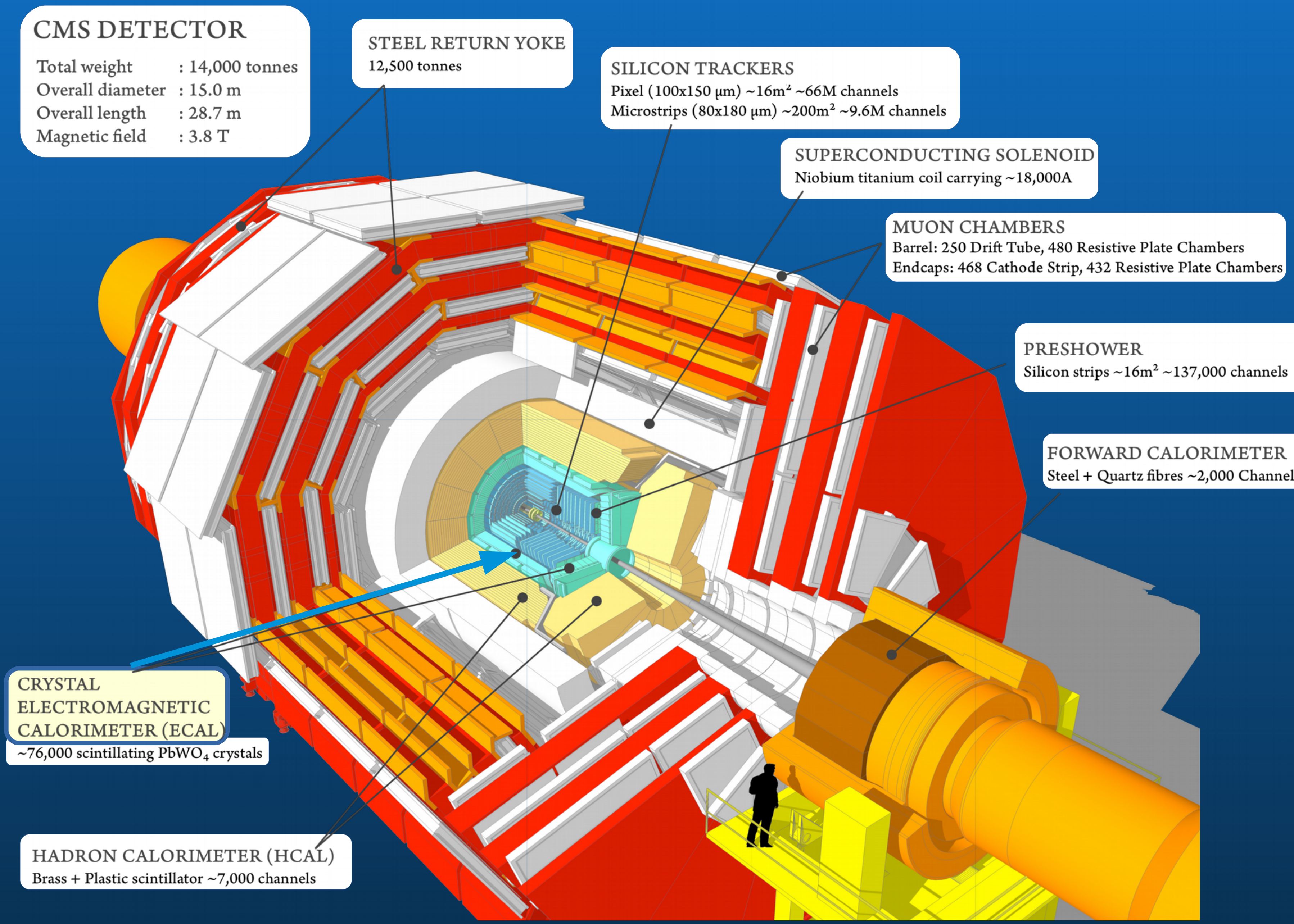
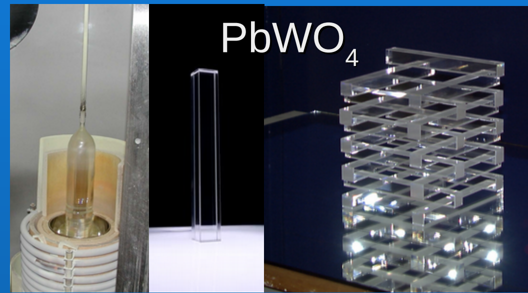
Upgrade of the CMS electromagnetic calorimeter barrel readout electronics for the High-Luminosity LHC



