CMS Upgrade and Future

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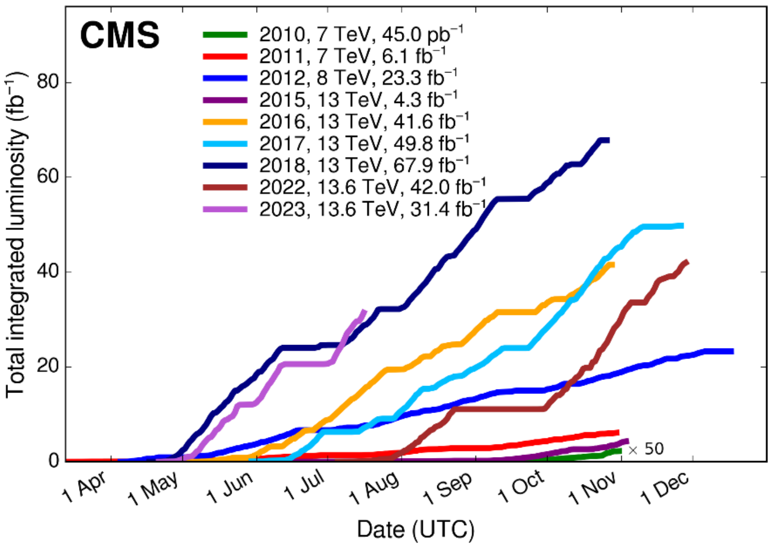
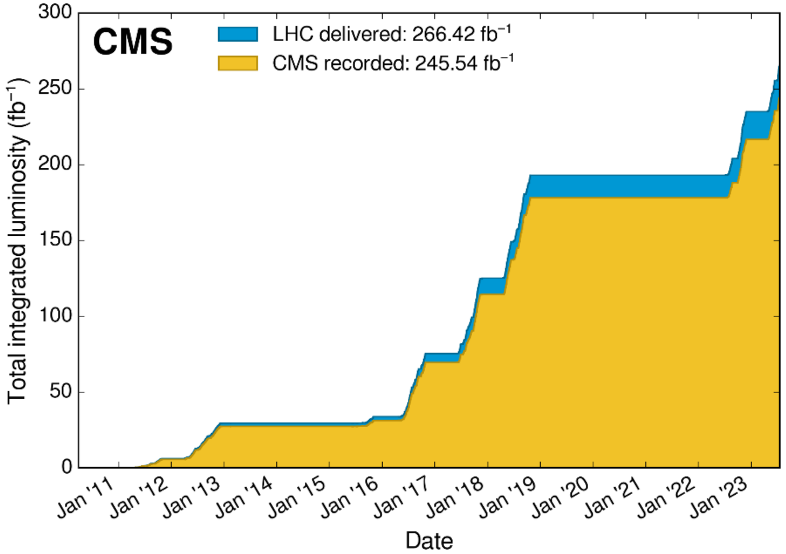
On behalf of the CMS collaboration

Outline

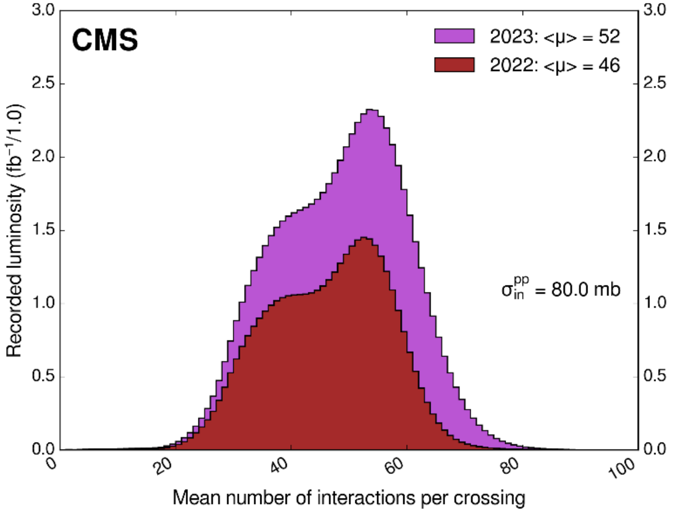
- **Where we stand now**
  - LHC and CMS Performance
  - Current CMS Detector
- **High Luminosity-LHC (HL-LHC)**
  - Motivations
  - Challenges
- **Phase II Upgrade**
  - Tracker
  - Muon System
  - Calorimeters

LHC and CMS Performance



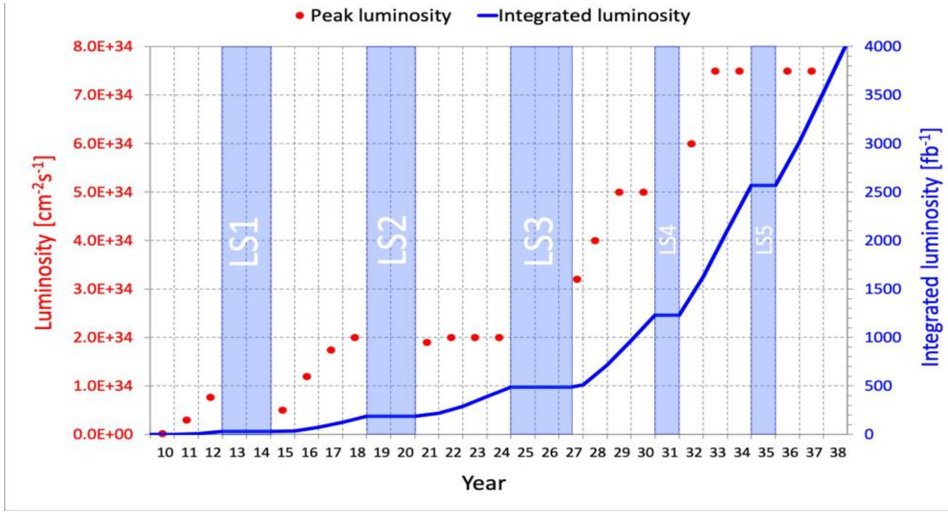


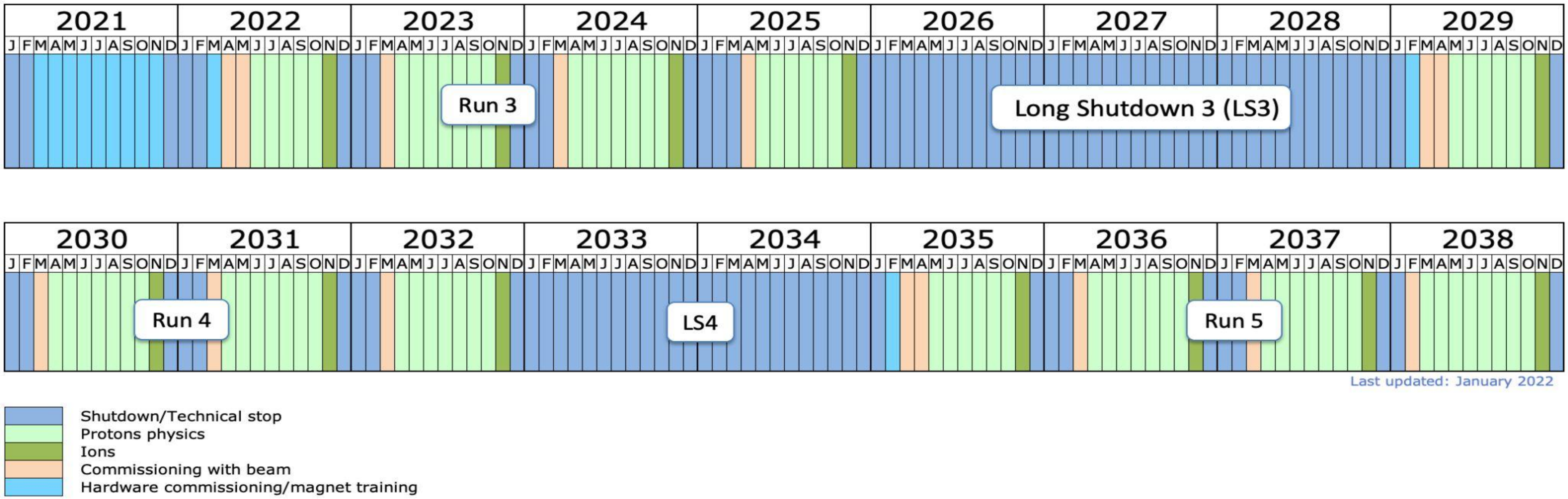
CMS recorded above 245 fb^{-1} of integrated luminosity to date.



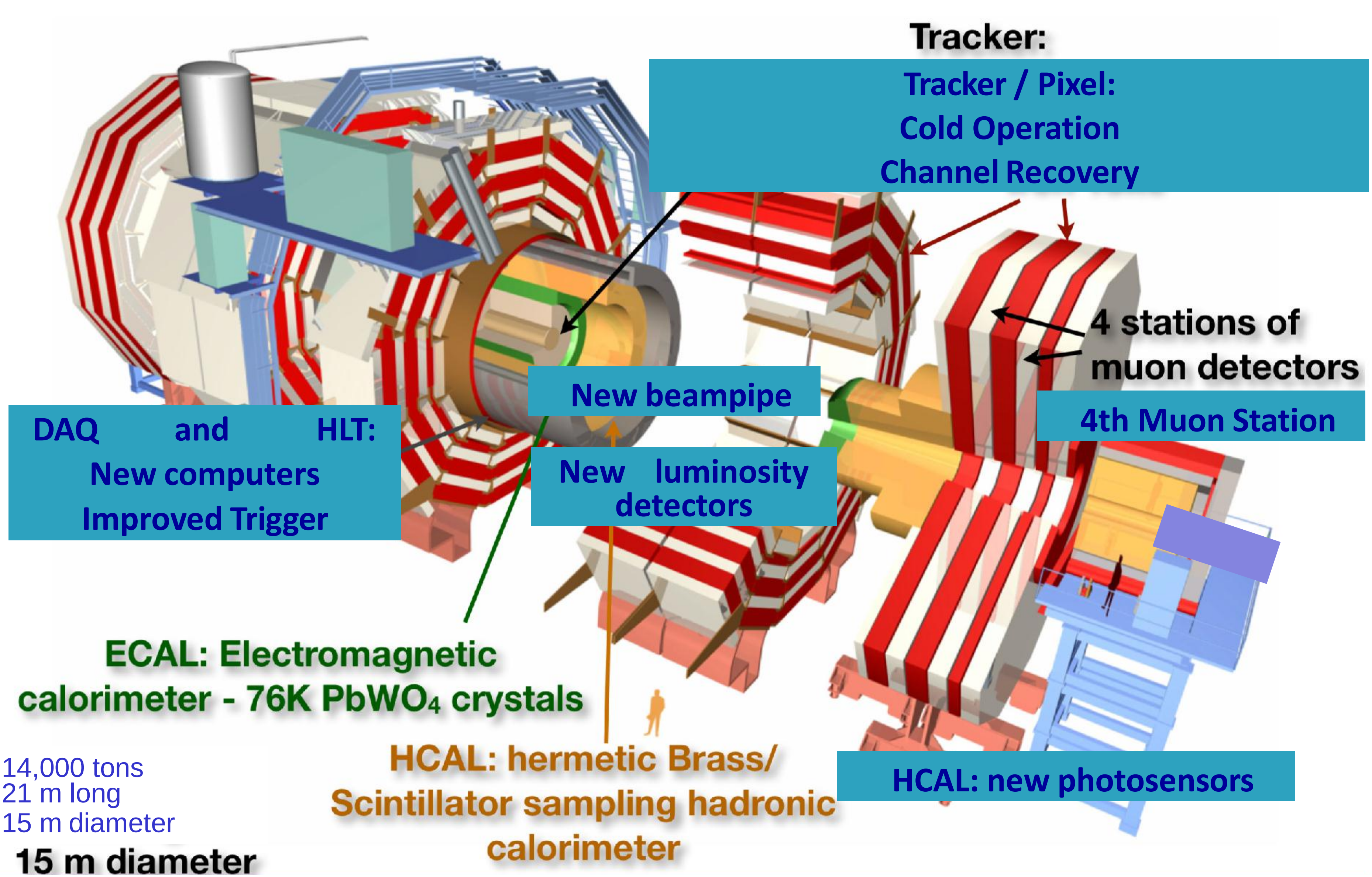
The road to HL-LHC

HL-LHC goal is to achieve ≈20x more data than recorded so far





Where we stand: the current CMS detector



Why HL–LHC?

