# Precision Timing Detectors

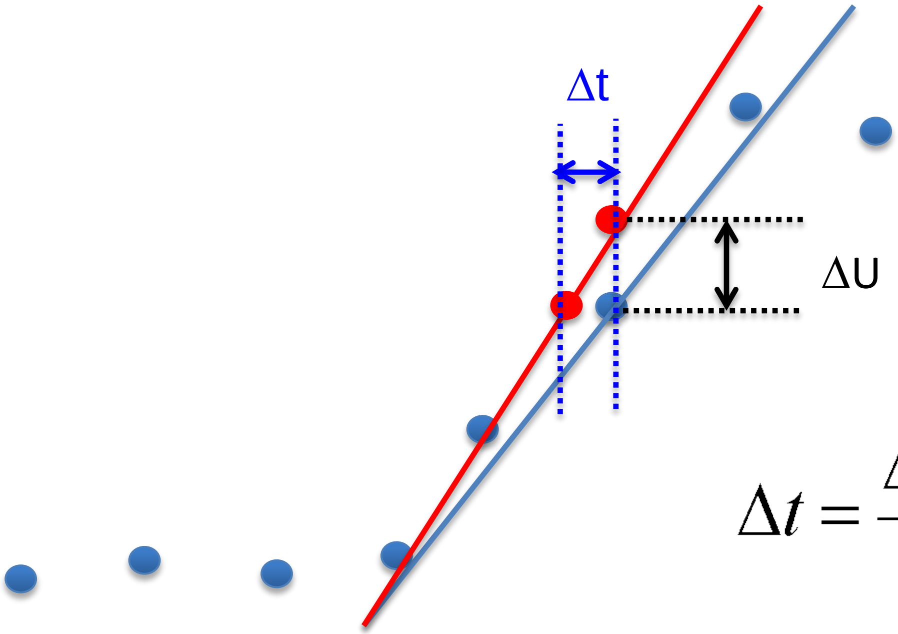
**Adi Bornheim**

**Caltech**

**Terascale Detector Workshop**

**February 28, 2018**

# Fast Timing Fundamentals

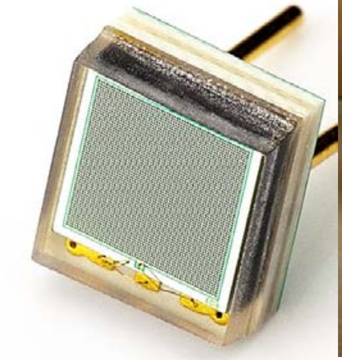


$$\Delta t = \frac{\Delta U}{U} t_{rise} = \frac{1}{U} \frac{\Delta U_i}{\sqrt{n_{samples}}} t_{rise}$$

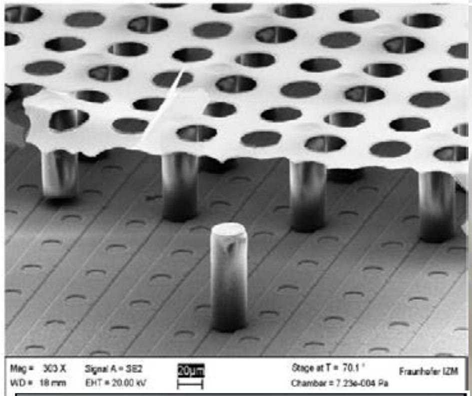
**For good time resolution, need:**

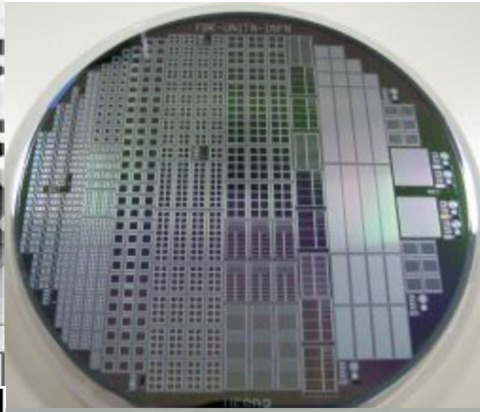
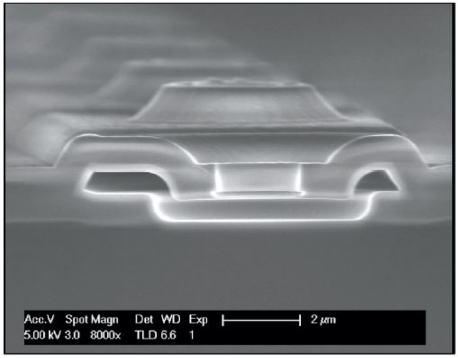
- **Fast rise time ($t_{rise}$)** ⇒ **primary signal rise time scintillation (LYSO) ~30 ps, Si pad sensors ~1ns, Cherenkov light instantaneous (!)**
- **Low Signal-to-Noise (ΔU/U)** ⇒ **primary signal amplitude : LYSO 30k photons/MeV (1.07 MeV/mm MIP) , Si sensors ~30k e/h pairs in 300 μm for a MIP**
- **More time samples ($n_{samples}$)** ⇒ **uniform pulse shapes required**
- **Better readout electronics (low noise amplifiers, fast TDCs)** ⇒ **power consumption may be a limitation**

# Sensor Technology



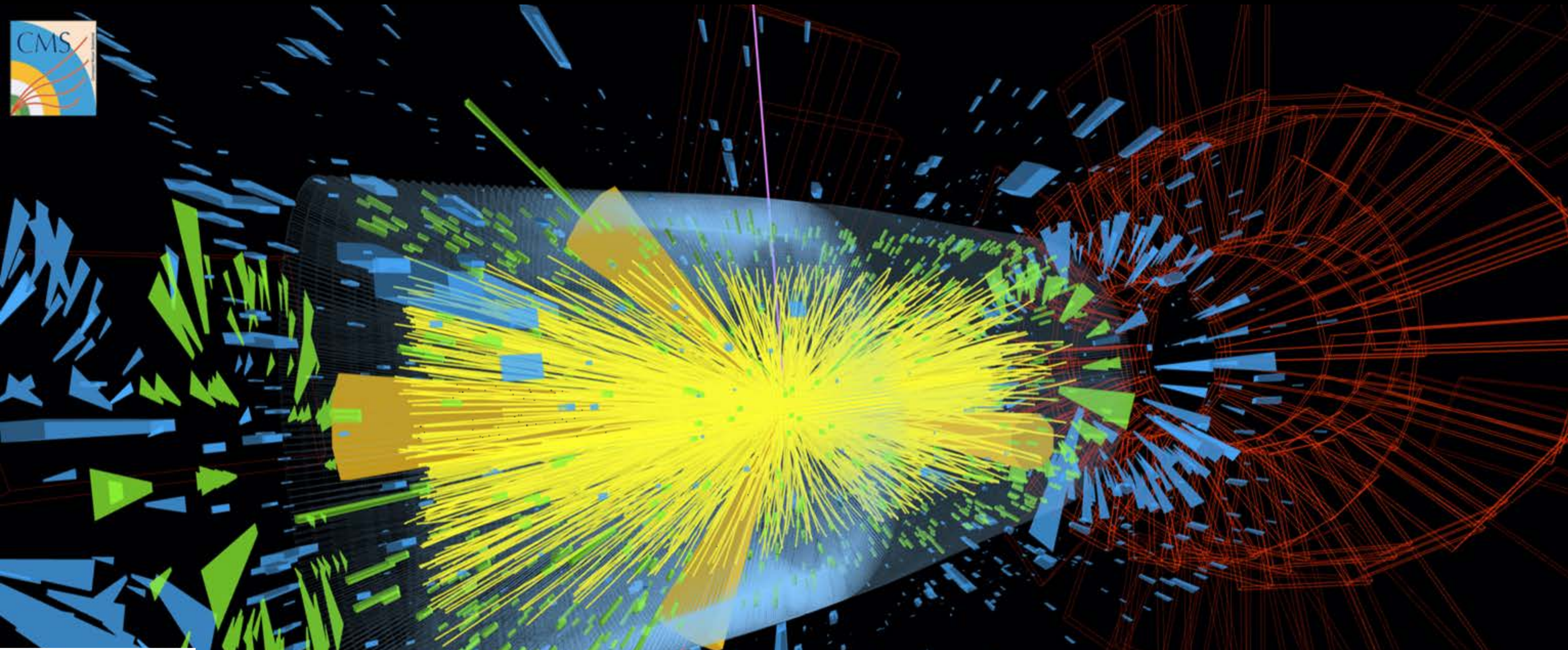




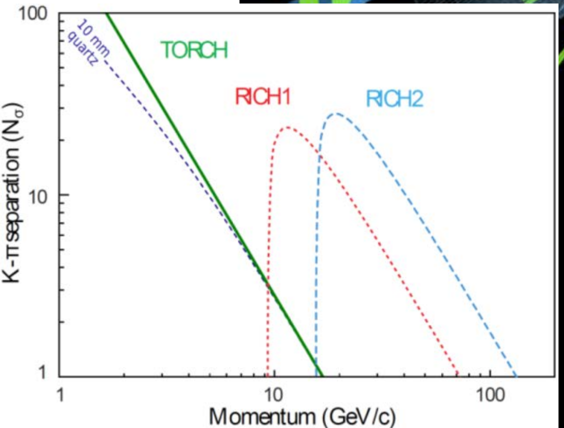



- **Photo sensors :**
  - **PMT : ~ns rise time, very good S/N**
  - **SiPM/APD : rapid technology evolution**
  - **MCP-PMT : ps level performance**
  - **Streak camera : sub ps**
- **Semi-conductor sensors :**
  - **Silicon : Require internal gain**
  - **CdTe : Large primary signal**
- **Gas based sensors :**
  - **Micromegas : micro fabrication**
- **Advanced sensors :**
  - **TIPSY, Quantum Dots, Nano-wires**
- **ASIC technology :**
  - **NINO, TOFPET, DRS, OMEGA, …**

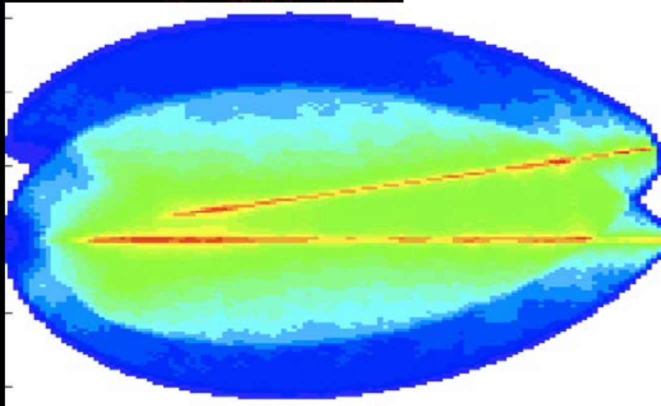
# Physics at HL-LHC



Particle ID

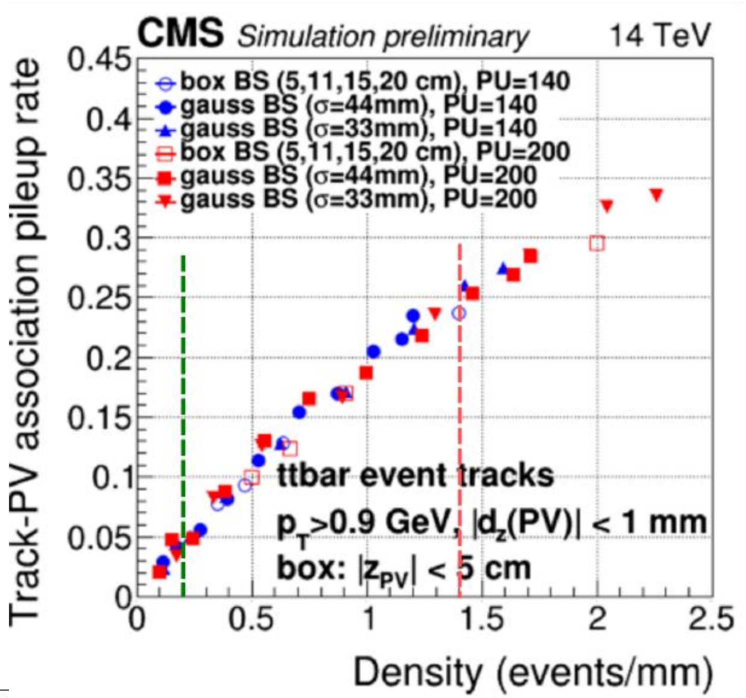


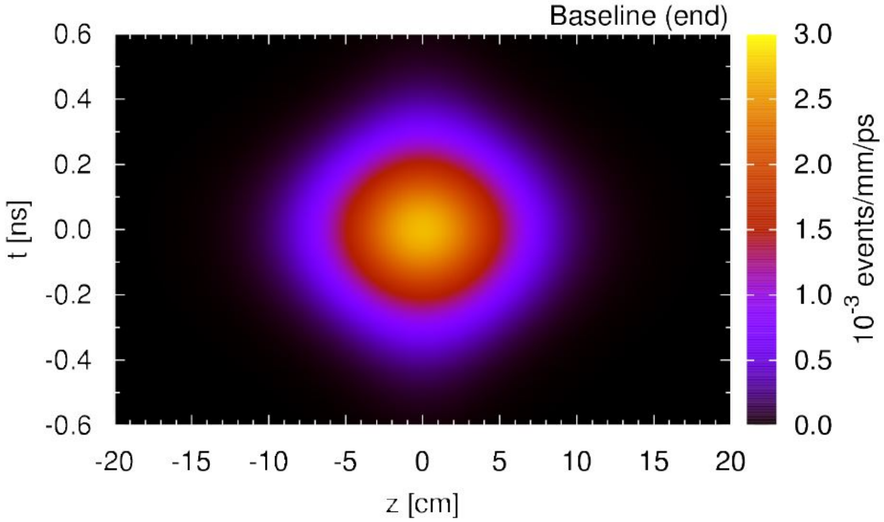
Optical TPC

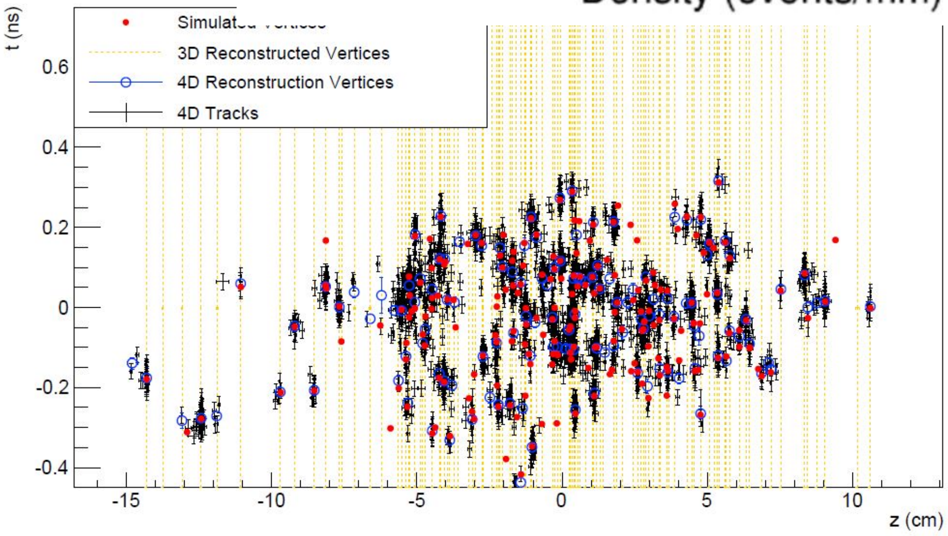


# Pileup-Mitigation at HL-LHC

- **Luminous region ~10 cm along beam axis, ~150 ps time dispersion.**
- **200 simultaneous pp collisions, thousands of tracks, many more stubs from conversions and nuclear interactions.**
- **Higher level object reconstruction (isolation, tagging, track vertex assignment) using timing.**
- **Equivalent technique for neutral particles requires calorimeter timing.**

