The CMS Outer Tracker Upgrade for the High Luminosity LHC

on behalf of the CMS collaboration

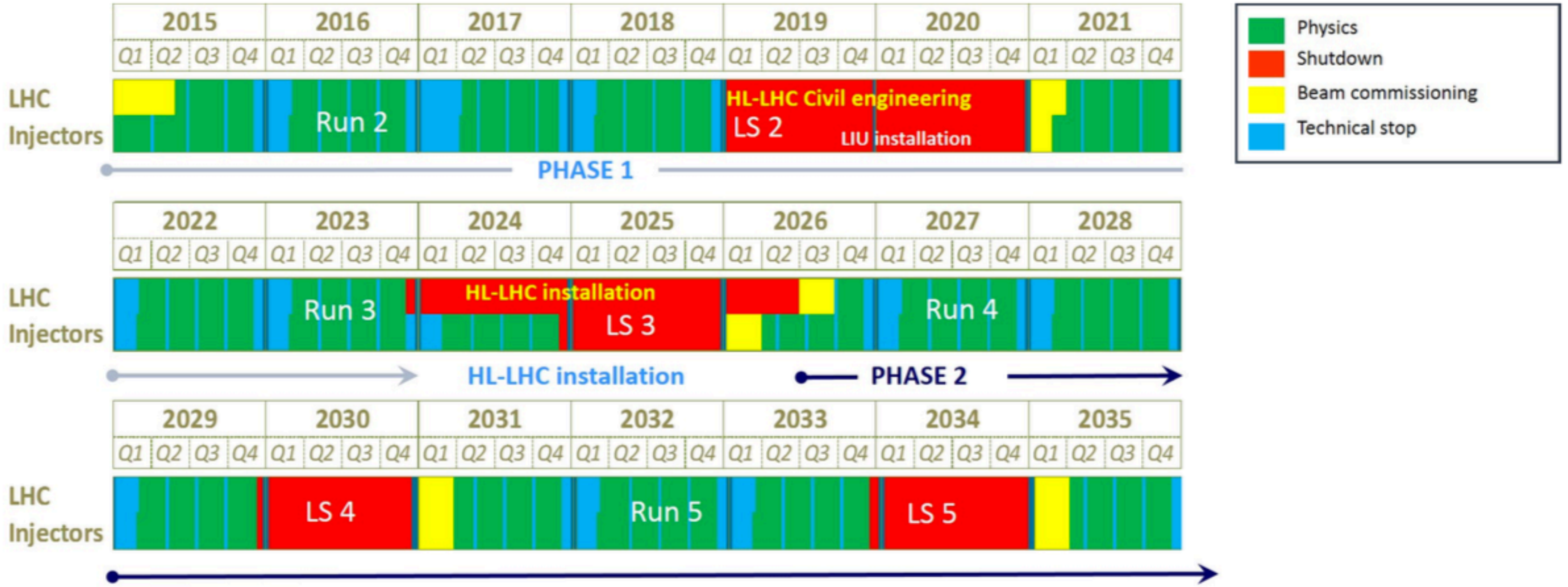
University of BRISTOL S. SEIF EL NASR-STOREY

Slide Material From :
K.Klein’s Overview of The Phase-2 Upgrade of the CMS Tracker
F.Vasey’s Overview of The Electronics of the CMS Outer Tracker Upgrade
TDR, CERN-LHCC-2017-009

CMS Phase 2 Tracker Upgrade

Main objectives for High-Luminosity LHC (HL-LHC) Upgrade (PhII)

- CERN Accelerator complex will be upgraded during long shutdown 3 (LS3) to increase instantaneous luminosity of the LHC by a factor of 5 to 5×10^{34} $cm^{-2}s^{-1}$



- CMS plans to replace the current tracker during the last LHC shut-down before HL-LHC
- Technical Design Report approved in December 2017
- This talk will
  - describe the challenging operating conditions expected at the HL-LHC
  - describe the new proposed layout
  - describe the pT module concept used in the Outer Tracker [OT]
  - highlight a few recent developments in the R&D program for the OT

CMS Phase 2 Tracker Upgrade

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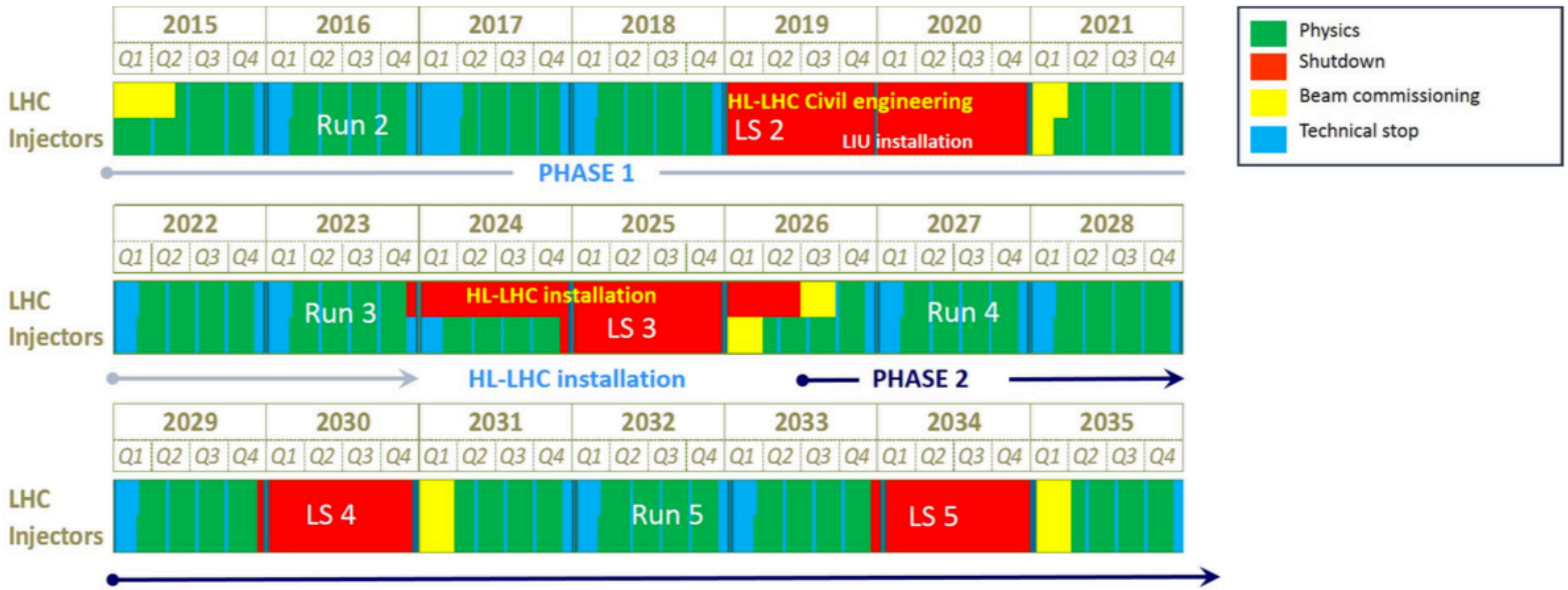
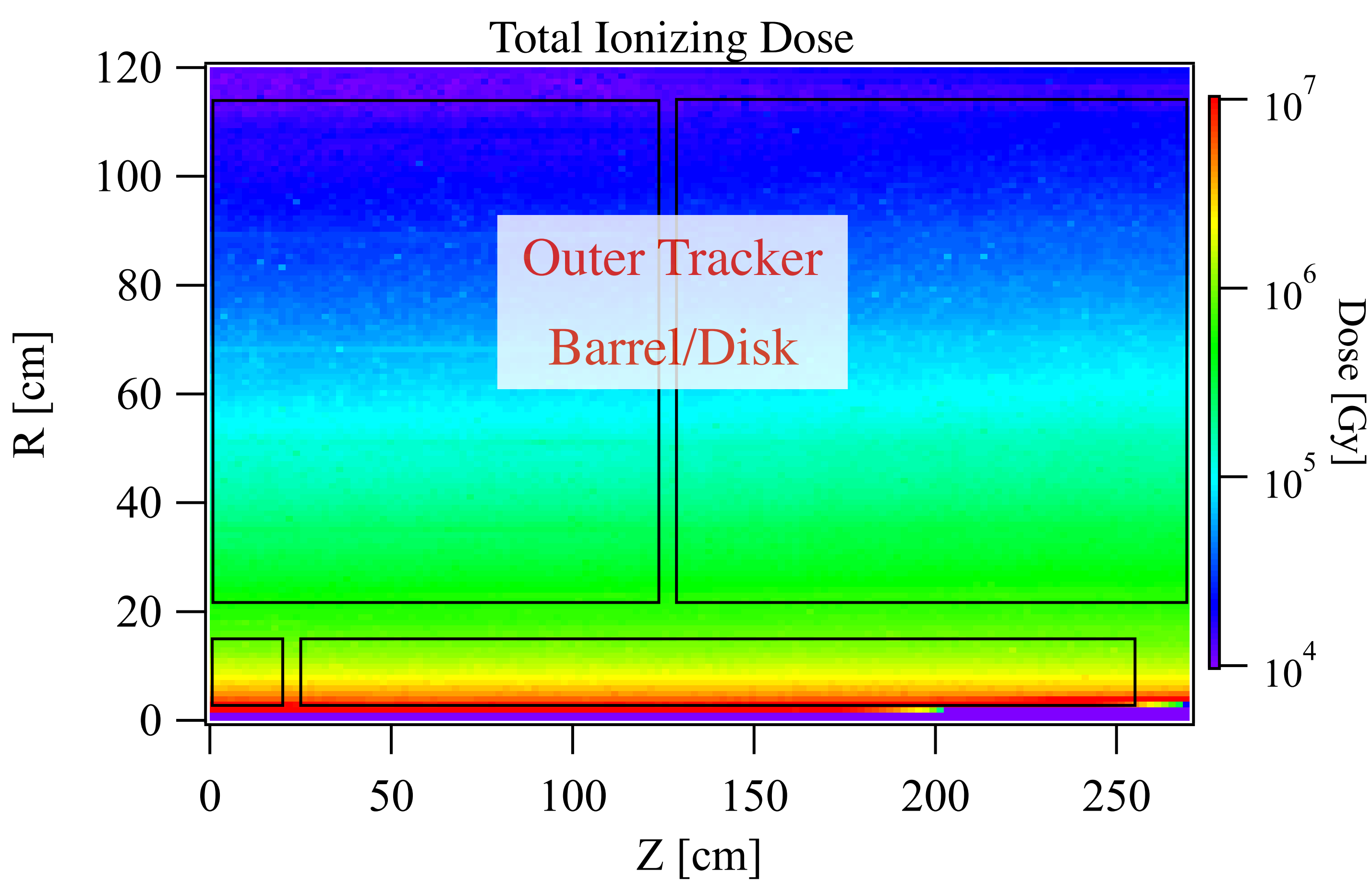


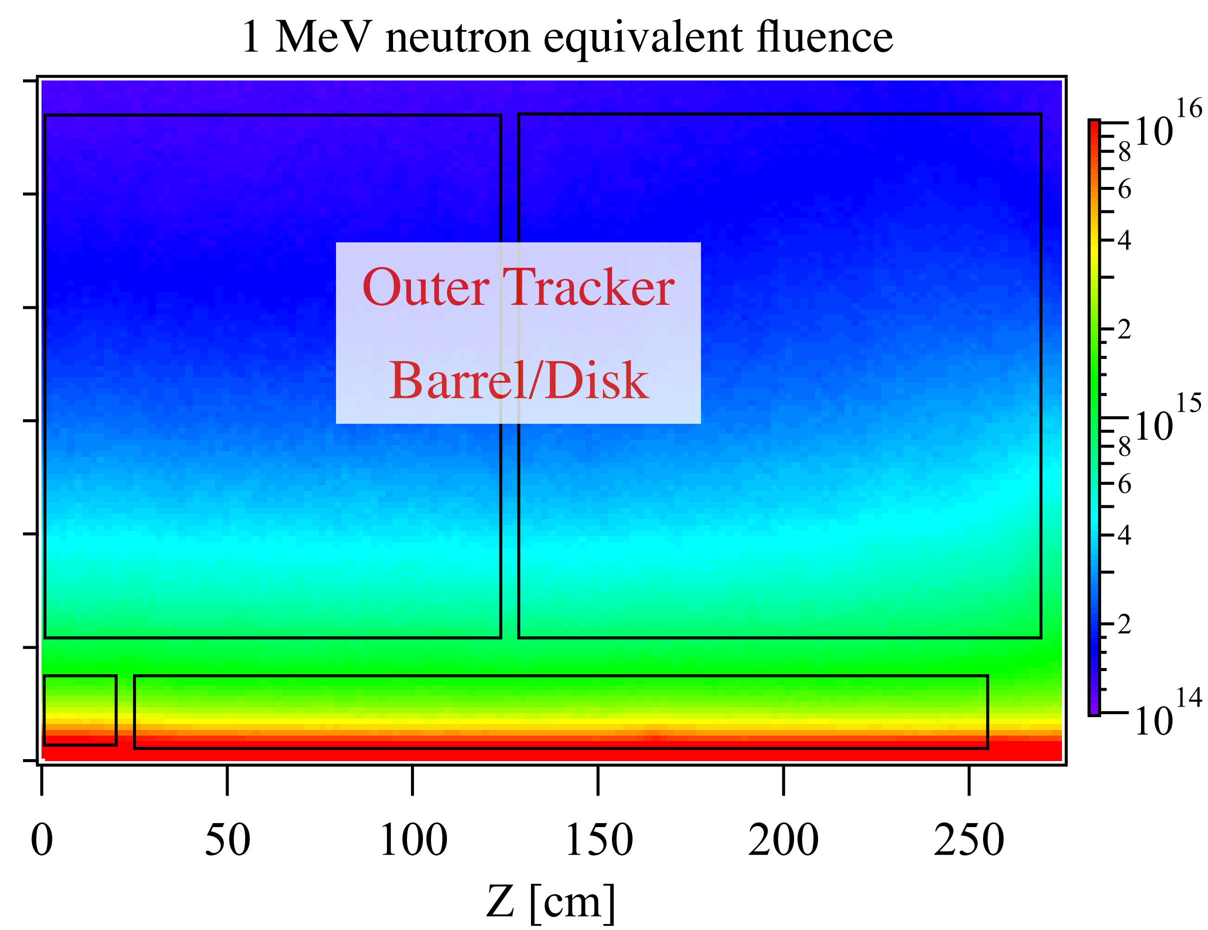
- CMS plans to replace the current tracker during the last LHC shut-down before HL-LHC operation to achieve :
  - increased radiation resistance
  - fast and efficient track finding which contributes to the Level-1 trigger decision
  - an increased channel granularity to maintain a high reconstruction efficiency at the increased pile-up conditions (200 pile-up)
  - reduced material budget and extended tracking acceptance
  - improved two-track separation to resolve tracks in high pT jets

CMS Phase 2 Tracker Upgrade

Radiation Environment PhII CMS [Simulations, FLUKA 3.7.20, 3000 fb^{-1}]

- Expected radiation levels within CMS [fluence/total ionizing dose] from FLUKA simulations at 7 TeV and after 3000 fb-1 of proton-proton collisions :

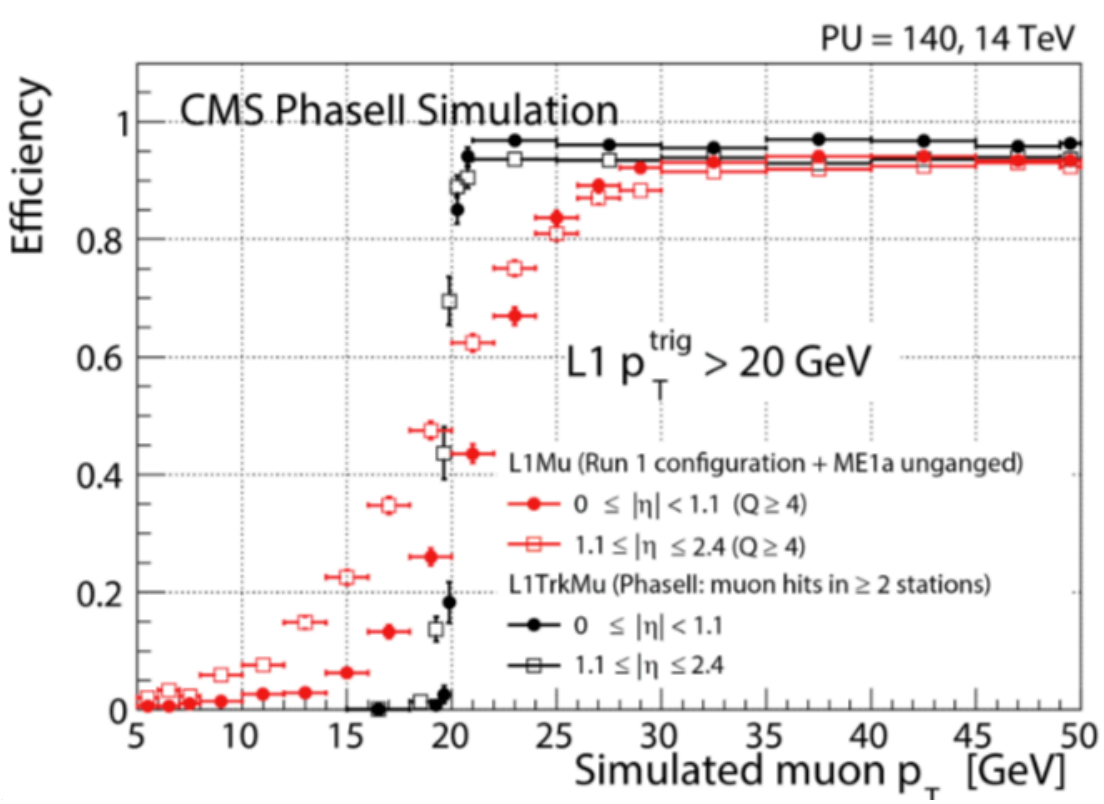




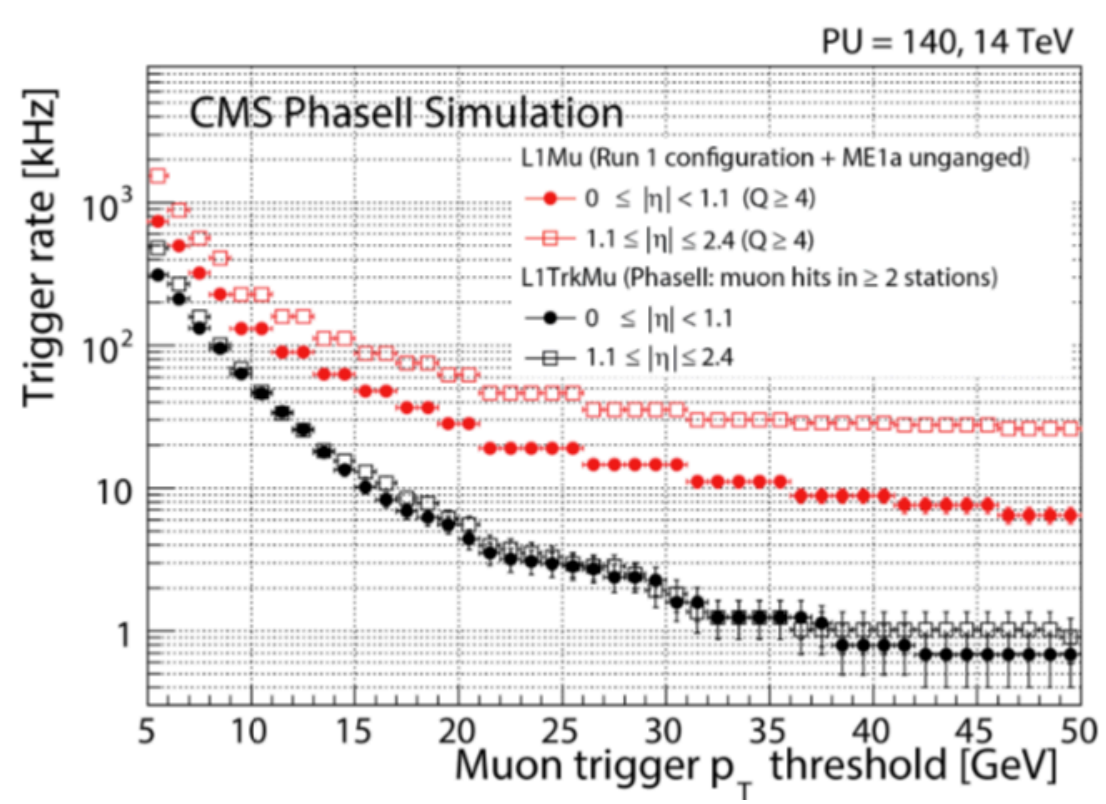
- Tracker must work efficiently up-to 3000 fb^{-1}
  - Maximum levels for inner tracker :120 MGy [1.2 Grad] , 2.3 x 10^{16} n_{eq}/cm^2
    - can be extracted during shutdowns to extract degraded parts
  - Maximum levels for outer tracker : 560 kGy [56 Mrad] , 9.6 x 10^{14} n_{eq}/cm^2
    - believe we have about 50% margin

