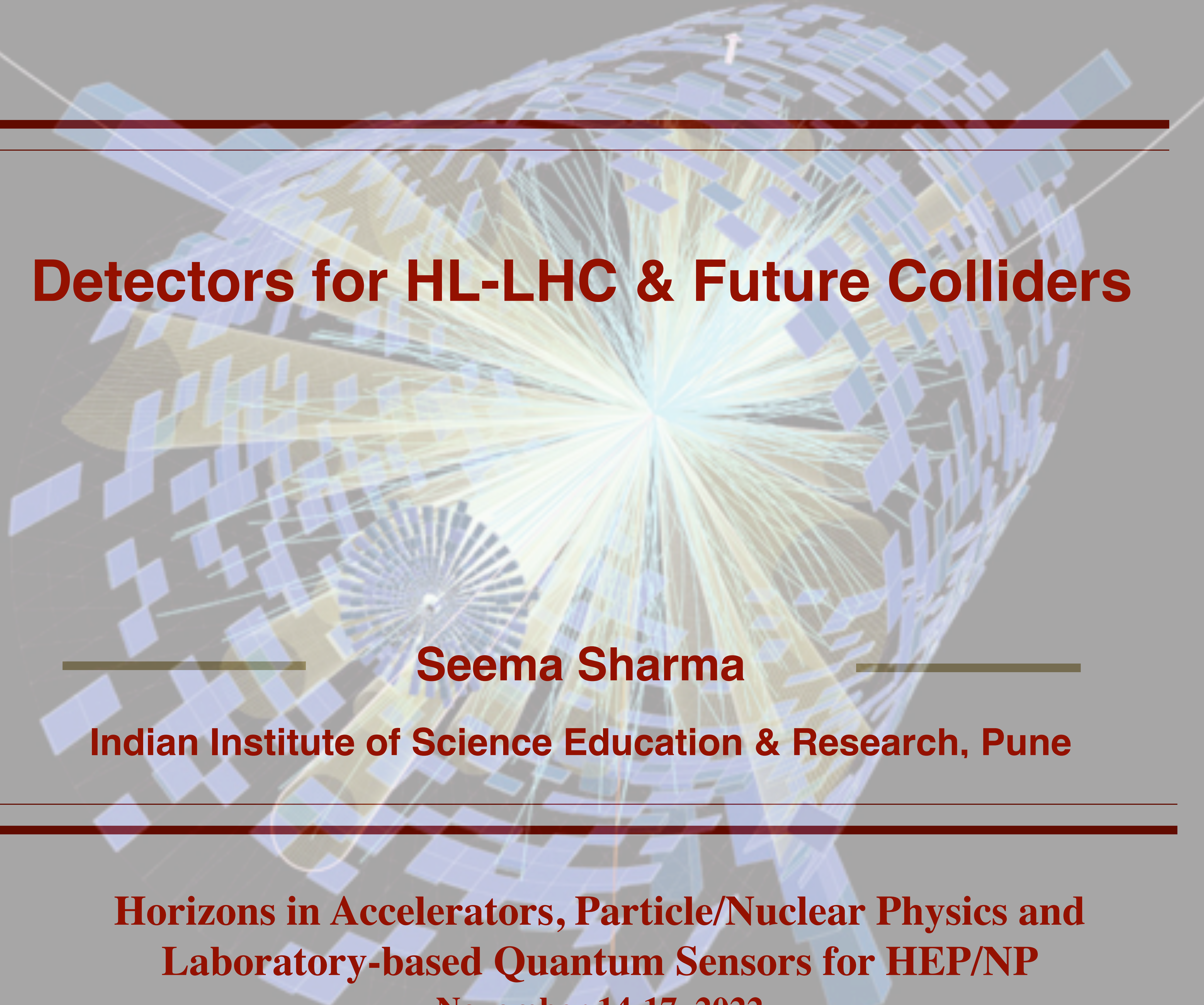


Detectors for HL-LHC & Future Colliders

Seema Sharma

Indian Institute of Science Education & Research, Pune

Horizons in Accelerators, Particle/Nuclear Physics and Laboratory-based Quantum Sensors for HEP/NP

November 14-17, 2022

Image credit

Detectors for HL-LHC & Future Colliders

Disclaimer:
Main focus on HL-LHC
Biased towards CMS
LHCb/ALICE not discussed

Seema Sharma

Indian Institute of Science Education & Research, Pune

Horizons in Accelerators, Particle/Nuclear Physics and Laboratory-based Quantum Sensors for HEP/NP

November 14-17, 2022

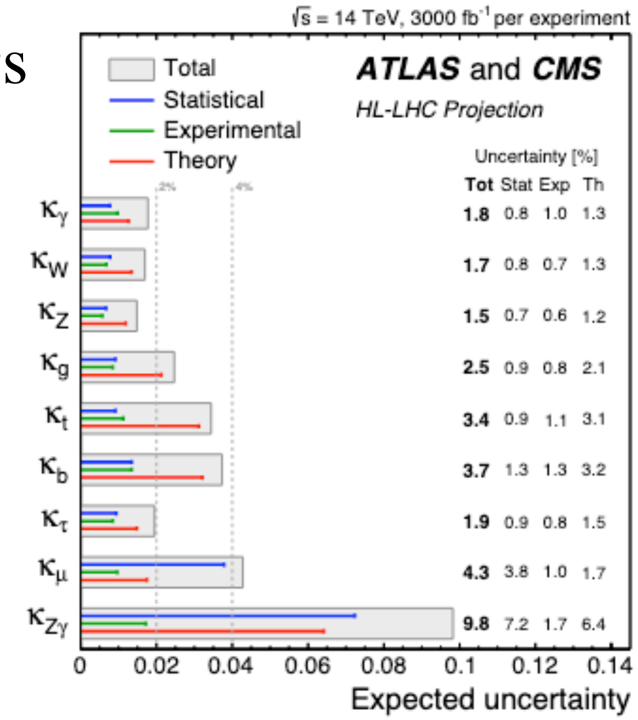
Image credit

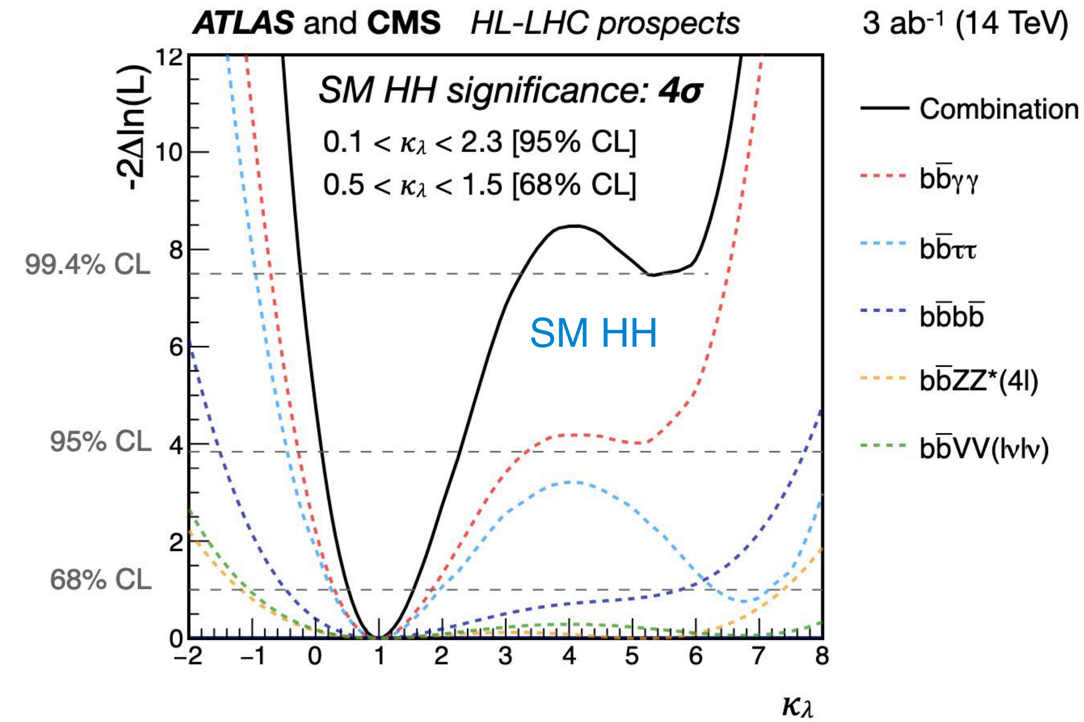
HL-LHC Physics Goals

SM precision measurements

Higgs sector

- Higgs properties, self-couplings
- Higgs rare and exotic decays
- Search for light psedoscalars





Top properties

- Precision measurements & t/H interplay

Precise EWK measurements:

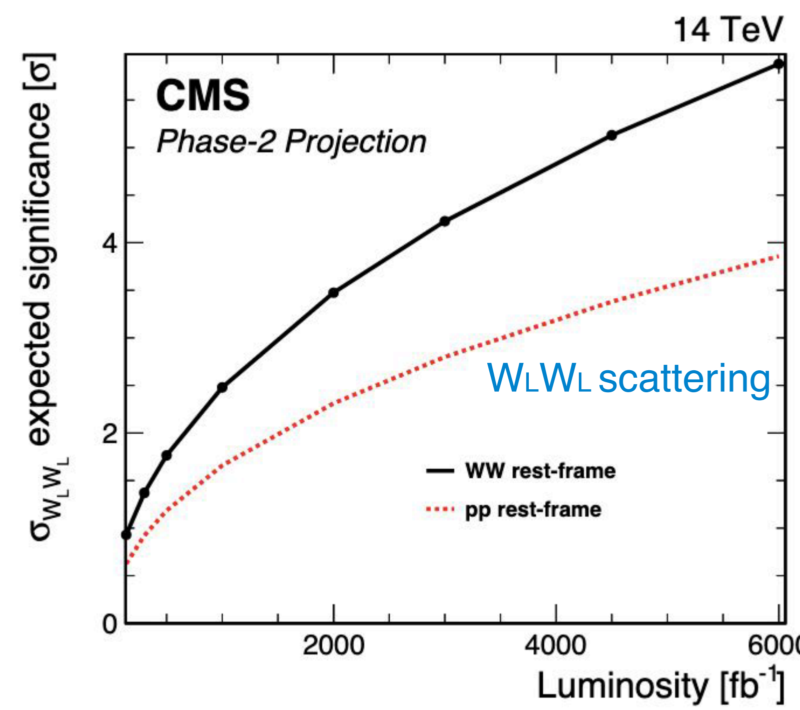
- Longitudial W scattering

Flavor (explore complementarity in low-pT & high-pT)

- CKM metrology and QCD spectoscopy
- Rare decay & flavour anomalies

Heavy Ions

- Precision study of material properties of QCD media
- Study HI-like behavior in small systems (pp and pA)
- Precise differential measurements



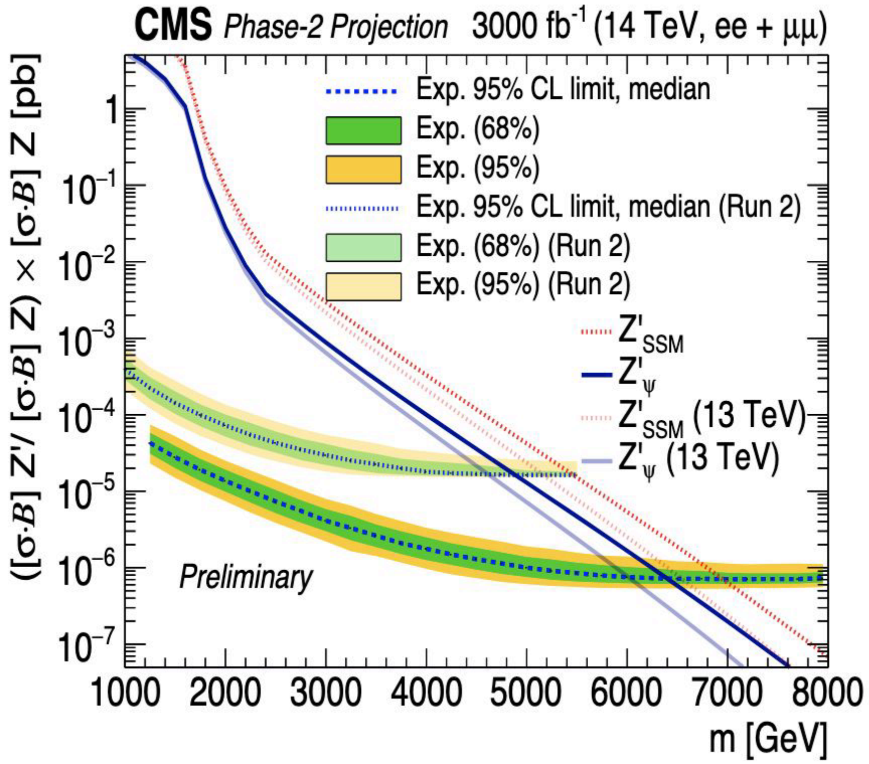
Precision measurements can also open windows to various BSM scenarios.

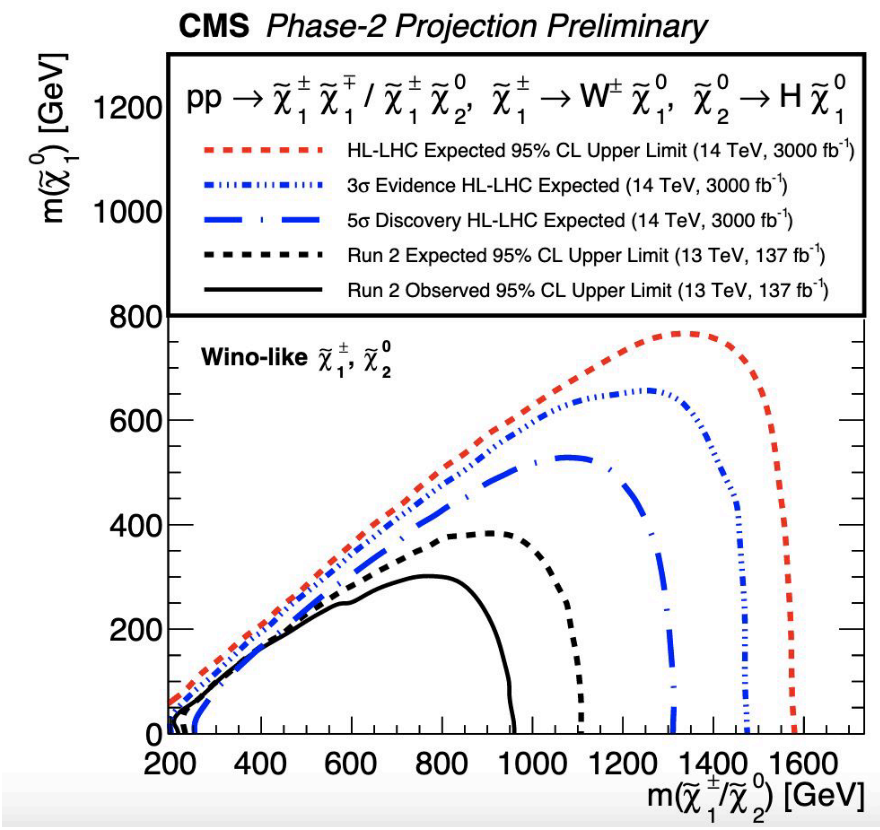
HL-LHC Physics Goals

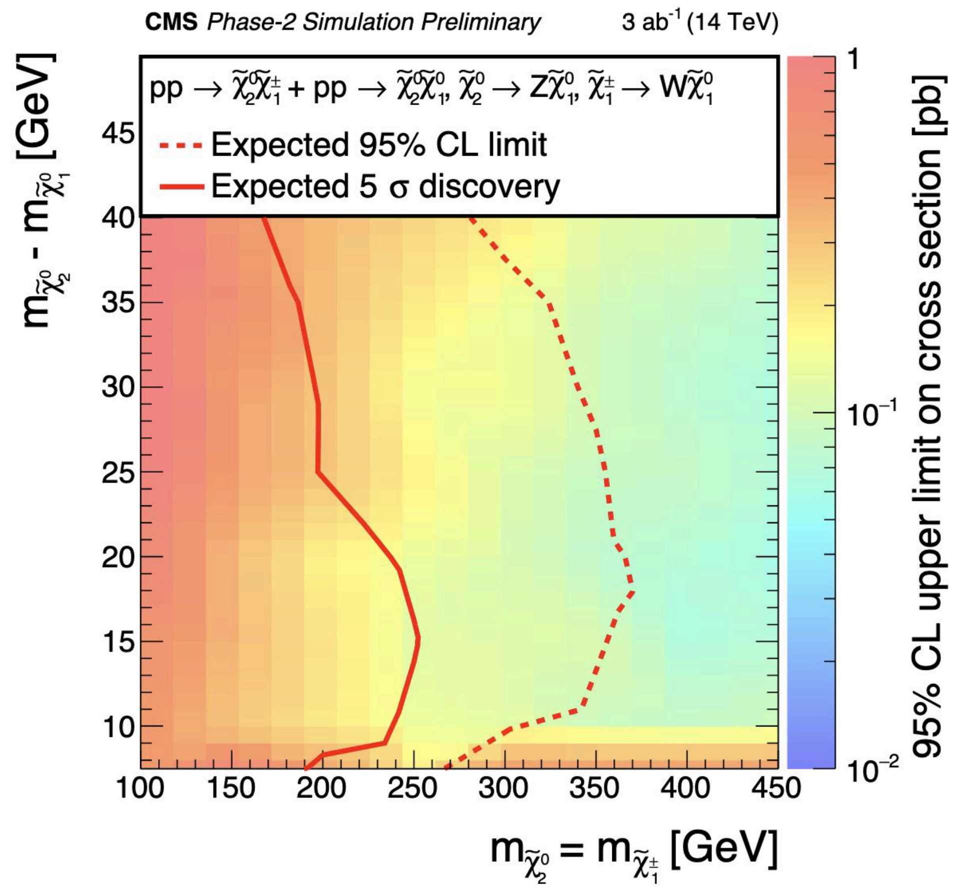
Direct searches for new physics

- Dark matter, Supersymmetry
- Lepton flavor violation
- Resonances

Massive particles, compressed spectra, long lived particles etc.

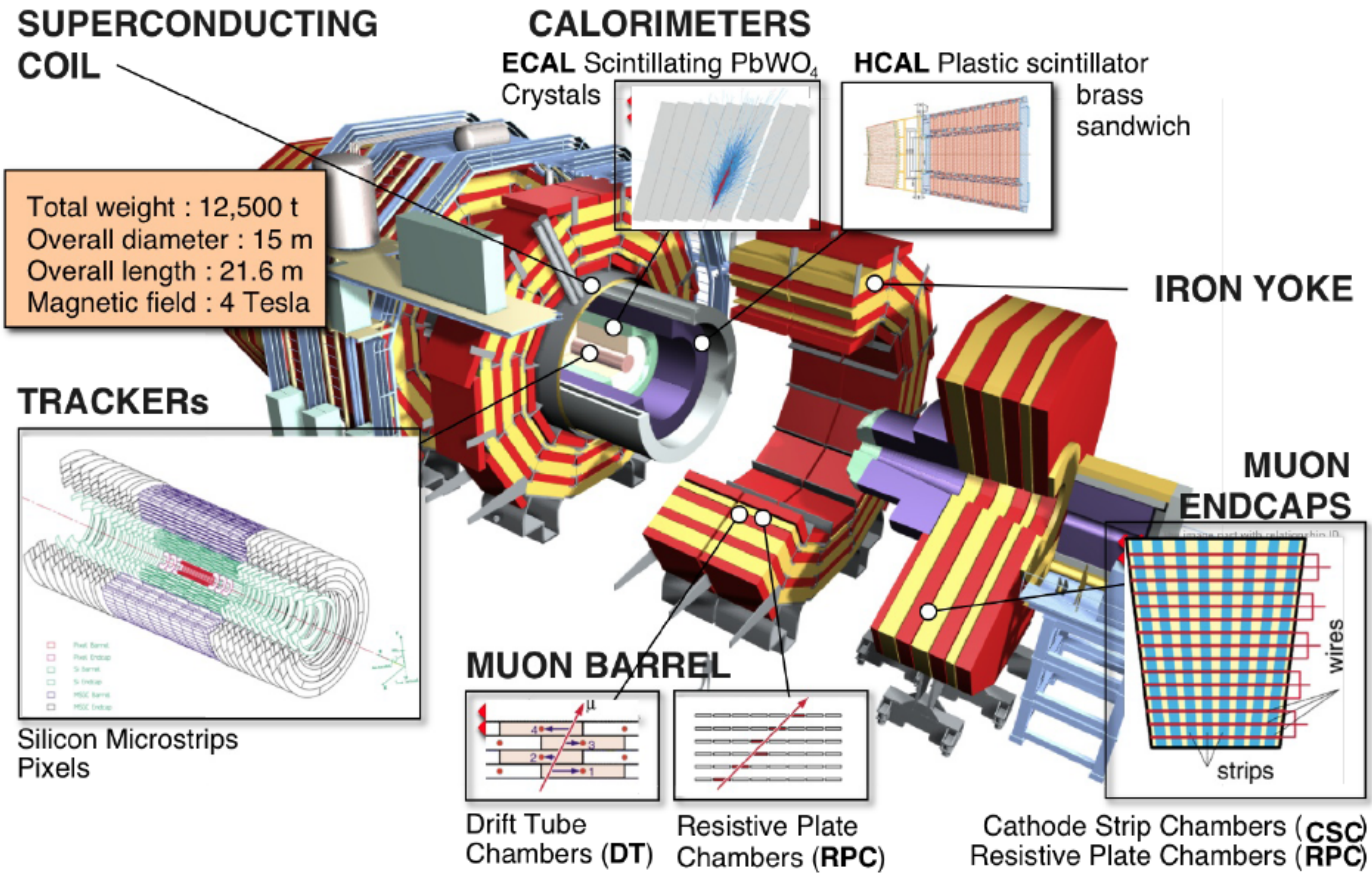






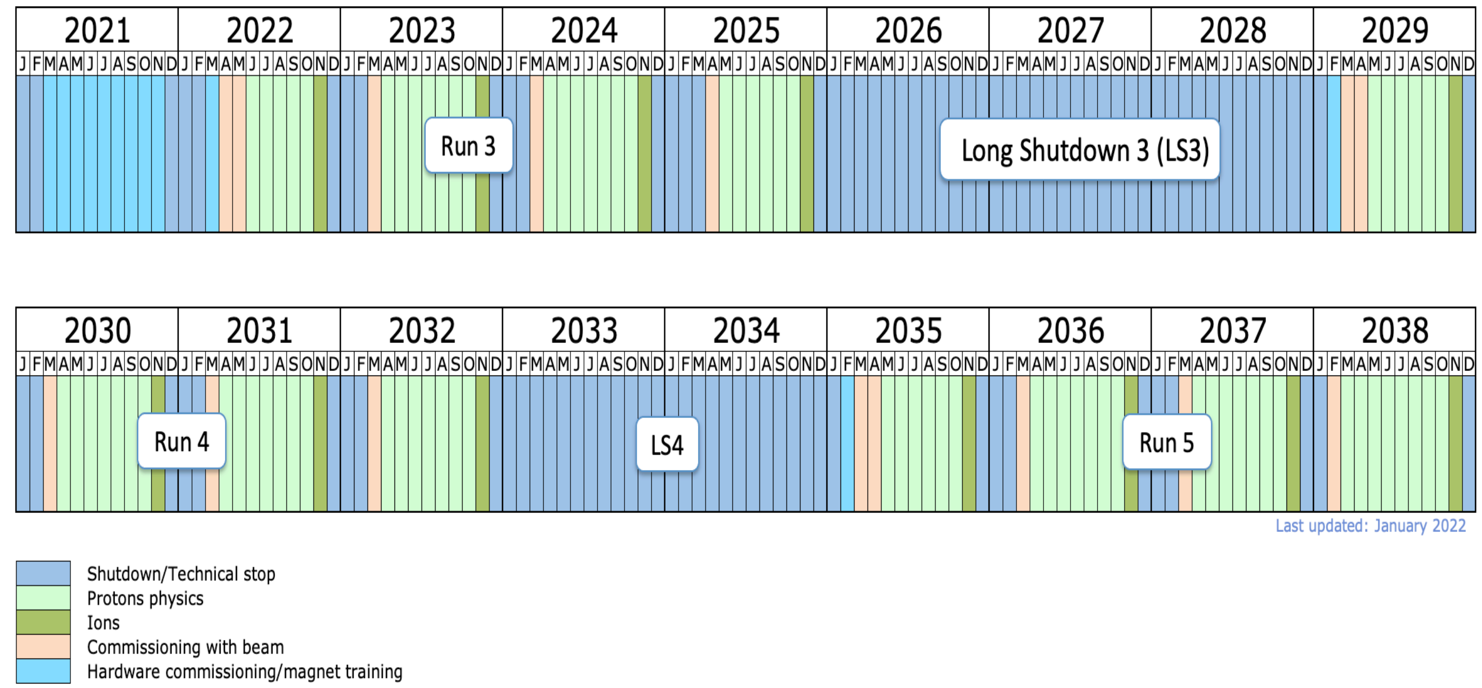
Novel approaches & better detectors for stringent tests of BSM scenarios

