Perspectives on R&D: HL-LHC

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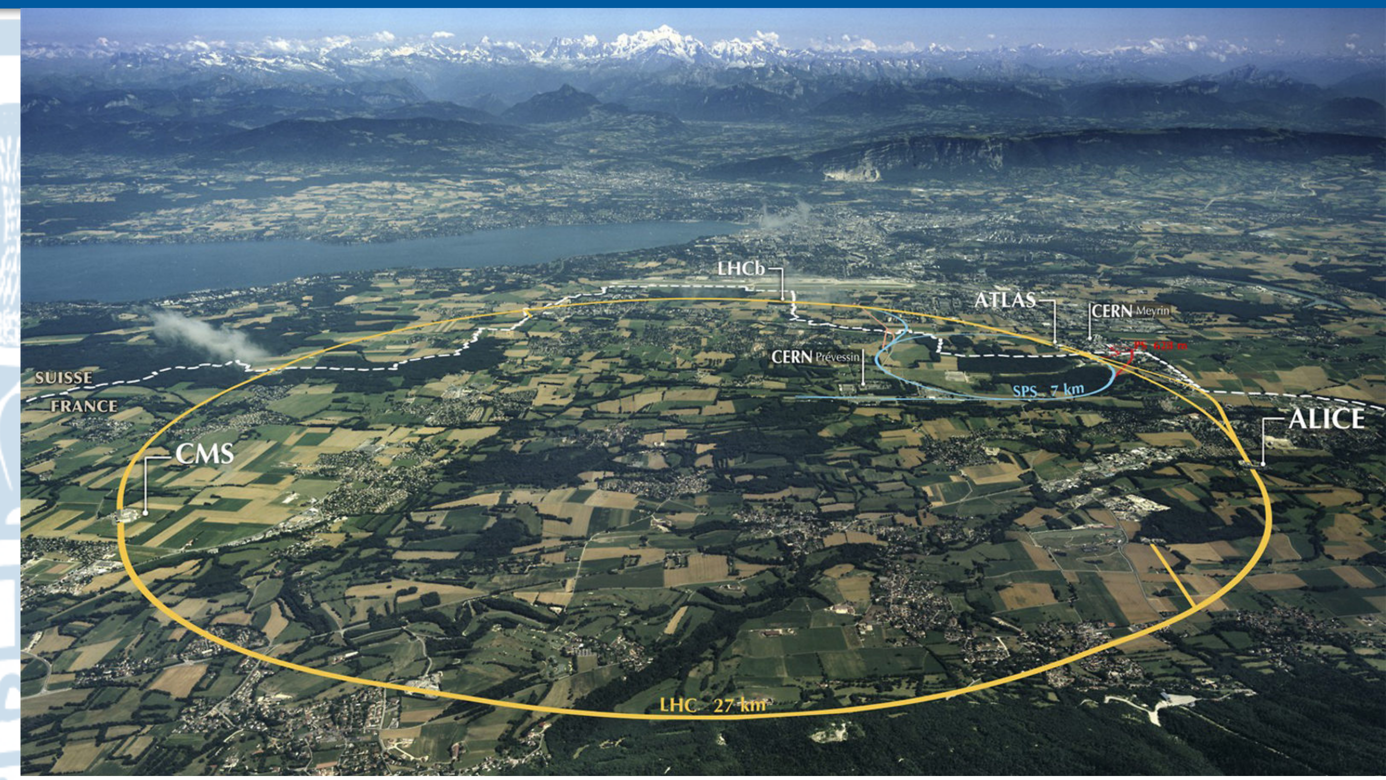
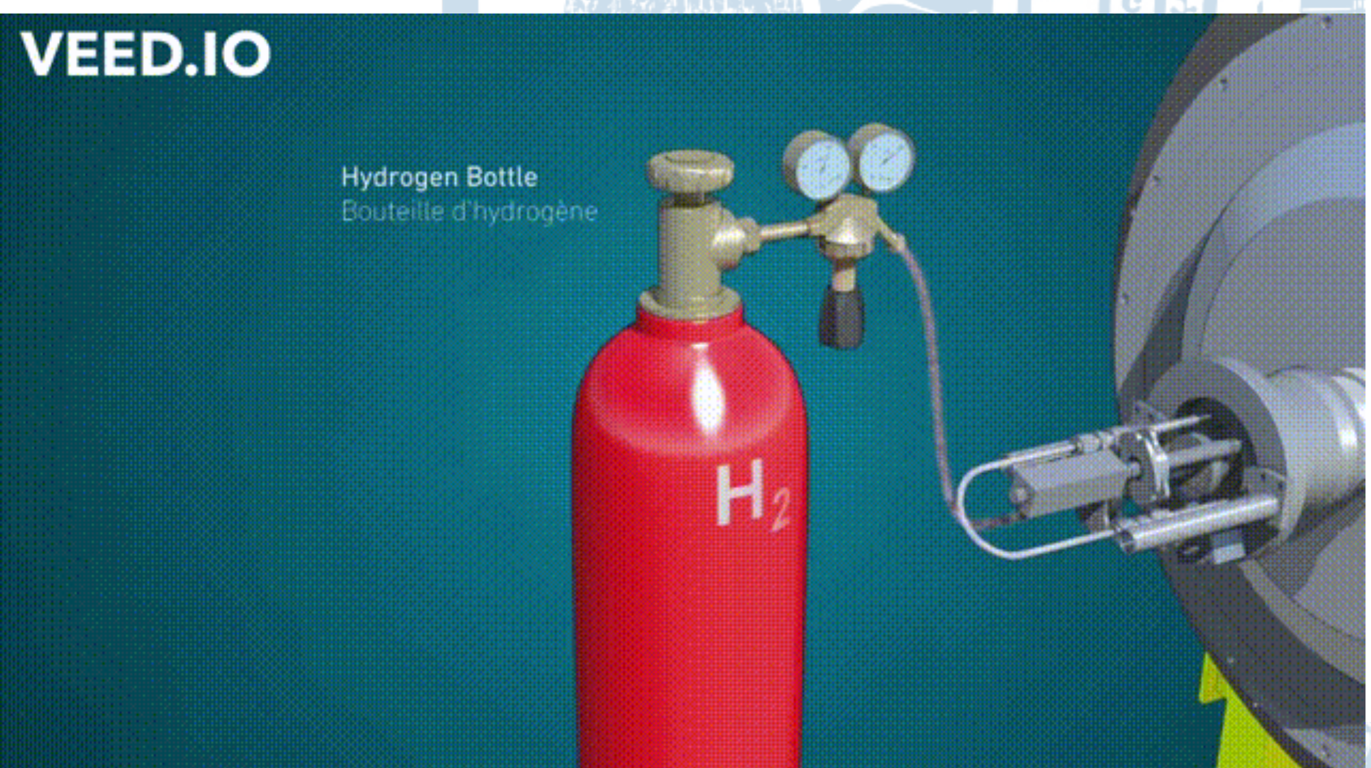
CMS Collaboration

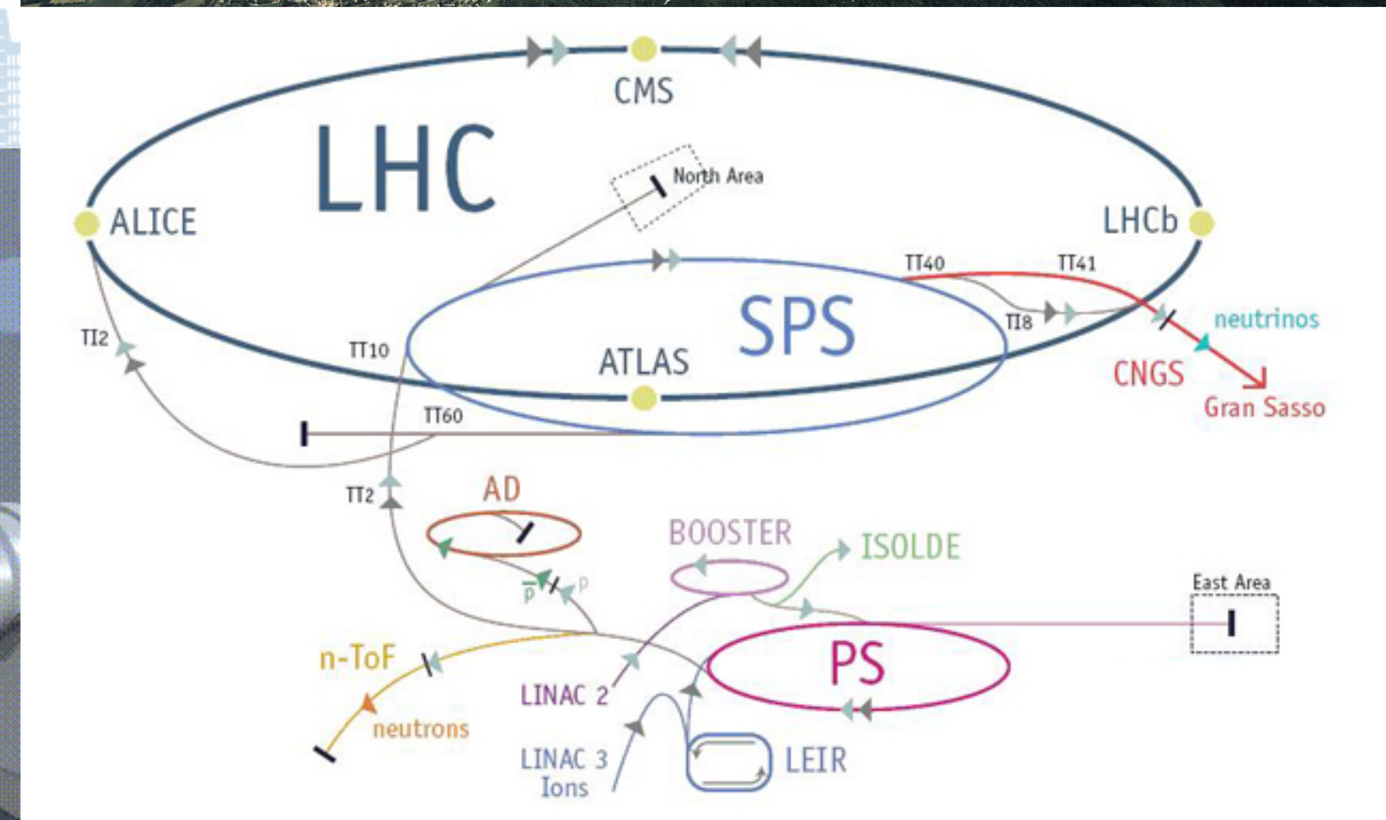
54th Annual Users Meeting
August 3rd, 2021

The LHC

- The LHC accelerates protons to 7 TeV using 5 different accelerators
- Proton bunches cross every 25ns (40 MHz)
- ~10^{11} protons per bunch

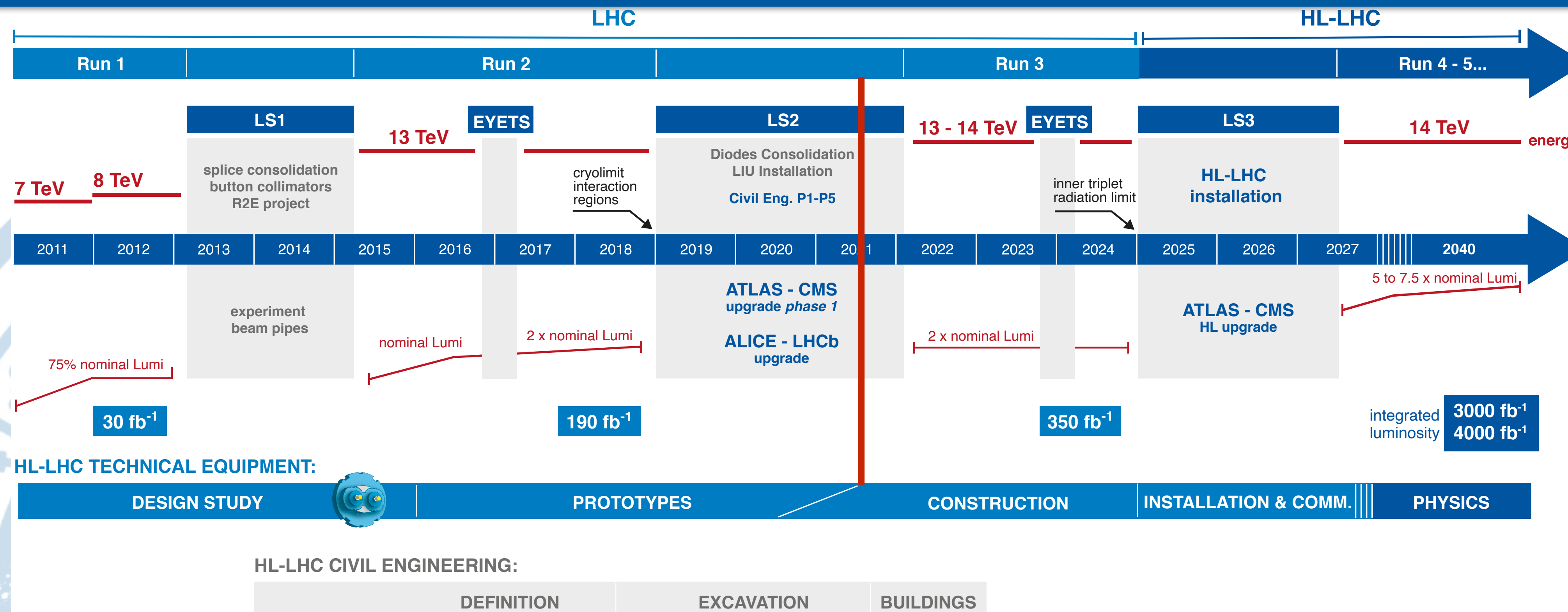


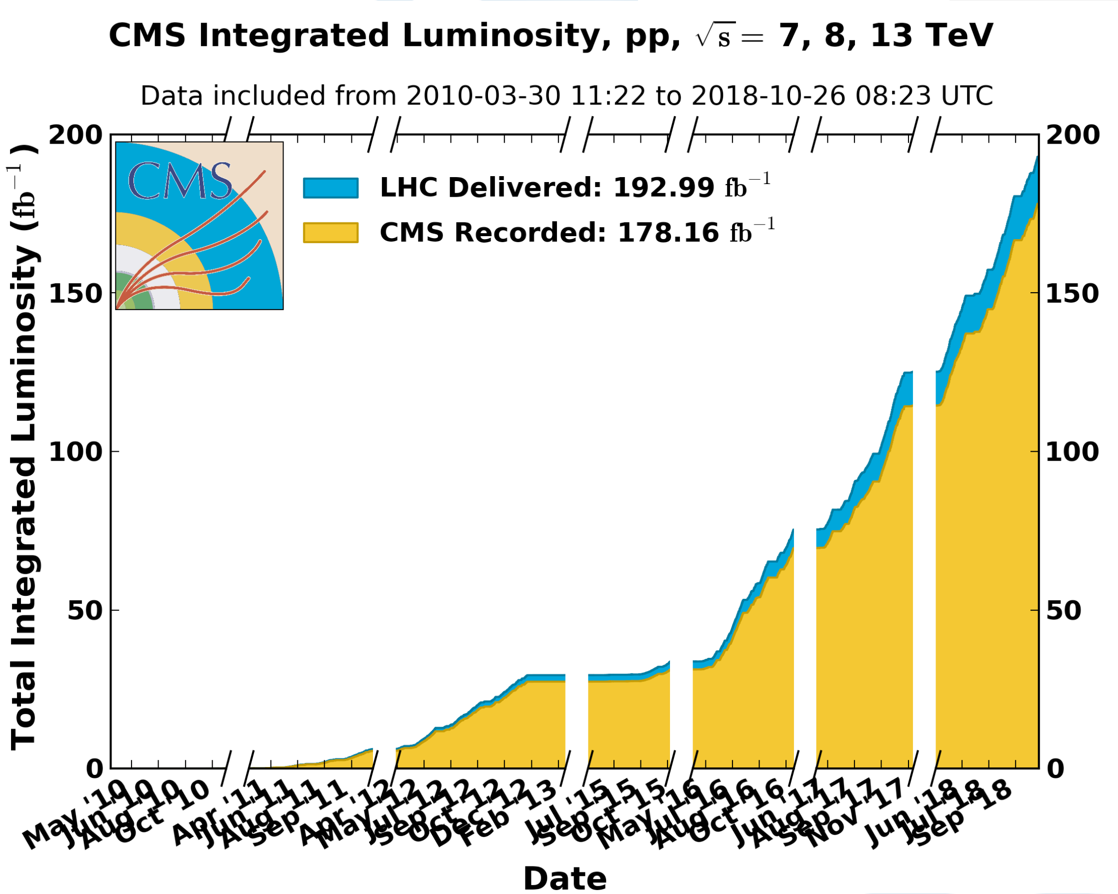


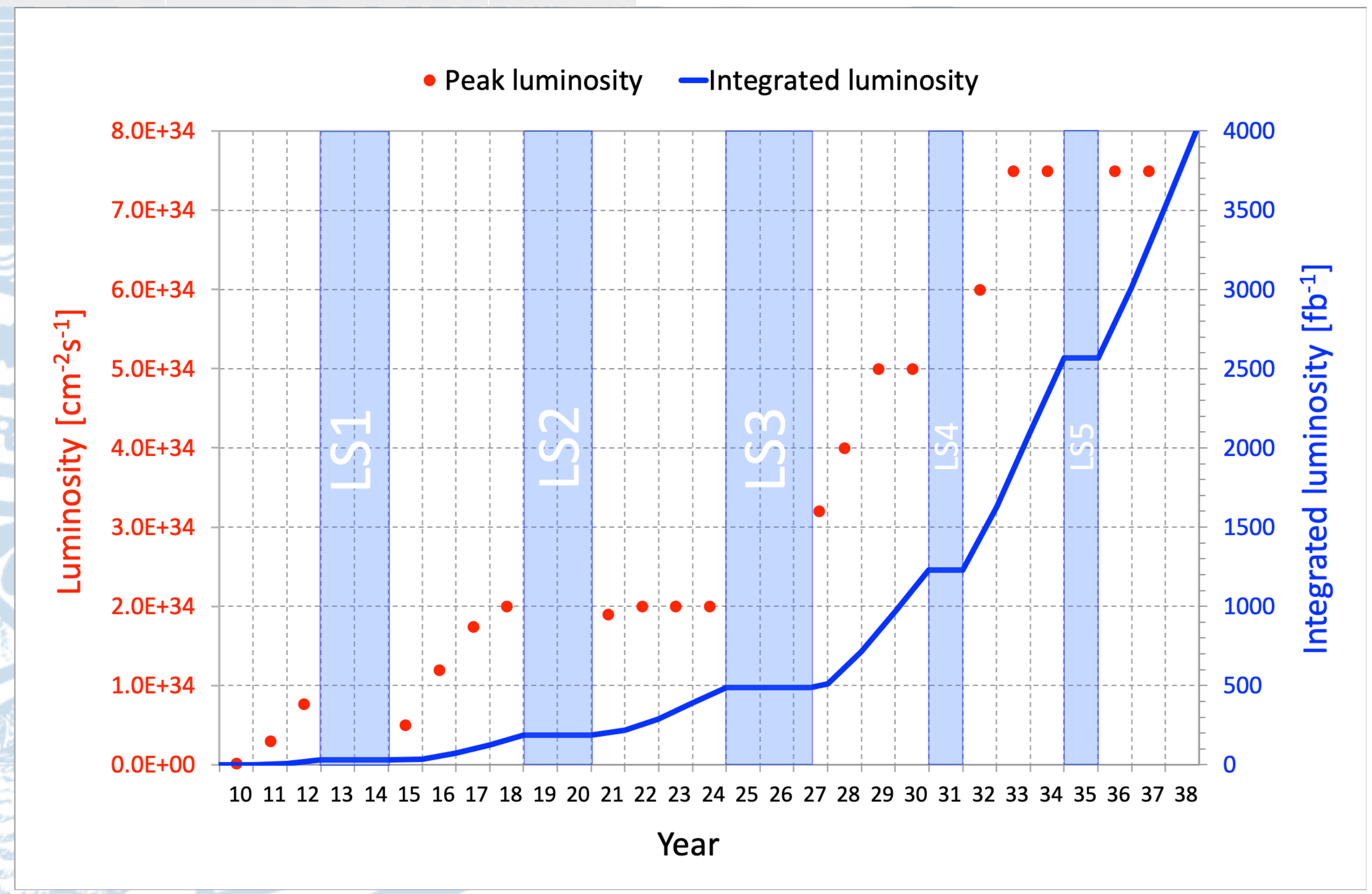


LHC/HL-LHC Timeline

- HL-LHC will produce ~8E9 collisions per second
- Peak luminosity of 7.5E34 $cm^{-2}s^{-1}$ (75 nb^{-1}/s)
  - 6.48 fb^{-1} in 24 hours
  - Entire 2011 7 TeV dataset (6.1 fb^{-1})
  - ~130,000 Higgs bosons per day

