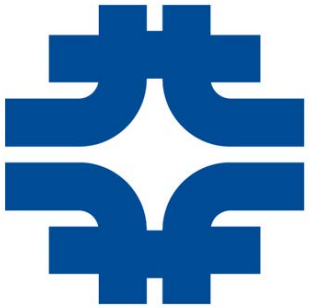


ATLAS & CMS Detector Upgrade for High-Luminosity LHC

+ Prospects for Flavor Physics

Yangyang Cheng

HL/HE-LHC Workshop

April 5, 2018

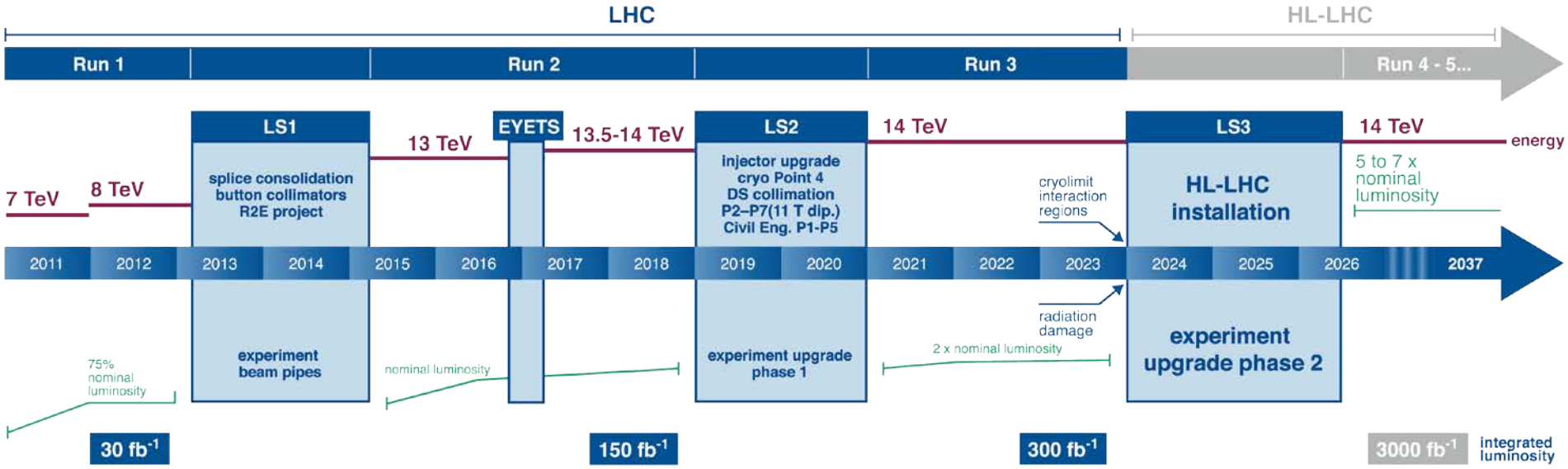
Prospects for Flavor Physics@HL-LHC

Flavor physics in a nutshell (c/o V. Vagnoni)

- Precision measurements and probes of rare decays e.g. $B^0_{(s)} \rightarrow \mu\mu$
- Flavor anomalies with hints of new physics e.g. $b \rightarrow s l^+ l^-$
- Spectroscopy

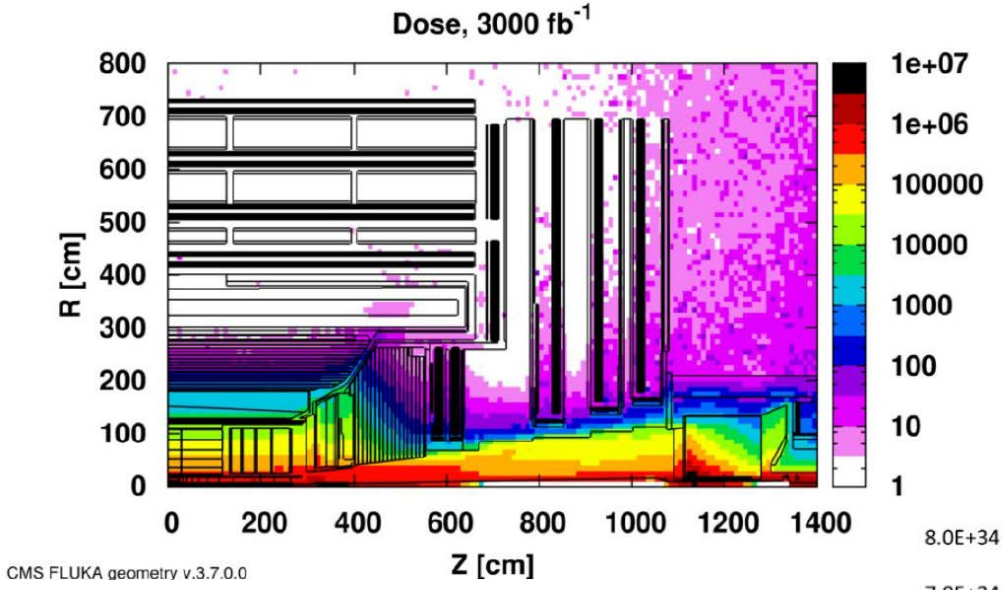
Prospects at HL-LHC:

- More data
- Enhanced capabilities: e.g. tracking, track trigger, precision timing, …



Challenges from HL-LHC

Radiation Dose

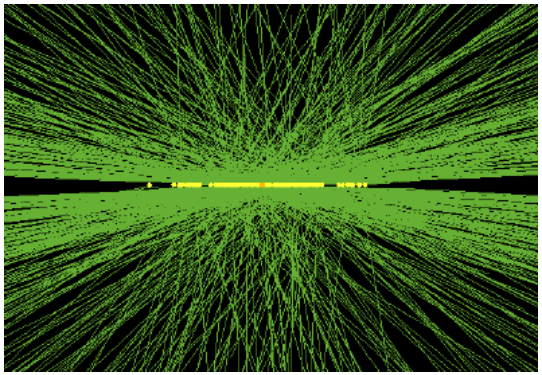


Detector elements and electronics exposed to high radiation dose
→ limits equipment lifetime & degrades signal

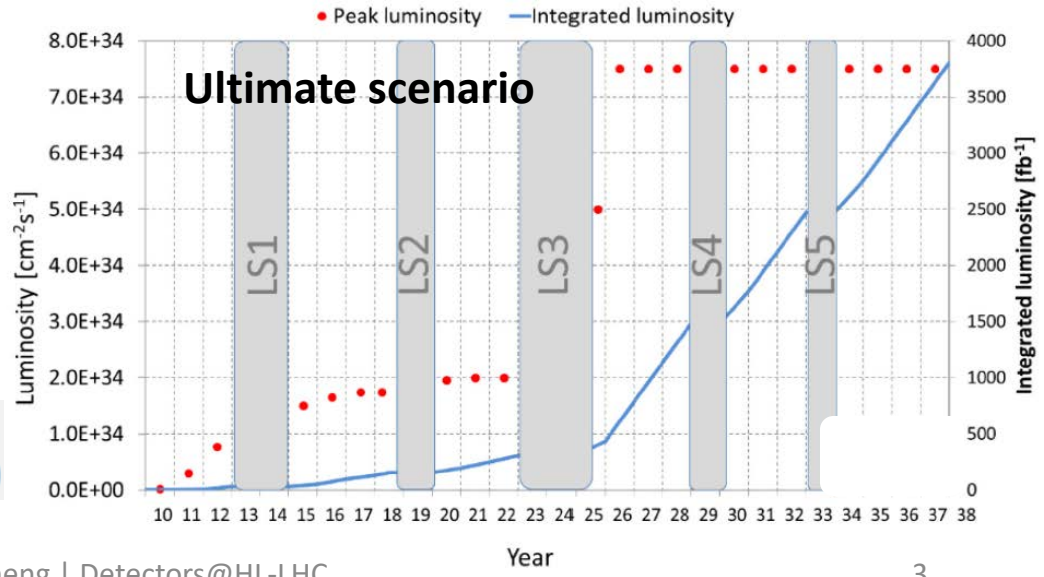
7. 5 x 10^{34} Hz/cm^2 ,
Pile-up <μ> = 200

