

The CMS Tracker Upgrade for the High Luminosity LHC

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Overview & Motivation



CMS Phase-2 Tracker Upgrade for HL-LHC



• A new silicon tracker will be installed in CMS in Long Shutdown 3 (2025-2027)

- Outer Tracker (OT) replaces original silicon strip tracker
- Inner Tracker (IT) replaces Phase-1 silicon pixel detector (installed in 2017)

• Main design goals:

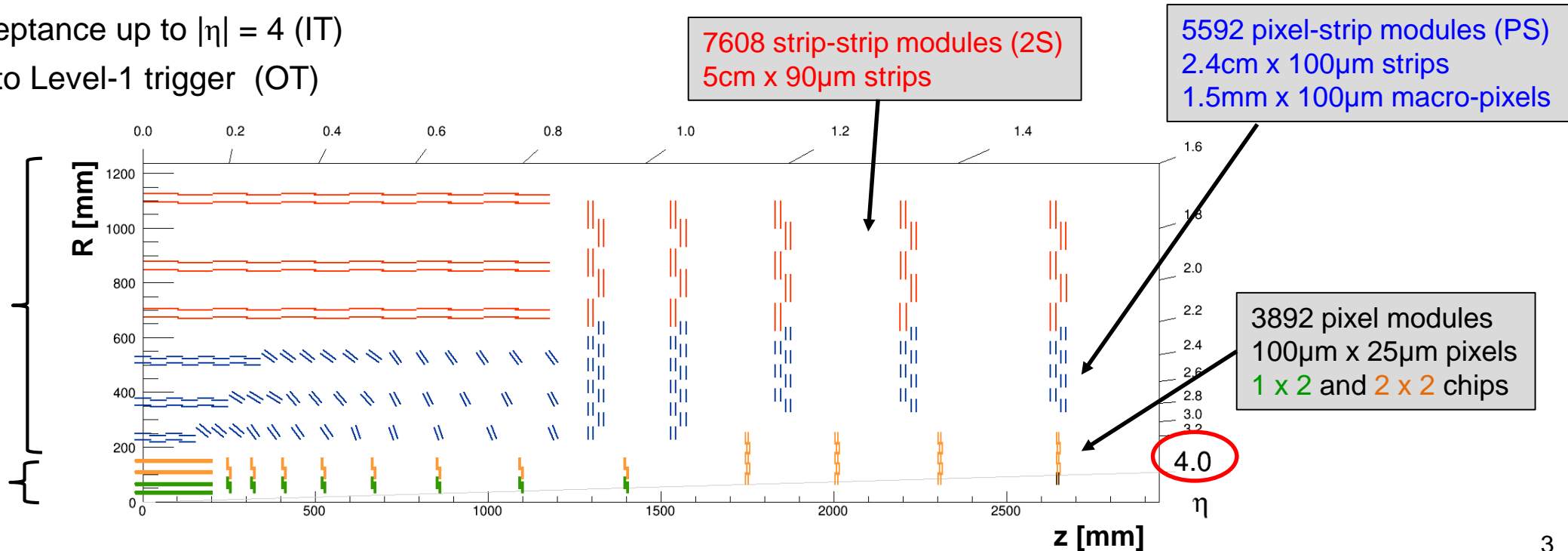
- Capable to deal with data rates expected for an instantaneous luminosity of $5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$
- Radiation-tolerance up to $2.3 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ and TID of 1.2 Grad (IT Layer 1)
- Increased granularity
- Tracking acceptance up to $|\eta| = 4$ (IT)
- Contribution to Level-1 trigger (OT)

