CMS Upgrade and Perspectives

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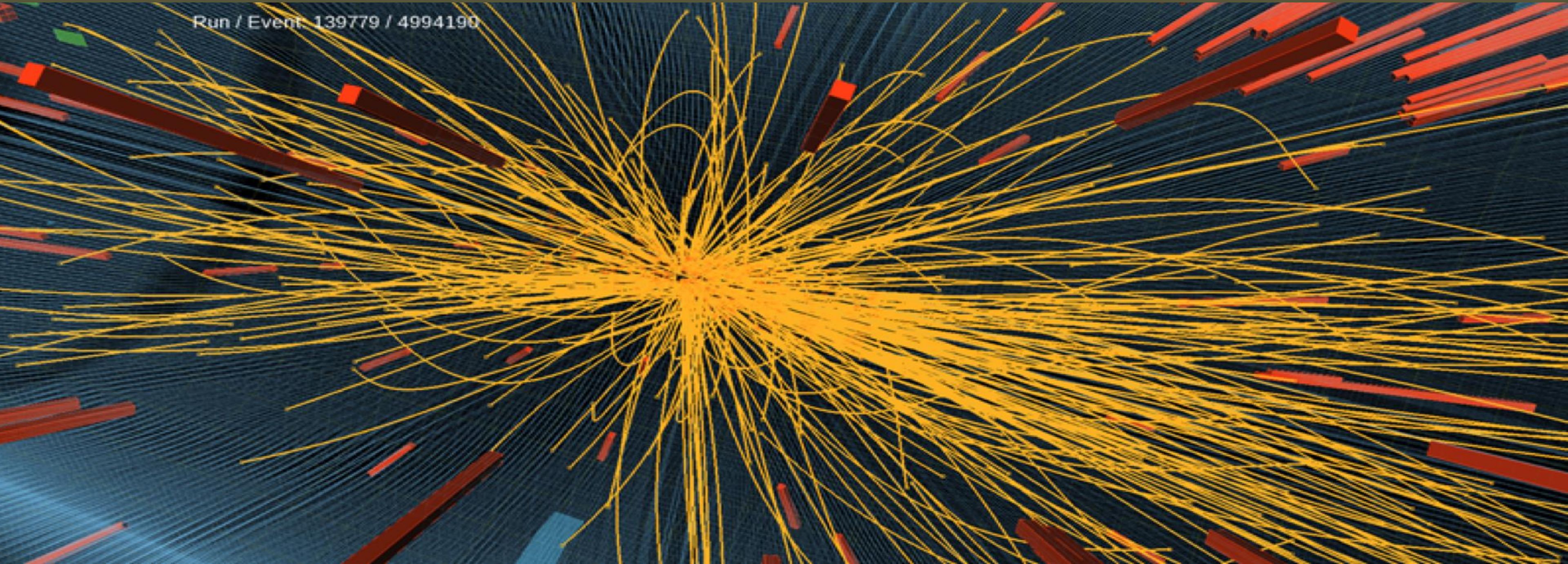
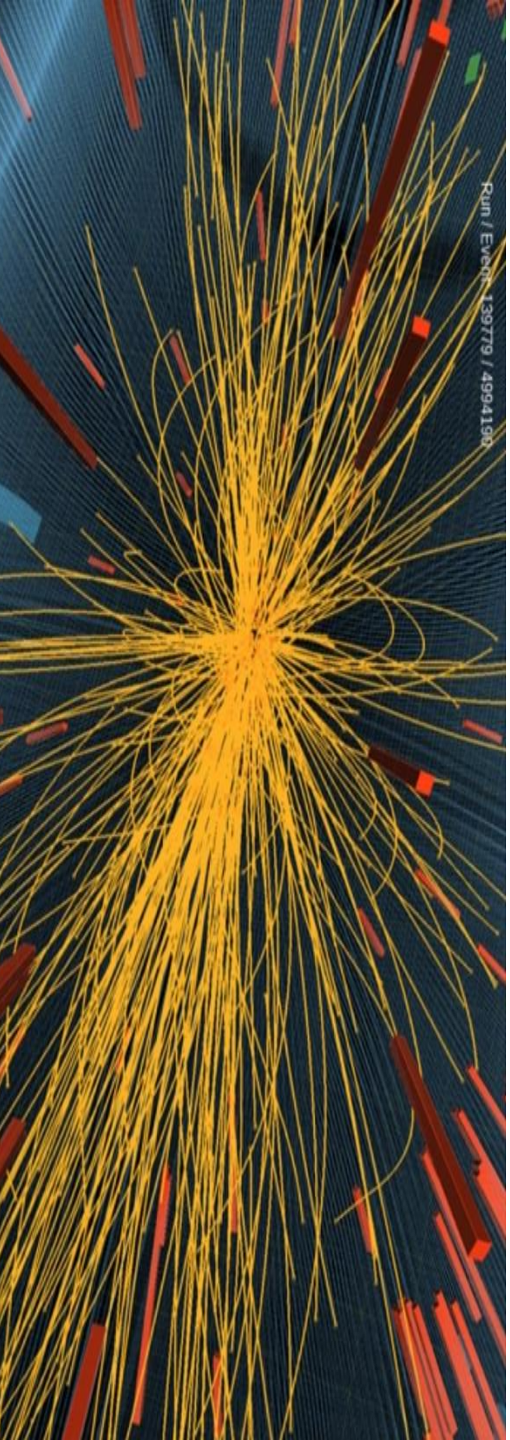
On behalf of the CMS collaboration

CMS Upgrade and Perspectives
Vienna JetMET workshop Aug 2014

Getting ready for 13 TeV: Vienna workshop on jets and missing energy, 25-27 August 2014





Outline

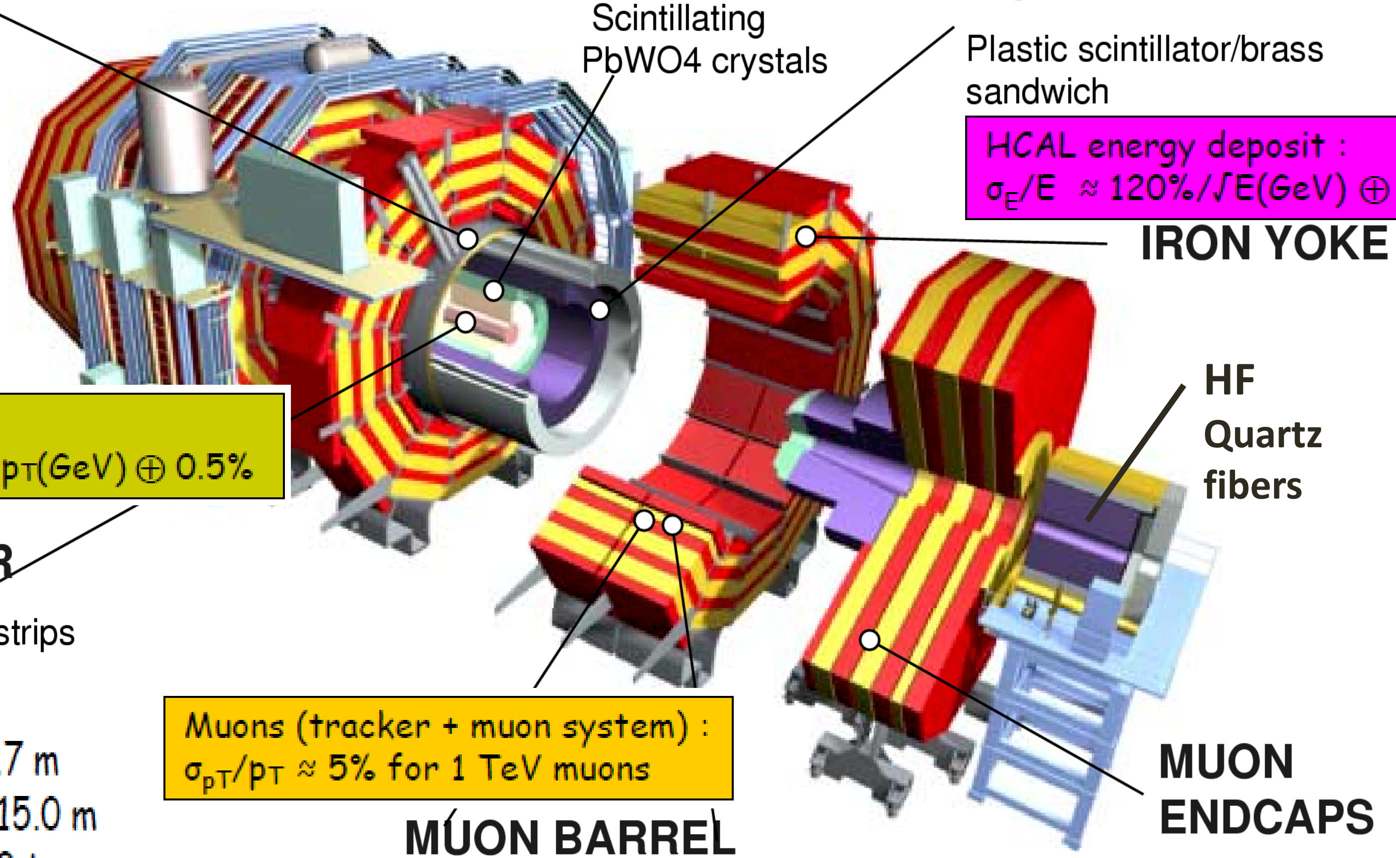
1. **The present CMS detector**
2. **LHC present and future performance**
3. **Consequences for CMS**
4. **Upgrade of the inner tracker**
5. **Upgrading forward calorimetry**
6. **Muon forward upgrade**
7. **Summary**

Emphasis on high-luminosity LHC (>2025) requiring substantial detector upgrades!

Compact Muon Solenoid (CMS)

[CMS coll.: JINST **3** (2008), no. S08004]

Emphasis on electron and photon energy measurement, full silicon tracker providing high momentum resolution



SUPERCONDUCTING COIL

CALORIMETERS

ECAL energy deposit : $\sigma_E/E \approx 2.9\%/\sqrt{E(GeV)} \oplus 0.5\%$

ECAL

Scintillating PbWO4 crystals

HCAL

Plastic scintillator/brass sandwich

HCAL energy deposit : $\sigma_E/E \approx 120\%/\sqrt{E(GeV)} \oplus 6.9\%$

IRON YOKE

Tracking : $\sigma_{p_T}/p_T \approx 1.5 \cdot 10^{-4}\, p_T(GeV) \oplus 0.5\%$

HF

Quartz fibers

TRACKER

Silicon Microstrips
Pixels

Muons (tracker + muon system) : $\sigma_{p_T}/p_T \approx 5\%$ for 1 TeV muons

MUON BARREL

Drift Tube Chambers (**DT**)

Resistive Plate Chambers (**RPC**)

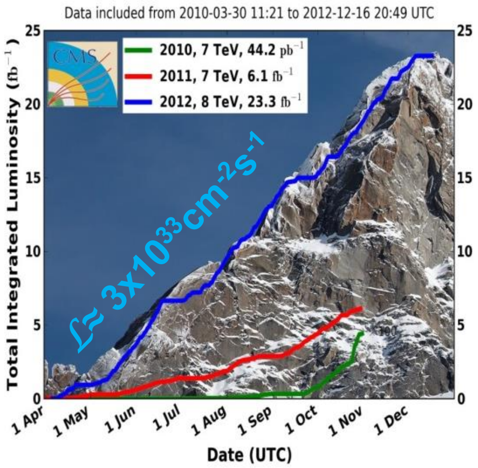
MUON ENDCAPS

Cathode Strip Chambers (**CSC**)
Resistive Plate Chambers (**RPC**)

Overall length : 28.7 m
Overall diameter : 15.0 m
Total weight : 14000 tons
Magnetic field : 3.8 T

LHC performance

LHC very successful up to now!
Run-1 provided 30 fb^{-1} of high quality data
~200 publications

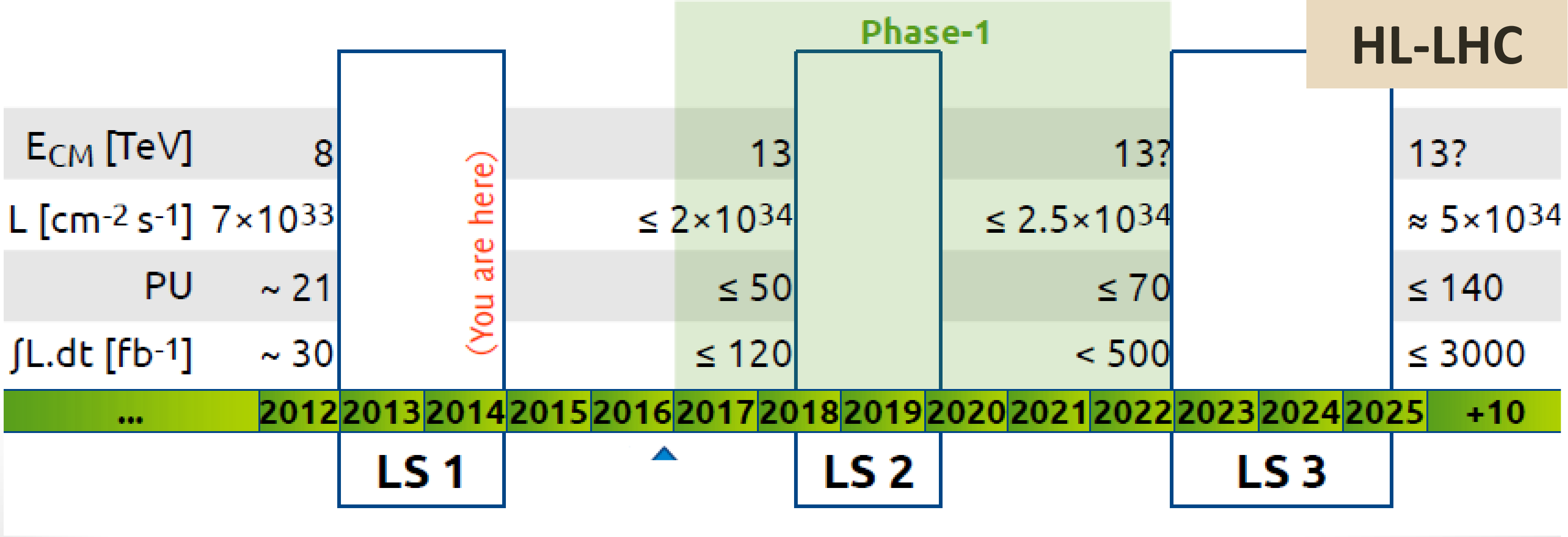


For LHC phase-2 increase luminosity. Consequences for detectors:

→ Higher rates would imply increased trigger thresholds w/o upgrade

→ Detector ageing

→ More bandwidth needed



E_{CM} [TeV]	8		13		13?		13?
L [$cm^{-2} s^{-1}$]	7×10^{33}		$\leq 2\times10^{34}$		$\leq 2.5\times10^{34}$		$\approx 5\times10^{34}$
PU	~ 21		≤ 50		≤ 70		≤ 140
∫L.dt [fb^{-1}]	~ 30		≤ 120		< 500		≤ 3000
...	2012	2013 2014	2015 2016 2017	2018 2019	2020 2021 2022	2023 2024 2025	+10
		LS 1		LS 2		LS 3	

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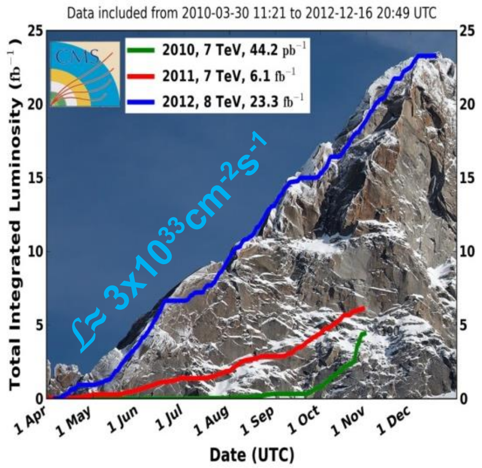

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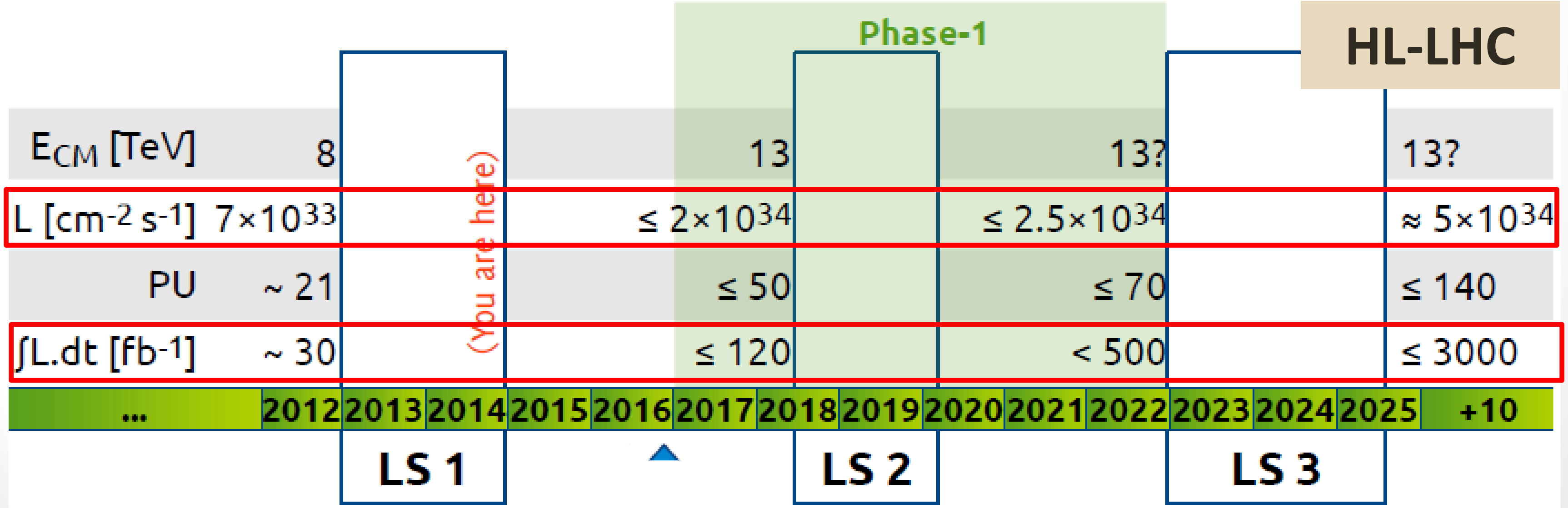

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HL gives access to rare processes and allows precision measurements.

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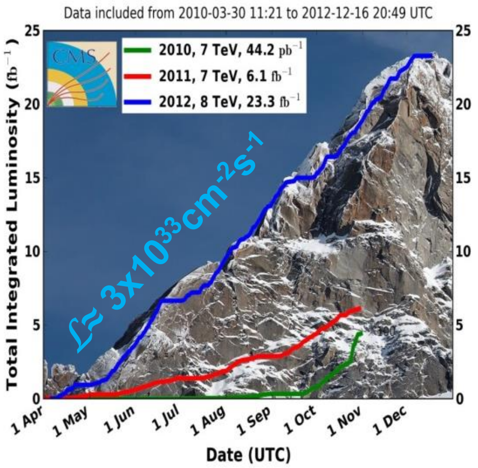

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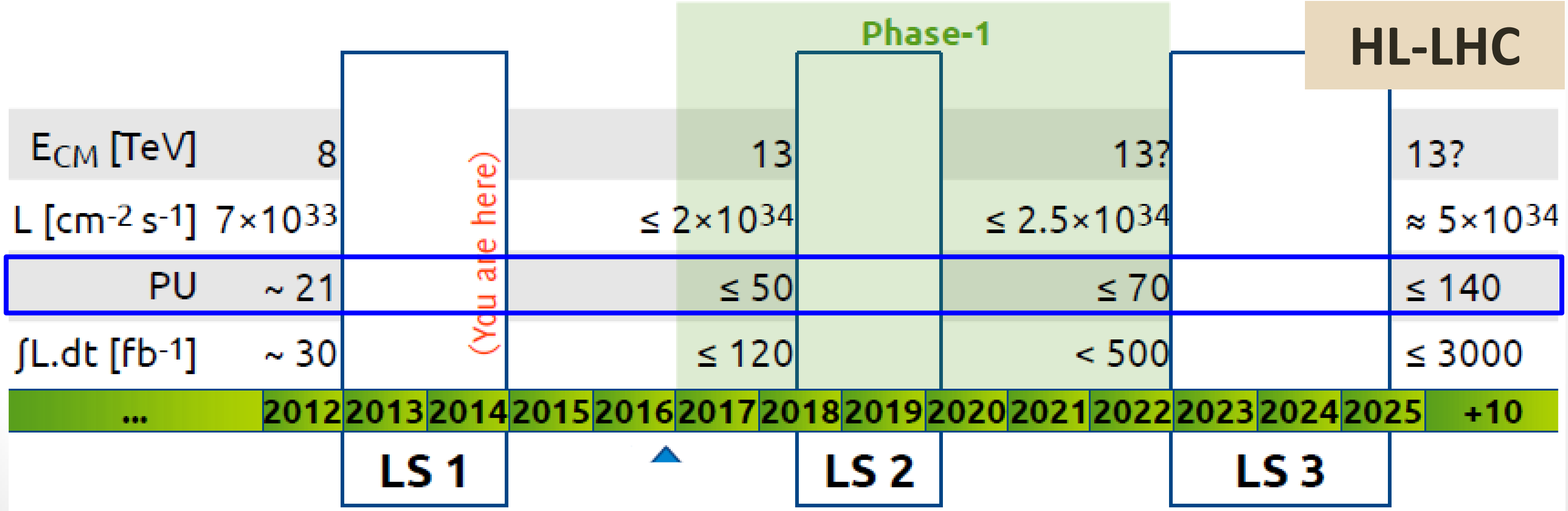
Phase-1

HL-LHC

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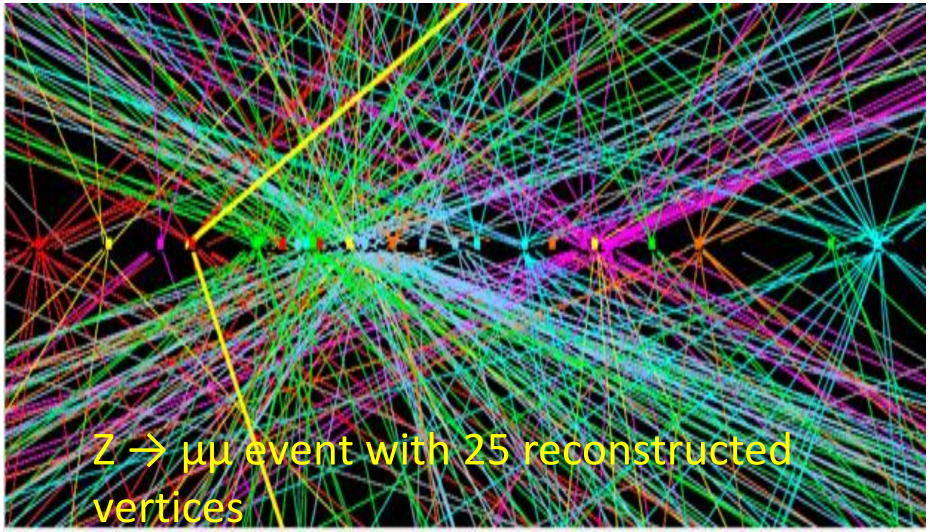
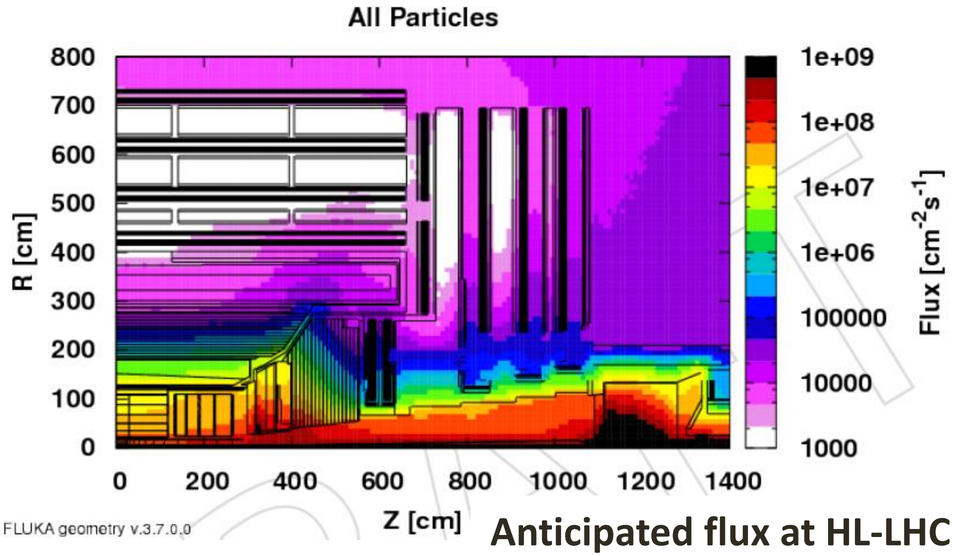
∫L.dt [fb^{-1}]	~ 30		≤ 120		< 500		≤ 3000
…	2012	2013 2014	2015 2016 2017	2018 2019	2020 2021 2022	2023 2024 2025	+10
		LS 1		**LS 2**		**LS 3**	

Higher luminosity results in more pile-up (PU) in detectors.

