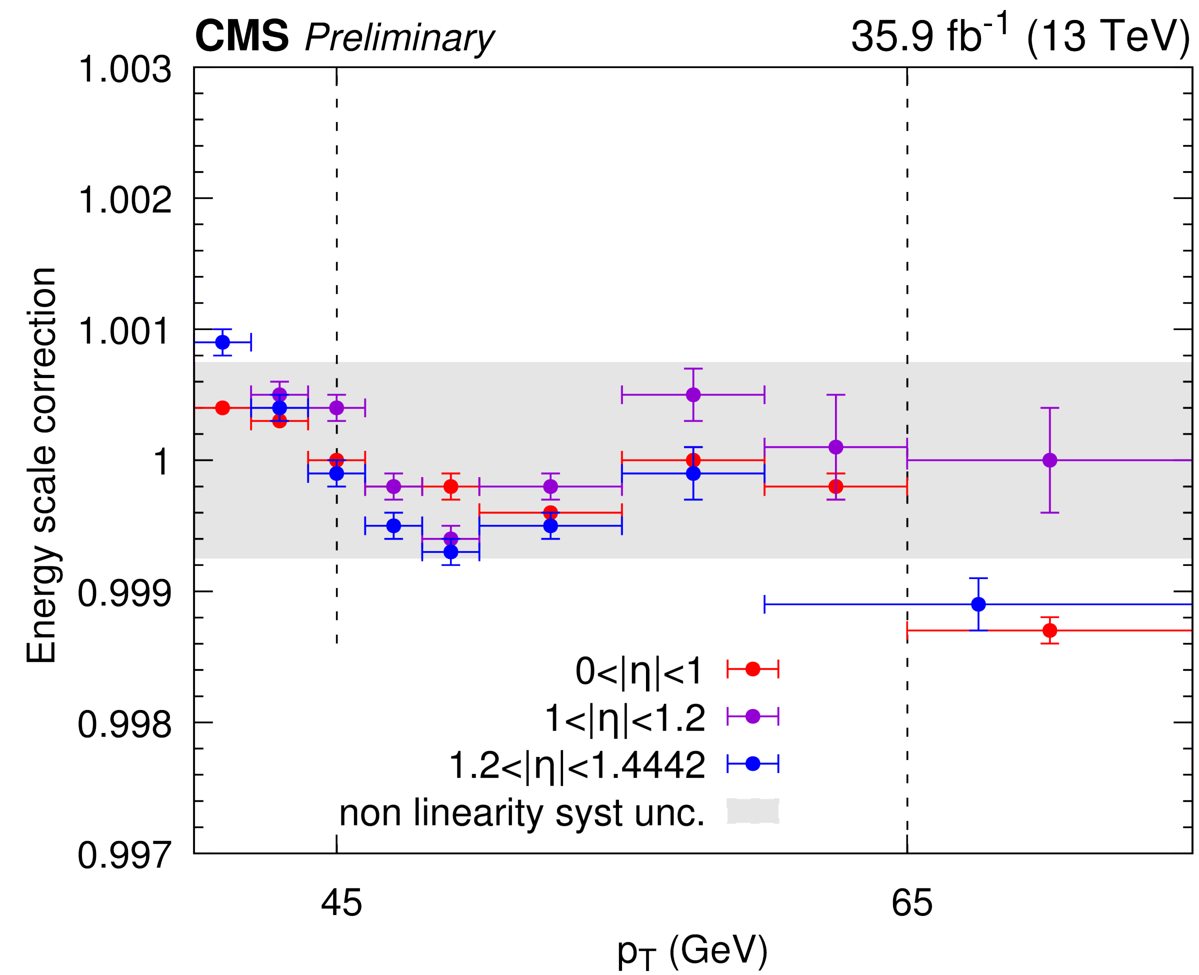
Excellent energy resolution maintained throughout entire LHC Run1 & Run2
- laser monitoring system allowing to track crystal transparency variation at 0.1%
- in-situ calibration at crystal level <1% (π^0/η, $Z \to ee$, $W \to e\nu$)



Physics with CMS ECAL

Physics Letters B 716 (2012) 30–61





ECAL performing as expected:
Excellent γγ mass resolution (<1%)

Higgs discovery with H→γγ in 2012

Prominent ECAL role in all CMS physics program. E.g. Higgs mass:
- γ energy scale well known (<0.1% level).
- Enables Higgs mass to be measured with ~0.1% systematic error (CMS HIG-19-004)

THE HL-LHC CHALLENGE (>2026)

HL-LHC (>2026): exploit the LHC full potential!
- Higgs couplings (at % level), access Higgs self-coupling (HH)
- Precise SM measurements and search for new physics

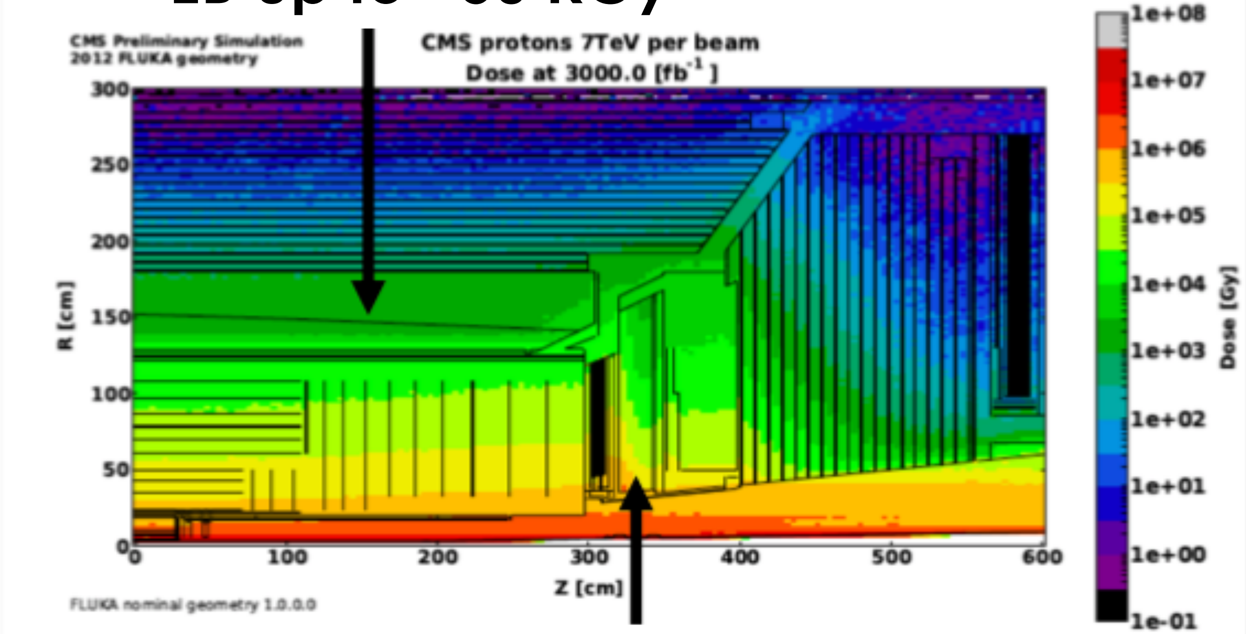
Challenging experimental conditions

	LHC	HL-LHC baseline	HL-LHC ultimate*
$\mathcal{L}_{inst}(\mathrm{cm}^{-2}\mathrm{s}^{-1})$	2×10^{34}	5×10^{34}	7.5×10^{34}
PU (n_{vtxs})	40-60	140	200