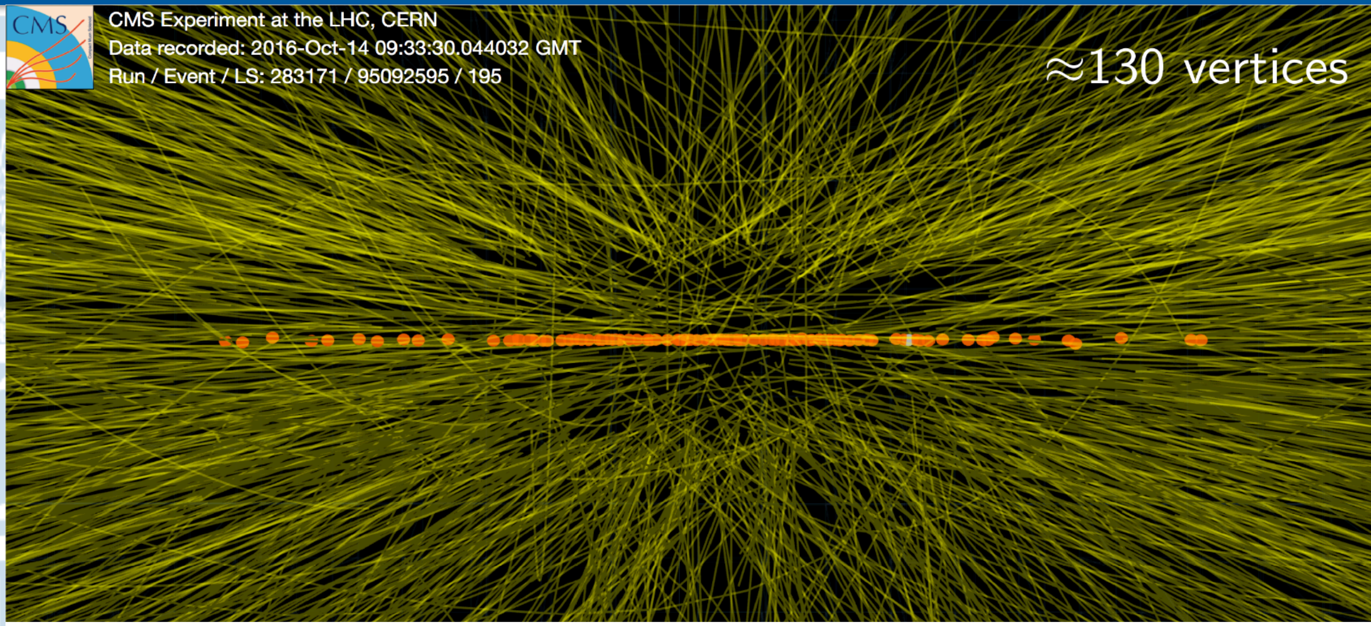


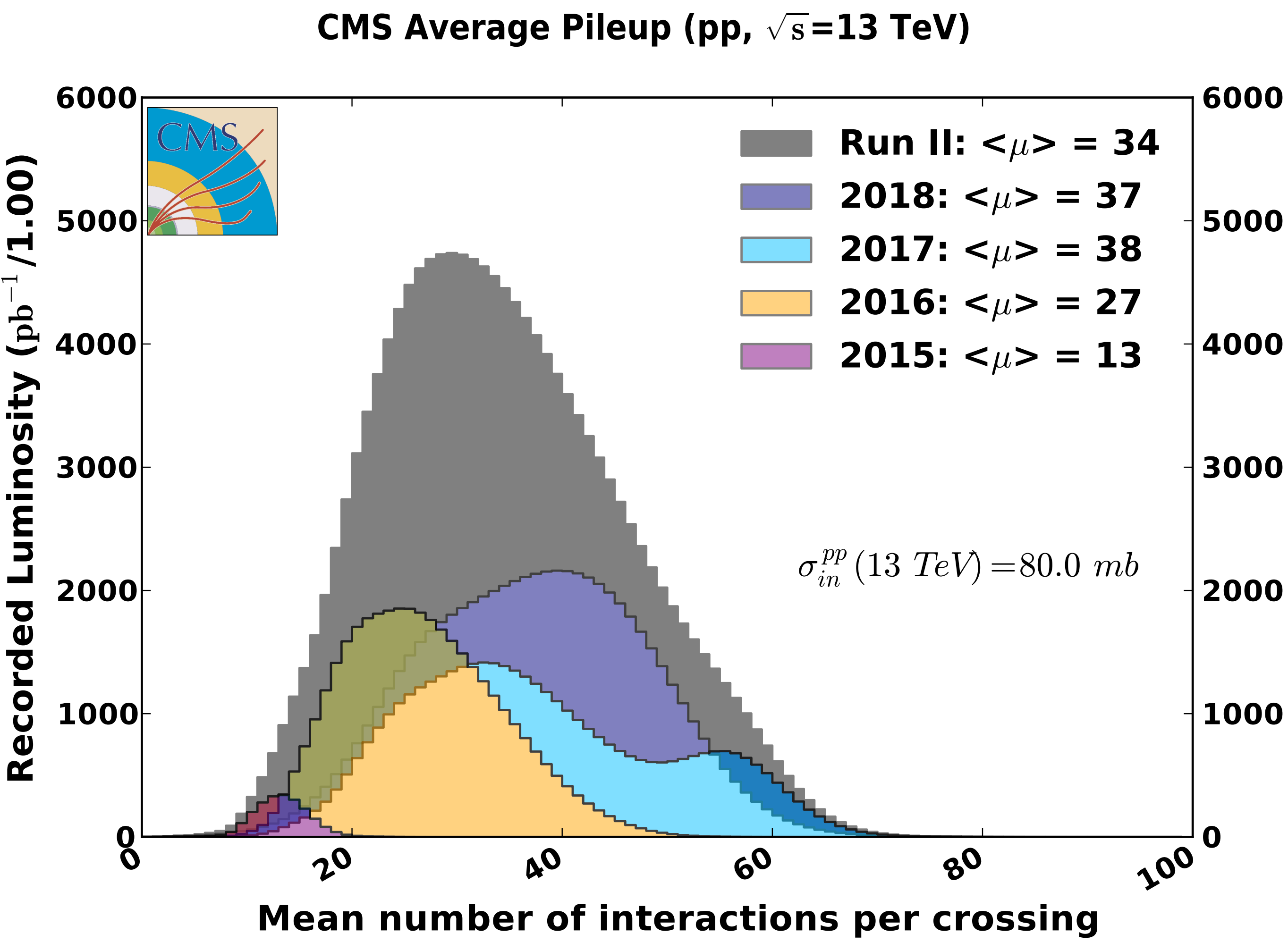


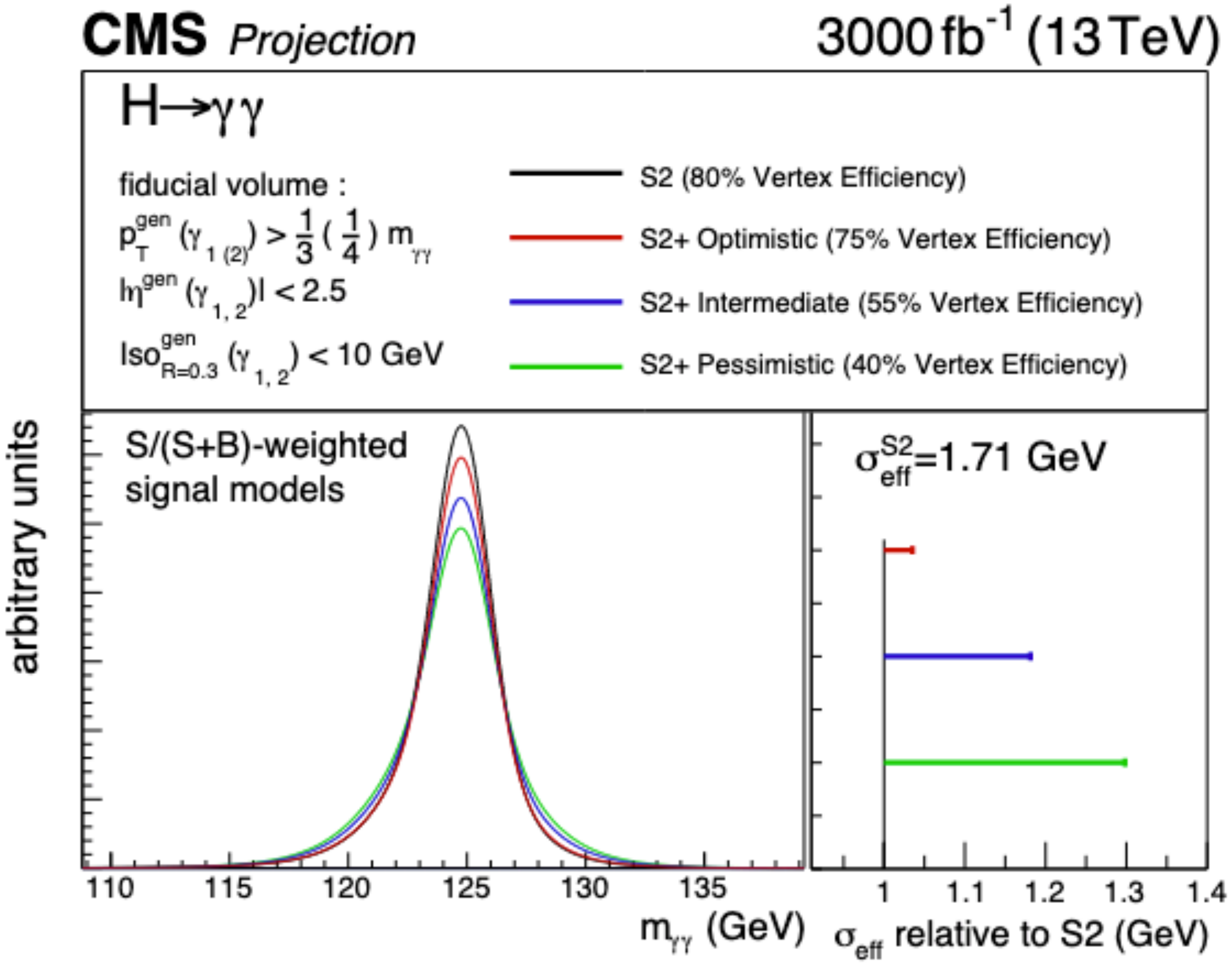


Event Occupancy

- The number of collisions per bunch crossings increases with luminosity
  - Up too 200 collisions per event
  - Very high occupancy on inner detectors
  - Critical to associate detector hits and physics objects with the correct vertex



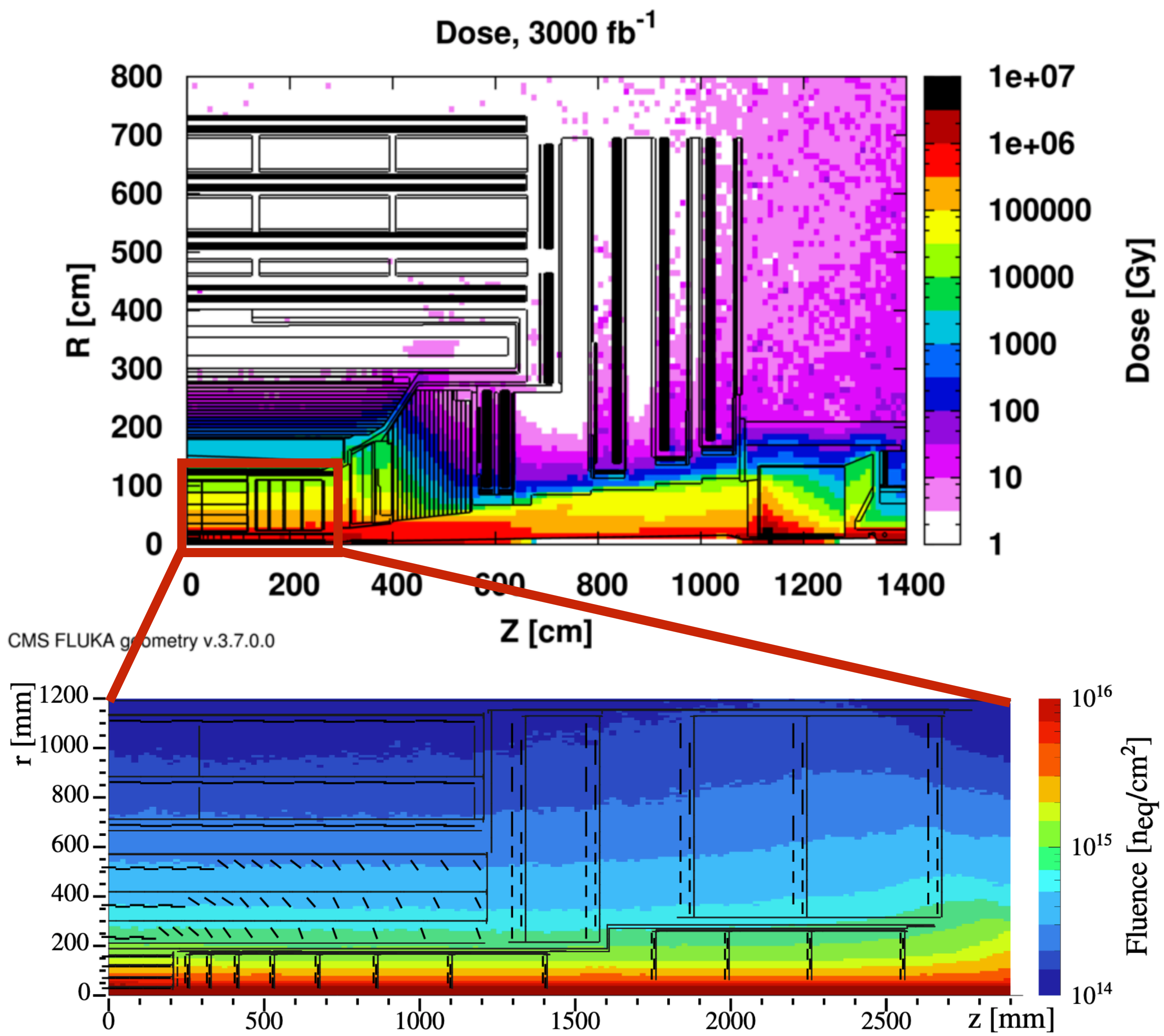




Radiation Damage

- Increase in luminosity causes more radiation damage
  - Detector will experience fluences up to 2.3E16 n_{eq}/cm^2
    - Integrated dose up to 12 MGy
    - Requires integration of radiation hard detector materials
      - Radiation hard integrated circuits and readout electronic

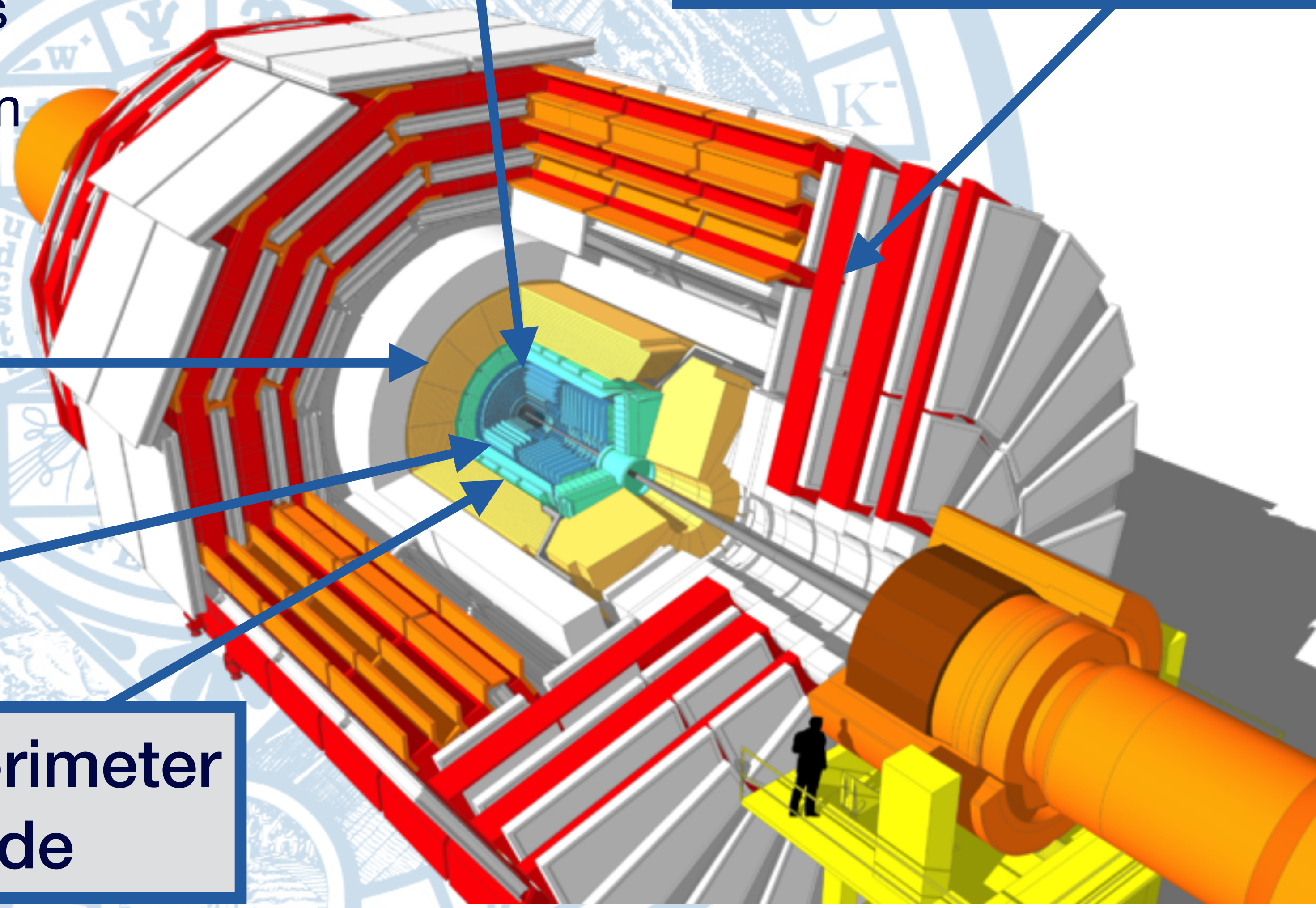
HL-LHC CMS Radiation Fluence



HL-LHC CMS Tracker Radiation Fluence

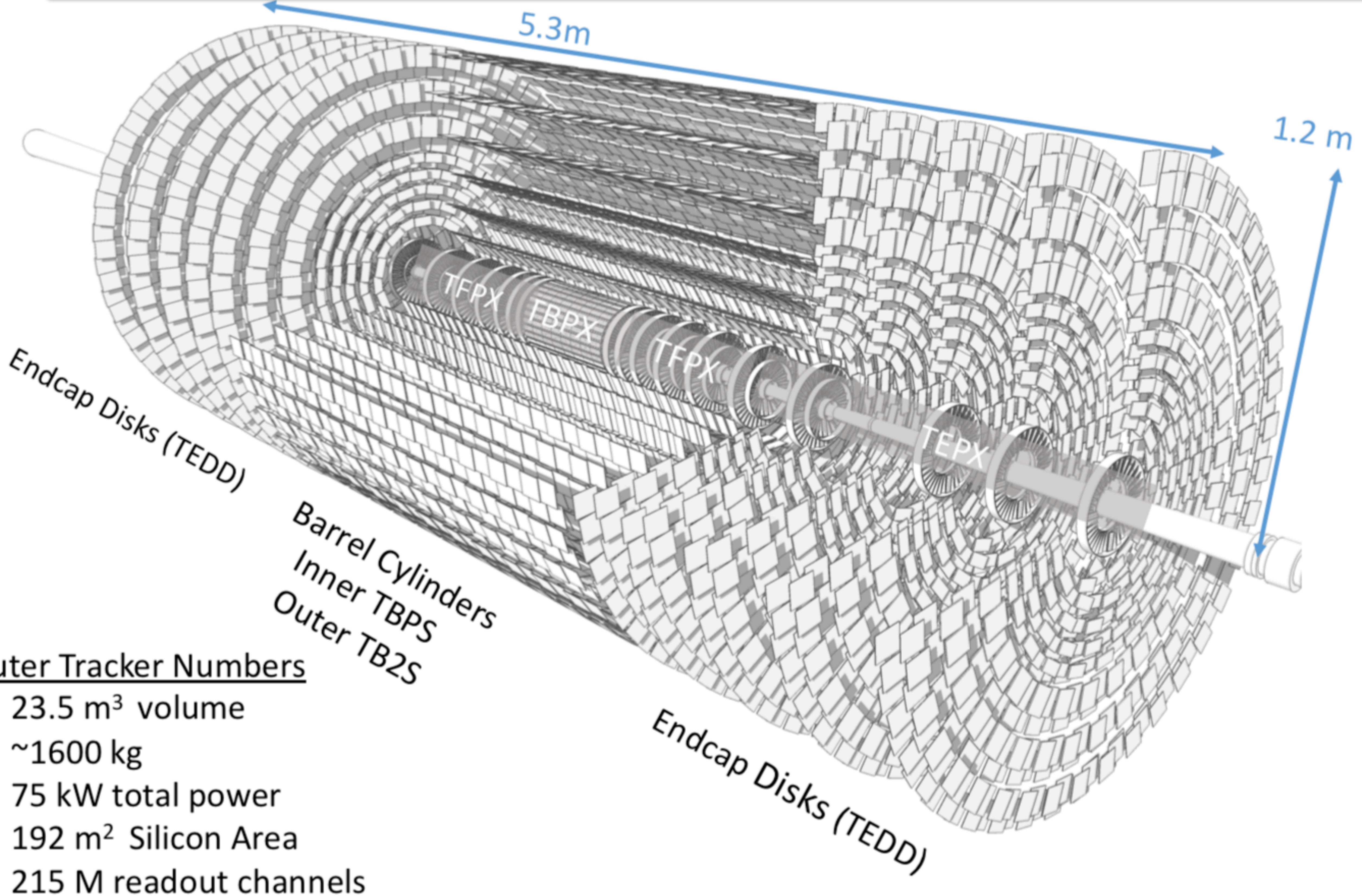
HL-LHC Detector Upgrades

- Replacement of the entire tracking detector
    - Replace pixel detector with inner tracker
    - Replace strip detector with outer tracker
- Add a MIP Timing Layer
- Replace the calorimeter endcaps
- Upgrade barrel calorimeter electronics
- Expand and upgrade the muon system
- Improve trigger and DAQ electronics



