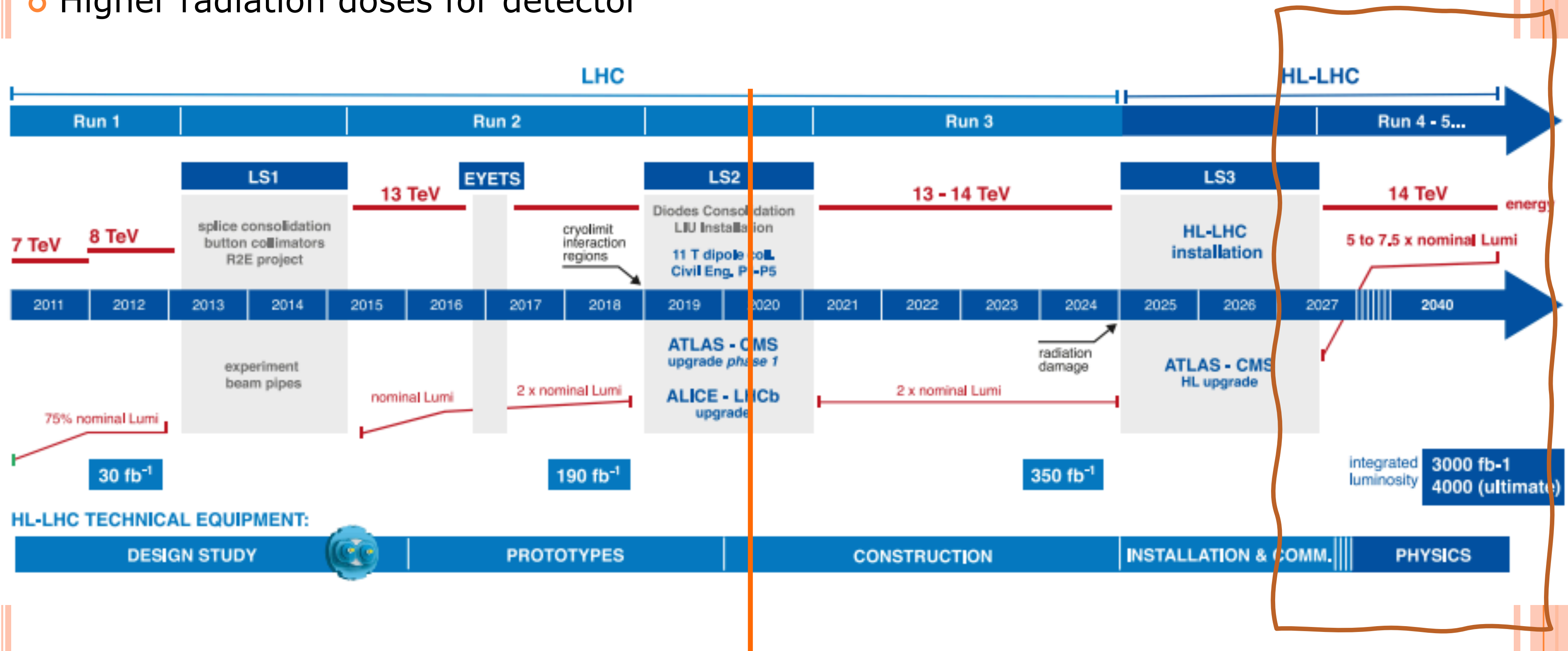
The CMS Outer Tracker Upgrade for the High Luminosity LHC

V.Mariani for the CMS Collaboration

THE LHC SCHEDULE

- High Luminosity LHC is expected to start after LS3:
  - Peak luminosity up to 7.5e34 $cm^{-2}s^{-1}$
  - Expected integrated luminosity ~ 3000 fb^{-1}
  - PU up to 200 interactions per bunch crossing
- Higher radiation doses for detector



We are here

HOW CMS WILL UPGRADE FOR THE HL-LHC

L1-Trigger/HLT/DAQ
https://cds.cern.ch/record/2283192
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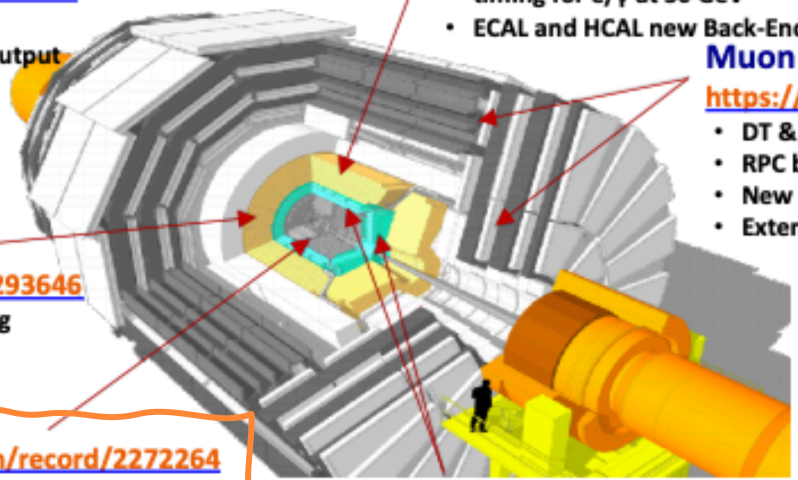
- Tracks in L1-Trigger at 40 MHz
- PFlow-like selection 750 kHz output
- HLT output 7.5 kHz

Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$



Calorimeter Endcap
https://cds.cern.ch/record/2293646
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure
https://cds.cern.ch/record/2020886

Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

MIP Timing Detector
https://cds.cern.ch/record/2296612
Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

An intense upgrade programme is foreseen for the whole experiment

New design and technology are required to fully exploit the HL-LHC scenario!

THE NEW CMS TRACKER DETECTOR

The current CMS tracker was designed to operate up to an integrated luminosity of 500 fb^{-1}, and an average PU of < 50.
It could not operate in HL-LHC scenario due to either leakage current or full depletion voltage limitations at 1 ab^{-1} => **a new tracker detector is needed for CMS**

Requirements:
- High granularity
- Reduced material budget
- **Contribution to the L1 trigger**
- Extended acceptance
- Radiation tolerance

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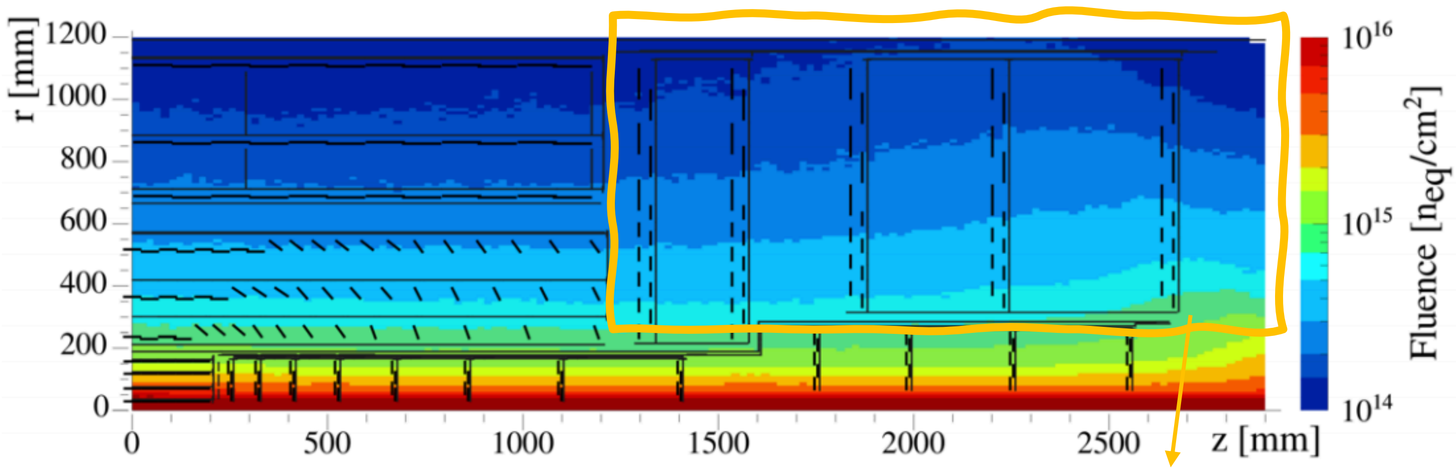
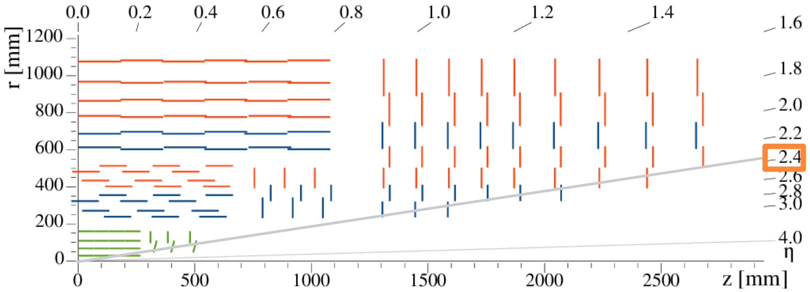


