Challenges and New Technologies for HL-LHC at CMS

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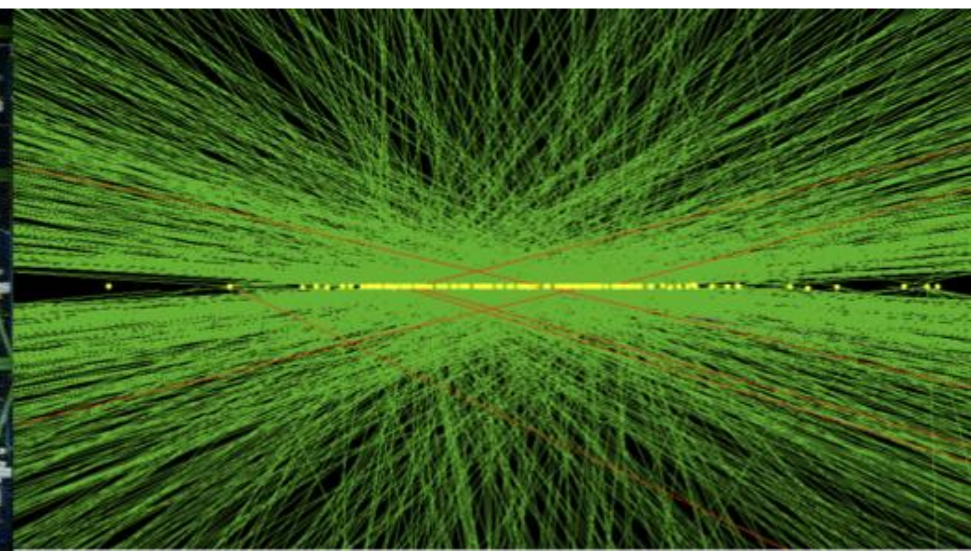
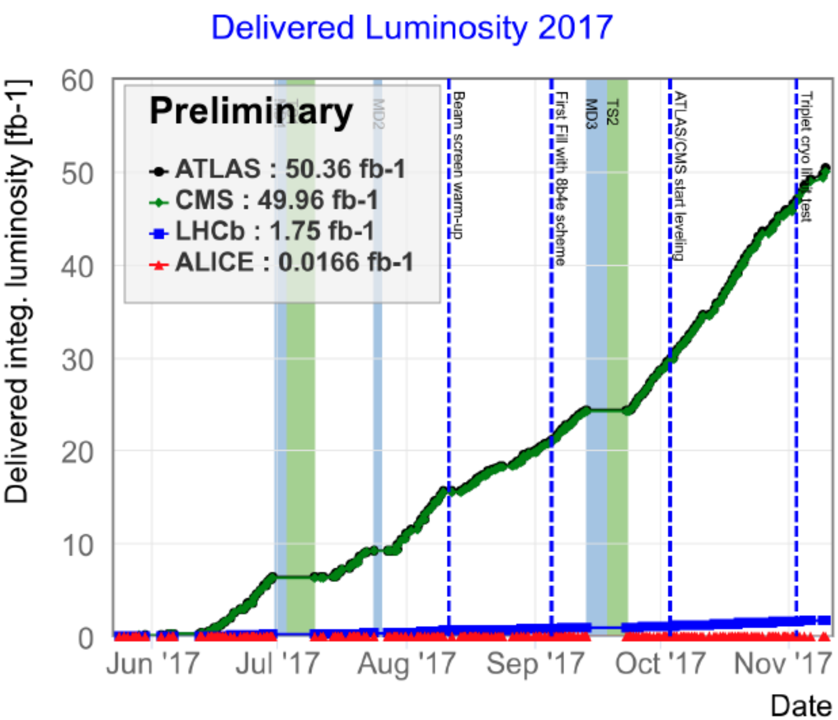
Triggering on New Physics at HL-LHC

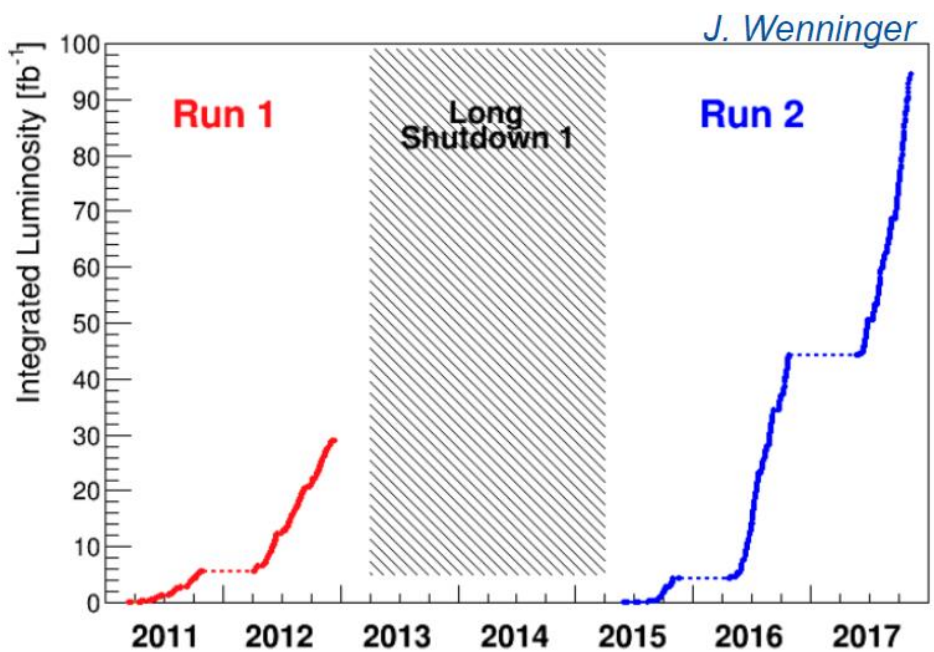
Jan. 15-17, 2018



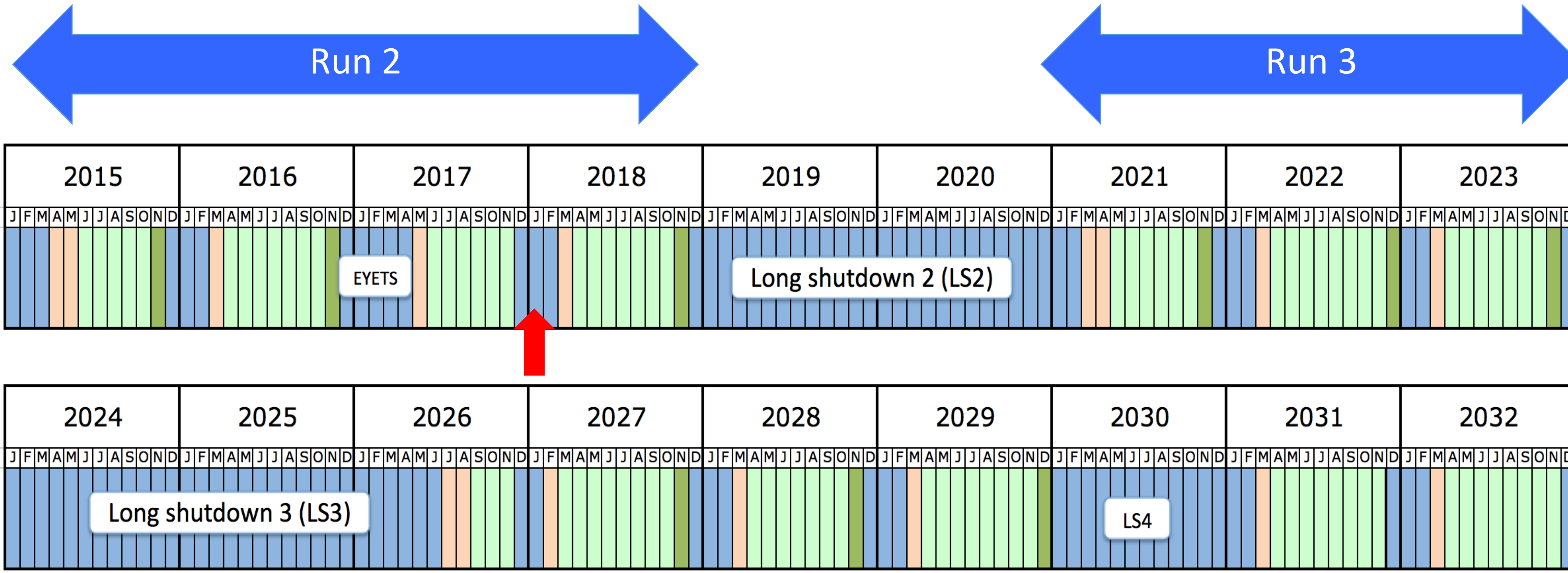
Run 2 LHC Performance

- 50/fb delivered to ATLAS and CMS in 2017!
- Peak luminosity 2.05 x 10 ^{34}/cm^2/s, peak pileup ~50
- Best fill 0.77/fb, best week 5.3/fb
- Run 2 int.lumi. is 100/fb delivered + >50/fb on the way in 2018