Joint DOE/NSF Project

Tracker Upgrade



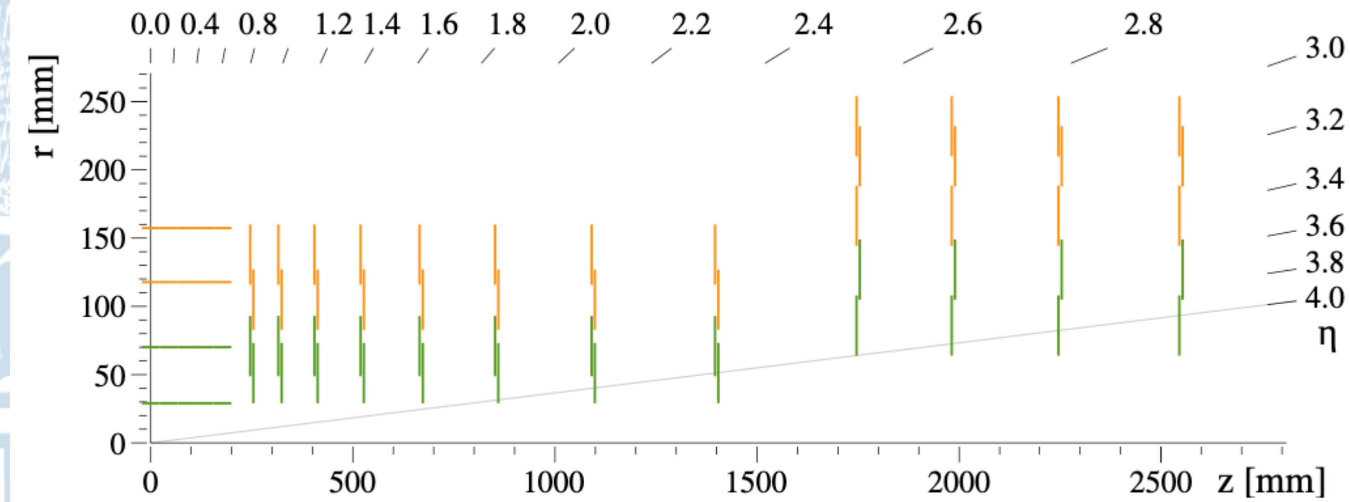
Outer Tracker Numbers

- 23.5 m^3 volume
- ~1600 kg
- 75 kW total power
- 192 m^2 Silicon Area
- 215 M readout channels

Inner Detector Upgrade

- Maintains or improves on phase-I pixel tracker
  - Creates seeds needed for particle flow (PF)
- Can operate under a fluence of 3 GHz/cm² ≈ 200 Collisions
- Narrower pixel pitch than phase-I detector
  - 25x100 pixel-pitch baseline
- Coverage up to |η| < 4
- Increased hit capacity and radiation tolerance
- Capable of real-time luminosity measurement
- Carbon fiber support with CO_2 cooling system
  - 50 kW power requirement

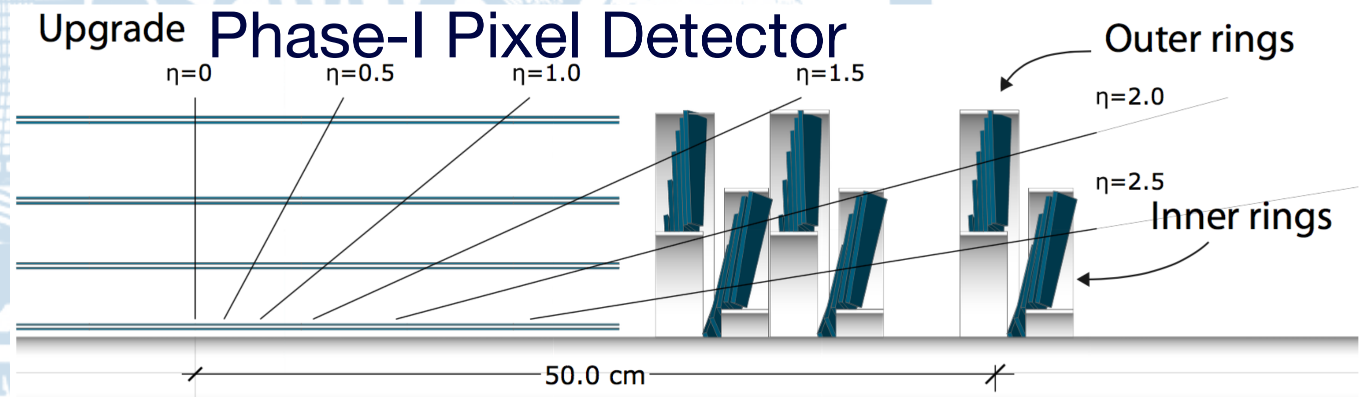
HL-LHC CMS Inner Tracker Detector

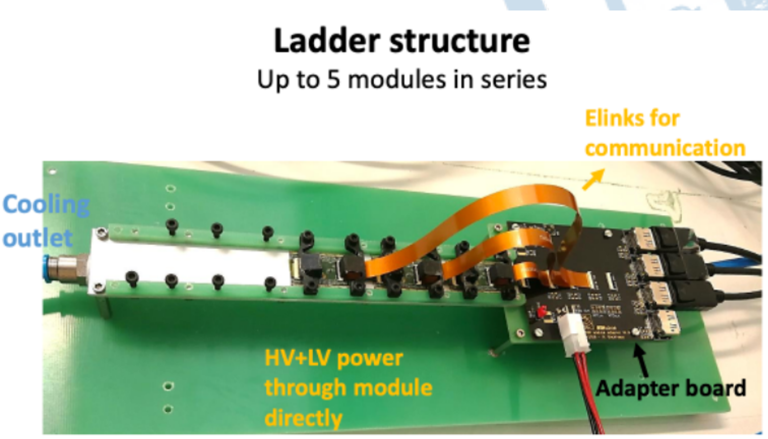


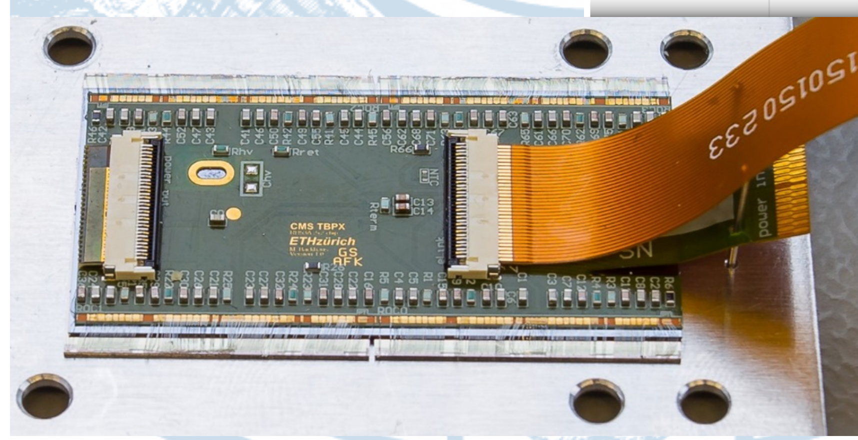
4 ROC Pixel Modules

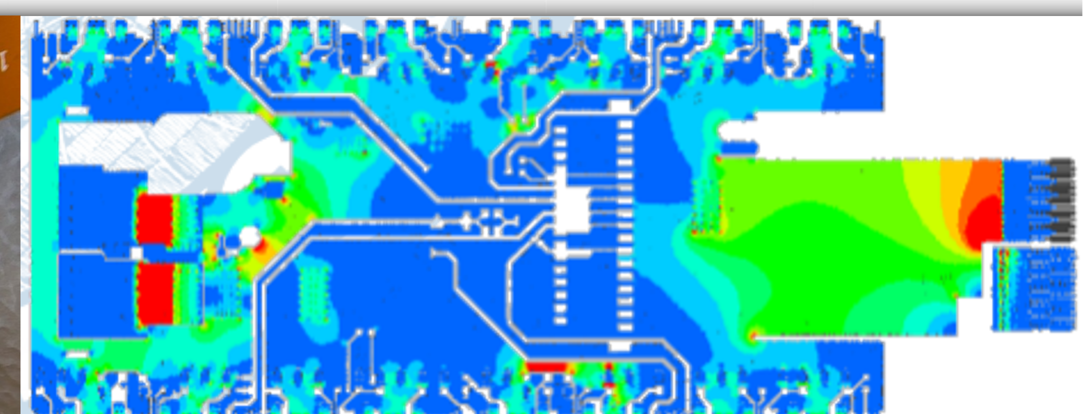
2 ROC Pixel Modules

Upgrade Phase-I Pixel Detector





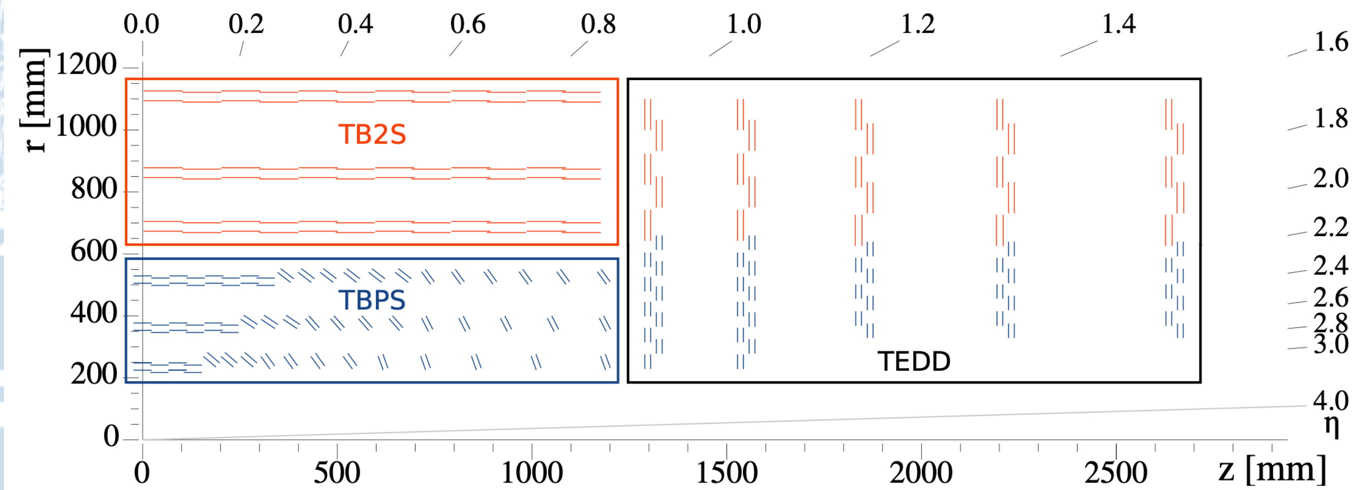




Outer Tracker Upgrade

- Maintains or improves physics performance of the original ~~strip~~ outer tracker
- Covers same area as the original outer tracker
- Intricate dual layer module design
  - Enables 2 GeV L1 tracker trigger
    - Critical for Trigger at HL-LHC Luminosity
- Completely new carbon fiber and composite structure
- CO_2 cooling system
  - 25 kW thermal foot print

