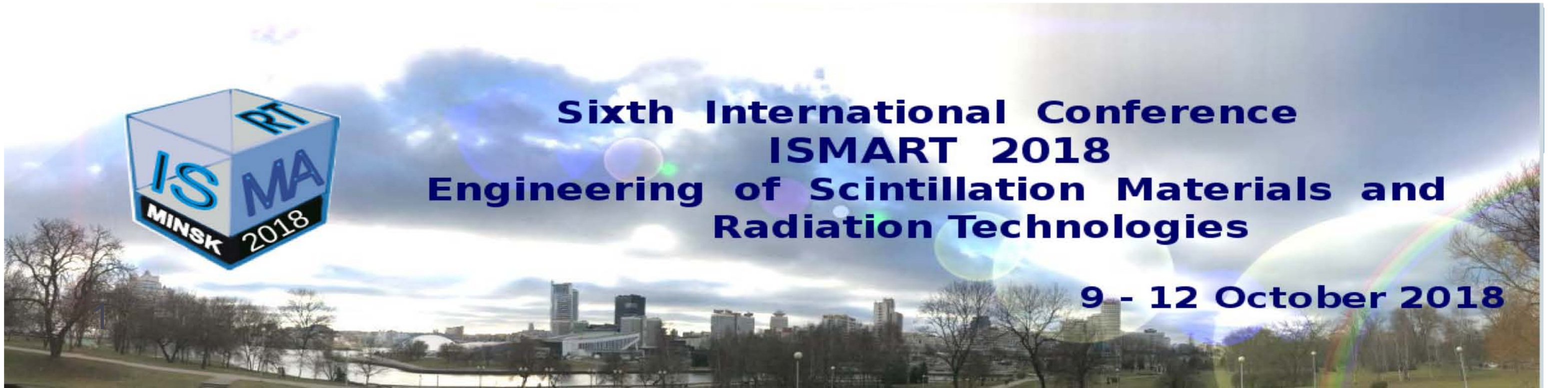
CMS ECAL Upgrade for Precision Crystal Calorimetry and Timing at the HL-LHC

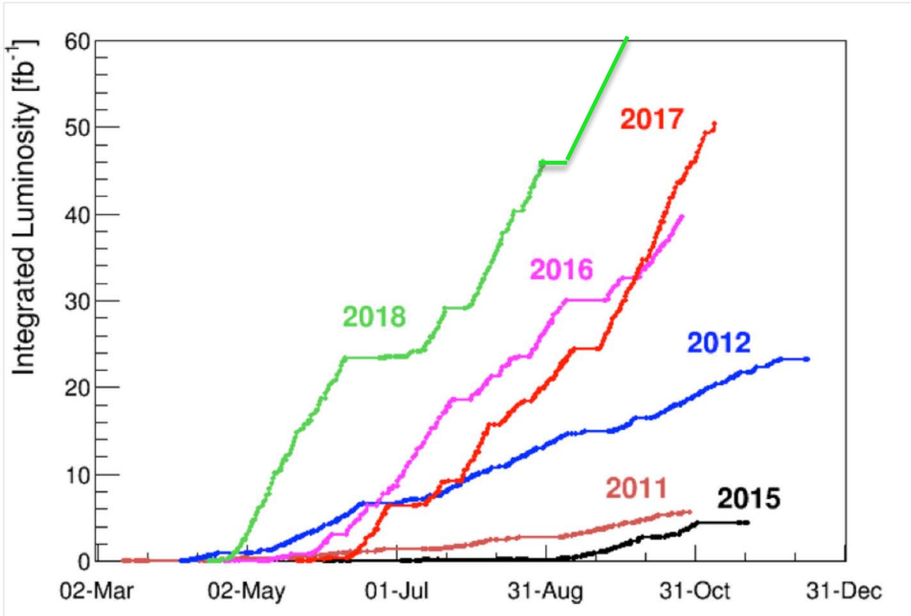
A.Singovski,
On behalf of CMS Collaboration



