The CMS Tracker Upgrade for HL-LHC

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Overview

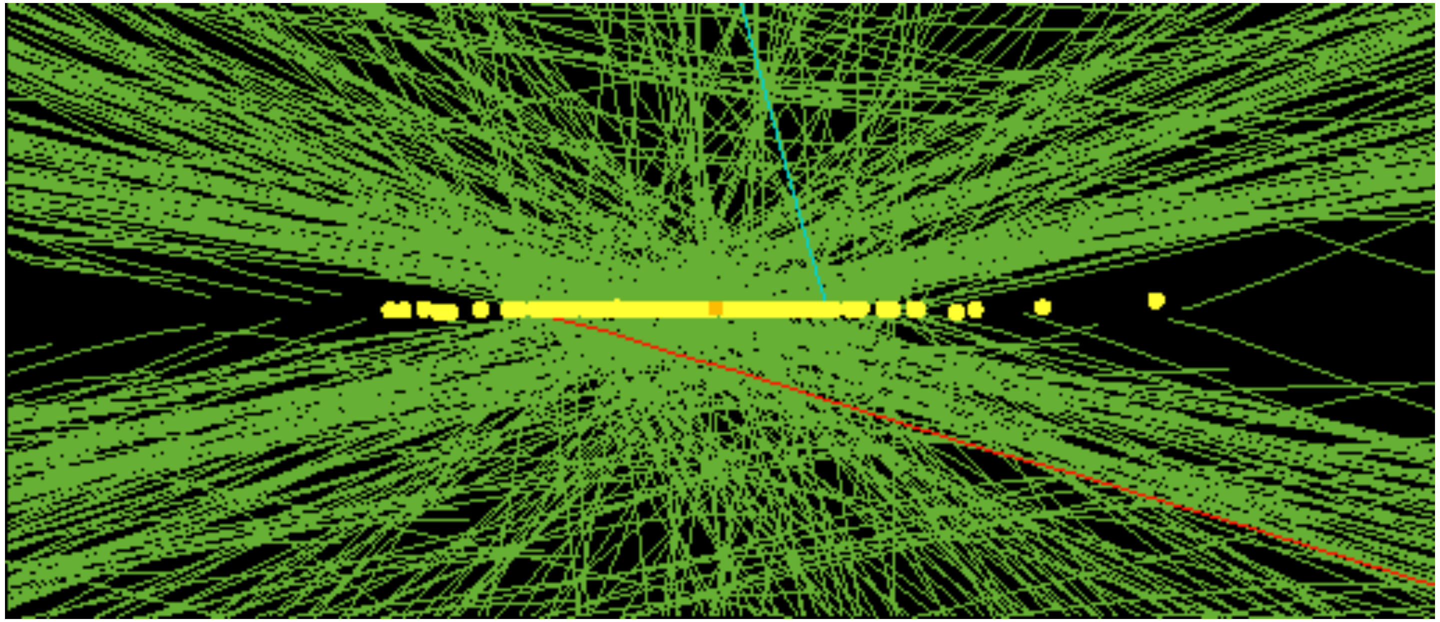
HL-LHC & CMS

Tracker for HL-LHC

- Inner tracker
  - Specifications
  - Modules
- Outer Tracker
  - p_T modules
  - L1 Track Finding

Performance results

Summary



High pile up event with 78 reconstructed vertices (pp)

High Luminosity-LHC & CMS

2010 - 2013	*2016 - 2018*	*2021 - 2023*	*2024 & beyond .....*
Run I	***Run II***	***Run III***	***HL-LHC***
7 - 8 TeV	**13 TeV**	**14 TeV**	**14 TeV**
7 x 10^{33} cm^{-2} s^{-1}	**1 x 10^{34} cm^{-2} s^{-1}**	**2 x 10^{34} cm^{-2} s^{-1}**	**5-7.5 x 10^{34} cm^{-2} s^{-1}**
21 pileup	**27 pileup**	**50 pileup**	**140 – 200 pileup**
30 fb^{-1}	**~ 150 fb^{-1}**	**300 fb^{-1}**	**3000 fb^{-1}**

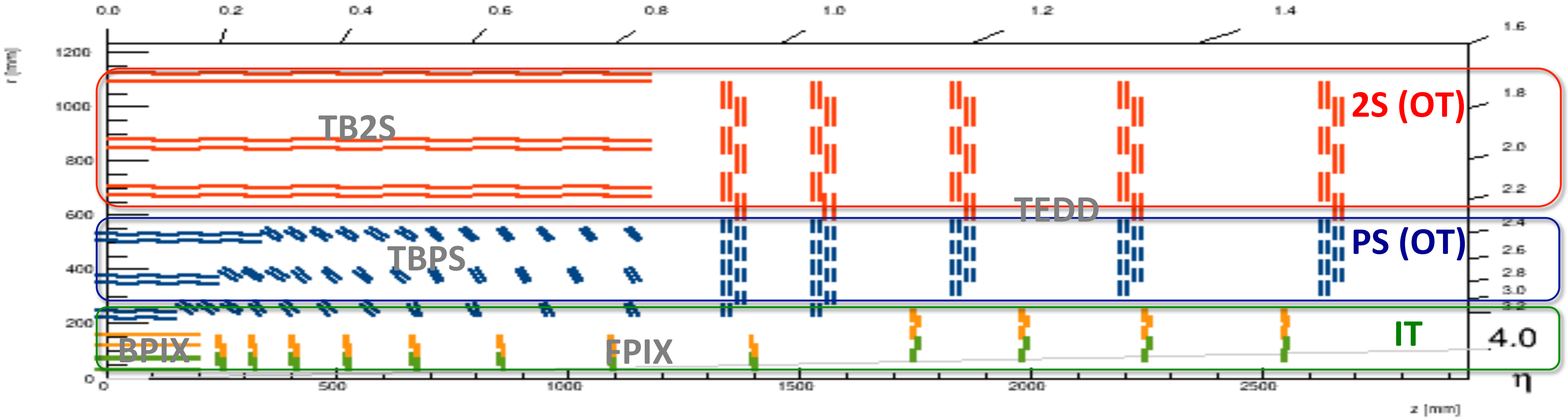
For HL-LHC, CMS requires upgrade of its *ECAL, HCAL* (front end electronics), *Muon chambers*, *L1 trigger* rate & latency, new Silicon based *High Granularity Calorimeter* & a ***Complete Replacement of the Tracker***

Current CMS tracker

- Needs improved radiation hardness (up to 3000 fb^{-1})
- Higher detector granularity (reduce occupancy)
- Improved trigger capability: utilize high p_T tracks from tracker for L1 trigger (acceptable rates)
- Increase in bandwidth
- Optimize design for covering physics goals - extend eta coverage (forward region), reduce material budget (better resolution)

More details about the current Tracker: *Construction and commissioning of the Phase I upgrade of the CMS pixel detector – R. Bartek*
Performance and track-based alignment of the upgraded CMS pixel detector – V. Botta

Phase II Tracker for CMS



Extended Eta coverage in the forward region (up to 4.0)

Inner Tracker

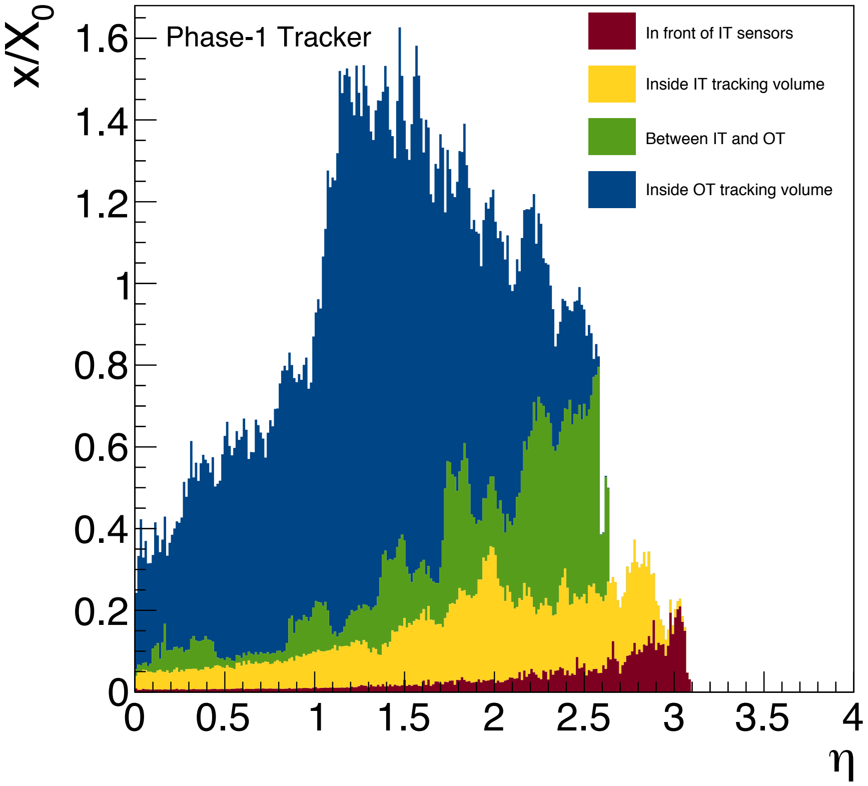
- 4.9 m^2, 2 x 10^9 pixels, two types of hybrid pixel modules: 1x2 chips (1960) and 2x2 chips (2392)
- Shorter barrel detector (reduces material budget)

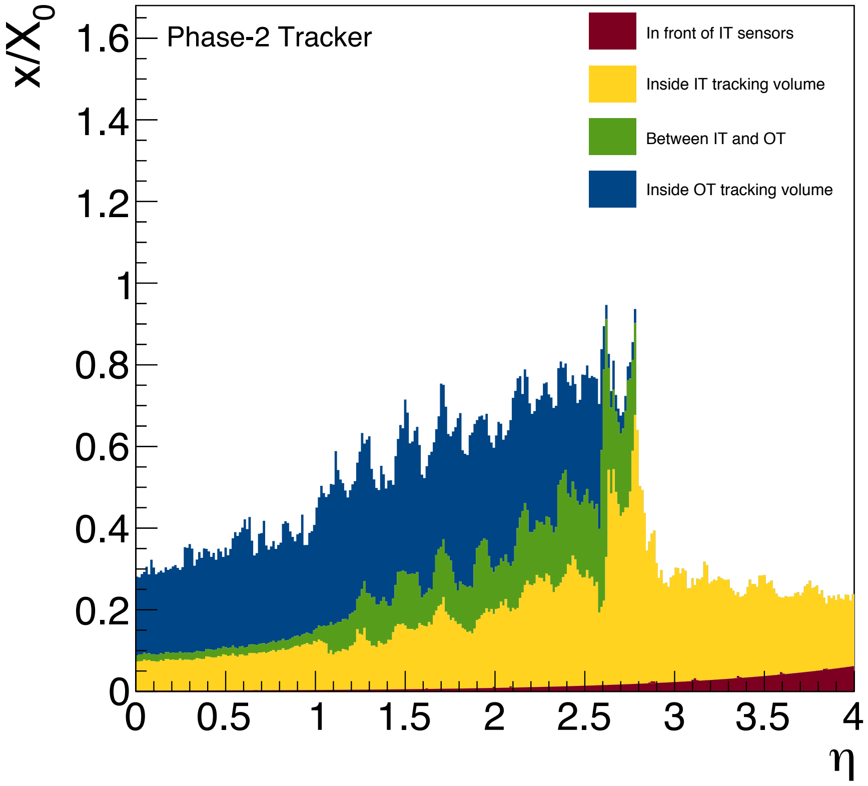
Outer Tracker

- Three layers of PS modules: provide accurate z coordinate (TBPS), partially tilted (inner barrel) to mitigate stub inefficiency
- 13296 modules (7680 (2S) & 5616 (PS)) , 192 m^2, 42M strips, 170M macro-pixels (25 m^2)