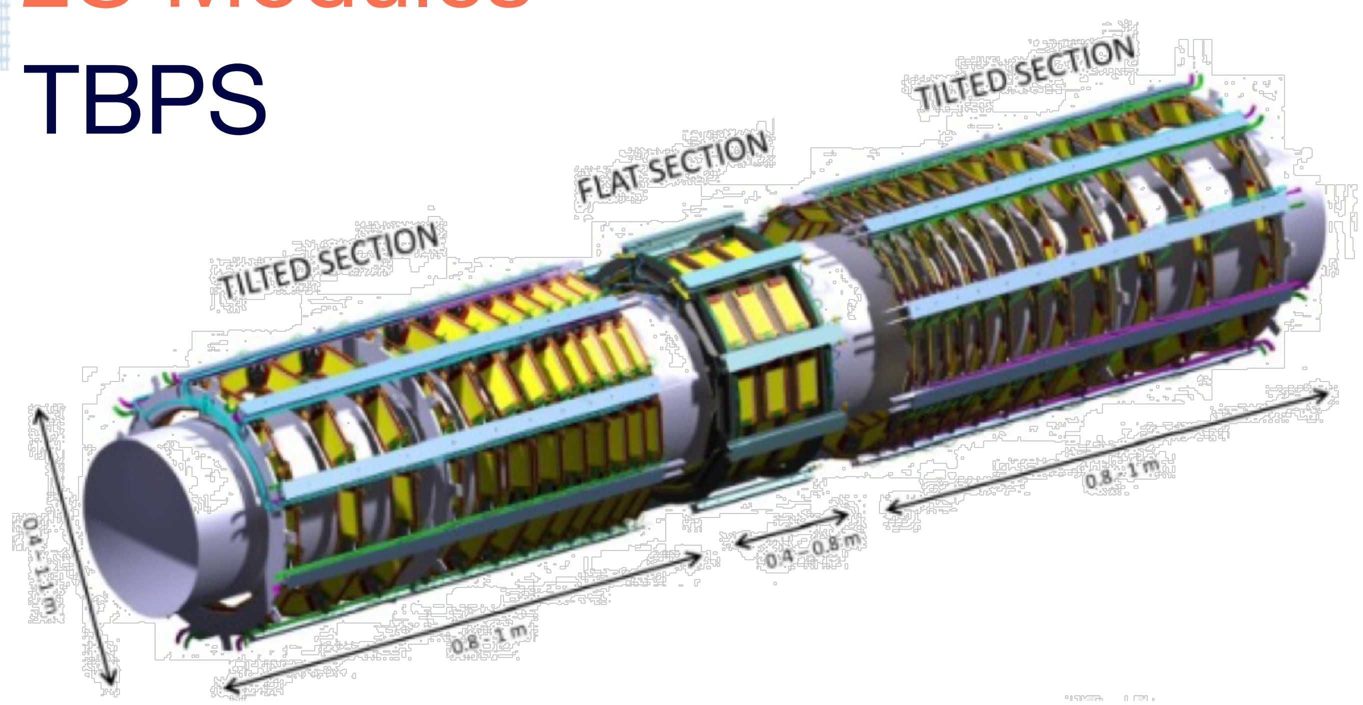
HL-LHC Outer Tracker



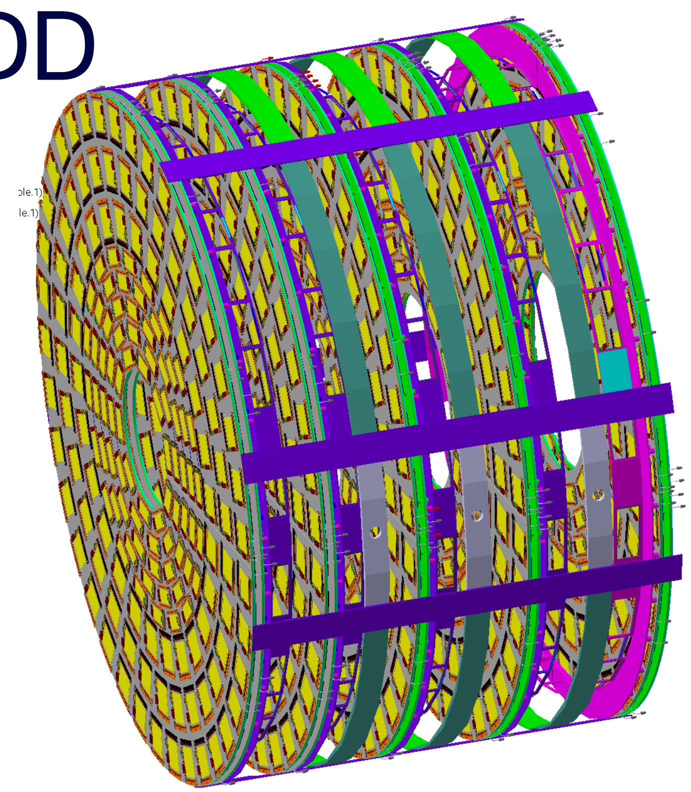
PS Modules

2S Modules

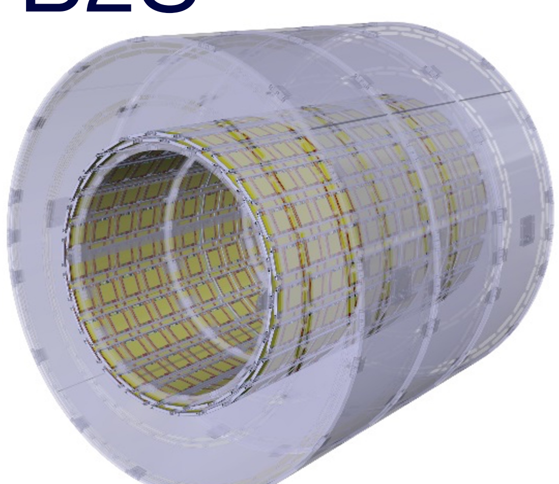
TBPS



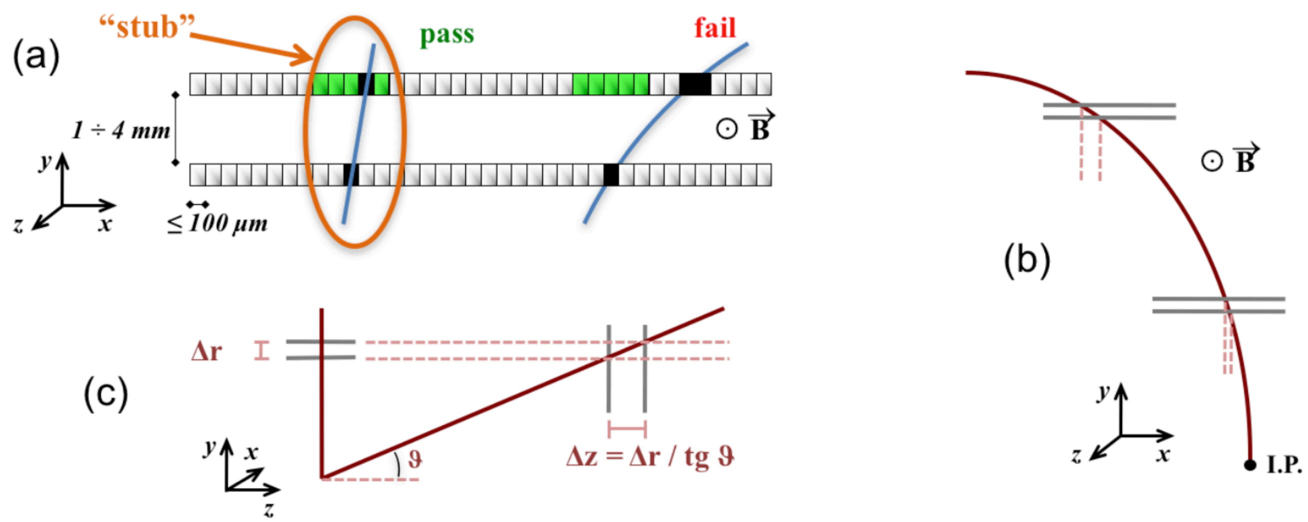
TEDD



TB2S

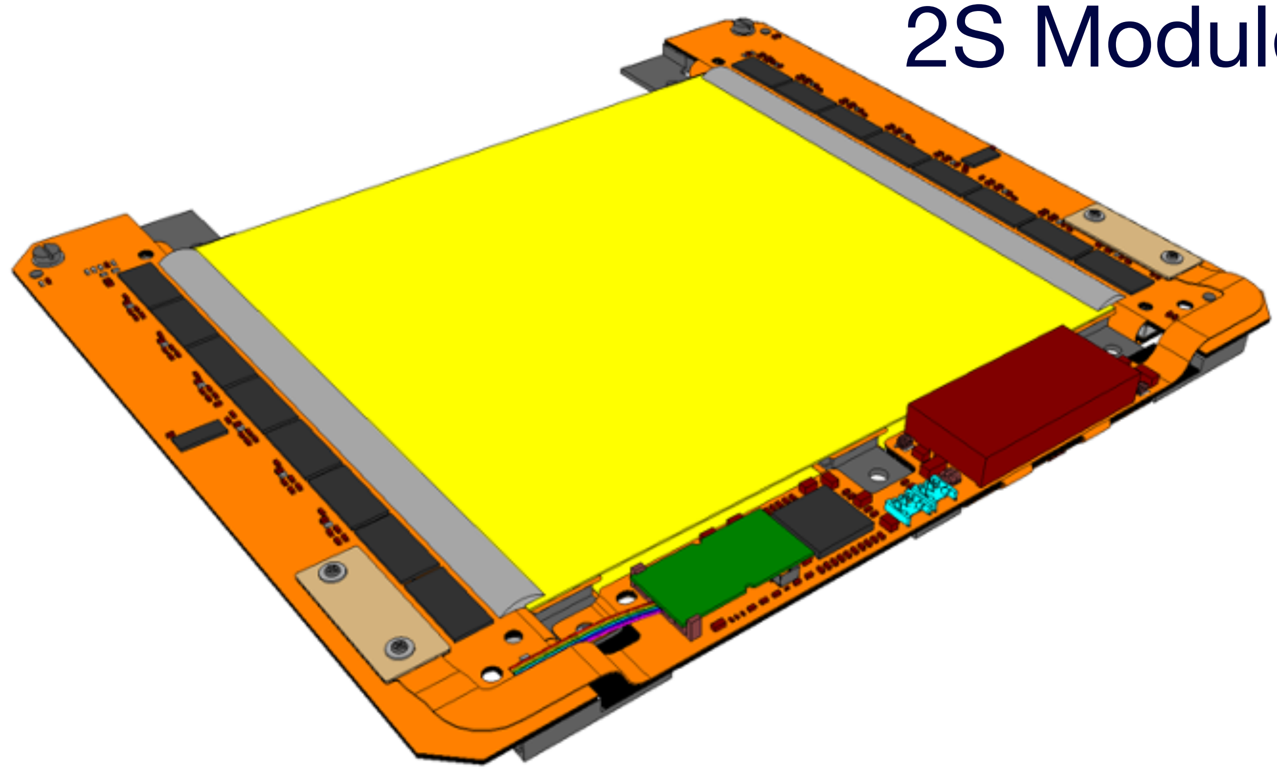


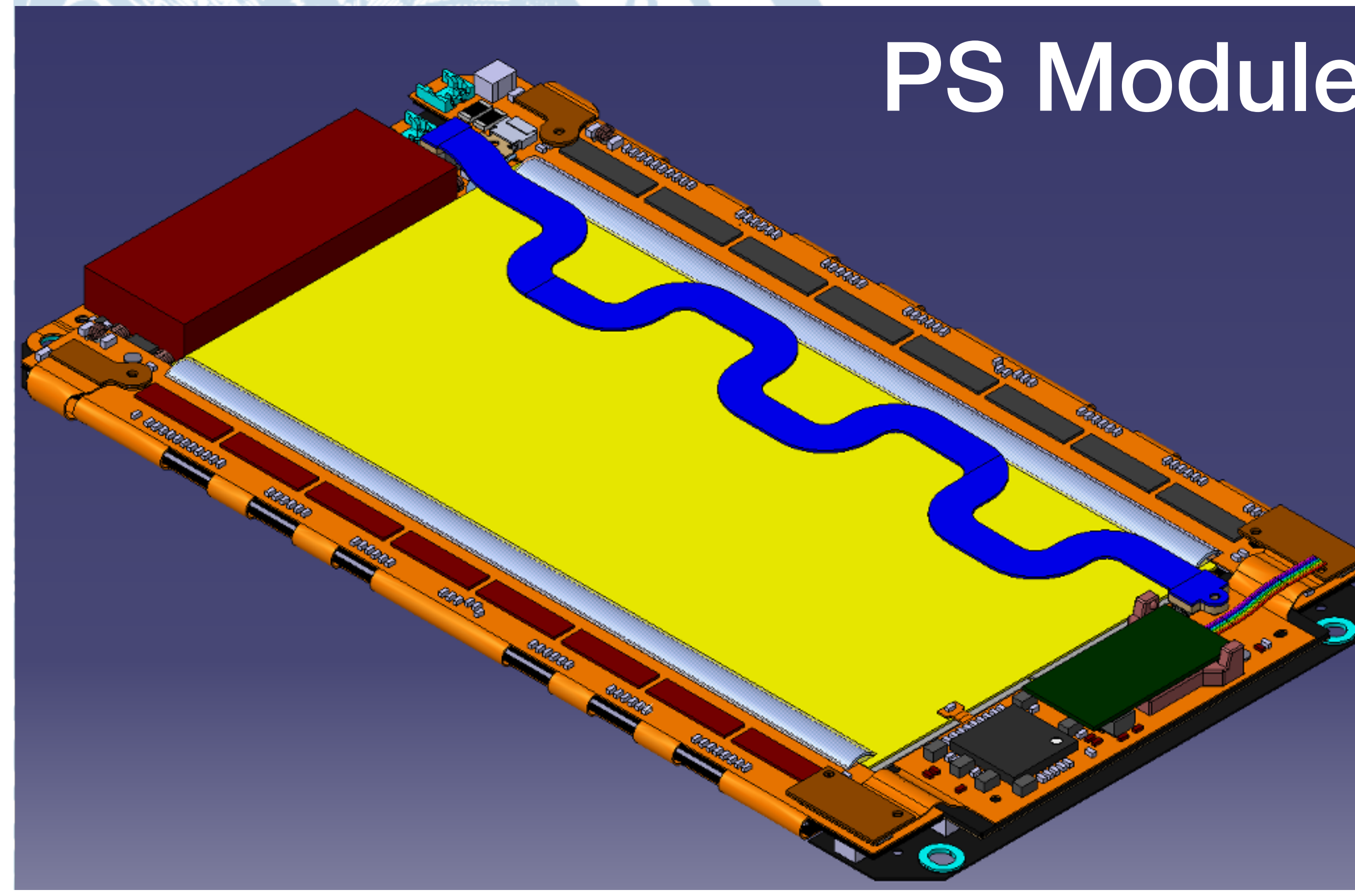
Outer Tracker Modules

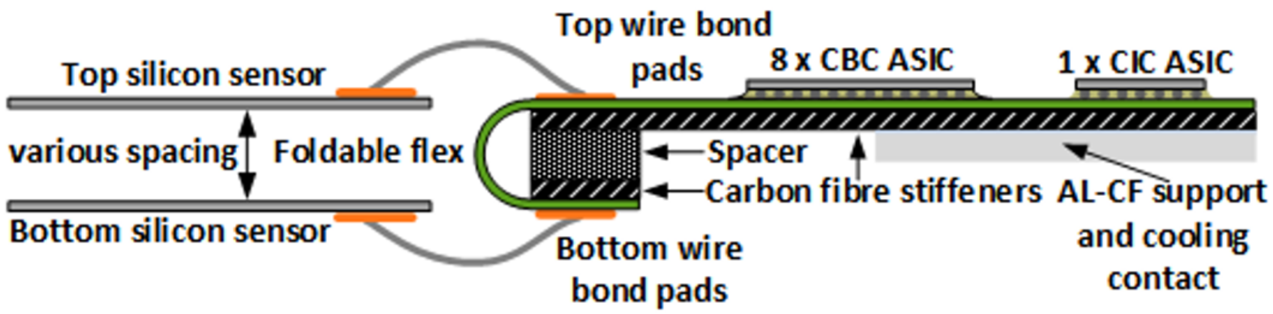


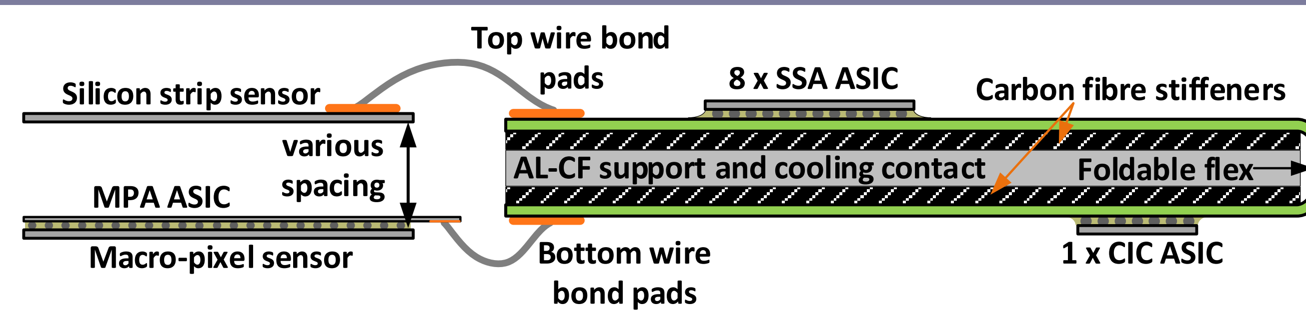
- Two modules types
  - 2S and PS Modules
  - Two sensors capable of p_T measurements
  - Cross-layer correlation facilitated by flexible hybrid circuit

2S Module



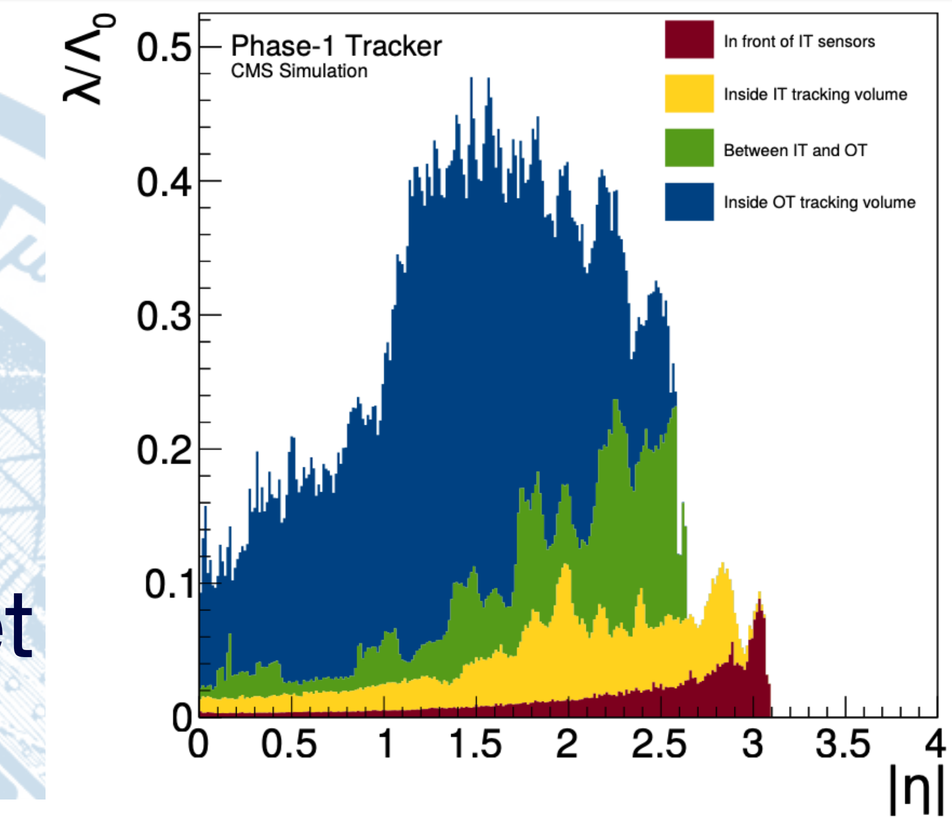


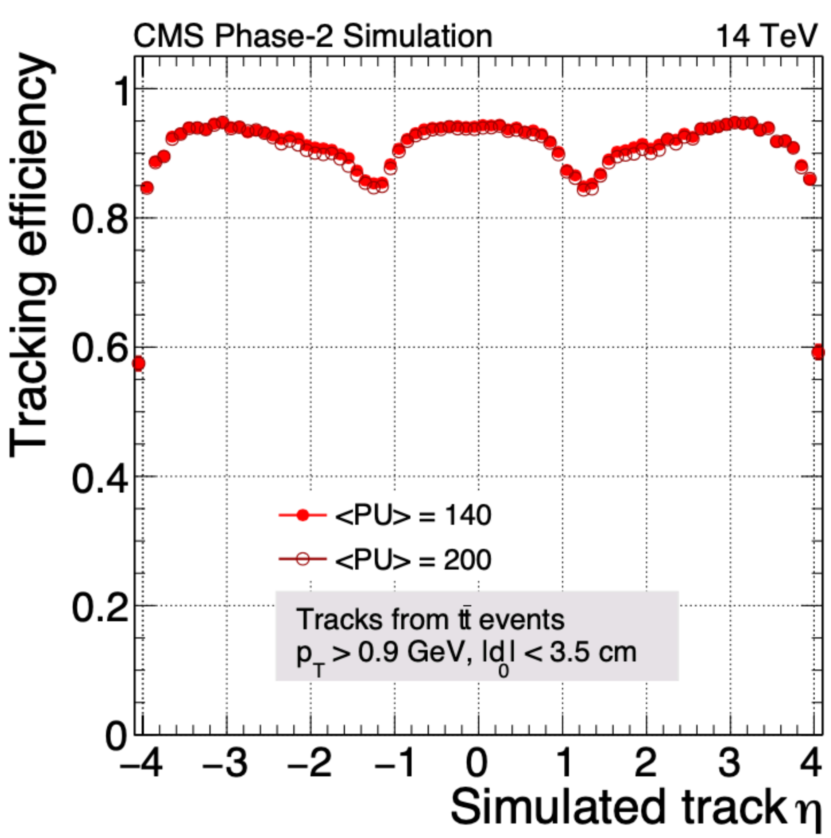


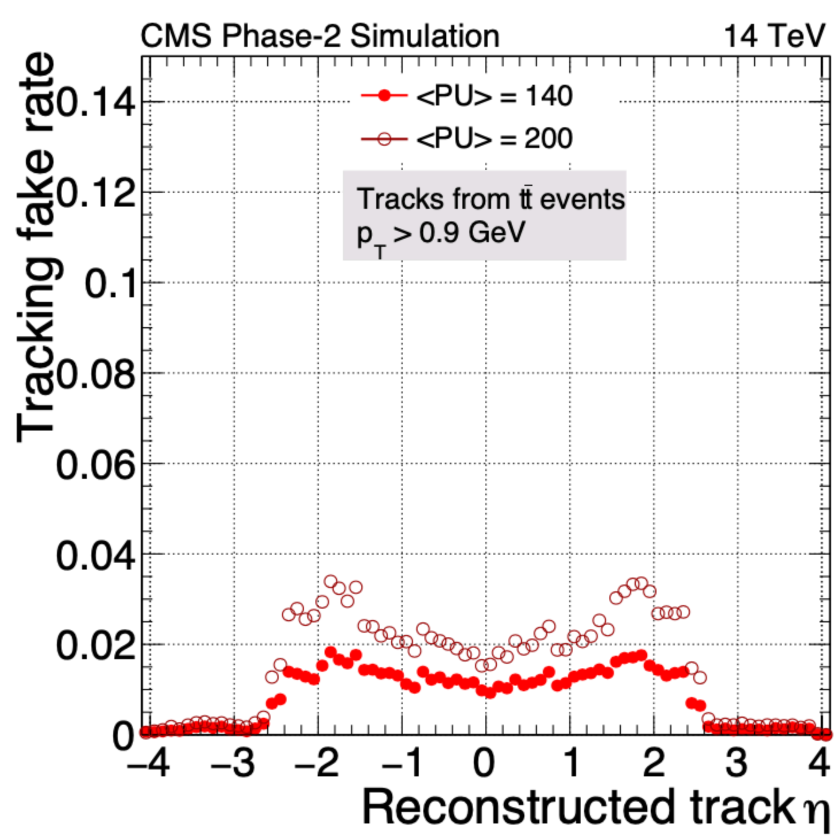


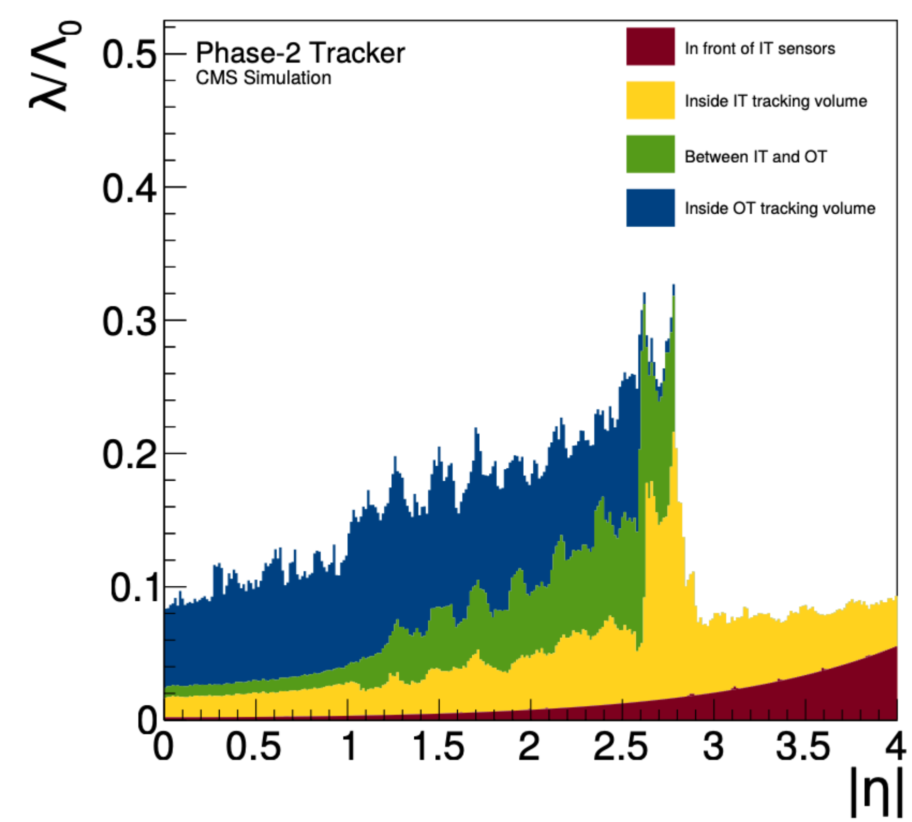
HL-LHC Tracker Performance

- >80% tracking efficiency (p_T > 0.9 GeV) in $t\bar{t}$ high-pileup events
- Low level (<4%) of fake tracks at high pileup
- Substantial reduction of material budget