Pile-up

140 - 200 additional pp collisions on top of process of interest



Display of a 140 PU event



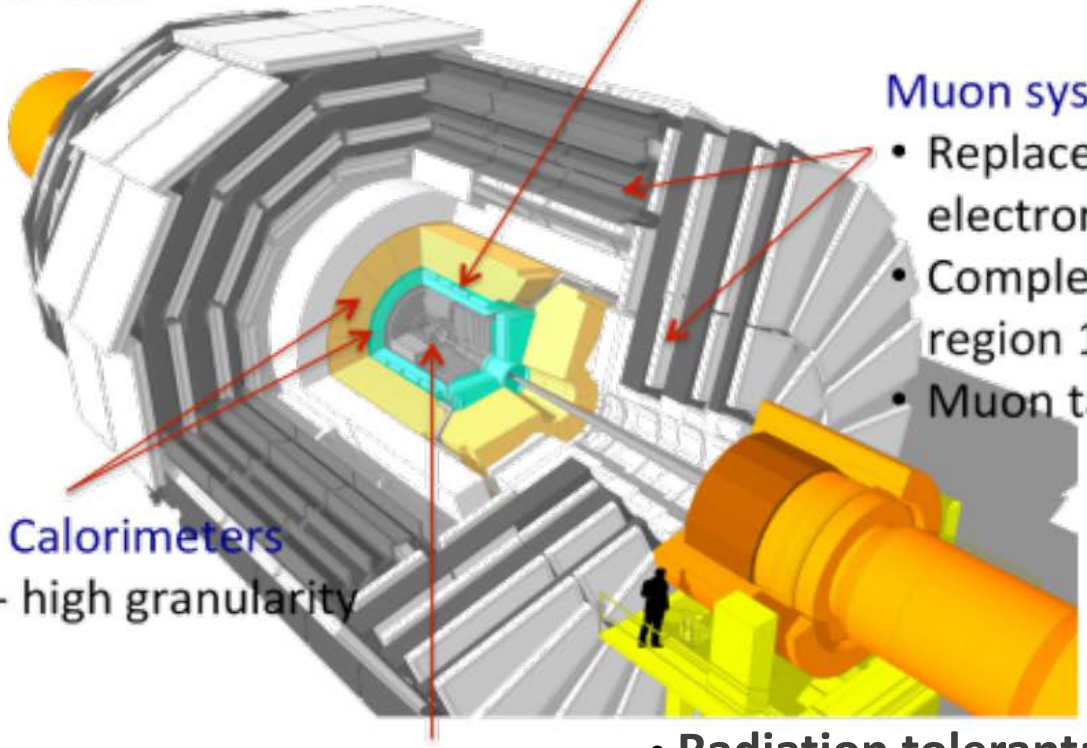
HL-LHC Upgrade: Objectives

- Replace components:
  - parts too damaged by the time of HL-LHC
  - parts that will not survive HL-LHC environment
- Extend coverage:
  - tracker extension, muon system extension etc.
- Improve function:
  - higher resolution tracker&endcap calo; L1 tracking etc.
- New detector(s):
  - Fast timing detectors
- Increase bandwith:
  - trigger & DAQ

HL-LHC Upgrade: CMS Overview

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

Barrel EM calorimeter
- Replace FE/BE electronics
- Lower operating temperature (8◦)



Muon systems
- Replace DT & CSC FE/BE electronics
- Complete RPC coverage in region $1.5 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$

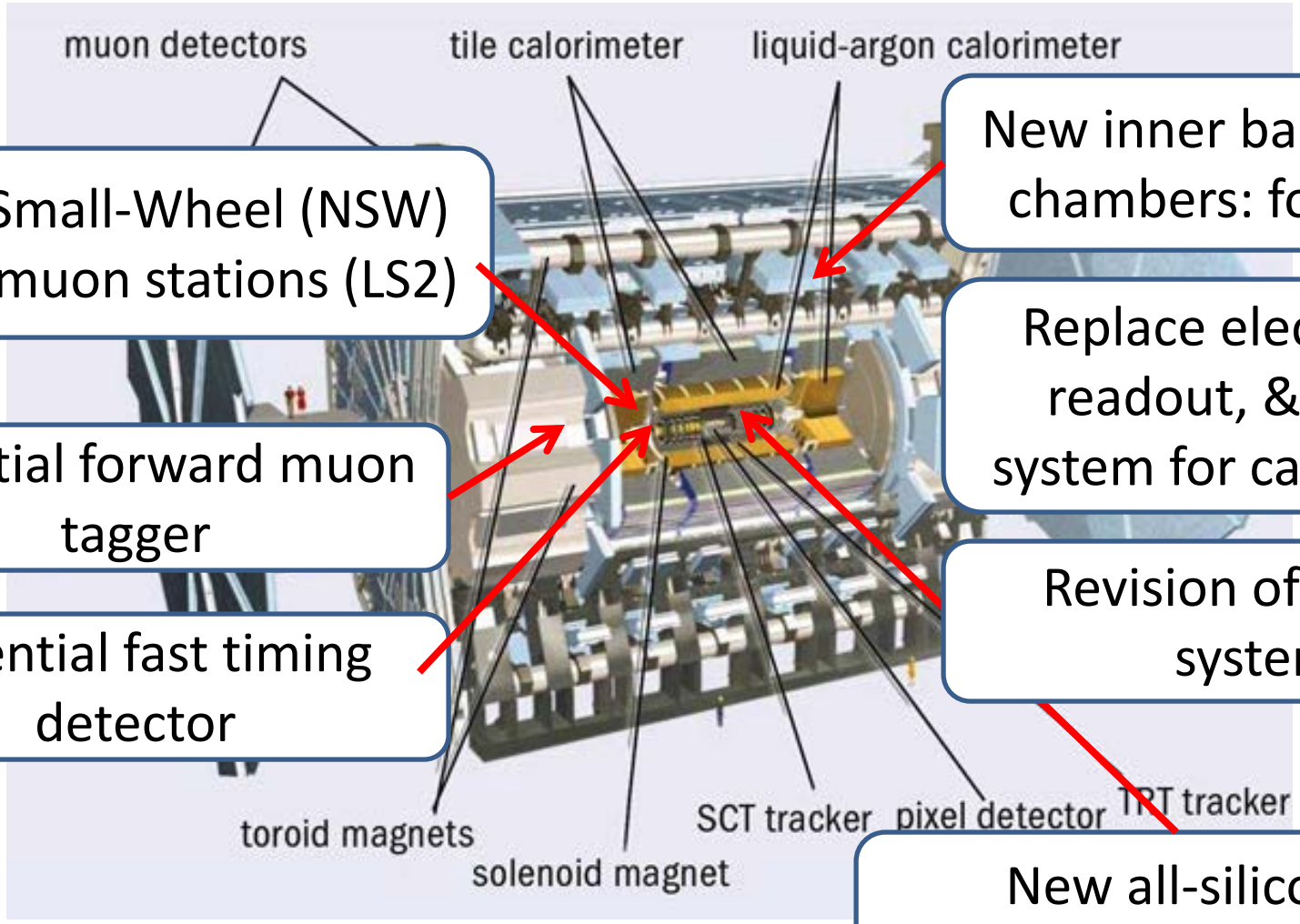
Replace Endcap Calorimeters
- Rad. tolerant - high granularity
- 3D capability

+Timing layer
(outside tracking volume)

Replace Tracker

- **Radiation tolerant; high granularity**
- **Extend $|\eta|$ coverage up to 4**

HL-LHC Upgrade: ATLAS Overview



New Small-Wheel (NSW) inner muon stations (LS2)