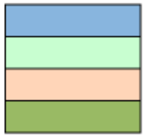


Long term schedule

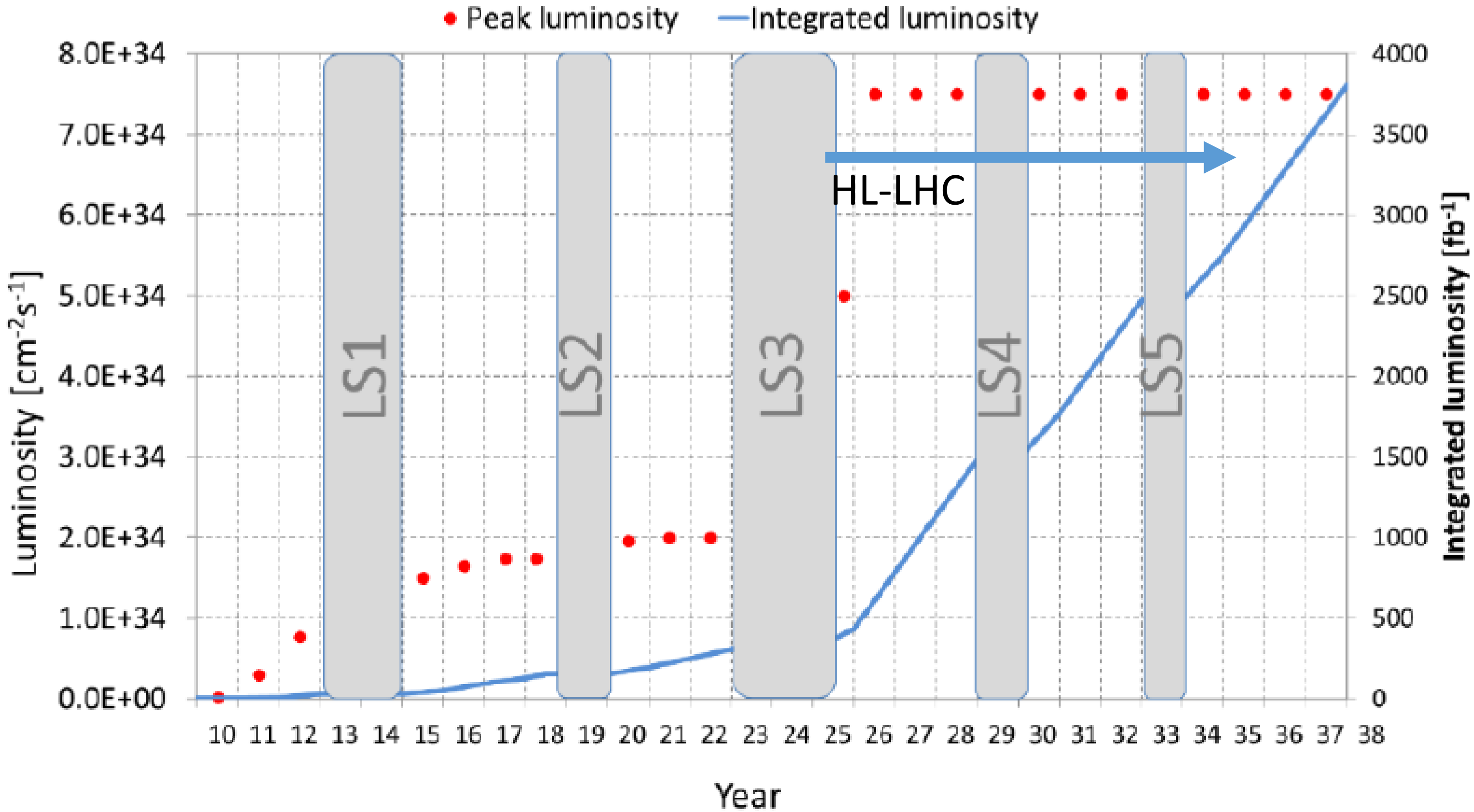


HL-LHC → Up to 3-4/ab through 2037

- Run 2 ends this year, >150/fb total lumi expected
- Injector upgrade during LS2, Run 3 is >150/fb@14 TeV
- Main HL-LHC upgrades in LS3
- Run 4 ~1-1.5/ab starting fall 2026



HL-LHC Expected Luminosity



- Initially improving from 1-2E34/cm^2/s pre-HL-LHC → 5-7.5E34/cm^2/s

- Similar number of bunches, 2x p/bunch, 4x smaller beta*
  → 2E35/cm^2/s peak capability → leveled to 5 to 7.5E34/cm^2/s

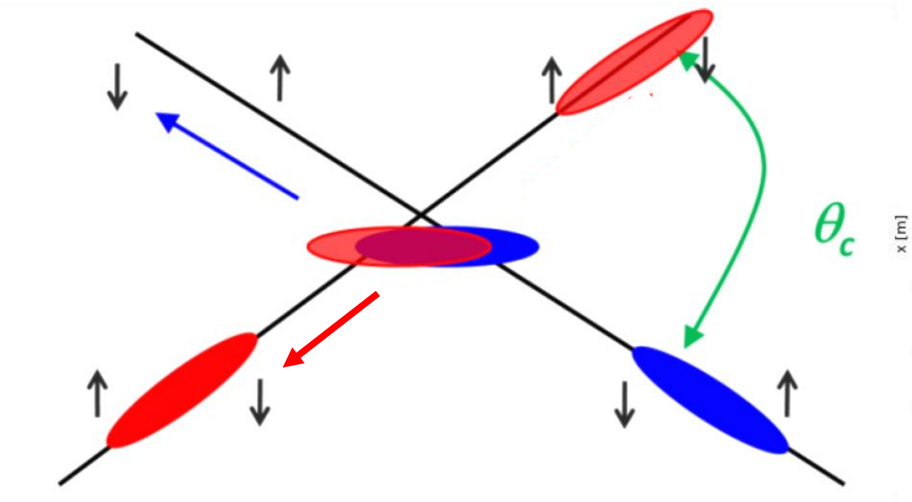
- Run for ~10 years at 250-400/fb/yr → 3-4/ab by 2038

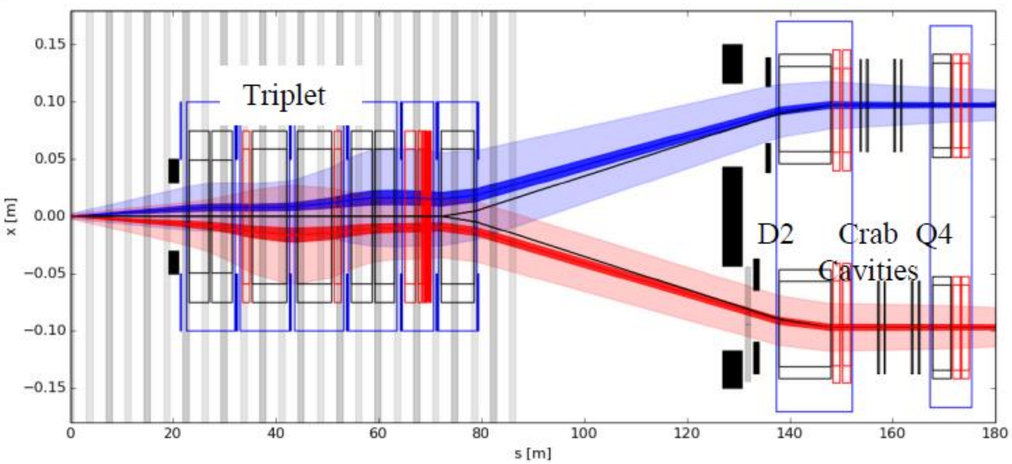
HL-LHC Interaction Region

Key new components are inner triplet and quadrupole crab cavities (high-field NbSn)

Higher beam currents, lower beta* require larger crossing angle to avoid beam-beam interactions (crossing angle increases from 300 → 600 μrad)

To make sure bunches overlap maximally at IP, tumble the bunches just so (“crab crossing”)

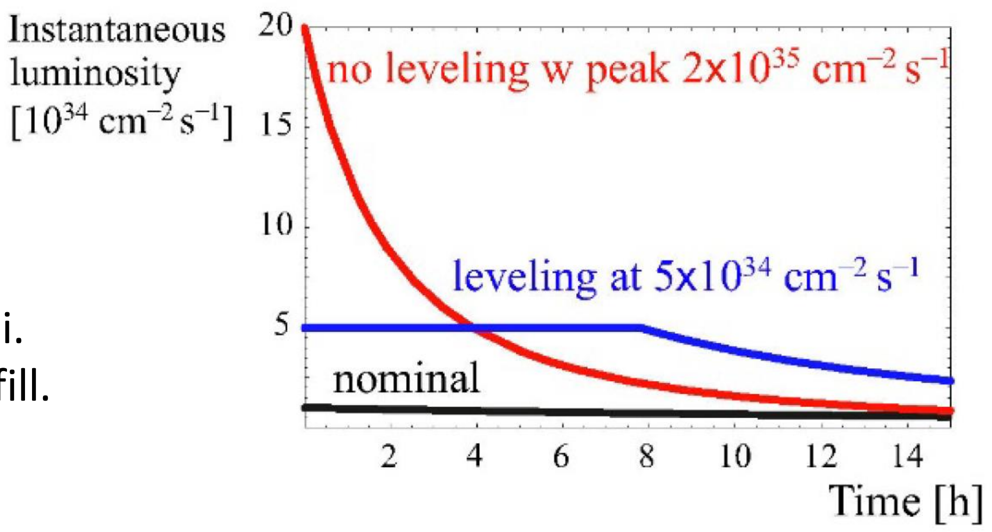




HL-LHC Expected Operations

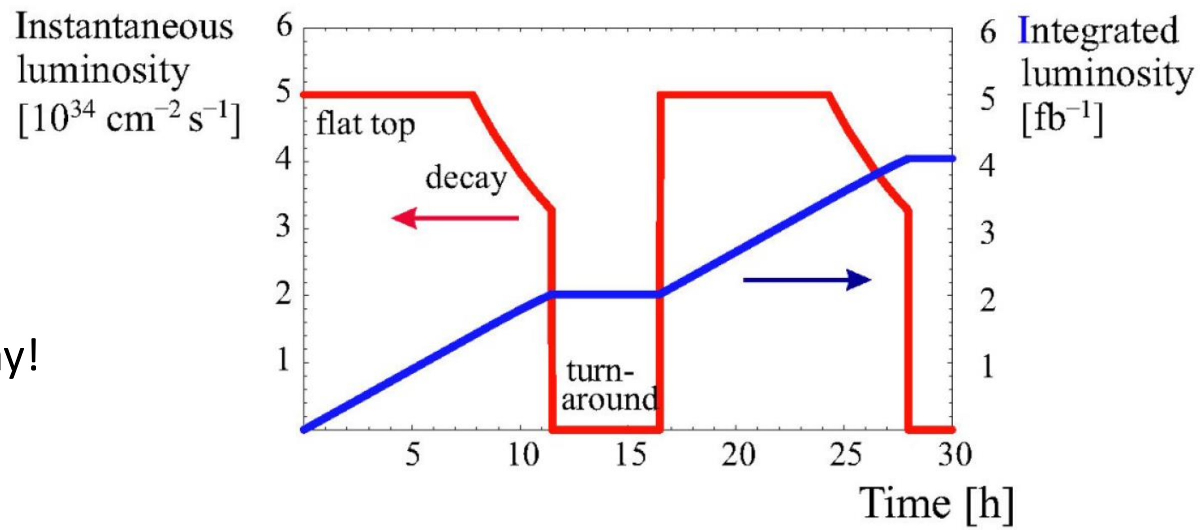
To avoid highest pileup,
lumi is leveled at 5-7.5E34
via beam separation ("crab-kissing")

Longer beam lifetime leads to int.lumi. comparable to unleveled for a single fill.