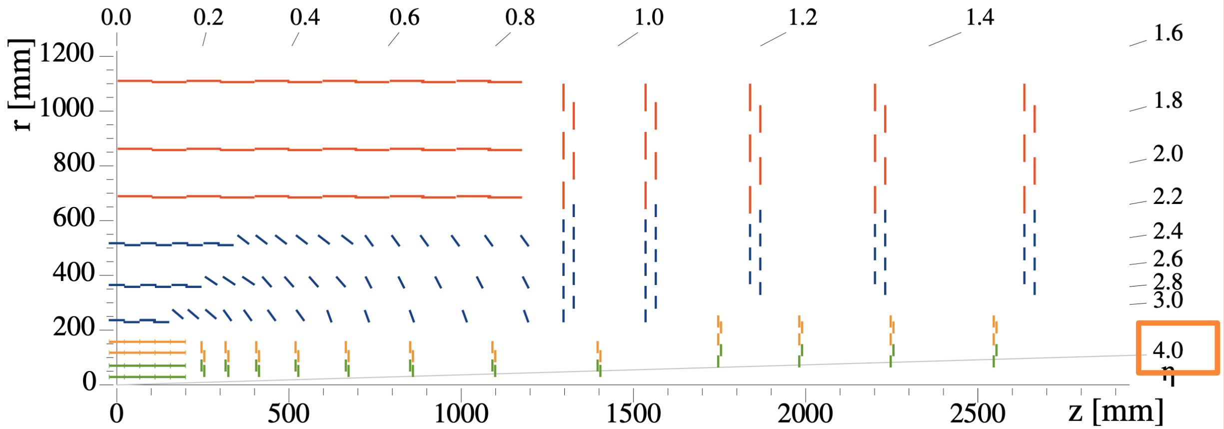
Outer layers "far away" will see >10^{14}MeV neutron equivalent fluence
More than innermost strip tracker layers at 20 cm for today's trackers after 10 years of LHC running

The new CMS Tracker detector

Current tracker (phase 1)



Phase 2 tracker



The new CMS Tracker detector

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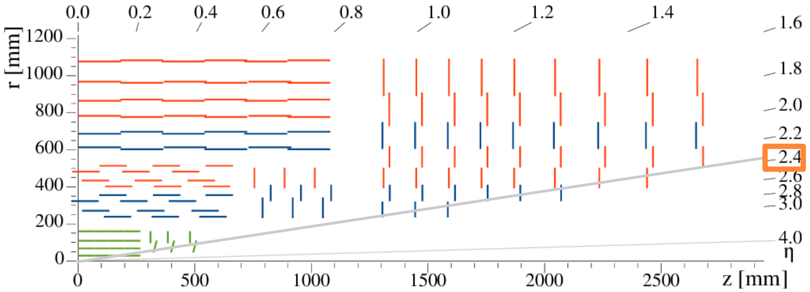
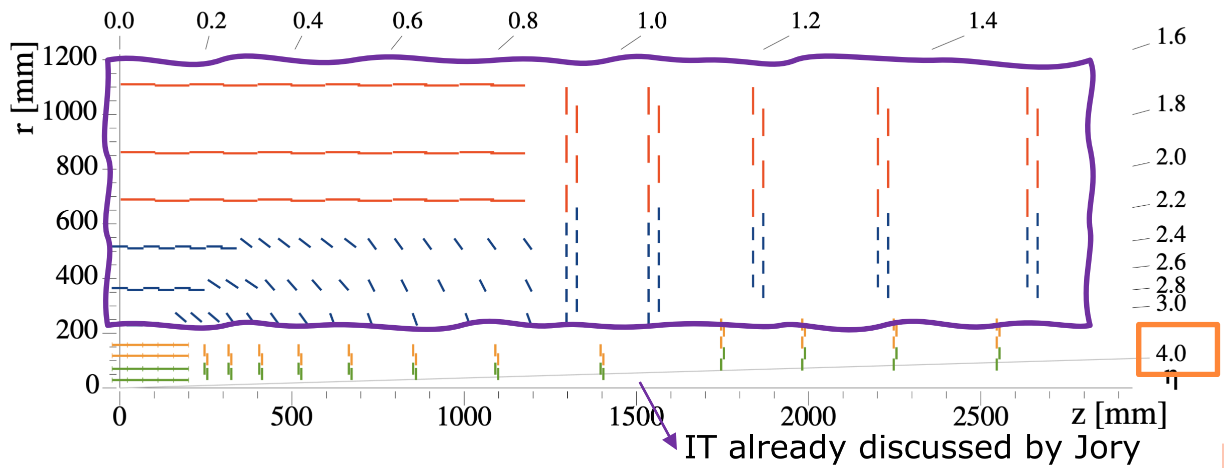


Phase 2 tracker



- The OT coverage will be up to η ~ 2.5 -> global tracking up to η ~ 4 thanks to IT
- Tilted barrel geometry for better trigger performances and reduction of the number of modules
- **pT modules** will be used with two different type of technologies: macro-pixels and micro-strips

THE CONCEPT OF P_T MODULES

- The target L1 rate ~ 750 kHz with a trigger latency of 12.5 μs
- Keep data rate under control in high luminosity && large PU scenario is challenging

Tracks will be used in the L1 decision

Since most of the tracks have low p_T the idea is to perform a selection on track p_T at module level to reduce the L1 tracking input size

The concept of p_T modules

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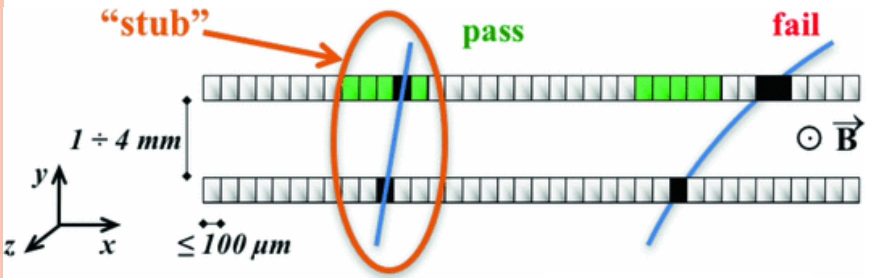
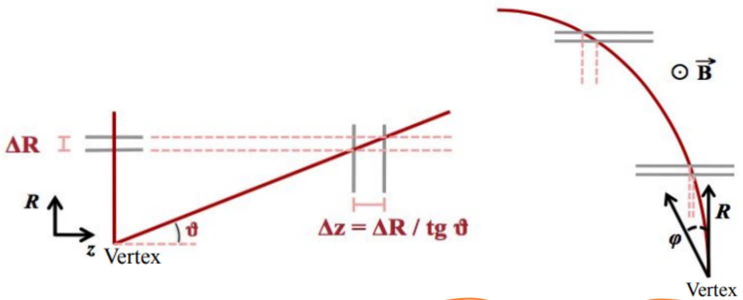




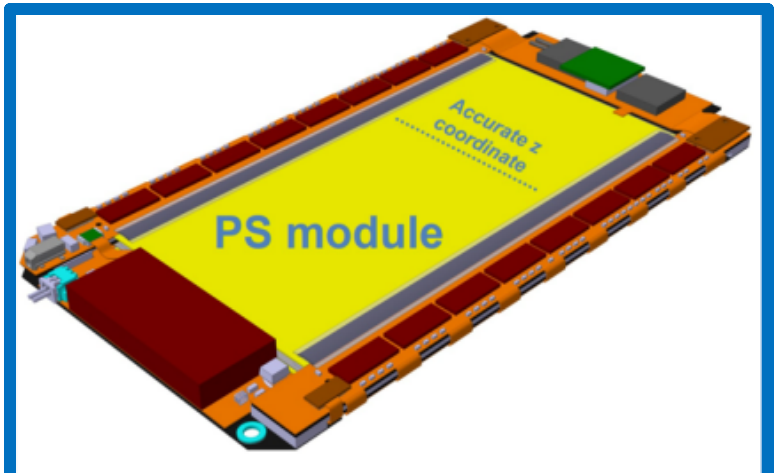
The new modules will be capable rejecting signal from particles below a certain p_T threshold => **p_T modules**

Two single-sided closely-spaced sensors read out by a common set of front-end ASICs that correlate the signals and select the hit pairs => **stub**

Different sensor spacing for different detector region and tunable correlation windows

With a 2GeV threshold, a data reduction by an order of magnitude is achieved enabling stub readout at 40MHz

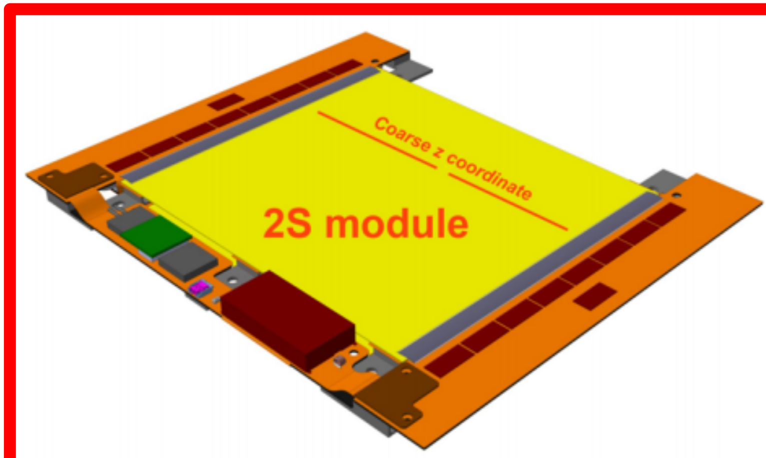
Outer tracker Modules



PS module

1 macro pixel + 1 micro strip sensor

3 different spacing : 1.6mm, 2.6mm & 4mm
Strip sensor with 2.5 cm x 100µm strips
Pixel sensor with 1.5 mm x 100µm pixels
Sensor dimension are 5 cm x 10 cm:
two column of 960 strips+32x960 pixels

