Precision Timing with the CMS MTD Barrel Timing Layer for HL-LHC

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LIP Seminar, Feb. 4, 2021

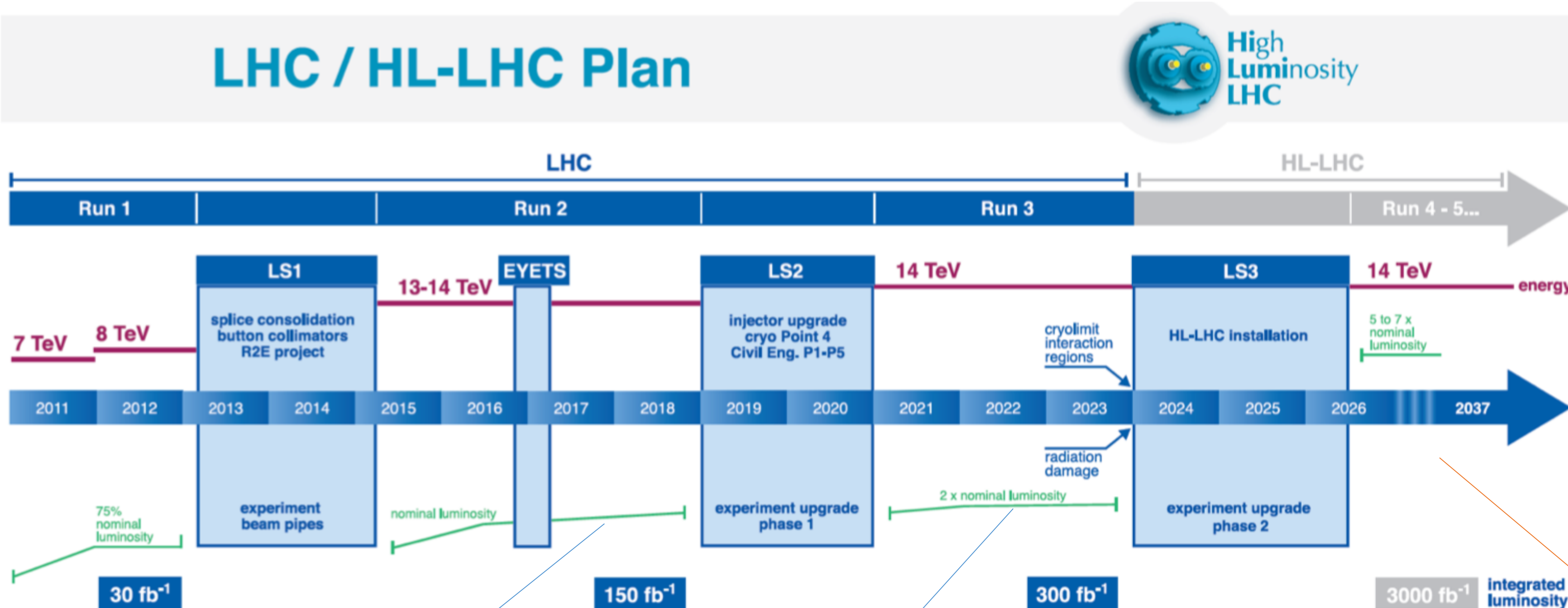
Outline

- The challenge: pileup at the HL-LHC
- Detector requirements
- Impact on performance for physics objects and physics analysis
- CMS MIP Timing Detector
  - Endcap Timing Layer
  - Barrel Timing Layer
- Summary

Outline

- The challenge: pileup at the HL-LHC
- Detector requirements
- Impact on performance for physics objects and program
- CMS MIP Timing Detector
  - Endcap Timing Layer
  - **Barrel Timing Layer → LIP is leading the development of the readout electronics**
- Summary

Path to High Luminosity LHC



Run2:
$L = \ 10^{34}\, cm^{-2}s^{-1}$
For $150\, fb^{-1}$

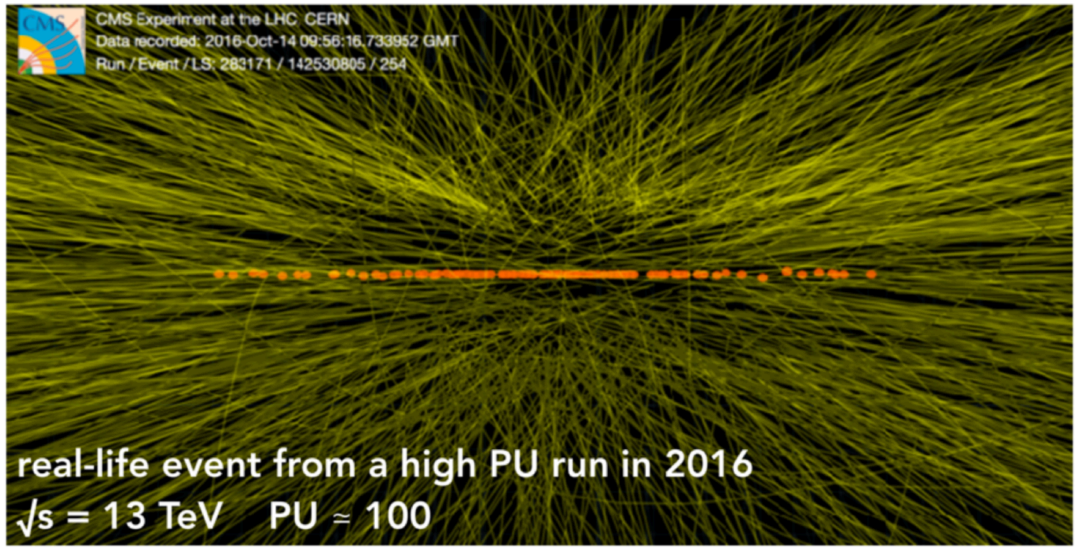
Run3:
$L = \ 2{\times}10^{34}\, cm^{-2}s^{-1}$
For $300\, fb^{-1}$

HL-LHC
Nominal scenario:
$L = \ 5{\times}10^{34}\, cm^{-2}s^{-1}$
For $3000\, fb^{-1}$
Ultimate scenario
$L = \ 7.5{\times}10^{34}\, cm^{-2}s^{-1}$
For $4000\, fb^{-1}$

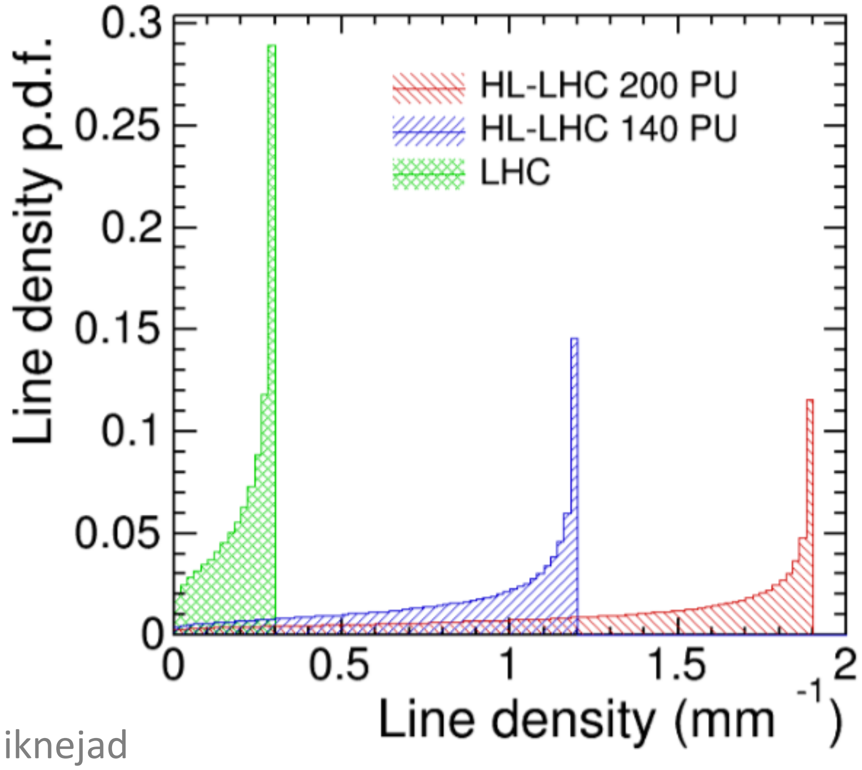
- High Luminosity - Large Hadron Collider will deliver 10 times more integrated luminosity.

Phase II Detector Requirement

- **HL-LHC challenges**
  - High intant. luminosity $> 5 - 7.5\ 10^{34}\, cm^{-2} s^{-1}$
    - → High pileup 140-200 for every bunch crossing (x5 higher vertex density)
  - High integrated luminosity target of $3000 - 4000\, fb^{-1}$
    - → High irradiation
- **Phase II Detector Upgrade:** Significant upgrades of ATLAS and CMS for HL-LHC conditions
  - Radiation hardness
  - Mitigate physics impact of high pileup
  - High trigger and readout rate

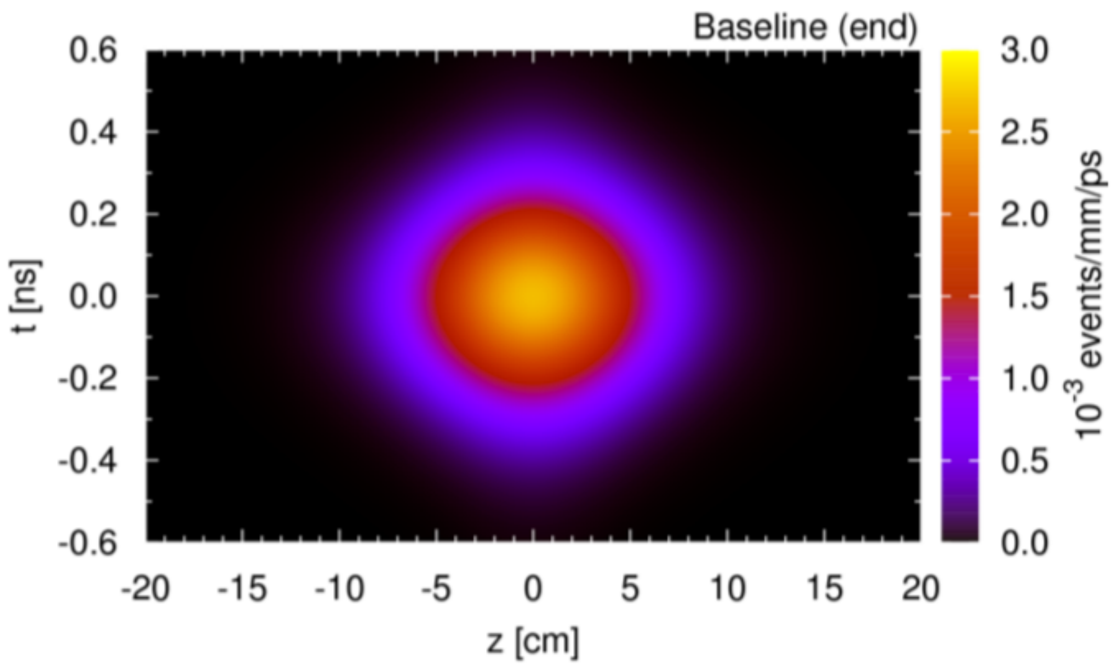


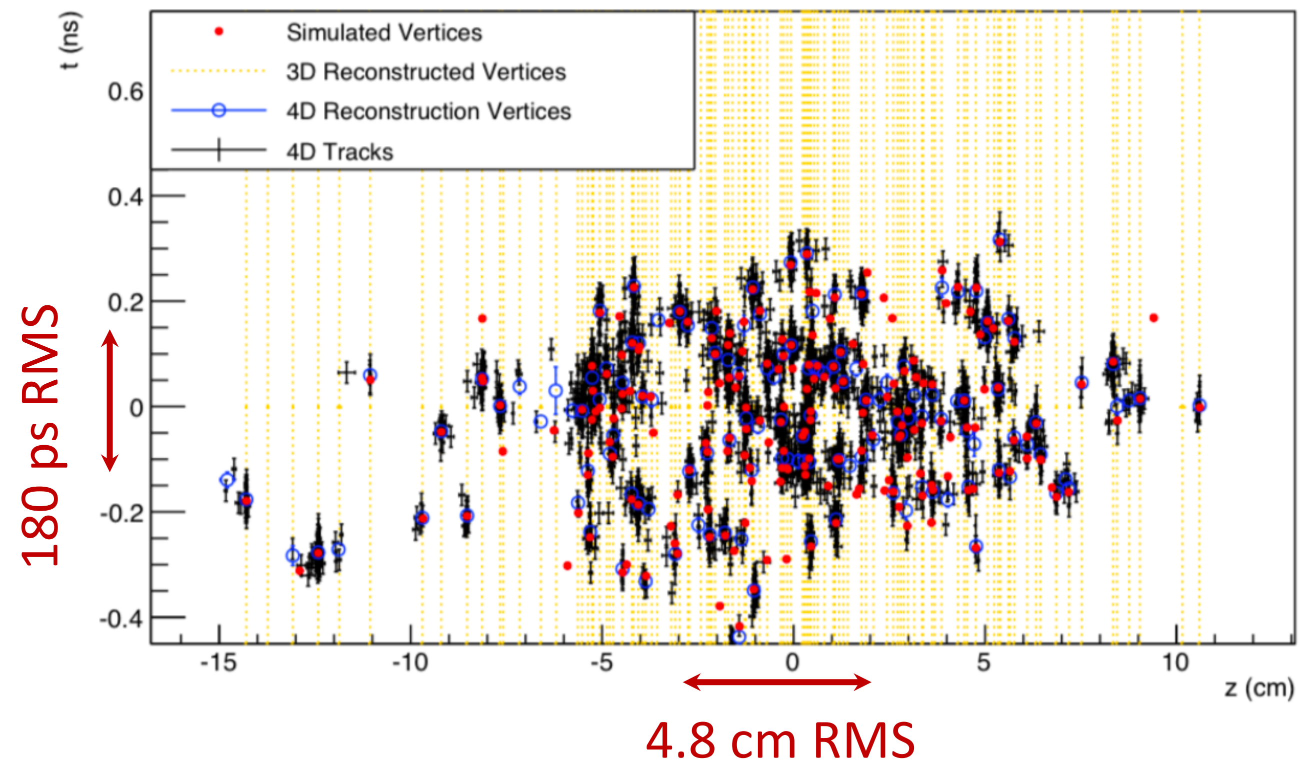
Real-life event with HL-LHC-like pileup from special run in 2016 with individual high intensity bunches



Time Tagging at the HL-HC

- Vertices at the HL-LHC have a distribution in time with ~ 180 ps rms
- The MIP timing Detector (MTD) allows timing of charged particles with a precision of 30-50 ps



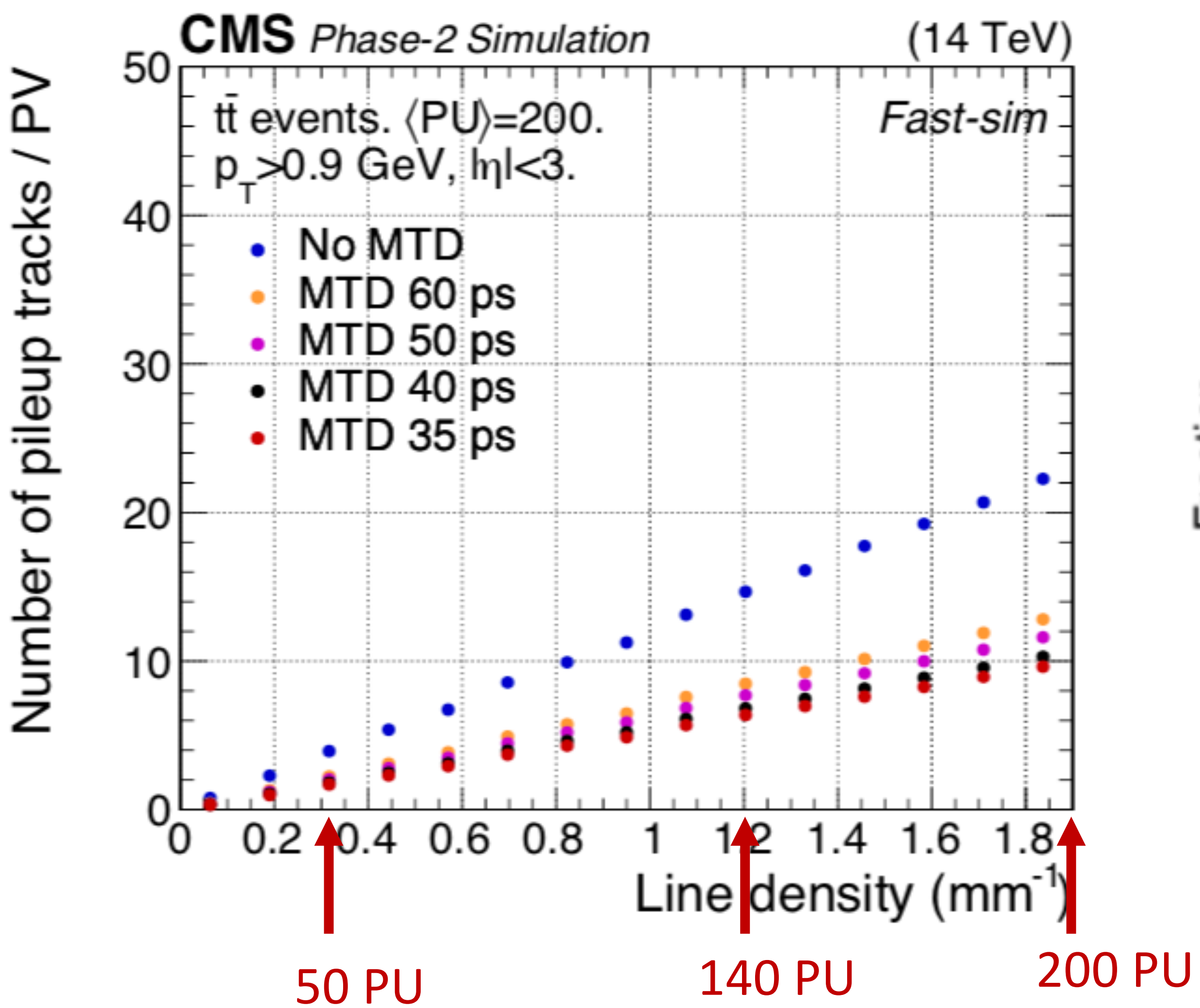


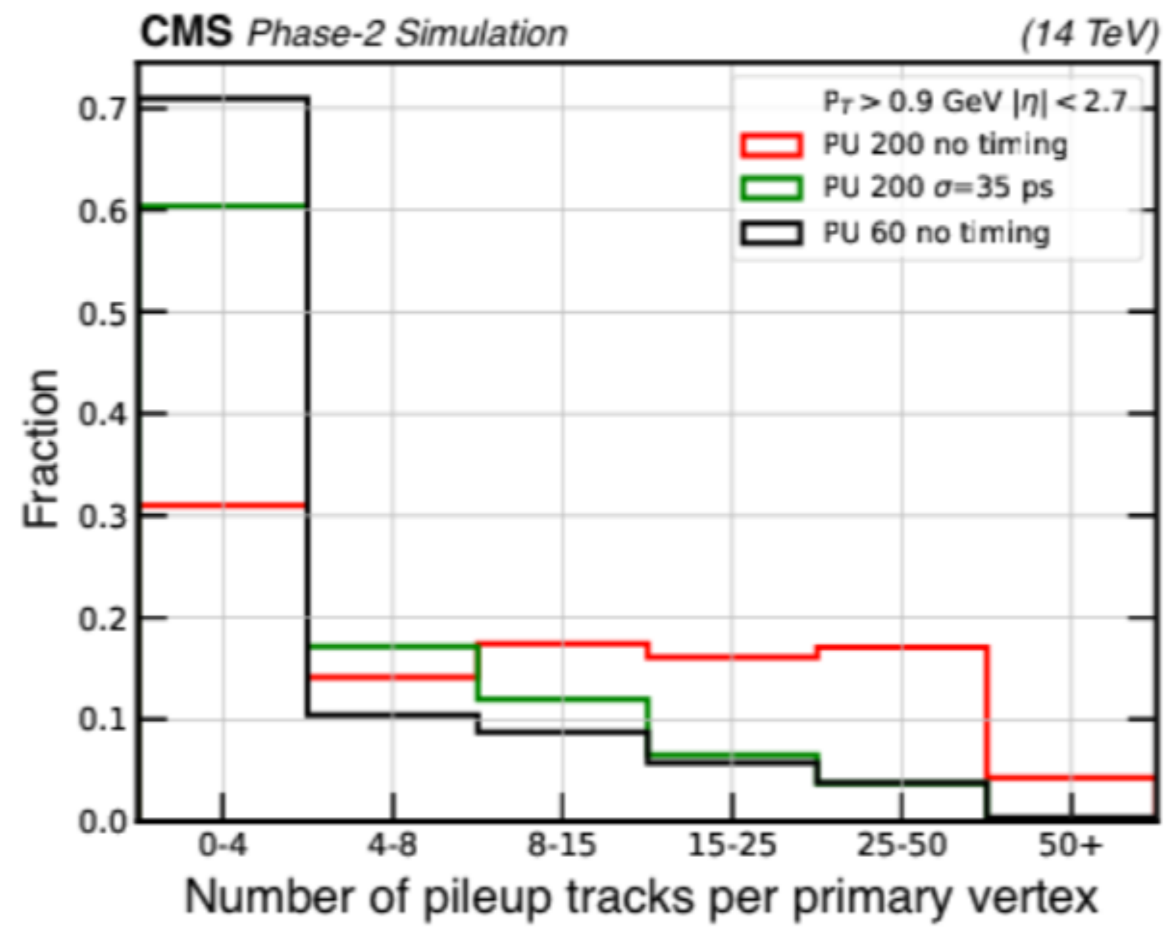
➢ Beam spot: time spread of 180 - 200 ps, largely uncorrelated with the spread in z

➢ **4D vertex reconstruction**

- Disentangle overlapping vertices in space with precision timing.