Level1 (L1) Triggering at the HL-LHC

- Two level trigger system currently implemented in CMS
  - Level 1 (L1) hardware trigger using information from calorimeters and muon detectors [design specification : 100 kHz, latency of 3.2 μs]
  - High Level Trigger (HLT) software trigger including information from the tracker
- Increase in luminosity will lead to increased production rates and pile-up [53 at the highest instantaneous luminosity reached in 2016 → 200 at HL-LHC] which poses a challenge for the current L1 trigger system. Therefore upgrade of the L1 system also expected for HL-LHC
  - target specification for L1 trigger for HL-LHC is 750 kHz and a latency of 12 μs
  - include tracker information to improve L1 trigger performance



sharper turn-on curves

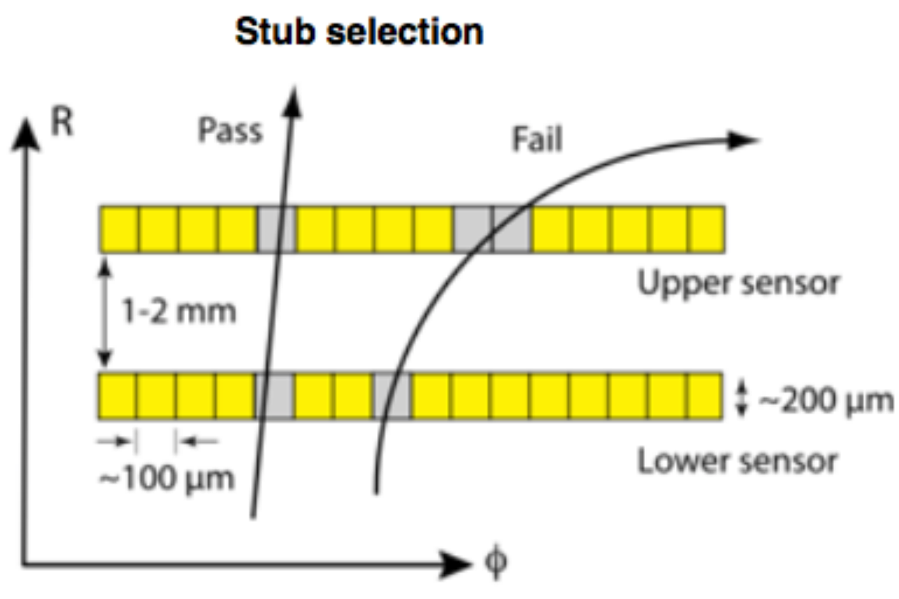


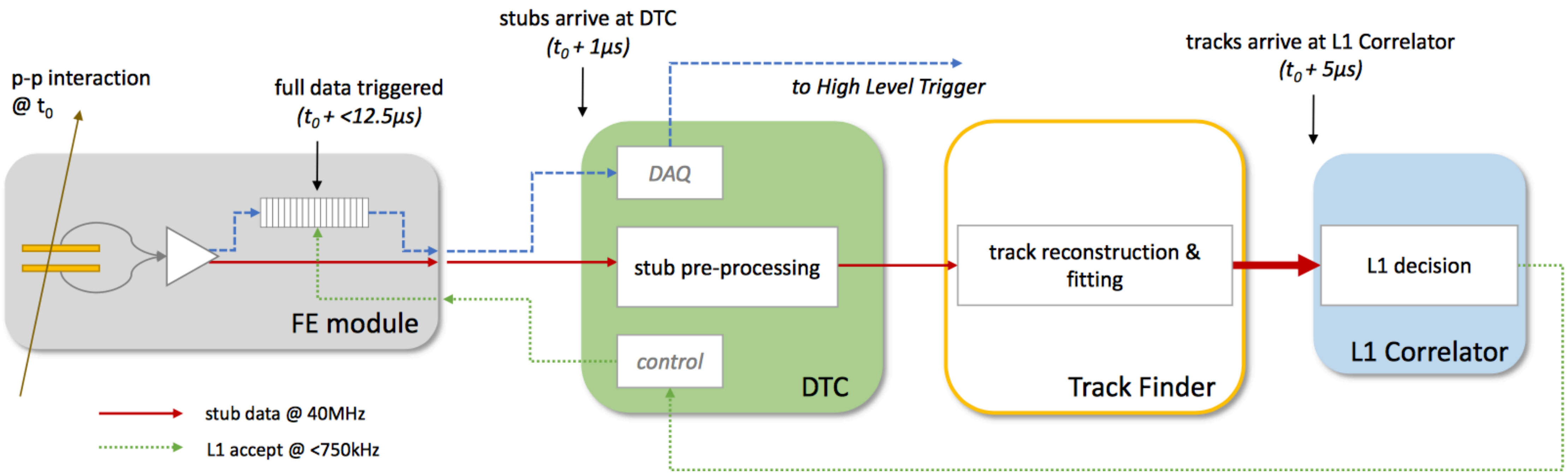
reduced trigger rates

CMS Phase 2 Tracker Upgrade

Level1 (L1) Triggering at the HL-LHC

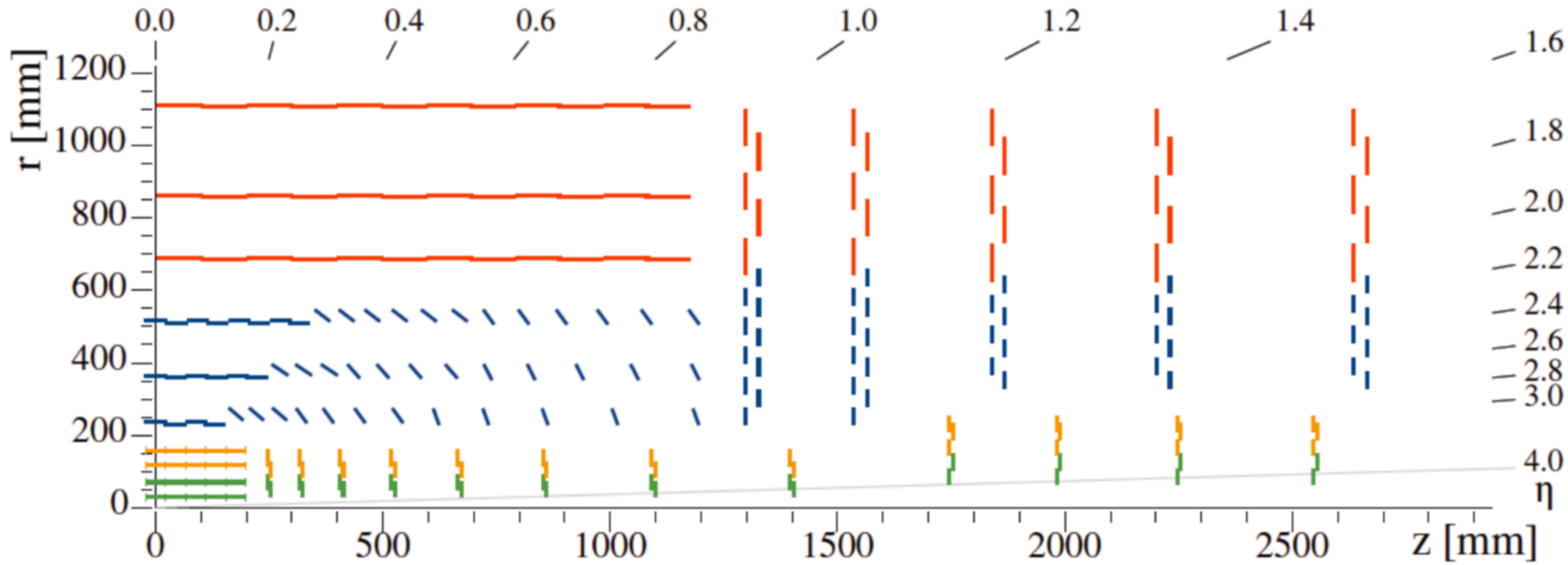
- All tracker data cannot be read out at bunch crossing frequency (40 MHz) therefore a reduction in the amount of data on the module used for L1 tracking is required which has led to the pT module concept :
  - module sensing element made up of two sensors separated by a few mm along the track direction
    - correlating clusters in the two sensor layers allows discrimination between high and low pT momentum tracks (charged particles bend in CMS's 3.8T field)
    - stubs [high pT tracks] can then be transmitted off module to the L1 track finding system at 40 MHz
    - tracks are combined in the L1 trigger system with calorimeter and muon information





Tracker Layout : Increased acceptance and higher channel count

- CMS PhaseII Tracker constructed from four types of modules and has an acceptance of |η| ~ 4
  - Inner Tracker [radius < 15 cm] 4.9 m^2 and $2x10^9$ pixels
  - Outer Tracker [radius > 15 cm] 192m^2 , $4.2x10^6$ strips, $1.7x10^8$ macro-pixels



Current tracker :

|η| ~ 2.5

1 m^2 of pixels [66M channels] 210 m^2 of strips [9.3 M channels]

8 module types for pixels, 27 module types for strips

reduced material budget by :

improved routing of services

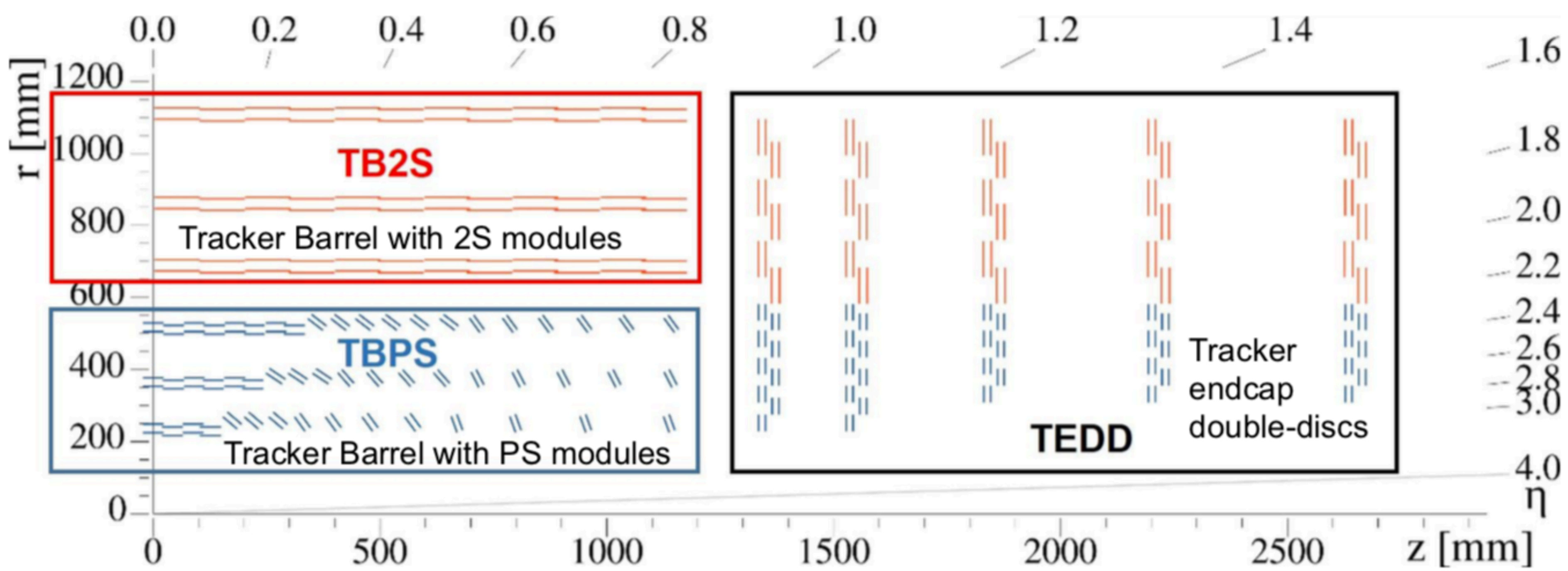
light module assembly

tilted section in the tracker barrel

CMS Phase 2 Tracker Upgrade

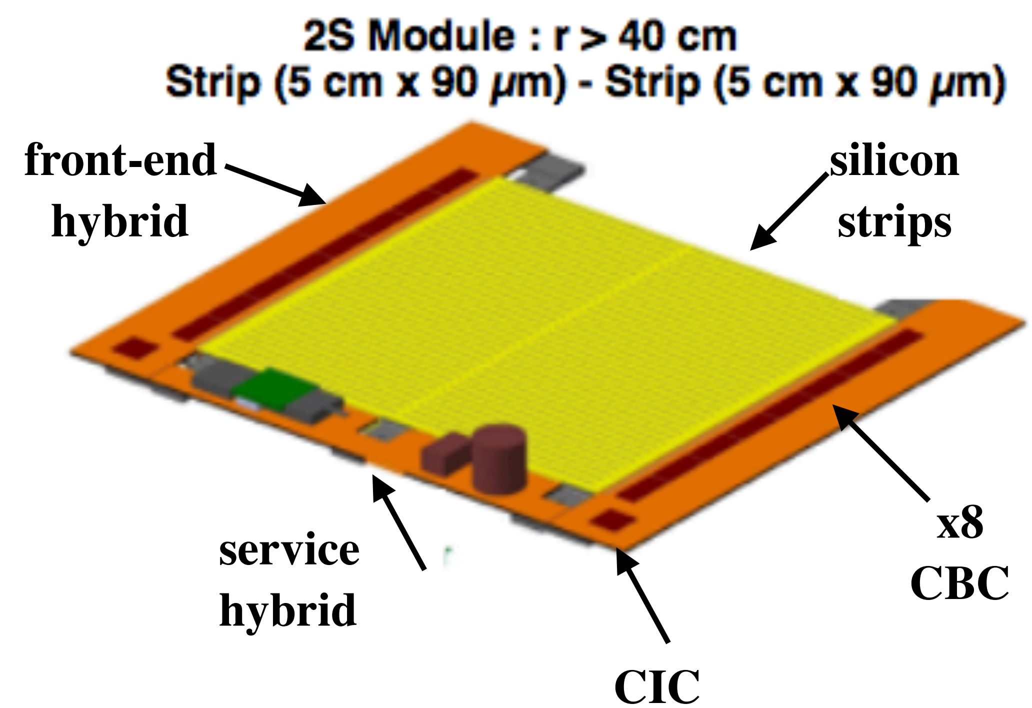
Outer Tracker Layout : Outer tracker modules

- CMS PhaseII Outer Tracker constructed from two types of modules and has an acceptance of |η| ~ 3
  - Two types of pT modules : strip-strip [2S] and macro-pixel strip [PS]

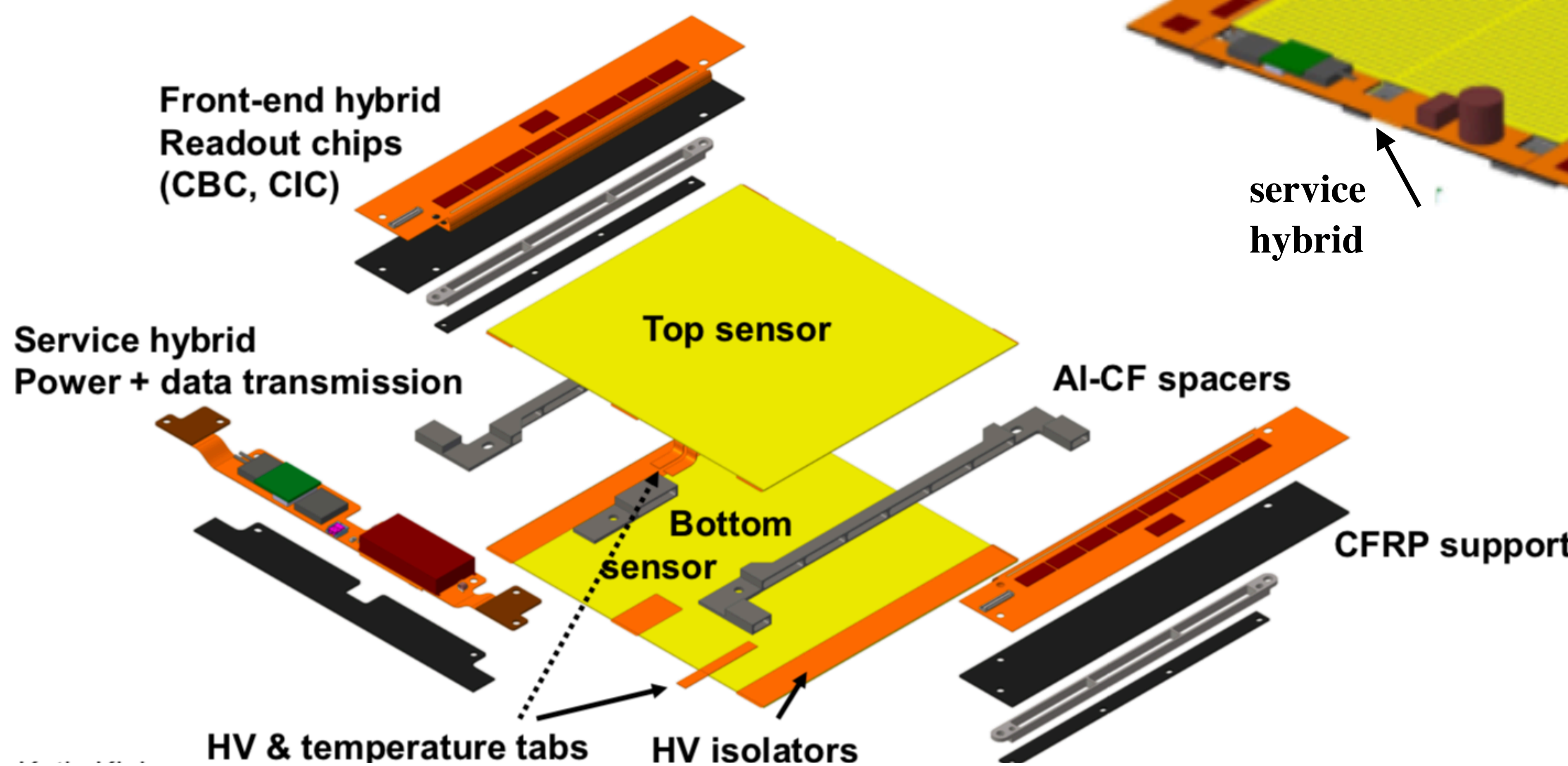


Outer tracker modules : Strip-Strip [2S] Modules - 1.8 mm and 4.0 mm

- 10 cm x10 cm
- 2 sensors (top and bottom) each with 2 rows (left and right) of 5 cm long strips
- 90 μm pitch
- 4064 channels per module

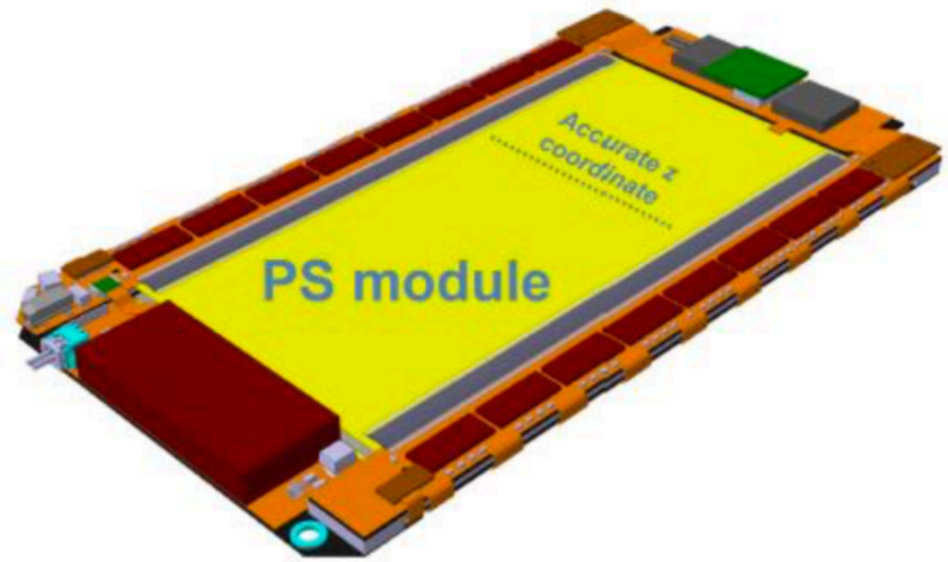


variants differ in Al-Cf spacers and connection tabs between readout and service hybrids



Outer tracker modules : Macro Pixel-Strip [PS] Modules - 1.6 mm, 2.6 mm and 4.0 mm

- 5 cm x10 cm
- 2 sensors (top and bottom) :
  - top sensor with 2 rows of 2.3 cm long strips
  - bottom sensor with 1467 μm long macro pixels
- 100 μm pitch