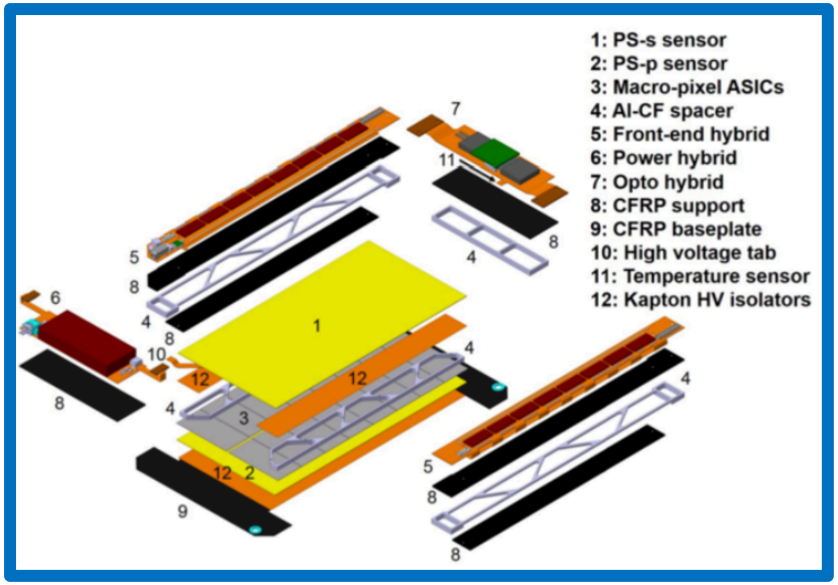


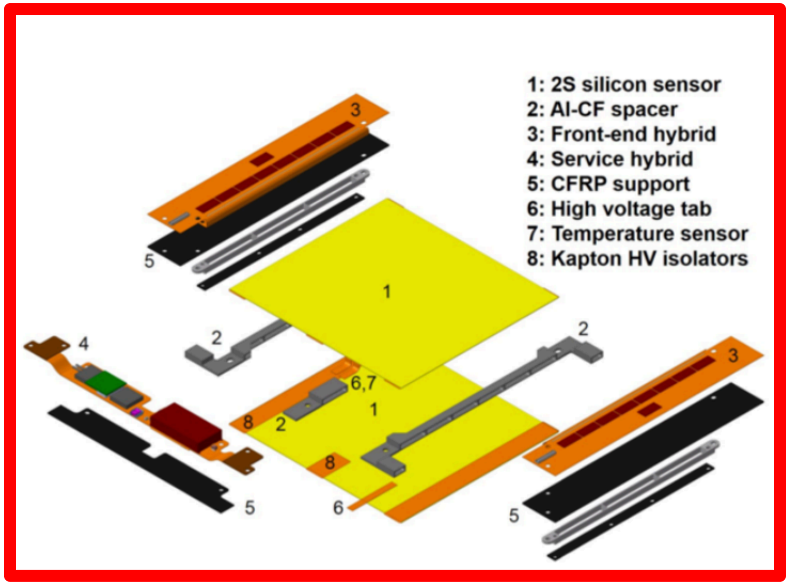
2S module

2 micro strip sensors

2 different spacing : 1.8mm & 4mm
Both micro strip sensors with
5cm x 90µm strips
Sensor dimension are 10cm x 10cm:
two column of 1016 strips

OUTER TRACKER MODULES – SERVICE SYSTEM



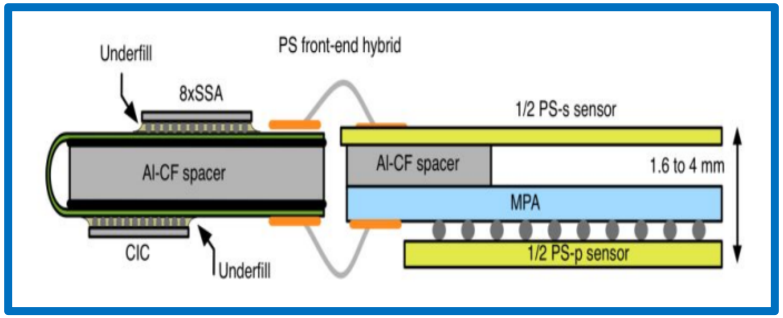


- Module houses both frontend and service hybrids
- Service hybrid(s) has:
  - lpGBT = low powering Gigabyte Transceiver
  - VTRx+ = versatile Link Plus Transceiver
  - DCDC converters
- Frontend hybrids have readout chip and data concentrator

Each module is a functional unit individually connected to:

- backend power system
- DTC (Data, Trigger and Control) system via Optical link
- no token control rings
- no intermediate power grouping

Outer Tracker Modules – Readout

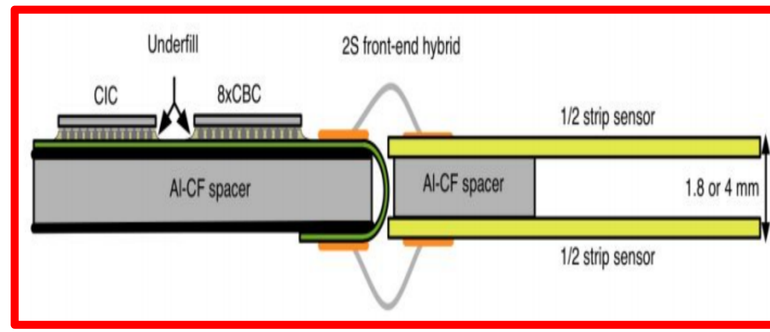


PS Module ASICS

- PS modules readout by MPA and SSA chips
- Short Strip ASIC(SSA)
  - Reads strip data
- Macro-pixel ASIC (MPA)
  - Reads macro-pixel data
- MPA receives the clusters from SSA and forms stubs.

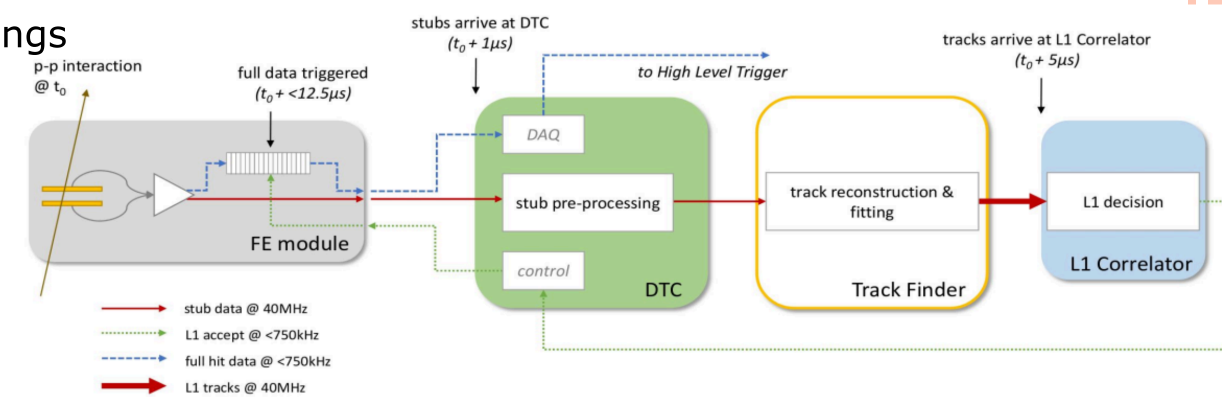
2S Module ASICs

- 2S modules readout by CMS Binary Chip (CBC)
- Both sensors read out by same chip
- 254 channels per chip



Common ASIC

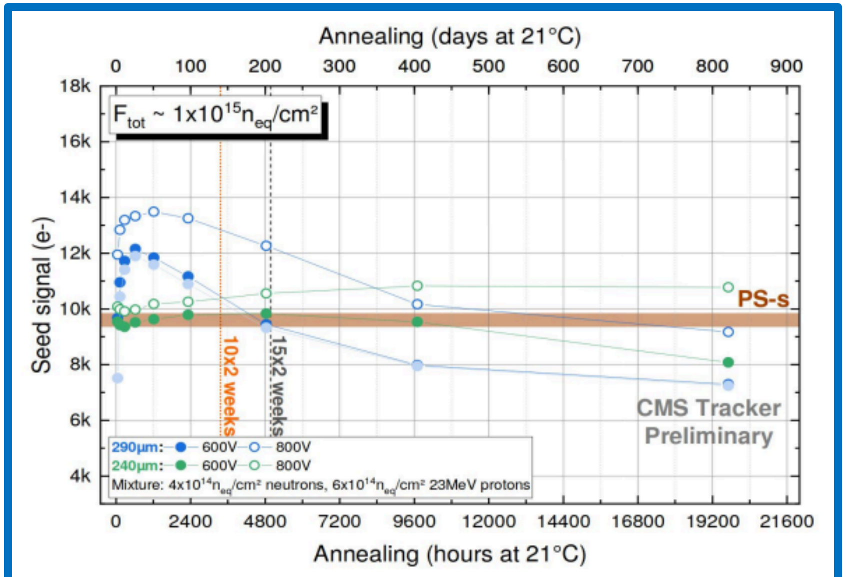
- Data from the CBC/MPA are formatted by Concentrator Integrated Circuit(CIC) chips.
- 2CIC chips per module
- Packs data for 8 bunch crossings
- Priority to Trigger data.