Compact Muon Solenoid (CMS) Detector

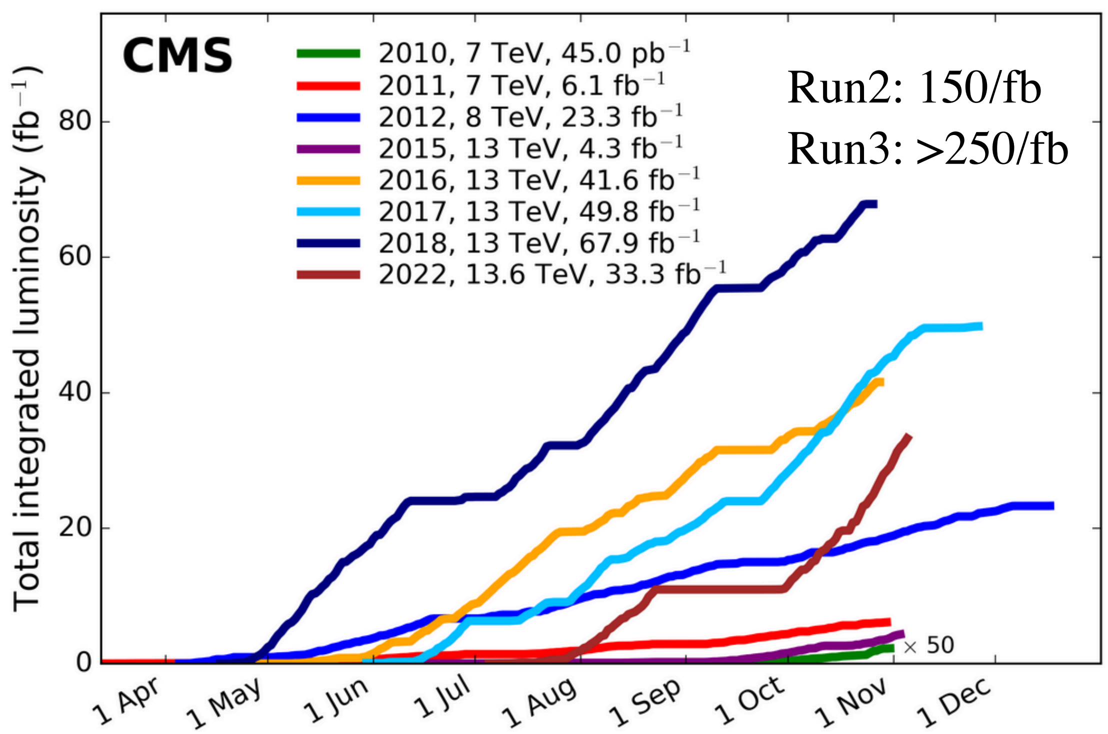


Why detector upgrades ?

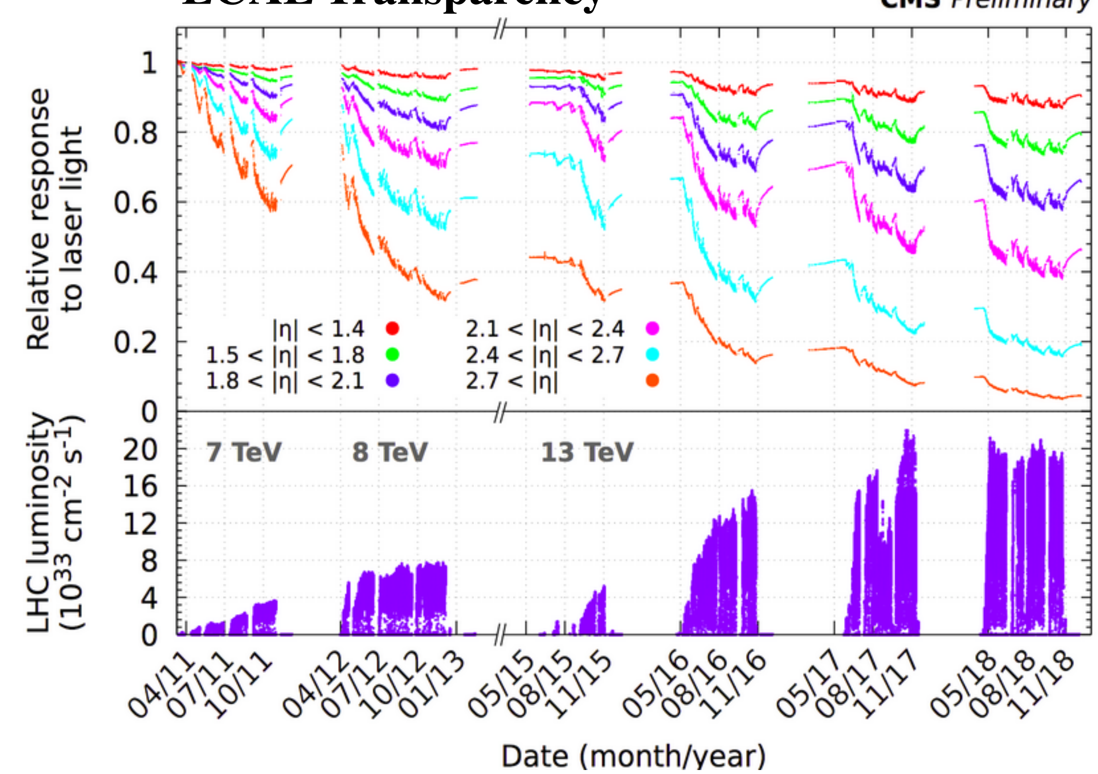
- HL-LHC is our "the opportunity" to meet various physics goals
  - Integrated luminosity of **3 to 4 ab^{-1}** for pp collisions over a span of a decade.



Integrated luminosity



ECAL Transparency



Present detector components need to be upgraded to maintain physics performance to an acceptable level beyond the Phase-I data taking.

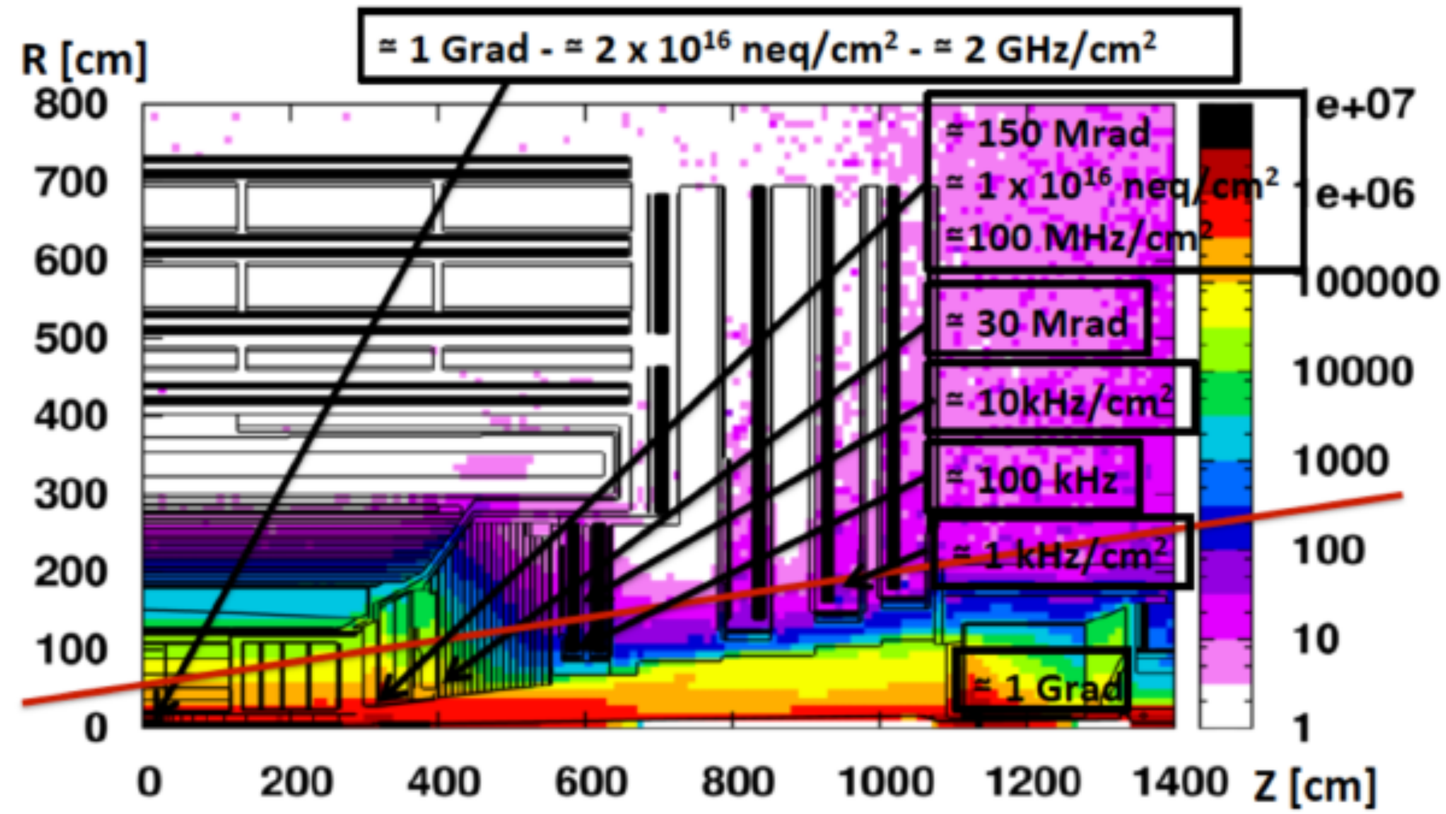
Basic Requirements for CMS & ATLAS @ HL-LHC

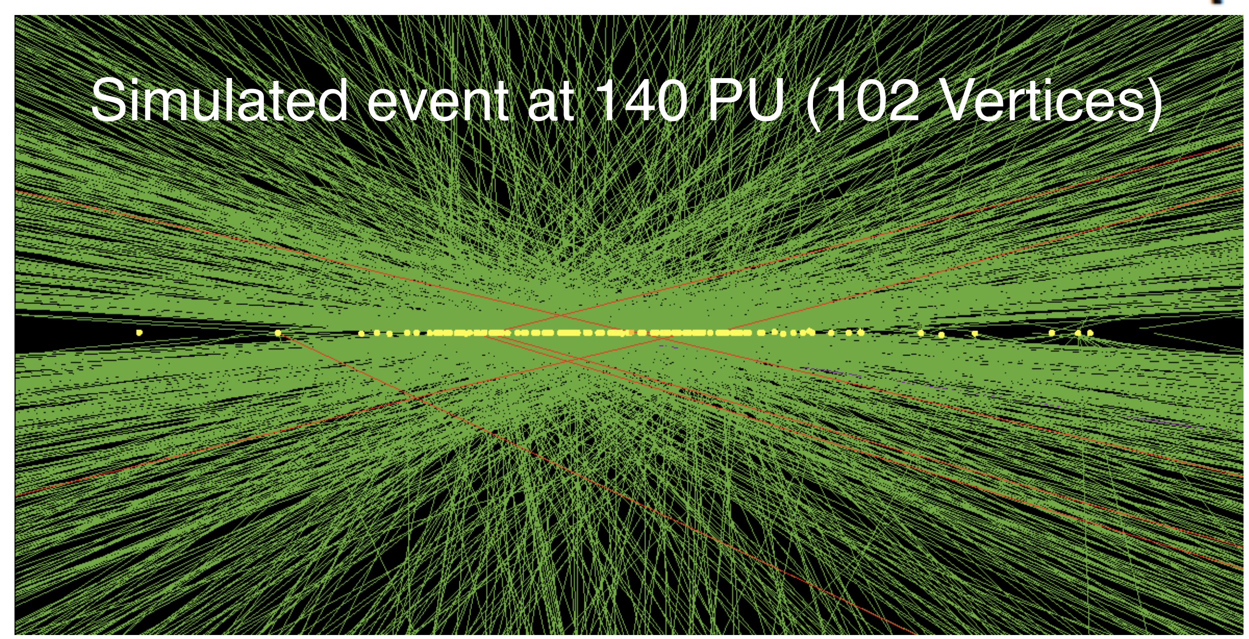
Radiation hardness

- Cumulative radiation exposure: radiation levels up to 2×10^{16} neq /cm^2
- Requires radiation hard detectors and electronics.

High granularity

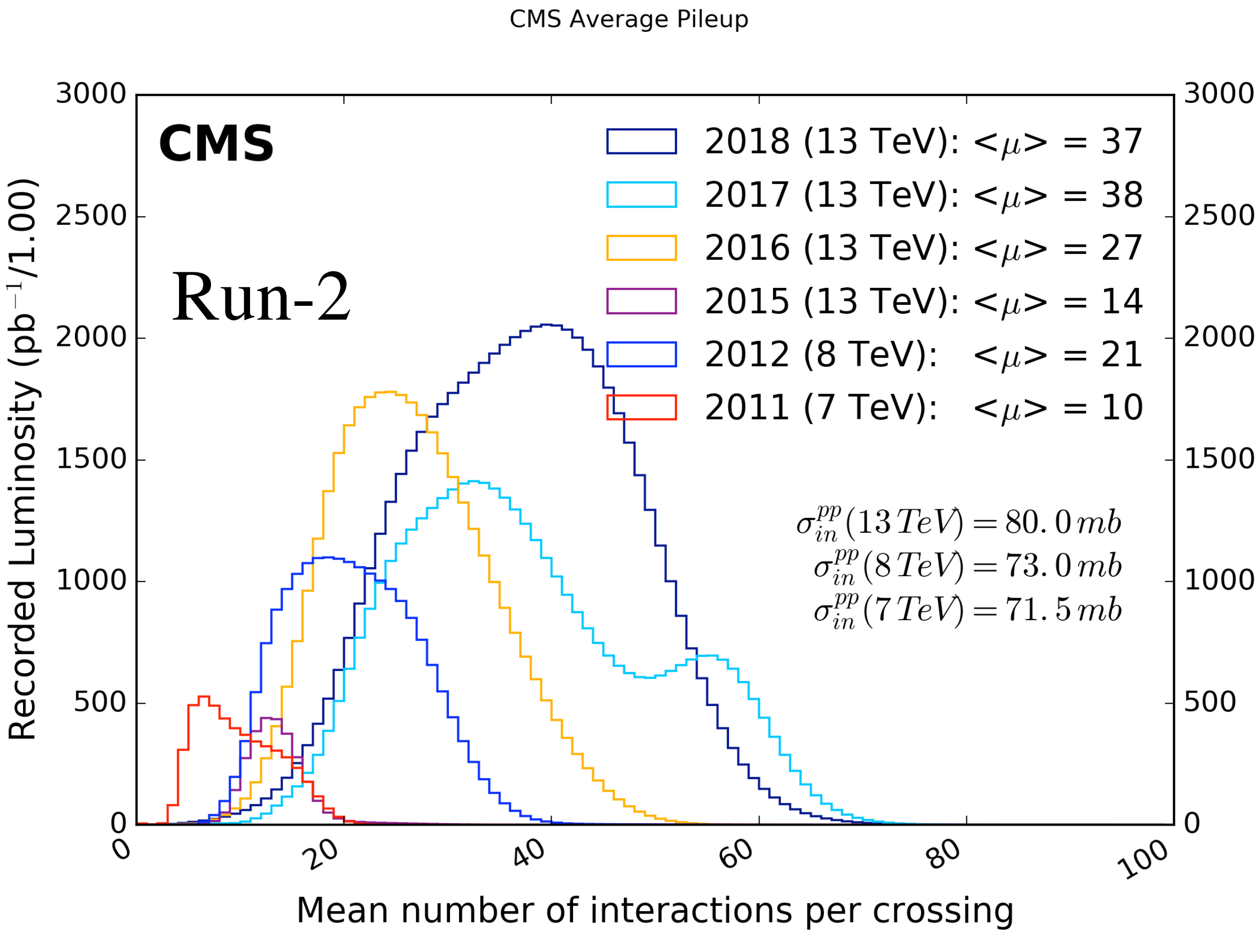
- High instantaneous luminosity → high pileup (number of overlapping hard interactions per bunch crossing): $\langle\mu\rangle$=140-200
- More particles per event → higher detector occupancy
- Require higher granularity of detectors → high data volumes to be processed



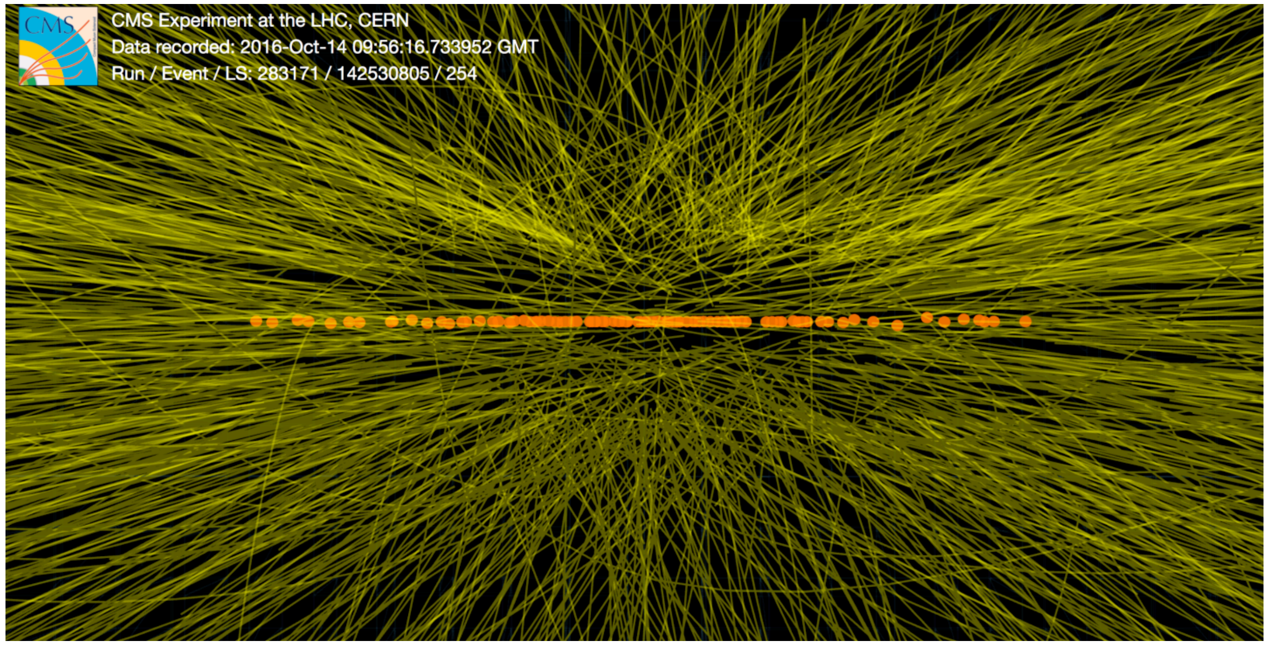


Improve performance: reduce material in tracking volume to reduce rates of nuclear interaction, photon conversions, Bremsstrahlung etc., improve performance of low pT as well as high pT physics object (e, μ, τ, b-tagging, jets & MET) both for triggering and offline analysis.