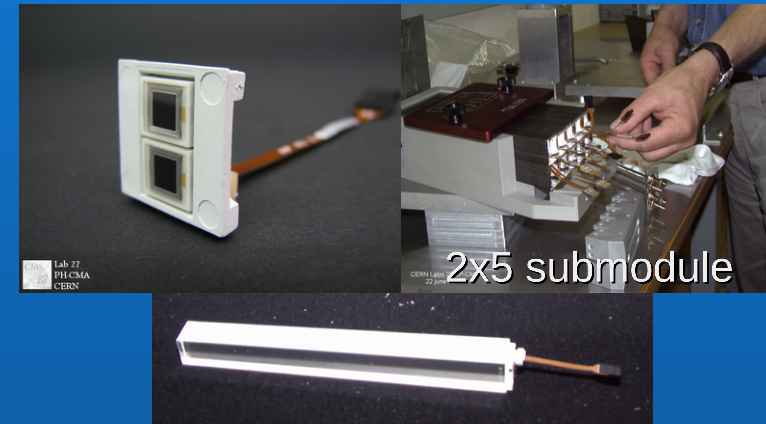
Bob Hirosky U. Virginia

The CMS EM Barrel Calorimeter

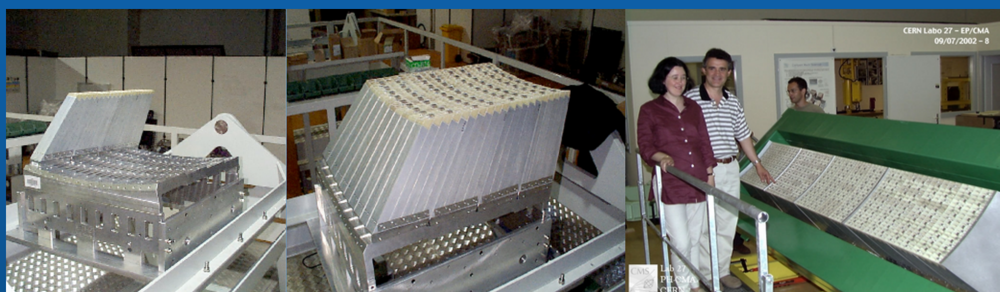


Lead Tungstate Crystals

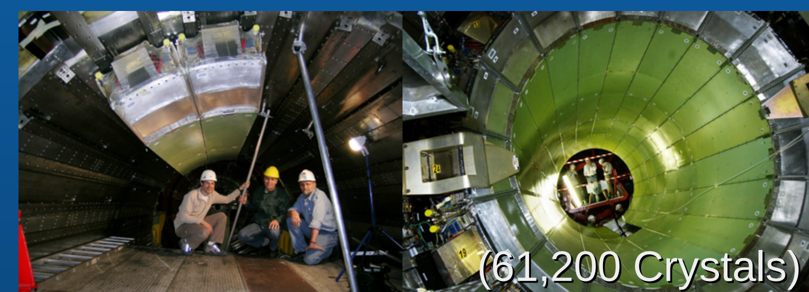
Assembly with APD readout



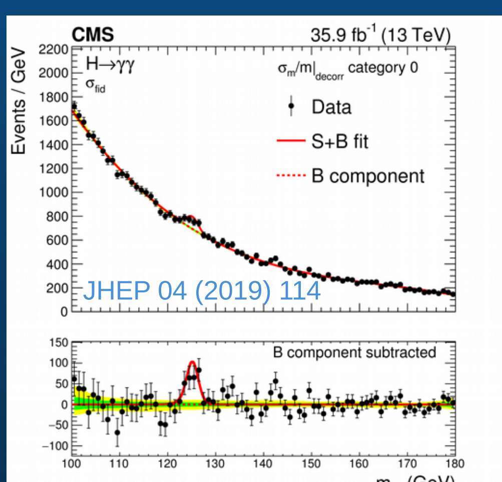
Assemblies of modules and supermodule

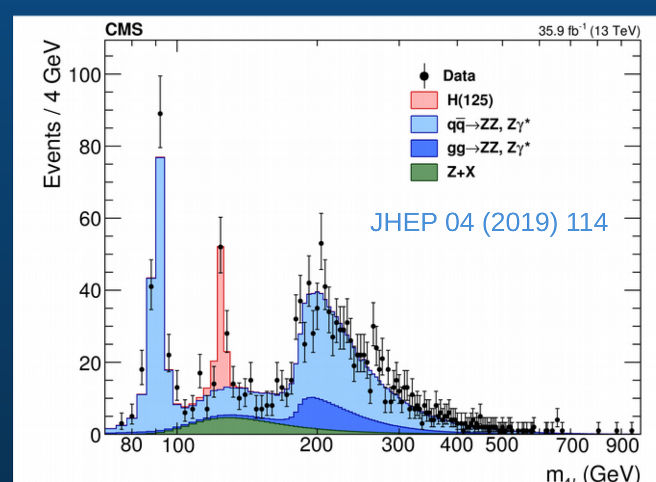


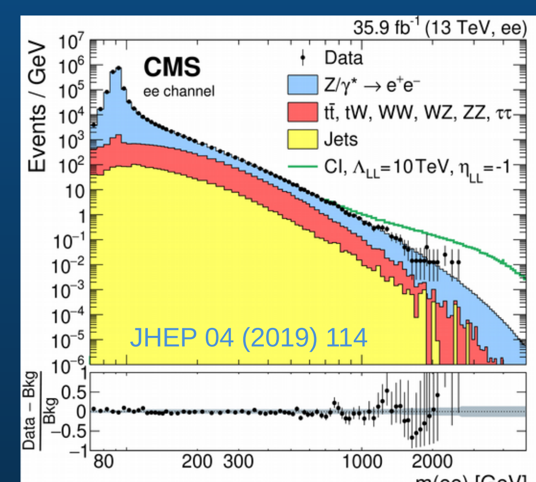
Installation of 36 supermodules w/in CMS 3.8T Solenoid



Essential for standard model, precision measurements, and new physics search programs



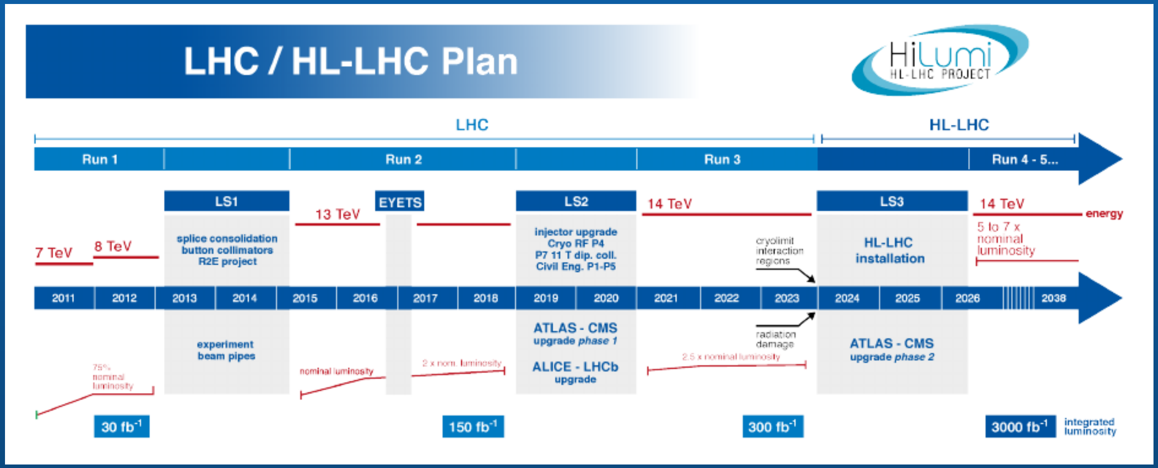




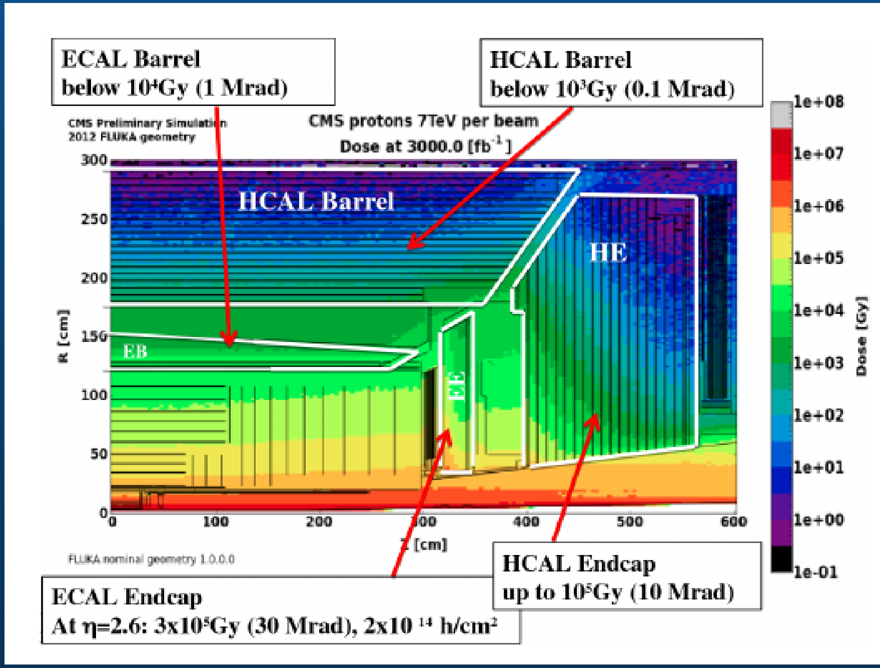
High Luminosity LHC

×10 larger data set for physics (wrt Run 3)

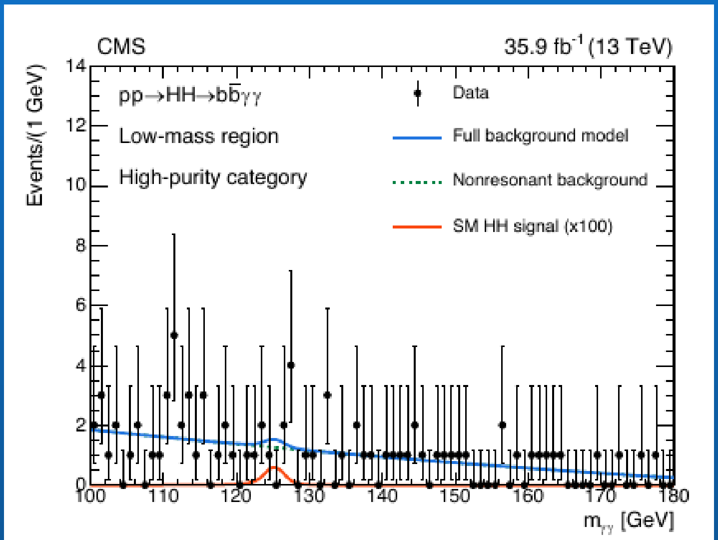
	LHC	HL-LHC	
$E =$	7–14	14	TeV
$\mathcal{L}_{peak} =$	2	5–7.5	$\cdot 10^{34} cm^{-2} s^{-1}$
$PU_{peak} =$	40–60	150–200	
$\int \mathcal{L} =$	≥50	250–320	fb^{-1} /year
$\int \mathcal{L} =$	300–500	3000–4000	fb^{-1} total



- **A challenging environment for physics and detector components**
- **Numerous preparations underway for running in 2026 and beyond**