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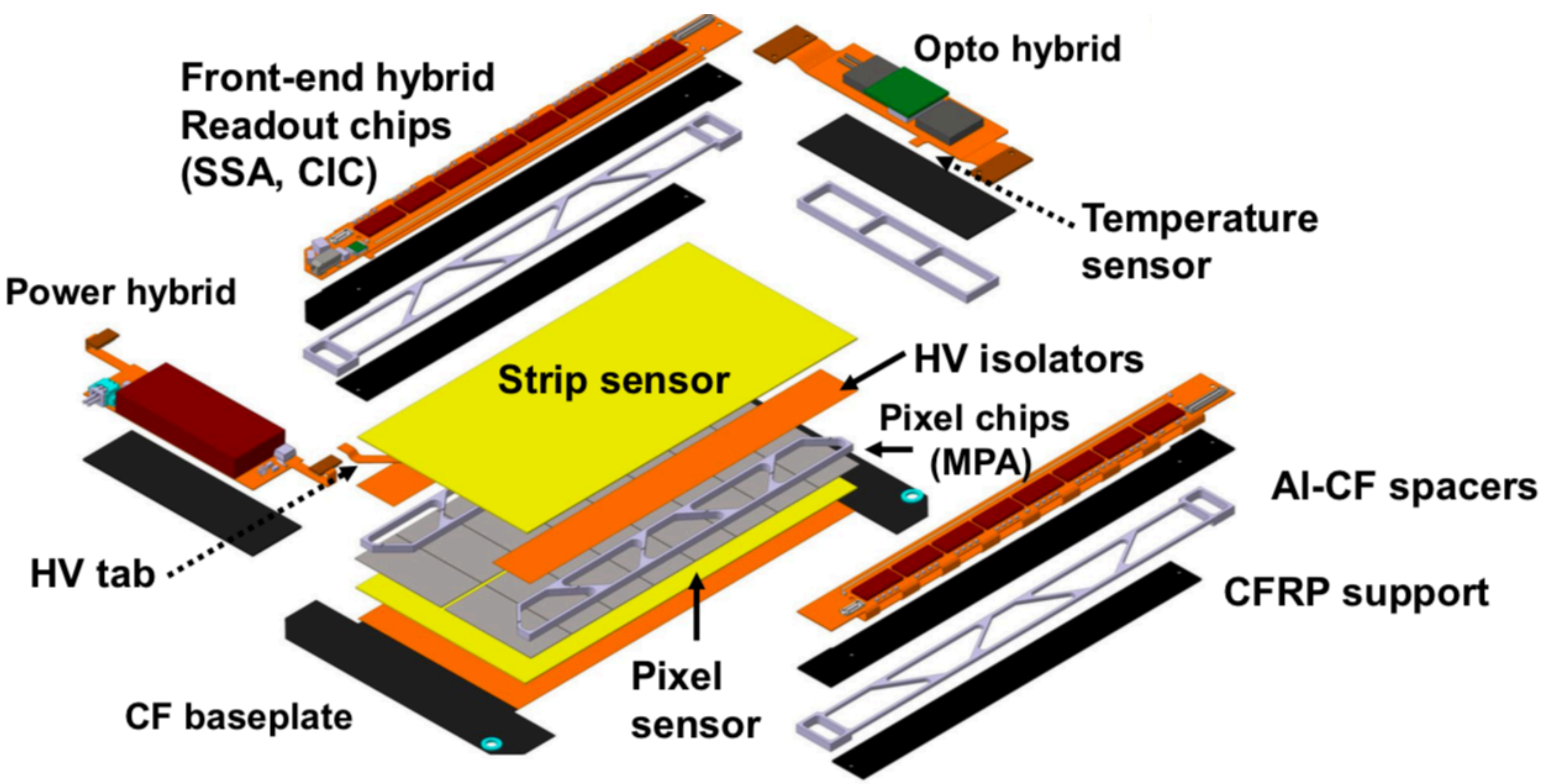
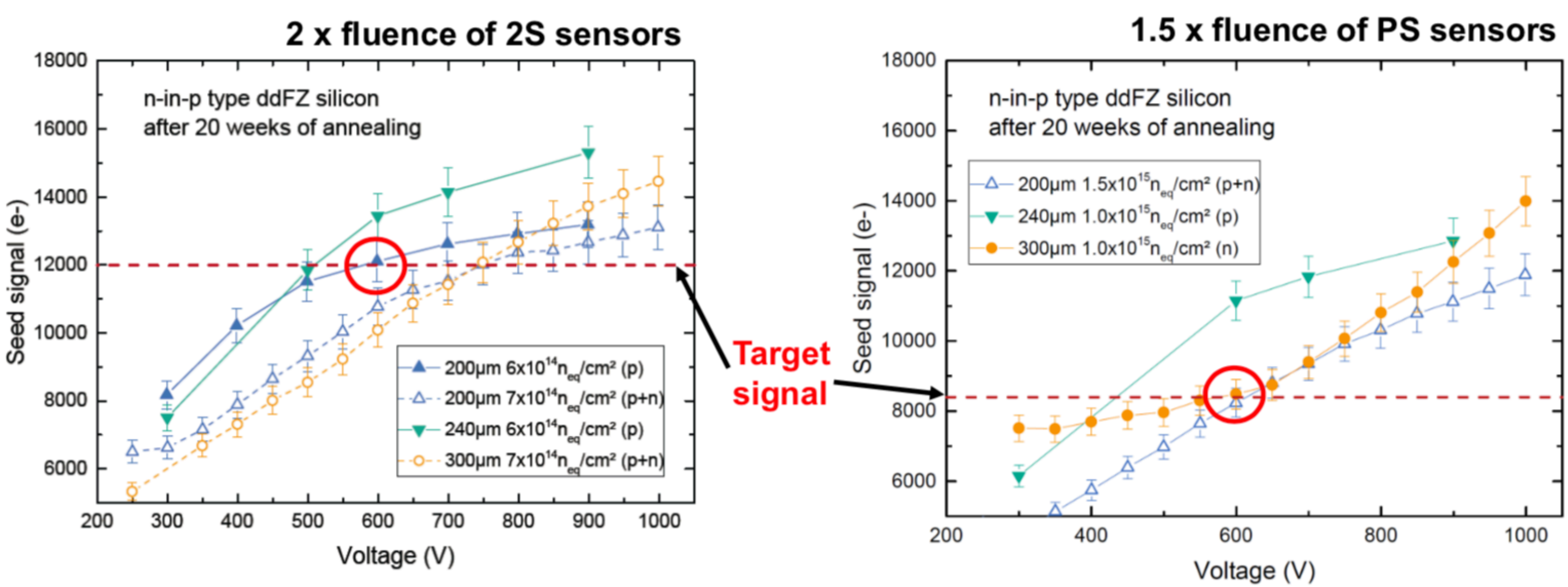


Sensors for Outer Tracker Modules

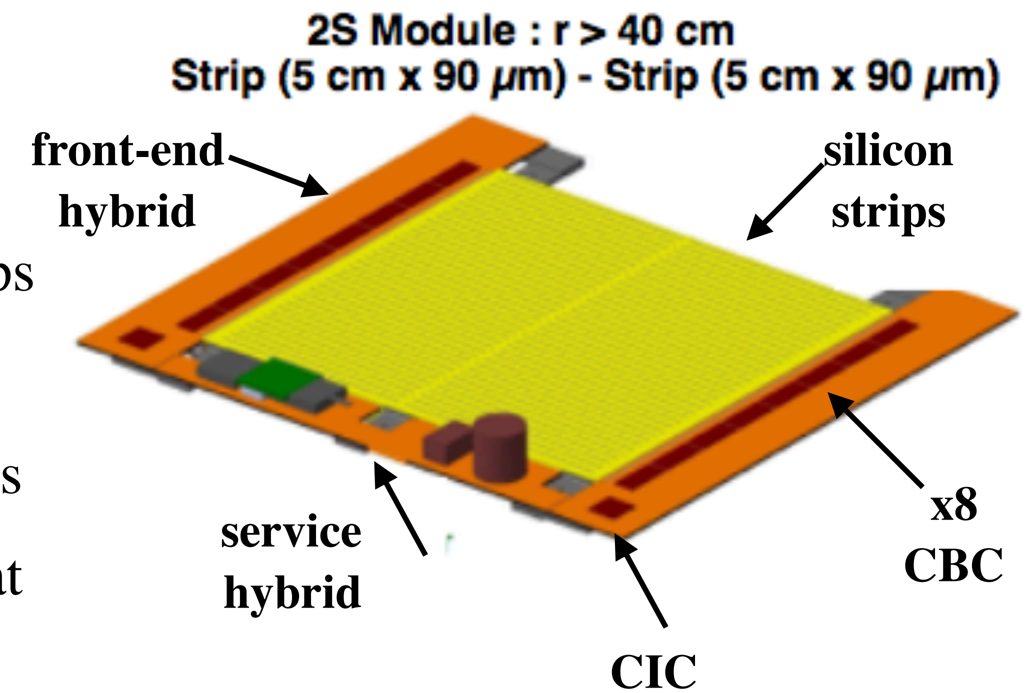
- In total three types of sensors used in the outer tracker :
  - 5 cm strips for the 2S modules
  - 2.3 cm strips for the PS modules
  - 1467 μm macro-pixels for the PS modules
- Decided on n-in-p type sensors, 200 μm active thickness (240 μm under study) from 6“ wafers
- Final decision on material and isolation technique still on-going
- Nominal bias of 600 V - possible to increase to 800V

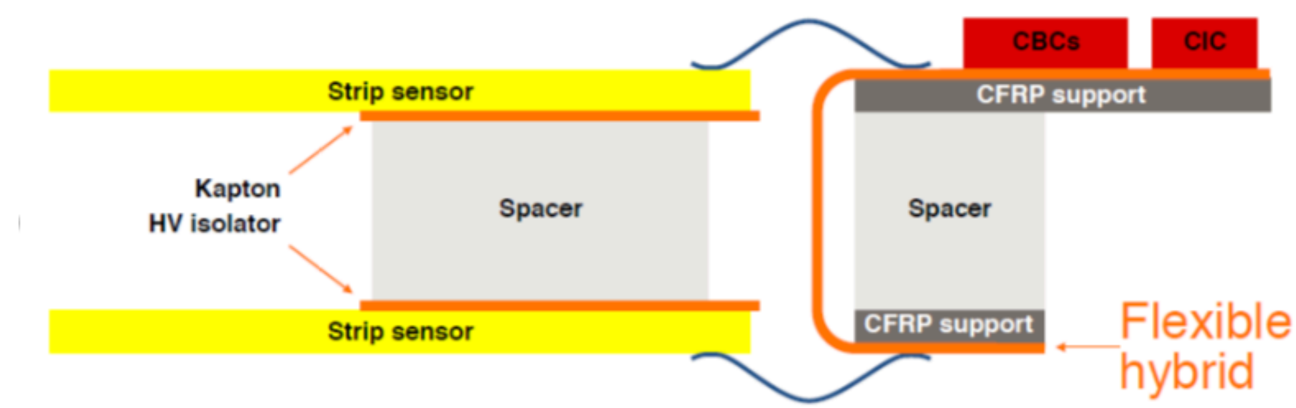


Required signal size reached at nominal fluence (w/ 50% margin)

ASICs for Outer Tracker modules : Strip-Strip [2S] Modules Read-out

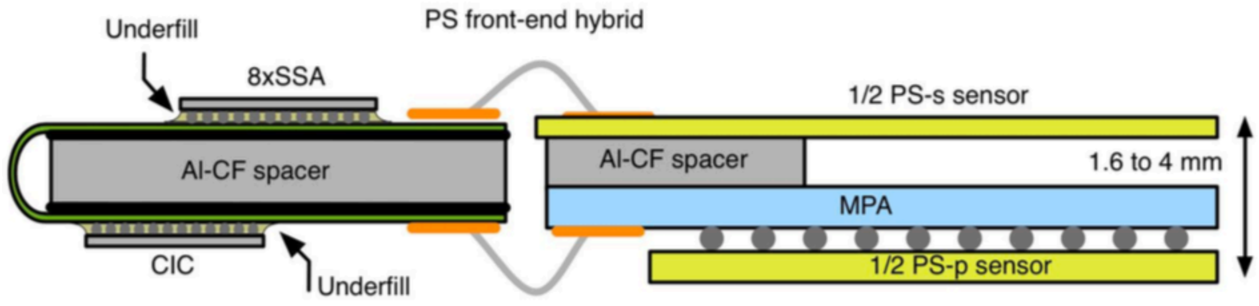
- CMS Binary Chip (CBC) in 130 nm CMOS
- Unsparsified binary readout
- Provides stub data at 40 MHz and read-out data at 750 kHz
  - even/odd channels on chip used to read-out top/bottom strips
  - data combined to select hit pT tracks (stubs)
    - communication across the chip boundaries to form stubs
  - full stub information sent off the chip on 5 dedicated lines at 320 MHz
  - expect 1000 e- noise
  - 20 ns peaking time, 50 ns return to baseline





ASICs for Outer Tracker modules : Macro Pixel-Strip [PS] Modules Read-out

- 65 nm CMOS technology
- Zero-suppressed binary readout



- Short Strip ASIC (SSA) readout for strip sensor data
  - expected noise 700 e-
- Macro-pixel ASIC (MPA) readout for macro-pixel sensor data
  - expected noise 200 e-
  - receives SSA trigger data and produces stubs
- MAPSA Light
  - initial prototype using small prototype versions of the MPA
  - see K. Nash’s talk in tomorrow’s morning session

Recent Developments in Outer Tracker R&D :ASICs

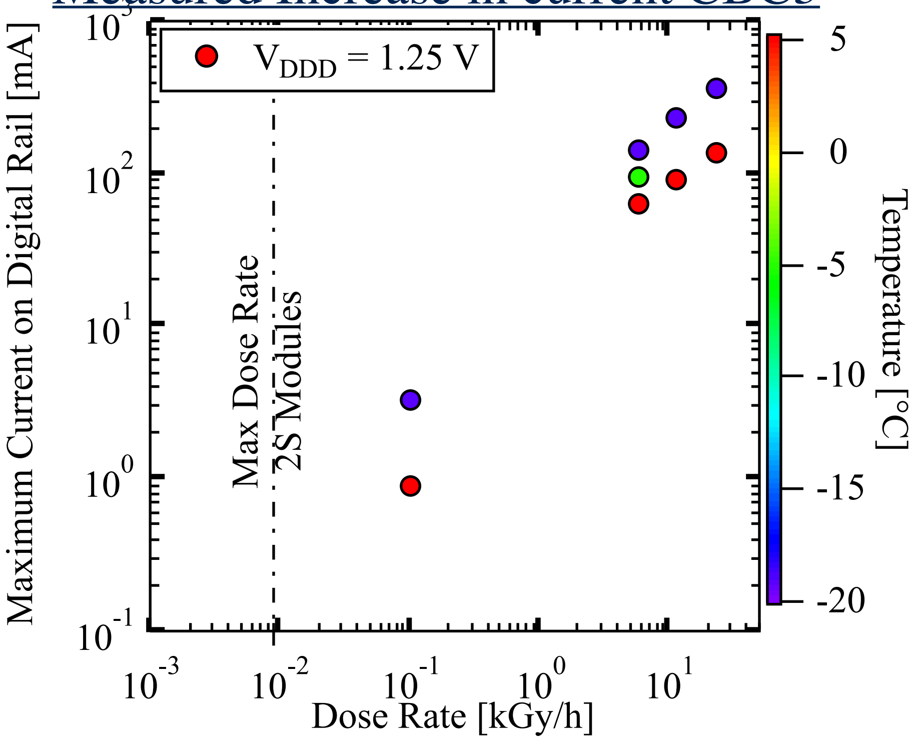
- Third prototype (CBC3) with full functionality delivered in late 2016 and tested/qualified in 2017
  - See K.Urchida's talk at HSTD11
  - Radiation tests performed in first half of 2017 show improved radiation resistance compared to earlier version

Estimated number of errors in I2C registers at x3 HL-LHC fluence for innermost 2S modules

CBC version	# I2C bits	ϕ_{LiF} [$cm^{-2}\ s^{-1}$]	# bit flips [LIF]	σ_{SEU} [x $10^{-11}\ cm^{-2}$]	ER_{HL-LHC} [bit flips/h]
3	2640	2.2E+08	0.36 ± 0.07	**0.27 ± 0.05**	0.069 ± 0.013
2	2456	2.5E+08	2.8 ± 0.5	**1.9 ± 0.3**	0.47 ± 0.084

error rates estimated using data from SEU test using
65 MeV protons (~2.3x$10^8\ cm^{-2}\ s^{-1}$) at the LIF facility in Louvain-la-Neuve

Measured Increase in current CBC3



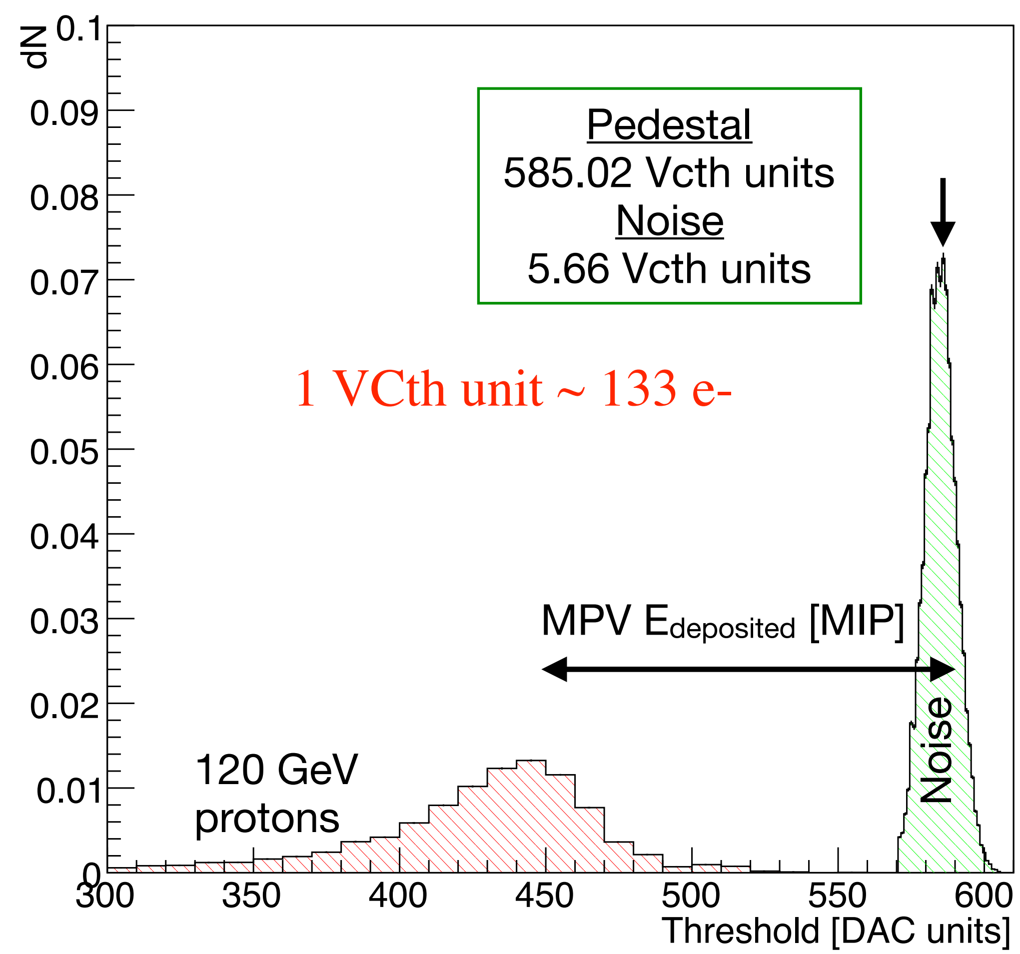
- confident that current increase measured in accelerated conditions using the CERN X-ray irradiation facility represents a worst-case scenario for the ASICs
- expected increase on power consumption of a single 2S module due to leakage in CBC3 expected to be < 2%

