International meeting on

"Tracking detectors for particle colliders - present and future"

Tracking detectors for CMS upgrade

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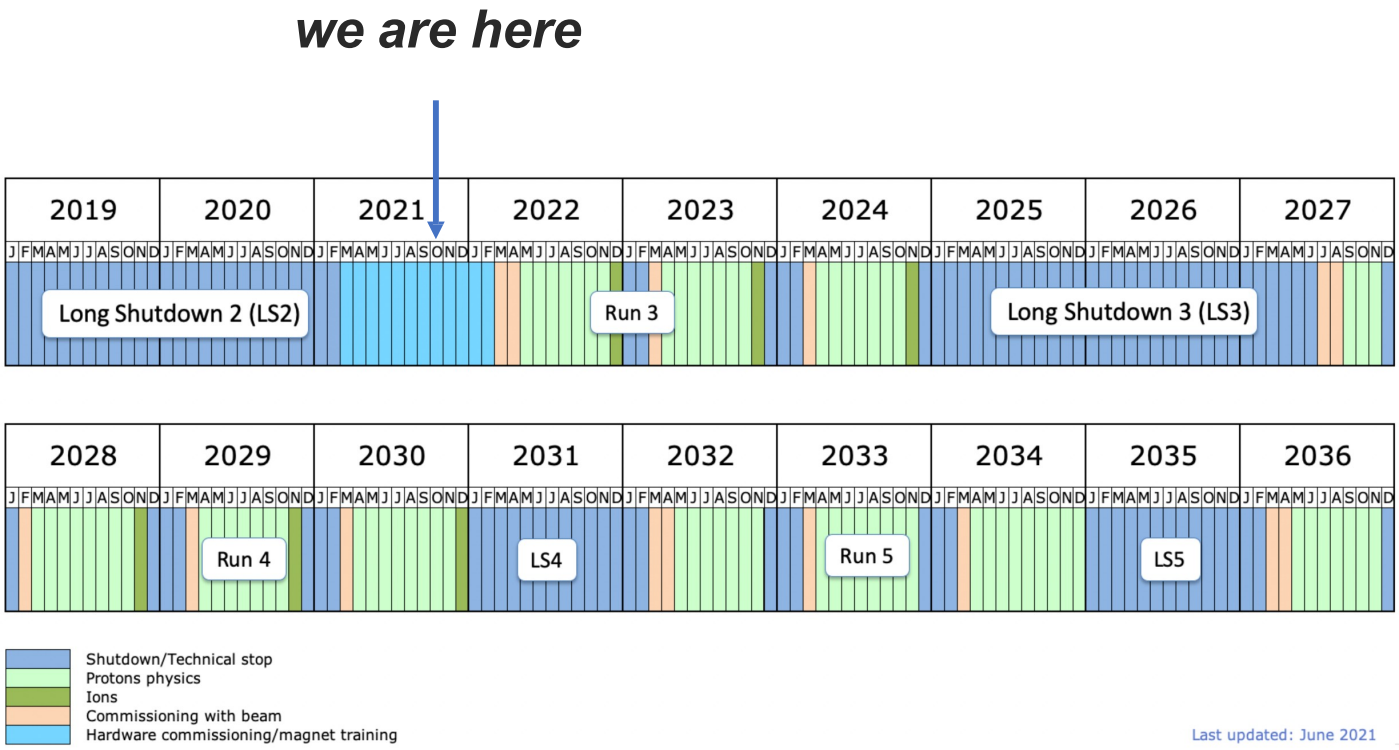
Foreword

- The potential for new physics in running the LHC without a significant luminosity increase may be negligible.
- The run time necessary to reduce the statistical error in the measurements will be more than 10 years.
- LHC need to have a decisive increase on its luminosity in the coming years.
- The CMS detector will be upgraded to maintain the high level of performance for better precision and improved physics output required for upcoming discoveries.



CMS in the High-Luminosity LHC Era

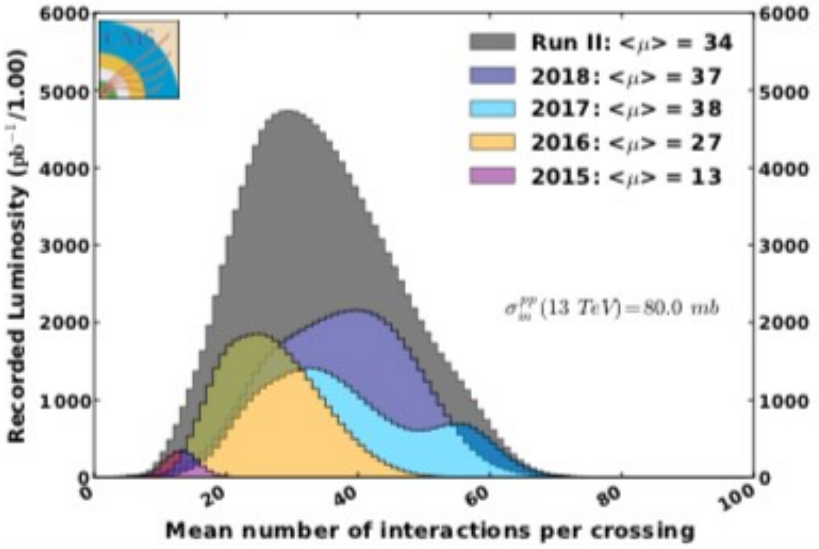
Running conditions for LHC to HL-LHC

- Pileup (PU) would be enormous (30 →200)
- Increase in Hit rate from 0.58 to 3.2 GHz/cm^2
- Radiation: shall be efficient up to ~ 4000 fb^{-1}

forces stringent requirements on the tracking detectors of the CMS, such as

- Maintaining detectors performance high in terms of
  - Efficiency
  - Resolution
  - Background rejection
- High pileup (~ 200) scenario demands
  - Improved granularity e.g. 1200 tracks / unit of eta (at or below the percent level)
- High integrated luminosity (radiation)
  - Replacement of Tracker and Endcap Calorimeter
- Reduced material budget for improving tracking performance
- Huge amount of data (computing and storage)
  - Overhauled Trigger and DAQ systems

CMS Average Pileup (pp, $\sqrt{s}$=13 TeV)



Upgrade of the CMS Si Tracker

New silicon tracker would be installed in LS3 (2025-2027)

- Outer Tracker (OT) replaces legacy silicon strip tracker
- Inner Tracker (IT) replaces legacy silicon pixel detector

Design goals

- Tracker operate efficiently and withstand HL-LHC luminosity
- Compatibility to deal with higher data rates expected for an instantaneous luminosity of $7.5 \times 10^{34} cm^{-2} s^{-1}$
  - Improved two-track separation, to resolve tracks in high-pT jets
- Trigger latency (3.2 μs →12.5 μs)
- Increased radiation-hardness
- Higher granularity, low material budget
- Increased forward acceptance for Inner Tracker, up to $|\eta| = 4$
- Tight FE power requirements:

  8 W (+ 1.4 W Sensor) for the PS module, 5 W (+ 1 W Sensor) for the 2S module
- Contribution of Outer Tracker to Level-1 trigger, < 750 KHz

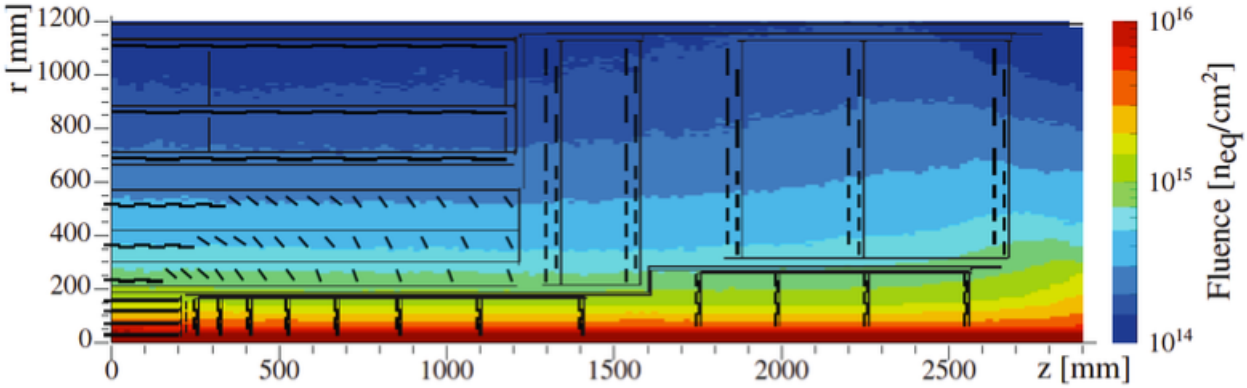
Radiation Environment

Innermost layer: 1.9x10^{16} n_{eq}/cm^2

upto LS5

Service cylinder: 1.8x10^{15} n_{eq}/cm^2

Full HiLumi Program

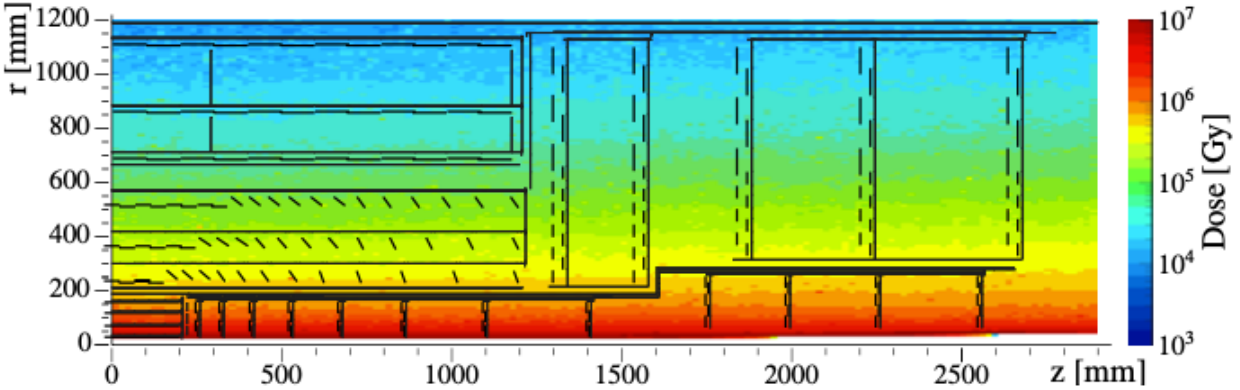


Innermost layer: 1.0 Grad

upto LS5

Outer & Service cylinder: 220 Mrad

full HiLumi program



Fluence (1-MeV neutron equivalent)
& **Total Ionizing Dose (TID)** maps

Ultimate luminosity scenario for HL-LHC (4000 fb-1)