OT

- 190m²
- 213M channels

IT

- 5m²
- 1.9G channels



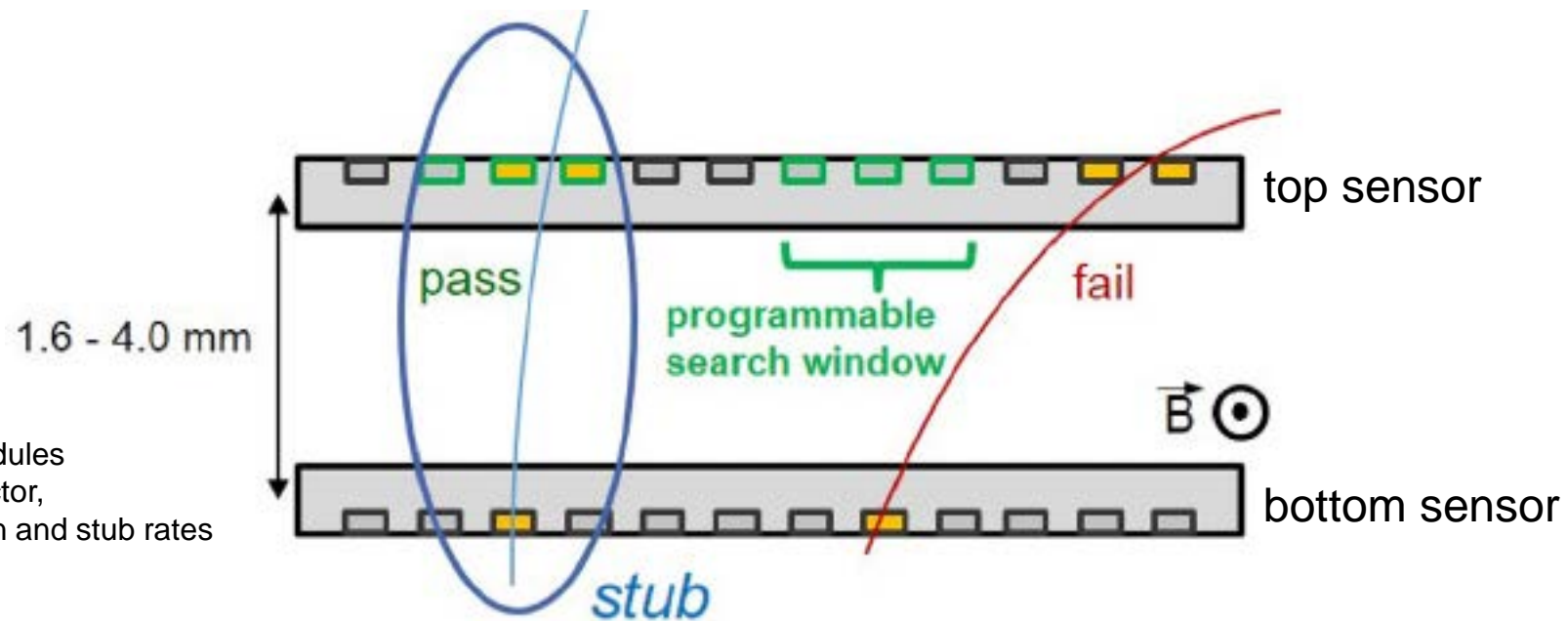
Outer Tracker



Design Driver: Use of Tracking Information at L1 Trigger



- Presently only muon & calorimeter information used in L1 trigger → provision of tracking information will enhance performance
- Cannot read out all information at 40MHz → **reduction of data volume at front-end needed**
- Vast majority of hits is from low p_T tracks → **select hits from tracks with $p_T > 2-3 \text{ GeV}$**
- **Each module has two sensor planes → compare hit patterns, which depend on the bending in 3.8T B field**
- “Stubs” are sent to the back-end at 40MHz → track reconstruction → L1 trigger decision
- On receipt of a L1 trigger, the complete event information is read out (750kHz)



3 (2) spacings for 2S (PS) modules depending on location in detector, for optimization of p_T resolution and stub rates



- Electrically, the basic building block is the module – no common service boards
- Each module is a self-contained unit and connected with 3 wires and 2 fibers directly to the back-end

Service hybrid (SEH)

Power distribution
Data serialization
Opto-el. conversion

2S module

Front-end hybrids (FEH)

8 CBC3 readout ASICs
1 Concentrator (CIC) ASIC

Strip sensors (top & bottom)

10cm x 10cm
5cm x 90µm cell size

Power hybrid (POH)

Macro-pixel sensor (bottom)

1.5mm x 100µm macro-pixels
Bump-bonded to MPA readout ASICs

Strip sensor (top)

5cm x 10cm
2.4cm x 100µm strips

PS module

Front-end hybrids (FEH)

8 SSA readout ASICs
1 Concentrator ASIC

Readout hybrid (ROH)

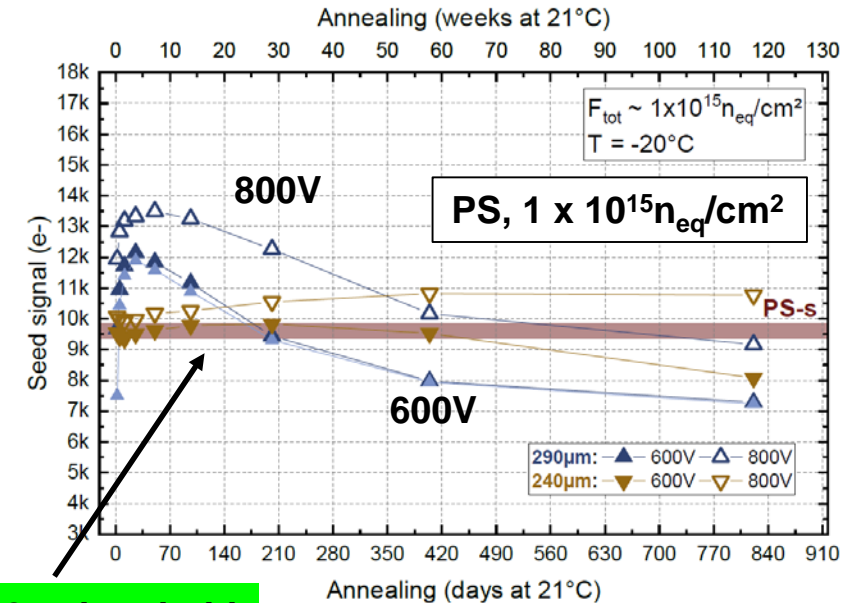
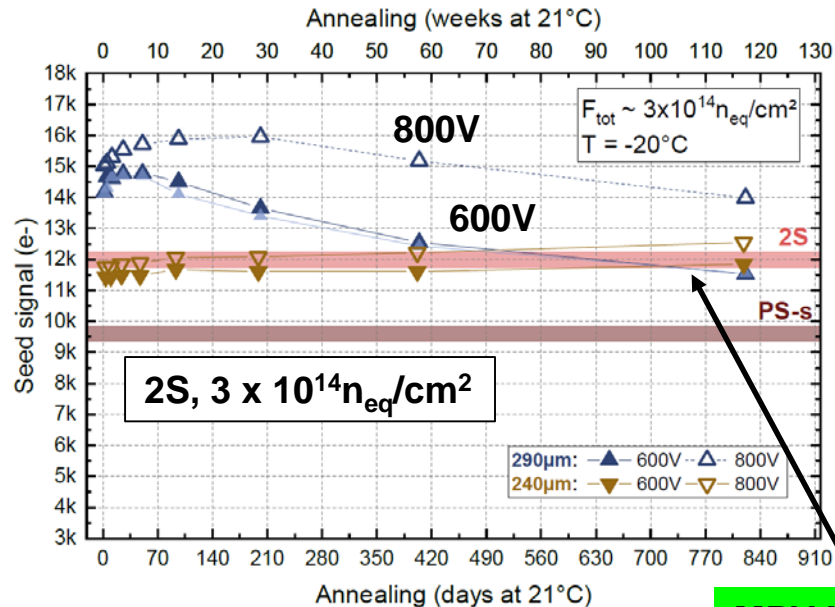
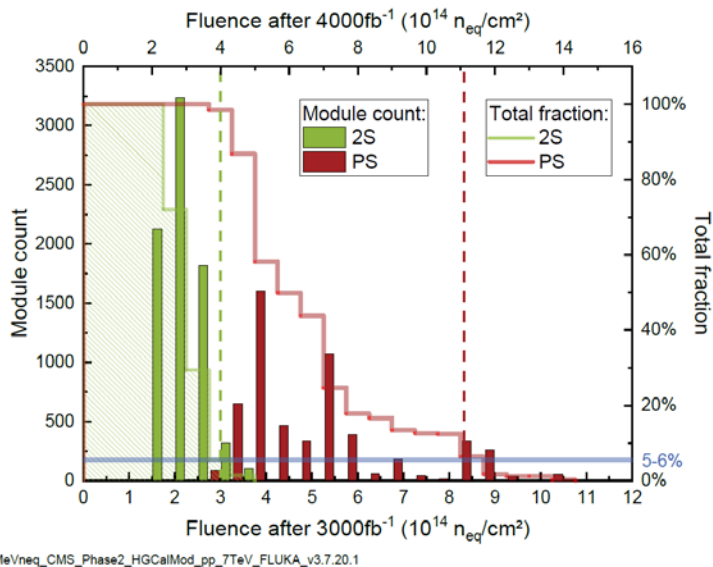
Data serialization
Opto-el. conversion