x 10 total luminosity (>3000 fb^{-1})
High radiation doses

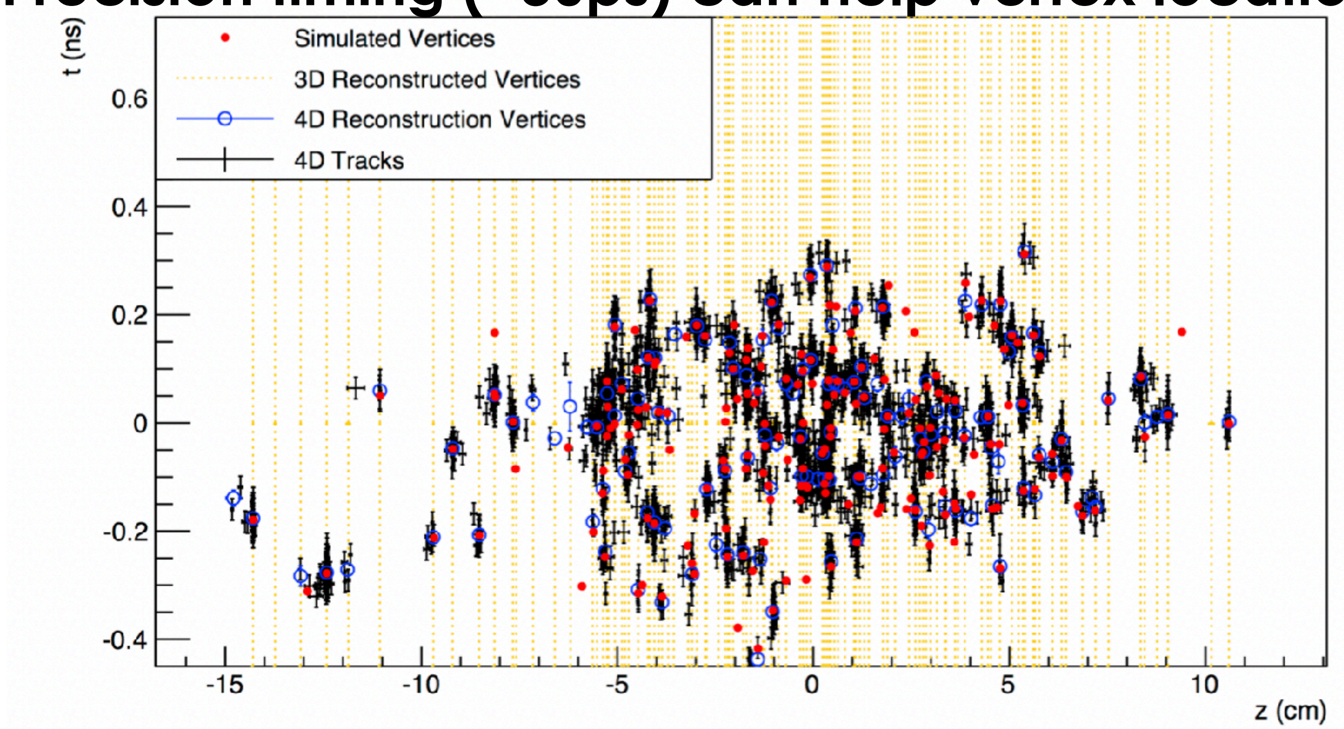
x 5-7 inst. luminosity (>5E34 cm^{-2}s^{-1})
High pile-up (>150)

EB up to ~50 KGy



EE up to ~10^3 KGy

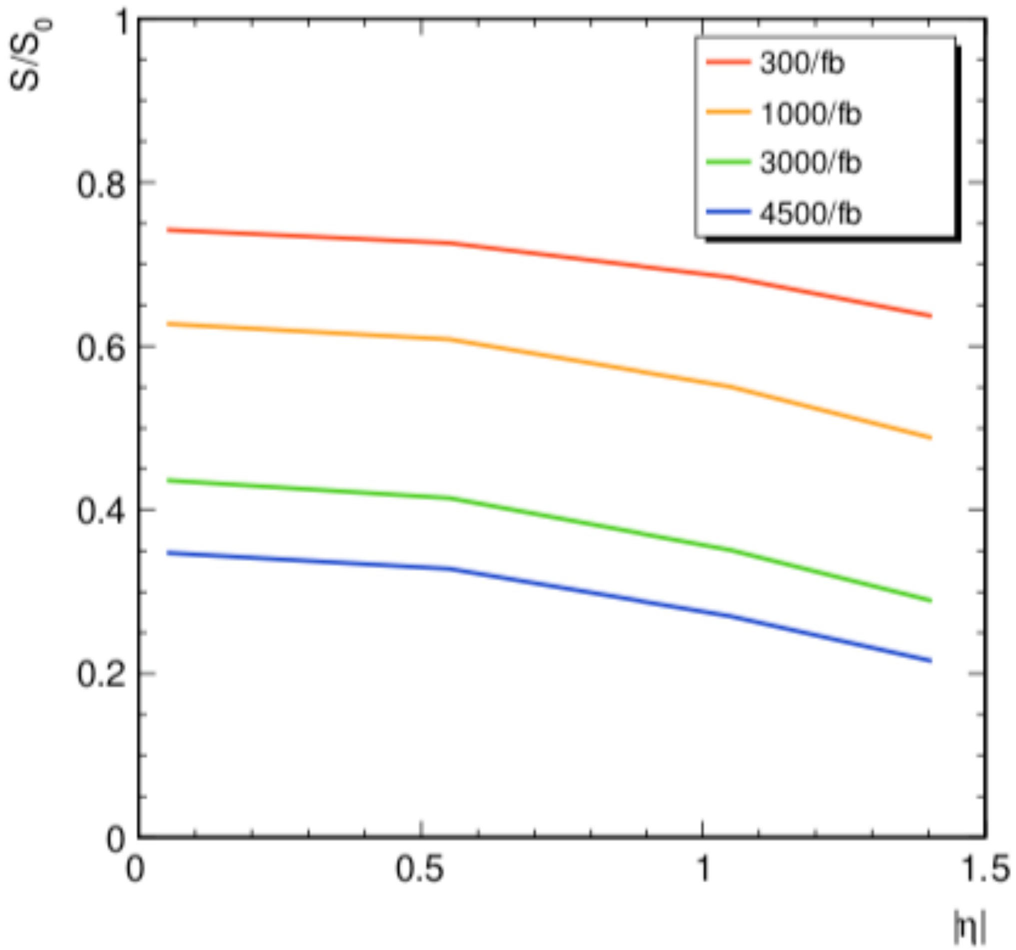
Precision timing (~30ps) can help vertex location



CMS ECAL designed for 300 fb^{-1}@ 1E34 cm^{-2}s^{-1}: upgrade is required

ECAL Sensors @ HL-LHC

Crystal signal loss vs η vs lumi

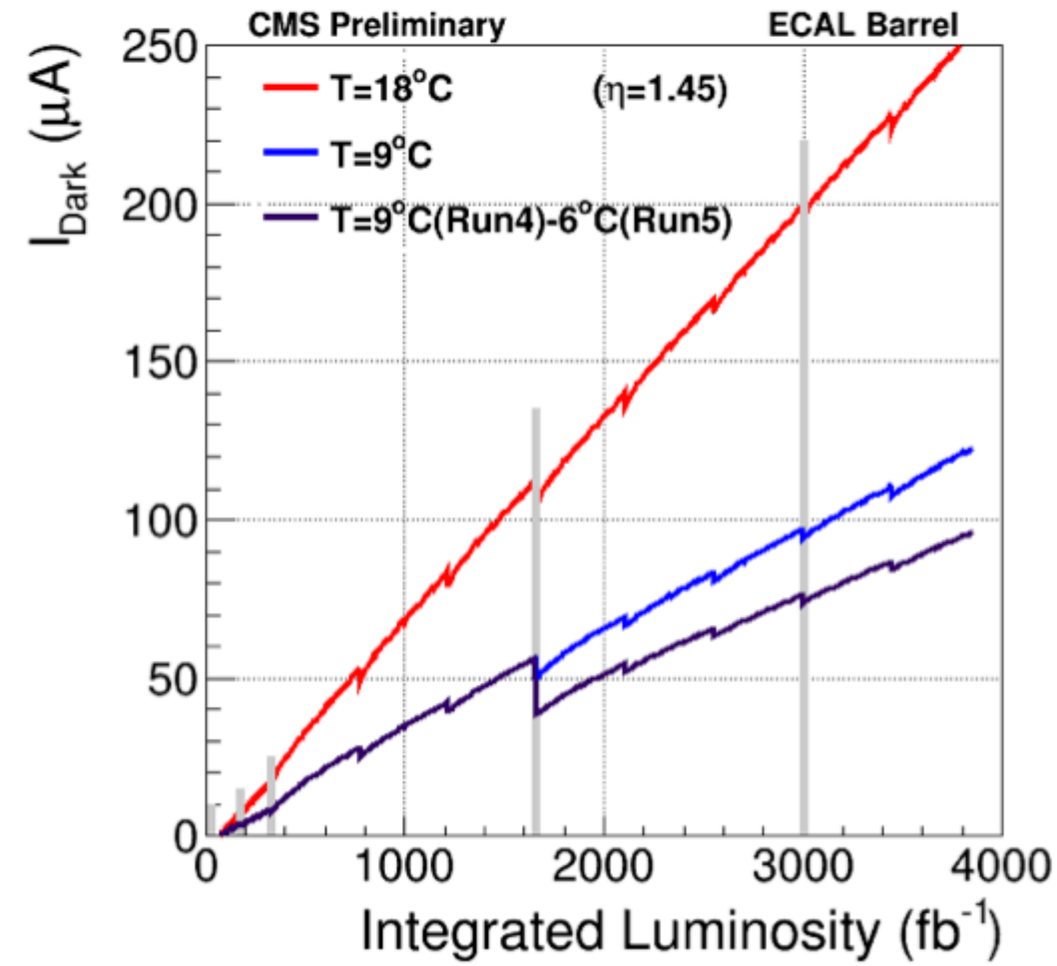


@3000 fb^{-1}: expected LO loss in ECAL barrel from 55% to 70% (|η| 0→1.5)