25 Vertices in 2012 → 140 Vertices in 2025



Z → μμ event with 25 reconstructed vertices



Anticipated flux at HL-LHC

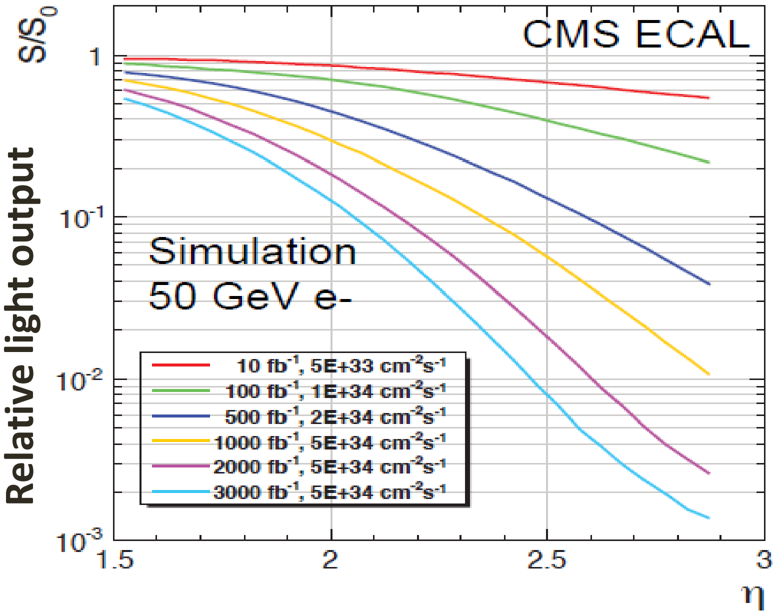
Radiation six times higher than nominal LHC design

By ~2025 detectors are operational for ~20 years. Built in technology from ~30 years ago (in particular electronics and computing)

→ Redesign electronics, trigger and DAQ

Consequences

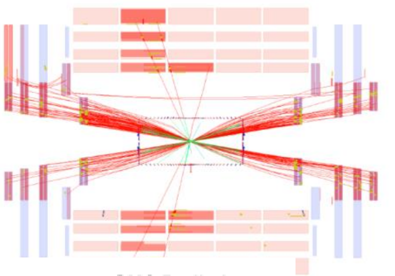
Detector will age and performance deteriorate

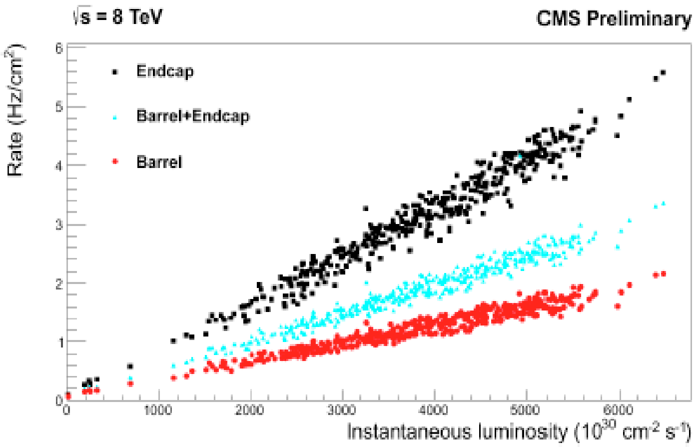


Many high rate testbeam campaigns, aging projections and simulations

→ Need to replace tracker and forward detectors with radhard material

Higher rates, in particular in the forward





RPC backgroound rates vs luminosity

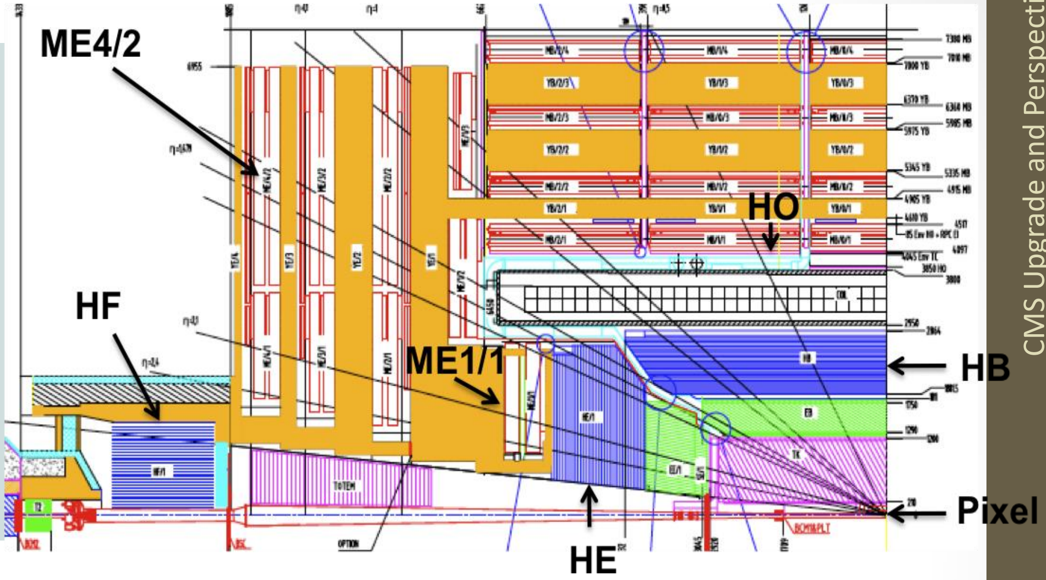
Triggers need to stay efficient (MHz→kHz). Keep trigger thresholds low for Higgs and particles from cascade decays

→ Finer granularity detectors and larger trigger bandwidth

Upgrades Activities–Overview

During LS1
Upgrades 2013/14 ongoing

- Completes muon coverage (ME4)
- Improve muon operation (ME1), DT electronics
- Replace HCAL photo-detectors in Forward (new PMTs) and Outer (HPD→SiPM)
- DAQ1 → DAQ2



LS1 LS2 LS3

During LS2
Phase 1 Upgrades 2018/19 (TDRs)

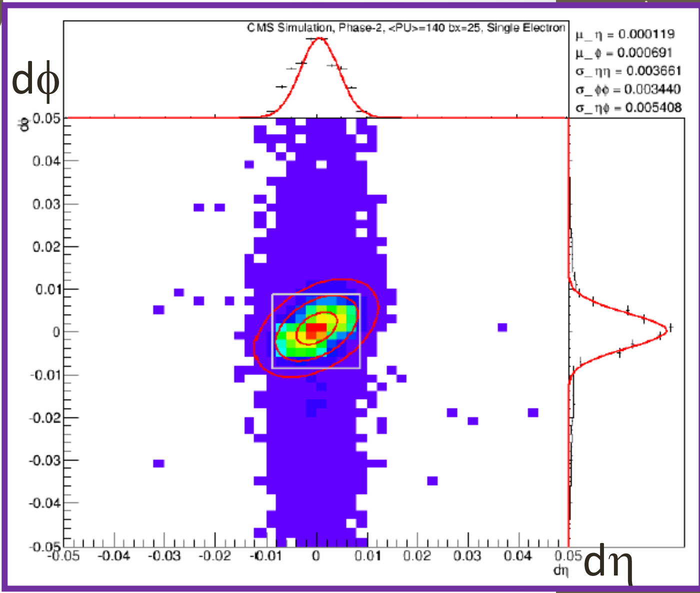
- New Pixels, HCAL electronics and L1-Trigger
- GE1/1 under cost review
- Preparatory work during LS1
  - New beam pipe
  - Install test slices (*Pixel cooling, HCAL, L1-trigger)*
  - Install ECAL optical splitters (*L1-trigger upgrade)*

During LS2
Phase 2: 2023-2025 now being defined

- Tracker Replacement, Track Trigger
- Forward : Calorimetry and Muons and tracking
- Further Trigger and DAQ upgrade

→ THIS TALK

Trigger with 140 PU



Increase L1 Trigger **latency 3.4 µs → 12.5 µs**

& L1 Trigger **rate 100 kHz → 750 kHz**

- New readout electronics, including sub-detectors that will not be replaced (ECAL barrel, muon)

The trigger challenge: keep the **thresholds** at 5x higher PU. Sharpen **turn-on** curves and reduce **fake** triggers. Tools:

- **Single ECAL crystal readout** improves track matching, spike rejection (noise) and timing
- Additional muon detectors (GE1/1) enable **measurement of bending angle** in forward region → reduce mis-measurement
- Tracking information at L1 (tracking trigger)

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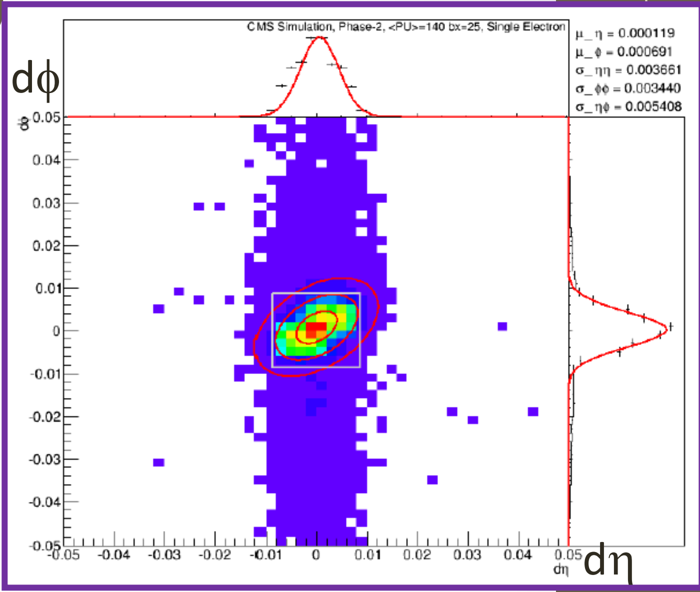

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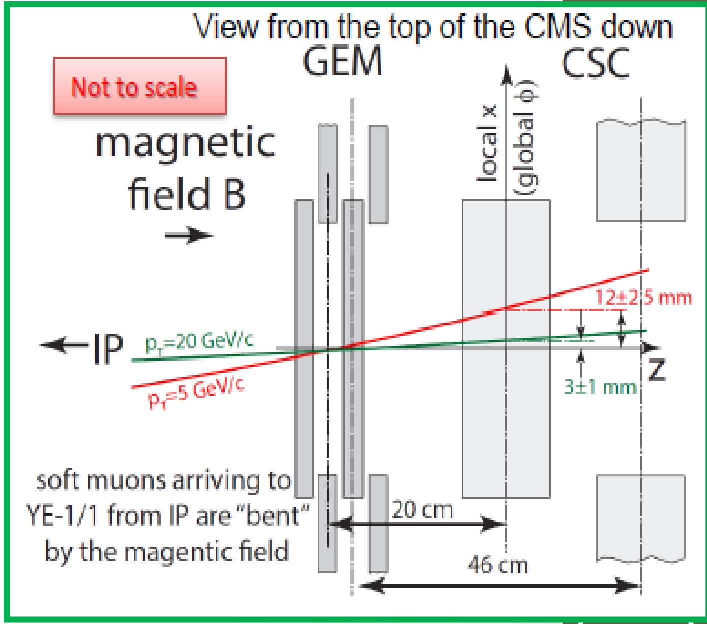

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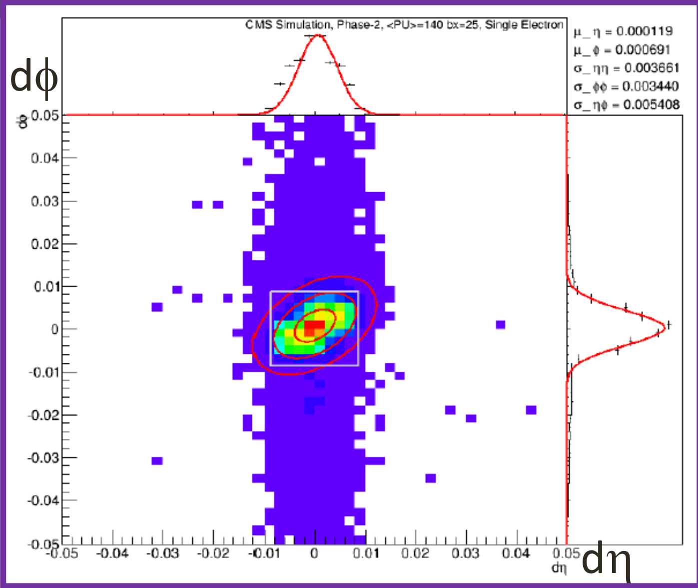
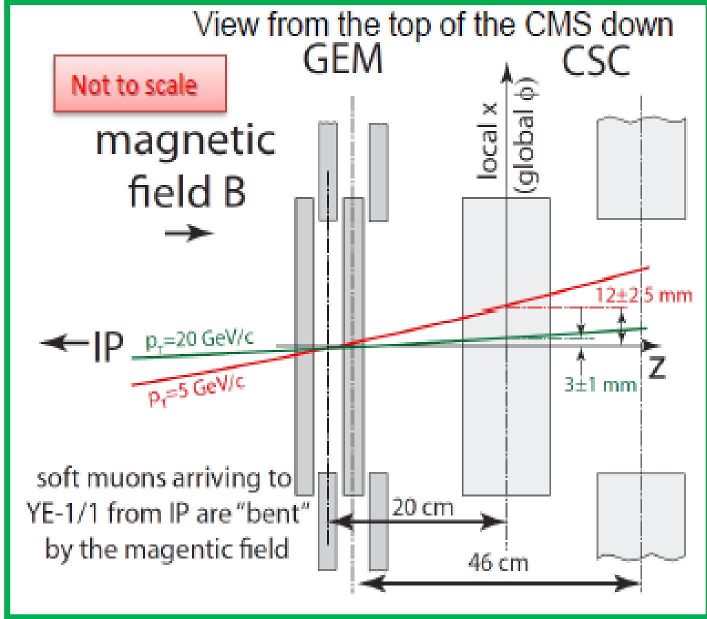