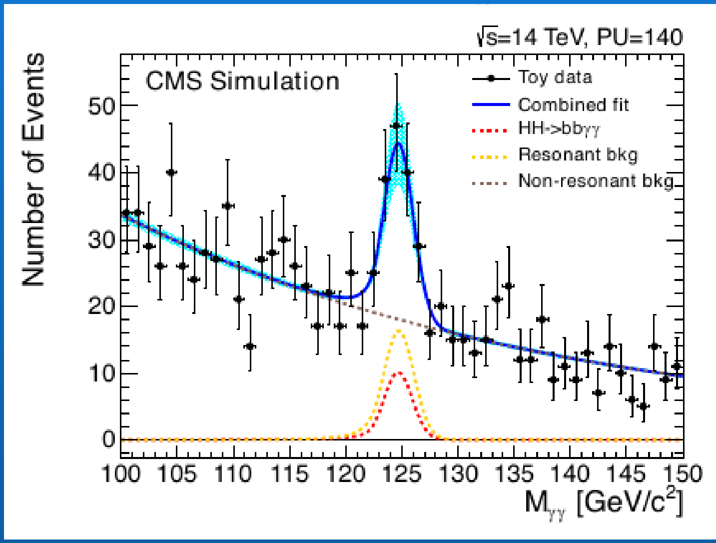


Physics with ECAL at HL-LHC



LHC => HL-LHC

- Determine Higgs couplings ≲10% level, differential meas.
- Higgs self-coupling
- New physics via EW channels, Jets/MET, …



Precision energy measurement / resolution required

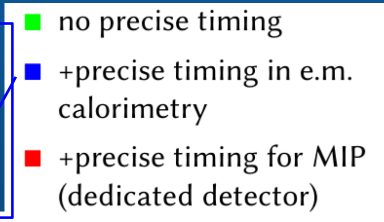
However, high luminosity running results in many interaction vertices (pileup).

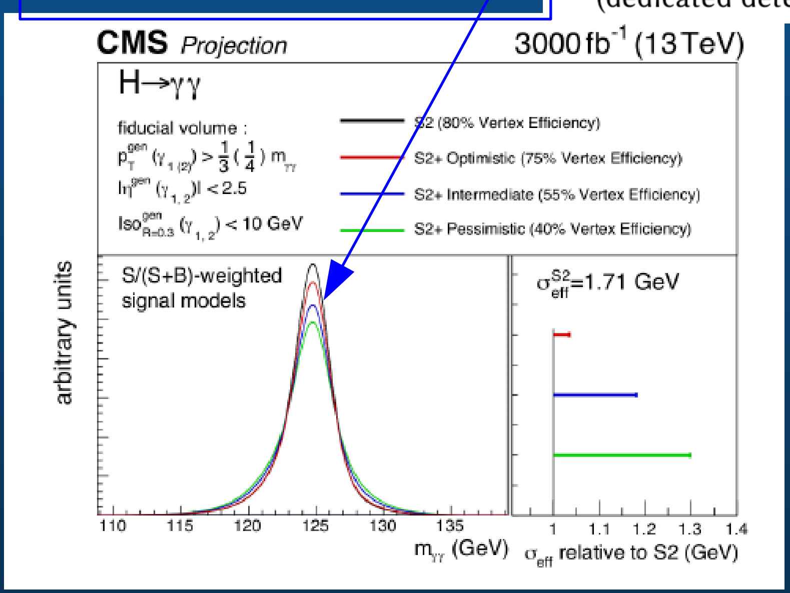
Choosing an incorrect vertex reduces resolution for event reconstruction

Precision timing can be used to reduce pileup effects at high lumi, eg:

- ECAL timing for photon pointing
- "4D" tracking to improve vertex localization in time and space (see talk by Si Xie)

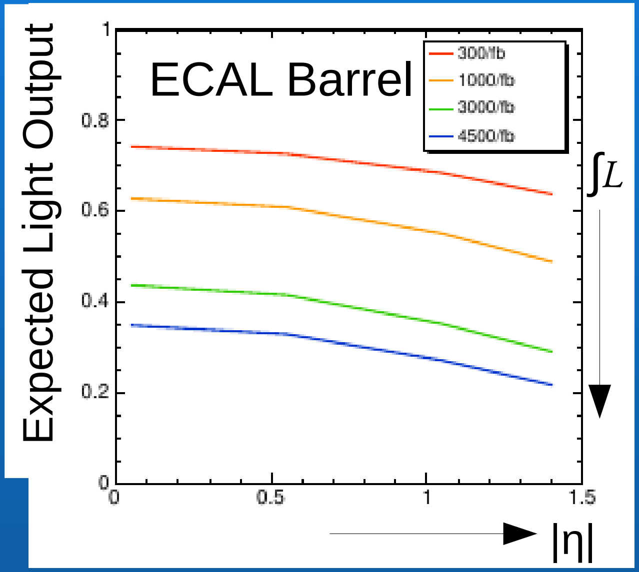
H→γγ mass resolution for different vertex efficiency scenarios

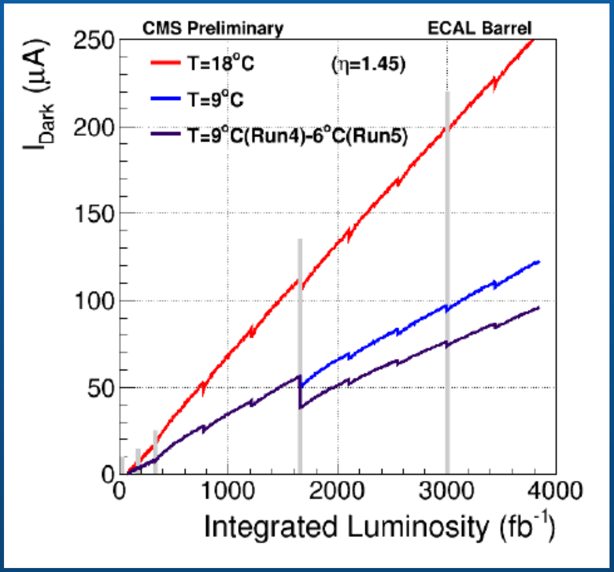




Performance of detector components at HL-LHC

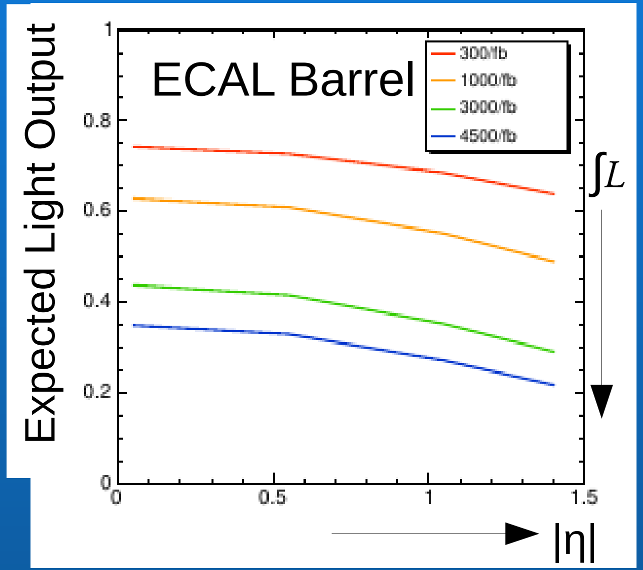
- Crystal transparency affected by radiation damage
  - Transparency loss in barrel < 50% over HL-LHC running => no need for replacement*
- APD dark current will increase with integrated luminosity and become a dominant contribution to σ_E
  - x10 more noise after 3000/fb
- Dark current depends on temperature
  - Mitigate by cooling the calorimeter to 9°C (currently at 18°C)
  - Will also enhance the light yield of $PbWO_4$ by ≈20% ($\Delta S/S = -2\%/°C$)
- Further suppressed by reducing amplifier shaping time





*ECAL (+ HCAL) endcaps need complete replacement. See high granularity, silicon/scintillator based, sampling calorimeter talk by Maral Alyari