Effect of Precision Timing on Track-PV Association

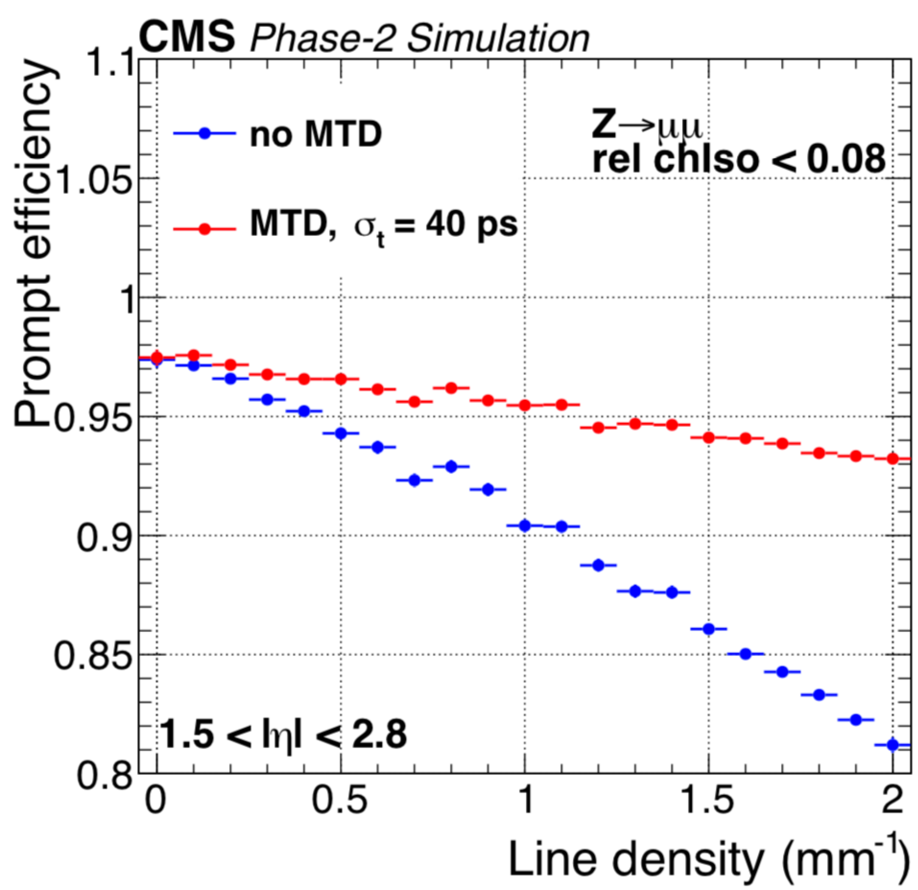


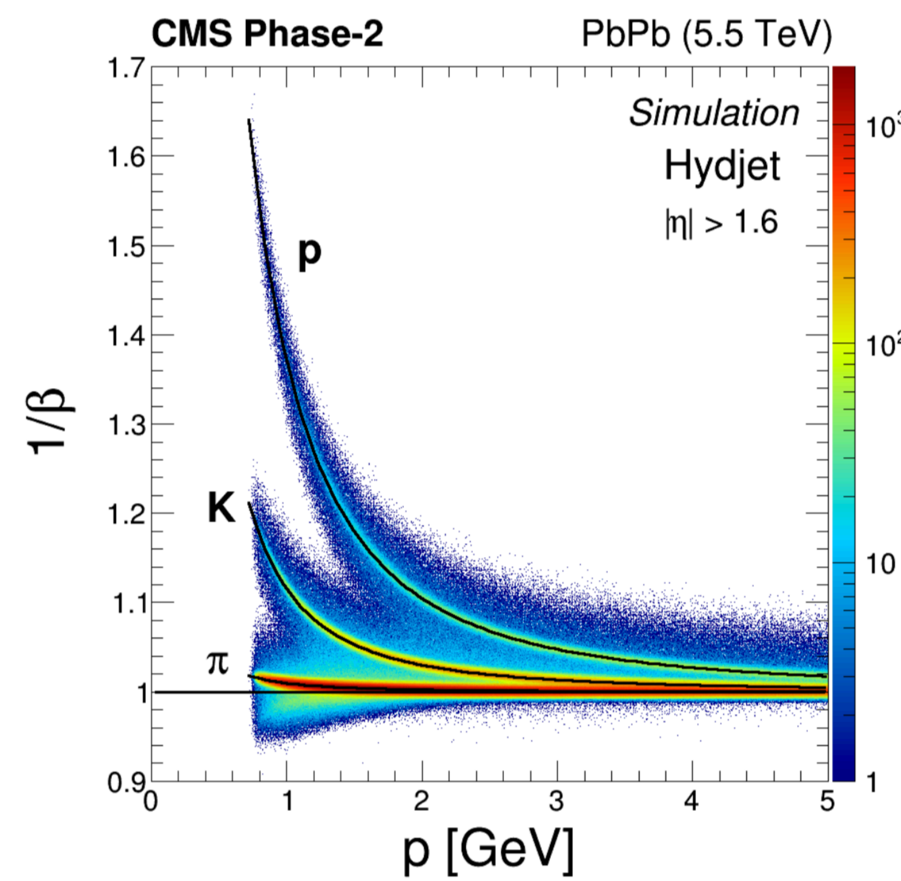


- Timing significantly reduces the “effective” vertex line density
  - 200 PU equivalent to current LHC PU (~50 PU)
- Recover performance in several observables

Improving Physics Object Performance

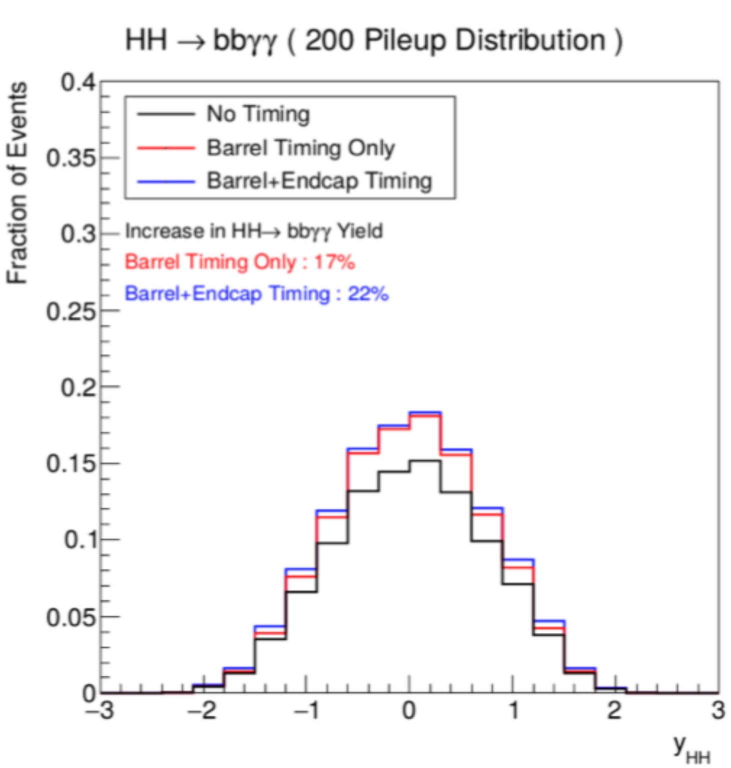
- Time information improves the quality of the reconstruction of physics objects:
  - Track time association allows to remove spurious pile-up tracks from reconstruction
  - Impact on fake jet reconstruction, lepton isolation and ID, b-tagging, pt_{miss} resolution
  - Also adding the possibility to perform Time-of-Flight particle identification (important in b-physics and heavy-ion collisions)





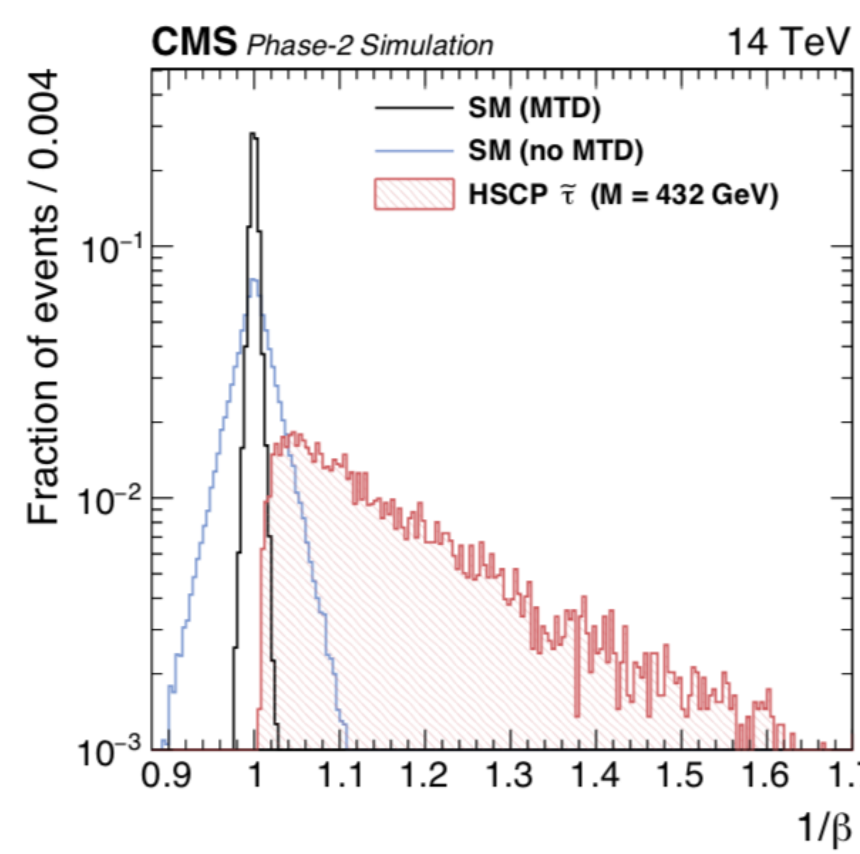
Impact on Physics Analysis

- Improved object reconstruction has an impact on the reach of physics analysis
  - Example: efficiency of HH→bb$\gamma\gamma$ improved more than 20% due to better RECO
  - Luminosity of HH channel is increased by ~20-26%
- Unique physics opportunities profiting from the time information
  - Example: Heavy Stable Charged Particles → Improved discrimination through the measurement of HSCP speed



HH production sensitivity (sigmas) at 3 ab^{-1}

Channel	No MTD	$\langle\sigma_t\rangle$ 35 ps	$\langle\sigma_t\rangle$ 50 ps
bbbb	0.89	0.95	0.94
bb$\tau\tau$	1.3	1.58	1.48
bb$\gamma\gamma$	1.7	1.85	1.83
bbWW	0.53	0.579	0.576
bbZZ	0.38	0.423	0.418
Combined	**2.4**	**2.71**	**2.63**
Luminosity gain	-	**+26%**	**+20%**



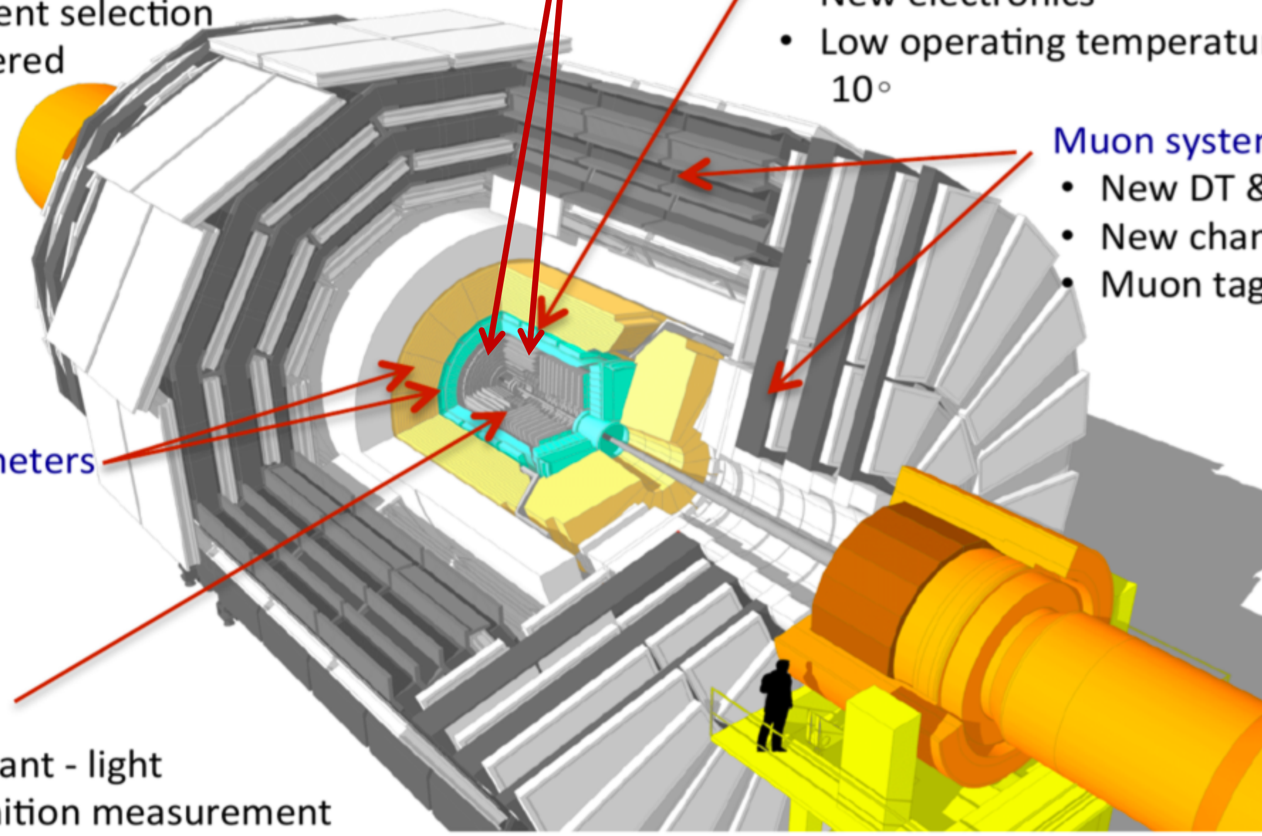
Summary of CMS Upgrade for HL-LHC

MIP Timing Detector
- Barrel and Endcap timing layer
- Precision timing
- $|\eta| < 3$

Trigger/HLT/DAQ
- Track information in hardware event selection
- 750 kHz hardware event selection
- 7.5 kHz events registered

Barrel EM calorimeter
- New electronics
- Low operating temperature ≈ 10∘

Muon systems
- New DT & CSC electronics
- New chambers $1.6 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$



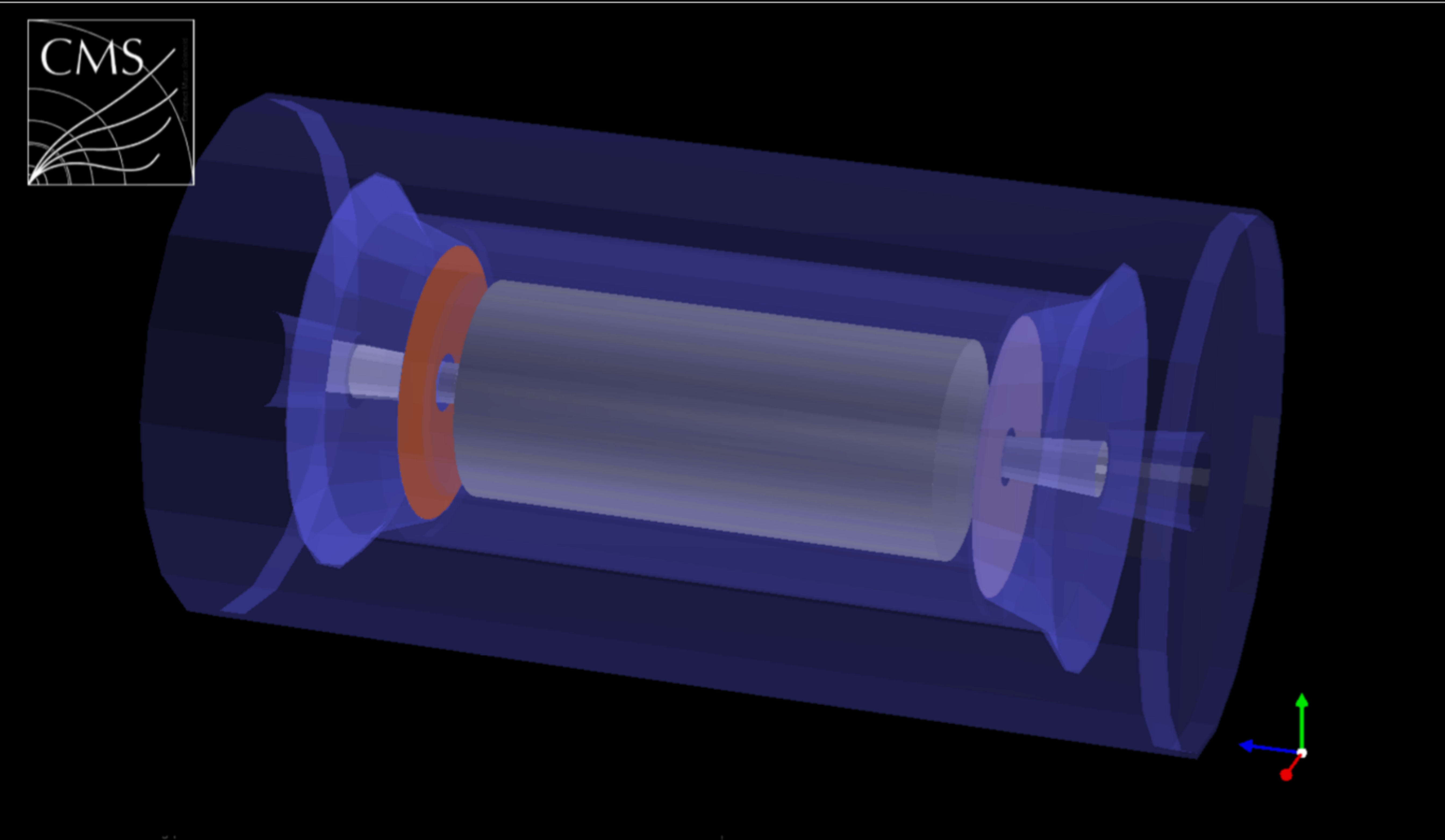
New Endcap Calorimeters
- Rad. Tolerant
- 5D measurement

New Tracker
- Rad. Tolerant - light
- High Definition measurement
- 40 MHz selective readout for hardware trigger
- Extended Pixel coverage to $\eta \approx 3.8$

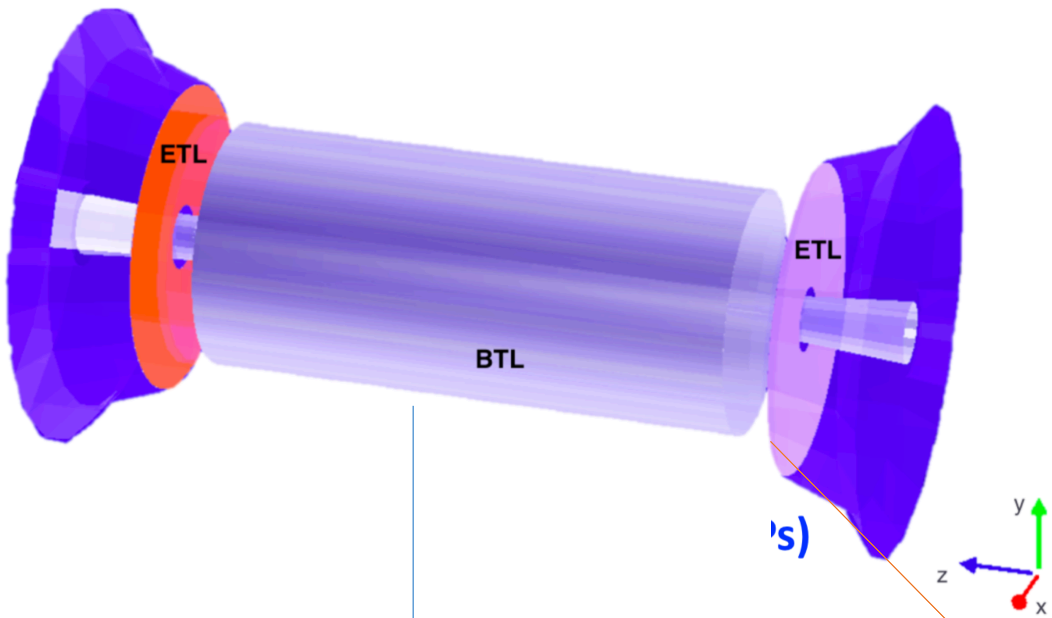
Beam radiation and luminosity
Common systems and infrastructure

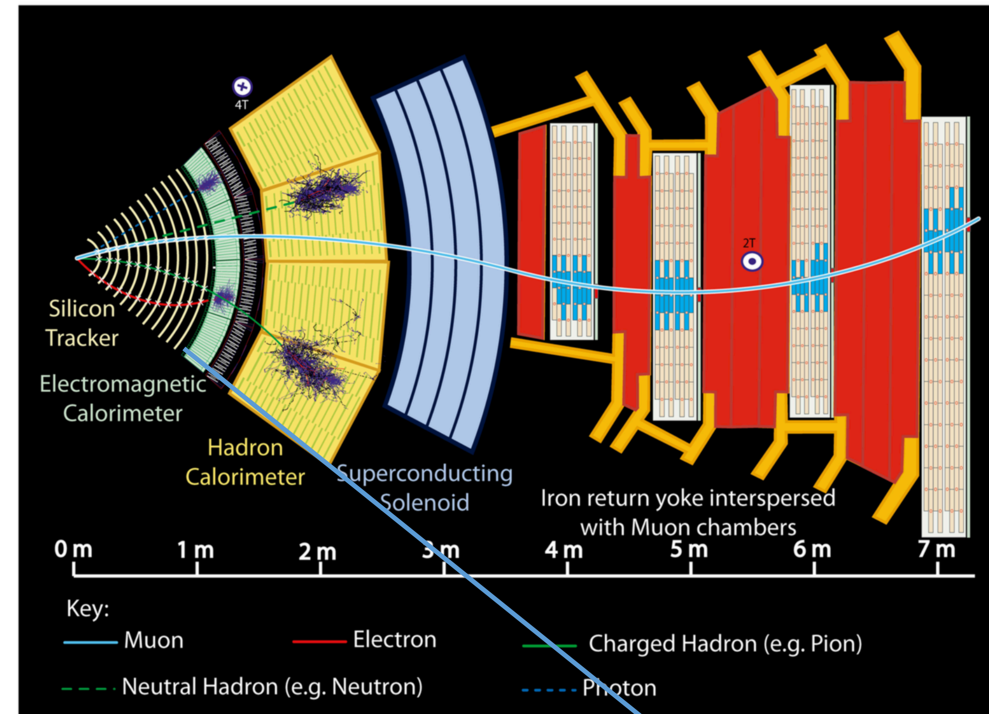
→ Upgraded calorimeters can provide precision timing of electromagnetic showers with a precision of 30-50 ps above the p_T of a few GeV

MIP Timing Detector (MTD)



MIP Timing Detector



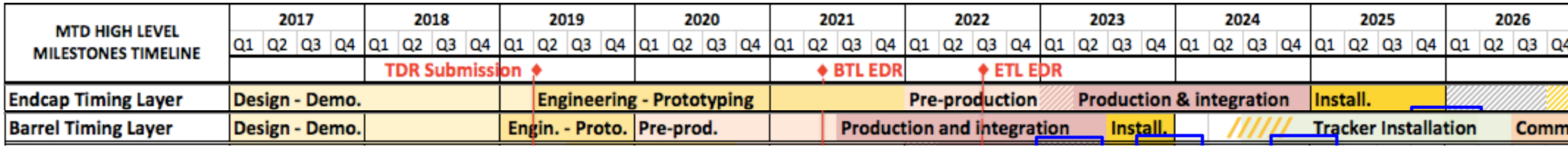


MTD

Barrel Timing Layer (BTL)
LYSO bars + SiPM readout:
TK/Ecal interface: $|\eta| < 1.45$
Inner radius: 1148 mm (40 mm thickness)
Length: $\pm 2.6\ m$ along z
Surface: $\sim 38\ m^2$, 332k channels
Fluence at $4\ ab^{-1}$: $2\times10^{14}\ {}^{n_{eq}}/_{cm^2}$

Endcap Timing Layer (ETL)
Si with internal gain (LGAD):
On the CE nose: $1.6 < |\eta| < 3$
Radius: $315 < R < 1200\ mm$
Position in z: $\pm 3.0\ m$ along z (45 mm thick)
Surface: $\sim 14\ m^2$, ~8.5M channels
Fluence at $4\ ab^{-1}$: up to $2\times10^{15}\ {}^{n_{eq}}/_{cm^2}$

MTD Timeline



- The project is approved!
    - TDR is public:

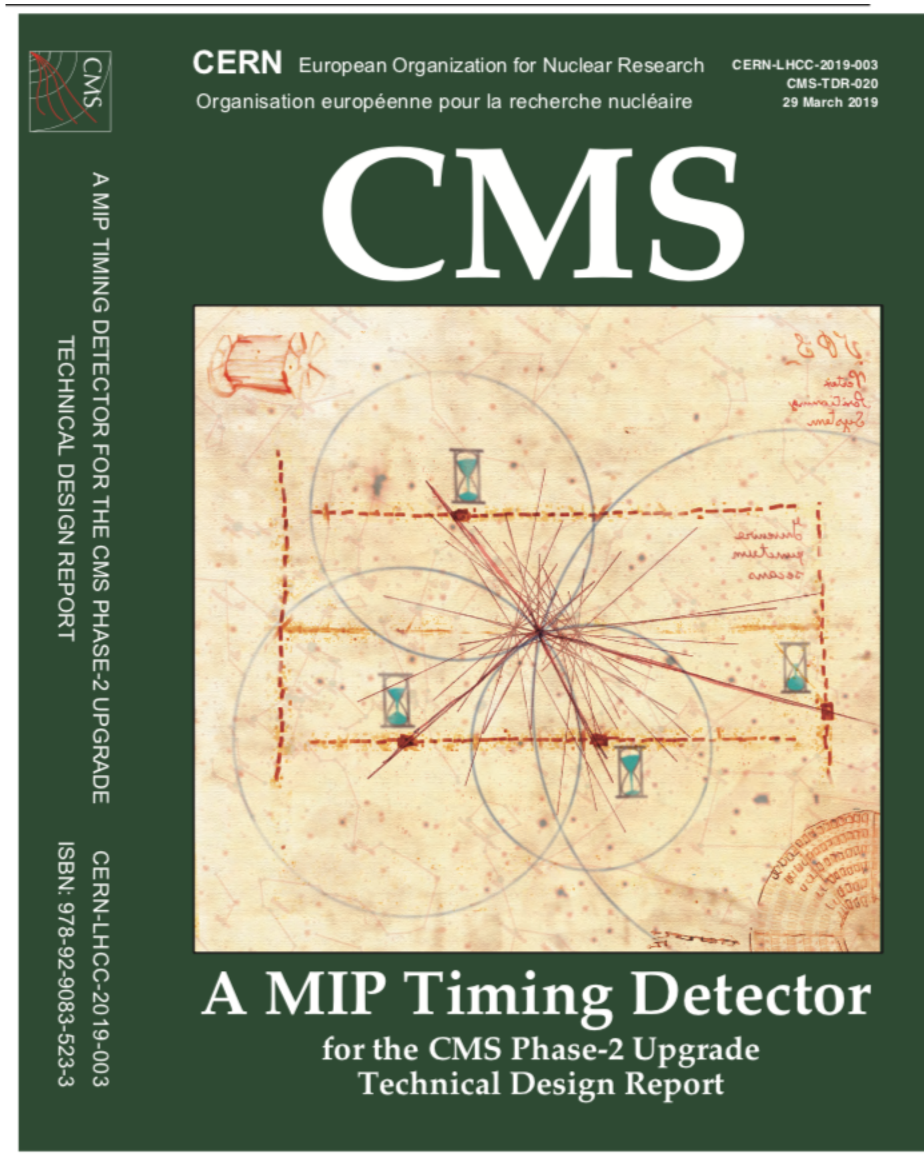
https://cds.cern.ch/record/2667167/files/CMS-TDR-020.pdf