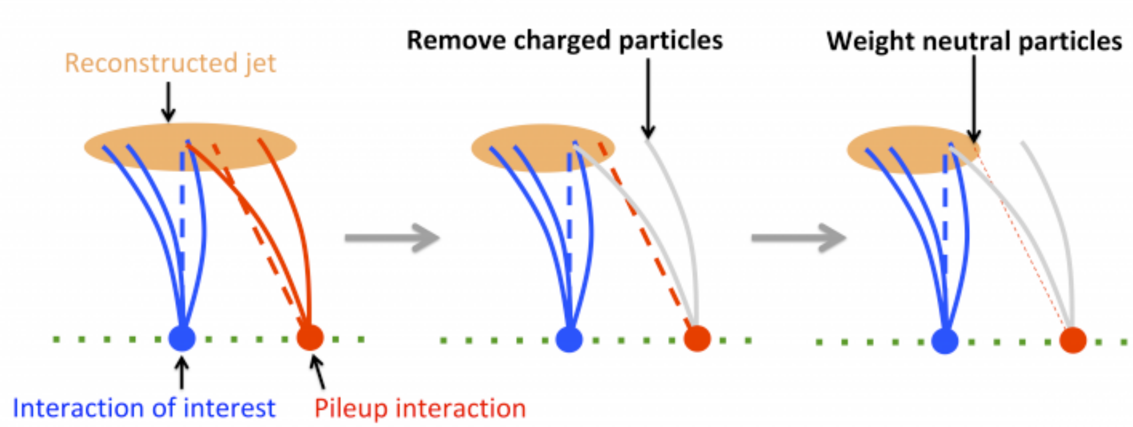
Pileup Interactions & Mitigation



2016 special run with average pilep of ~100 (Ref)

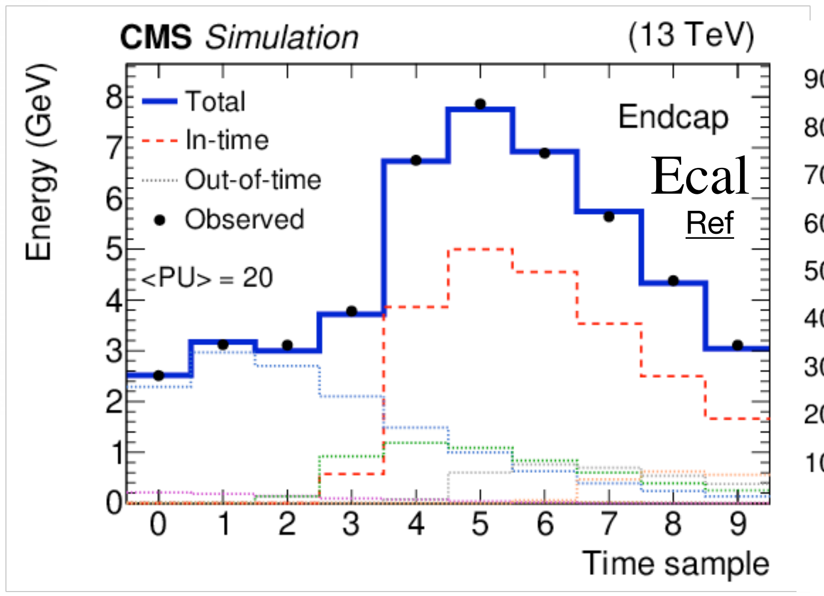


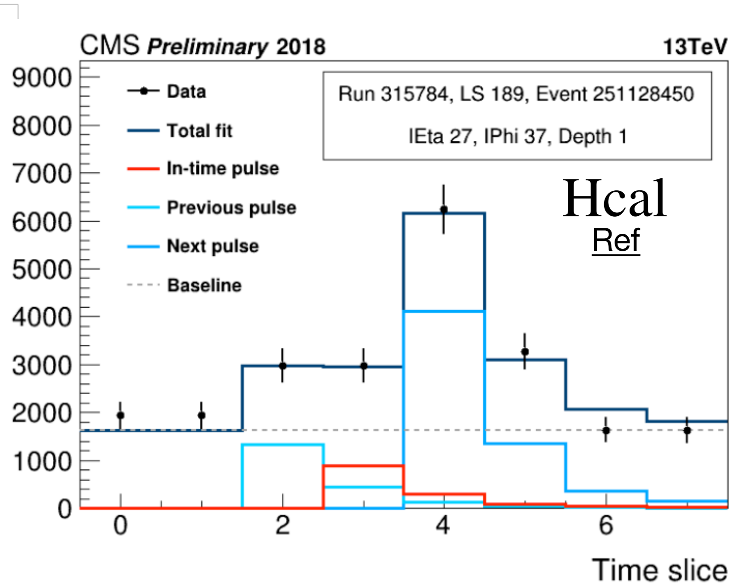
In-time pileup: remove tracks associated with non-primary reconstructed vertices.



Contribution of neutral particles cannot be directly accounted for.

Out-of-time pileup - detector signal developing over a few bunch crossings. Subtracted at channel level reconstruction e.g. calorimeters.





CMS Phase2 Upgrade Overview

L1-Trigger/DAQ/HLT
Complete replacement
- Tracks in L1-trigger at 40 MHz for 750 kHz output
- Particle flow like selection
- HLT output 7.5 kHz

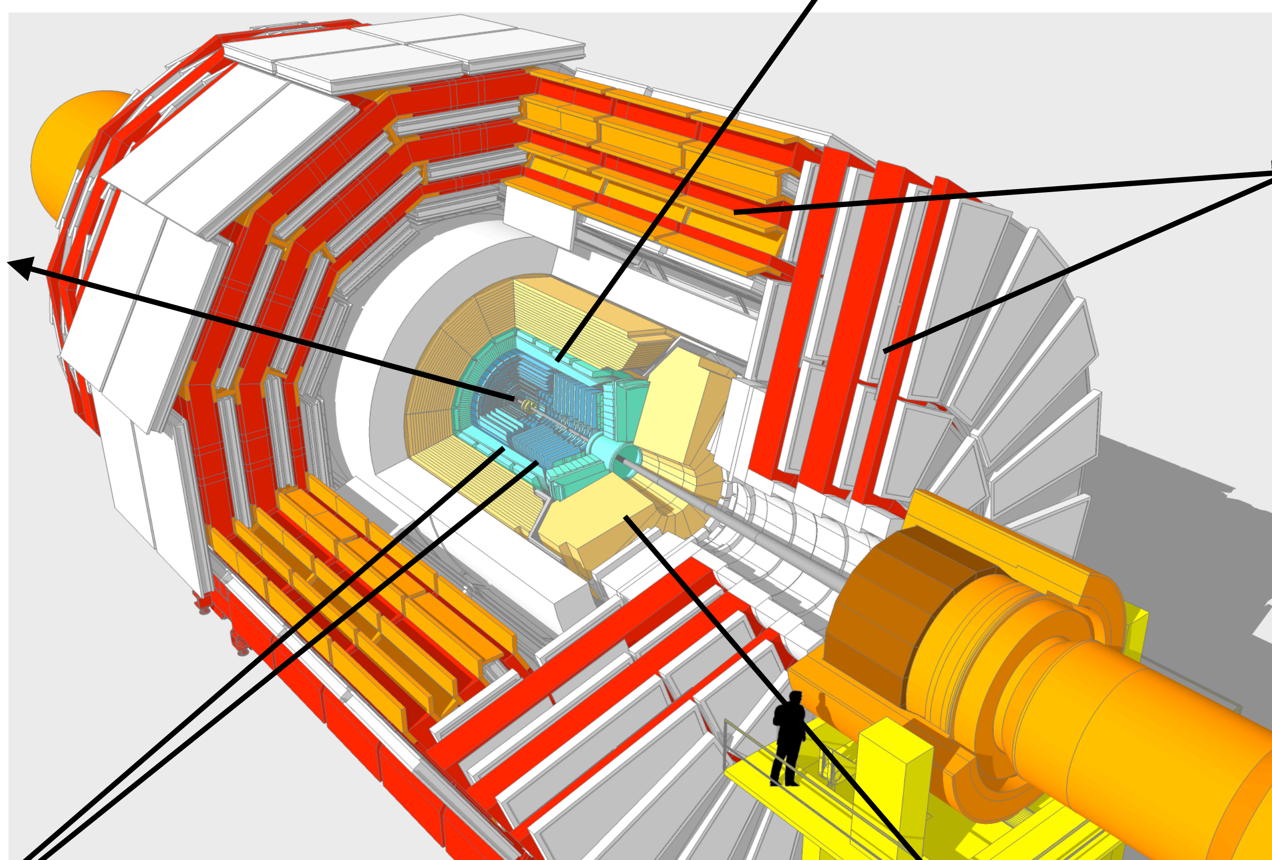
ATLAS - replacement

Barrel Calorimeters
- HCAL & ECAL readout boards
- ECAL crystal level readout at 40 MHz for triggering with timing for e/gamma at 30 GeV

ATLAS - new FE for trigger

Tracker
Complete replacement
- Increased granularity for Si strip & pixels
- Extended coverage to $|\eta| < 3.8$
- Enabling tracking in L1-trigger

ATLAS - complete replacement of tracker.



Muon Detectors
- New GEM/RPC $1.6 < |\eta| < 2.4$
- DT & CSC new FE/BE readout
- RPC back-end electronics
- Extended GEM coverage to $\eta \simeq 3$

ATLAS - new FE for trigger

Beam Radiation Instrumentation and Luminosity, common systems and infrastucture

MIP Timing detector
New addition between tracker and ECAL
- Precision timing (30 ps resolution) for pileup mitigation
- Barrel: LYSO:Ce crystals+SiPMs
- Endcap: Low Gain Avalanche Diodes

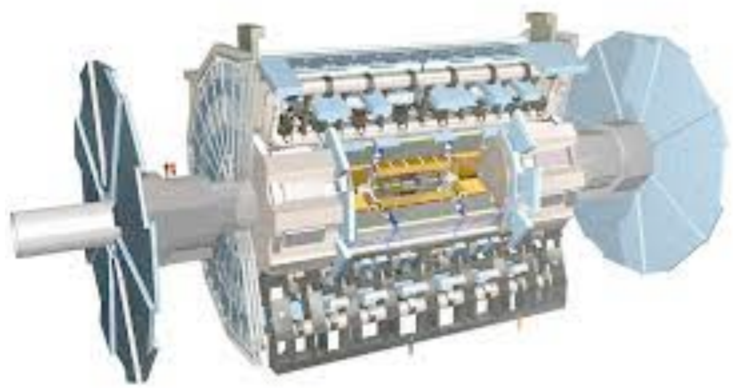
ATLAS - Endcap MIP timing detectors.

Endcap Calorimeters
Complete replacement
- High longitudinal and transverse granularity
- Precision timing
- Si & Sci-SiPMs in Pb/W/CuW & staintless steel (sampling calorimeter).

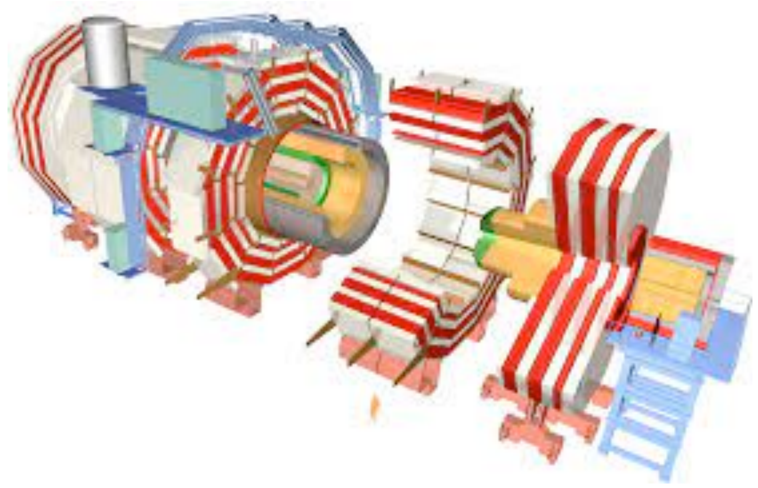
Trigger & Data Acquisition (DAQ)

Trigger/DAQ:
- New trigger concepts needed to cope with HL-LHC.
- μ, *e* and jet rates would exceed 100 kHz at high luminosity. Physics goals require the pT thresholds to be kept low (surely not to exceed the current ones).
- In addition, increased backgrounds to muons and tracks because of accidental coincidences of hits.

Solution
- Upgrades, add tracking at Level-1 trigger, new electronics
- Improve bandwidth and processing for triggering, increase in latency



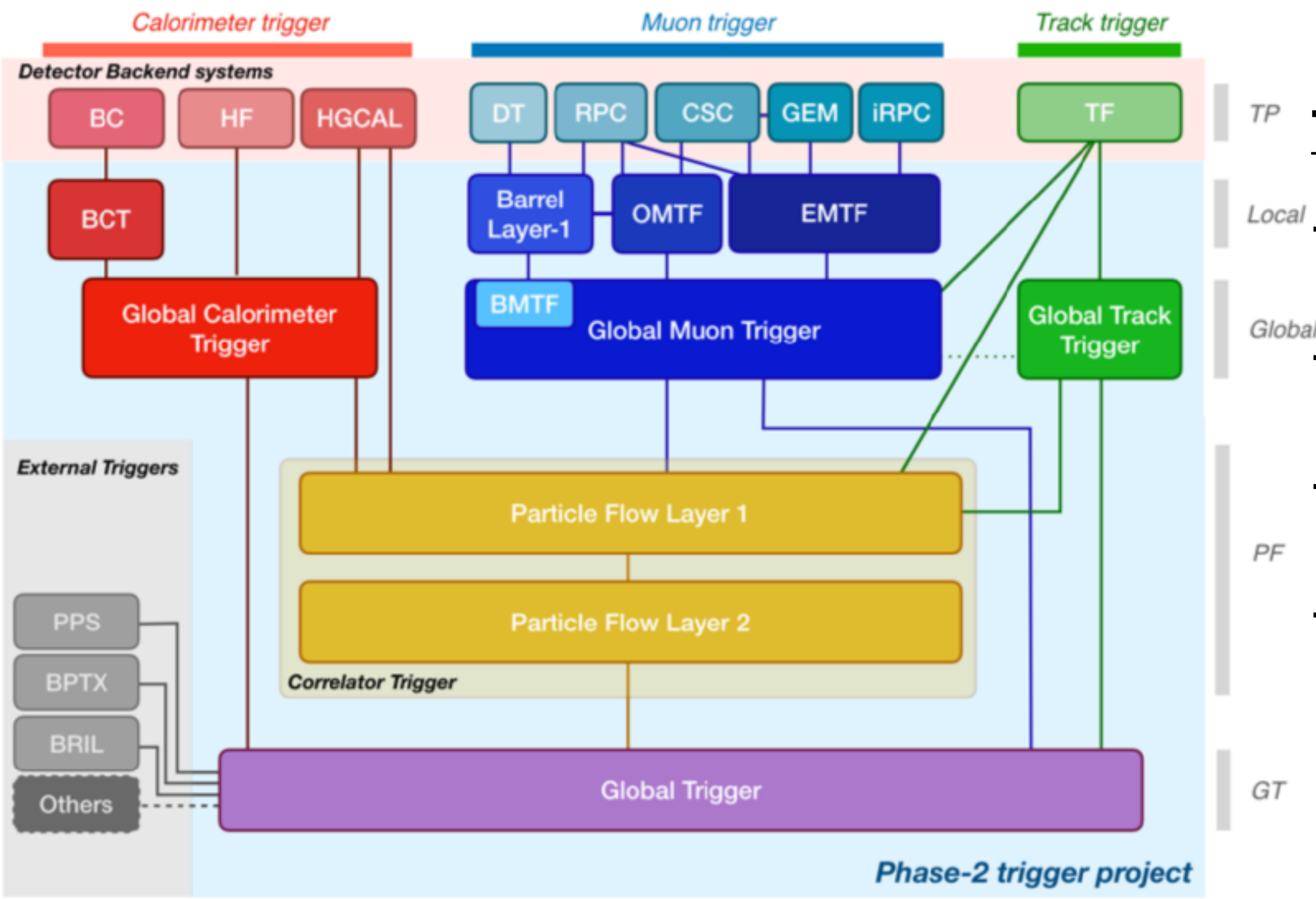
Choice of trigger has direct impact on tracker design both for the CMS & ATLAS experiments.



Technologies: latest FPGAs, ATCA, GPUs, ML …

Challenges: power delivery, thermal management, system integration

CMS - Trigger and DAQ Upgrade



Trigger parameters

- Trigger primitives input rate ~ 63 Tb/s
- L1 trigger rate of **~ 750 kHz @ 200PU** (now 100 kHz)
- L1 latency of **12.5 μs** (now 3.4 μs)
- High-Level Trigger (HLT) rate **~ 7.5 kHz** (now 1 kHz)

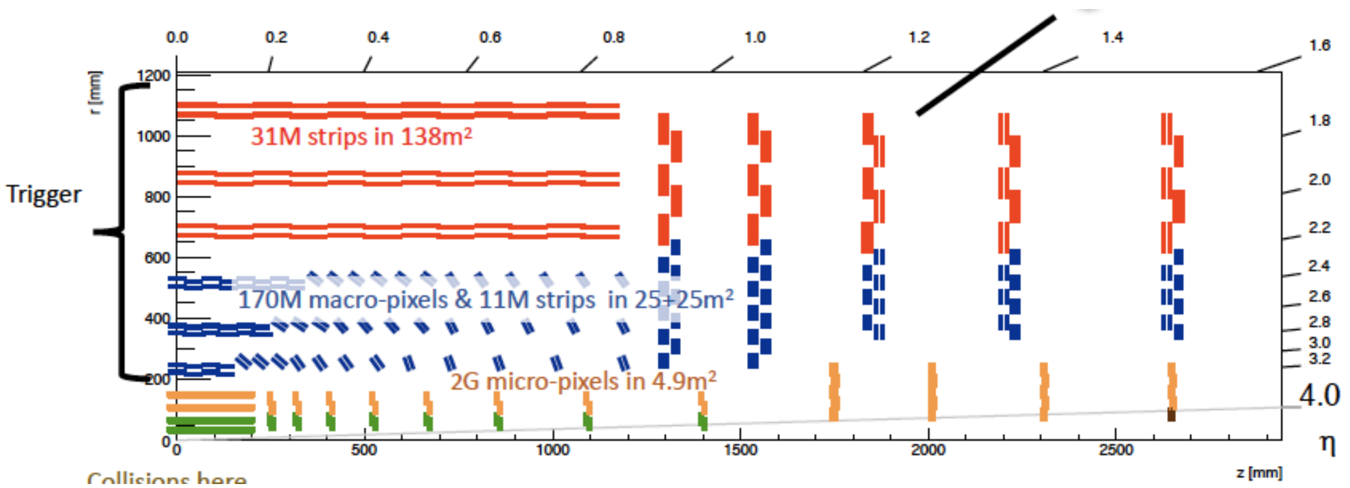
Salient features

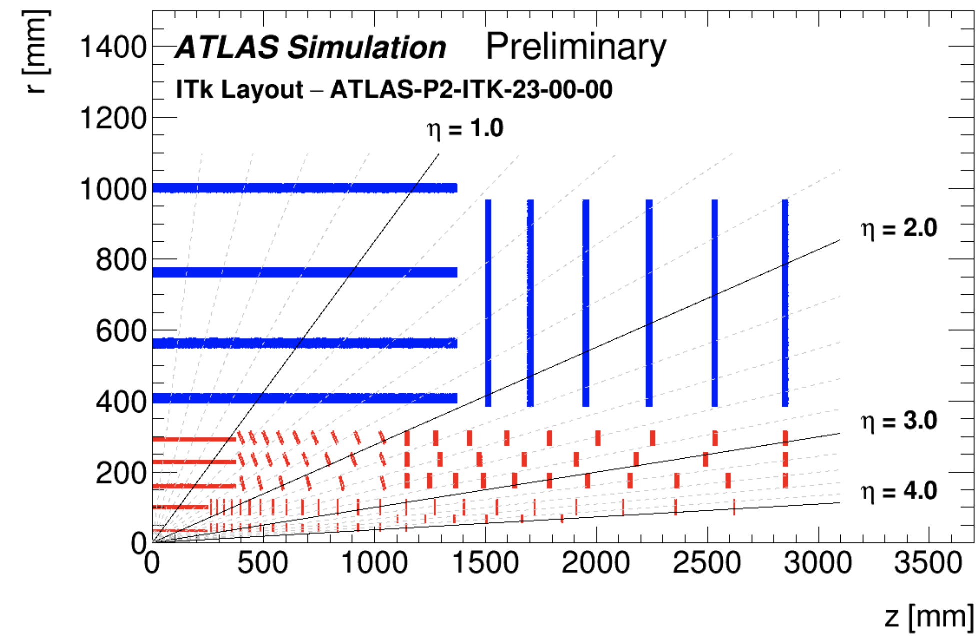
- Tracking at Level-1 Trigger - better lepton p_T resolution @ 40 MHz
- More sophisticated algorithms for pattern recognition in general
  - More granular calorimeter information
  - Additional muon chambers for |η|>1.6
  - Electronics to handle higher trigger rates & longer latency for each sub-detector
- Made possible by high speed optical links (10 Gb/s) and GHz FPGA's

Tracking Detectors

Upgrade of Tracking Detectors

New all silicon tracking detectors for CMS and ATLAS with extended coverage to |η|<3.8(4)





Key features

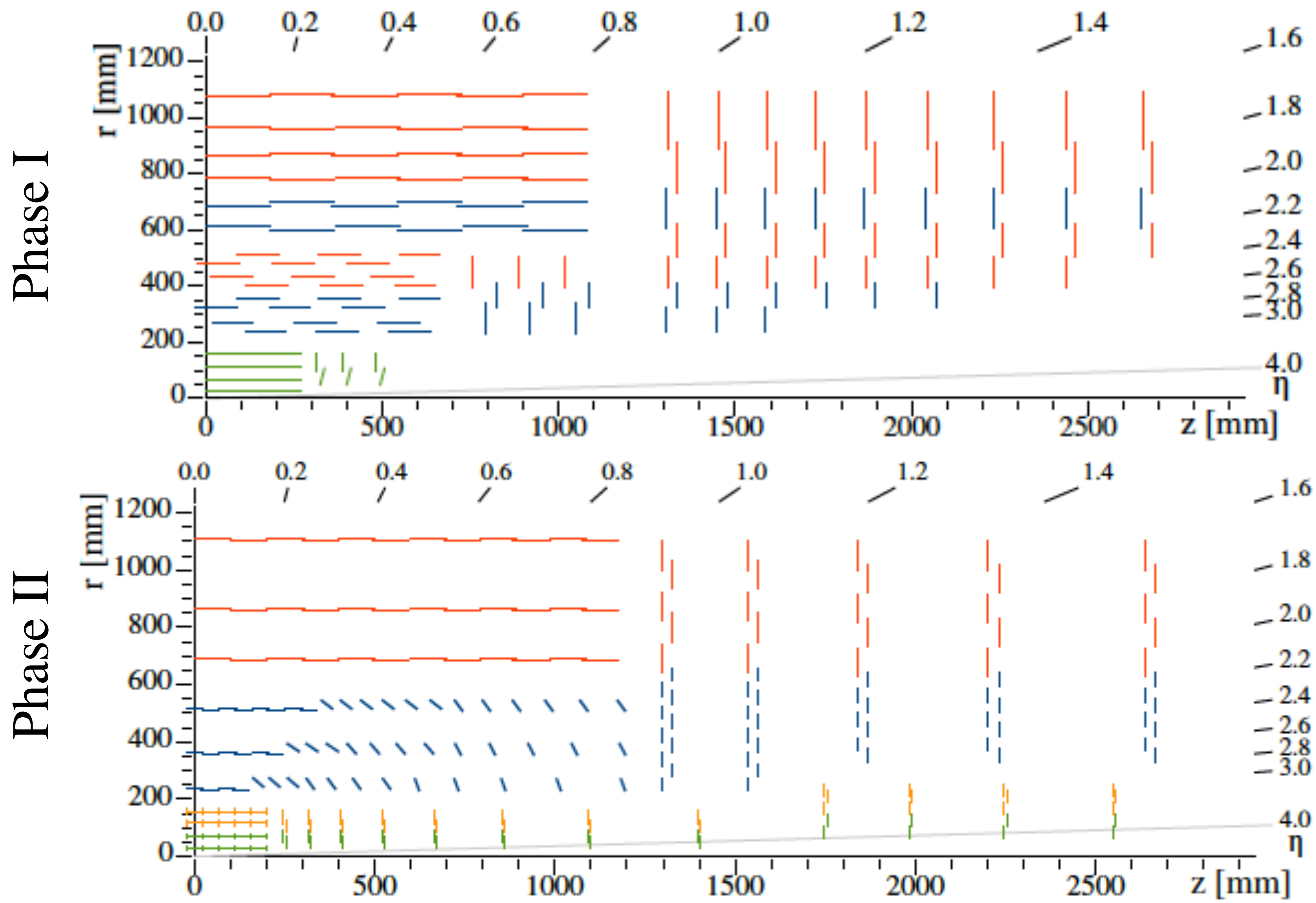
- n-in-p silicon sensors (radiation hard), higher granularity
- Extended coverage to forward region
- Fast data transmission with low power giga-bit data transmission
- Serial powering of pixel detectors, DC-DC converters for strips
- CO_2 cooling (thinner pipes)
- Carbon structures for mechanical stability
- Lower material budget (< 2 X_0) and efficient powering

	CMS	ATLAS
Strip pitch (um)	90-100	70-85
Strip length (cm)	2.5-5	2.5-8
Strip thickness (um)	300	300
Pixel size (um^2)	25x100, 1.5 mm macro-pixels	50x50 (planar L1-L4), L0 3D in rings 50x50, 25x100 in flat
Pixel thickness (um)	≤ 150	≤ 150

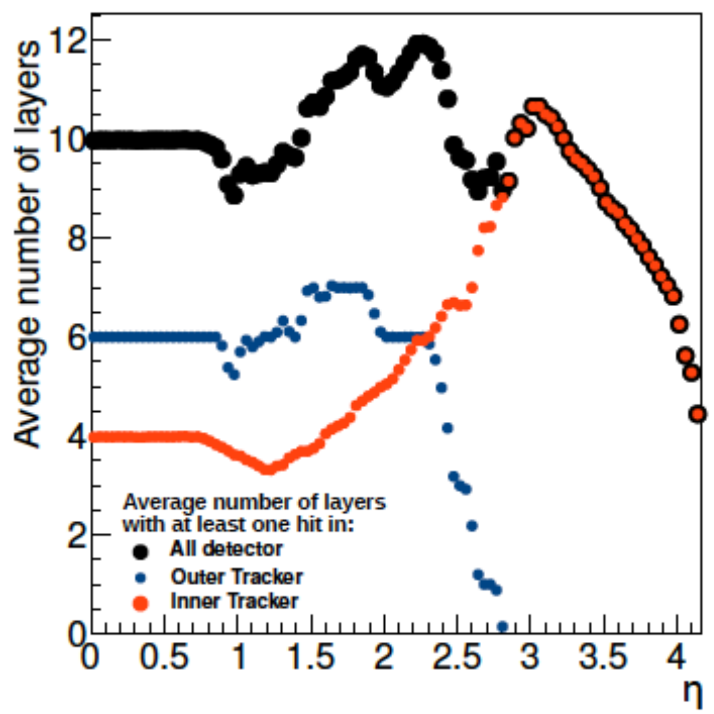
Joint CMS-ATLAS collaboration for development of readout chips (65nm CMOS).