Performance of detector components at HL-LHC



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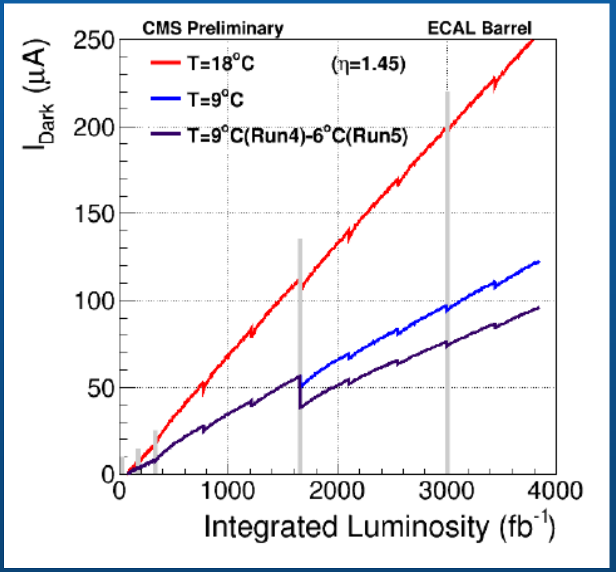
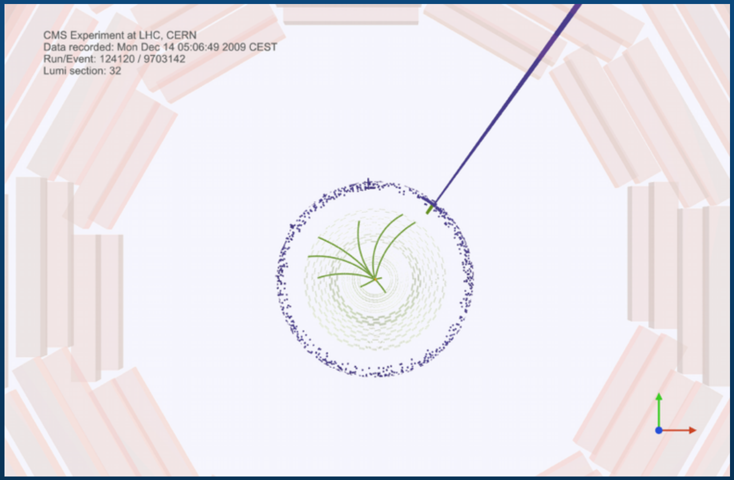


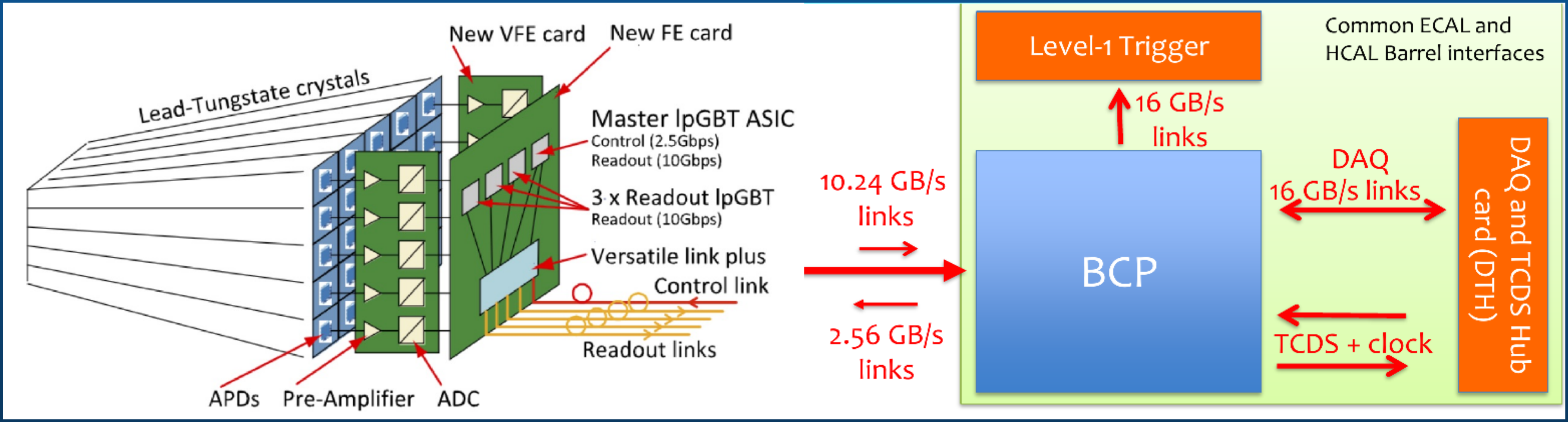


- Will need improved discrimination of direct ionization signals (spikes), associated with particles striking the APDs and rarely interacting to produce secondaries

Upgrades for HL-LHC

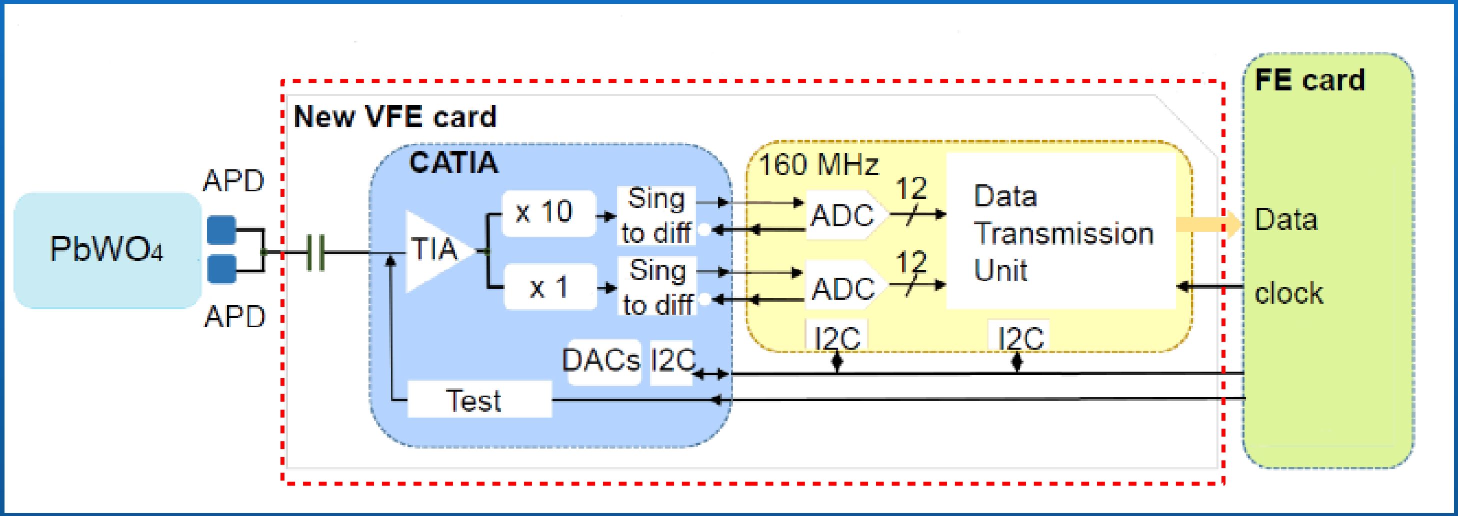
- **Major requirement:** larger trigger rates and latencies to exploit higher luminosity
  - Level 1 rate 750 kHz, 12.5 μs latency (currently 100 kHz, 4 μs)
  - spike mitigation mandatory for L1 rate
- Front-end and off-detector electronics need replacement
- Requires removal, refurbishment, re-installation, re-commmissioning of 36 EB supermodules

- **Opportunity to maintain and enhance performance goals w.r.t. Phase 1:**
  - same excellent energy resolution
  - fast response for pileup mitigation and noise reduction
  - timing resolution and improved granularity at trigger



Complete replacement of front end (on detector) and off detector electronics

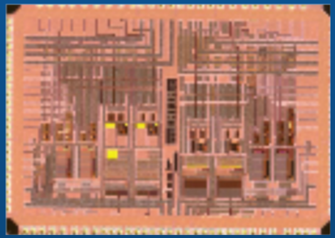
Very Front End Upgrade



The readout system upgrades satisfy new requirements for: bandwidth, conversion and transmission rates and radiation tolerance