Crystal replacement NOT needed in ECAL Barrel

ECAL Endcap needs to be fully replaced → High Granularity Calorimeter

APD dark current at η=1.45 vs lumi

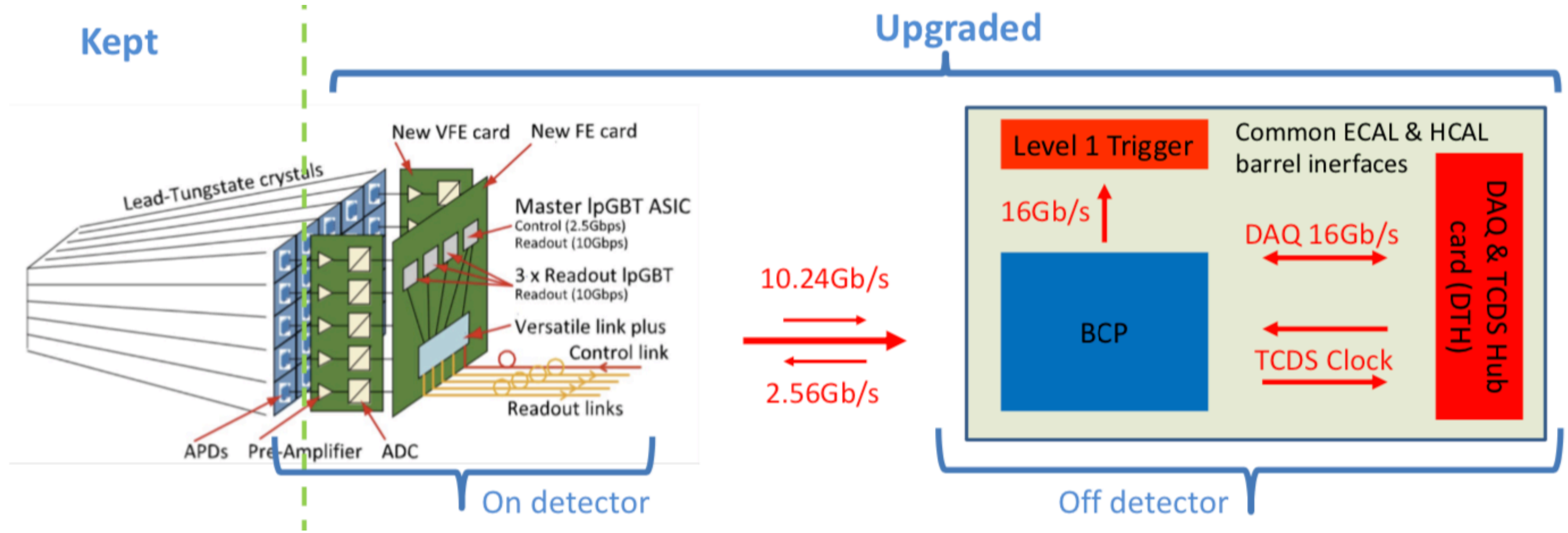


APD increased dark current (higher noise)

Decrease operating temperature 18°C→9°C

- APD dark current reduced by 50%
- LO increased by 18%

ECAL ELECTRONICS @ HL-LHC



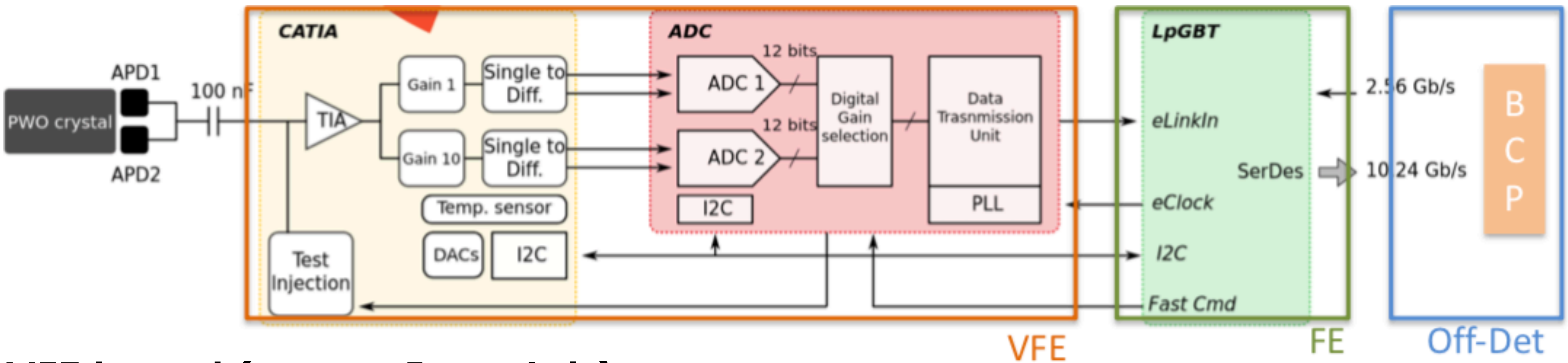
Faster front-end electronics

– Improve timing resolution (H→γγ vertex identification at high pile-up)
– Improve discrimination between scintillation and direct hits in the APD ("spikes")

New off-detector electronics

– Cope with increased CMS-wide L1 rate (100 kHz → 750 KHz) and latency (3.4μs →12.5 μs)
– Improve trigger flexibility: stream all crystal data off-detector

UPGRADED READOUT SCHEME



VFE board (serves 5 crystals)

- New faster preamplifier: Trans-impedance amplifier (TIA), CATIA ASIC
  - bandwidth 35 MHz (x2)
  - 2 gains (x1 and x10)dynamic range from 50 MeV to 2 TeV
- New ADC: Lite-DTU ASIC
  - 12 bit @ 160 MS/s (x4 sampling rate), data transmission with compression

FE (serves 5 VFEs)

- Fast optical links to stream all crystal data off-detector @ 40 MHz using LpGBT
- VFE clock distribution using LpGBT eClock

Off-detector: Barrel Calorimeter Processor (BCP)

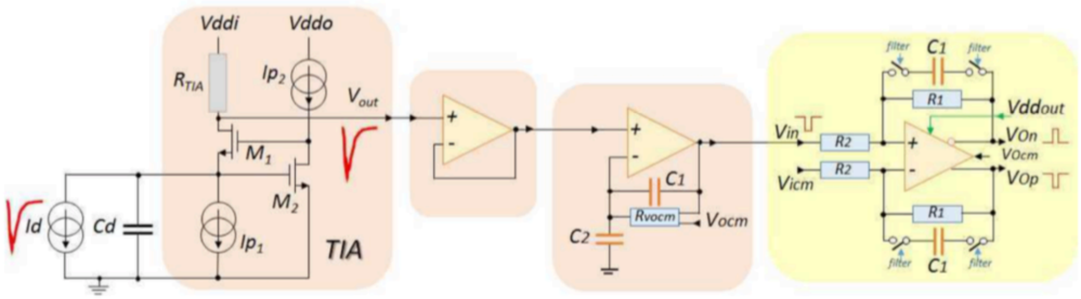
FPGA based

- Pulse reconstruction
- Zero suppression
- Spike rejection
- L1 trigger primitives
- Receive & distribute LHC clock to FE

CATIA

CAlorimeter **T**rans-**I**mpedance **A**mplifier

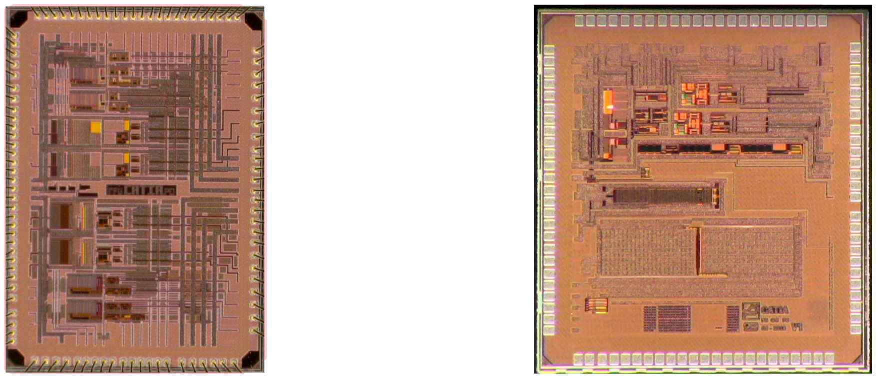
- bandwidth 35 MHz (imposed by APD/kapton impedance)
- TSMC 130nm CMOS
- 2 gains (x1-x10), test pulse, ADC calibration