High uptime/short turnaround time crucial to meeting multi/fb daily operations goals

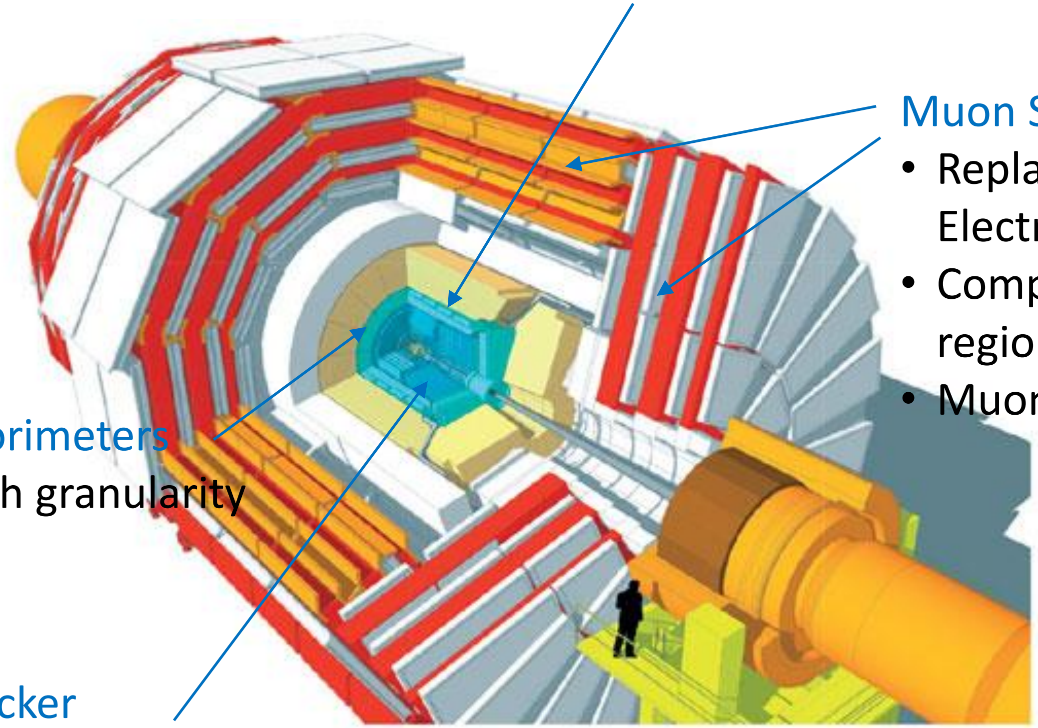
Ex. Two 12-hour, 2/fb fills per day!



CMS Upgrade Overview

Trigger/HLT/DAQ
- Track information in L1-Trigger
- L1-Trigger: 12.5 μs latency – output 750 kHz
- HLT output 7.5 kHz

Barrel ECAL/HCAL
- Replace FE/BE electronics
- Lower ECAL operating temp. (8 ←C)

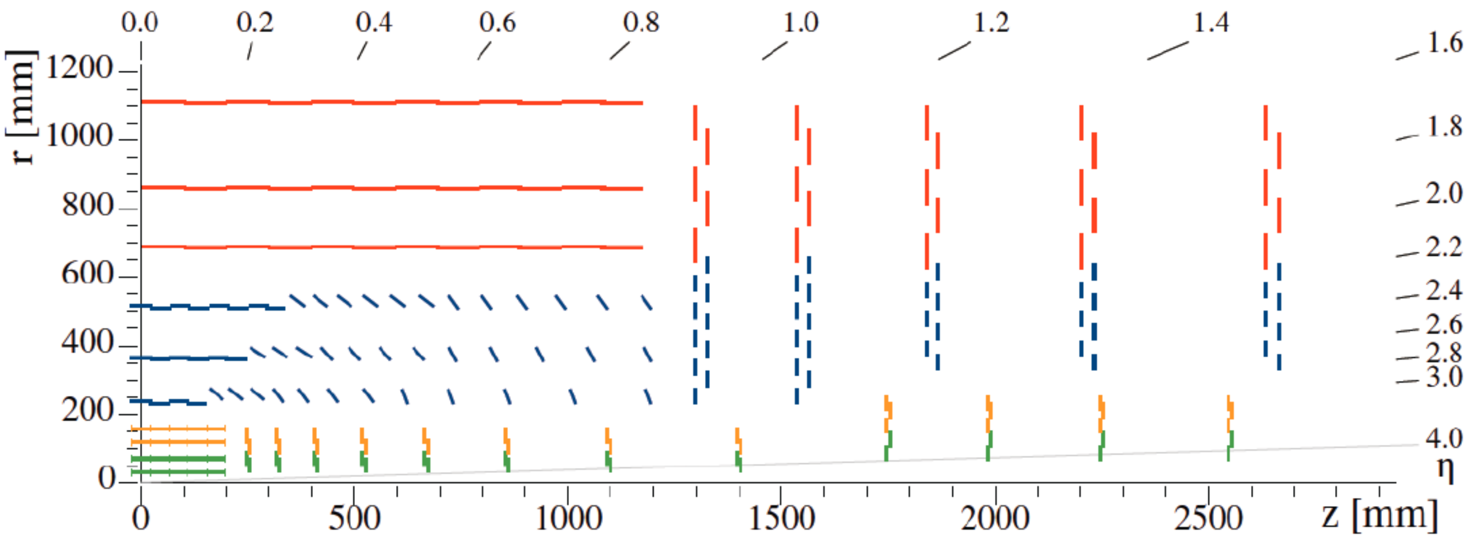


Muon Systems
- Replace DT & CSC FE/BE Electronics
- Complete RPC coverage in region $1.5<\eta<2.4$
- Muon tagging $2.4<\eta<2.8$

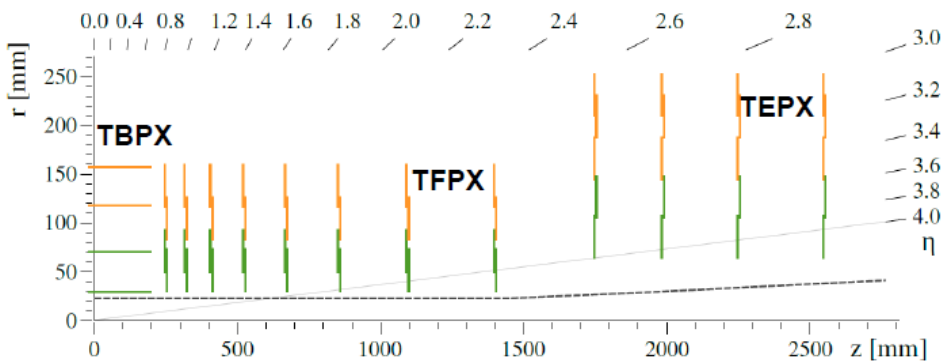
Replace Endcap Calorimeters
- Rad. tolerant – high granularity
- 3D capable

Replace Tracker
- Rad. tolerant – high granularity – significant less material
- 40 MHz selective readout (p_T>2 GeV) in Outer Tracker for L1 -Trigger
- Extended coverage to η=4

Phase 2 Tracker System



Outer tracker coverage from r = 25 to 110 cm and eta<3
Pixel coverage from r=3 to 16 cm and eta<4
Material budget cut in ~half for eta<2
Outer tracker has double-layer geometry for L1 track trigger stubs

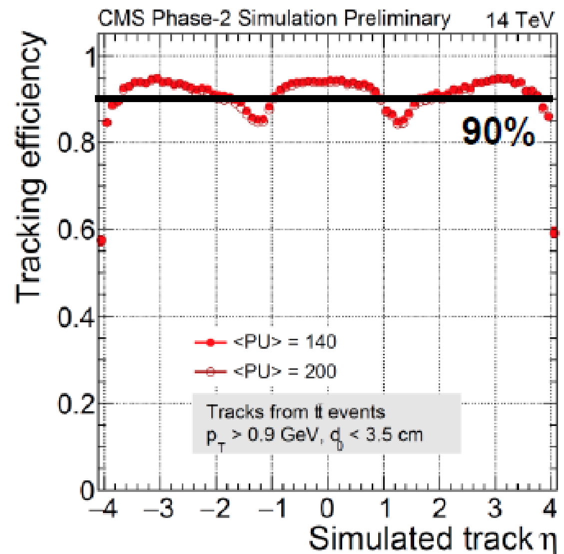


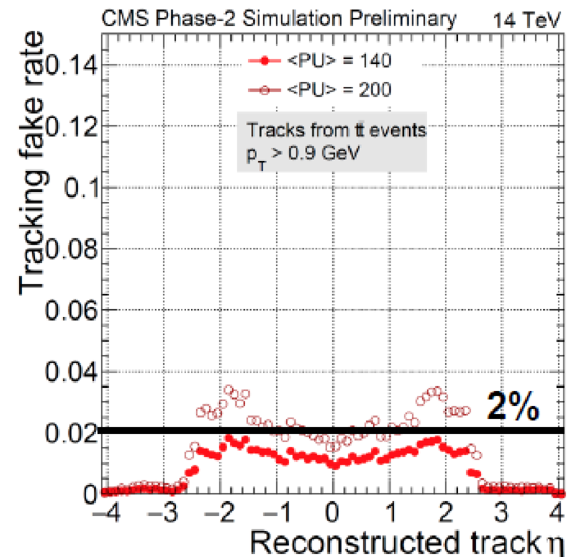
TBPX: Tracker Barrel Pixel Detector
TFPX: Tracker Forward Pixel Detector
TEPX: Tracker Endcap Pixel Detector