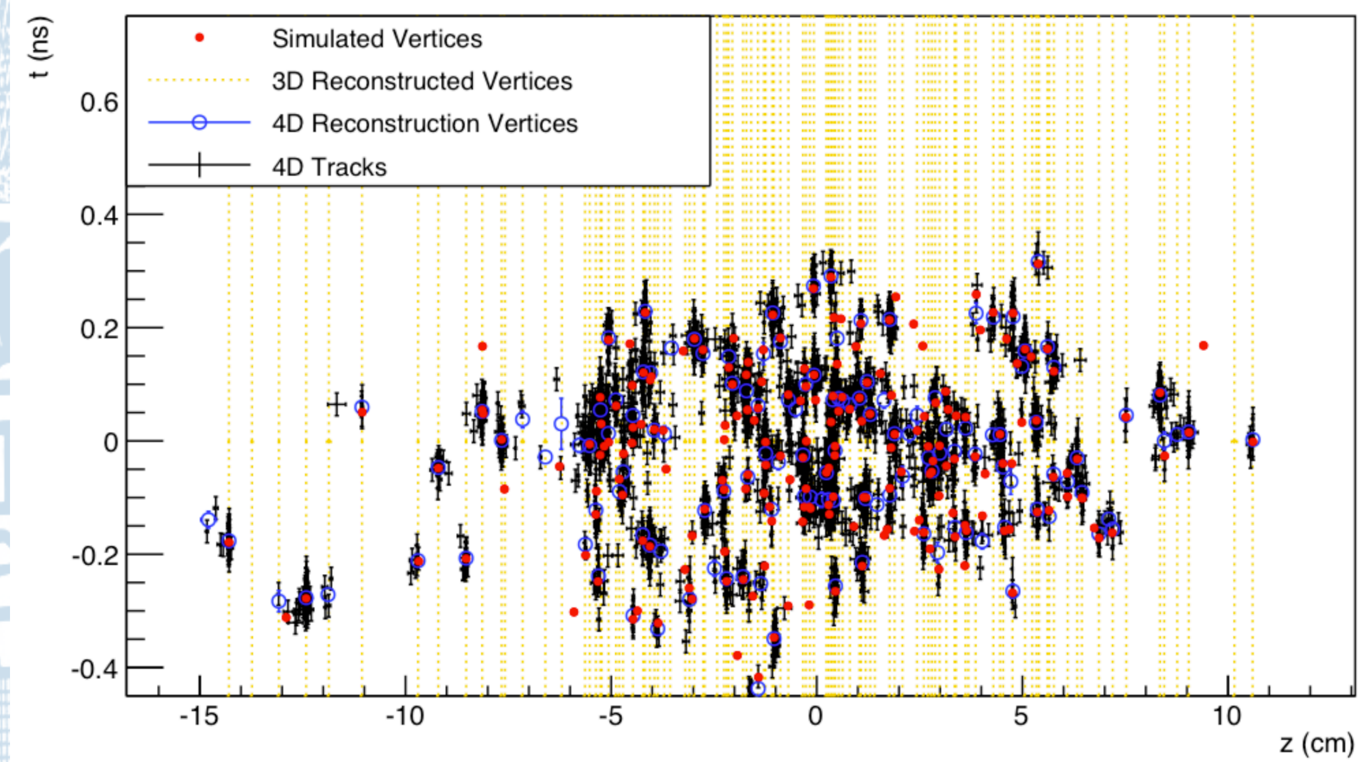


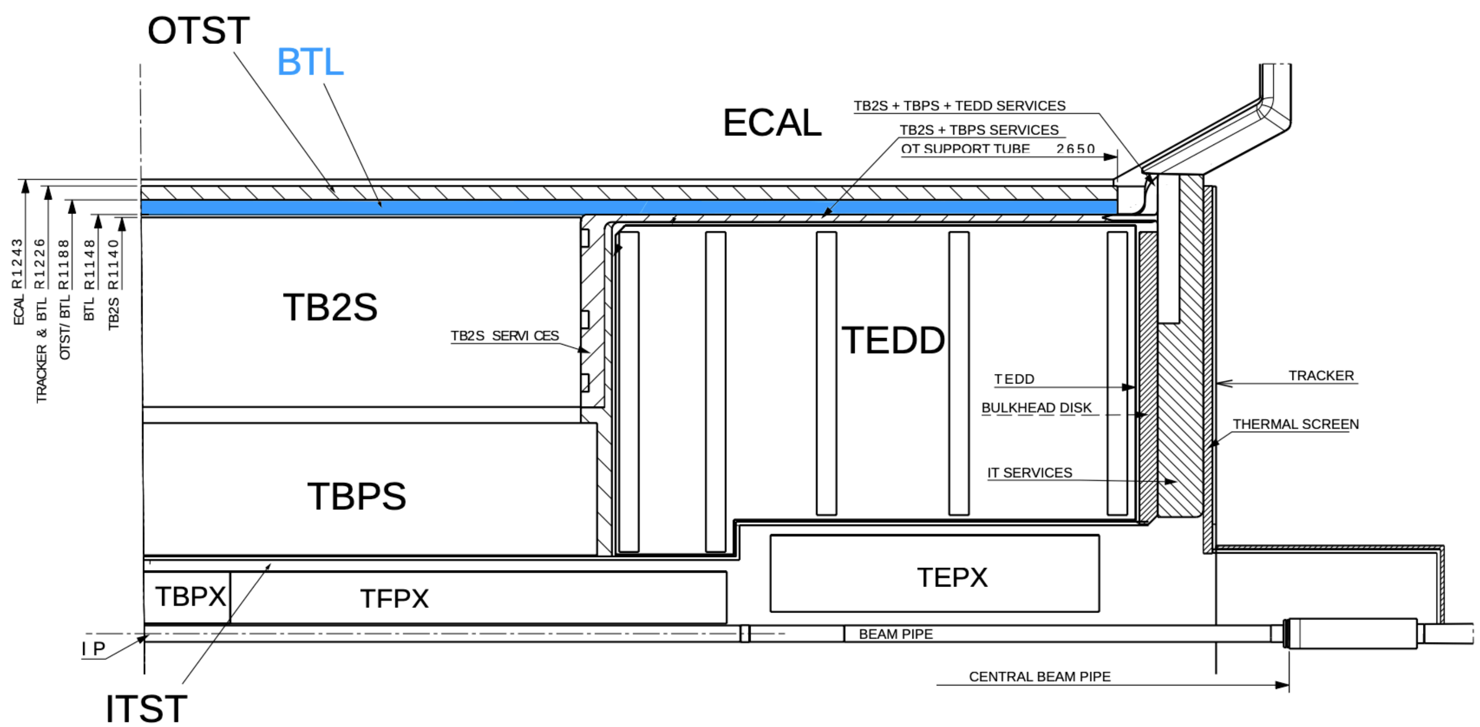


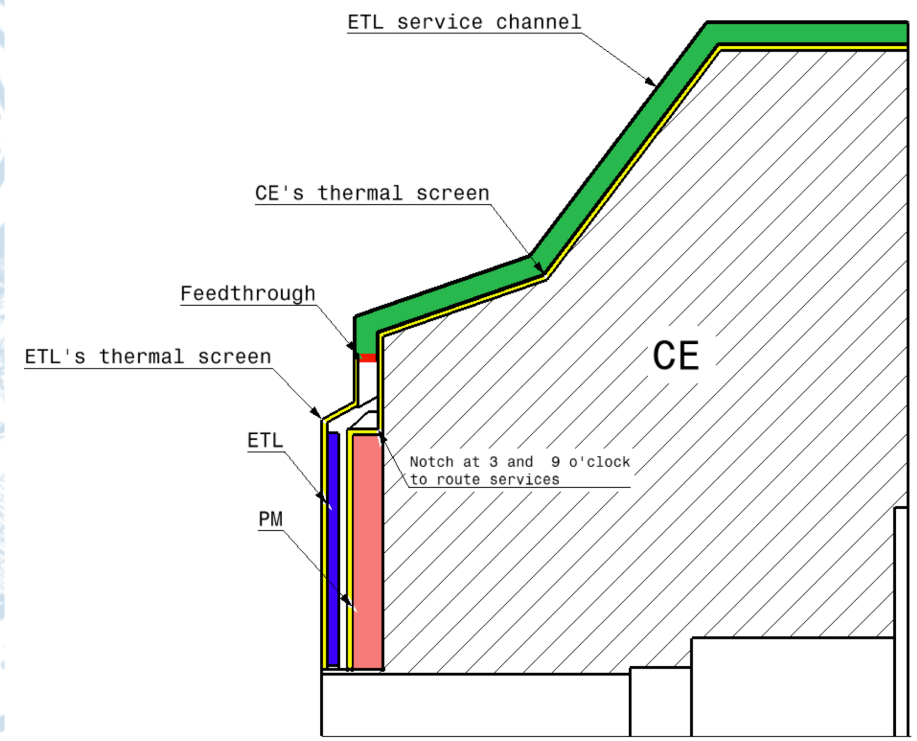
New Timing Layer

- **Brand New Detector Layer!**
- 30-40 ps time resolution on traversing charged particles
- Assigns charged tracks to proper vertex
- Coverage for particle up to $|\eta| < 3$
- Barrel region covered by scintillator (LYSO) and Silicon Photomultipliers
- The endcap region is covered by Low Gain Avalanche Detectors (LGADs)
  - Active gain silicon detectors

2-D Vertex Location

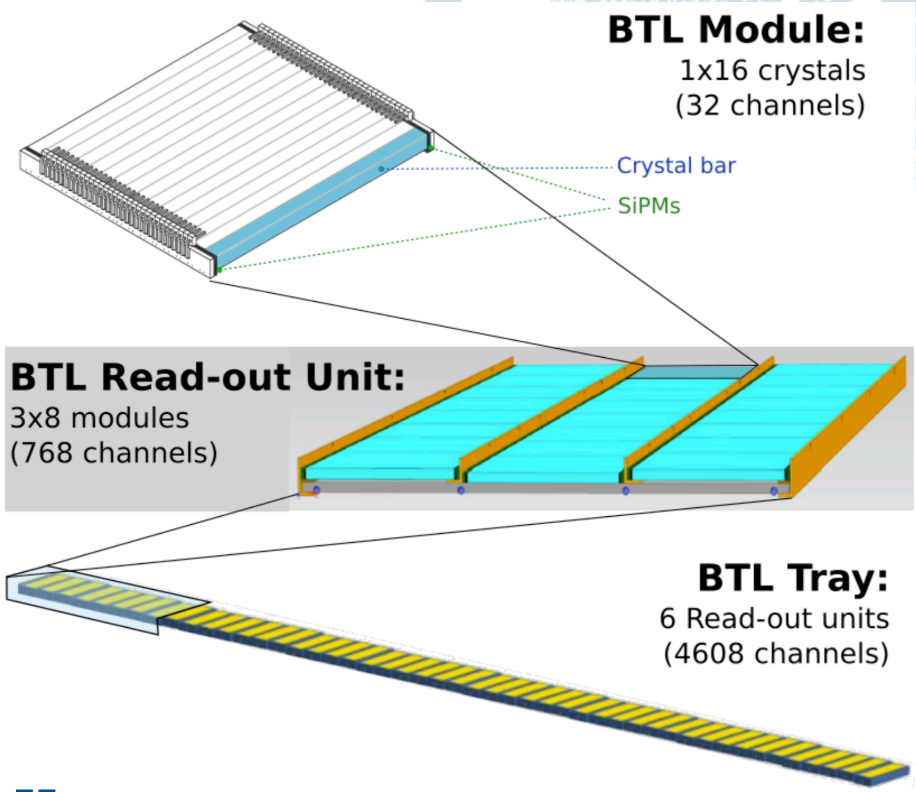


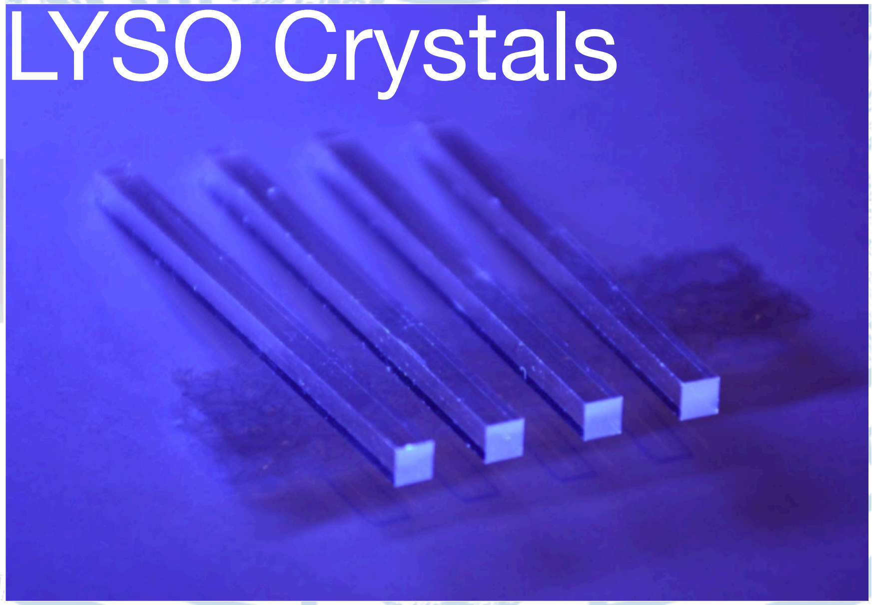


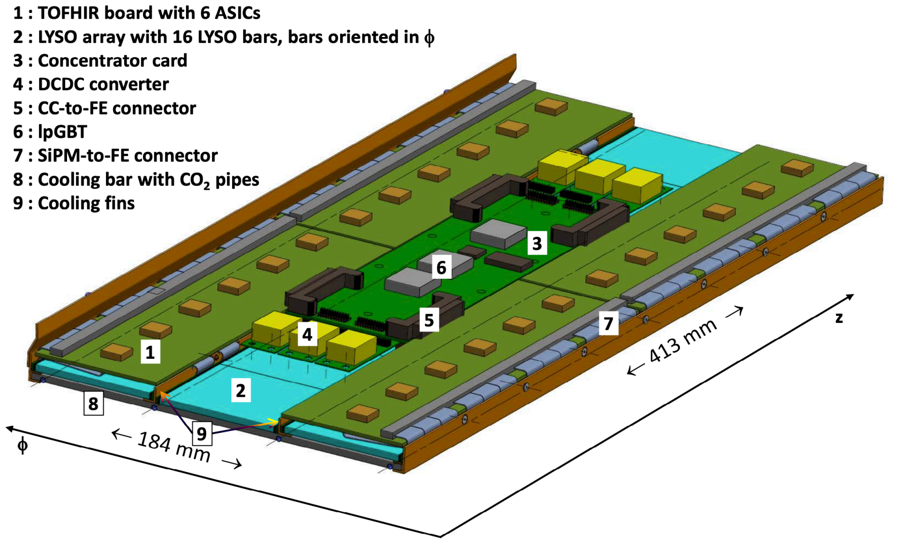


Barrel Timing Layer

- LYSO bars with SiPM Readout
  - Covers up to Tracker/ECAL gap at $|\eta| < 1.45$
  - Inner radius of 1148 mm (40 mm thick)
  - Length 5.2 m along z
  - Surface area of ~38 m^2
    - Total of 332k channels
  - Operates at fluence of 2E14 n_{eq}/cm^2

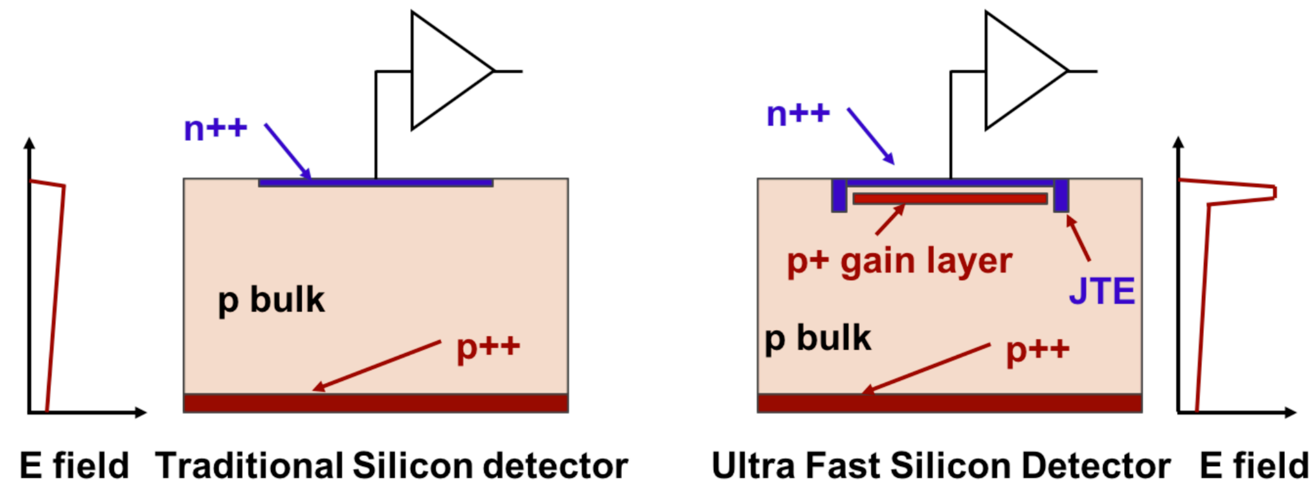


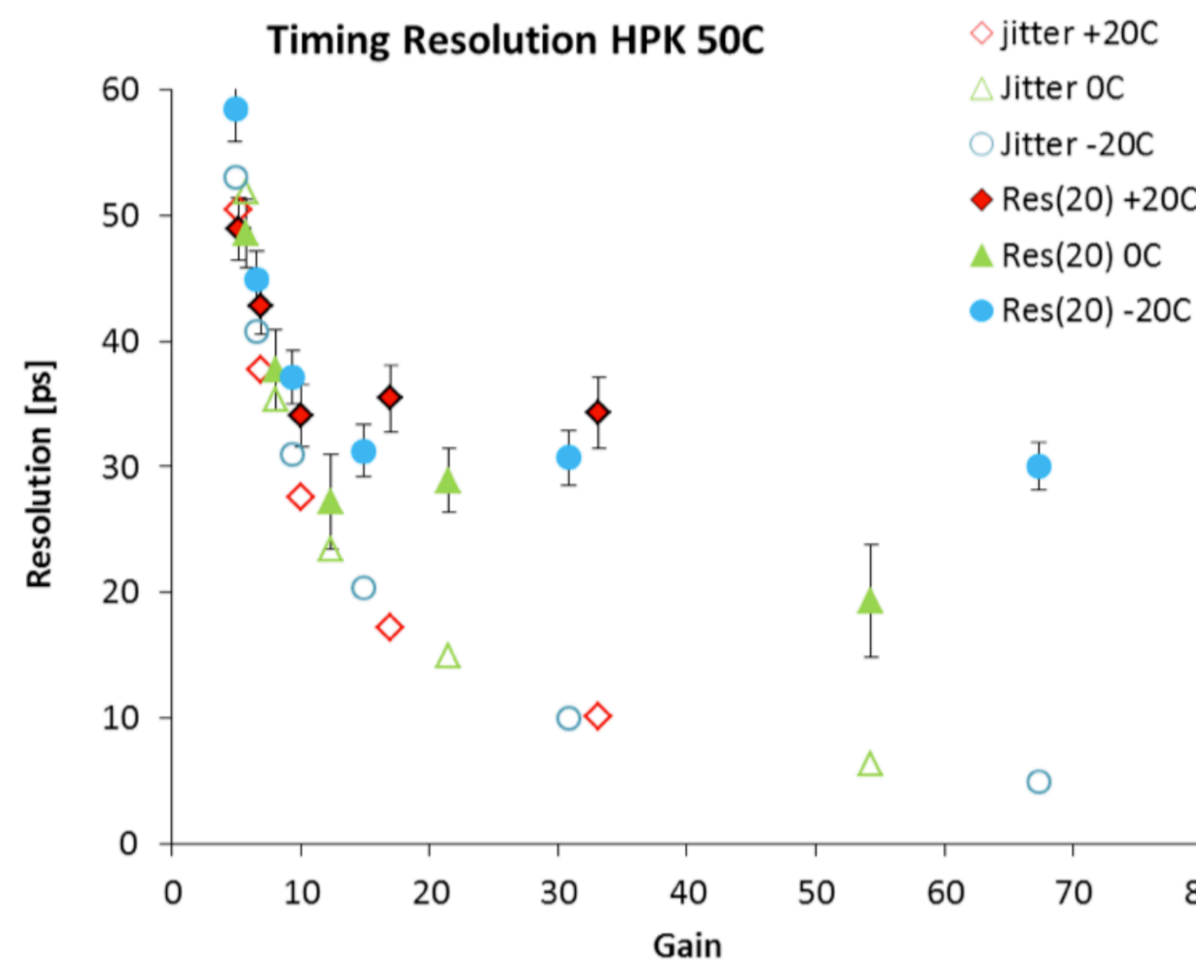




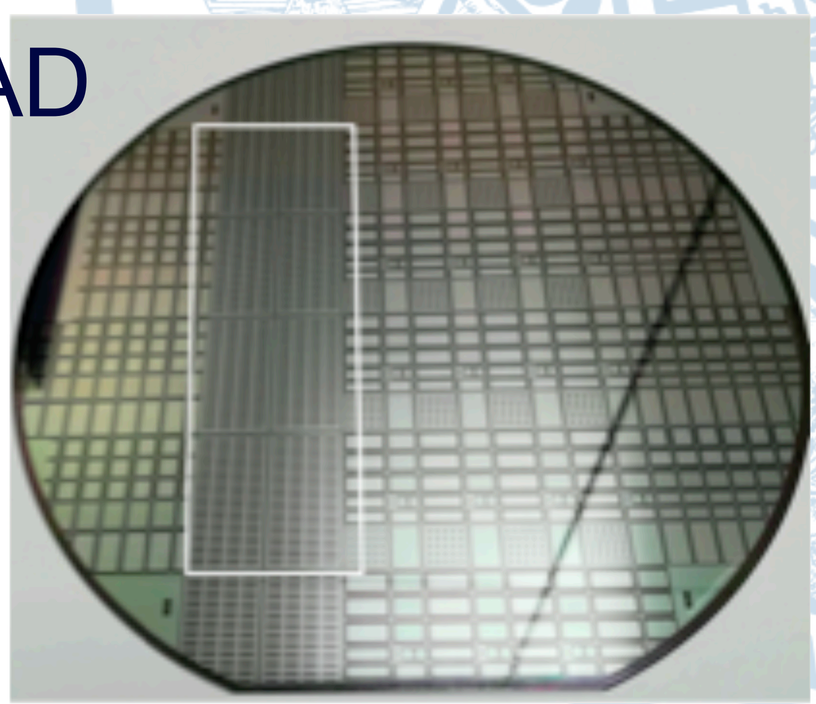
Endcap Timing Layer

- LGAD with internal gain layer
  - Covers $1.6 < |\eta| < 3.0$
  - Z position of 3.0 m
    - 45 mm thick
    - $315 < r < 1200$ mm
  - Surface area of ~14 m^2
  - Operates at a fluence of 2E15 n_{eq}/cm^2