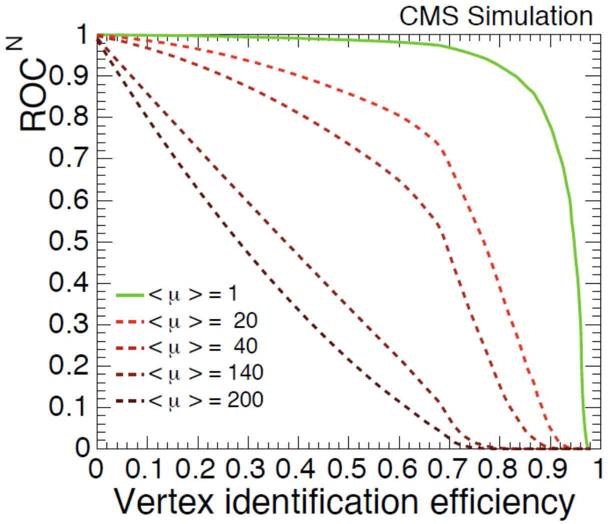


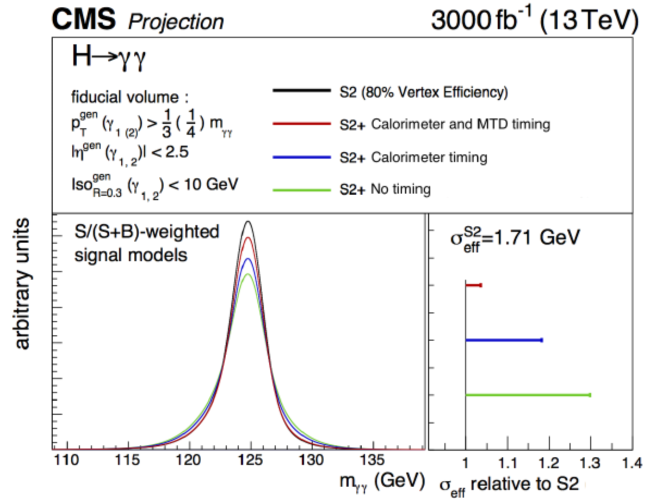


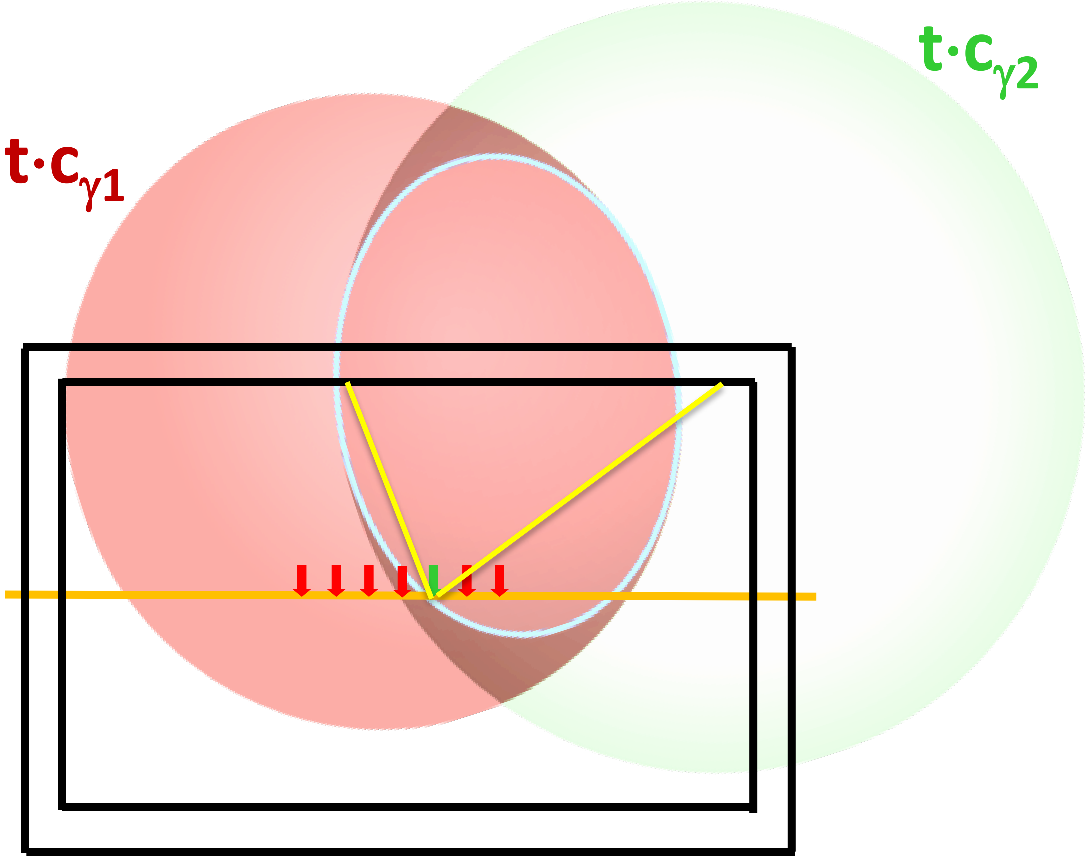


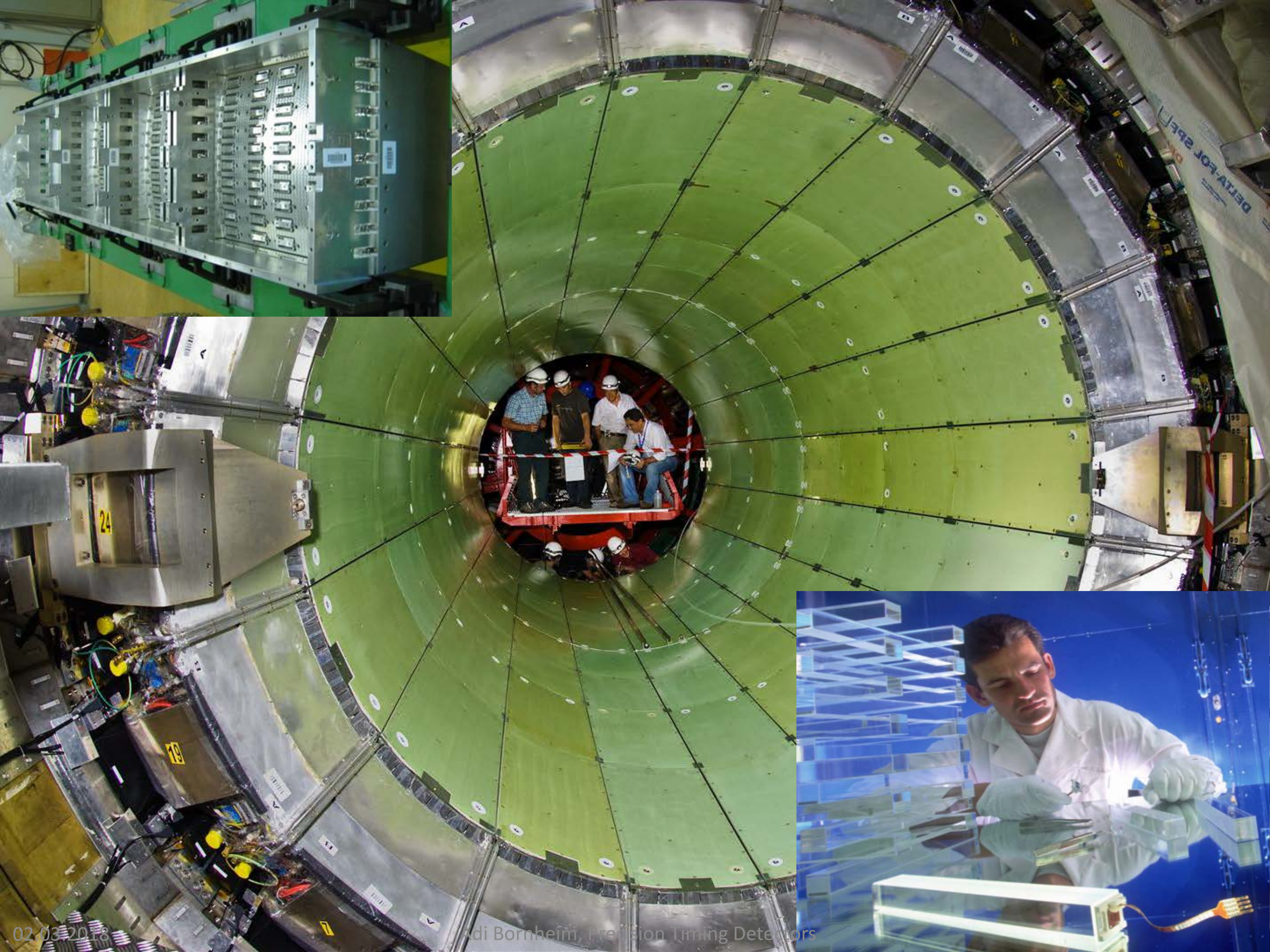
# 4D Photon Vertexing

- H→γγ important for precision higgs physics & Standard candle for HH→ bbγγ.
- Two time and position measurements, constraint from beam axis x/y allows to calculate vertex z and t - Equivalent to GPS with two satellites.





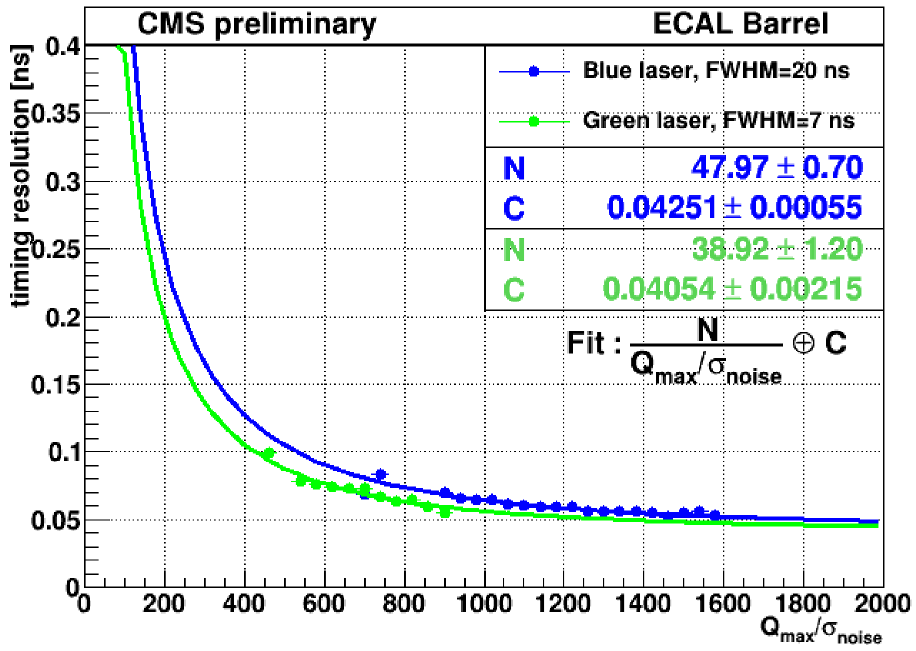


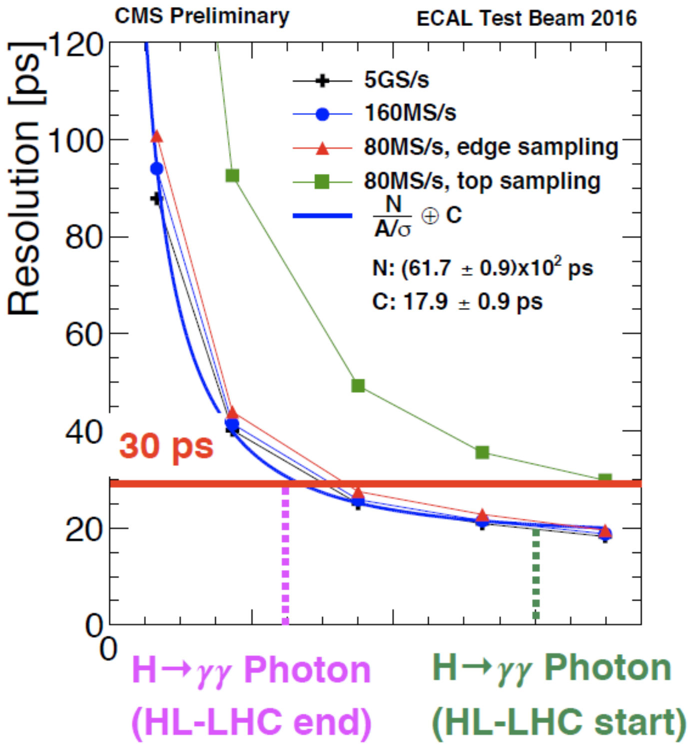

24
19
DELTA-FOL SPE

# CMS ECAL Barrel HL-LHC Upgrade

- ECAL timing from LHC Run I : 150 ps global (70 ps local).
- New Very Front End (VFE) with Trans-Impedance Amplifier (TIA) & Oversampling (optimal with 160 MS/s).
- Full detector readout, L1 accept rate 750 kHz @ 12.5 µs latency.
- Timing performance limited by the APD/cable to VFE.
- Timing resolution expected at 30 ps down to about 20 GeV.