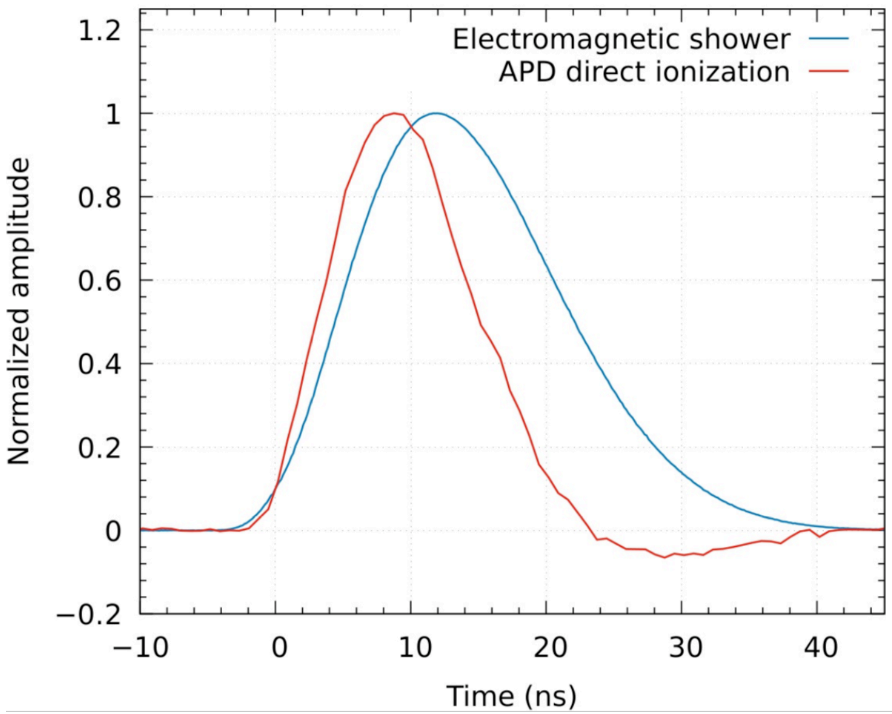
Two prototypes (V0 & V1) already tested in lab and in test beam

- performance as expected for noise and linearity
- preliminary radiation hardness tests encouraging

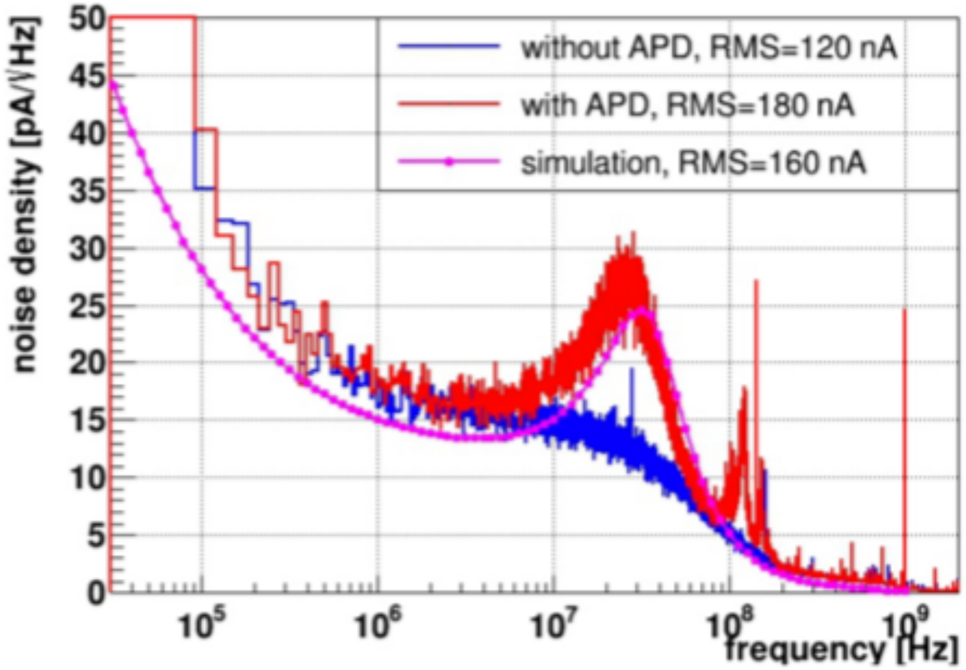
V0 V1



Last iteration v2: foreseen in 2020



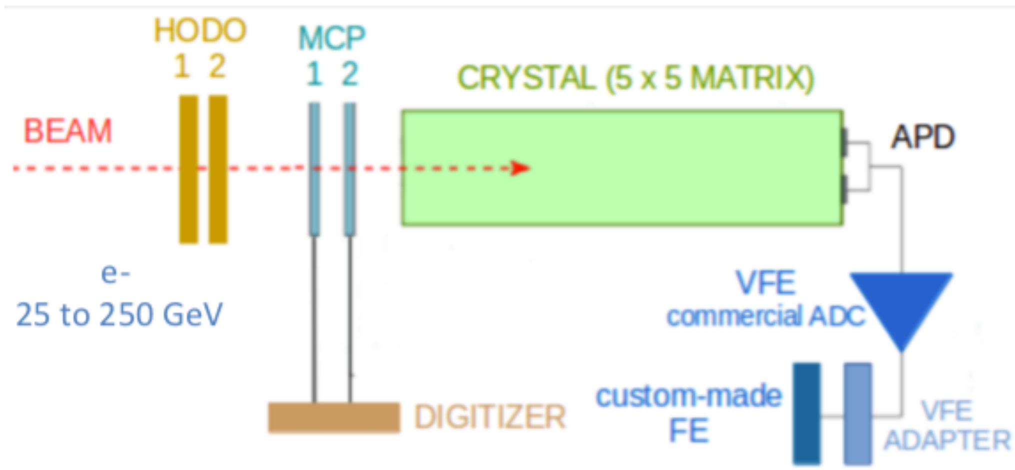
Much improved separation between scintillation/spikes