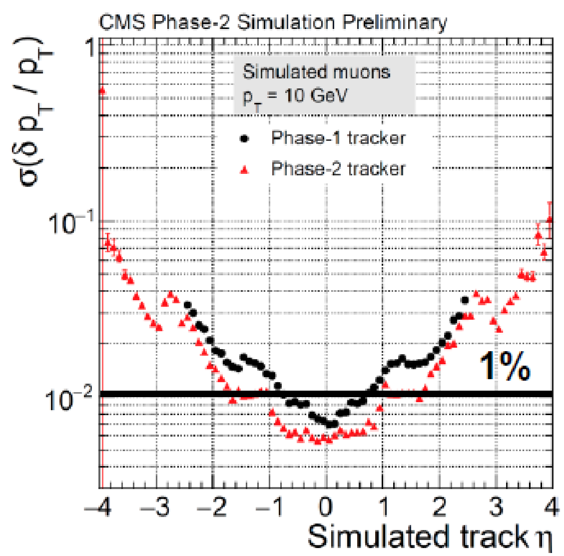
Phase 2 Tracker Performance

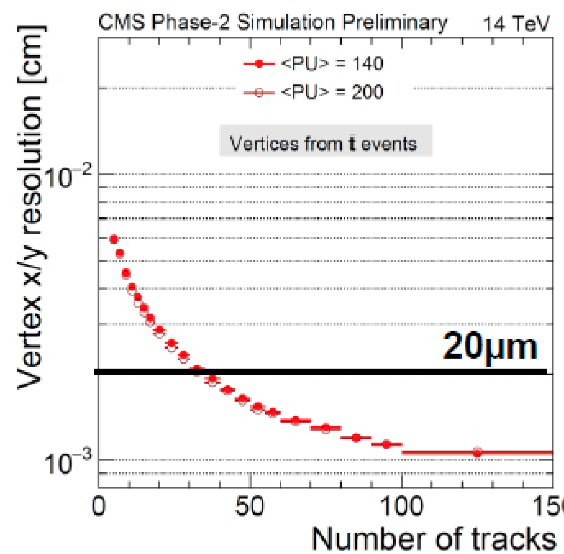
Good efficiency, fake rate, PT resolution, and vertex Resolution