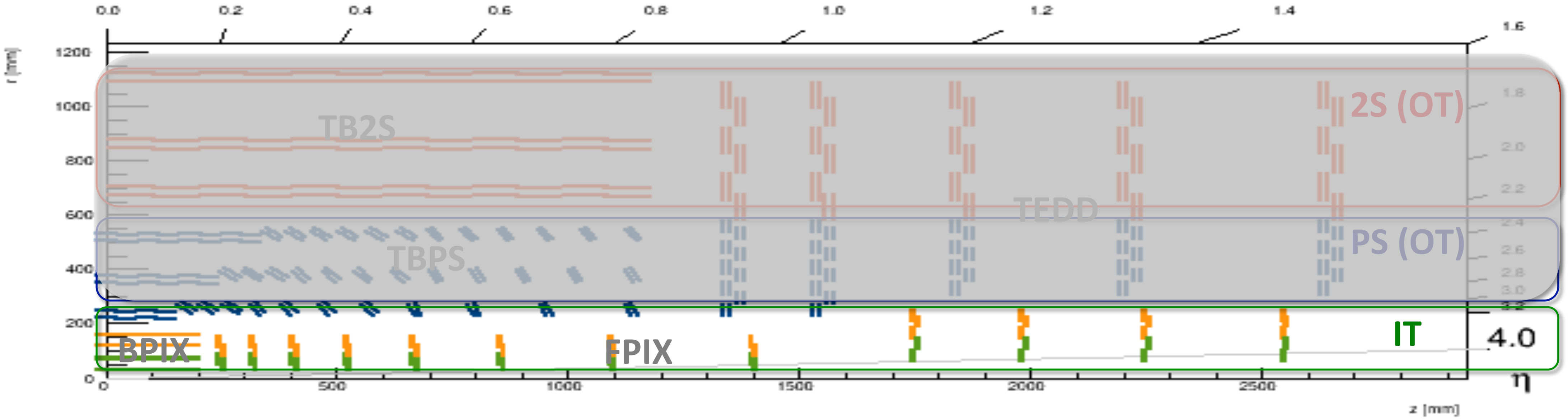
Material budget

Significant reduction in material around eta ~ 1.5





Phase II Tracker (Inner Tracker)



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Inner Tracker

Factor of 6 reduction in pixel area

- Low occupancy, improved track separation

TEPX provides luminosity measurement

Extractable (potential to exchange degraded parts, if required)

Narrow pitch & high granularity

- 50 x 50 or 25 x 100 μm^2 cell size

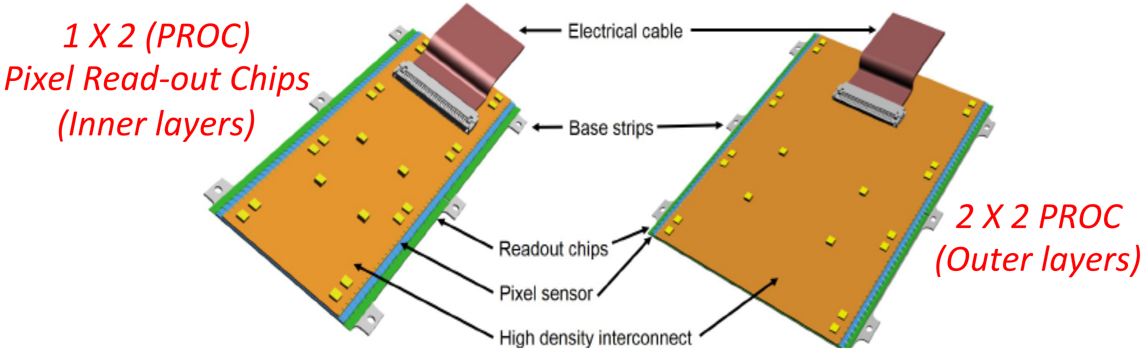
Deals with high radiation levels & hit rates

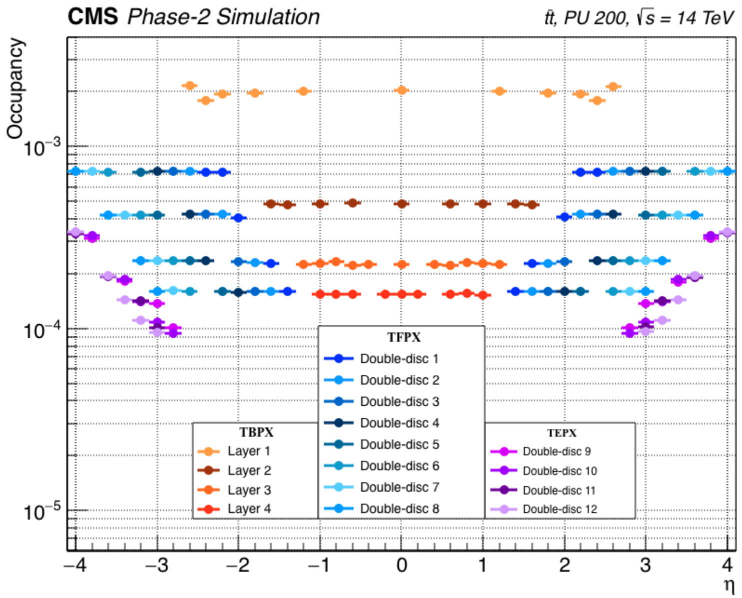
Two types of modules (similar to Phase I)

- Hermetic arrangement in endcaps

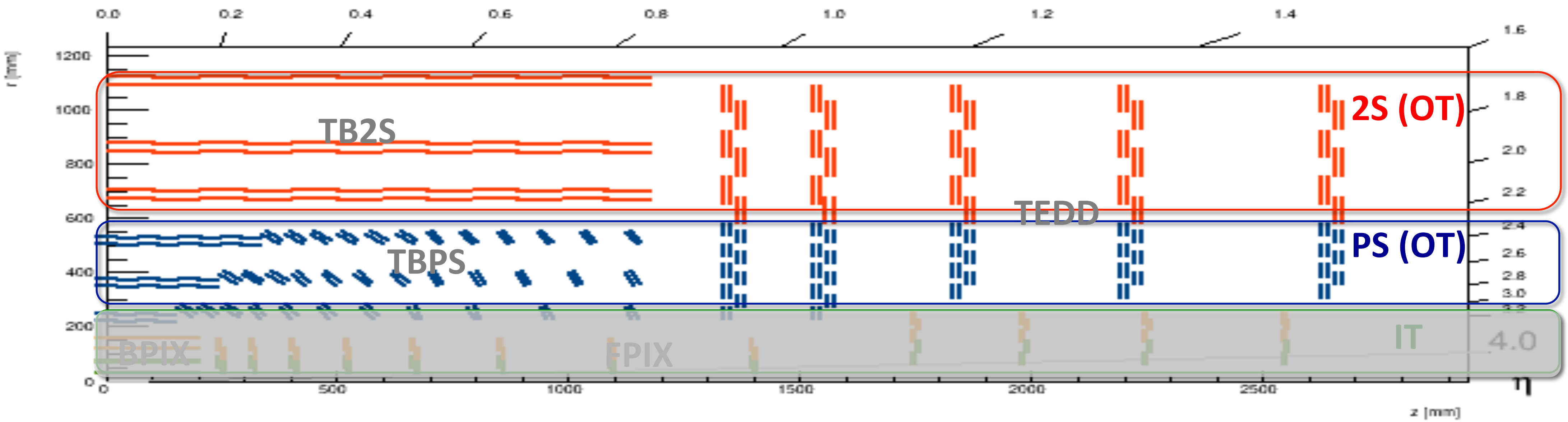
Sensor technologies (n-in-p)

- Planar Silicon pixel sensors for the outer layers (thickness: 100-150 μm)
- 3D silicon sensors for inner layers (alternative option), for TBPX and ring 1 in TFPX





Phase II Tracker (Outer Tracker)



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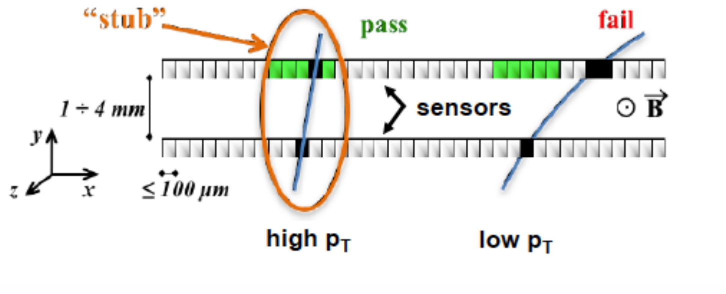
p_T module concept

Outer Tracker design driven by implementation of track finding at L1

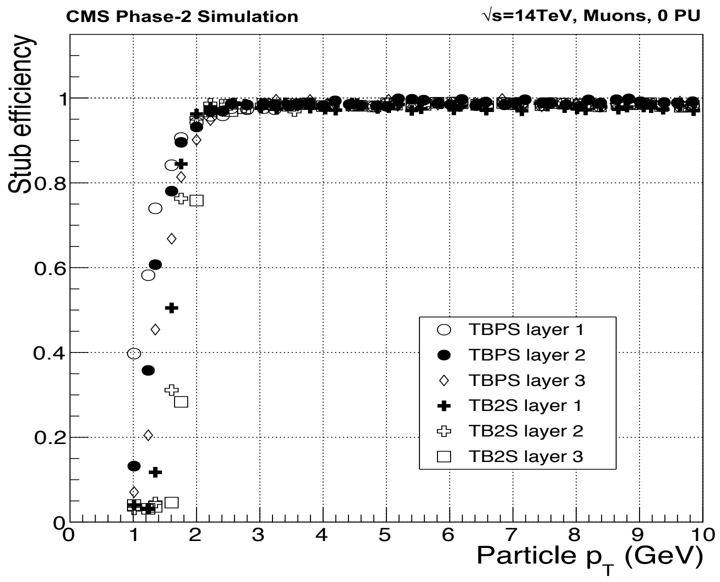
Enables p_T-discrimination for tracks in the strong CMS magnetic field