	LHC run 4+5		LHC run 4+5+6	
	1e16 n_{eq}/cm^2	Grad	1e16 n_{eq}/cm^2	Grad
TBPX L1	1.88	1.03	3.51	1.91
TFPX R1	1.25	0.81	2.34	1.50

Out of reach scenario, Irrespective of Sensor Technology

1 Gy =100 rads

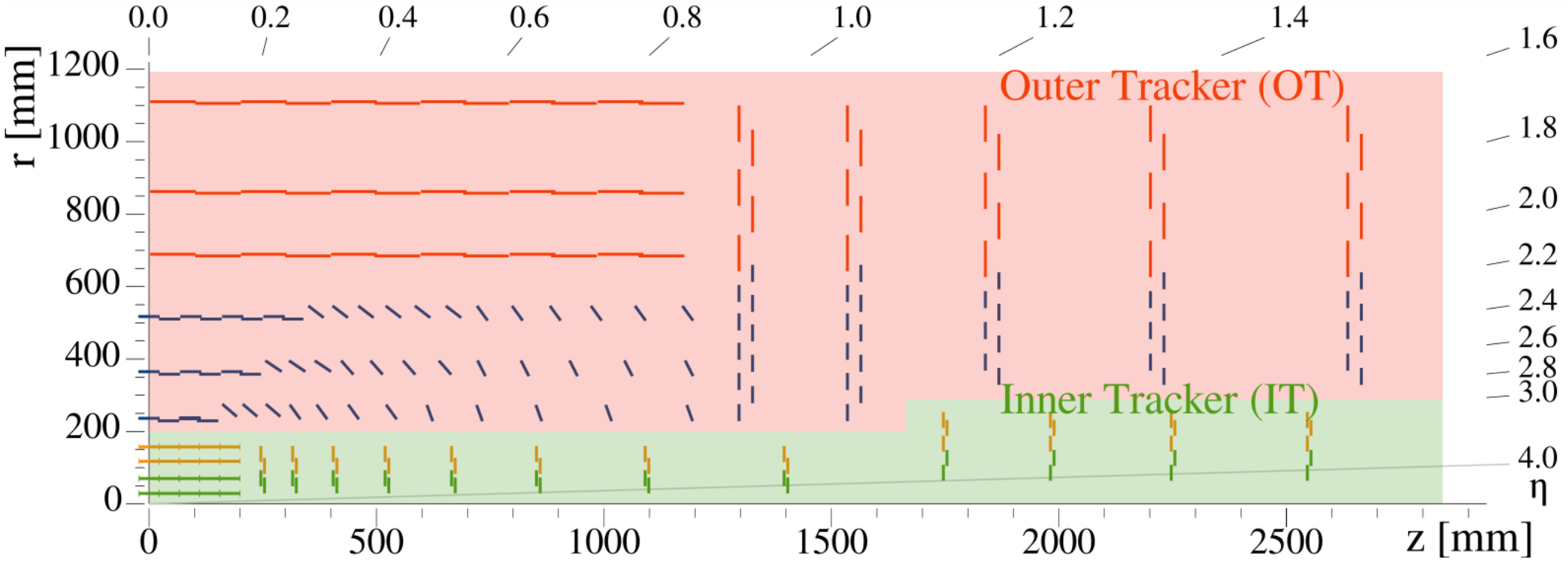
Layout of Si Tracker upgrade

Inner Tracker: 4 barrel layers, 8 small disks, 4 large discs per side

Pixel size options: 50 x 50 μm^2 ,25 x 100 μm^2

Outer Tracker: 6 barrel layers, 5 discs per side

9.5 million channels, 44M strips + 174M macropixels



1/4th of total tracker

Track Trigger

- CMS uses a 2-level trigger system:
  L1 (Hardware) trigger and High Level Trigger (HLT)

- Presently only muon & calorimeter contributes in L1 trigger
  Tracker used at the HLT

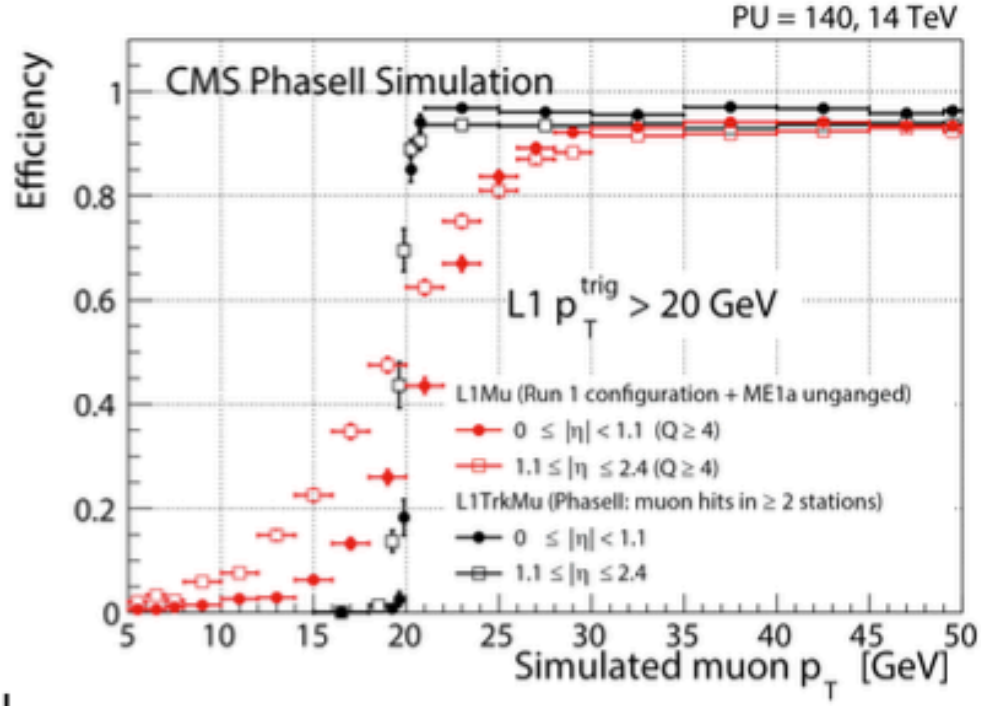
- L1 Trigger Challenges:
  High rates, high pileup environment,
  Selection algorithms become inefficient

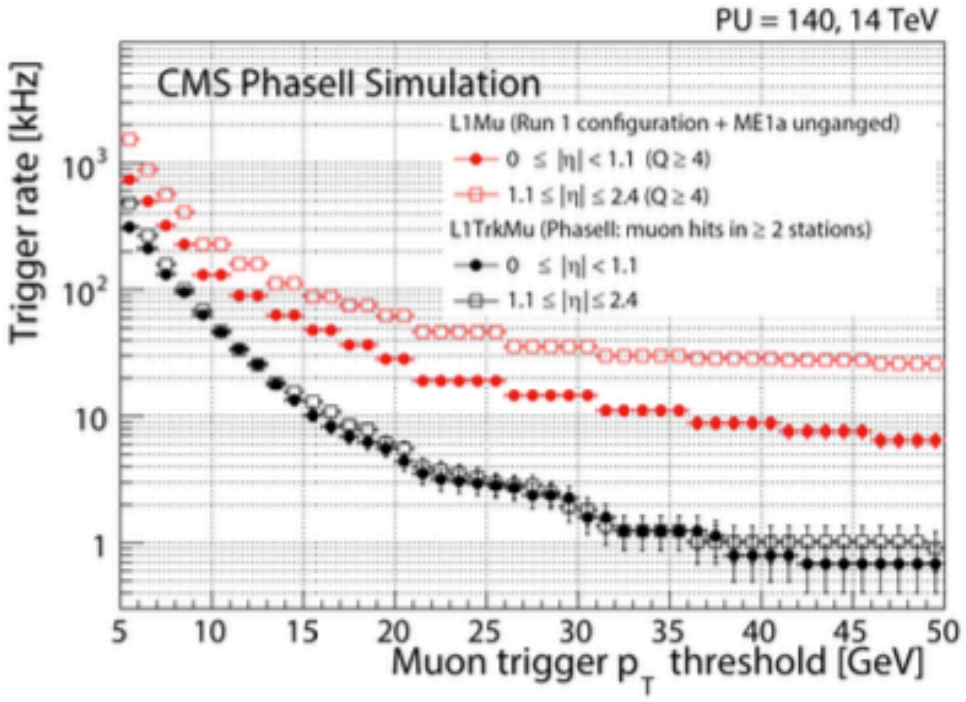
  Improved L1 trigger rate: 750 kHz, L1 trigger latency: 12.5 μs

- For reducing trigger rates→increase momentum/energy thresholds:
  - This can obviously hurt physics potential
  - Insufficient at HL-LHC rates
  - Without tracking, L1 output would be ~4000 kHz at 200 PU