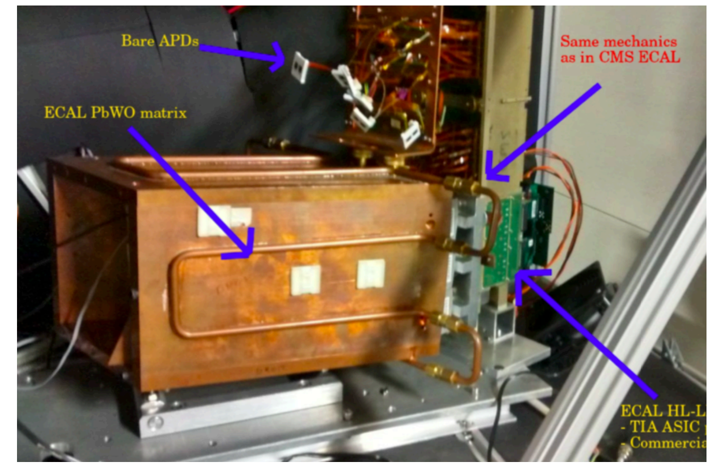


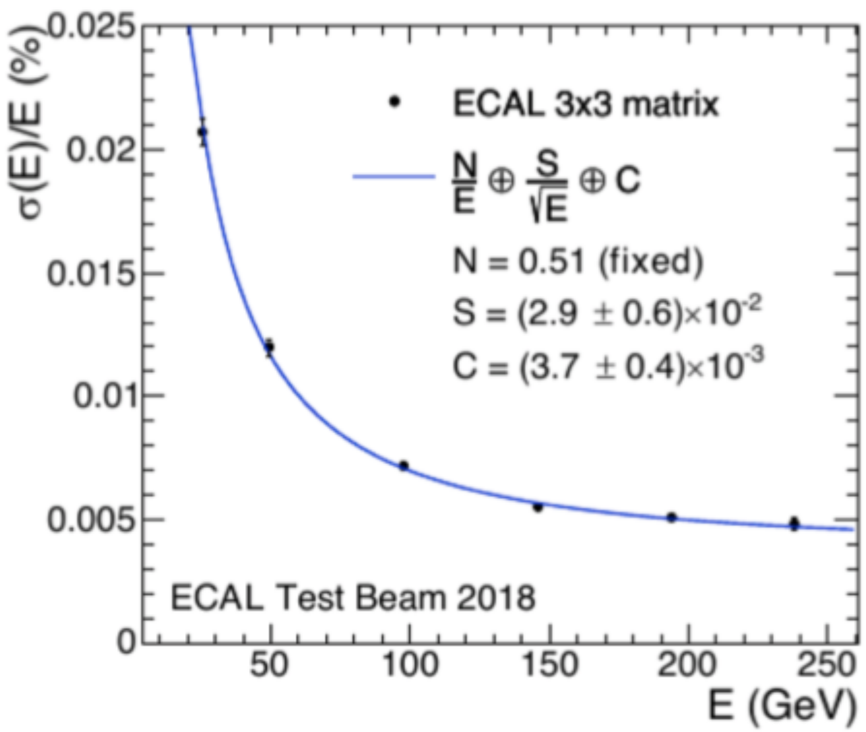
Noise within 10% from simulation

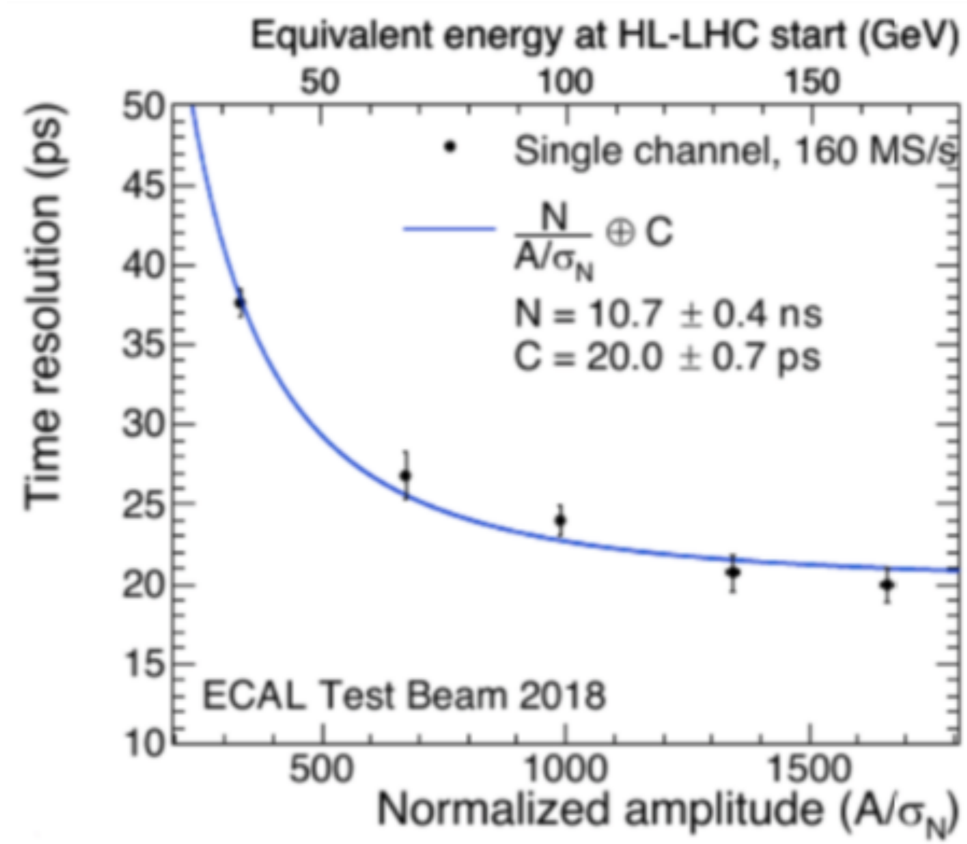
TEST BEAM 2018 RESULTS

Test beam 2018@ CERN: 5x5 matrix, prototype VFE with CATIA, commercial ADC @ 160 MHz









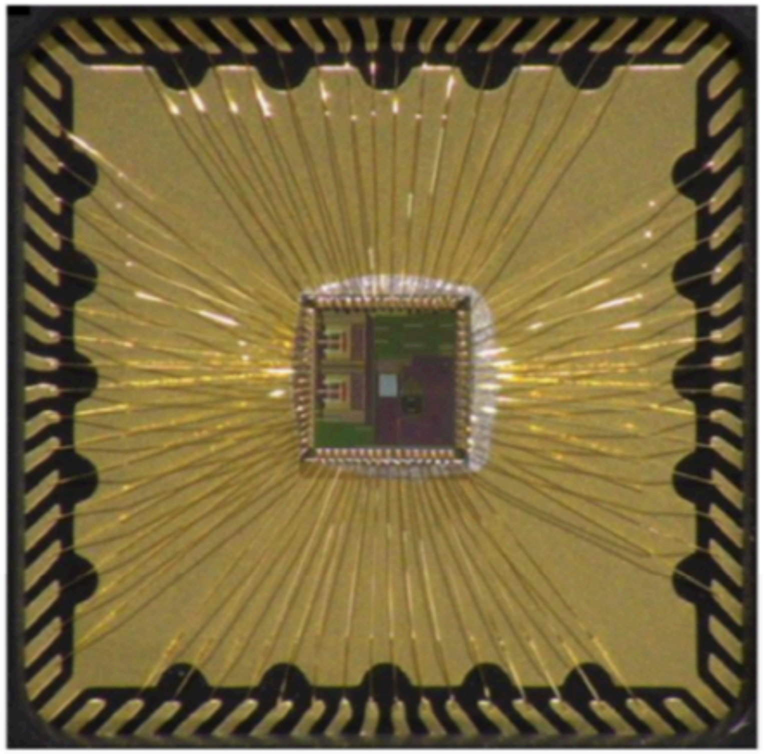
Energy resolution matching current performance

Time resolution <30ps for E>50 GeV matching ECAL HL-LHC target

LiTE-DTU

Digital ASIC in 65nm CMOS

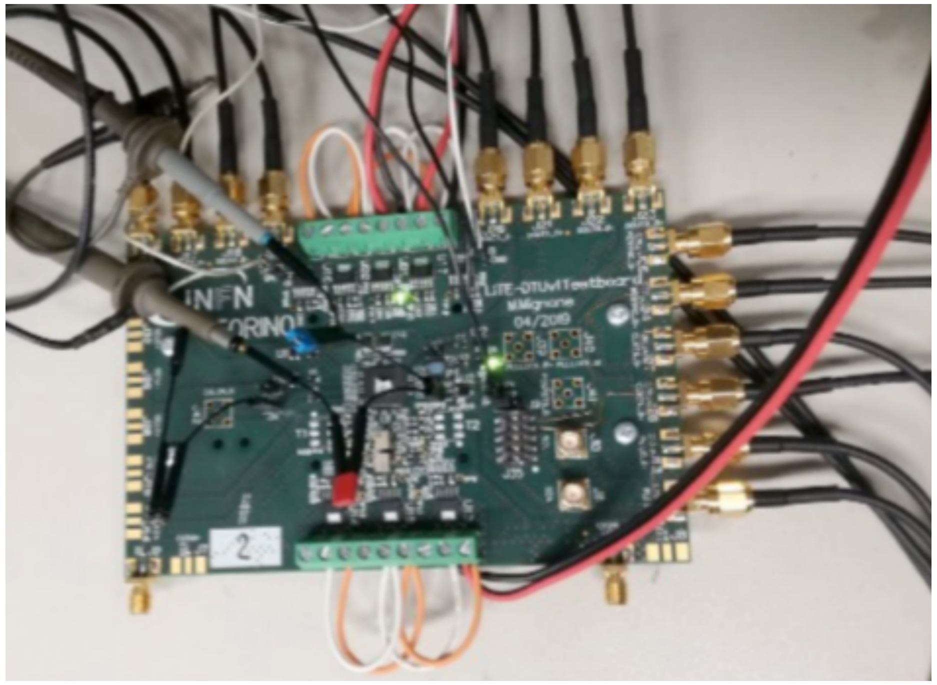
- 2 x 12bit 160MS/s ADC: commercial IP block
- Data Transmission Unit (DTU): baseline subtraction, gain selection, serialisation and lossless data compression
- PLL from LpGBT
- TID tolerance up to 100 KGy, SEU protected logic



LiTE-DTU v1 currently under test. Checking:

- ADC noise/linearity
- PLL and clock distribution
- selection and compression algorithms validation
- radiation hardness

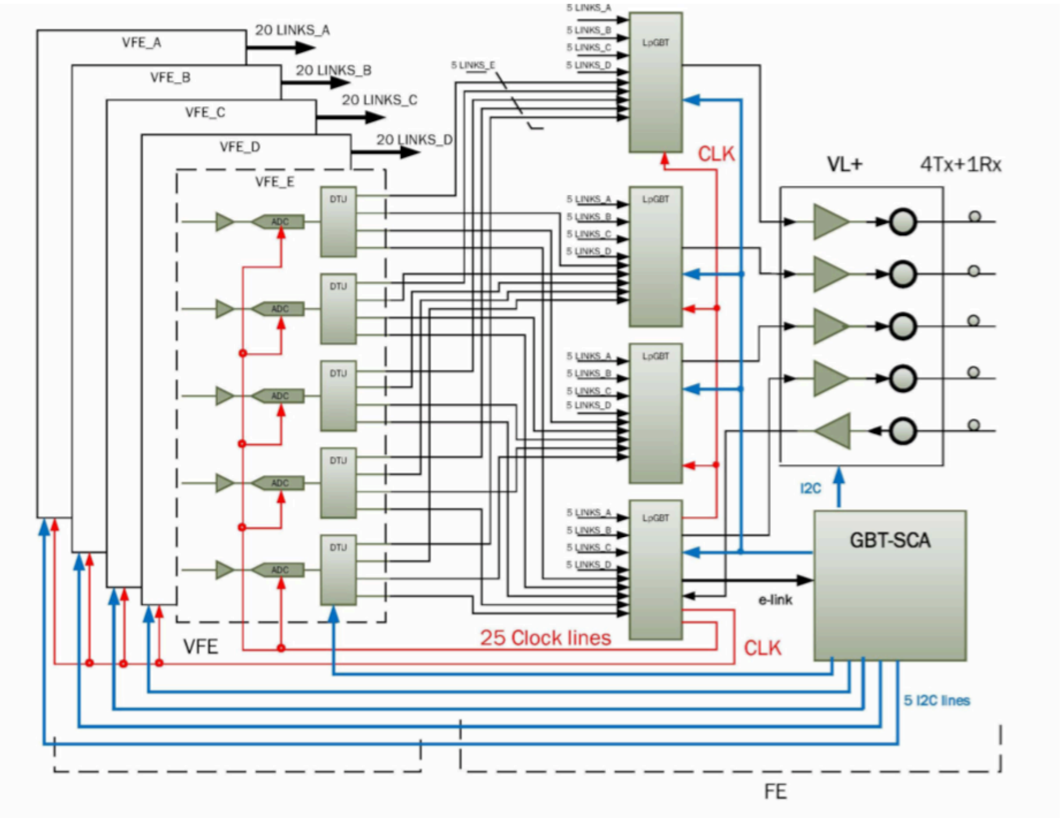
Foreseen also a combined test with CATIA v1