- Production:
    - BTL in 2022-2023
    - ETL in 2023-2024

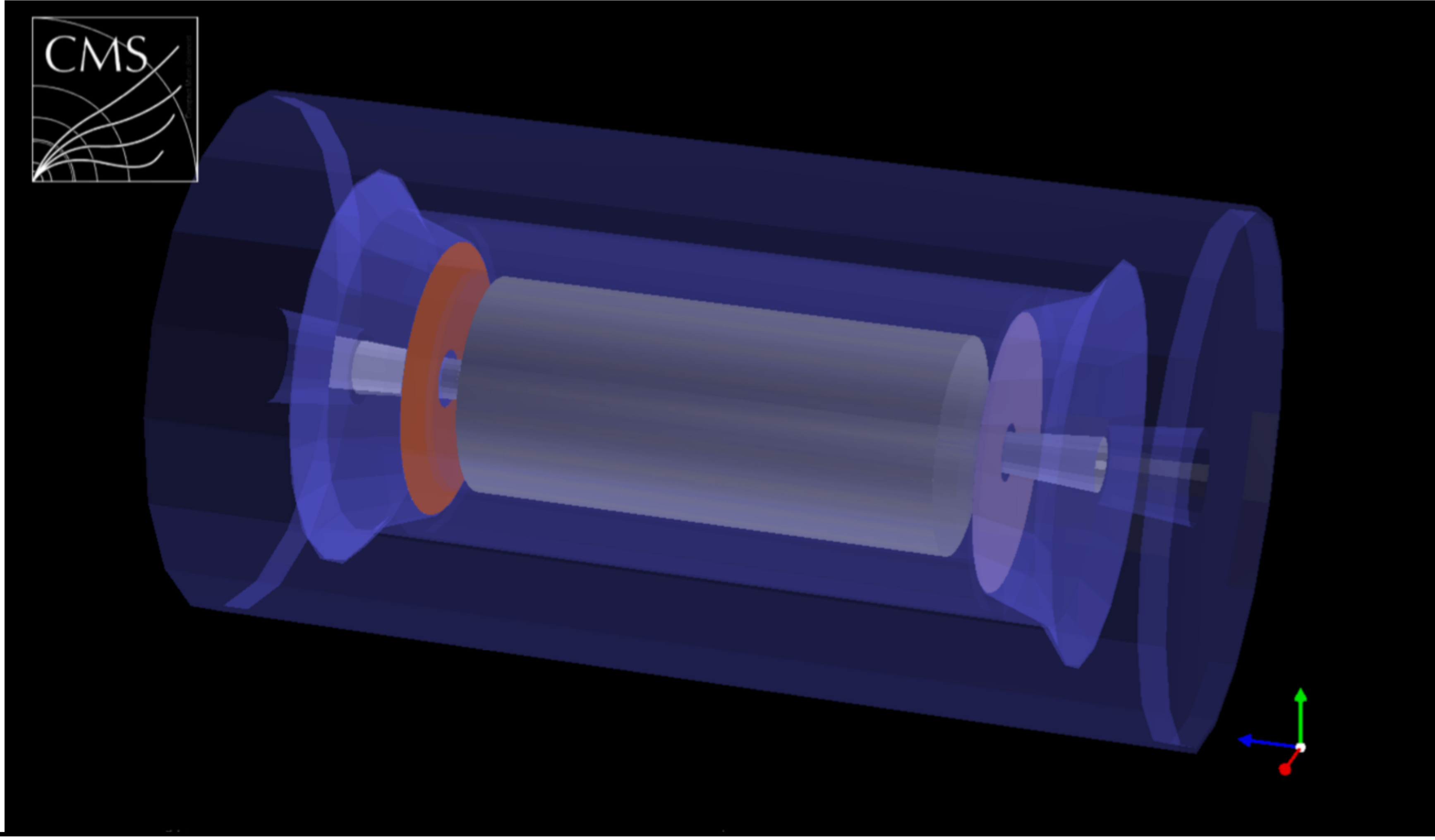
- Installation:
    - BTL in 2023
    - ETL in 2025

- 2026 commissioning

→ BTL has a very tight schedule: last detector to be approved, first to be installed!

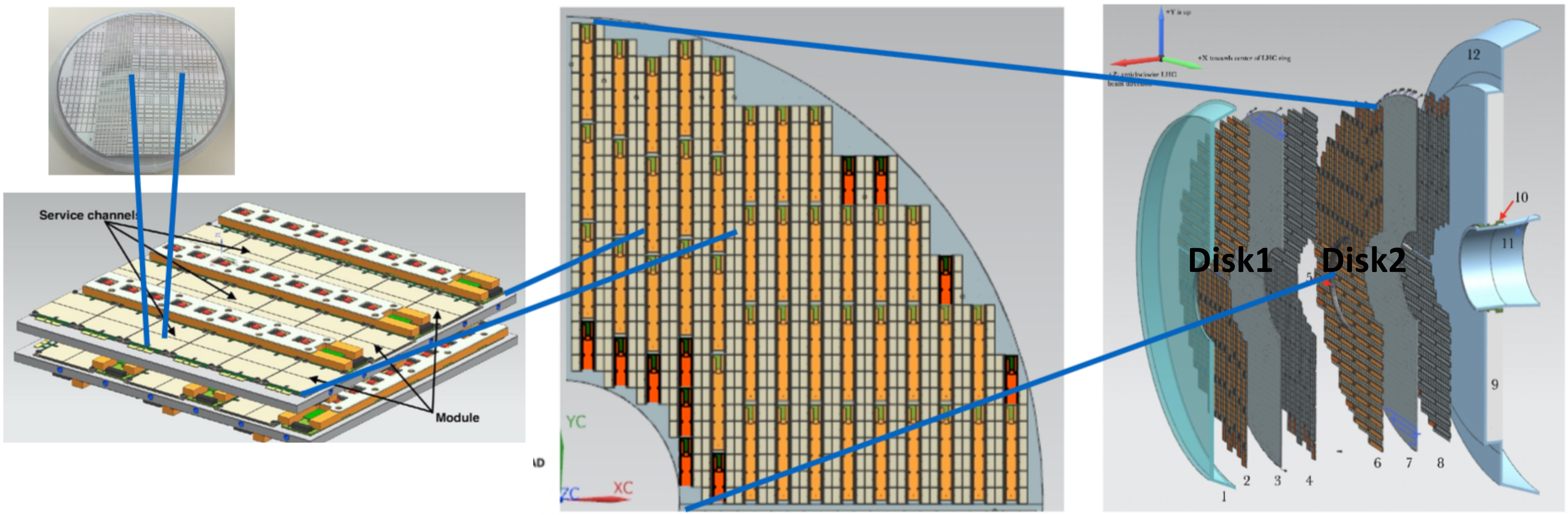


MTD



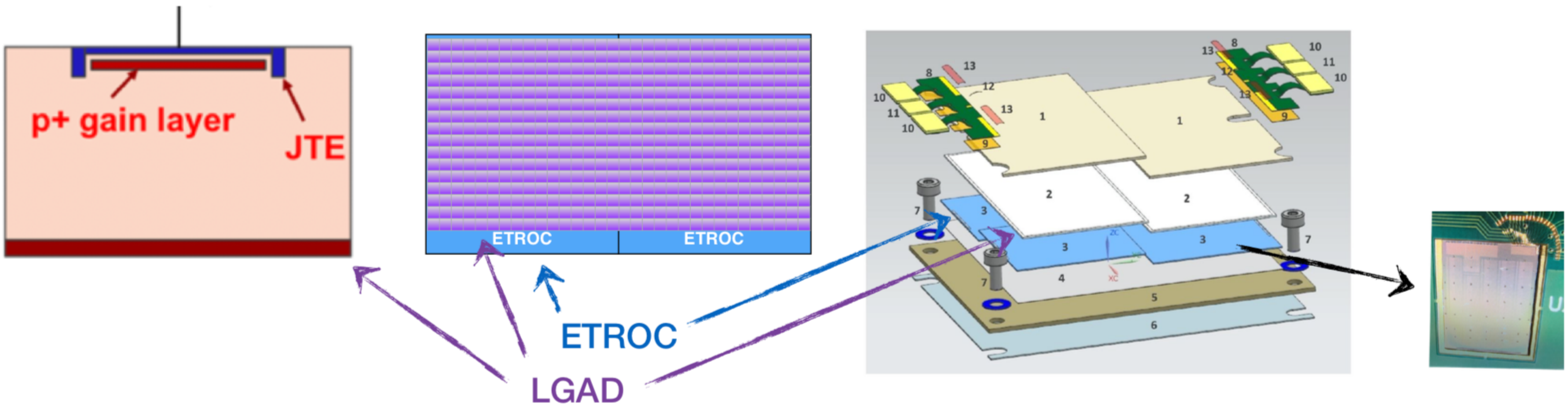
Endcap Timing Layer (ETL)

Endcap Timing Layer Layout

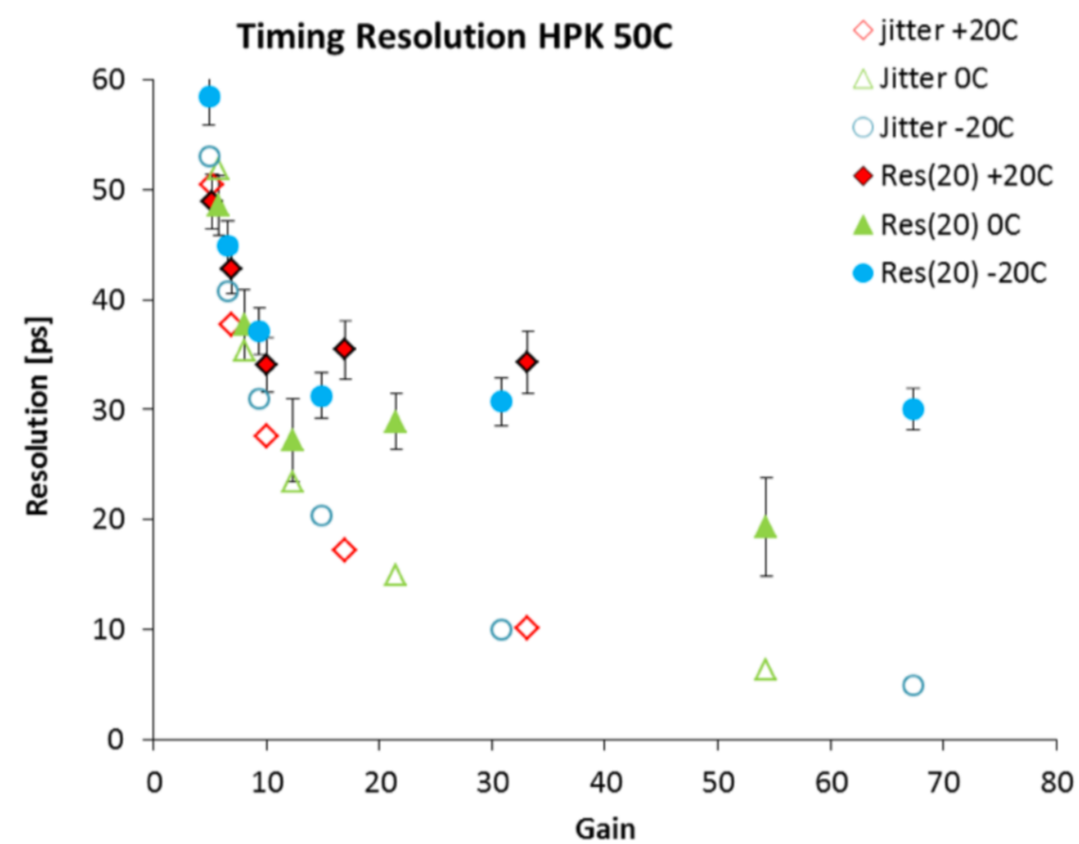


- End-cap Timing Layer(ETL): two disks system
- Sensor modules on two sides of each support disk.
- Low-Gain Avalanche Detector (LGAD) sensors
  - Sensors are organized in array of 16x32 with a size of 21.2×42 mm^2 (1.3×1.3 mm^2 pixels)
- Readout electronics ASIC: ETROC (ETL ReadOut Chip)
  - ETROC bump-bonded to LGAD, To handle 16x16 pixels, Each 1.3 mm x 1.3 mm
  - Each channel consists of a preamplifier, a discriminator, a TDC used to digitize the TOA (time of arrival) and TOT (time over threshold) measurements

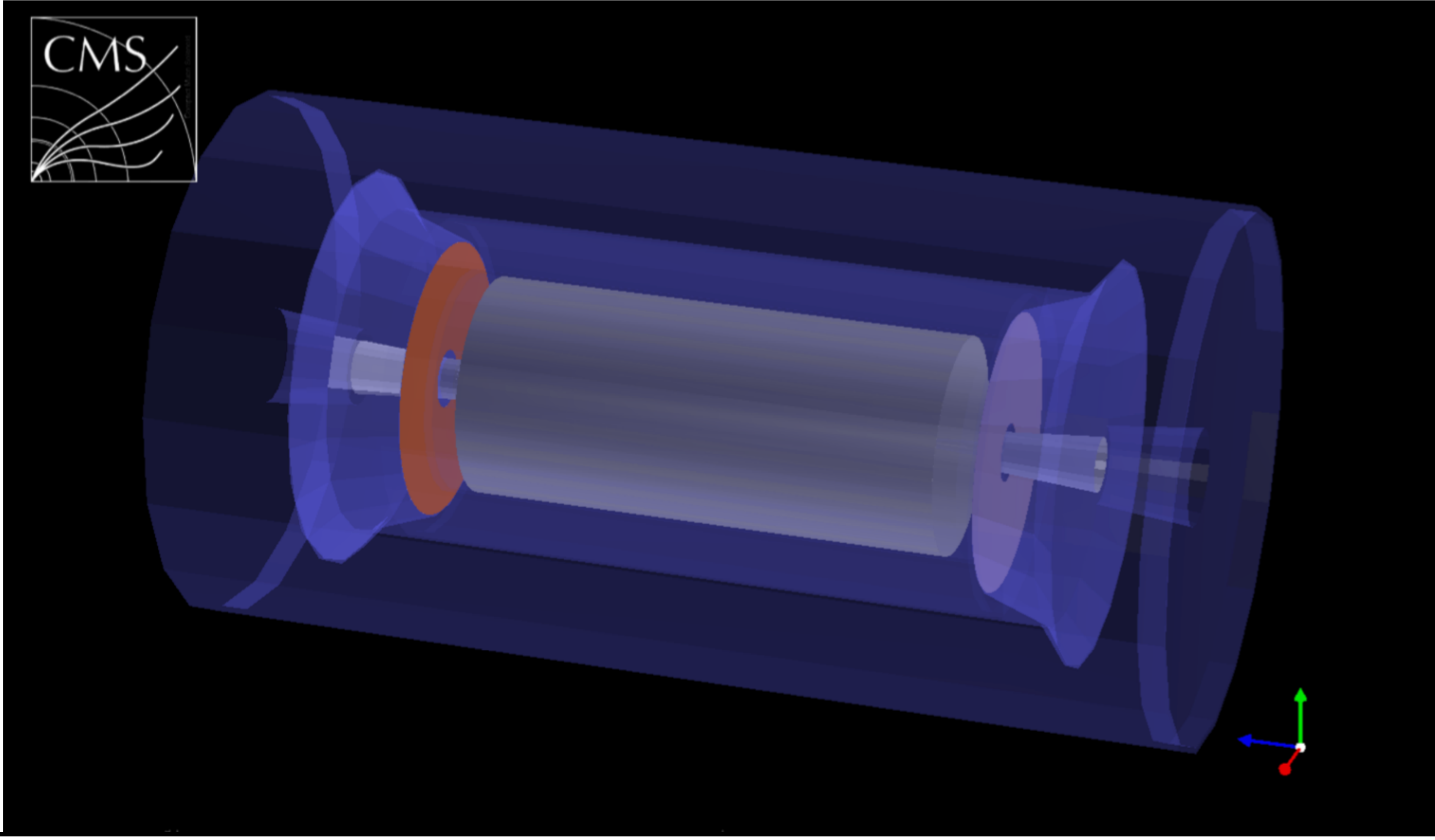
Endcap Timing Layer: Module design



- The **U**ltra **F**ast **S**ilicon Detectors (UFSD) can be achieve with an additional gain layer (LGAD) are optimized for timing
  - Common CMS and ATLAS development
  - Moderate internal gain (10-20)
  - Large signals, but low noise
  - Very high radiation tolerance, sufficient for the endcap fluence (2×10^{15} neq/cm^2)
  - Very good timing response:35 ps resolution at the beginning of lifetime, 45 ps resolution by the end of lifetime

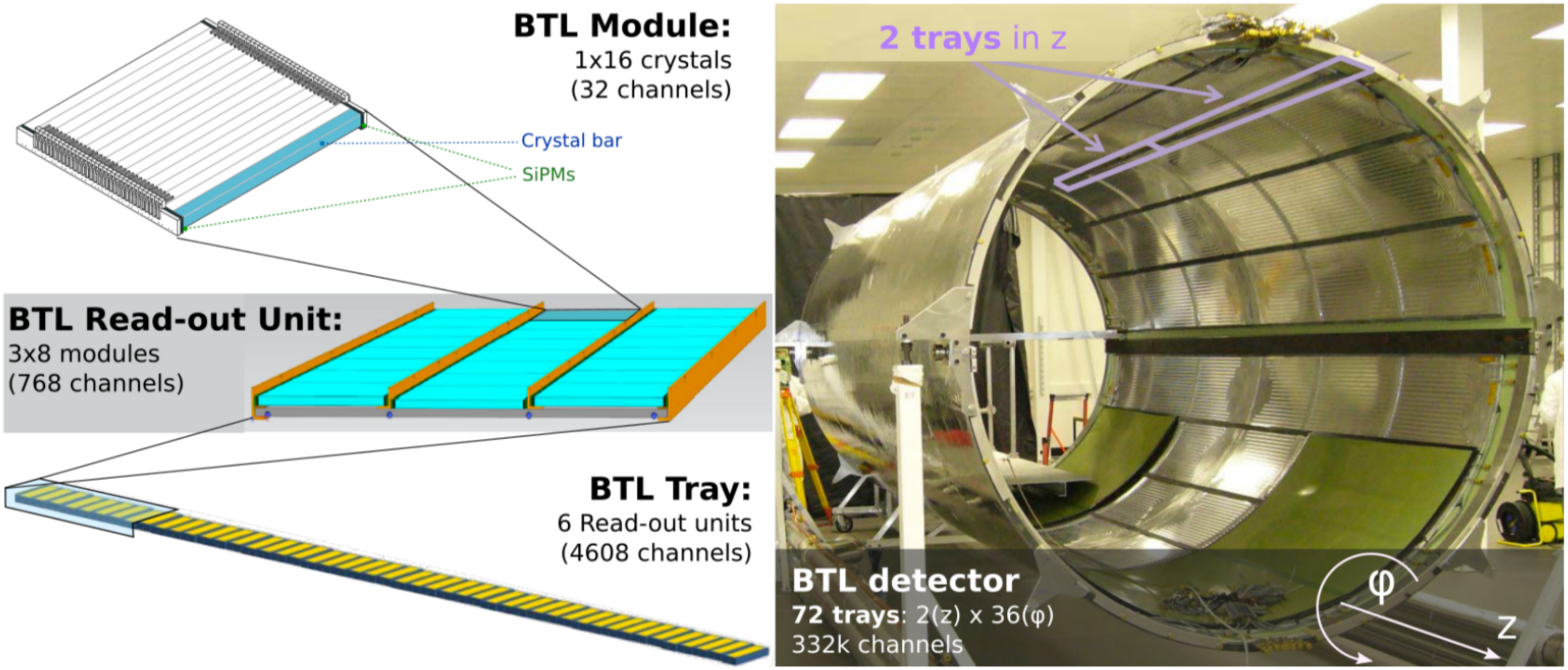


MTD



Barrel Timing Layer (BTL)

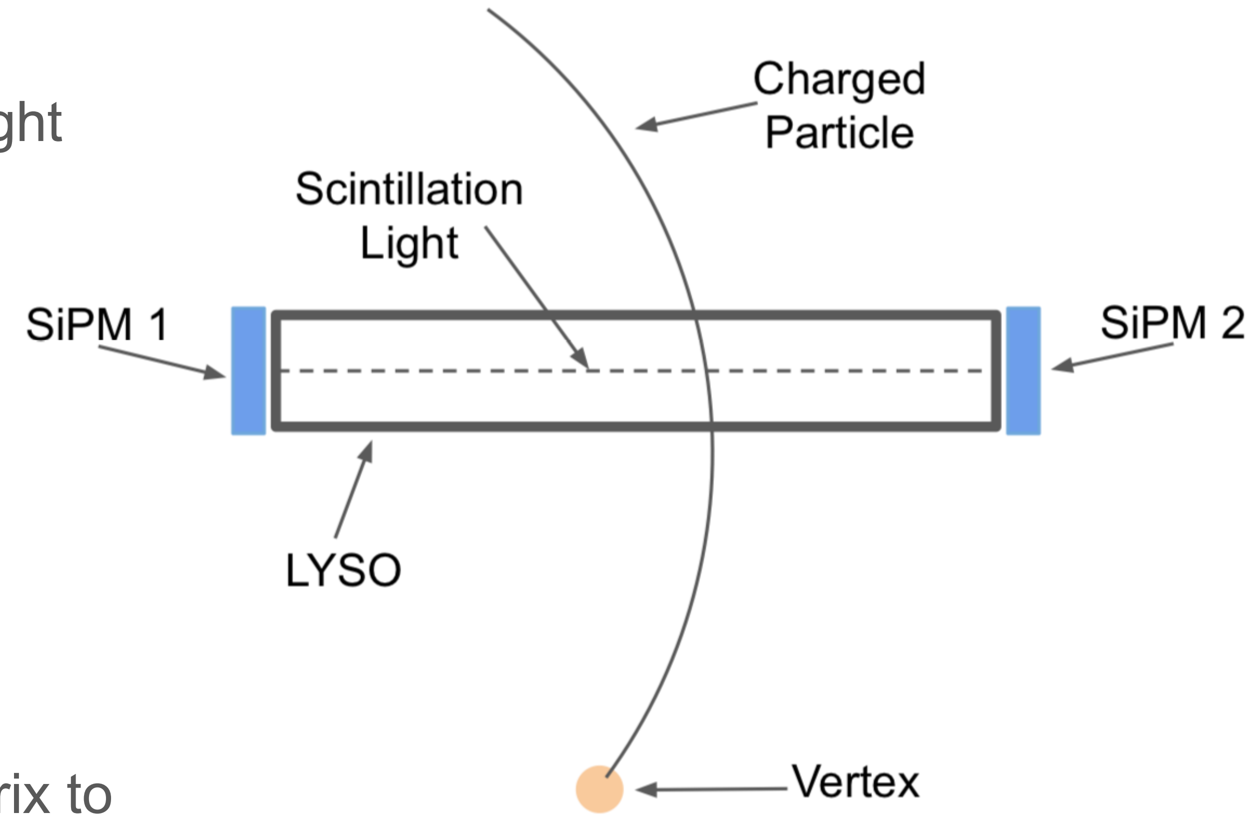
Layout of the Barrel Timing Layer

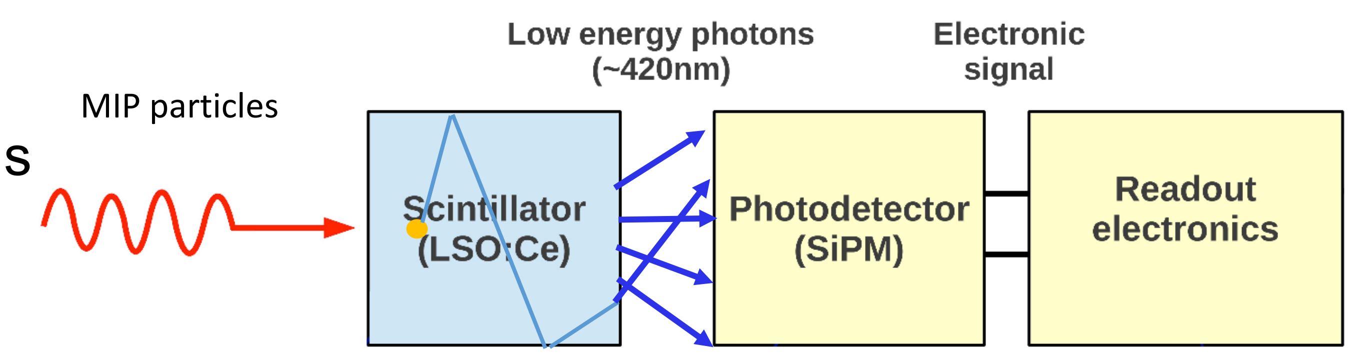


- Detector mounted on the inner surface of the Tracker Support Tube (TST)
- Single layer, 40 mm thick, segmented into 72 trays
- Each tray consists of 6 Readout Units with 24 modules each
- Sensor module : 16 LYSO bars, 2 SiPM arrays