OT Silicon Sensors



- **3 sensor types, all designs final: 2S, PS-strip, PS-macro-pixels** (AC-coupled strips, DC-coupled pixels)
- **Planar, n-on-p, float zone silicon, with 290 μm active / 320 μm physical thickness**
 - Many options investigated: p-on-n; MCz, epitaxial; deep-diffused or thinned (240 μm) material; different suppliers
- **Irradiation & annealing campaigns with realistic neutron+proton mixes**
 - E.g. seed signal vs. bias voltage and annealing \rightarrow 2S OK for 600V, PS may need 800V „boost voltage“
- **Sensors are ordered; all from one supplier**
 - Pre-series sensors are arriving, to be subjected to Quality Control machinery



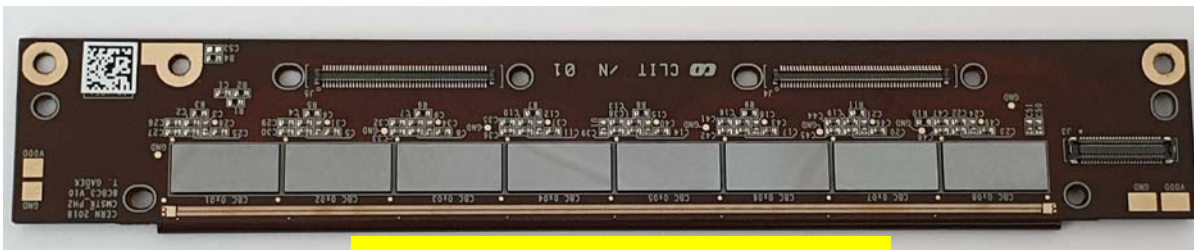
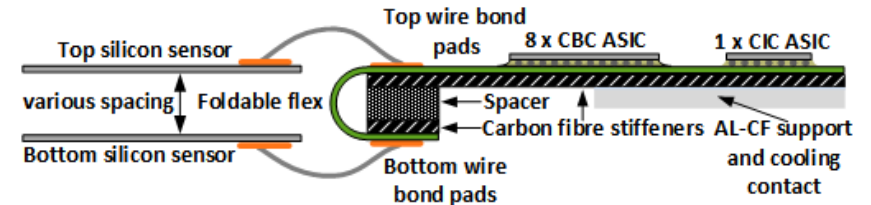
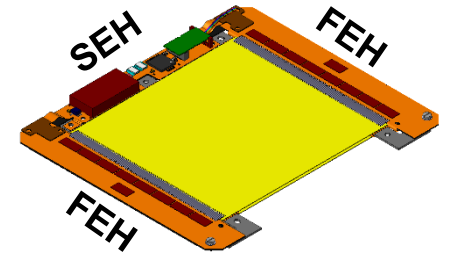
MPV !> 3 x threshold



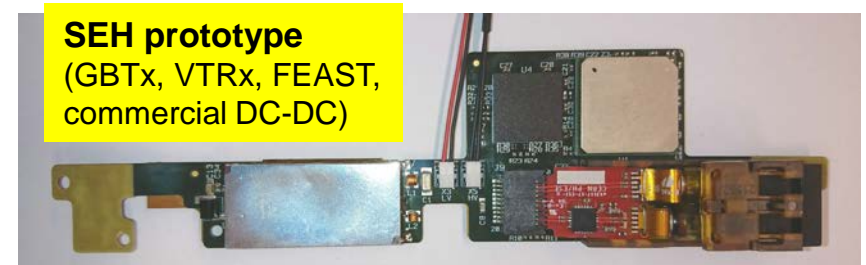
OT Module Electronics (2S Module as Example)



- **Front-end hybrids (FEH)** carry each 8 CBC readout chips and 1 Concentrator ASIC
 - Complex 4-layer flex with carbon fiber stiffener, high line density and tight fold-over
- **CMS Binary Chip (CBC)**
 - 130nm GF, unsparsified binary readout at 320 MHz
 - Reads 127 channels from each top and bottom sensor → correlation of hit patterns → stub detection
- **Concentrator Integrated Circuit (CIC)**
 - Purely digital chip, in 65nm TSMC
 - Receives data from CBCs via 48 lines → formatting, serialisation → 6 lines at 320Mb/s to LpGBT
- **Service hybrid (SEH)**
 - **LpGBT** receives data from 2 CICs and ships out at 5Gb/s
 - **VTRx+** for opto-electrical conversion
 - CERN bPOL12V and bPOL2V5 **DC-DC converters**
- CBC is in mass production, final prototypes of SEH and FEH being ordered



2S FEH prototype (no CIC yet)