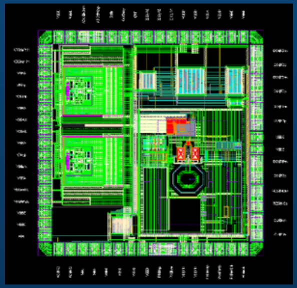
2 new custom (radiation hard) ASICs for the VFE upgrade

- **CATIA ASIC**: analog ASIC
  - Trans-Impedance Amplifier (TIA) architecture, **2x bandwidth of current MGPA**
  - Energy signals dynamic range: 50 MeV → 2 TeV
  - 2 outputs, gain values: (x1, x10), with (50, 500) MeV LSB



TSMC 130 nm

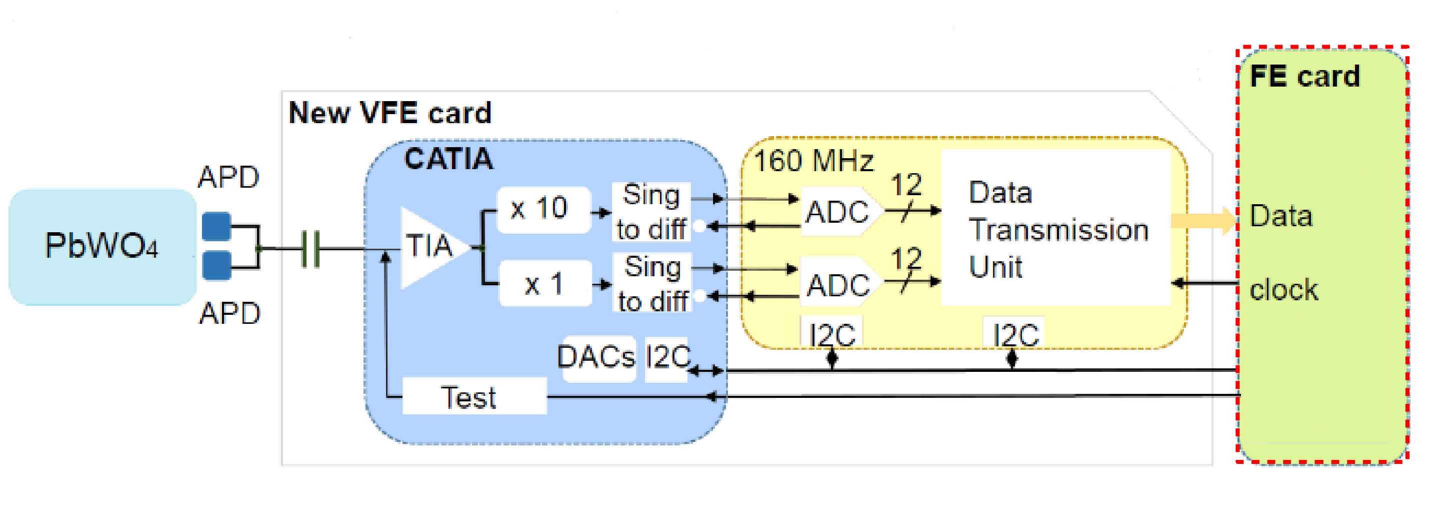
- **LiTE-DTU ASIC**: digital signal processing ASIC
  - ADC: resolution: 12-bit, sampling frequency: 160 MS/s
  - **Lossless data compression and transmission unit**



CMOS 65 nm

- Also low-voltage regulator card (LVR): 1.2, 2.5 V
  - Point-of-load FEAST DC/DC converters

Front End Upgrade



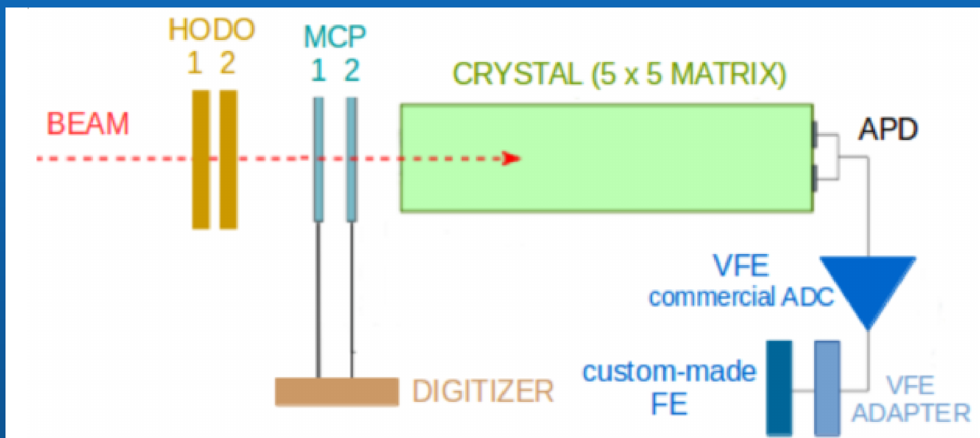
The readout system upgrades satisfy new requirements for: bandwidth, conversion and transmission rates and radiation tolerance

Front End (FE) cars

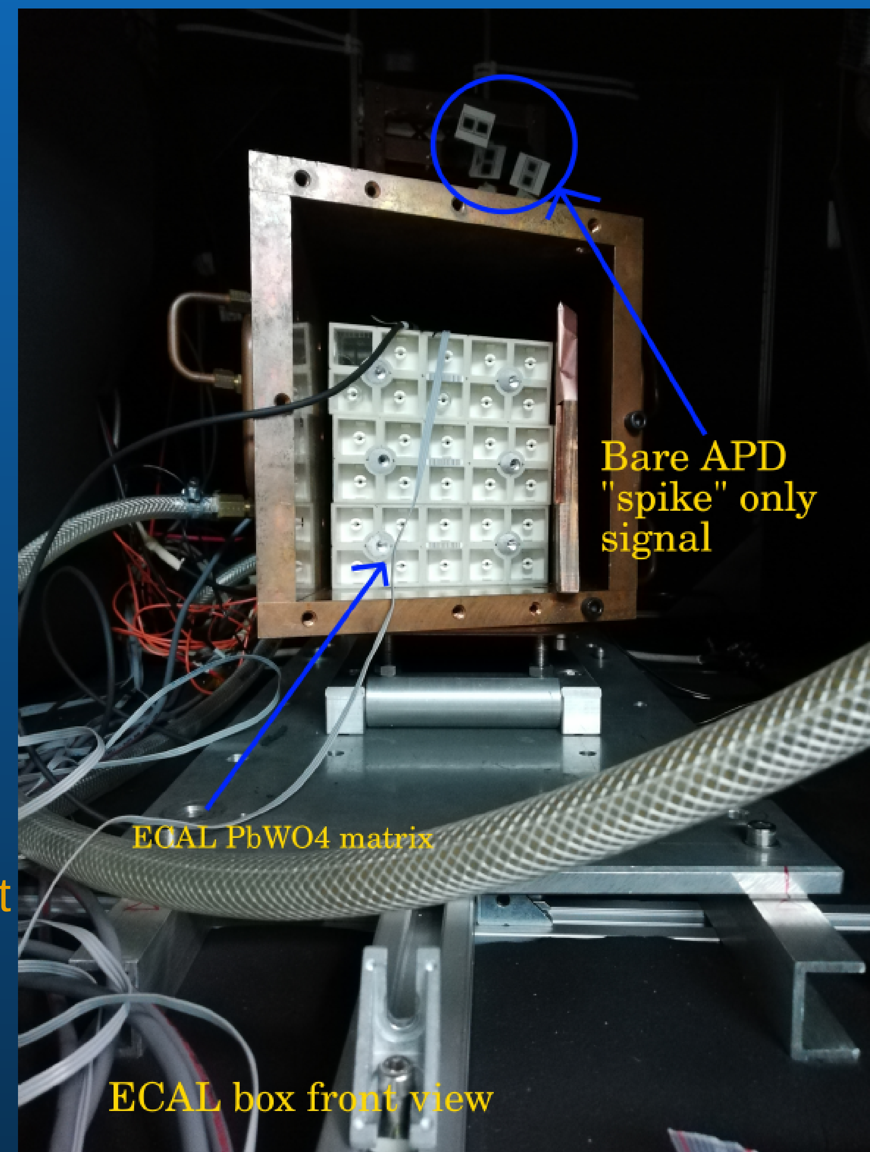
- FE: fast optical links to stream all crystal data off-detector at 40 MHz
  - lpGBT/VL+ components (4×10.24 Gb/s data links, 1×2.56 Gb/s control link)
  - eLink serial interface to ADC, clock and i2C interface
  - **~ 25x increase in bandwidth from legacy system**
- **Sufficient bandwidth to move all data processing off detector:** noise suppression, pulse reconstruction, trigger primitives generation, data buffering, etc moved to powerful FPGAs off detector)