Track Trigger

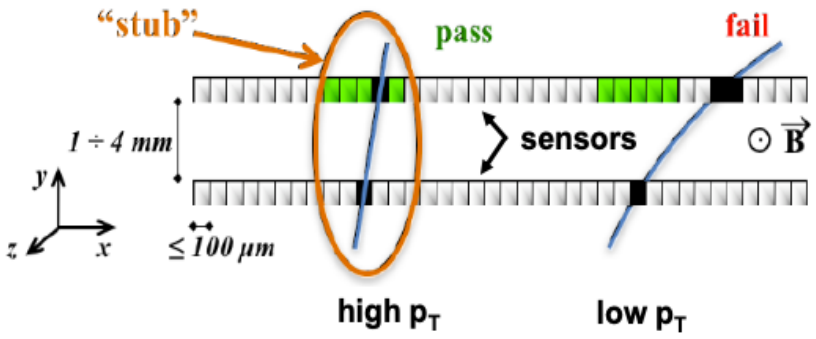
- The use of tracker in L1 trigger
  - A powerful alternative
  - Allow the exploitation of information on track
  - Improve the p_T resolution of various objects at L1 (e.g. jets, muons)
  - Better e/γ/τ identification
  - Contribute to the mitigation of pileup

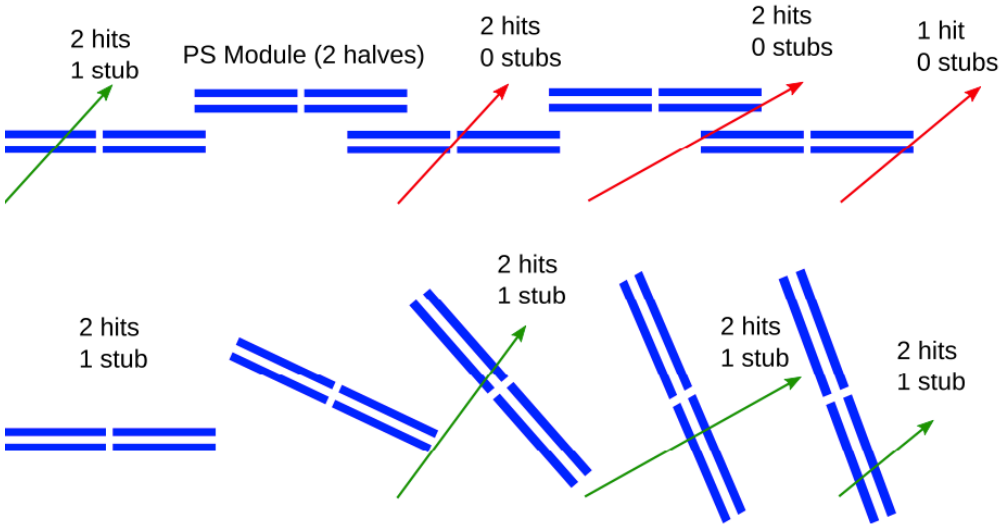


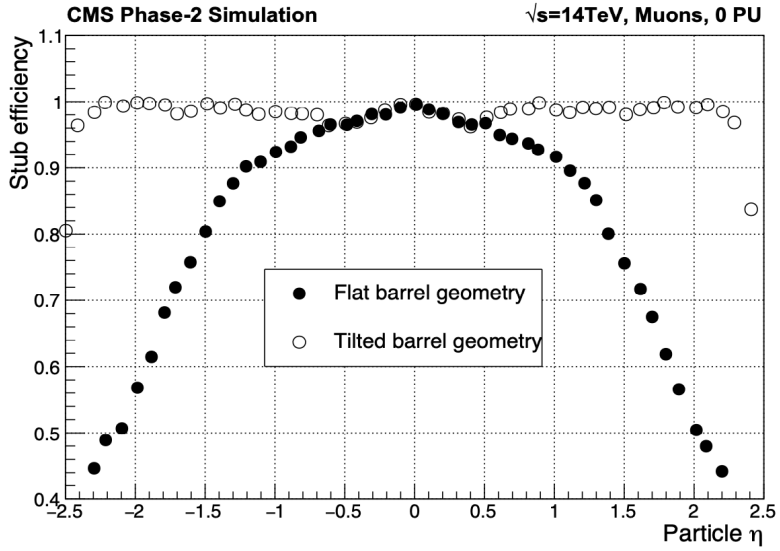


Design Concept

- L1 trigger is one of the main motivation for the OT Design
  - Impossible to transfer all data off-detector for decision logic at BC rate
- A reduction of data on the module itself is required
  → Exploits p_T dependent bending of tracks in B
- Compare pattern of hits in contiguous sensor elements → Each module has 2 sensor planes
  → Select Hit Pairs → STUBS
- Primarily depends on separation
  - Increasing separation worsens fake combinations
- p_T > 2 GeV → a data volume reduction of roughly one order of magnitude
- Stub efficiency is reduced for high η in flat barrel geometry due to impossibility to correlate hits between left half of lower and right half of upper sensor → motivation for tilted TBPS