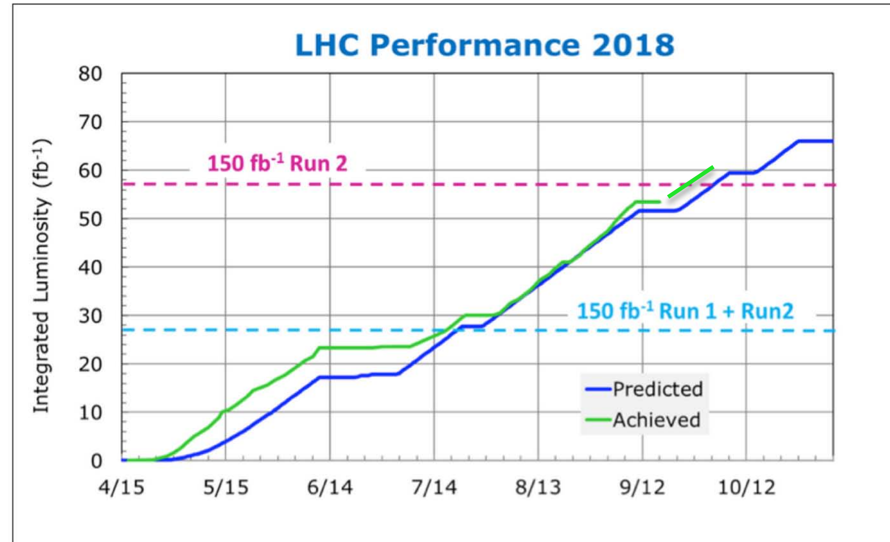
Outline

- Reminder: HL-LHC
- CMS detector upgrade
- CMS ECAL Barrel upgrade
  - New on-detector electronics
    - Fast sampling
    - Precise timing
  - Off-detector electronics
- Summary

LHC



Multi-annual overview of integrated luminosity, with 2018 well on track to become a record year for the LHC.



Projected (blue) and delivered (green) integrated luminosity of ATLAS and CMS. The magenta line corresponds to a Run 2 total of 150 fb−1.

- Excellent performance of LHC machine
- Currently running at x2 design luminosity
- Run 2 target $150 fb^{-1}$ was achieved this weekend

HL-LHC

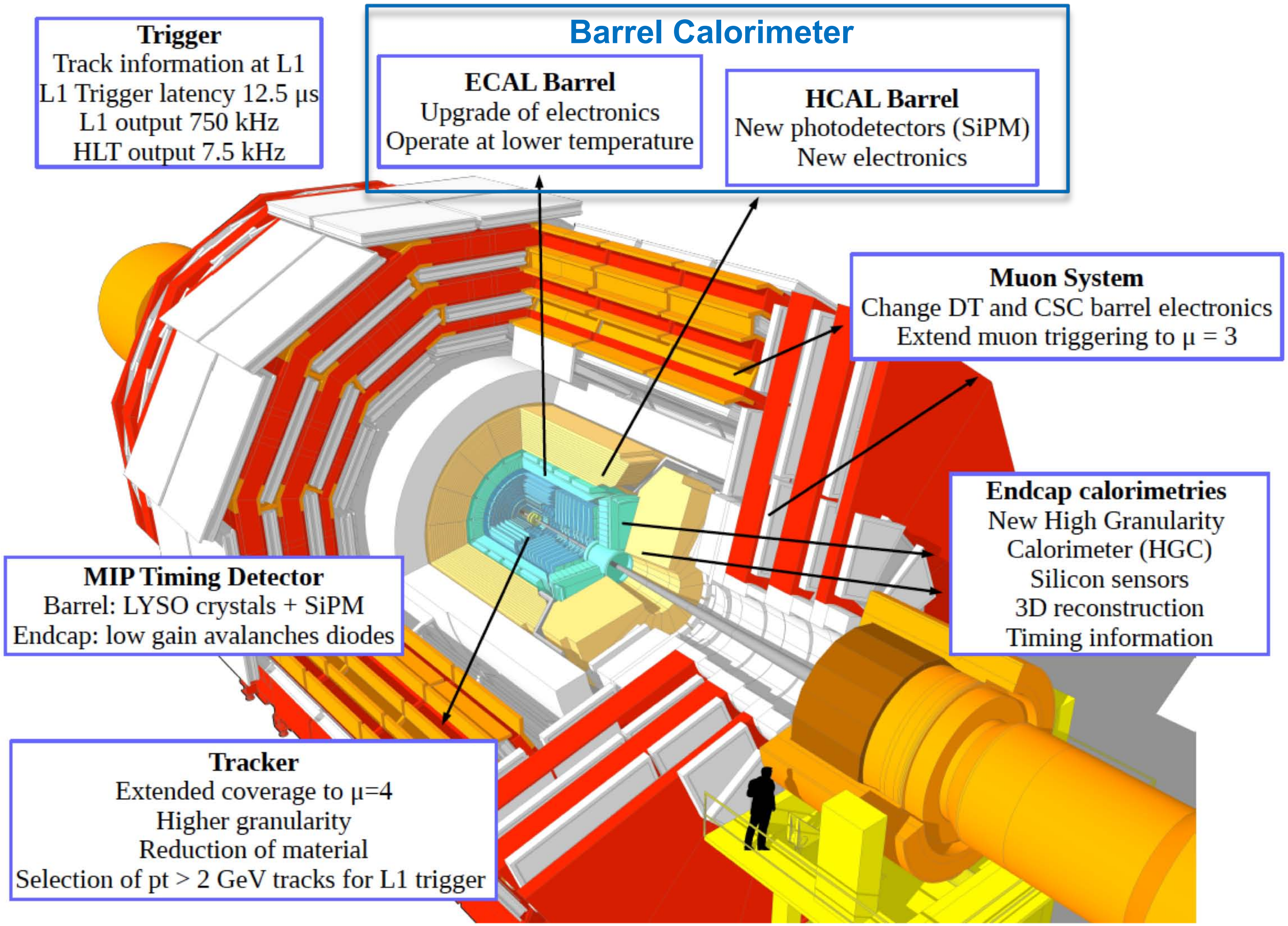
- **HL-LHC goal**: $\times 10$ **integrated luminosity** delivered to the experiments (ATLAS, CMS):

