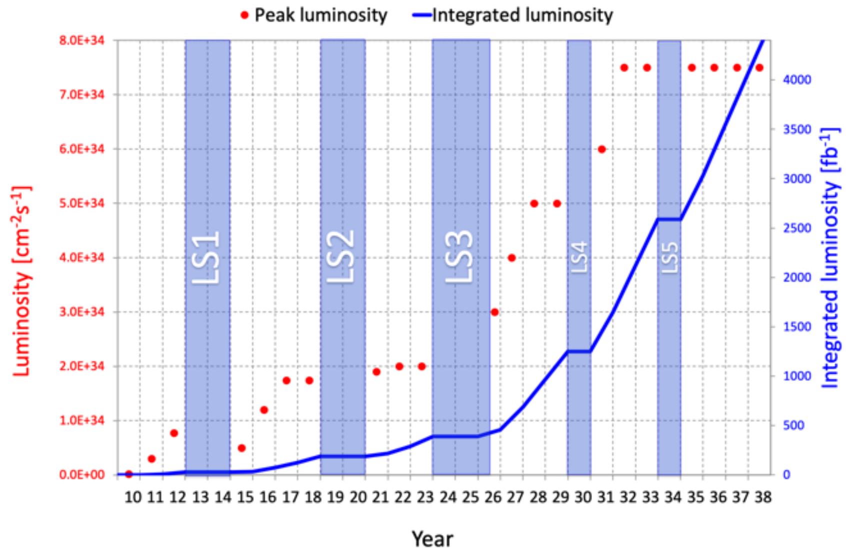
VERTEX 2019

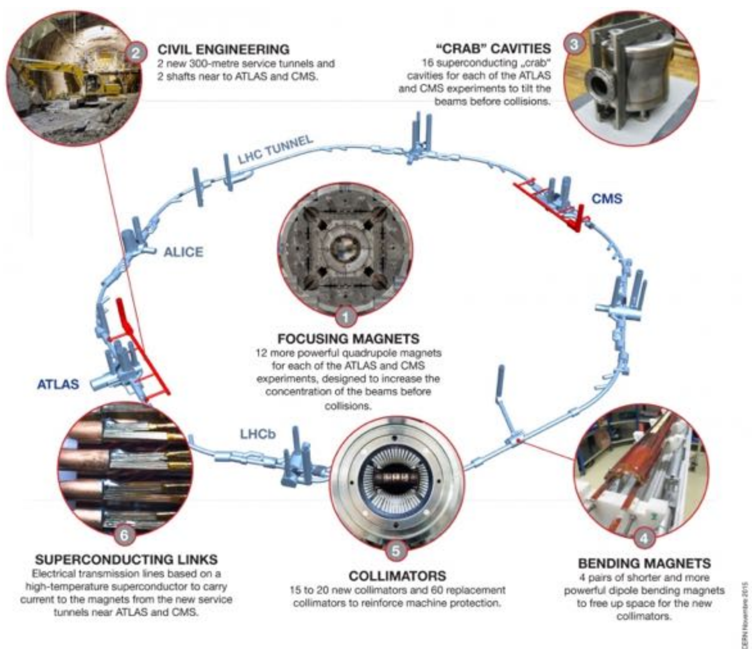
# CMS Outer Tracker Upgrade

ALESSANDRO ROSSI FOR CMS COLLABORATION

# LHC Schedule

- High Luminosity upgrade after LS3
- Peak Luminosity ~$7.5x10^{34} cm^{-2}s^{-1}$
- Expected Pile-up ~200
- Higher rates and radiation dose wrt Run3

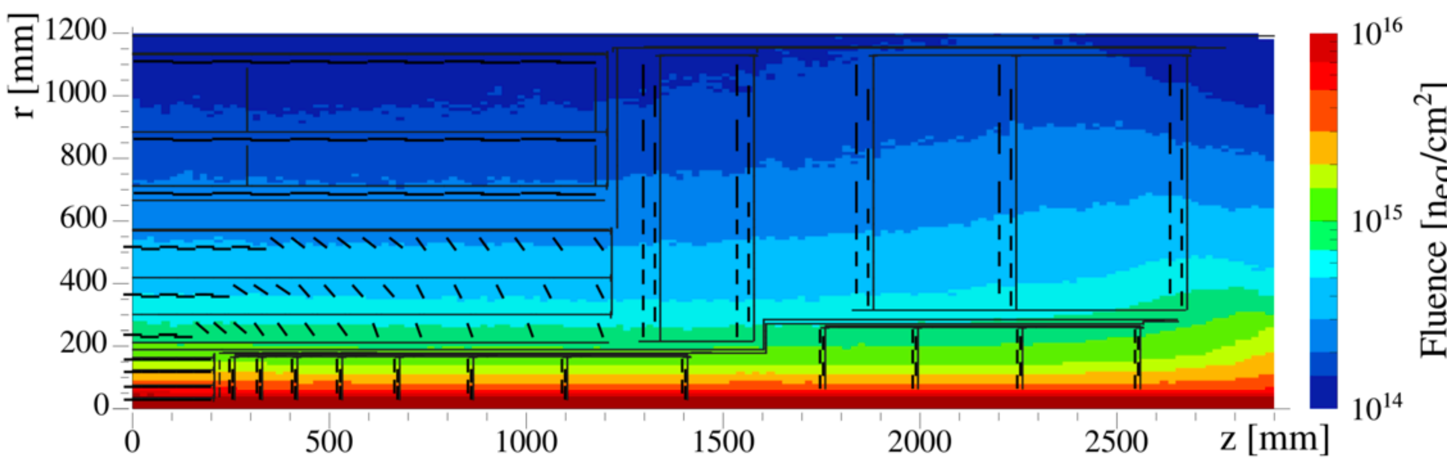



- Crab cavities
- (some) New Magnets (11T)
- Civil engineering:
  - New acces shafts
  - New service tunnels
- ...and more!

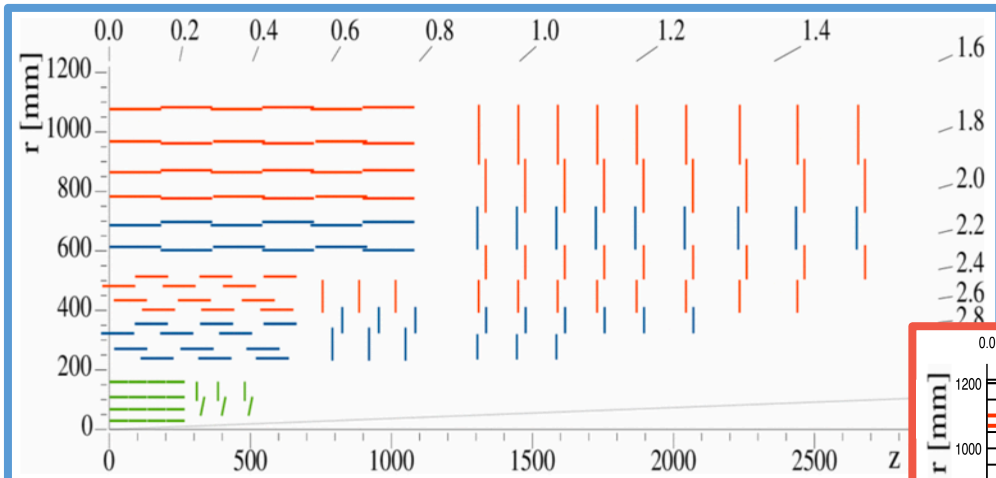
# High Luminosity Requirements

- ***Increased granularity:*** In order to ensure efficient tracking performance with a high level of pileup
- ***Reduced material in the tracking volume:*** The exploitation of the high luminosity will greatly benefit from a lighter tracker
- ***Contribution to the level-1 trigger:*** The selection of interesting physics events at the first trigger stage becomes extremely challenging at high luminosity
- ***Extended tracking acceptance:*** The overall CMS physics capabilities will greatly benefit from an extended acceptance of the tracker
- ***Radiation tolerance:*** The upgraded tracker must be fully efficient up to a target integrated luminosity of 3000fb$^{-1}$
  - Outer layers “far away” from interaction point 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

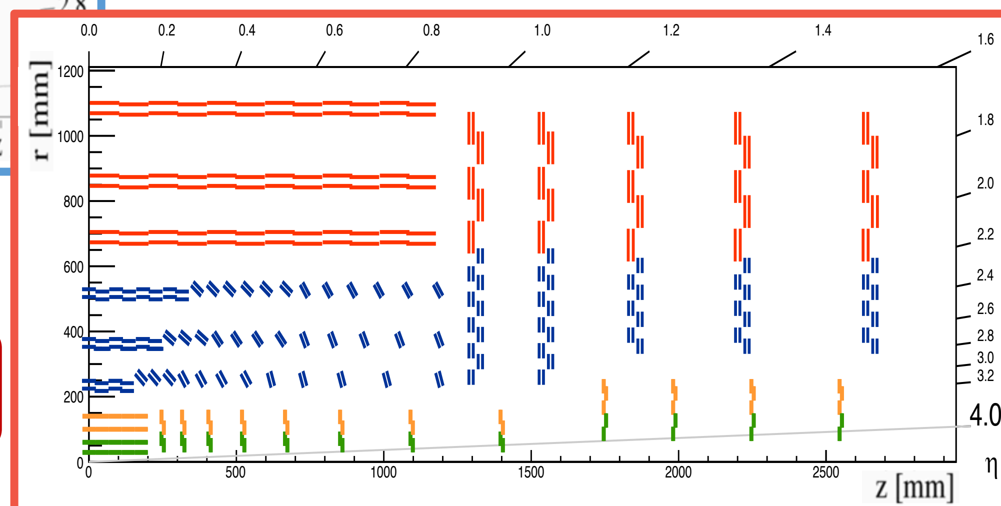


# Why change the current Tracker

- A big part of current strip tracker will become completely in-operational due to either leakage current or full depletion voltage limitations at 1 $ab^{-1}$
  - full tracker replacement needed for HL-LHC program