- Correlating hit patterns in 2 closely spaced sensors to filter high p_T tracks (≥ 2 GeV/c)
- Data reduction by a factor of 10-100
- Transmitted at 40 MHz BX frequency to L1



Hit pairs ("Stubs") sent to back-end form L1 tracks

- Combined with calorimeter & muon information
- Event readout at ~ 750 KHz (after L1 decision making)
- L1 Tracks reconstructed from 10K stubs within 4μs latency budget



Modules for Outer Tracker

Sensors: n-in-p planar technology

Radiation hard sensor materials; thinner sensors (200 µm)

PS module

Sensor size: 5 cm x 10 cm

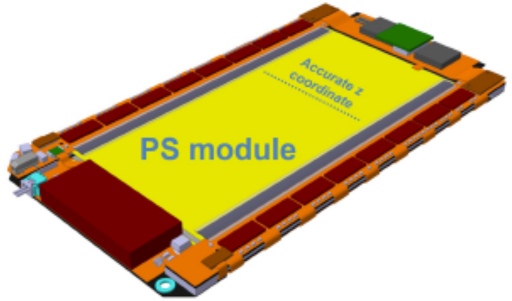
2 x 960 strips; 32 x 960 macro-strips

Strip (Top sensor): 2 rows 2.3cm long

Macro-pixels (Bottom sensor): 1467µm long (good z resolution)

Pitch of 100µm (both)

Read-out: SSA + MPA chip



2S module

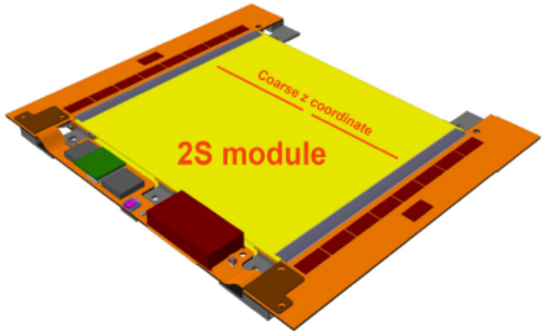
Sensor size: 10 cm x 10 cm

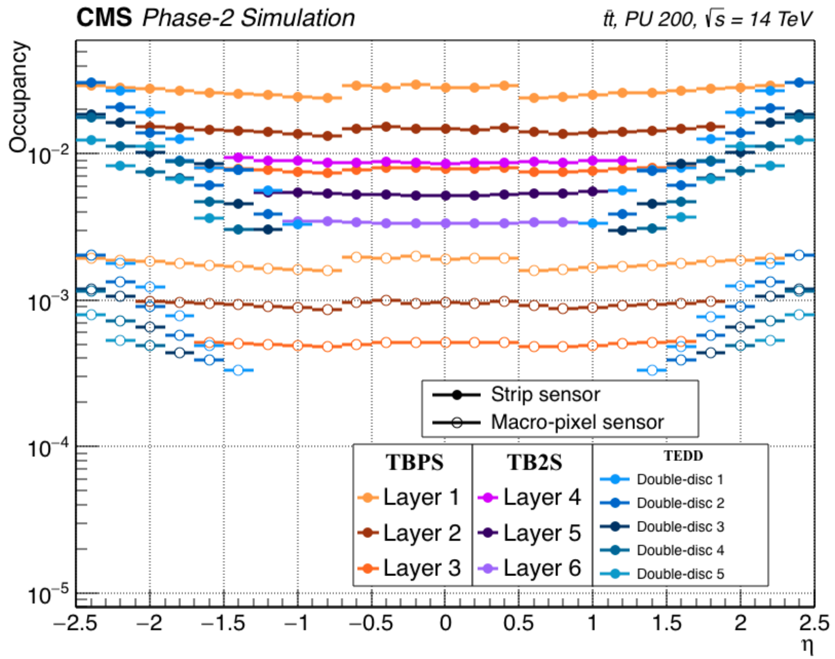
2 x 1016 strips (both)

Strip dimension: 5cm long (2 rows per sensor)

Pitch of 90µm

Read-out: 2 x CBC chip





Highest occupancy ~ 3% in Layer 1 Strips
Drop at eta ~ 1.5 (tilted geometry)

Outer Tracker: Front End Electronics

Use of a common data transfer system, based on LpGBT

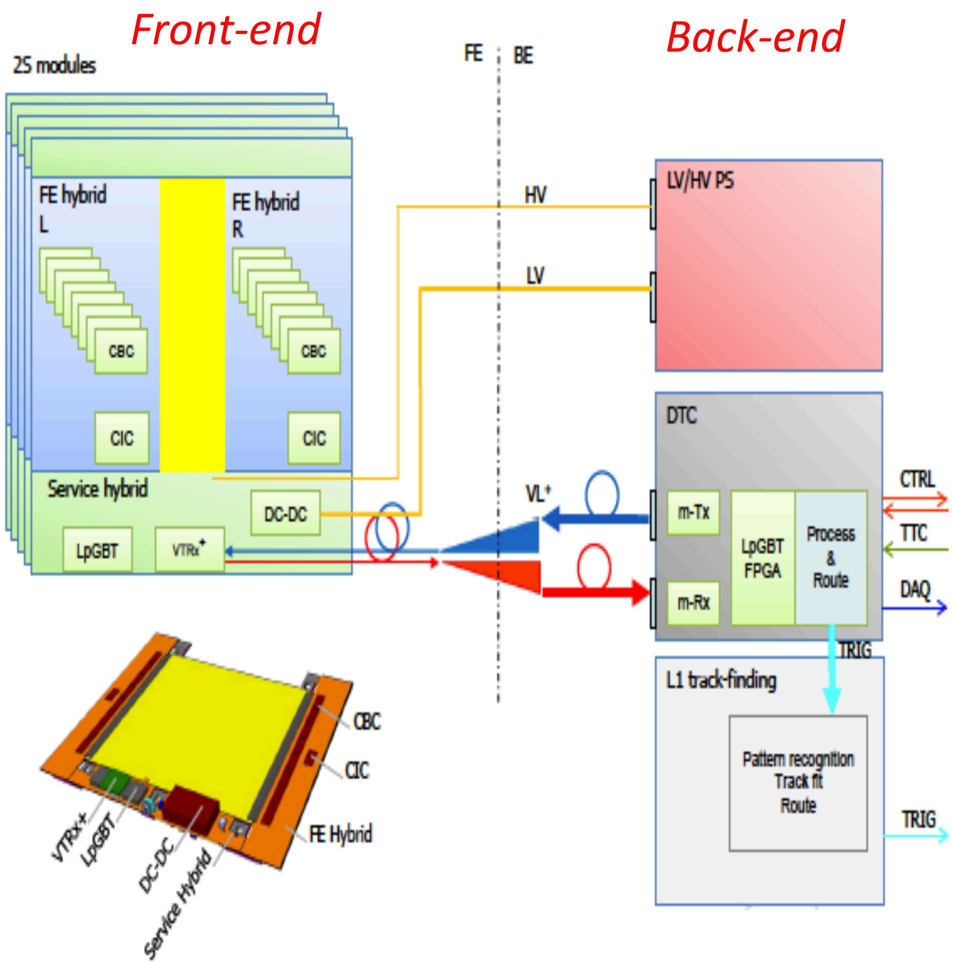
Technologies, architectures, and data formats kept similar for both systems (PS & 2S)

Dedicated read-out ASIC's for both

- CBC (2S) & SSA+MPA (PS)

Common aggregator chip (Concentrator Integrated Circuit, CIC)

- Block synchronous (8BX) transmission of stub data
- Sparsified transmission of readout data @ 750 kHz



L1 Track Trigger

Three approaches under investigation differing in Pattern Recognition (PR) techniques (using powerful FPGA based systems)

- Associative Memory ASIC's + FPGA, FPGA based Hough transform & FPGA based Tracklet

Hardware demonstrators setup for each show

- L1 track finding feasible with needed performance & within latency budget
- High efficiency, remarkable p_T & Z_0 resolution, low sensitivity to pile-up

Further studies ongoing (for all approaches) based on a FPGA-based reference design

- To further assess ultimate performance potential and limitation

AM + FPGA

- PR with custom designed AM chips
- Use coarse stub information to perform fast PR & stub selection
- Custom Pulsar 2b boards with PR mezzanines hosting AM chips & FPGA

Hough Transform (HT)

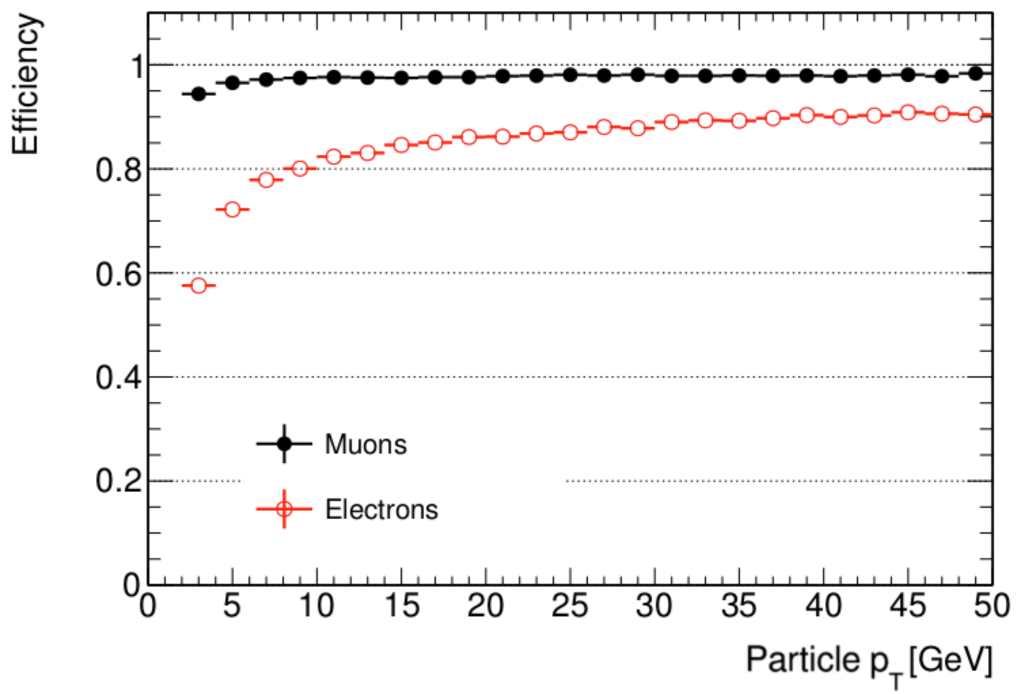
- Track candidates built based on (r,ø) HT
- Stub-data pre-duplicated at single node, minimizing number of regional boundaries
- µTCA based MP7 boards