CMS Tracker for HL-LHC

Complete overhaul of layout to be able to meet high particle density and trigger requirements.



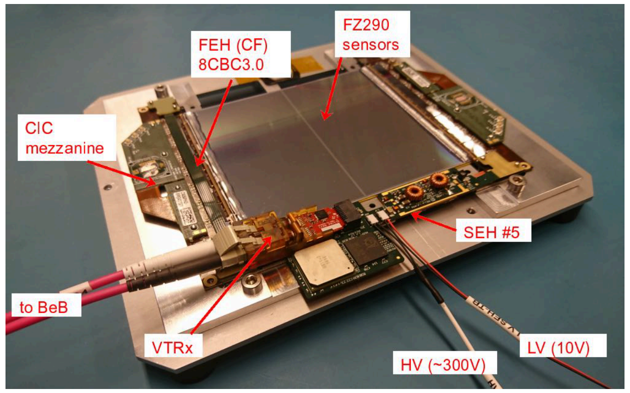
The upgraded tracking system extends efficient tracking up to about |η|<4

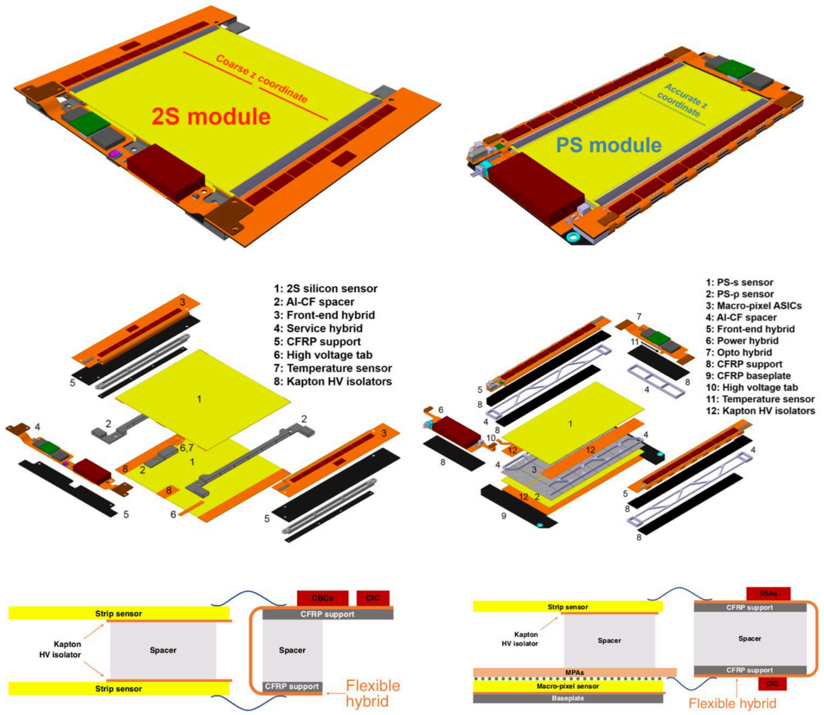


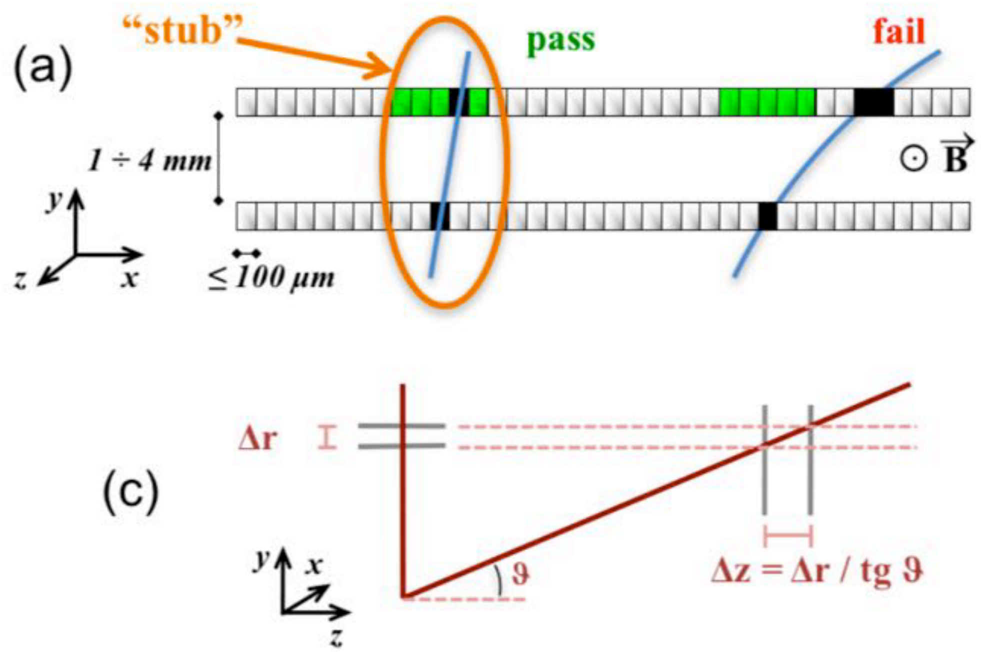
- 10x more radiation hard, 25x more readout channels.
- Inner tracker - sensor thickness of 100-150 μm, with 25x100 μm^2 or 50x50 μm^2 pixel sizes (six-seven times smaller pixel area as compared to current detector).
- Outer tracker - uses combination of 2-strip (2S) modules or Strip-MacroPixel (PS) modules.

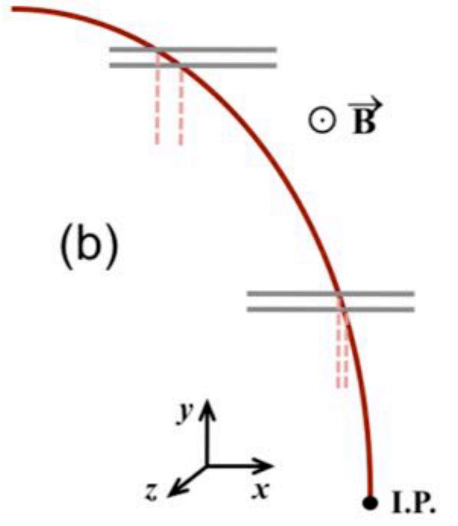
Tracking capabilities for L1 trigger

Outer tracker needs to provide tracks to L1-trigger @ 40 MHz.
This is achieved by having two kinds of sensor modules, the 2S and PS.









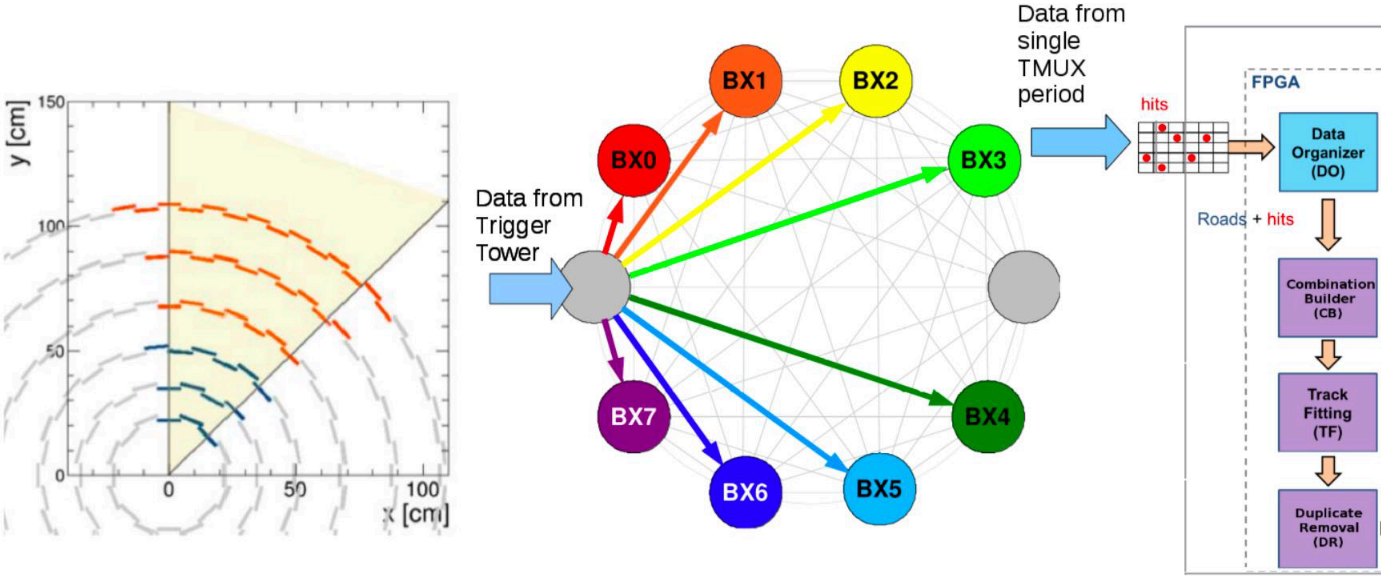
- pT Modules (PS & 2S) select pair of hits (stubs) consistent with tracks of pT>2 GeV while rejecting the softer ones. Achieves local data reduction for L1 Tracking Trigger @ 40MHz
- Tilted modules in endcap to maintain stub acceptance.

Challenge: requires precise measurement of misalignment between top and bottom sensors in modules: PS 800 μrad and 2S 400 μrad.

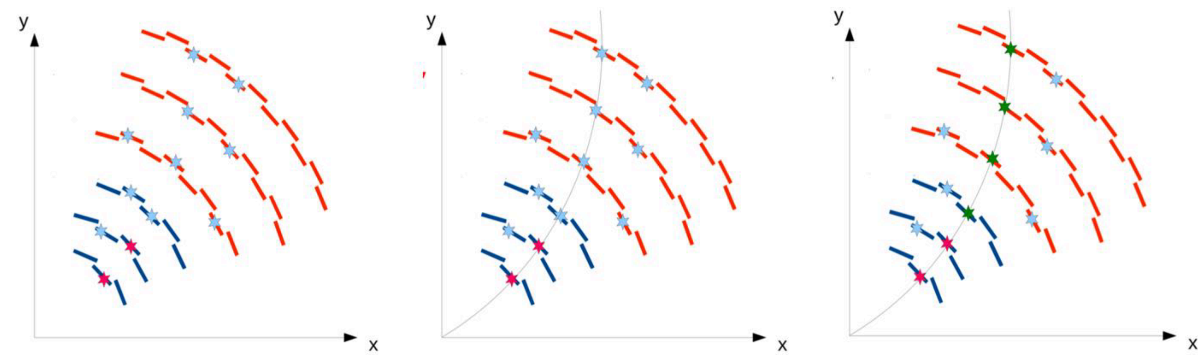
	2S module	PS module
Active area	**138 m²**	**50 m²**
Strip/pitch	**5 cm x 90 μm**	**2.4 cm x 100 μm (strips) 1.5 mm x 100 μm (macro-pixels)**
Channels	**31M**	**11M(strips) + 170M (m-pixels)**
FE power	**5 W**	**8 W**
Sensor power	**~ 1 W**	**1.4 W**