Potential forward muon tagger

Potential fast timing detector

New inner barrel muon chambers: for trigger

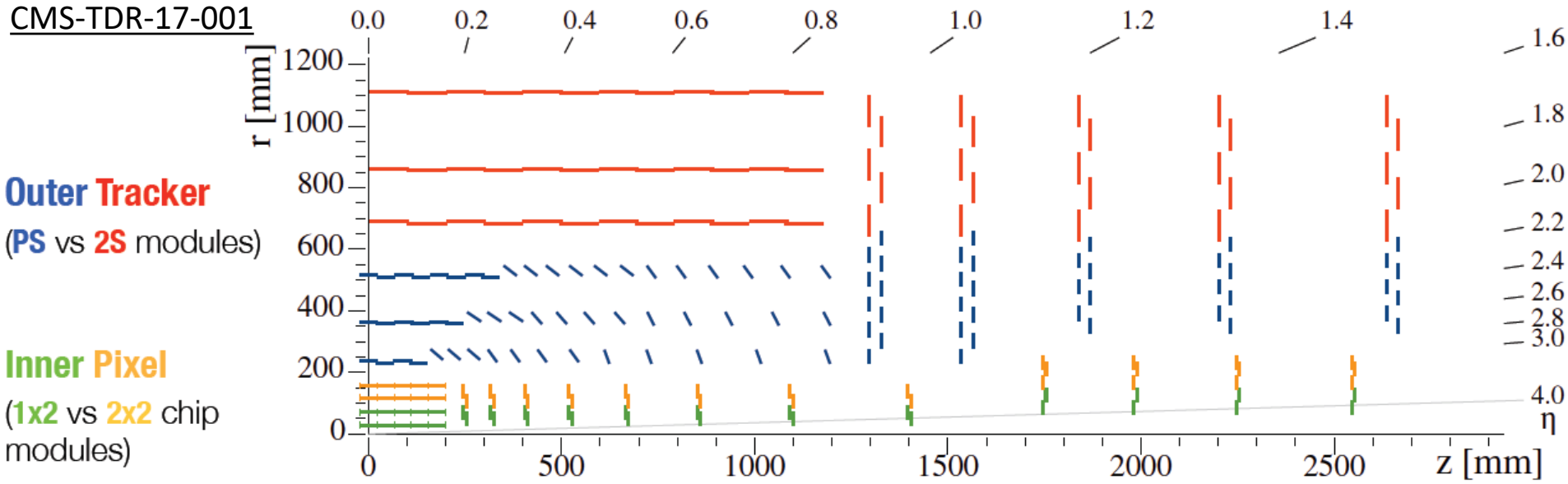
Replace electronics, readout, & power system for calorimetry

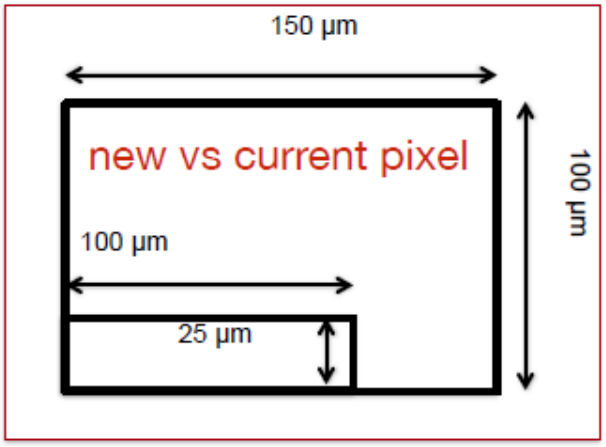
Revision of trigger system

New all-silicon inner tracker (ITK)

Tracker Upgrade: CMS

CMS-TDR-17-001





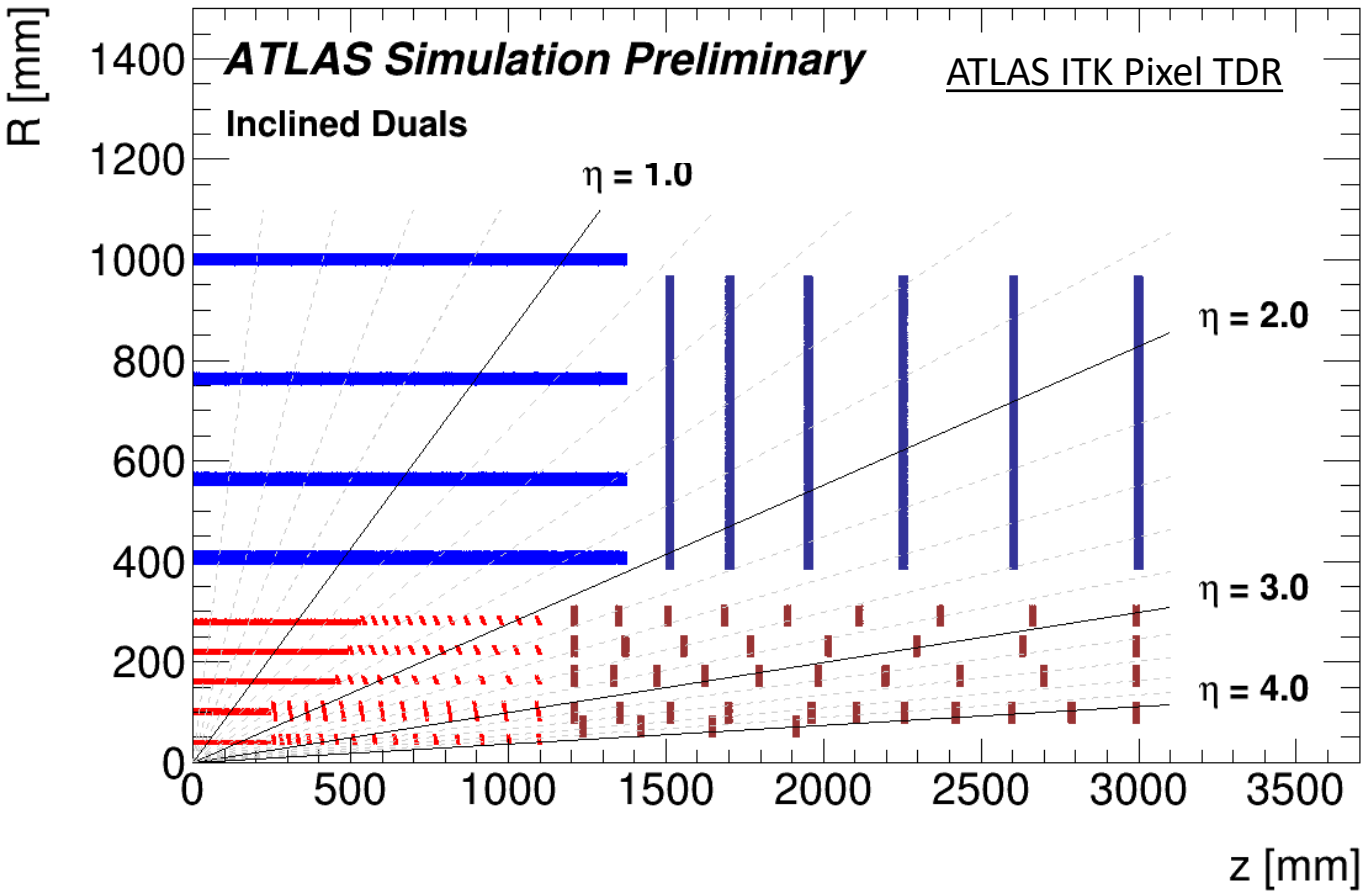
Inner pixel detector:

- 4 layers + (8+4) disks: increase coverage; $|\eta|$~2.5 → $|\eta|$~4
- Thinner pixels (285μm →150μm): radiation hard
- Smaller pixels: improve resolution, maintain occupancy

Outer Tracker:

- 6 layers + 5 disks of pixels-strip/ strip-strip modules
- Two-sided sensor modules → stubs → L1 tracking finding