Recent Developments in Outer Tracker R&D :ASICs

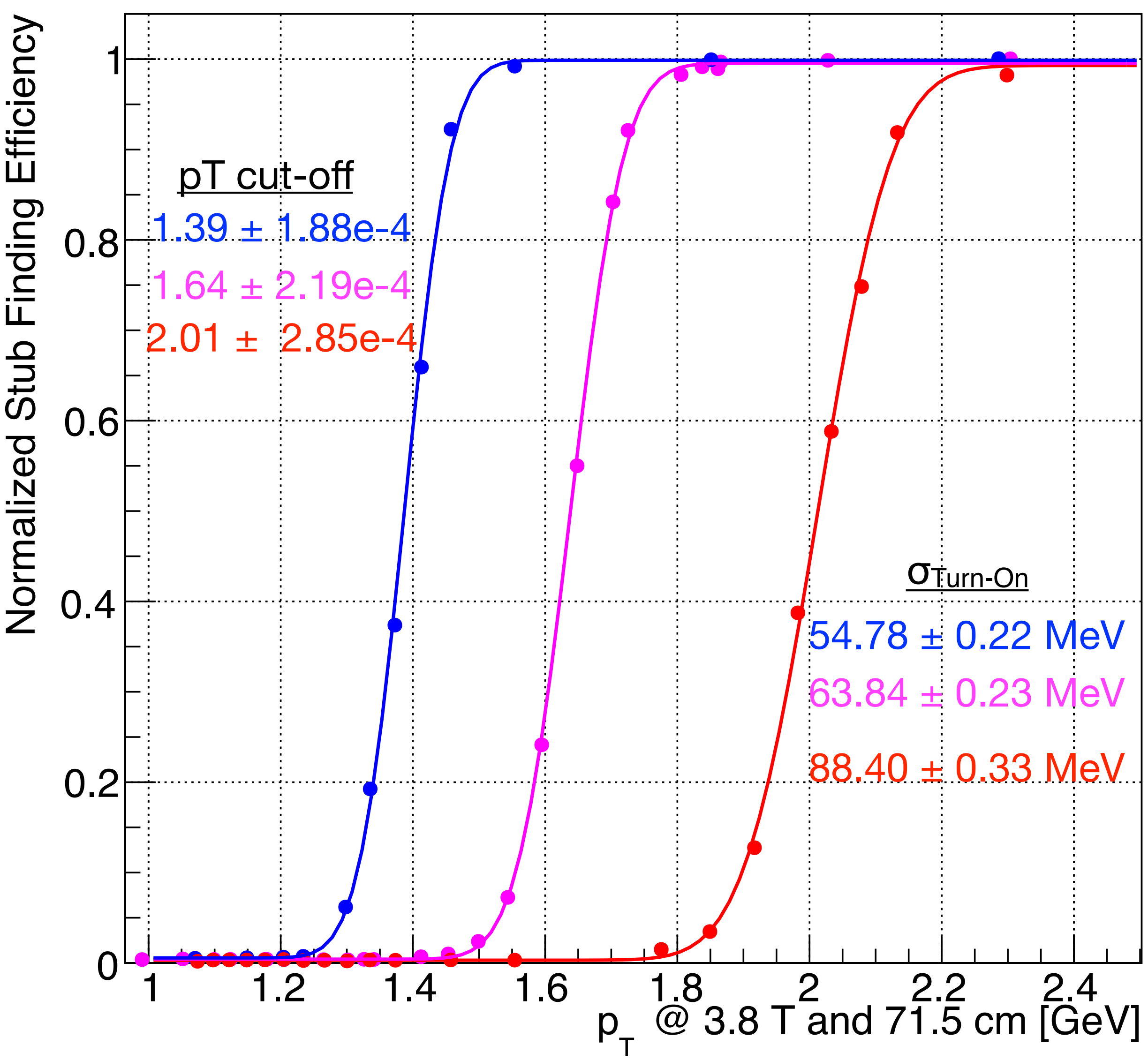
- Third prototype (CBC3) with full functionality delivered in late 2016 and tested/qualified in 2017
  - Radiation tests performed in first half of 2017 show improved radiation resistance compared to earlier version
  - Data collected with first prototype mini-module with x2 CBCs at the FNAL test beam facility

Preliminary Results From FNAL TB

Differentiating fraction of detected hits/event for : 120 GeV protons, no beam



Stub Turn-on Curves for different correlation windows

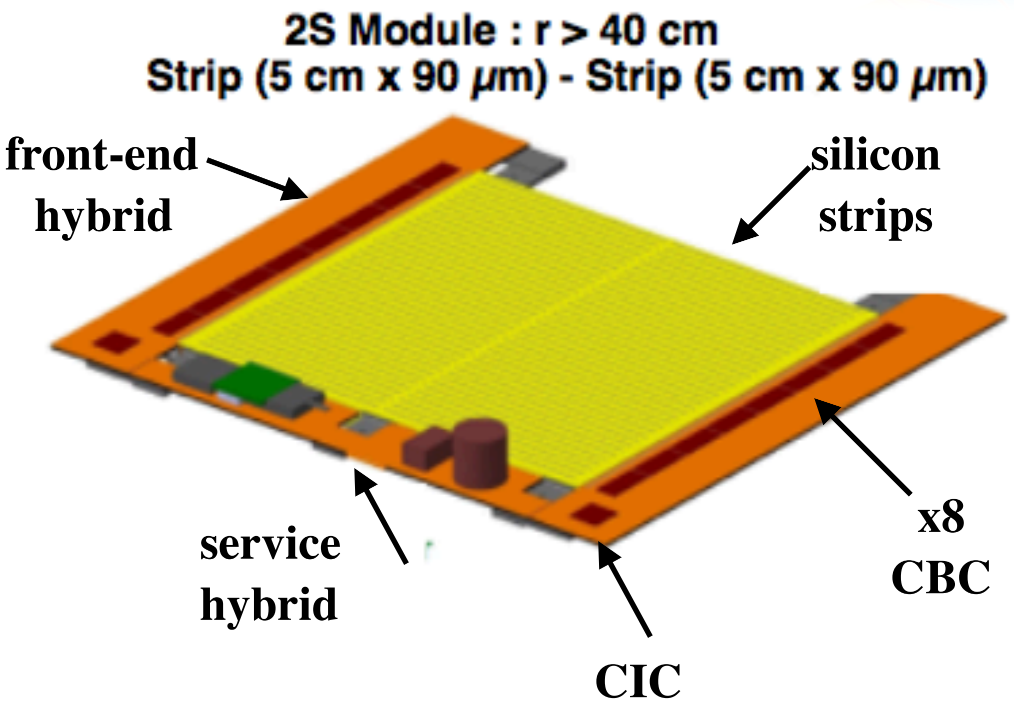


Recent Developments in Outer Tracker R&D :ASICs

- Third prototype (CBC3) with full functionality delivered in late 2016 and tested/qualified in 2017
  - Radiation tests performed in first half of 2017 show improved radiation resistance compared to earlier version
  - Data collected with first prototype mini-module with x2 CBCs at the FNAL test beam facility
- MPA and SSA ASIC submission completed in 2017
  - Delivery of single die wire-bonded PCBs to CERN January 2018
  - Preliminary results encouraging ; chips have passed :
    - power-up and chip reset tests
    - power consumption measurements
    - input/output communication tests
    - analogue front-end counting tests
    - digital functionality counting tests

ASICs for Outer Tracker modules : Concentrator

- 65 nm CMOS technology
- Concentrator Integrated Circuit [CIC]

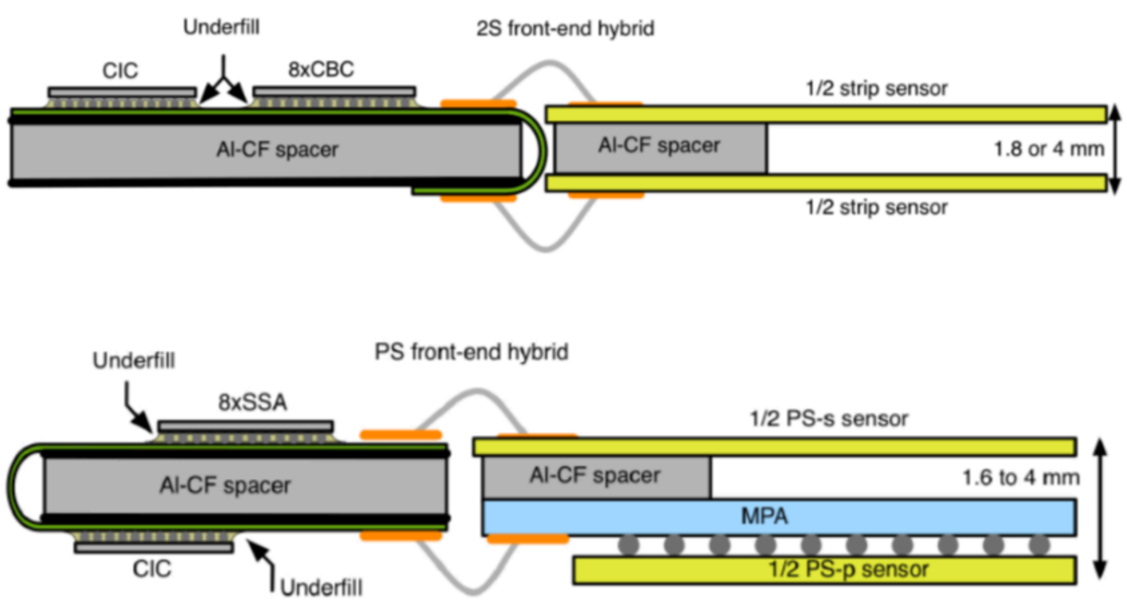


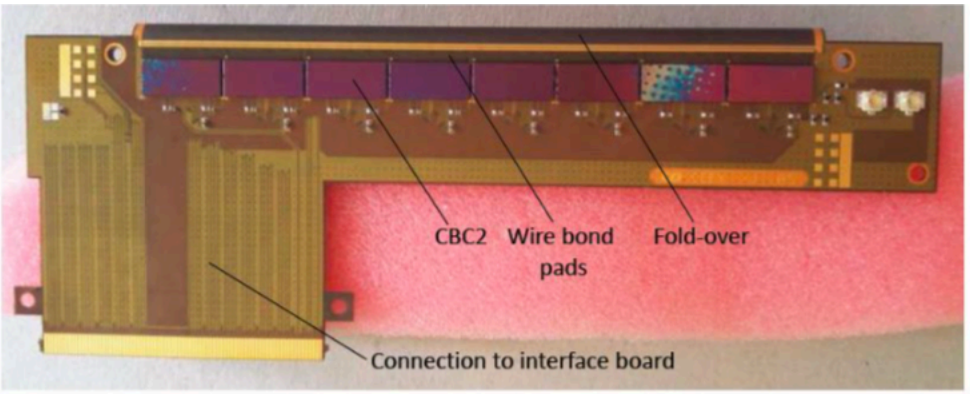
- Aggregates and sparsifies data from 8CBCs and 8MPAs
- Passes data to serializer/deserializer ASIC on service hybrid (lpGBT)
- Under design, submission scheduled for this year.

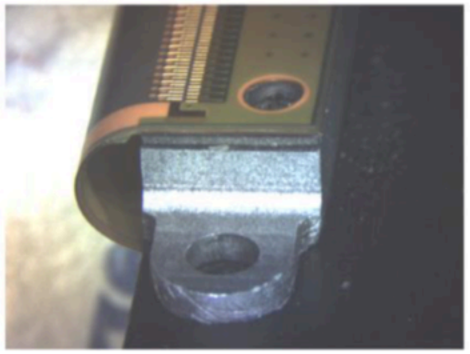
CMS Phase 2 Tracker Upgrade

Front-End Hybrids for Outer tracker modules

- Front-end hybrids wire-bonded to sensors and flip-chip bonded to ASICs
- High line density, 42 μm track width and space, 50 μm vias
- Four layer flexible printed circuit boards folded tightly around a carbon fibre stiffener
  - key to the pT module concept since it enables on-module stub finding







- Market survey closed 2016 ; 3 consortia of PCB manufacturers and assemblers identified
- Working prototypes for 2S variant produces and used in module prototyping
  - full-size modules built using earlier prototypes of the CBC [CBC2]
- Mock-ups for PS variant produced

Conclusions

- The Phase2 tracker upgrade is a crucial element of the CMS upgrade program which will
  - provide valuable input to the L1 trigger decision
  - maintain excellent tracking and physics performance even in scenarios with 200 pileup events
  - enable the CMS collaboration to pursue a broad and competitive physics programme during the next decade

- Developments for pT modules (2S/PS) modules are well underway
  - all concepts of CMS Outer tracker validated
  - need to ramp-up prototyping and focus on production
- DAQ and BE developments for OT also ongoing (not covered here)

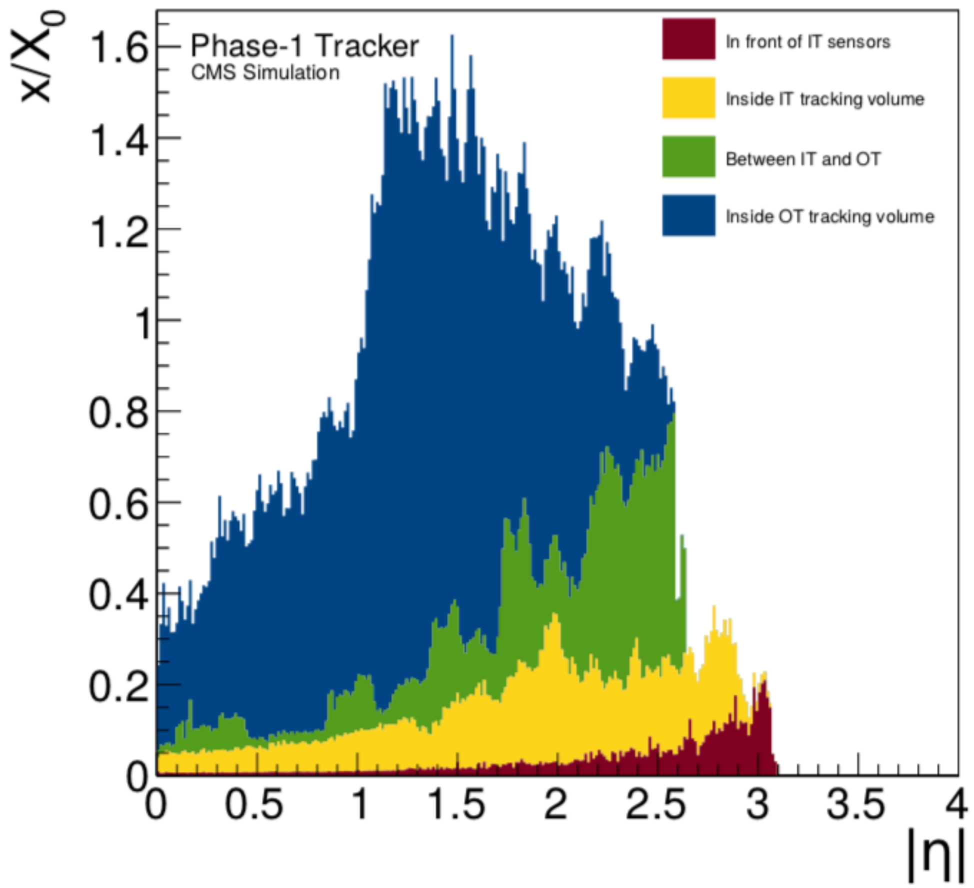
Back-Up Material

CMS Phase 2 Tracker Upgrade

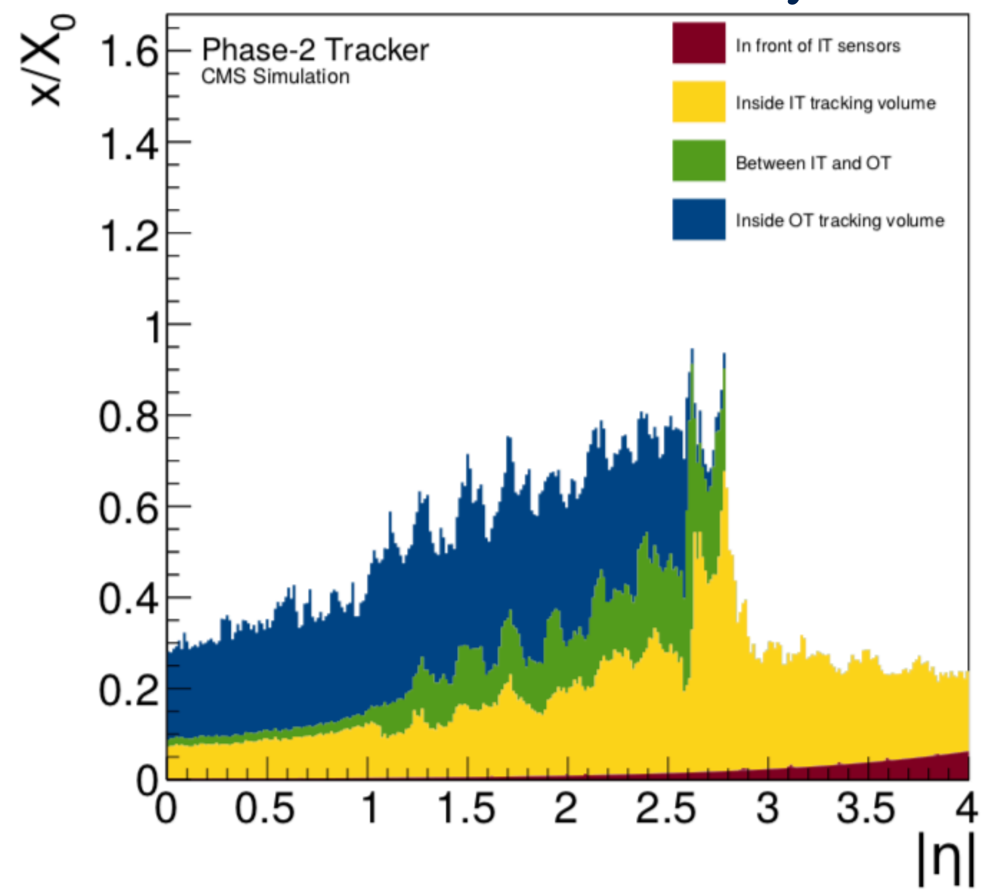
Tracker Layout : Reduced material budget

- CMS PhaseII Tracker constructed from four types of modules and has an acceptance of |η| ~ 4
  - Inner Tracker [radius < 15 cm] 4.9 m^2 and 2×10^9 pixels
  - Outer Tracker [radius > 15 cm] $192 m^2$, 4.2×10^6 strips, 1.7×10^8 macro-pixels

Phase I Tracker : standard CMS SW



Phase II Tracker : tkLayout



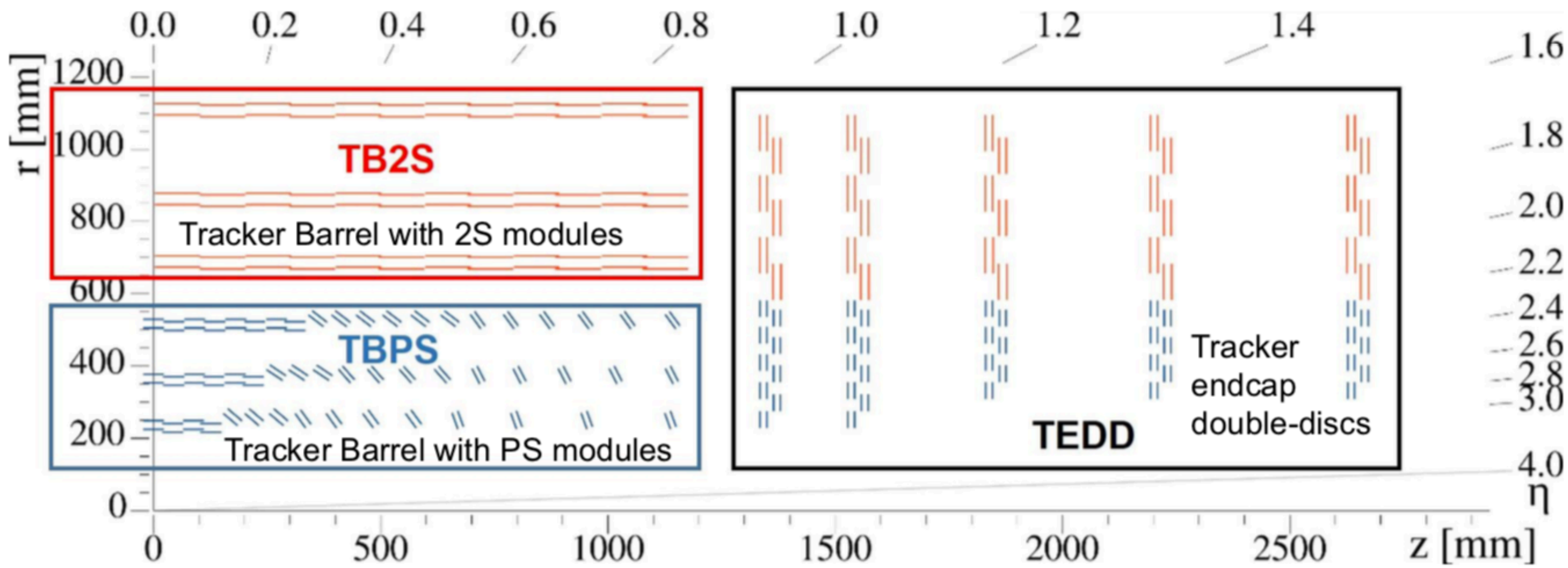
improved routing of services

light module assembly

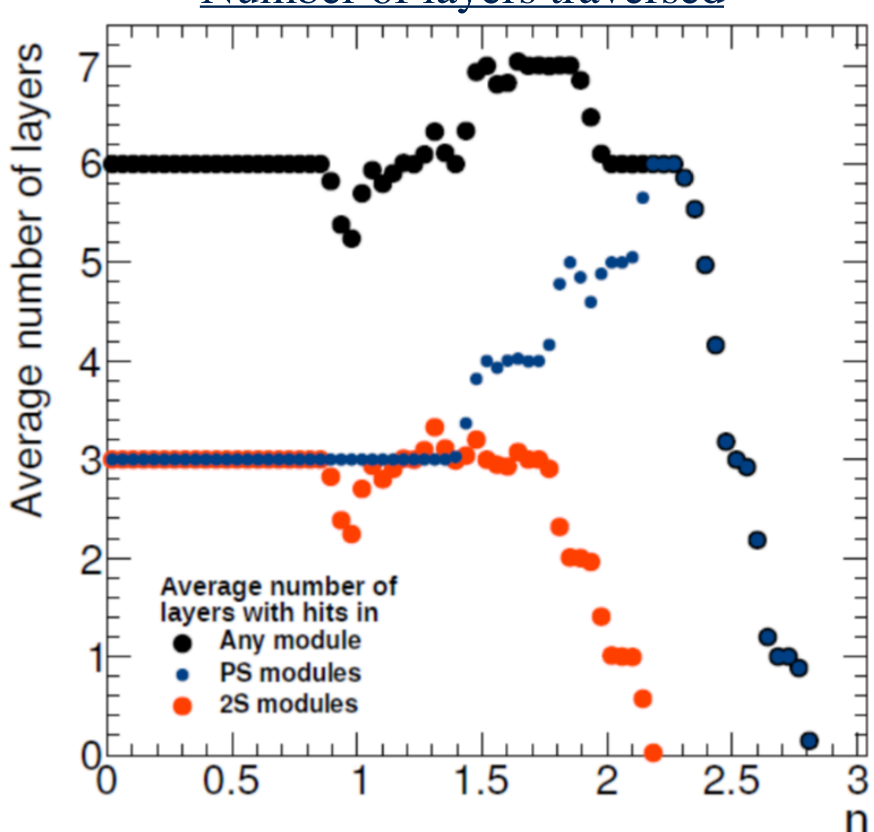
tilted section in the tracker barrel

Outer Tracker Layout : Robust L1 tracking and vertexing

- CMS PhaseII Outer Tracker constructed from two types of modules and has an acceptance of |η| ~ 3
  - Two types of pT modules : strip-strip [2S] and macro-pixel strip [PS]