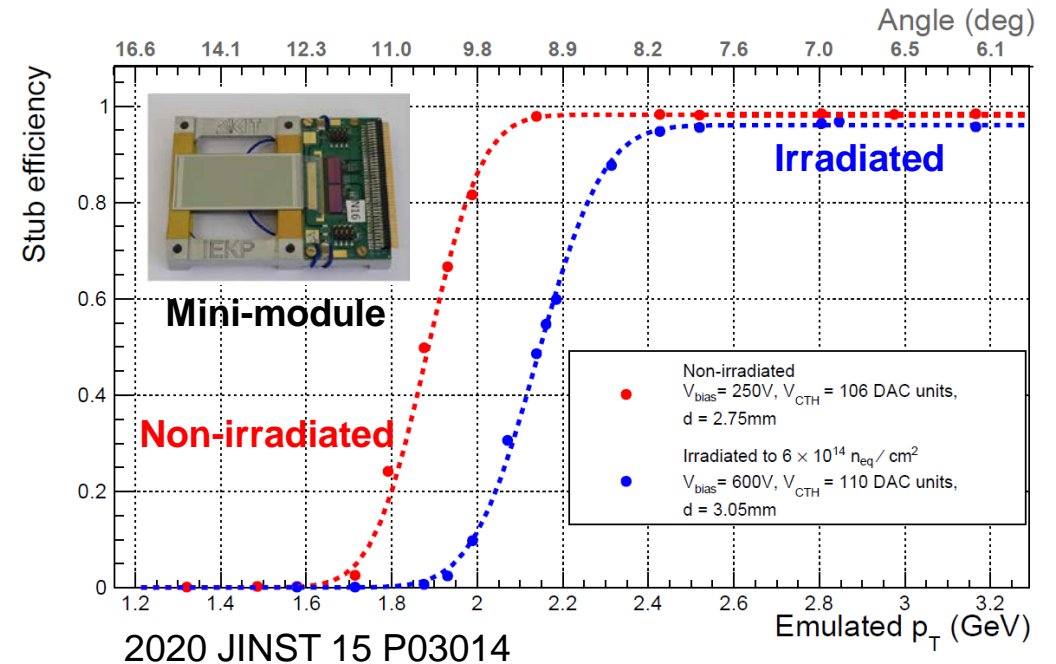
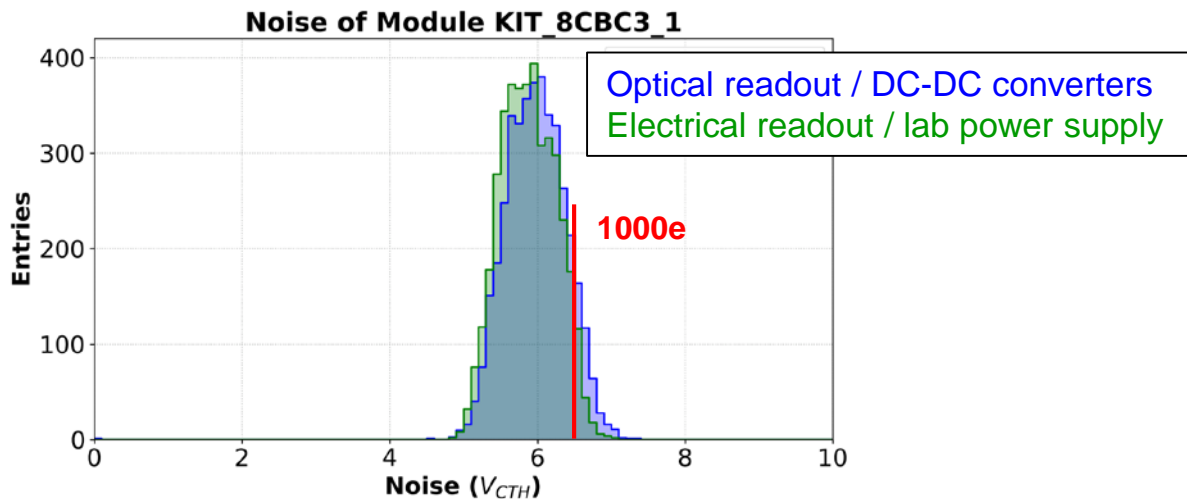
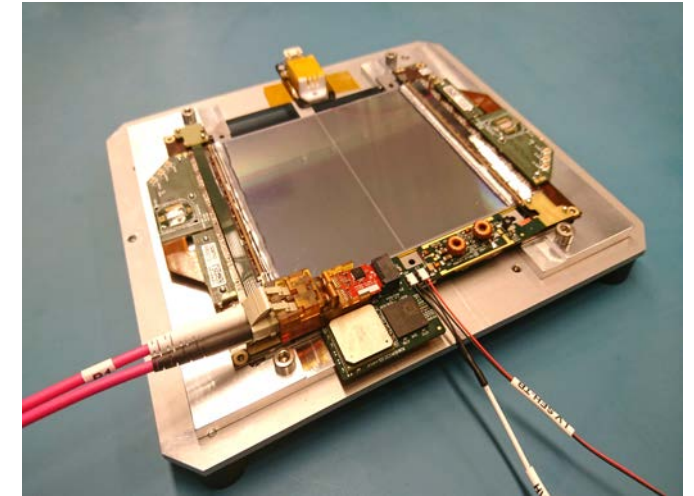
SEH prototype (GBTx, VTRx, FEAST, commercial DC-DC)



2S Module Performance

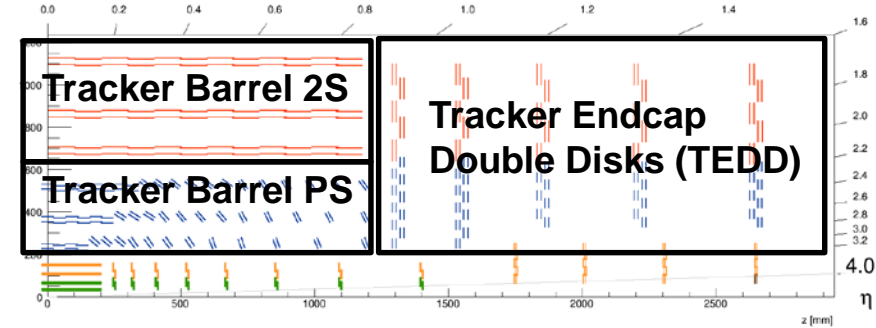


- **About 20 functional modules of various generations were built**
 - Full readout chain established and exercised in various system and beam tests
 - CIC on mezzanine card
- **Noise is $\leq 1000e$, as specified**
 - No significant increase of noise due to DC-DC converters
- **Stub mechanism tested on “mini-modules“ with beam**
 - Stub efficiency measured vs. emulated p_T (rotation of module in beam)
 - High efficiency (97-99%) and good p_T resolution (5-6%) before and after irradiation to twice expected fluence
 - Turn-on at different value due to different sensor spacing





- **Modules are mounted on carbon fiber (CF) / foam support structures**
 - Prototypes / mock-ups to study flatness, precision, service arrangement etc.
- **Only 3 wires and 2 fibers per module – routing still challenging (TEDD)**
- **2-phase CO₂ cooling, operated at -35°C**
 - Thin pipes: 2mm inner diameter, 100µm wall thickness
- **Module power is 5W (2S) and 10W (PS) → thermal management is crucial**
 - 2S modules: screwed at 5 points to AICF or Al inserts; PS modules: glued via phase-change material over full area



TB2S ladder

TBPS plank
(flat section)