- TeV scale provides a strong physics case for HL-LHC
  - Currently no direct evidence of new physics
  - Standard Model works beautifully – possibly beyond the TeV scale
  - Naturalness argument and low mass of Higgs boson provide strong motivation for new particles and/or interactions at the TeV scale
  - The standard model does not provide a dark matter candidate

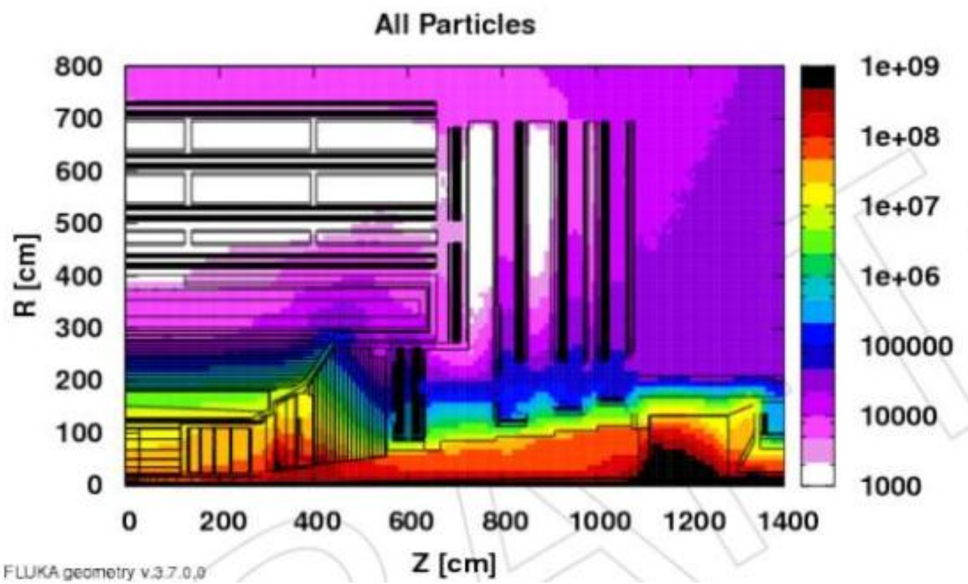
- Answers to many key questions in HEP may lie at the TeV scale

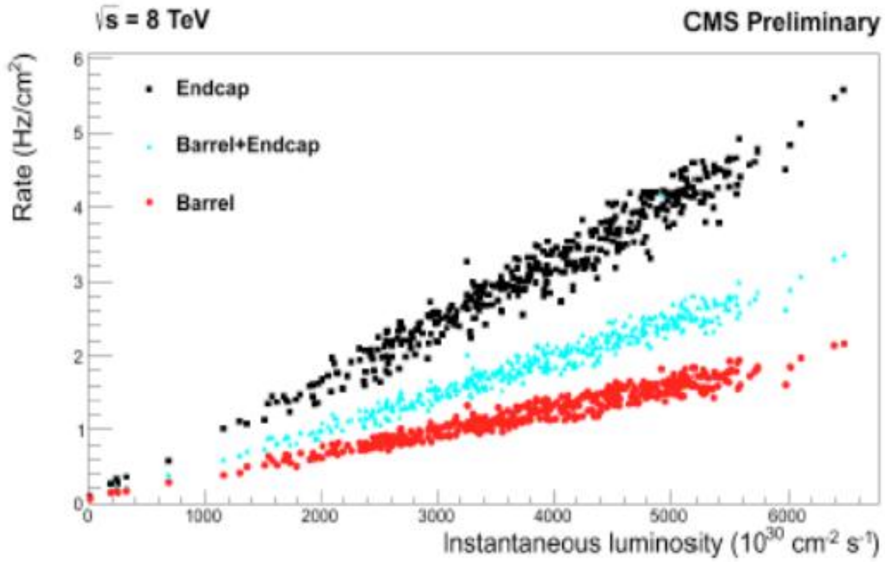
- HL-LHC is expected to deliver x100 today's data sample ($\rightarrow$ 3 ab^{-1}):
  - Study the Higgs boson in detail
    - Discriminate between possible BSM scenarios
  - Measure rare SM processes
  - Search for new particles/phenomena at the TeV scale
    - Top partner could provide solution to the hierarchy problem
    - Dark matter candidate
  - Investigate properties of new particles observed during Run2 & 3!

Why HL–LHC?

- CMS were designed to cope with L= 1-2 x10^{34} $cm^{-2}s^{-1}$

- Phase 2 Upgrade: 5x LHC design luminosity
  - Detectors have to be operated in an extreme environment, very high rates of radiation and pileup (10-15 x 2012)
  - Event pileup reaches ~140 collisions per beam crossing (@ 25 ns)





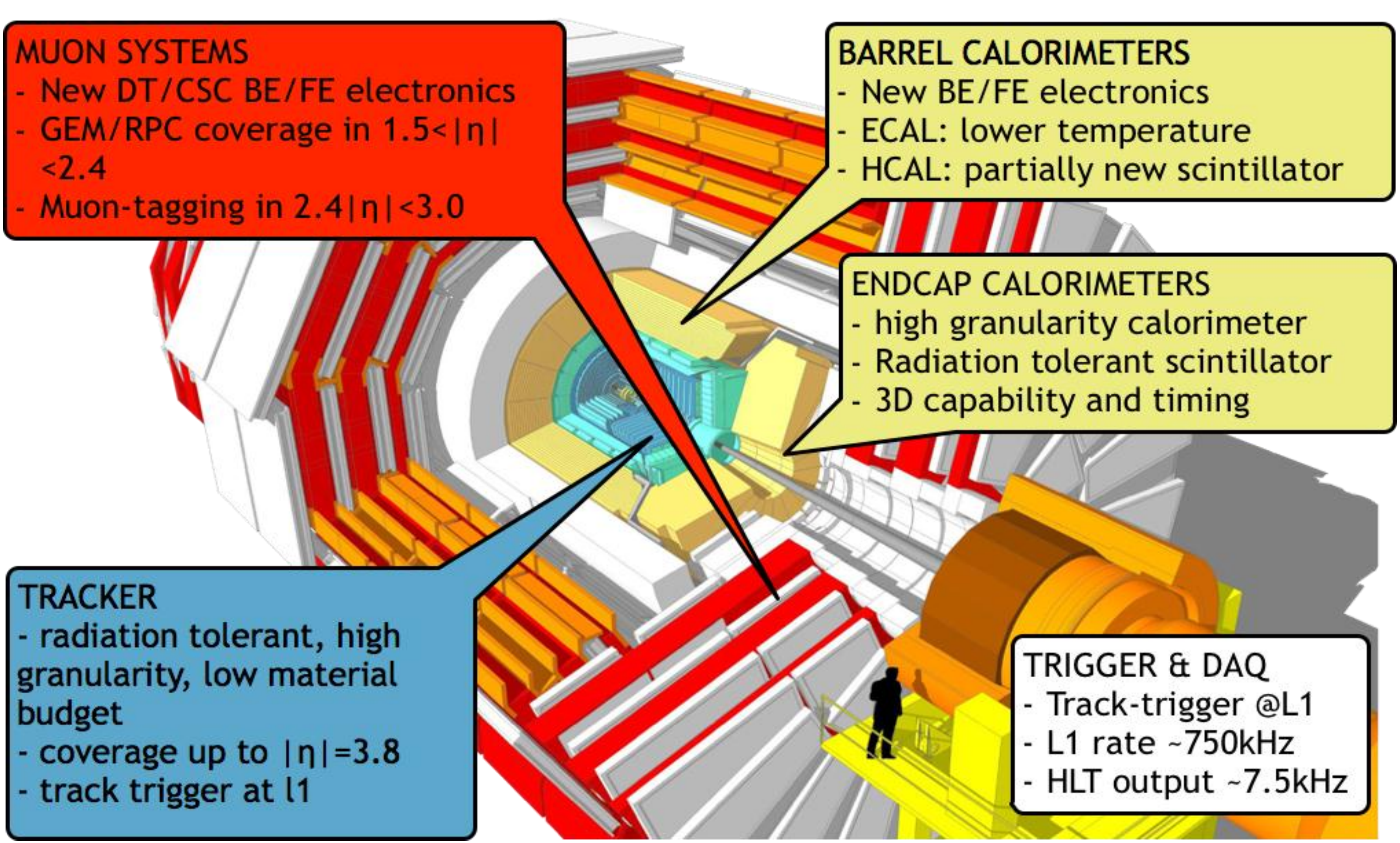
HL-LHC Challenge

- Pileup
  - Increases the combinatorial complexity and rate of fake tracks
  - Adds extra energy to calorimeter measurements
  - Increases the amount of data that has to be read out in each bunch crossing

- Pileup Mitigation
  - High granularity detectors (trackers, calorimeters) needed to identify particles associated with the primary hard scatter collision vertex with high efficiency
  - Precise timing measurement can unambiguously associate both tracks and neutral energy clusters to each vertex, providing ultimate pileup mitigation (under study).

- Radiation damage
  - Severe aging effects: by 2025 the detectors and electronics will be running (i.e. radiated) for 15 years
  - Detector elements and electronics are exposed to high radiation dose
  - Degrades signal and limits life time of detectors
  - Requires new tracker and endcap calorimeters, new forward muons

CMS Phase II Upgrade



Phase II Tracker

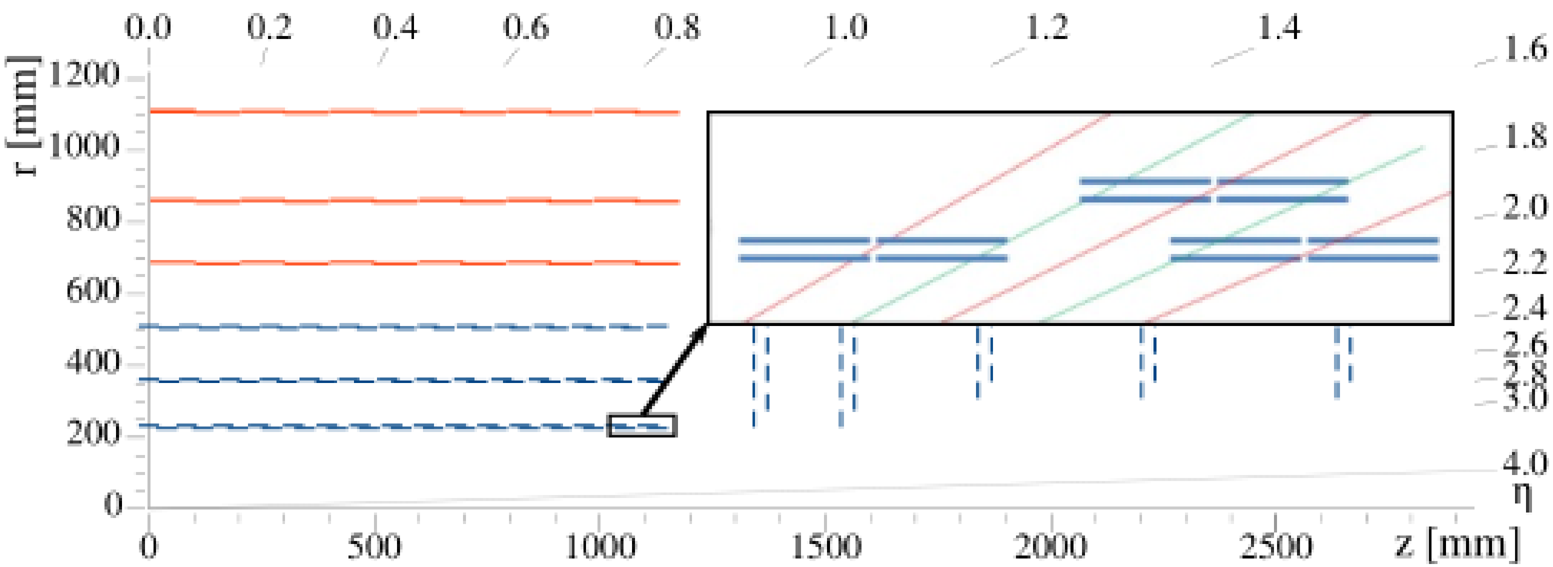
Goal: maintain at least the same performance of the current tracker in a harsh environment

- Various improvements are expected:
  - Increased η acceptance from <|2.5| to <|4.0|
  - Less material budget
  - L1 tracking capabilities
  - Increased track parameter precision

- The expected final integrated luminosity (3 ab^{-1}) and the good performance of the tracker allow to access new physics channels and to improve precision measurements

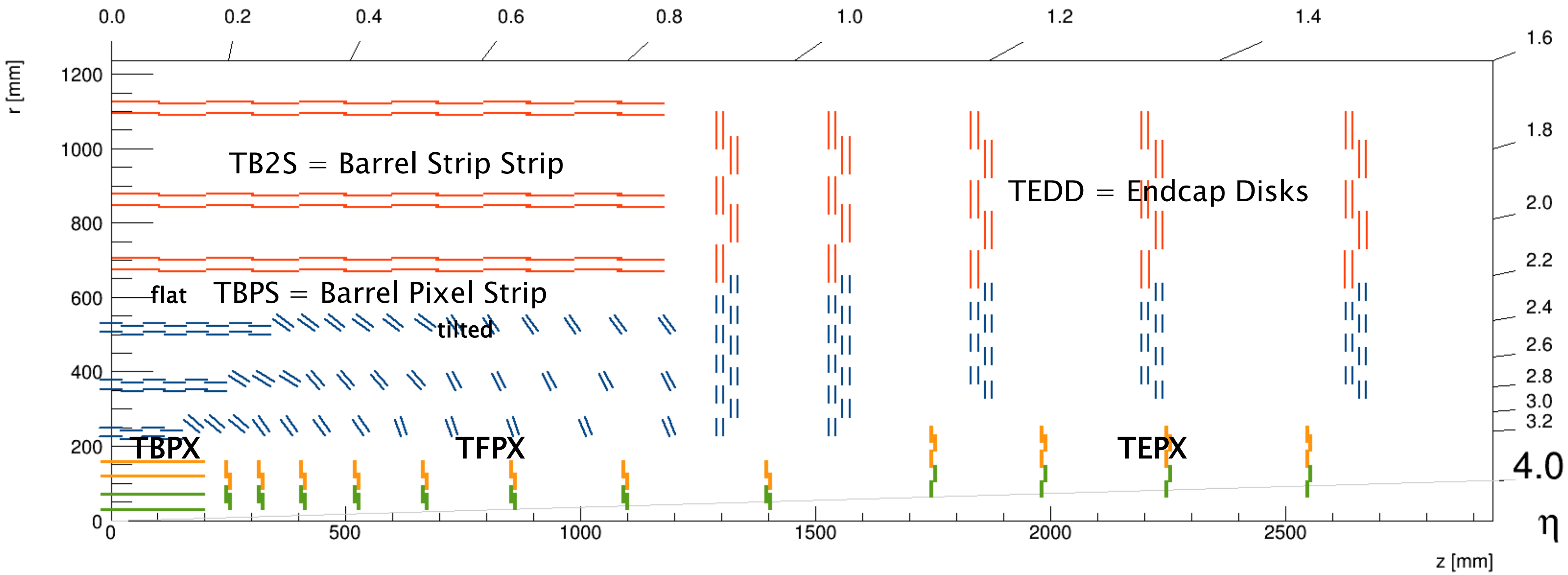
Phase II Tracker

- In a flat barrel layout, modules at the edge of the inner barrel would have large geometrical inefficiency
- This lead to inefficiency of stub finding >30% at the edge of the first barrel layer.