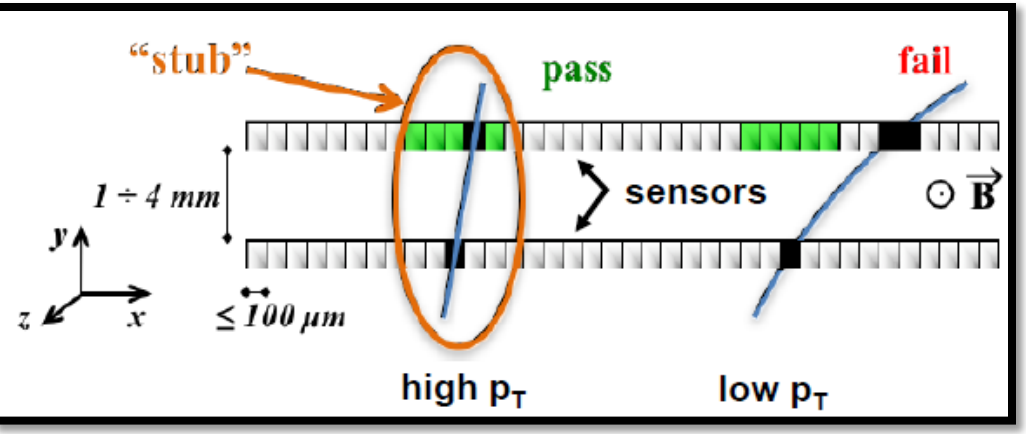
Tracker Upgrade: ATLAS



Outer strip detector:
- 4 barrel layers + 5 endcap disks
- covers |η|~2.6
- tilted modules at 52 (40) mrad in barrel (endcap) for 2D measurements

Inner pixel detector: small (50x50) & thin pixels with extended |η|~4
- 5 barrel layers with inclined sensors starting at |η|~1
- In endcaps: rings instead of disks to reduce material

Tracker Trigger Upgrade



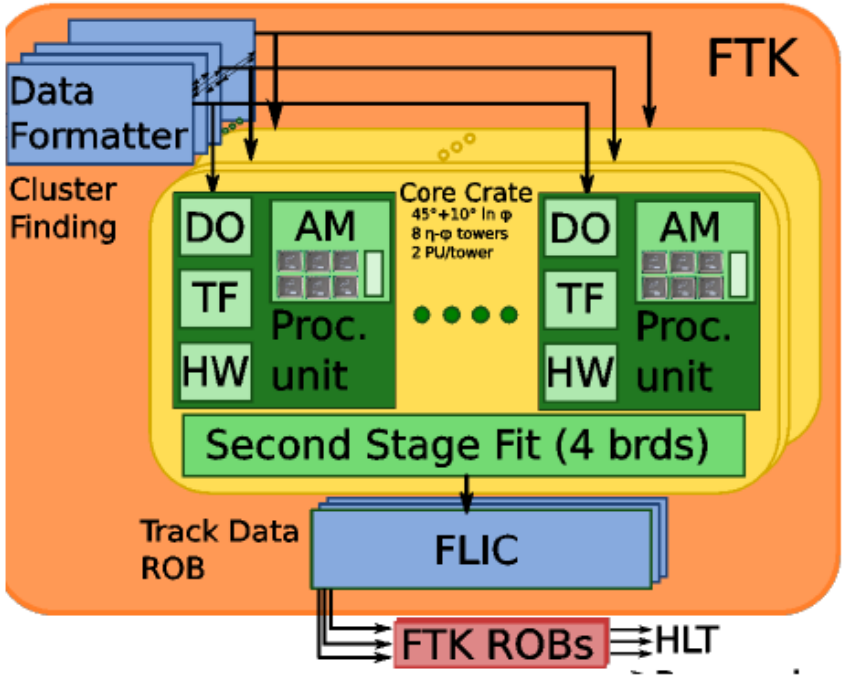
CMS L1 track trigger

- Two-sided sensor modules in OT →stubs: correlated hit pairs, consistent with >=2GeV track
- Stubs form input to track finding at L1 trigger rate of 750kHz (15-20k stubs/BX)
- 12.5μs latency (~4 μs processing time)

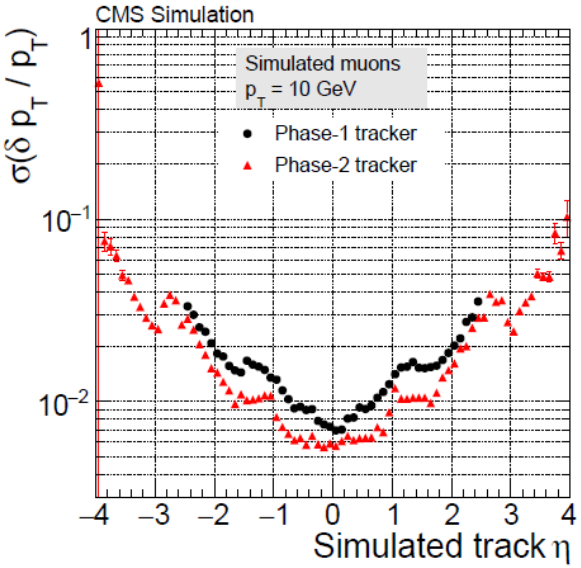
ATLAS Hardware-based track trigger

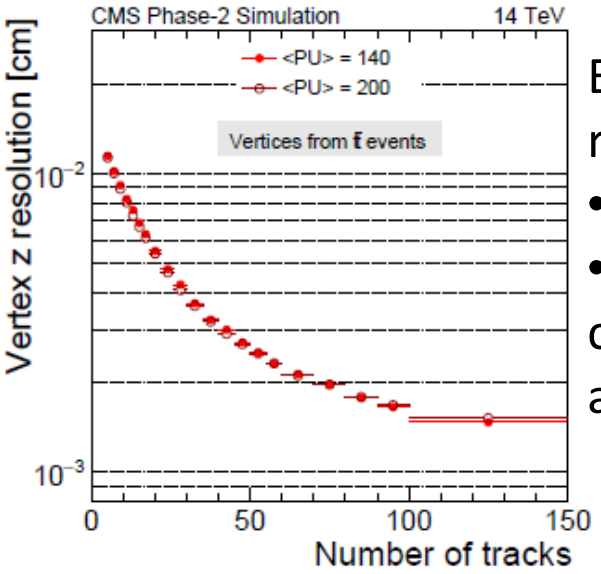
- FTK (current): >=1GeV tracks at 100kHz
- Update for HL-LHC conditions
  - Regional tracking: ~10% of detector, higher rate(1MHz), pT >2-4GeV
  - Global tracking: full detector, lower rate(~100kHz), pT >1-2GeV

Both experiments' tracker triggers adopt pattern recognition and massive parallel processing.