CMS ECAL Laser Timing



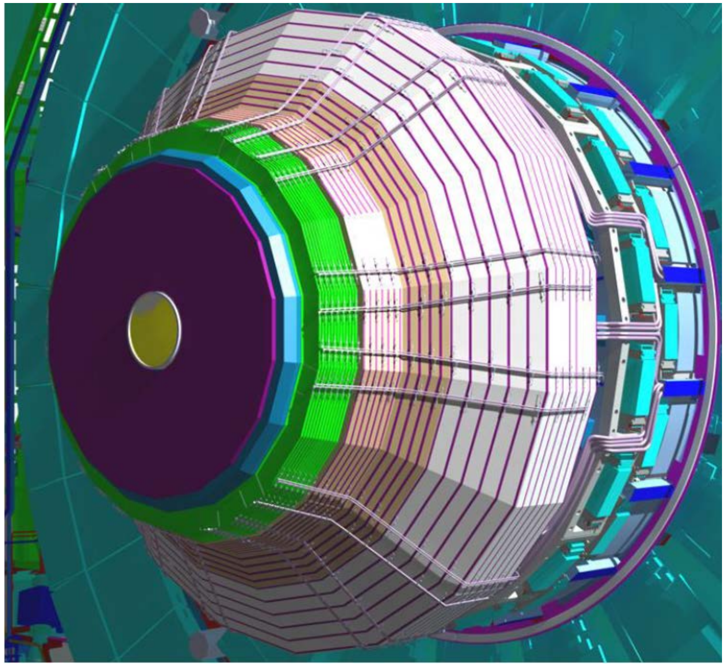


# Timing with Silicon Calorimeter

- **CMS will replace endcap calorimeter with a Si/W – Si/Fe (HGCAL) + Scint/Fe (BH) calorimeter for HL-LHC upgrade.**

**⇒ See presentation from Karl Gill.**

- **Better than 20 ps resolution achieved with a single Si pad sensor w/o gain if placed in an EM shower.**
- **Showers typically have a few 10 pads contributing to the measurement.**



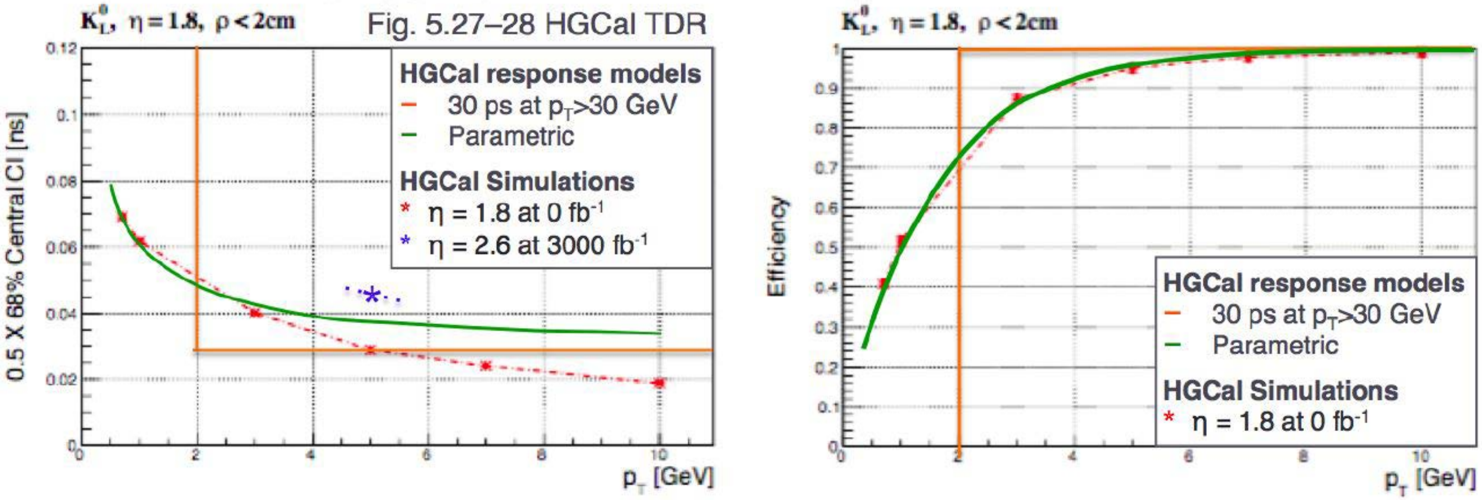
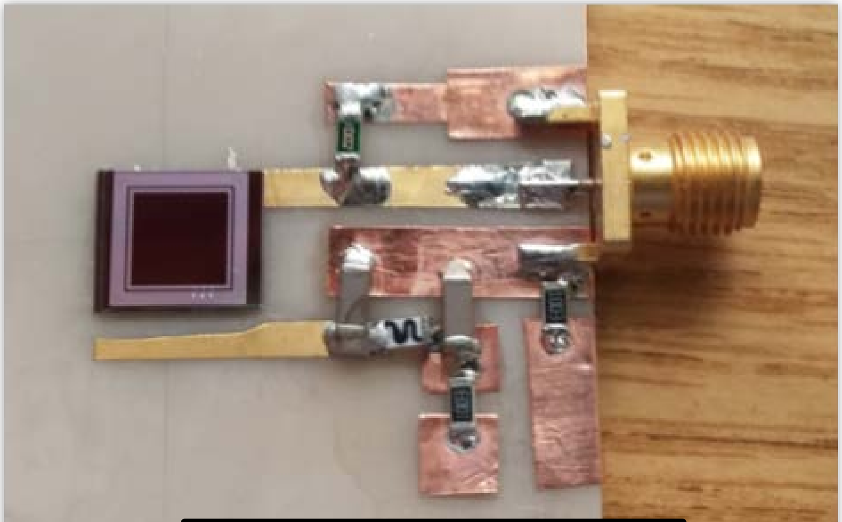
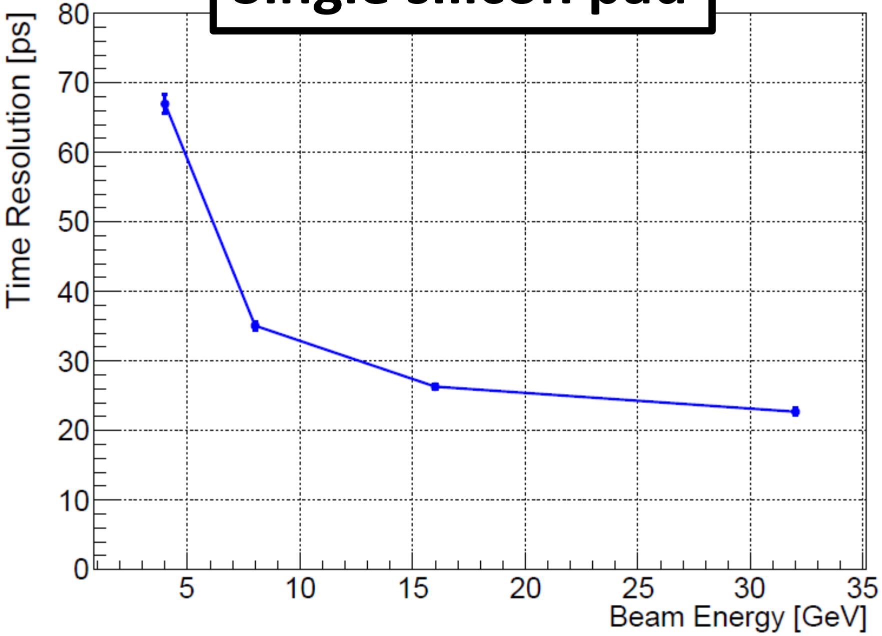


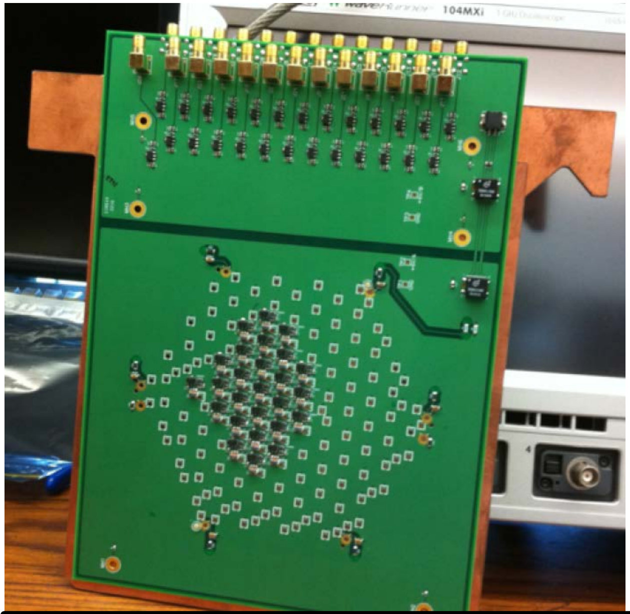
Fig. 5.27–28 HGCal TDR

# Si Pad Timing

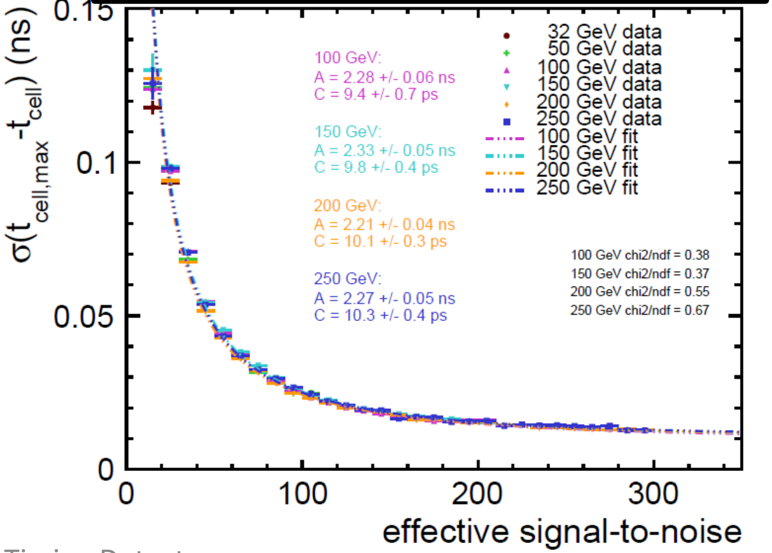


**Single silicon pad**

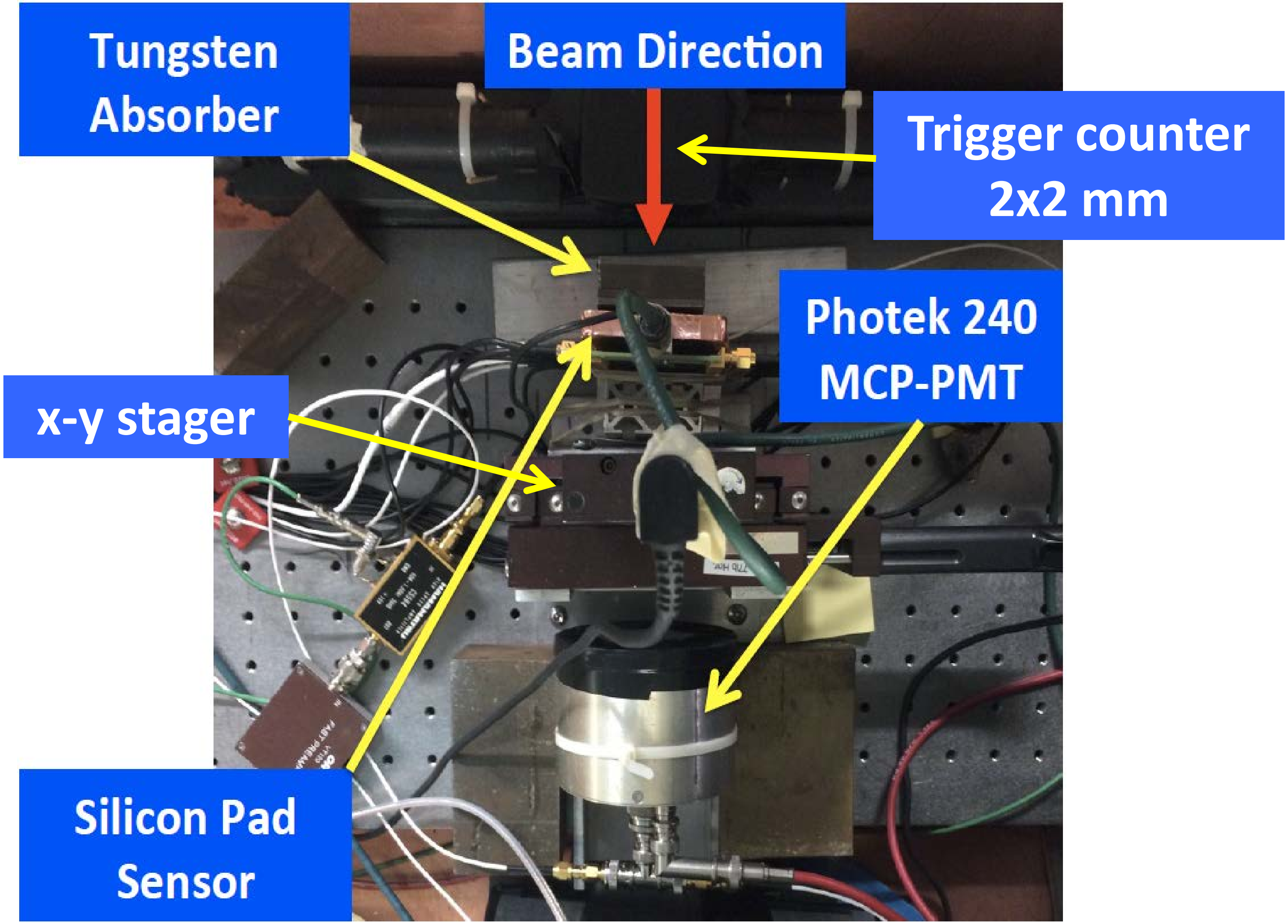




**Silicon sensor, 128 pads**



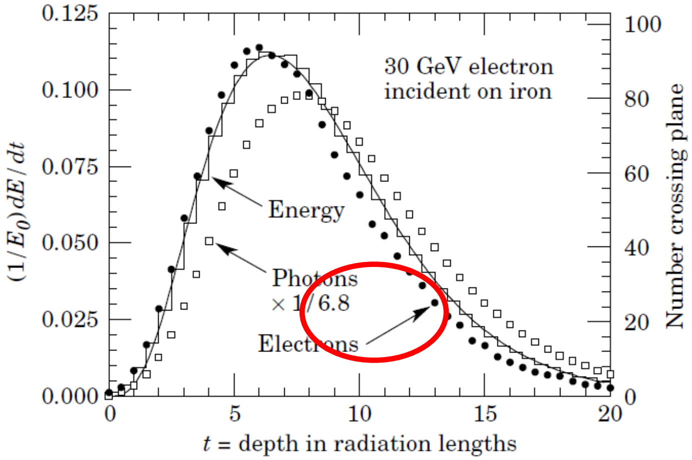
# Early R&D in Test Beam



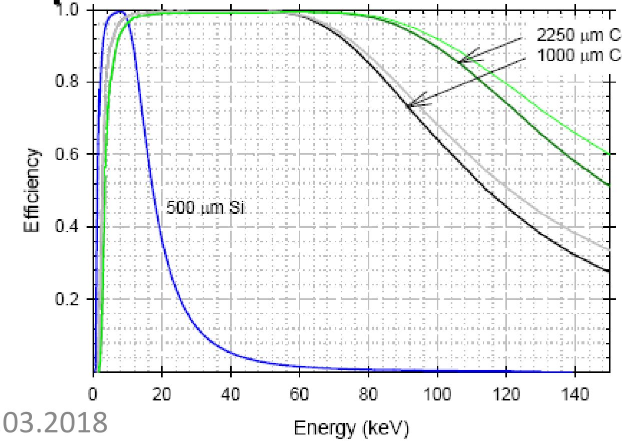
# Timing Calorimeter with CdTe

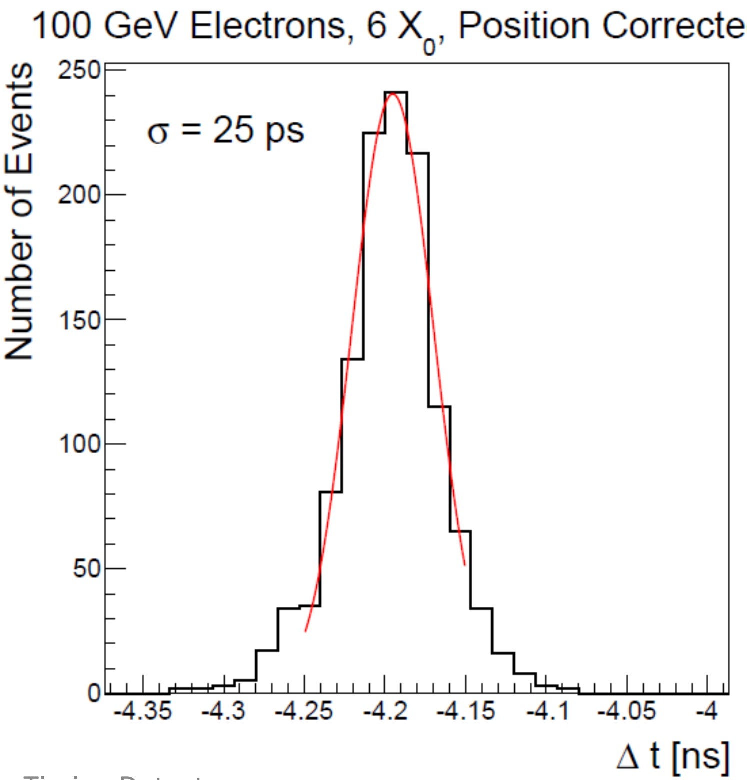
- **MIP : 50k electrons in 300 μm.**
- **CdTe density ~5.8 g/cm$^3$**
- **Sensor thickness (here : 1 mm).**
- **CdTe ideal for calorimeters**