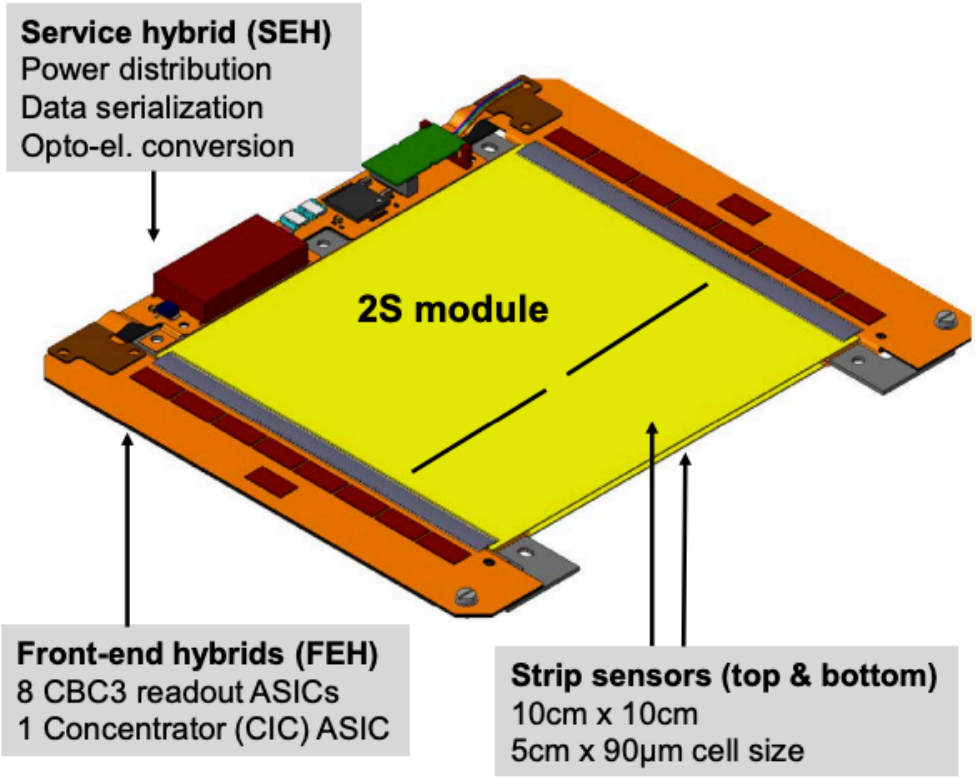


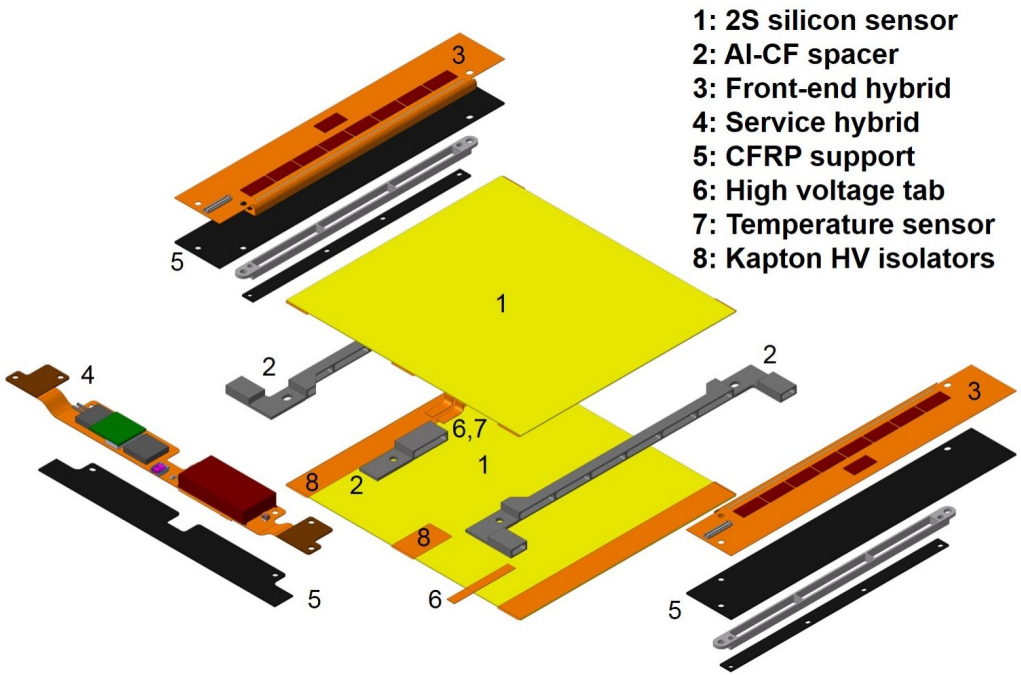




2S Module

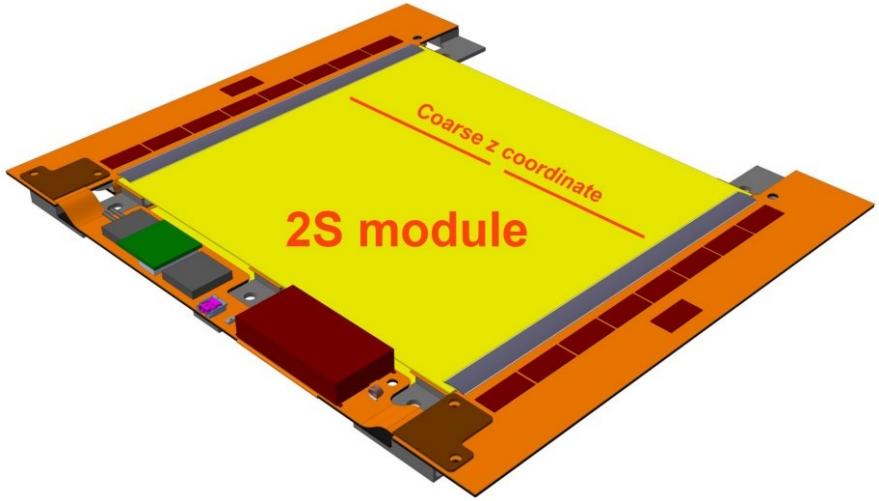
- Electrically, the basic building block is the module – no common service boards
- Each module contain
  - Front-end hybrids (FEH): readout and concentrator ASICs
  - Service hybrids (SEH): power and opt. comm.
  - AlCF-bridges: high thermal conductivity and similar CTE as silicon
  - HV isolation and HV connection





2S Module

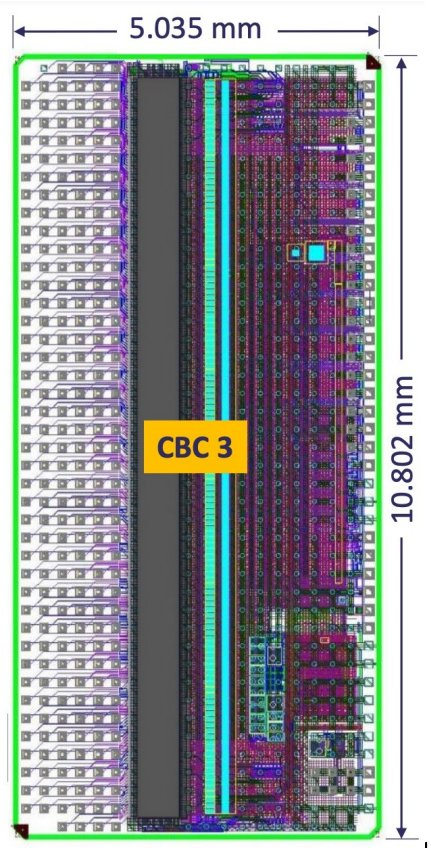
- Strip-Strip layout
- 2×1016 strips ~ $5\ \mathrm{cm} \times 90\ \mu\mathrm{m}$ per side
- $90\ \mathrm{cm}^2$ active area
- In region $60 < r < 120\mathrm{cm}$
- Spacing $1.8\ \mathrm{mm}$ and $4.0\ \mathrm{mm}$



2S ROC

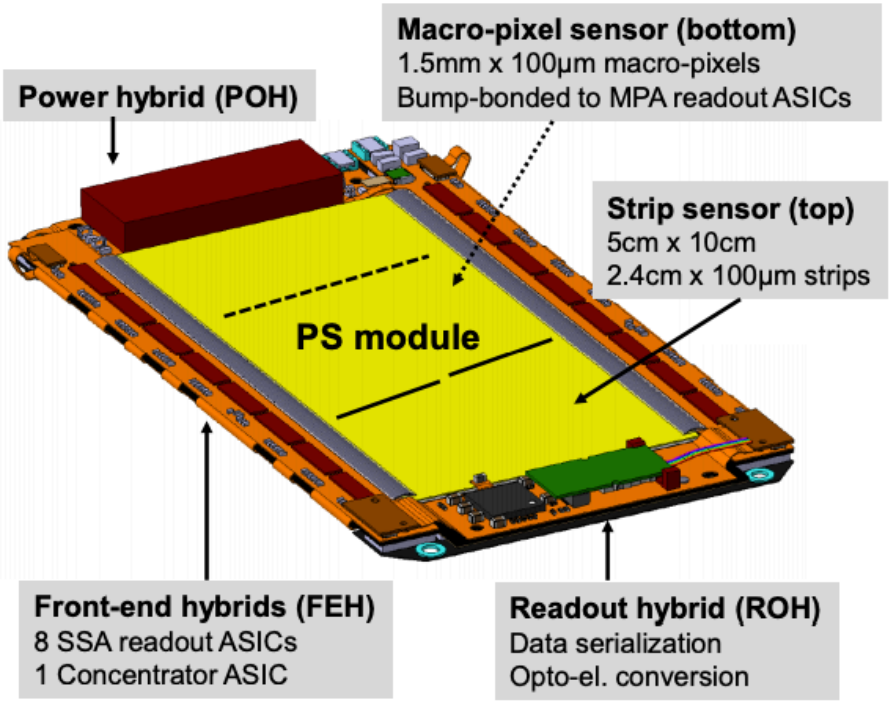
- CMS Binary Chip (CBC) ASIC
  130 nm CMOS, 254 strips (127 from top+bottom sensor)
- Bump bonded to hybrid, hybrid wire bonded to strip sensor
- Input hit array from both sensor planes

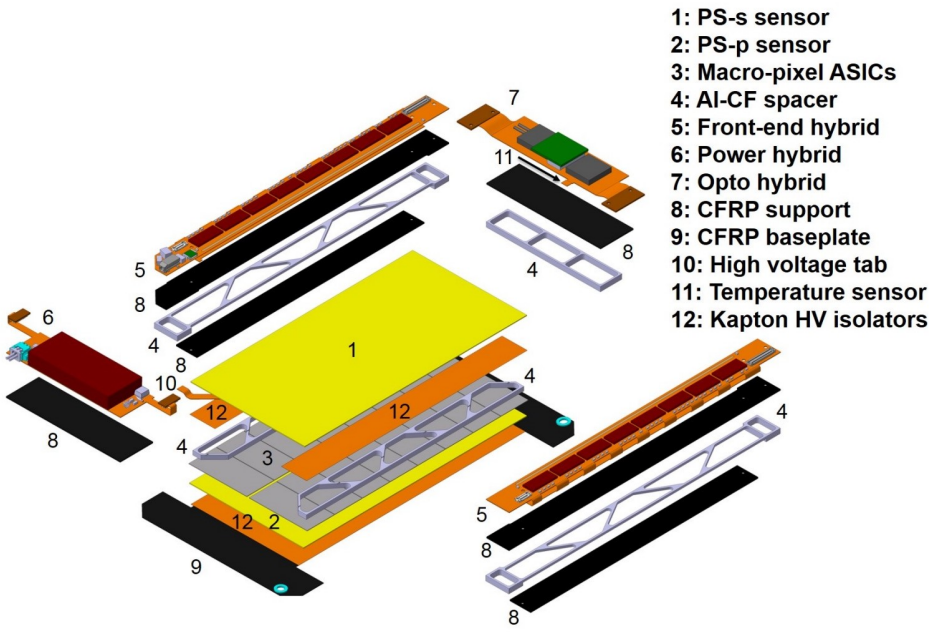
  Cluster and correlate to create stubs.
- Two data formats passed to 65 nm Concentrator Integrated Circuit (CIC)
  - L1 hits – Send full event clusters along single SLVS line
    Cluster = x centroid, width
  - Stubs – Send stub info along 5 SLVS lines
    Stub = x centroid, bend



PS Module

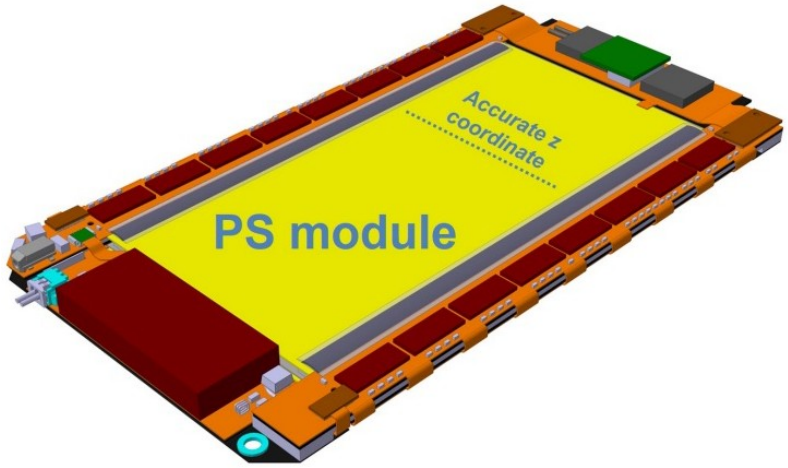
- Electrically, the basic building block is the module – no common service boards
- Each module is connected with 3 wires and 2 fibers directly to the back-end