BTL Sensor Design

- 3x3x57 mm^3 LYSO:Ce crystal bars with two 3x3 mm^2 SiPMs glued at each end
  - Passing charged particles emit scintillation light collected by each SiPM
- Two measurements per particle
  - Eliminates impact point dependence
  - √2 improvement in time resolution
- BTL will use crystal matrices of 16 bars
  - Thin layers of wrapping between bars in matrix to minimize light sharing
- Extensive testbeam and test-bench campaign to characterize performance of various wrappings/SiPMs/glues timing extraction methods



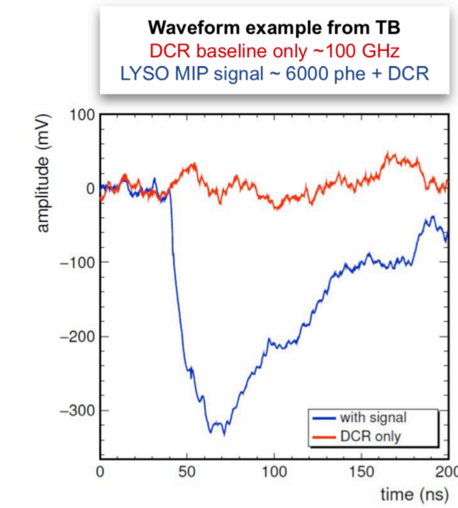


Time Resolution Drivers in BTL

$$\sigma_t^{BTL} = \sigma_t^{clock} \oplus \sigma_t^{digi} \oplus \sigma_t^{ele} \boxed{\oplus \sigma_t^{phot} \oplus \sigma_t^{DCR}}$$

contribution from sensors

$$\left\{ \begin{array}{l} \sigma_t^{photo} \propto \frac{1}{\sqrt{S}} \\ \sigma_t^{DCR} \propto \frac{N}{S} \end{array} \right\}$$



- The time resolution in BTL sensors is driven by the photon signal (**S**) and the noise term (**N**) due to radiation induced dark counts in the SiPM

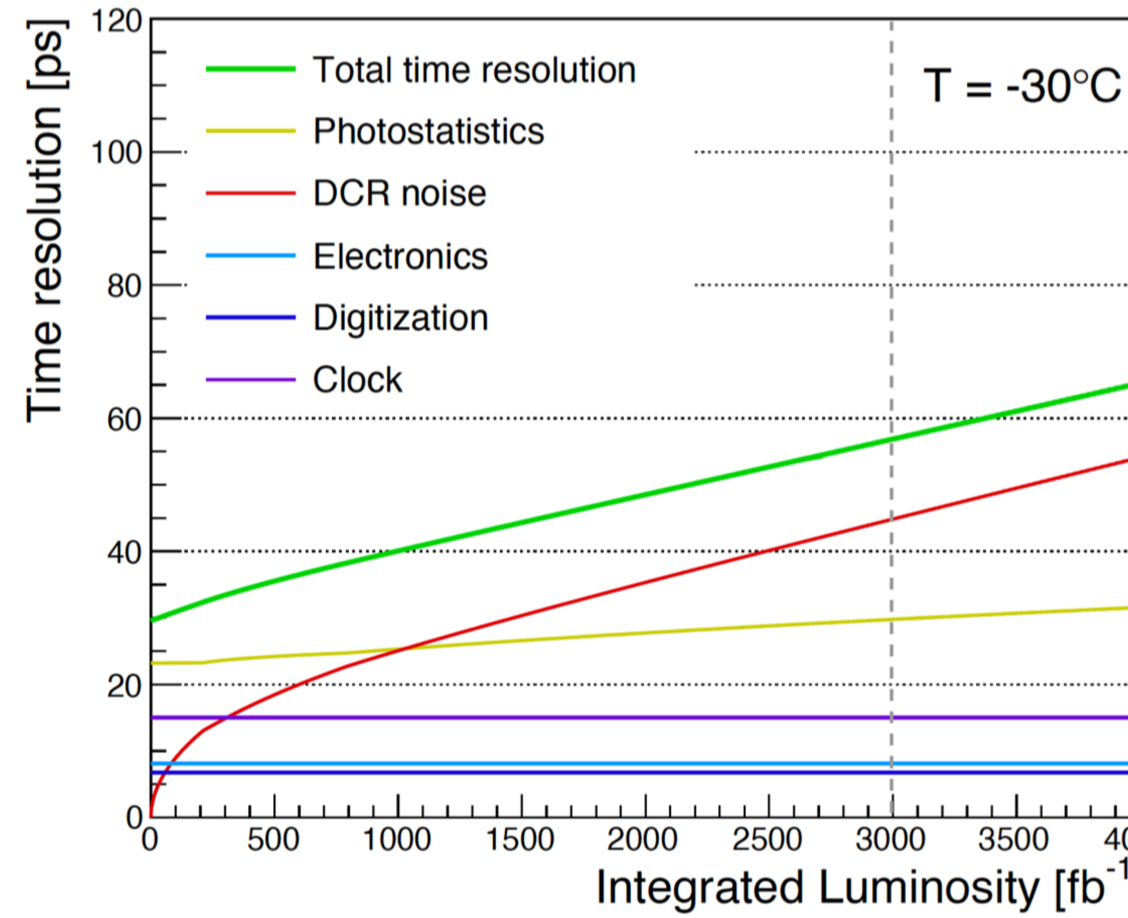
crystal | Crystal +SiPM | SiPM

$$S = \boxed{\frac{E_{dep} \cdot LY}{\tau_D}} \cdot \boxed{LCE} \cdot \boxed{PDE}$$

SiPM

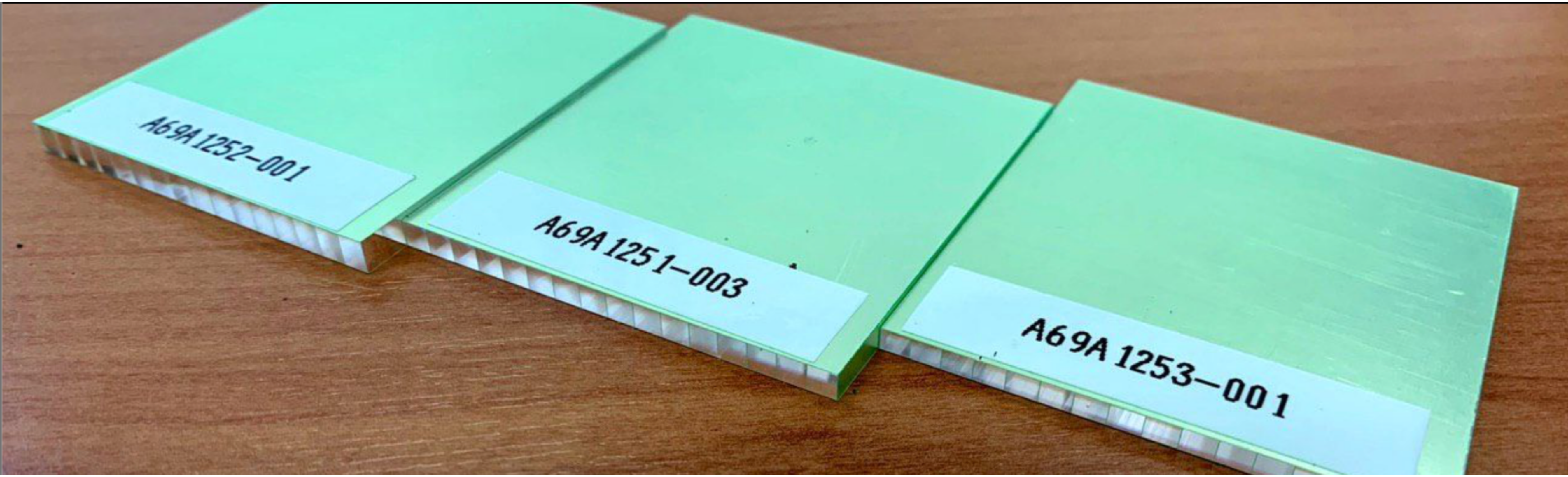
$$N = \boxed{\sqrt{DCR}}$$

Edep:	energy deposit by MIP
LY:	crystal light yield
τ_D :	scintillation decay time
LCE:	light collection efficiency
PDE:	photon detection efficie
DCR:	rate of dark counts



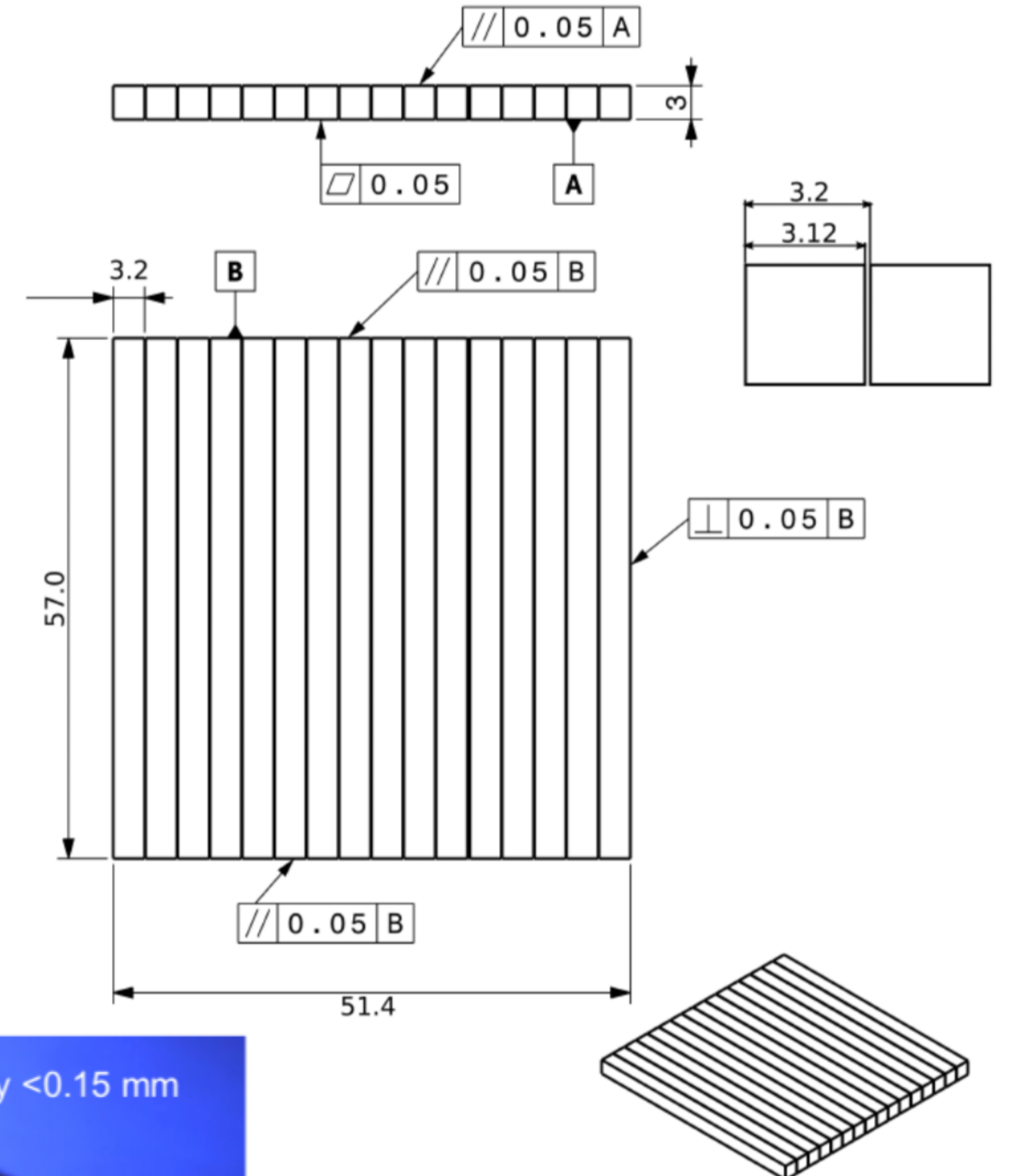
→ Red curve assumes an ideal DCR noise cancellation. The DCR cancellation method will be discussed later

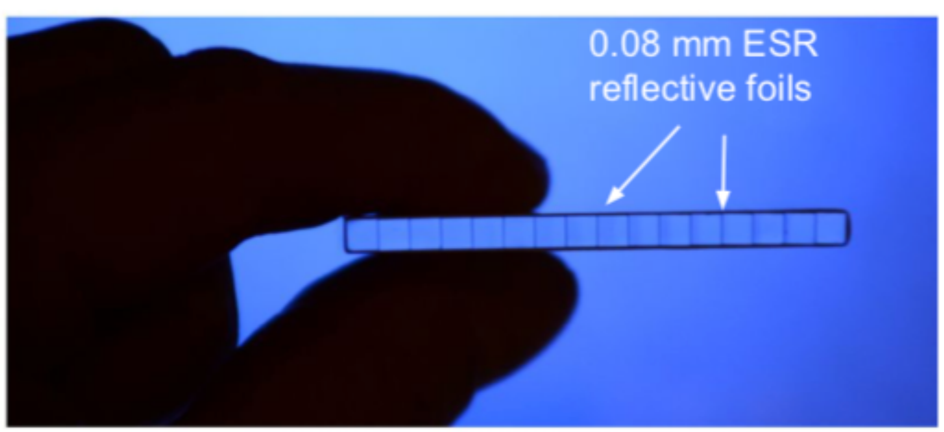
LYSO:Ce crystal arrays

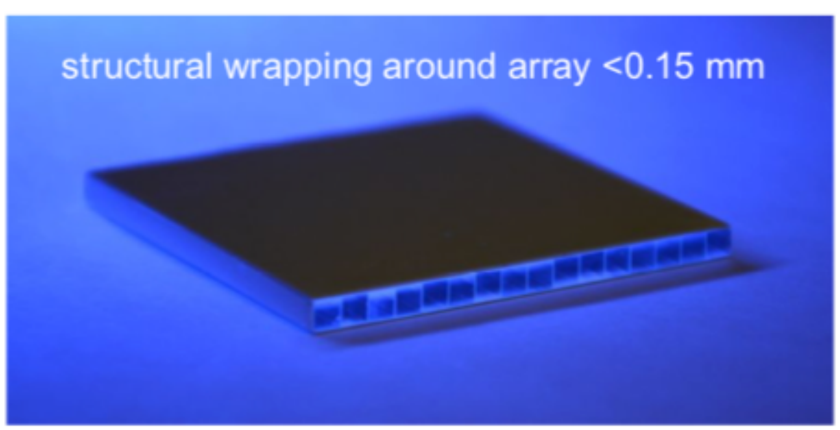


LYSO Crystal Arrays Specification

- **Lutetium-yttrium orthosilicate crystals activated with cerium (LYSO:Ce) as scintillator**
    - Excellent radiation tolerance
    - Dense (>7.1 g/cm3): a MIP deposits ~4.2 MeV including impact angle (0.86 MeV/mm)
    - Bright: light yield (LY) ~40k photons/MeV.
    - Fast rise time 100 ps and decay time ~40 ns

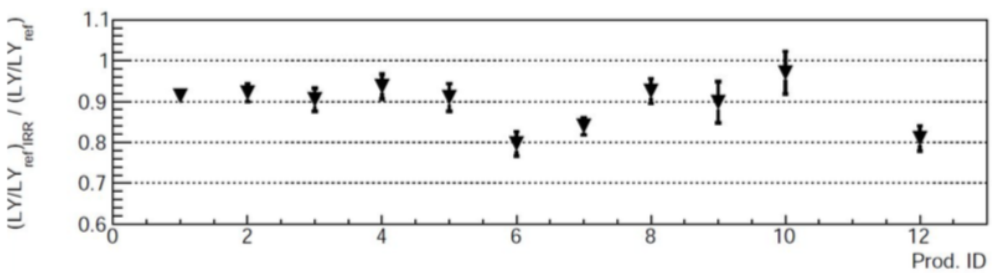


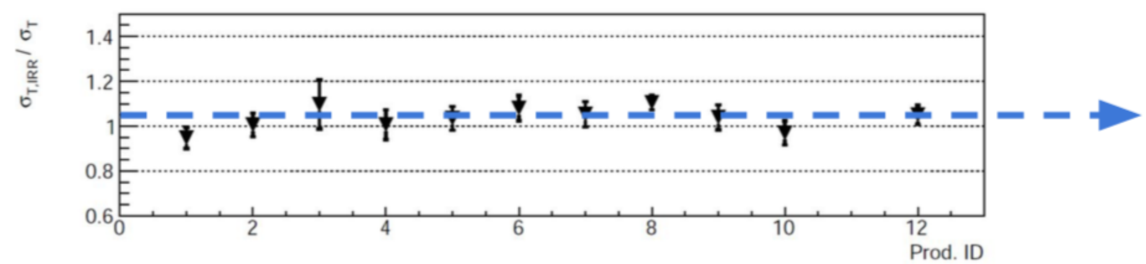




Crystal Array Characterization

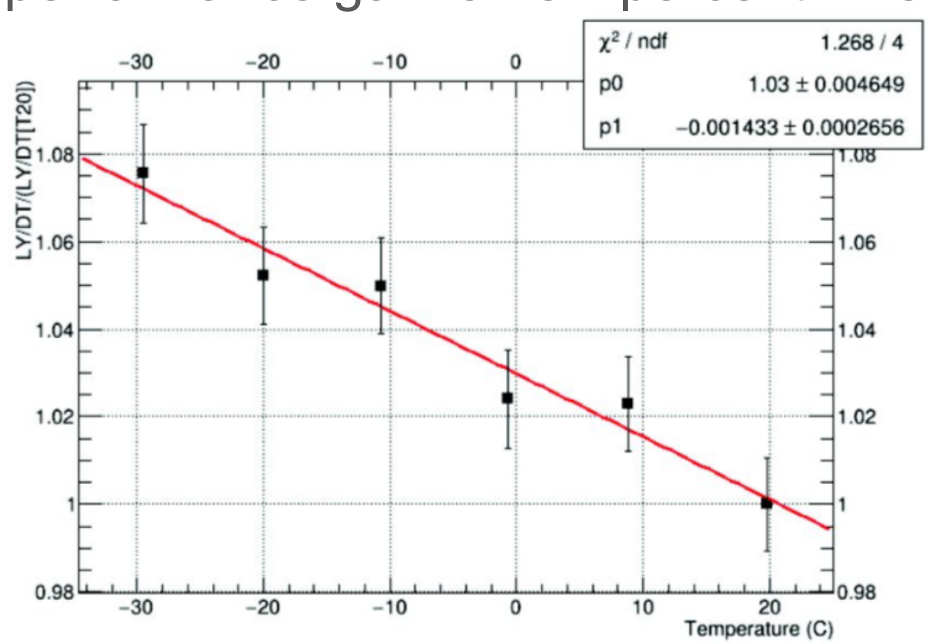
- **Irradiation tests**
  - Average light output and time resolution of 16 crystal bars within an array before and after irradiation to full ionizing dose (including 1.5x safety margin)

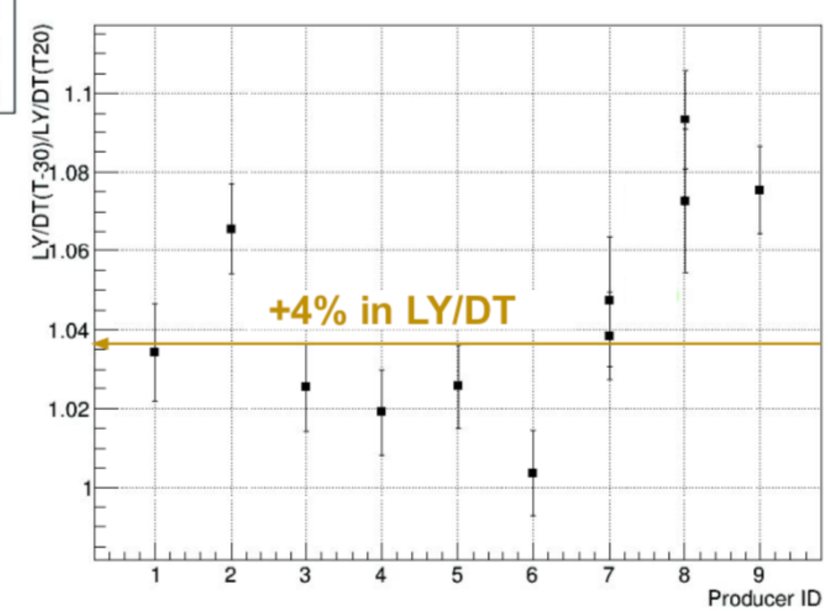




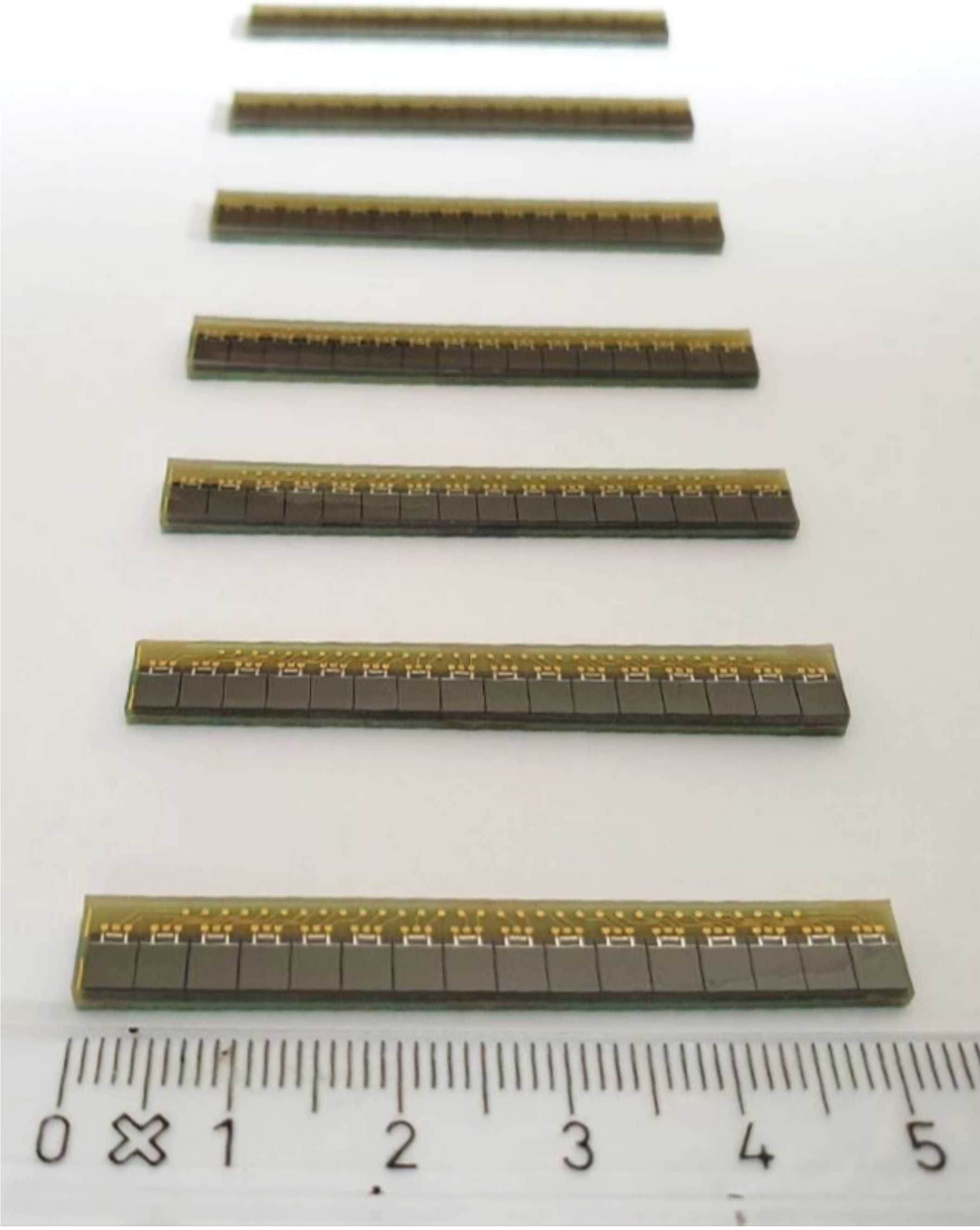
average radiation impact on time resolution ~ 5%