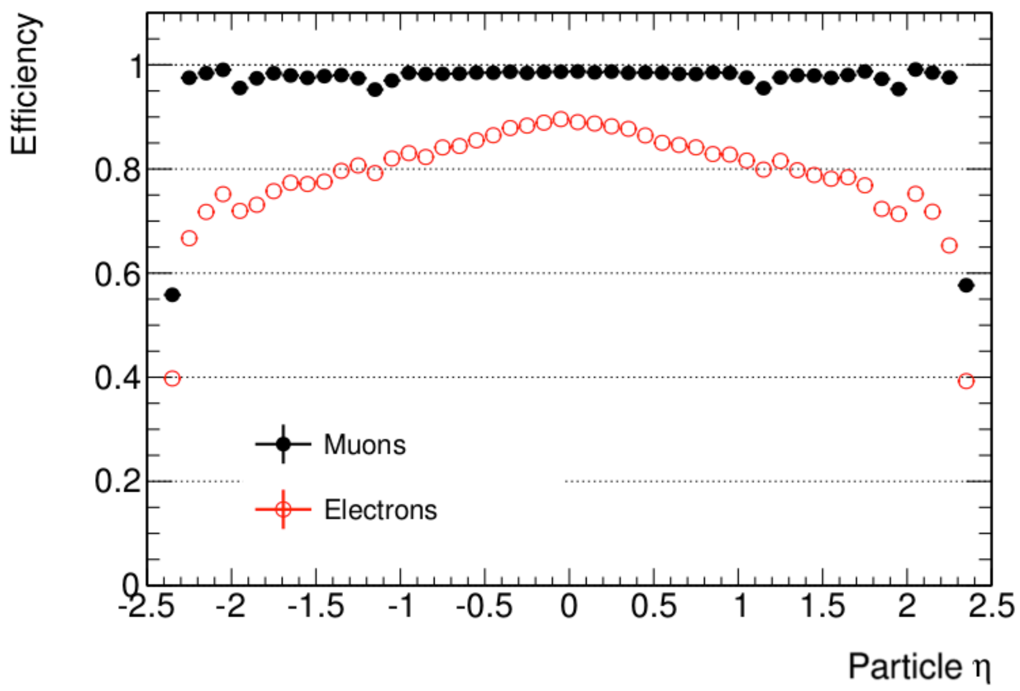
Tracklet

- Road based track search seeded by tracklets (stub pairs)
- Multiple seeding ensuring good coverage
- µTCA based CTP7 boards

Performance

Level-1 Tracking Performance



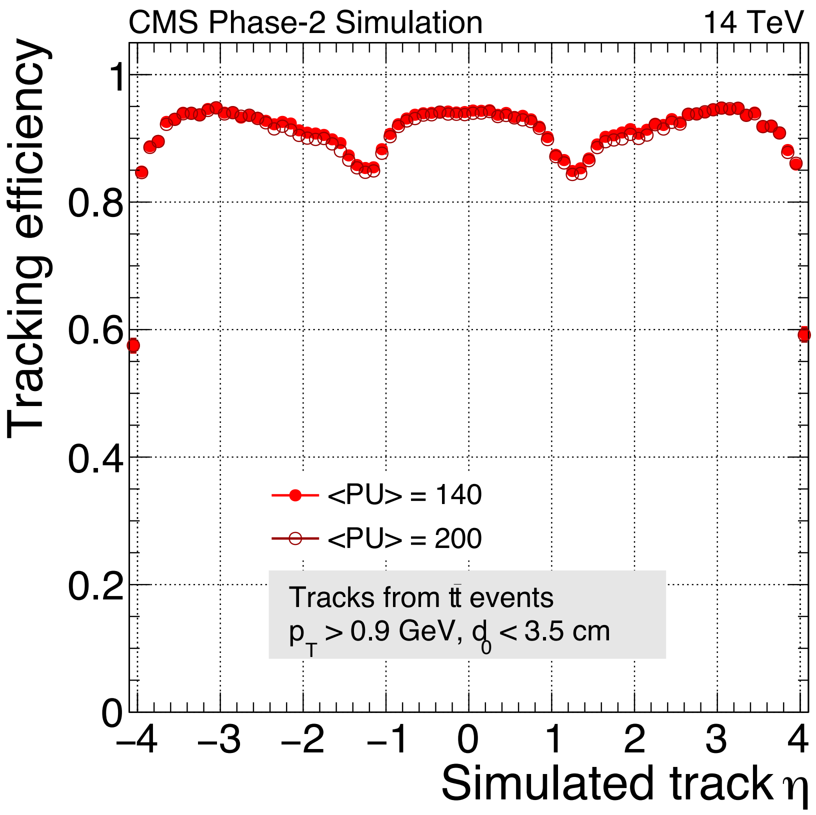


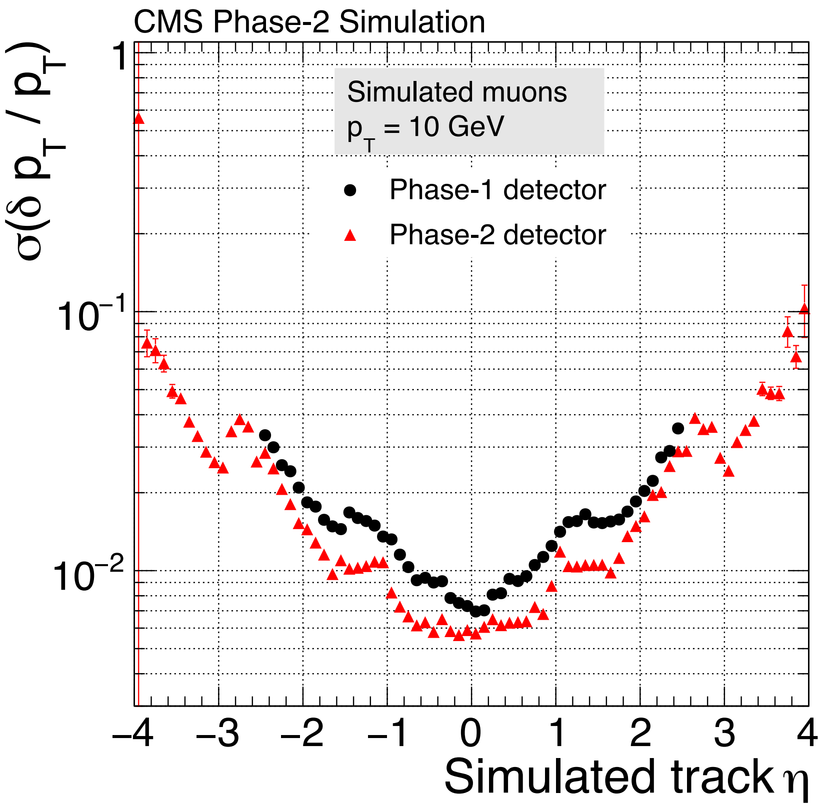
Using flat barrel geometry

Offline Tracking Performance

Tracker traversed by 6000 tracks on average each BX (for 200 PU)

High Purity tracks considered. Within 3.5 cm radially from the center of luminous region.

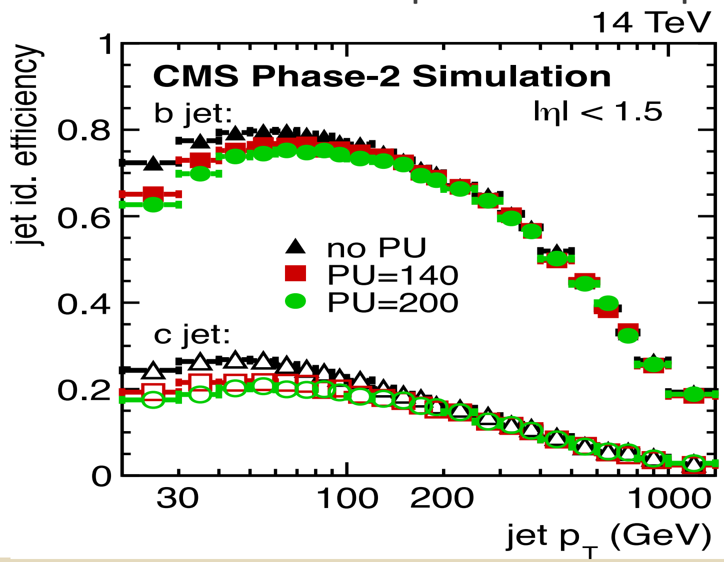




Physics Performance

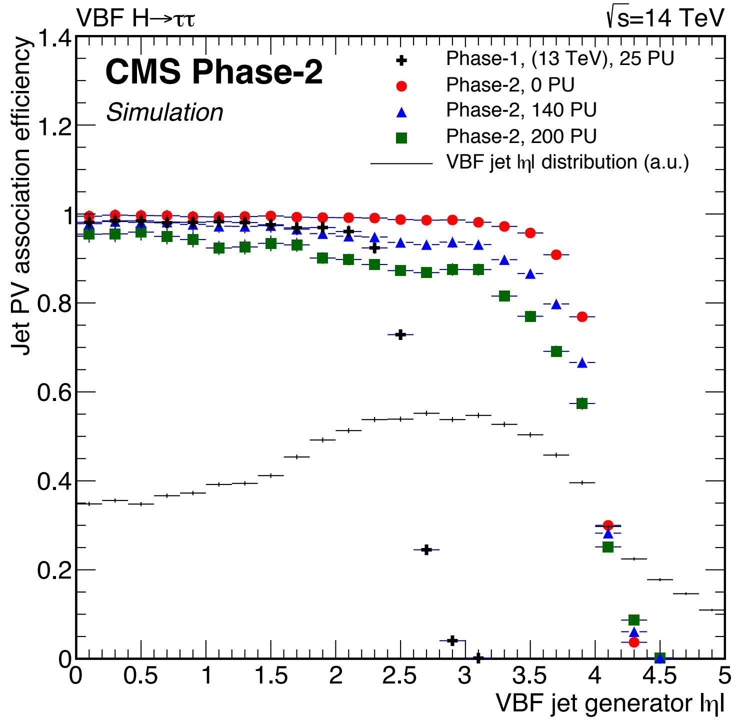
Excellent tracking performance shown earlier

- Major tools to achieve global event description that can stand high pileup.
  - Excellent performance of pileup mitigation algorithms.
  - High b/c-tagging efficiencies at high pileup.
  - B-tagging capability in high eta region.
  - Tau identification consistent as a function of pileup.
  - Jet substructure techniques efficient up to 2 TeV.