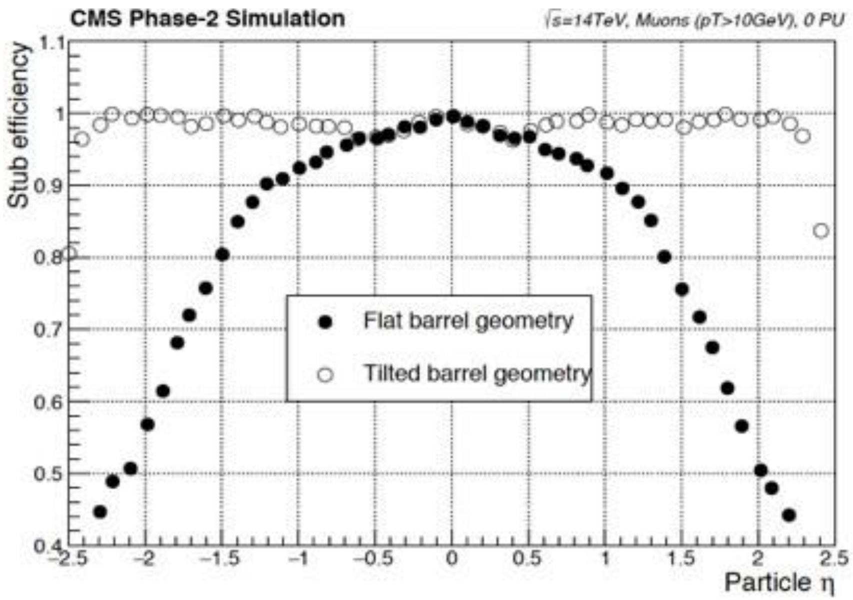


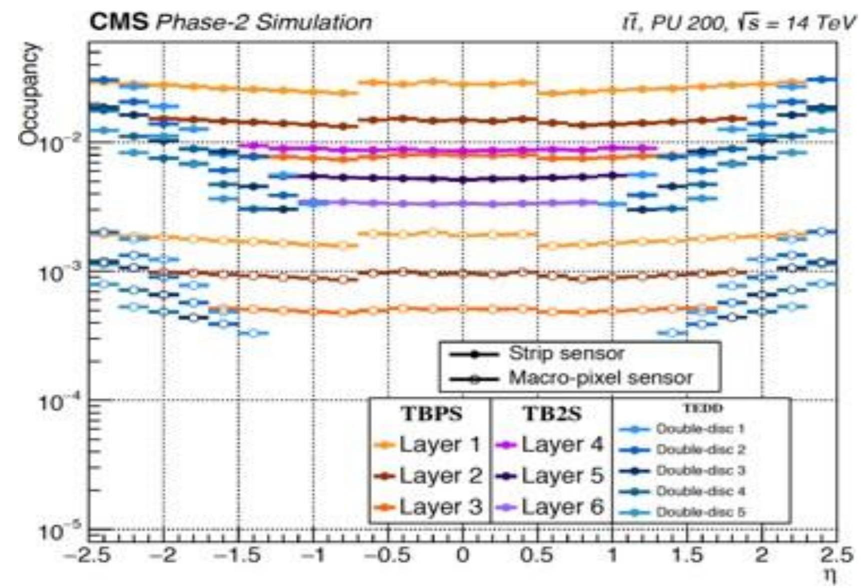
Phase II Tracker

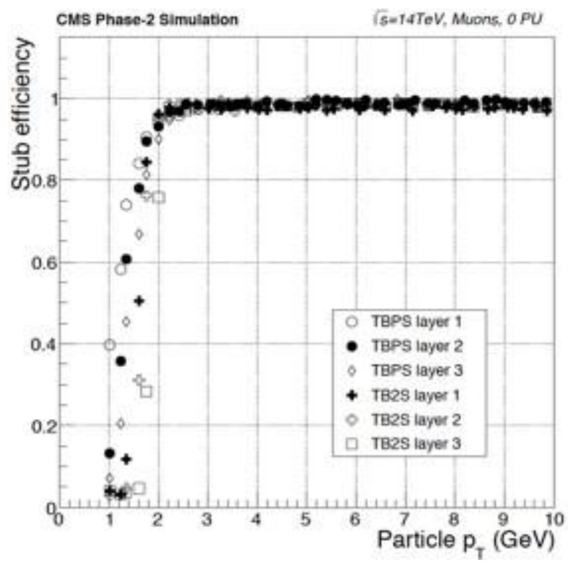
- Tracking acceptance up to η = 4
- L1 Track Trigger up to η = 2.4
- Inner Tracker : 4.9 m2, 2x109 pixels
- Outer Tracker : 192 m2 42 M strips, 170 M Macro Pixel (25 m^2)

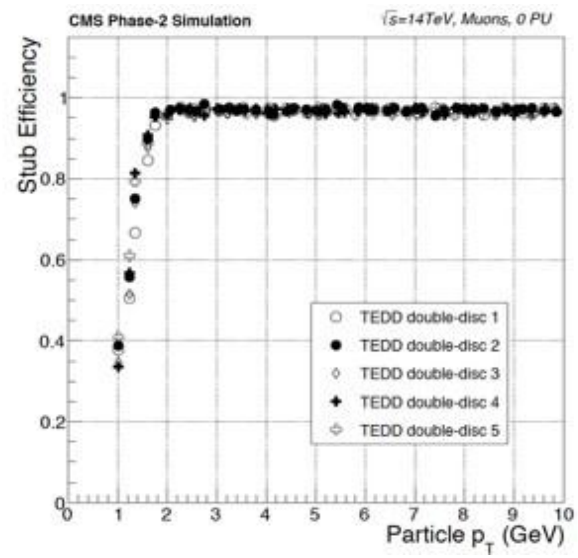


Tilted Geometry Benefits



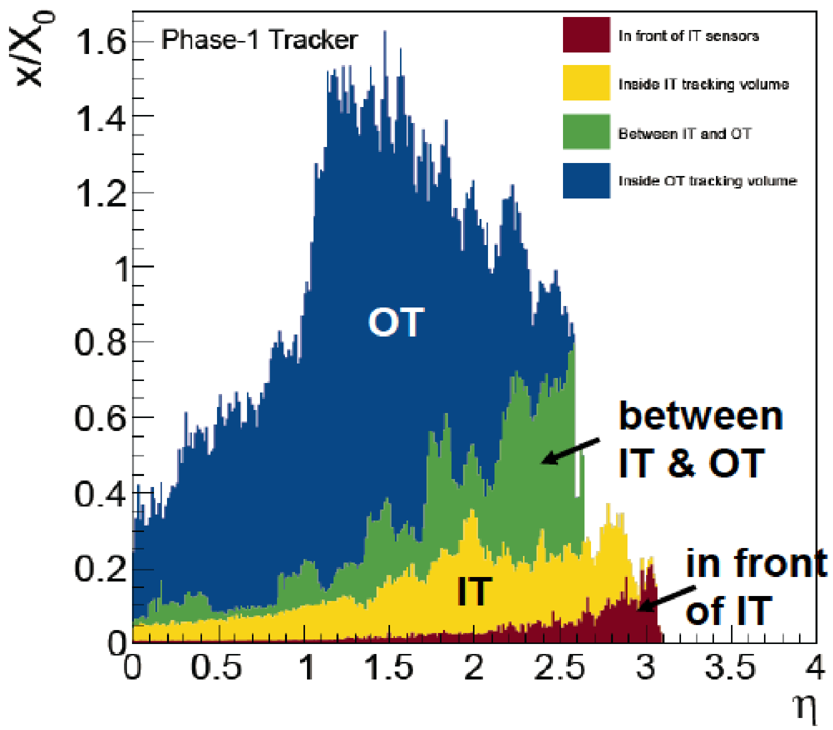


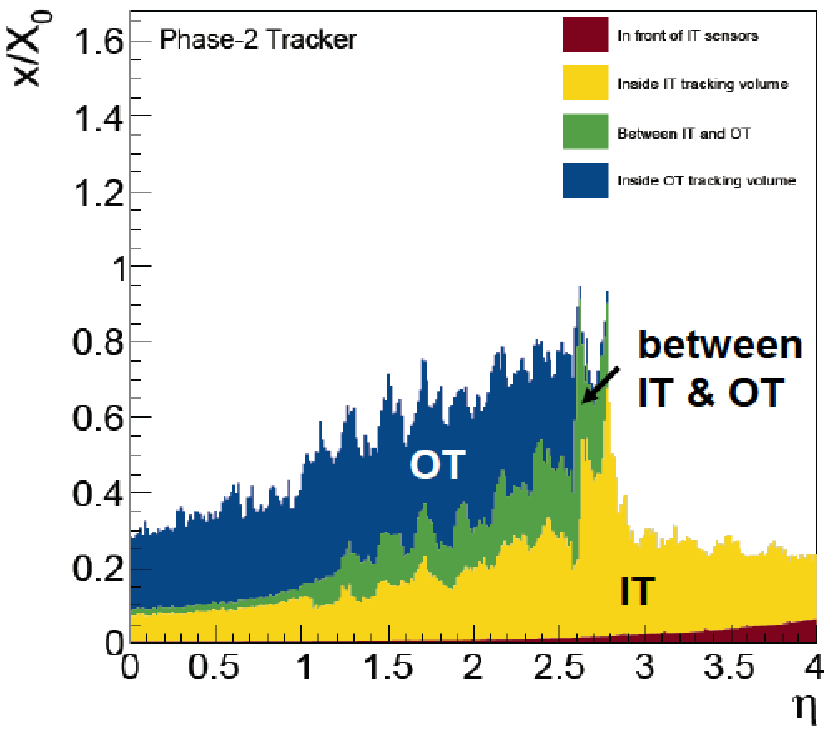




Material Budget

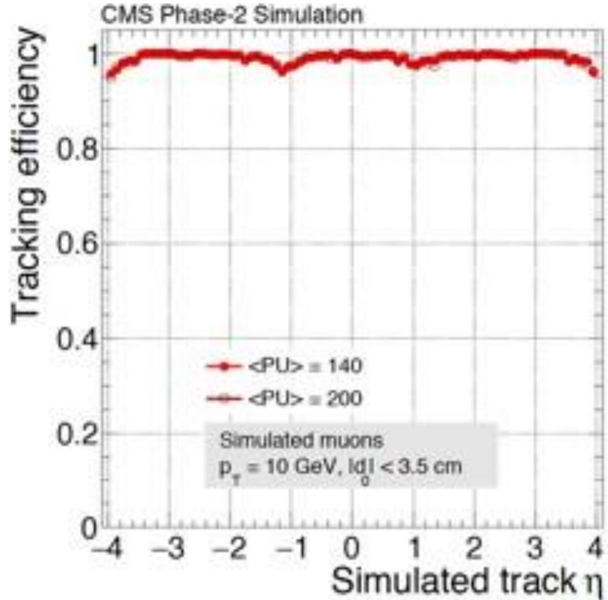
- Much reduced Material Budget with respect to present detector

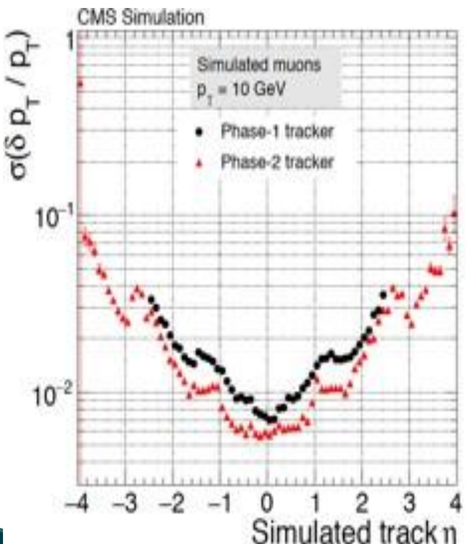


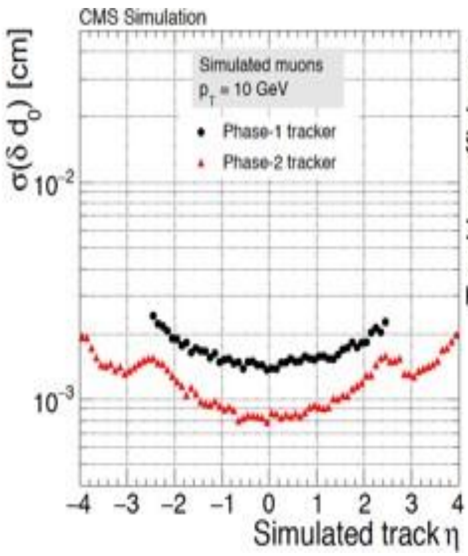


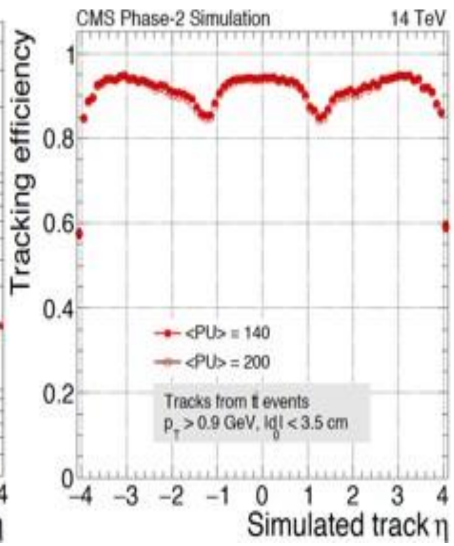
Tracking Performance

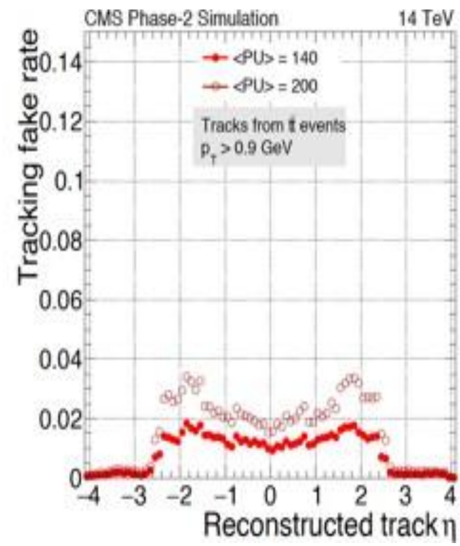
- 10 GeV muon efficiency ~100%
- High track efficiency
- Better momentum resolution
- Low track fake rate (performance @200PU in HL-LHC ~ @70PU now)