- **Characterization of crystals at -30°C**
  - LYSO:Ce scintillation behaviour vs temperature already studied in literature: time resolution unchanged (decrease of light yield compensated by faster decay time)
  - First results show overall performance gain of few percent when decreasing temperature from 20°C to -30°C





Silicon Photomultiplier (SiPM) arrays



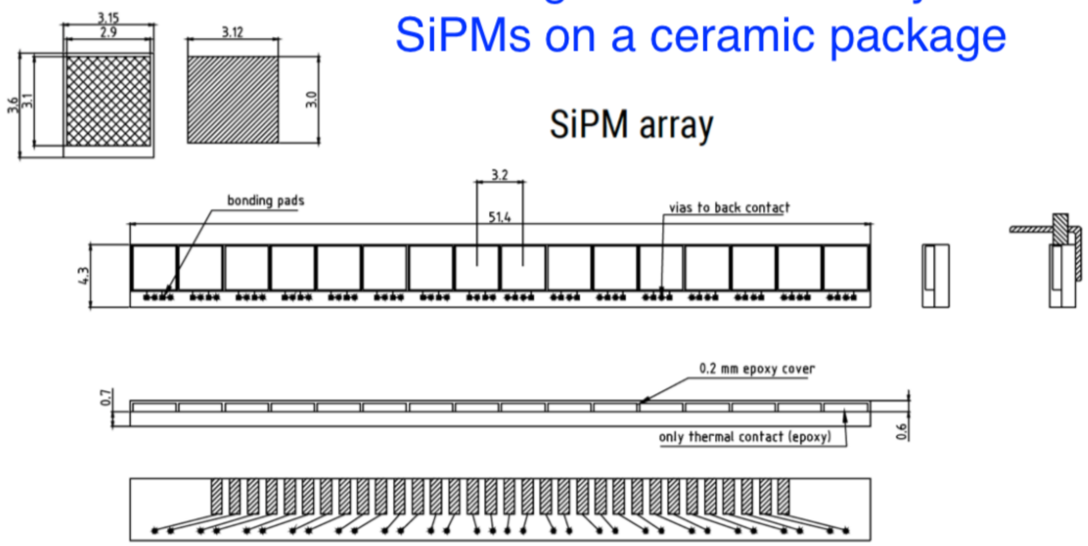
SiPM Arrays Specification

- **Silicon Photomultipliers as photo sensors**
  - Compact, fast (single photon resolution of 100 ps), insensitive to magnetic fields
  - Good radiation tolerance
  - Optimal SiPM cell size: 15 µm, balance between radiation tolerance and photon detection efficiency
  - Good (20-40%) Photon Detection Efficiency (PDE) at 420 nm
  - Gain: 1.5 − 4×10^5

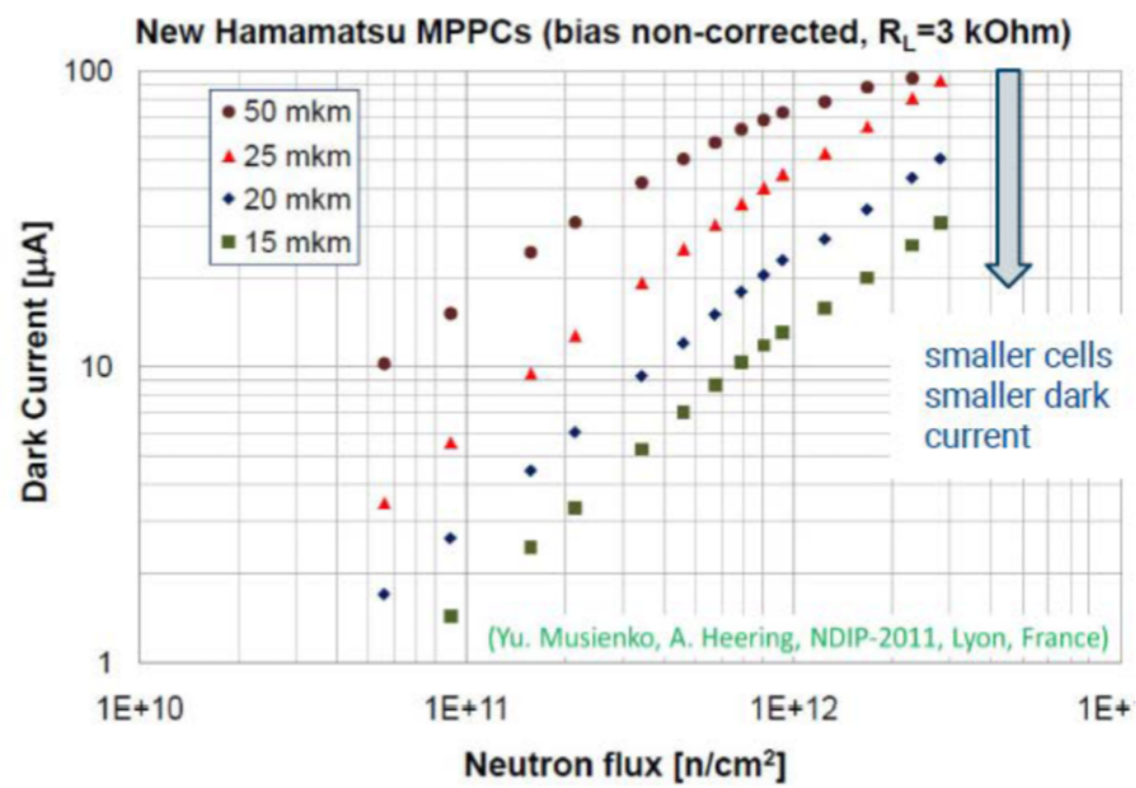
- **Drawback**: Dark current noise due to radiation damage

SiPM LYSO

Drawings of a linear array of 16 SiPMs on a ceramic package



Hamamatsu MPPC



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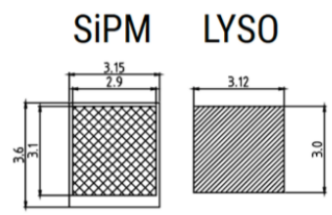

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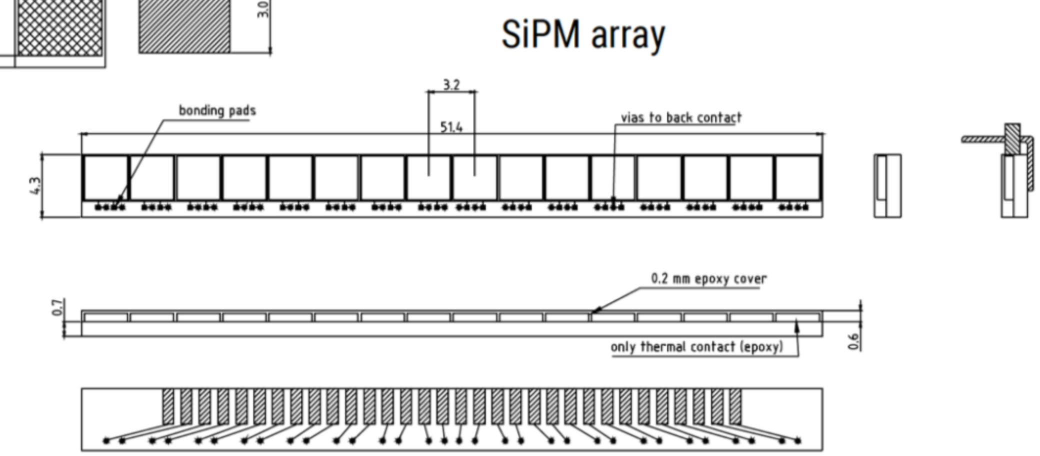


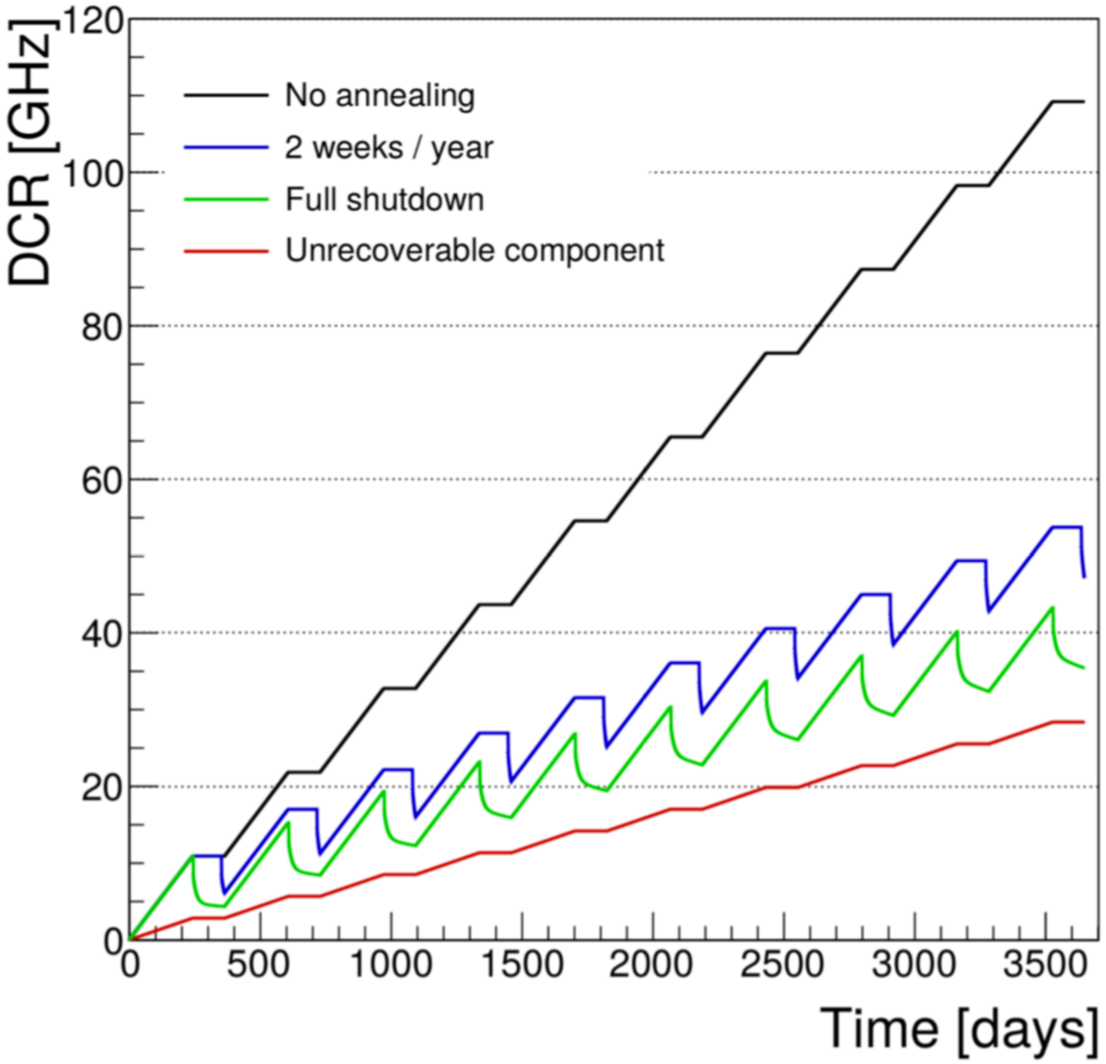
HDR2 SiPM parameters along BTL life

Integrated luminosity (fb-1)	Number of p.e.	SiPM gain	DCR (GHz)
0	9500	3.8 × 10^5	0
500	9000	2.9 × 10^5	20
1000	8000	2.5 × 10^5	30
2000	7000	1.9 × 10^5	45
3000	6000	1.5 × 10^5	55

End of life condition

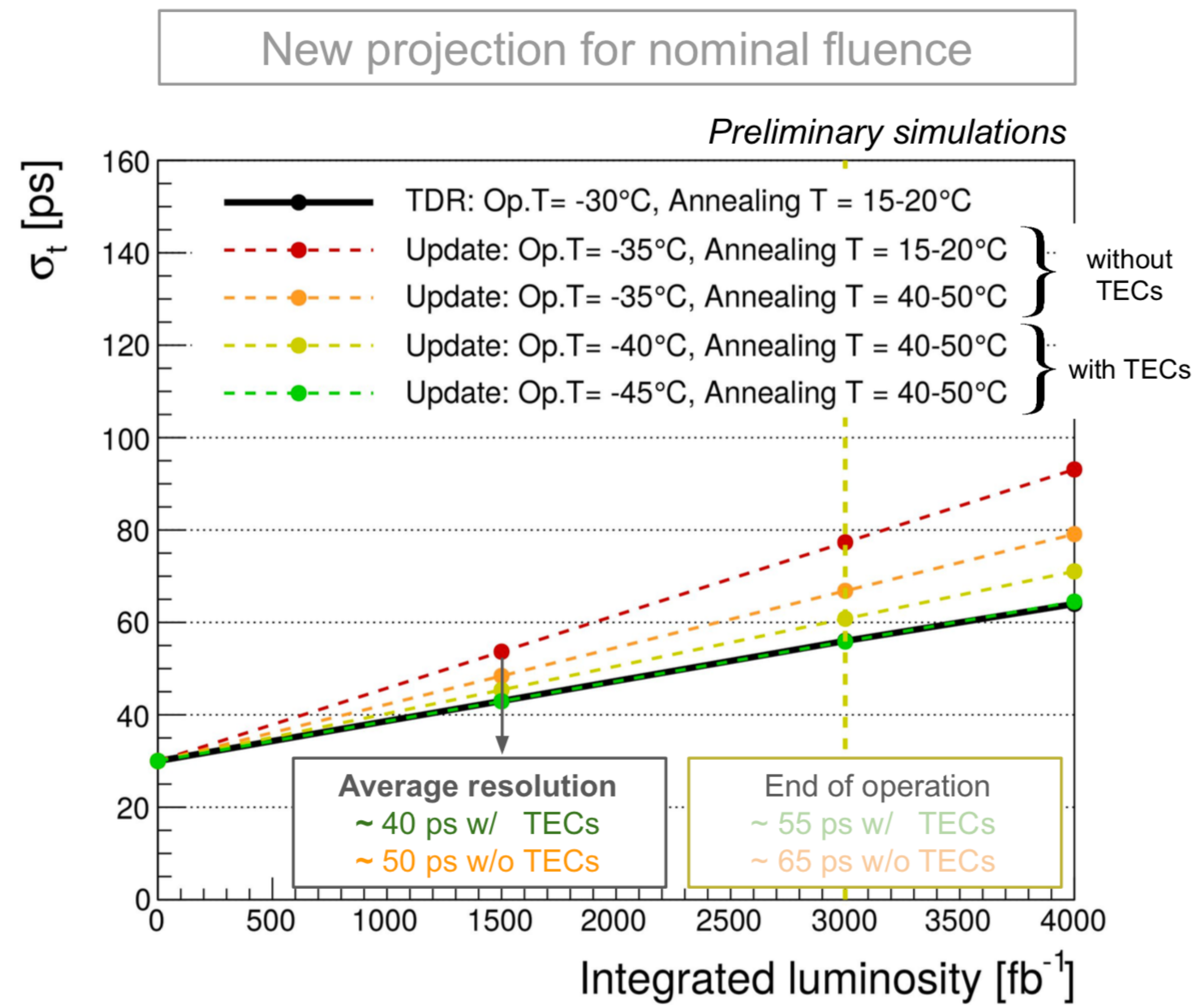
Mitigating SiPM Radiation Damage

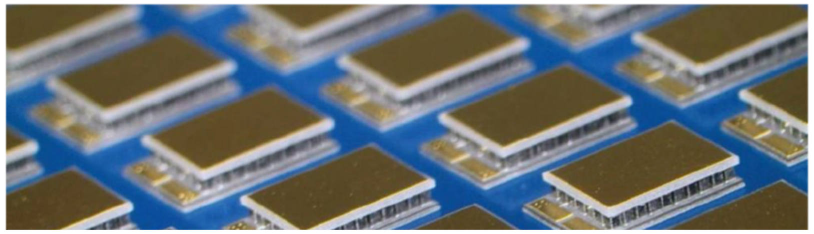
- DCR noise mitigation:
  - Lowering temperature of SiPM operation
    - CO2 cooling to -35 °C (DCR decreases by a factor 1.8 every 10 °C)
    - Additional cooling with ThermoElectric Coolers (TECs)
  - Annealing of SiPMs at 15-20°C during shutdowns
    - Reducing DCR
    - DCR decreases faster when lowering temperature (1.8→ 2.1x / 10 °C)
  - Dedicated noise cancelation circuit in front-end ASIC

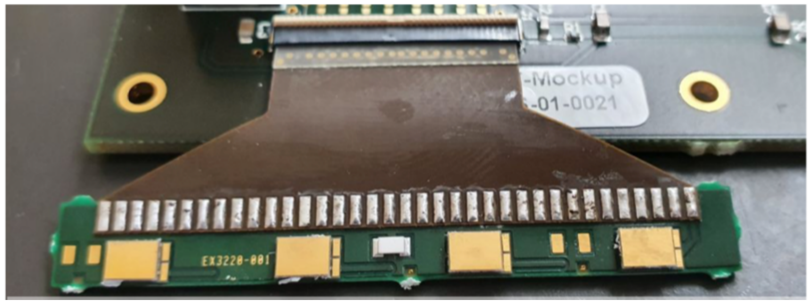


Thermoelectric Cooler Option

- Measurements after irradiation to full fluence (2×10^{14} neq/cm^2) showed larger DCR than extrapolations from 2×10^{12} used in the TDR.
- TECs can provide additional handle in lowering BTL operating temperature during operation and to enable better thermal annealing during shutdowns
  - Devices successfully tested under irradiation to full fluence and thermal cycles
- TECs (though several details need to be finalised) can provide:
  - Additional cooling around ΔT= -10°C,
  - Annealing up to +40-50°C, possibility for annealing during beam operations
- TECs allows to almost recover TDR expectations





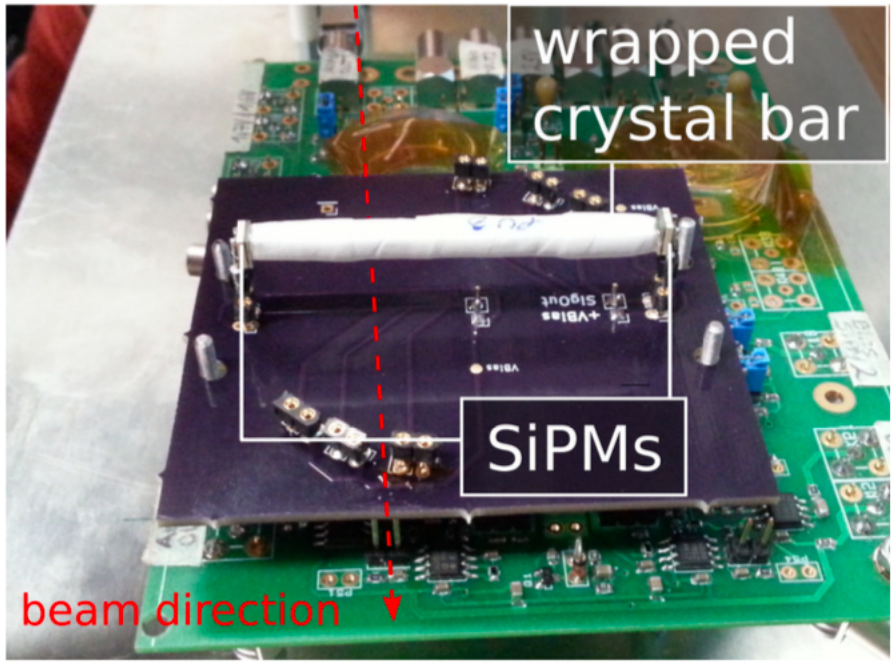


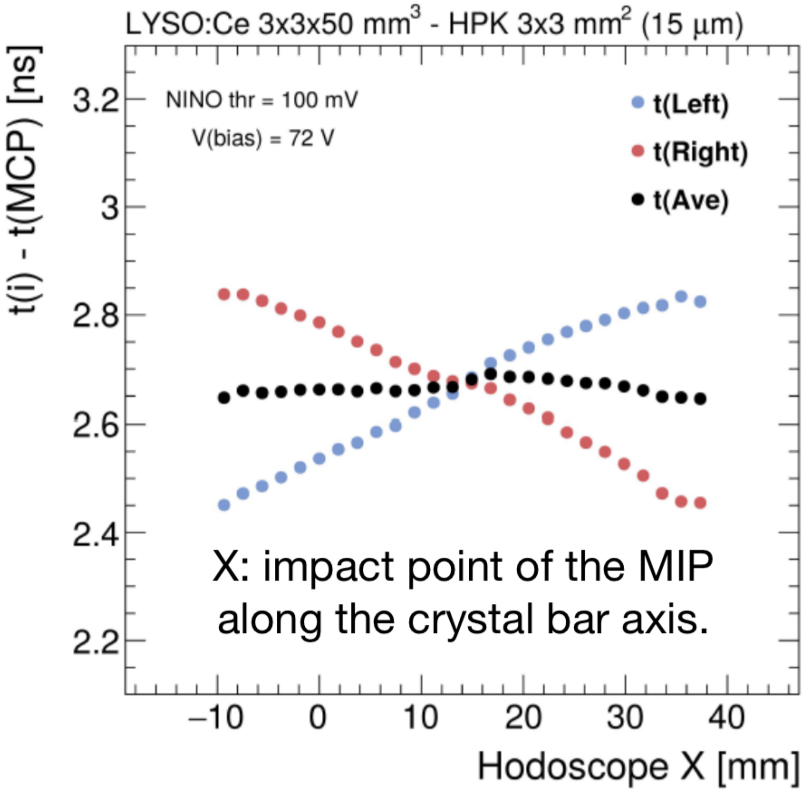
BTL Sensor Performance in Test Beam

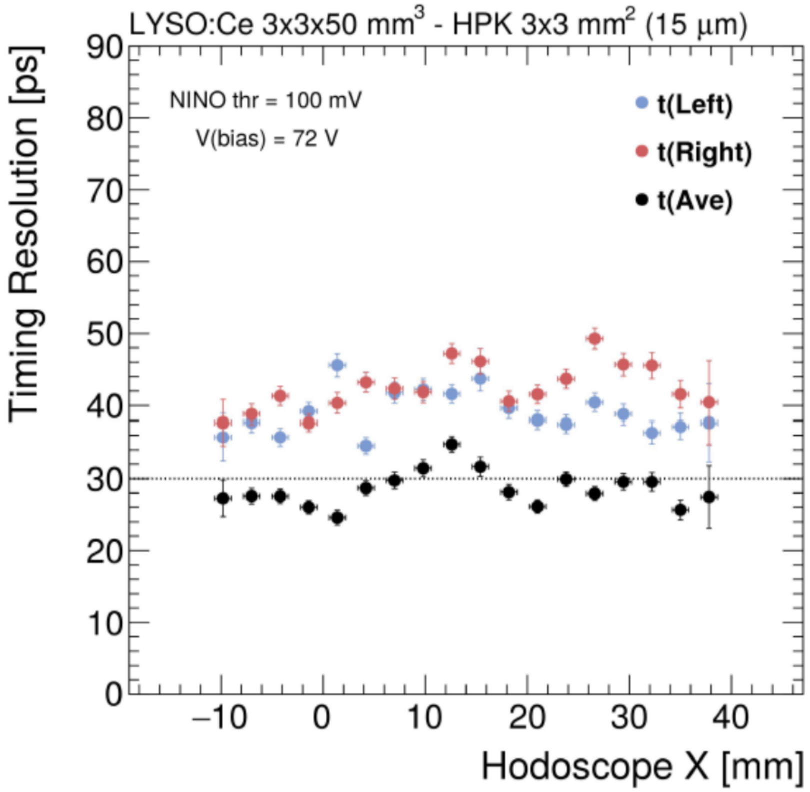
- Extensive R&D campaigns to prove target resolution
- Bars read-out by SiPMs at both ends → two different times per channel