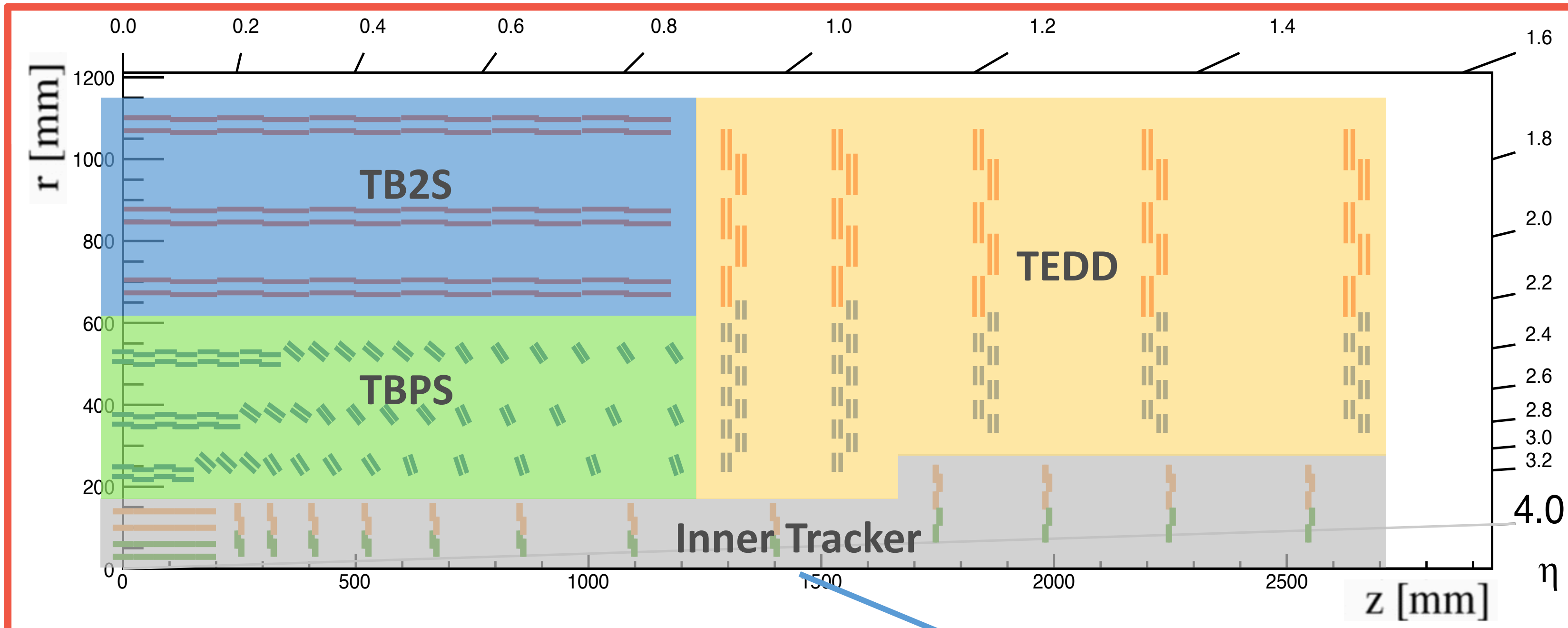



CMS Phase-1 Tracker




CMS Phase-2 Tracker

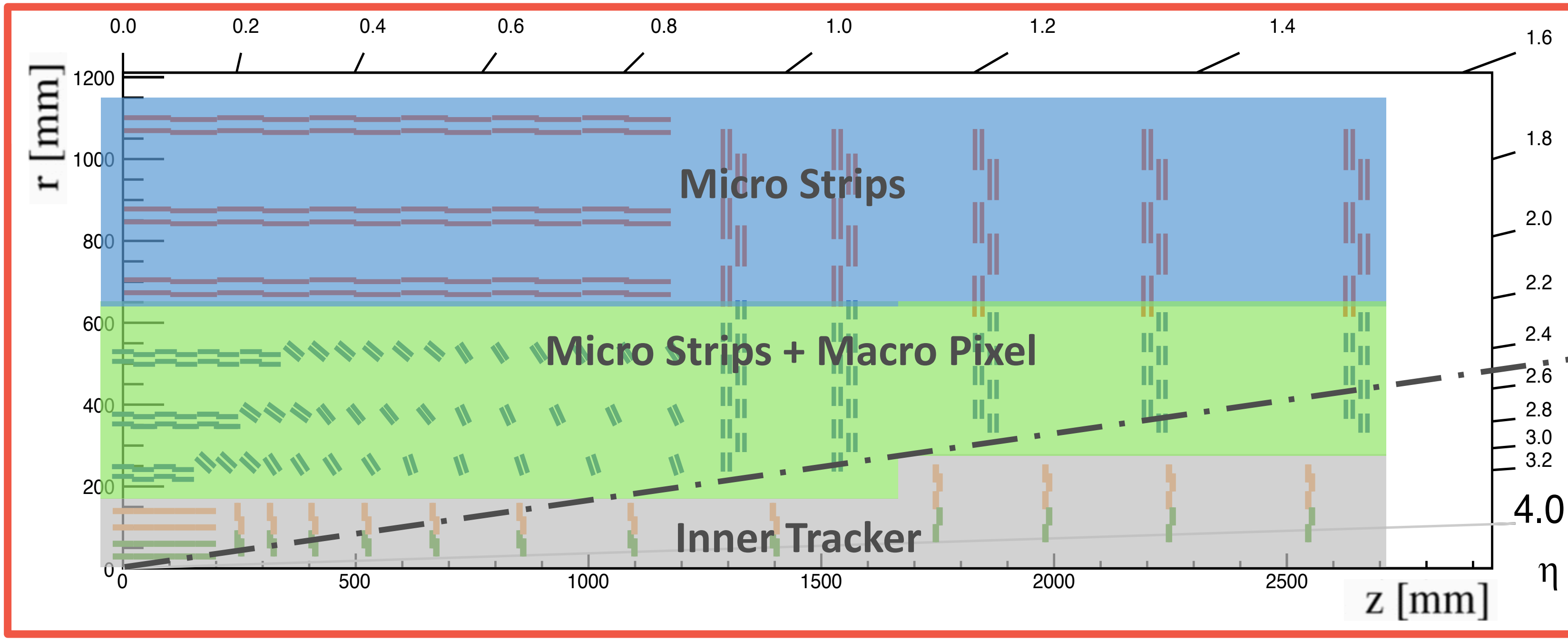
# Phase-2 CMS Outer Tracker




Dedicated Talk by **Panja Luukka**
**Tuesday 15th October 9:00**

- **TBPS** : **T**racker **B**arrel with **PS** modules
- **TB2S** : **T**racker **B**arrel with **2S** modules
- **TEDD** : **T**racker **E**ndcap **D**ouble **D**isk

# Phase-2 CMS Outer Tracker




- Outer Tracker coverage up to η~2.5
  - Tracking up to η~4 thanks to InnerTracker
- Two different type of technology: micro-strips and macro-pixels
- Tilted barrel geometry
  - Better trigger performances
  - Reduction on number of modules

# Tracks for L1 Trigger

- HL-LHC will deliver an high instantaneus luminosity with a high PileUp
  - It's fundamental to be more selective at L1 trigger in order to keep data rate under control

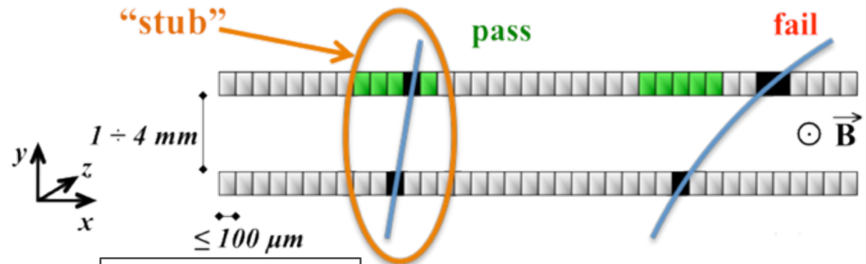
**Include Tracks on L1 decision**

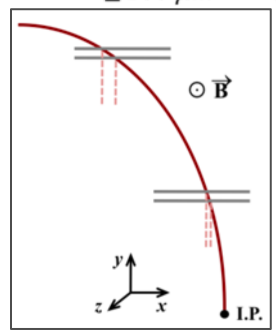
- Most of charged particles have low $p_T$
- Perform a $p_T$ selection at readout level in order to reduce the L1 tracking input data size

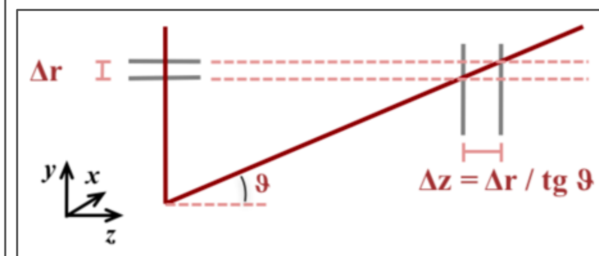
**pT Modules**

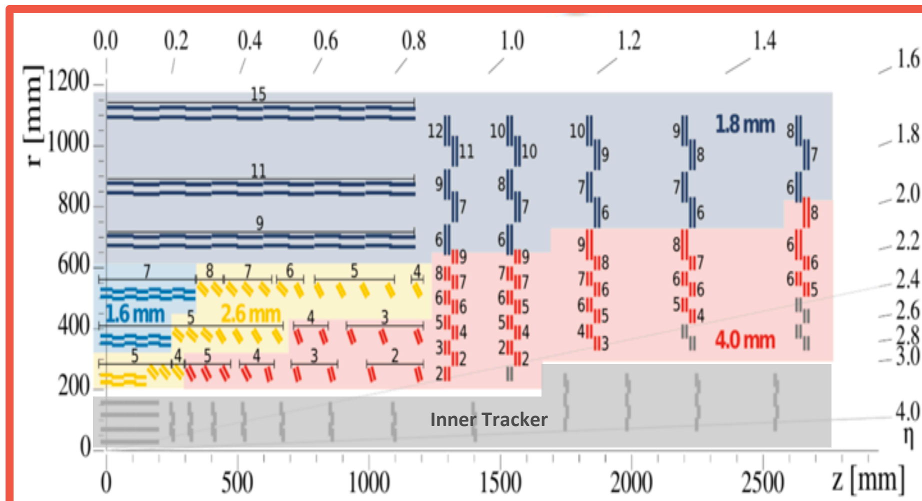
- Two silicon sensors with small spacing in a module
- Flex hybrid in order to get data from both sensors to one ASIC → Select track «stubs»
- Different sensor spacing for different detector region
- Tunable correlation windows