Tracker Upgrade: Object Performance

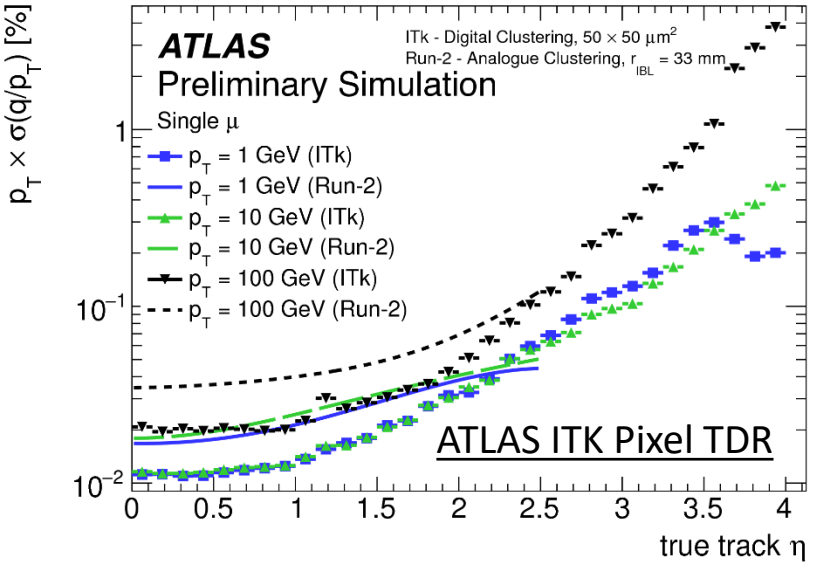


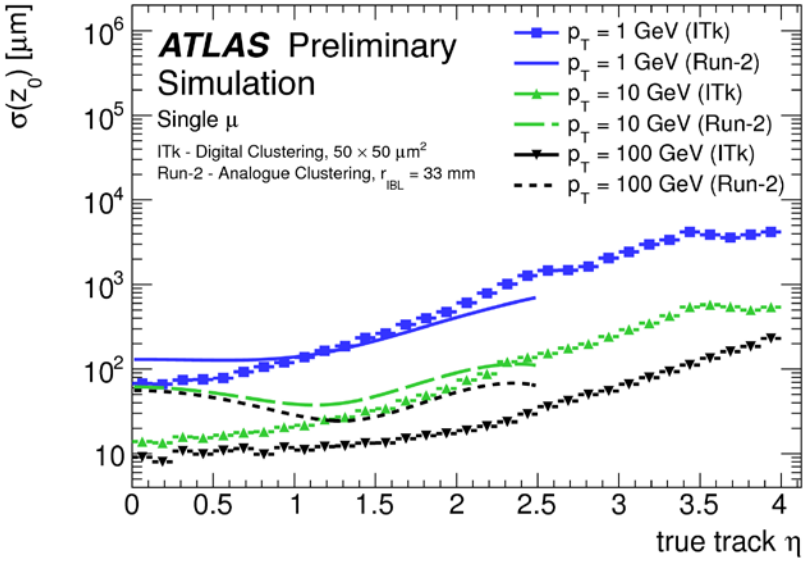


Excellent tracking and vertexing resolution and efficiency:

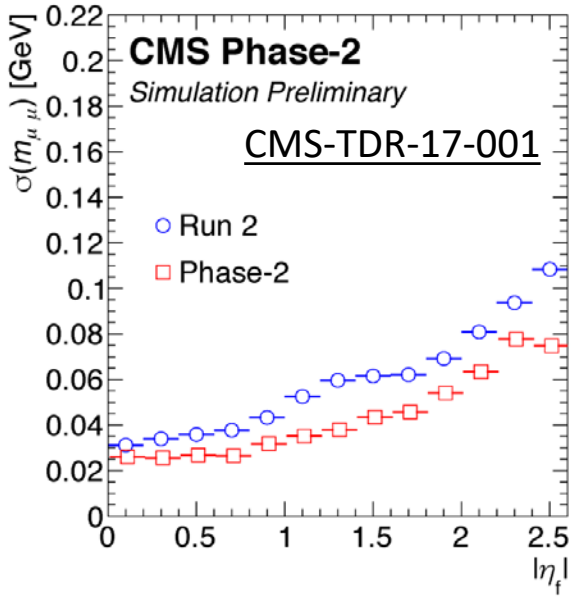
- increased coverage in forward
- maintain and improve upon current detector performance at HL-LHC conditions w/ 200PU

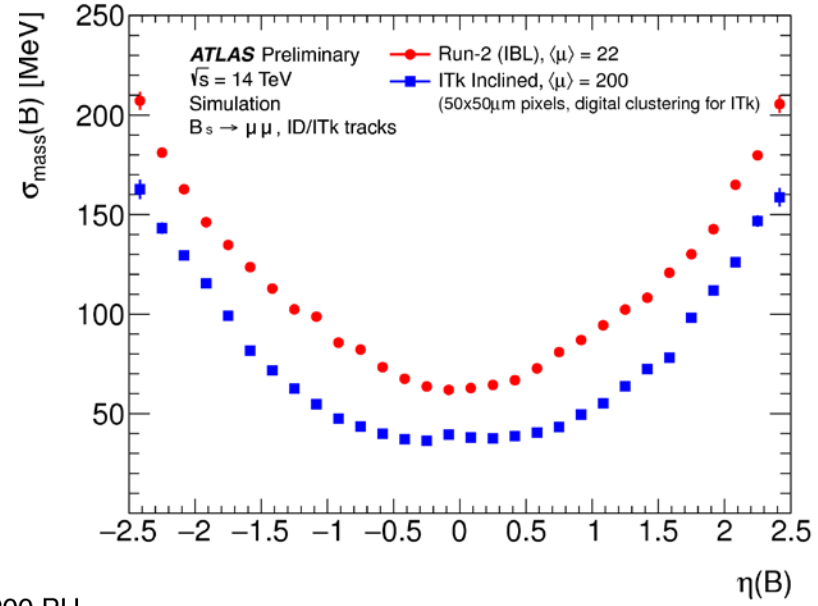
CMS-TDR-17-001





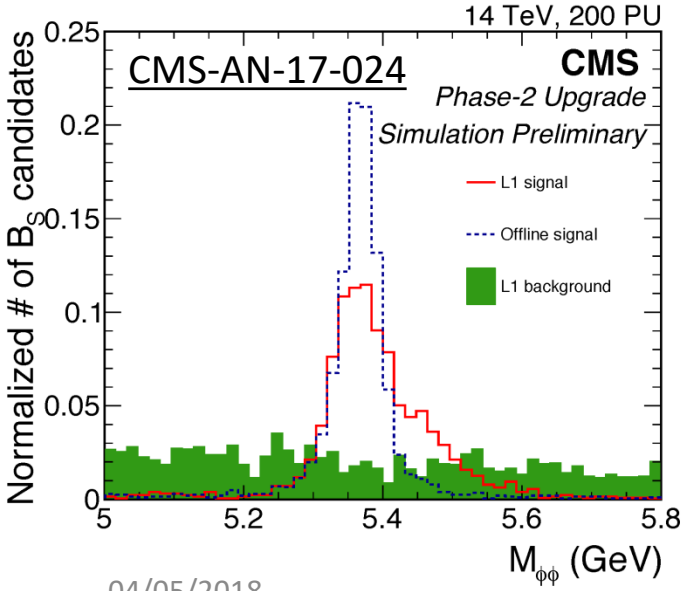
Tracker Upgrade: Flavor Physics



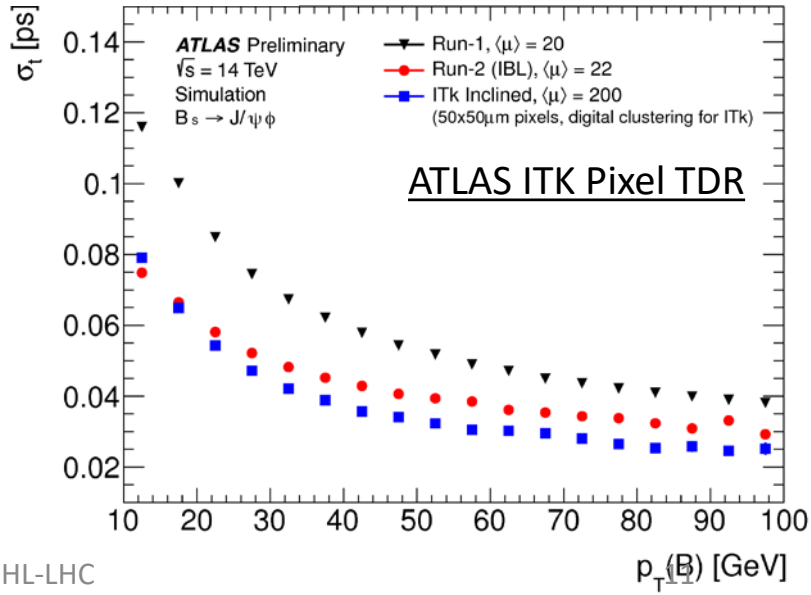


Improved mass resolution in $B_{d/s}$ →μμ → Better separation of B_d and B_s states