Large integrated luminosity (3000 fb^{-1}) at HL-LHC enables exploration of multi-TeV scale

- Searches with high masses or investigation with low cross section processes.



Summary

CMS upgrades for HL-LHC is a challenging task

HL-LHC requires complete replacement of the current Tracker

- Radiation damage, enormously high pileup, tracking at L1, increased detector acceptance, reduction in material budget

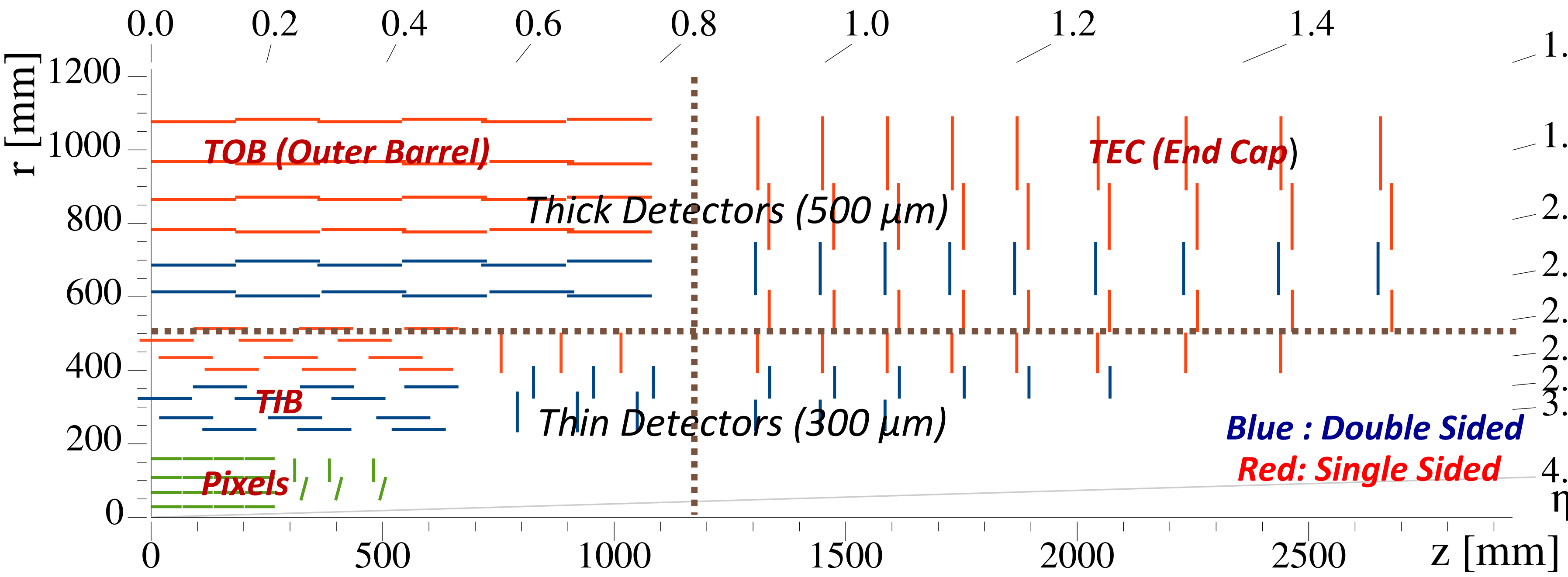
R&D performed for the Phase II Tracker Technical Design Report (TDR) presented

- Geometry, layout, module design, sensors, performance, etc.
- Phase II Tracker Upgrade is a lot more ground to cover (many years of R&D and still ongoing)
- Complete description of the CMS Phase II Tracker in the TDR *(*)*
- Major work still ahead of us …

<u>Reference</u>: *The Phase-2 Upgrade of the CMS Tracker, CERN-LHCC-2017-009 (*)*

Back-Up

Current CMS Tracker Configuration



Sensor : p-in-n
Design occupancy : 1-2%
Outer cell : ~ 20 cm x 100-200 µm
Inner cell : ~ 10 cm x 80 µm
Pixel cell : 100 µm² x 150 µm²

Present Strip Tracker designed to operate till 500 fb^{-1}

Original Pixels (inner tracker) already replaced by "Phase I" Pixel detector during the EYETS 2016/17

- Additional tracking layer, optimized material budget, improved ROC, increased bandwidth

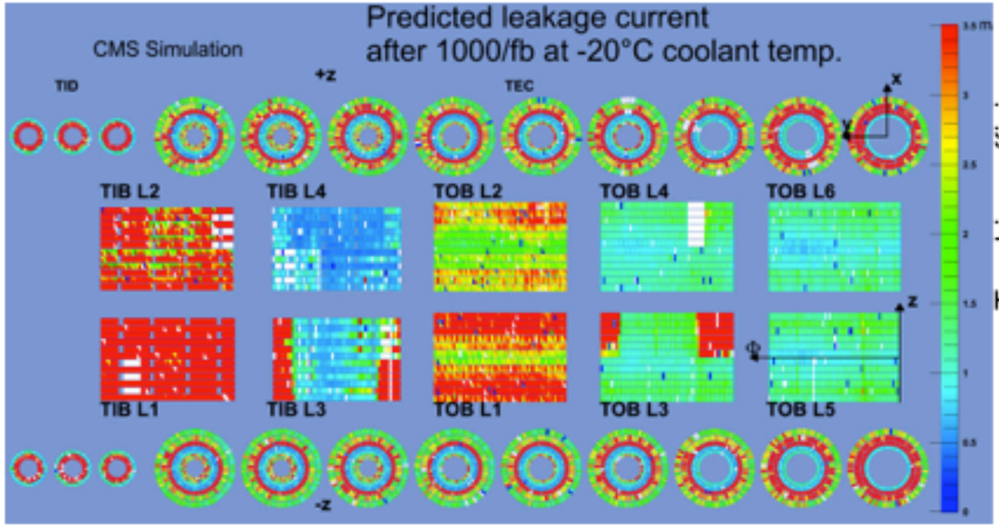
Degradation of the current tracker beyond 1000 fb^{-1}

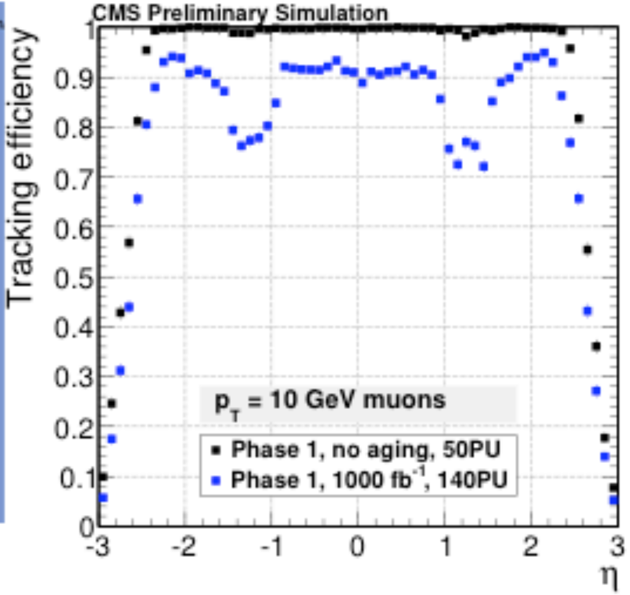
- Deterioration of tracking, physics performance affected (due to limited bandwidth & trigger latency)

Complete replacement of the current tracker required for HL-LHC

Radiation Damage

Radiation Damage



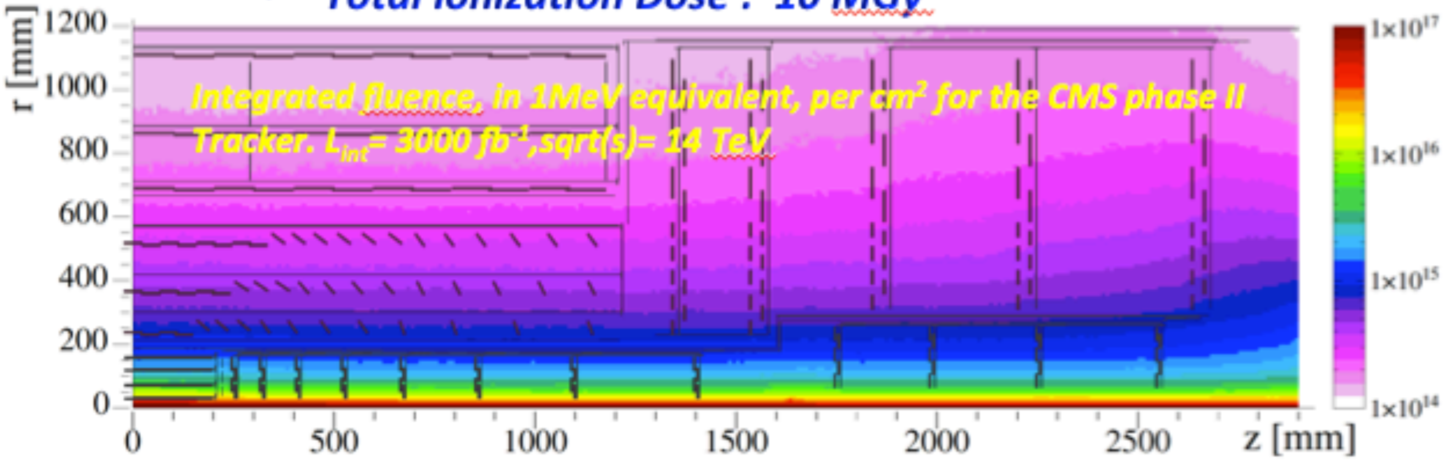


Total Tracker Replacement

Radiation Damage

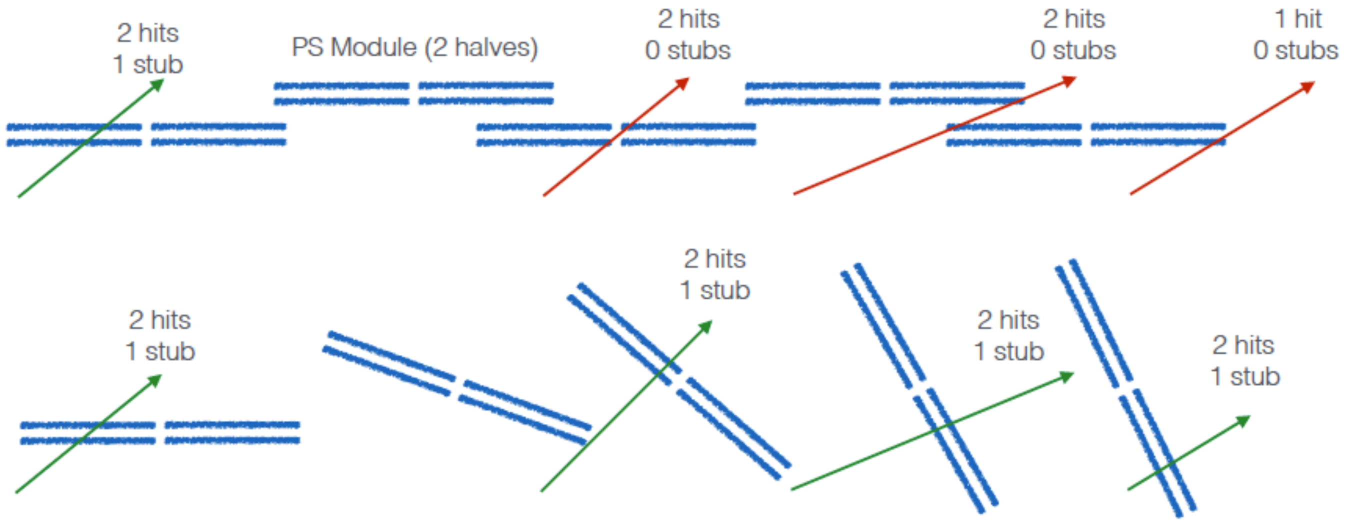
Radiation Damage :