**EM Showers are photon rich**

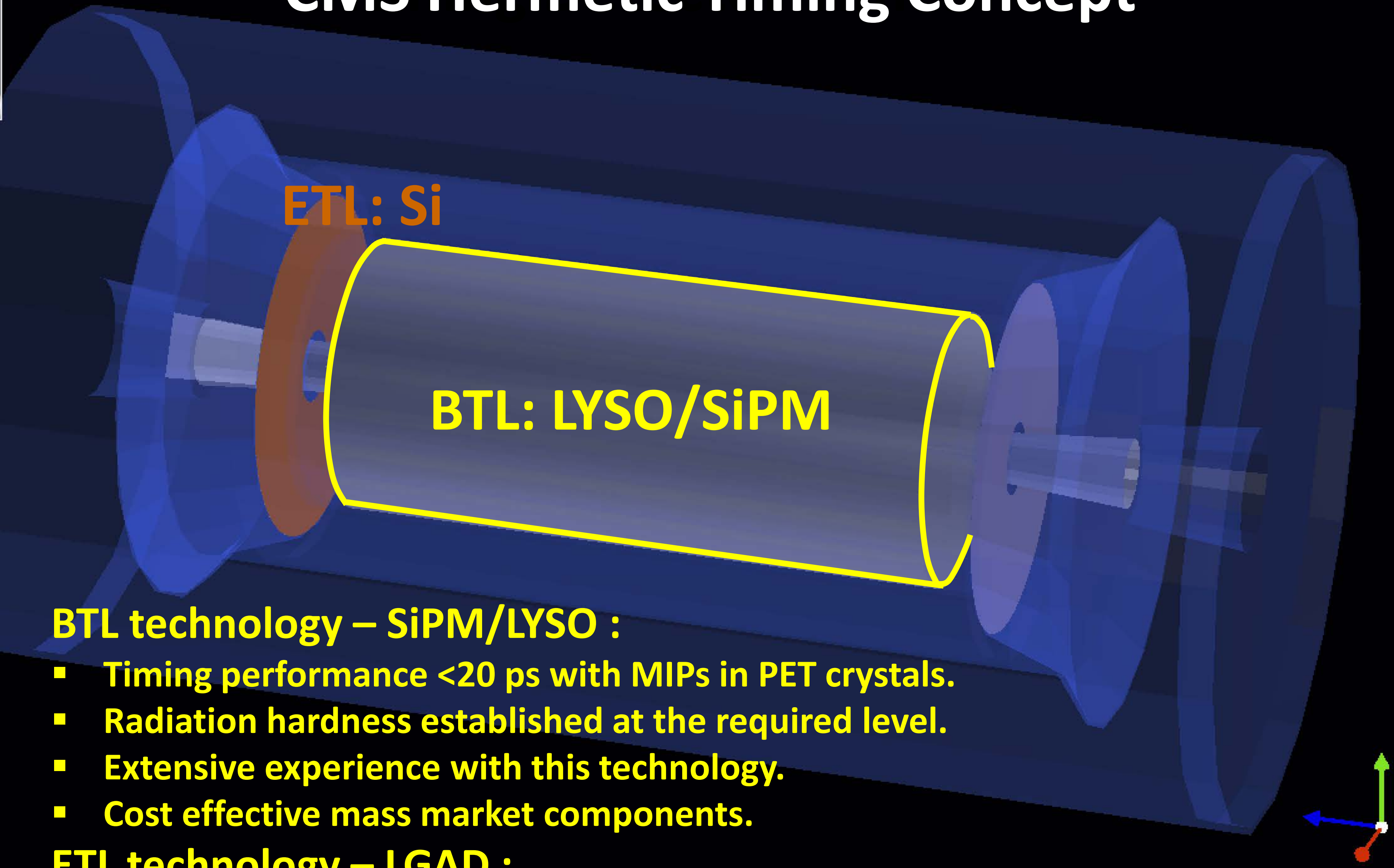


**photon detection with CdTe**





# CMS Hermetic Timing Concept



**BTL technology – SiPM/LYSO :**

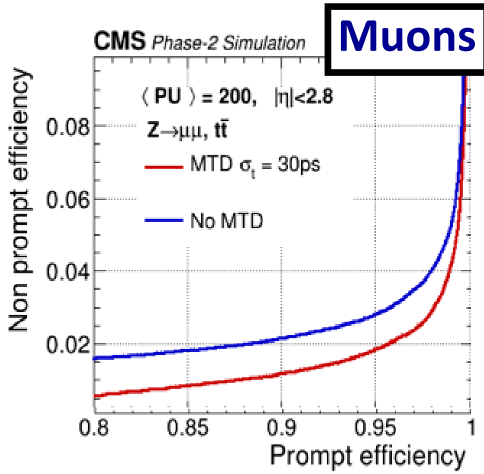
- Timing performance <20 ps with MIPs in PET crystals.
- Radiation hardness established at the required level.
- Extensive experience with this technology.
- Cost effective mass market components.

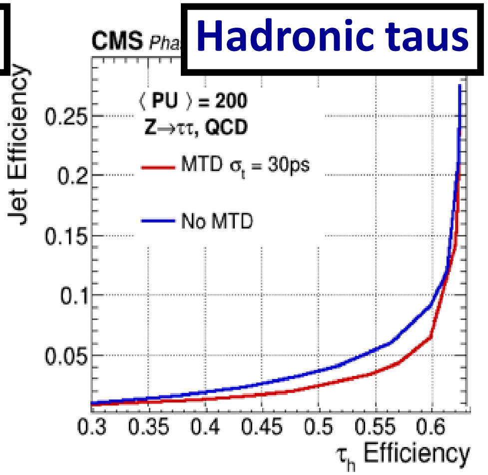
**ETL technology – LGAD :**

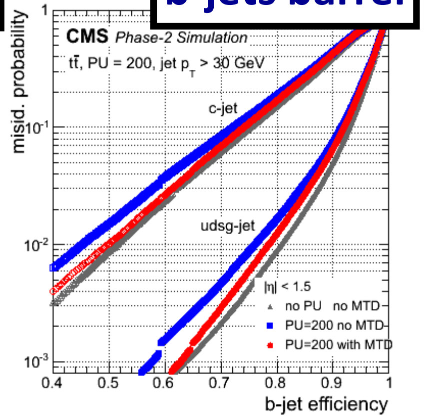
- Timing performance of 30 ps established with latest sensors
- Very radiation hard technology

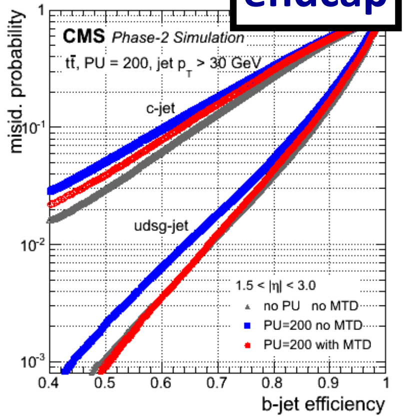
# Reconstruction benefits with MTD

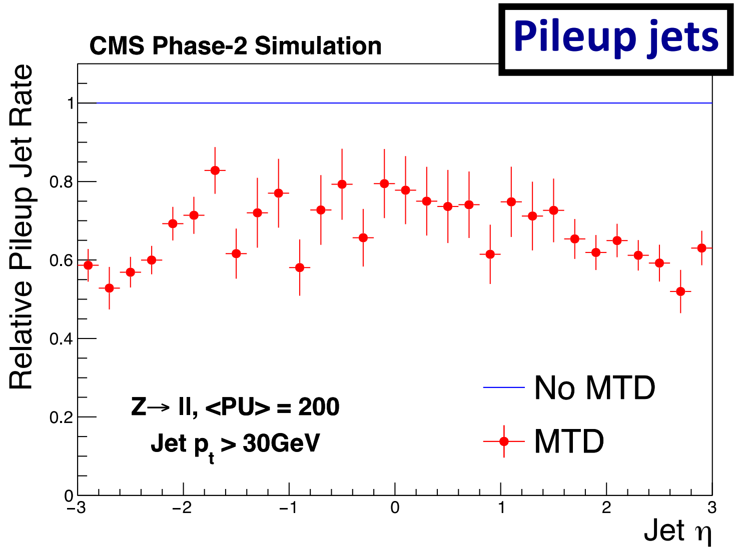
- **Single object gains compound in multi-object final states**

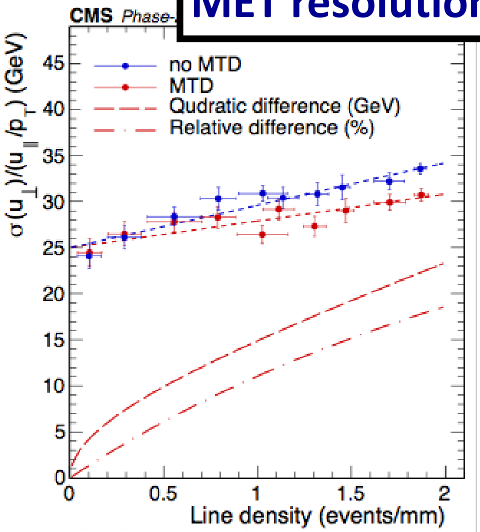

**Muons**

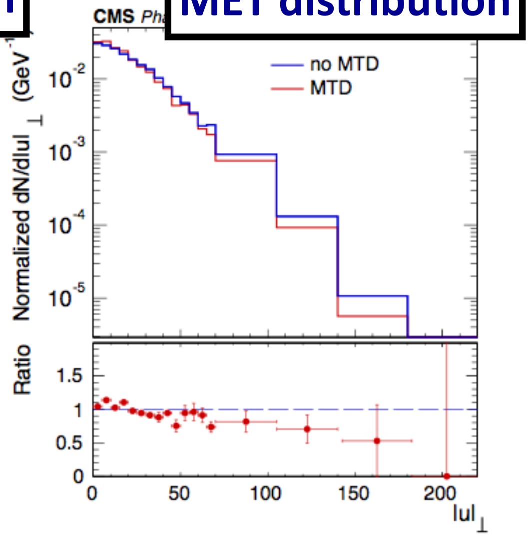

**Hadronic taus**


**b-jets barrel**


**endcap**


**Pileup jets**


**MET resolution**

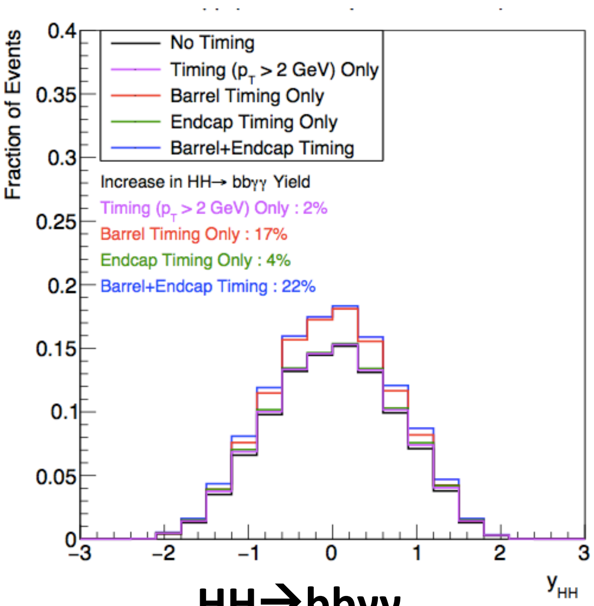

**MET distribution**

# H/HH acceptance gains from MTD

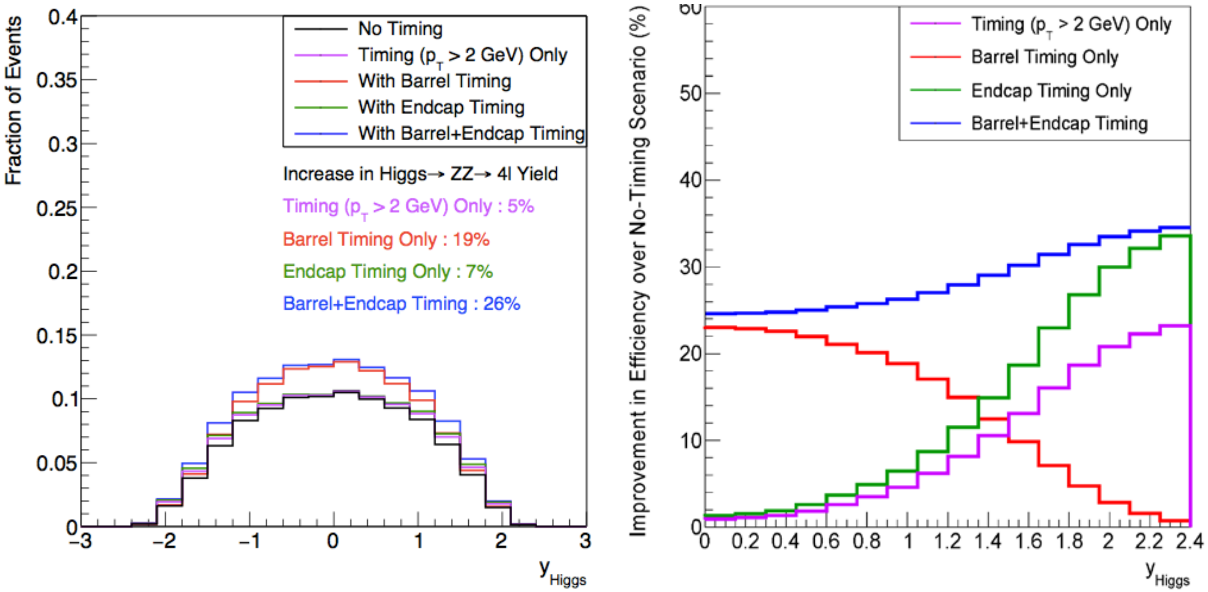
- **Gain in signal yields (i.e. effective luminosity): 18-26% (*)**

| | HGC | ETL | BTL | MTD | Localized observables |
|---|---|---|---|---|---|
| **HH→bbbb** | +2% | +4% | +14% | **+18%** | b-tagging |
| **HH→bbγγ** | +2% | +4% | +17% | **+22%** | b-tagging + photon identification |
| **H→4l** | +5% | +7% | +19% | **+26%** | Lepton isolation (**) |