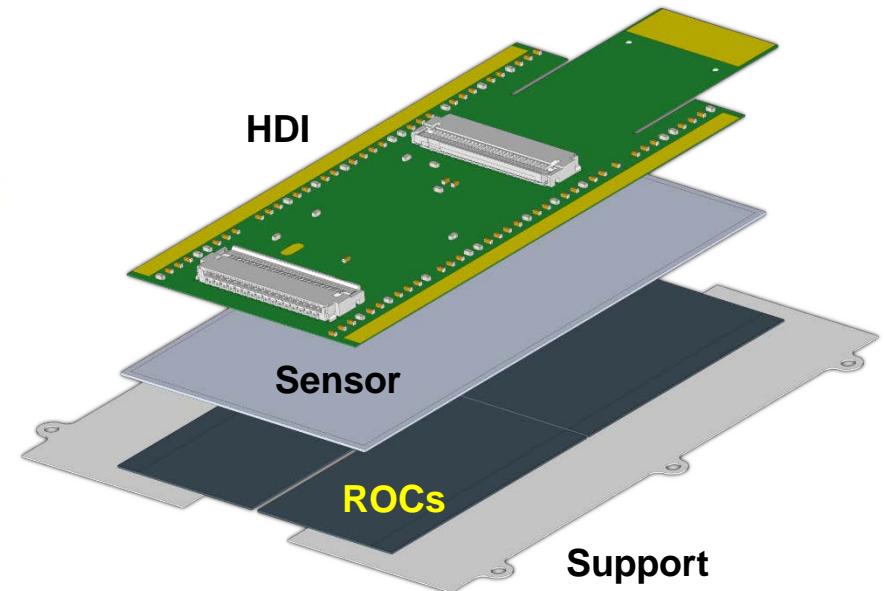
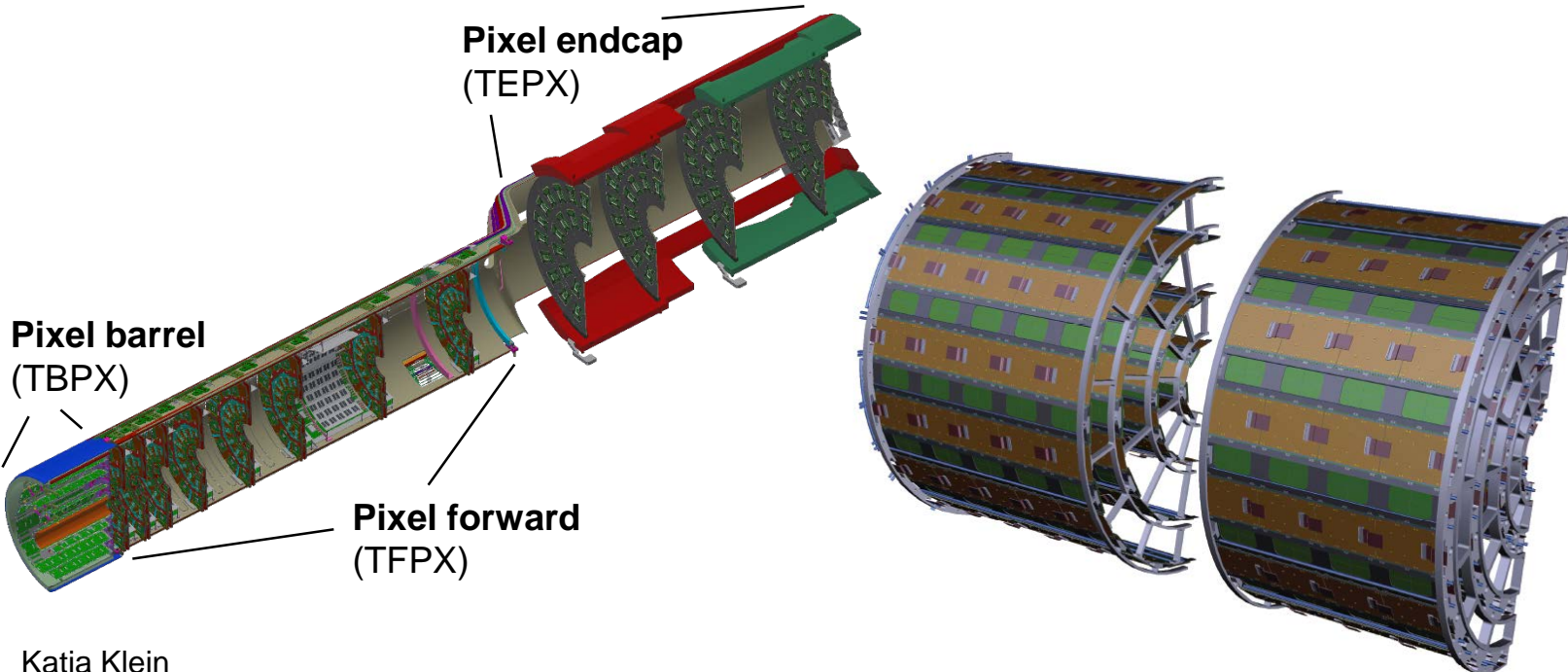
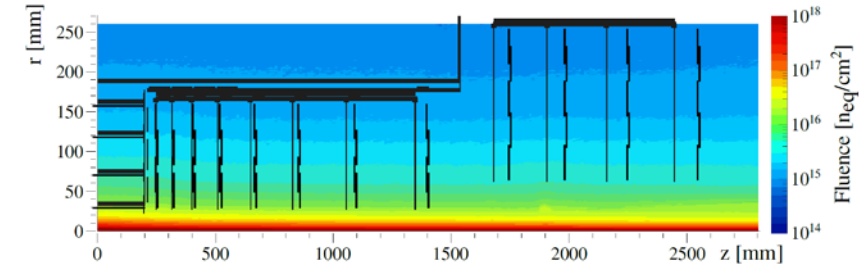
TBPS ring
(tilted section)

TEDD dee

Inner Tracker

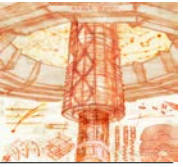


- **4-layer barrel, 8 small + 4 large disks**
- **High fluence and dose levels in particular in layer 1 and inner rings**
 - Half-shell design allows “easy” extraction with beam pipe in place
- **Hybrid pixel modules with 1 x 2 or 2 x 2 chips**
 - Sensor bump-bonded to readout chip (ROC), High Density Interconnect on top
- **ROC based on RD53 development (ATLAS & CMS): pixel chip in 65nm CMOS**
 - Hit rates of up to 3GHz/cm²