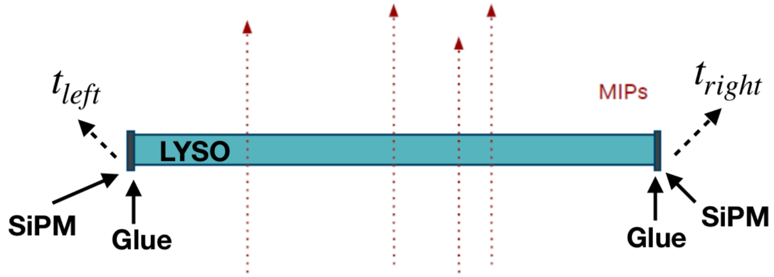
$$t_{ave} = (t_{left} + t_{right})/2$$

- Time is sensitive to the light propagation along bar
- Uniform time response and resolution across sensor area
- Achieved 30 ps time resolution per BTL sensor before irradiation

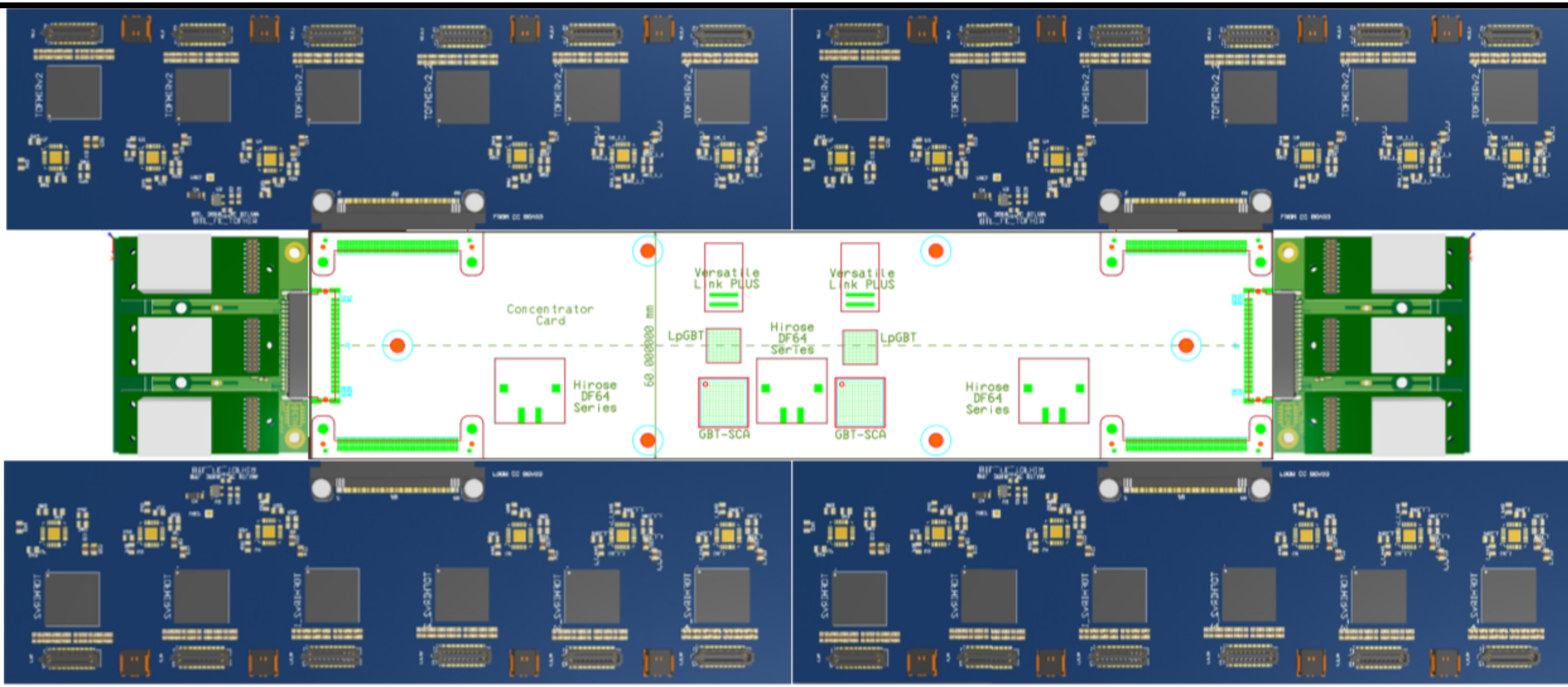




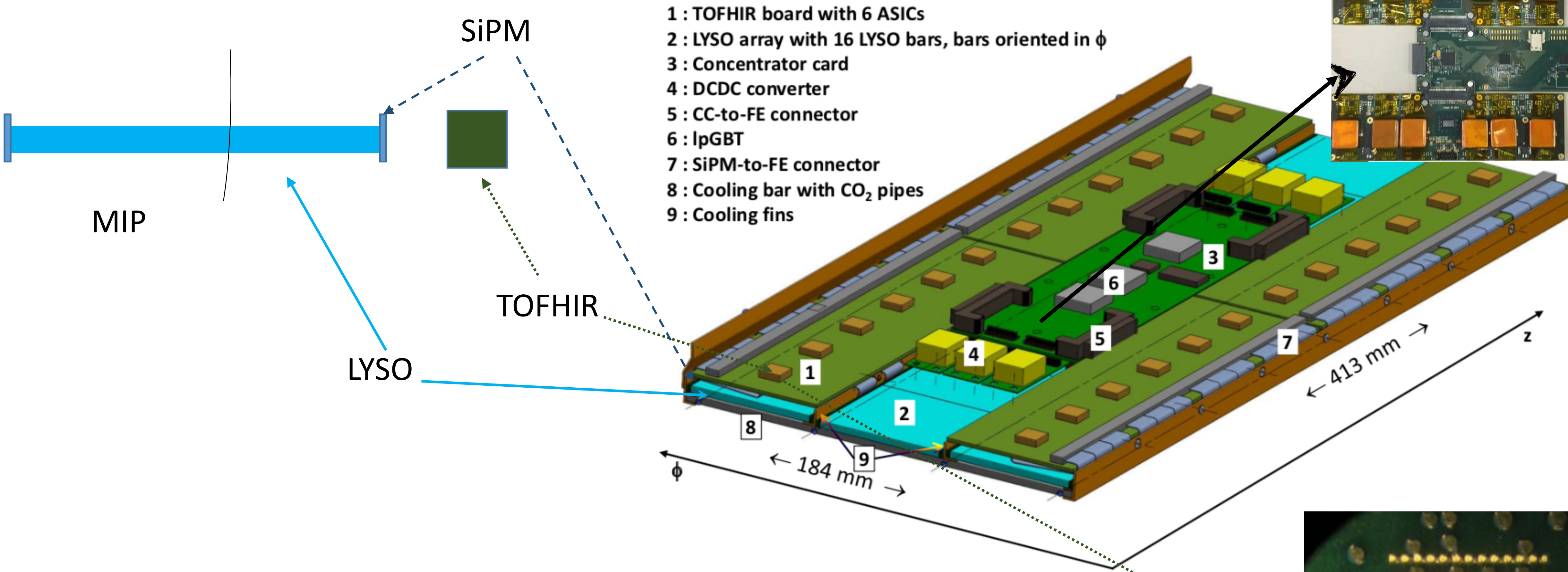


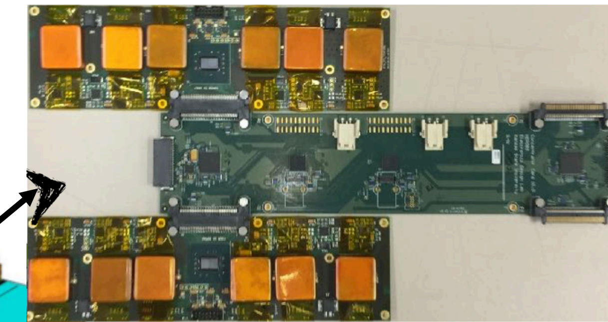


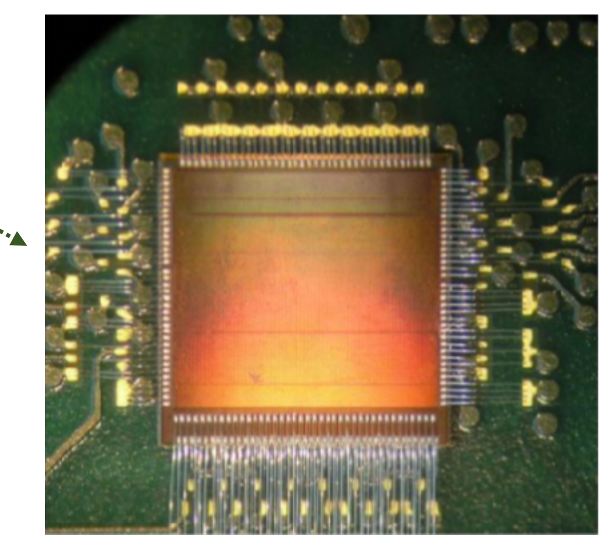
Readout Electronics



BTL Readout Electronics







- Readout electronics ASIC: TOFHIR (Time Of Flight HIgh Rate)
- Each board has 6 ASICs
    - each ASIC 32 independent channels that reads 32 SiPMS

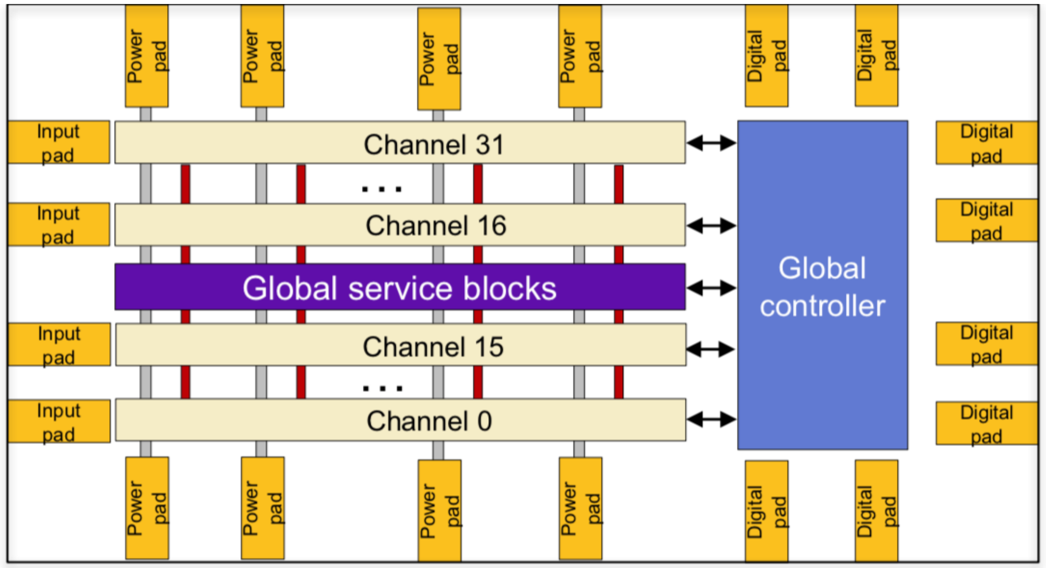
Front-End Requirements

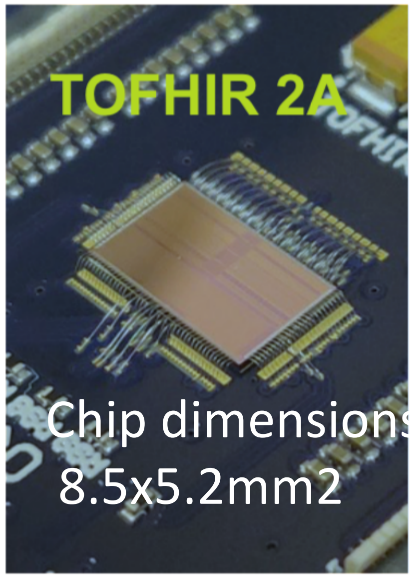
- MIP signal
  - Average light signal: 10-6 k p.e.
  - **MIP rate: 2.5 M hit/s/channel**
- Timing measurement
  - Timing given by the arrival of the first ~50 p.e.
  - **Electronics jitter ~ 20 ps**
- Amplitude measurement
  - Charge integration and ToT
  - **Accuracy <5% for time walk correction**
- Dark counts and out-of-time pileup
  - **Cope with large increase of SiPM dark count due to radiation**

TOFHIR Prototyping

TOFHIR ASIC is developed by PETsys electronics in collaboration with LIP

- TOFHIR1 (UMC 110 nm): received in 2019, enabled system level testing
  - Based on the ASIC developed for TOF-PET at LIP
- TOFHIR2 (TSMC 130 nm): new frontend design, **DCR noise cancellation circuit**
  - TOFHIR2A
    - Tests started on 15 July 2020
  - TOFHIR2X
    - Improved DCR cancelation and current discriminator
    - Submitted in November 2020
  - TOFHIR2B
    - Improved SEU protection
      - TMR protection of clock tree
    - MPW submission Apr 2021

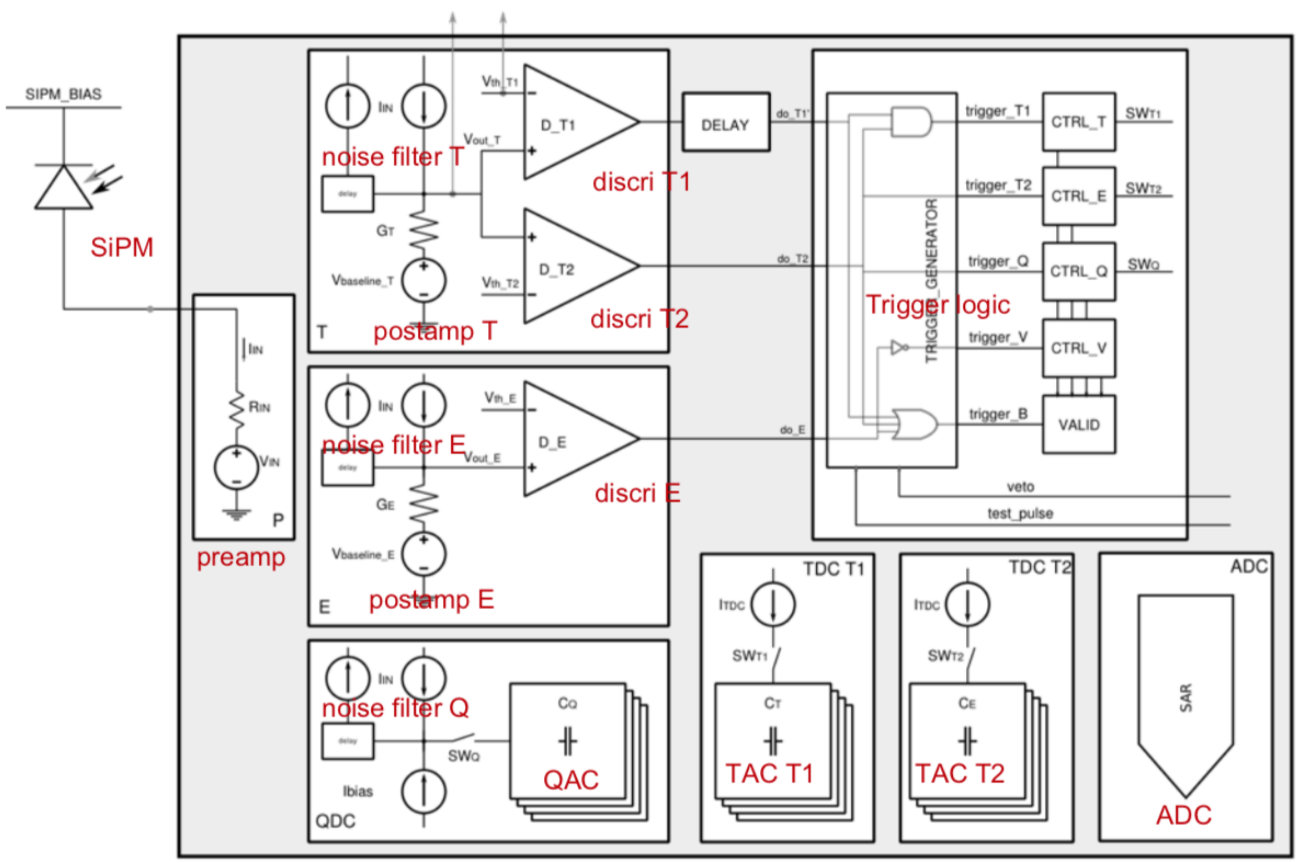




TOFHIR2 Channel

Challenges:

- Reduce impact of DCR noise and pileup
- Cope with high rate (2.5 MHz MIP + 5 MHz low E hits/channel)
- Handle the variation in dynamic range variation along detector life time
- Power budget 15mW/channel



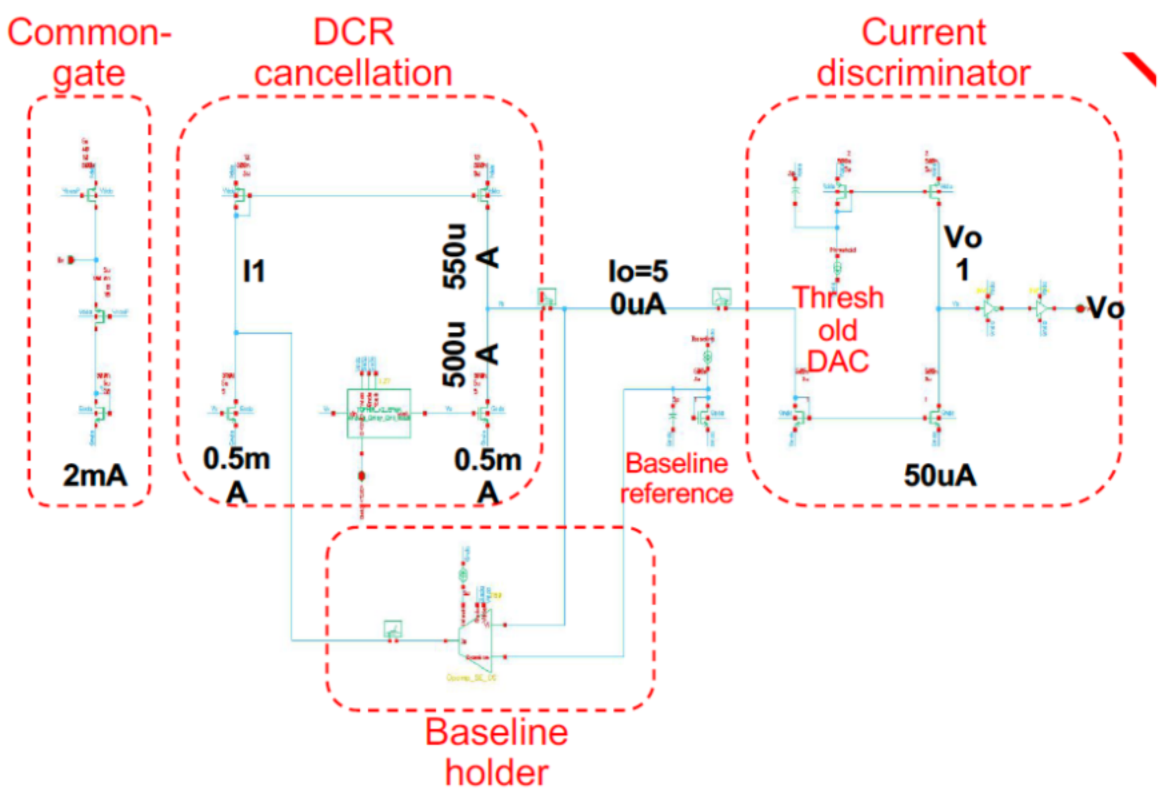
Features:

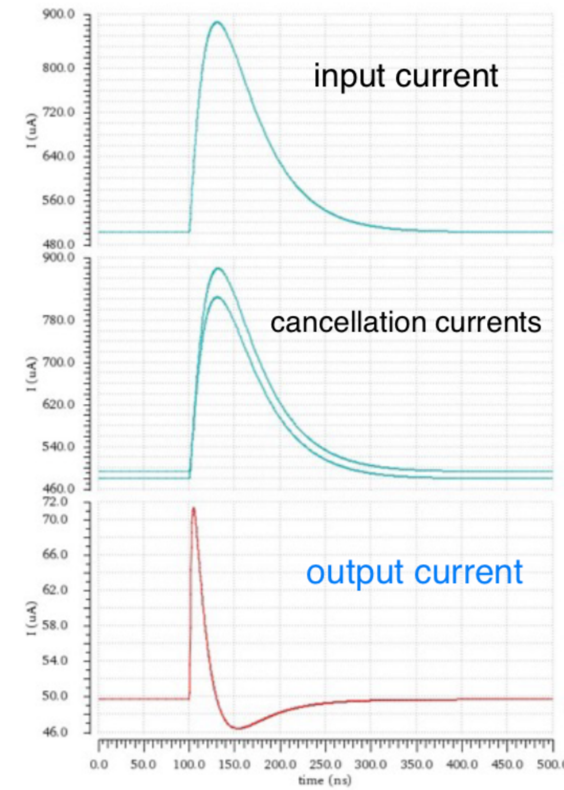
- Branches: T, E and Q
- Three leading edge discriminators
- Two TDCs, one QDC sharing 40 MHz SAR ADC
- Trigger logic

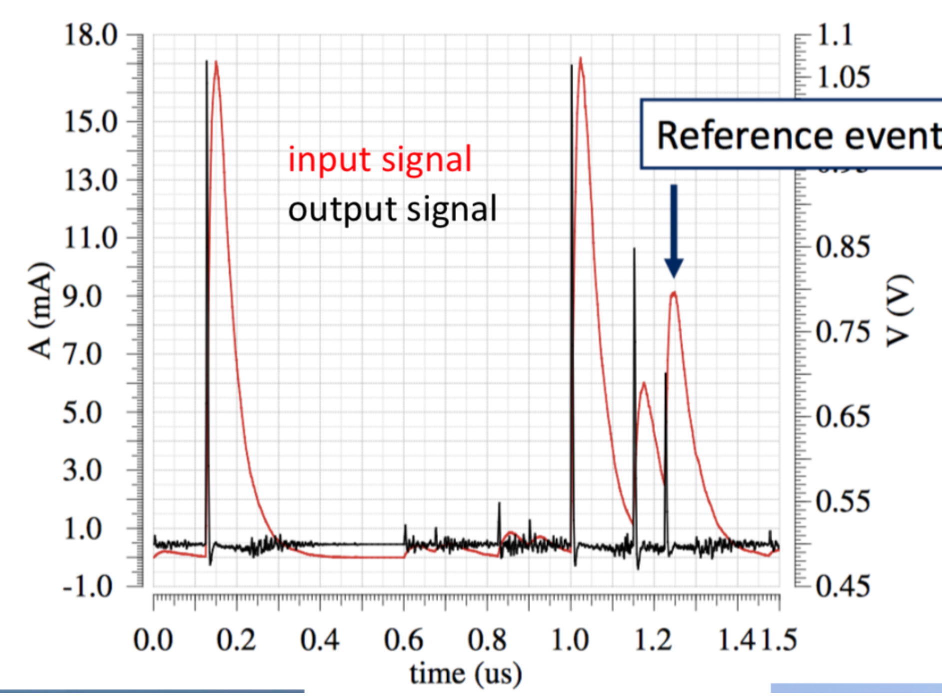
DCR Noise cancellation in TOFHIR

Method:

- Inverted and delayed pulse added to the original pulse,
    - Delay line is approximated by a RC net (200-500 ps)
    - Short output pulse (< 25 ns)
    - Noise and baseline fluctuations are mitigated







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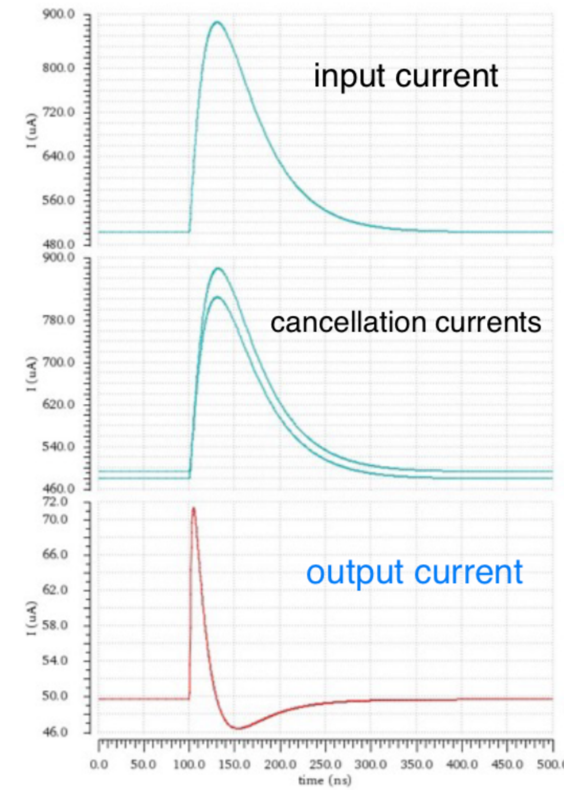


Simulation of time resolution:

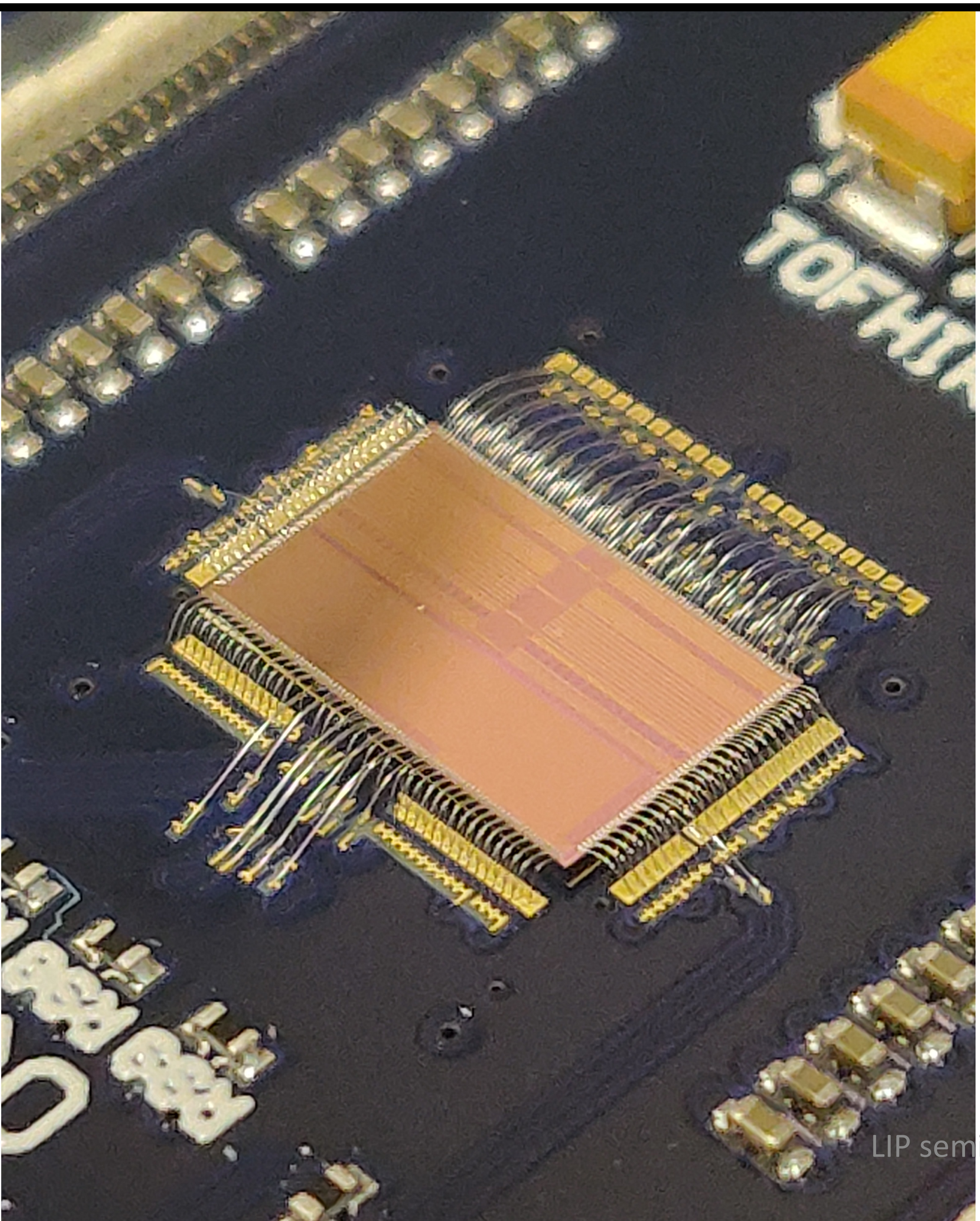
- TOFHIR2X
- End of Life conditions
  - Dark Count Rare: 55 GHz
  - Double readout of LYSO bar
  - MIP pulses with 6000 p.e.
  - SiPM gain: 1.5×10^5

$$\boxed{\sigma_{time} = {\sigma_{noise}}/{slew\ rate}}$$

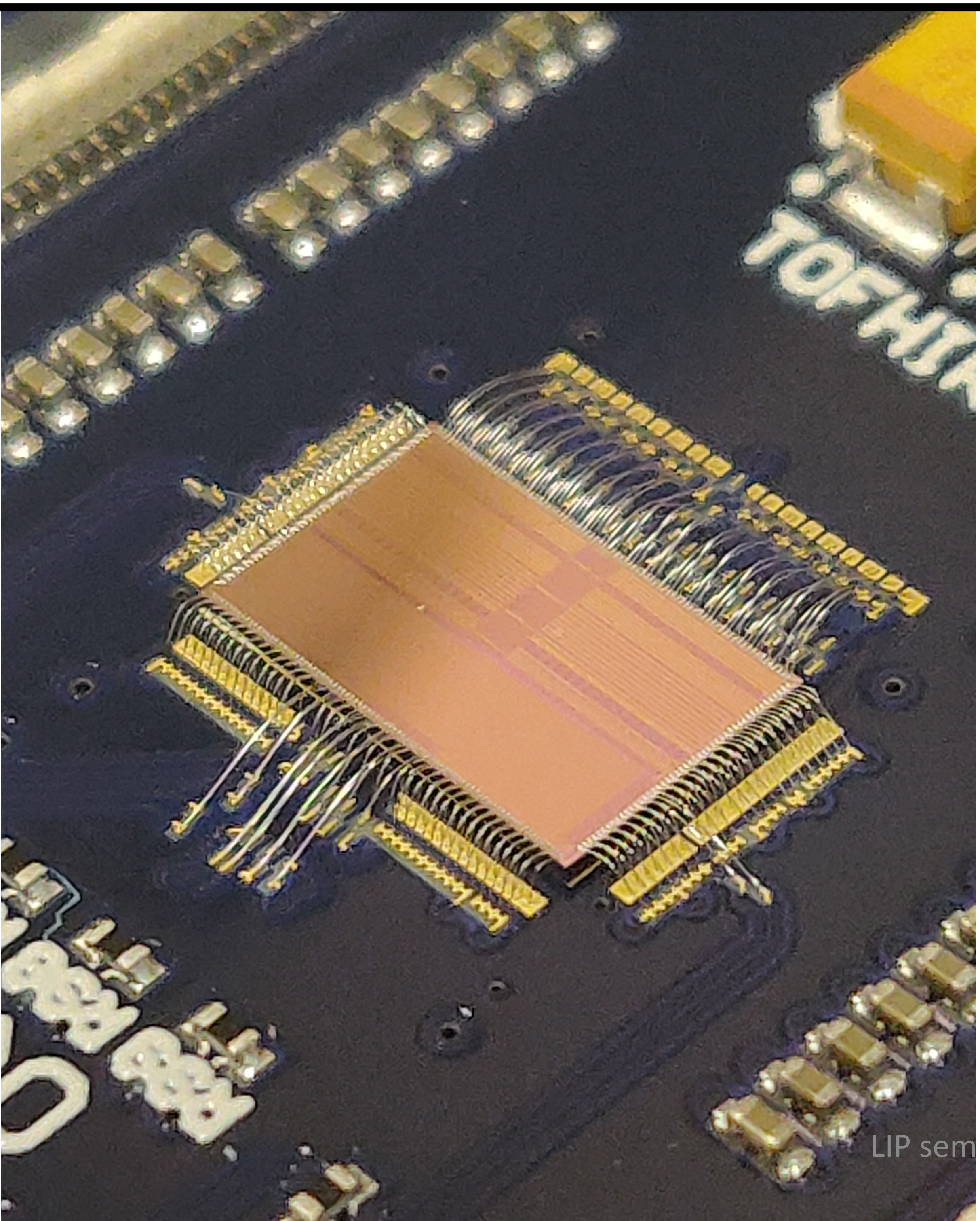
	SiPM output current	DCR module output current
Slew rate (A/ms)	135.9	9.93
Noise r.m.s (A)	2.45e-5	5.12e-7
σ_{noise}/ SR (ps)	180	52

→ Time resolution is improved by a factor 3.5

TOFHIR Performance



TOFHIR Performance



TOFHIR 1

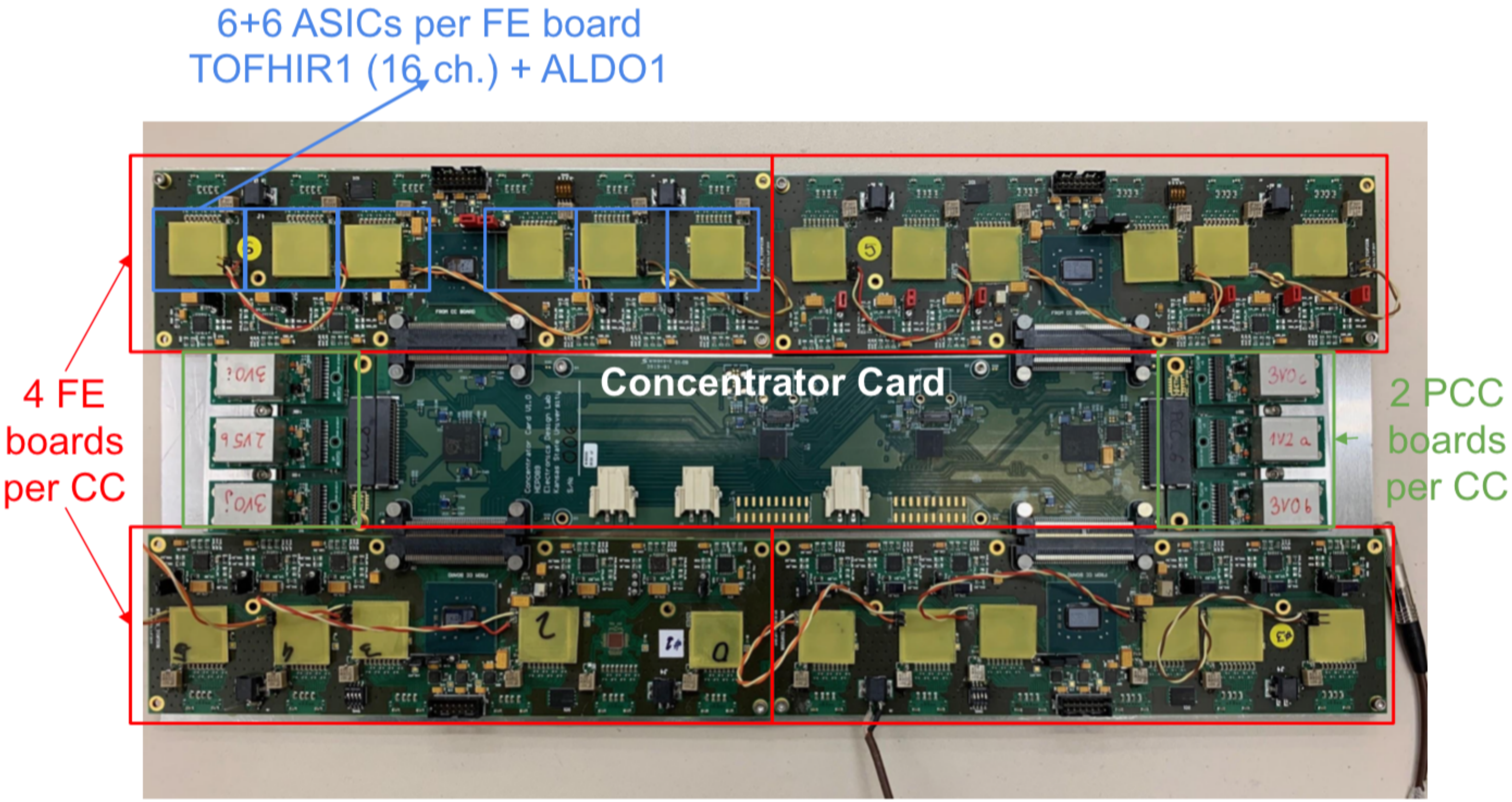
BTL System Test

Integration and readout test of the BTL system, using the first version of the electronics (**RUproto1)**

- Test the TOFHIR_v1 ASICs mounted on the FE board
- Read the FE boards through the Concentrator Card, powered through the Power Converter boards
- Acquire data through the prototype DAQ system

Goals: validate the full acquisition chain and assess the impact of the system noise in time resolution

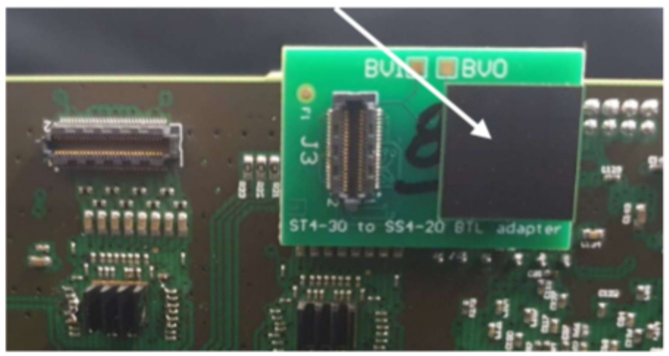
Readout Unit Prototype 1



Experimental Setup

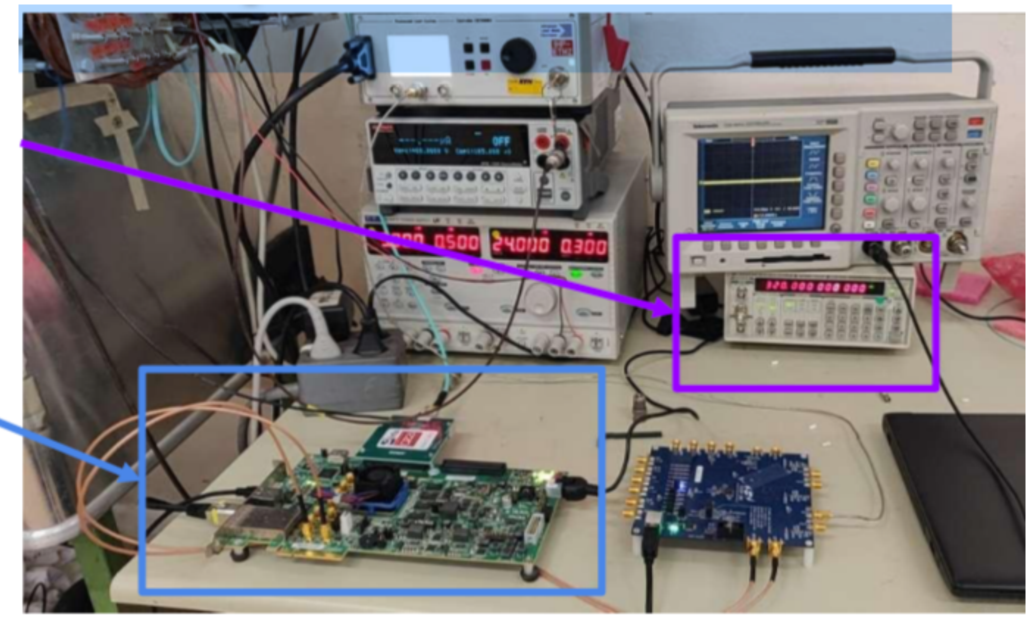
HPK S13361-3050 SiPM array

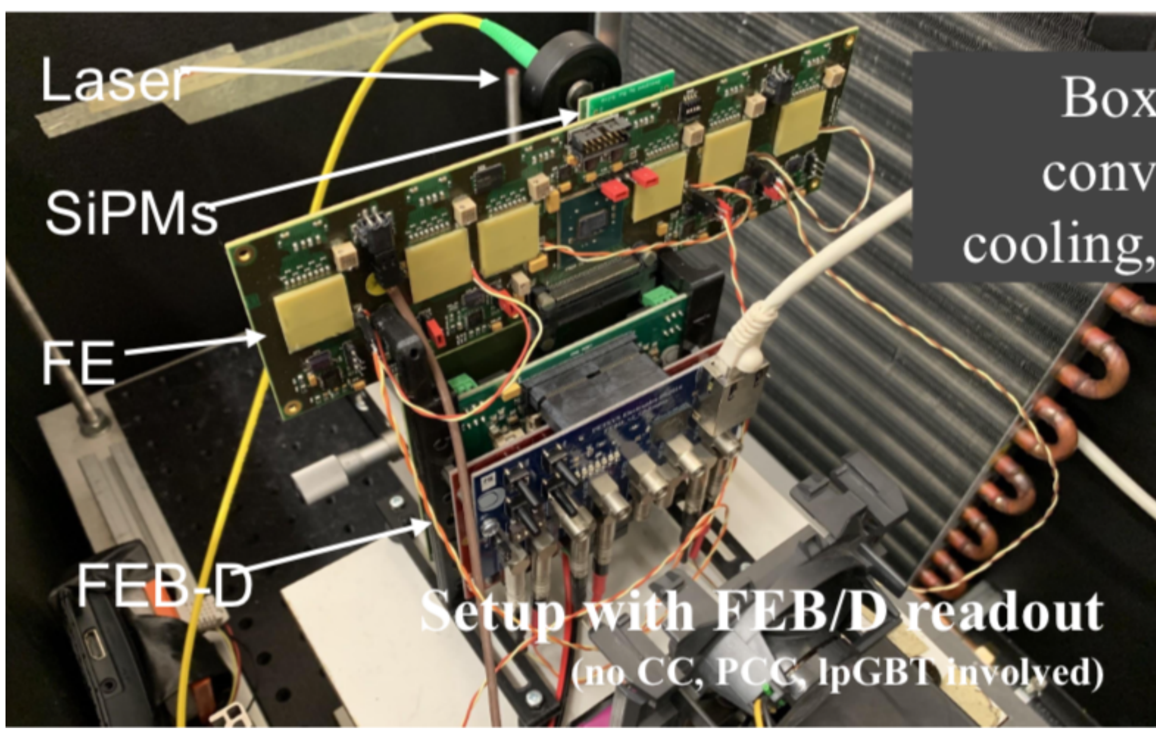
4×4 channels, $G = 1\times10^{6}$, PDE = 30% @ 2 V_{OV}