	LHC	HL-LHC baseline	HL-LHC ultimate
$\mathcal{L}$	2×10^{34}	5×10^{34}	7.5×10^{34}
PU (n_{vtxs})	40-60	140	200

CMS detector upgrade goals

- Maintain the best performance of all subsystem at HL-LHC conditions
  - x (5-7.5) design luminosity: (5-7.5) x $10^{34} cm^{-2} s^{-1}$
  - High pileup: 140 – 200
  - x10 design integrated luminosity → accumulated radiation load
- Readout electronics should fit to the new trigger and DAQ conditions:
  - L1 trigger latency 4.5μs → 12.5μs
  - L1 trigger rate 100kHz → 750kHz
  - HLT rate 7.5kHz
  - Track trigger
  - E.M. trigger granularity: 25crystals → 1 crystal

CMS detector upgrade



ECAL at HL-LHC

CMS ECAL is a unique high precision $PbWO_4$ crystal electromagnetic calorimeter working in the hadron collider environment, designed to sustain the hostile radiation environment

Two sources of the performance degradation:

- Instantaneous luminosity — x2 now, x7.5 at HL-LHC
  - Crystals transparency damage by e.m. radiation
  - Pileup
  - Spikes
- Integrated luminosity — x10 at HL-LHC
  - APD dark current
  - Crystals transparency damage by hadron radiation

10 years of the detector operation confirm that the performance can be maintained using the crystals transparency correction and custom analysis procedures. The barrel section of ECAL detector will continue to perform well in HL-LHC conditions and can remain unchanged. Readout electronics should be replaced.

Luminosity mitigation

- Instantaneous luminosity
  - Crystals transparency damage by e.m. radiation
  - Pileup
  - Spikes

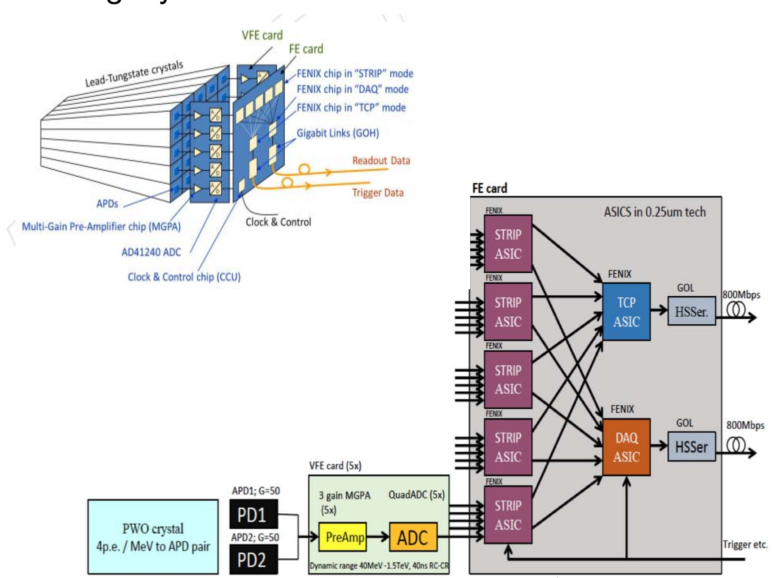
- ✓ Fast preamplifier 40ns → 20ns shaping
- ✓ x4 ADC sampling rate, 40MHz → 160MHz
- ✓ Improved time resolution : 30ps

The legacy crystal transparency correction system allow to maintain performance of ECAL EE which is operating now under radiation load similar to one expected for ECAL Barrel at HL-LHC. Hence the legacy light monitoring system will be sufficient for ECAL EB at HL-LHC.