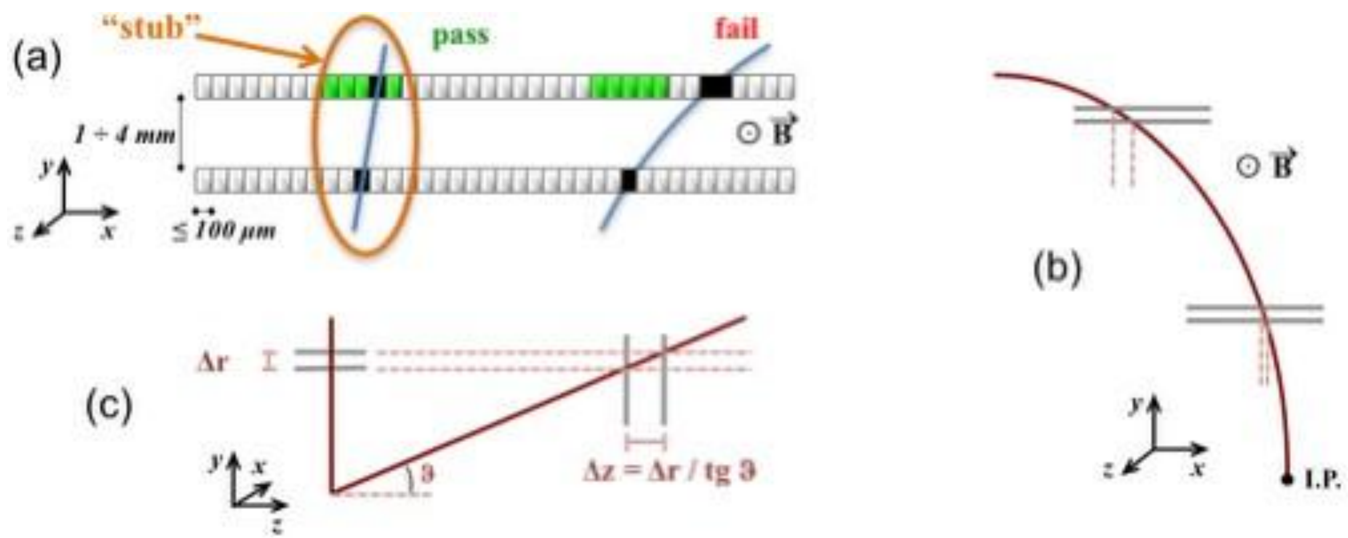






L1 Track Trigger

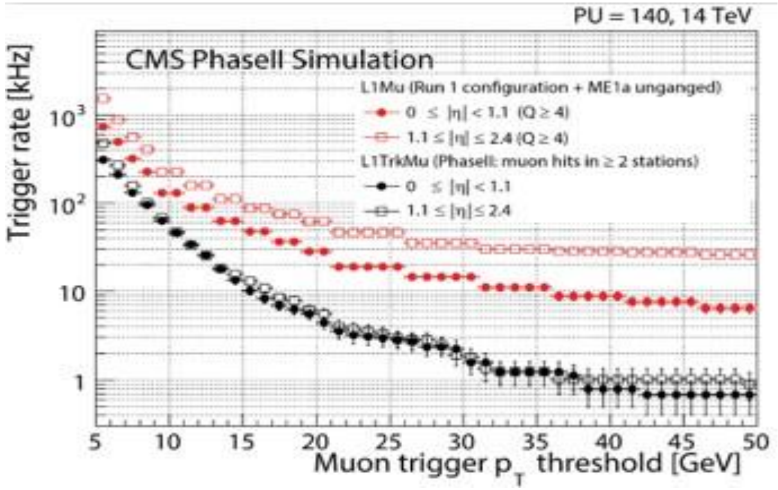
- Outer tracker provides hardware trigger capabilities
- Readout of full detector at 40 MHz is not feasible → p_T modules
  - two closely spaced sensors provide a local p_T measurement, allowing on-detector application of p_T thresholds for hardware trigger
- Hardware trigger receives track stubs with p_T > 2 GeV →
  - 10-100x reduction in data-volume
- Coverage up to |η| = 2.4

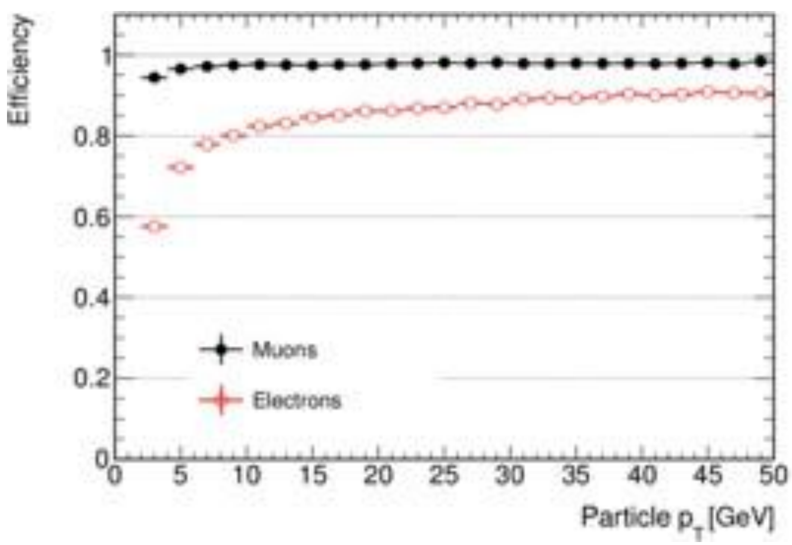


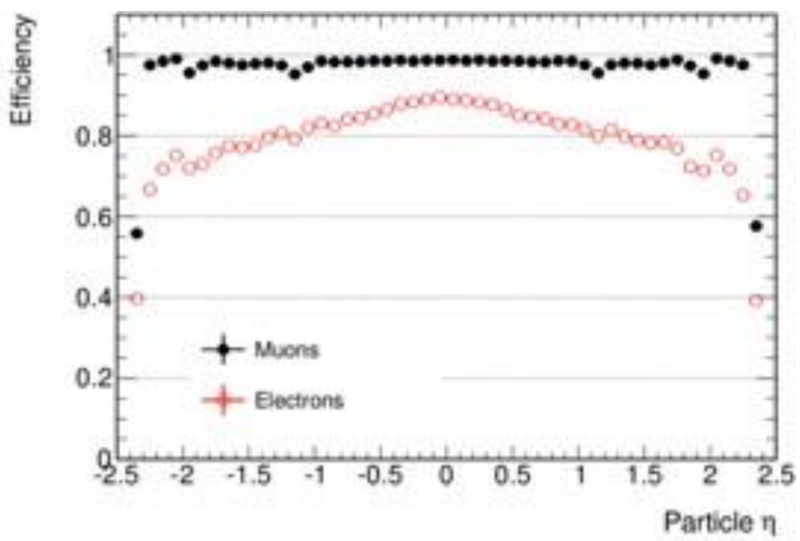
L1 Track Trigger Performance

Caveats: flat geometry studies, p_T > 3 GeV

- Improved lepton ID
- Track isolation
- Vertex determination
- Rate reduction







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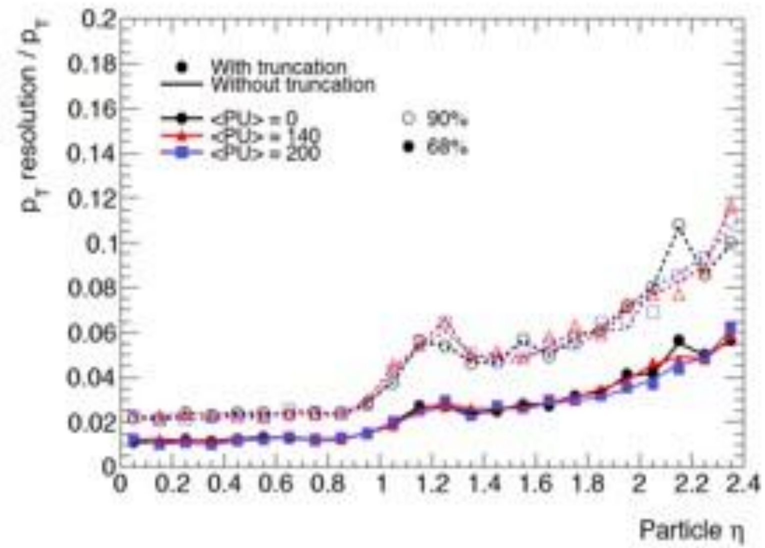
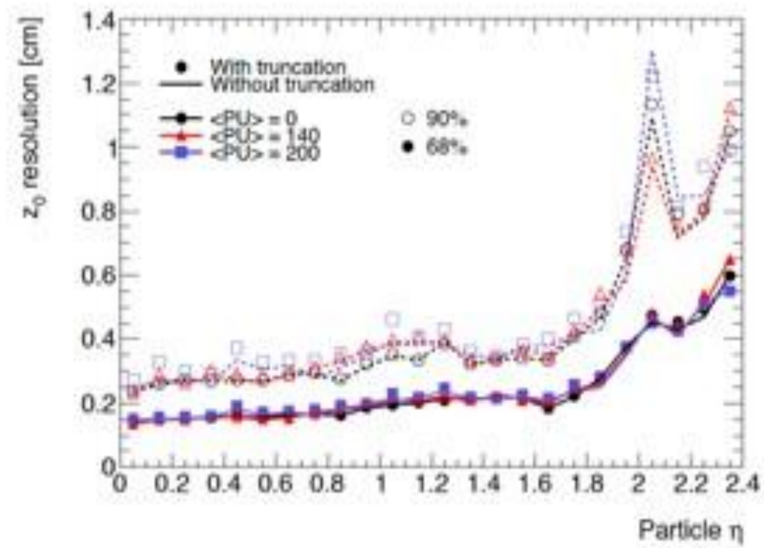


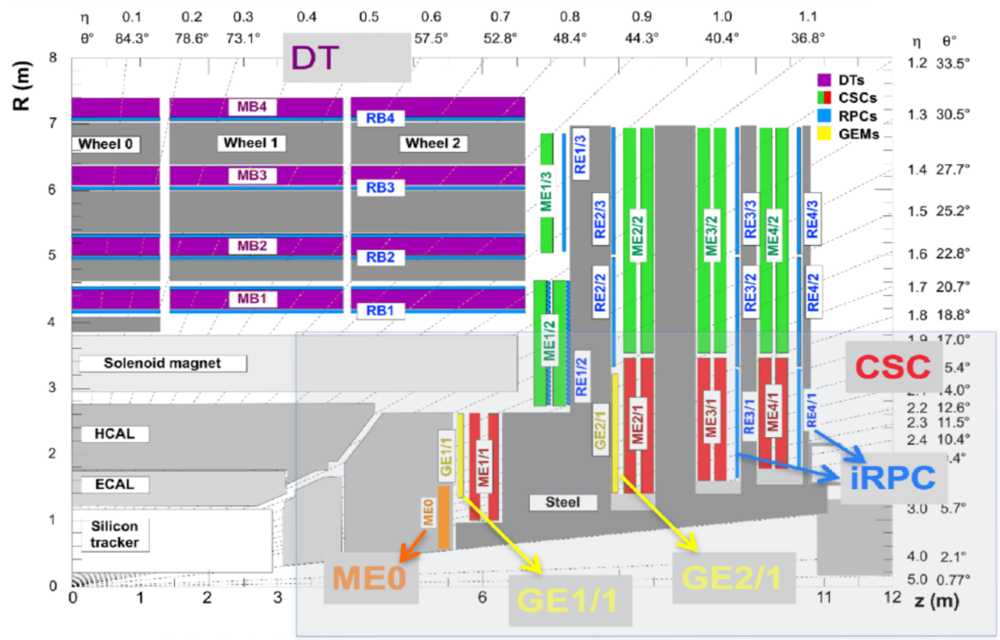


Phase II Muon System

Goal: maintain excellent triggering, ID, and measurement of muons under harsher HL- LHC conditions (instantaneous and integrated L) up to |η|< 3

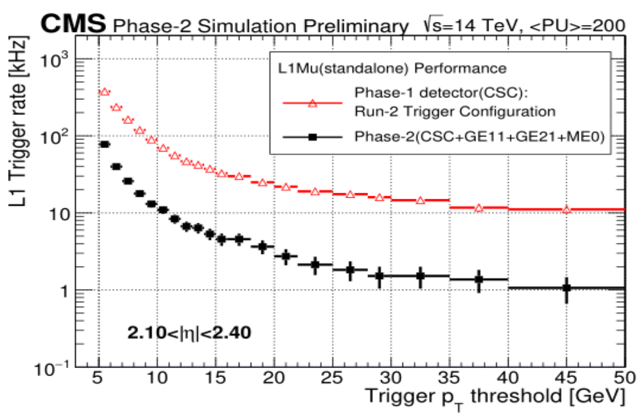
- **Existing Detector**
  - Upgrade electronics for radiation hardness and upgraded trigger/readout requirements

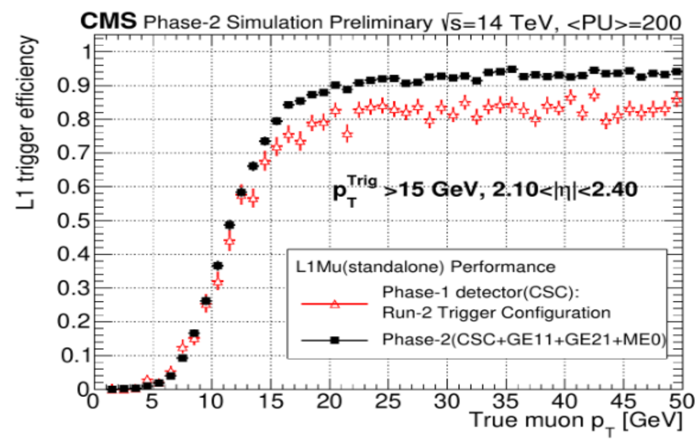
- **New Phase II Detector**
  - Additional GEM chambers in front of existing forward muon (CSC) system, and additional RPC's to improve trigger and reconstruction performance in region
    $1.6 < |\eta| < 2.4$
  - ME0: New GEM chambers to extend muon system coverage to $|\eta| = 2.8$ and further improve trigger and reconstruction performance up to
    $|\eta| \sim 3.0$