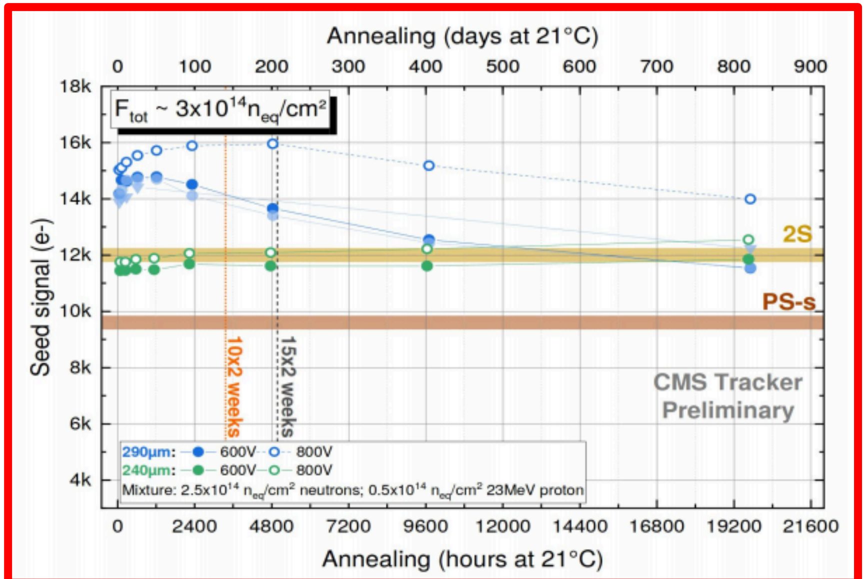
Outer tracker sensors

- Silicon sensors will be produced by Hamamatsu
  - n-in-p sensors

- Extensive irradiation and characterization campaign was undertaken to study the different sensor choices
  - FZ290 : 290 μm active thickness (Same material as current tracker)
  - FZth240 : 240 μm active thickness -> thinned material with physical ~ active thickness



Signal measurements:
- FZth240 only just above PS-s limit
- FZ290 is well above



Signal measurements:
- FZth240 barely reaches 2S limit
- FZ290 is well above

Outer tracker sensors

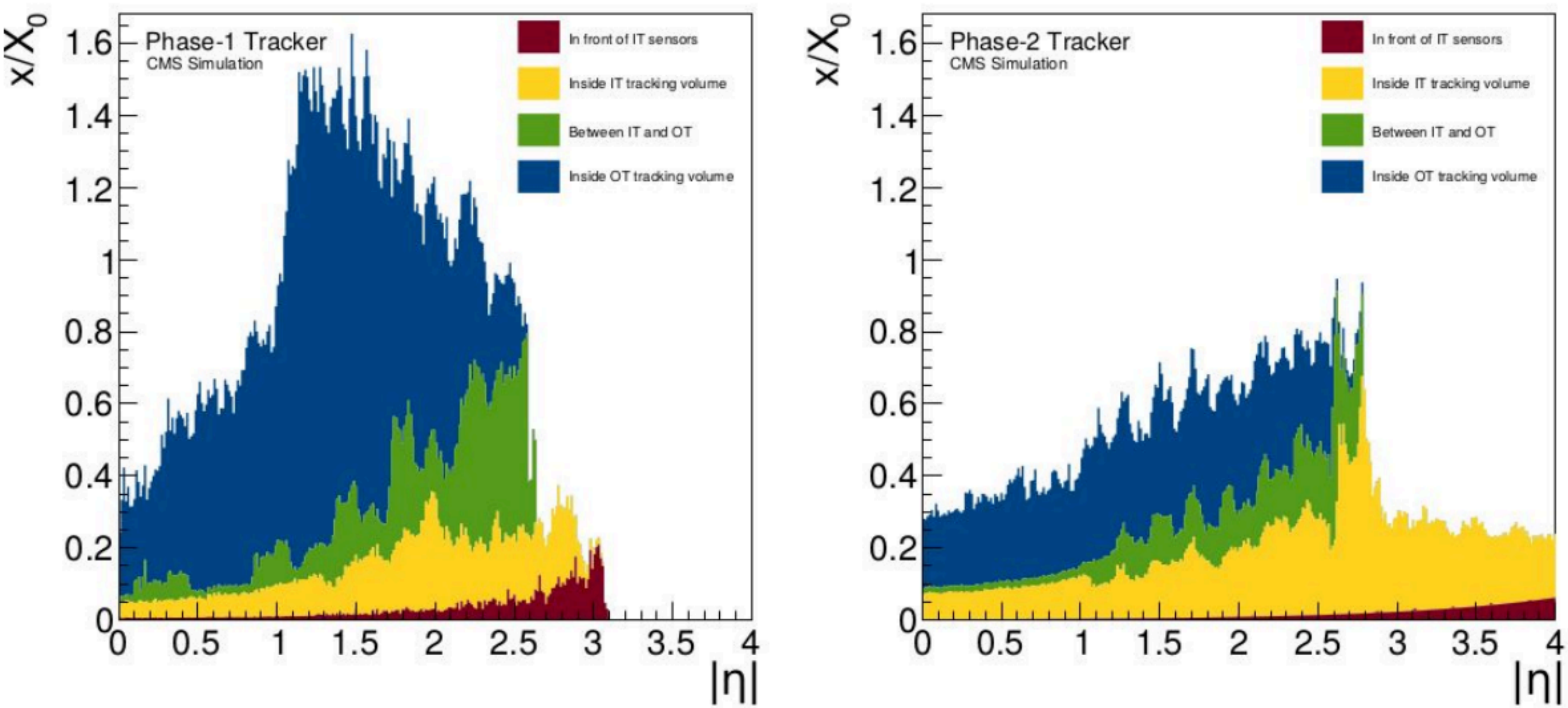
- Silicon sensors will be produced by Hamamatsu
  - n-in-p sensors

- Extensive irradiation and characterization campaign was undertaken to study the different sensor choices
  - FZ290 : 290 μm active thickness (Same material as current tracker)
  - FZth240 : 240 μm active thickness -> thinned material with physical ~ active thickness

There is not a clear benefit of FZth240 over the standard FZ290
FZ290 show excellent performance under the foreseen operation conditions

CMS will use FZ290 sensors for the entire Outer Tracker

Outer tracker: Material budget



Phase 0/1 → Phase 2

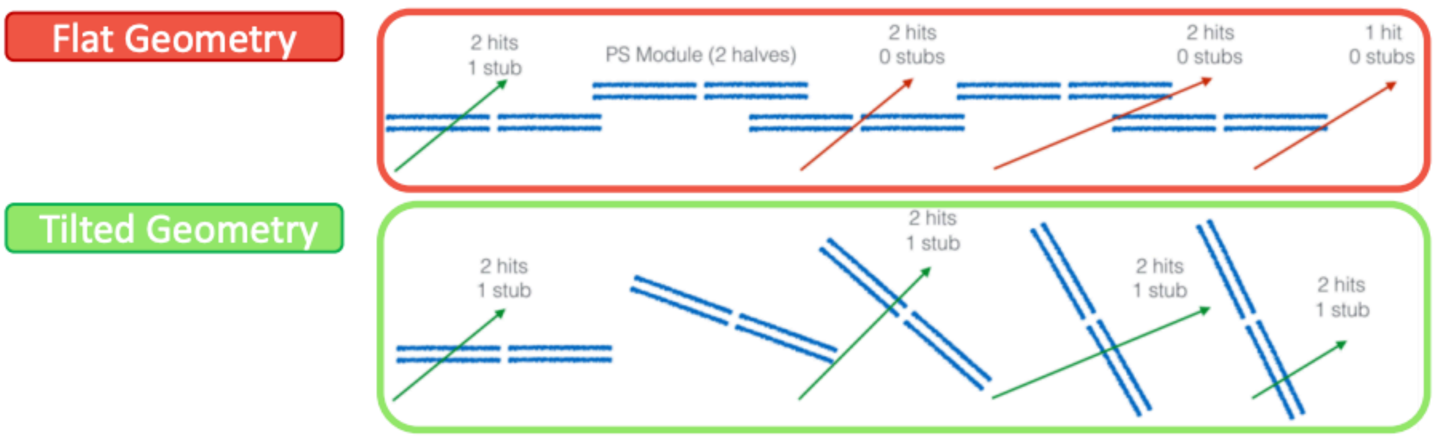
Material budget much reduced wrt Phase0/1 detector despite an increase in the number of channels thanks to:

- Fewer layers
- Lighter material
- Optimised service routine
- CO_2 cooling
- Inclined geometry

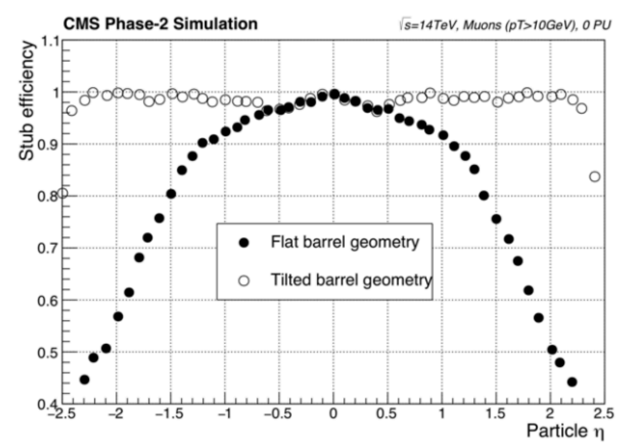
Outer tracker: Tilted geometry

Stubs generation works only if the charged particle cross the two sensors on the same halve of the same module

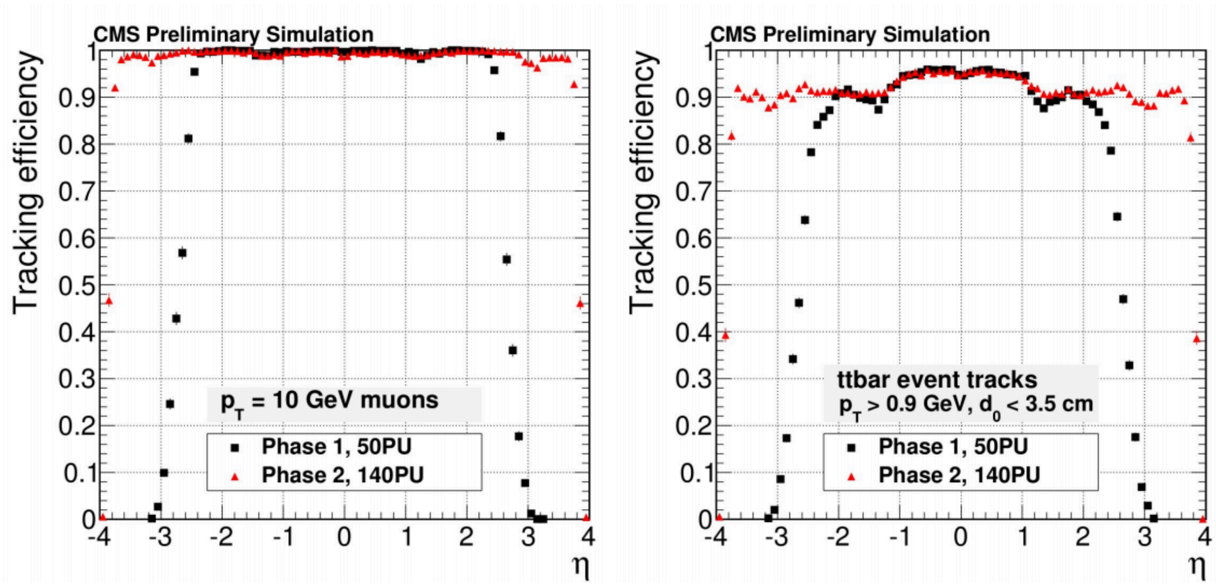
This is not true for (flat) barrel peripherical modules -> Tilt peripherical barrel modules introduced for this reason