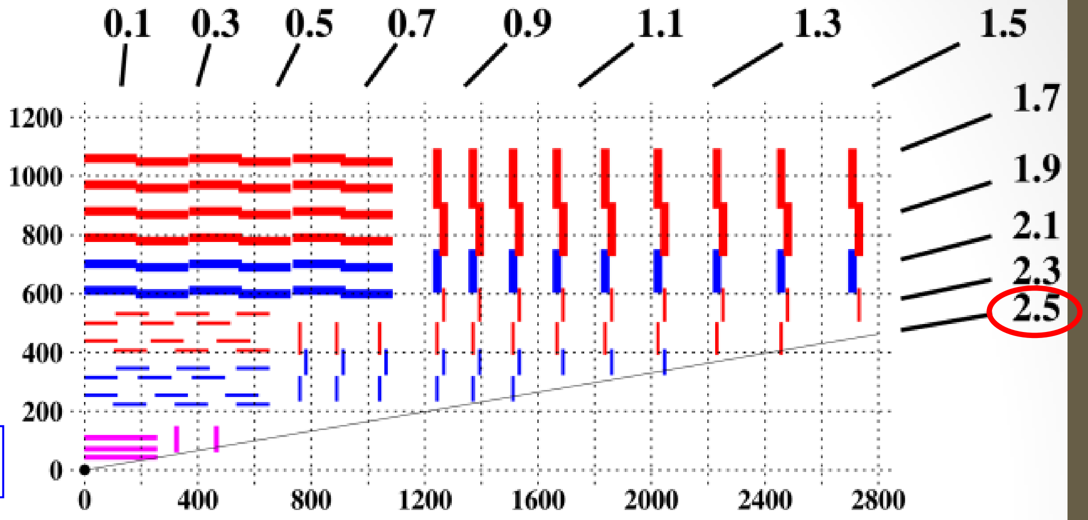


Present to Upgraded Tracker

CMS Si Tracker today

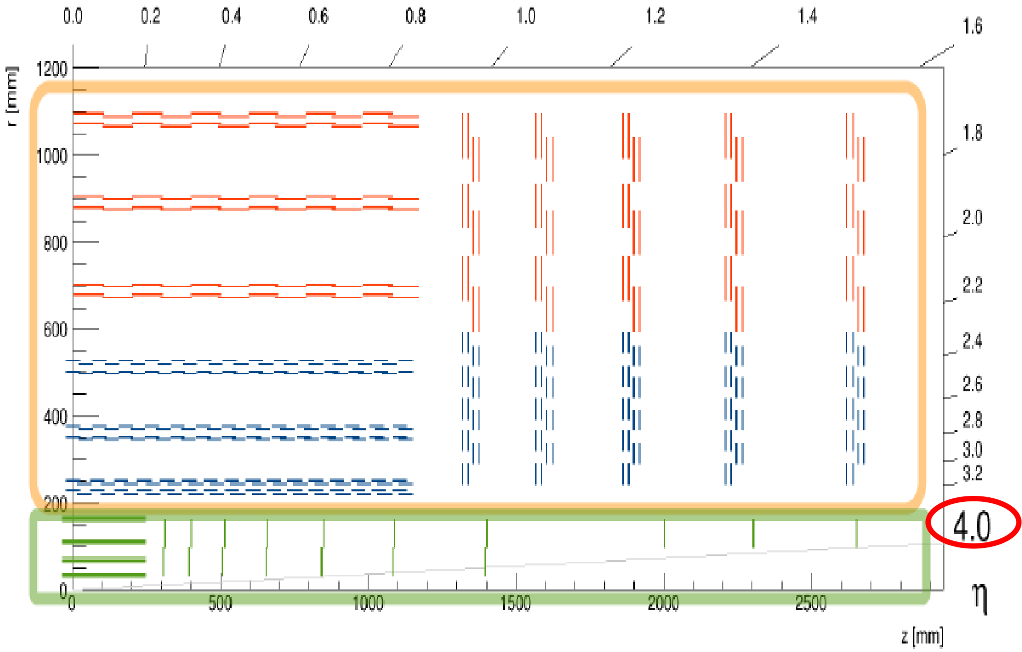
B=3.8T

Current & Phase1: Planar pixels



CMS Si Tracker as it could be in 2025

Outer Tracker, new Pt modules
3 more Pixelated layers
5 more Pixelated disks



Strip/Strip modules SS
in outer layers

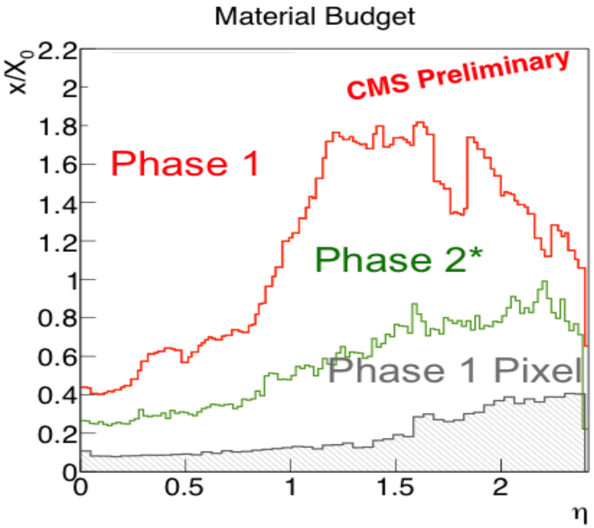
Macro Pixel/Strip modules PS
in inner layers (z-measurement)

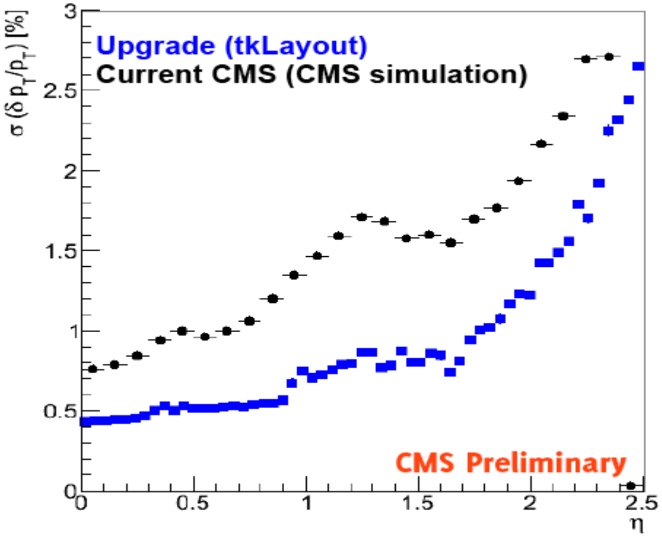
Pixel modules, new Disks to η=4
Possible pixel size ~25x100μm^2
Planar or 3D?

Upgraded Tracker: Lighter, Smarter, Better (acceptance)

Lighten up: DC-DC powering scheme, CO_2 cooling, low mass assemblies, reduced material within tracker volume, thinner sensors

- Physics gain: improved track p_T resolution. Reduced rate of γ conversions.





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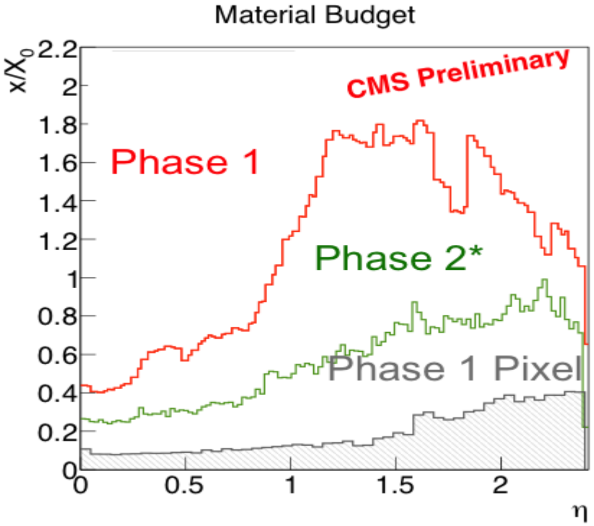
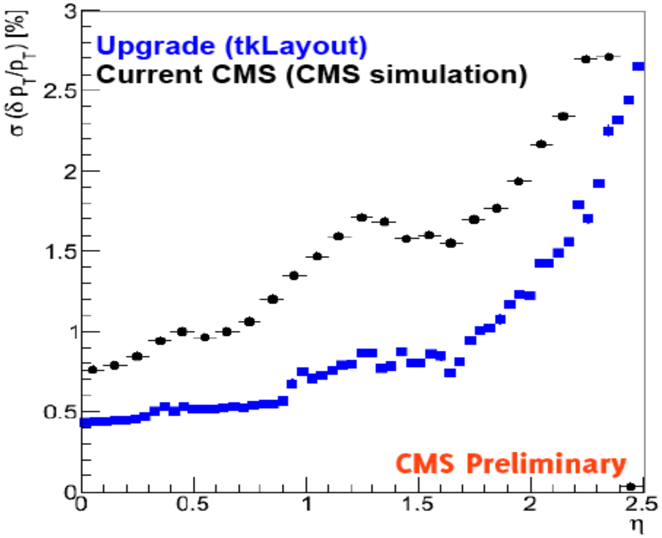
Larger coverage extend pixel acceptance to $|\eta|$~4.0.

- Physics gain: Reduces fake jets due to PU for VBF physics. Allows to separate signal jets (primary vertex) from PU jets.

Smart track trigger Including tracking information at L1 trigger

- Physics gain: helps controlling the rate, trigger thresholds can stay moderate

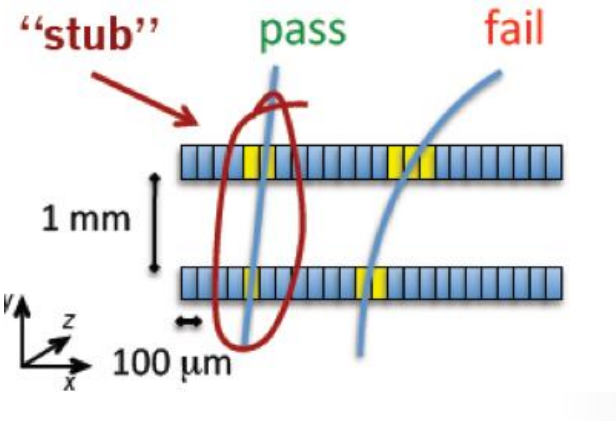




Phase-II Tracking Trigger

B=3.8T

Objective: reconstruct all tracks with p_T>2 GeV **at trigger level**. Identify primary vertex along beam line with ~1mm precision.

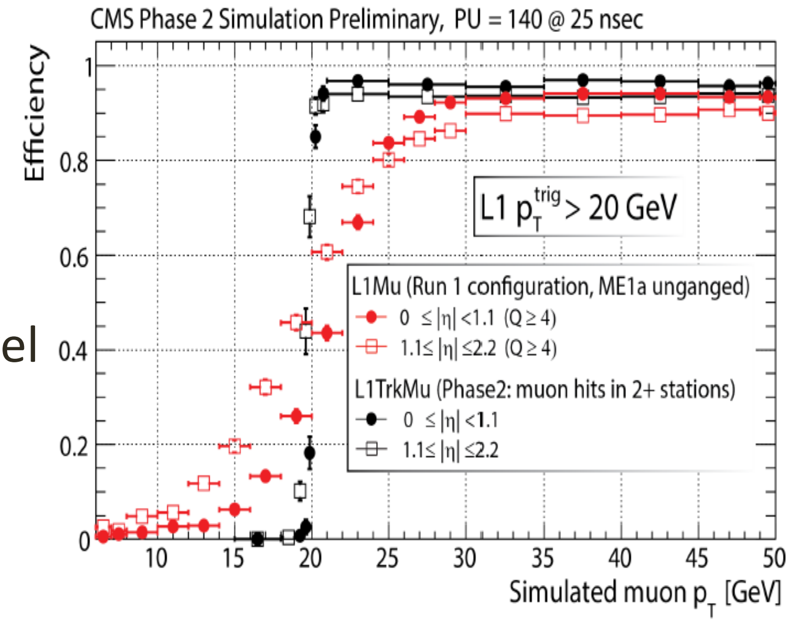


Conceptual design: to implement tracks in hardware trigger (40 MHz)

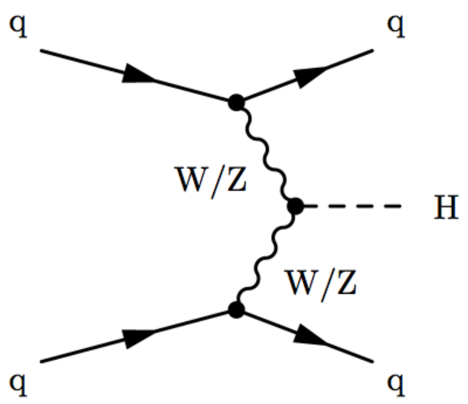
- Correlate hits in two closely-spaced sensors to provide vector ("stub") in transverse plane: angle is a measure of p_T
- Exploit the strong magnetic field of CMS

Physics benefit:

- Threshold can stay roughly at present level
- Sharp trigger turn on

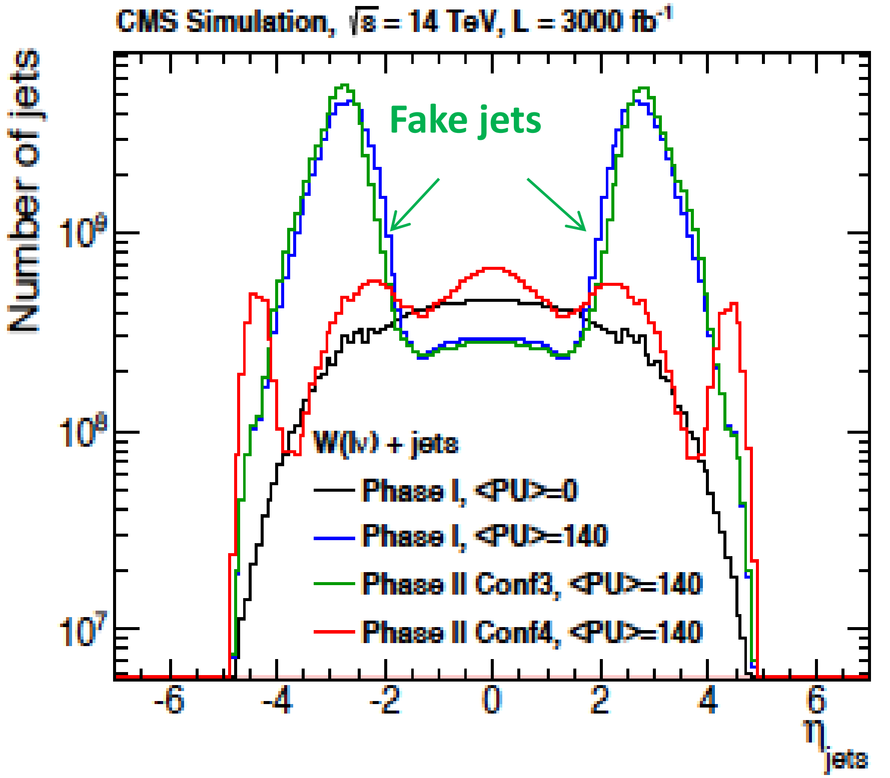


Benefit of Extended Coverage



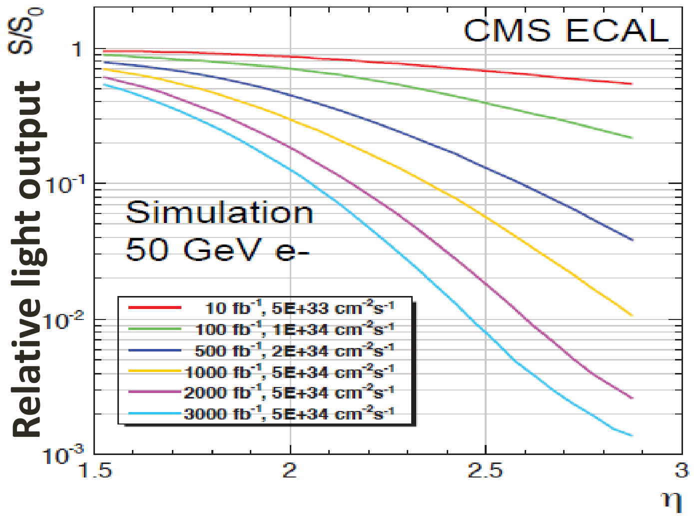
Provides critical benefits for Higgs, SUSY and VBF programs