(**) No precision timing for μ's in HGCal



**HH→bbγγ**

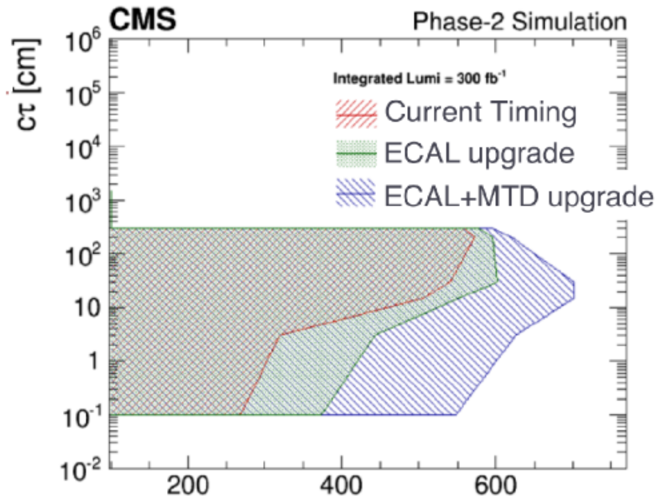


**H→4l:** more than 50% from ETL at $|y_H| > 1.4$

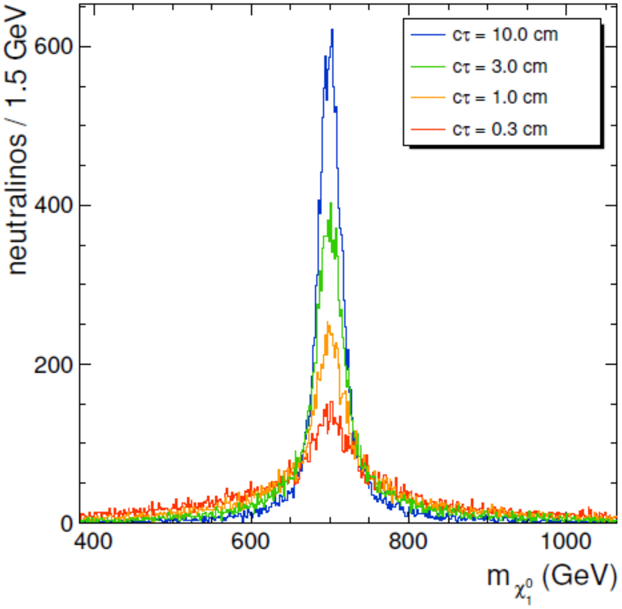
*(*) Projections at constant rejection power for the reducible background*

# Long-lived Particles

- **Nominal large increase in search reach for massive long-lived particles decaying to photons, combining calorimeter and MTD timing**
- **For a range of topologies, MTD allows reconstruction of a peaking mass variable, which introduces a qualitatively new capability for long-lived-particle searches**
- **BTL relatively more important for this case due to central signatures**



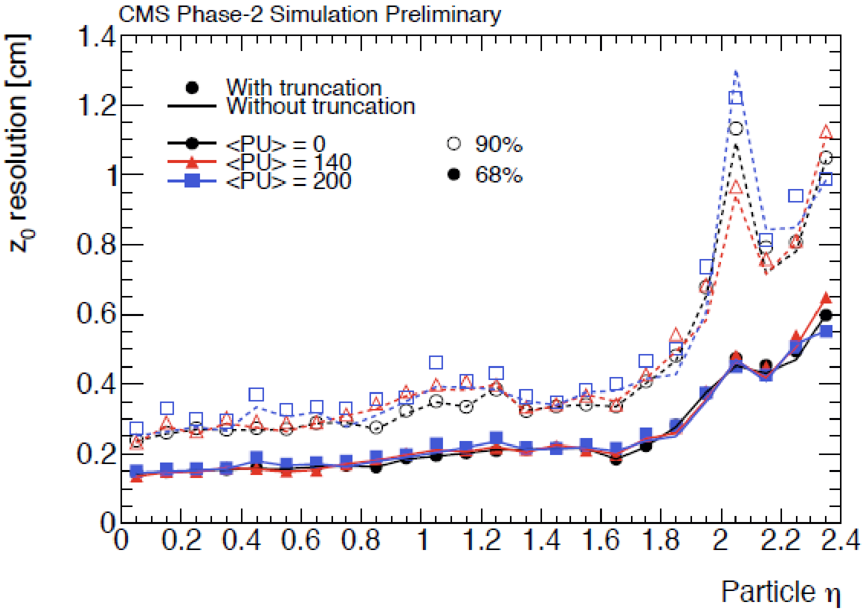
(a) $\chi_1^0 \to G + \gamma$ Limits



(b) $\chi_1^0 \to G + Z$ Peaking Variable

# MTD in the Trigger

- **Full set of object-level performance gains from timing can be realized also in the High Level Trigger**
- **Additional opportunity to save CPU time with timing-based cleaning early in trigger sequences**
- **Possible integration of MTD into hardware trigger could allow, together with track trigger, determination of primary vertex time and use of timing performance for Particle Flow**



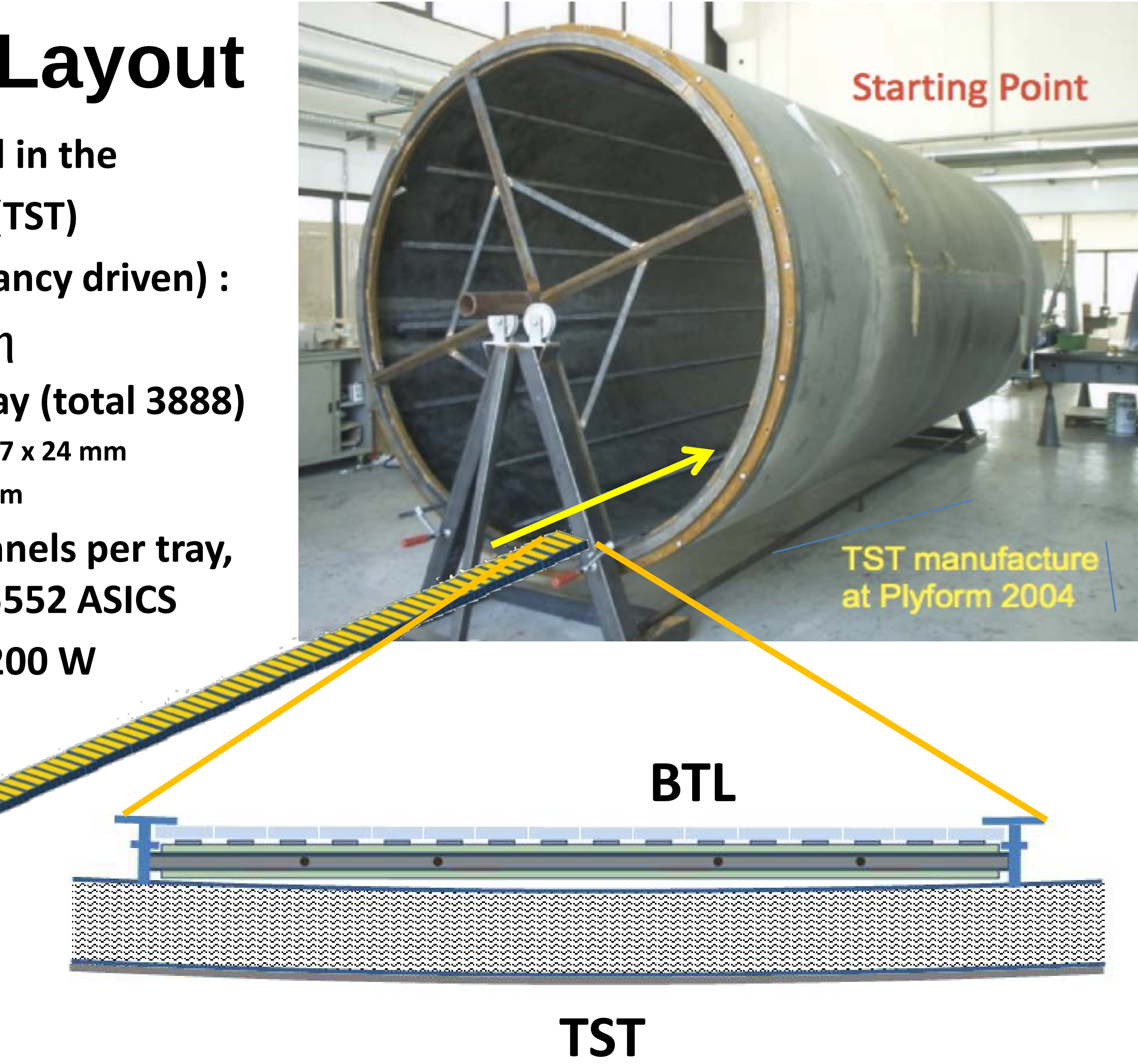
Track Trigger $z_0$ resolution

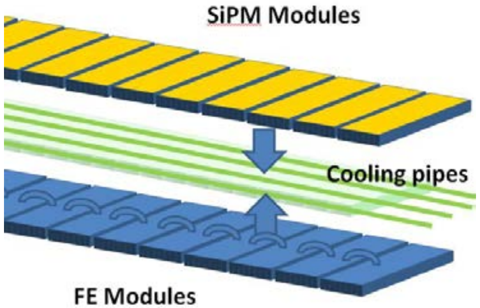
# BTL Layout

**BTL will be embedded in the tracker support tube (TST)**

**Segmentation (occupancy driven) :**

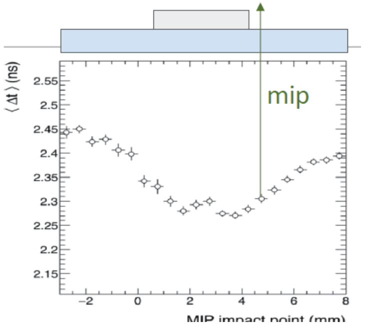
- **36 trays in φ, 2 in η**
- **54 Modules per tray (total 3888)**
  - **Module size : 185 x 47 x 24 mm**
  - **Tray length: ~2500 mm**
- **3456 crystals/channels per tray, 248832 in total, 15552 ASICS**
- **Each tray ~20 Kg, 200 W**
- **Operation at -30 C**



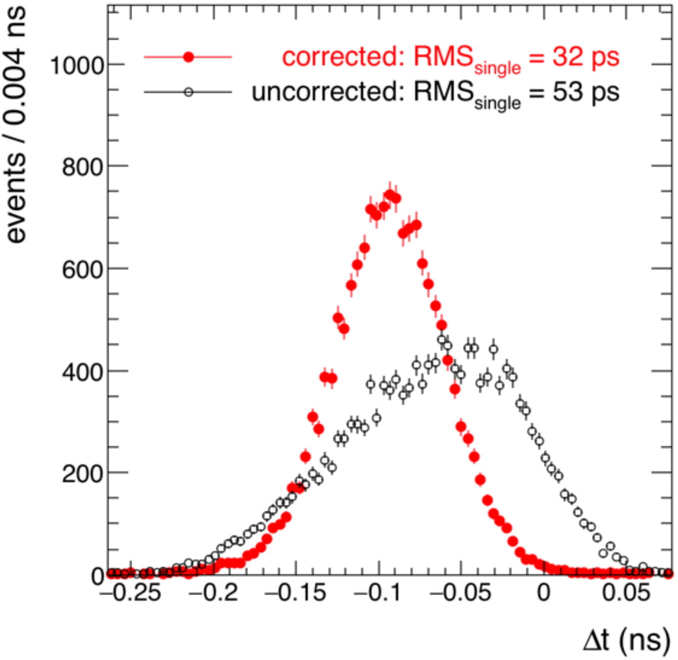


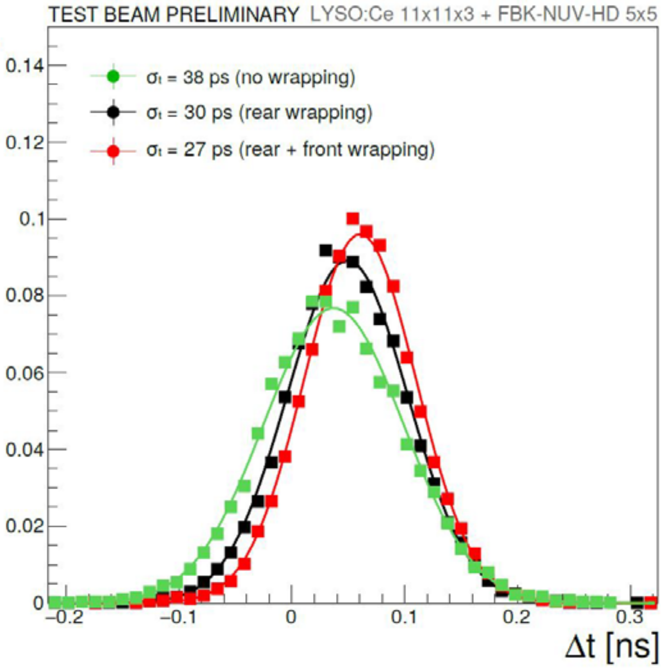
# BTL Sensors

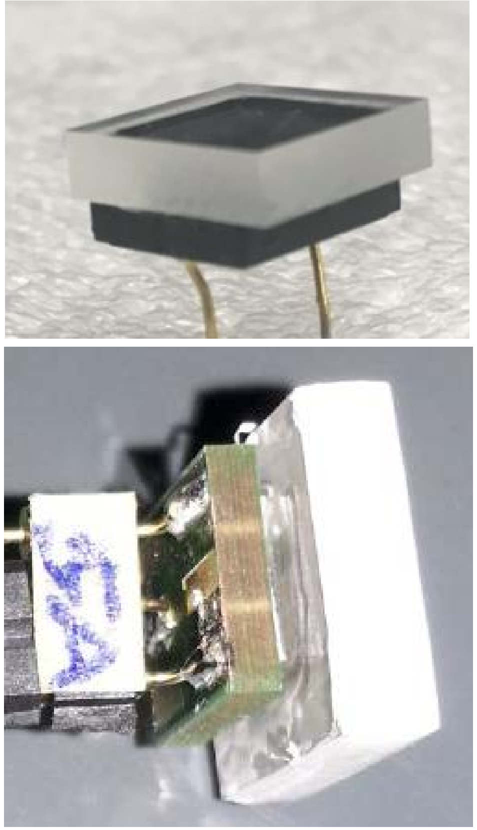
- **Nominal sensor geometry : 11 x 11 mm$^2$ LYSO + 4x4 mm$^2$ SiPM.**
  - **Slant thickness is ~4 mm**
  - **Scintillation light yield 7x larger than in PET, light collection efficiency lower.**



- **Sensor uniformity and light collection efficiency :**
  - **Left plot : Full sensor timing with and without impact point correction.**
  - **Right plot : Central impact with different wrapping**
  - **⇒ Optimize light extraction, SiPM/LYSO aspect ratio.**