Number of layers traversed



Robust L1 track finding performance given by six detection layers except for a small dip around η~1

L1 track finding with 5 modules extremely sensitive to loss of efficiency in some parts of the detector

Robust L1 vertex discrimination given by 3 layers of modules with good z resolution [PS]

at least two precise coordinated required to measure the polar angle of a track

CMS Phase 2 Tracker Upgrade

Outer Tracker Layout : Tilted Barrel

- CMS PhaseII Outer Tracker constructed from two types of modules and has an acceptance of |η| ~ 3
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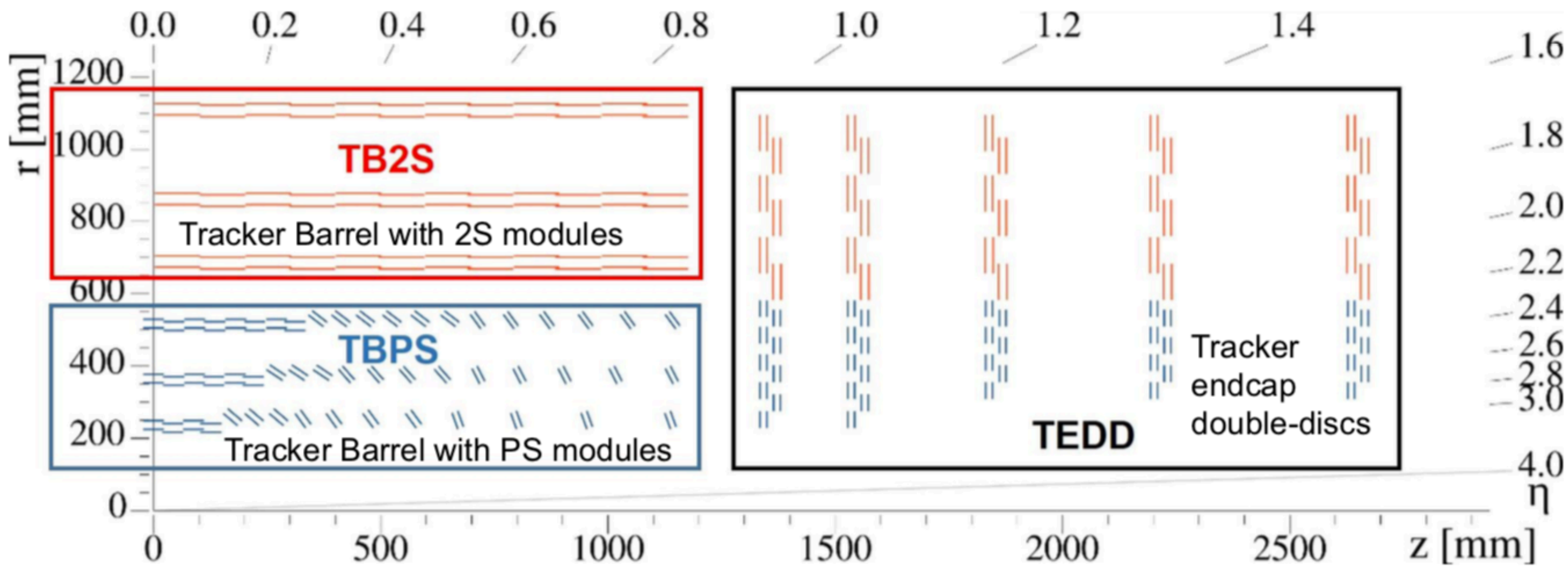
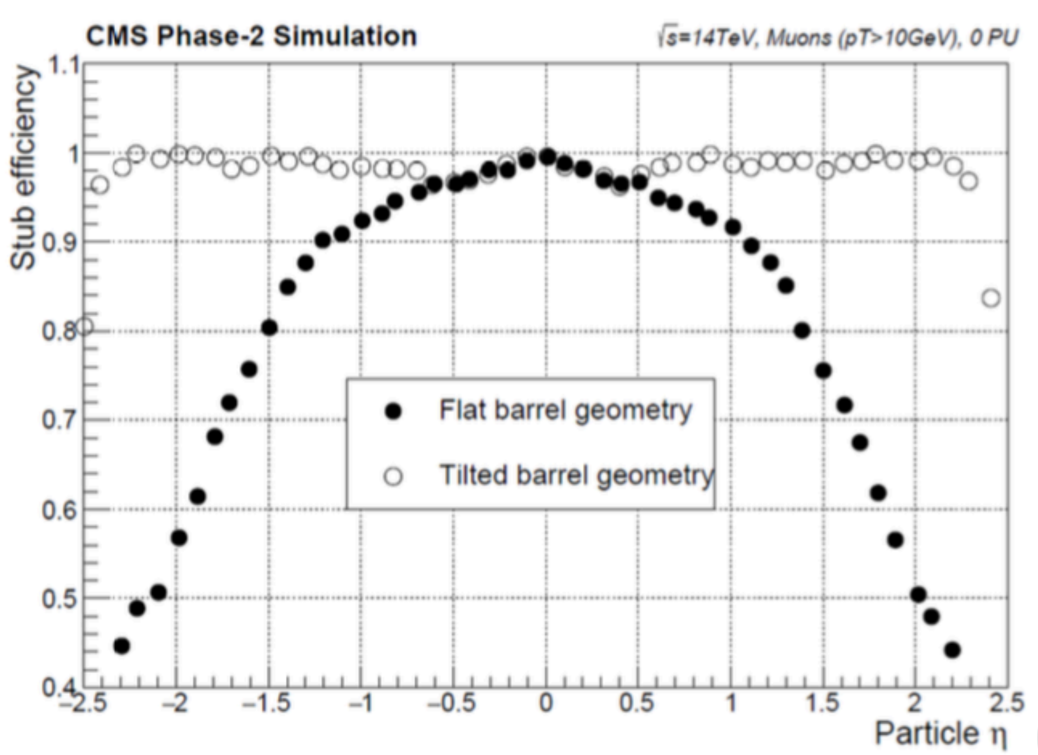




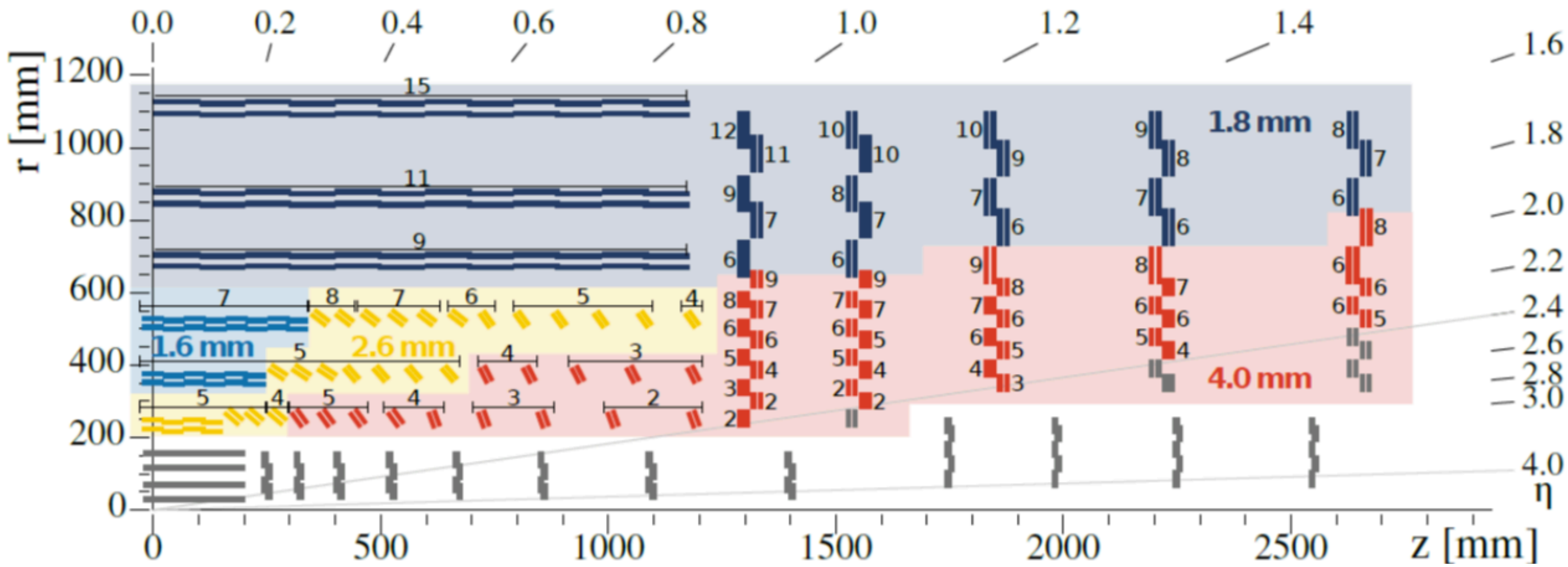
Excellent stub finding efficiency over entire OT acceptance

impossible to correlate hits between left half of lower and right half of upper sensor for high η in a flat barrel

Reduces material budget and cost for barrel

Outer Tracker Layout : Outer tracker modules

- CMS PhaseII Outer Tracker constructed from two types of modules and has an acceptance of |η| ~ 3
  - Two types of pT modules : strip-strip [2S] and macro-pixel strip [PS]
    - pT discrimination depends on sensor spacing and acceptance window
      - acceptance window (width and position) programmable on module
      - five values of sensor spacing to be used in module construction



Colours:
sensor spacings

Black numbers:
acceptance windows

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**	

CMS Phase 2 Tracker Upgrade

Outer Tracker Layout : Outer tracker modules

- CMS PhaseII Outer Tracker constructed from two types of modules and has an acceptance of $|\eta| \sim 3$
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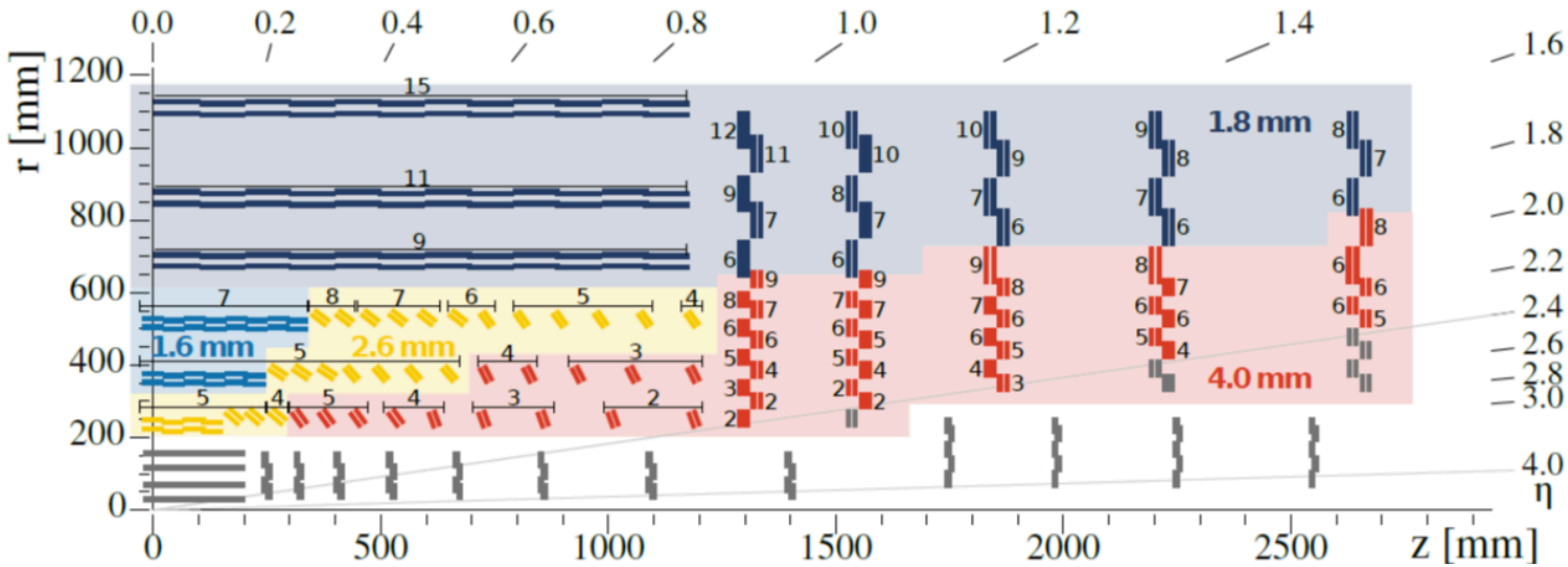

Colours: sensor spacings

Black numbers: acceptance windows

Small windows and spacing preferred in inner layers

Larger spacing (good pT resolution)

→ larger window for the same pT cut → more accidentals

$$p_T = \frac{0.57R}{\sin\theta} = 0.57R\sqrt{1 + (\frac{d}{w_C})^2}$$

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	
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	4.0 mm	584	0	2744	3328	
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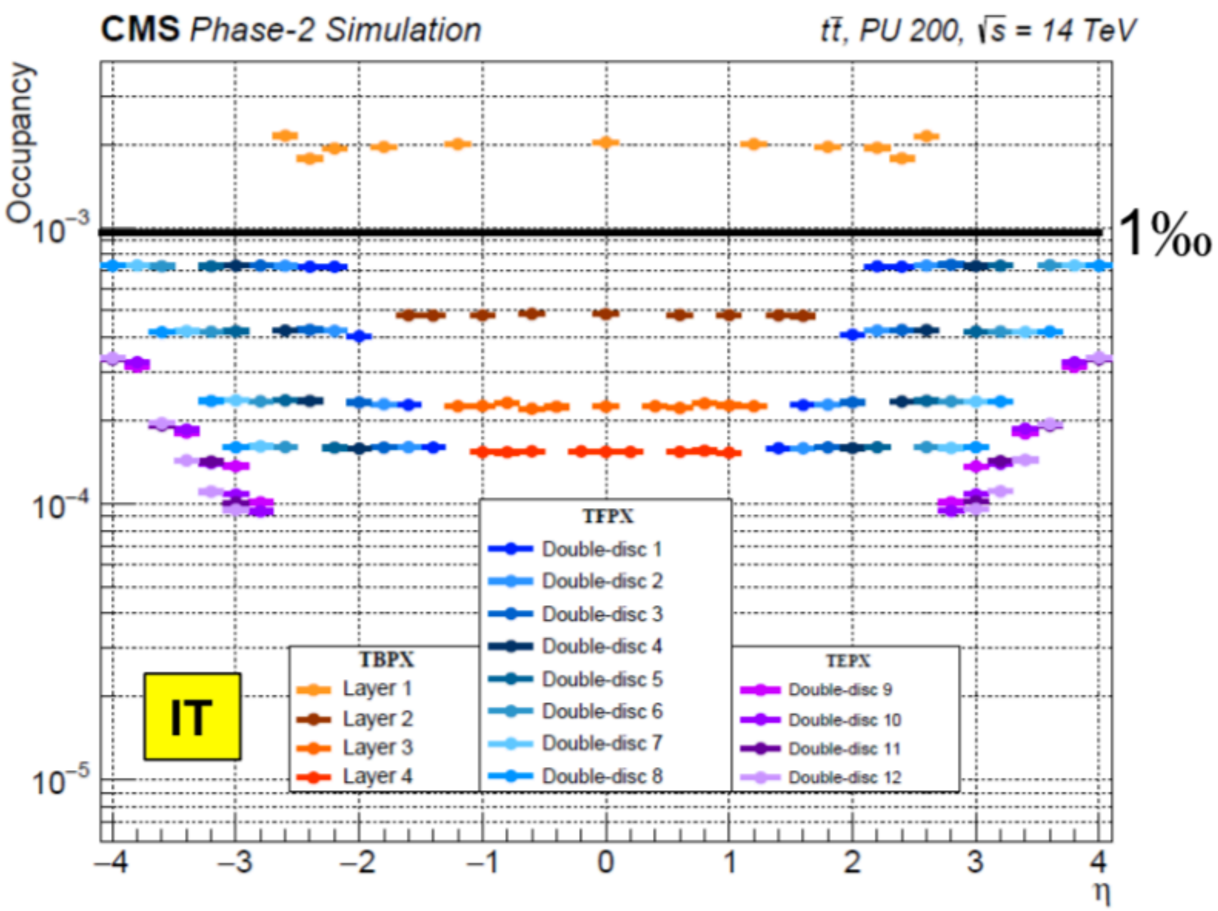
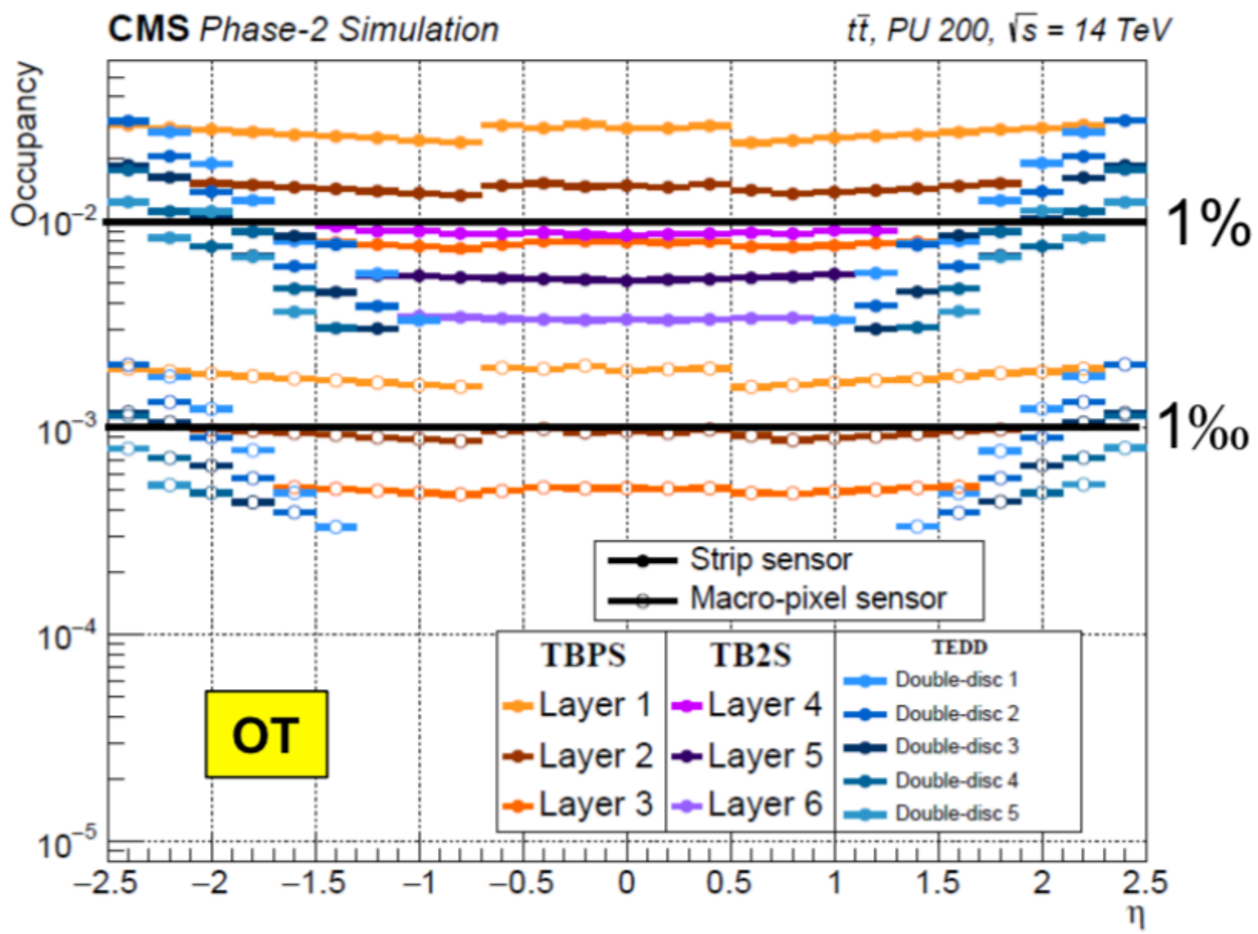
Hit Simulation and Performance