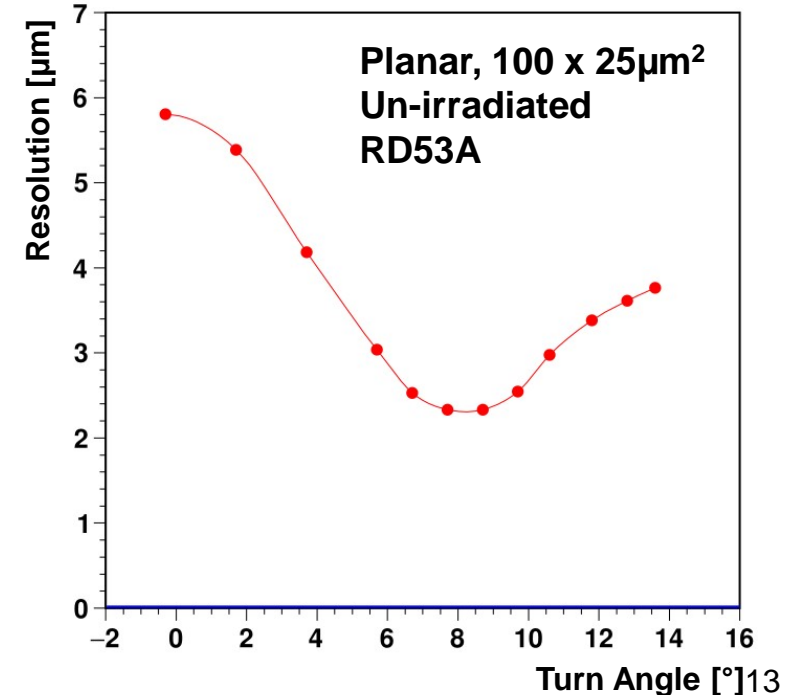
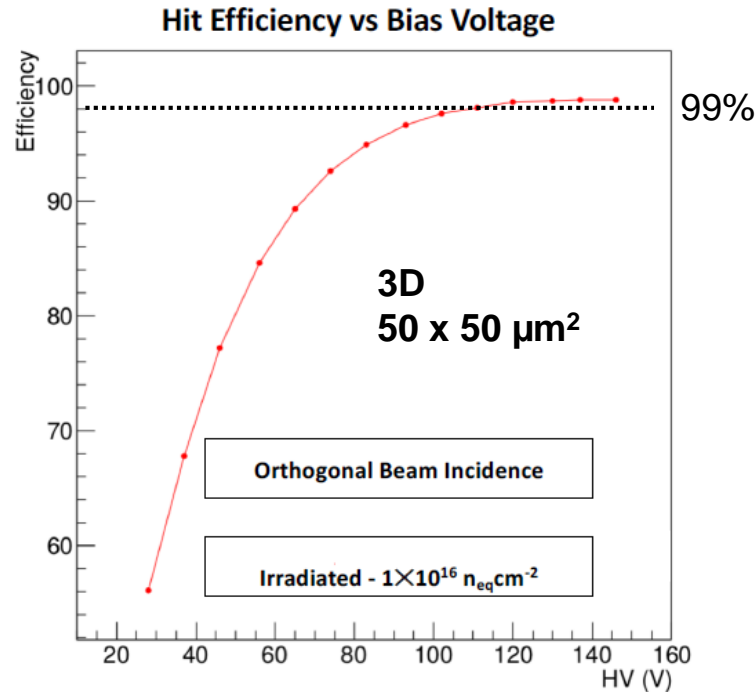
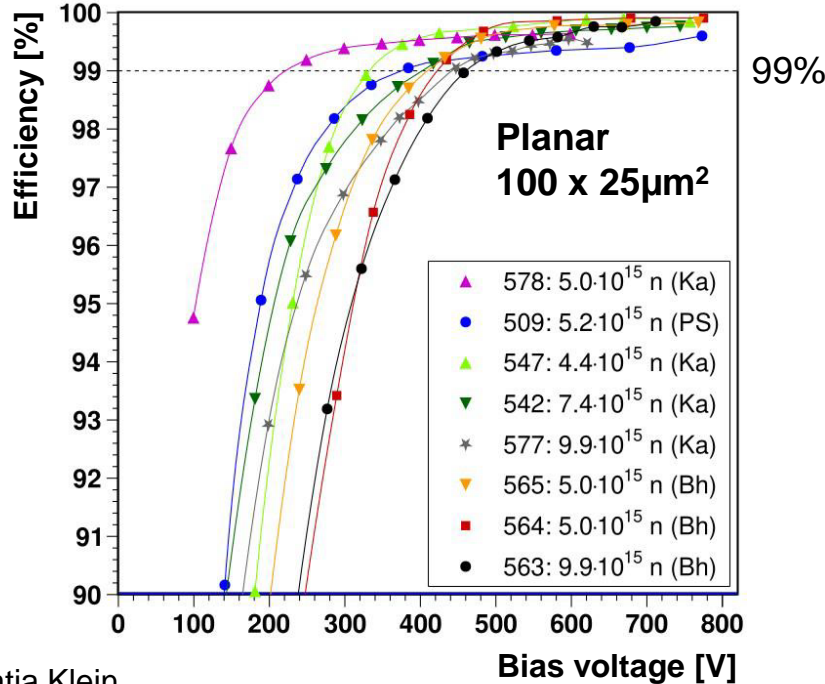
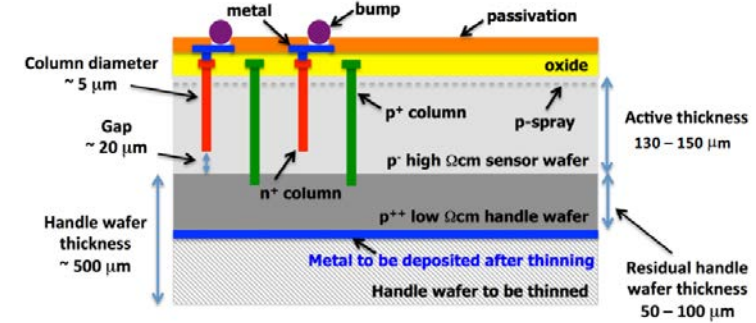