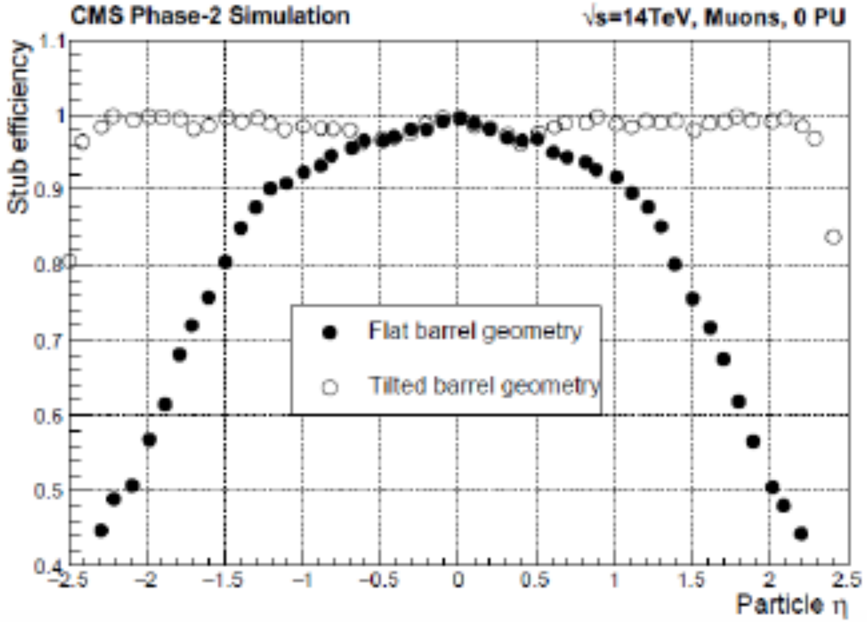
- *Fluence ~ 2.5 x 10^{16} n_{eq}/cm^2 in the center of CMS*
- *Total Ionization Dose : 10 MGy*



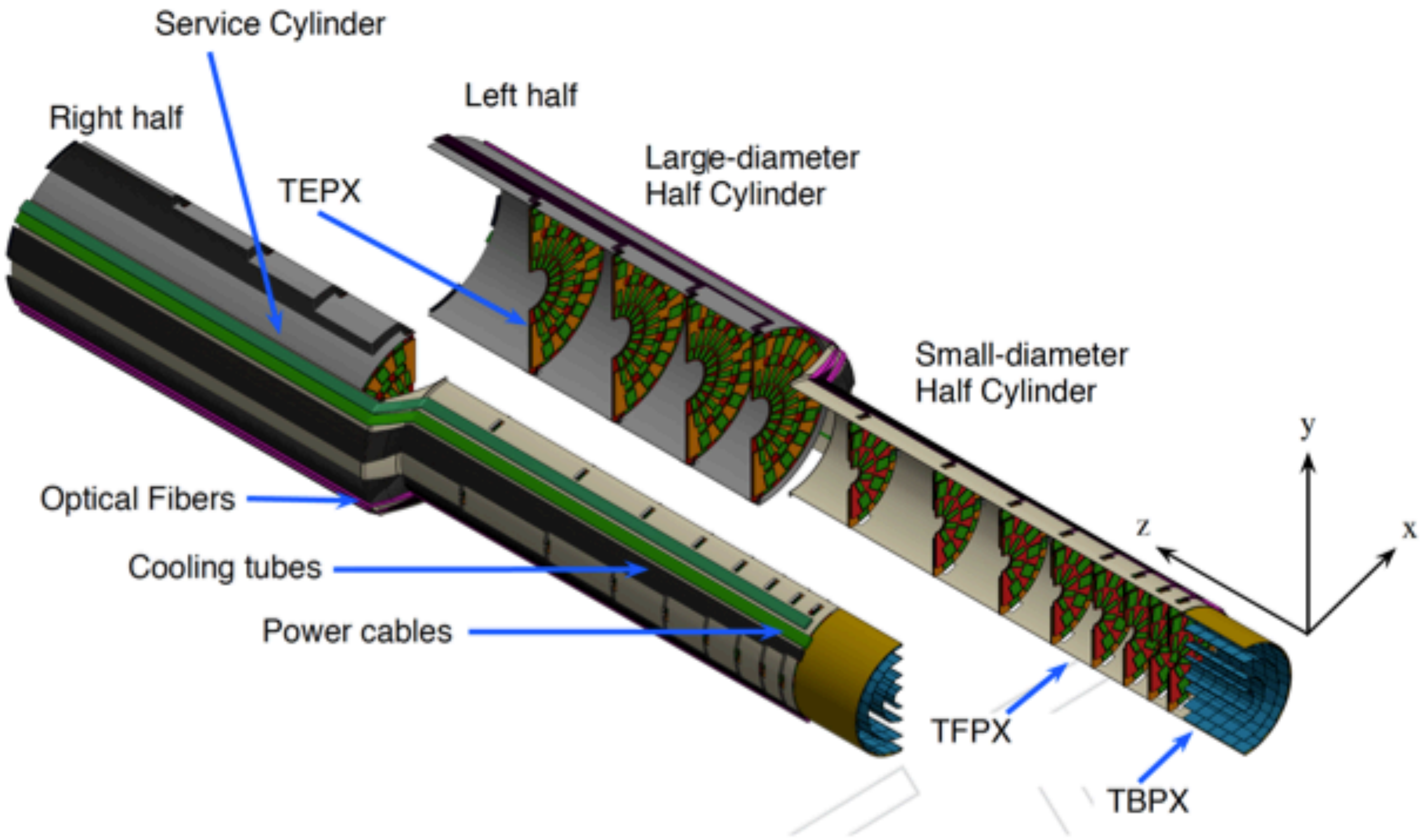
Region or component	Max. fluence [n_{eq}/cm^2]	r [mm]	z [mm]
IT barrel layer 1	2.5×10^{16}	28	0
IT barrel layer 2	5.2×10^{15}	67	0
IT barrel layer 4	1.5×10^{15}	156	0
IT support cylinder	1.3×10^{15}	166	260
OT 2S modules	3.0×10^{14}	644	2670
OT PS modules	9.6×10^{14}	225	148

Flat VS Tilted





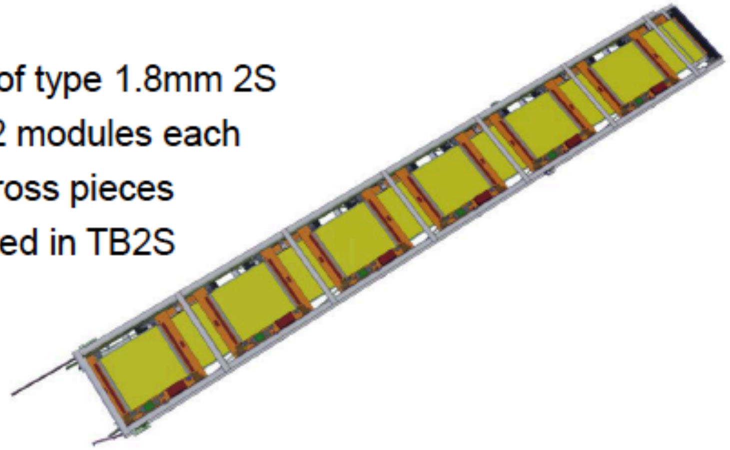
Inner Tracker: mechanics

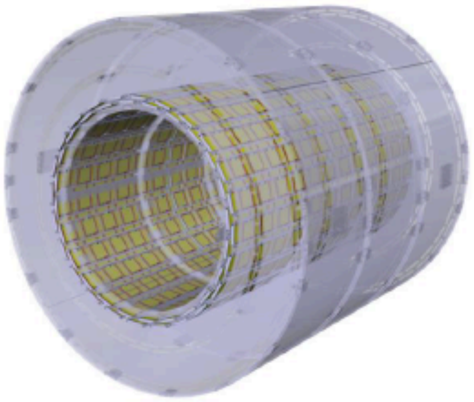


Outer Tracker: barrel mechanics

TB2S:

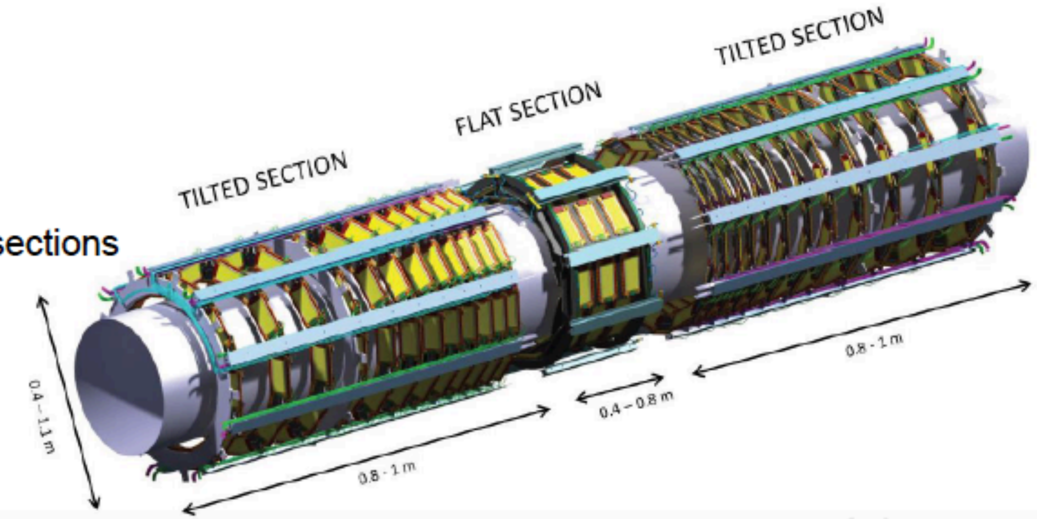
- 4464 modules of type 1.8mm 2S
- 372 ladders, 12 modules each
- CF profiles + cross pieces
- Ladders mounted in TB2S wheel (CF)