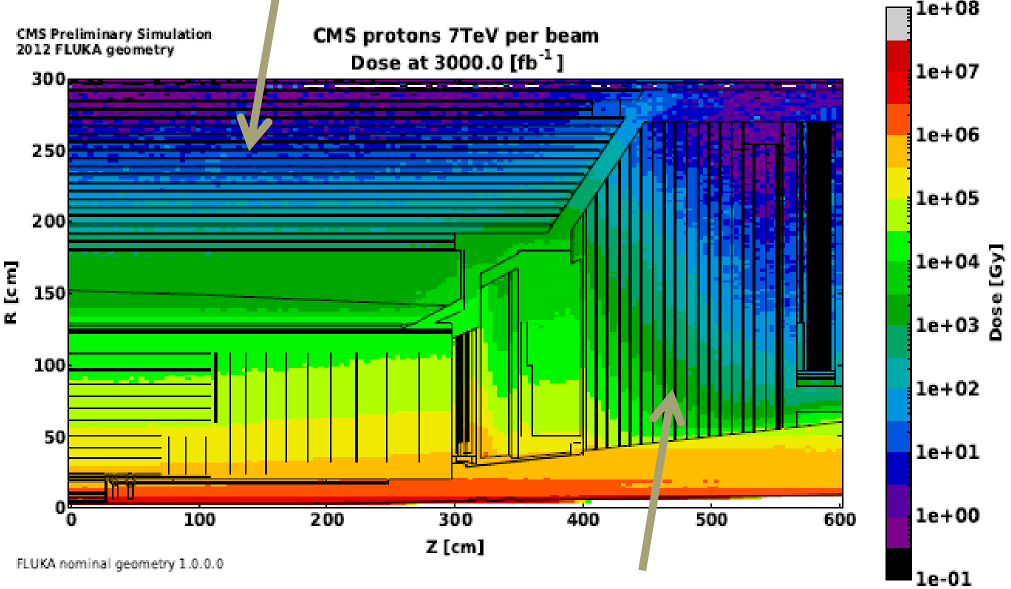
- Pileup mitigation: correcting/removing jets with tracks from pileup vertices
- Vector Boson Fusion:
  - Remove pileup jets leading to wrongly-calculated rapidity gap
  - Improved q/g identification
- SUSY cascade decays with multiple leptons in final state
  - All needed for kinematic reconstruction
  - "Lost lepton" one of the major backgrounds

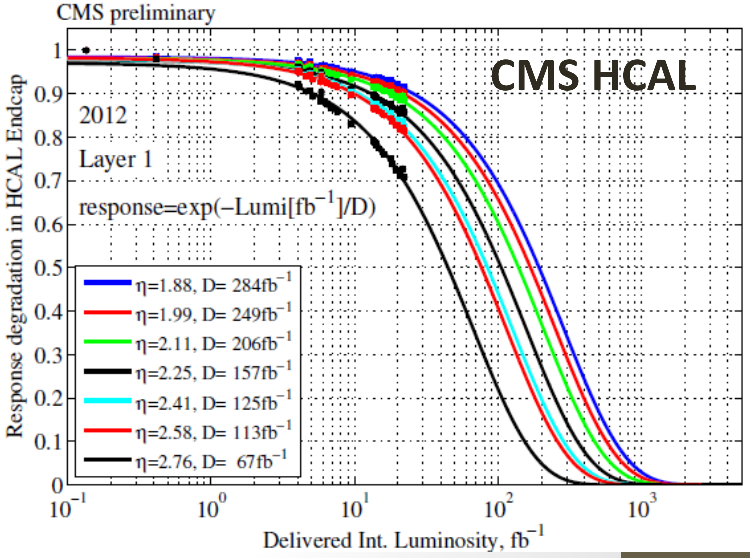


Calorimeters

- At present $PbWO_4$ crystals in ECAL barrel and scintillator-tile HCAL.
- Active detectors can stay in barrel where rad damage is less. Electronics needs replacement to cope with new trigger rates/latency







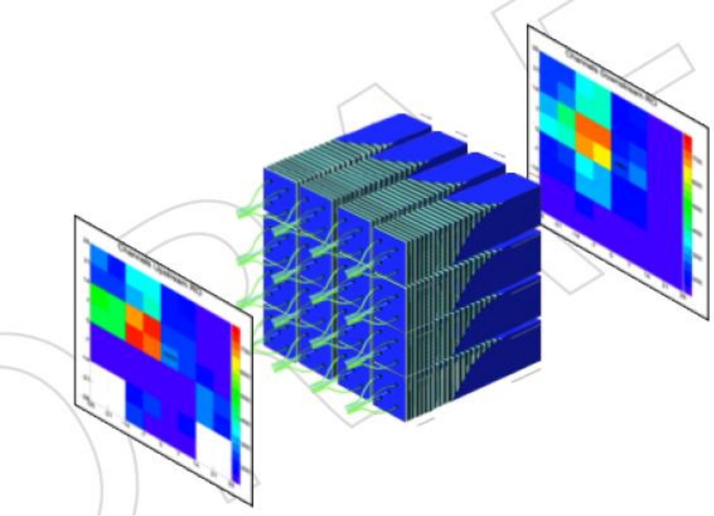
Radiation dose strong function of eta. Variation in forward region by 100.

Two Scenarios for Forward Calorimetry

Need to replace forward calorimeters after 500/fb due to ageing damage

Scenario 1

- Maintain present geometry with ECAL and HCAL stand-alone
- ECAL Endcap in Shashlik design
- HCAL Endcap re-build as radhard



Scenario 2

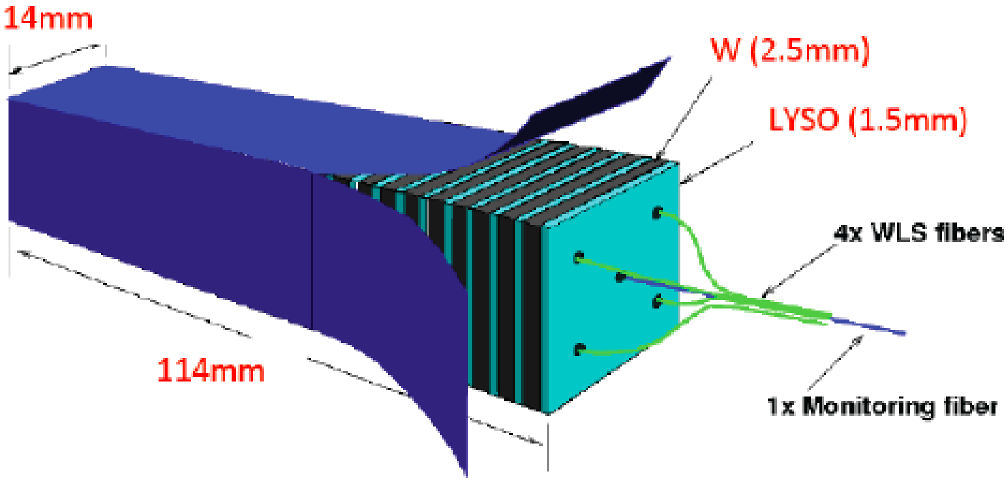
- New integrated design as a High Granularity Calorimeter (HGC)
- Particle flow imaging calorimeter

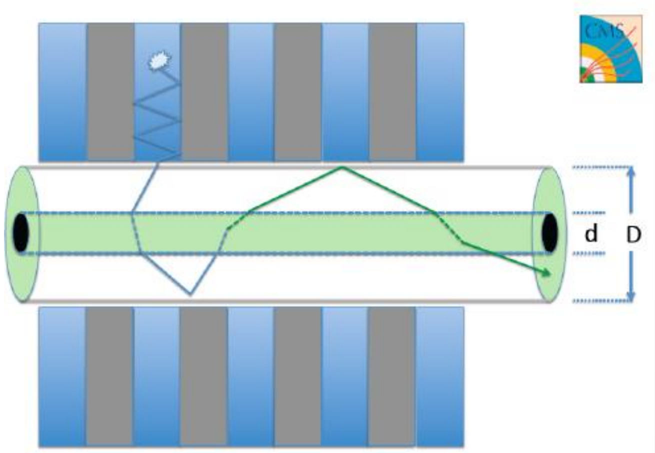
Opens up possibility to extend to |η|~4

Scenario 1: Shashlik ECAL

Sampling calorimeter w/out depth segmentation, very compact X_0~25

- Radhard inorganic scintillator. Best performance with LYSO and tungsten & brass as absorber
- Light readout with WLS in shashlik configuration
- Readout with GaInP photosensors (radhard due to larger band gap)





- **Good energy resolution $\Delta E/E = 10\%/\sqrt{E}$**
- Very compact and highest light yield
- Small Moliere radius (14mm) provides **fine granularity** for pile up mitigation (matching with tracker)

Two Scenarios for Forward Calorimetry

Need to replace forward calorimeters after 500/fb due to ageing damage

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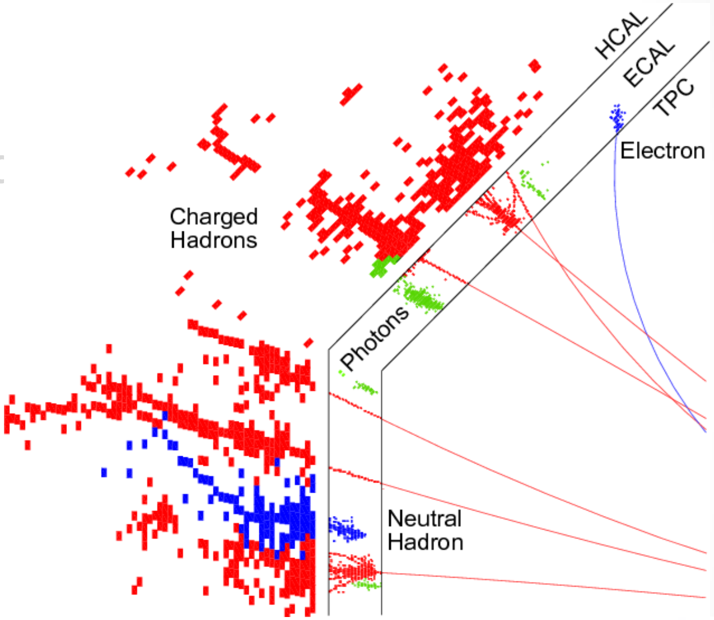
- EE in Shashlik design
- HE re-build as radhard



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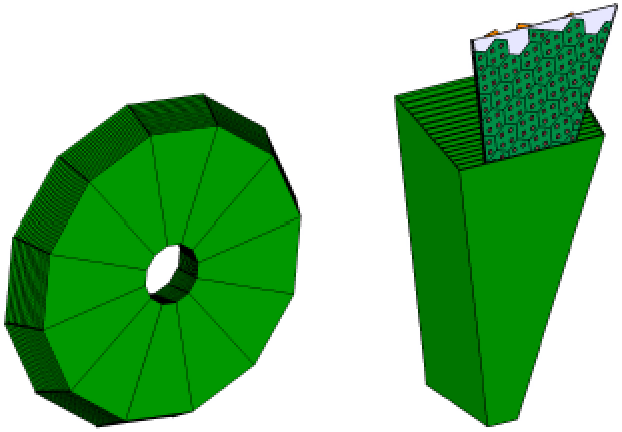
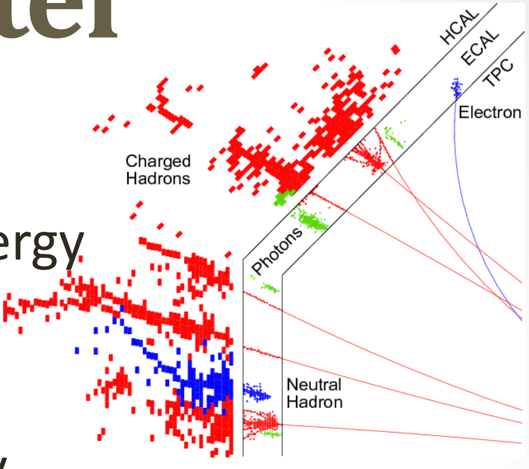


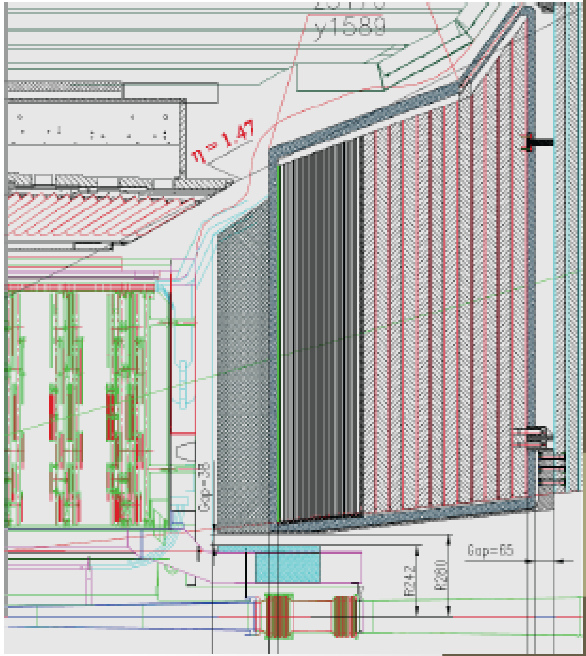
Scenario 2: High-Granularity Combined Calorimeter



High granularity calorimeter (HGCAL) based on ILC/CALICE development. Key point: “visualize” energy flow through fine granularity and longitudinal segmentation.