Details in presentation of T.Dimova later this afternoon

On-detector electronics upgrade

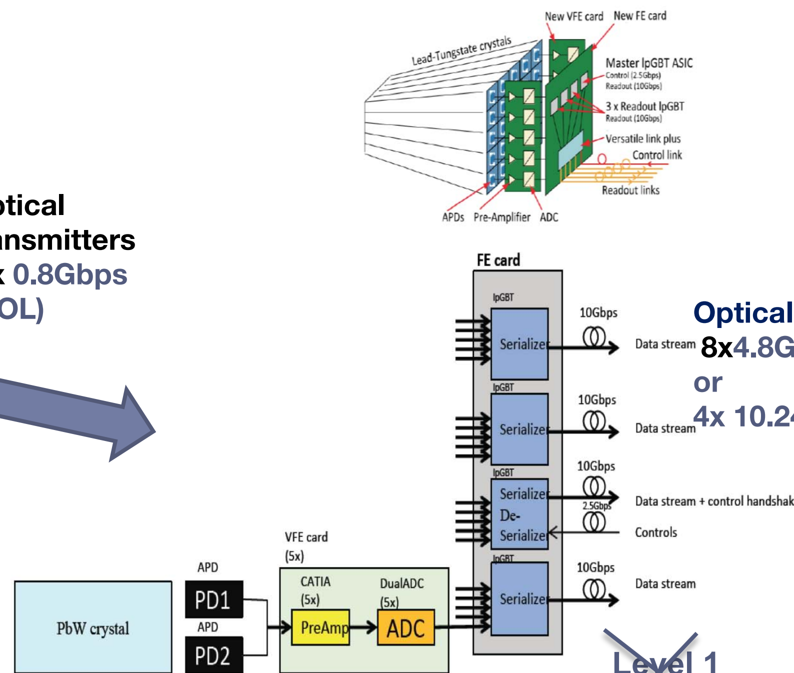
ECAL legacy on-detector electronics



Optical transmitters 2x 0.8Gbps (GOL)

Level 1 trigger

ECAL Upgrade on-detector electronics



Optical transmitters
8x4.8Gbps (GBTx)
or
4x 10.24Gbps (lpGBT)

~~Level 1 trigger~~

Data rates:

Per crystal:
- Pre-amp 3 ranges
- 12 bit ADC
- 14 bit data @ 40 MHz
- 560 Mbps data flow

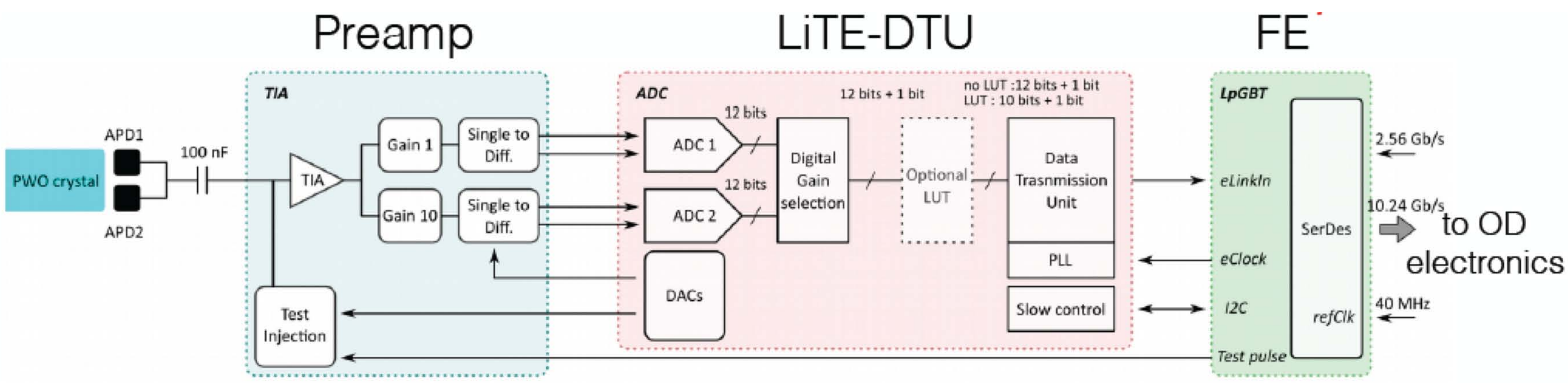
Per VFE card:
- 5 crystals
- **2.8Gbps** @ 40 MHz sampling

Per Trigger Tower:
- 5 VFE cards
- **14Gbps** @ 40 MHz
- **→ 0.8Gbps** TRIGGER primitives
- L1 trigger → **0.8Gbps** DATA

Per VFE card:
- 5 crystals
- 10.4Gbps @ 160 MHz
- 5.4Gbps @ 160Mhz @ compression

Per Trigger Tower:
- 5 VFE cards
- **52Gbps** @ 160 MHz
- **27Gbps** @ 160Mhz @ compression

Upgrade on-detector electronics



TIA pre-amplifier

- 20ns shaping
- Two gains x1 and x10
- 2 TeV dynamic range

ADC-LiteDTU

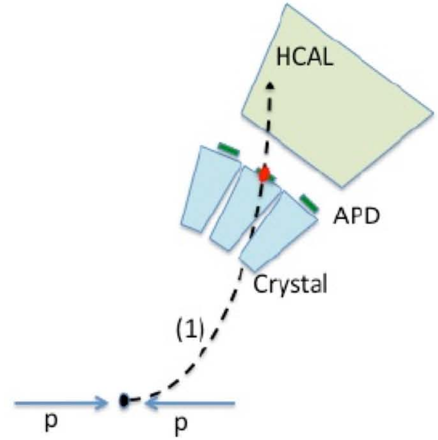
- 12bit ADC
- 10MeV LSB
- Dual channels with gain selection logics
- 160MHz sampling
- DTU with data compression capability