Tests of first VFE prototypes

- Staged approach: discrete components first, minimal prototype with TIA only, full prototype (TIA + i2C + test pulse), full prototype in final package
  - Commercial ADC for 1st tests, data transmission units via custom adapter card

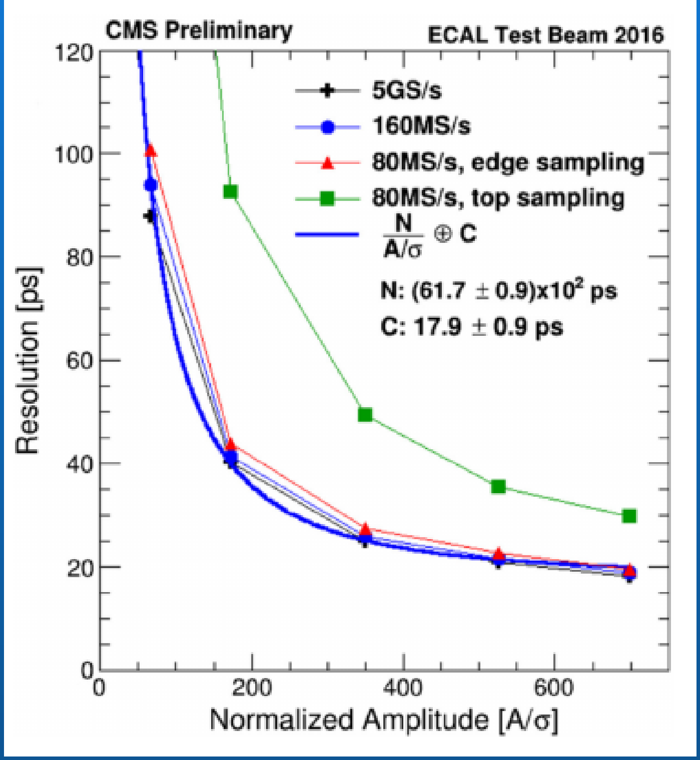


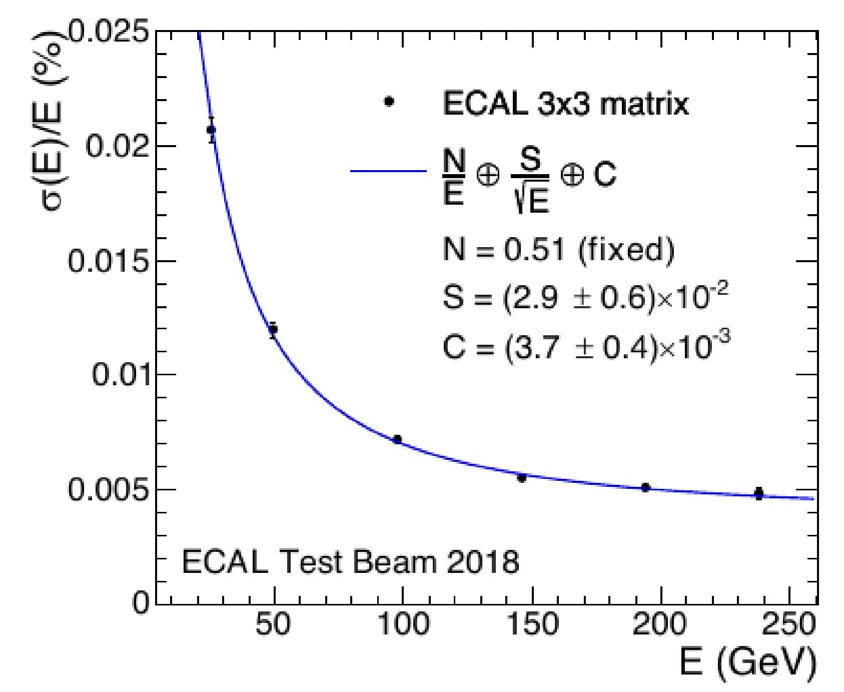
- First characterization in lab with laser light + crystal + APDs
- Extensive tests performed at the CERN H4/H2 beam line on a 5×5 crystal matrix
  - H4: very pure electron beam, $\Delta p/p = 0.5\%$ with $20 < p < 250$ GeV
  - H2: pion beam for APD direct ionization
  - Plastic fiber hodoscopes for position measurement
  - 2 Micro Channel Plate devices (1.2 cm diameter, $<1\ X_0$) for time reference

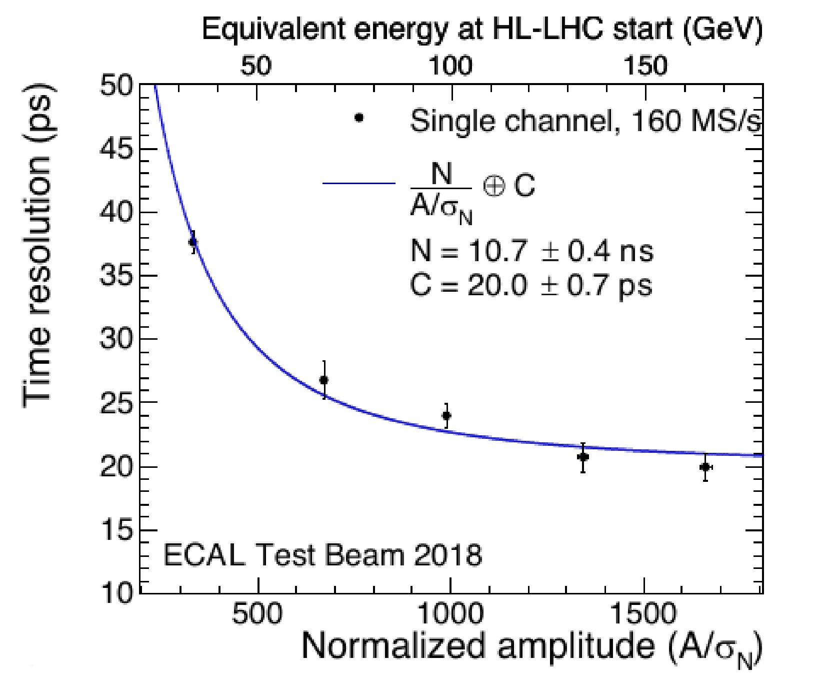


Tests of first VFE prototypes

- **2016: discrete component TIA + DRS4 readout at 5 GS/s**
  - different sampling rates emulated offline
  - 160 MHz optimal, at lower frequencies dependence on the phase between APD signal and ADC clock
- **2018: first prototype ASIC TIA chip + commercial ADC at 160 MHz**
  - Realistic noise performance
  - Energy resolution matches legacy electronics
  - Time resolution matches target (<30 ps @ 50 GeV)