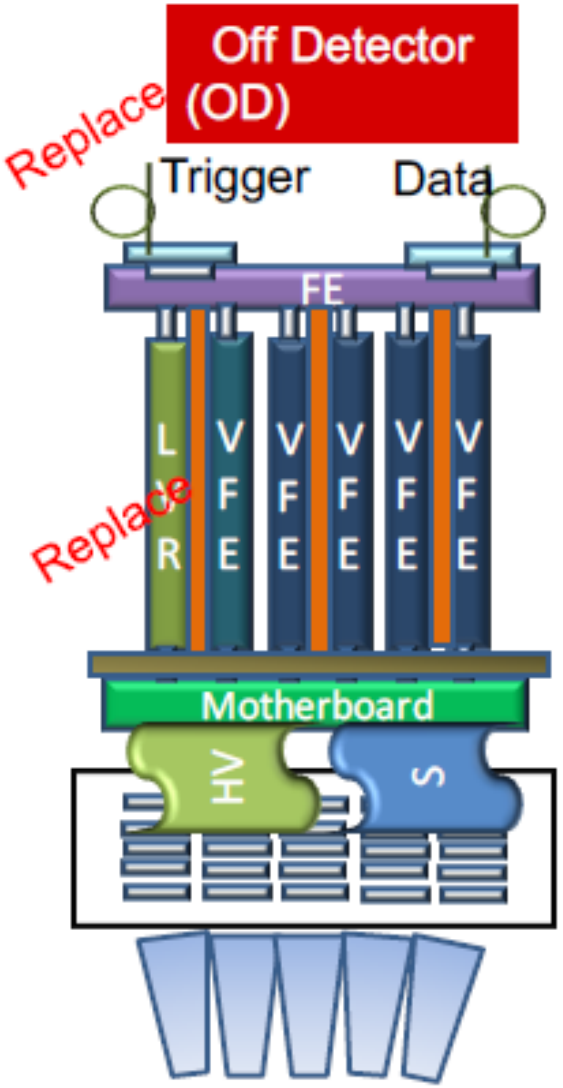
B^0_s proper decay time resolution also improves w/ upgrade



B_s →φφ→4K is an important benchmark for L1 track finding @CMS: low pT tracks in rare process



Calorimetry Upgrade: Barrel



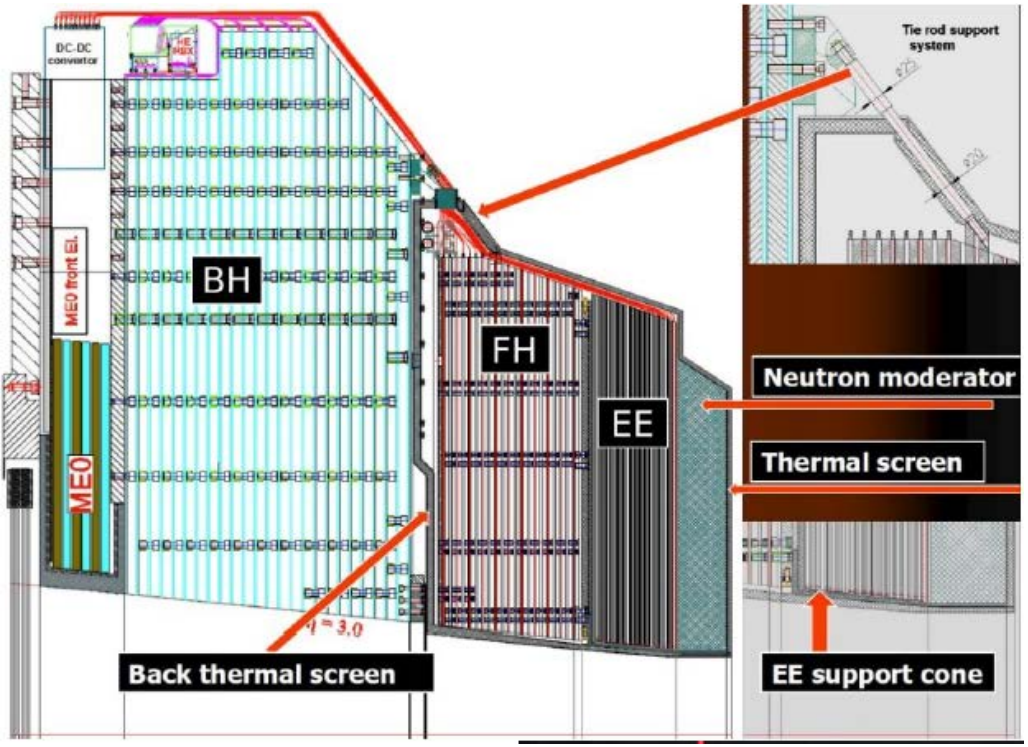
For the CMS detector:

- The crystals in the ECAL will be kept for duration of LHC
- The **FE & BE electronics will be replaced** for more precise timing, useful in both pile-up mitigation and searches for new physics
- Target (hardware fundamental limit): **~30ps for E > ~30GeV** (1/10 of current limit)
- Current studies on HCAL Barrel radiation damage suggest no need for replacement at HL-LHC: pending further study

For the ATLAS detector:

- The liquid argon ECAL and tile HCAL are expected to be functional through the lifetime of the LHC
- The front & back end electronics, and power supplies will be replaced for HL-LHC conditions
- Readout upgrade will allow high res. info at L0 trigger

Calorimetry Upgrade: Endcap



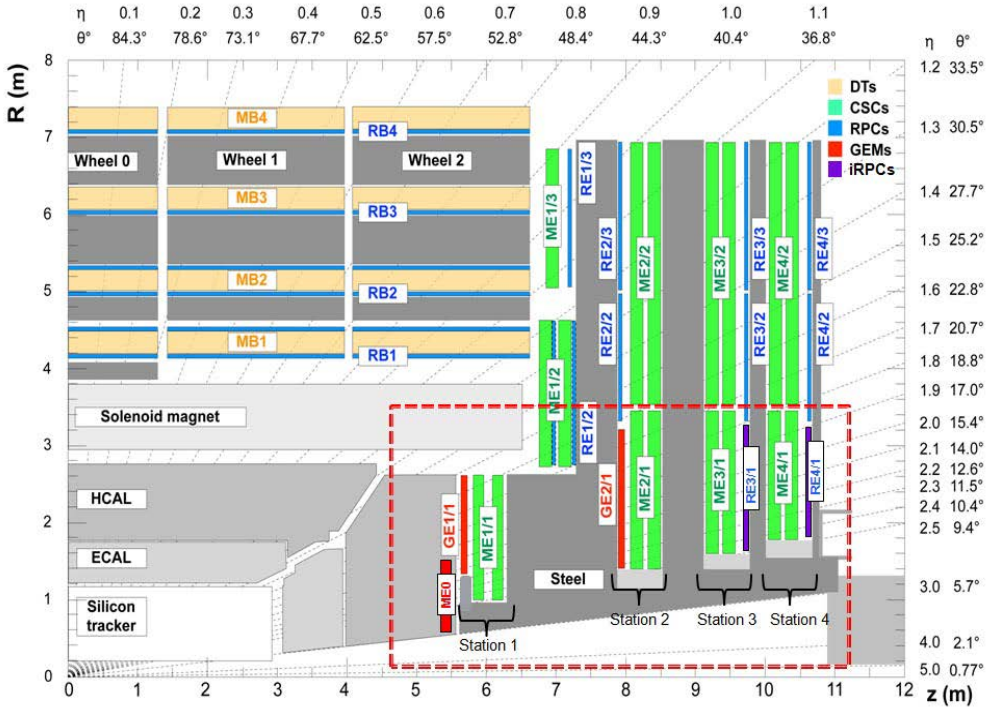
<u>For the CMS experiment</u>, the endcap calorimeter will be replaced with a silicon-based calorimeter (**HGCAL**):

- High granularity and 3D imaging to help mitigate PU
- Fast signal collection (<10ns) and **fast timing capability (few tens of ps)**

→ 4D info in space-time to reconstruct showers

- Other than the CMS endcap calorimeter (HGCAL), upgrades to calorimetry is limited
- Better timing resolution on electronic upgrades, and more calo info at trigger level, should help with hadronic/γγ/ee reconstruction
  - ~30ps timing resolution for particles of tens of GeV @ CMS upgrade
- HGCAL@CMS offers high granularity spatial and timing resolution for charged particles & photons: prospects for B physics?