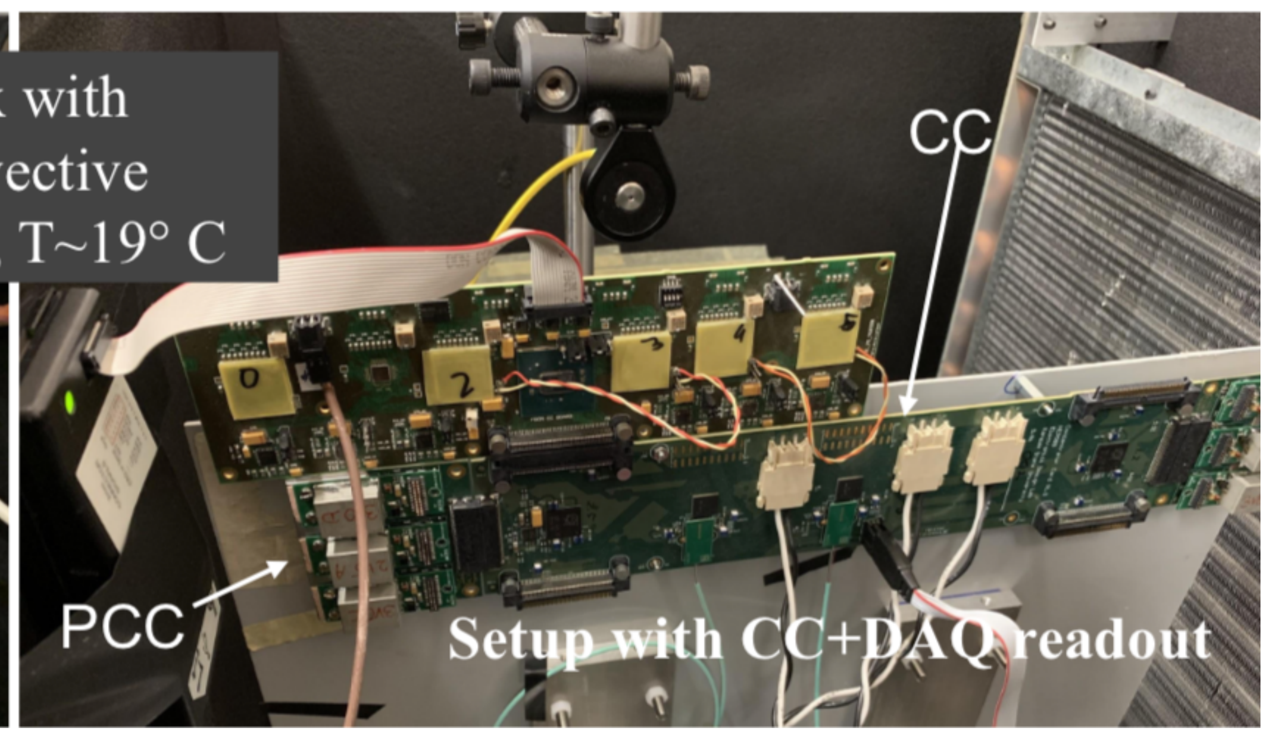


Clock generator

Xilinx KCU105 + Samtec FireFly

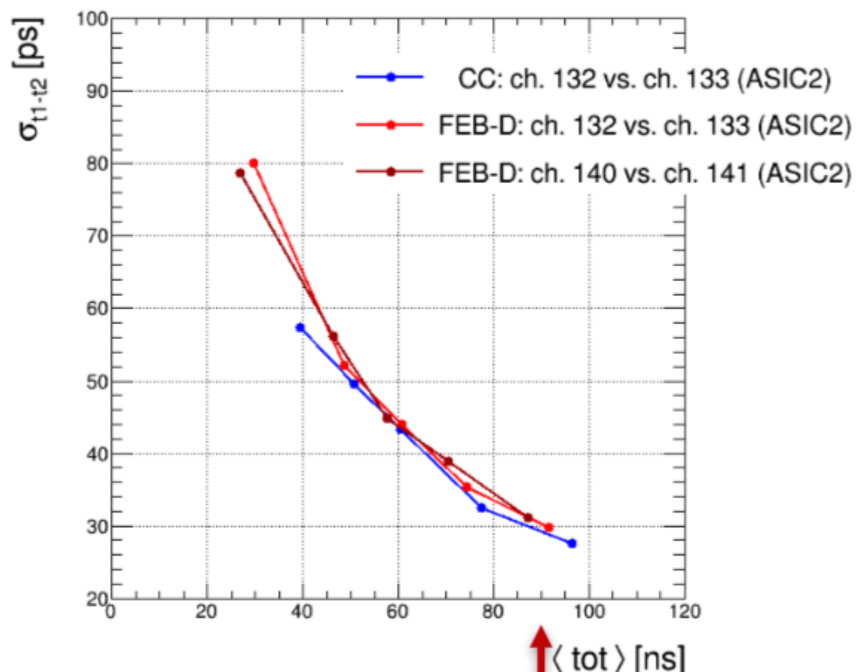




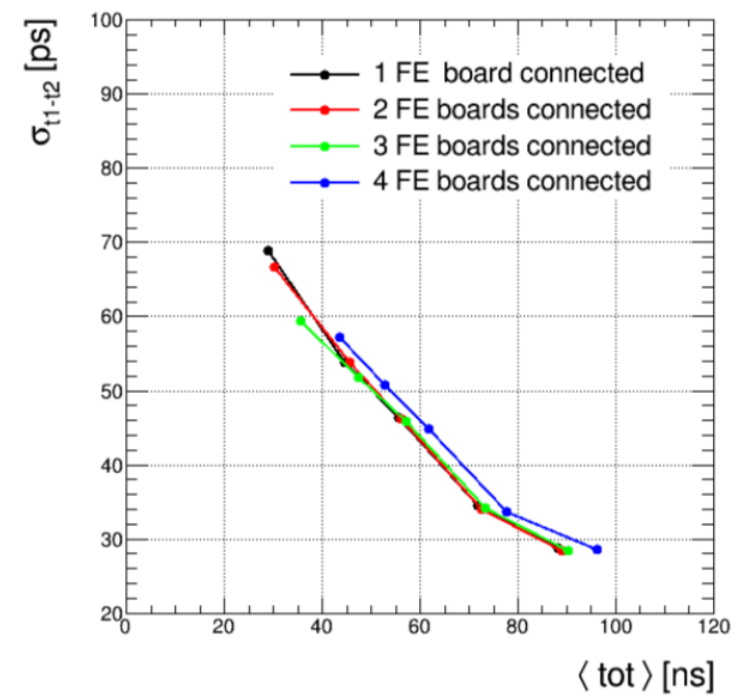


Coincidence Time Measurement in Different Scenarios

Same-ASIC channels

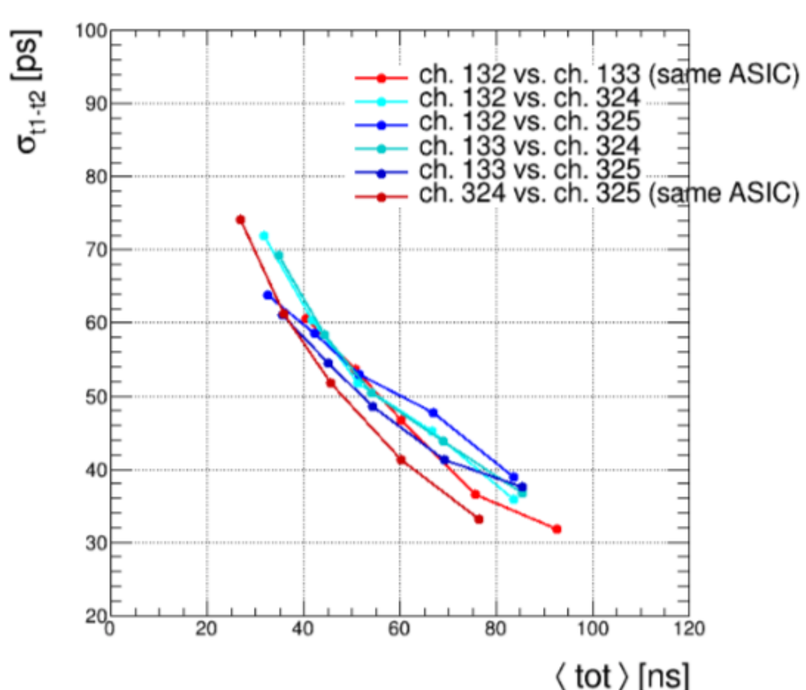


Same-ASIC channels

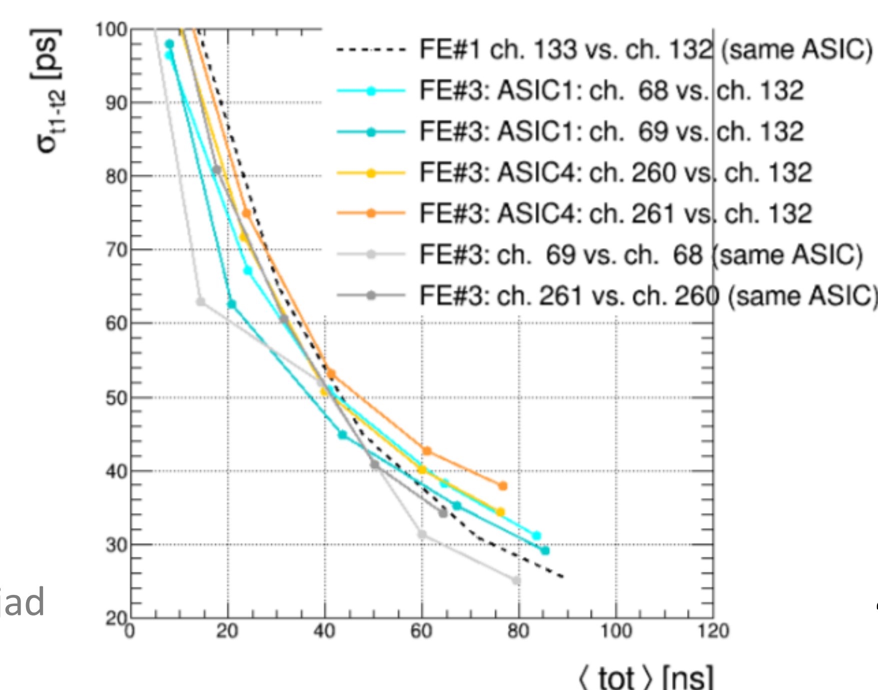


Laser pulse (ToT 90 ns) with similar slew rate as LYSO pulse

Pairs of channels in different ASICs on the same FE board



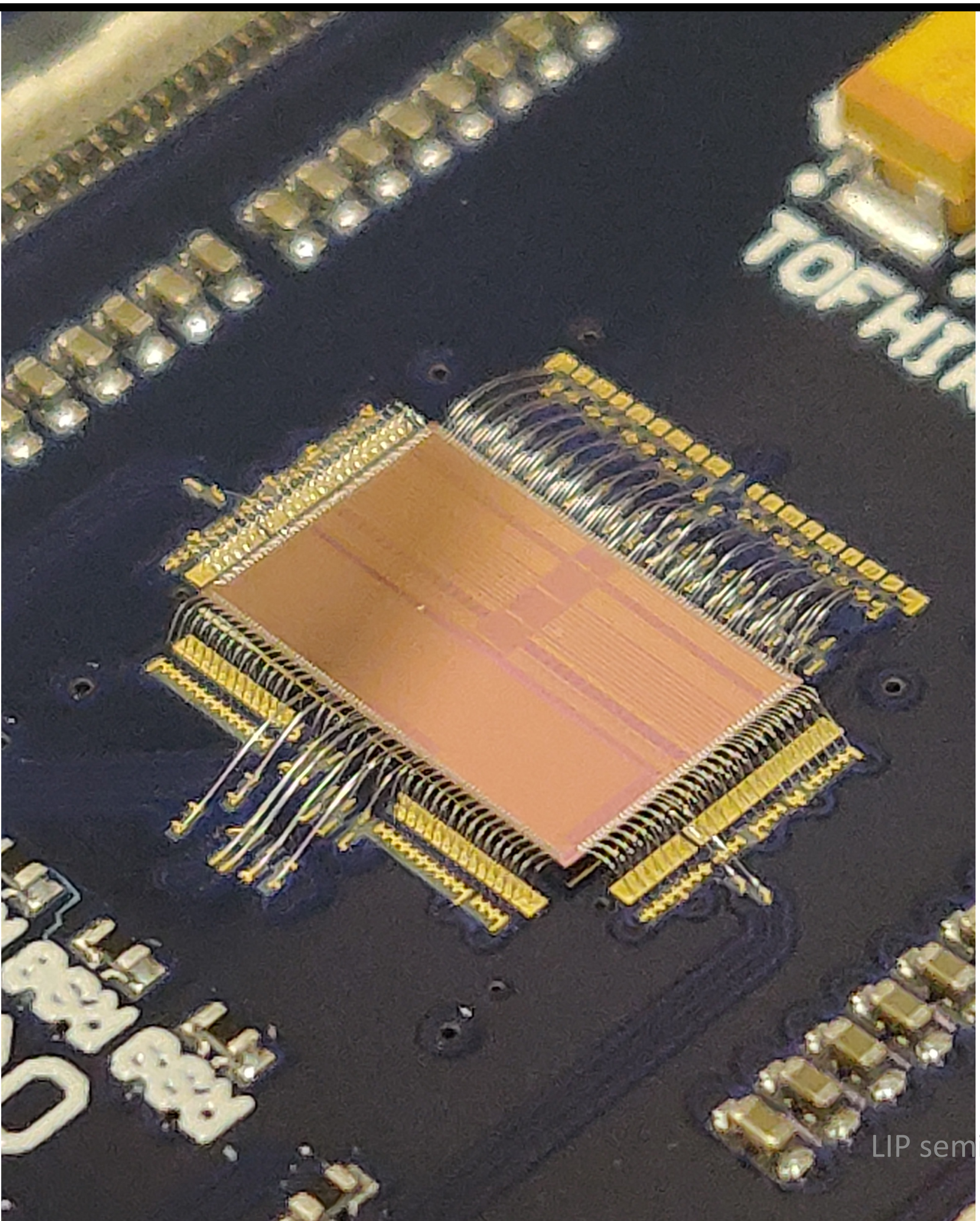
Pairs of channels in different ASICs on different FE boards



Summary of the System Test

- The results indicate that the system (FE + CC + PCC) is working well
    - Coincidence time resolutions below 40ps are measured in all conditions
        - 40 ps CTR→ 28 ps on the single channel→20 ps on the bar resolution
- The system noise does not deteriorate the intrinsic performance significantly

TOFHIR Performance



TOFHIR 2

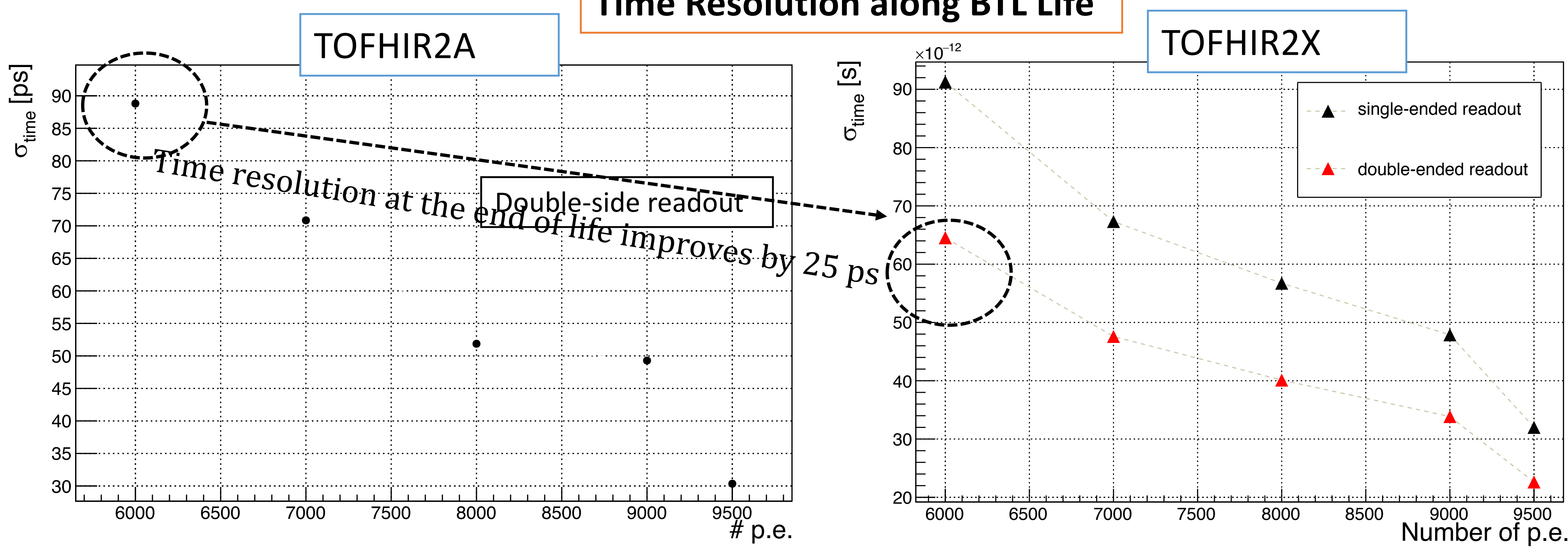
Expected Time Resolution

- Time resolution at discriminator output
  - LYSO photo-statistics included
  - TDC digitization added (20 ps)
  - SiPM jitter included (100 ps)
  - SiPM cross-talk included

HDR2 SiPM parameters along BTL life

Integrated luminosity (fb-1)	Number of p.e.	SiPM gain	DCR (GHz)
0	9500	3.8×10^5	0
500	9000	2.9×10^5	20
1000	8000	2.5×10^5	30
2000	7000	1.9×10^5	45
3000	6000	1.5×10^5	55

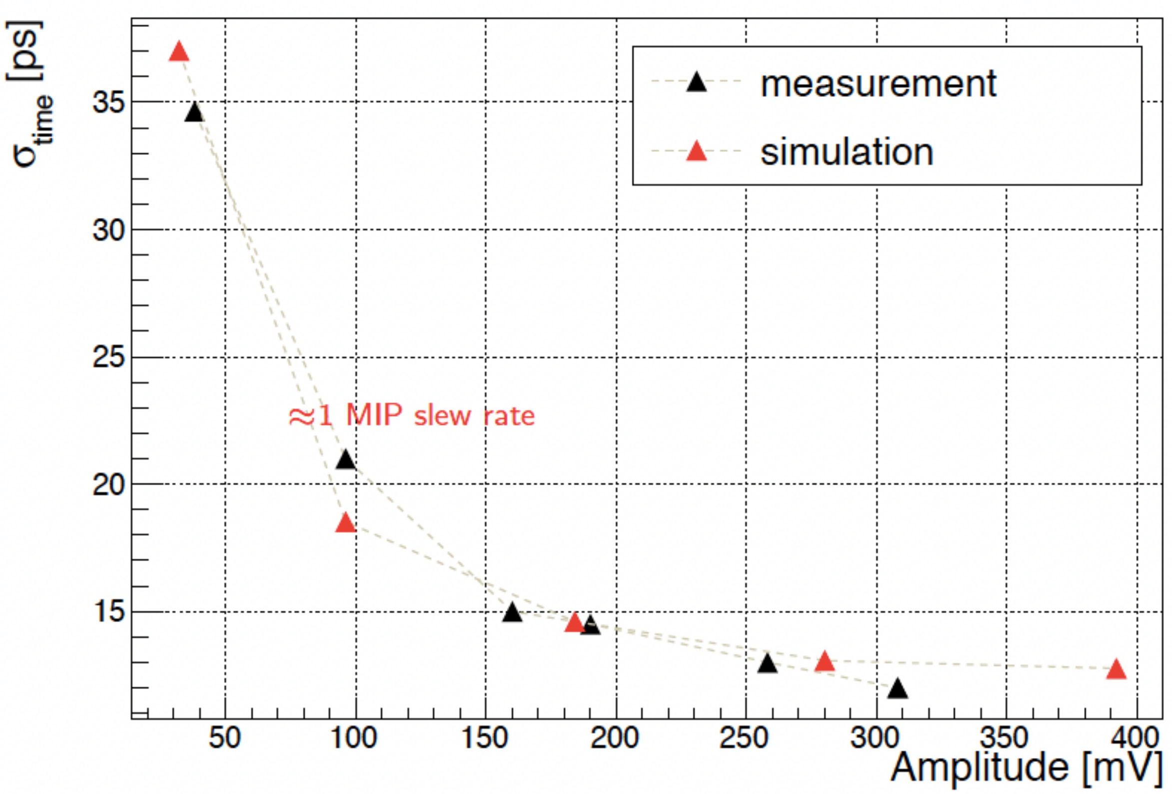
Time Resolution along BTL Life

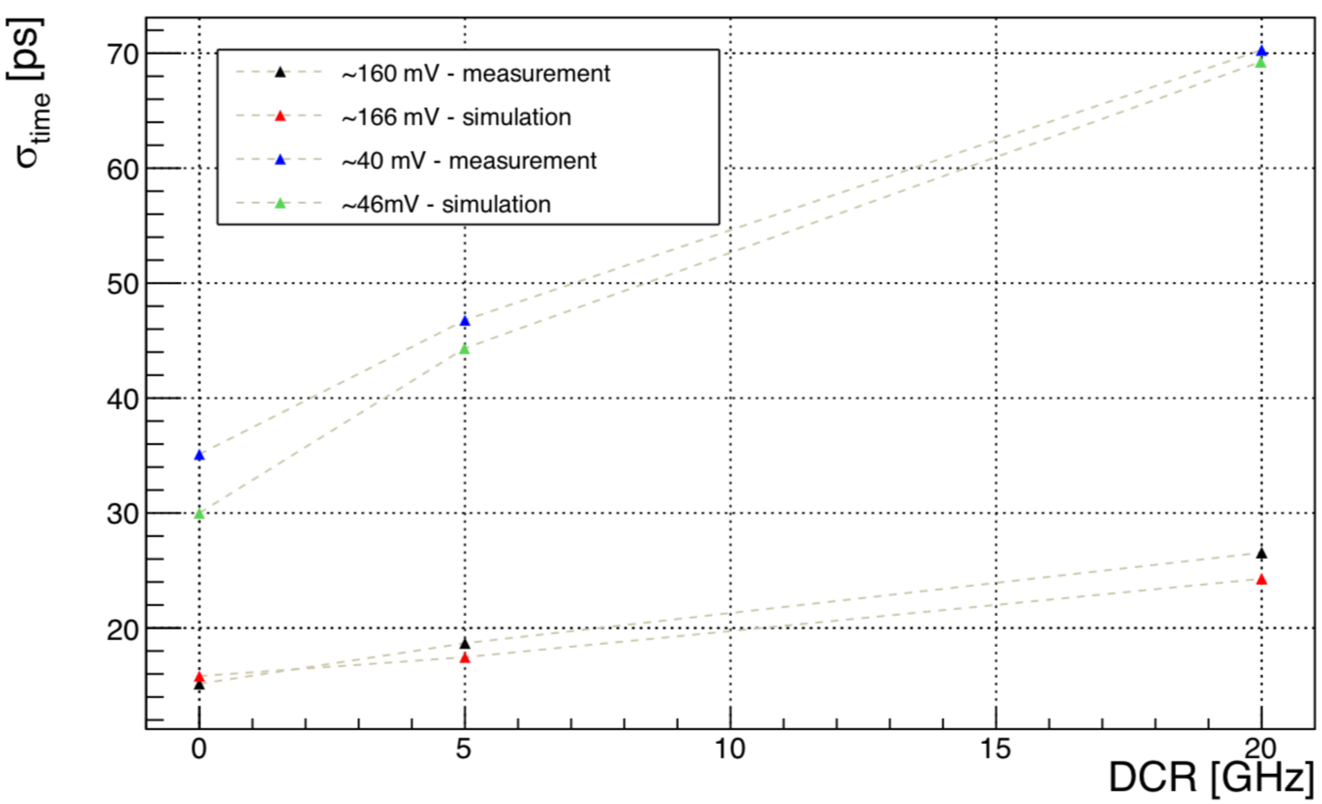


→ TOFHIR2X simulation achieves a result very close to the ideal model in slide 20

Channel Time Resolution with Laser: TOFHIR2A

- HDR2 SiPM (3.8 x10^5 gain) triggered by picosecond pulsed laser

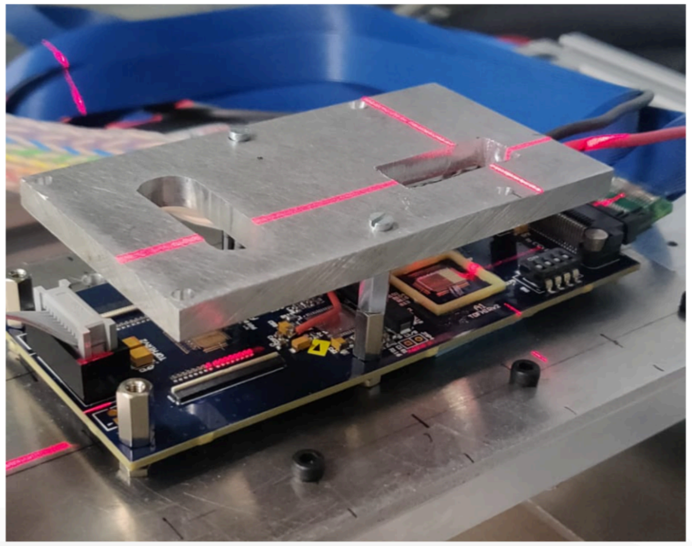


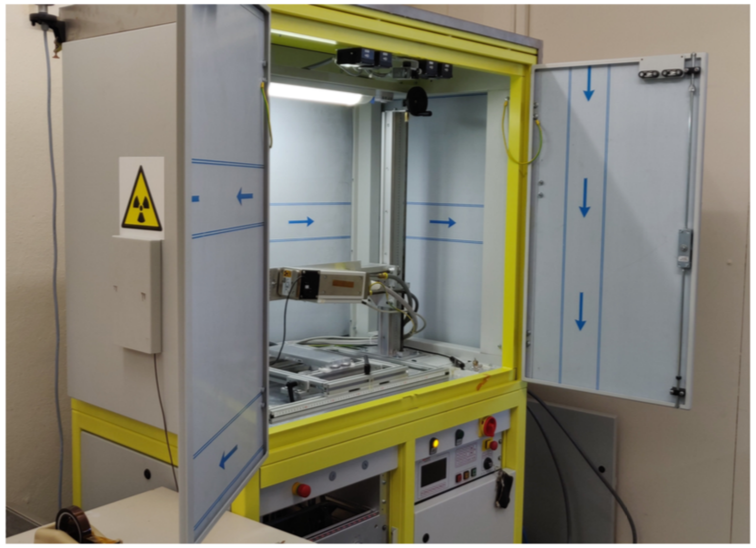


- Contribution of electronics to time resolution is expected to be the same for a given slew rate for either laser or LYSO.
- DCR is emulated with LED light
  - LED is calibrated to yield SiPM current equivalent to DCR

Radiation Test of TOFHIR2A (TID and SEU)

X-ray Irradiation facility at CERN





- Max expected dose in BTL is 2.9 Mrad
- ASIC was irradiated up to 7 Mrad
- No sizable effects up to 7 Mrad on the frontend amplifiers, TDC and QDC.

Heavy Ion Facility (HIF) at Louvain-la-Neuve

- Facility to test the response of electronic components to single event effects (SEE).
- ASIC was irradiated with different ions covering a wide range of LET and ranges
- We validated that TMR in the configuration registers is operating as expected

Summary and Final Remarks

- Large Hadron Collider will undergo a High Luminosity upgrade
  - Aims to deliver ten times more integrated luminosity
    - But five times more pileup interactions
- CMS phase-2 upgrade will include a new MIP timing detector with a time resolution of 30-60 ps to mitigate harsh pile-up condition at HL-LHC
  - Expand CMS HL-LHC physics reach: enhancement of physics object reconstruction, open up new territory in CMS Heavy Ion Physics and long-lived particle search
- LIP is leading the development of the BTL readout electronics
- BTL and ETL are rapidly progressing towards engineering solutions
  - Challenges to achieve TDR performance being addressed.

Backup

Evolution of SiPM Operating Parameters