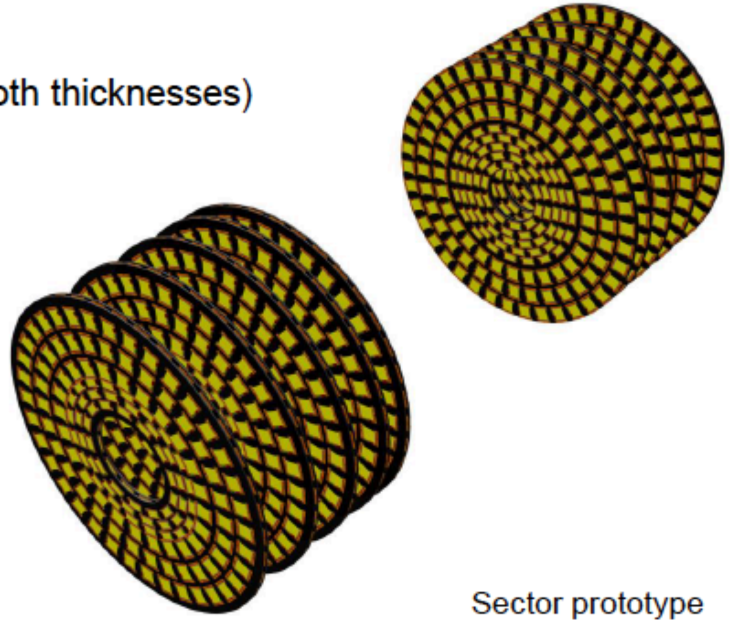
TBPS:

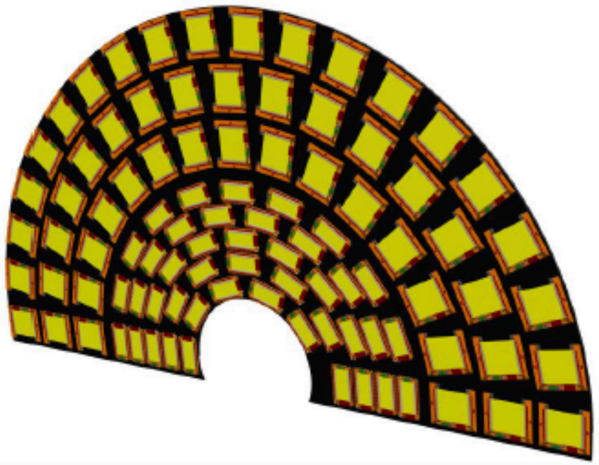
- 2872 PS modules
- Central flat section & tilted sections
- Modules mounted on planks and rings

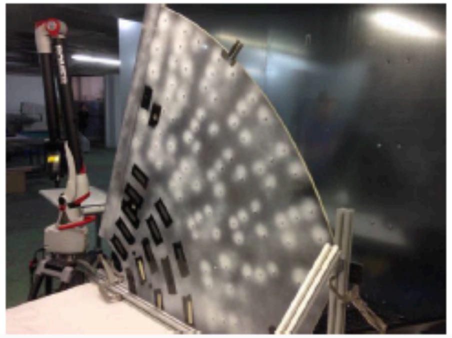


Outer Tracker: endcaps mechanics

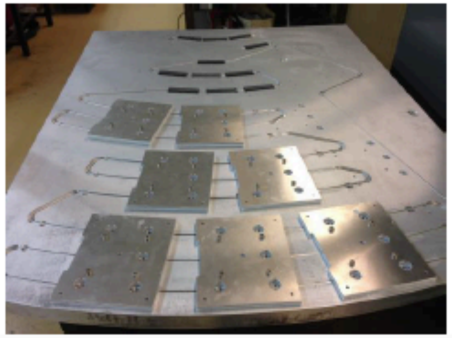
- Rectangular modules
- 2744 PS modules (4mm), 3216 2S modules (both thicknesses)
- Elementary unit: a dee (Airex foam & CF skins)
- 8m long cooling pipes running inside the dees
- Carbon foam blocks (PS) & cooling inserts (2S)