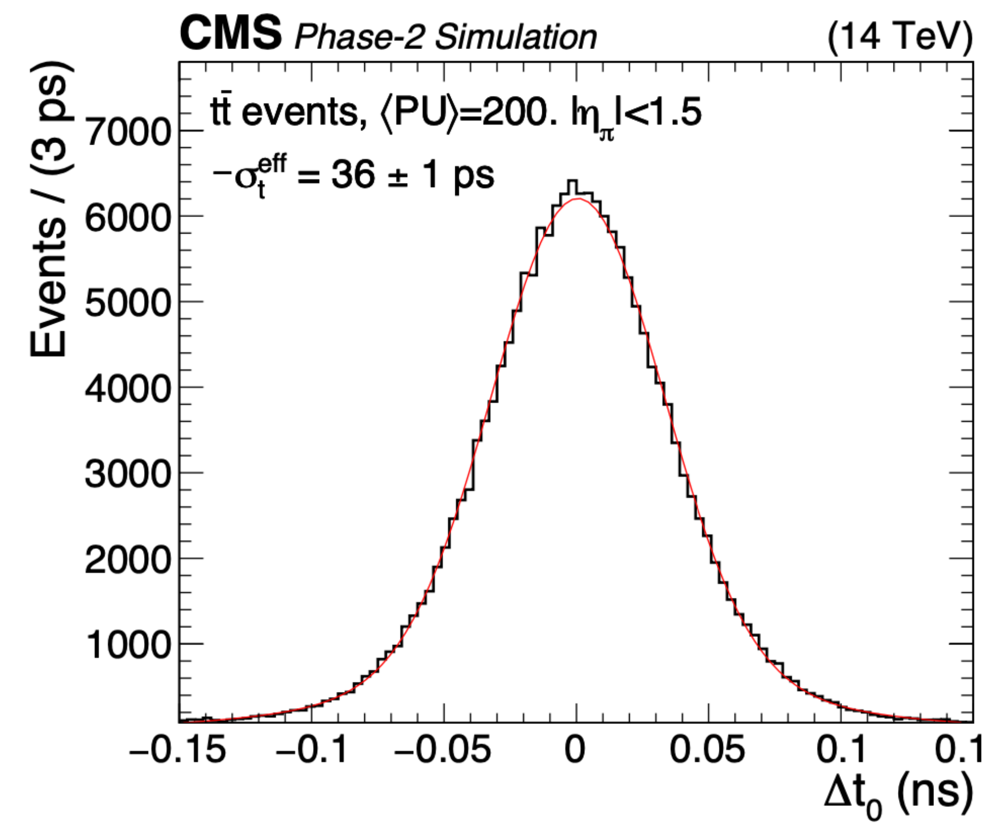


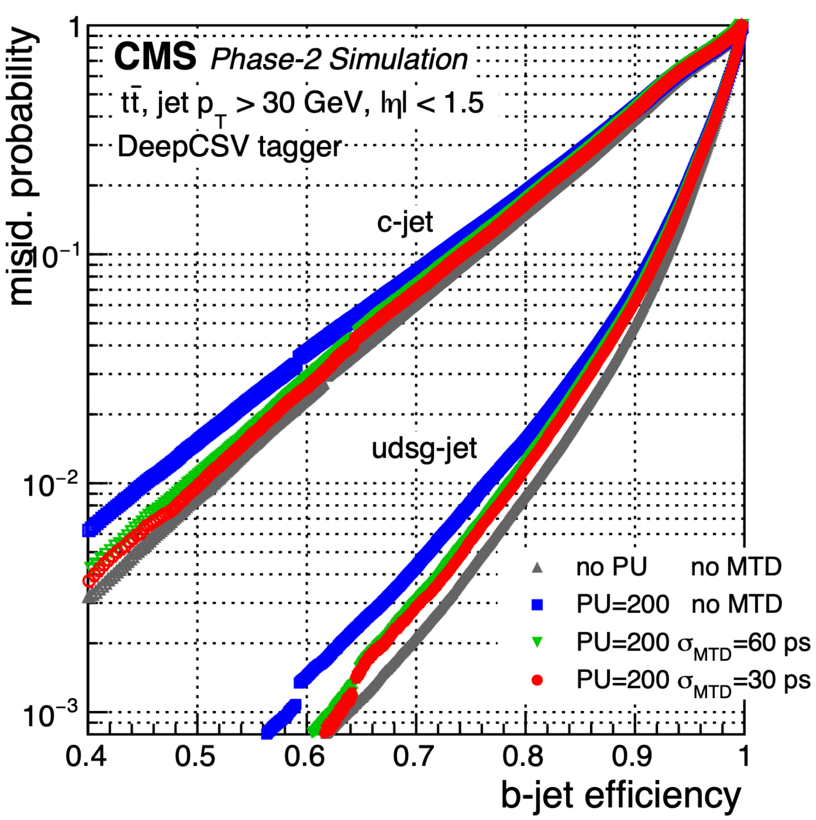
ETL LGAD Wafer

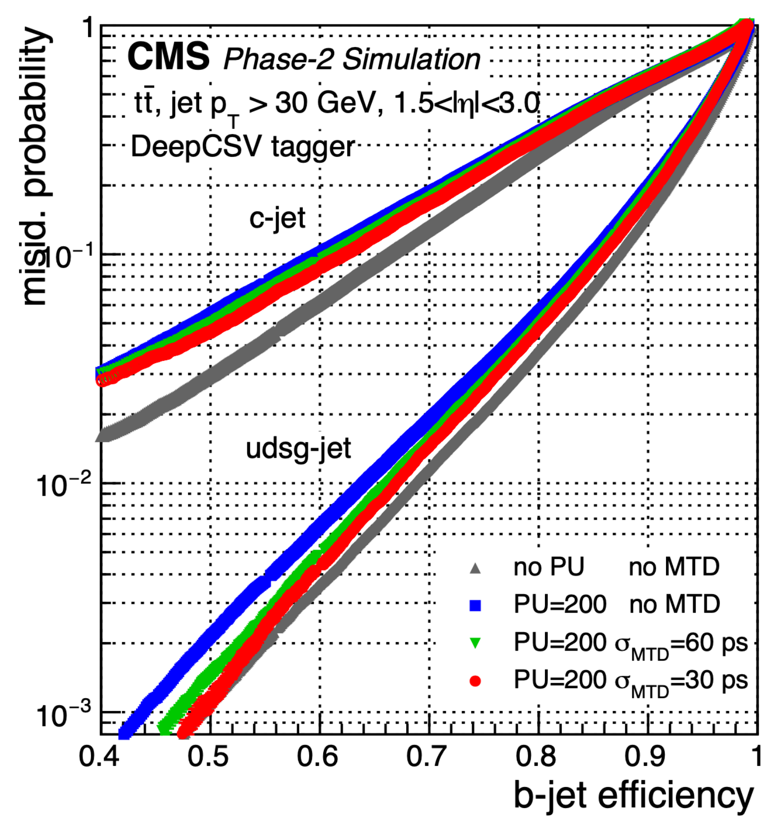


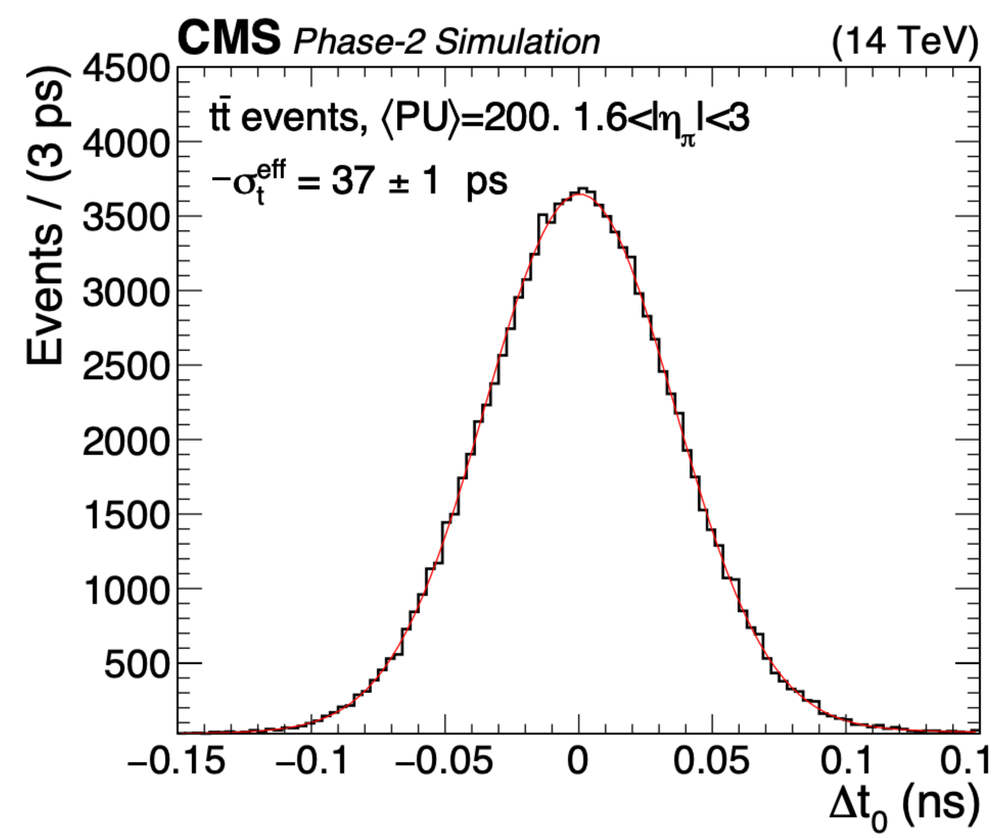
Timing Layer Performance

- Expected excellent initial timing resolution
  - Timing resolution expected to degrade with radiation damage
- 5x reduction in the number of tracks associated with a vertex
- Significant improvement in b-tagging performance at high-pileup



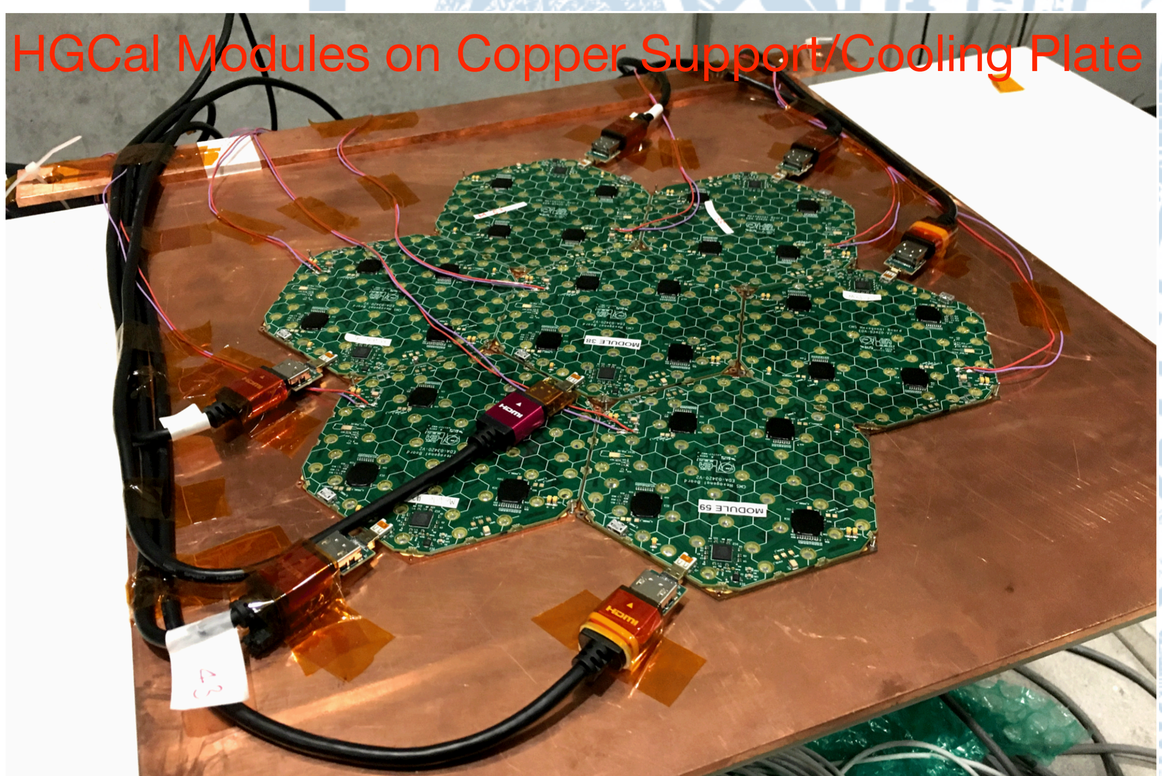






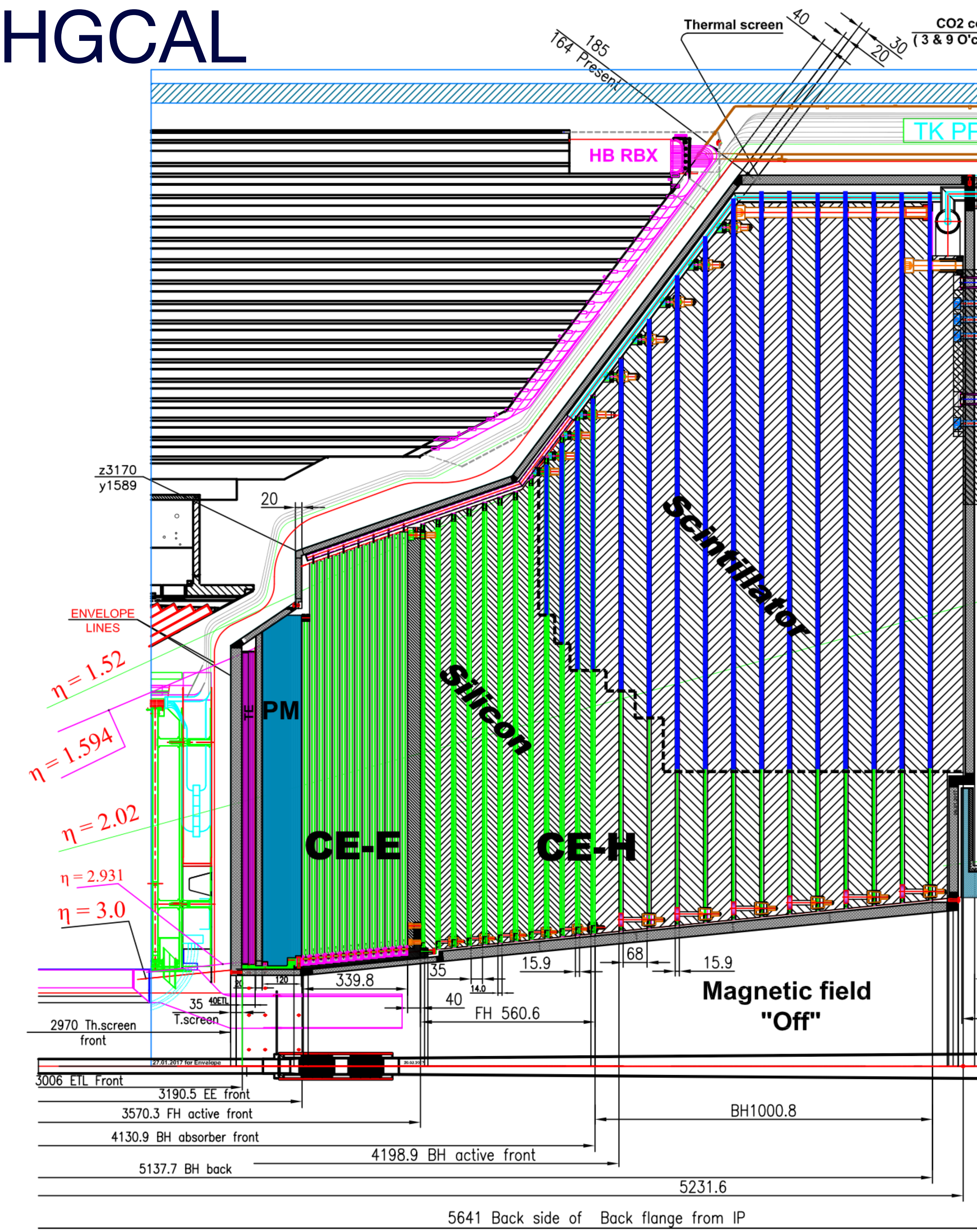
HGCAL Upgrade

- Sampling calorimeter that will replace the ECAL and HCAL endcap
- Layered WCu (75% and 25%) and steel absorber and silicon sensors or scintillating plastic
- Covers $1.5 < |\eta| < 3.0$
- Silicon sensors segmented into ~1 cm hexagonal cells
  - Maximizes use of 8” silicon wafer
- 28 active EM sampling layers
  - Double sided sensors
  - 26 radiation Lengths
- 24 active Hadronic sampling layers
  - 10.7 total hadronic interaction lengths
- System operated of -30 C



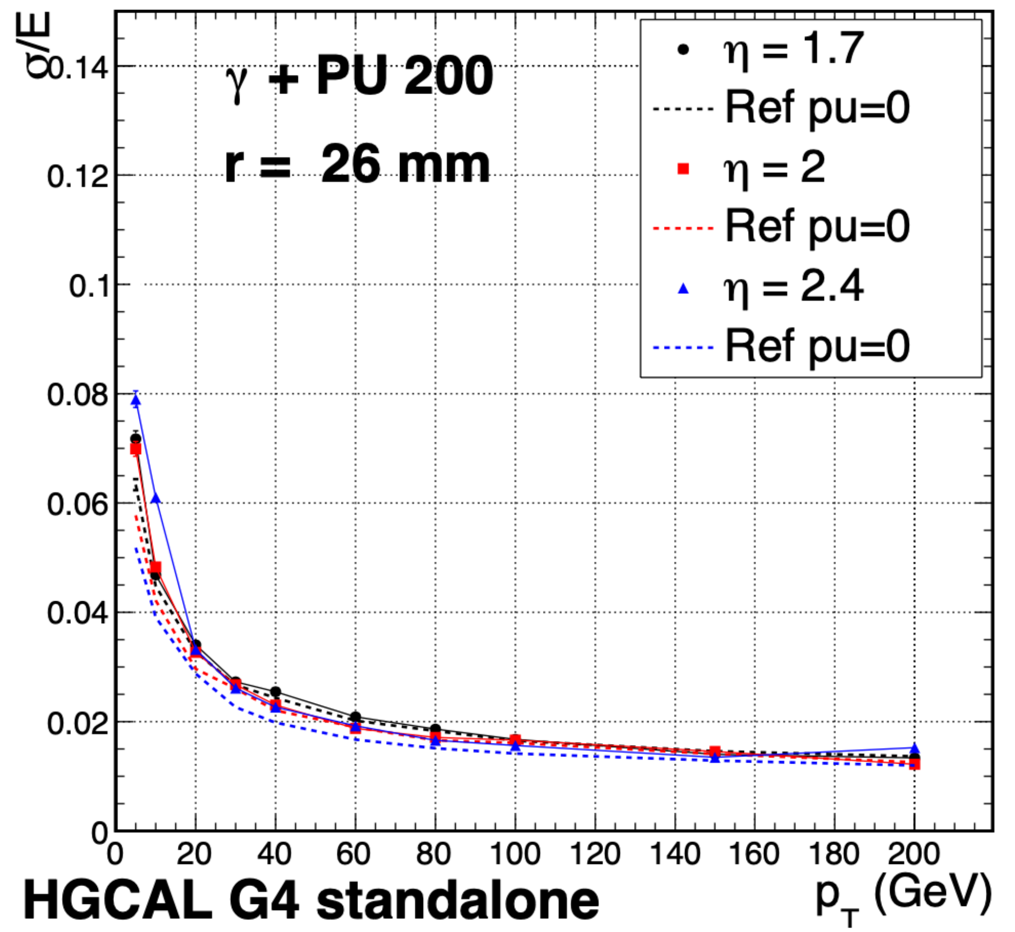
HGCal Modules on Copper Support/Cooling Plate