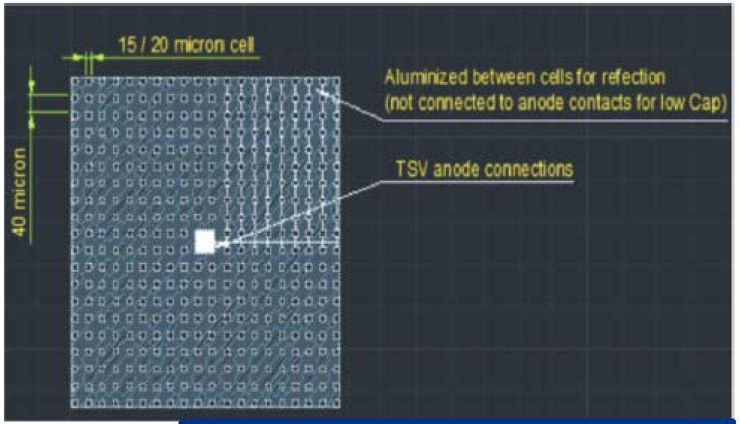




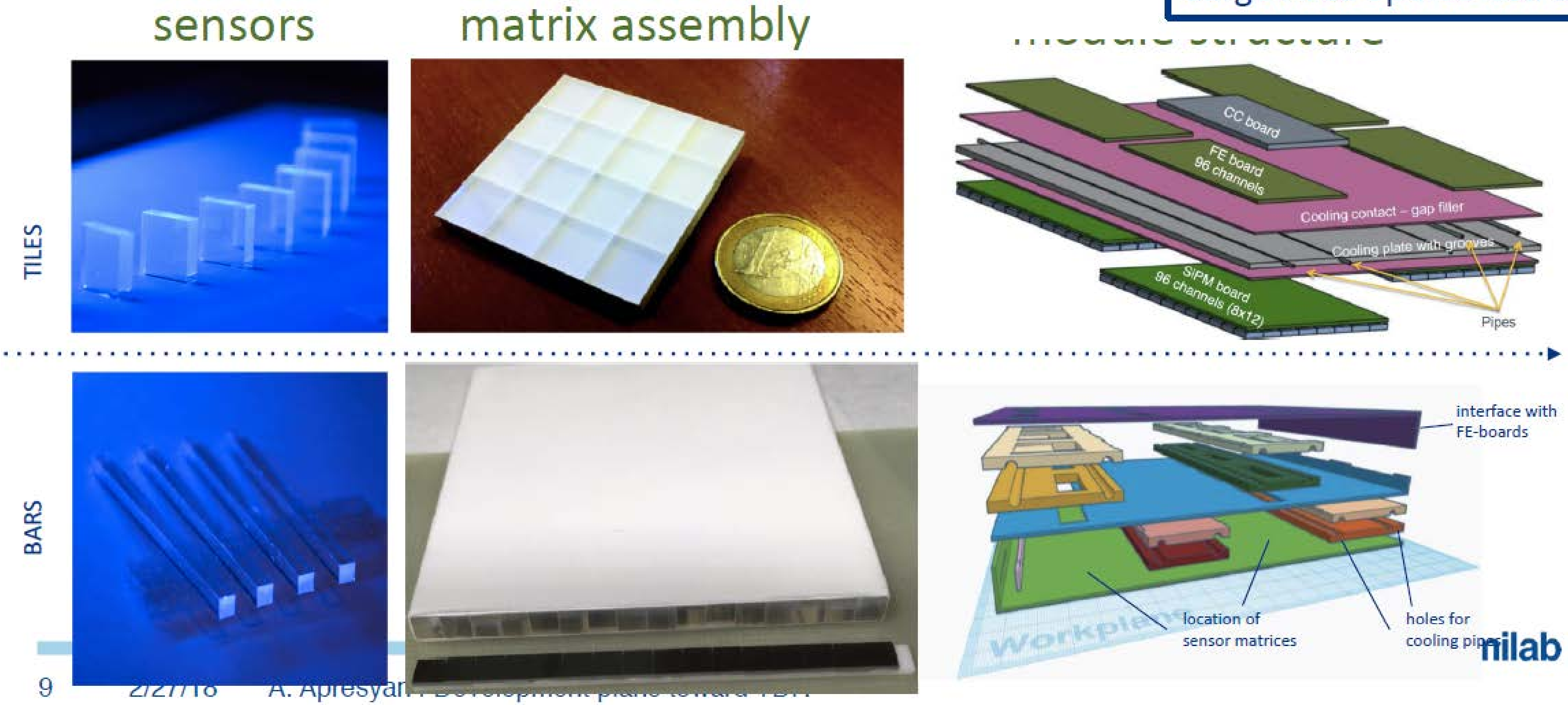


# BTL module R&D

- **Two LYSO geometries considered, tiles and slabs.**
- **Slabs reduce impact point dependency.**
- **R&D on SiPMs for tile geometry improve uniformity.**

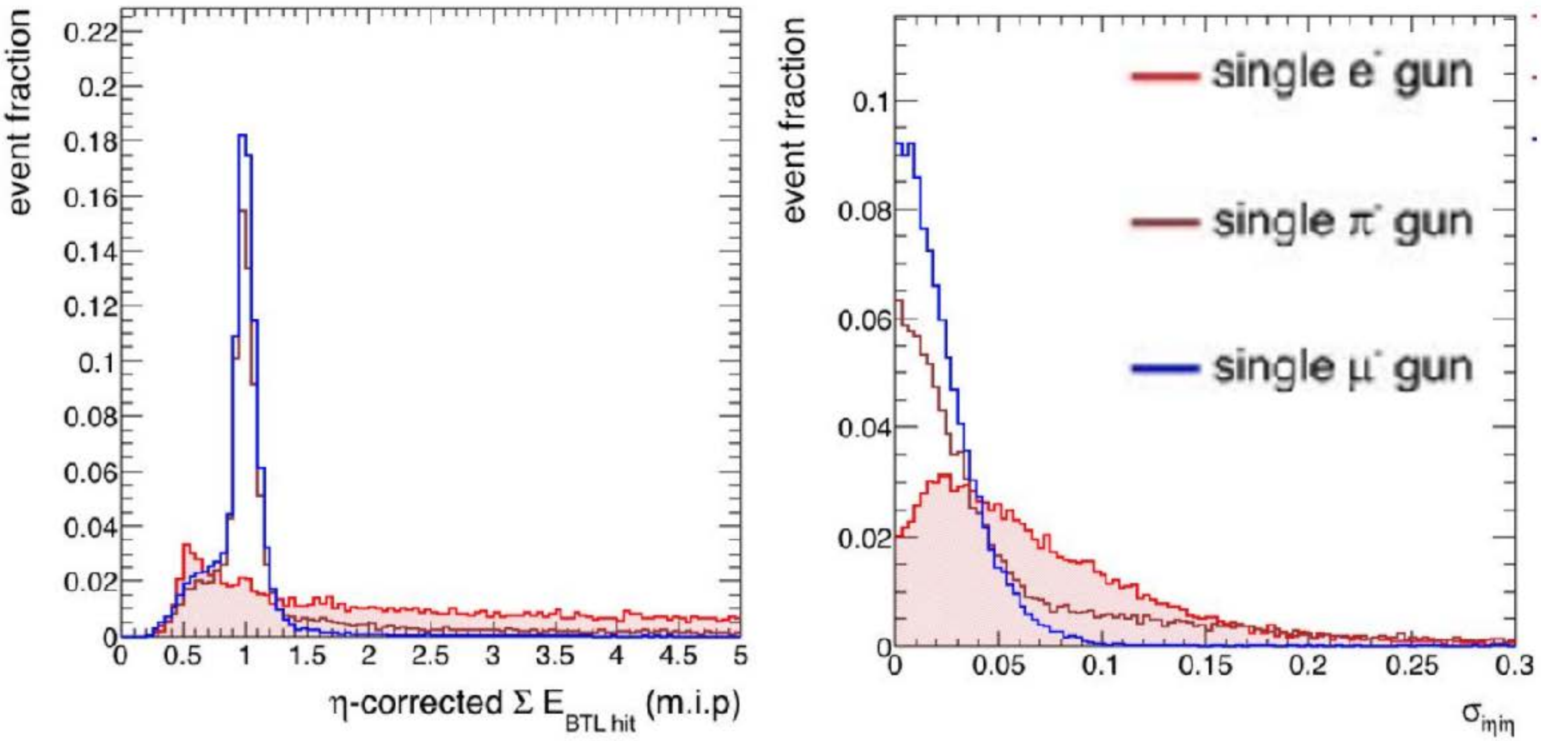


Large Area Sparse Cell SiPMs



# Further Applications of BTL

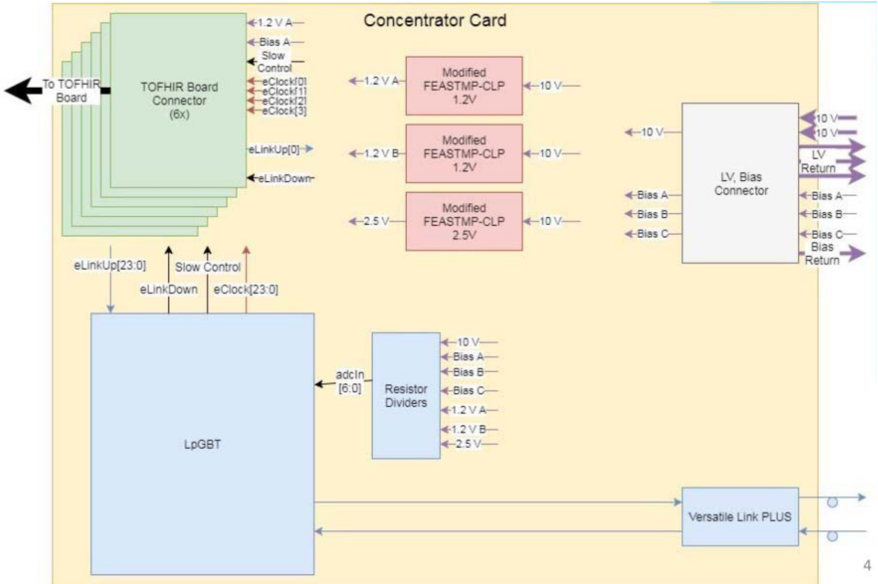
- **BTL sensors have good energy resolution for very low energy particles.**
- **Allows to utilize energy deposits for electron ID, energy corrections for showering electrons, etc.**



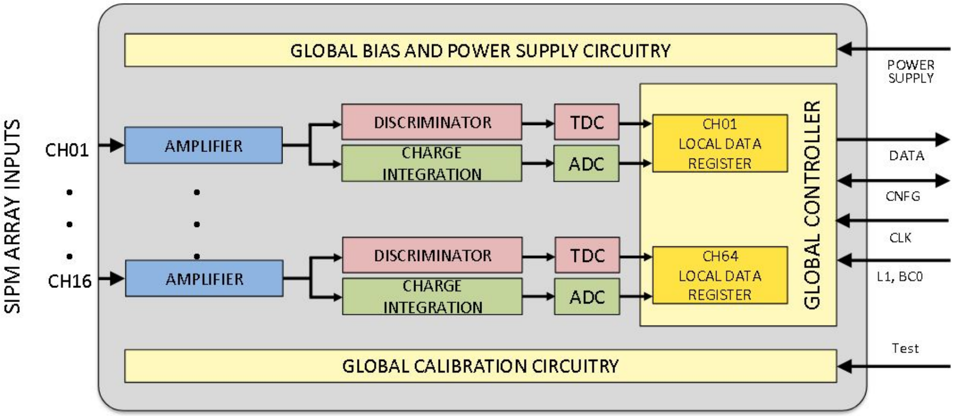
# BTL Electronics

- **TOFHIR (Time Of Flight at High Rate) derived from TOFPET, to be submitted 03/2018.**
- **Concentrator cards serve 6 TOFHIR chips, connecting to lpGBT**

**Concentrator Card**

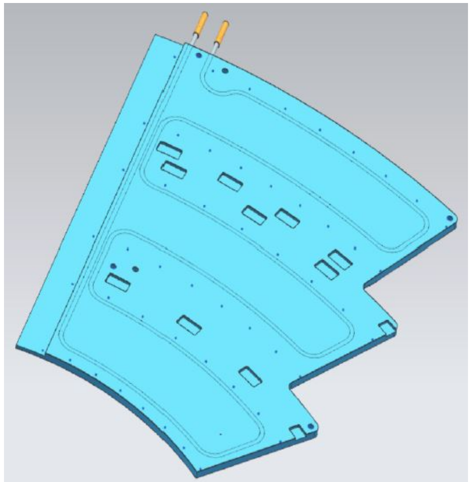


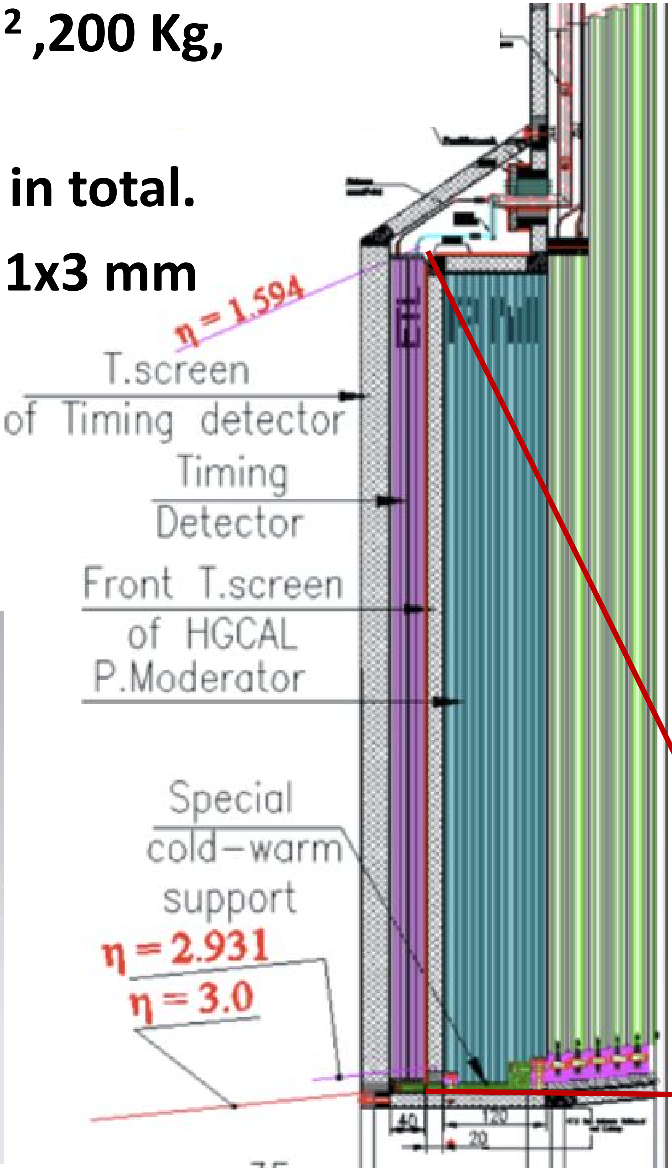
**TOFHIR diagram**

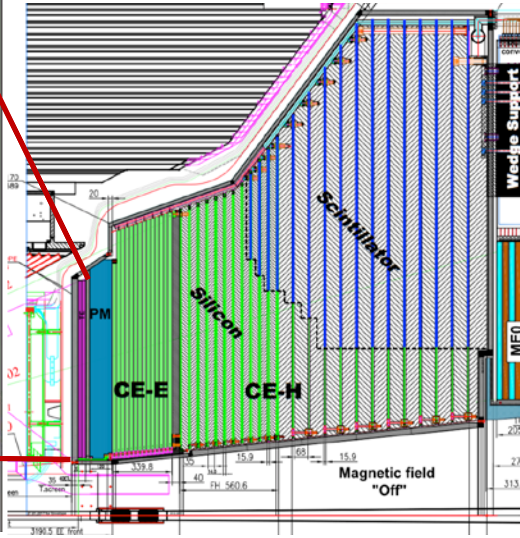


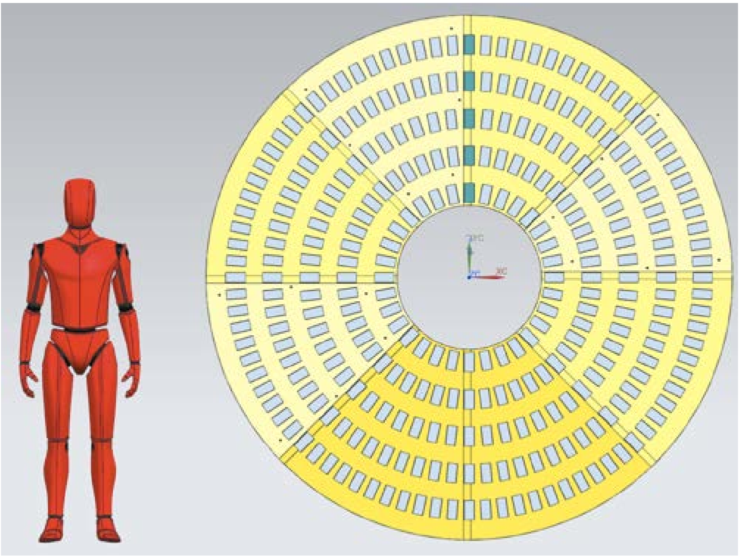
# Endcap Timing Layer

- **Embedded in the neutron moderator in front of HGCAL, size 6 m$^2$ ,200 Kg, thickness 42 mm.**
- **Modules of 5x10 cm, 2624 in total.**
- **Each sensor made of 1536 1x3 mm pads.**