Dedicated Talk by **Fabio Ravera**
**Thursday 17th October at 17:30**

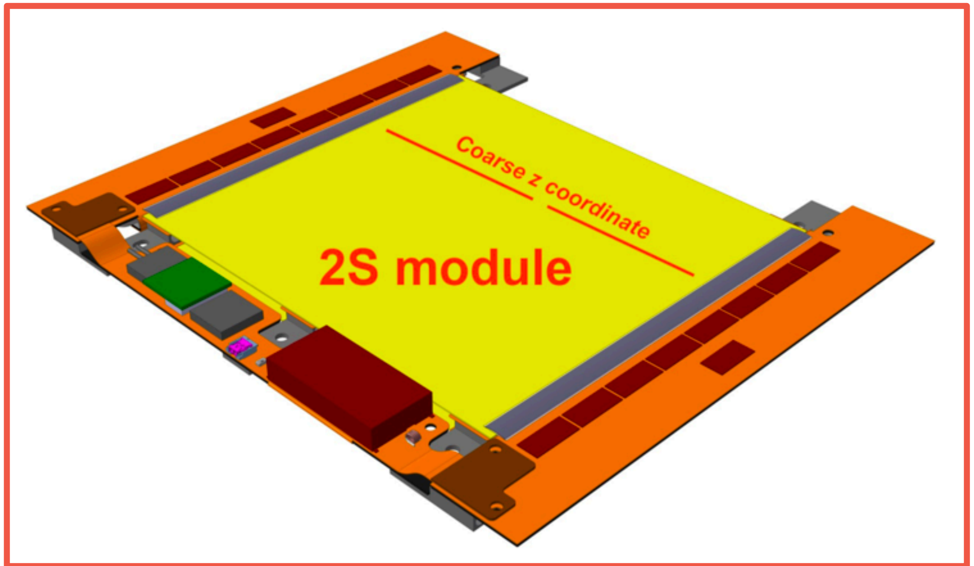


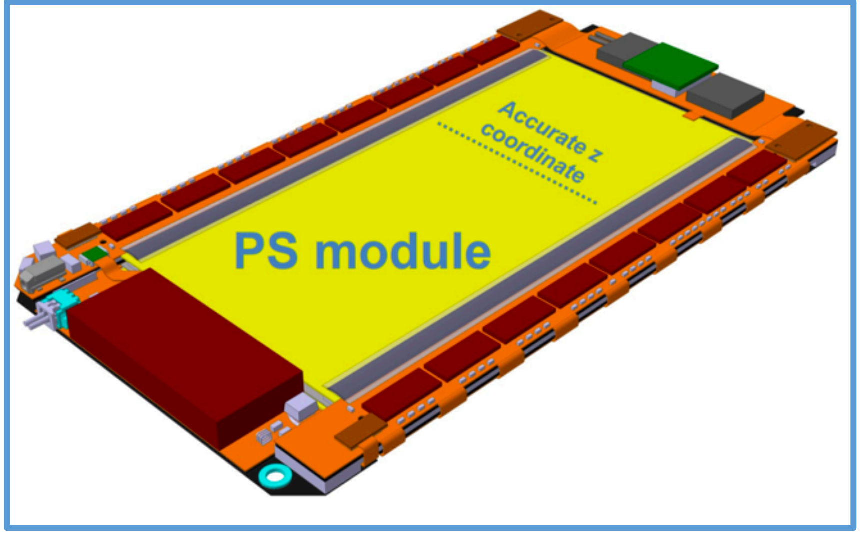



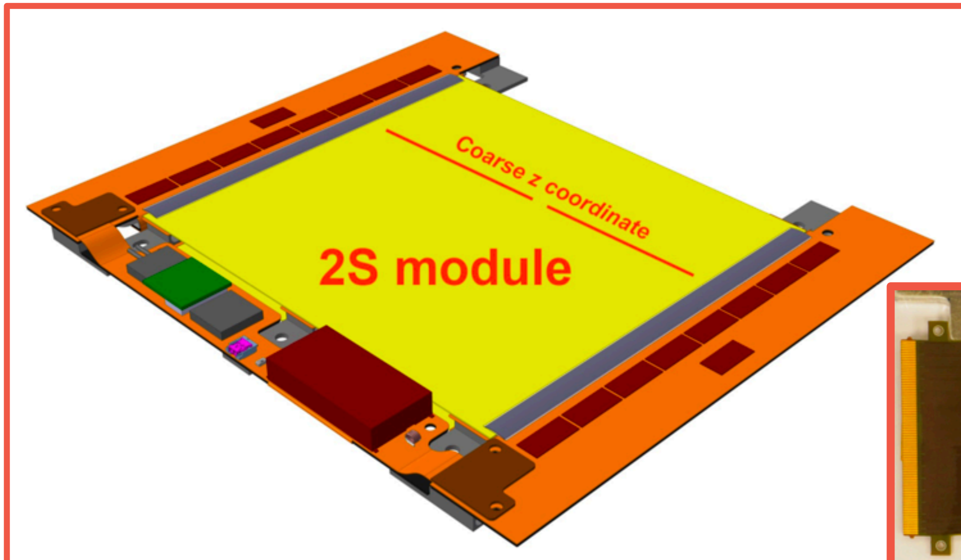
# Phase-2 Tracker Modules

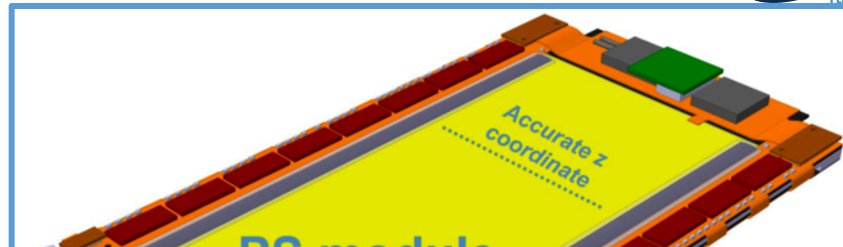


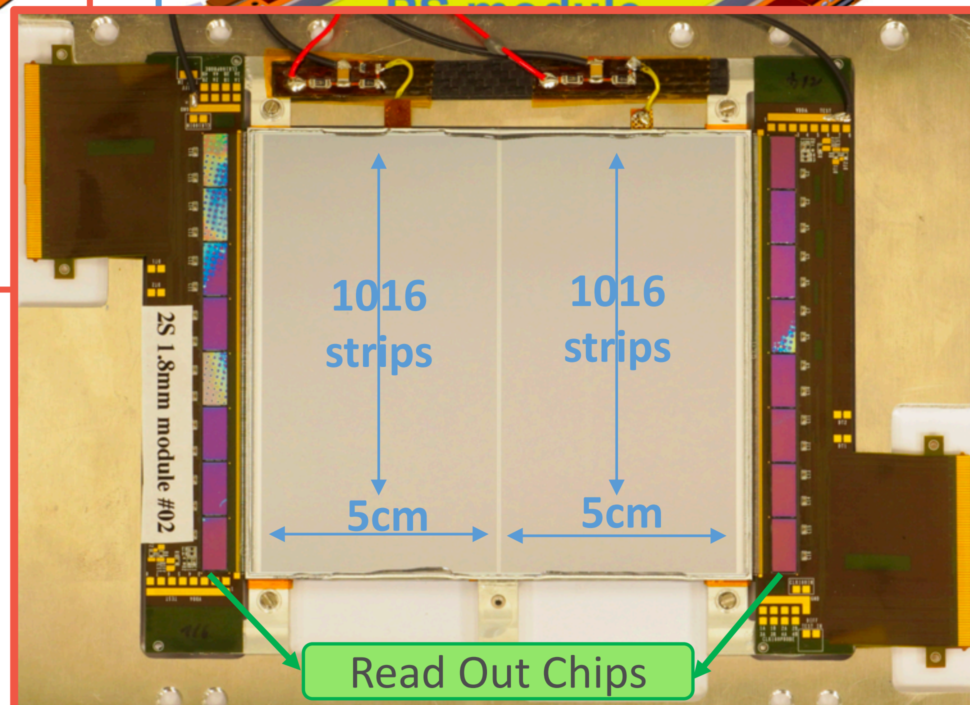




- Two type of modules:
  - 2S Modules
    - 2 different spacing : 1.8mm & 4mm
    - 2 micro strip sensors with 5cm x 90µm strips
    - Sensor dimension are 10cm x 10cm
      - two column of 1016 strips
  - PS Modules
    - 3 different spacing : 1.6mm & 2.6mm & 4mm
    - One strip sensor: 2.5cm x 100µm strips
    - One macro Pixel sensor : 1.5mm x 100µm pixels
    - Sensor dimension 5cm x 10 cm
      - two column of 960 strips
      - 32x960 pixels

# Phase-2 Tracker Modules



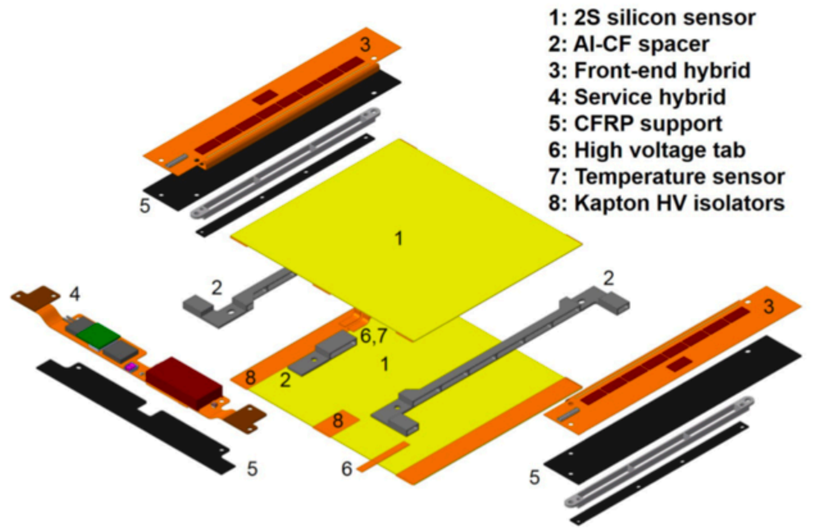



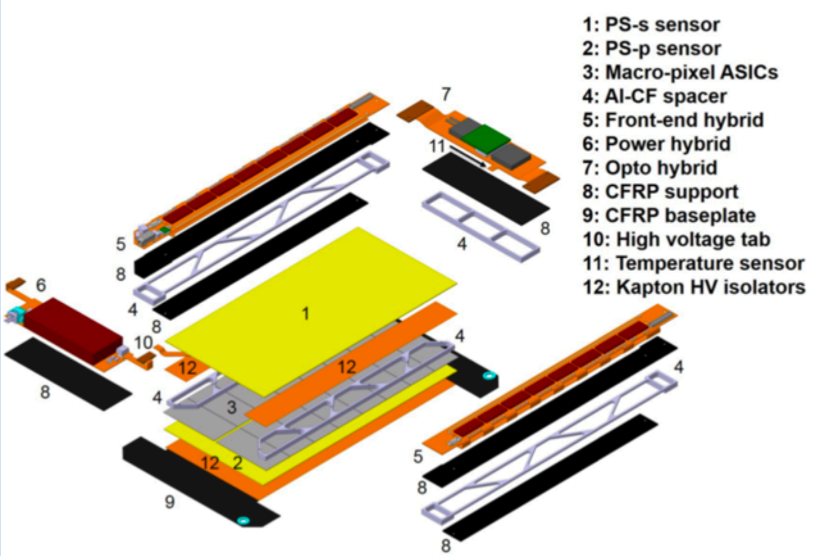




- Two type of modules:
  - 2S Modules
    - 2 different spacing : 1.8mm & 4mm
    - 2 micro strip sensors with 5cm x 90µm strips
    - Sensor dimension are 10cm x 10cm
      - two column of 1016 strips