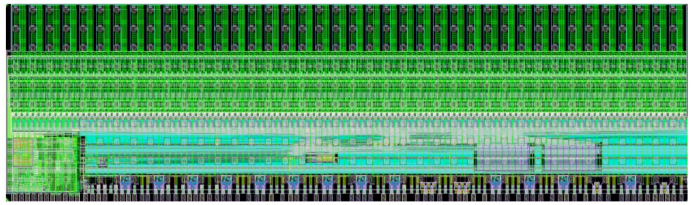
PS Module

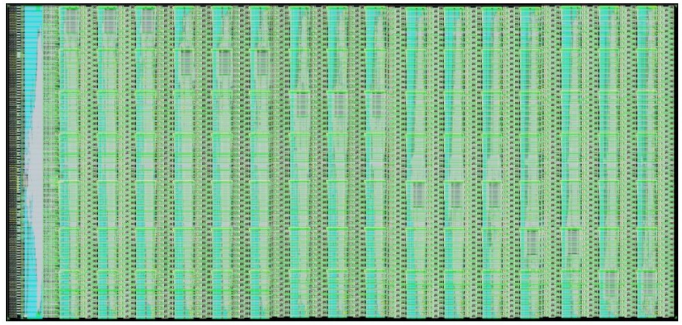
- Pixel-Strip layout
- 2×960 Strips ~ 2.5 cm $\times$ 100 μm
- 32×960 macro-pixels ~ 1.5mm $\times$ 100 μm
- 45 cm^2 active area
- In region $20 < r < 60$ cm
- Spacing 1.6 mm, 2.6 mm and 4.0 mm



PS ROC

- 65 nm CMOS Short-Strip ASIC (SSA) - 120 strips (100 μm)
- Bump bonded to hybrid, hybrid wire bonded to strip sensor
- Two data formats passed to MPA
  - L1 hits – Send full event clusters along single SLVS line
  - Stub preliminary – Send strip centroids along 8 SLVS lines
- 65 nm Macro-Pixel ASIC (MPA) - 120 x 16 pixels (100 μm x 1446 μm)
- Bump bonded to pixel sensor, wire bonded to hybrid
- Perform clustering and stub association using data passed along stub lines

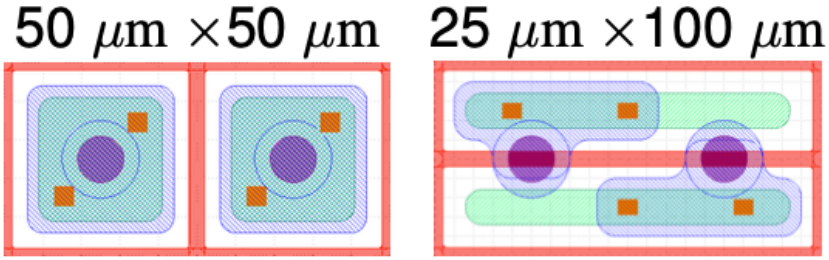




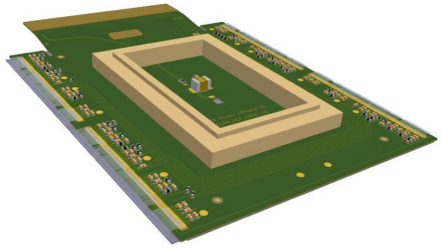
Inner (Pixel) Tracker

- Reduction in pixel area by factor of 6 compared to earlier CMS Pixel Detectors →enabling low occupancy and improved two track separation

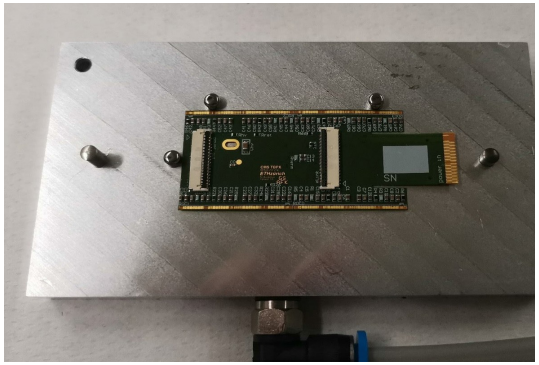
- n in p type Si sensors of thickness 150 μm thickness segmented into pixel sizes of 25 x 100 μm^2 (long side along z in barrel and along r in endcaps) or 50 x 50 μm^2 for better resolution



Two options



TEPX

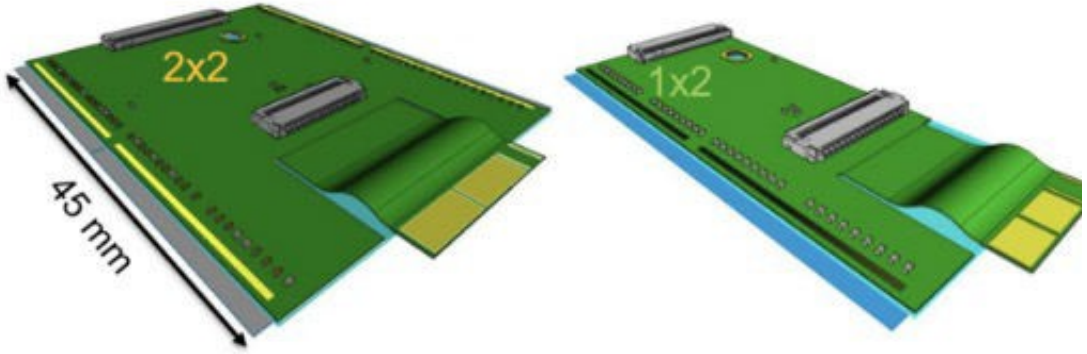


TBPX

- TBPX : 4 Barrel cylindrical layers (2.9 cm, 7 cm, 11.8 cm,15.7 cm)
- TFPX : 8 small Double Discs at each end (25 cm, 32 cm, 41 cm, 52 cm, 67 cm, 85 cm,110 cm, 140cm)
- TEPX : 4 large Double Discs at each end (175 cm, 198.5 cm, 225 cm, 255 cm)

- 1 x 2 modules (with 2 chips) in inner 2 layers of TBPX and inner 2 rings of TFPX and TEPX.

- 2 x 2 modules (with 4 chips) in outer 2 layers of TBPX and outer 2 and 3 rings of TFPX and TEPX



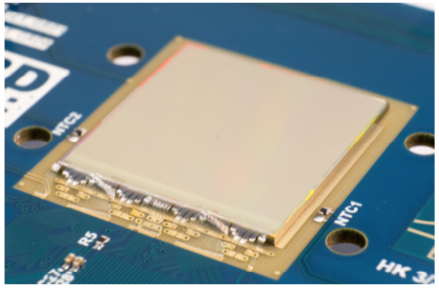
TEPX Disk 4 Ring 1 is dedicated to lumi measurements, independent readout and control

Inner (Pixel) Tracker Electronics

Occupancy < 0.1%

65 nm C-ROC developed as variant of the RD53B chip

- Linear front-end, 432 x 336 pixel array
- Binary readout plus time-over-threshold and serial powering features.
- Preliminary versions tested up to 1 Grad (high dose rate)

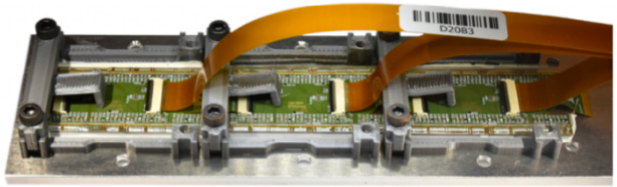


RD53B on single-chip test card

Serial powering up to 12 modules / chain

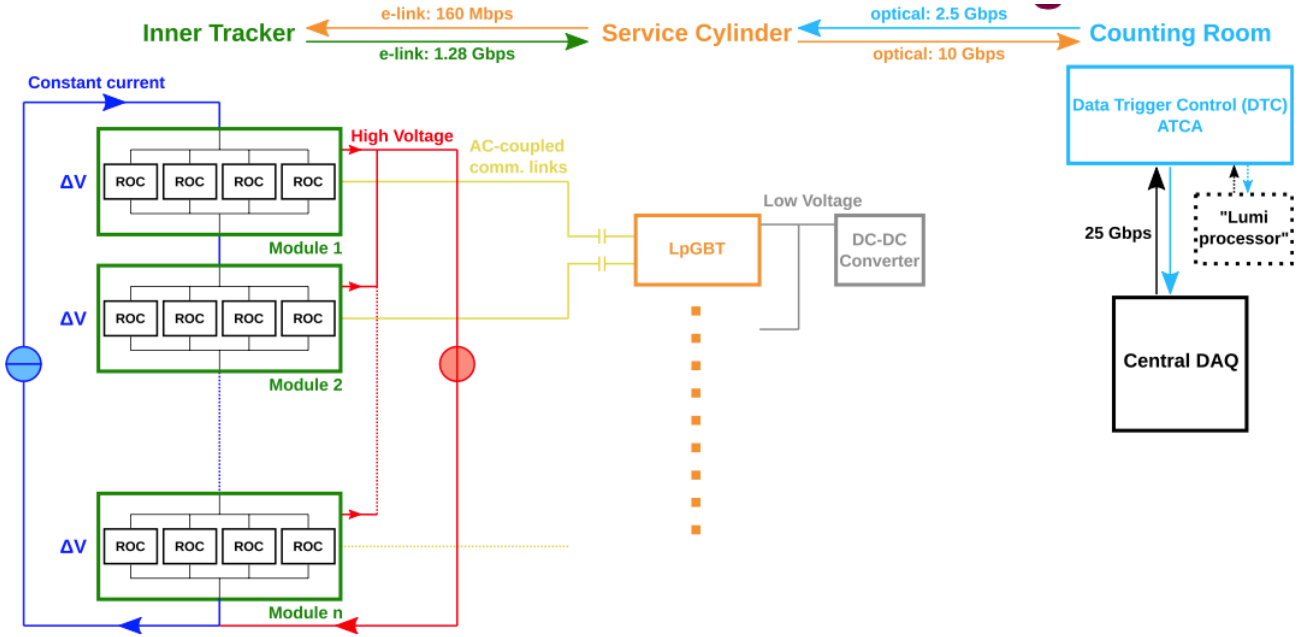
- ROCs share constant input current
- Generate the necessary operational voltage

Serial powered chain of 2x2 digital modules



Modules connected with up to 1.6m electrical links to port cards at periphery

- ~ 6 electrical up-links @1.28 Gb/s per module to LpGBT
- 1 electrical down-link @160 Mb/s per module from LpGBT
- ~ 6 e-links at 1.28Gb/s per LpGBT (AC-coupled)
- 28 DTC (Data, Trigger, Control) boards required for CMS IT