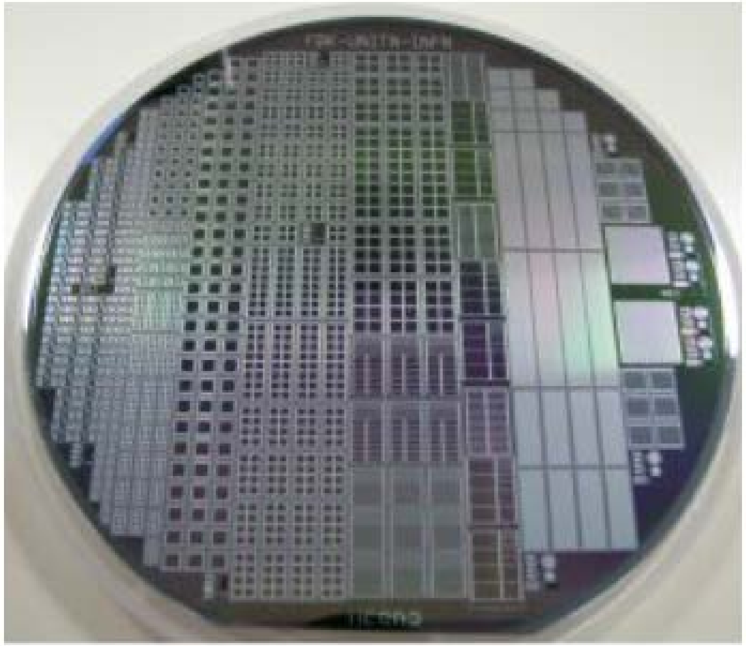


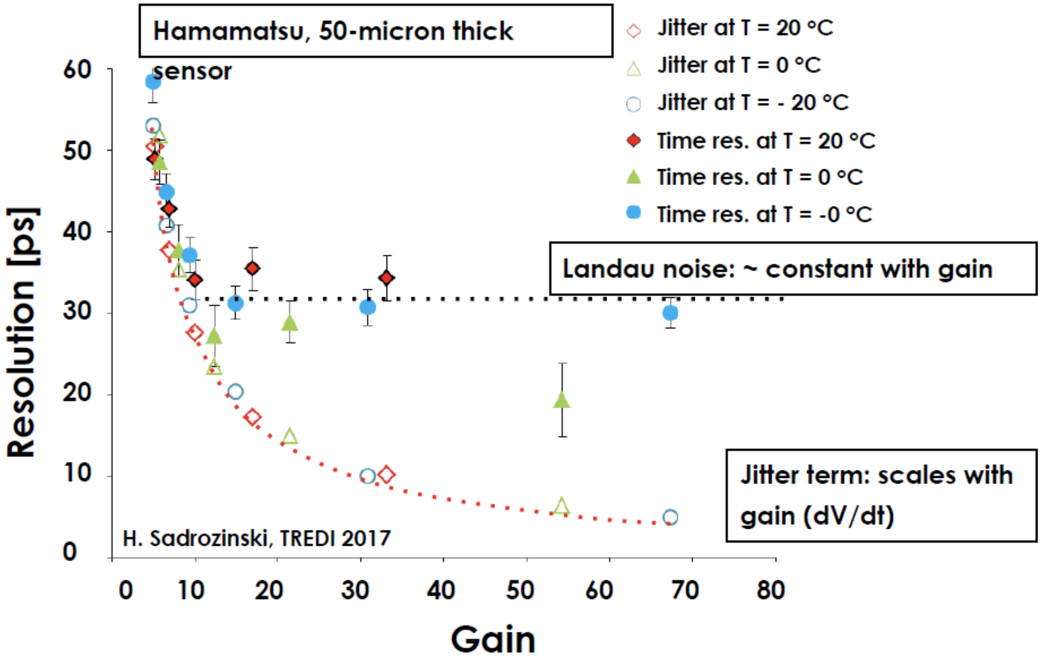




# ETL Sensor R&D

- **LGAD sensors – talk by Joern Lange (Tuesday).**
- **Very active R&D to improve radiation hardness, packing fraction and timing performance.**
- **Technology synergies with silicon trackers.**





Hamamatsu, 50-micron thick sensor

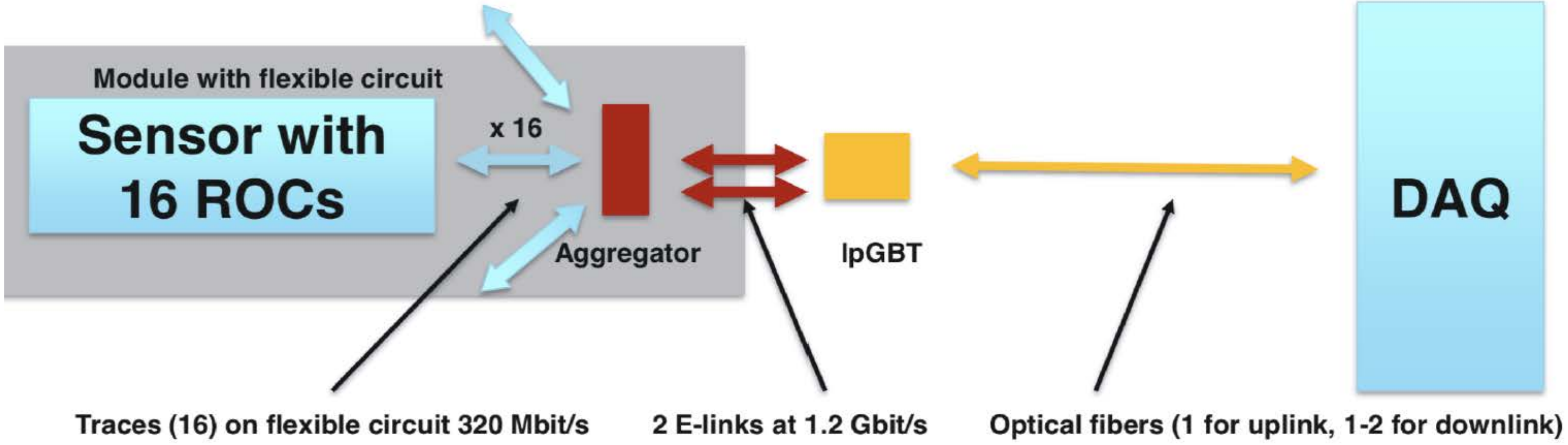
Landau noise: ~ constant with gain

Jitter term: scales with gain (dV/dt)

H. Sadrozinski, TREDI 2017

# ETL Readout Electronics.

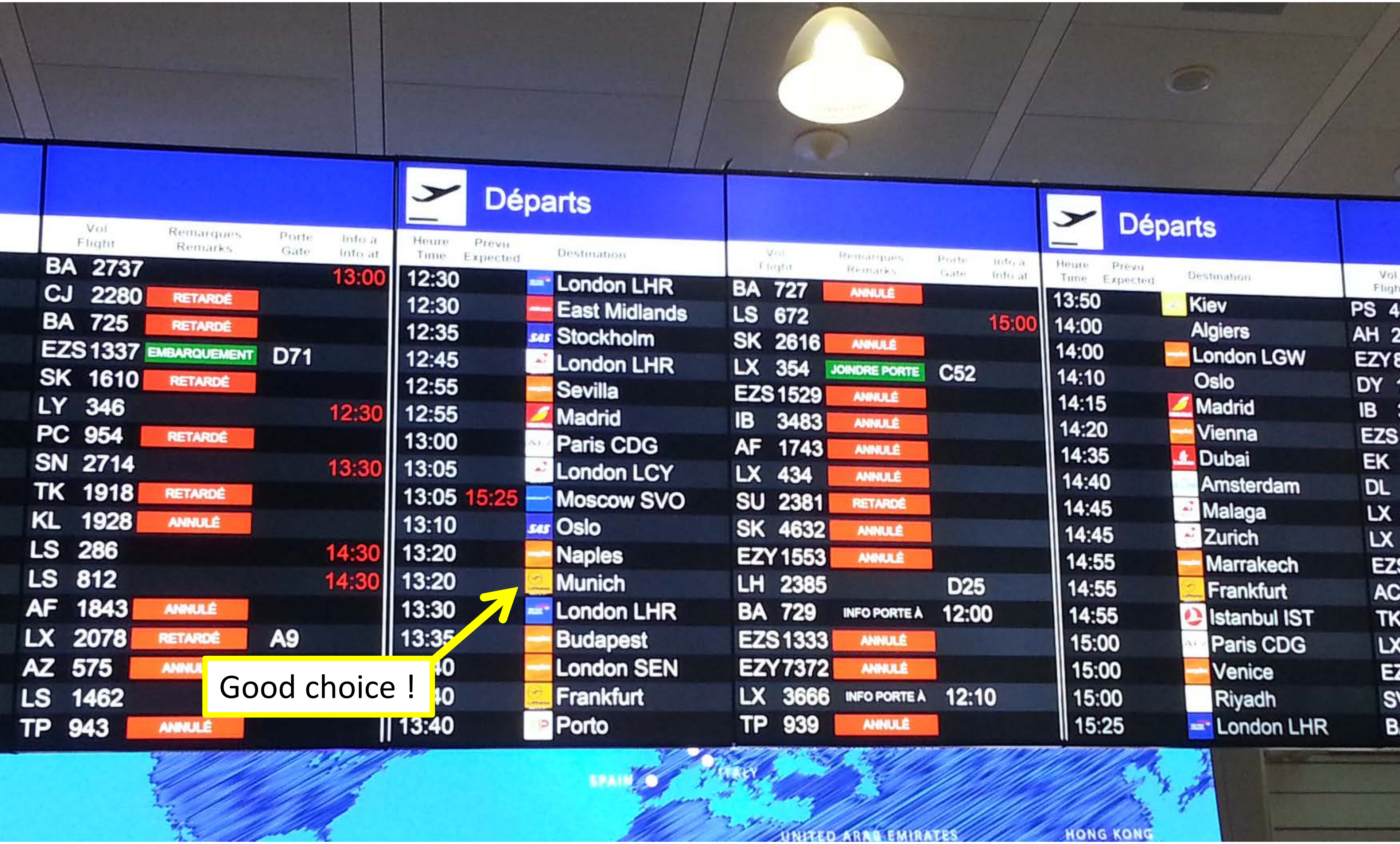
- **ETL ASIC :**
  - – **Specifications and architecture elements designed**
  - – **One chip: matrix of 4x24 LGAD pixel, 3mW/ch, 12.5 us buffer, 20 ps TDC binning**
  - – **TSMC 65nm: experience, libraries, rad. dam models from RD53 & lpGBT**
- **Q4/2018 : digital prototype submission to test :**
  - – **global 20 ps all digital DLL, differential delay elements with digital control/programmability of delay, differential drivers distribute 20 ps timing lines across large chips**
  - – **implementation of radiation hardness by design TMR**
- **Q3/2018 : analogue prototype submission to test :**
  - – **fast pre-amplifier, leading edge discrimination, ToT vs CFD measurement with 20 ps**
  - – **implementation of radiation hardness**



# Summary

- The Phase II upgrade of CMS will have precision timing capabilities for the Calorimeters and tracks.
- The MIP timing detector will provide time tagging for tracks at the level of 30 ps.
- Yesterday, the LHCC recommended to proceed to a TDR for the CMS MTD by the end of 2018
- Very active R&D for precision timing detectors, working towards 1 ps resolutions – 1 ps = 0.3 mm.

# Thank you !

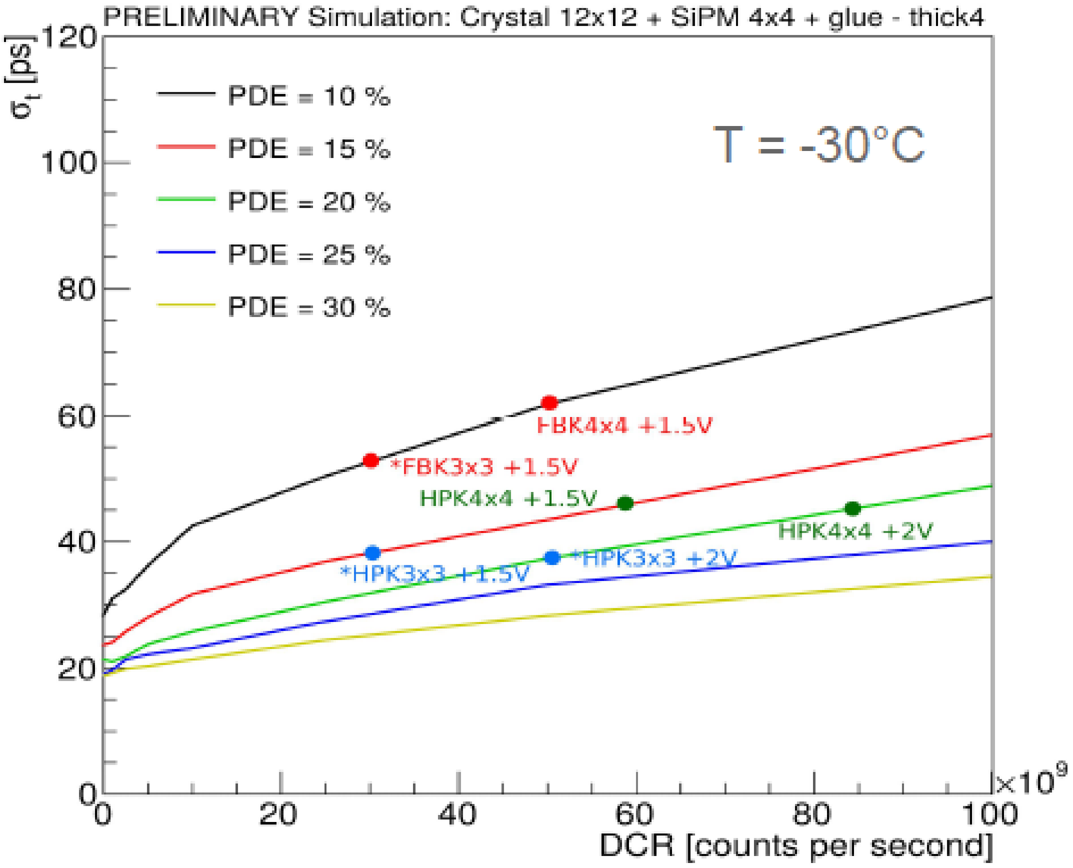


Good choice !