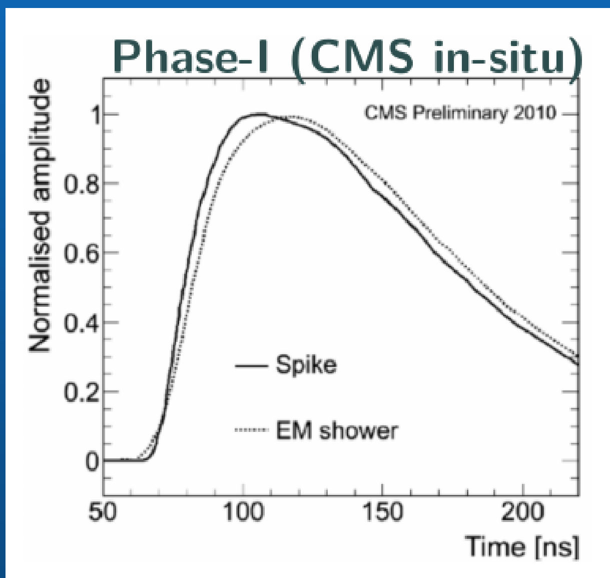


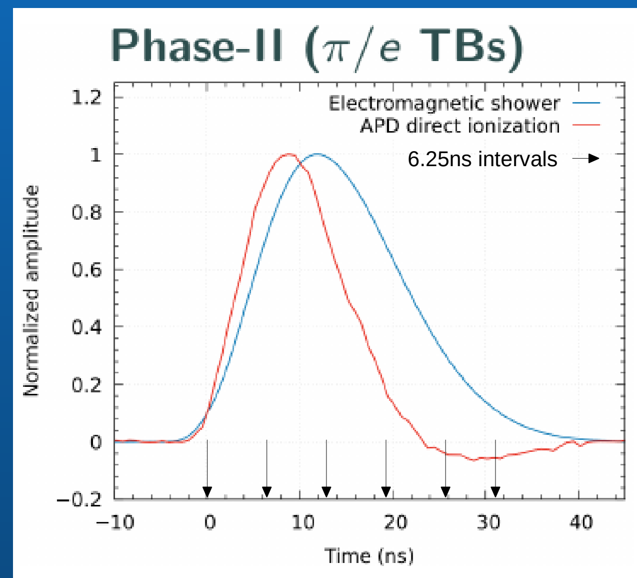


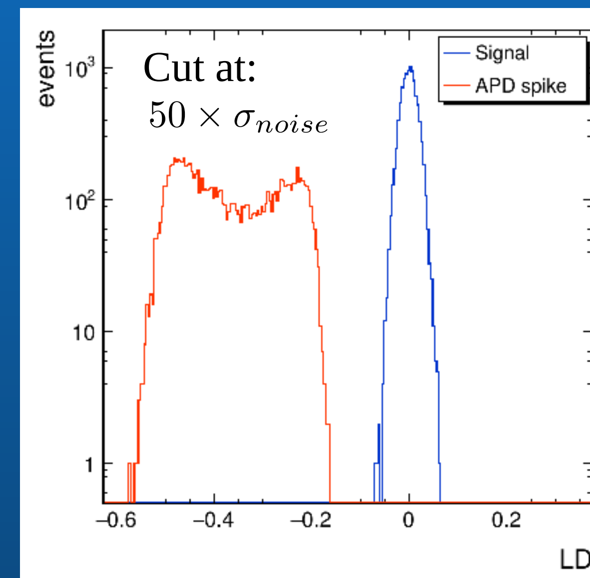
Results shown for 18°C (Data also taken at 9°C)

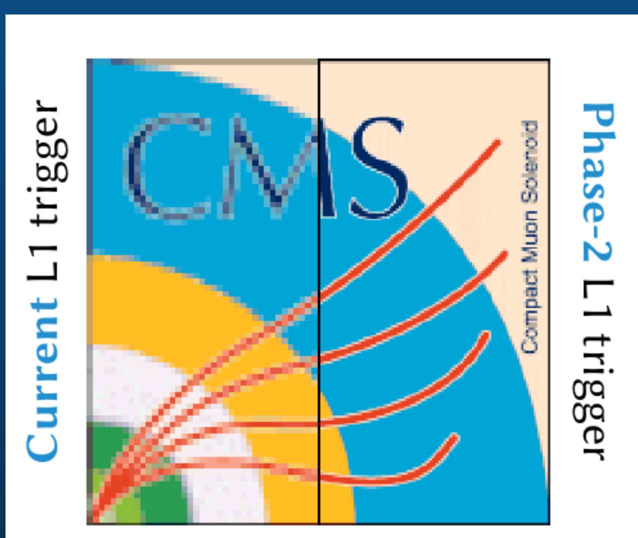
Impact of upgrade on trigger

- **Target for spike discrimination: 1 kHz L1 rate for E_T >5 GeV**
- With faster shaping and 160 MHz sampling frequency => strong pulse shape discrimination for spikes and scintillation signals





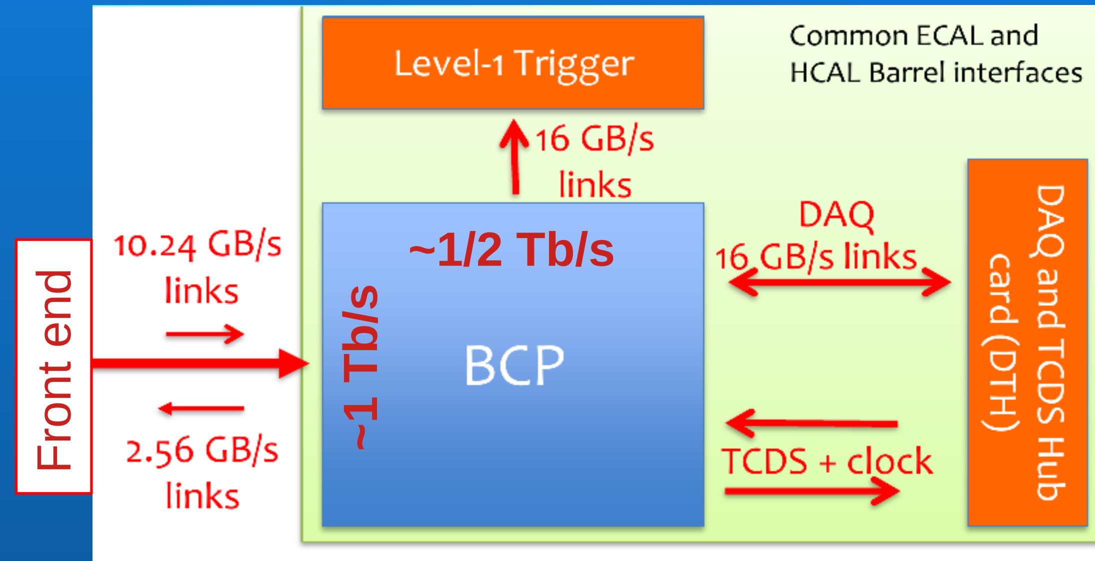




- **Single crystal level available at L1**
  (×25 better granularity than legacy system)
  - More sophisticated trigger algorithms
  - Improve resolution, PU/background rejection
  - Pulse shape method can be combined with topology for spike suppression