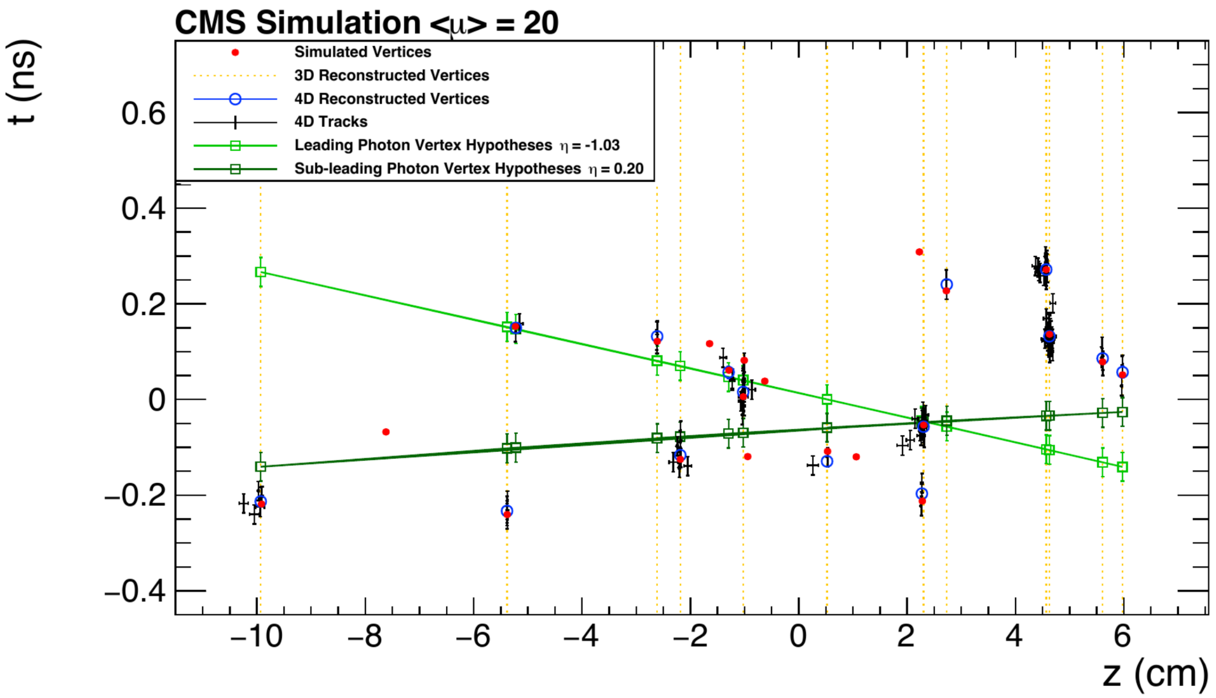
HGCAL

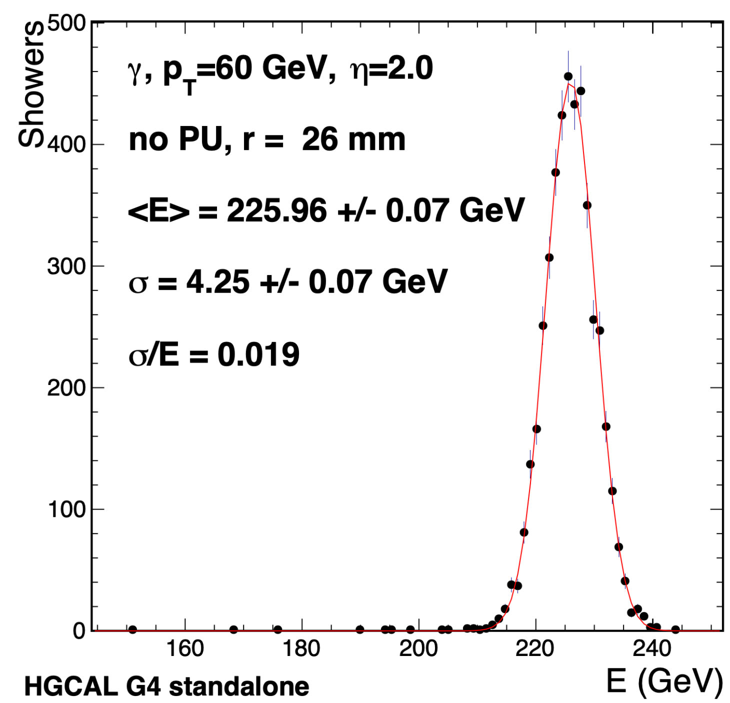


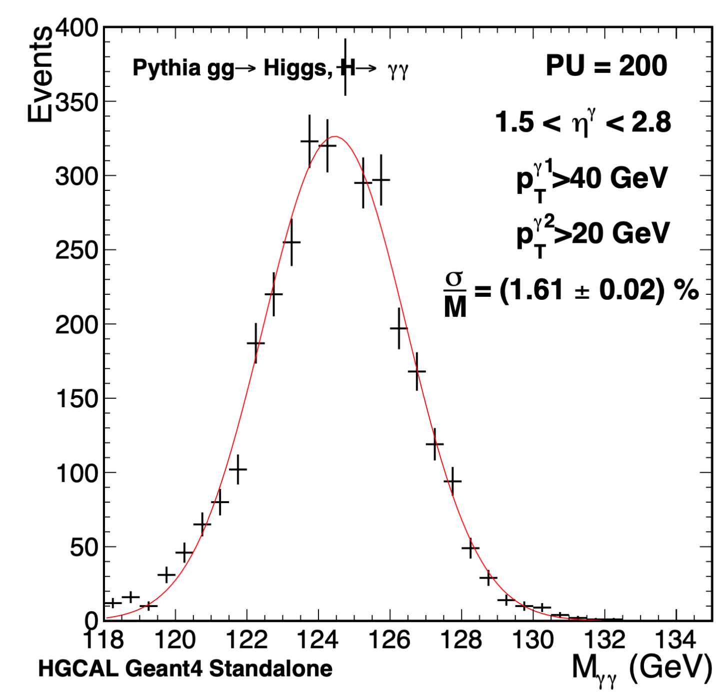
HGCal Performance

- Expected energy resolution below 5% for 300μm-thick sensor area
- Time information enables 4-D shower shapes for vertexing
  - Target resolution of 30 ps for 5 GeV clusters
- Improved PF reconstruction at high η





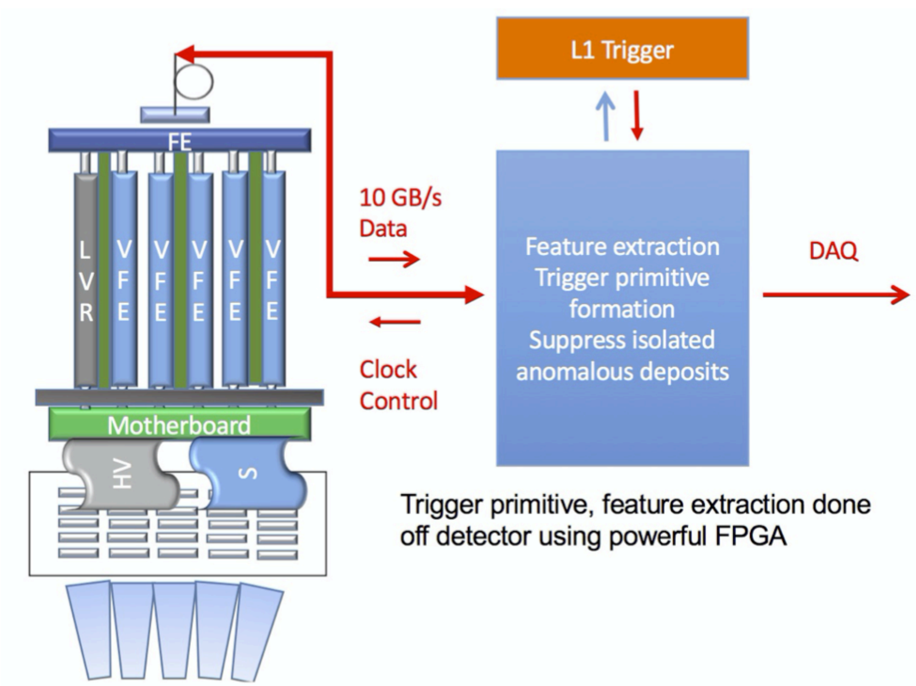


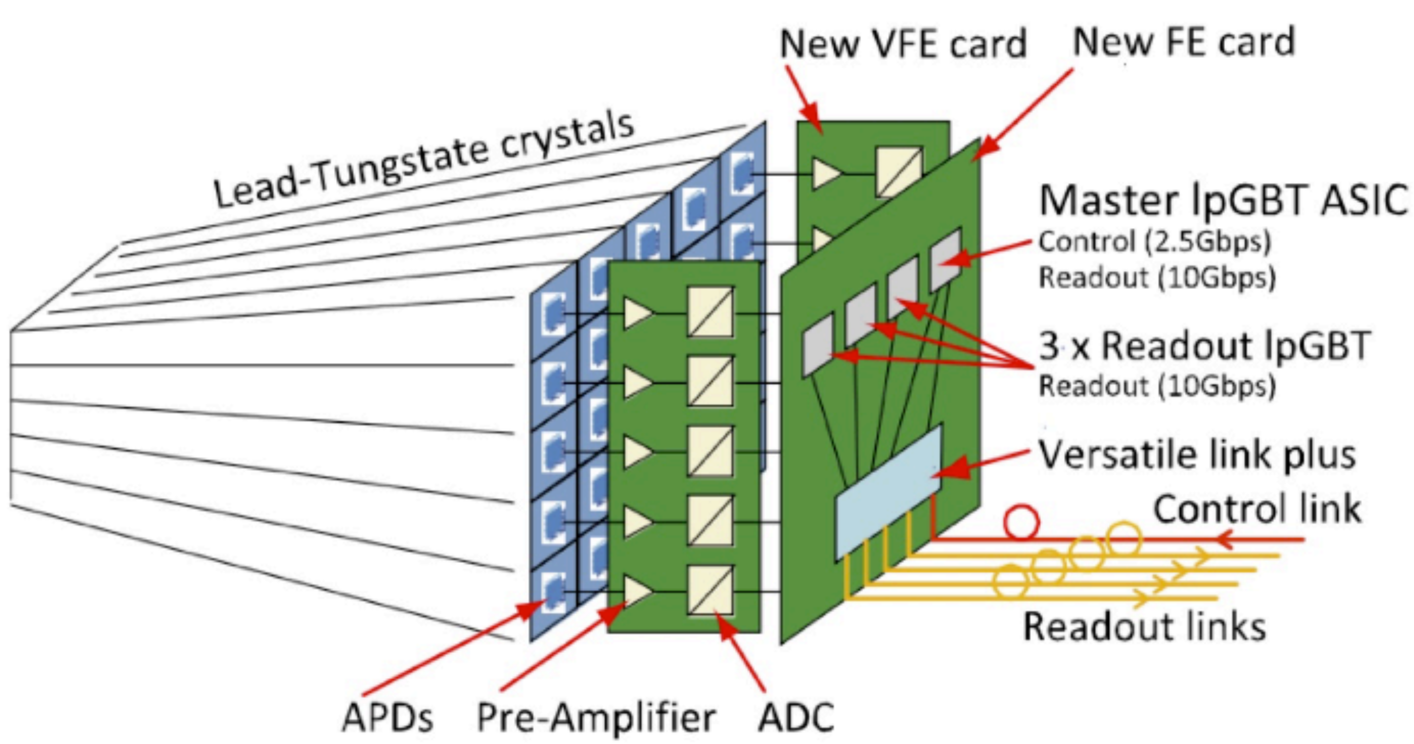


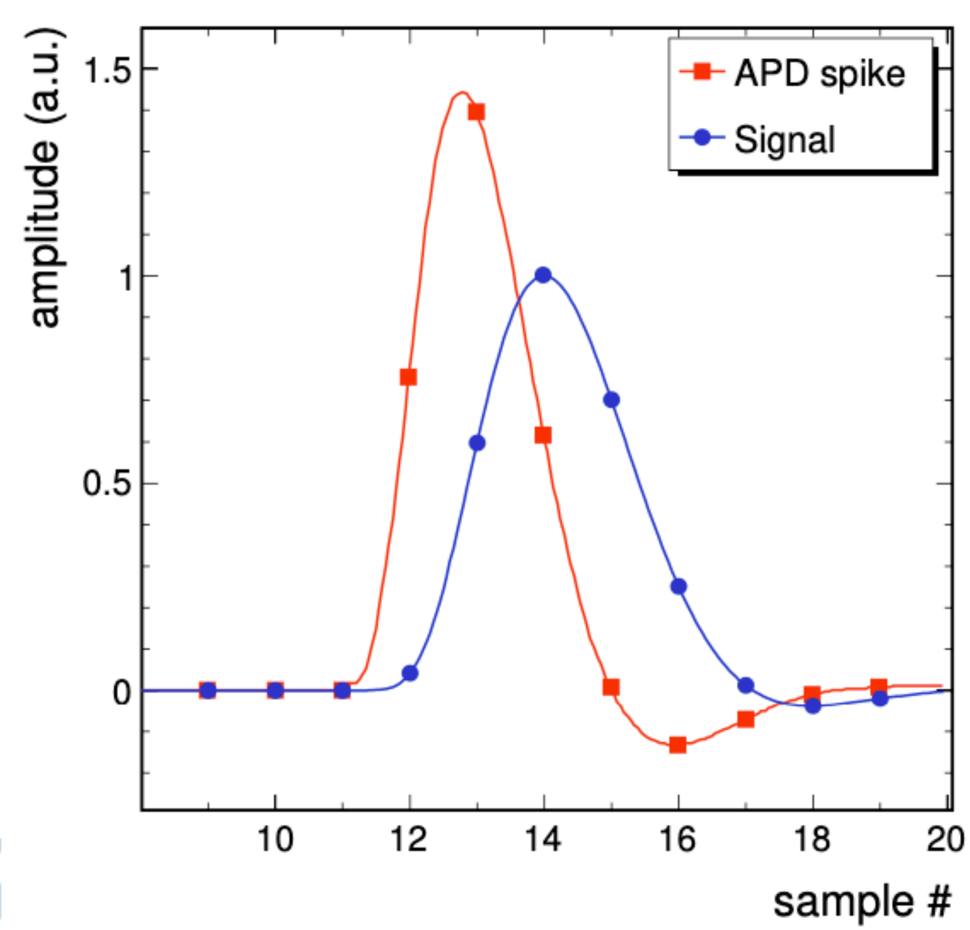
ECAL Barrel Upgrade

- Upgrade will keep $PbWO_4$ crystals and APDs
- Increase maximum trigger latency from 4 μs to 12.5 μs
- Accommodate new L1 rate of 750 kHz (from 100 kHz)
- Will provide single crystal granularity at L1
  - Upgraded from 5x5 trigger tower
- A new very front end (VFE) will remove spikes from the APDs at L1
- Reduce the operating temperature from 18 to 9 C

Diagram of upgrade EB electronics

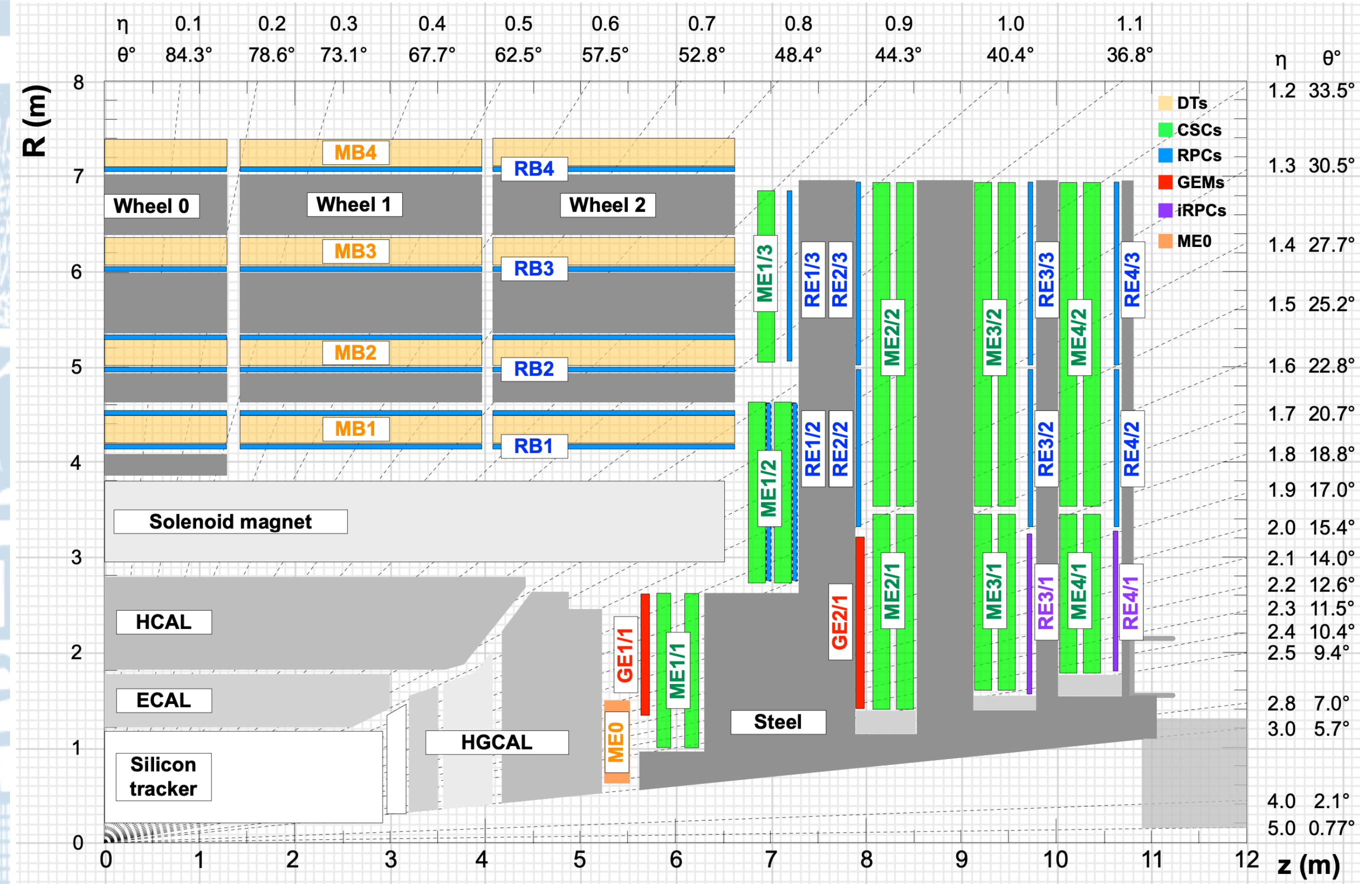


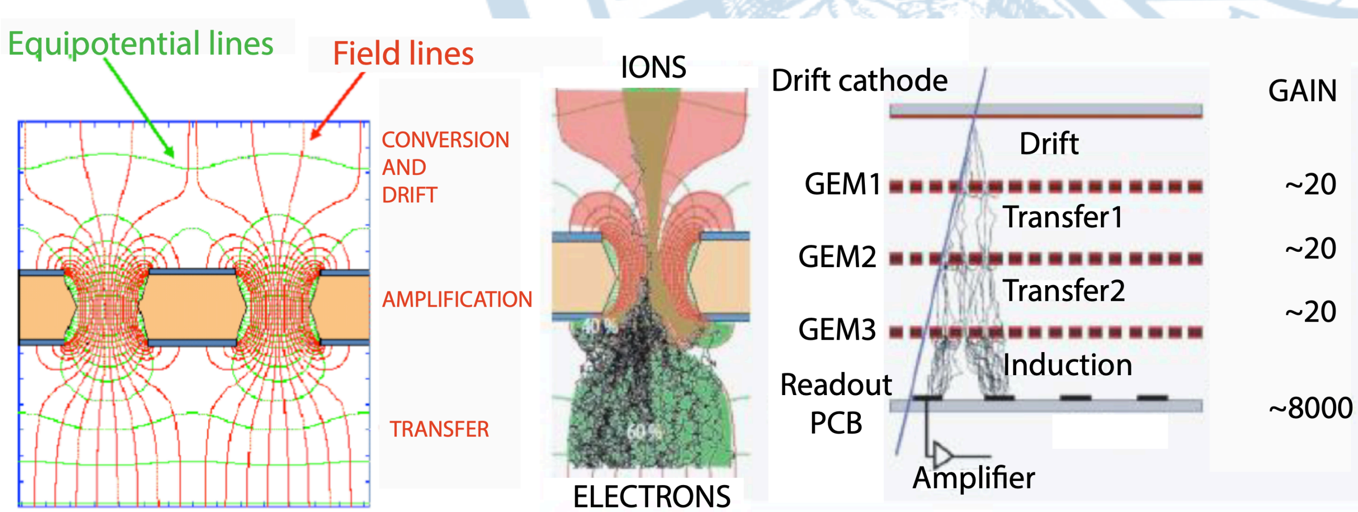




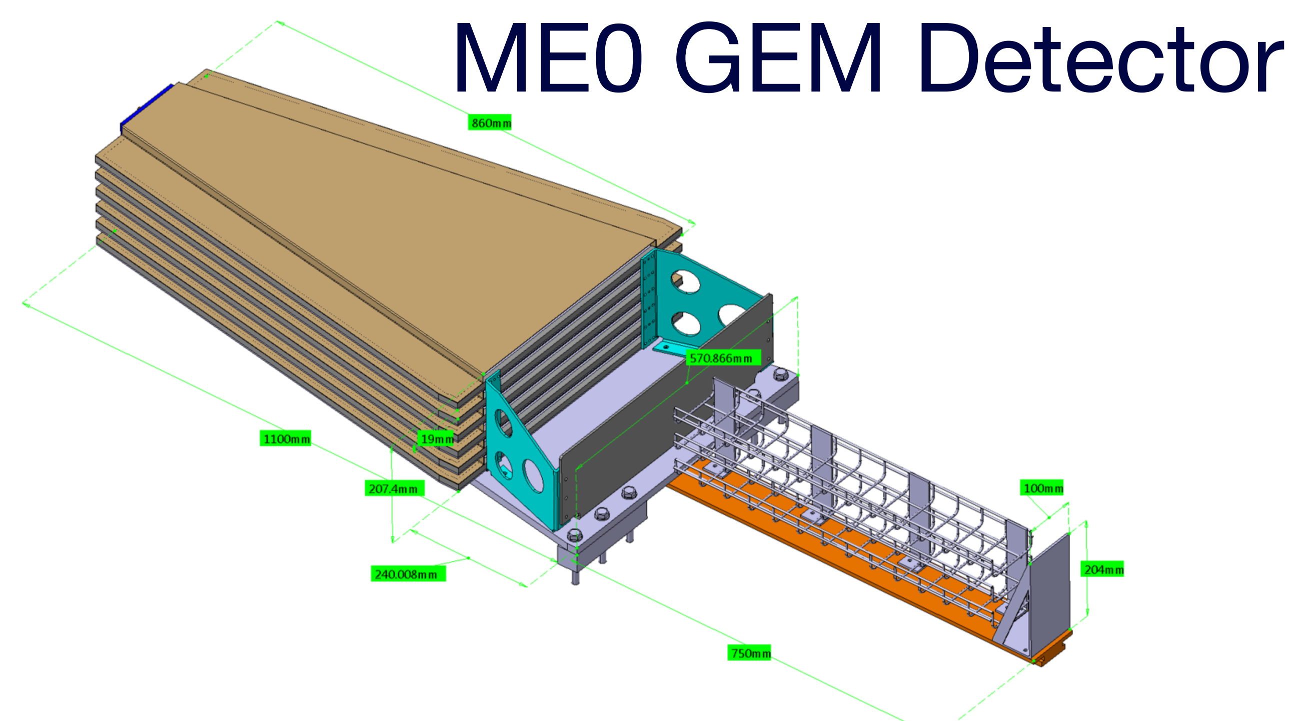
Muon System Upgrade

- New detectors for high η muons
  - GEM and RPCs cover $1.6 < |\eta| < 2.4$
  - ME0 extends muon coverage to $|\eta| < 2.8$
  - Improved hit coverage
    - Lower background rate at high η
- Upgrade frontend and backend electronics to handling increased hit rate and trigger latency