- Sensor dimension 5cm x 10 cm
  - two column of 960 strips
  - ~30k pixels

# Modules Service Systems



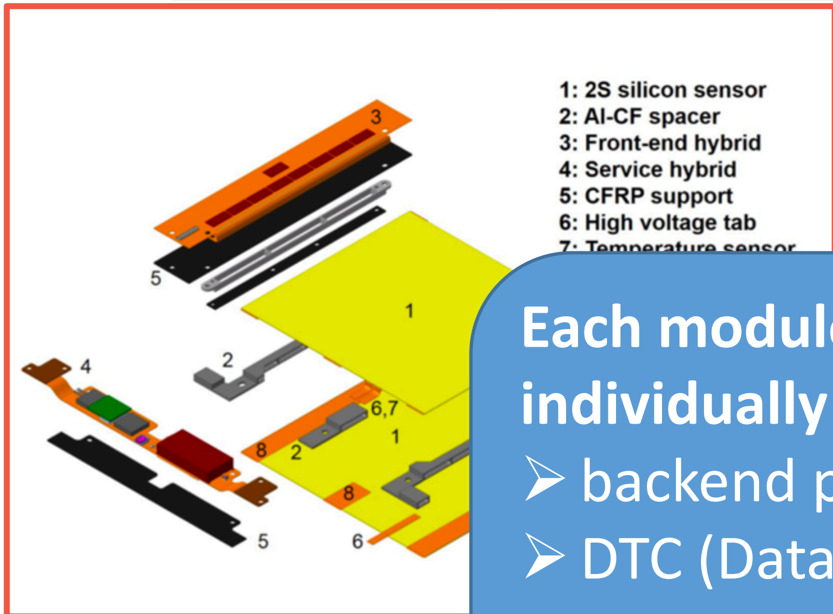



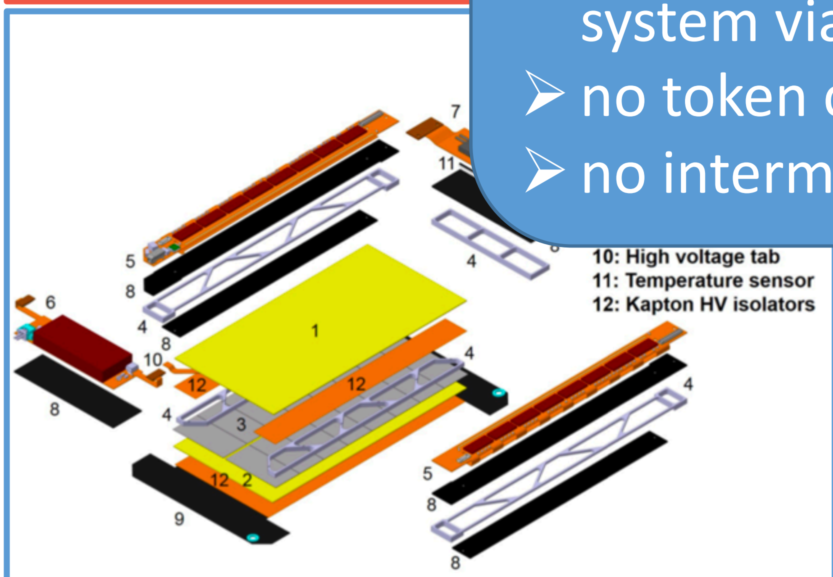

- Module houses both frontend and service hybrids
- Service hybrid(s) has:
  - lpGBT
    - Low Power Gigabit Transceiver
  - VTRx+
    - Versatile Link Plus Transceiver
  - DCDC converters

HL-LHC common development

- Frontend hybrids have readout chip and data concentartor

# Modules Service Systems




- Module houses both frontend and service hybrids

**Each module is a functional unit individually connected to:**

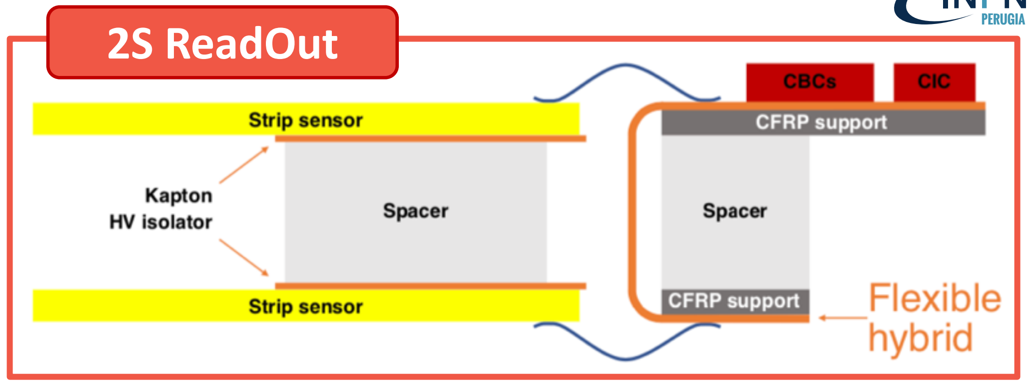
- ➢ backend power system
- ➢ DTC (Data, Trigger and Control) system via Optical link
- ➢ no token control rings
- ➢ no intermediate power grouping

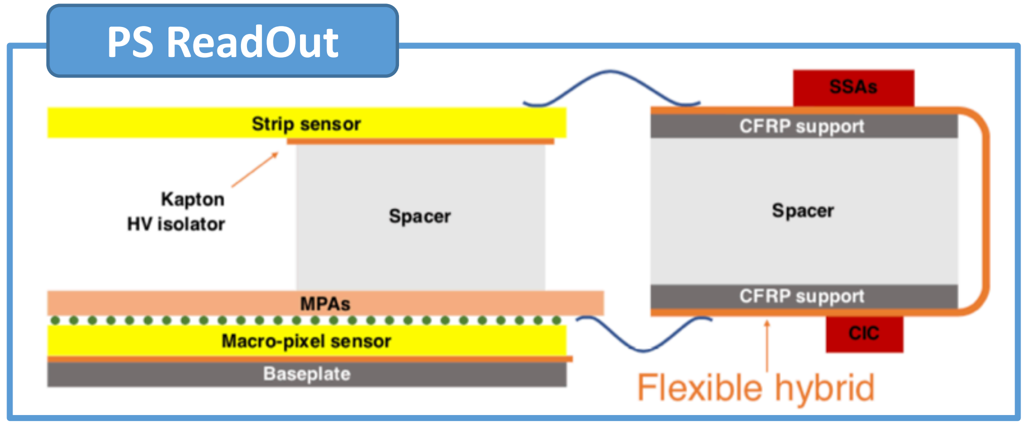
HL-LHC common development

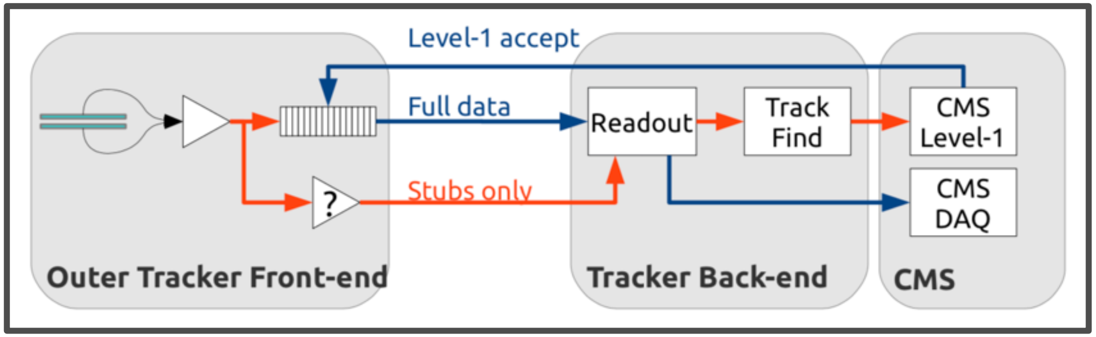
- Frontend hybrids have readout chip and data concentartor

# Modules ReadOut

- 2S Module ASICs
  - CMS Binary Chip (CBC) for readout and stub finding for L1
    - both sensors read out by same chip
  - 254 channels per chip
    - 127 from each sensor
  - Implemented in 130 nm technology
- PS Module ASICS
  - Macro-Pixel ASIC (MPA) and Short-strip ASIC (SSA) for readout of sensors
  - Stub finding performed by MPA
    - SSA sends cluster and L1 information to MPA to enable match in space and time
  - Both chips done in 65 nm technology
- Common ASIC:
  - CIC concentrator chip Receives L1 information and readout data
  - “Data hub” to service hybrid
  - Done in 65 nm technology

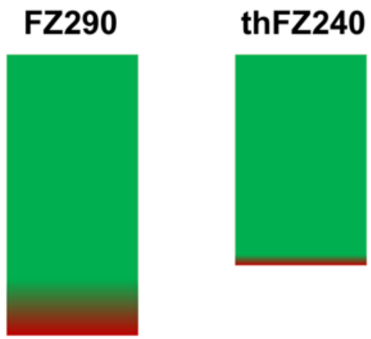


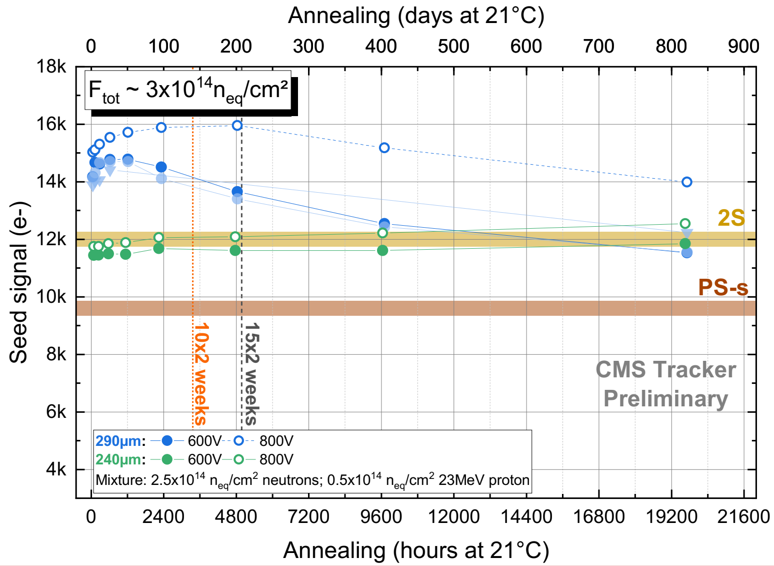
# Sensors

- Silicon sensors will be produced by Hamamatsu
  - n-in-p sensors
    - Showed better behavior after irradiation
- HPK lost confidence in deep diffused material as substrate for mass production
  - baseline for TDR
- Options left:
  - standard material: 320µm physical and 290µm active (**FZ290**)
    - same material as in the current tracker
  - thinned material with physical ~ active thickness (**thFZ240**)
    - same substrate as FZ290, but backside ground down to desired thickness, followed by polishing
    - more expensive