IT Silicon Sensors



- **Planar sensors as baseline, 3D sensors are an option for the innermost layer**
 - Replacement of inner layer(s) after e.g. half the lifetime considered
- **n-in-p, 150 μ m active thickness, baseline 100 x 25 μ m² (alternative: 50 x 50 μ m²)**
 - Details of the pixel cell being optimized (bias dot, implant size, metallization shape)
- **~99% efficiency after 50% of layer 1 fluence for ~450V for planar sensors**
 - ... and for ~150V for 3D sensors (smaller drift distance)
- **Excellent spacial resolution measured in test beam**





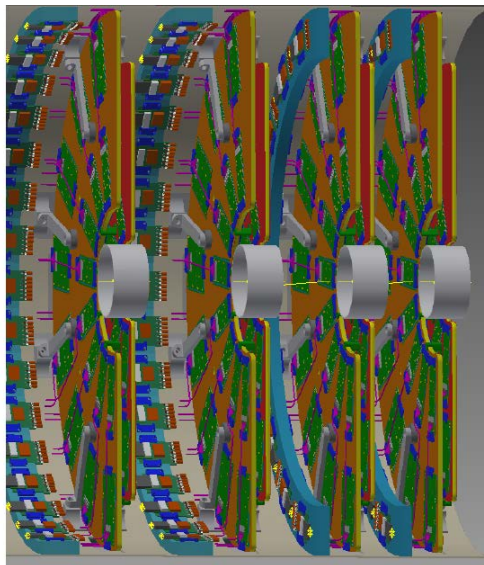
IT Electronics System



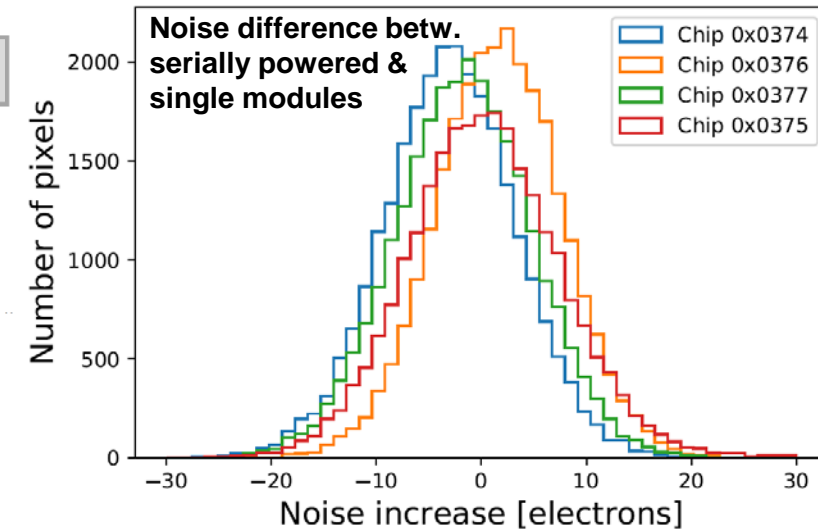
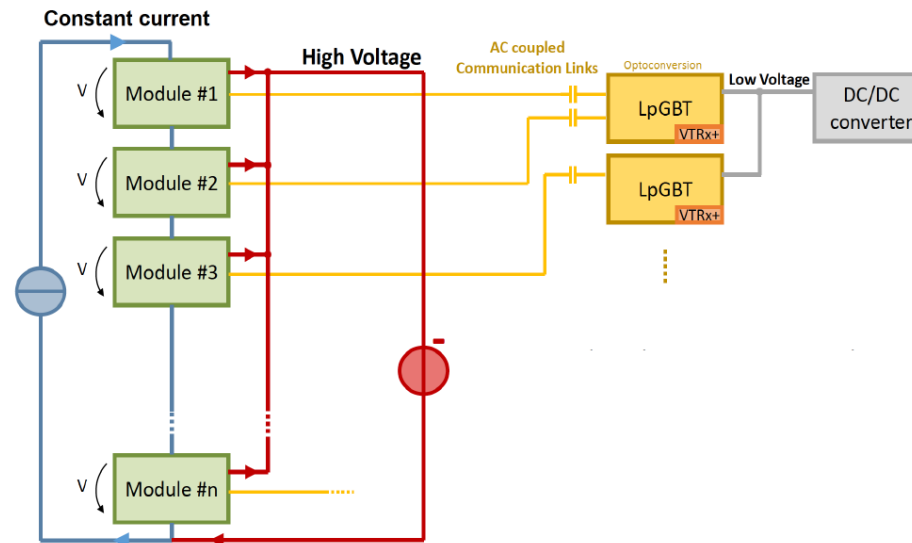
- **C-ROC developed as variant of the RD53B chip: submission in Q4/2020**
 - Linear front-end, 432 x 336 pixel array, binary readout plus time-over-threshold feature, Shunt-LDO for serial powering
 - RD53A tested up to 1Grad (high dose rate), RD53B to be tested (also SEU/SET effects)
- **Serial powering → low material budget in spite of 50kW FE power**
 - Up to 12 modules / chain; chips in a module connected in parallel
 - Tested with 3 module prototypes (without sensor), no showstoppers
- **Modules connected with up to 1.6m electrical links to port cards at periphery**
 - Port cards feature 2 LpGBTs and 2 VTRx+, powered via cascaded DC-DC converters
 - Up to 6 e-links at 1.28Gb/s per LpGBT (AC-coupled)



Disks with port cards



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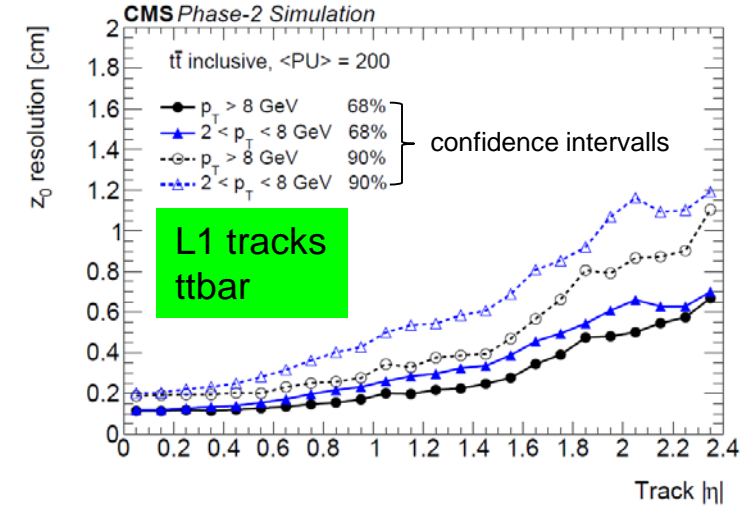
Expected Performance