- Good **resolving power for single particles** in very dense jets. ΔE/E = 10%/√E

- Planes of Si separated by layers of Pb/Cu or brass
- Exploits developments on Si rad.hardness and price



Structure:

- Varying granularity and absorber material
- B(back)-HCAL as HE re-build

High Granularity Calorimeter

Fine depth segmentation

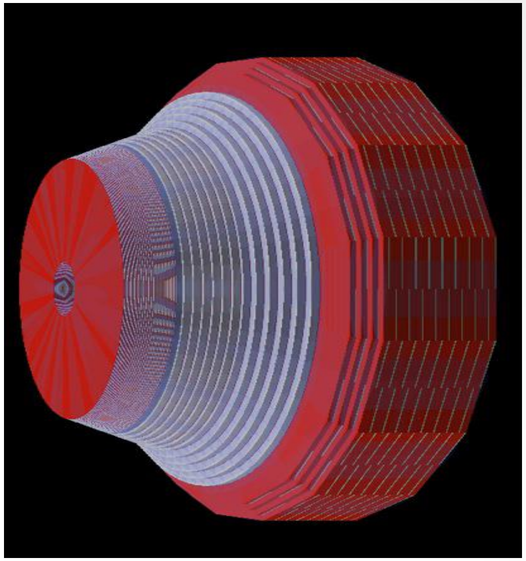
ECAL: ~33 cm, 25 X_0, 1λ, 31 layers:

- 11 planes of Si separated by 0.5 X_0 of lead/Cu
- 10 planes of Si separated by 0.8 X_0 of lead/Cu
- 10 planes of Si separated by 1.2 X_0 of lead/Cu

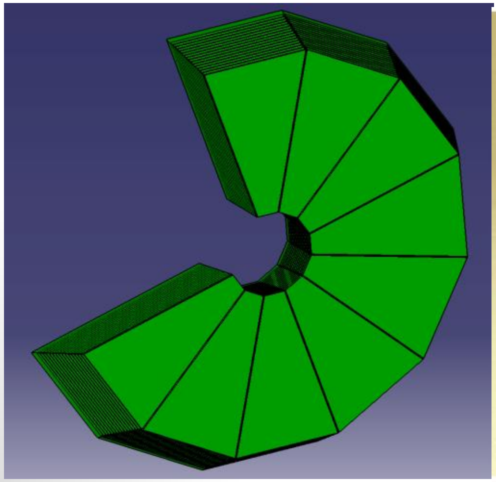
HCAL: ~66 cm, 4λ:

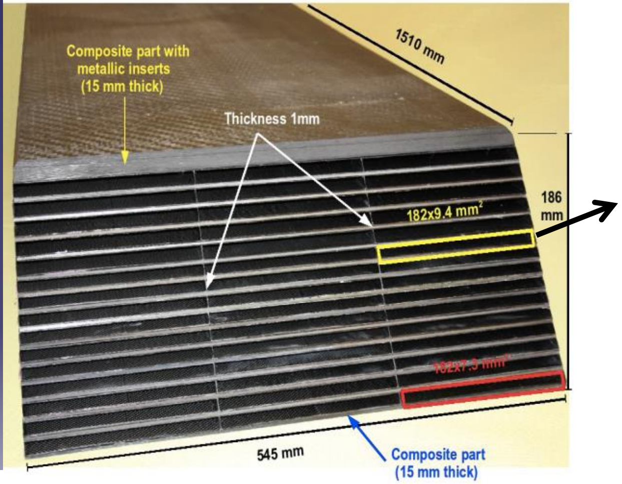
- 12 planes of Si separated by 40 mm of brass

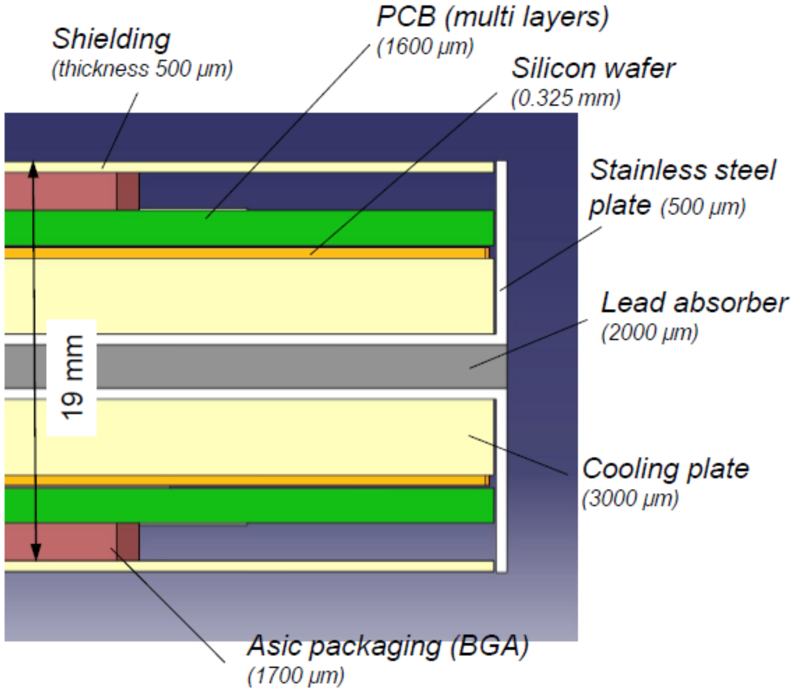
- Fine grain pads 0.9 cm^2 to 1.8 cm^2
- 3.7/1.4 Mch & 420/250 m^2 Si in E/H



Back HCAL as HE re-build 5λ with increased transverse granularity



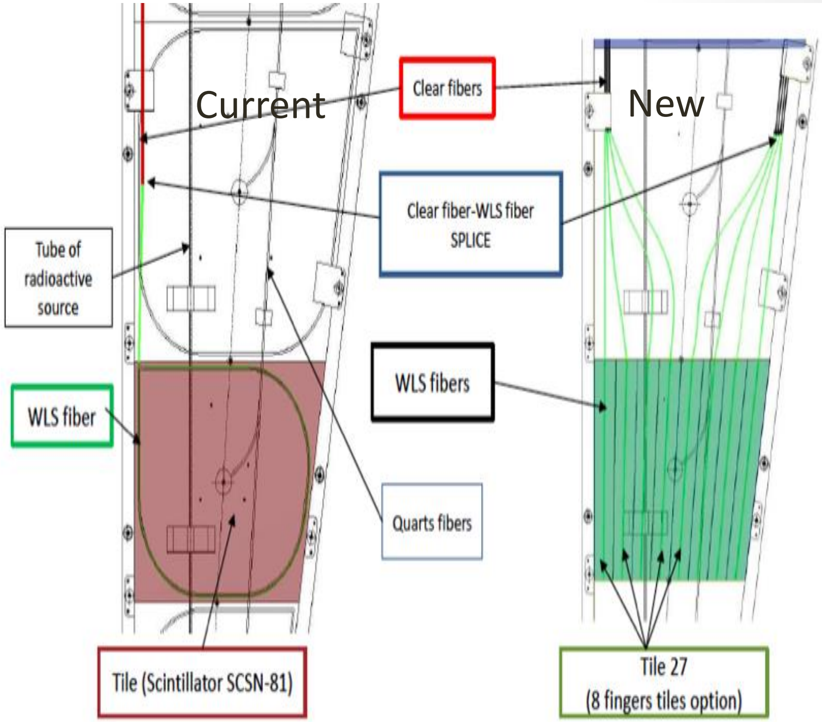




The HE Re-build

Brass and scintillating tiles with increased radiation hardness

- Higher granularity in (η/ϕ) x 2
- Longitudinal & extension towards EE Shashlik (resolution)
- Different routing of WLS fibers (in finger geometry) to reduce light path (80%)
- Investigating new plastic and liquid scintillators or radiation tolerant scintillating fibers quartz/glass/ crystals doped with Ce3 for innermost region



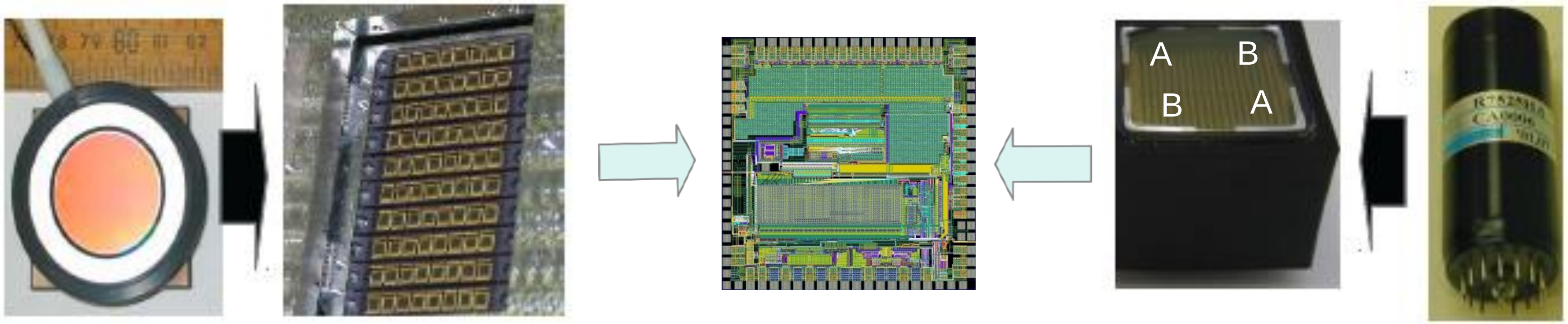
Establish Depth Segmentation

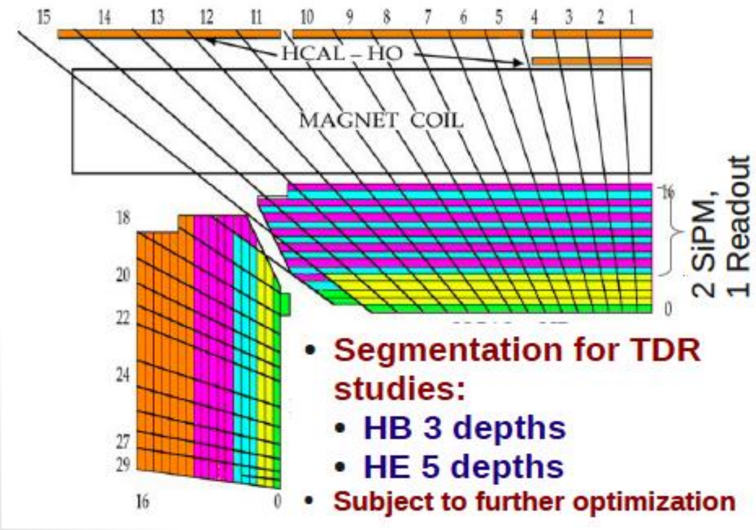
Phase I CMS HCAL Read-Out Upgrades

Replace Photo-transducers to reduce noise & improve performance. Improve with new FE Chip.

HB/HE/HO
From HPD to SiPM's

HF
From single to multi-anode PMT's





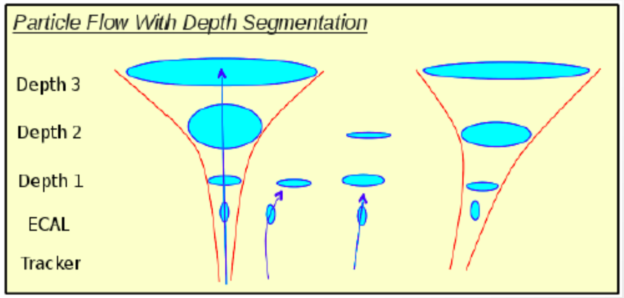
- **Segmentation for TDR studies:**
  - **HB 3 depths**
  - **HE 5 depths**
- **Subject to further optimization**

SiPM's to increase HB/HE Depth Segmentation

- Improved PF Hadronic shower localization

Provides effective tool for PU mitigation at HL

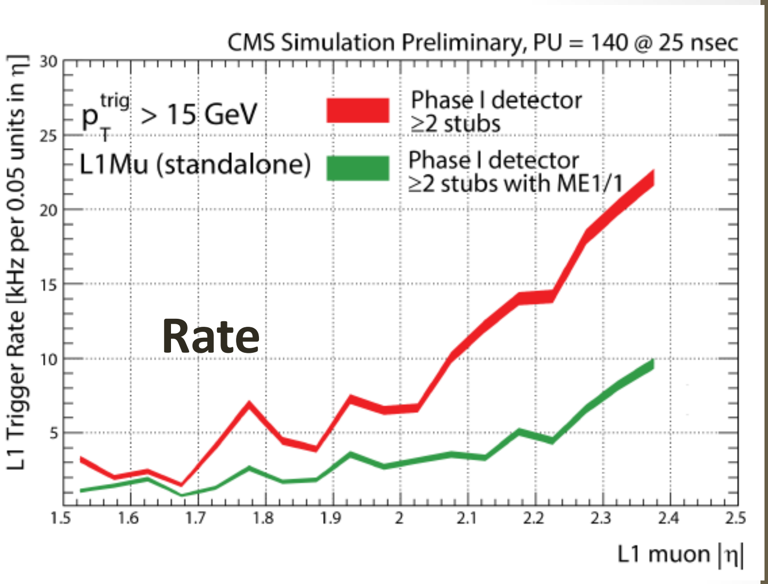
- Mitigate radiation damage to scintillator & WLS fibers