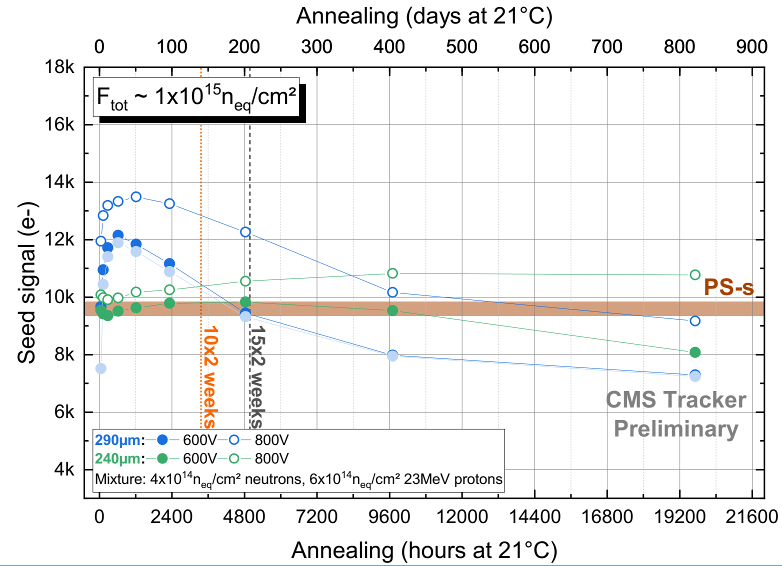


# Sensors

- Irradiation campaign to study the sensors behavior and perform a technology choice:
  - Take nominal expected max. fluences for outer (2S) and inner (PS) regions after $3000 fb^{-1}$
  - Consider the approximate mixture of neutrons and charged hadrons




- Expected max. 2S fluence after $3000 fb^{-1}$
- Signal measurements:
  - **thFZ240 barely reaches 2S limit**
  - **FZ290 is well above**

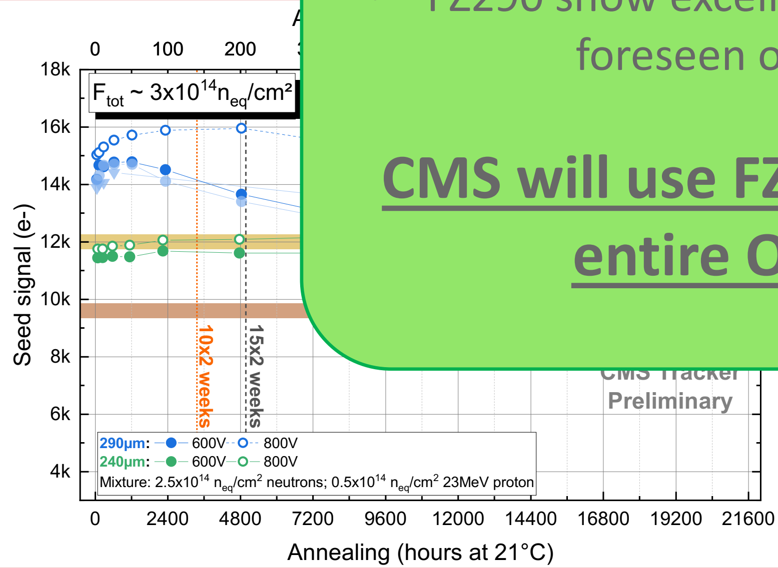


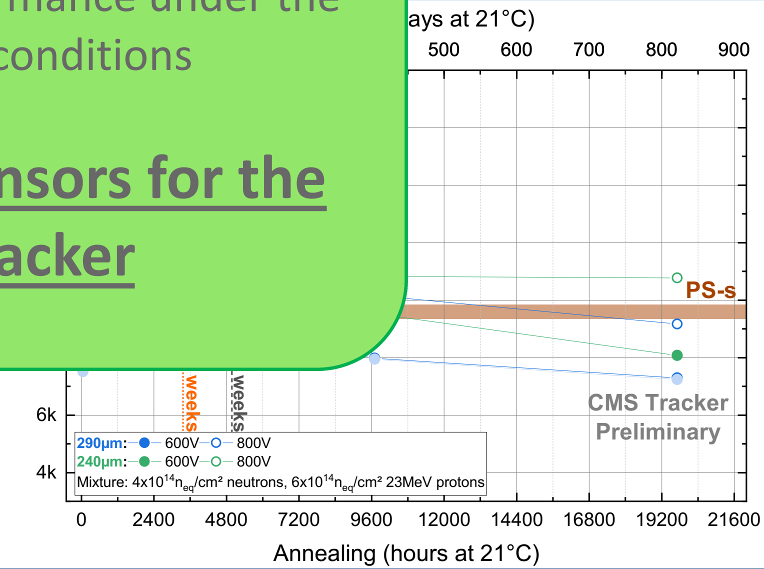

- Expected max. PS fluence after $3000 fb^{-1}$
- Signal measurements:
  - **thFZ240 only just above PS-s limit**
  - **FZ290 comfortably above with 800V**

# Sensors

- Irradiation campaign to study the sensors behavior and perform a technology choice:
  - Take nominal expected max. fluences for outer (2S) and inner (PS) regions after 3000fb$^{-1}$
  - Consider the [...] hadrons

> - There is not a clear benefit of thFZ240 over the standard FZ290
> - FZ290 show excellent performance under the foreseen operation conditions
>
> **<u>CMS will use FZ290 sensors for the entire Outer Tracker</u>**




- Expected max. 2S fluence after 3000fb$^{-1}$
- Signal measurements:
  - <u>**thFZ240 barely reaches 2S limit**</u>
  - <u>**FZ290 is well above**</u>

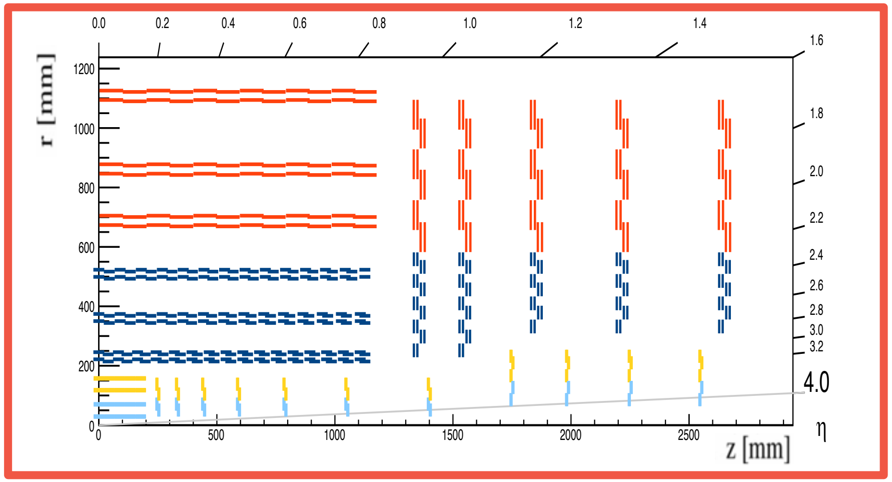
- Expected max. PS fluence after 3000fb$^{-1}$
- Signal measurements:
  - <u>**thFZ240 only just above PS-s limit**</u>
  - <u>**FZ290 comfortably above with 800V**</u>

# Tilted Barrel Geometry

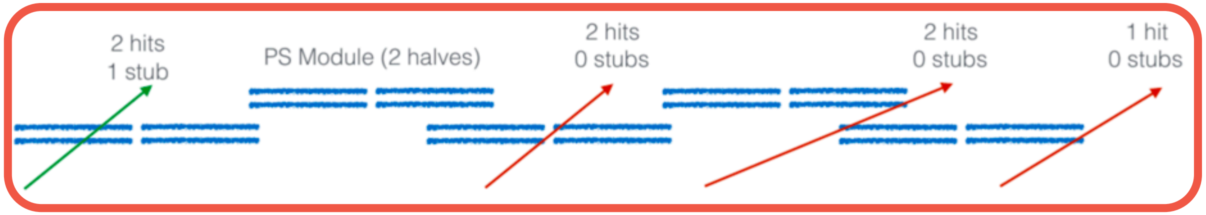
- Stubs generation works only if the charged particle cross the two sensors on the same halve of the same module
- This is not true for (flat) barrel peripherical modules