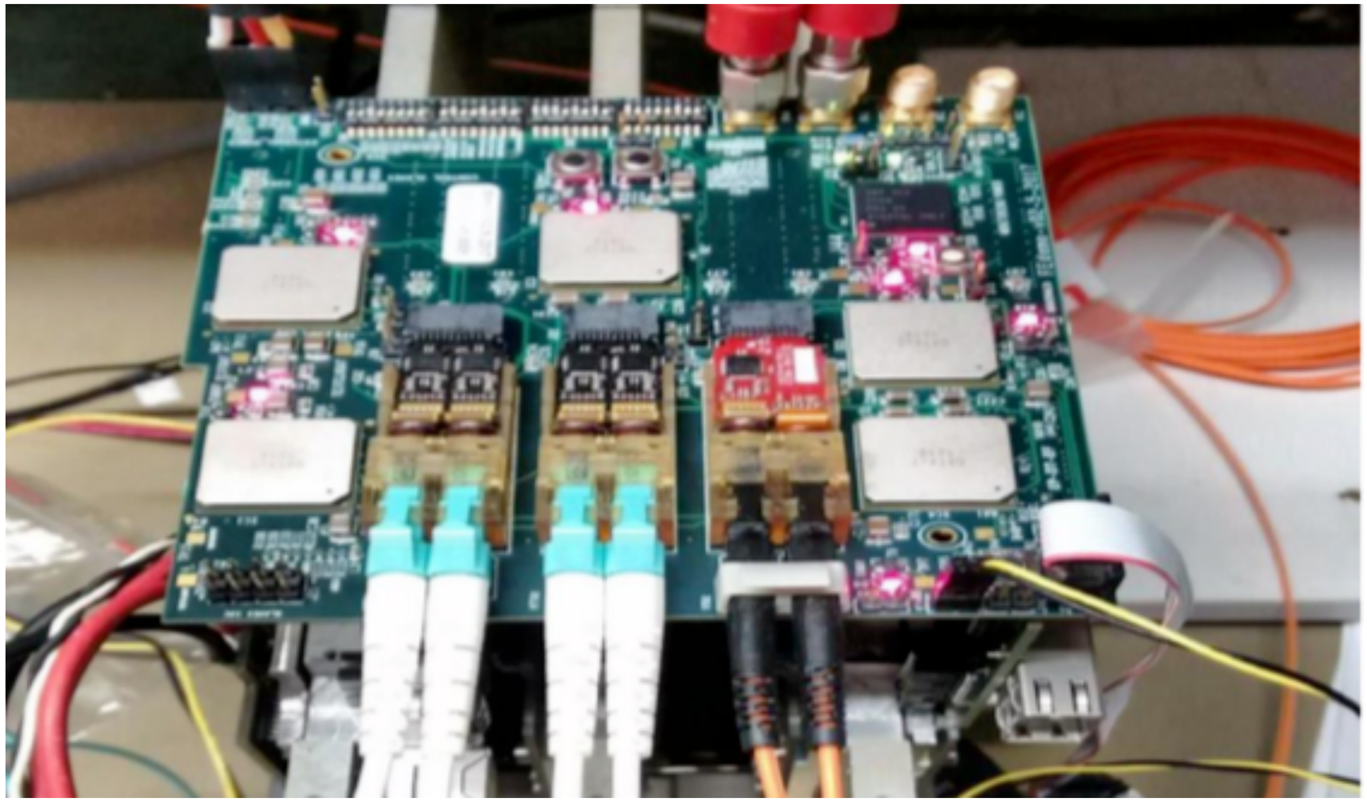
FE Card

Streaming VFE digitised data off-detector
Precise clock distribution to VFE
Initialisation and control of VFE

- 4 uplinks @ 10.24 Gb/s
- 1 uplink @ 2.56 GB/s
- eLink serial interface to ADC
- i2C interface



v1 prototype
- 5 Gb/s links (using GBTx)
- 1 VTRx + 2 VTTx VL modules



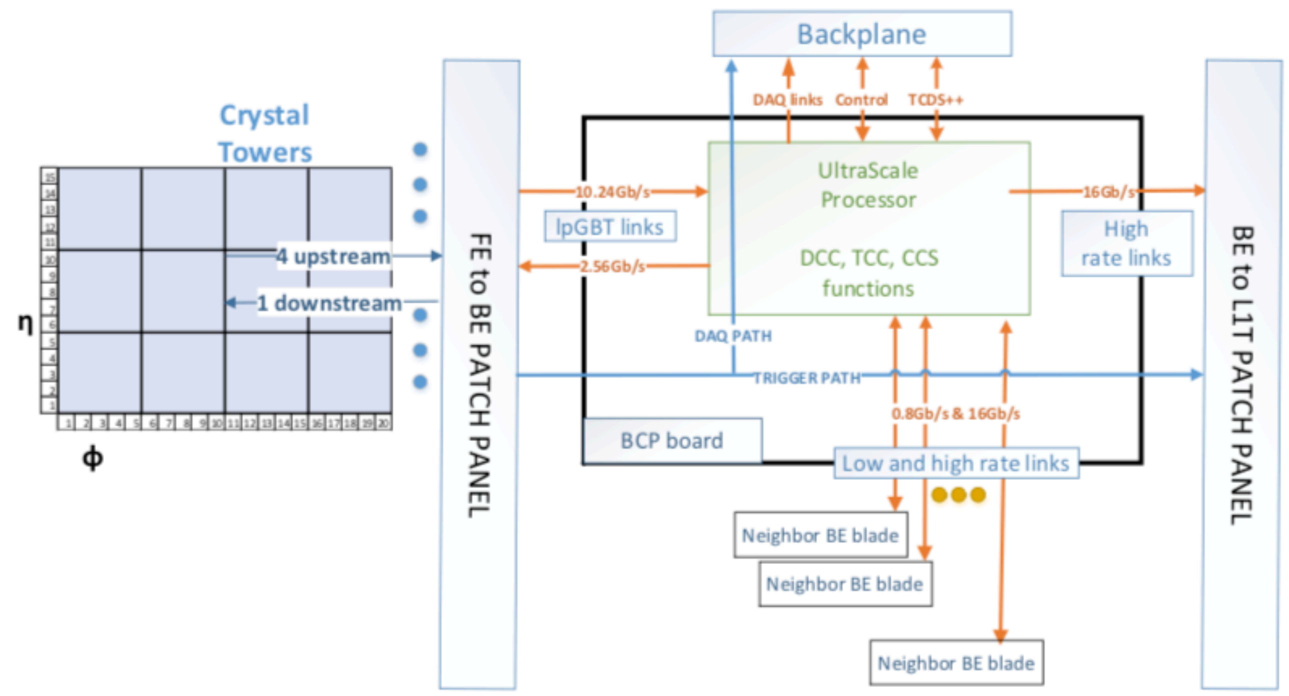
Next steps:
v2: 10 Gb/s links
v3: fine tuning and bug fixes

OFF-DETECTOR & TRIGGER

BCP in numbers: 9 ATCA crates, 108 ATCA blades, 216 FPGAs, 3060 optical links to FE

Barrel **C**alorimeter **P**rocessor

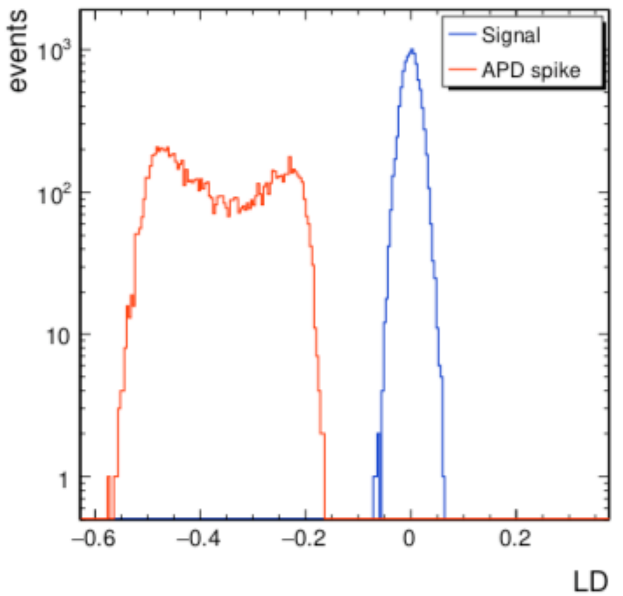
- Control & data readout, decompression, clock distribution, trigger primitives formation, common for ECAL and HCAL
- FPGA based, ATCA blade form factor