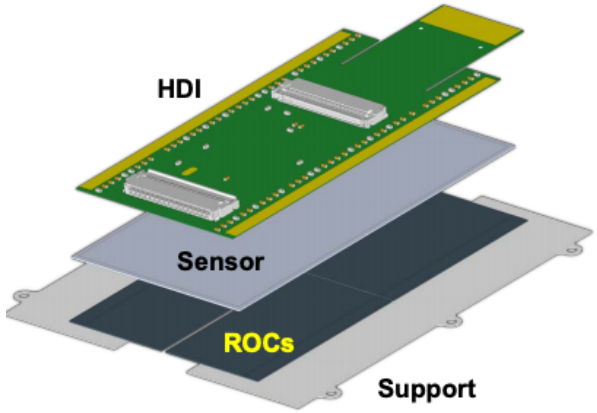


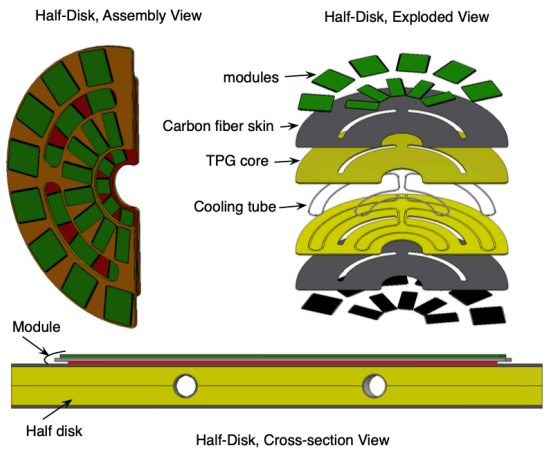
Inner (Pixel) Tracker assembly

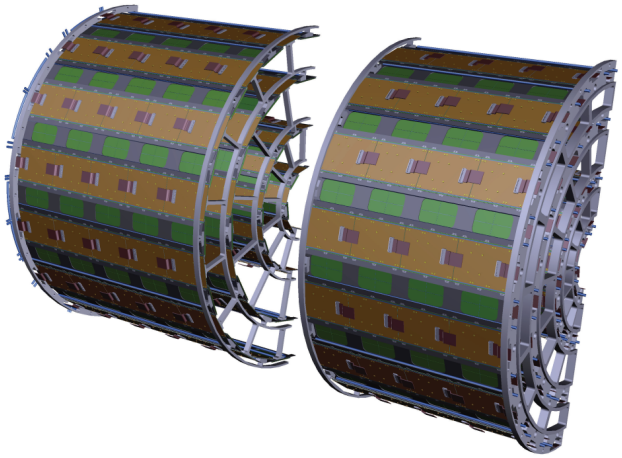
- Readout chips (ROCs) bump bonded to sensor
- High density interconnect (HDI) on top collects the data & distributes signals & power
- ROC based on RD53 development:
  Pixel chip in 65 nm CMOS →Hit rates of upto 3 GHz/cm^2

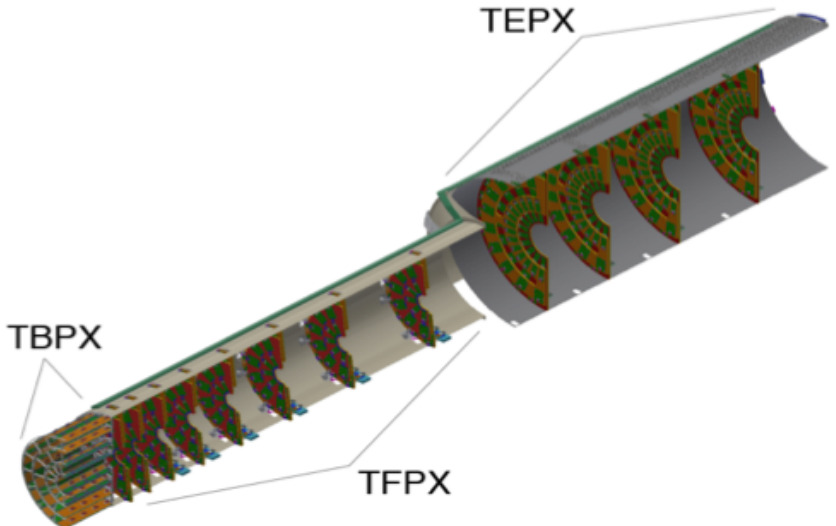
- No active components
  - HDI wire bonded to the ROC
  - Base strips with high thermal conductivity support the module, also facilitate handling & mounting
  - Electrical cables (e-links) connect modules with LpGBT boards

- All modules rectangular, two types
- Double-discs formed by 4 “dees”
  →modules arranged hermetically on 4 layers
- Structures supported by Carbon Fiber cylinders







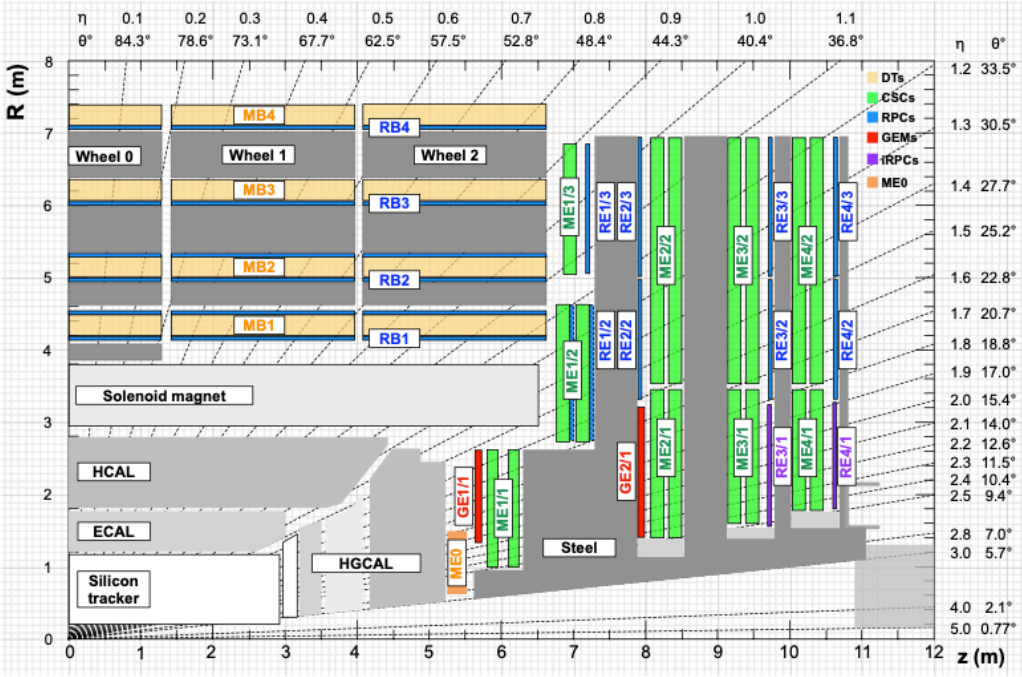


Phase-2 Muon tracking stations

Legacy Muon stations

(DT, CSC, and RPC detectors)

- DT and RPC: new readout with improved z and time precision
- CSC forward: new readout at high bandwidth
- shielding to reduce neutron background on top part of detector

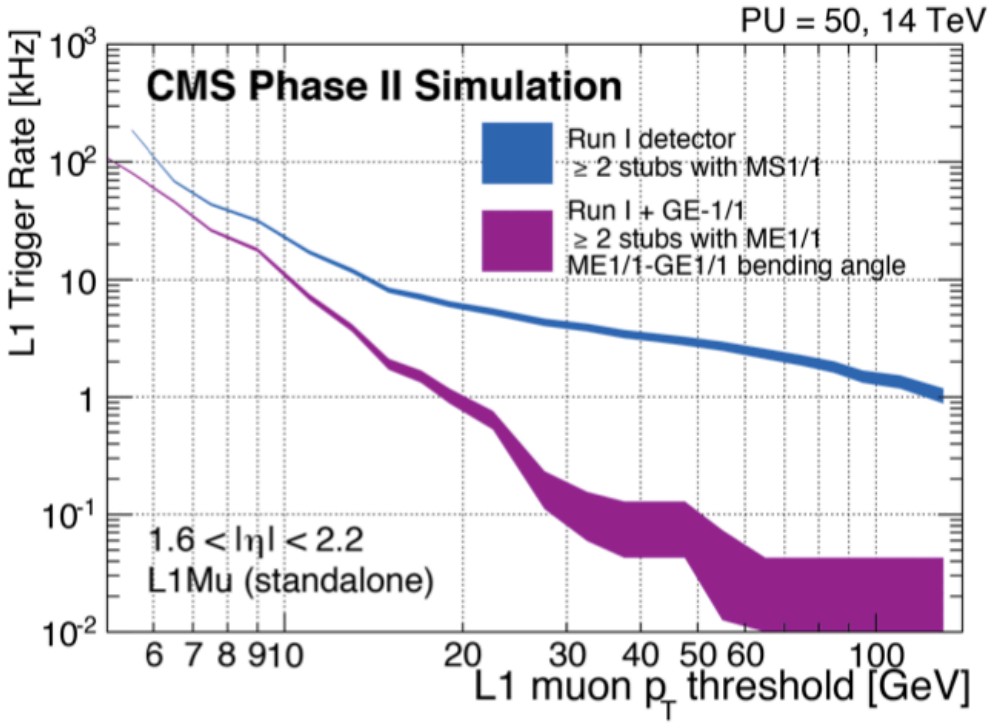


New Muon stations

- iRPC: RE3/1 and RE4/1
  Short electrode recovery, reduction in total charge produced in a discharge