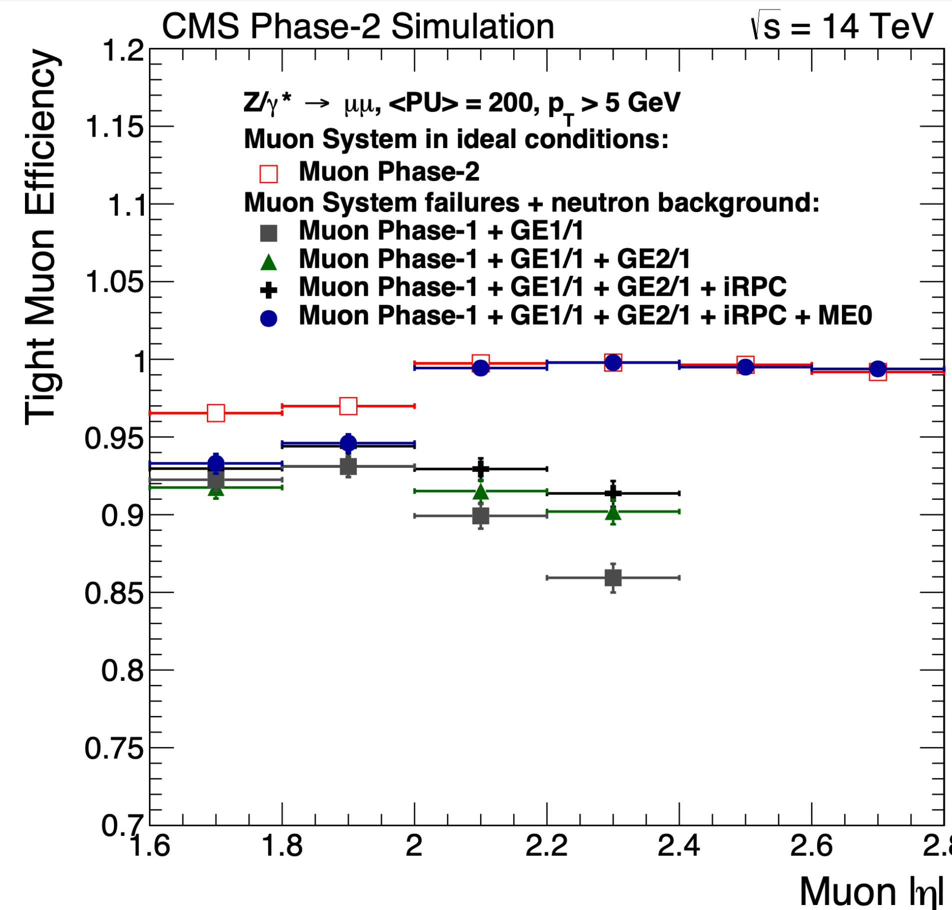


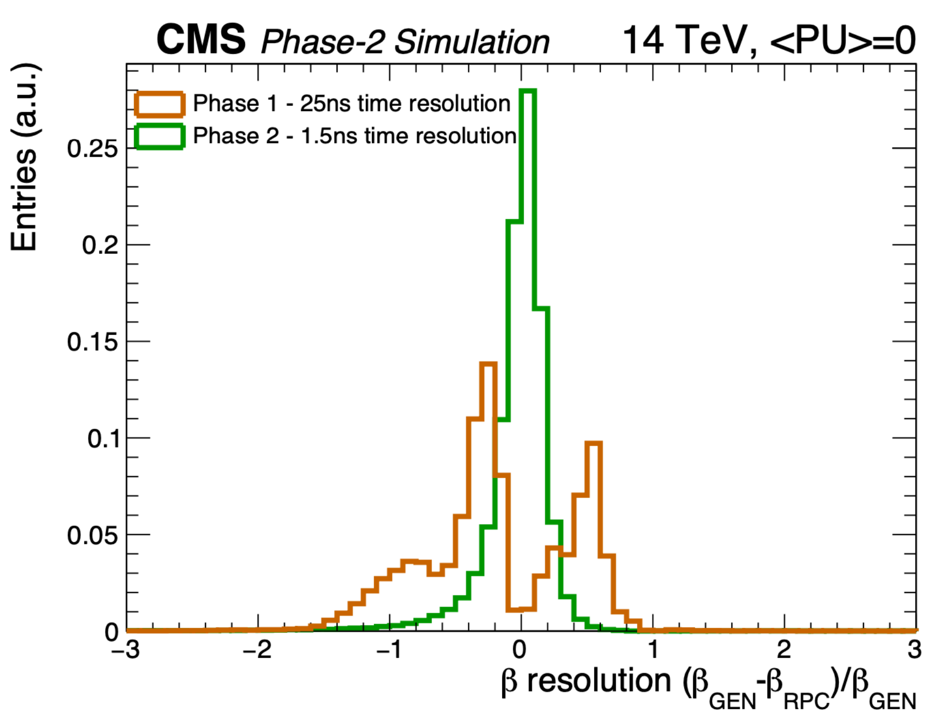
ME0 GEM Detector

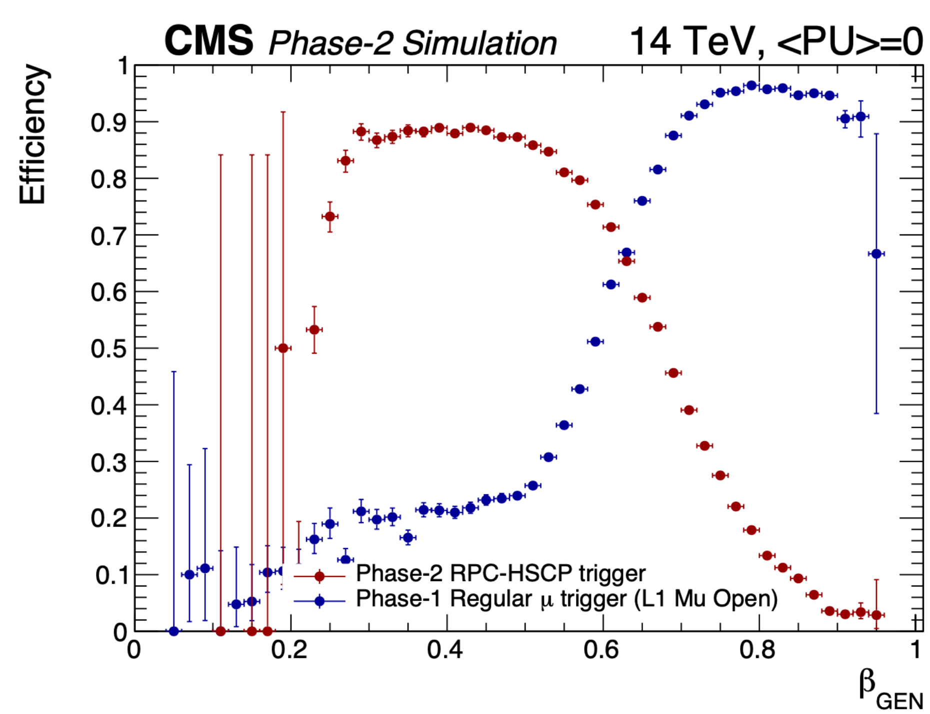


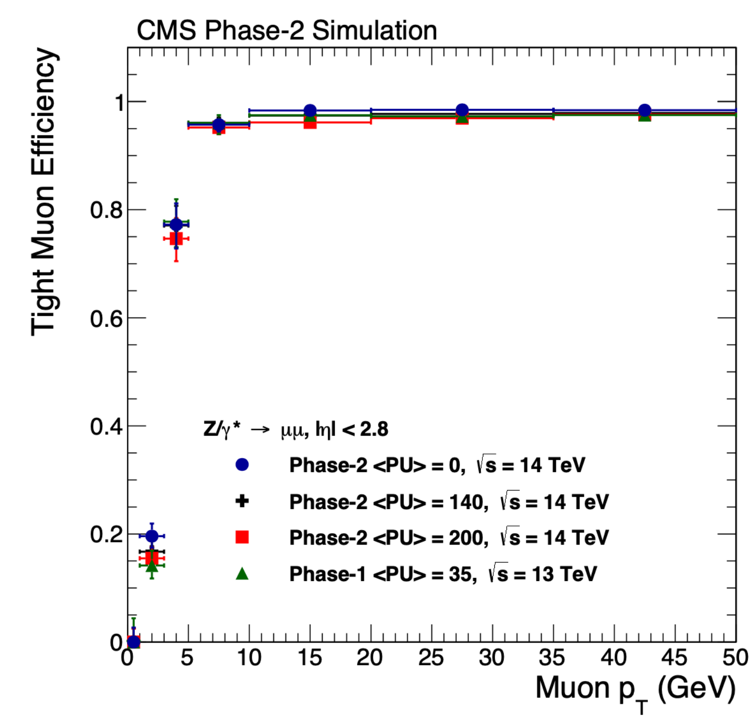
Upgrade Muon System Performance

- Upgraded muon system will maintain physics performance in the HL-LHC era
  - Extents muon detection to |η| < 2.8
- Significant improvements in time resolution
- Ability to include BSM physics triggers (HSCP)



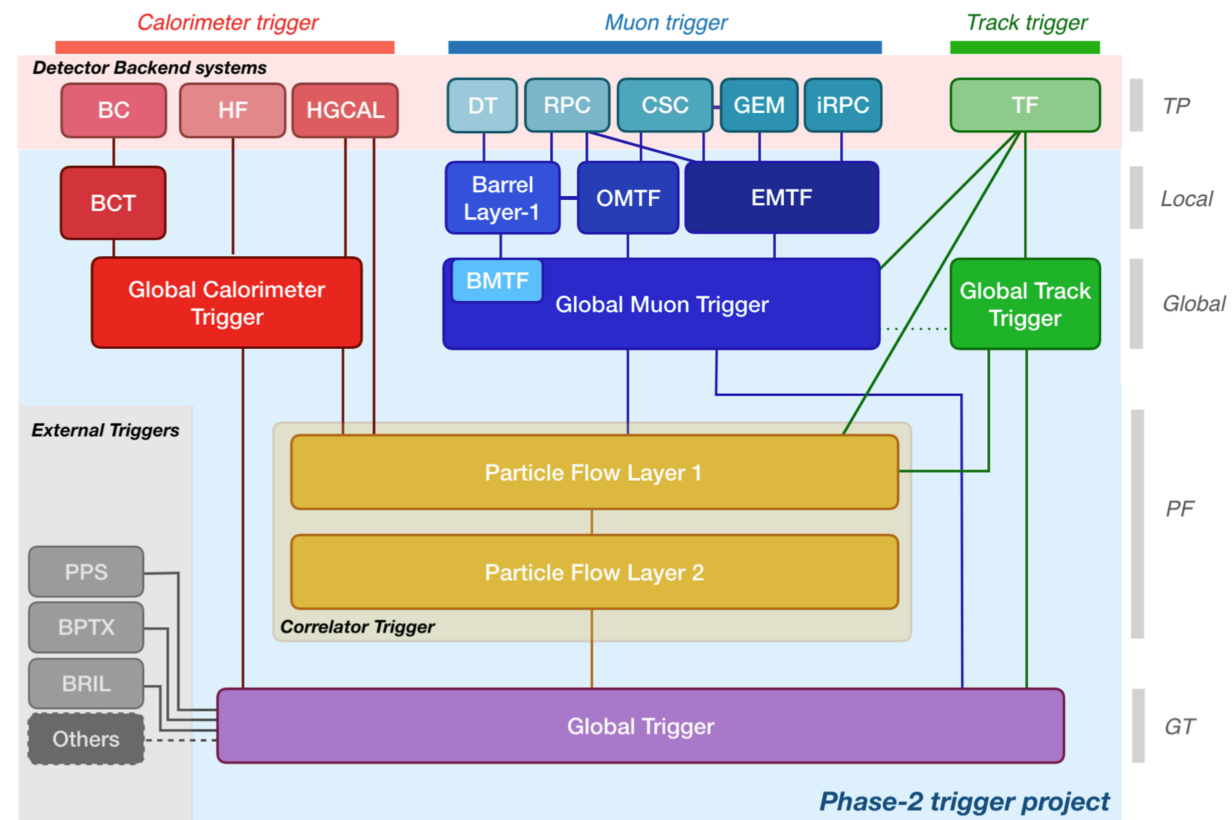


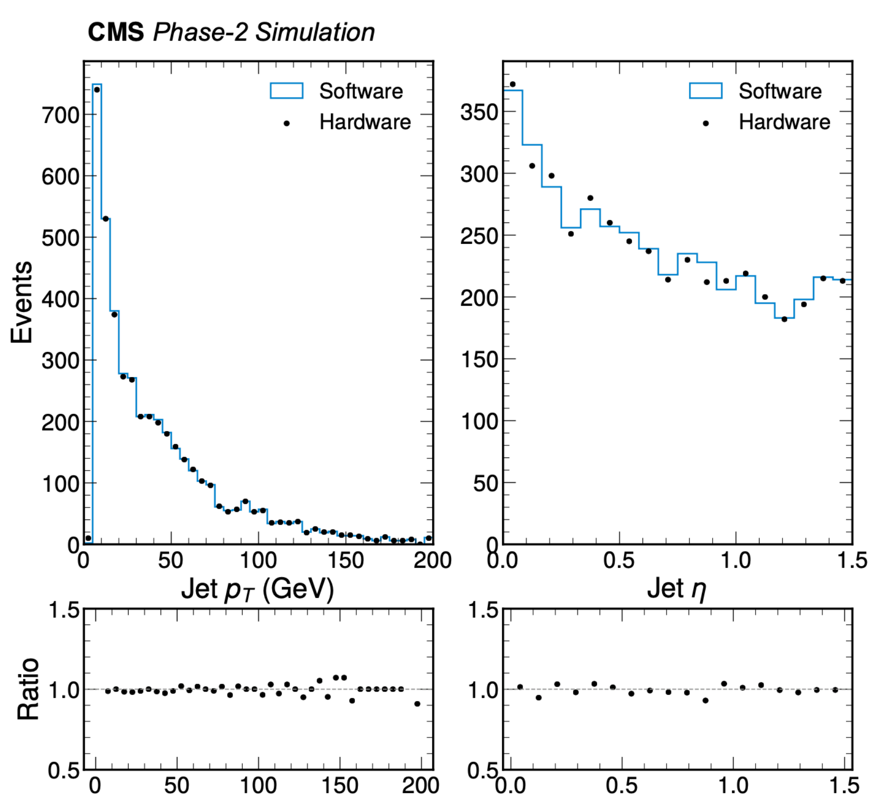


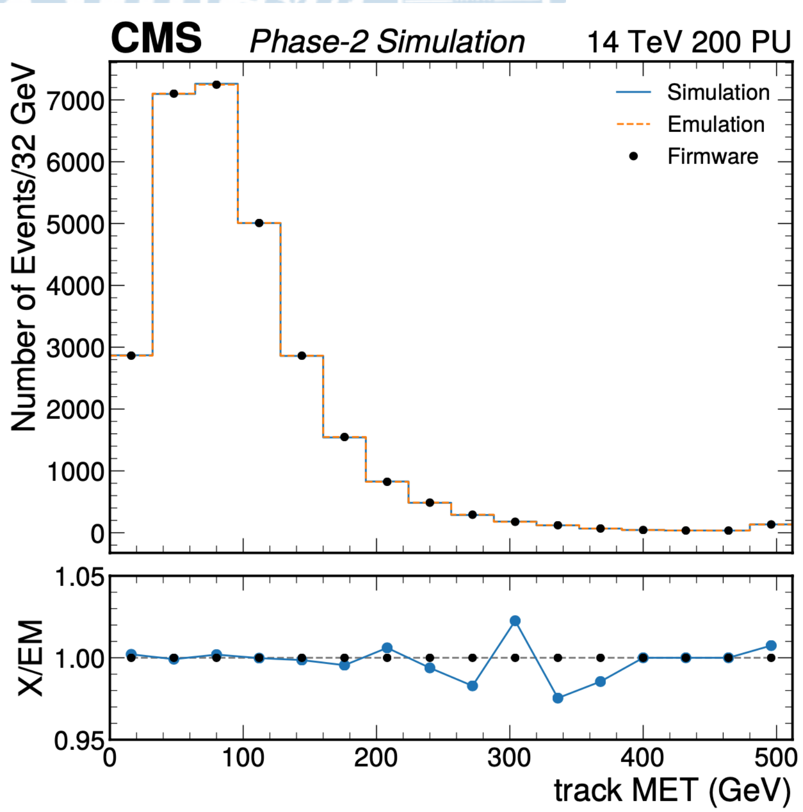


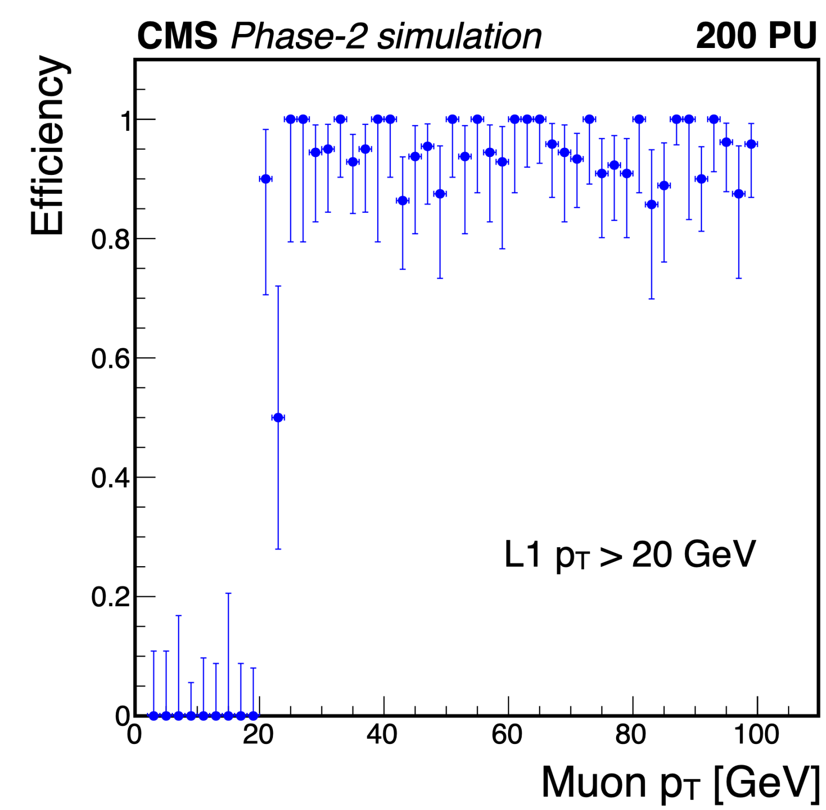
Trigger and DAQ Upgrade

- Readout systems and data acquisition system improved to handle the higher trigger rates
  - L1 trigger rate increased from 100 kHz to 750 kHz
  - HLT rate increased from 1 kHz to 7.5 kHz
- L1 trigger moved to FPGA based system
  - Includes tracking information at L1
    - A first for CMS
  - New correlation trigger to combine information of multiple sub-systems at L1
  - Particle flow can now be implemented at L1









Summary

- HL-LHC will produce up to 4000 fb-1
  - ~20x more data than currently collected
    - 4x current instantaneous luminosity
- High-occupancy environment requires substantial detector upgrades
  - Completely replace tracking detector
  - <60 ps picosecond timing resolution used for vertex identification
  - High-granularity endcap replaces current calorimeter endcap
  - Extend physics object identification for $|\eta| < 4.0$
  - Substantially increase trigger rates
    - 7.5x L1 and HLT trigger rate
    - Tracker information and PF included at L1
- Expect CMS to maintain physics performance in HL-LHC era