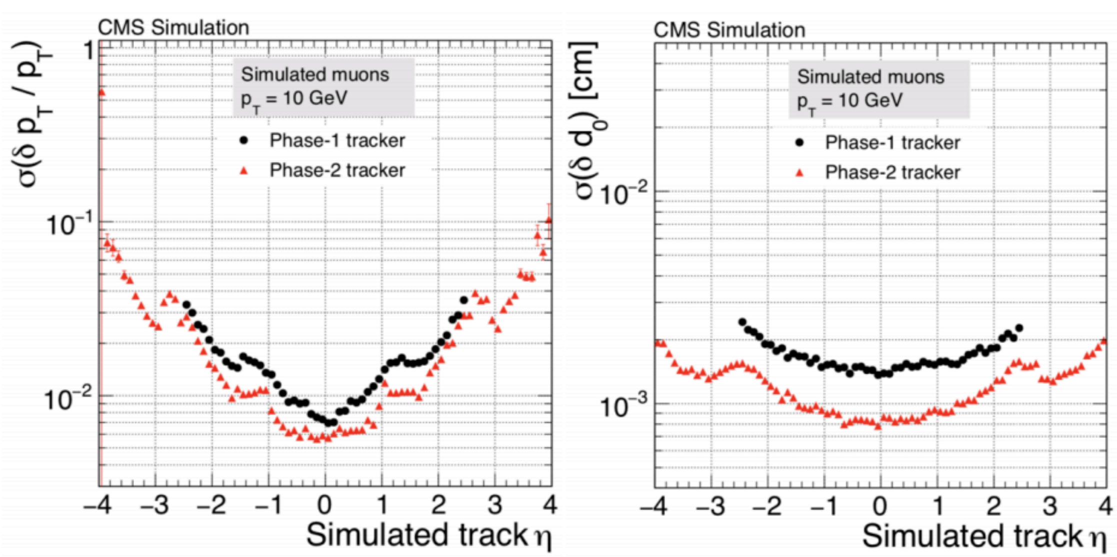


Sizable reduction on the number of modules needed → From ~15k (flat) to ~13k (tilted)



PERFORMANCES: PHASE 1 VS PHASE 2



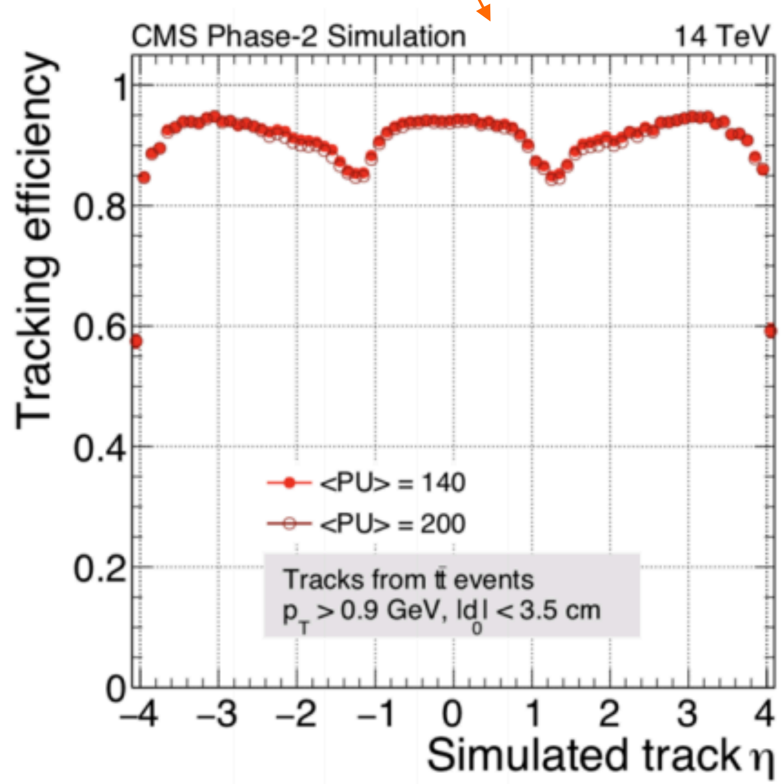


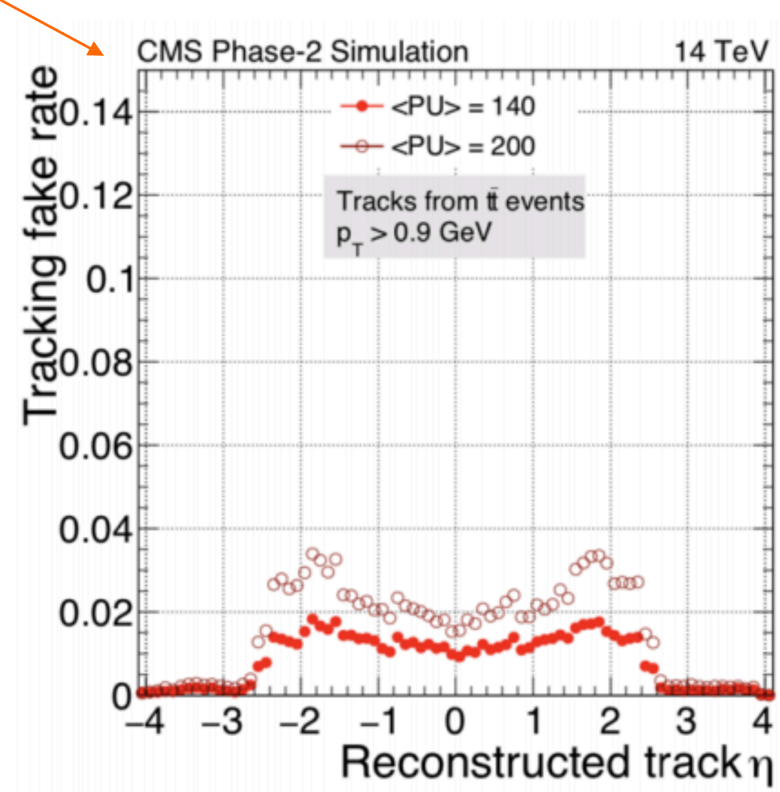
Comparing tracking efficiency and track parameters resolution between Phase 1 and Phase2 tracker an improvement is shown thanks to higher granularity and less material.

Significant extension at higher η

PERFORMANCES AT HIGH PU

Comparing two different scenario of high PU: <PU> = 200 and <PU>=140 in terms of tracking efficiency and fake rate





Almost the same tracking efficiency between the two scenario but the fake rate increase by a factor 1.5 – 2 at higher <PU> value

CONCLUSION

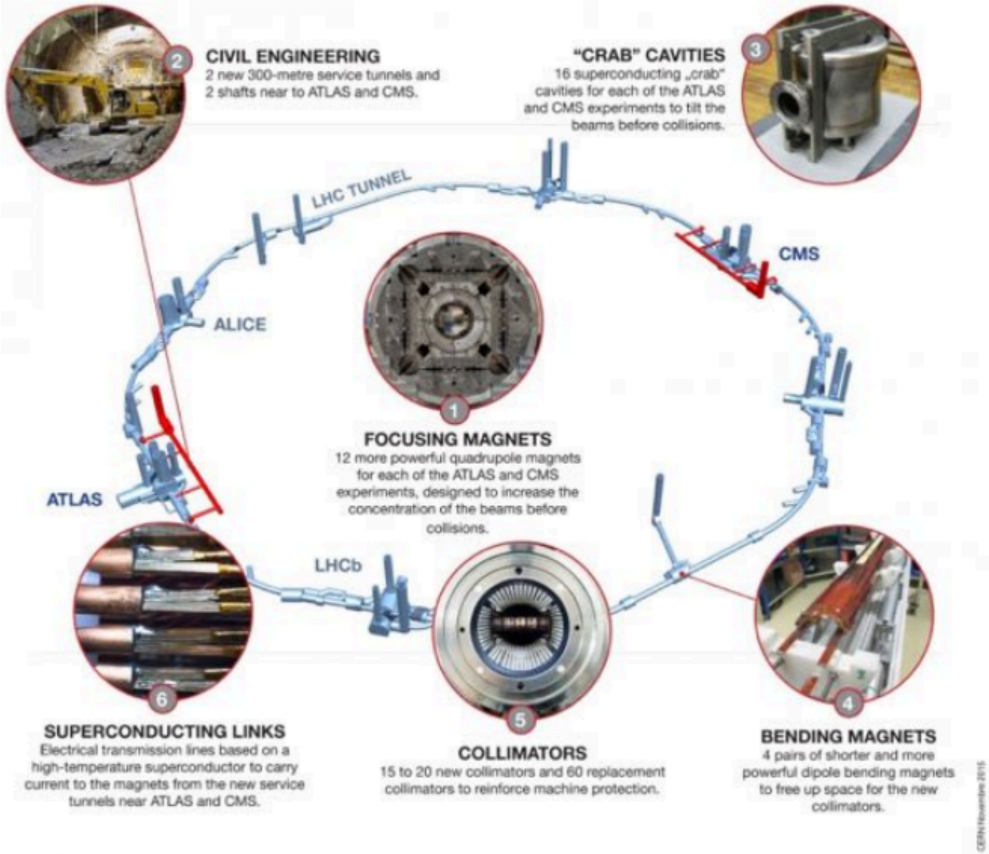
- The Phase2 upgrade of the CMS tracker is an important project to ensure efficient performance of the CMS detector in the HL-LHC era.
- Designed to operate even at high pileup environment ~200 keeping excellent performances despite the challenging radiation level foreseen.
- Participate in L1 trigger decisions
  - Tracks above 2 GeV as L1 primitives at 40MHz
- Improvements result in the tracker being more performant and yet more light-weight compared to its predecessor
- Advanced layout and integration studies

Looking forward to Phase 2!