From Stubs to L1 Tracks @ 40MHz

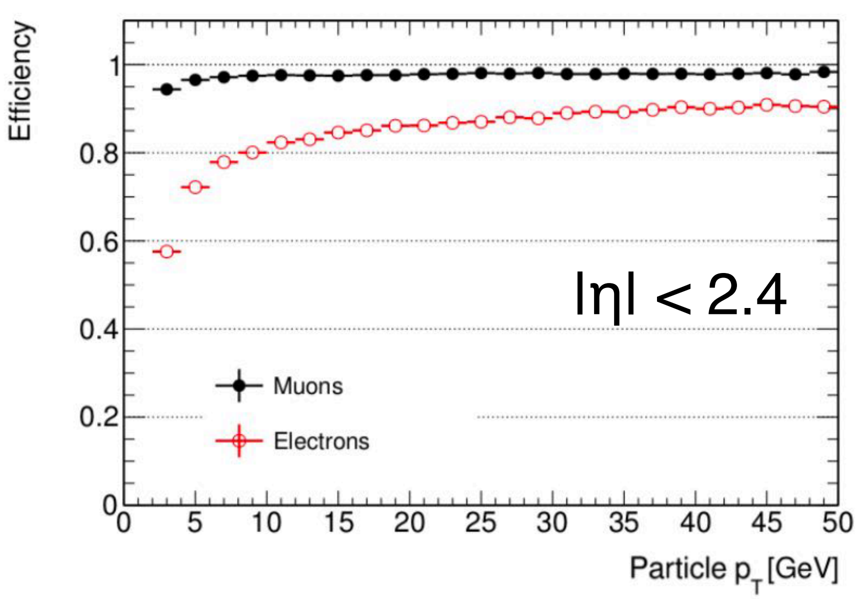
Associative Memory+FPGA approach

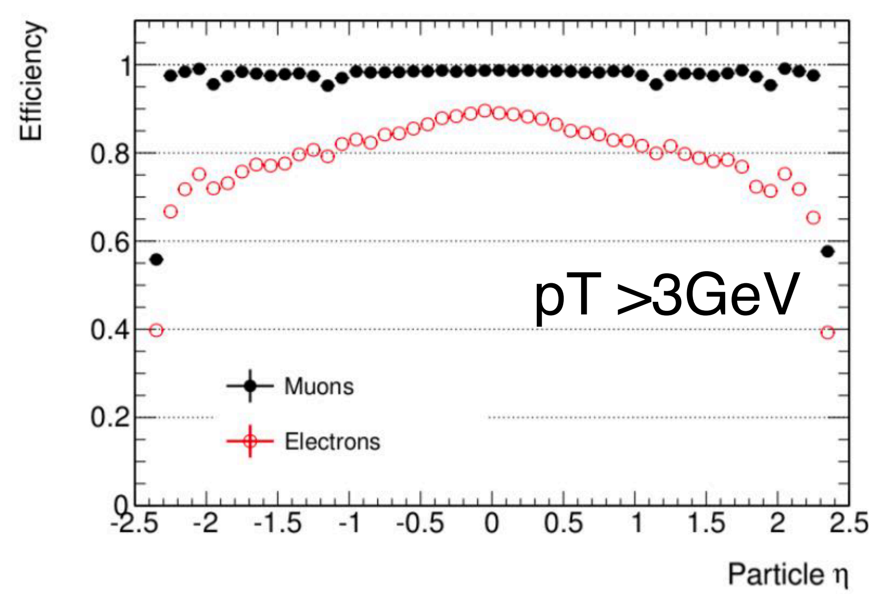


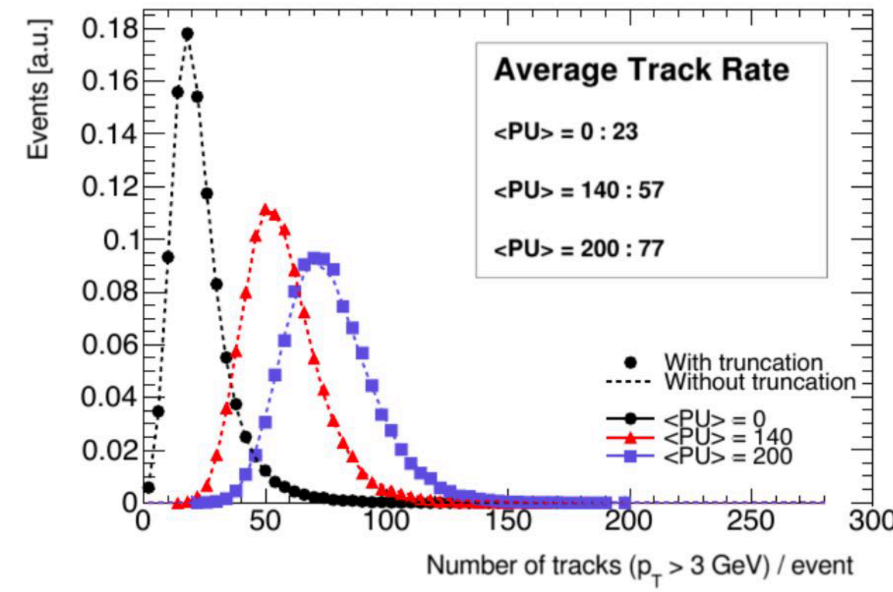
FPGA-based tracklet approach



ttbar events with <PU>=200

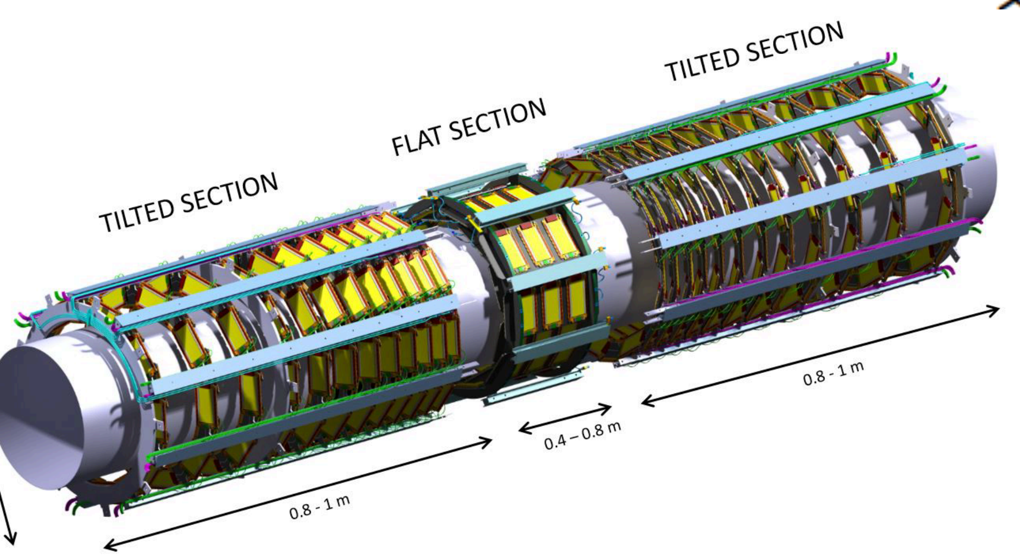


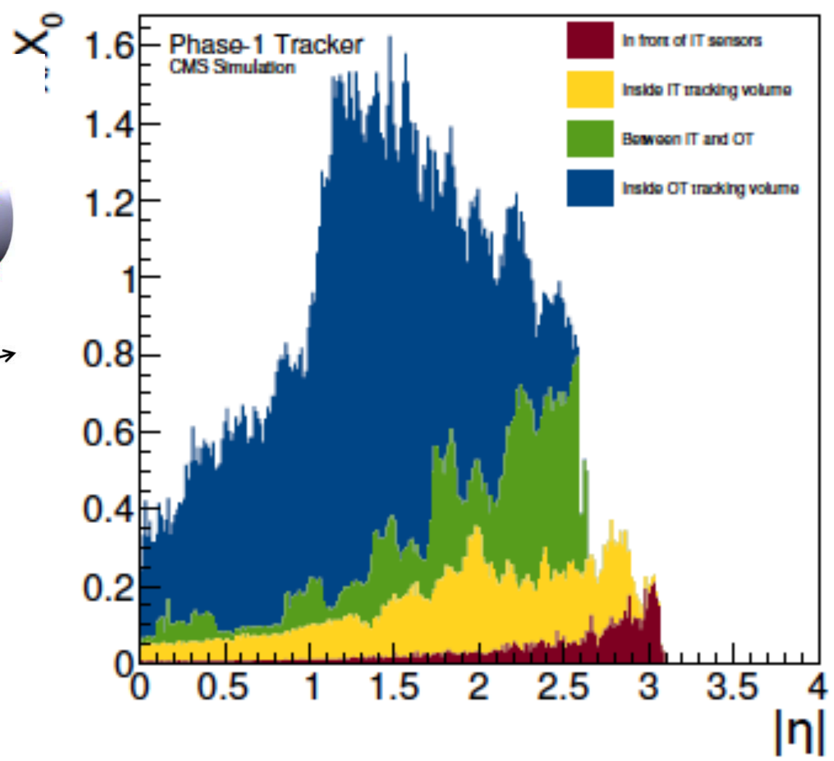


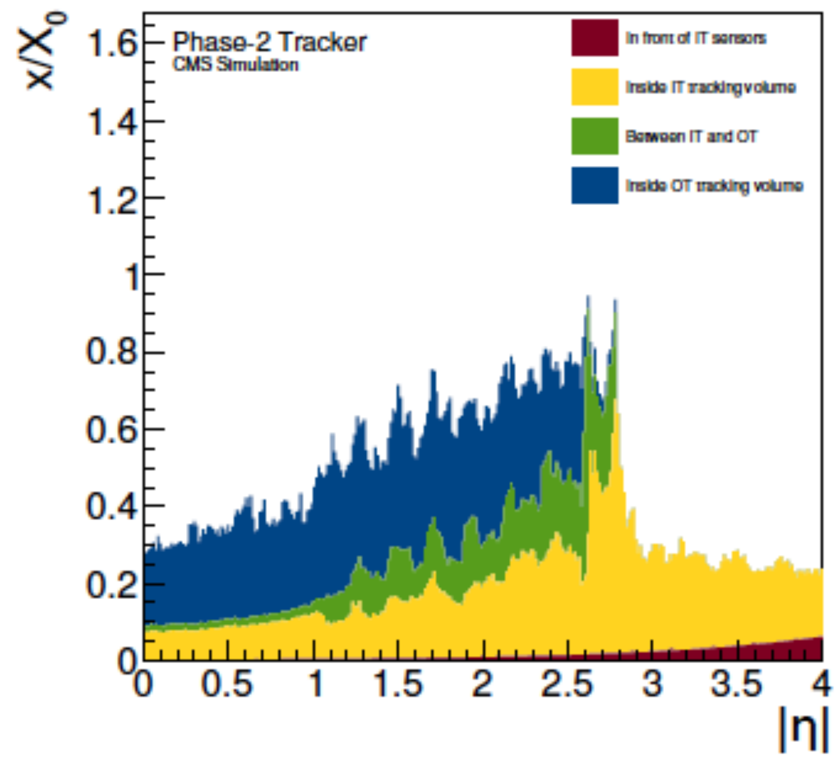


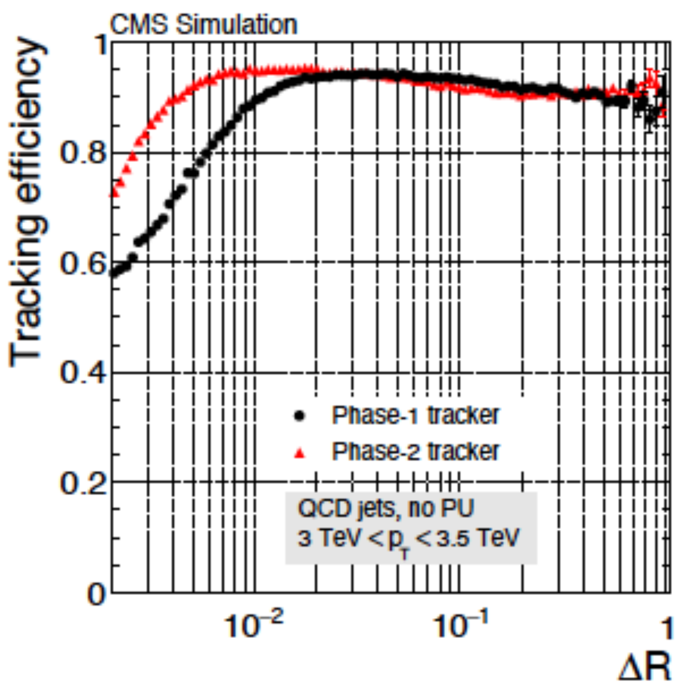
CMS Tracker for HL-LHC

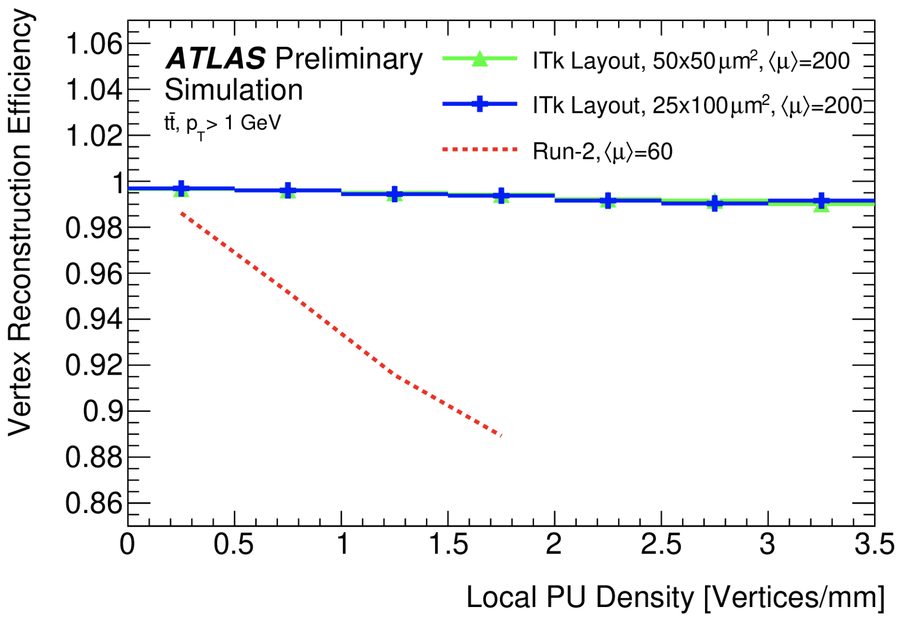
Design consideration to significantly reduce material budget - improves tracking & calorimetric performance, reduction in photon conversions etc.

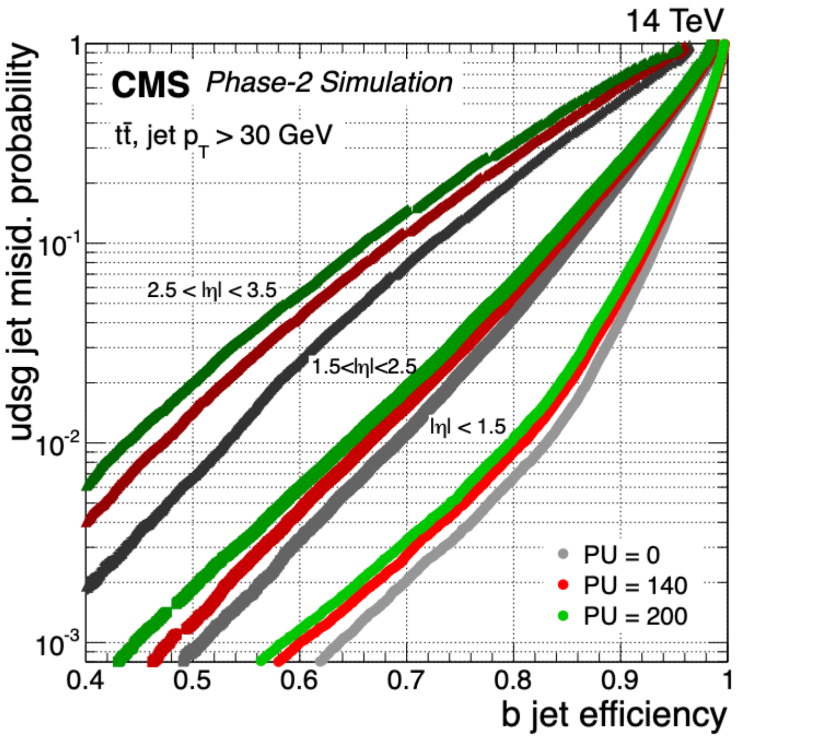








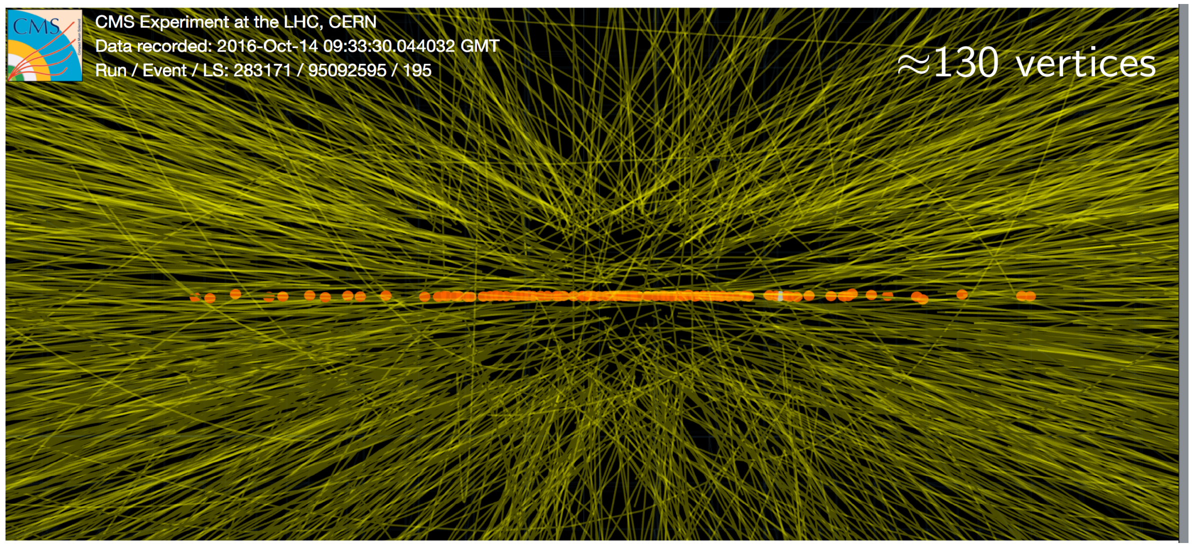


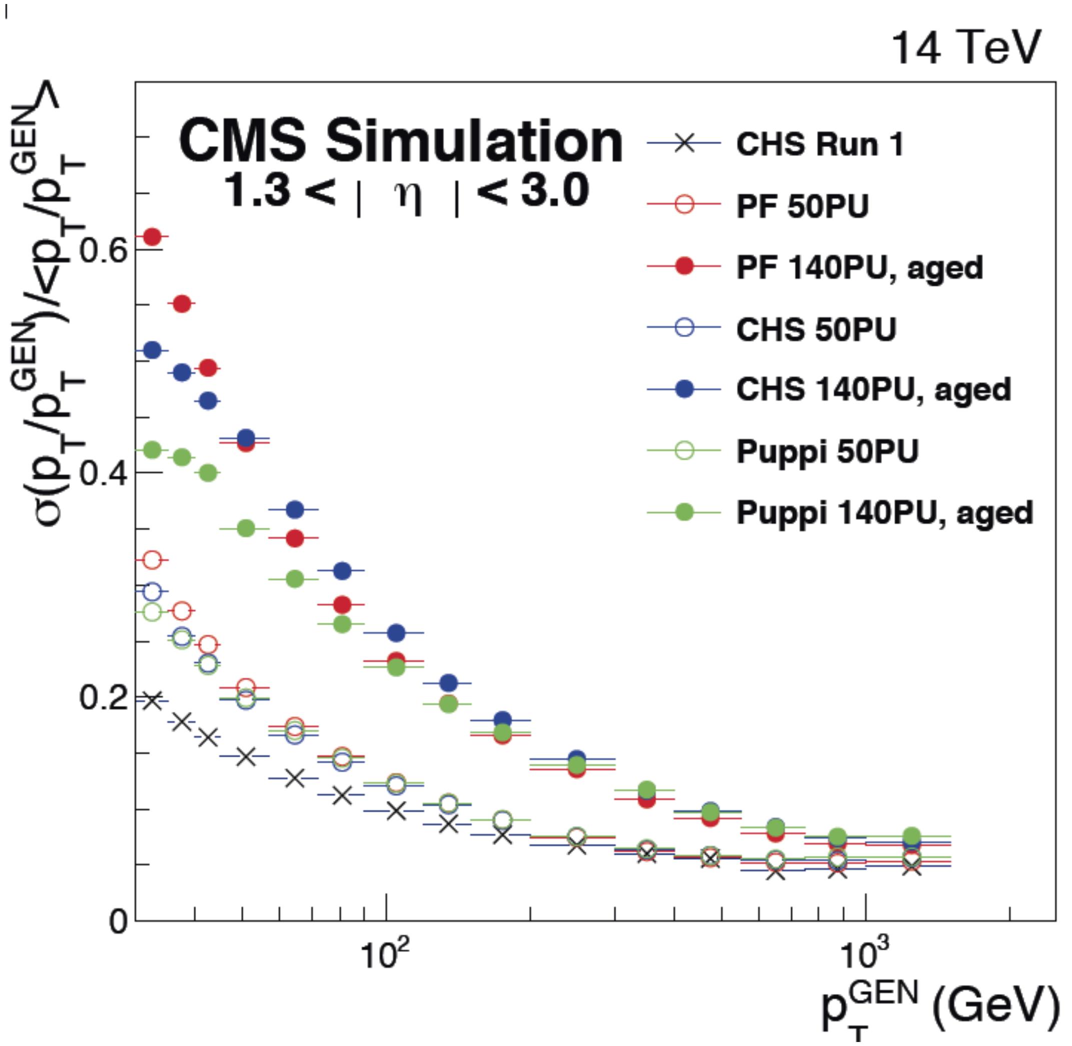


Timing Detectors

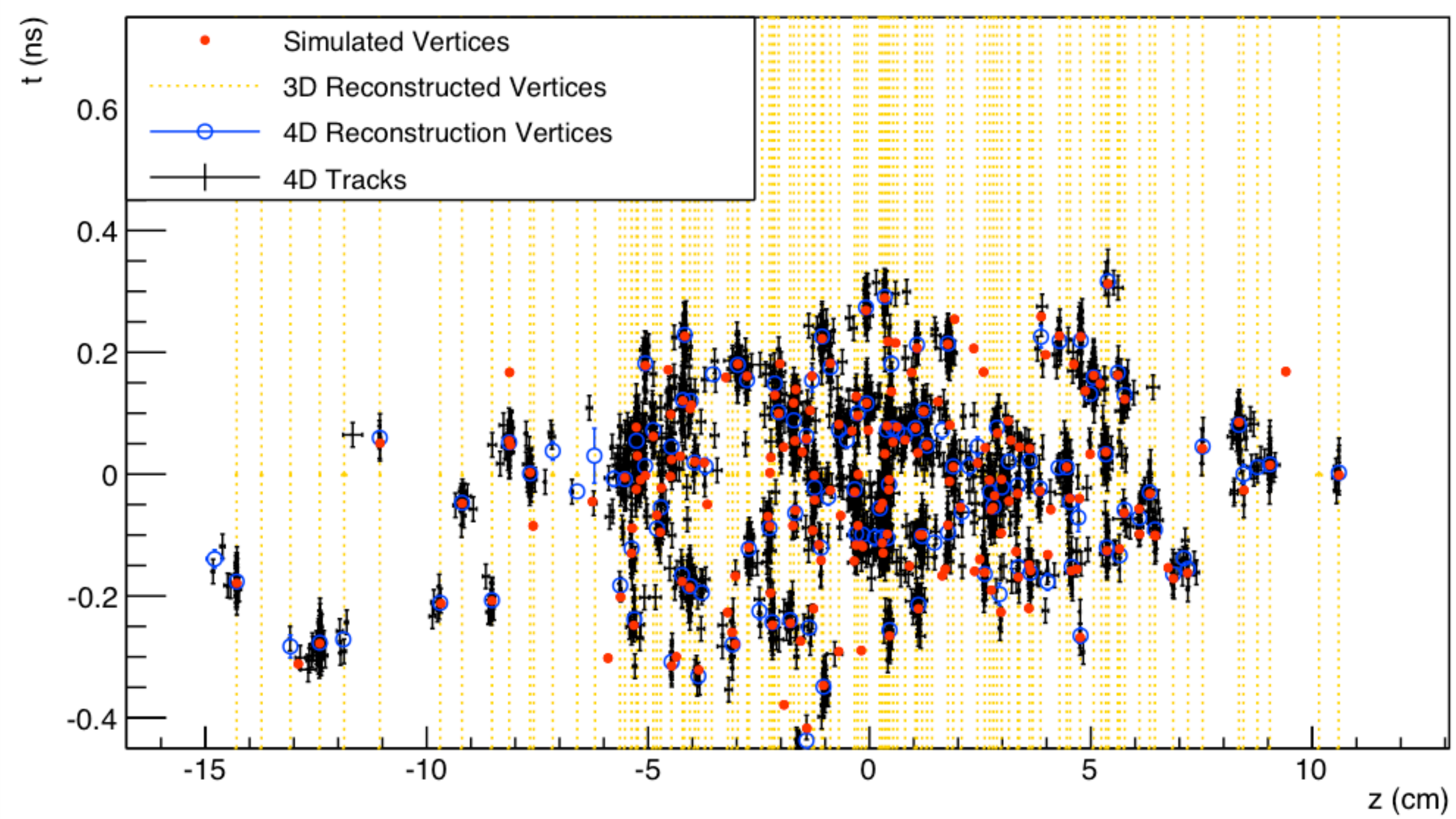
Timing Detectors to Mitigate Pileup

Vertices overlapping within effective tracking resolution:
- pileup tracks start getting associated with hard interactions
- charge PU mitigation degrades resulting in degradation of charged isolation, jet/MET resolution, b-tagging etc.





Exploit the time dimension



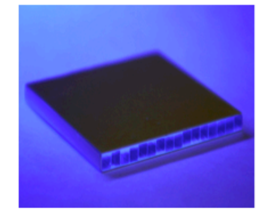
Timing Detectors

- For good timing resolution, we need
  - fast signal rise time
  - low signal to noise ratio
  - more time samples as signal is rising

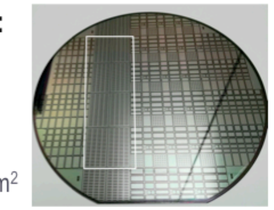
- ATLAS & CMS - both designs based on large pitched **Silicon Low Gain Avalanche Diodes (LGADs)** in endcap regions.
  - cell size < 2 mm^2
- CMS - Barrel timinig layer based on **LYSO:Ce crystals readout with SiPMs**.
  - thickness 3.7-2.4 mm as |η|
- Time resolution - 30 ps at the beginning (expected to decrease to 60 ps)

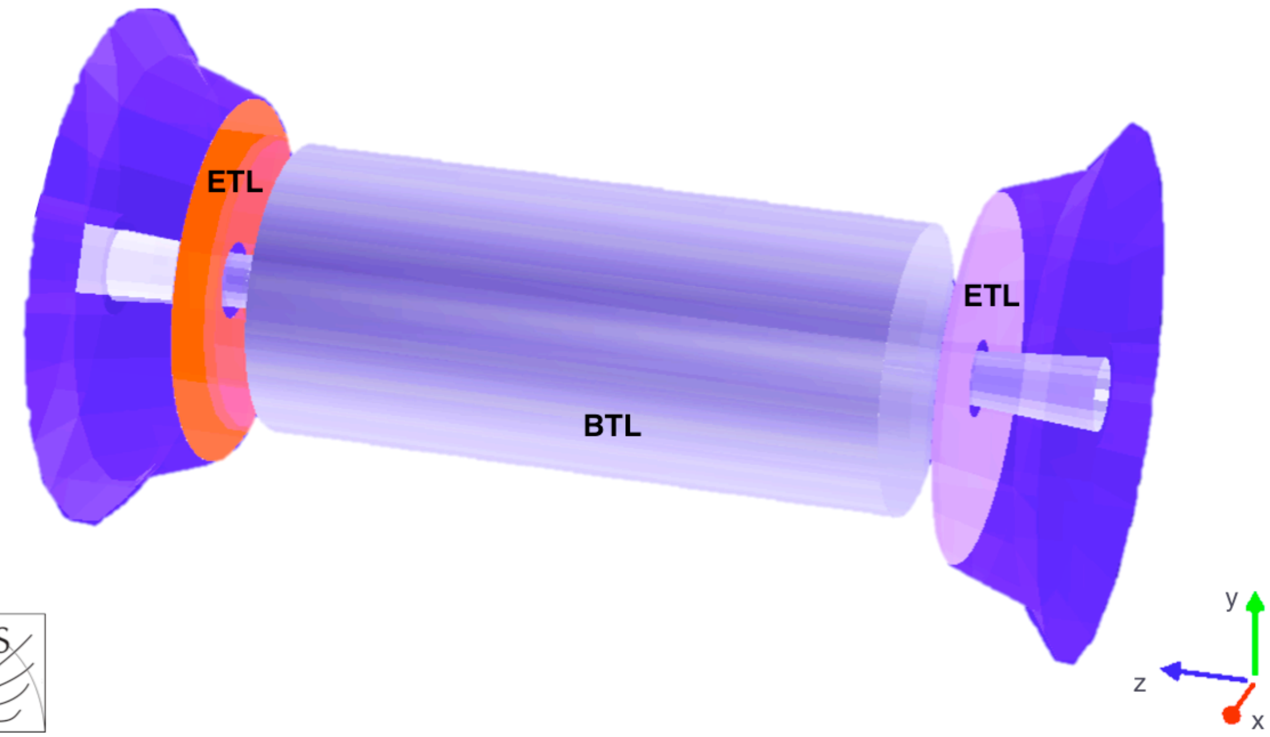
- Timing detector layers to be used for
  - timestamping the tracks
  - time of flight (PID)

BTL: LYSO bars + SiPM readout:
- TK / ECAL interface: |η| < 1.45
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: 2x10^{14} n_{eq}/cm^2



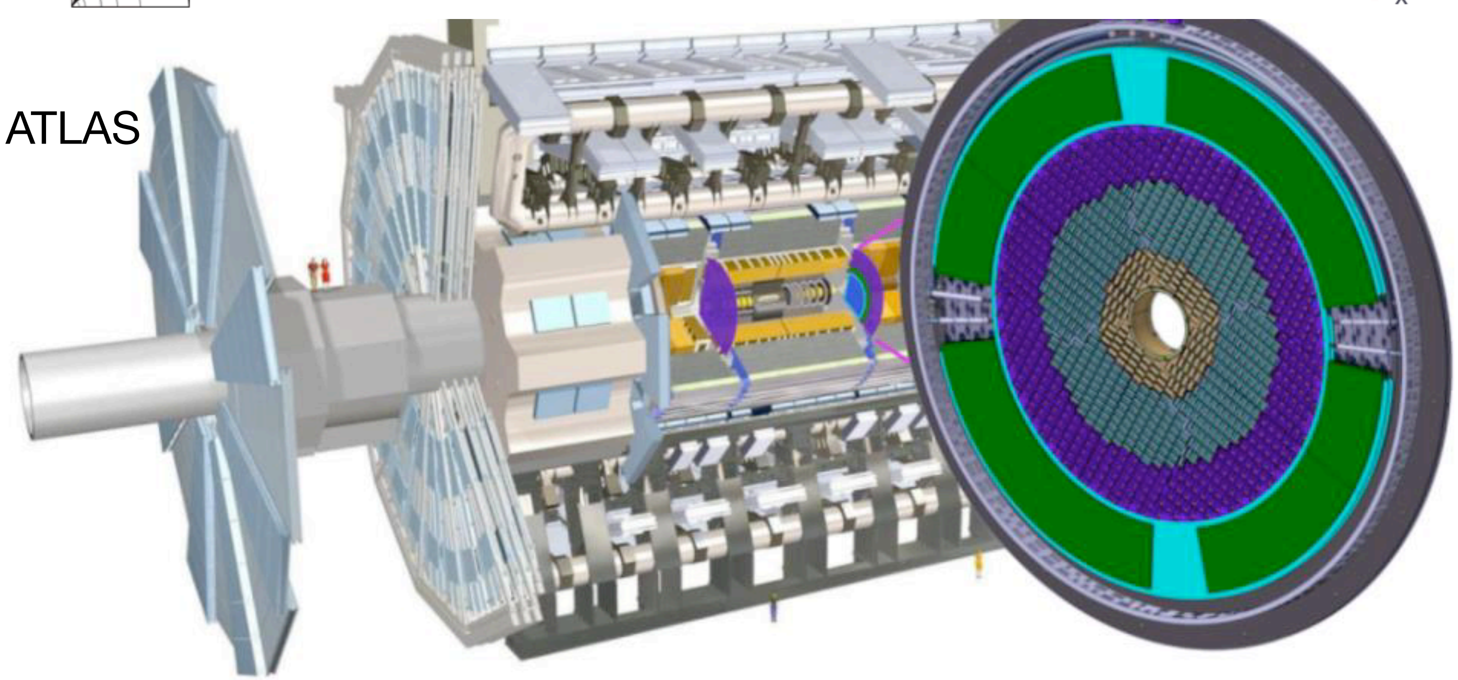
ETL: Si with internal gain (LGAD):
- On the CE nose: 1.6 < |η| < 3.0
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to 2x10^{15} n_{eq}/cm^2