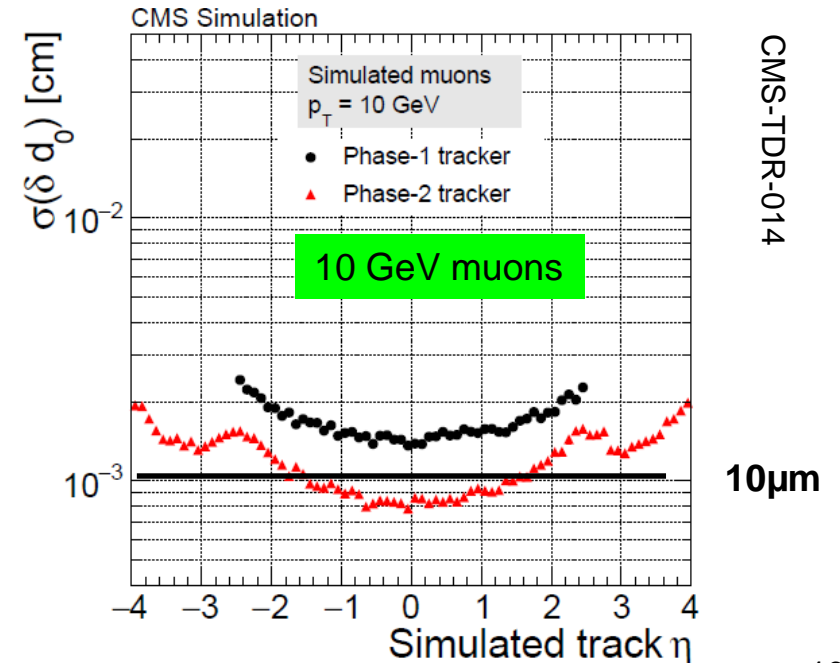
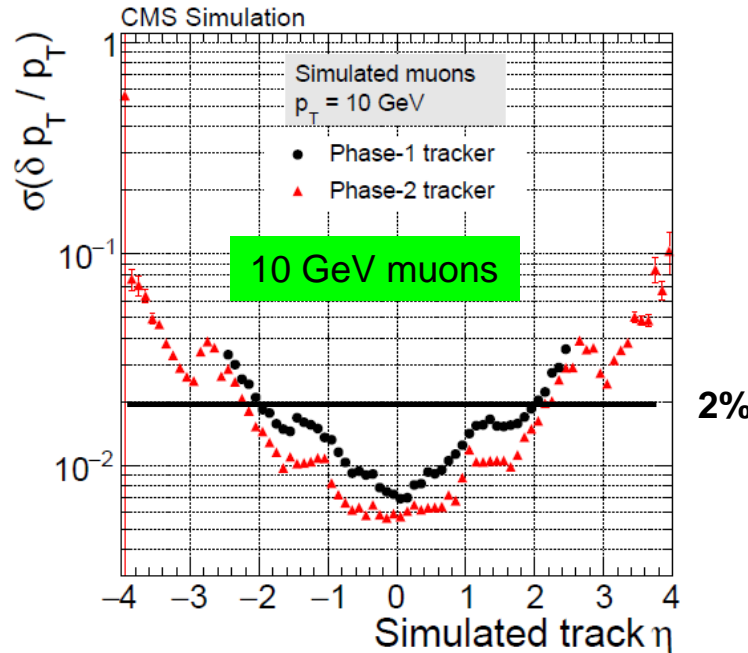
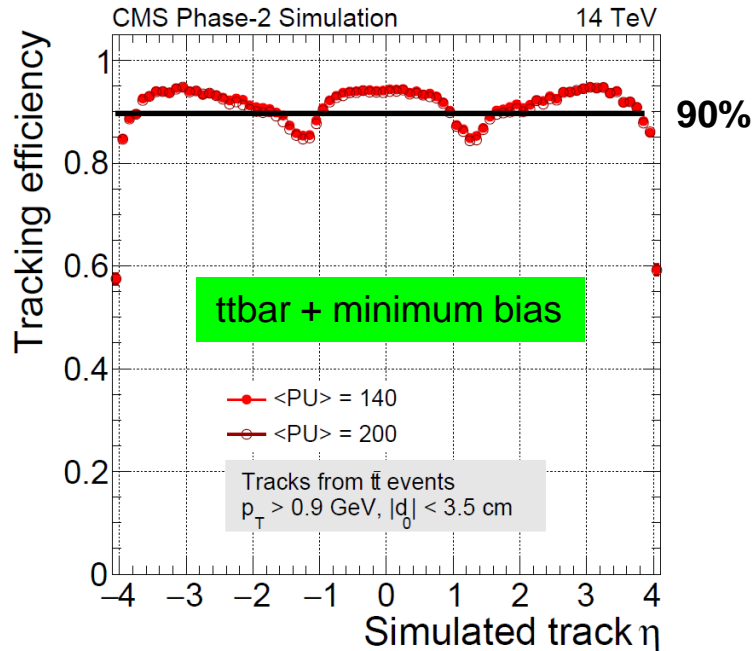
Tracking Performance at L1 Trigger and Offline



- **High efficiency and low (2-3%) fake rate for ttbar events at 200 pileup**
 - Similar to Phase-1 tracker at 70 pileup
- **Resolutions in relative p_T and impact parameters excellent**
 - Much improved with respect to Phase-1 detector
- **Very good performance also for L1 trigger tracks**
 - E.g. z_0 resolution ~ 1 mm for ttbar at 200 pileup, due to macro-pixels



2020 JINST 15 P06024



CMS-TDR-014



Conclusions



- **Design requirement to deliver tracking information to the L1 trigger leads to an innovative, yet challenging detector design**
- **Project is overall in good shape and so far on-track for installation in LS3**
 - Outer Tracker project is in prototyping phase, with first items entering (pre-)production phase
 - Inner Tracker project is entering prototyping phase
- **Phase 2 CMS tracker will surpass the performance of the current CMS tracker, under much harsher conditions**
 - Physics output will be boosted by its capability to trigger on tracks at the first trigger level