Streaming all samples off-detector. Allows:

- Granularity at crystal level for L1 trigger primitives (instead of 5x5 matrix)
- Large flexibility for developing pulse reconstruction/selection algorithms: PU subtraction, anomalous signal rejection, …

Discrimination using digital filter on crystal samples for scintillation/spike



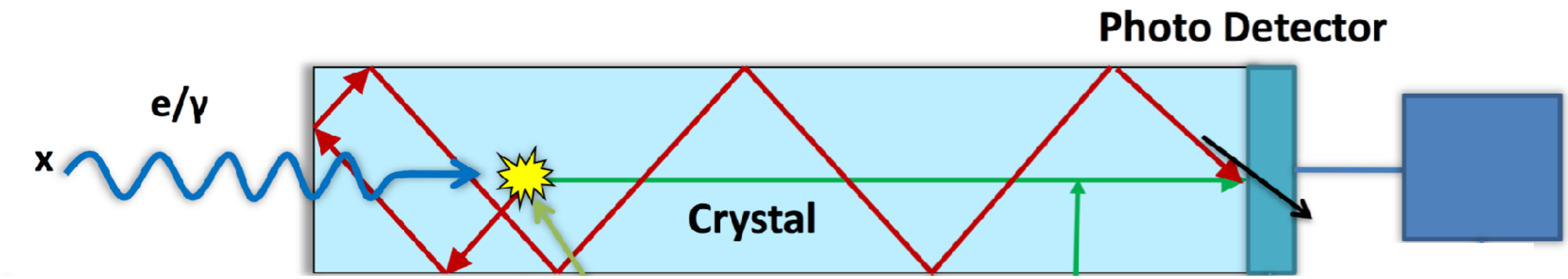
SUMMARY

HL-LHC exciting physics opportunities but also significant experimental challenges: high radiation dose and >5 increase in detector occupancy

CMS ECAL Barrel will be upgraded bringing improved readout/ trigger flexibility, maintaining excellent energy resolution and improve timing resolution (~30ps @ 50 GeV)

- keep crystals and photosensors, lowering operating temperature from 18 °C → 9 °C
- new readout chain:
  - faster front-end
  - higher sampling rate
  - stream all data off-detector, trigger primitives formation off-detector

Precision Timing with Crystals



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

Current ECAL Timing Performance

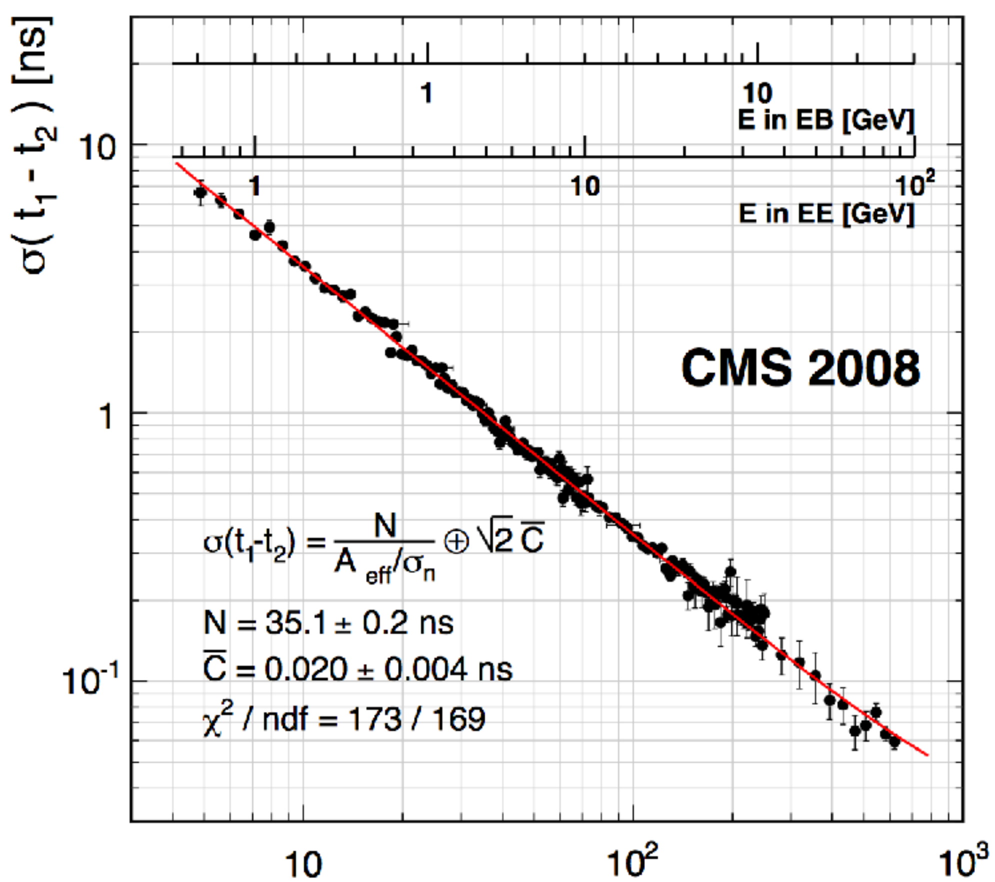
Test beam (2008)

- 2 crystals in the same EM shower: **20 ps constant term**

In-situ (Run1)

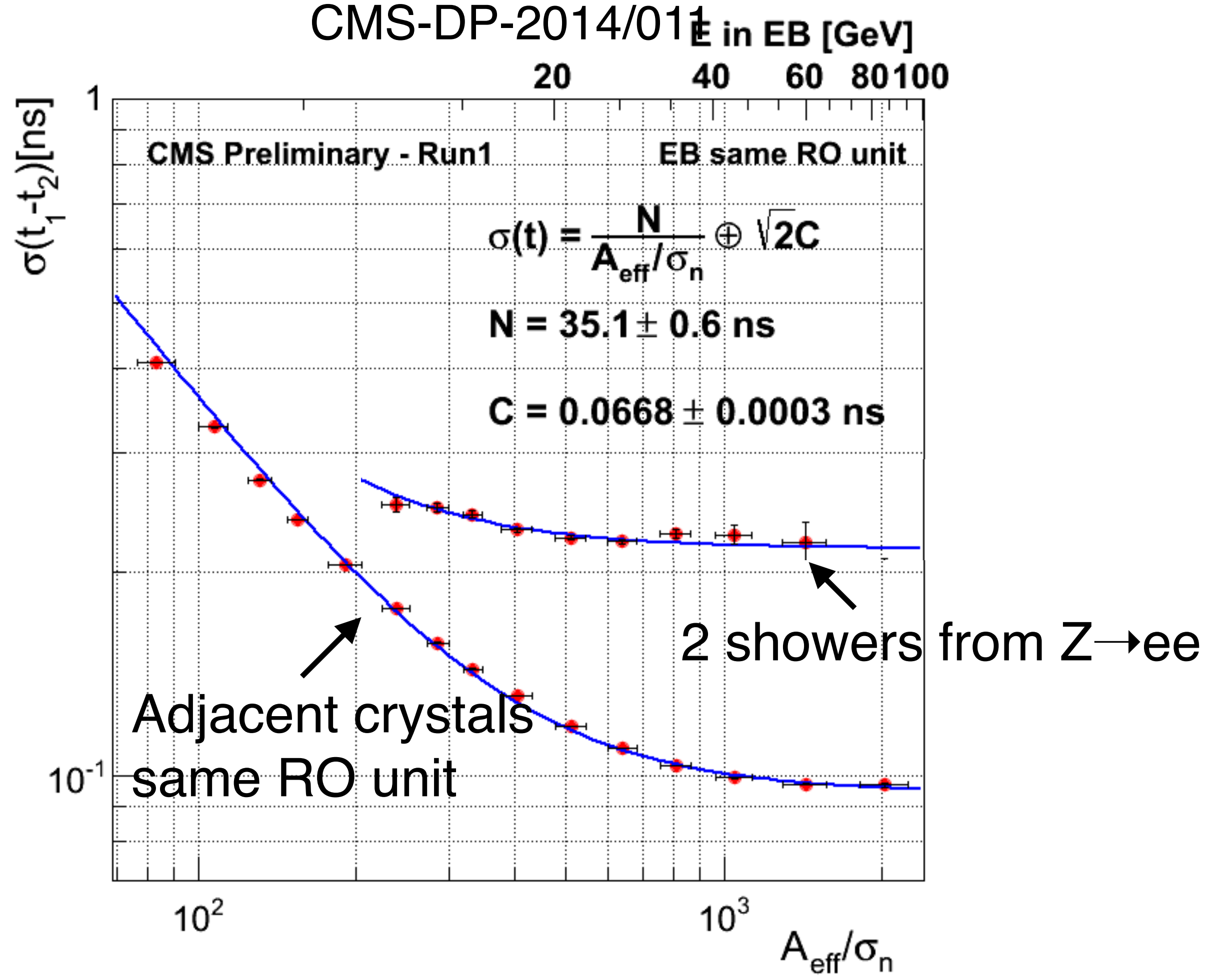
- 2 crystals in the same EM shower & same readout unit: **70 ps constant term**, degradation due to time calibration stability
- 2 crystals in different showers from Z→ee: **150 ps constant term**, additional degradation from clock distribution