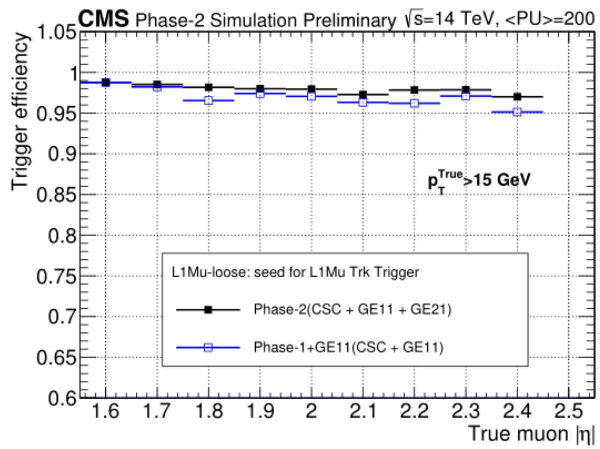
L1 Muon Trigger

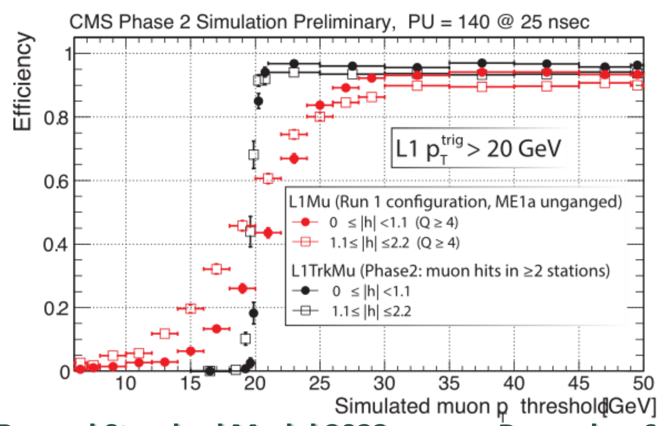
- Improved measurement of forward muons drastically reduces trigger rate and increase efficiency





- High efficiency maintained over full trigger coverage
- Combination with track trigger drastically improves momentum resolution

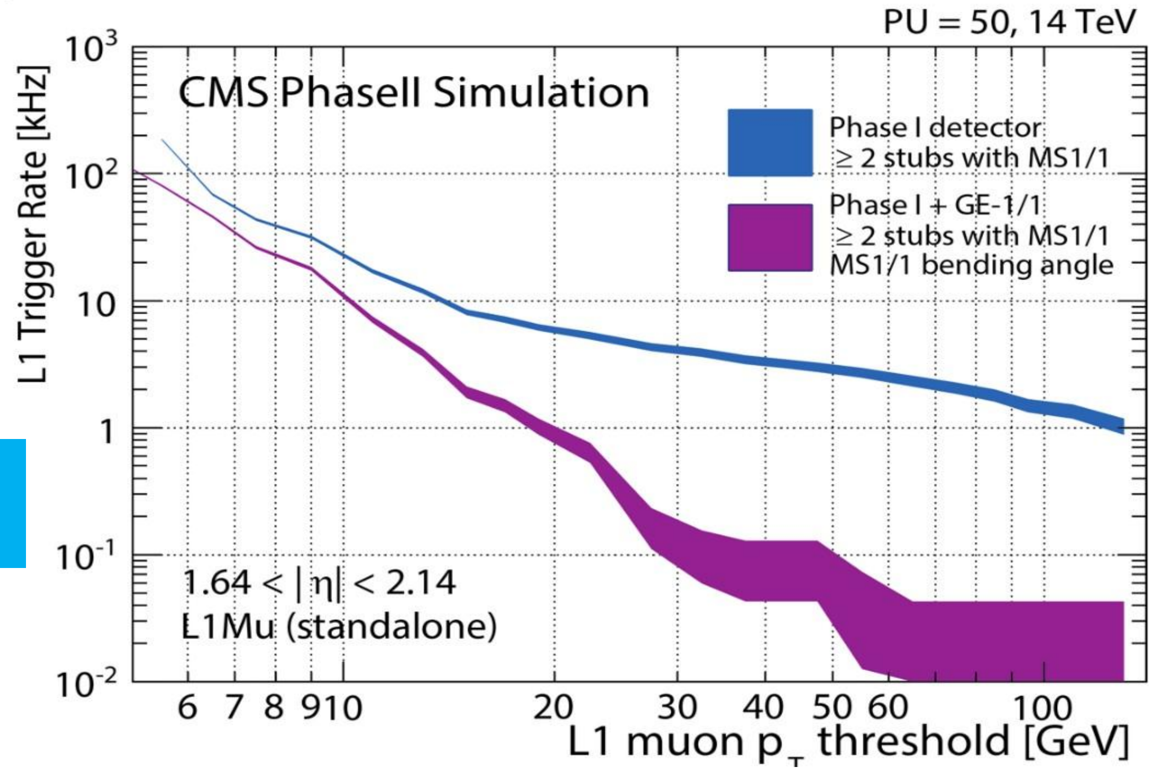




L1 Muon Trigger

- Improves p_T resolution for L1 trigger muons
- Muon ID to η ~ 3.0
- Pilot system (5 super- chambers) installed at Muon endcap station 1

Muon trigger rate reduction by adding GE1/1



Phase II Calorimeters

Goals:

- Move L1 trigger off-detector for max flexibility
- Cope with increased latency
- Improve timing (30 ps) for vertexing and spike rejection (99.9% L1)

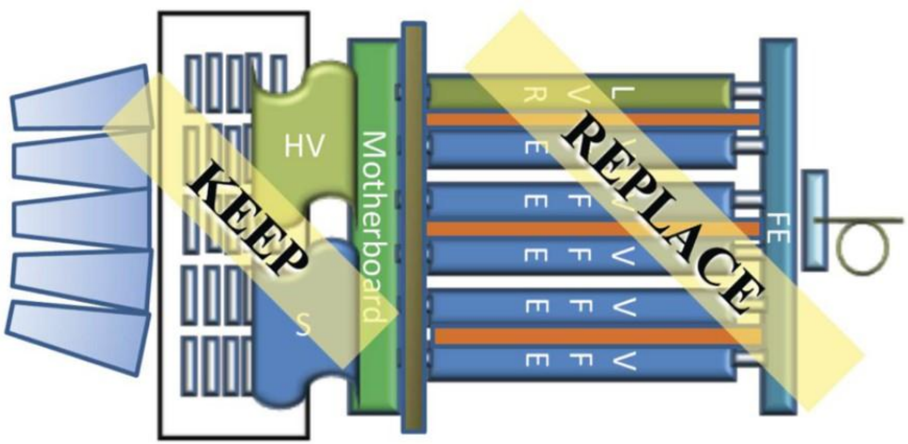
Strategy:

- Assure radiation hardness of components
  - replace damaged detectors (EE + ES + HCAL endcaps)
  - operate EB colder to reduce APD noise
  - SiPMs in HCAL barrel to replace HPDs
- Account for high demanding L1: 12.5µs latency and 750kHz rate
  - new on-detector and off-detector electronics
- Exploit precision timing
- Increase granularity

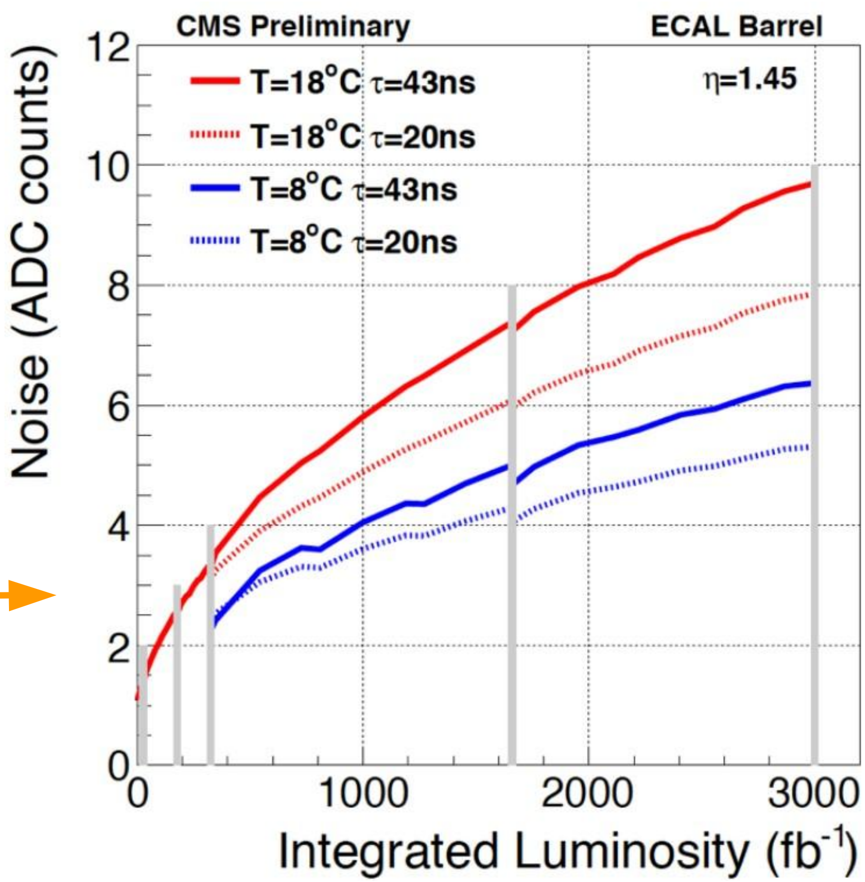
Phase II Barrel EM Calorimeter

Keep lead tungstate crystals and avalanche photodiodes (APD)

Replace electronics for L1 trigger
- single-crystal readout (instead of 5x5 tower) at 40 MHz



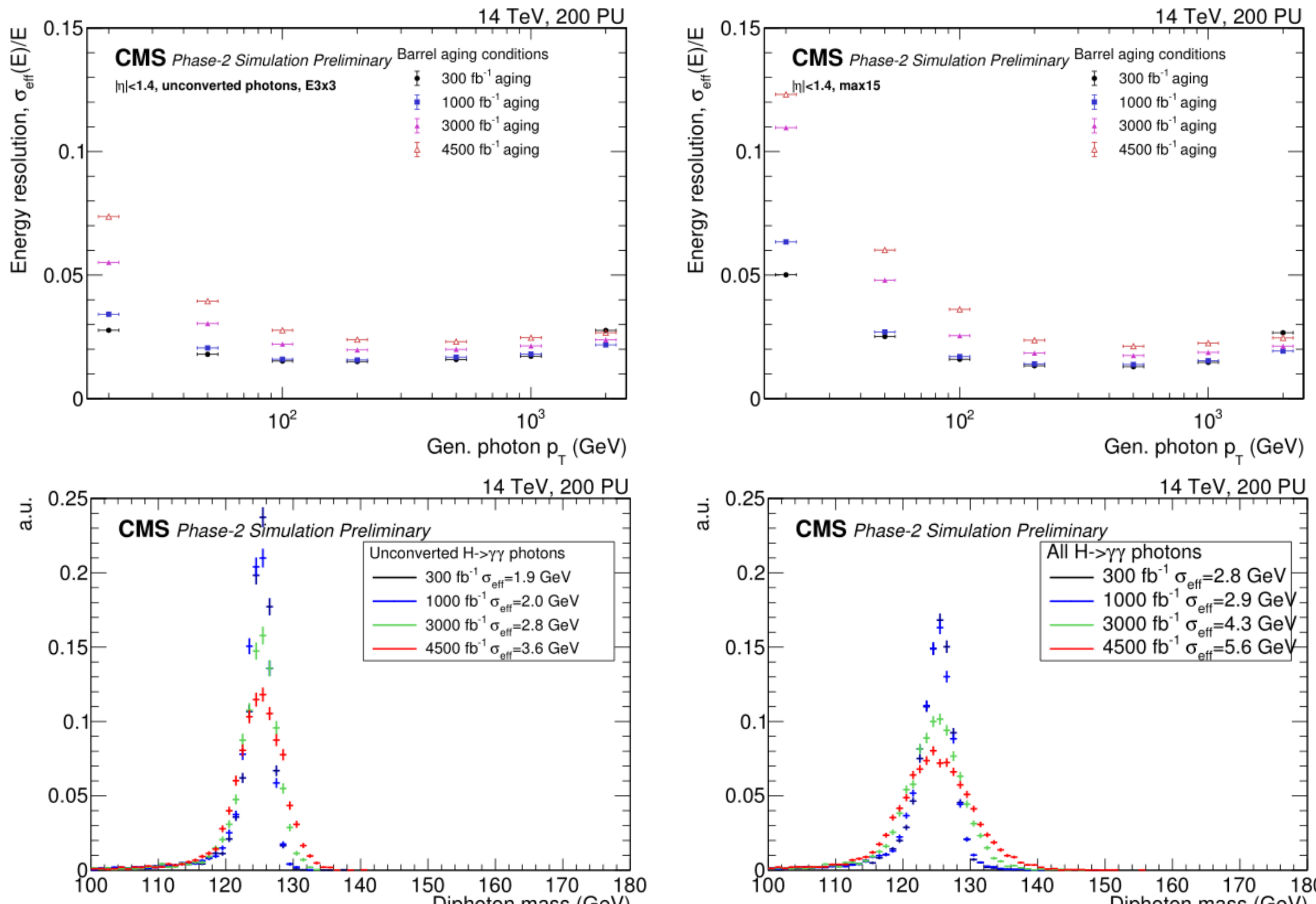
Mitigate APD noise
- lower operating temperature
- optimized readout shaping time



Phase II Barrel EM Calorimeter Performance

Photon Energy resolution

Performance expected to be close to current detector with optimization of clustering, pileup suppression and multivariate energy corrections.