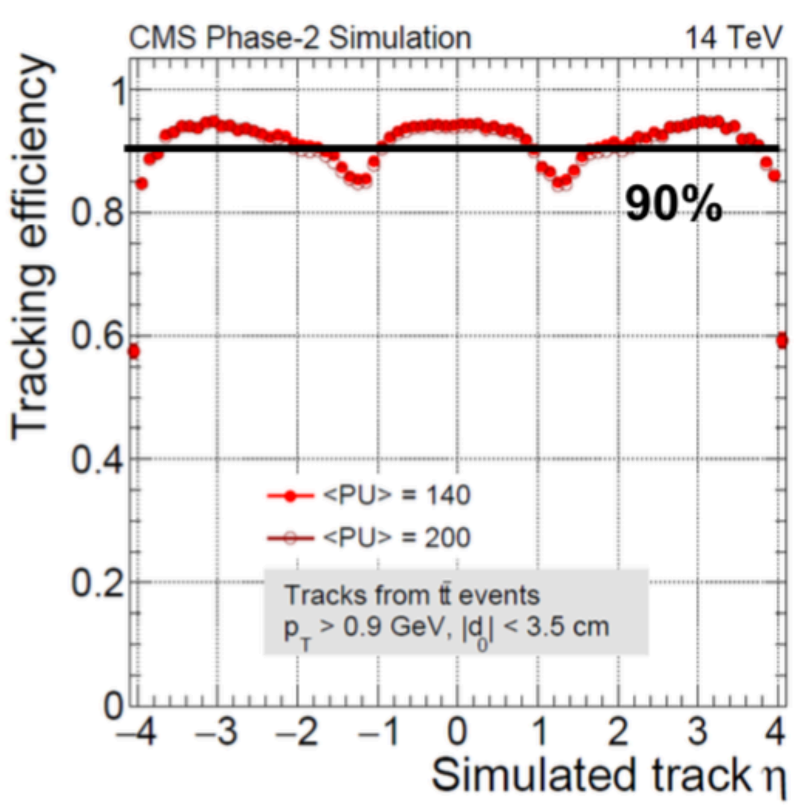
- Simulation of charge creation and migration in sensors with CMSSW + Geant4
- Simulation of electronics (threshold, noise, cross talk) → digitized hit → input for tracking
- Electronics parameters derived from test beam (2S modules) or specifications (PS, pixel)
- Occupancies can be simulated: %-level for OT strips, ‰-level for pixels and macro-pixels
- High simulated hit efficiencies
- Cluster properties (size, residuals) also studied

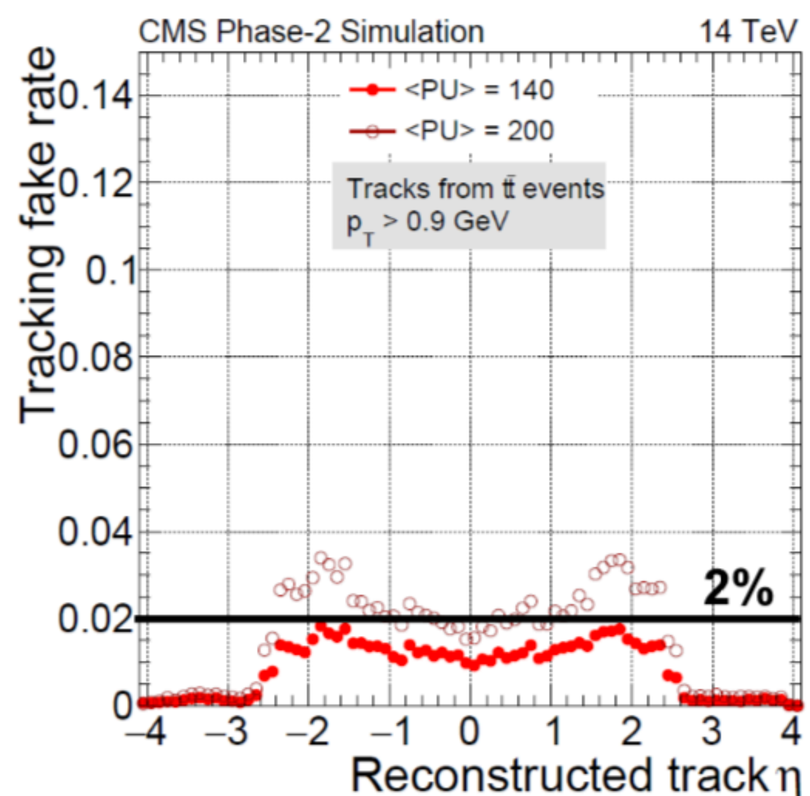


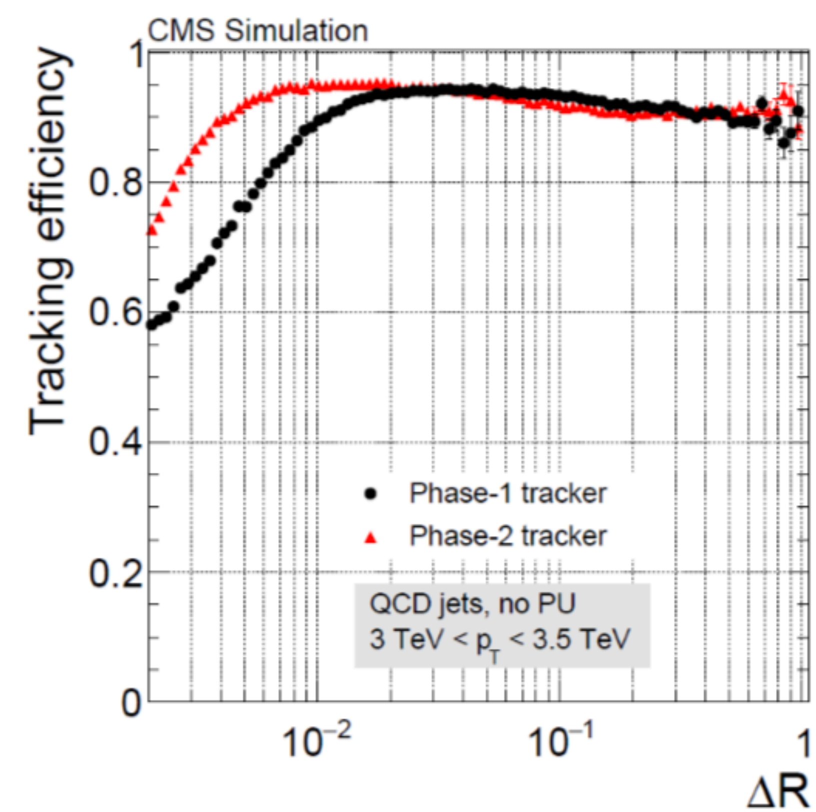


Hit Simulation and Performance

- For 200 pileup events, tracker is traversed by ~6000 charged particles
- Iterative procedure with 8 tracking iterations, using different seeding configurations
- In each step: seeding, track finding, track fitting, track selection
- High efficiency in muon and ttbar events, low fake rate
- Improved two-track separation in high-p_T jets
- Optimization ongoing, active R&D in many directions (further dedicated iterations, use of vector hits, tracking on GPUs, ...)







Katia Klein

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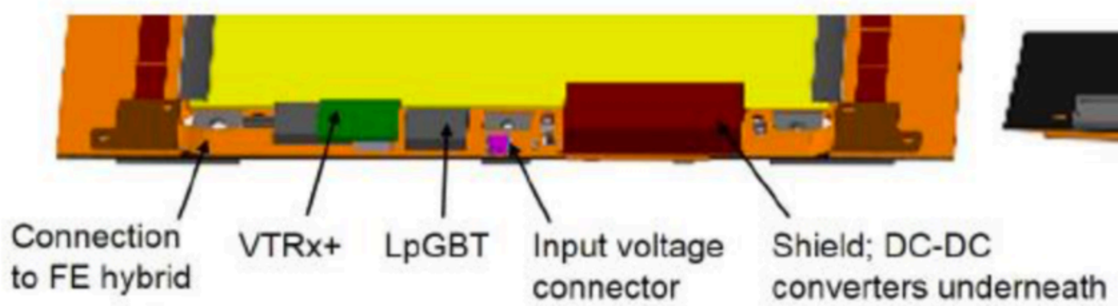
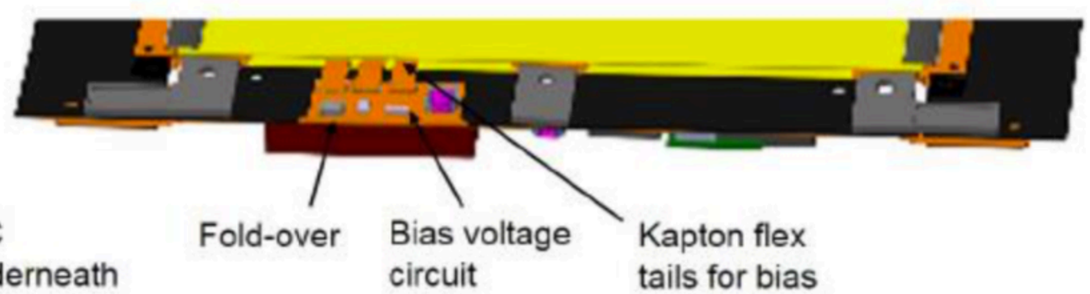
Service Hybrids for Outer Tracker Module

- Service hybrids provide low and high voltage , data aggregation, optical-electrical conversion :
  - 2 step DC-DC conversion powering scheme : CERN bPOL12V bPOL2V5 buck converters
  - LpGBT serializer/deserializer aggregates data from front-end ASICs and implements slow control functionality
  - VTRx+ for optical-electrical conversion and optical data transmission

2S Service Hybrid (top)



2S Service Hybrid (bottom)



- All chips are still under development
- 2S prototypes made using early/existing prototypes of ASICs

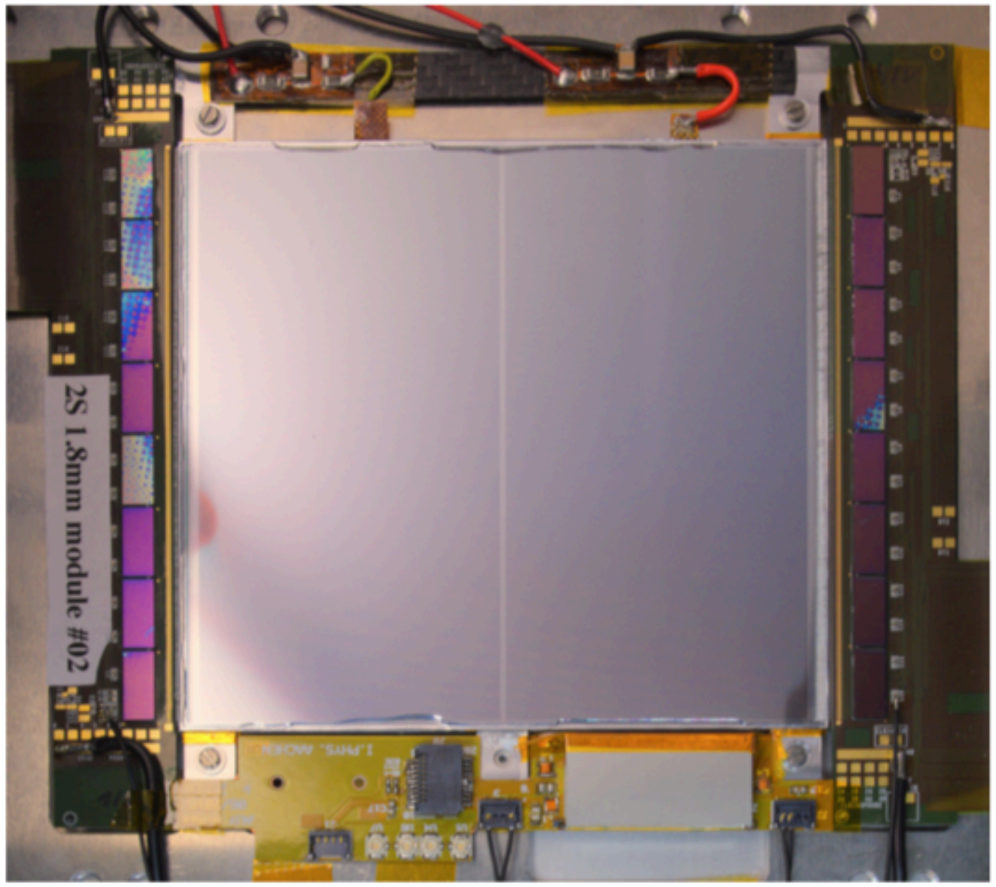
CMS Phase 2 Tracker Upgrade

Service Hybrids for Outer Tracker Module : Demonstrating Power

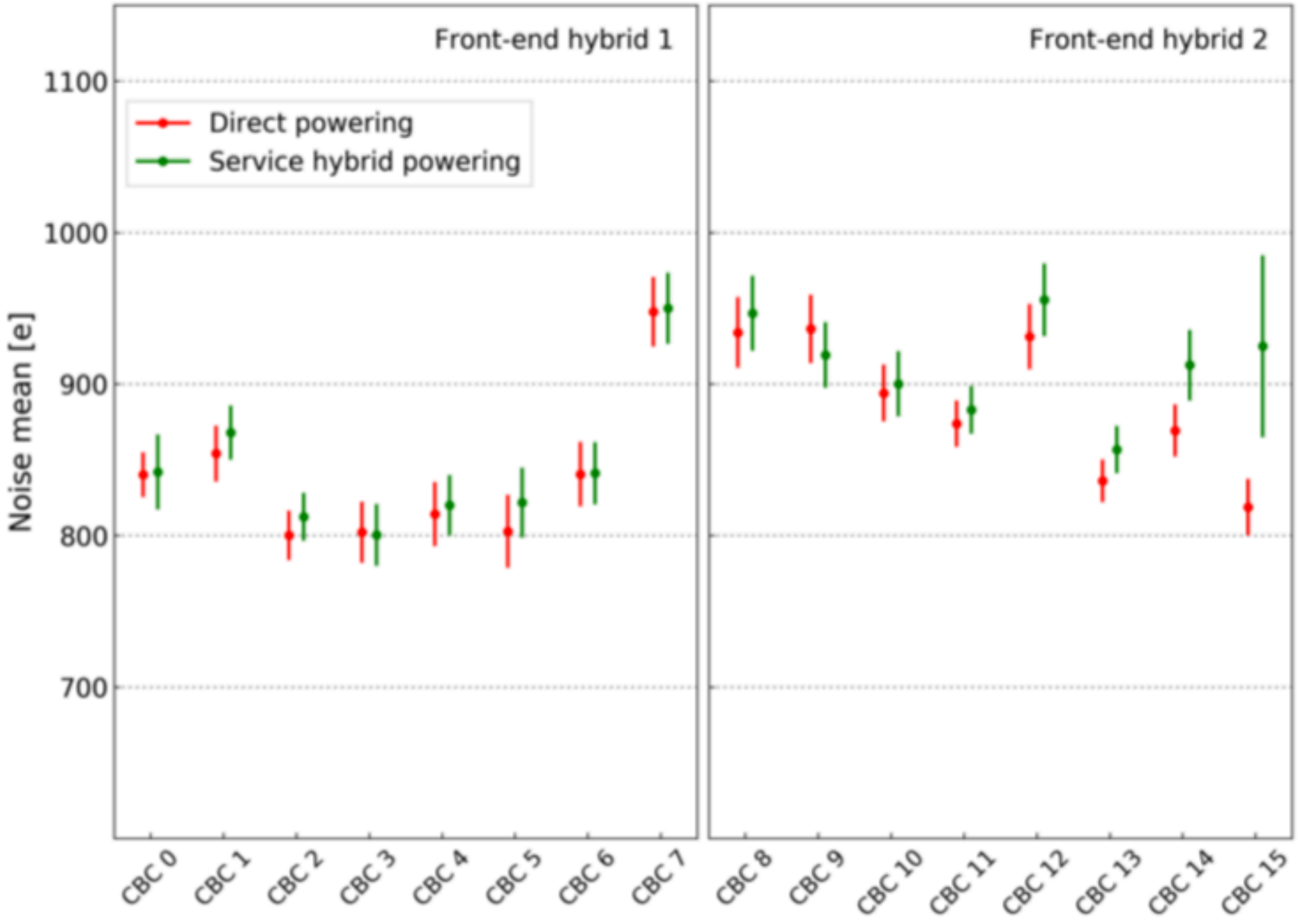
- Service hybrids provide low and high voltage , data aggregation, optical-electrical conversion :
- 2S prototypes made using early/existing prototypes of ASICs , most recent version under development :
  - FEAST2 & Commercial DC-DC converters replacing POL12V bPOL2V5 buck converters
  - GBTx+SCA replacing LpGBT
  - Connector for VTRx present

Full Size 2S Module + Service Hybrid

Arranged as final module



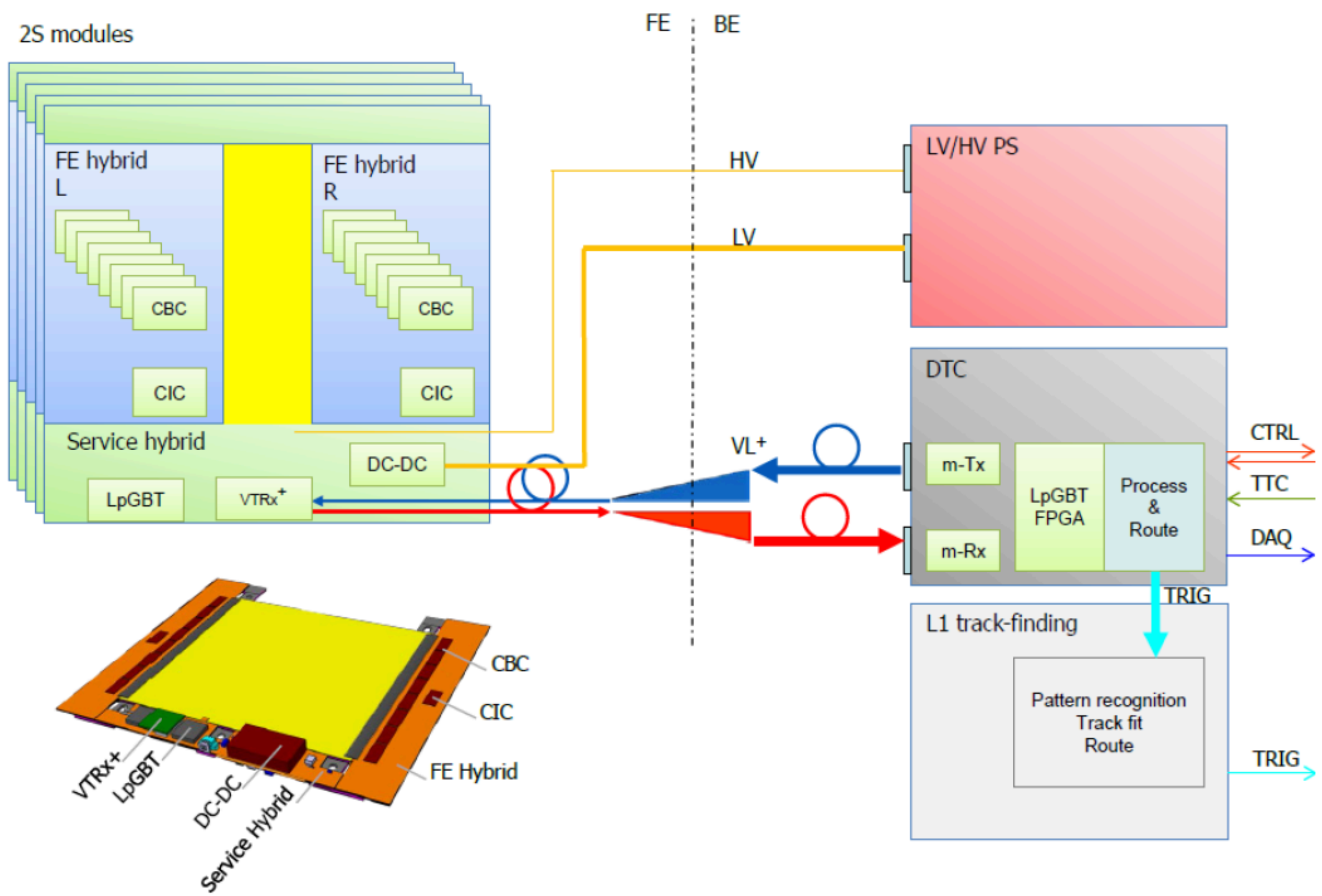
Measured Noise using different powering schemes



most recent version under development can read data from 1CBC/ 1CBC per side (full size module w/ 8CBCs)