JINST 5:T03011,2010

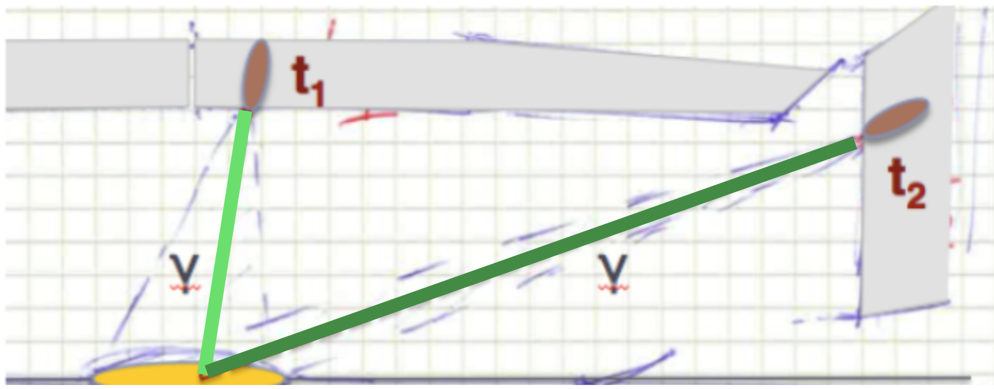


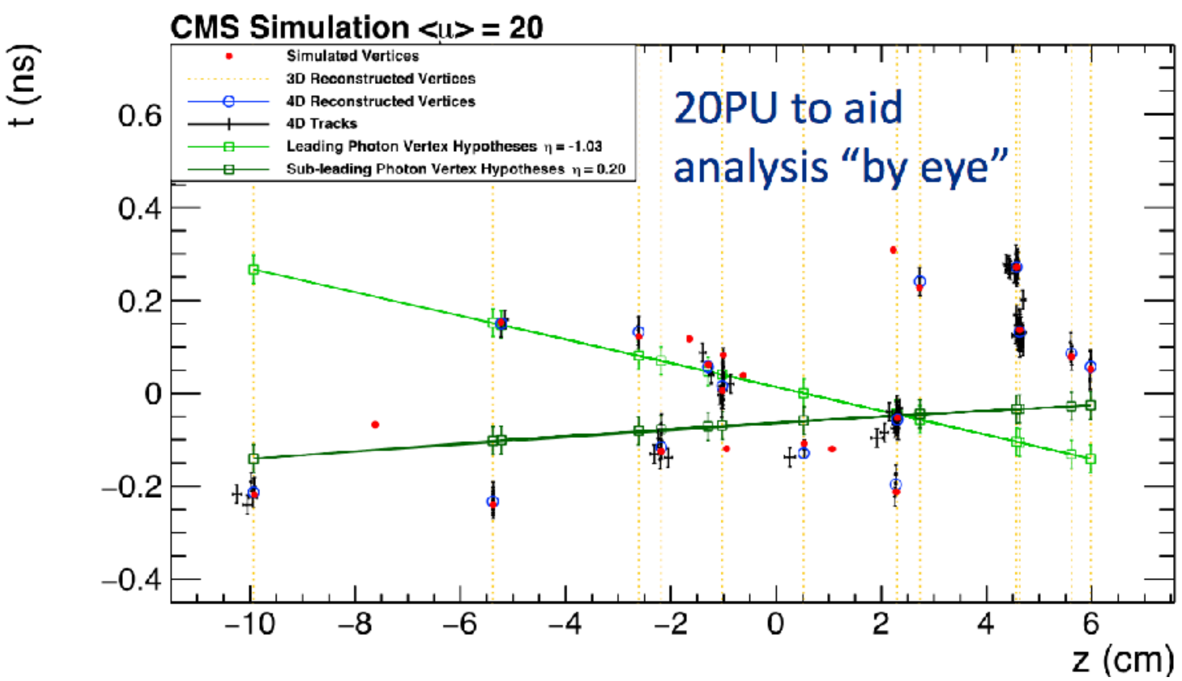
$A_{\rm eff} = A_1 A_2 / \sqrt{A_1^2 + A_2^2}$

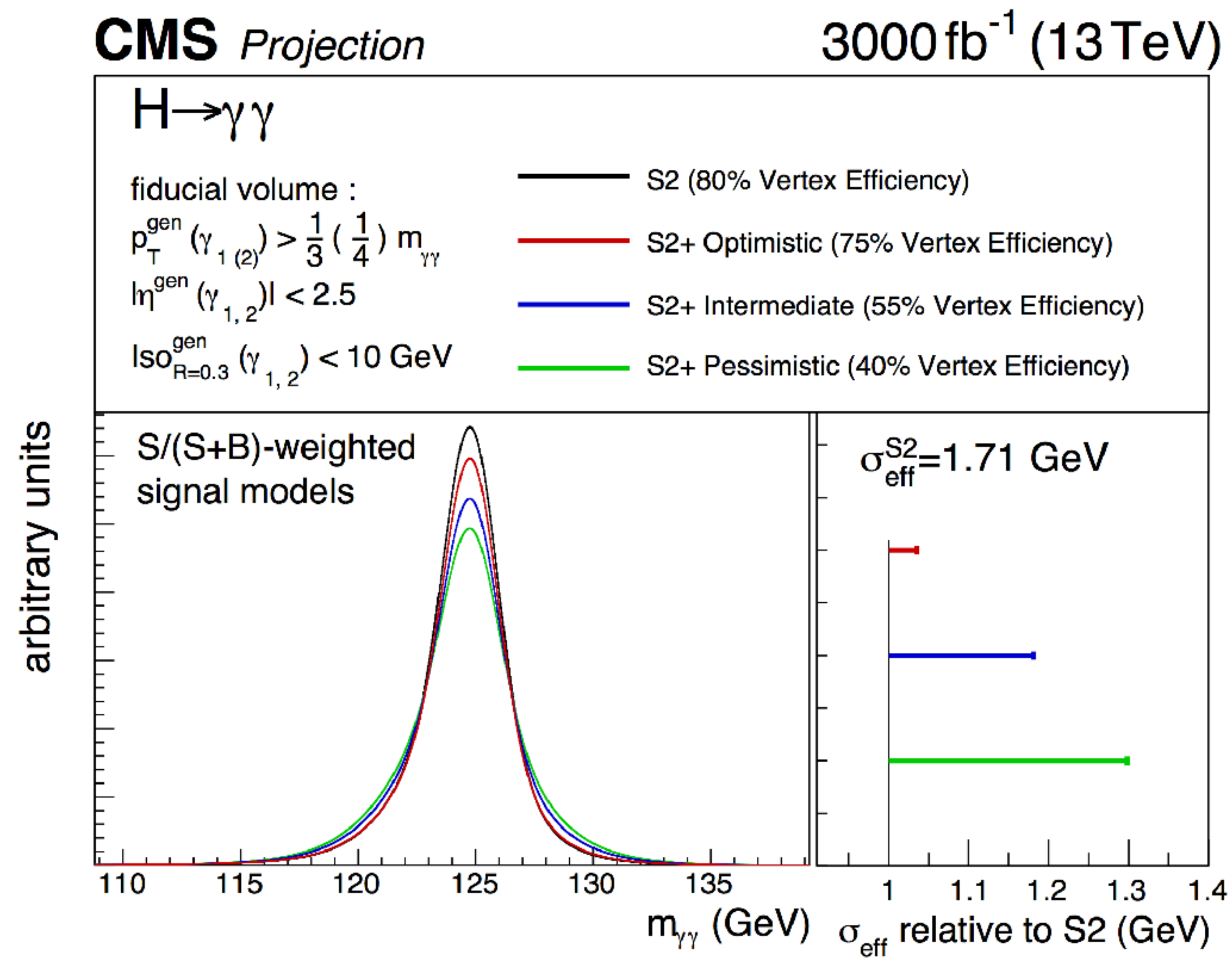
CMS-DP-2014/011



PHOTON TIMING & H→γγ







Photon timing (<30ps) allows to determine di-photon interaction vertex position (and time)

Vertex currently determined using recoiling tracks properties. Efficiency ~80% with current pile-up LHC conditions, will become 30% @ PU200

ECAL+track precision timing allows to ~ keep current vertex efficiency @ PU200