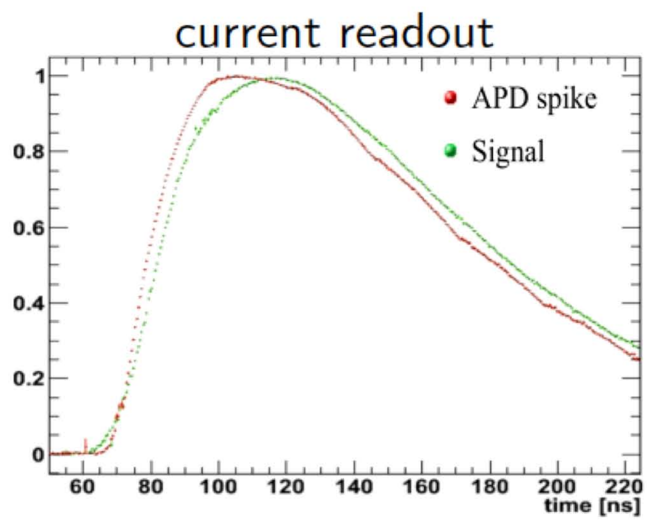
FE card

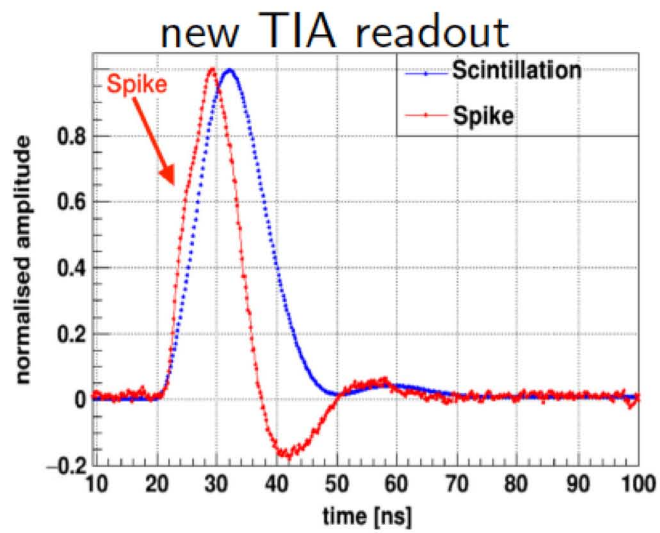
- Data streaming at LHC clock rate
- 4x 10Gbit/s optical uplinks (lpGBT)
- 1x 2.5Gbit/s optical downlink

Anomalous APD signals (spikes)

- Hadron interaction in APD
  → anomalous signals (*spike*)
  - → **faster pulse** than scintillation signal
  - → exploit **pulse shape for discrimination**