Back-End Schematic

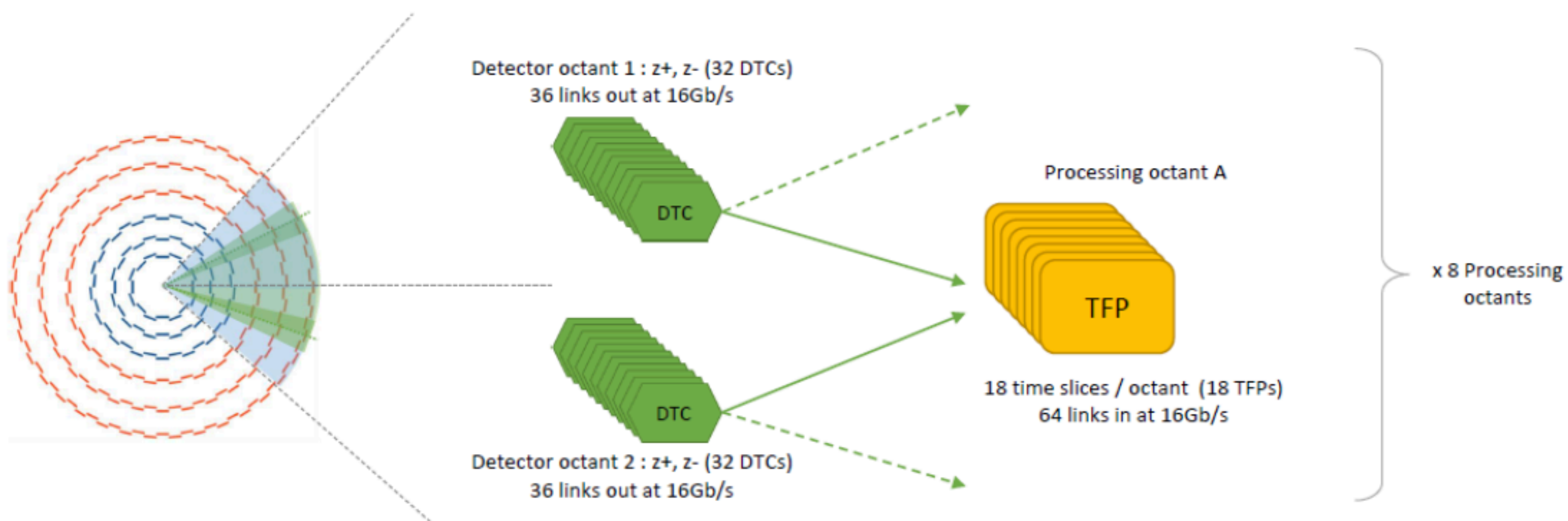
- Cartoon schematic of back-end for OT

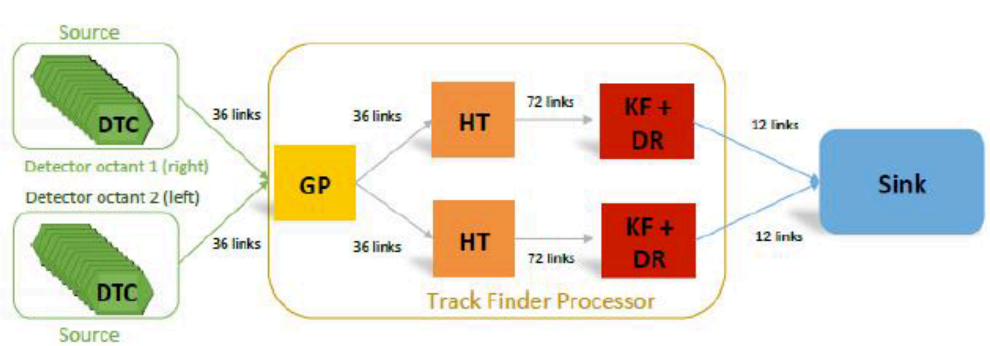


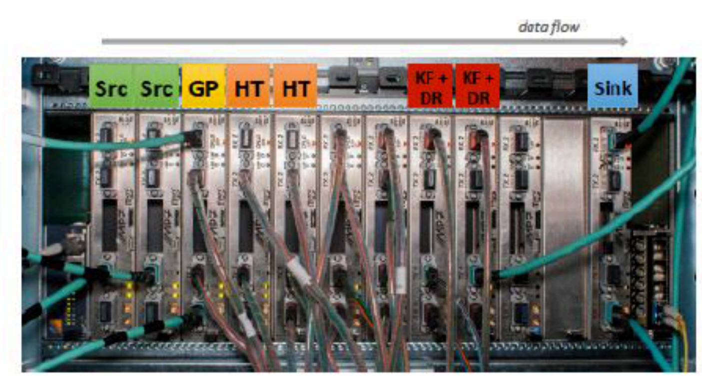
A. Dierlamm's "CMS Outer Tracker for HL-LHC" , HSTD11

L1 Track Finder : Demonstrators

- Parallel processing of geometric sectors and time slices
- Two base-line approaches using FPGAs both demonstrated latency [< 4 μs and good performance]
    - ***Hough Transform***
    - Tracklets







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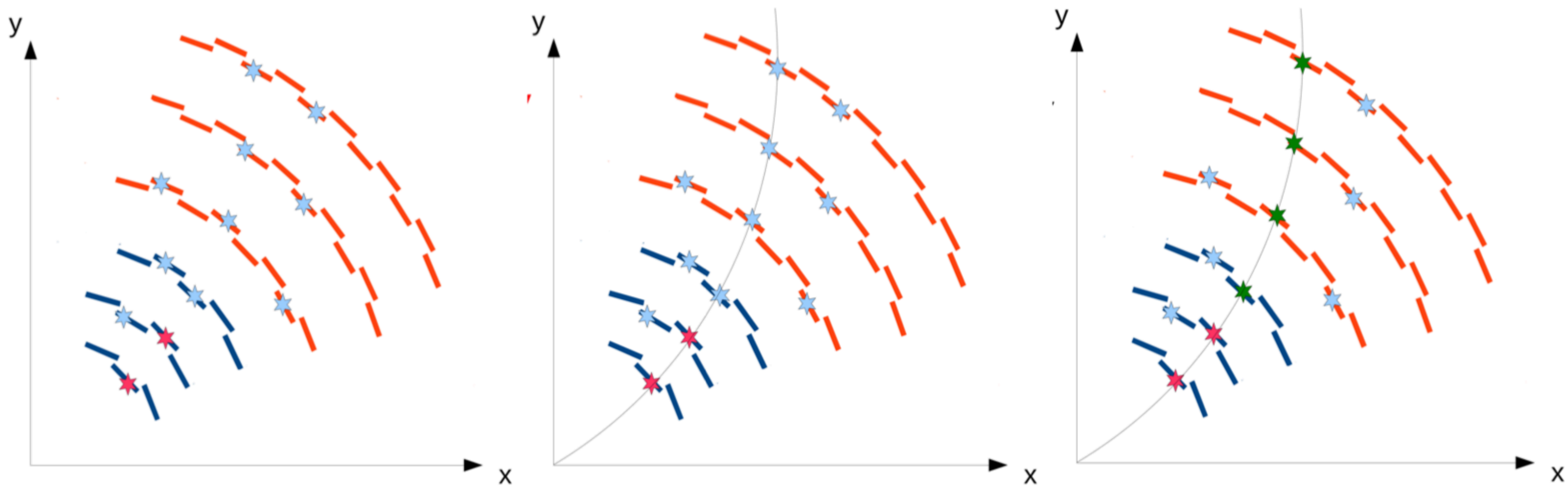


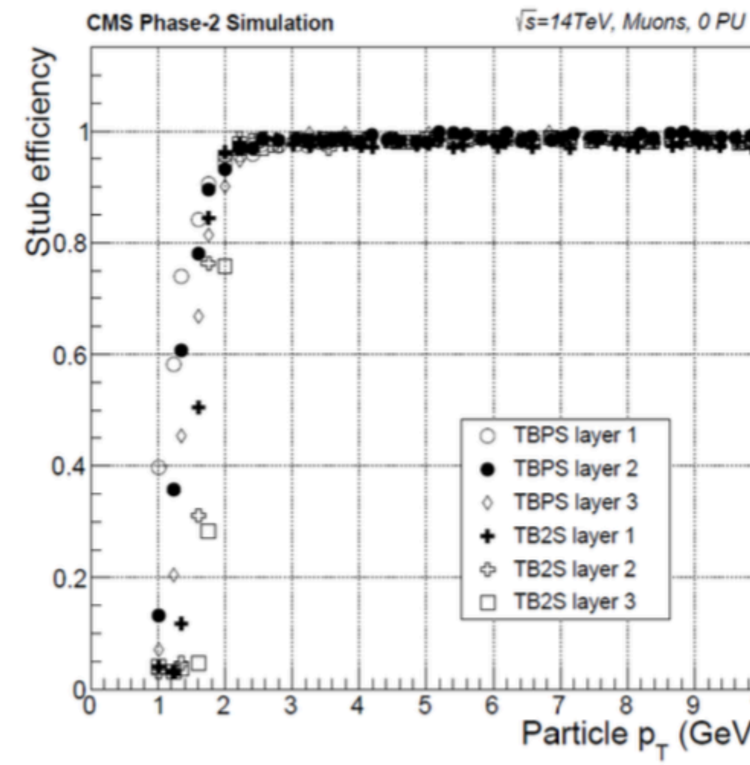
Figure 1: The steps of the tracklet algorithm are illustrated starting with a) where pairs of stubs in neighboring layers are combined to form the seeds, tracklets. In b) the tracklets are projected to the other layers and matching stubs are found. In the last step c) the matched hits are included in the final track fit.

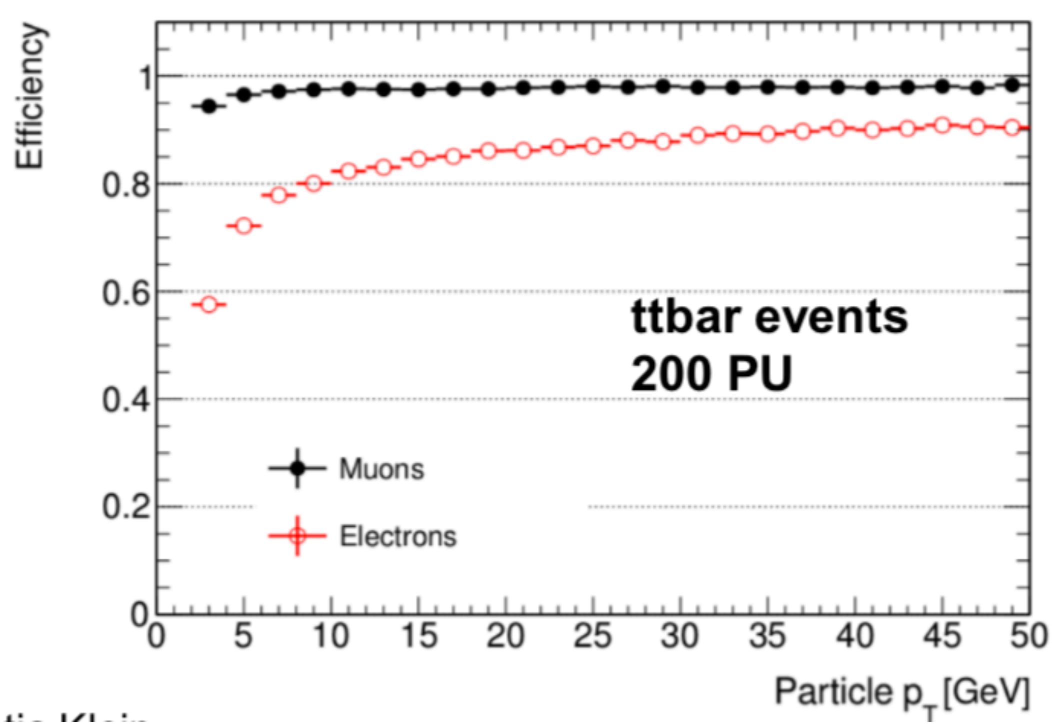
J. Chaves et. al : L1 Tracklet-Based Track Finding and Fitting

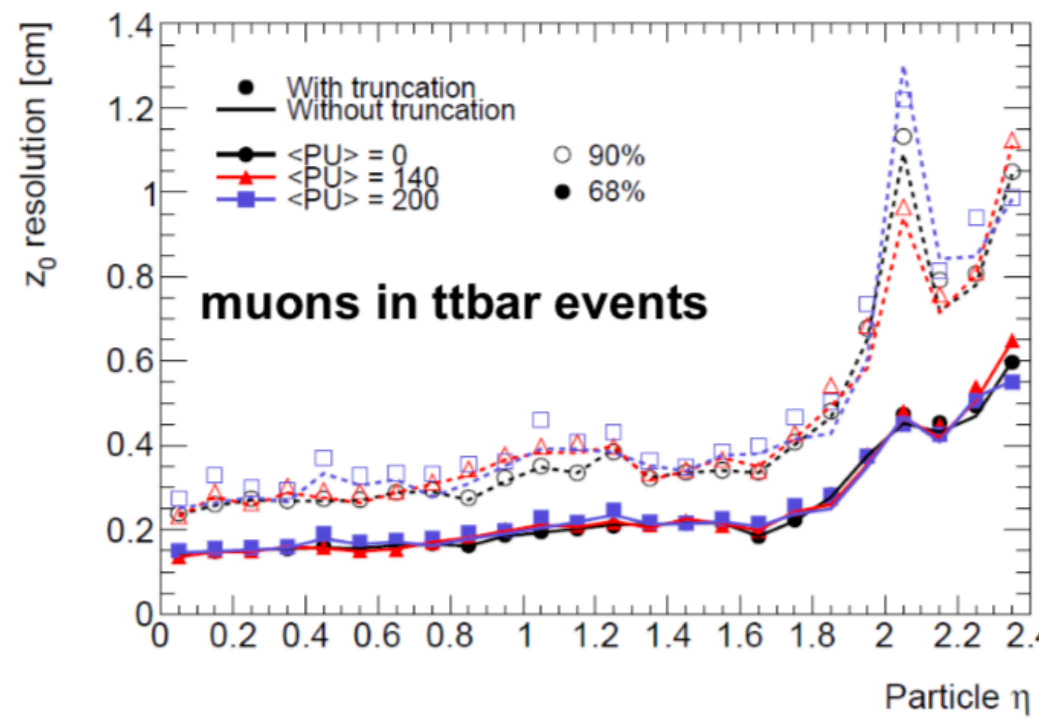
Stub Simulation & L1 Tracking

- Simulation of stubs
  - Sharp turn-on and high efficiency for muons
  - Significant margin in average stub rates

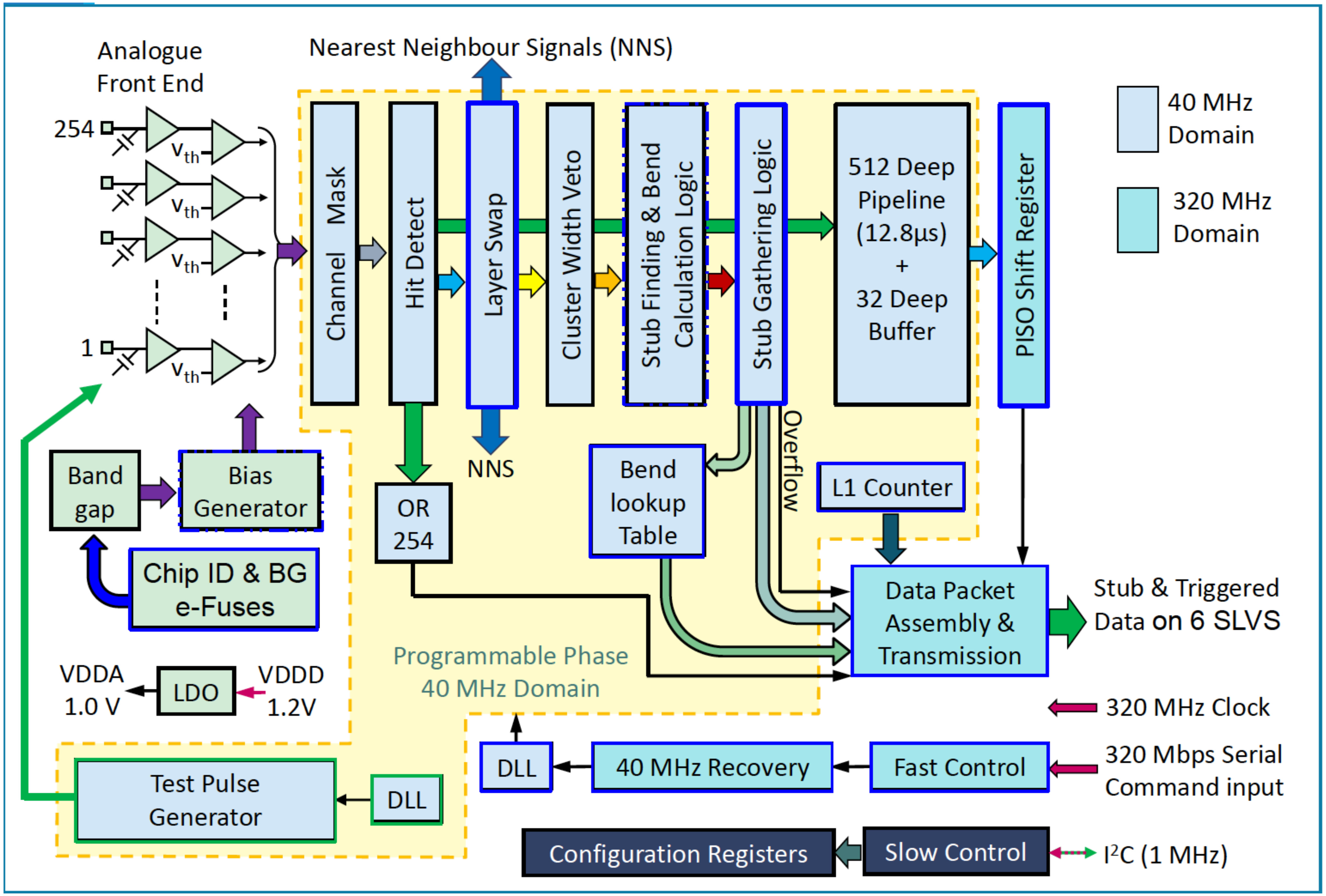
- L1 tracking performance studied with demonstrator systems
  - Sharp turn-on and high efficiency for muons
  - Decent performance also for electrons
  - Excellent resolutions, robust with respect to pileup