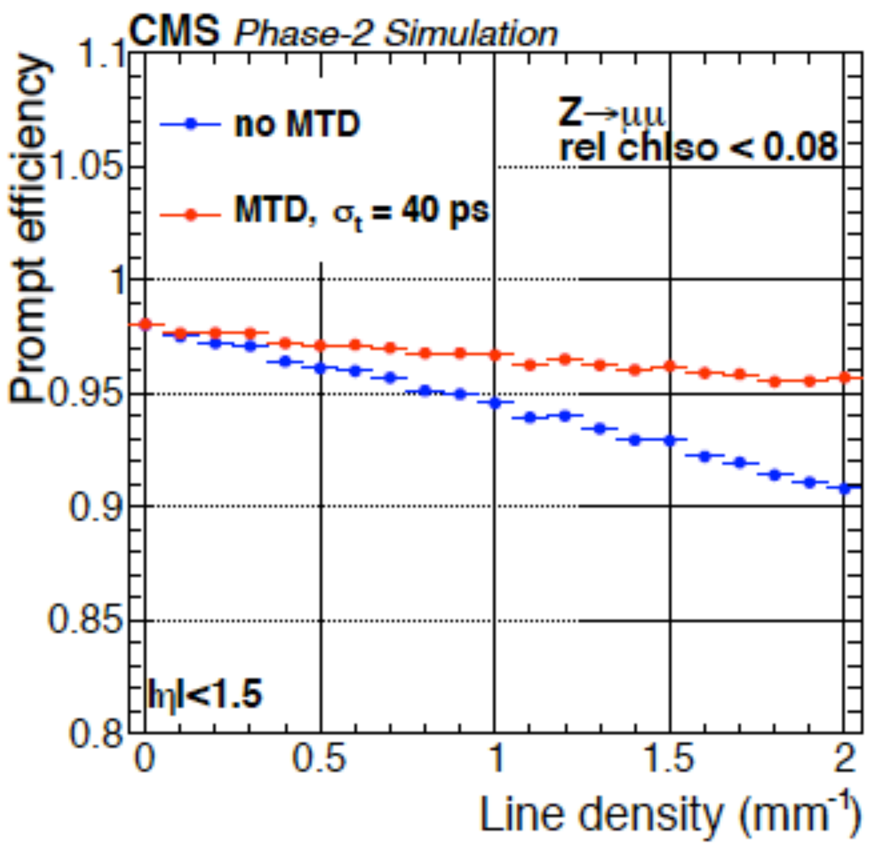
CMS

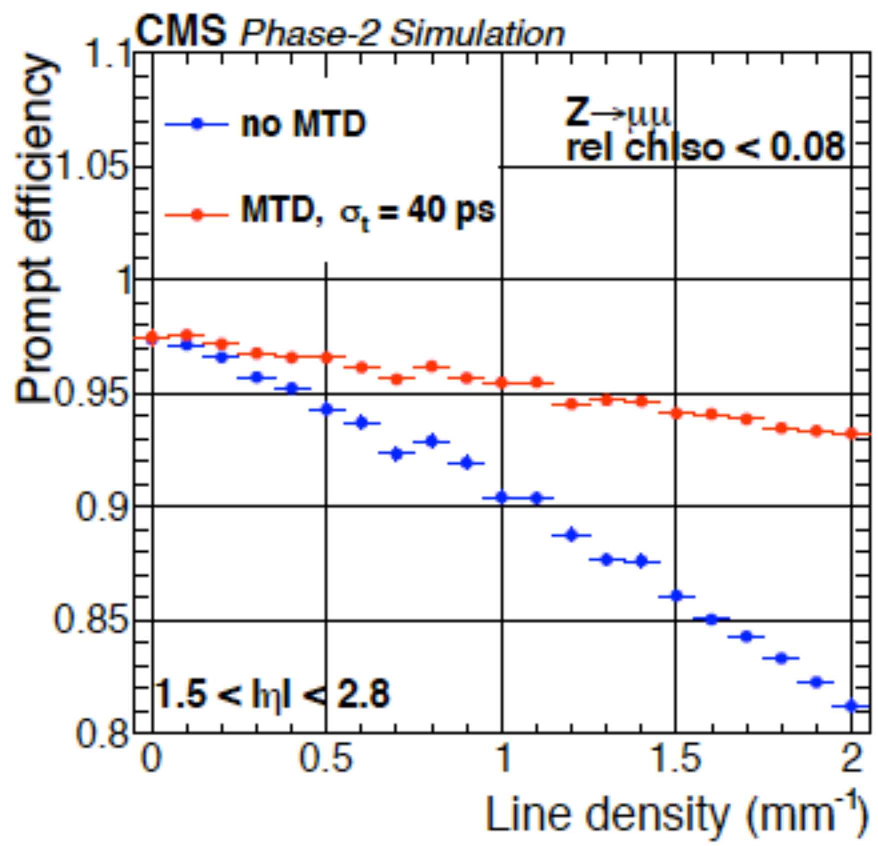
ATLAS

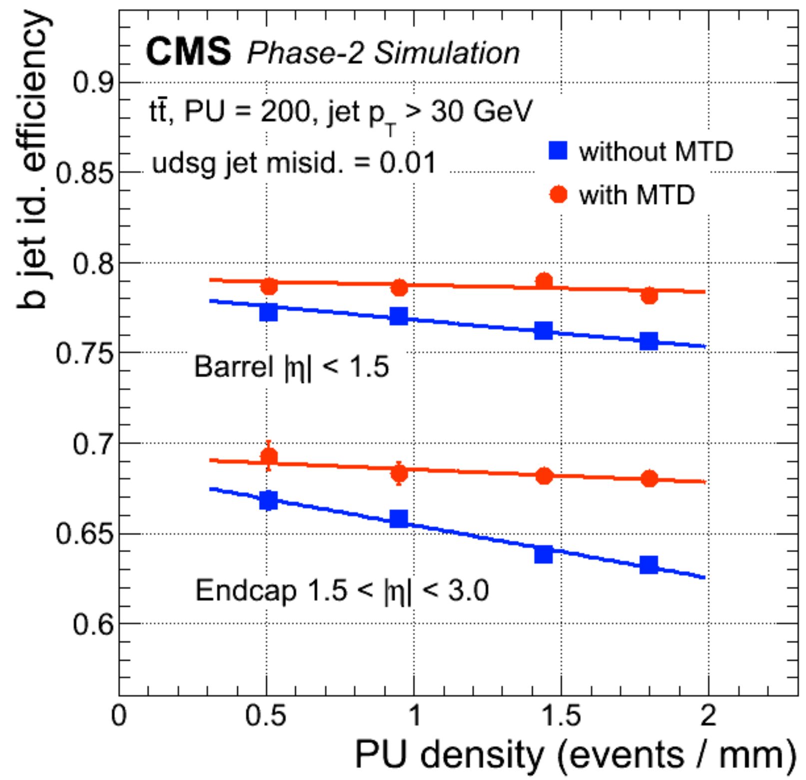


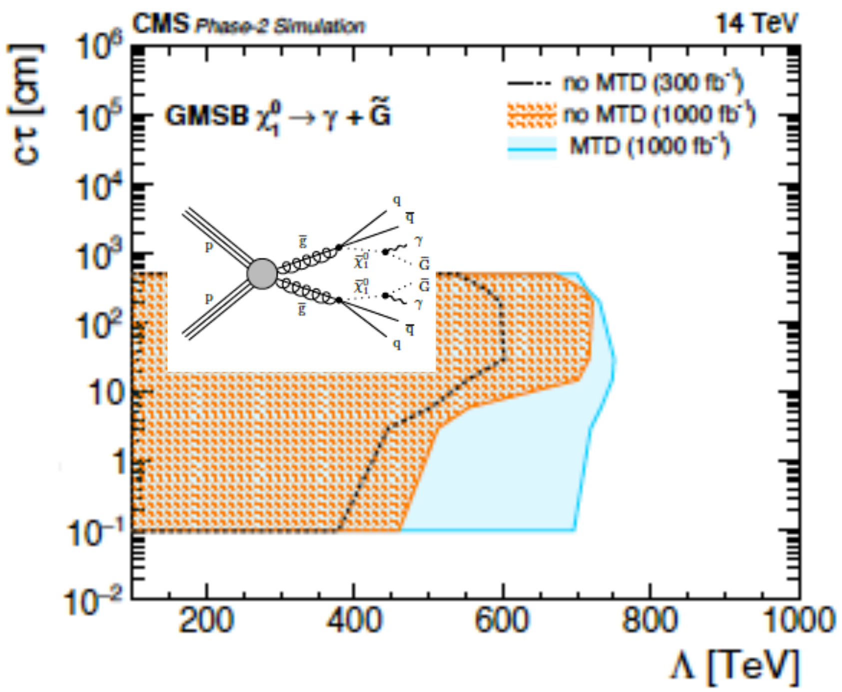
CMS MIP Timing Detectors

Pileup rejection by improving track-to-vertex association, lepton isolation, heavy flavor tagging









Signal	Physics measurement	MTD impact
$H \to \gamma\gamma$ and H→4 leptons	+15 – −25% (statistical) precision on the cross section → Improve coupling measurements	Isolation and Vertex identification
VBF→H→ $\tau\tau$	+30% (statistical) precision on cross section → Improve coupling measurements	Isolation VBF tagging, p_T^{miss}
HH	+20% gain in signal yield → Consolidate searches	Isolation b-tagging
EWK SUSY	+40% background reduction → 150 GeV increase in mass reach	MET b-tagging
Long-lived particles (LLP)	Peaking mass reconstruction → Unique discovery potential	β_{LLP} from timing of displaced vertices

Timing capabilities at LHC essentially means effective gain in luminosity

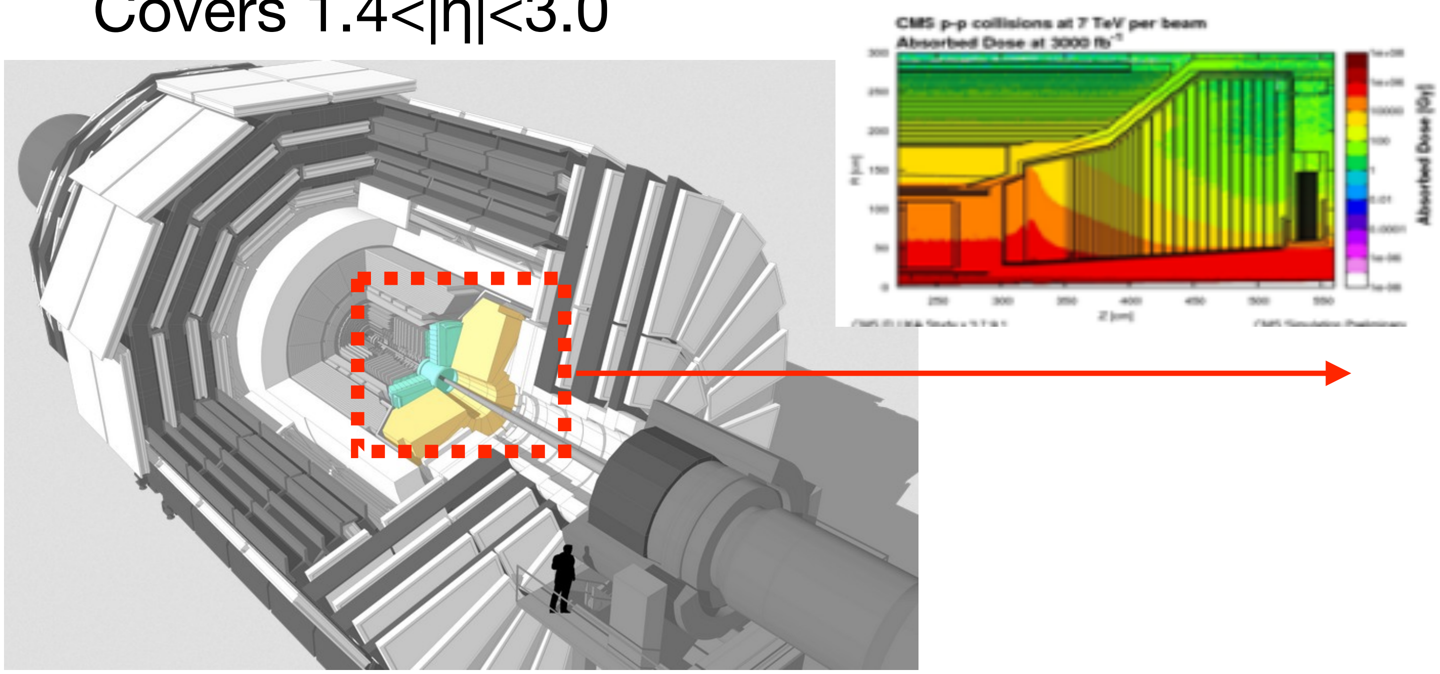
CMS High Granularity Calorimeter

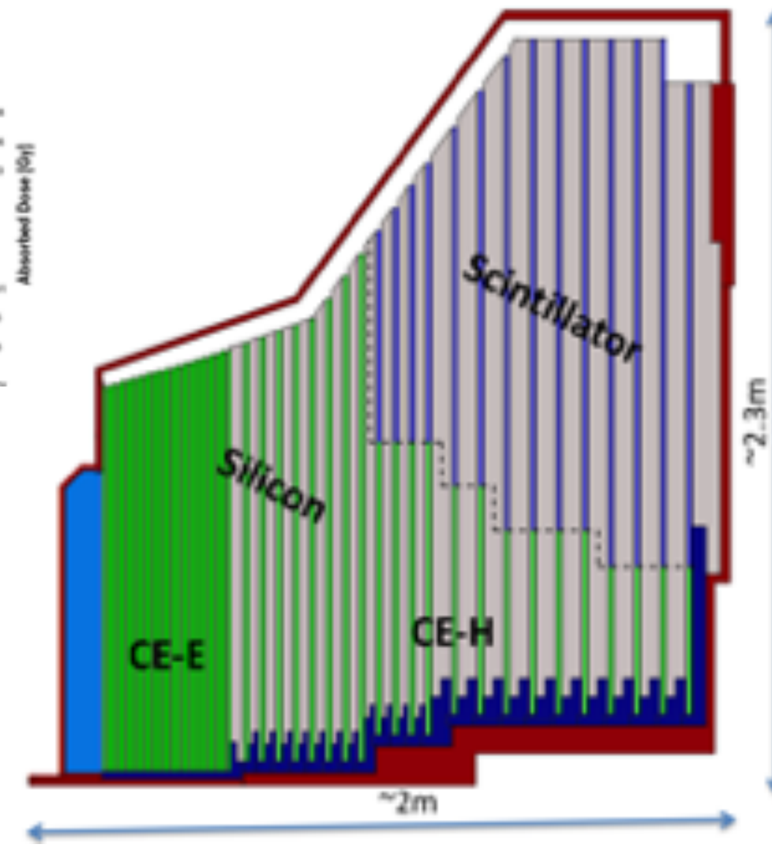
CMS Calorimeter upgrade for HL-LHC

Replace the existing endcap calorimeters with high granularity sampling calorimeters

Driven by CALICE activities

Covers $1.4<|\eta|<3.0$





Si based CE-E and high radiation regions, Scintillator tiles directly readout by SiPMs otherwise

Active Elements:

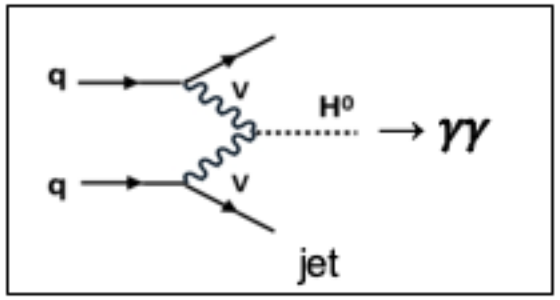
- **Electromagnetic part: CE-E**
  - Si sensors as active layers, Cu/CuW/Pb absorber
  - **28 layers, 25 X_0** and **~ 1.3 λ_{int}**
- **Hadronic part: CE-H**
  - Si & scintillator as active layers, steel absorbers
  - **22 layers, ~ 8.5 λ_{int}**

- High granularity detectors !
  - Si cells of 1.1 or 0.5 cm^2
  - 6M Si and 240k Sci readout channels
  - ~22000 Si modules
  - ~600 m^2 of silicon sensors
  - ~500 m^2 of scintillators
  - Full system maintained at -30 deg C

Capable of 5D calorimetry → ideal for particle flow reconstruction techniques.

HGCAL - Precision Timing, PU mitigation

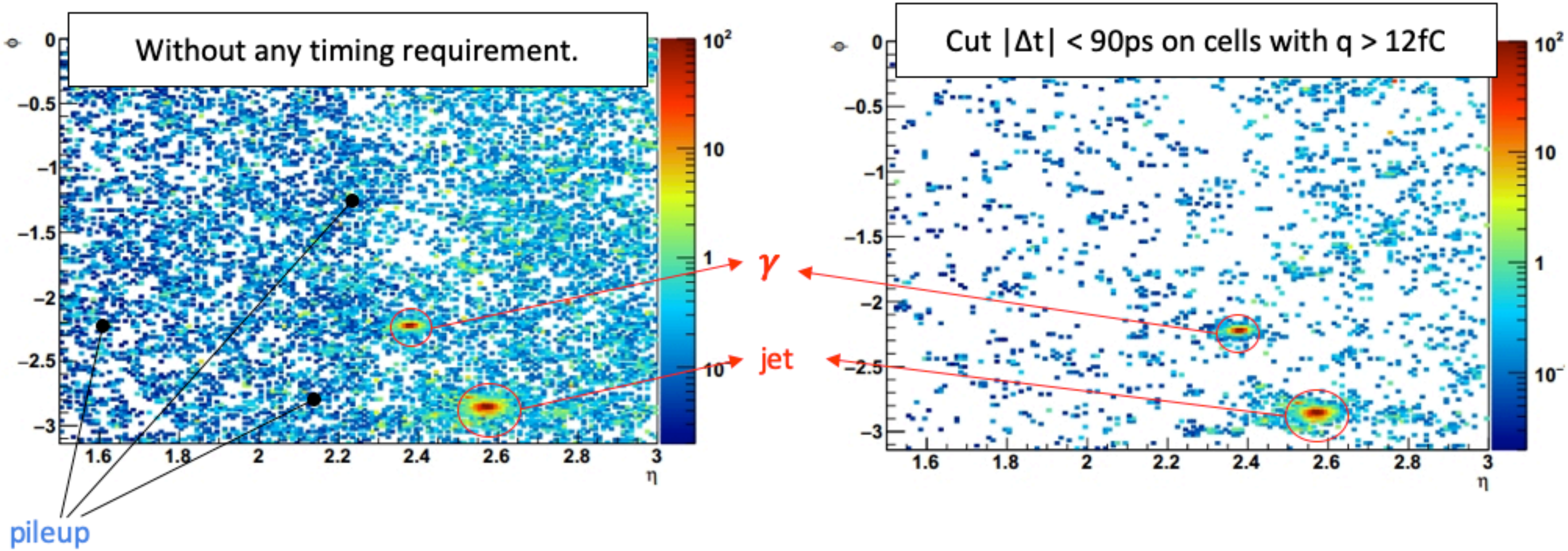
Improved particle ID, energy resolution (narrow and merged jets) and pile-up rejection



PU=200 event

➢A VBF ($H \to \gamma\gamma$) event with one γ and VBF jet in the same quadrant.

➢Image projected onto the front face of HGCAL.

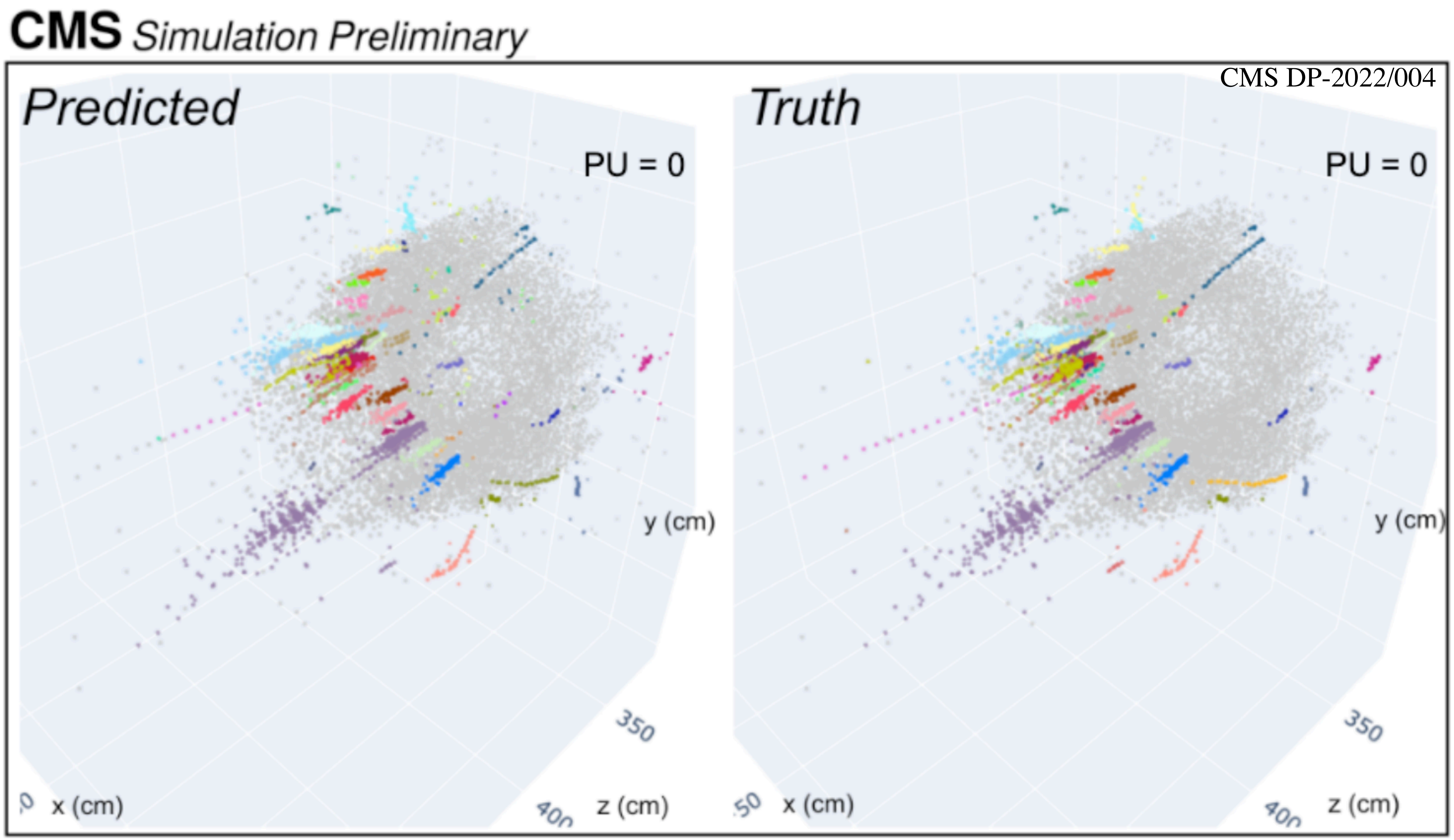


➢ Significant reduction in pileup after requiring timing cut.