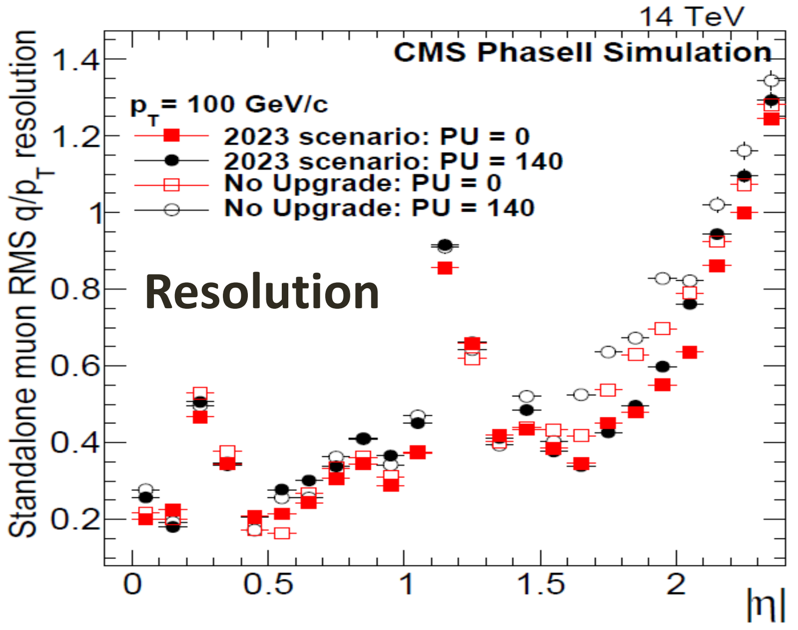


Forward Muon Challenge

Challenging rates:

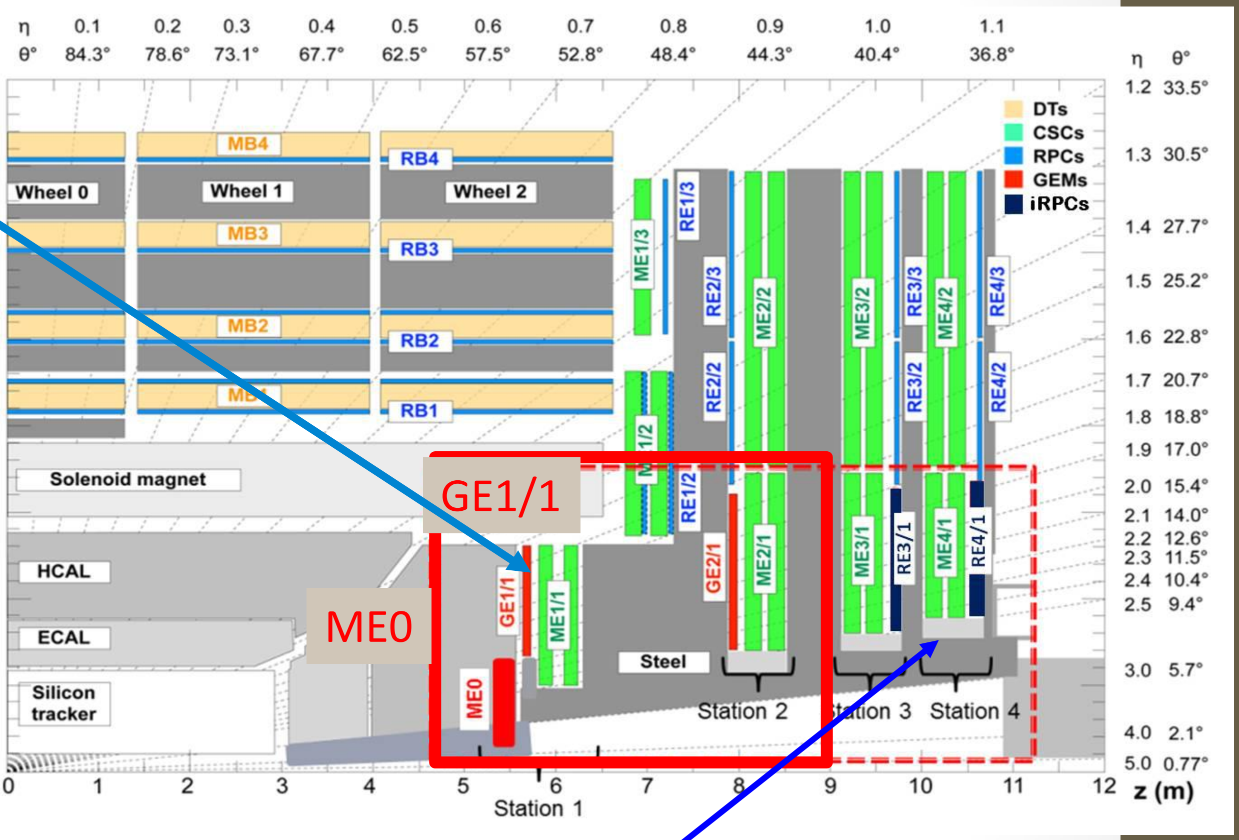
- Forward region |η|≥2.0 with rates in 10's of kHz/cm^2 and higher towards higher η
- Reduced resolution and longevity issues
- New requirements often exceed capabilities of the existing
- One place to gain physics acceptance
- Highest background rates yet least redundancy
- Challenging B-field topology





Forward Muon Upgrade

Triple GEM detector (GE1/1): precision chambers to **improve trigger momentum selectivity and reconstruction** already in late LHC phase-1. Installation in LS2 (2018).



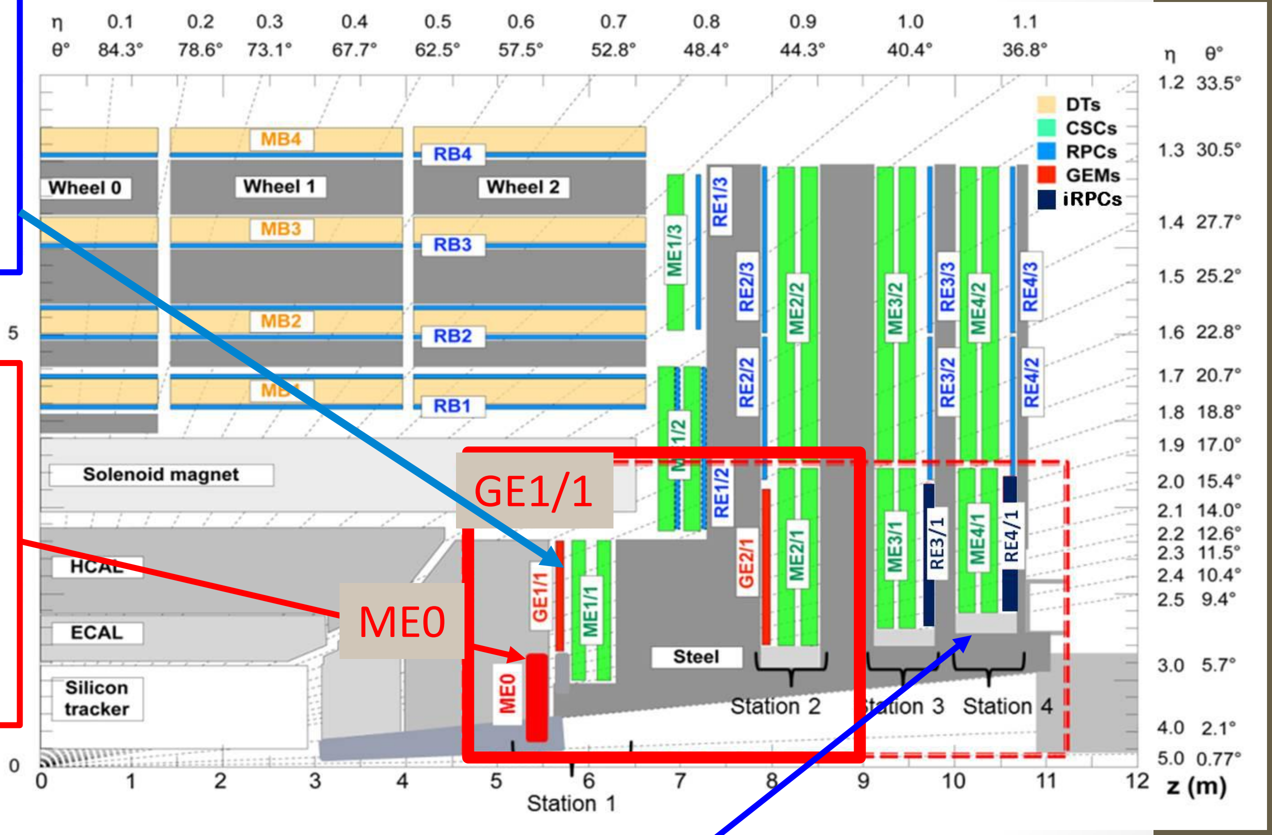
Enhance region without redundancy 1.6 < |η| < 2.4 with **maximum rate.** Technology = GEM (GE2/1) and improved high-rate RPC (RE3/1 and RE4/1)

Forward Muon Upgrade

Triple GEM detector (GE1/1): precision chambers to **improve trigger momentum selectivity and reconstruction** already in late LHC phase-1. Installation in LS2 (2018).

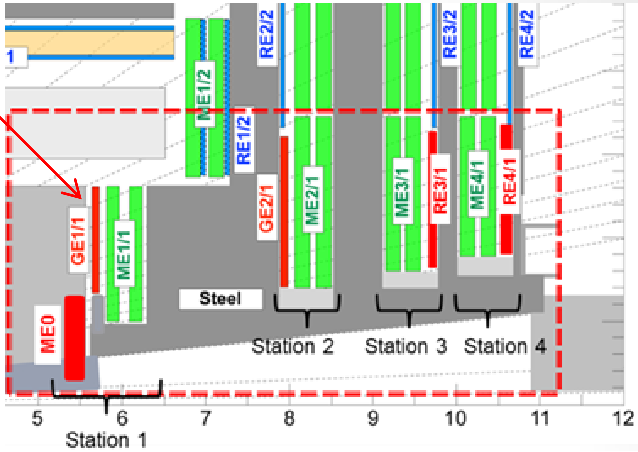
Extended coverage provides muon **tag** in forward region |η|<3

Several tens of kHz expected → GEM technology



Enhance region without redundancy 1.6 < |η| < 2.4 with **maximum rate.**
Technology = GEM (GE2/1) and improved high-rate RPC (RE3/1 and RE4/1)

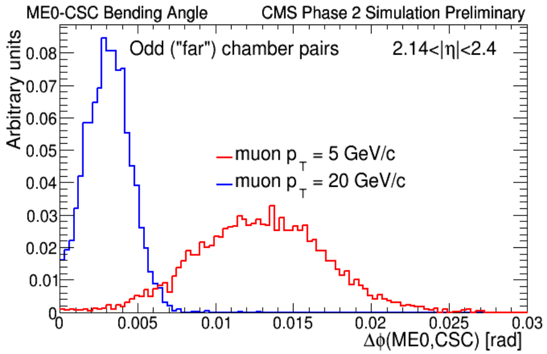
Benefit of GE1/1

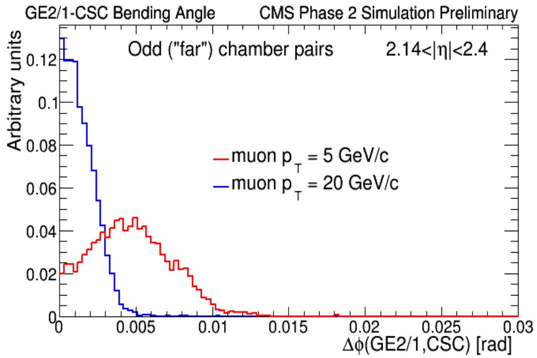


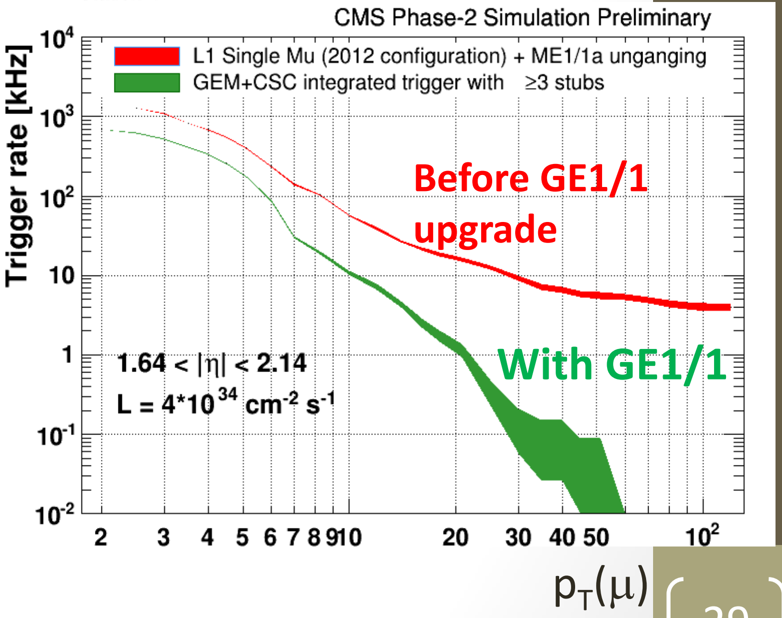
Additional GEM station (next to ME1/1) **in LS2** to help before LS3 tracker upgrade

Goal: large reduction of (fake) trigger rate using bending angle

- Need good spatial resolution & rate capability
- Larger lever arms using new detectors and existing CSC chambers in the same station
- Must measure bending angle in station 1