Minimal performance loss at higher range of HL-LHC pileup

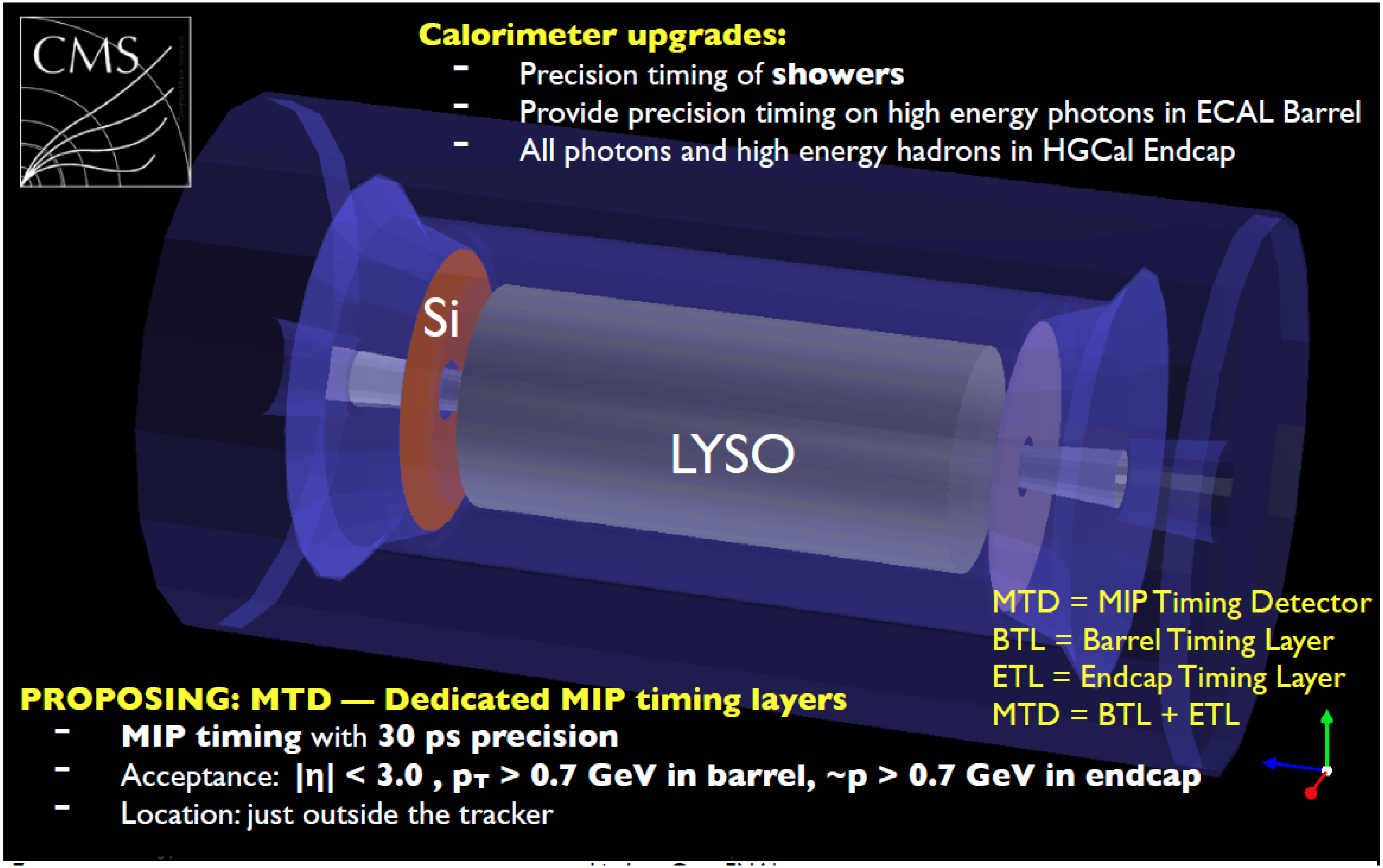








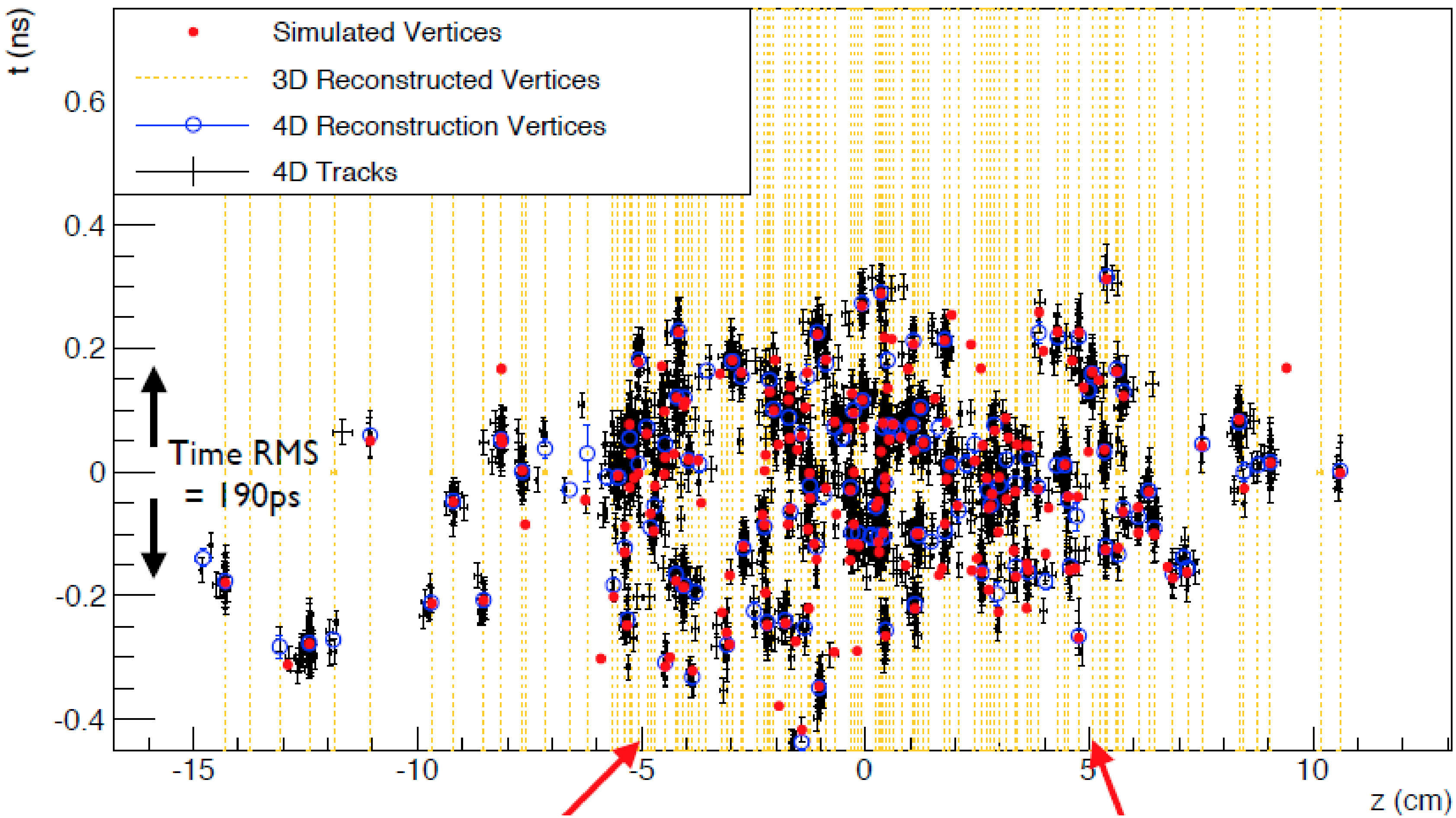
Phase 2 MIP Timing Detector



BTL: LYSO with SiPM ETL: Si with LGAD

30ps timing out to eta of 3.0 for MIP Pt >0.7 GeV

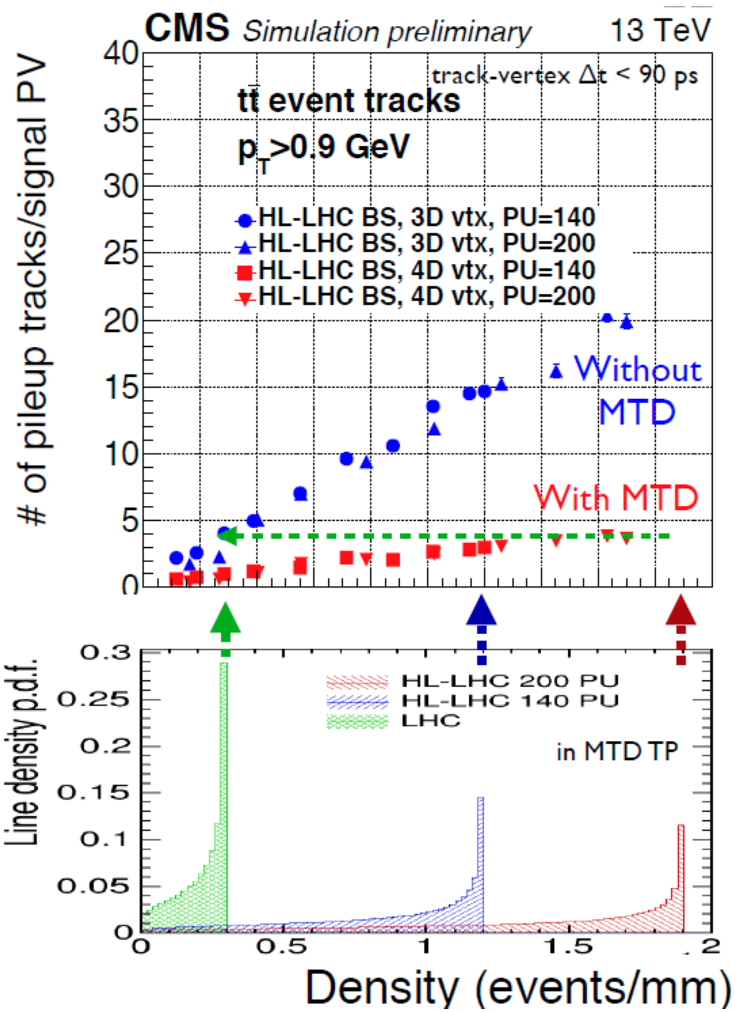
Phase 2 MIP Timing Detector: **4D tracking**



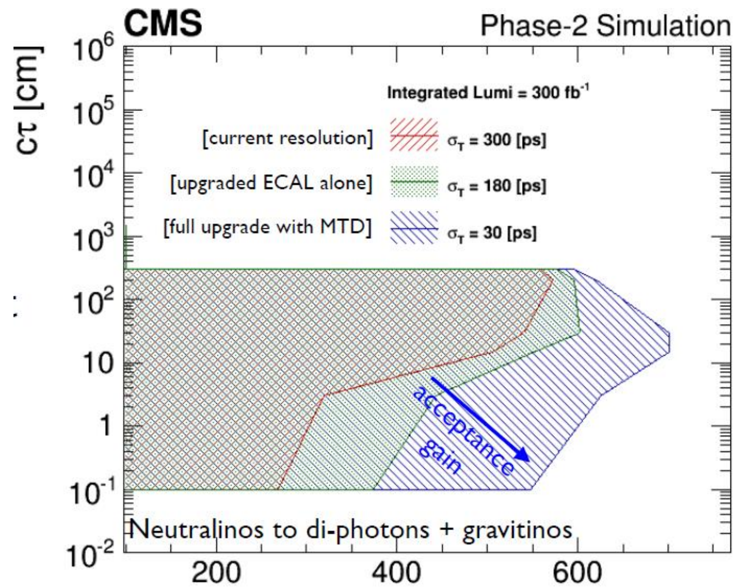
~30 ps time measurement is an independent discriminator for charged track-vertex association at 4-5X level: makes **HL-LHC charged PU=200 look like 2017 PU=50 conditions**

Phase 2 MIP Timing Detector

Simulation studies show 3-4x reduction in pileup tracks being mis-assigned to signal vertex



Extended sensitivity to LLP



Plus:

~+20% Higgs and di-Higgs statistics

Reduces MET tails

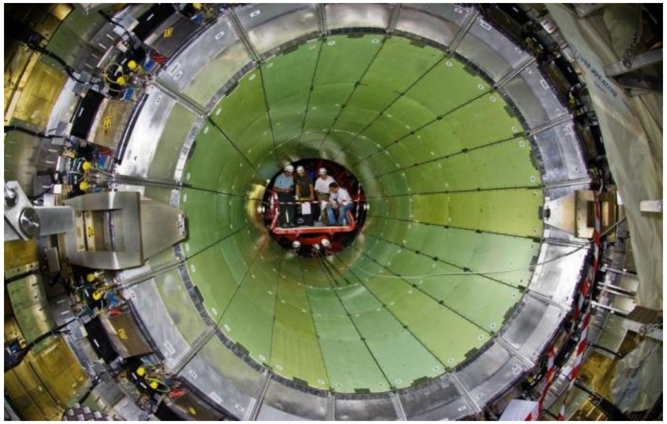
Improves b-tag efficiency

Improves pile-up jet rejection

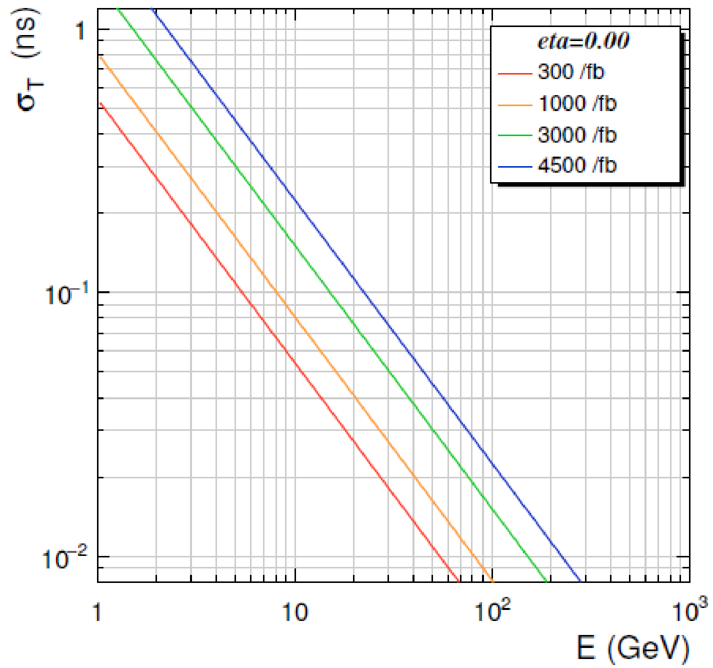
Mass reconstruction in some LLP scenarios

Phase 2 Barrel Calorimeter -- ECAL

- 36 Supermodules in eta < 1.5 region will be refurbished.
- All on board active electronics will be replaced.
- Only 61200 crystals and their APDs left untouched.



- Cool APDs to 8C to **reduce radiation-induced noise.**
- Change shaping time of preamp to reduce noise, improve background spike rejection, and allow for **30 ps timing resolution@ 50 GeV** (H→ γγ vertexing)



Upgrade readout electronics to output 750 kHz of data to DAQ and send **single crystal energies and timing data to L1 trigger** (was 5x5 energy sums) 0.0174x0.0174 in eta-phi

Quantity	N bits
E_T	10
time	5
spike flag	1
Total	16

Phase 2 Barrel Calorimeter -- HCAL

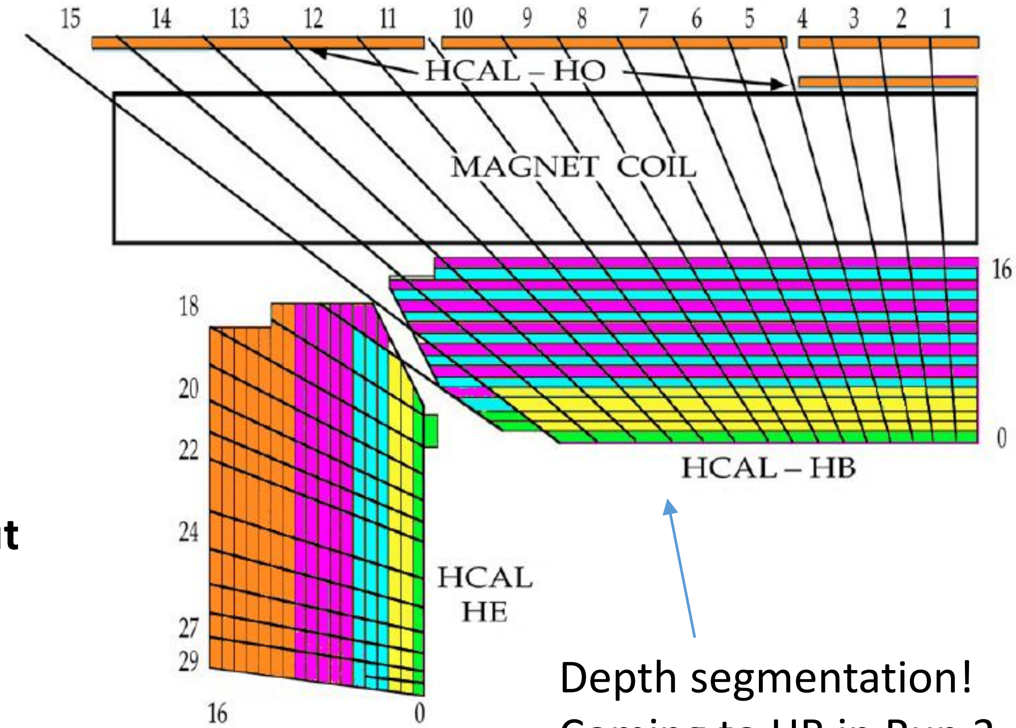
HCAL Barrel and HF readout electronics upgraded/expanded to accommodate 750 kHZ output to DAQ

Same FPGA boards used for HB as will be used for ECAL upgrade

Summing 4 readout depths per trigger tower,

10 energy bits + 6 "feature bits" output to L1 trigger, still under definition and study

Offline HB (HF) data payload includes 8 (3) time samples of each channel and 4 (2) bunch crossing of trigger primitives