- GEM based GE1/1 and GE2/1
  Improved L1 μ trigger in endcap

- GEM based ME0 detector
  Extension in eta coverage to $|\eta| = 2.8$ (7° w.r.t beam axis)



Expected Performance

Upgraded muon system will maintain physics performance at the HL-LHC

- Much better resolution
- Much better rate capability

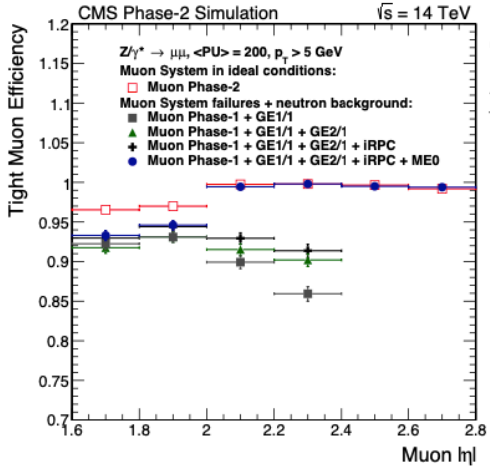
Muon trigger and reconstruction

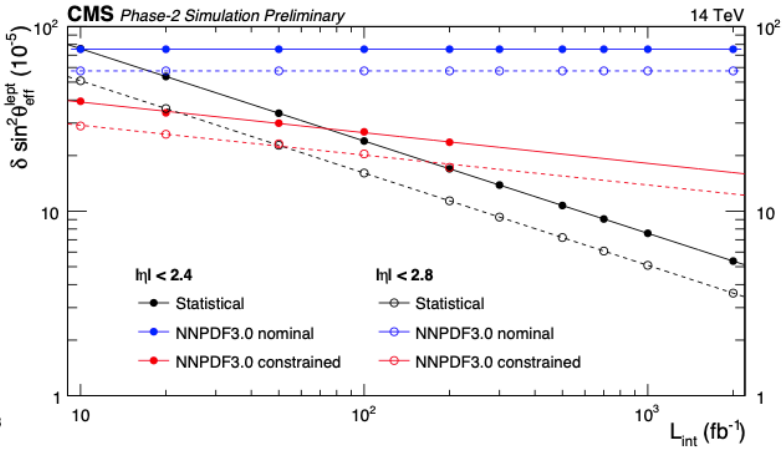
- Increased trigger efficiency
- Lower trigger rate
- Extended eta coverage
- Better redundancy

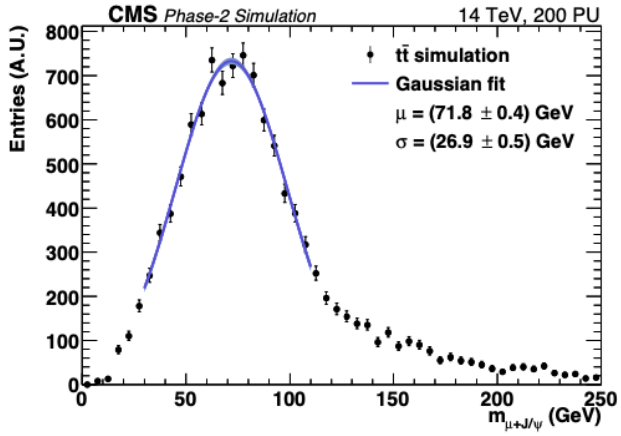
Physics improvements

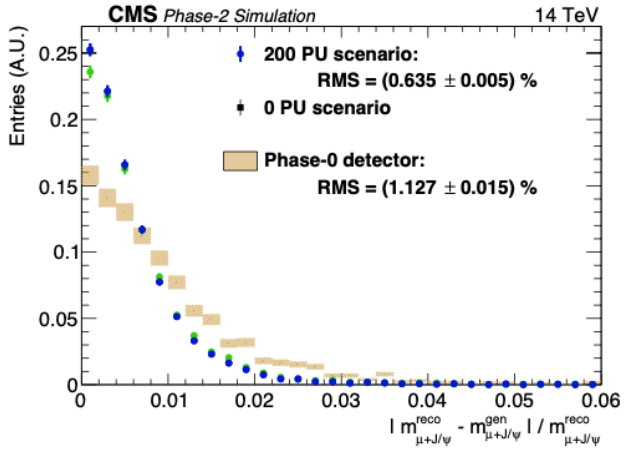
- Increase in Higgs (4μ) signal strength (7%)
- Improved weak angle measurement
- Top quark mass in

  $t \longrightarrow J/\psi\,(\mu\mu)\mu + X$ decays









Stations with new detectors

GE1/1 (Installed in LS2, Commissioning ongoing)

- ✓ 36 superchambers (SC) per endcap
- ✓ 2 triple GEM detectors per SC
- ✓ 10° in φ
- ✓ $1.5 < \eta < 2.0$

GE2/1 (installation during LS3)

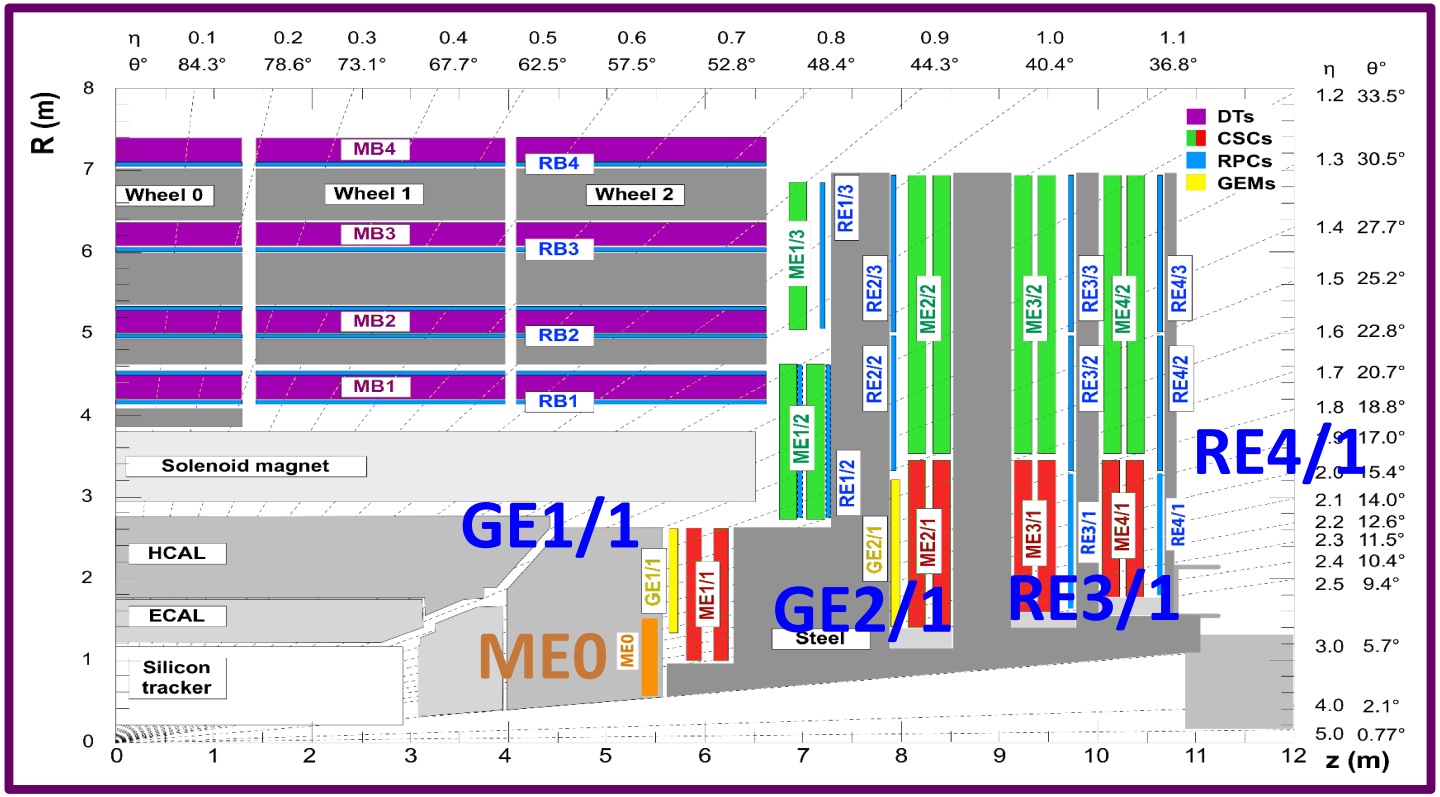
- ✓ 18 superchambers (SC) per endcap
- ✓ 2 triple GEM detectors per (SC)
- ✓ 20° in φ
- ✓ $1.6 < \eta < 2.4$

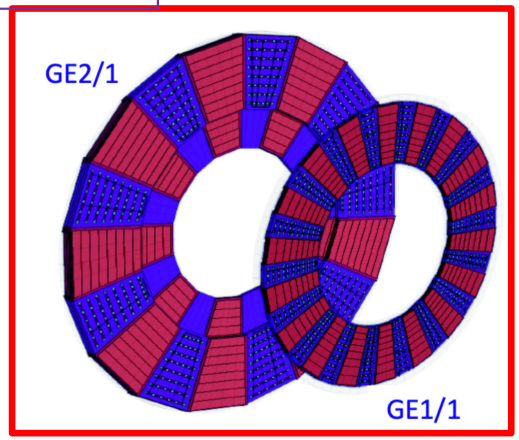
ME0 (installation during LS3)