BACKUP

UPGRADE FOR LHC:

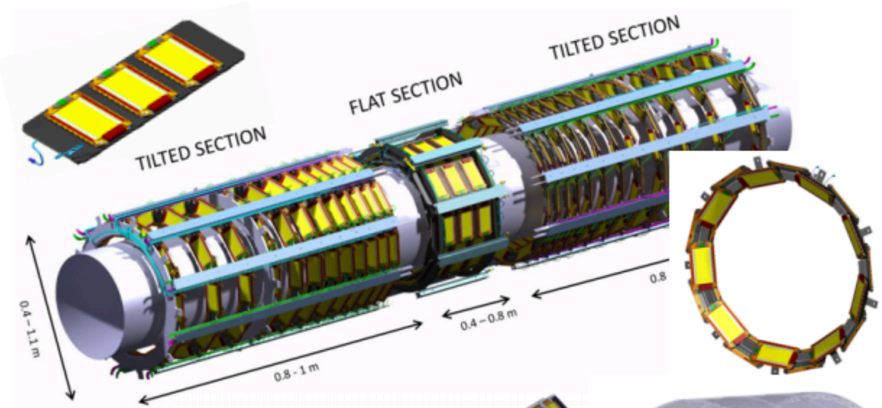
- Reduction of $\beta *$ -> Crab cavities that rotates the bunches overlapping perfectly at the collision point.
- New and more powerful magnets to collimate the beam
- Civil engineering started in 2018 for new access points and service tunnels
- …

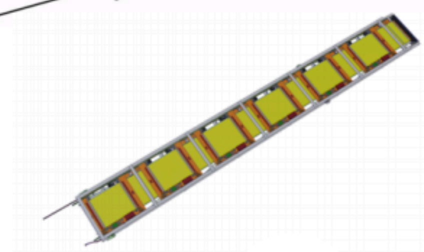


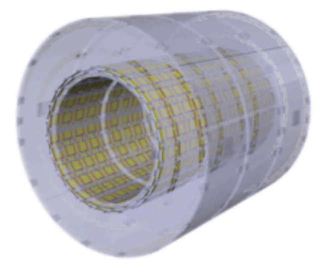
LHC timeline

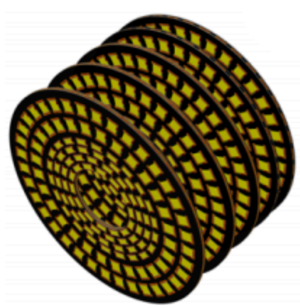
MECHANICS

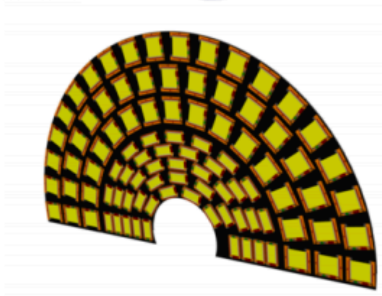
- TBPS
  - Flat Part: planks
  - Tilted Part: rings
- TB2S
  - Ladder support structure
- TEDD
  - Building block: DEE (half disk)
  - Double-Disk to be hermetic also with rectangular modules







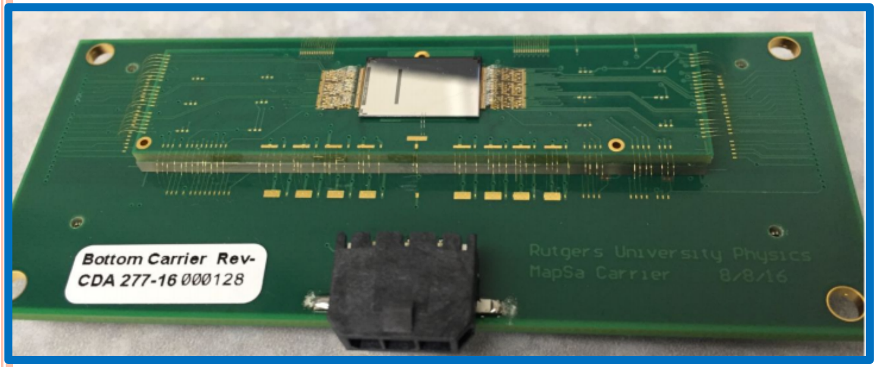


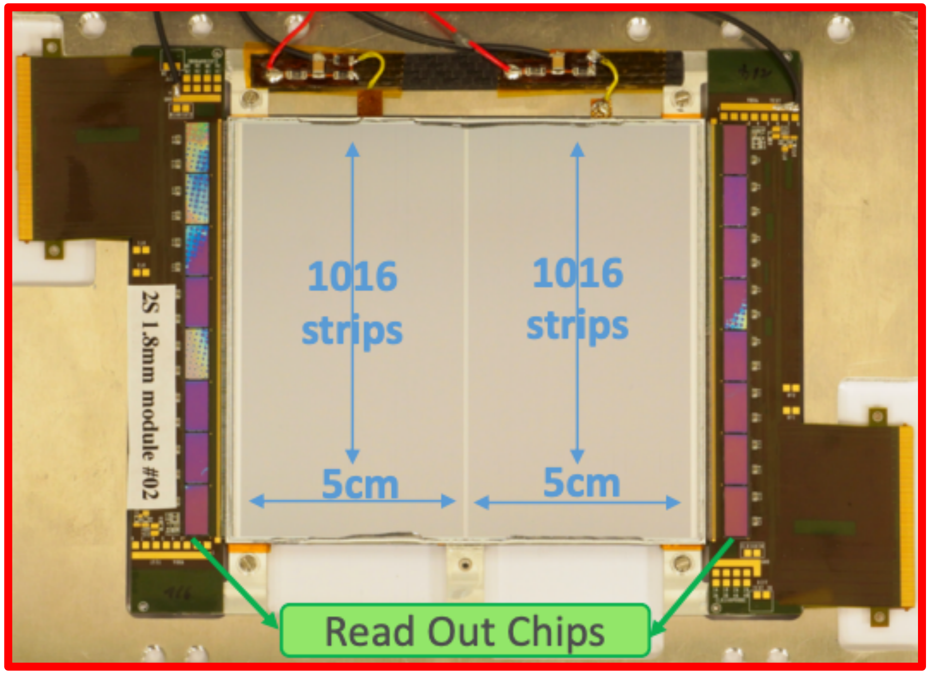


Outer tracker Modules

Module type and variant		TBPS	TB2S	TEDD	Total per variant	Total per type
2S	1.8 mm	0	4464	2792	7256	**7680**
	4.0 mm	0	0	424	424	
PS	1.6 mm	826	0	0	826	**5616**
	2.6 mm	1462	0	0	1462	
	4.0 mm	584	0	2744	3328	
Total		**2872**	**4464**	**5960**	**13296**	

Outer tracker Modules – Prototypes





Fully functional PS module prototypes produced

MaPSA-light module : 6 MPA chips bump bonded to PSp sensors with 48 channel readout channels each

PS micro module: two MaPSA-light module stacked.

MPA and SSA communication being checked on a test bench.

Functional hybrid expected by 2020

Single MaPSA module - beam test studies performed.

Fully functional 2S module prototypes produced

mini-modules with 2 X CBC2 and CBC3 readout.

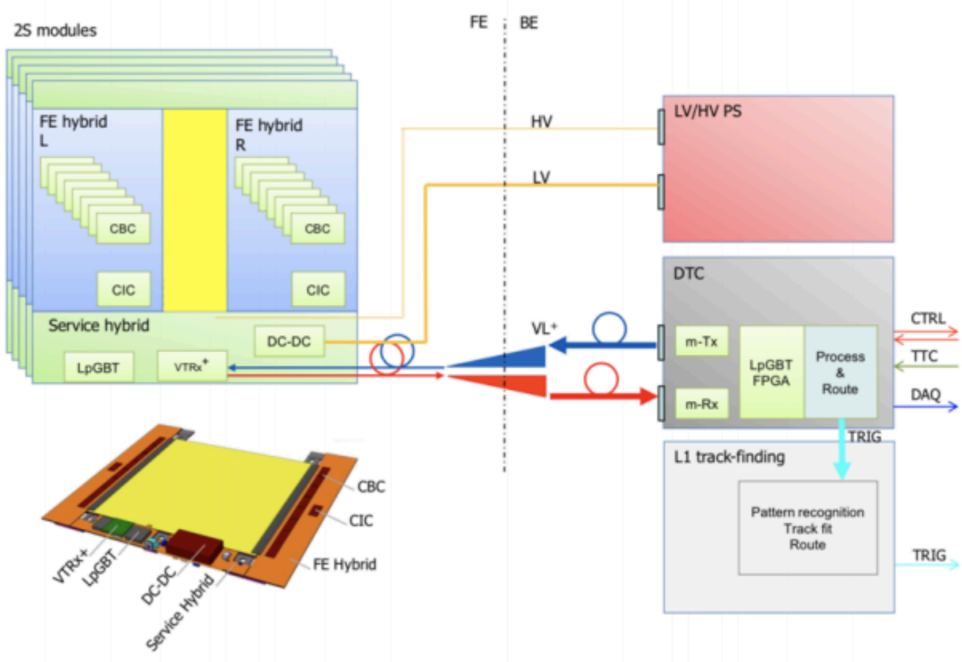
full size module with 16 CBC readout(both CBC2 and 3 readout).

irradiated mini module with CBC2 readout.