→ **(increasingly) Tilt peripherical barrel modules**

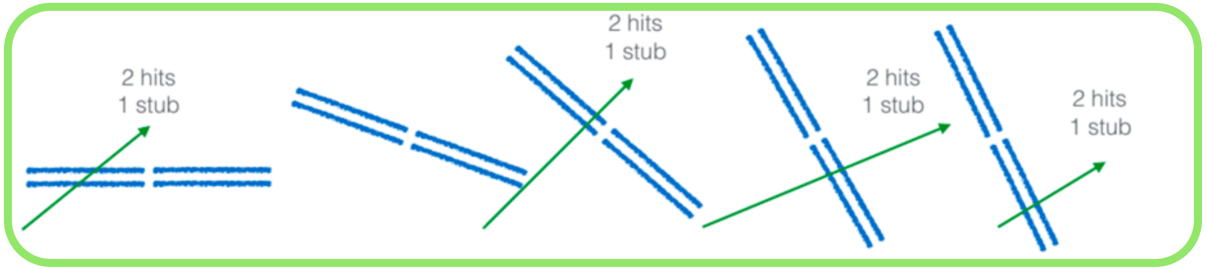
Technical Proposal Geometry




Flat Geometry




Tilted Geometry



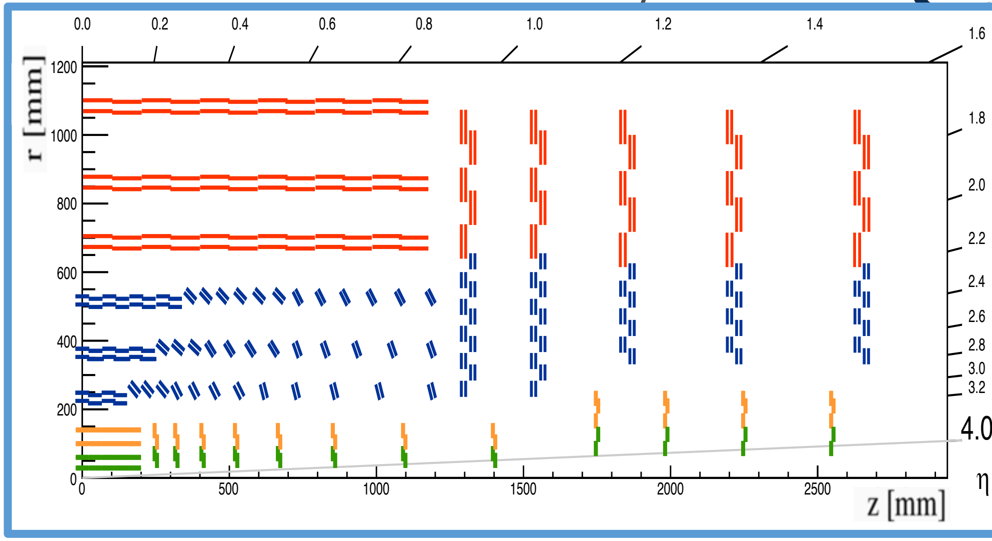
# Tilted Barrel Geometry

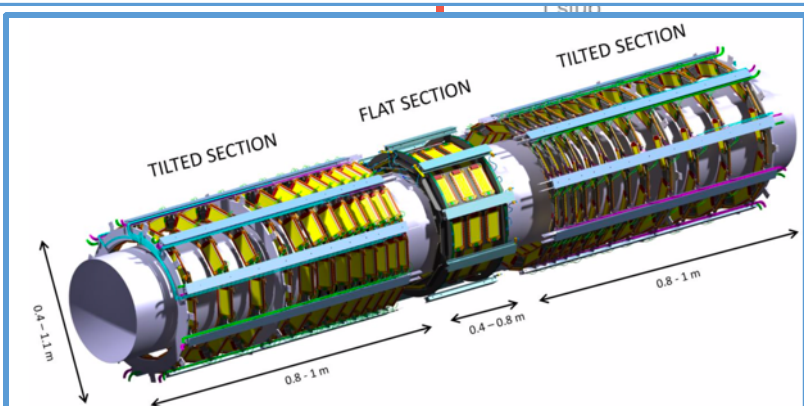
- Stubs generation works only if the charged particle cross the two sensors on the same halve of the same module
- This is not true for (flat) barrel peripheral modules

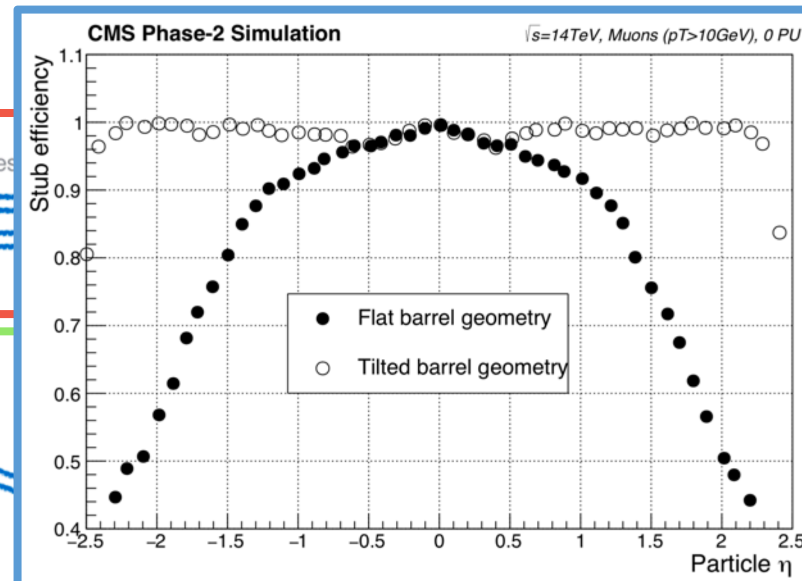
→ **(increasingly) Tilt peripherical barrel modules**

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

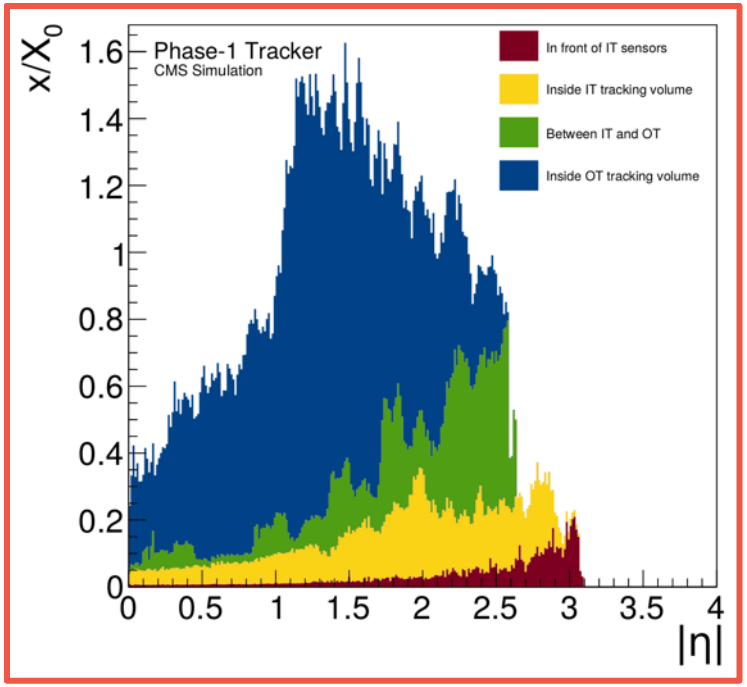
Tilted Barrel Geometry

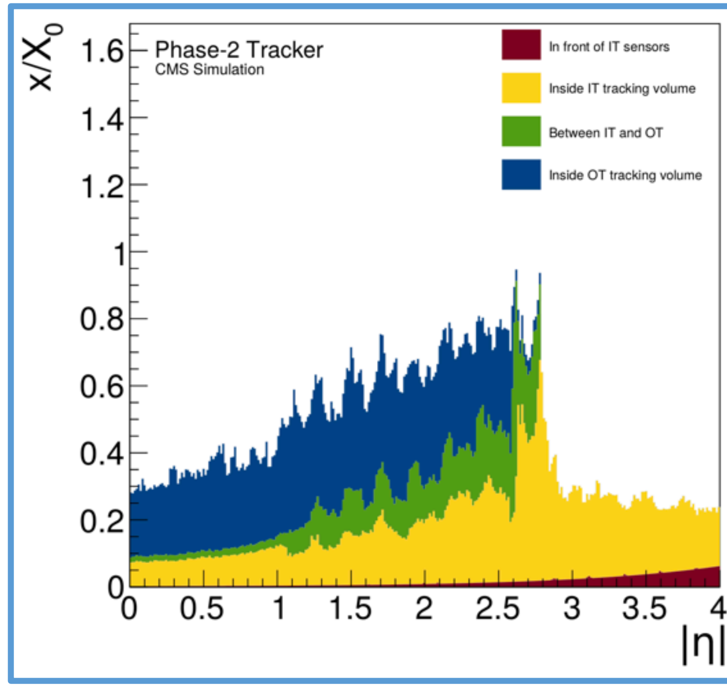


# Material Budget



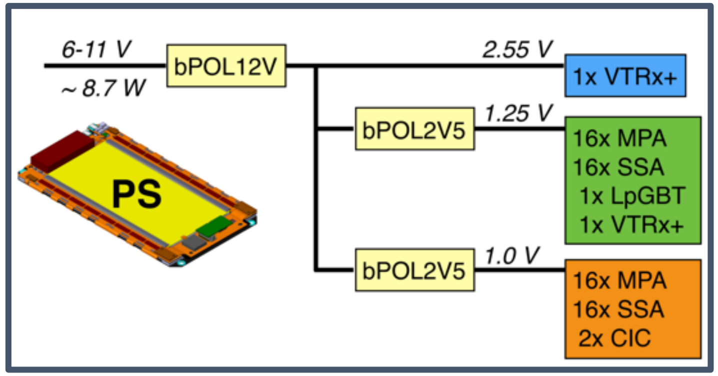



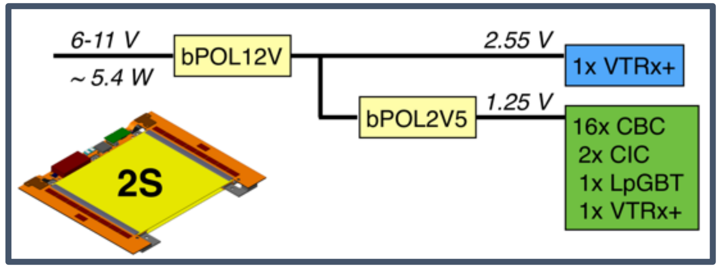

- Material budget much reduced wrt Phase0/1 detector despite an increase in the number of channels

  - *DCDC converters*
  - *Fewer layers*
  - *Lighter materials*
  - *Optimized service routing*
  - *CO2 cooling*
  - *Inclined geometry*

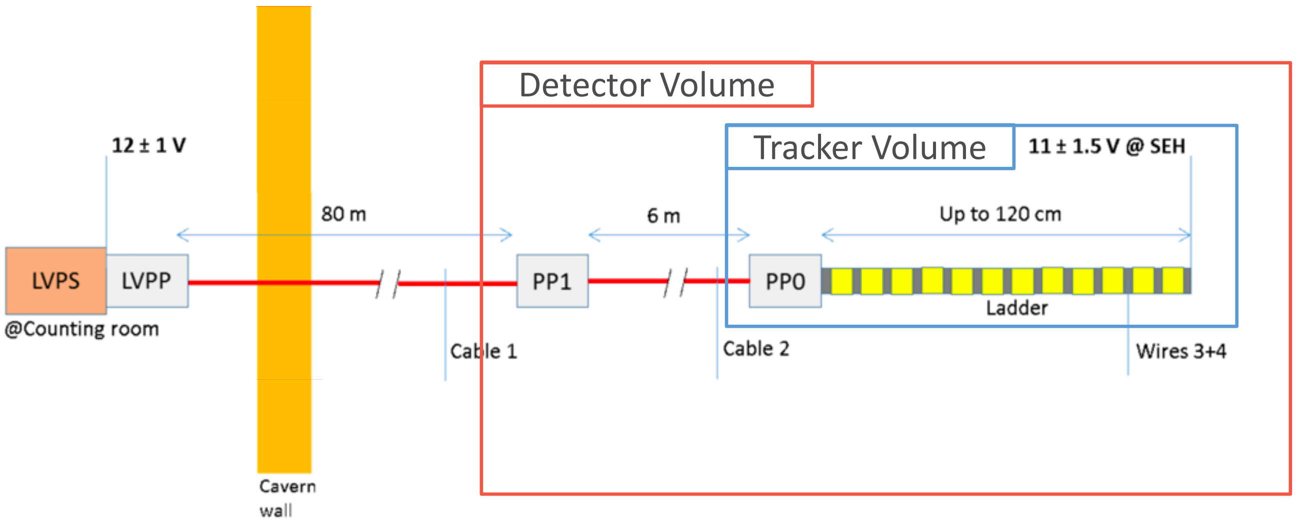
# Powering & Cooling

- **Large Area + High Granularity**
  - **High Power Budget : Outer Tracker ~100kW**
    - **Parallel Powering with on-module conversion**