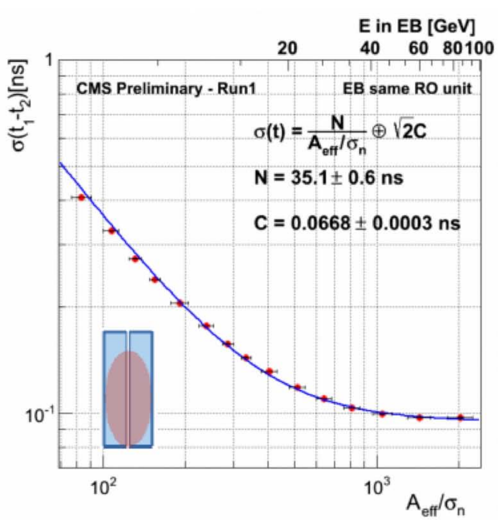


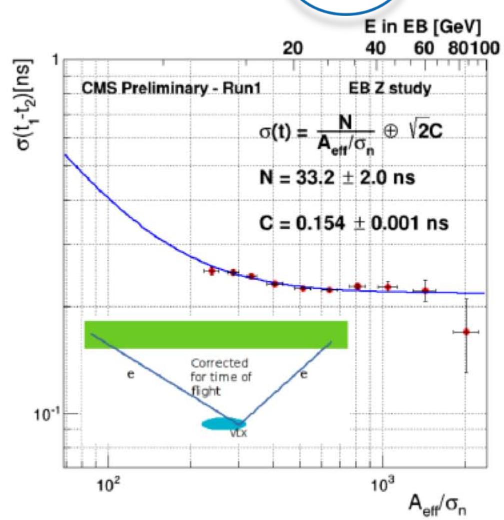


Time resolution

Current situation

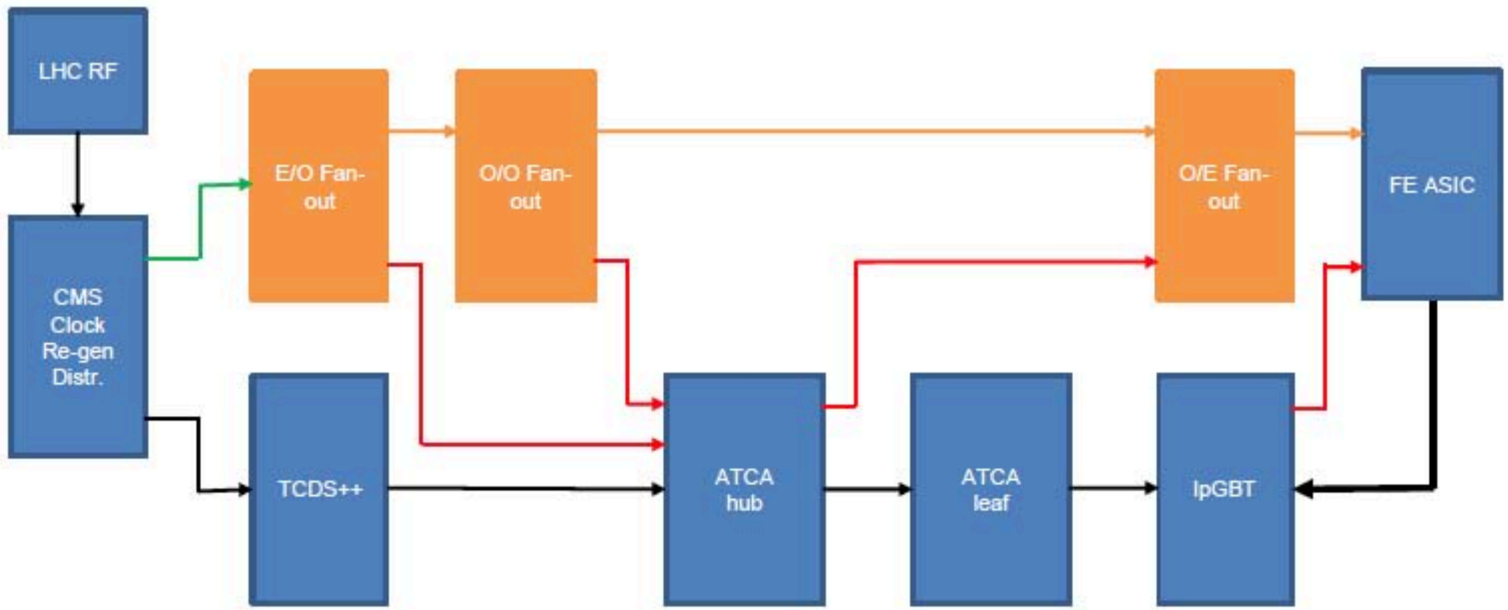
- $PbWO_4$ crystals **intrinsic time resolution** measured at test beam:
  - $\rightarrow$ $\sim$ **20 ps constant term**
- In-situ measurements:
  - $\rightarrow$ **close-by crystals** (same readout unit) of the same shower $\sim$ **70 ps**
  - $\rightarrow$ crystals in **different clusters** with $Z \rightarrow ee$ events $\sim$ **150 ps**





The difference between PWO-APD intrinsic time resolution and the observed one is due to the relatively low precision of the clock distribution system, which **was not** designed for the 50-70 ps time resolution