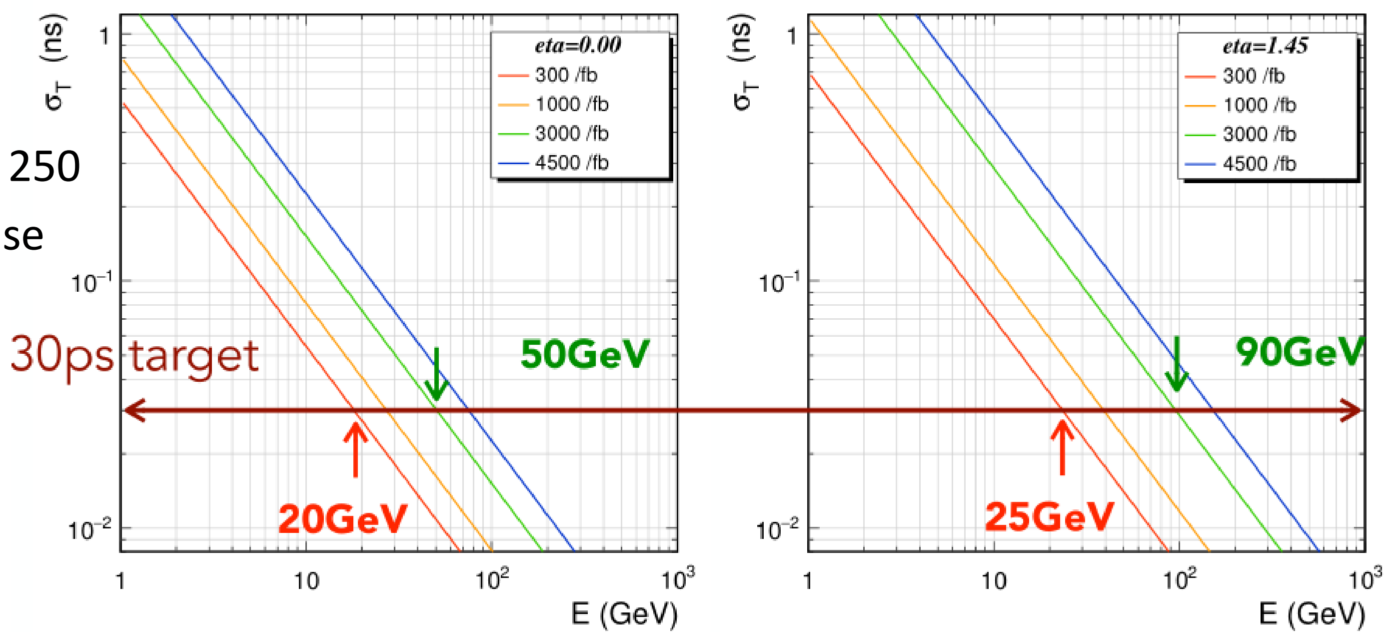


Phase II Barrel EM Precision Timing

- Timing resolution limited by the APD dark current rather than the crystals themselves
- Target resolution of 30 ps achievable for moderate energy photons
- Precision timing can help matching of photons to primary vertices for photon id, di-photon, invariant mass
- Precision limited by noise contribution

30ps resolution at S/N = 250

- 20GeV beginning (noise ≈100MeV)
- 50GeV end (noise ≈200MeV)



Phase II Endcap Calorimeter

New! High Granularity Calorimeter (HGC)

Hexagonal silicon sensors

1 or 0.5 cm² hex cell size, 6M channels

Excellent longitudinal and transverse segmentation

Rad-hard

Endcap EM section
28 tungsten and copper plates,
25 radiation and 1.5 interact. lengths

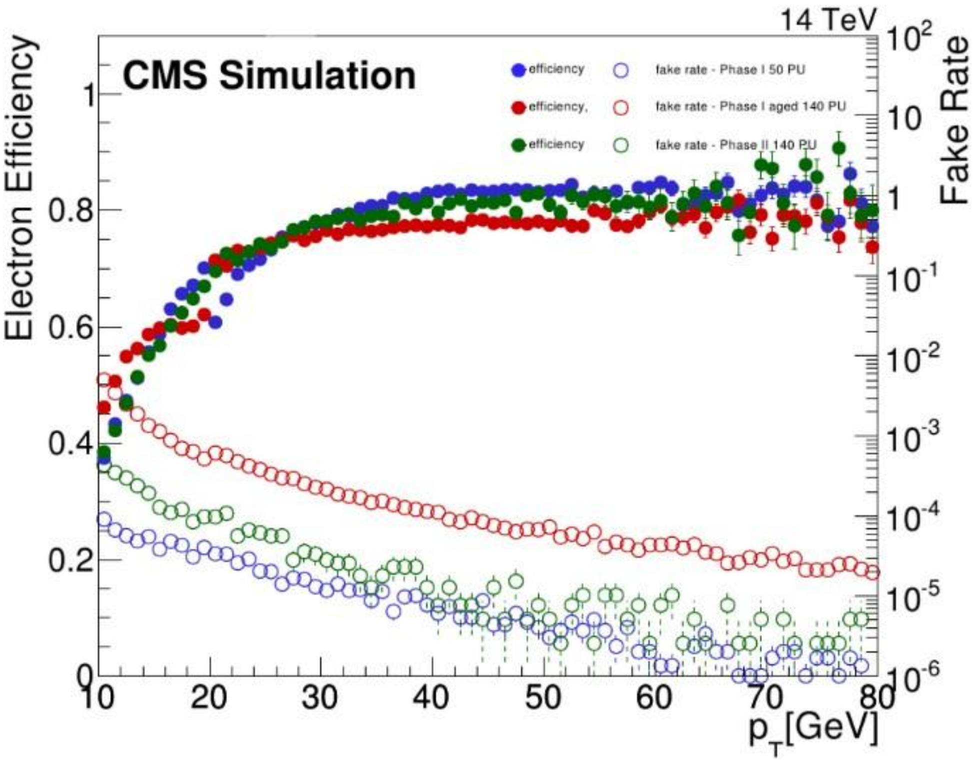
Front Hadron section
12 brass and copper plates,
3.5 interaction lengths

Backing Hadron section
Brass plates + plastic scintillating tiles, 5 interaction lengths

Phase II Endcap Calorimeter Performance

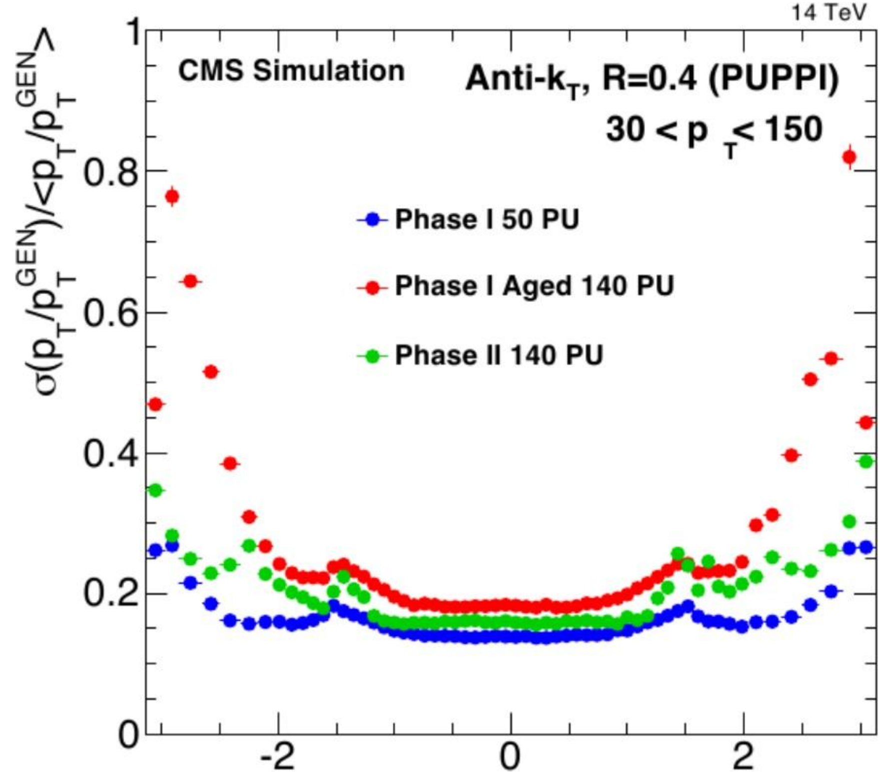
Simulated Performance

Electron ID efficiency



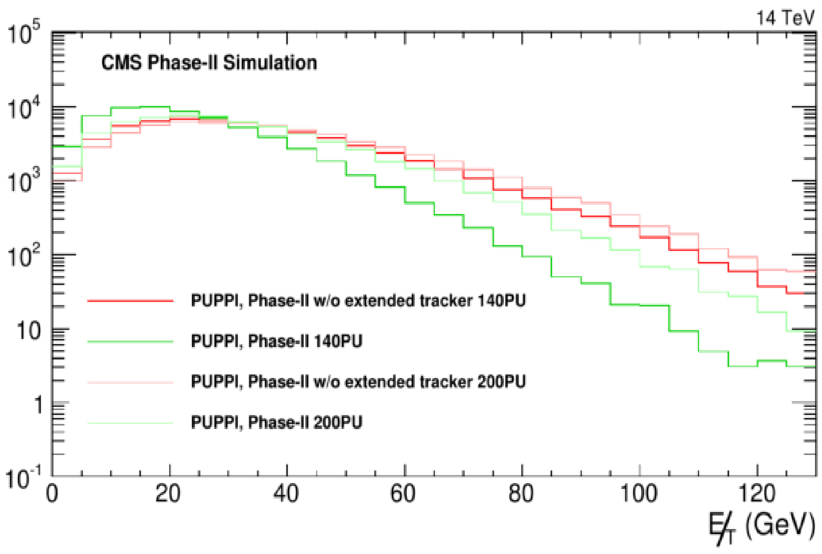
Electron ID fake rate

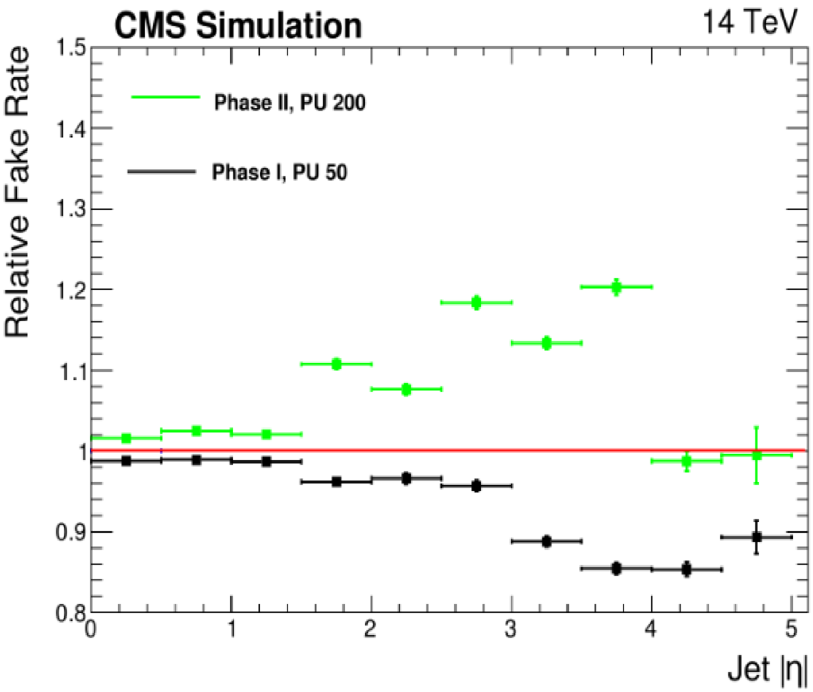
Jet Energy Resolution



Impact of Pileup

- Missing Transverse Energy and Jets fake rate affected
  - Significant impact on physics reach





Pileup Impact Mitigation: Precision Timing

- Calorimeter upgrades: precision timing of showers
  - High energy photons in ECAL
  - All photons and high energy hadrons in HGCal