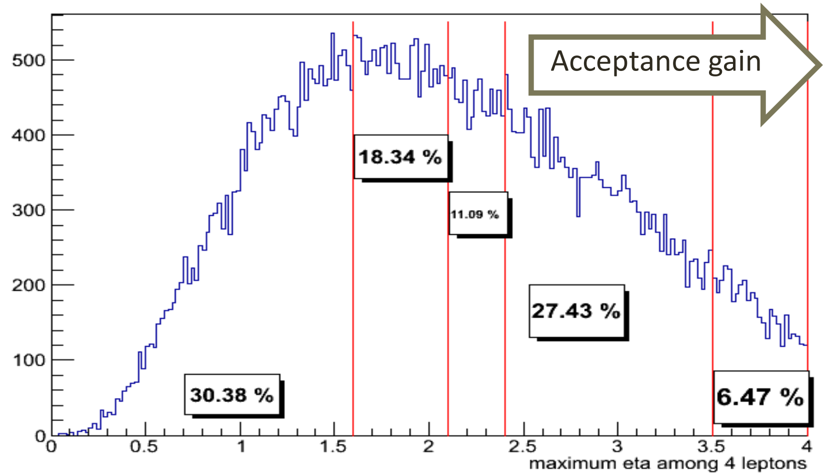
Else radial B-field and multiple scattering quickly diminish discrimination

Expect x5-10 rate reduction with new detectors

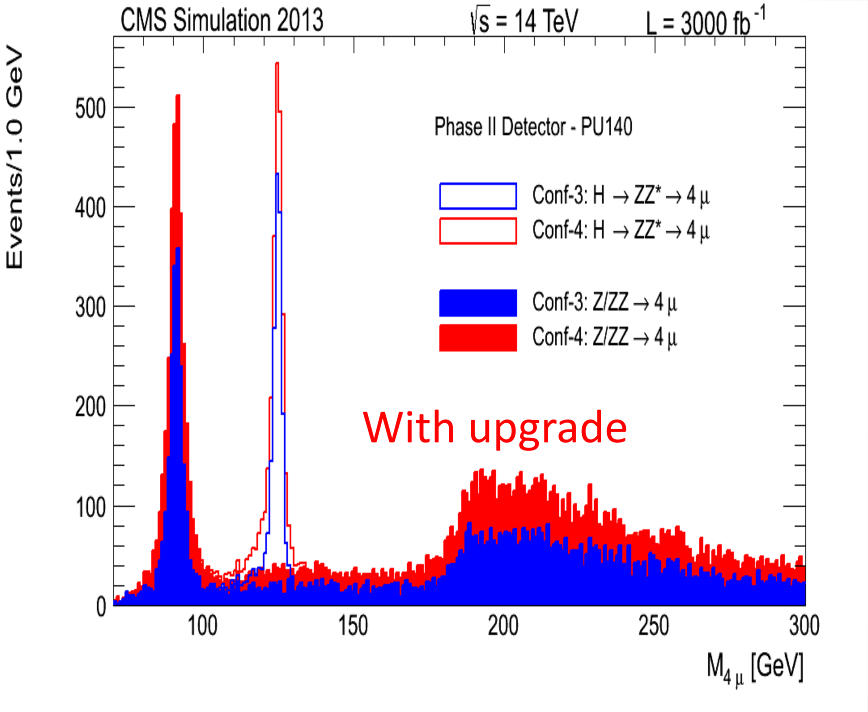
Benefit of Extended Acceptance

Considered extension to |η|~ 4.0 provides critical benefits for physics

e.g. H → ZZ → 4μ (note: lower mass resolution, also increase in bkgr)



H→ZZ→4μ : acceptance increase
60%→94% if η_{max}=2.4→4.0

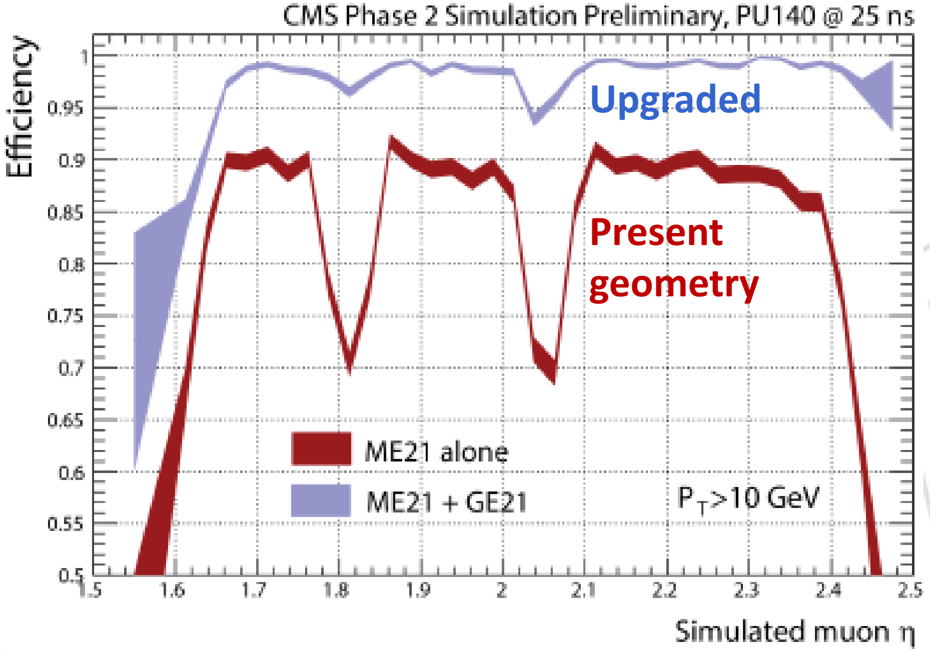


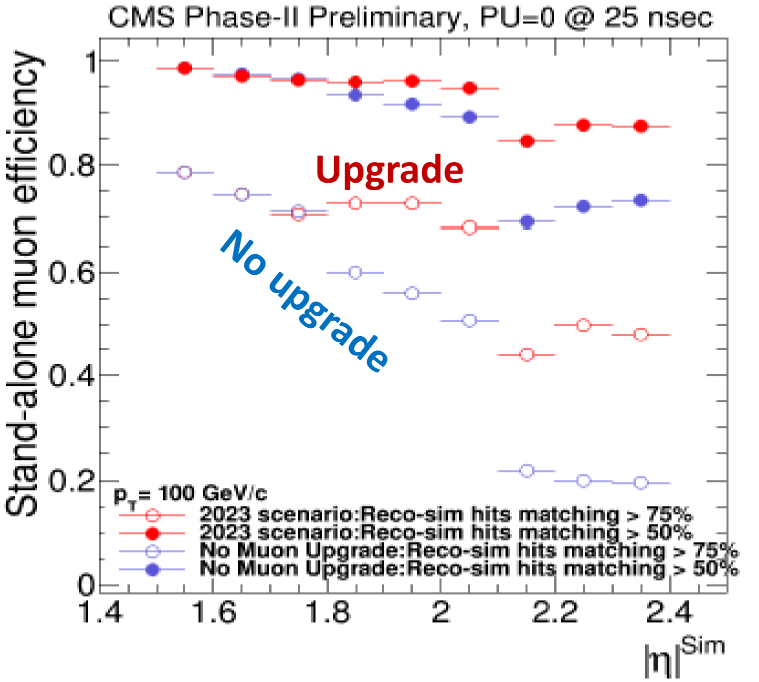
Also increased sensitivity for e.g. Z´→μμ studies (40% to 10% depending on Z´mass).

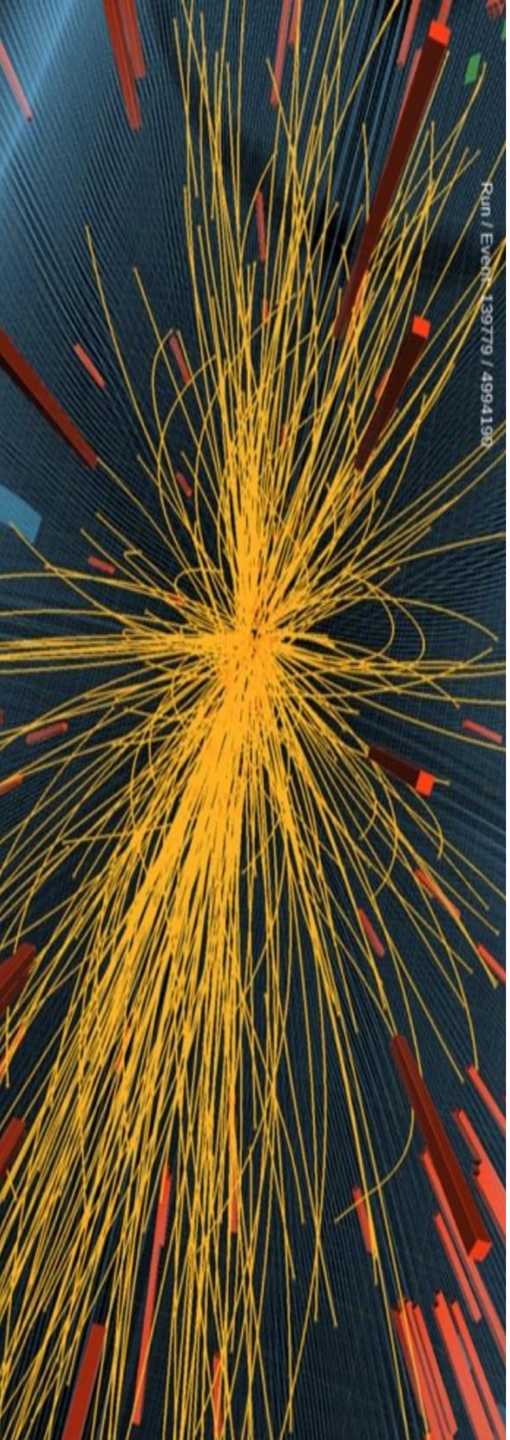
SUSY searches benefit from reduction of "lost lepton" background.

Additional Detectors: Benefit

Additional detectors yield extra hits → Increased efficiency







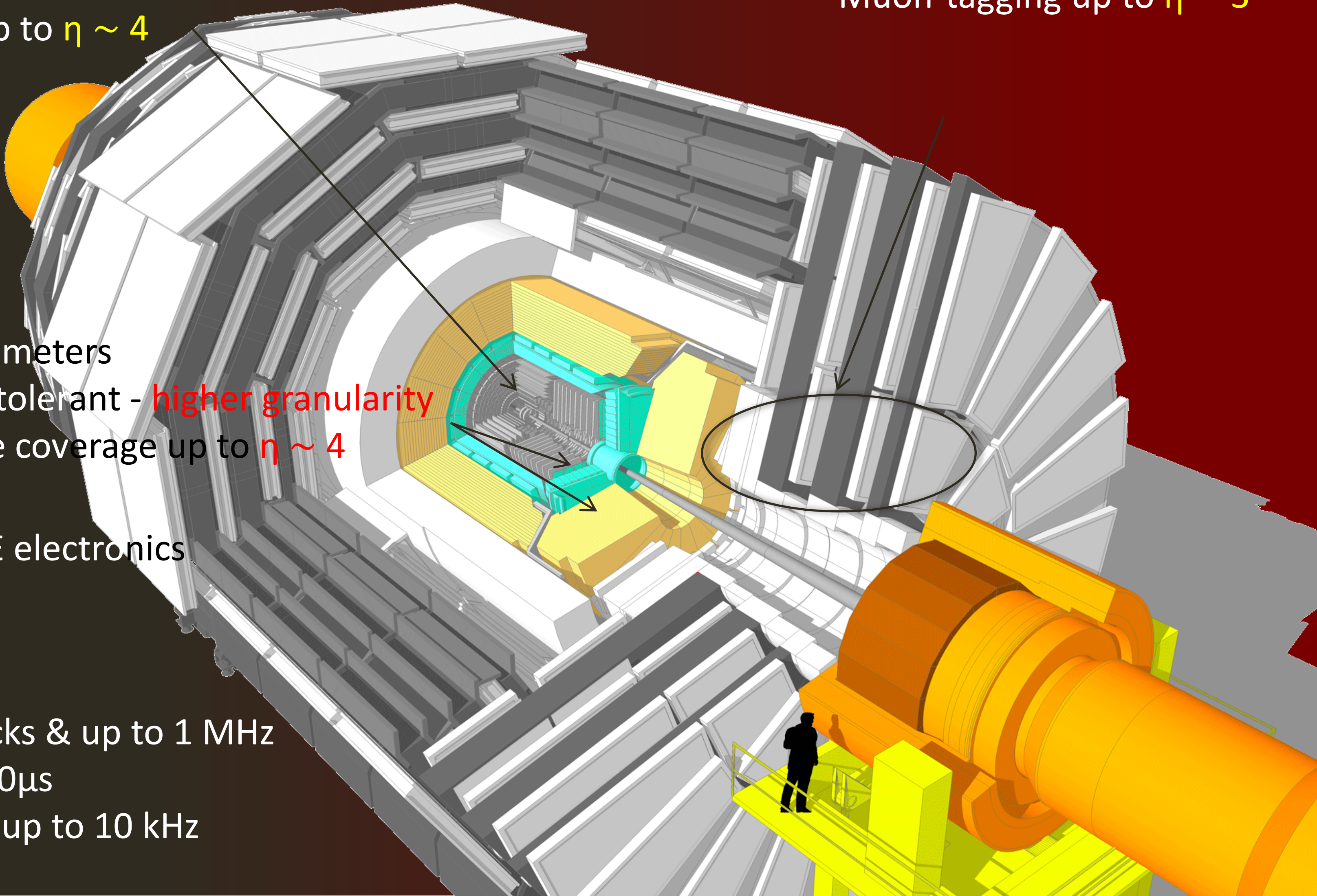
Summary

It is time to prepare for LHC high-luminosity operation in ≥2025. Expected to record up to 3000/fb of pp data.

Ageing and radiation damage requires to rebuild the inner tracker and forward detectors. New trigger concepts implemented. Larger bandwidth requires upgrade of electronics.

New detectors designed to cope with high rates, high pile-up and radiation.

Summary CMS Phase 2 Upgrades



Tracker
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to η ~ 4

Muons
- Additional detectors |η|>1.6
- Muon-tagging up to η ~ 3

Endcap Calorimeters
- Radiation tolerant - higher granularity
- Investigate coverage up to η ~ 4

Barrel ECAL
- Replace FE electronics

Trigger/DAQ
- L1 with tracks & up to 1 MHz
- Latency ≥ 10μs
- HLT output up to 10 kHz