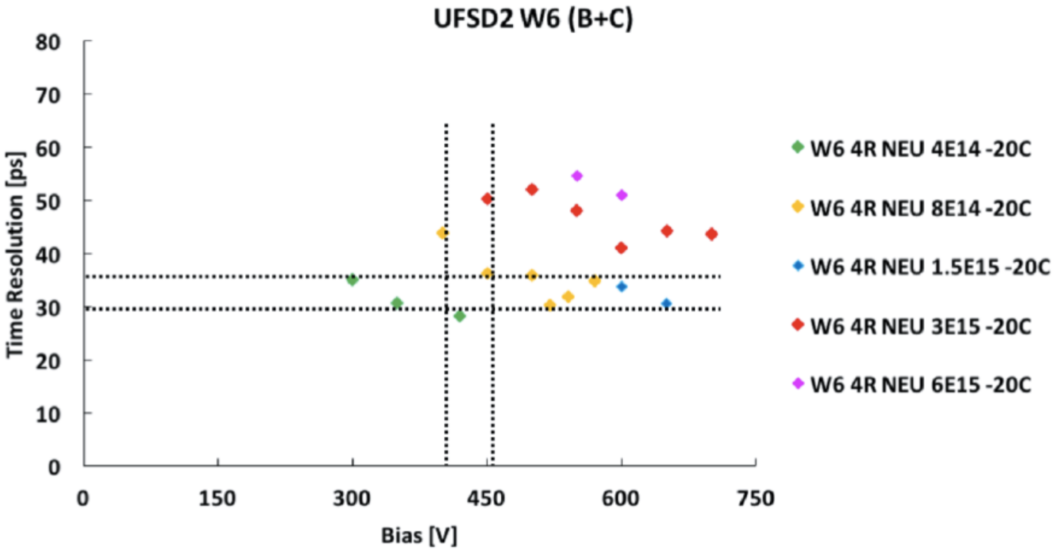
# Backup

# BTL Radiation Hardness

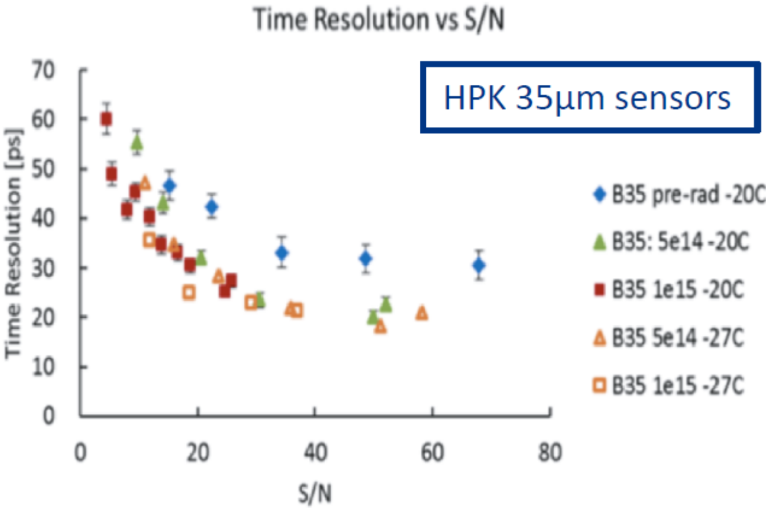
**Goal : <40 ps at the end of HL-LHC**



# ETL Radiation Hardness



Achieved 30 psec up to 1.5x$10^{15}$ n/cm$^2$



HPK 35µm sensors

H. Sadrozinski @HSTD11

# BTL Schedule

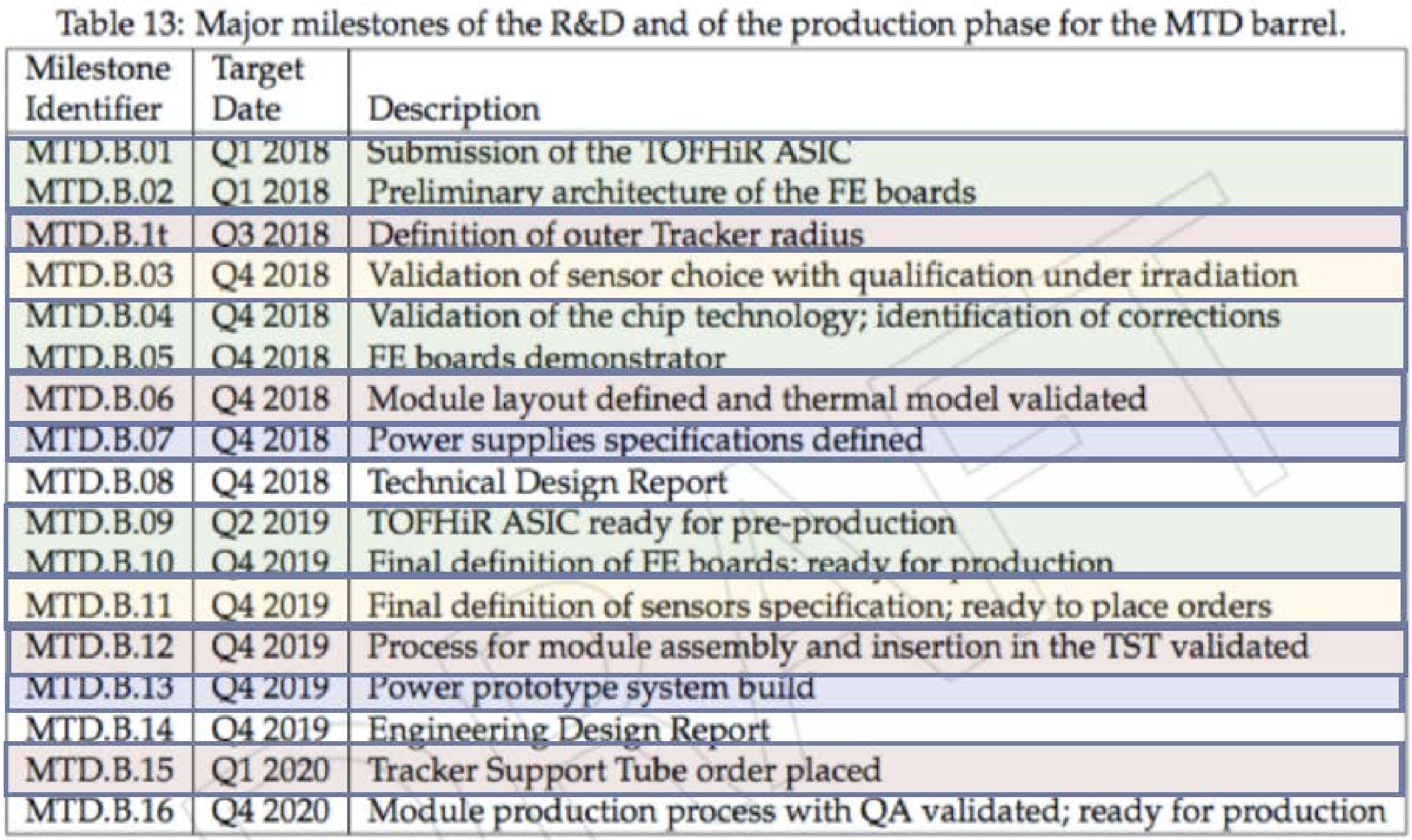


Table 13: Major milestones of the R&D and of the production phase for the MTD barrel.

| Milestone Identifier | Target Date | Description |
|---|---|---|
| MTD.B.01 | Q1 2018 | Submission of the TOFHiR ASIC |
| MTD.B.02 | Q1 2018 | Preliminary architecture of the FE boards |
| MTD.B.1t | Q3 2018 | Definition of outer Tracker radius |
| MTD.B.03 | Q4 2018 | Validation of sensor choice with qualification under irradiation |
| MTD.B.04 | Q4 2018 | Validation of the chip technology; identification of corrections |
| MTD.B.05 | Q4 2018 | FE boards demonstrator |
| MTD.B.06 | Q4 2018 | Module layout defined and thermal model validated |
| MTD.B.07 | Q4 2018 | Power supplies specifications defined |
| MTD.B.08 | Q4 2018 | Technical Design Report |
| MTD.B.09 | Q2 2019 | TOFHiR ASIC ready for pre-production |
| MTD.B.10 | Q4 2019 | Final definition of FE boards; ready for production |
| MTD.B.11 | Q4 2019 | Final definition of sensors specification; ready to place orders |
| MTD.B.12 | Q4 2019 | Process for module assembly and insertion in the TST validated |
| MTD.B.13 | Q4 2019 | Power prototype system build |
| MTD.B.14 | Q4 2019 | Engineering Design Report |
| MTD.B.15 | Q1 2020 | Tracker Support Tube order placed |
| MTD.B.16 | Q4 2020 | Module production process with QA validated; ready for production |

🟨 SENSORS

🟩 ELECTRONIC

🟥 MECHANICS

🟦 SYSTEM

# ETL Schedule

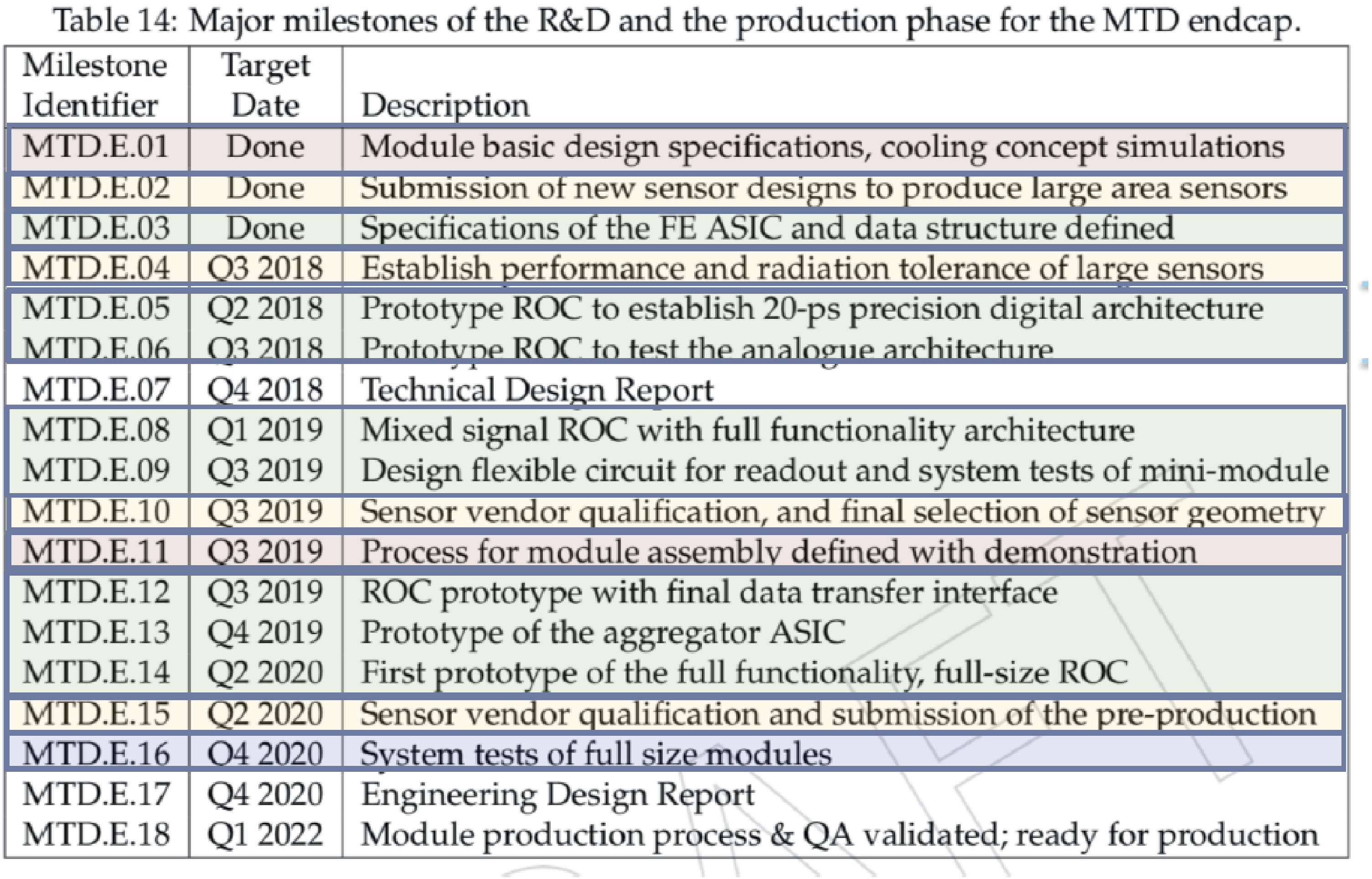


Table 14: Major milestones of the R&D and the production phase for the MTD endcap.

| Milestone Identifier | Target Date | Description |
|---|---|---|
| MTD.E.01 | Done | Module basic design specifications, cooling concept simulations |
| MTD.E.02 | Done | Submission of new sensor designs to produce large area sensors |
| MTD.E.03 | Done | Specifications of the FE ASIC and data structure defined |
| MTD.E.04 | Q3 2018 | Establish performance and radiation tolerance of large sensors |
| MTD.E.05 | Q2 2018 | Prototype ROC to establish 20-ps precision digital architecture |
| MTD.E.06 | Q3 2018 | Prototype ROC to test the analogue architecture |
| MTD.E.07 | Q4 2018 | Technical Design Report |
| MTD.E.08 | Q1 2019 | Mixed signal ROC with full functionality architecture |
| MTD.E.09 | Q3 2019 | Design flexible circuit for readout and system tests of mini-module |
| MTD.E.10 | Q3 2019 | Sensor vendor qualification, and final selection of sensor geometry |
| MTD.E.11 | Q3 2019 | Process for module assembly defined with demonstration |
| MTD.E.12 | Q3 2019 | ROC prototype with final data transfer interface |
| MTD.E.13 | Q4 2019 | Prototype of the aggregator ASIC |
| MTD.E.14 | Q2 2020 | First prototype of the full functionality, full-size ROC |
| MTD.E.15 | Q2 2020 | Sensor vendor qualification and submission of the pre-production |
| MTD.E.16 | Q4 2020 | System tests of full size modules |
| MTD.E.17 | Q4 2020 | Engineering Design Report |
| MTD.E.18 | Q1 2022 | Module production process & QA validated; ready for production |

SENSORS

MECHANICS

ELECTRONIC

SYSTEM