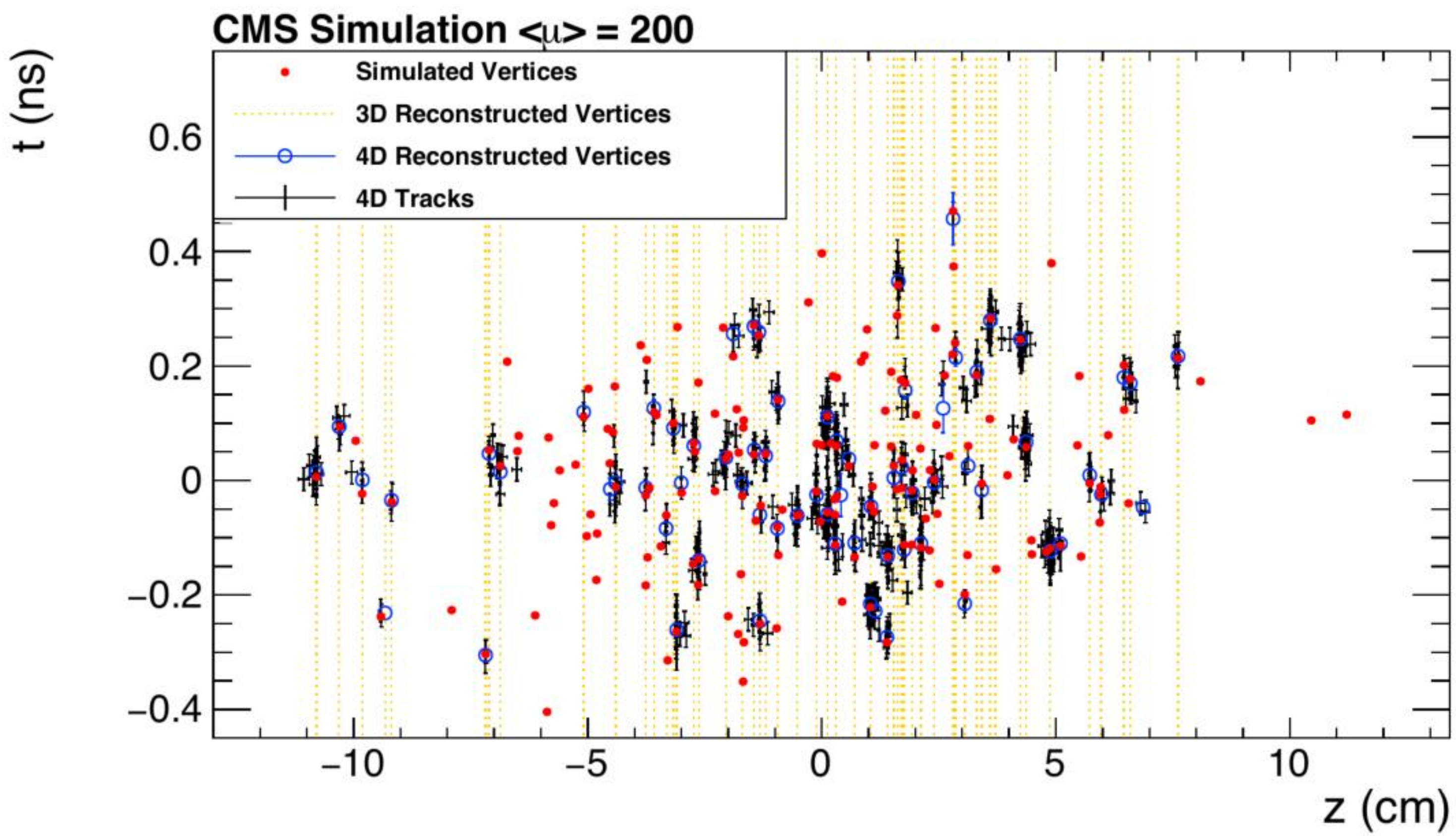
- Interactions are distributed with a spread of 150-200 ps, so a detector with 10's of ps timing resolution could meaningfully distinguish between interactions on the basis of timing

- If beam-spot sliced in successive O(30) ps time exposures, effective pileup reduced by a factor 4-5:
  - ~ 15% merged vertices reduced to 1%
  - Phase-I track purity of vertices recovered

- Mip Timing Detector (MTP) between Tracker and ECAL for precision timing of tracks
  - A single layer between the tracker and the calorimeters
  - Acceptance: $|\eta| < 3.0$
  - $p_T > 0.7$ GeV barrel; $p > 0.7$ GeV endcap

Pileup Impact Mitigation: Precision Timing

- With sufficient time resolution and coverage for charged particles, traditional three-dimensional vertex fit can be upgraded to a four-dimensional fit



Conclusions

- In the coming 15 years LHC will continue to increase its luminosity
  - Goal is to accumulate an integrated luminosity of 3000 fb^{-1}
  - 140-200 pileup interactions/crossing

- Comprehensive set of upgrades in progress in order to cope with increased radiation dose

- Main challenge is mitigation of large number of pileup interactions
  - Trigger – more bandwidth, new capabilities (eg track trigger)
  - Increased detector granularity and acceptance in η
  - Timing measurements will add an additional dimension to pileup rejection

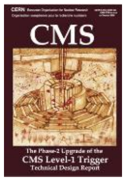
- Baselines for the upgraded detectors have been defined
  - New results will come out from current TDR studies and implementation of recent Run2 analysis tools

Backup

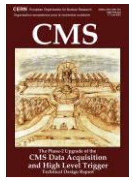
Thank you

Backup

The CMS Phase-2 Upgrade

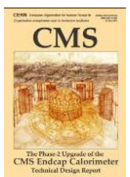


Level-1 Trigger
https://cds.cern.ch/record/2714892
- Tracks in L1 Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting

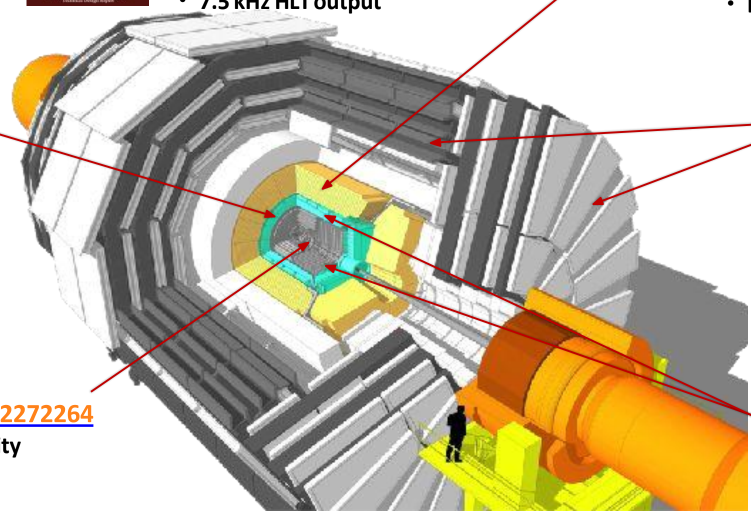


DAQ & High-Level Trigger
https://cds.cern.ch/record/2759072
- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

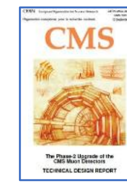
Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL single crystal granularity readout at 40 MHz with precise 30 ps timing for e/γ at 30 GeV
- Spike rejection
- ECAL and HCAL new Back-End boards

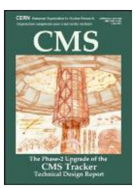


High-Granularity Calorimeter Endcap
https://cds.cern.ch/record/2293646
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/Cu-W/SS



Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC BE electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

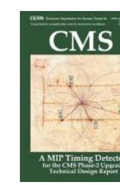


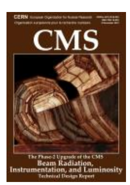


Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Extended coverage to $\eta \simeq 4$
- Design for tracking in L1 Trigger

MIP Timing Detector
https://cds.cern.ch/record/2667167

Precision timing with:
- Full coverage to $\eta \simeq 3$
- 30-50 ps time resolution for MIPs
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes





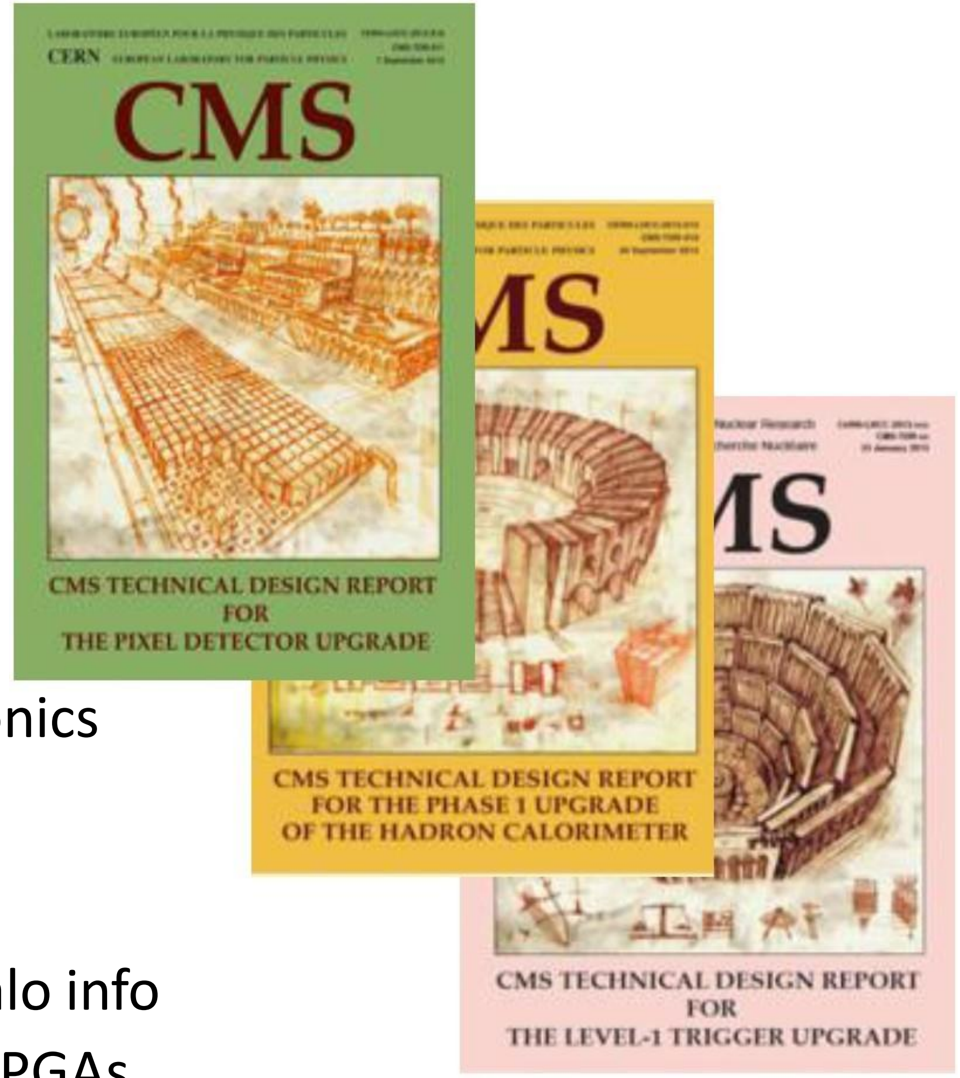
Beam Radiation Instrumentation and Luminosity
http://cds.cern.ch/record/2759074
- Beam abort & timing
- Beam-induced background
- Bunch-by-bunch luminosity: 1% offline, 2% online
- Neutron and mixed-field radiation monitors

References

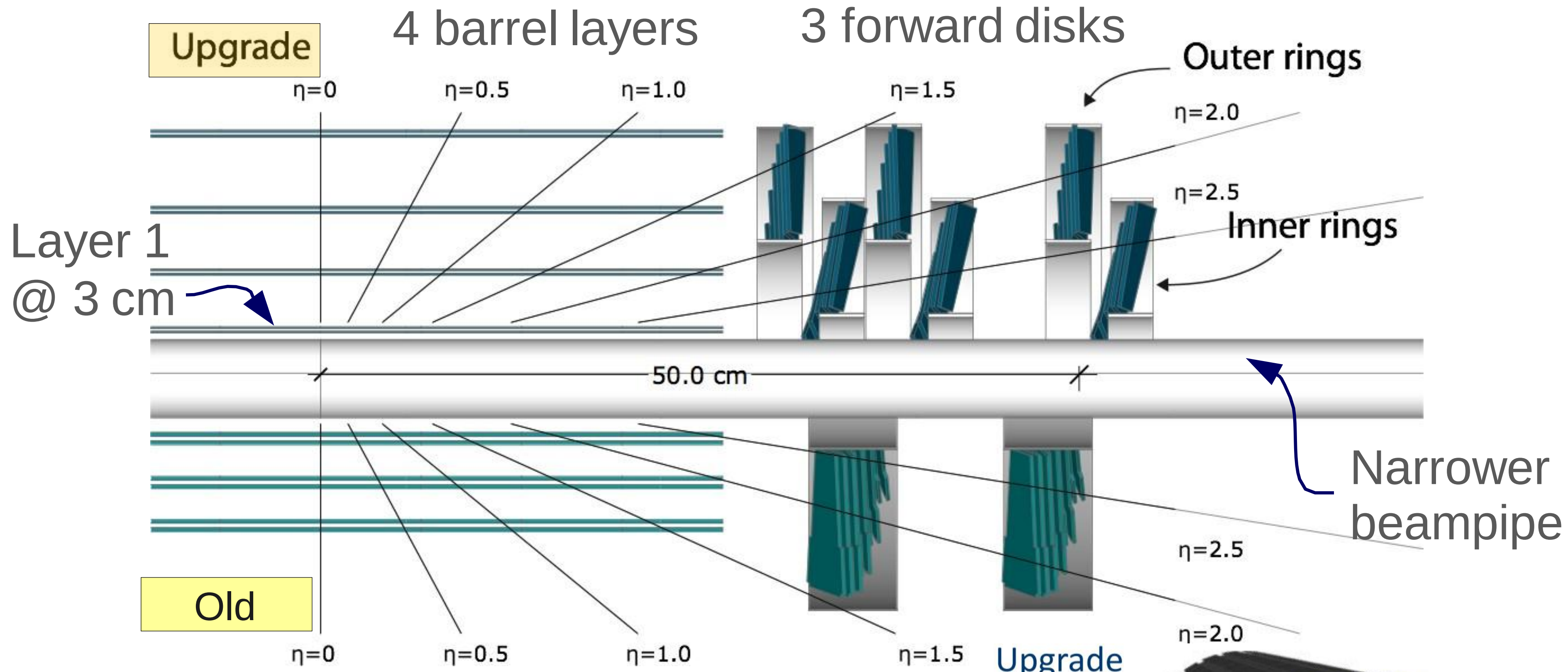
- Technical Proposal for the Phase I Upgrade (CERN-LHCC-2011-006).
- Technical Proposal for the Phase-II Upgrade (CERN-LHCC-2015-010, LHCC-P-008, 2015).
- Phase II Upgrade Scope Document (CERN-LHCC-2015-019).
- CMS scope document (LHCC-G-165, 2015).
- Documents on CMS Public Results pages.