➢ With HGCAL timing info alone (not counting MTD input yet)

HGCAL - An Imaging Detector

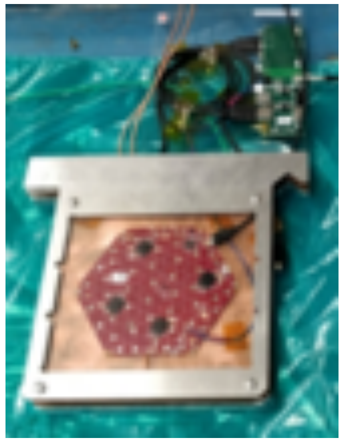
A Graphical Neural Network (GNN) based algorithm is trained to predict clusters of hits originating from the same incident particle (two τ leptons) by labelling the hits with the same cluster index.



Beam test setup in October 2018

- Prototype HGCAL detector setup comprised of Si-based electromagnetic (CE-E) and hadronic (CE-H) sections **followed by scintillator tile-based CALICE AHCAL**

A sampling layer of CE-E

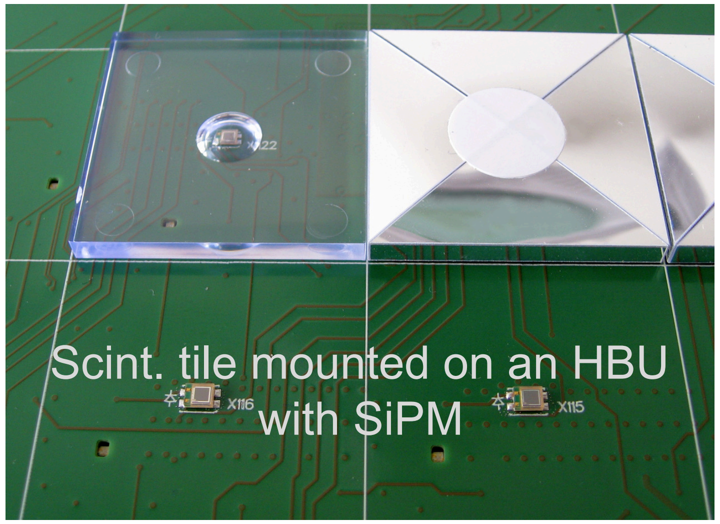


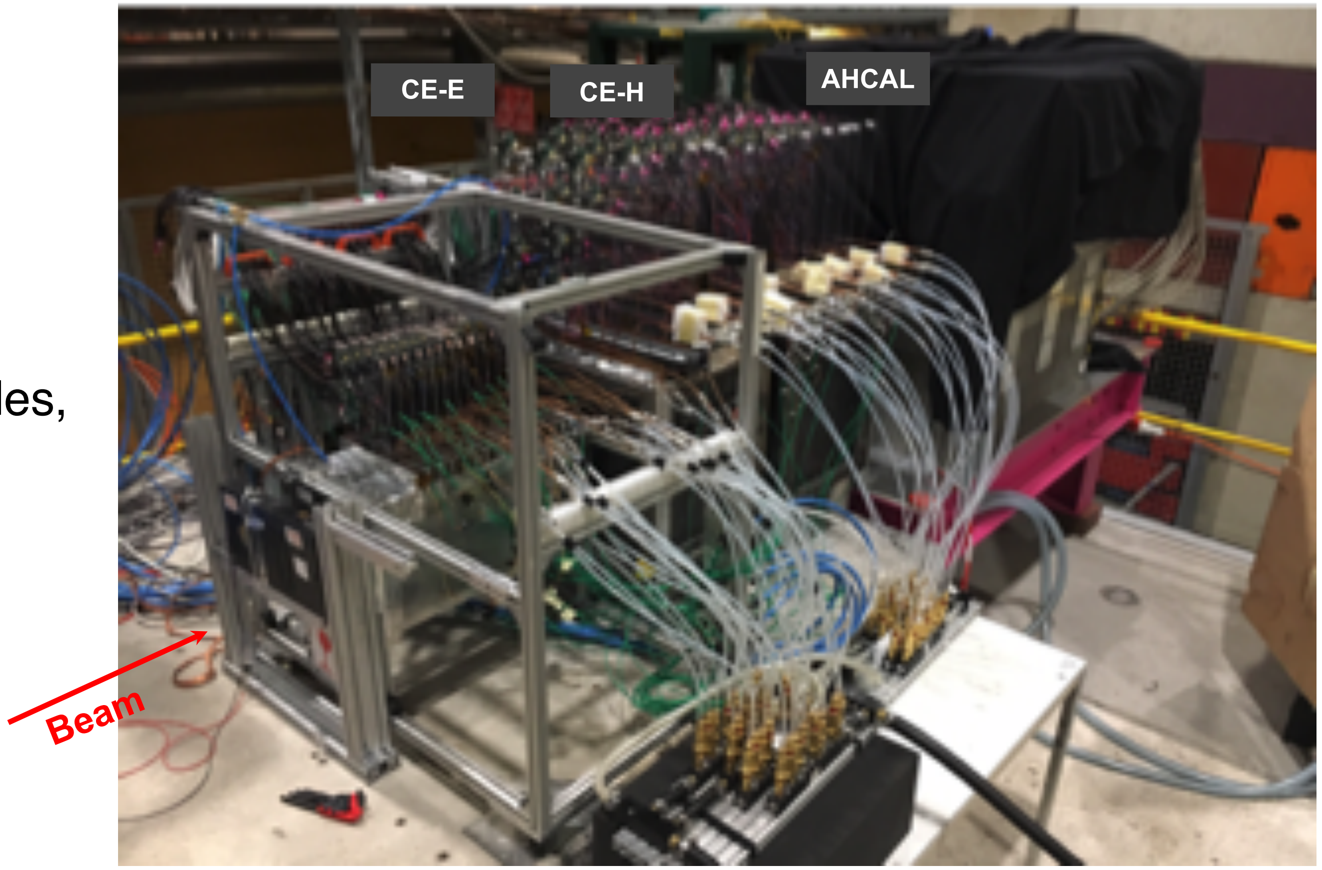
EM section: CE-E prototype
- Hanging file structure
- 28 sampling layer
- 14 double sided mini-cassettes
- Pb/Cu/CuW absorber
- ~ 28 X_0, 1.4 λ_{int}

Had section: CE-H prototype
- Hanging file structure
- 12 sampling layers
- Modules arranged in daisy structure
- Steel absorber
- ~ 3.4 λ_{int}

Had section: CALICE AHCAL prototype
- Scintillator-on-SiPM
- 39 sampling layers
- Steel absorber
- ~ 4.4 λ_{int}

CALICE AHCAL

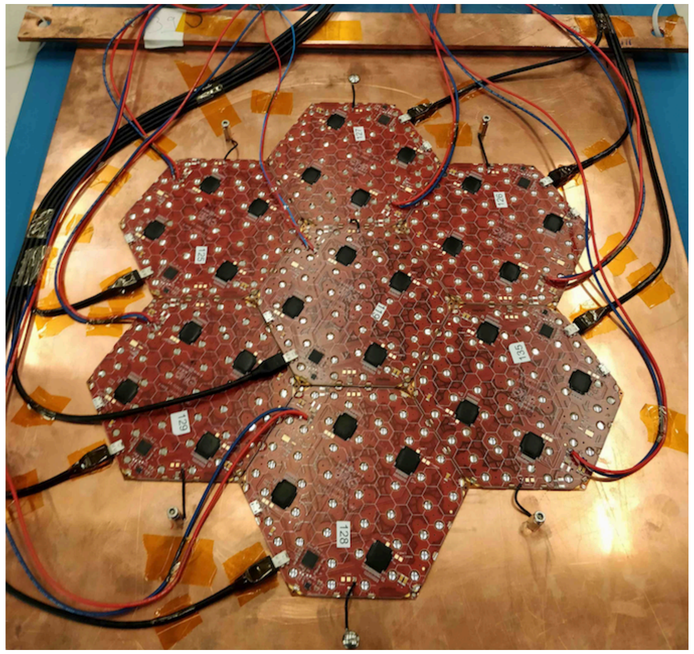




Si: 94 sensor modules, 12k channels

Scint AHCAL 22k channels

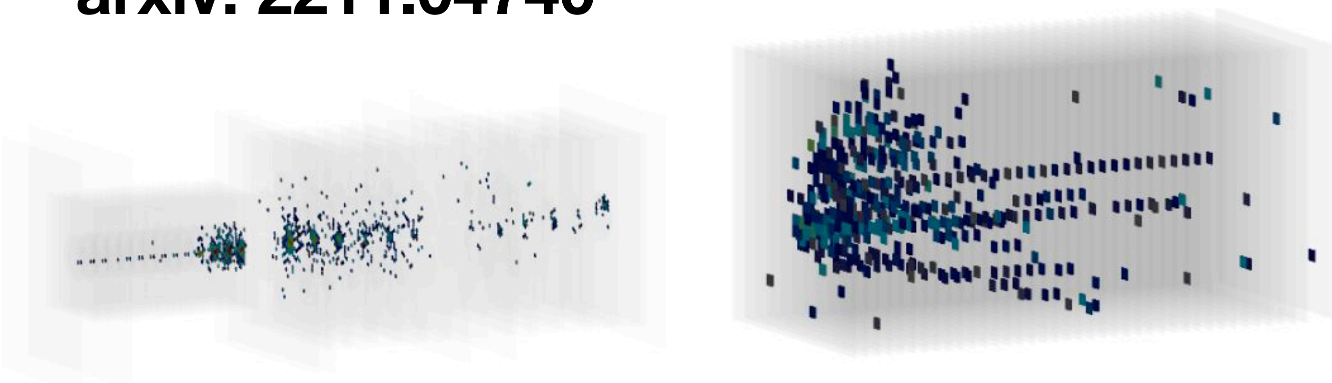
A sampling layer of CE-H

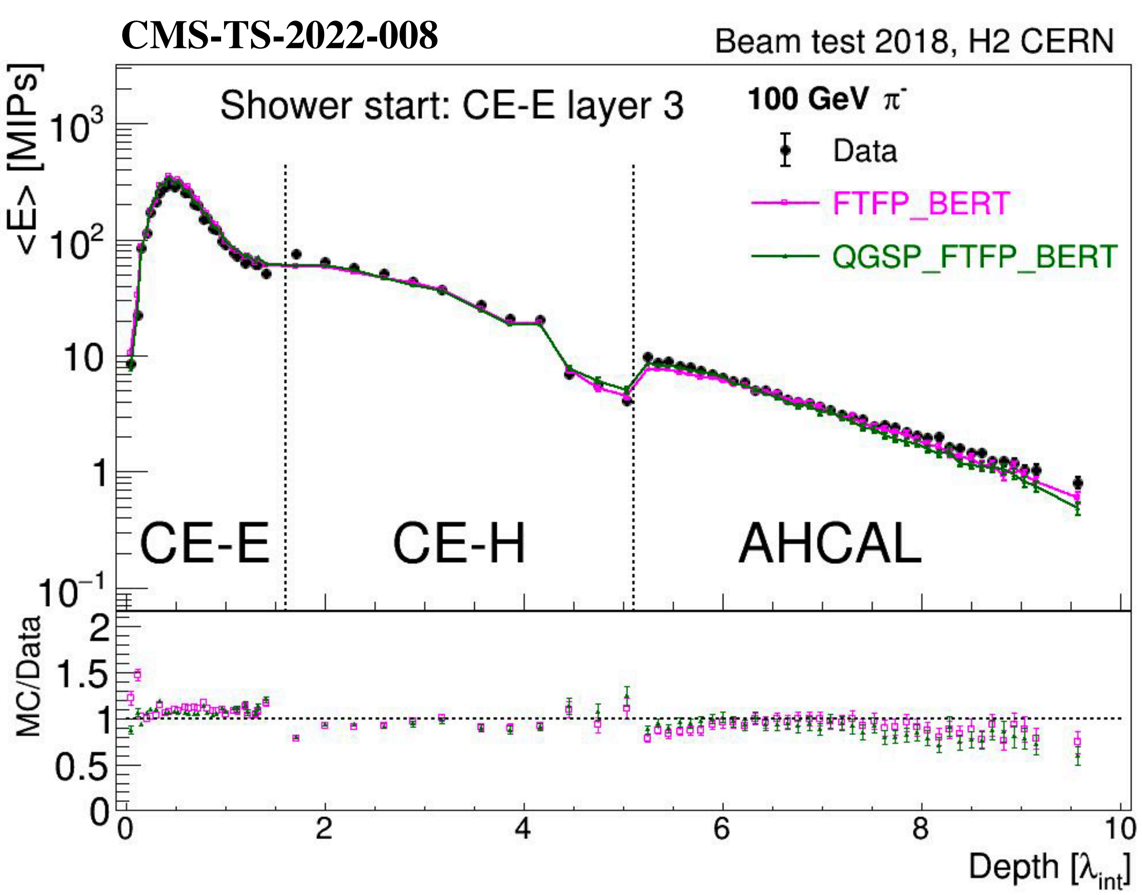


- Exposed to e^+ and π^- beams of energies ranging from 20 – 300 GeV.

HGCAL - Beam Test Results for Hadrons

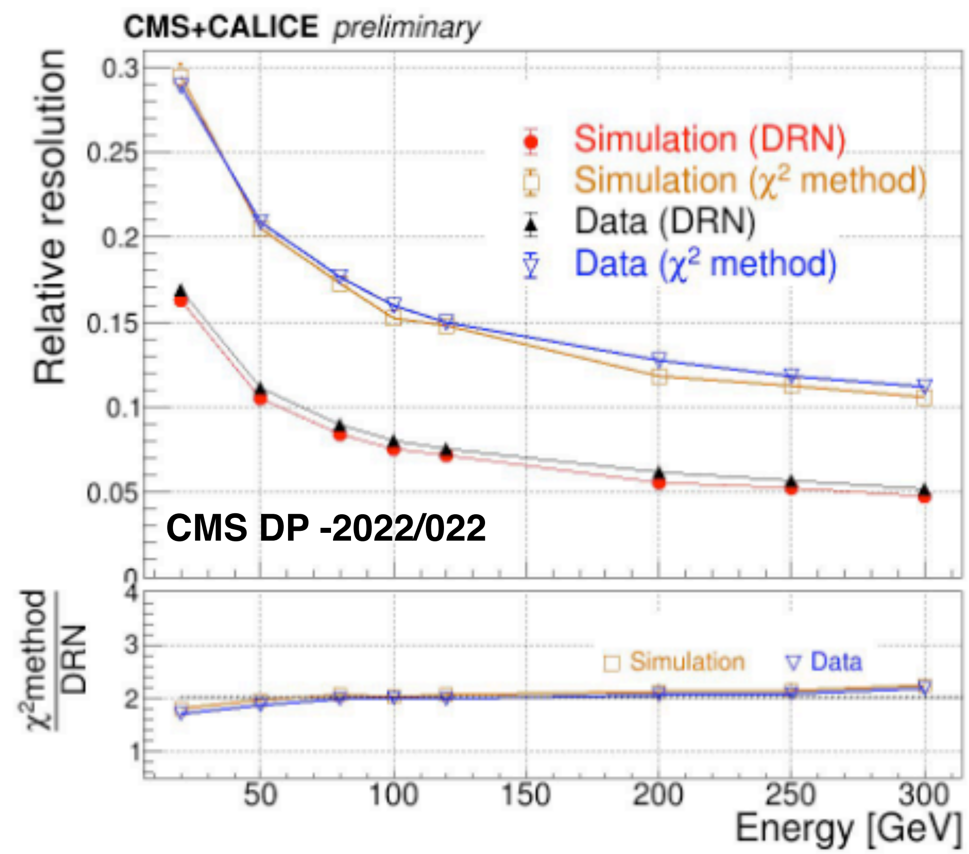
arxiv: 2211.04740

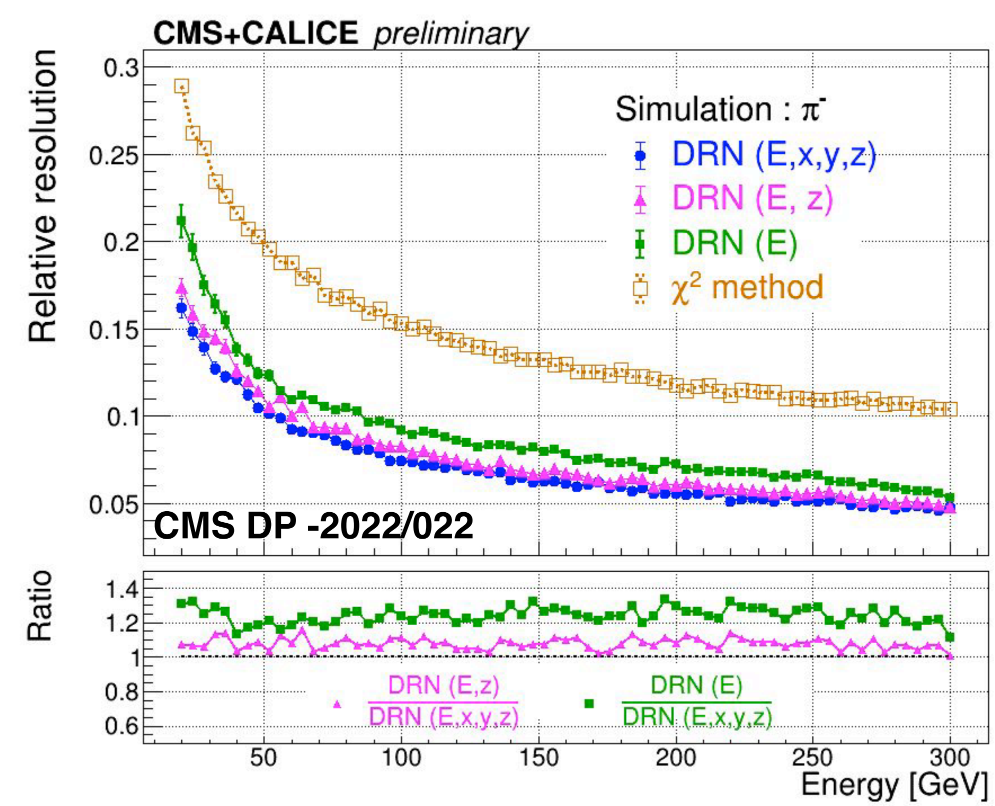




For more details about instrumentation, DAQ, calibration, and simulation, please refer to 2021 JINST 16 T04001, 2021 JINST 16 T04002 and 2022 JINST 17 P05022.

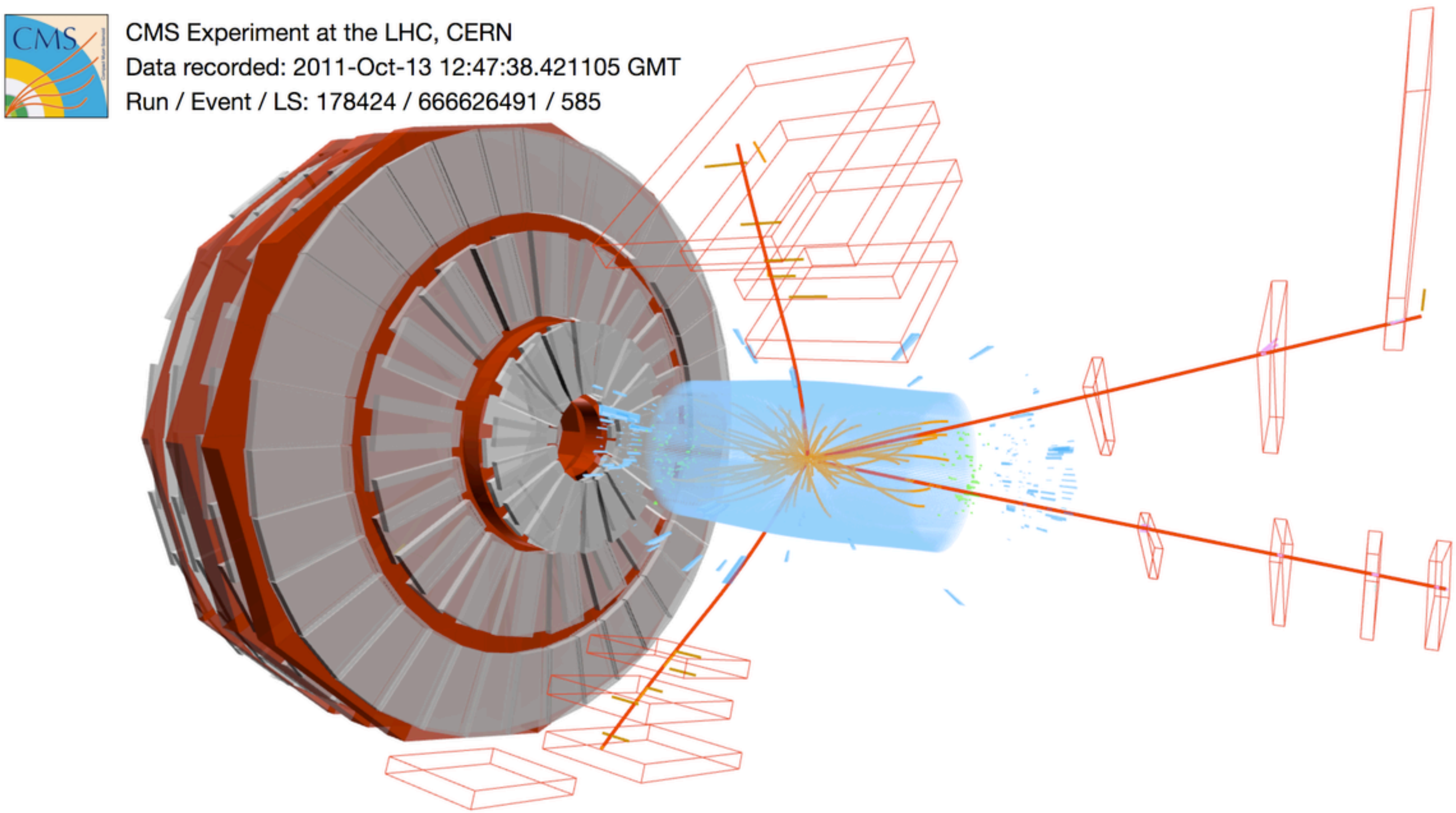
Exploring GNNs for hadron energy regression



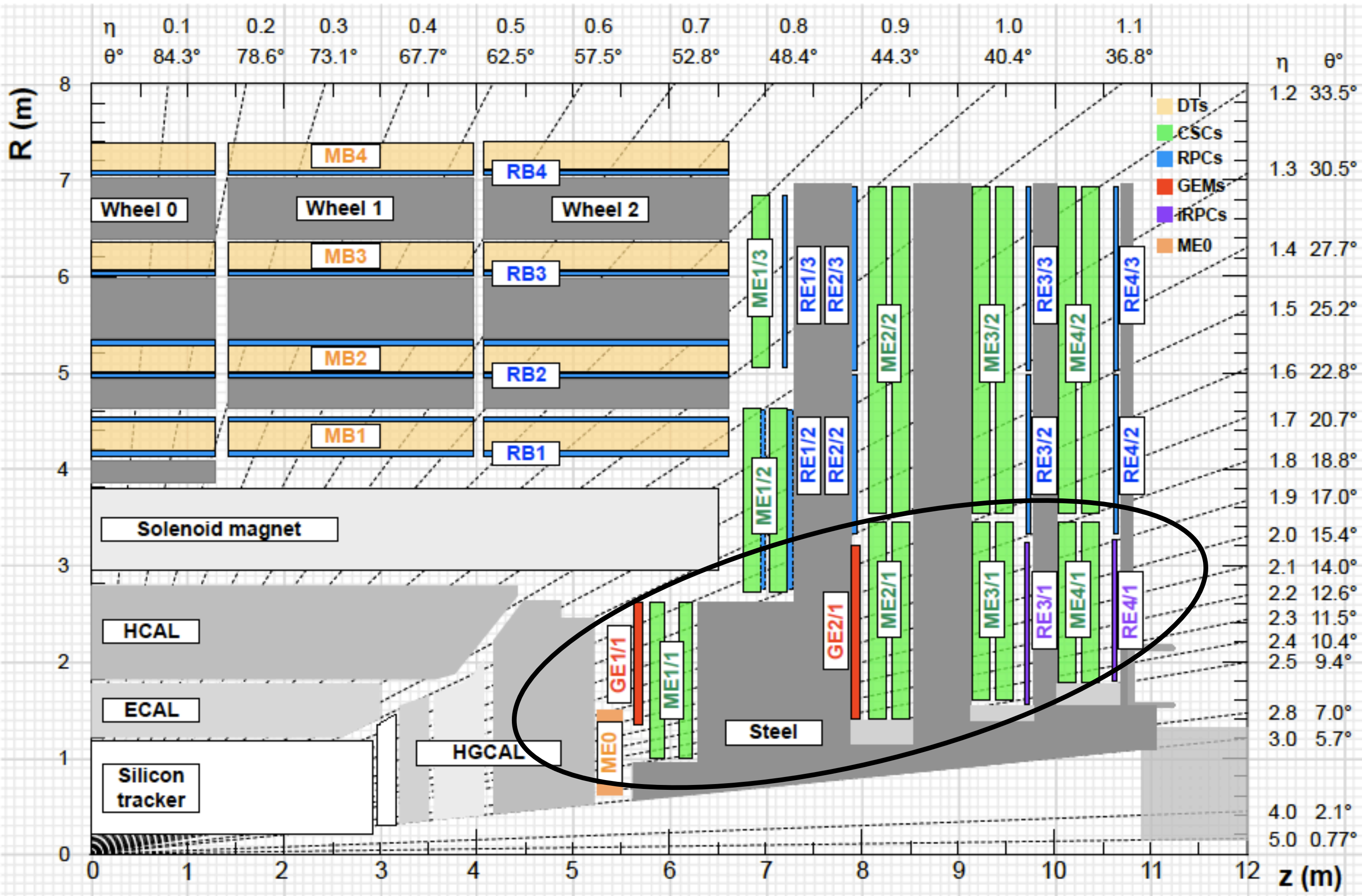


Upgrade of Muon Detectors

Precision measurements crucially depend on how well we can measure muons.