Studies at beam tests with both mini and full sized modules

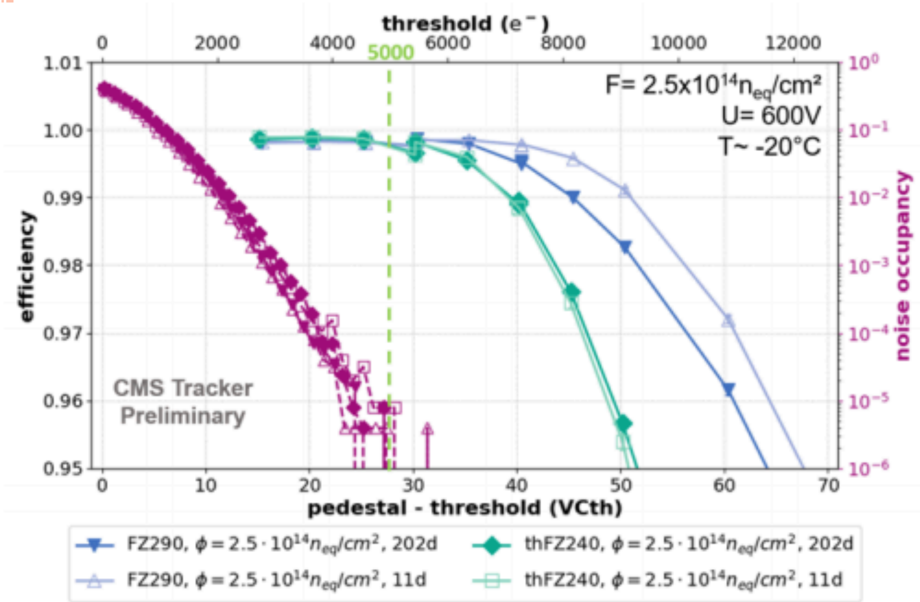
BACKEND

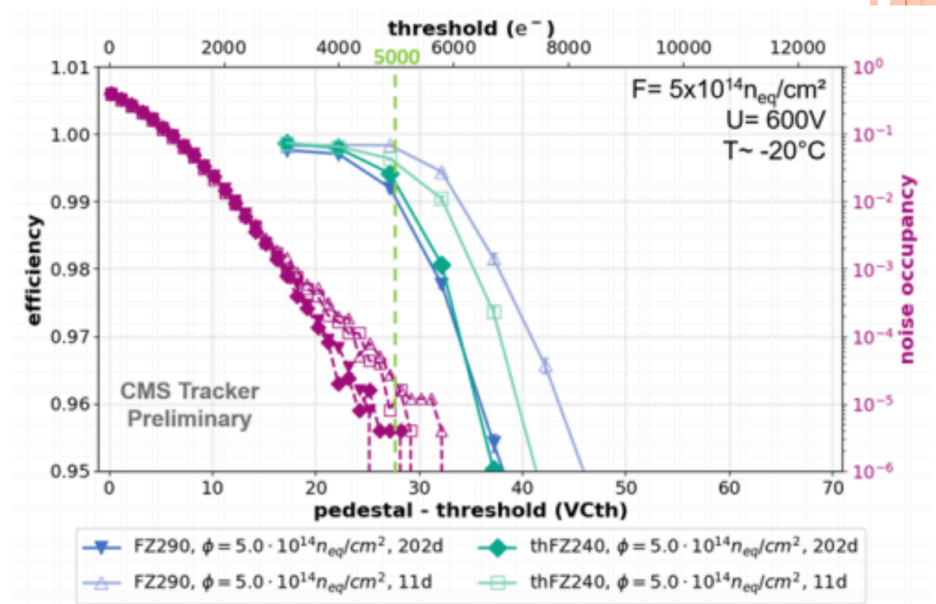
- DTC (Data, Trigger and Control) boards readout and control module
  - ACTA standard
- Bi-directional optical links
  - 2.56 Gb/s DTC → Module
    clock, trigger, fast-commands and programming
  - 5.12 or 10.24 Gb/s Module → DTC
    L1 and DAQ data
- L1 data at 40 MHz
- DAQ data (after L1) at 750 kHz



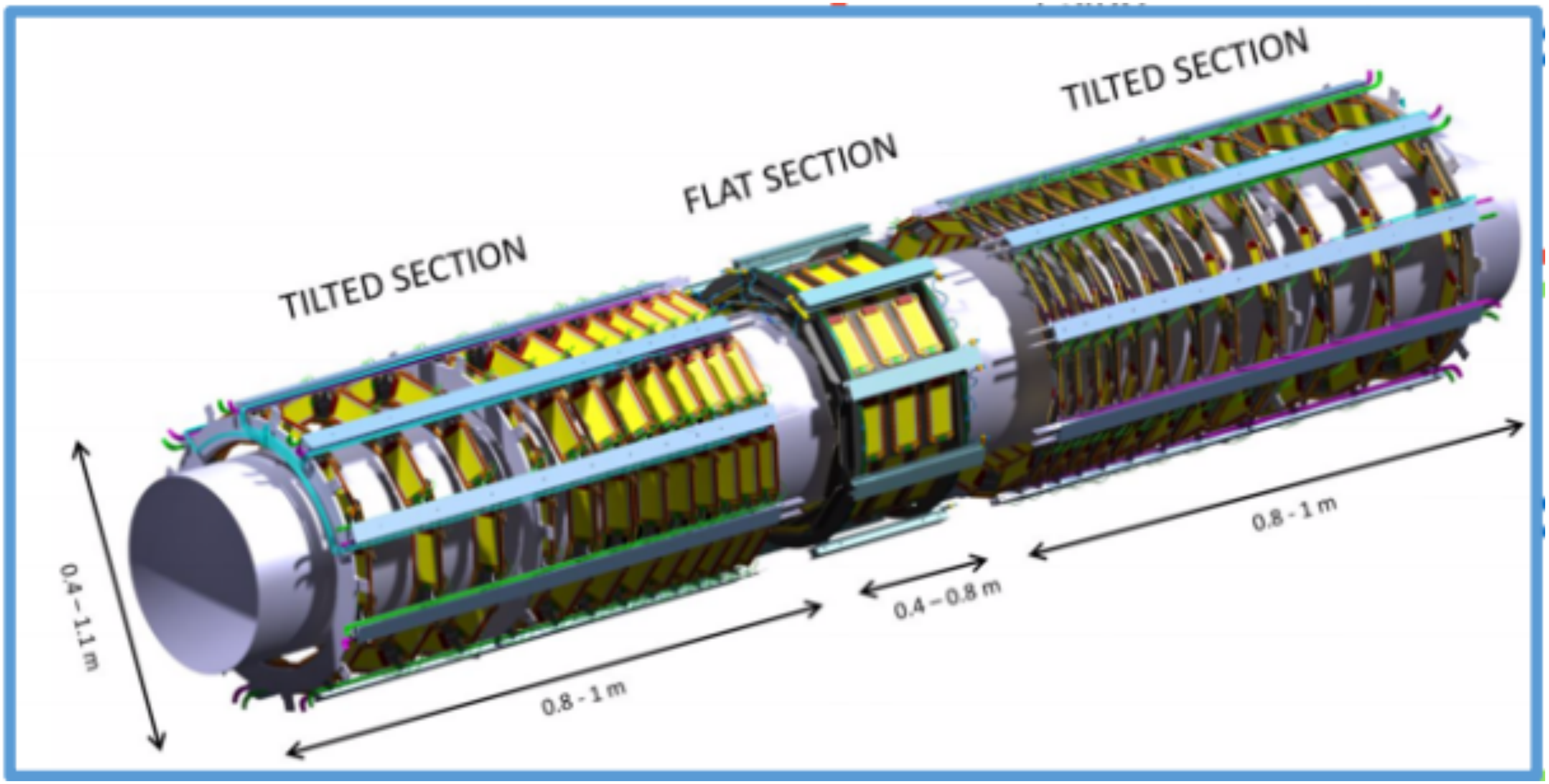
Irradiated Sensors at Beam Test

- Sensor irradiated with neutron only at JSI
- CBC3 readout chip
- Charge collection reflected in hit efficiency as a function of threshold
  - FZ290 can tolerate higher thresholds
  - Only after long annealing (200 days) at ultimate $5x10^{14}$neq/cm² both materials are comparable
- dark noise occupancy was measured:
  - lower than 10^{-5} while expected hit occupancy is ~10^{-2}
  - Scale with annealing (current) and not with thickness