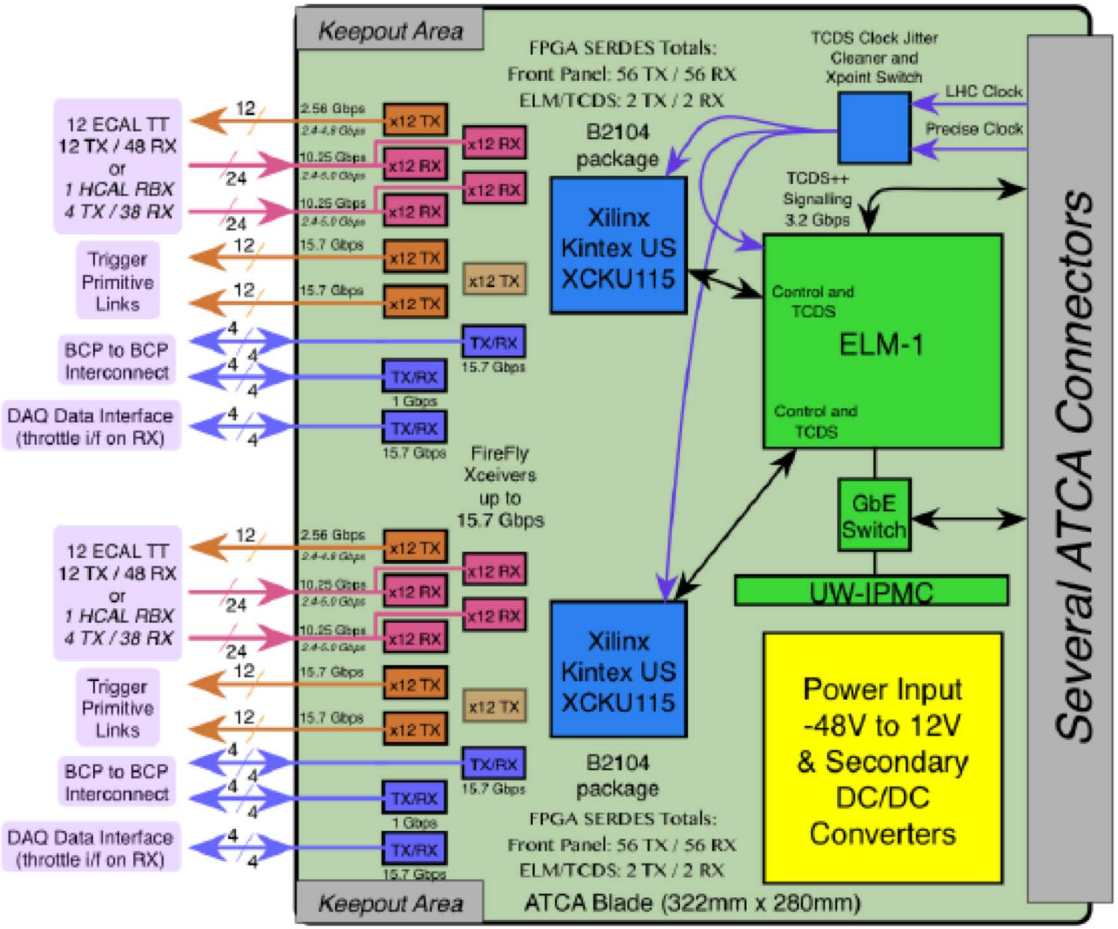
Precision clock distribution



Three options

1. Basline: via TCDS++ - ATCA backplane – lpGBT downlink
   - Design lpGBT e-link clock jitter < 5ps
2. Fully custom: clock distribution via special clock optical downlink and dedicated fanout on the Front-End card
3. Mixed: via ATCA hub and optionally lpGBT downlink

Off-detector: Barrel Calorimeter Processor



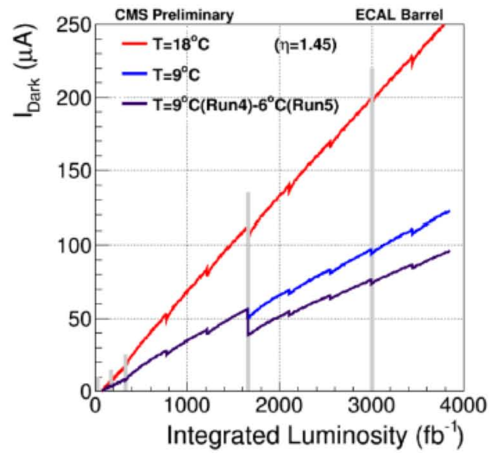
- Combine DAQ and Trigger functions
- One FPGA per 12 towers
- 10.54 Gbps input links from FE
- 16 or 25 Gbps links to L1 trigger and DAQ

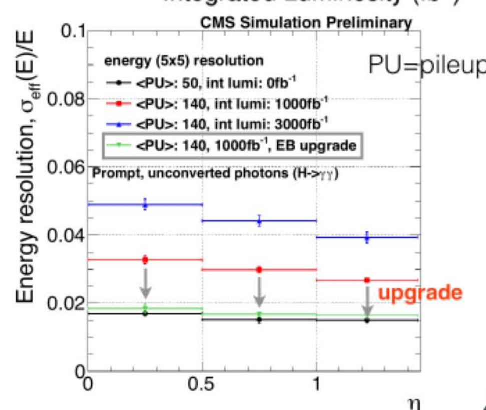
More on luminosity mitigation

- Integrated luminosity
  - APD dark current
  - Crystals transparency damage by hadron radiation

The legacy light monitoring system will be sufficient for ECAL EB at HL-LHC.

- ECAL barrel photo-sensors will continue to operate during HL-LHC:
  - → Increase in APD leakage current due to radiation damage →**APD noise will dominate HL-LHC energy resolution**.
  - → **Mitigation**:
    - → **Lower ECAL operation temperature** $6-9°C$ (now $18°C$).
    - → **Shorter pre-amplifier shaping time (reduce PU impact, better S/N)**.