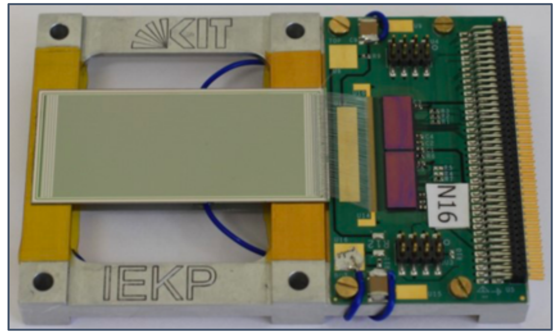



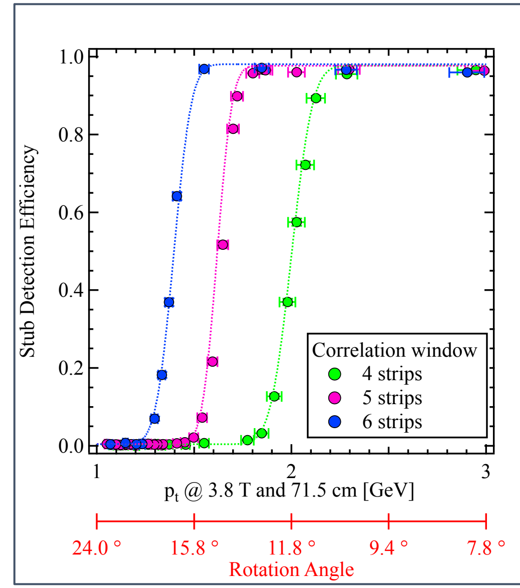

**Powerful cooling system**:
- (4+1) x 50W cooling plants
- based on two-phase $CO_2$ cooling system (-30°C set point)
- small pipes



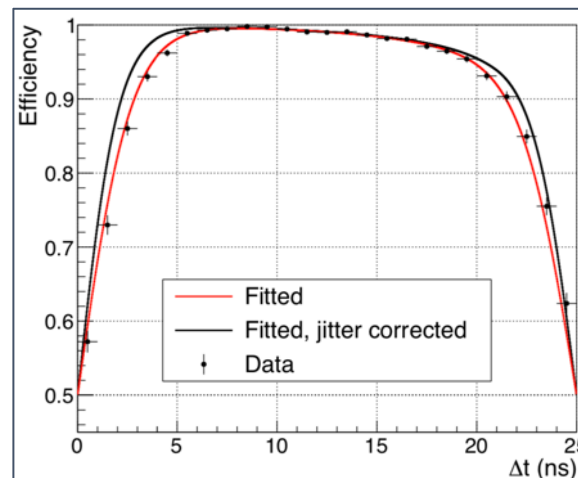
# Some highlights from beam tests

- Different module prototypes tested in particle beam



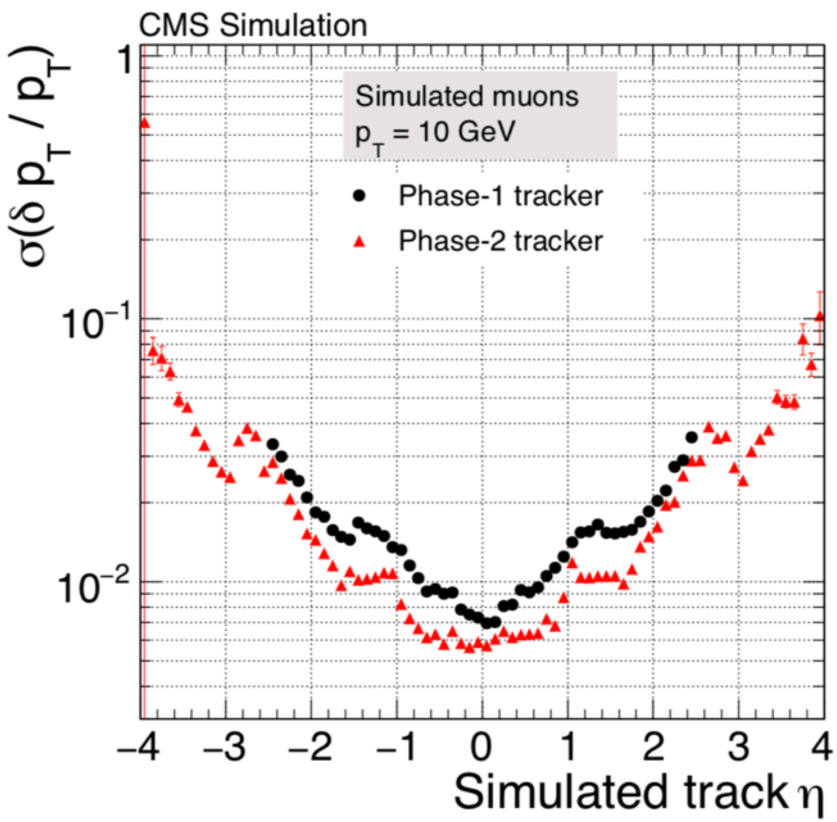

- **2S**
  - Full size module and mini-module has been tested
  - No services and no data Concentrator
  - Stubs finding capabilities tested
    - Magnetic bending «simulated» with module rotation

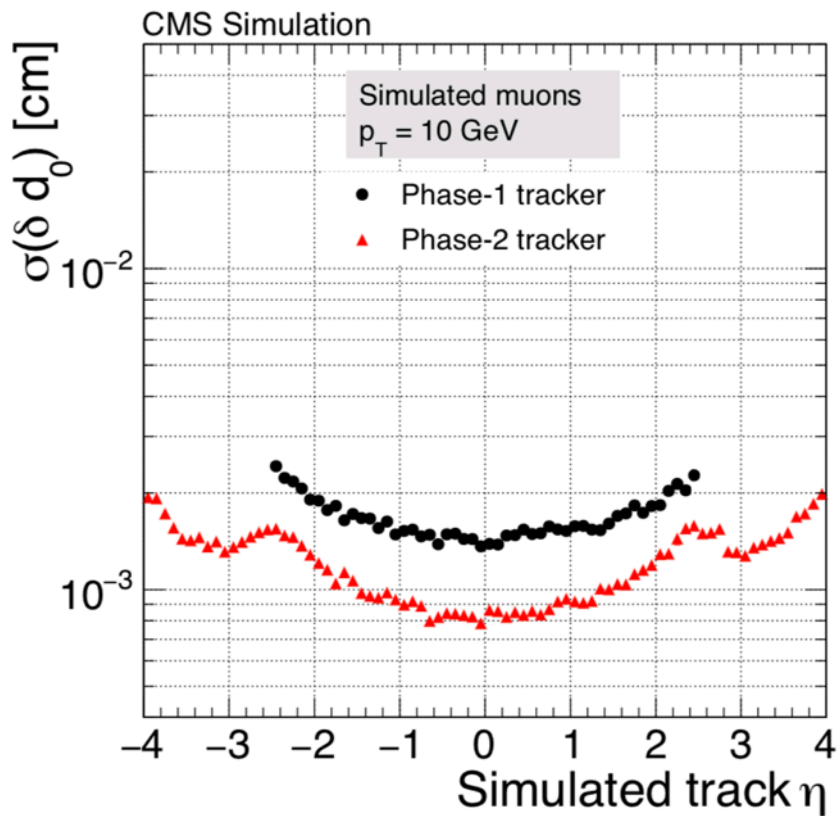



- **PS**
  - Single sensor (pixel) with MPA readout
    - No stub info
  - MPA+SSA intercommunication was tested on bench

# Performances: Phase-1 vs Phase-2

- Track parameters resolution of Phase-2 tracker improve wrt Phase-1
  - Higher granularity and less material
- Significant extention at higher η