Depth segmentation!
Coming to HB in Run 3

Phase 2 Endcap Calorimeter

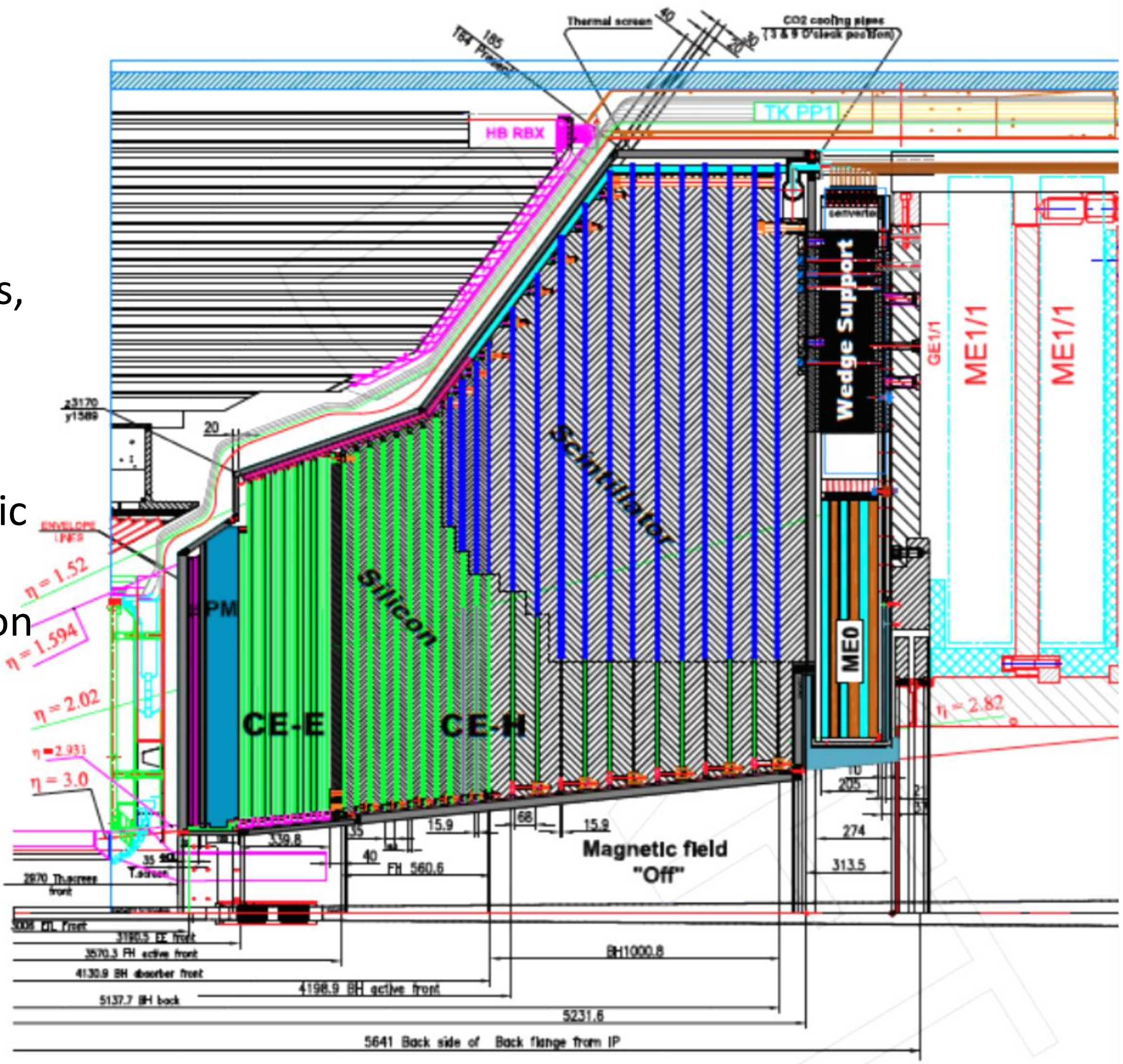
Brand new endcap calorimeter spanning 1.5 < eta < 3.0

SS/Cu/WCu+Si sensors in front layers,
SS+Si in forward hadronic layers
Scintillating tiles+SiPMs in the back

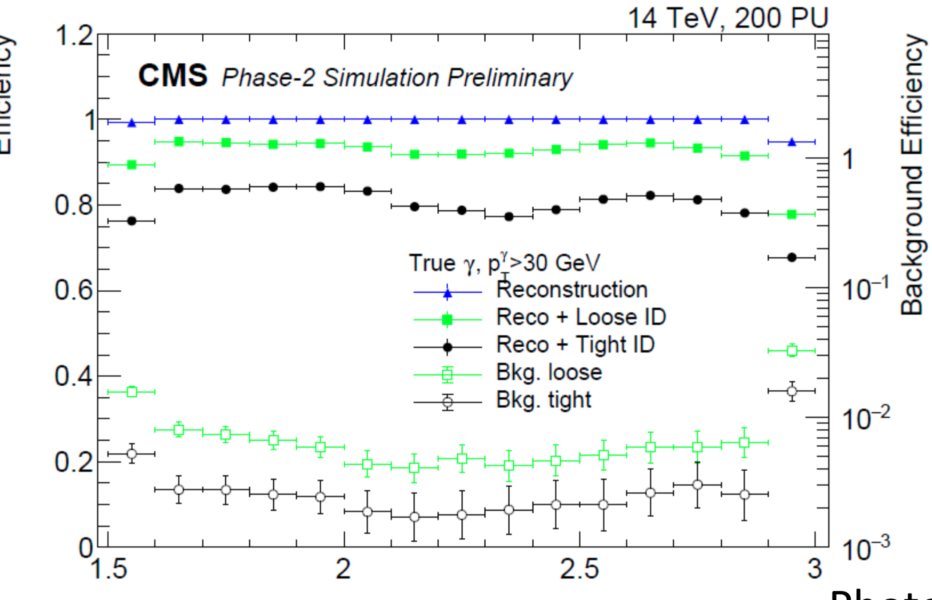
28 sampling layers in electromagnetic section “CE-E”
24 sampling layers in hadronic section “CE-H”