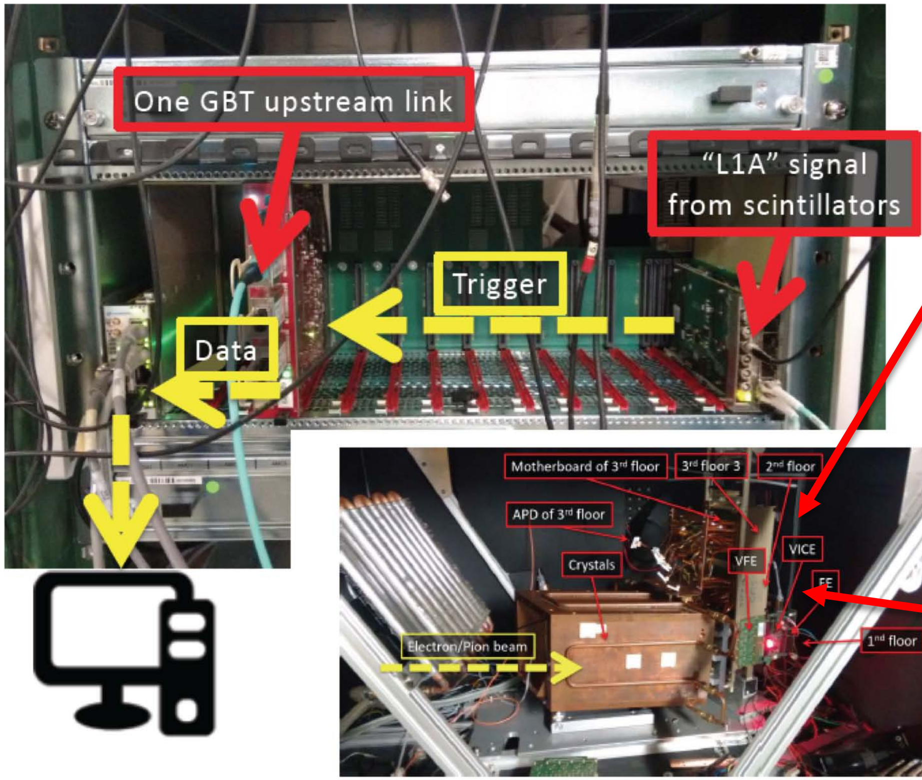




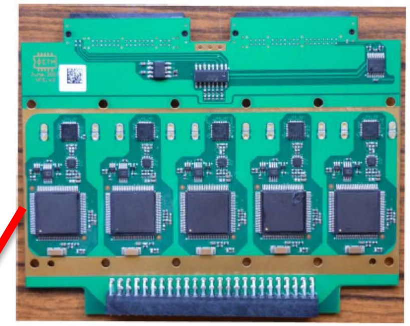
Current status

- VFE
  - Custom preamp chip: CATIA v1
  - ADC-LiteDTU: first prototype submission — Q4 2018
  - VFE card, basic functionality: CATIAv1 + commercial ADC — Q4 2018
- FE
  - lpGBT custom chip: submitted, available for users — Q1 2019
  - GBTx – based Prototype 1 5xGBTx, data streaming @40MHz — testing
- BCP
  - Demonstrator, one Kintex Ultrascale FPGA, design on-going — Q1 2019
- Precision clock distribution
  - GBTx – based baseline system — testing
  - Custom system Prototype 1 — Q4 2018

Lab @ beam tests in 2018

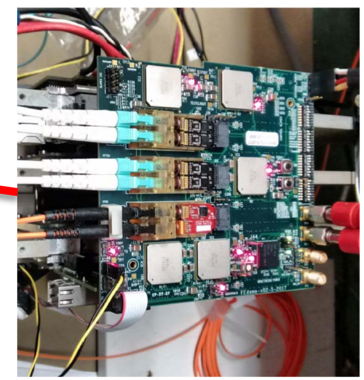


Test setup @ H4 beam



VFE

- ✓ CATIA V0 chip
- ✓ Commercial ADC
- ✓ 160MHz sampling



FE

- ✓ 5 x GBTx
- ✓ Versatile link TTx, TRx
- ✓ 5Gb/s optical links
- ✓ 80 – 320 Mb/s e-links

Plan to build a full chain in Q3 2019:

- VFE: Catia_V1 @ LiteDTU
- FE: lpGBT @ VL+
- BCP: Demonstrator

Summary

- CMS ECAL performance will remain an important factor of the overall detector operation
- Upgrade is needed to maintain great performance throughout HL-LHC
  - Barrel detector remains unchanged. Operation temperature reduced to 9^{o}
  - Upgraded readout electronics
    - Fast preamplifier, 20ns shaping time
    - 12 bit ADC, 160MHz sampling rate, 2TeV range
    - Fast readout, dead-time-less data streaming off-detector
  - Powerful off-detector BCP processor
  - Precision clock distribution
    - Target clock jitter <10ps
- Good progress. Prototypes of all key components either available or expected early 2019