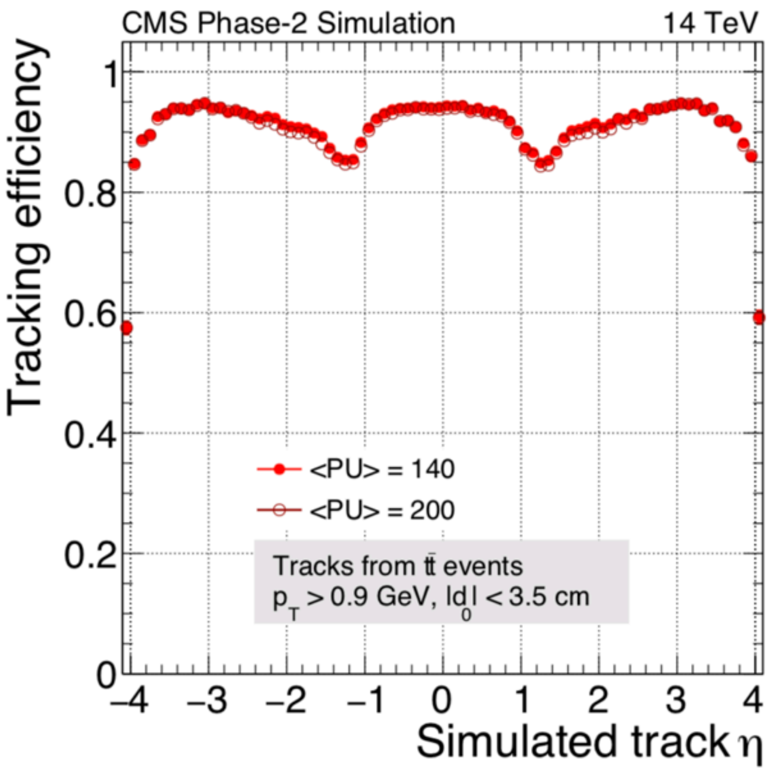


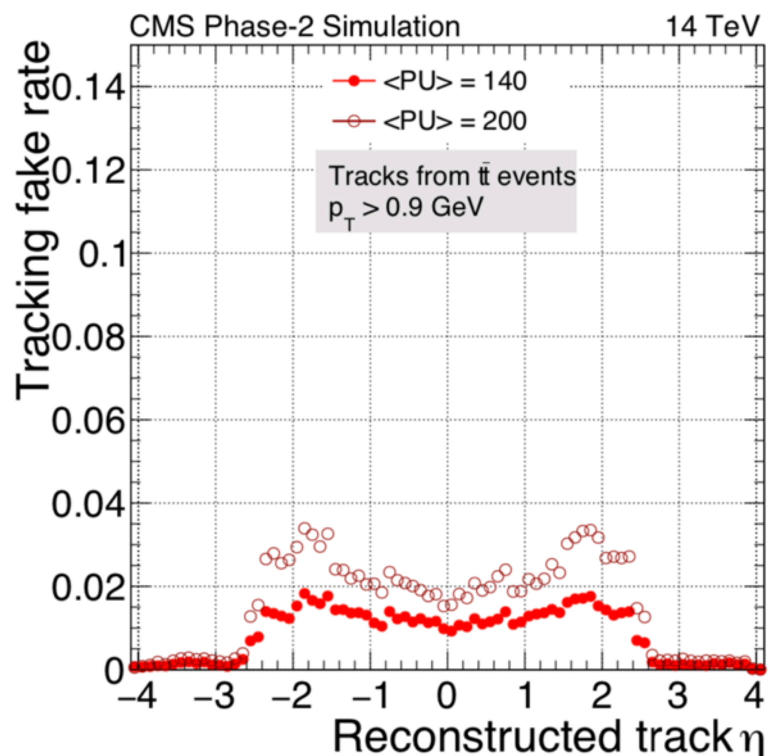



# Performances: High PileUp

- High tracking efficiency (~90%) also at 200PU
  - Fake rate below 2(4)% at 140(200)PU

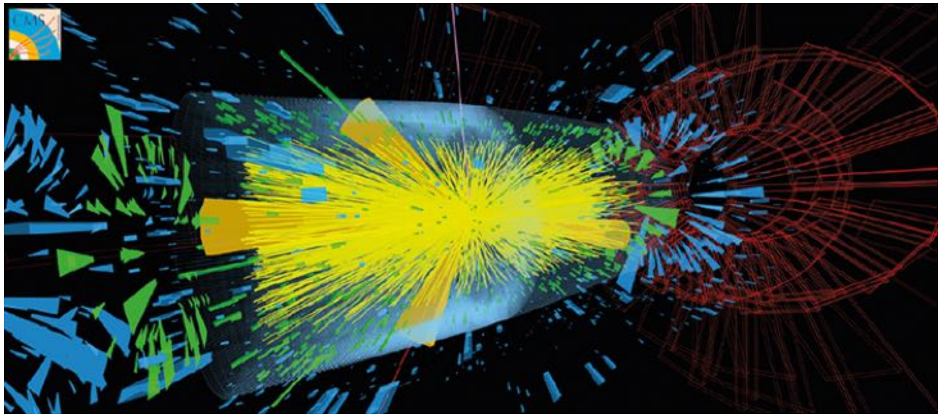
- *Dip around ±1.2η due to Barrel/endcap transition in Inner Tracker*
  - *Due to TDR geometry, reduced by a factor ~2 with optimized geometry*



# Conclusions

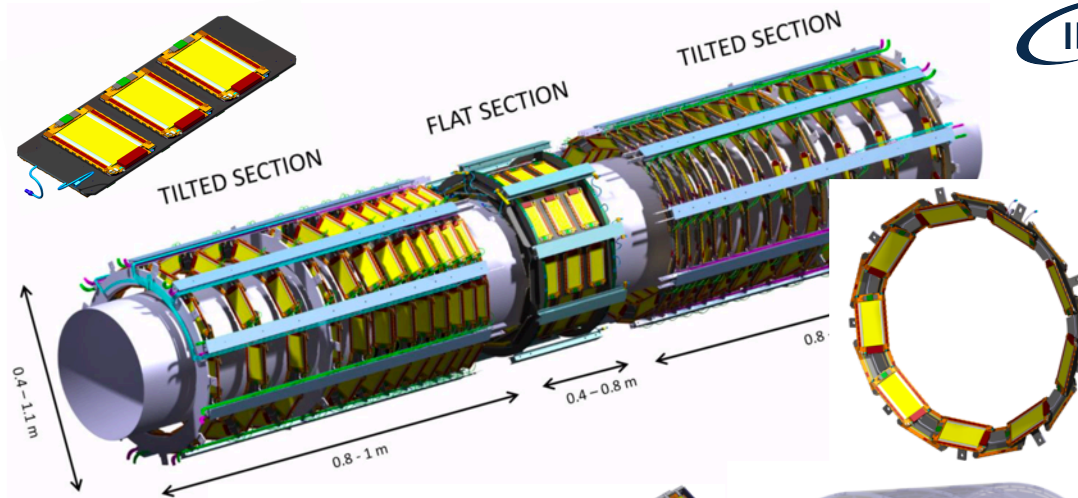
- Ambitious upgrade project underway for the CMS Outer Tracker for the HL-LHC running
  - Designed to maintained or improve tracking performance compared to current system even in the presence of up to 200 pile-up events
  - Tracks above 2 GeV as L1 primitives at 40MHz
- Improvements result in the tracker being more performant and yet more light-weight compared to its predecessor
- Advanced layout and integration studies
- First fully equipped module prototype in 2020
- …a long way toward 2026!

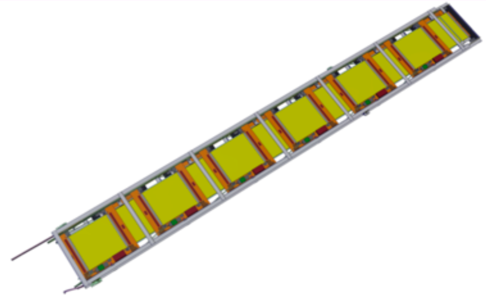


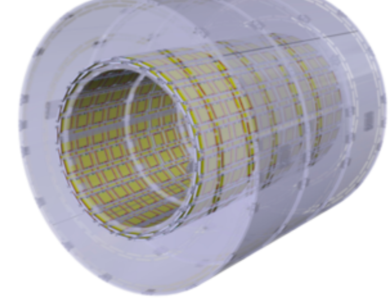
# Backup

# Mechanics

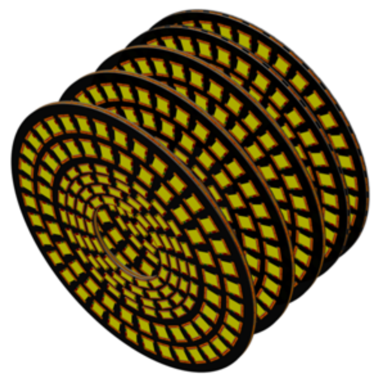
- TBPS
  - Flat Part: planks
  - Tilted Part: rings
- TB2S
  - Ladder support structure
- TEDD
  - Building block: DEE (half disk)
  - Double-Disk to be hermetic also with rectangular modules

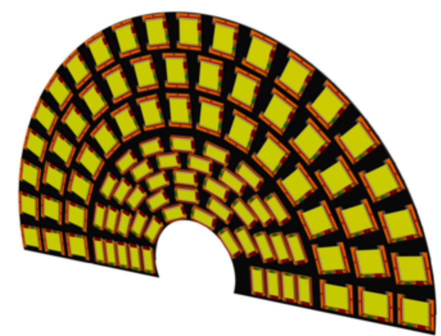




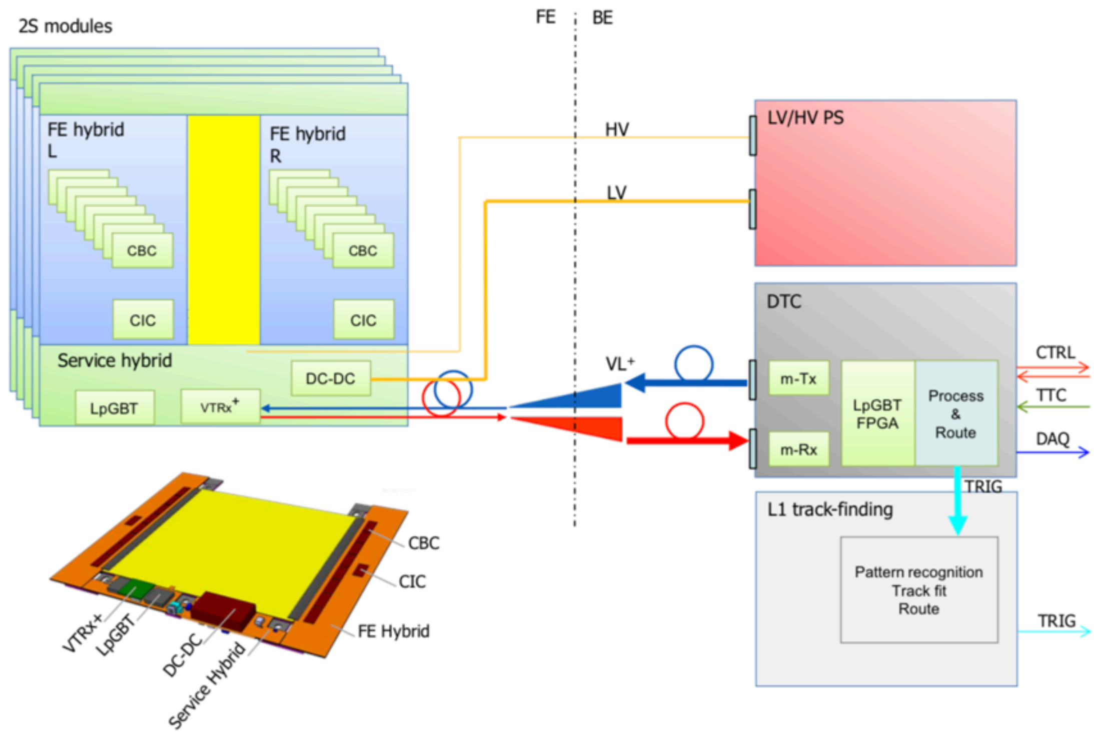
| Module type and variant | | TBPS | TB2S | TEDD | Total per variant | Total per type |
|---|---|---|---|---|---|---|
| 2S | 1.8 mm | 0 | 4464 | 2792 | 7256 | **7680** |
| | 4.0 mm | 0 | 0 | 424 | 424 | |
| PS | 1.6 mm | 826 | 0 | 0 | 826 | **5616** |
| | 2.6 mm | 1462 | 0 | 0 | 1462 | |
| | 4.0 mm |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





# Backend

- DTC (**D**ata, **T**rigger and **C**ontrol ) 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 (almost final)
- 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