Upgrade of Muon Detectors



CMS muon system comprises Drift Tube chambers (DT), Cathode Strip Chambers (CSC) and Resistive Plate Chambers (RPC).

New stations:

- GEM: **GE1/1**, GE2/1,
- iRPC: RE3/1, RE4/1: $1.6 \leq \eta \leq 2.4$

GEM: ME0 extended coverage $2.0 \leq \eta \leq 2.8$

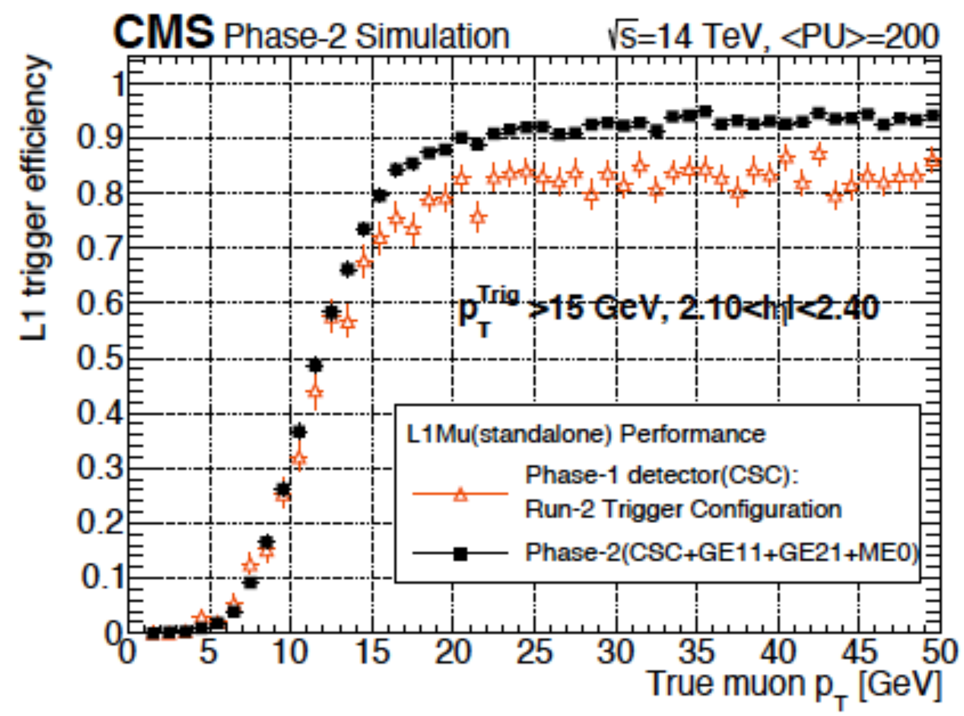
The current muon detectors are expected to withstand the HL-LHC radiation levels.

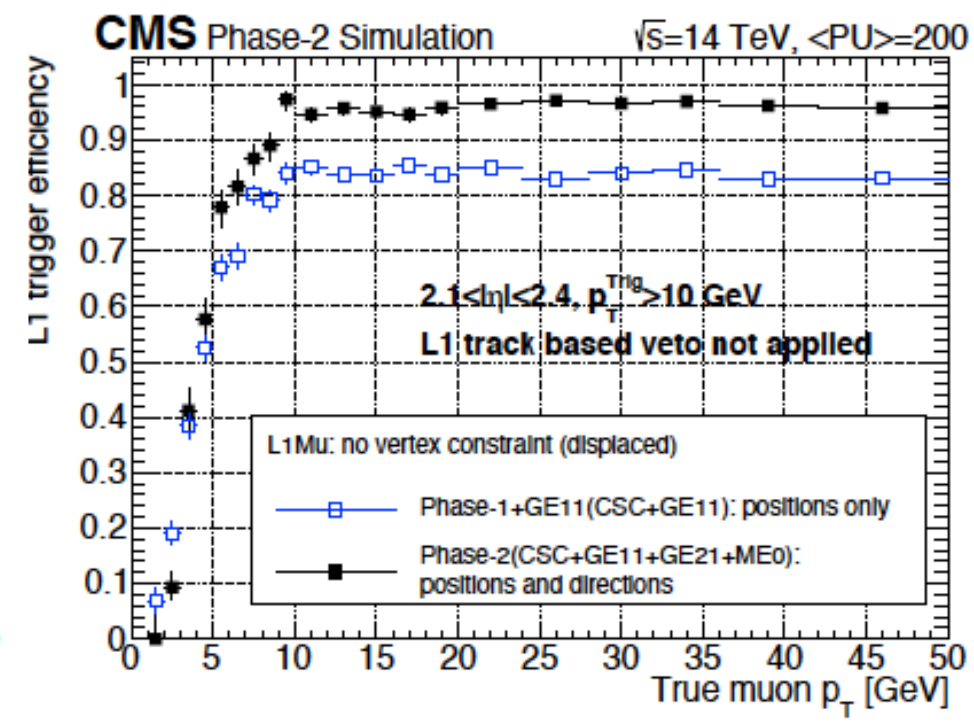
The upgrades focus on :

- Upgrading/replacing the electronics of the existing DTs, CSCs and RPCs to ensure longevity and to improve the trigger performance.
- Extending the coverage of the muon system to $|\eta| \simeq 3$ in order to benefit from the extension of the tracker and HGCAL as well as new features of the L1-trigger

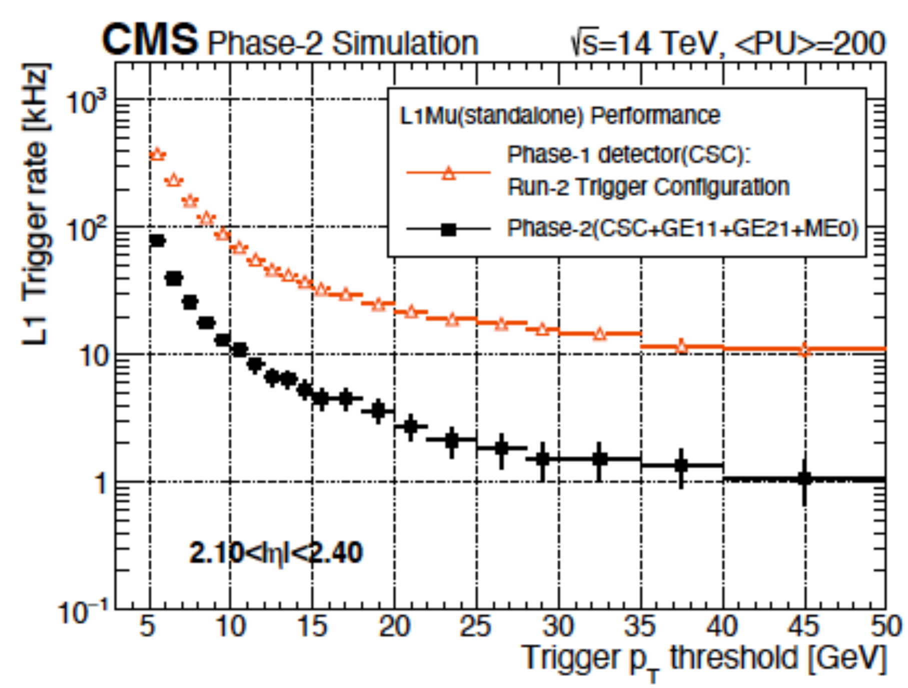
Upgrade of Muon Detectors

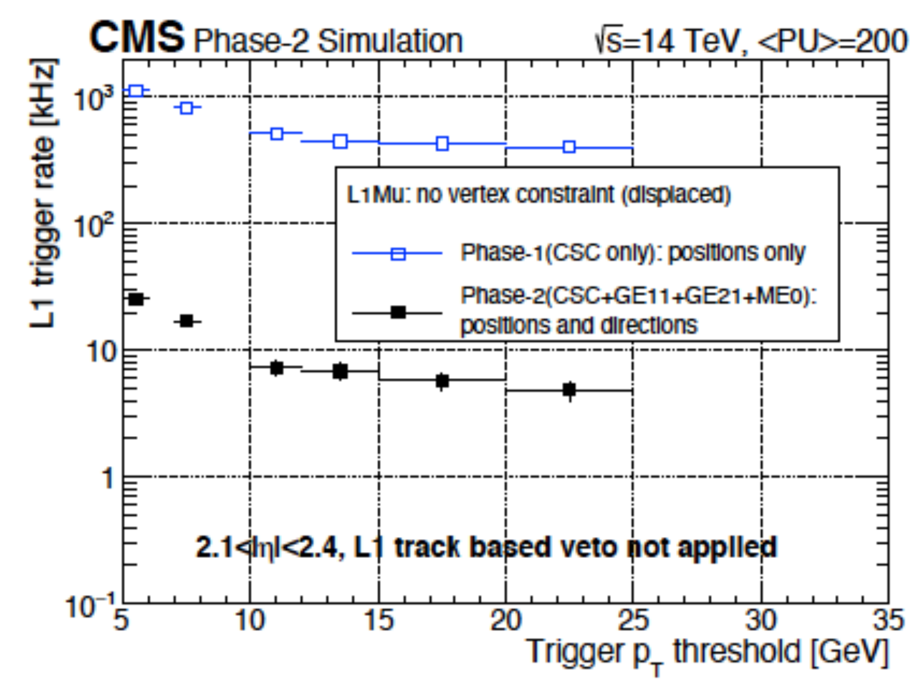
Adding GEM detectors: Gain in trigger efficiency for muons with pT>15 GeV in the endcap forward region 2.1<|η|< 2.4





Rduction in trigger rates by a factor of 5–10, which will allow CMS to maintain a single muon trigger with a pT threshold as low as 15 GeV

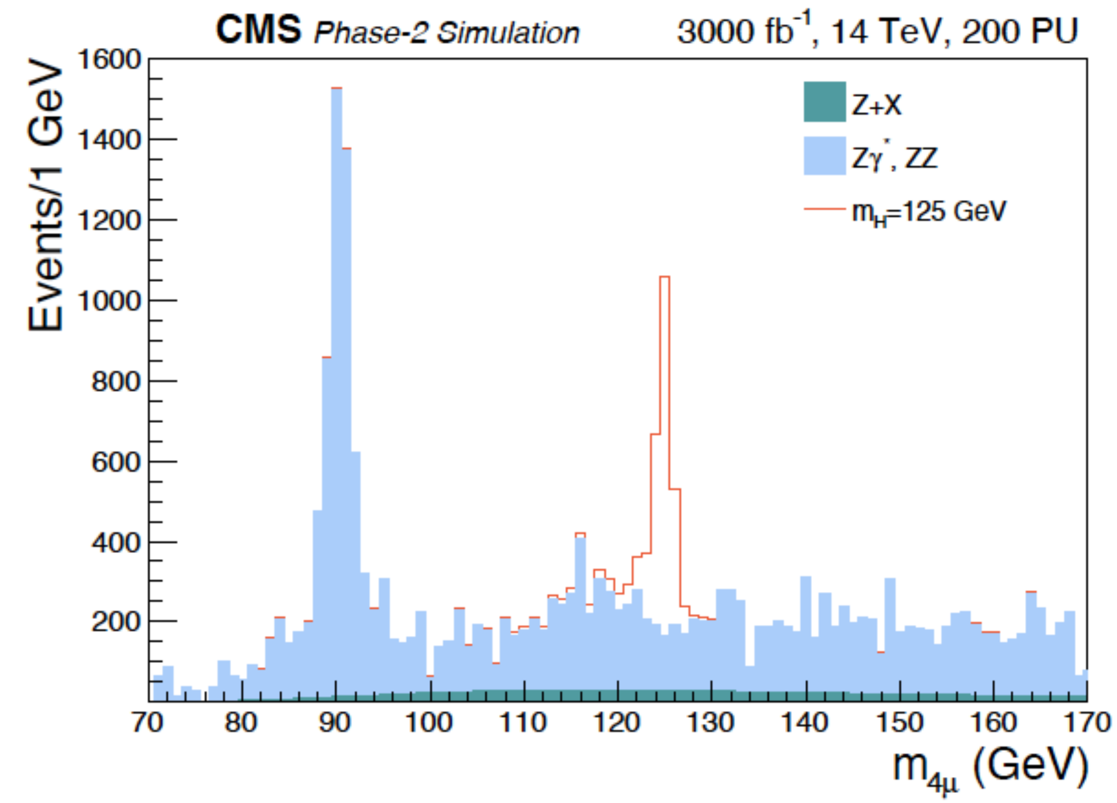




Physics gains of extended Muon Detectors

The ultimate measurement of Higgs mass is expected to be obtained from the H →ZZ →4μ channel at HL-LHC

- Significantly benefits from better efficiency.
- Forward extended muon systems allow larger detector & low pT acceptance
- The upgraded muon system increases the signal acceptance by 17%.



analysis topic	parameter of interest (POI)	sensitivity gain in POI
$H \to ZZ \to 4\mu$	signal strength	7 %
Double-parton scattering	slope of $d\sigma/d(\eta_1\eta_2)$	factor 1.5
$\tau \to 3\mu$	$B(\tau \to 3\mu)$	17 %
Drell-Yan FB asymmetry	$\sin^2\theta^{lept}_{eff}$	factor 1.3
BSM same-sign dilepton search	BSM cross section	15 %

IISER PUNE

Summary

The LHC experiments are well on the way to update Detectors and Triggers/DAQ to cope up with the challenges of HL-LHC.

- Radiation hardness & precision timing capabilities
- Fast readout electronics & triggers to handle large data volumes.

For FCC-hh, radiation hardness & pileup are default challenges.
Good coverage of forward detector regions will be important:

- Precision muons up to $|\eta|\sim4$
- Calorimetry up to $|\eta|\sim6$

Close cross-collaboration with ongoing activities wherever possible/applicable.

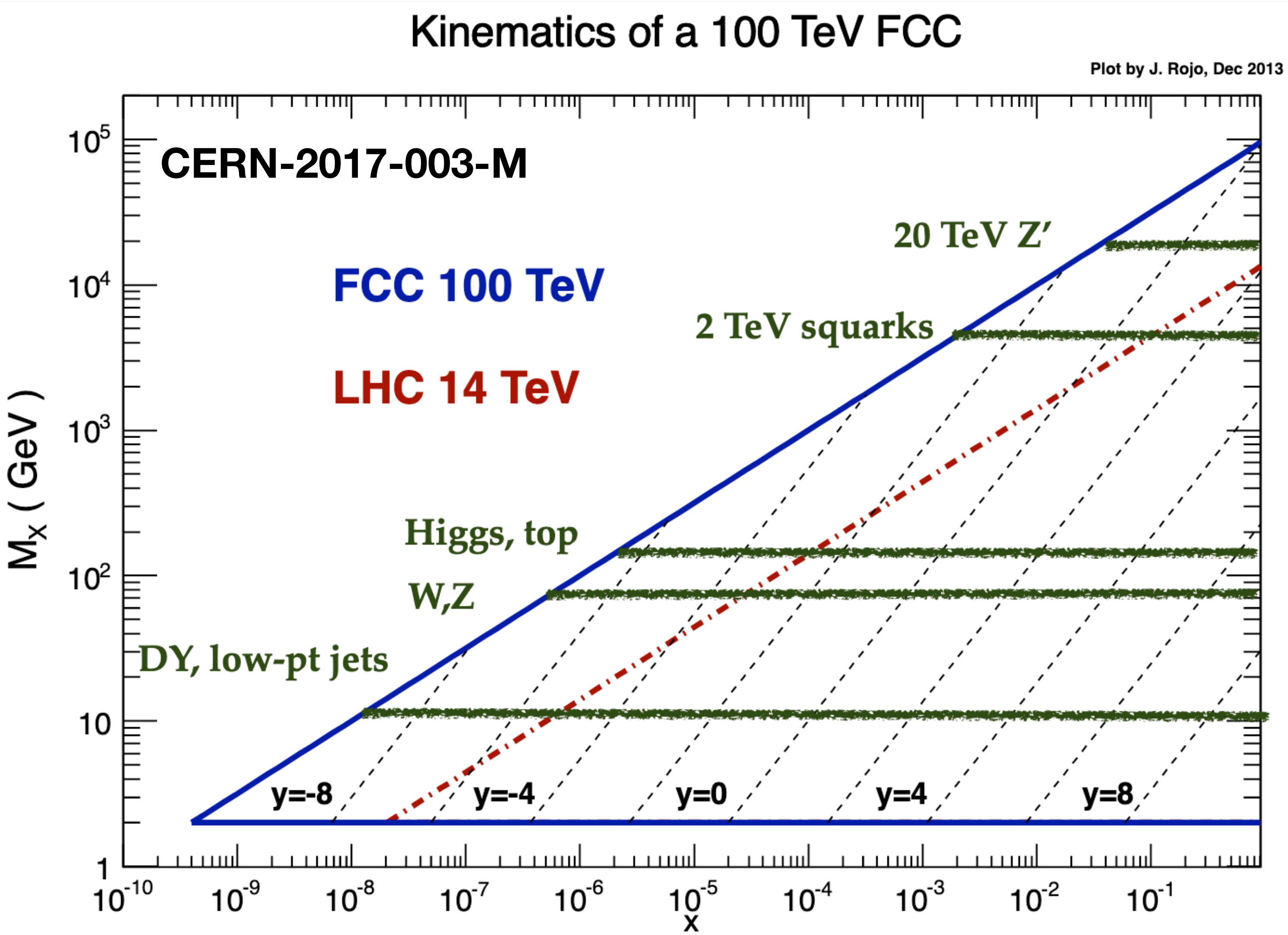
***Detectors for lepton colliders by Junping Tian (Tokyo U)**

LHC in near future

To increase the discovery potential, the LHC will be upgraded to run at 10 times its current potential (starting 2027/28) : High Luminosity LHC.

Towards Detectors for FCC-hh

Towards Detectors for FCC-hh



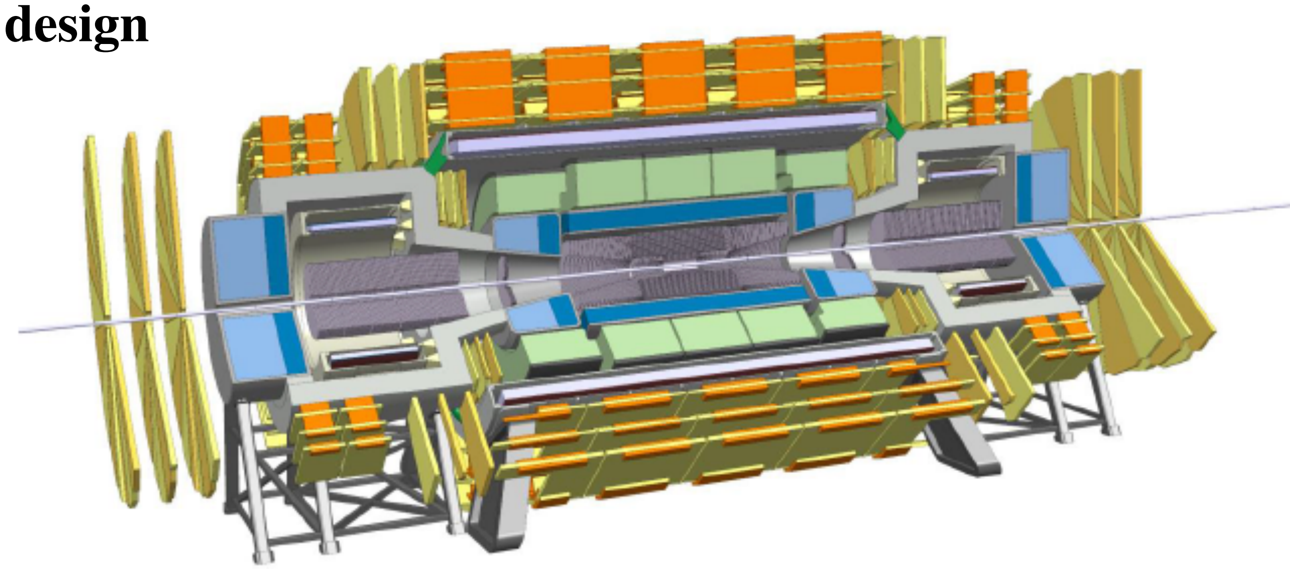
Default challenge: Pileup & Radiation Exposure

More forward physics: relevant for EWK too.

Good coverage of forward detector regions and reliable PDFs are the key for FCC detector designs:

- Precision muons up to |η|~4
- Calorimetry up to |η|~6

A potential design



- 4T 10m solenoid
- Forward solenoids
- Silicon tracker
- Barrel ECAL Lar
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr

***Detectors for lepton colliders by Junping Tian (Tokyo U)**