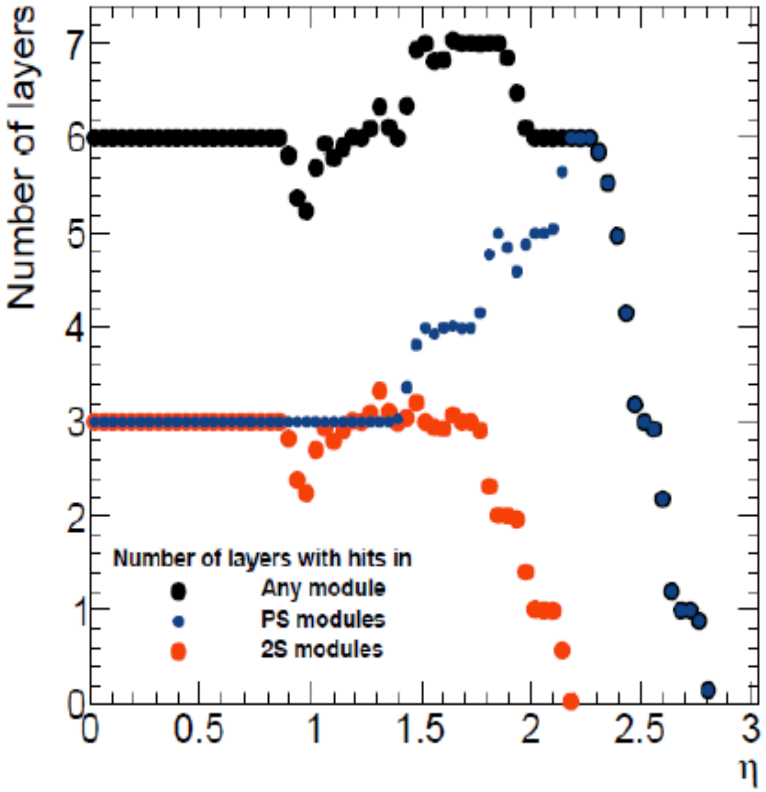




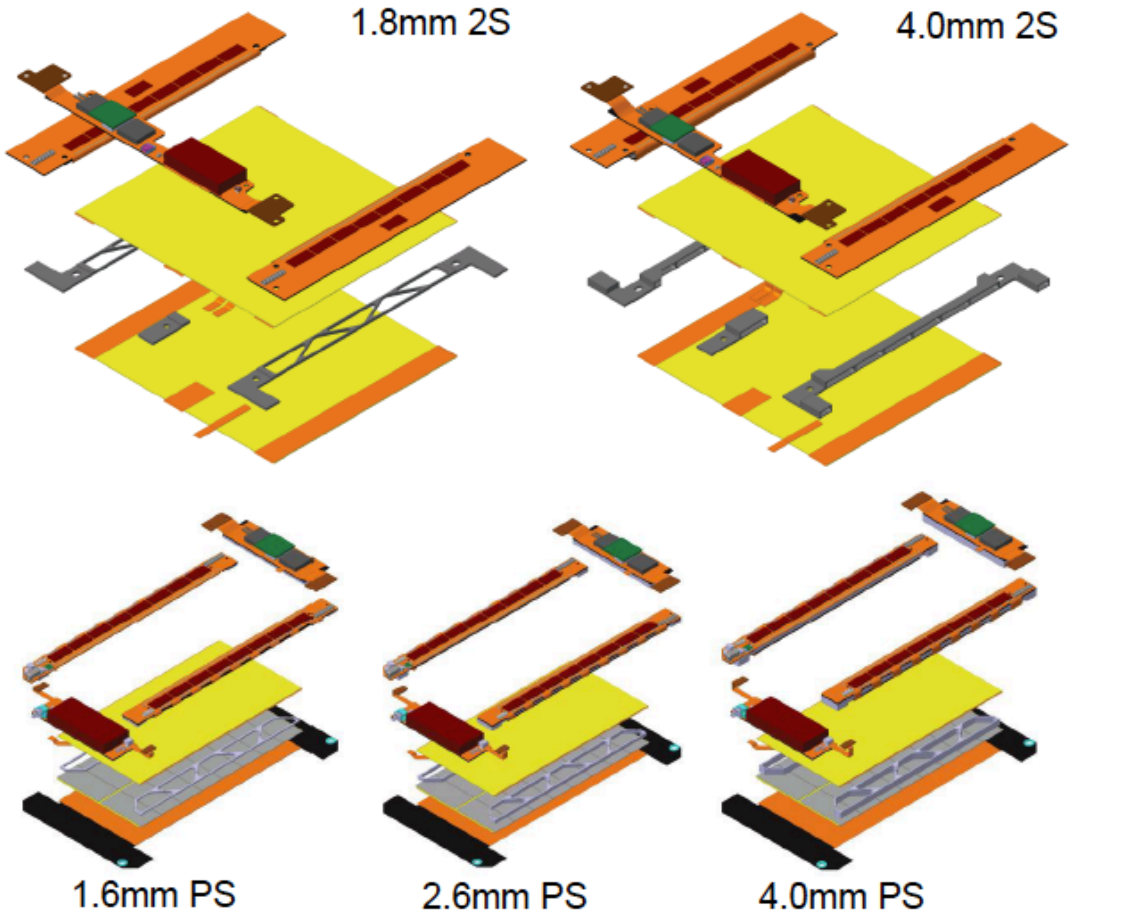
Sector prototype



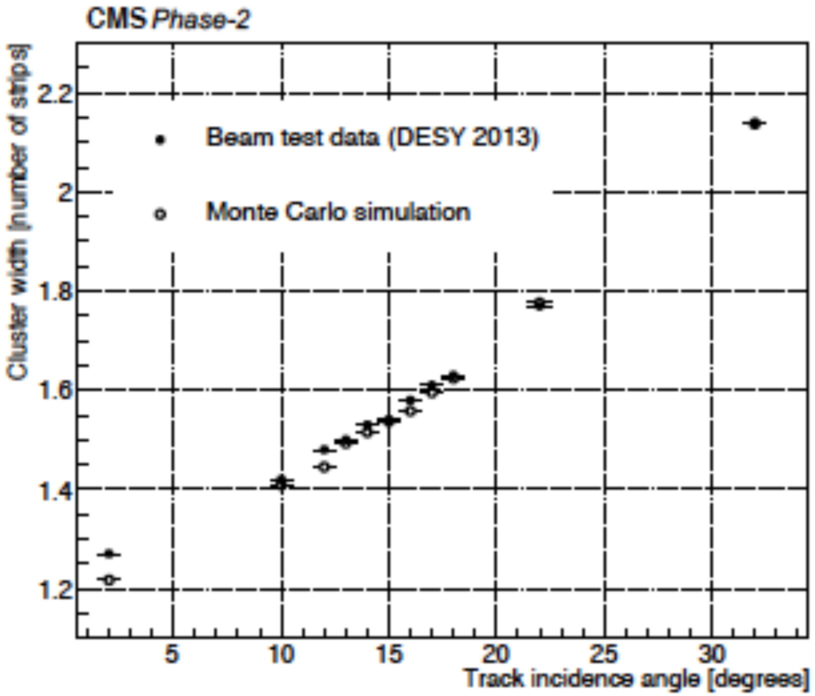
Outer Tracker

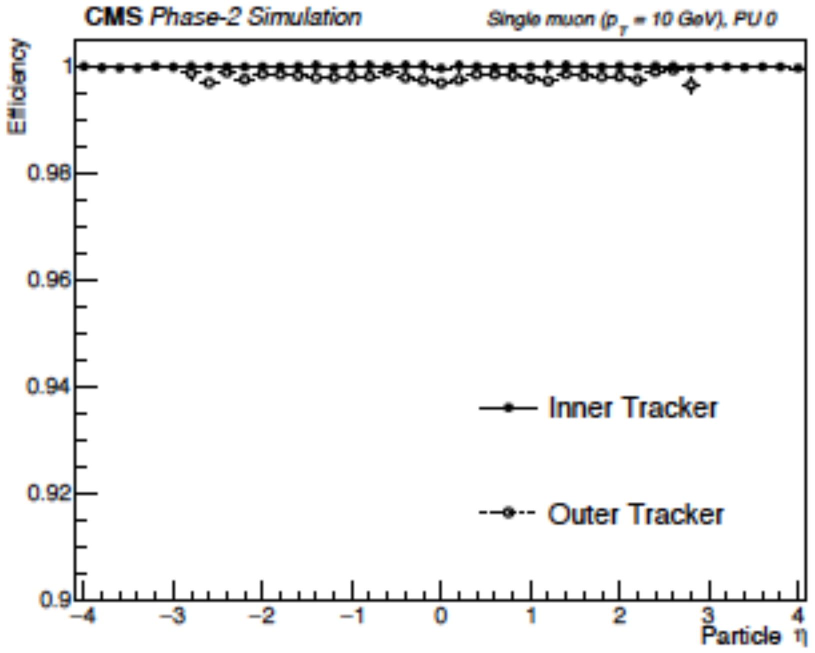


2S & PS sensors

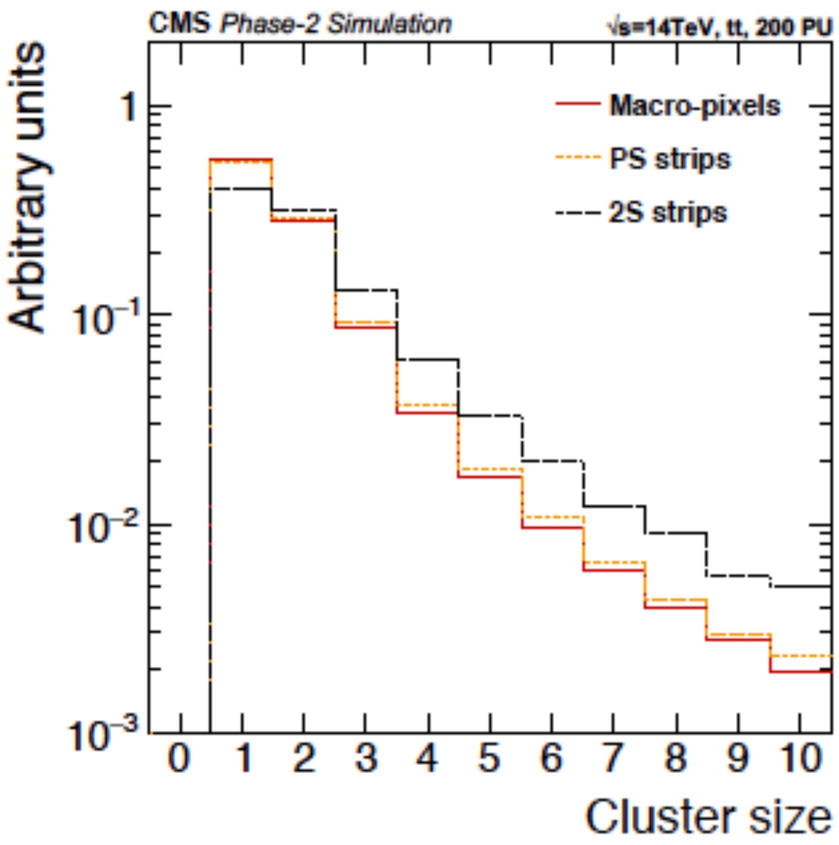


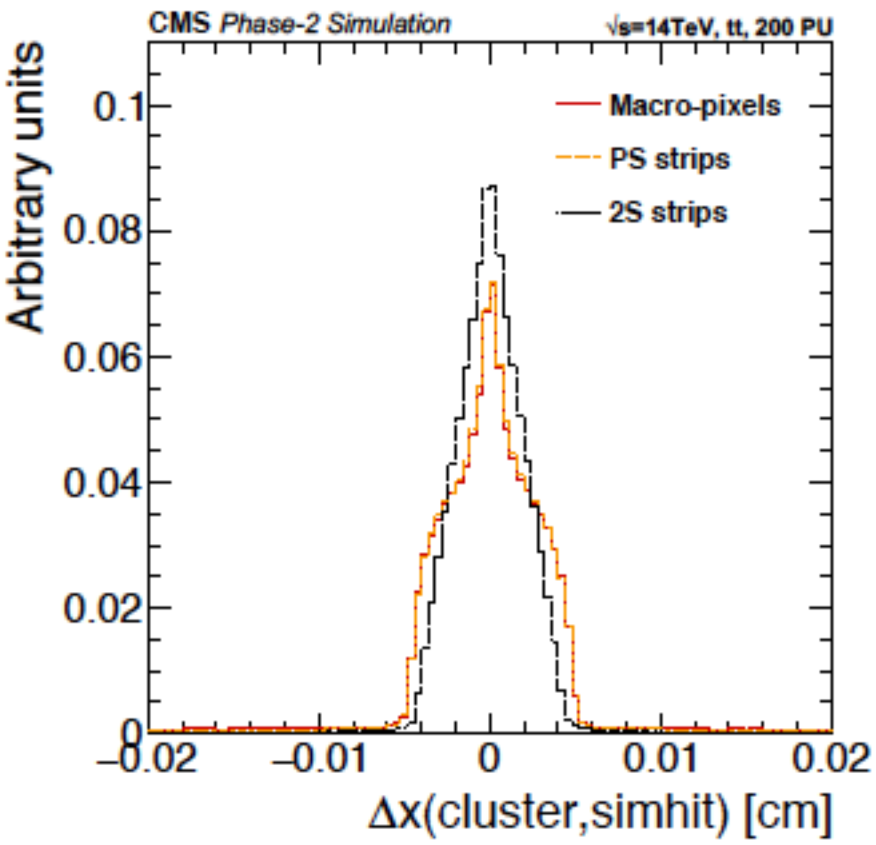
Digi properties (OT)



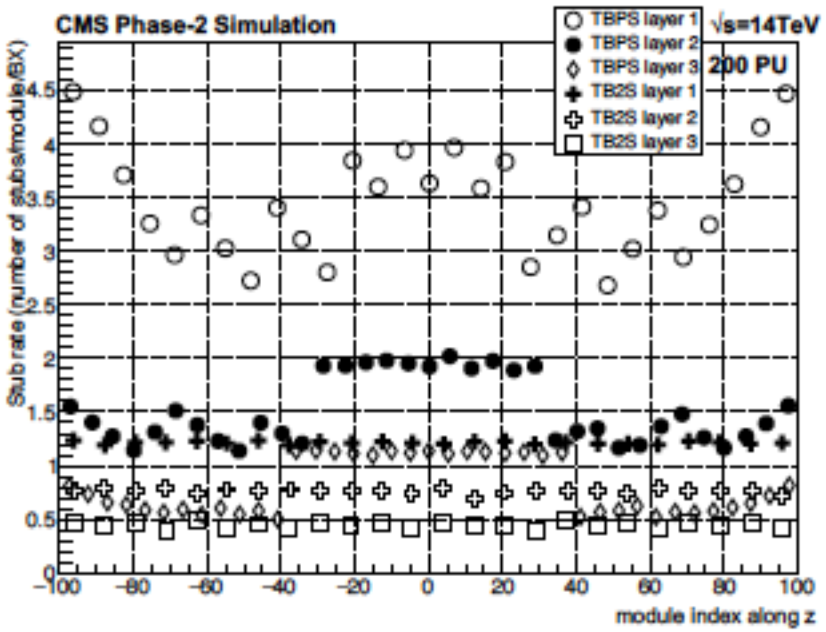


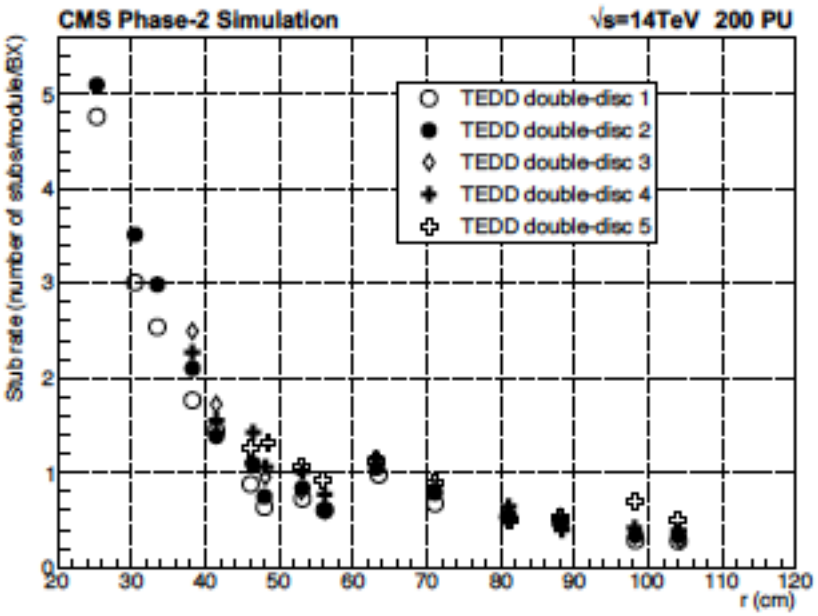
Cluster properties (OT)





Stub rates (OT)





Tracking performance (vs p_T)