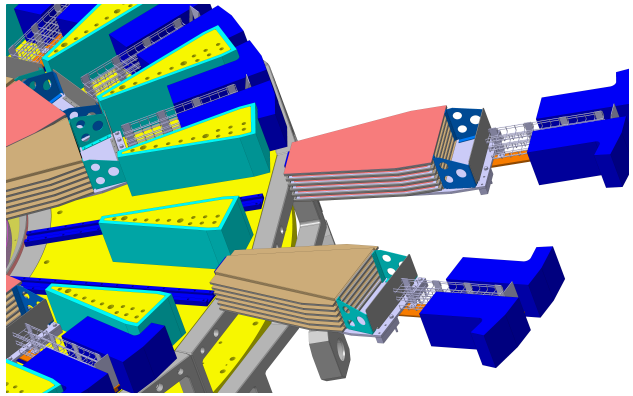
- ✓ 18 stacks per endcap
- ✓ 6 layers of triple GEM detectors per stack
- ✓ 20° in φ
- ✓ $2.0 < \eta < 2.8$

RE3/1, RE 4/1 (installation during LS3)

- ✓ 72 new RPC chambers
- ✓ 20° in φ
- ✓ $1.8 < \eta < 2.5$

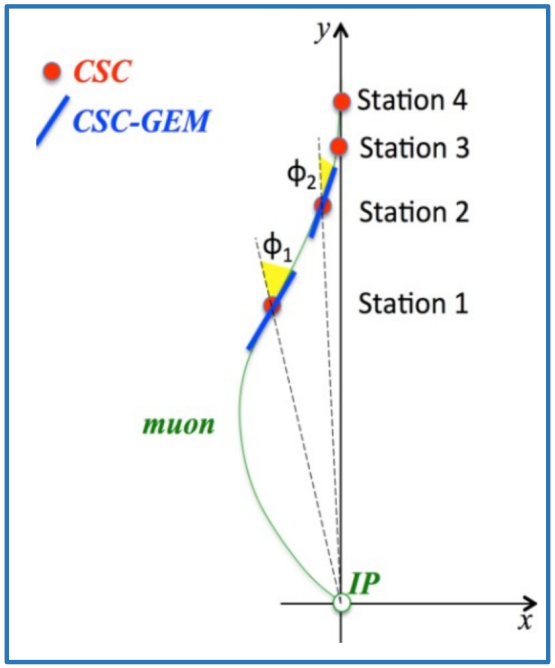


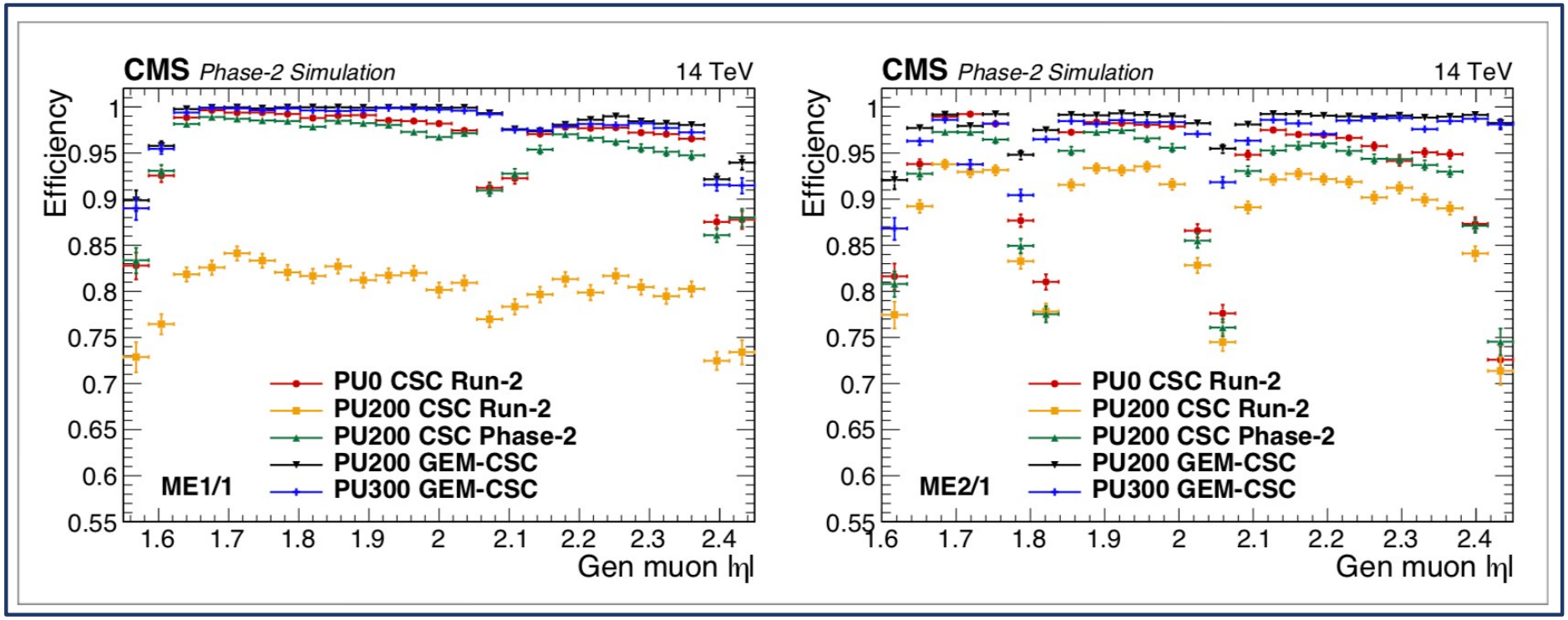




GEM - CSC Trigger

- Adding GEM chambers significantly increases the local lever arm for the segment reconstruction with respect to the CSC-only system (by factor of > 2).
- There are no iron yoke elements in between the GE2/1 and ME2/1 chambers, the multiple scattering is small.
- The additional local lever arm is important for displaced vertices, for which the vertex constraint cannot be exploited. Here two independent direction measurements, in endcap stations 1 and 2, allow a standalone momentum measurement in the muon system in the Level-1 trigger.

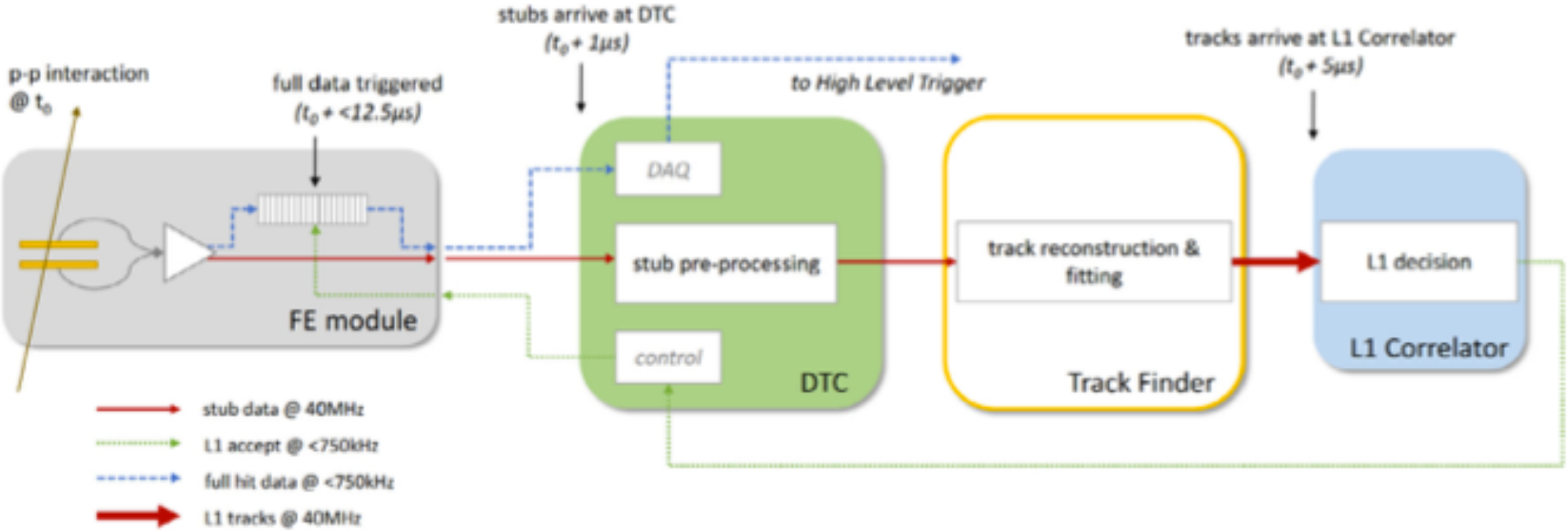




Summary

- The HL-LHC upgrade offers a large improvement to the instantaneous luminosity alongwith new challenges for detector technology
- The CMS outer tracker has been completely redesigned for high radiation environment and sufficient granularity
- Typical tracking accuracy: spatial precision O(100) micron, and time resolution less than few ns are achievable.
- Muon (outer) tracking stations coverage is going to be extended and new technologies improvises position resolution, rate capability and radiation susceptibility under harsh environment.
- CMS would maintain the excellent performance of the CMS muon system within large geometrical acceptance in more challenging data-taking conditions

- **Electronics use programmable search window to accept high-pT tracks & form stubs (hit position + bend info)**
- **"Stubs" sent to the back-end at 40 MHz → track reconstruction→ L1 trigger decision**
- **On receipt of a L1 trigger, the complete event information is read out at 750 kHz**



Layout of Si Tracker upgrade

Inner Tracker: 4 barrel layers, 8 small disks, 4 large discs per side

Pixel sizes: 50 x 50 μm^2 , 25 x 100 μm^2

Outer Tracker: 6 barrel layers, 5 discs per side

9.5 million channels, 44M strips + 174M macropixels

7608 strip-strip modules

3892 pixel modules
100μm x 25μm pixels

5592 pixel-strip modules (PS),
2.4cm x 100μm strips

OT
- 190m^2

IT
- 5m^2