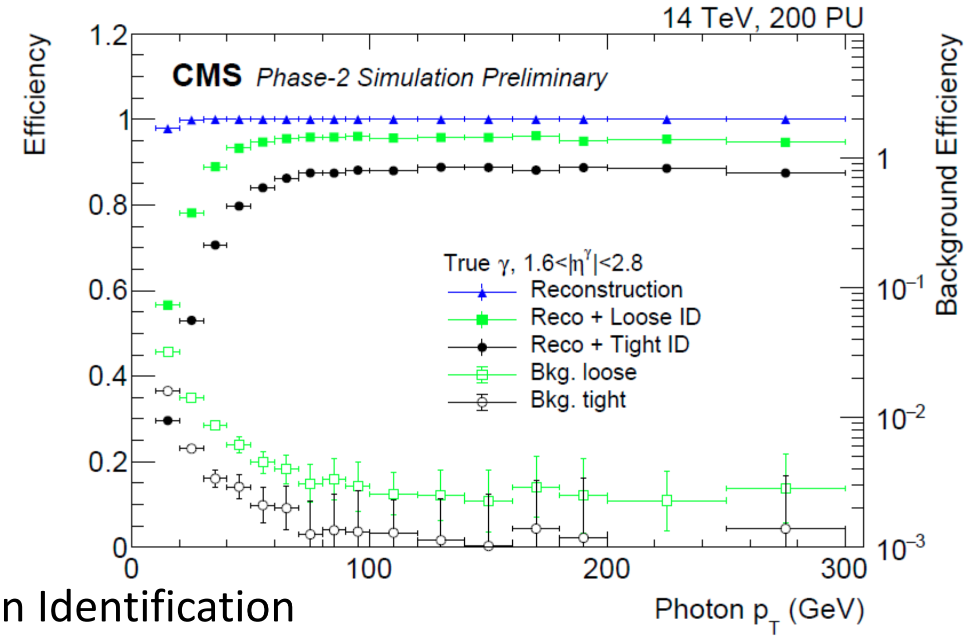
3-D shower reconstruction

~25ns shower max timing capability

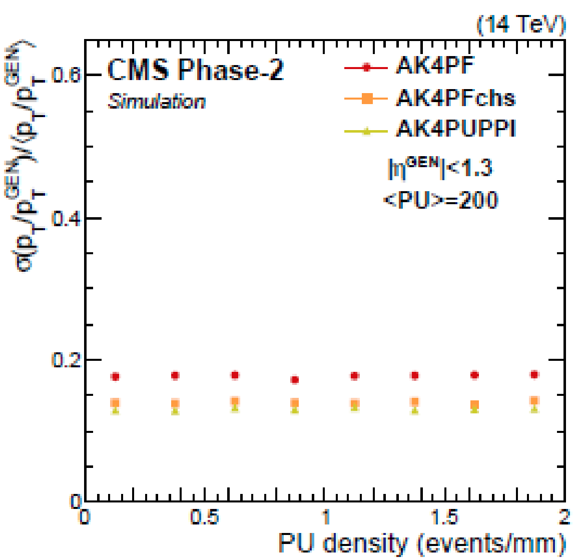


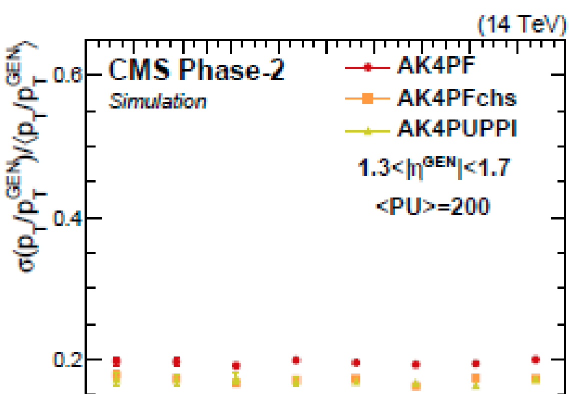
Phase 2 Endcap Calorimeter

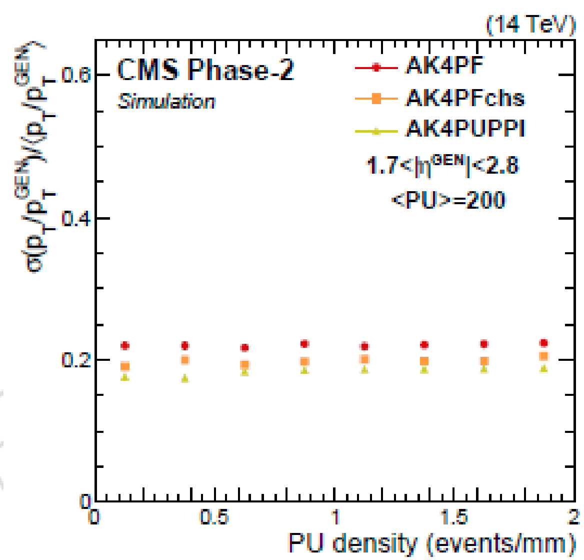




Photon Identification



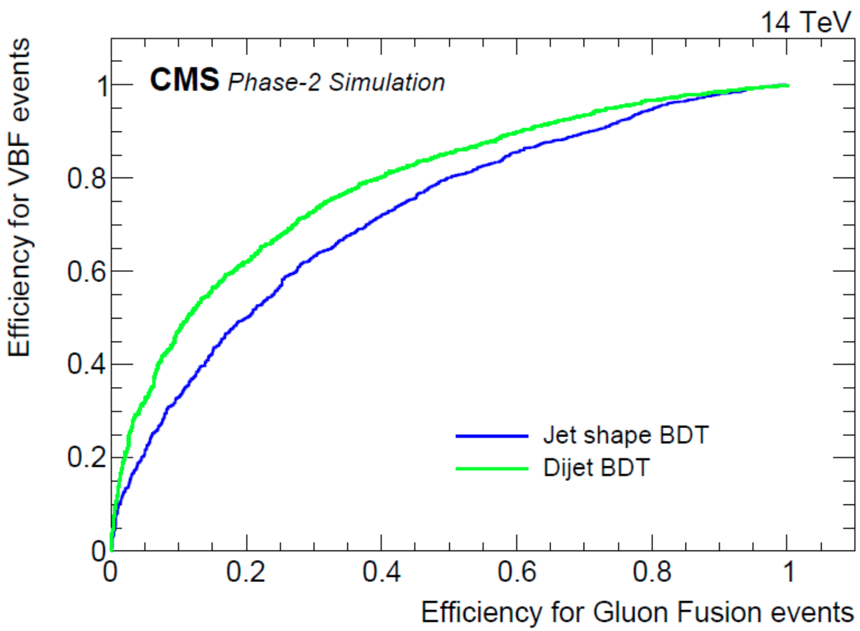




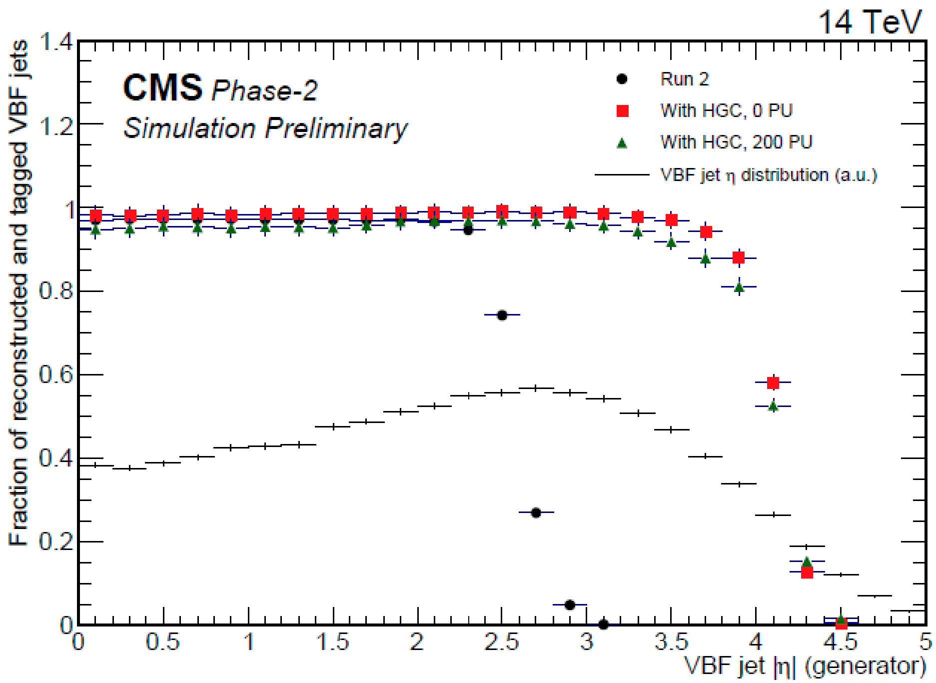
Jet response

Phase 2 Endcap Calorimeter

Good discrimination of ggH and qqH



Excellent VBF jet reco performance out to eta=4



Plus:

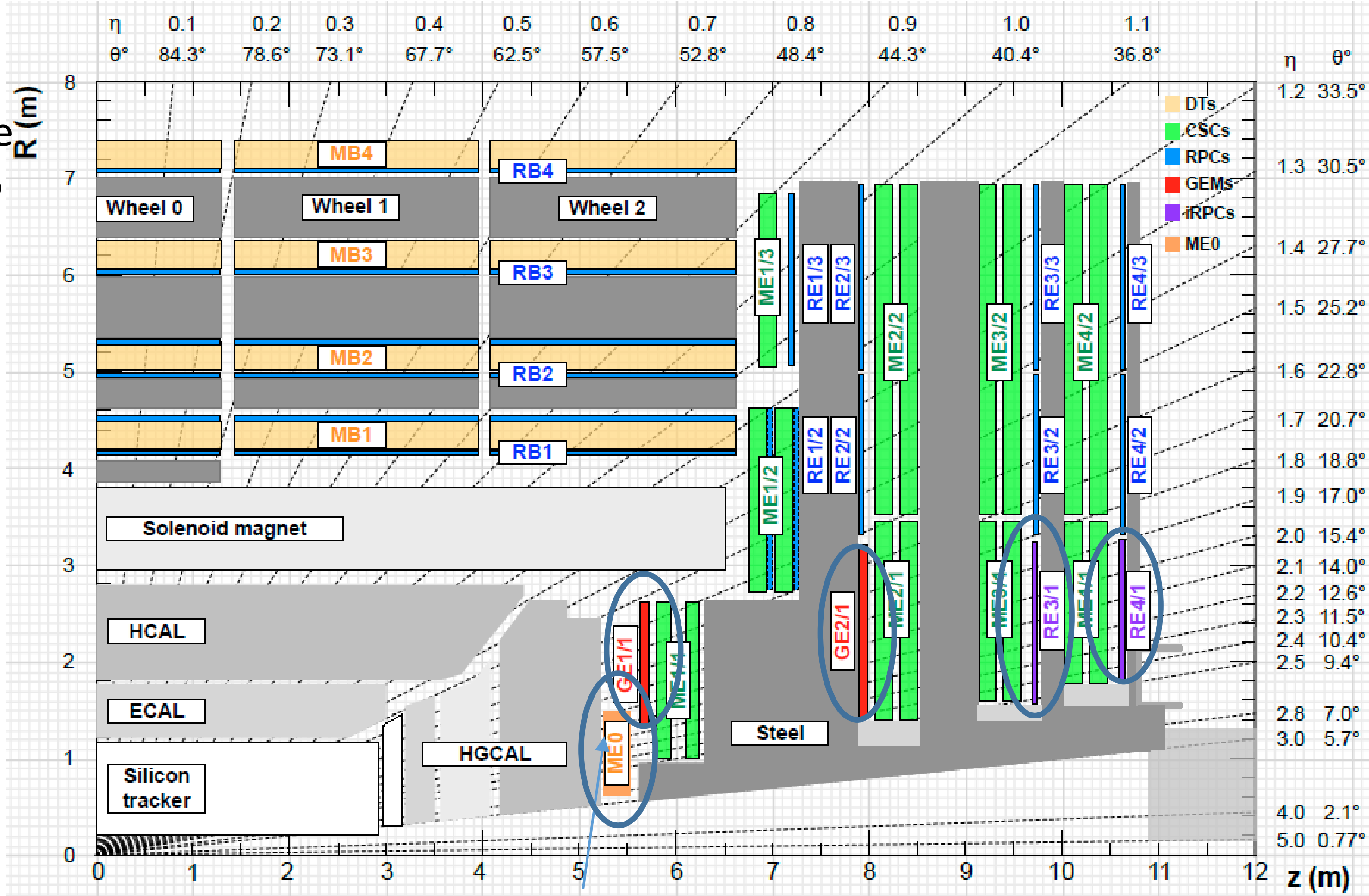
~+12% Higgs to gg stats with much better endcap performance

Improved b-tagging and tau reco

Phase 2 Muon System

New electronics throughout to reduce latency and accommodate 750 kHz output to DAQ