Phase I Upgrades

- **Pixel Tracker**
  - New detector
  - High-rate readout chip
- **Hadronic Calorimeter**
  - Improved photodetectors
  - Faster & more robust electronics
- **L1 Trigger System**
  - Exploit additional muon & calo info
  - Move to high-performance FPGAs



Phase I Upgrades: Pixels



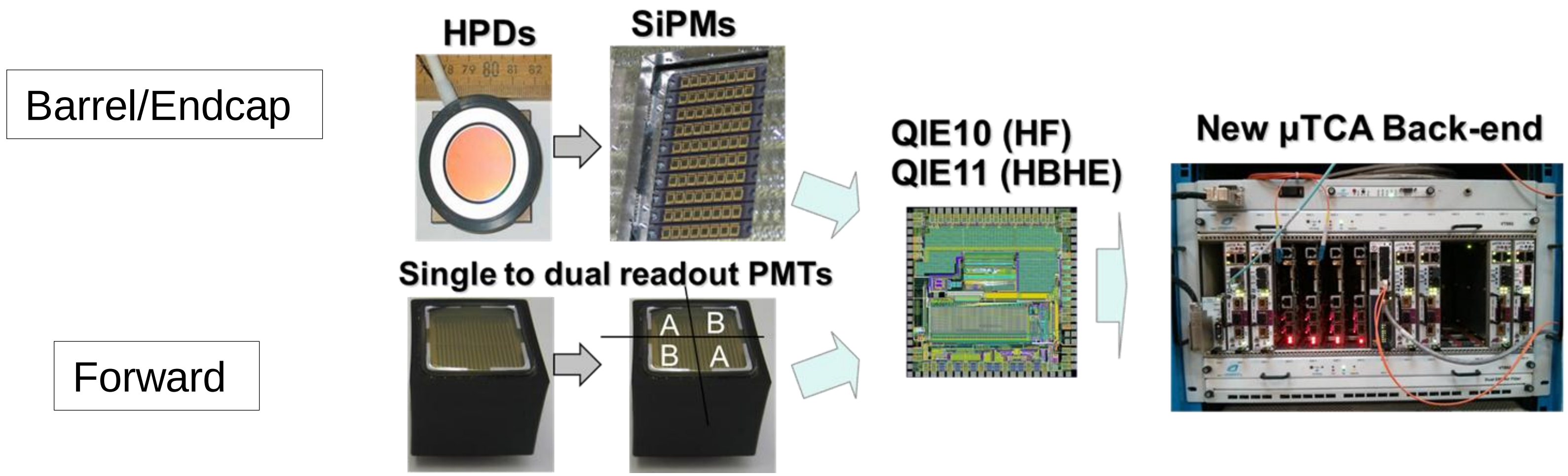
- Rad-hard (~ 500 fb^{-1})
- Less material
- New readout chip
  - recovers efficiency up to PU ~ 100

Phase I Upgrades: Hadronic Calorimeter

Photodetectors

solve frequent elec. discharges (better noise, gain, longevity)

forward: suppress anomalous signals (particles in PM tubes)



Front-end

new chips: @25 ns readout (= 40 MHz)

Back-end

new μTCA board (large data volumes)

Phase I Upgrades: Level 1 Trigger

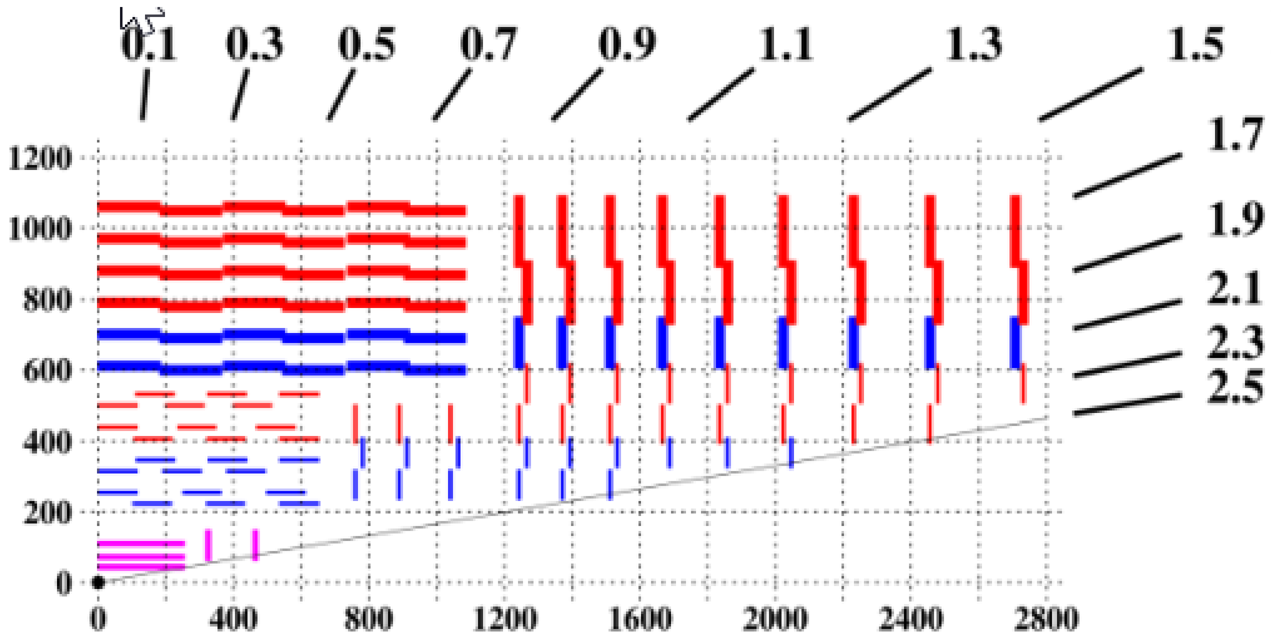
- Goal: maintain performance in Run2 and Run3
  - increase in rate ~ x6
  - need to subtract PU
  - improve efficiency & resolution
  - keep it flexible!

- Sophisticated algorithms (FPGAs) in μTCA to exploit
  - full granularity of CALO info
  - additional MUON info

- In operation since 2015!

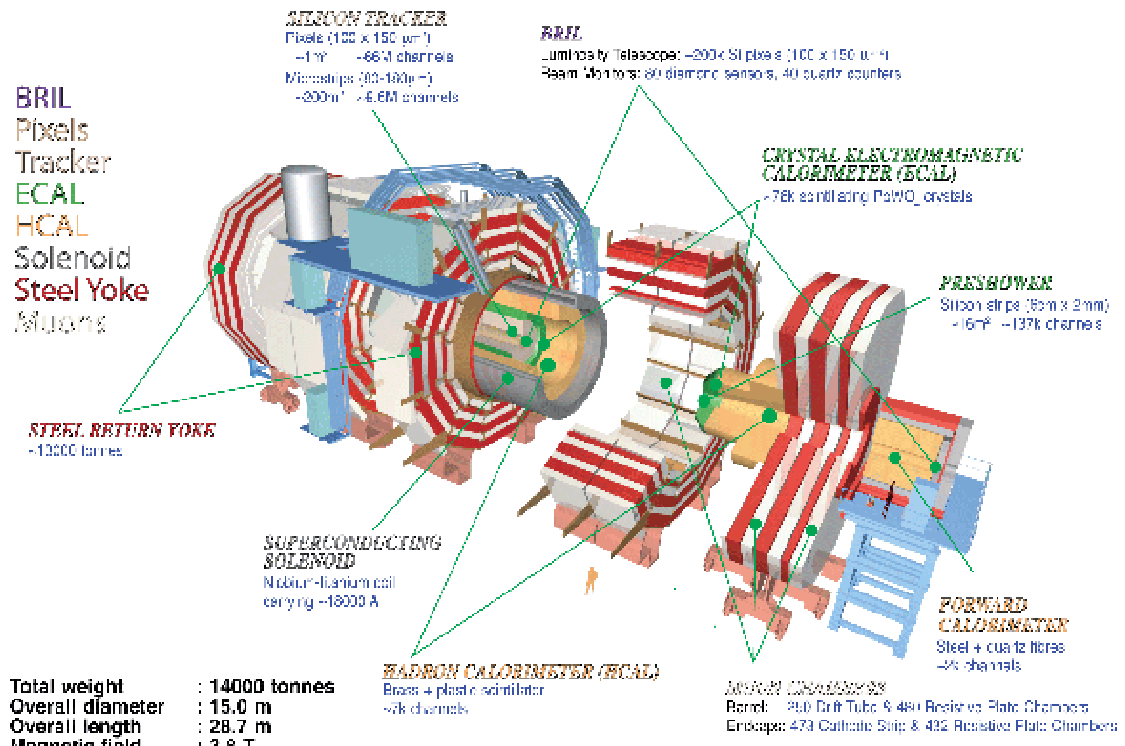
Phase I Tracker

- The current silicon strip tracker will age severely during phase I
- The present tracker covers |η|=2.5
- About 10 barrel layers and endcap disks
- Material thickness of about 1-1.5 X_0



Additional Timing Capabilities

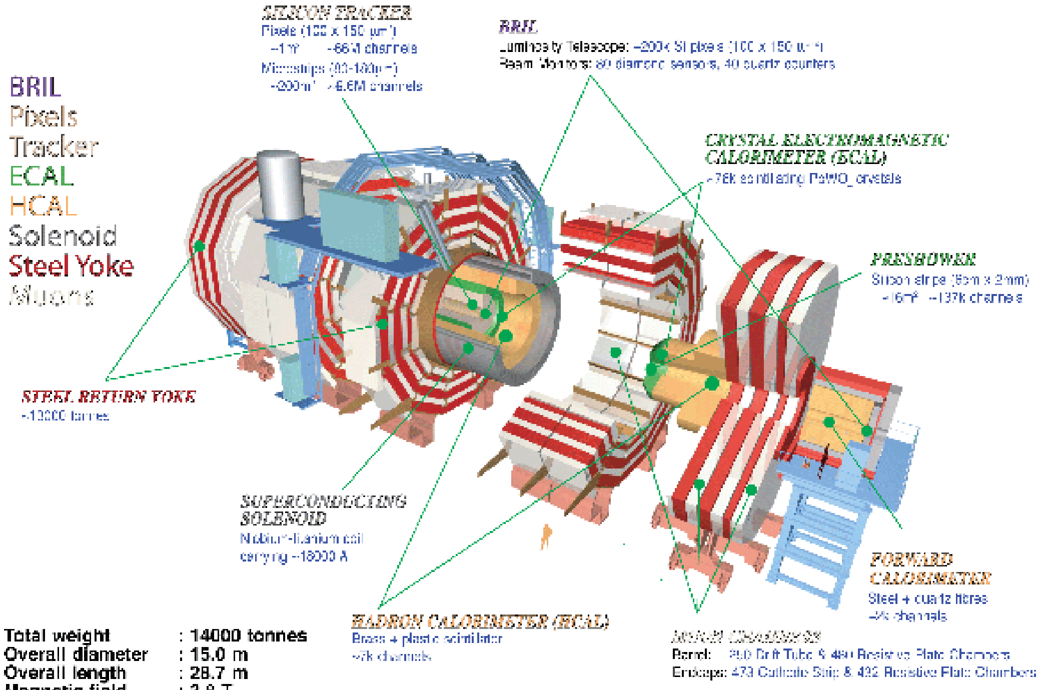
- Calorimeter upgrades can already provide precision timing for high energy photons in the central region, moderate energy photons, and higher energy hadrons in the forward region
- Additional capabilities: MIP timing to cover large fraction of charged particles in the event
- Targeting σ_t= 30 ps
- Extension to Phase-II Upgrade: MIP timing layer

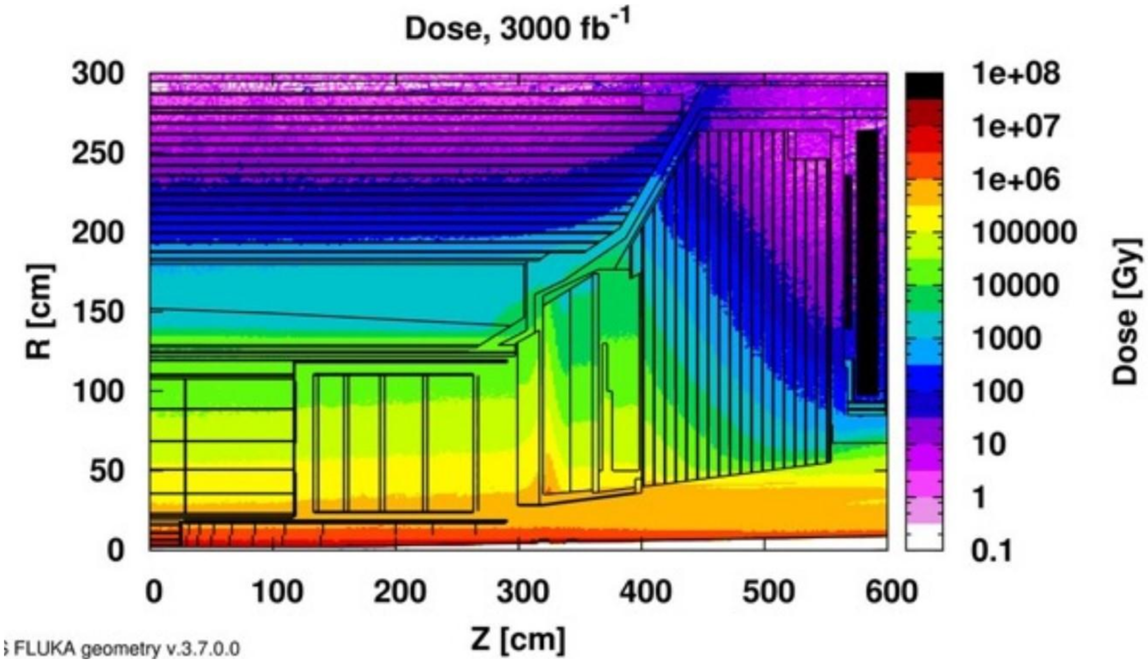


- Concept for central region: Thin LYSO + SiPM layer built into tracker barrel support tube (in between tracker and ECal Barrel) → precision timing for charged particles and converted photons

- Concept for forward region (more stringent radiation hardness requirements): LGAD (Silicon with Gain), with baseline location as additional final layer of strip tracker

- **TP in preparation**





Dose, 3000 fb^{-1}
R [cm]
300
250
200
150
100
50
0
0
100
200
300
400
500
600
Z [cm]
1e+08
1e+07
1e+06
100000
10000
1000
100
10
1
0.1
Dose [Gy]
FLUKA geometry v.3.7.0.0