Tilted geometry

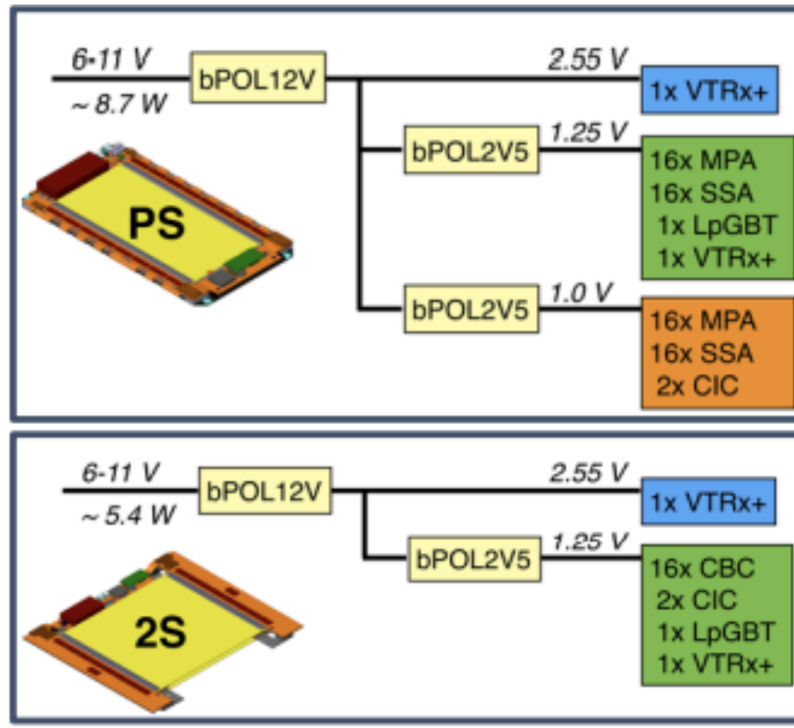


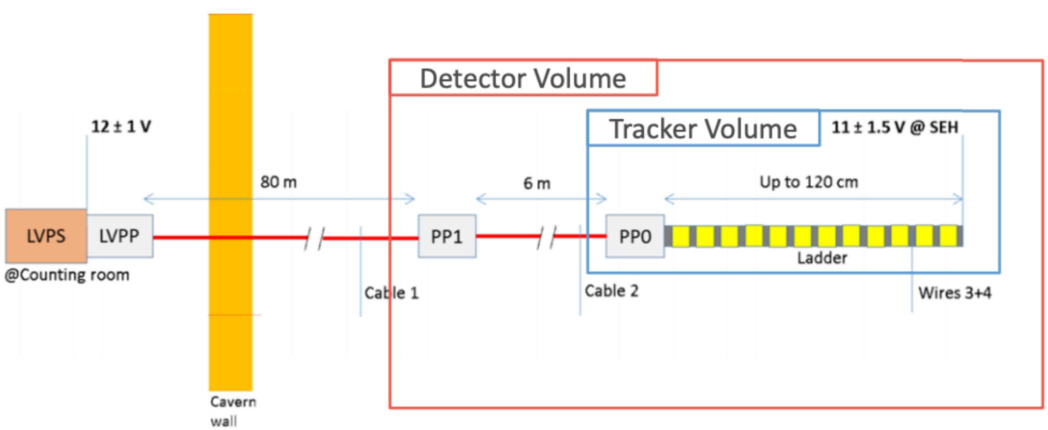
Powering and cooling

Large area + High Granularity

-> High Power budget :
Outer tracker ~ 100 kW

-> Parallel powering with
on-module conversion

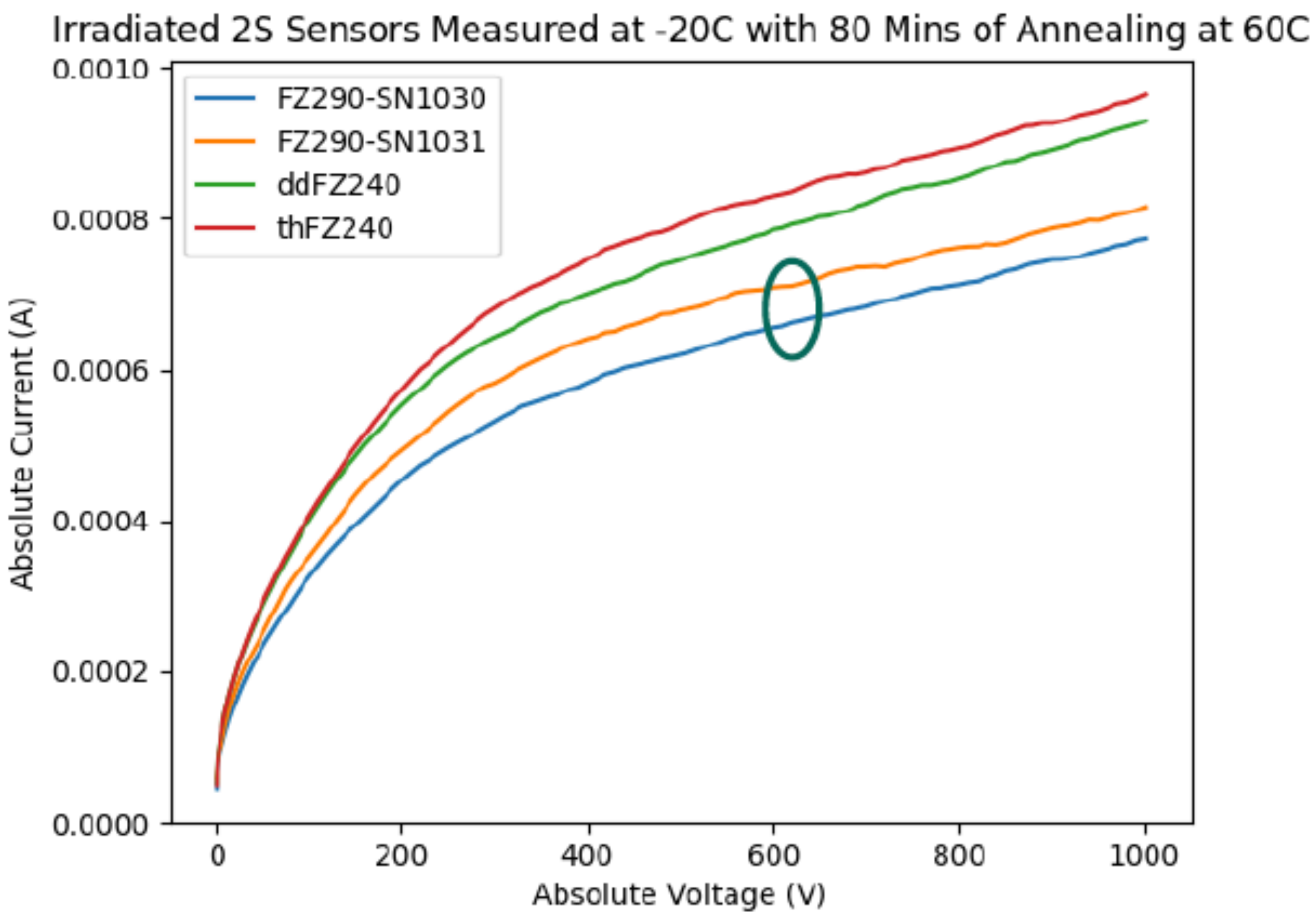




Powerful cooling system:

- (4+1) x 50W cooling plants
- based on two-phase CO2 cooling system (-30°C set point)
- small pipes

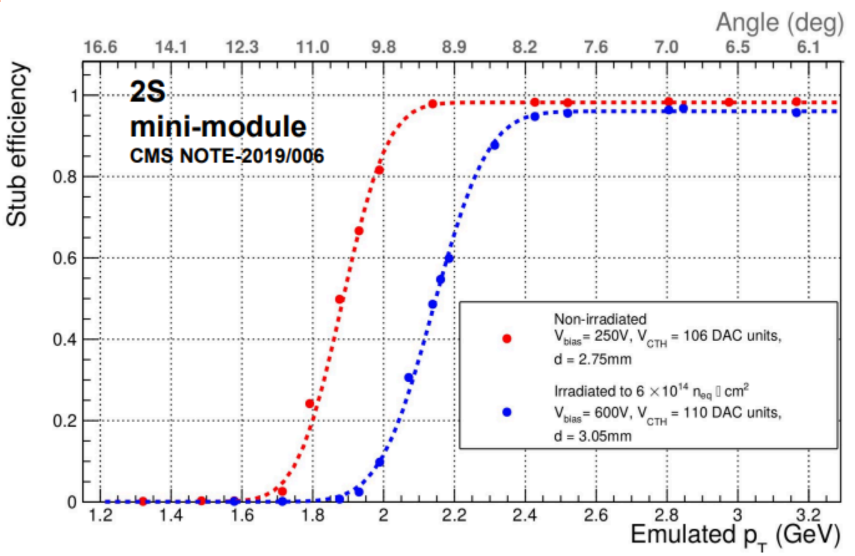
SENSORS

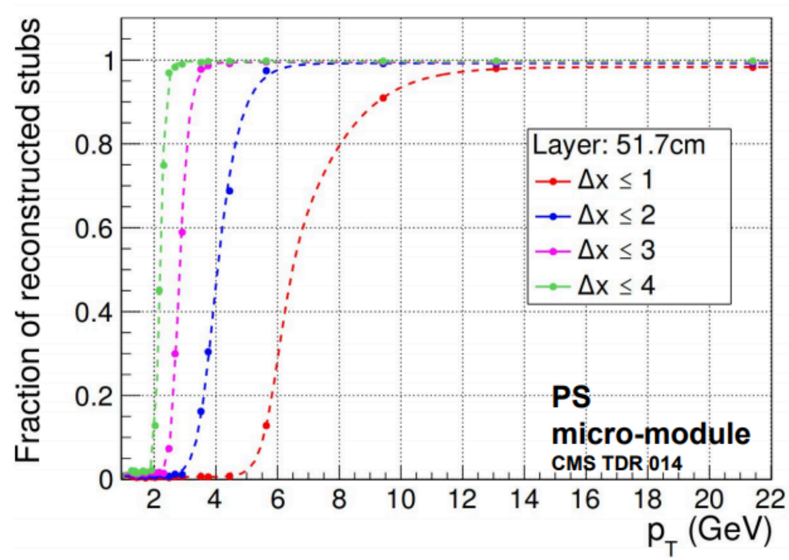


IV after the irradiation -> FZ290 structures show a better behavio ur than thinned sensors.

HIGHLIGHTS FROM THE TEST BEAM

Bending of charged particles inside the magnetic field emulated by rotating the modules w.r.t beam direction.





- Stub efficiency measured as a function of emulated pT.
- The modules demonstrate the power to discriminate tracks with pT < 2 GeV
- The difference in the turn-on threshold for the irradiated module compared to non-irradiated one is due to different sensor spacing.
- No significant loss of efficiency even after irradiation.

- Stub efficiency measured as a function of emulated pT for different correlation window(Δx in units of macro-pixel)
- Discriminating power for tracks below pT < 2 GeV

The concept of pT discrimination works!