Muon Upgrade: CMS

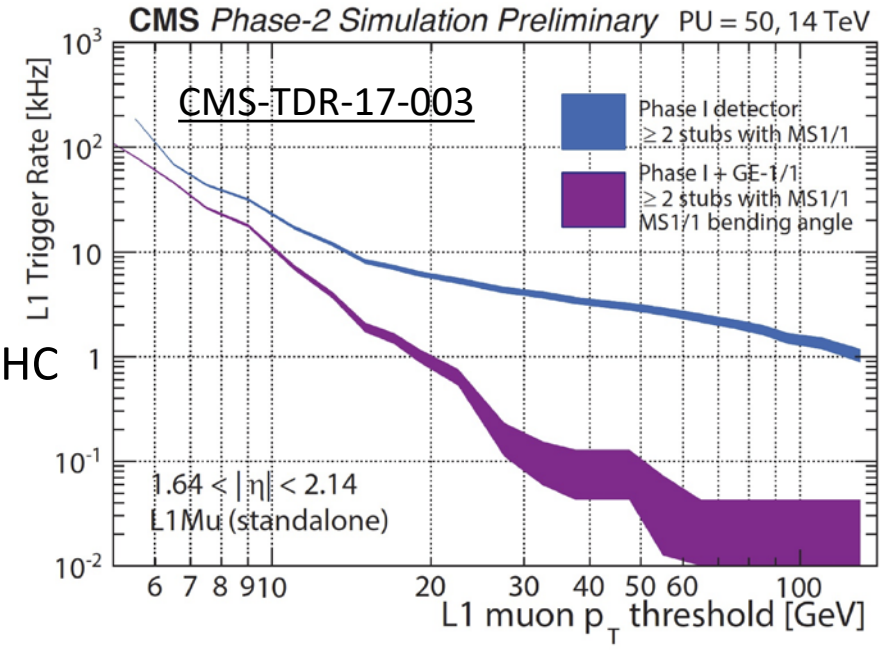


Muon system upgrade scope for HL-LHC:

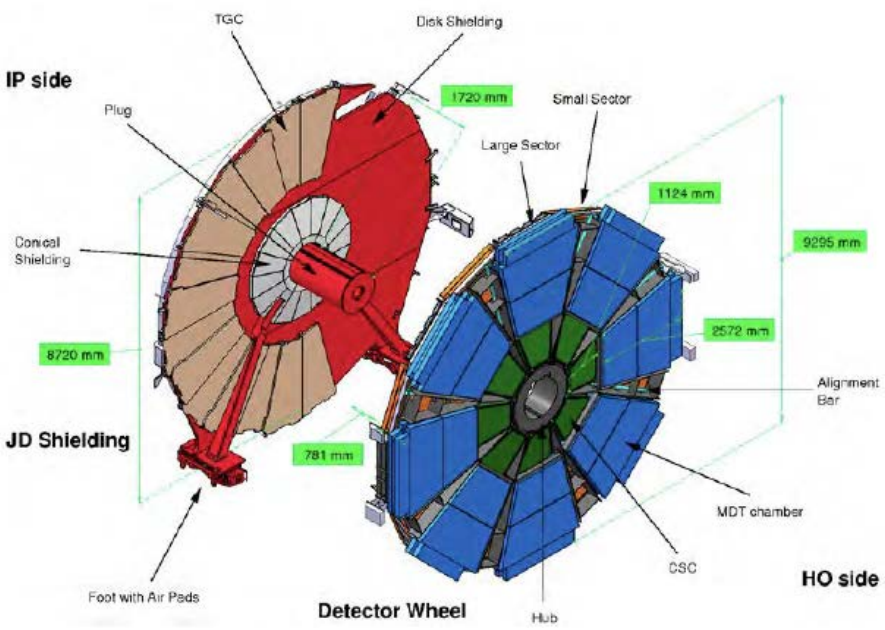
- Existing detectors:
  - upgrade barrel DT and endcap CSC electronics for 40MHz readout
- Extend forward coverage:
  - GEM & RPC detectors: 1.6<η<2.4
  - ME0 (for trigger): 2.4< η<2.9

Standalone muon trigger at L1:

- Keep rate under control:
  - single muon threshold 20-25GeV @ HL-LHC
- Provide good resolution and efficiency
- Provide capabilities not covered by L1 track trigger, e.g. displaced tracks & slow moving particles



Muon Upgrade: ATLAS



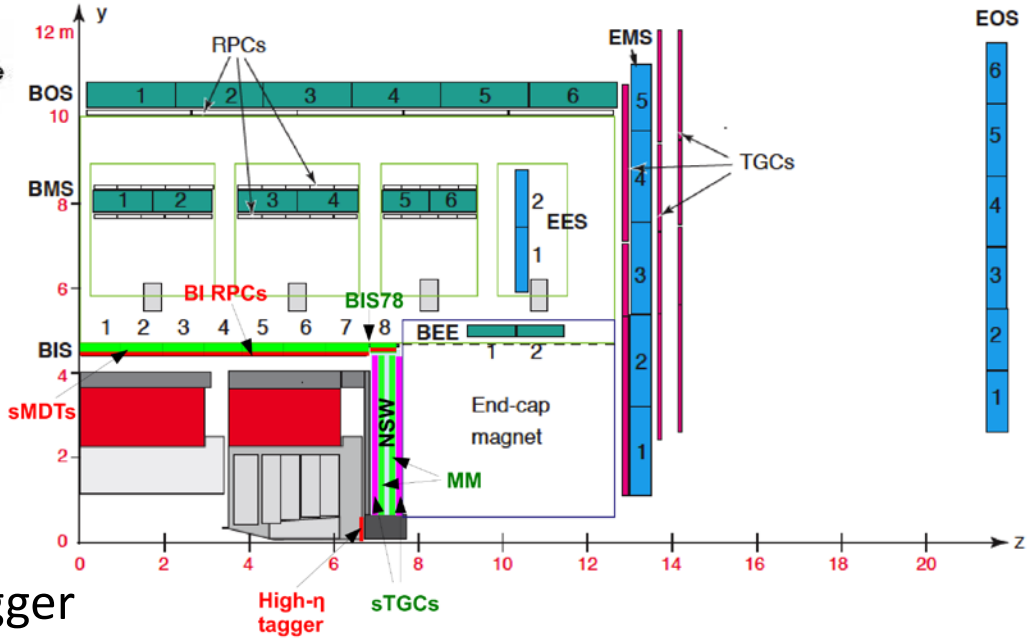
Phase-1 (ongoing, installation during LS2):

- New Small Wheel (NSW) with Micromegas (MM) & small-strips Thin Gap Chambers (sTGC) to replace the innermost endcap
- Upgrades to barrel RPCs

→ Maintain momentum resolution and keep single muon trigger rate under control

Phase 2 (for HL-LHC)

- NSW will be kept for HL-LHC
- Major upgrades to the muon barrel to increase acceptance&robustness
  - new inner RPC stations
  - remove some old MDTs
- MDT info added to hardware trigger
- Potential addition of forward muon tagger