GEMs and new RPCs to improve forward coverage and redundancy



New ME0 layer expands coverage from 2.4 < eta < 2.8

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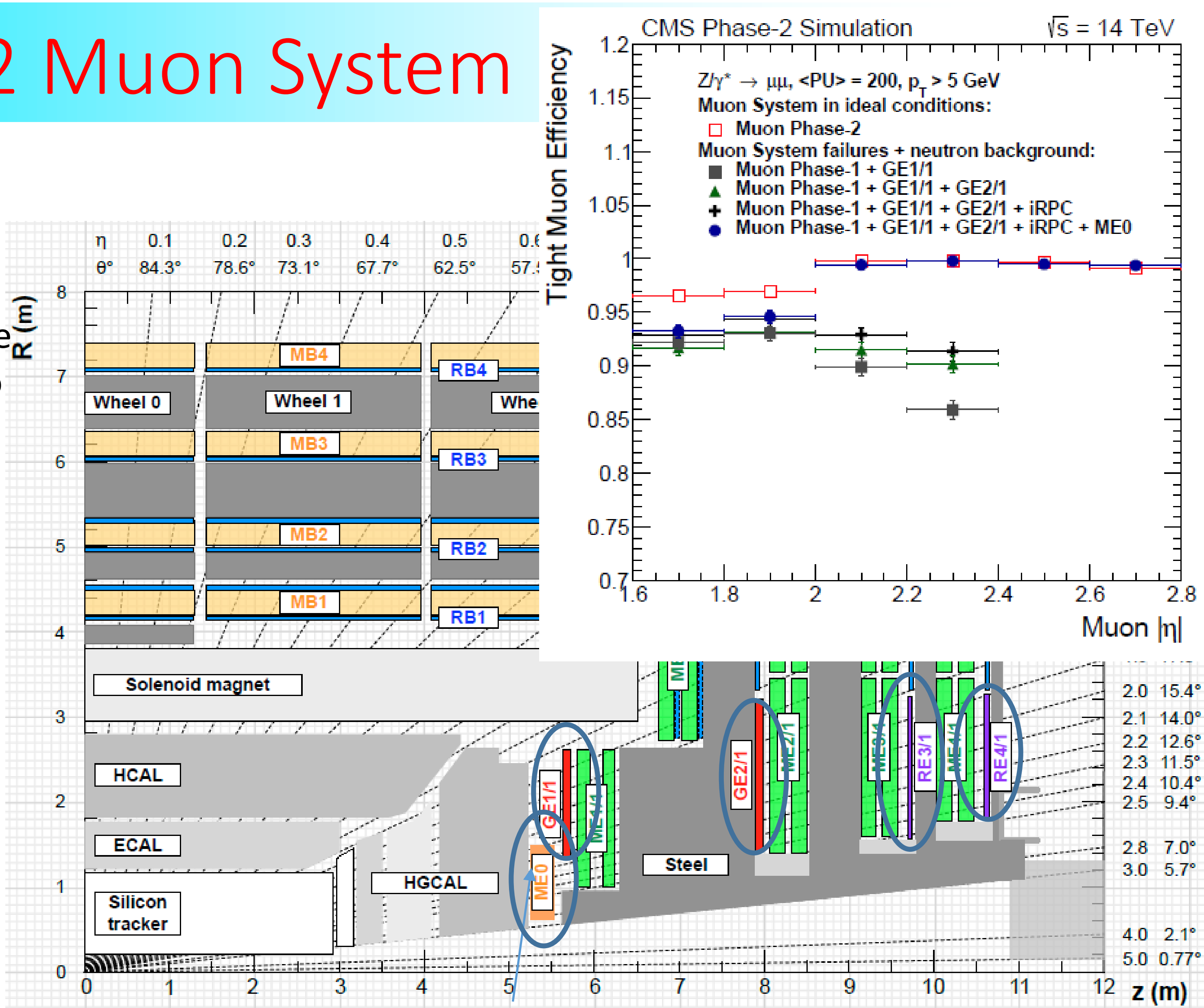
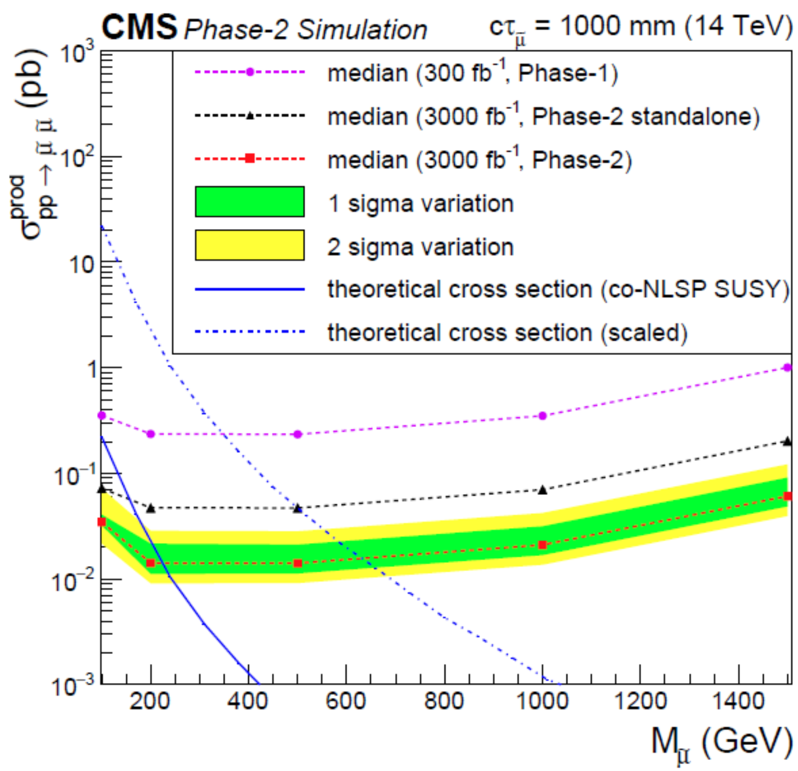


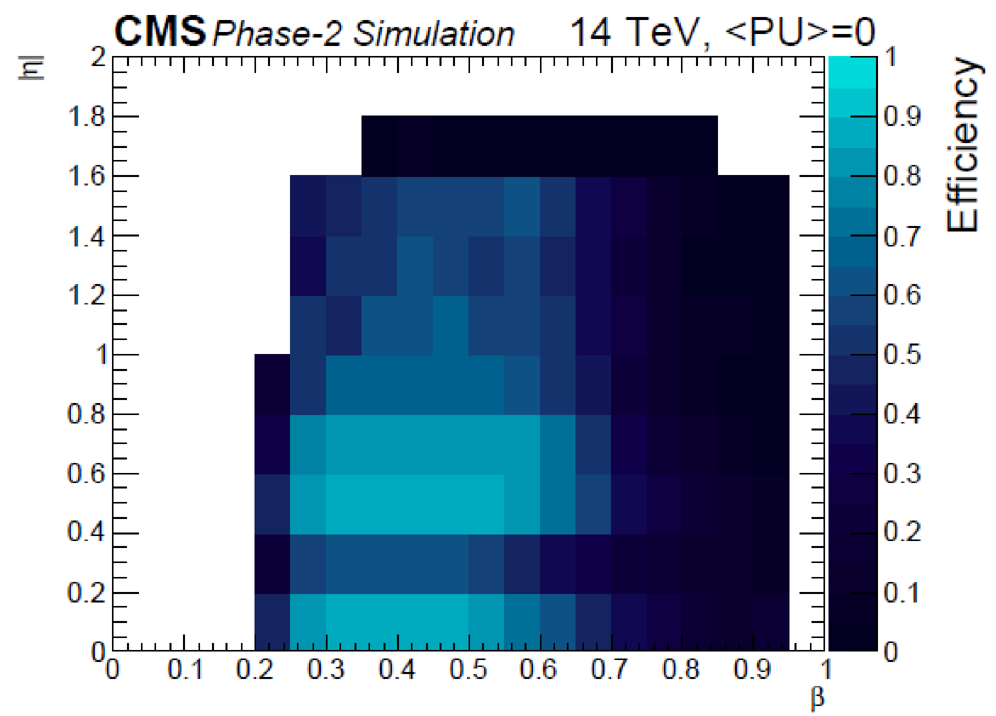
New ME0 layer expands coverage from 2.4 < eta < 2.8

Phase 2 Muon System

With standalone tracking precision aided by GEMs, displaced muon (ct<100cm) sensitivity improves by 3X

New RPCs will extend HSCP sensitivity down to β ~0.2





Plus:

Tau → 3mu sensitivity 2x better

H →4mu acceptance up 17%

Trigger/DAQ Scope and Motivation

- Phase 1 DAQ capable of readout at **100 kHz and 4 us** latency for a L1 trigger decision. Phase 2 will have 5-7x more inst.lumi. How do we upgrade to have the same or better trigger menu and efficiency we enjoy today?

- **Expand DAQ capability to 750 kHz and 12.5 us latency.**

- DAQ expansion keeps up with rising signal rates.

- It does not keep up with rising background rates at higher PU.

L1 trigger selection must improve.

- Trade in more latency for better algorithms,

- Adding more/better data and computing power.

Trigger/DAQ Scope and Motivation

- **New strategies for background rejection:**

- Exploiting the **more refined data** from new subdetectors (HGC, GEM, RPC) and electronics upgrades of existing subdetectors (CSC, DT, EB, HB).

- Combine the tracking data from the **Track Trigger** and the rest of the detector to provide best resolution for particle energy/momentum and remove the effects of pileup.

- **Offline-like (Particle flow + Puppi)** reconstruction techniques

- **Requires rebuild of entire backend + L1 system**

Summary

We are enjoying **today** the epoch where LHC is **exceeding design performance!**

Upgrade plans underway to **improve annual luminosity by 5-7x from today at the expense of 3-4x higher pileup than today.**

CMS detector upgrade primarily intended to **preserve current performance** in this environment while **strategically expanding some capabilities and coverage** to maximize scientific potential

- New electronics to expand DAQ capacity and enhance trigger input
- Timing measurements in ECAL and MTD
- L1 track trigger capability
- 3d shower reconstruction in HGCAL
- Tracker coverage to eta<4 and Muon coverage to eta<3

Fall 2026 is far away but CMS trigger design decisions are not. **Which of these new capabilities can be best exploited in the trigger system to expand the discovery potential of HL-LHC?**

HL-LHC Parameters

Parameter	Nominal LHC (design report)	HL-LHC (standard)
Beam energy in collision [TeV]	7	7
Particles per bunch, N [10^{11}]	1.15	2.2
Number of bunches per beam	2808	2748
Number of collisions in IP1 and IP5*	2808	2736
N_{tot} [10^{14}]	3.2	6.0
Beam current [A]	0.58	1.09
Crossing angle in IP1 and IP5 [μrad]	285	590
Normalized long-range beam–beam separation [σ]	9.4	12.5
Minimum β^* [m]	0.55	0.15
ε_n [μm]	3.75	2.50
ε_L [eVs]	2.50	2.50
r.m.s. energy spread [0.0001]	1.13	1.13
r.m.s. bunch length [cm]	7.55	7.55
IBS horizontal [h]	105	18.5
IBS longitudinal [h]	63	20.4
Piwinski parameter	0.65	3.14
Total loss factor R_0 without crab cavity	0.836	0.305
Total loss factor R_1 with crab cavity	(0.981)	0.829
Beam–beam/IP without crab cavity	0.0031	0.0033
Beam–beam/IP with crab cavity	0.0038	0.011
Peak luminosity without crab cavity [10^{34} cm^{-2} s^{-1}]	1.00	7.18
Virtual luminosity with crab cavity $L_{peak} \times R_1/R_0$ [10^{34} cm^{-2} s^{-1}]	(1.18)	19.54
Events/crossing without levelling and without crab cavity	27	198
Levelled luminosity [10^{34} cm^{-2} s^{-1}]	-	5.00†
Events/crossing (with levelling and crab cavities for HL-LHC)‡	27	138
Maximum line density of pile-up events during fill [event/mm]	0.21	1.25