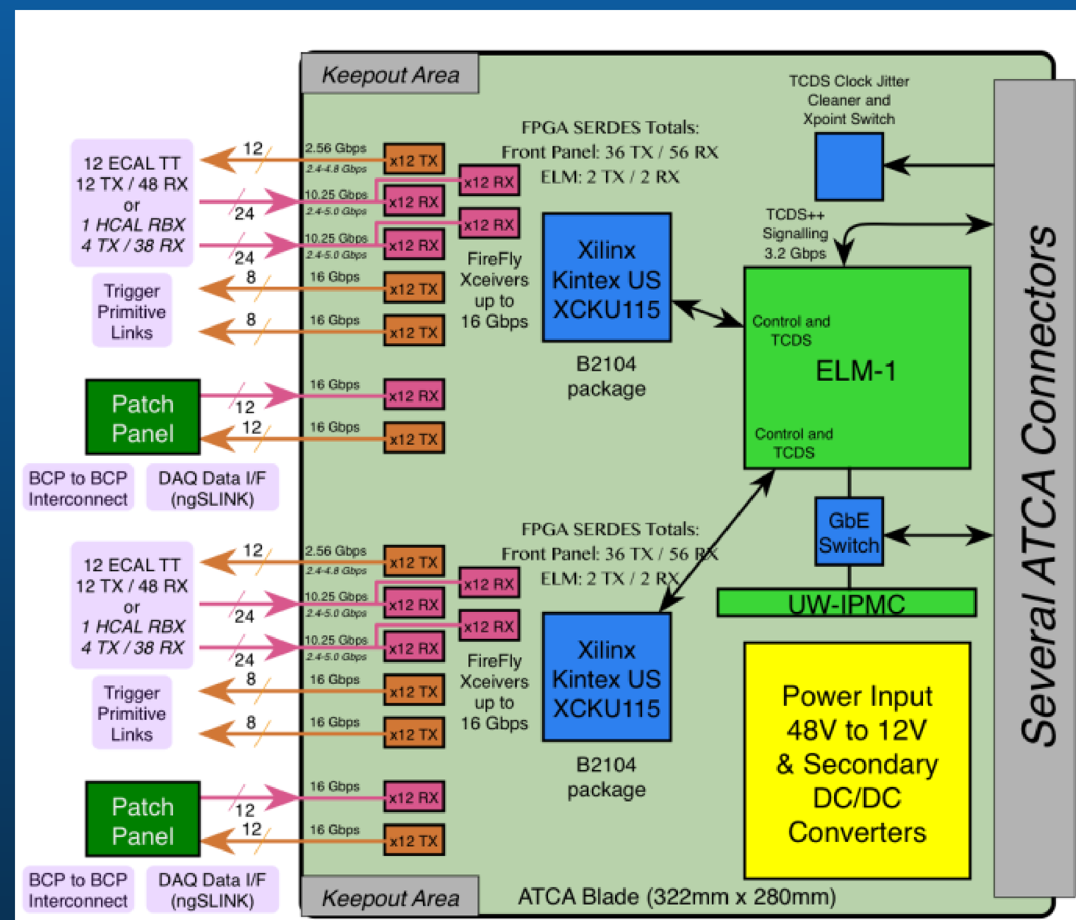
Off detector electronics

- **Barrel Calorimeter Processor**
  - ATCA form factor
  - Main processing by two powerful Xilinx Kintex FPGAs
  - Embedded LINUX and real time OS systems for board monitoring, configuration, and control



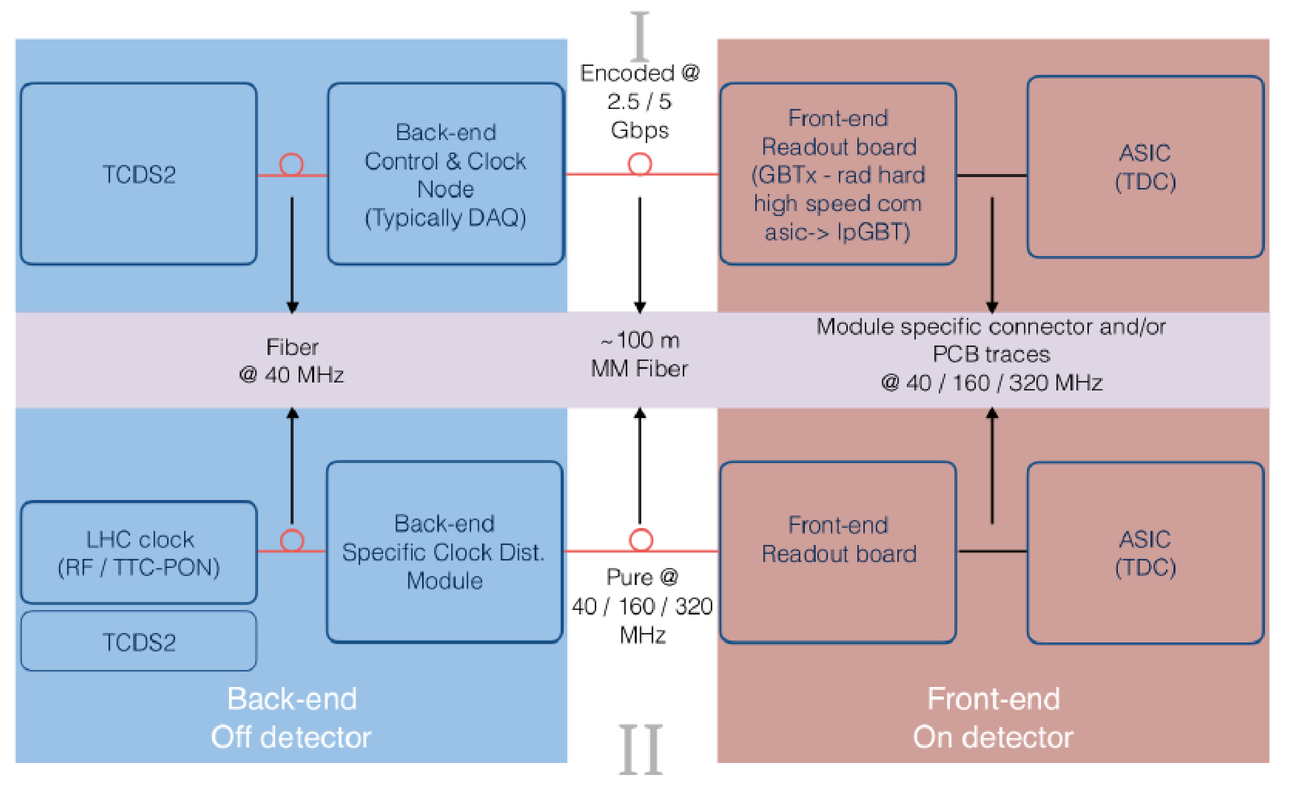
108 boards for ECAL Barrel

- **BCP functions**
  - Concentrate detector raw data
  - Pulse reconstruction and noise suppression, build trigger primitives and transmit them to L1 Trigger
  - Receive the LHC clock and distribute with high precision to the on detector electronics.
  - Buffer and send event data to DAQ upon L1 Accept
  - Handle slow-control of on-detector electronics via lpGBT interfaces

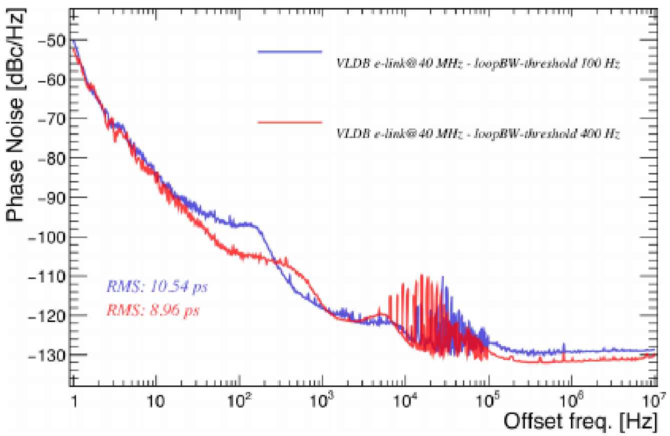


Clock distribution

- The limiting factor in timing resolution with the current ECAL electronics (optimized for energy resolution only!)
- A well implemented back-end and FE capable of precision clock distribution should deliver ≈10 ps RMS (random) jitter
- Dedicated studies on the currently available GBTx serial link
  - Preliminary results indicate better performance with prototype of new lpGBT
- Alternate clock distribution schemes under evaluation also capable of satisfying jitter requirements



Example: GBTx chip tested with a dedicated board



- [1 Hz, 100 Hz]: 7.3 ps RMS
- [100 Hz, 10 MHz]: 5.2 ps RMS

Summary

- **The HL-LHC phase will bring exciting and challenging opportunities for precision measurements and new physics searches**
- Motivated by trigger and physics requirements, redesigned BCAL electronics will provide:
  - equivalent energy resolution to Phase 1/legacy system
  - precise timing for electrons and photons
  - mitigation of pileup effects
  - mitigation of increased APD noise
  - anomalous signal filtering at L1 trigger
  - 25x higher granularity at L1 trigger
- **With these upgrades, the CMS ECAL barrel will continue its excellent performance throughout HL-LHC**