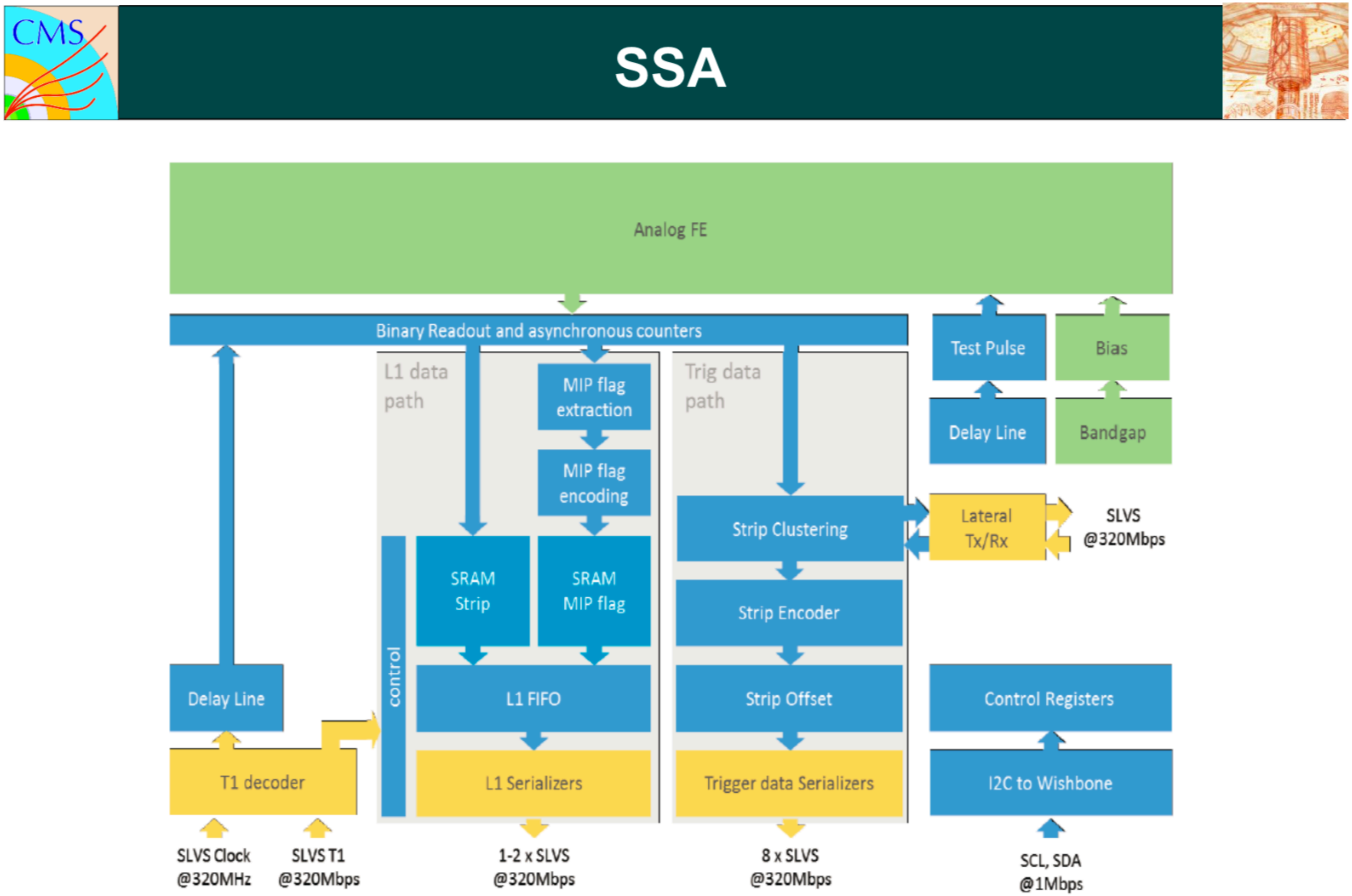


CBC3 Schematic



K. Urchida's "The CBC3 Readout ASIC For CMS 2S Modules"

SSA Schematic



MPA Schematic

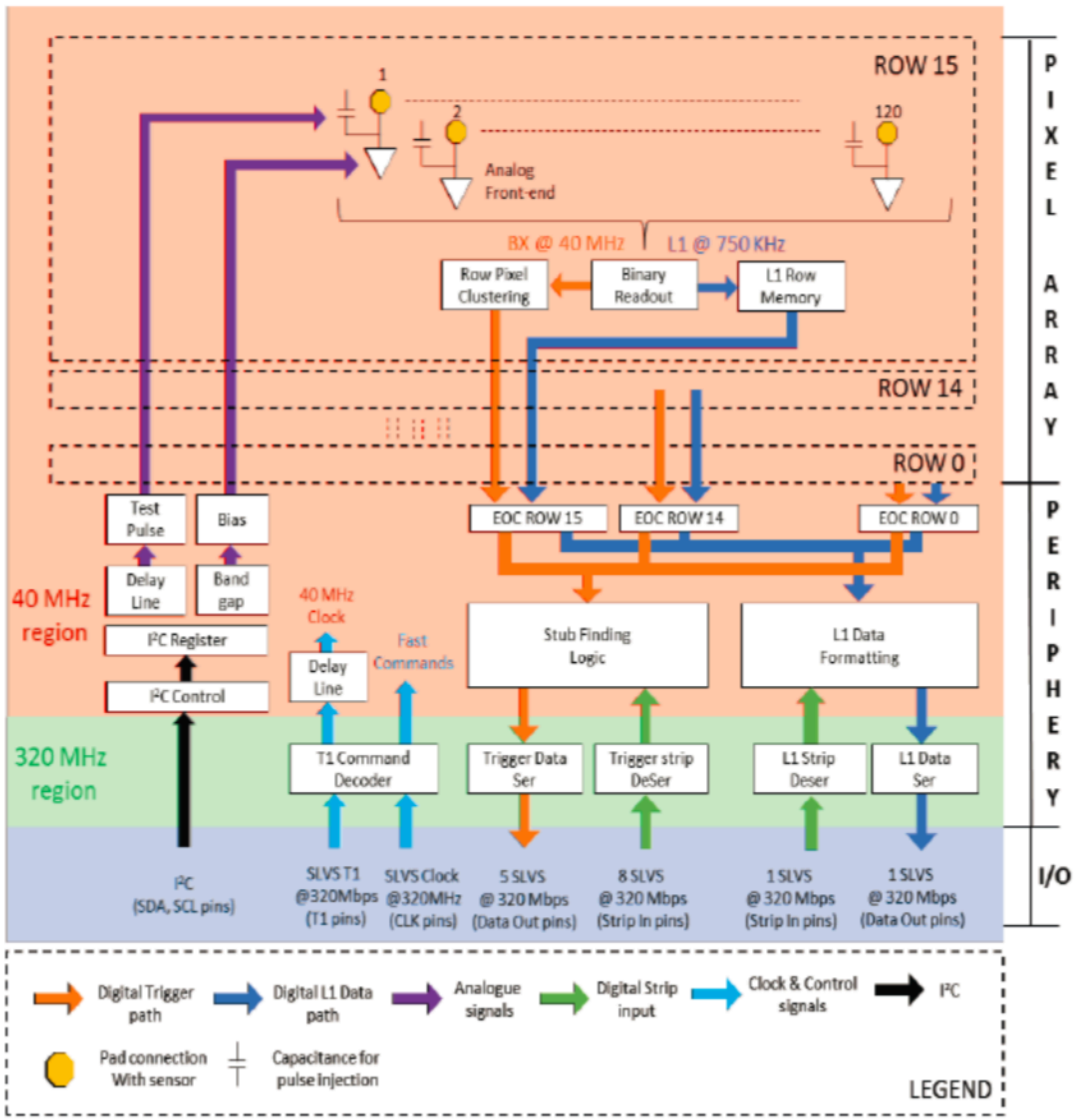
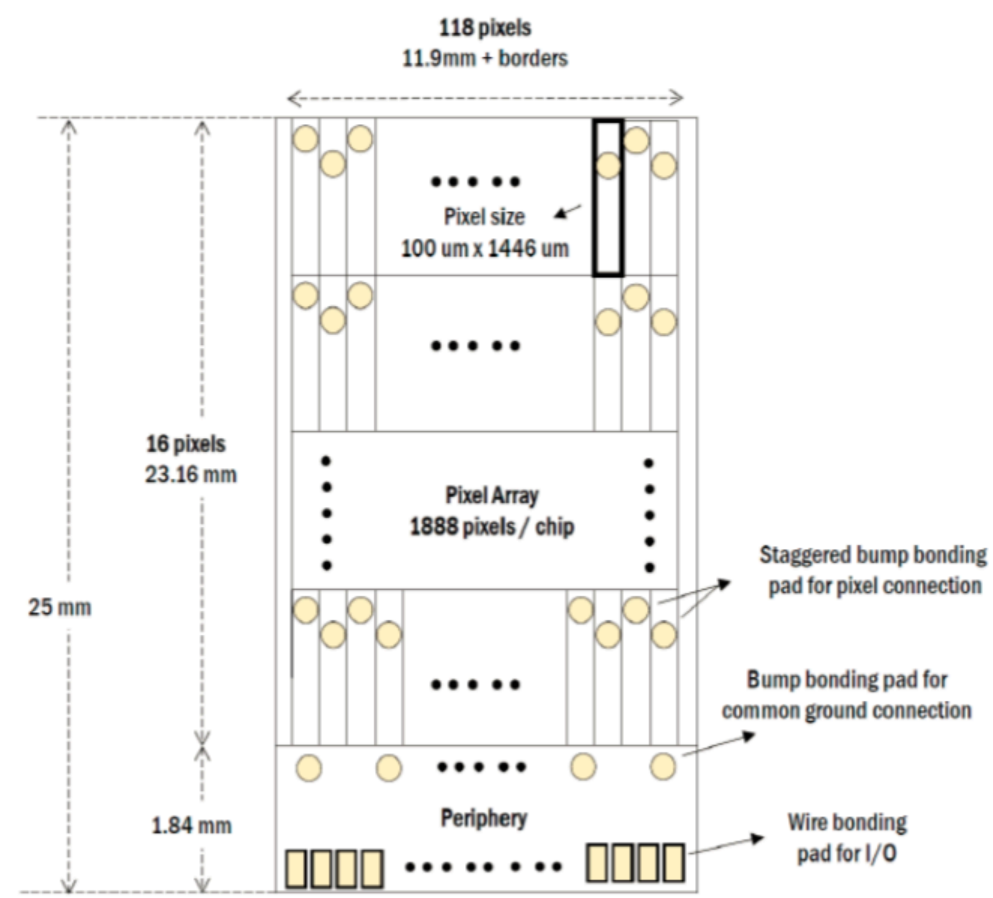
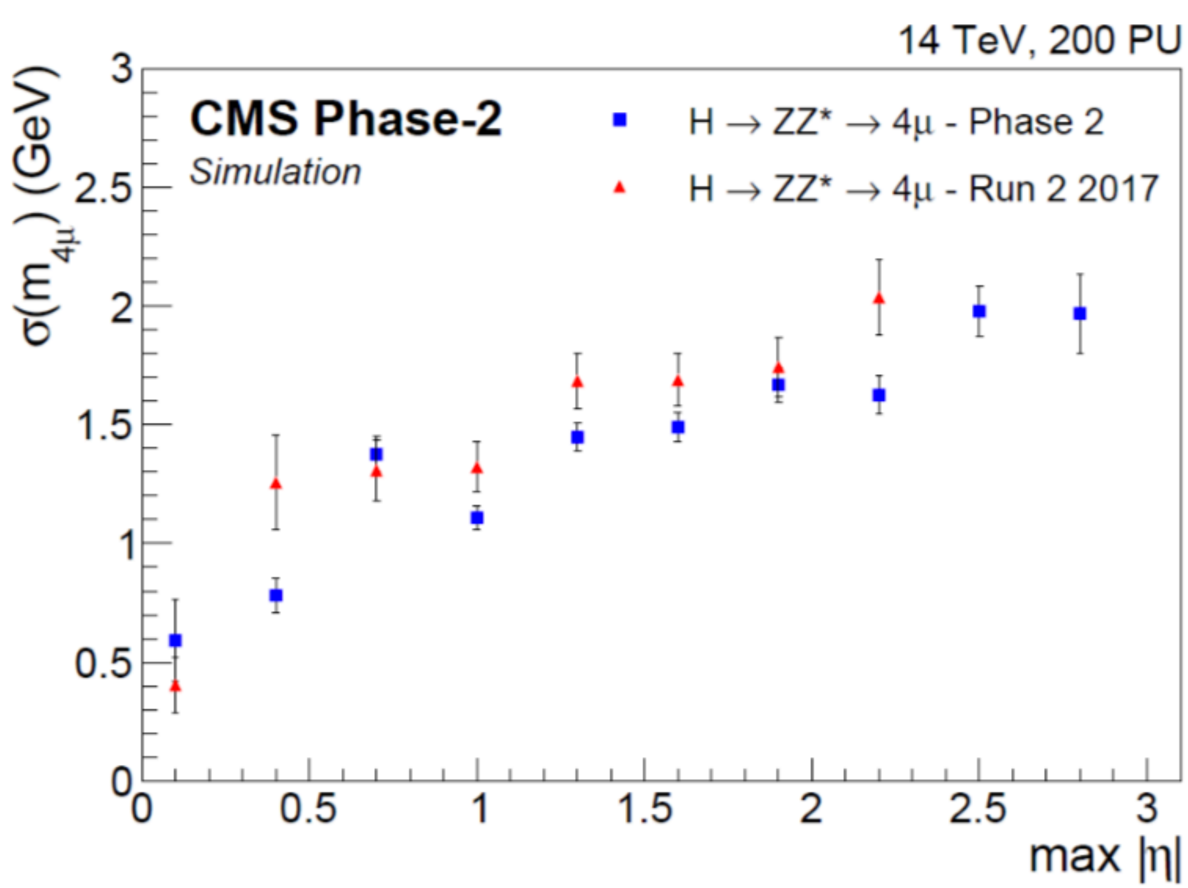


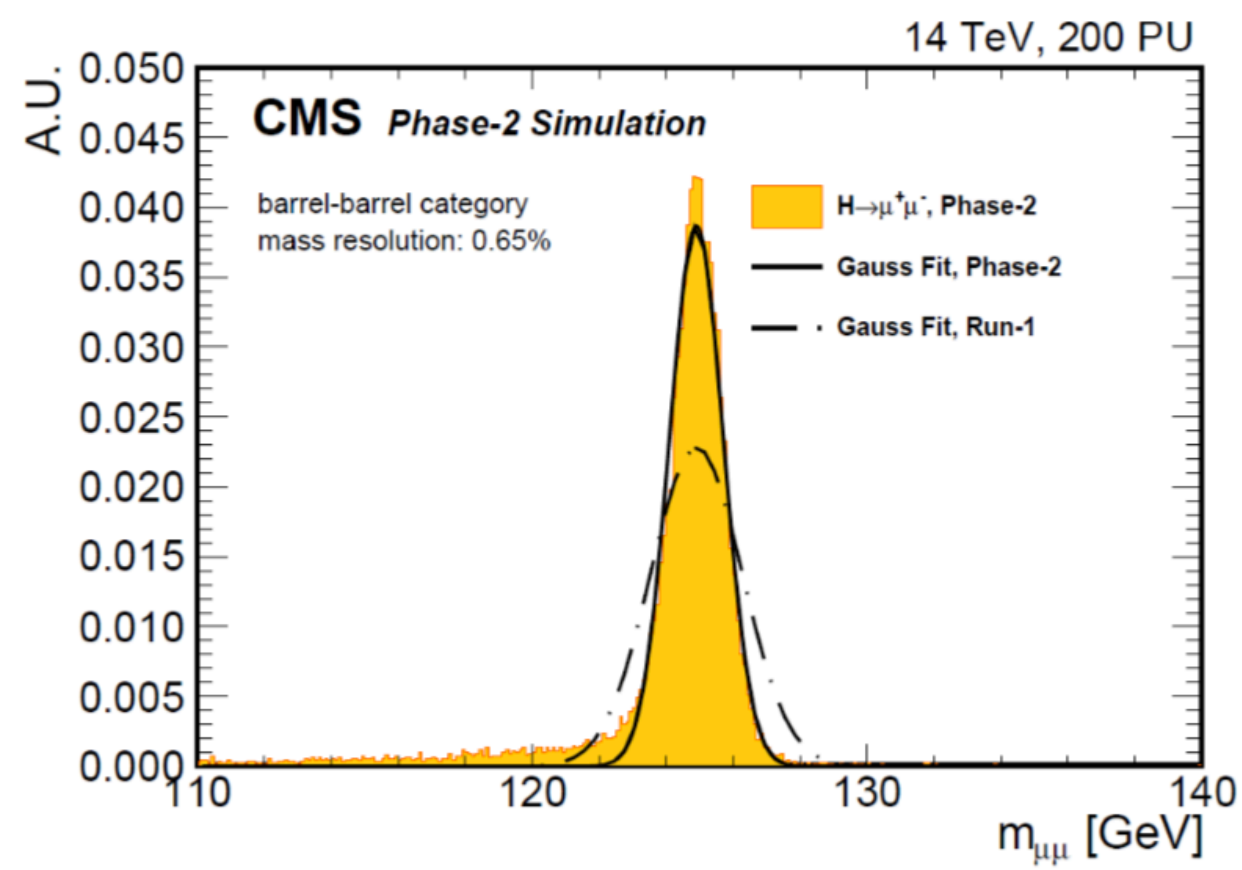
Figure 9.18: Block diagram of the MPA.



Physics Performance

- We demonstrate good performance for seven selected physics channels
- H → ZZ* → 4μ: excellent mass resolution for 200 PU up to eta ~ 3
- H → μμ: mass resolution improved significantly (spatial resolution, material budget)
- Heavy stable charged particles: analyses feasible inspite of binary readout in OT, by identifying highly ionizing particles with second threshold in the PS modules' SSA chip
- Top quark mass reconstruction from J/psi + l system (J/psi → μμ): improved mass resolution

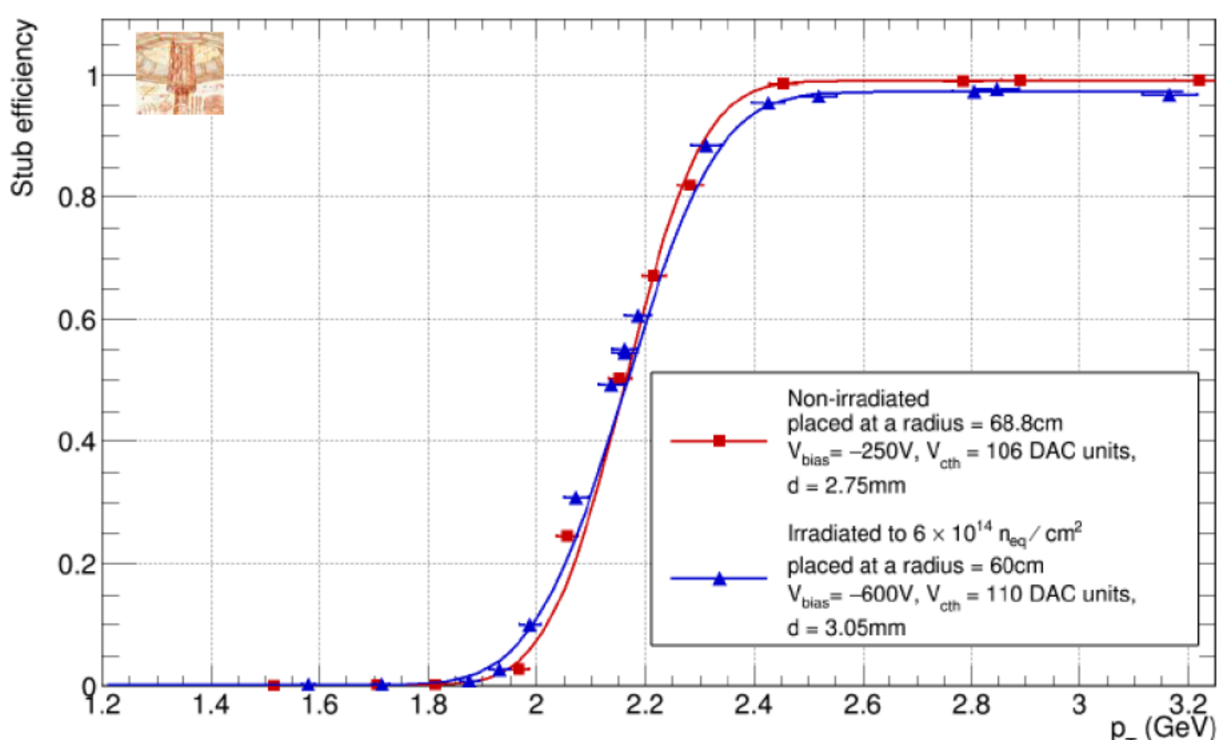




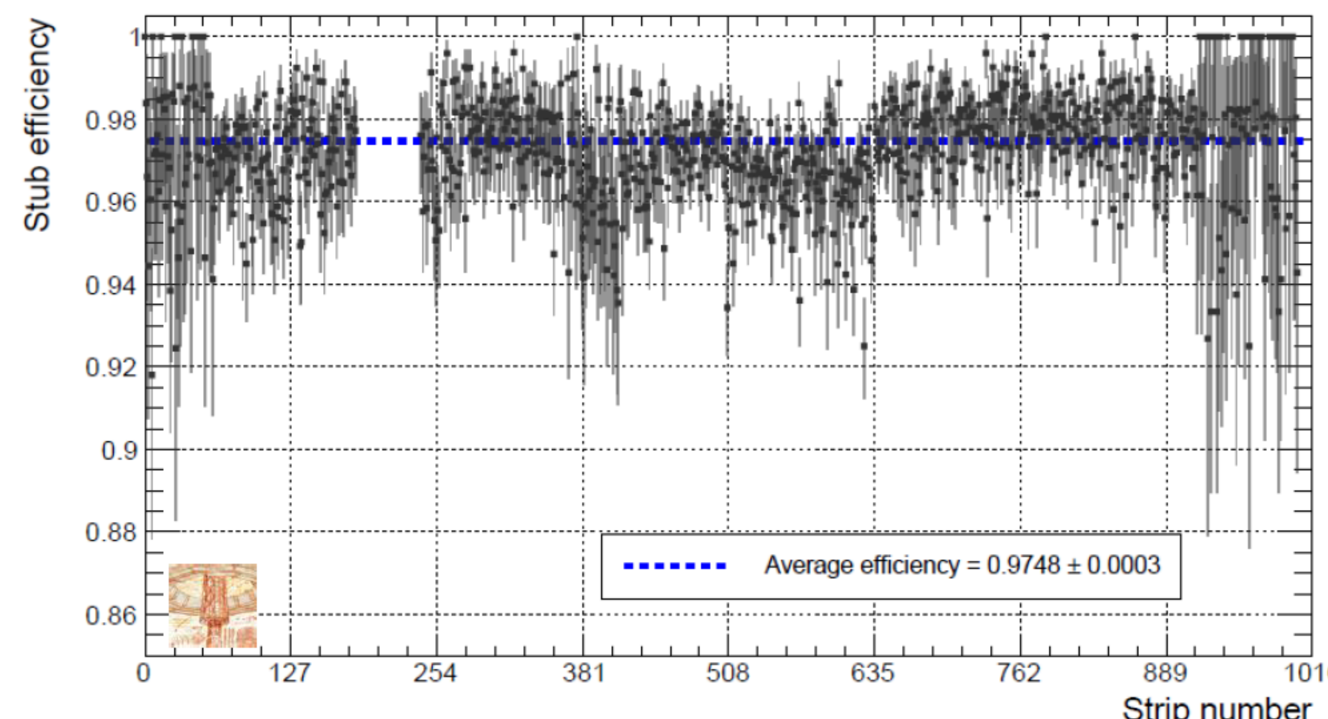
Prototyping 2S Module

CBC2 Read-out

- Full size 2S module operated in beam
  - uniformity of simple stub logic (yes/no) validated
  - response post-irradiation measured using a mini-module



Turn-on curves for irrad. and non-irrad. mini-modules



Uniformity of stub efficiency

A. Dierlamm's "CMS Outer Tracker for HL-LHC" , HSTD11