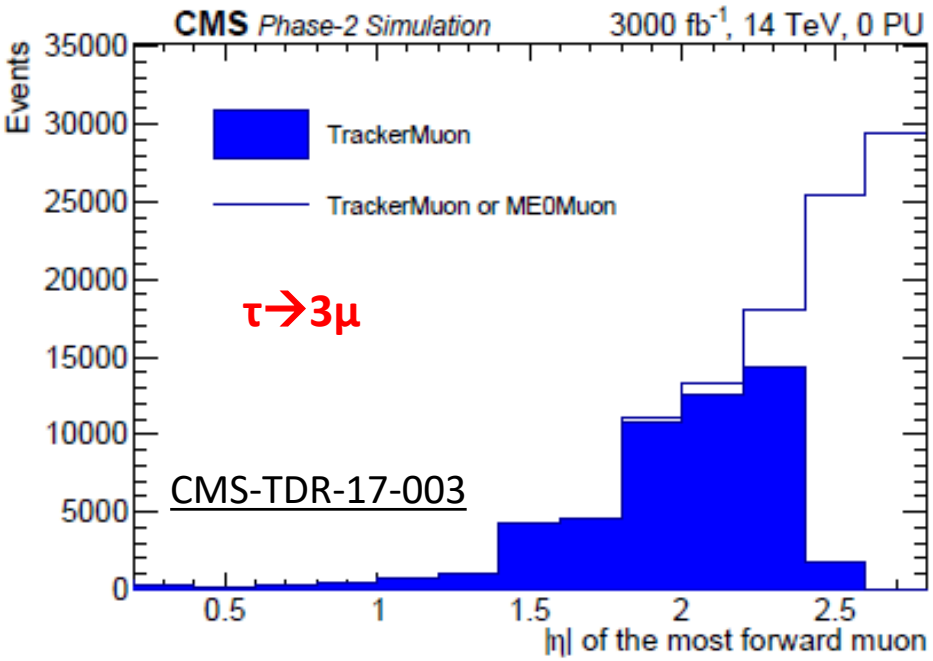


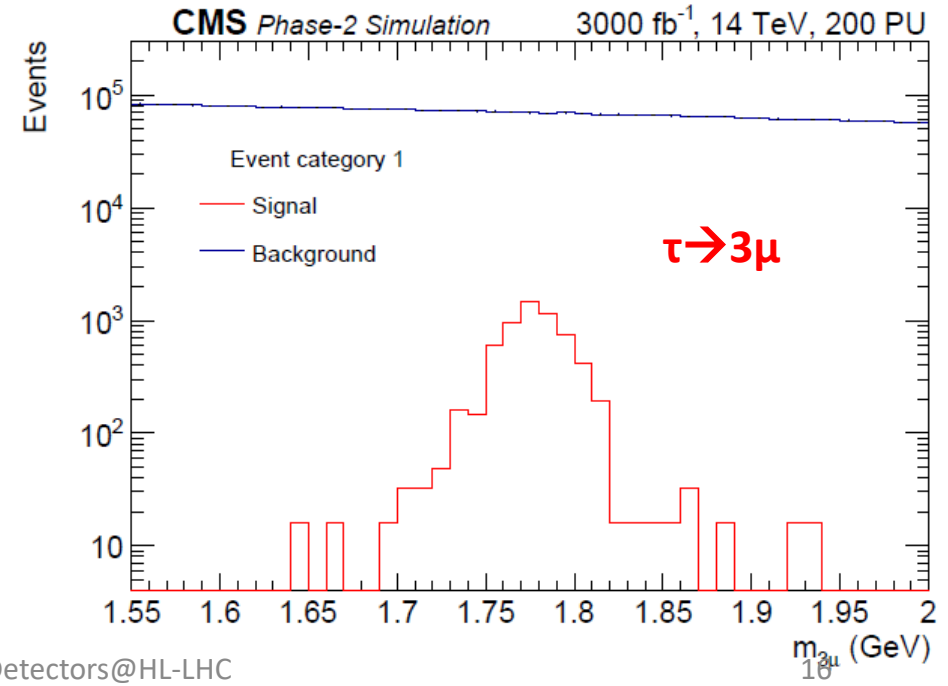
Muon Upgrade: Performance

Improved performance with HL-LHC upgrade: (CMS example)

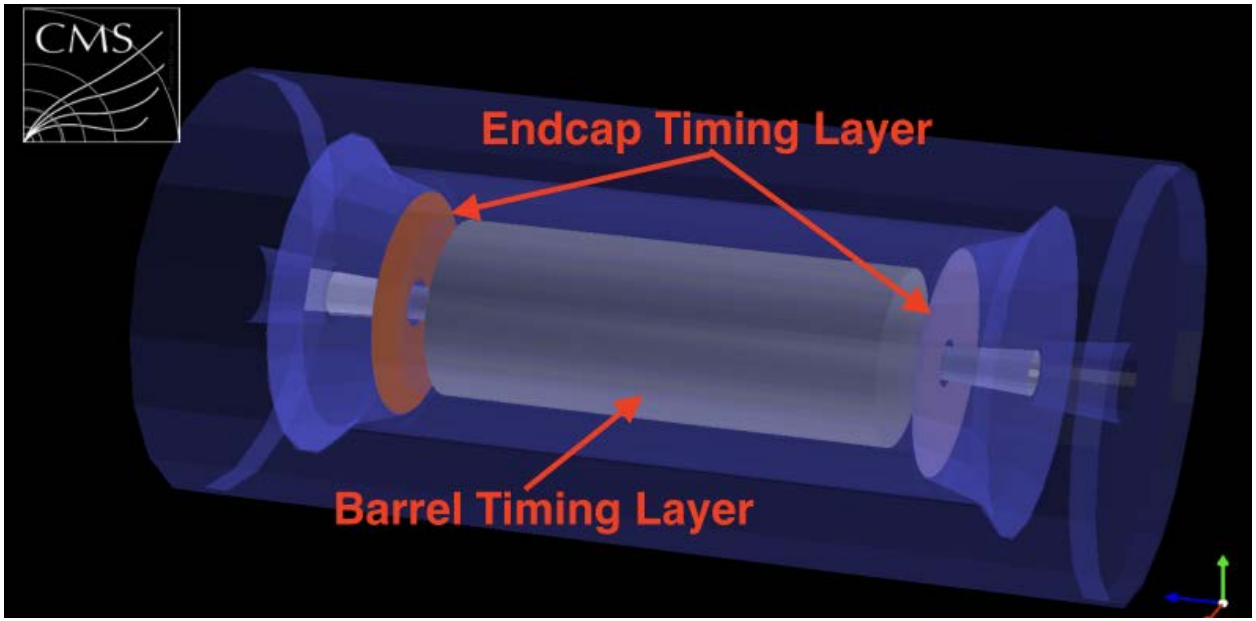
- Higher efficiency & lower rate (purer sample): minimal dependency on pile-up
- Improved timing resolution w/ eletronics upgrade
- Extended forward coverage : $|\eta|<2.4 \rightarrow |\eta|<2.8$
- Benefits from the L1 track trigger for prompt muons, incl. the lower pT regime

One of the "cleanest" channels for Lepton Flavor Violation (LFV) is **τ→3μ**, where finals state muons have low momenta and are significantly boosted in forward direction:

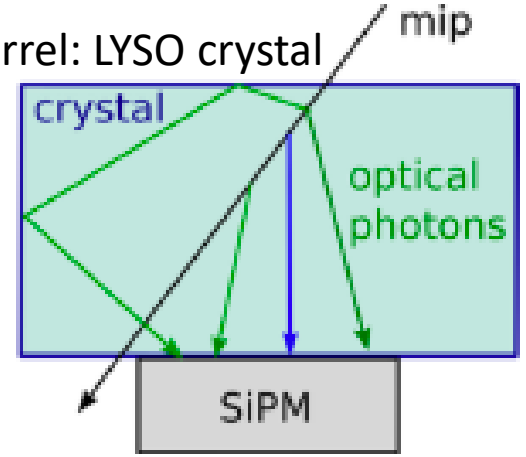




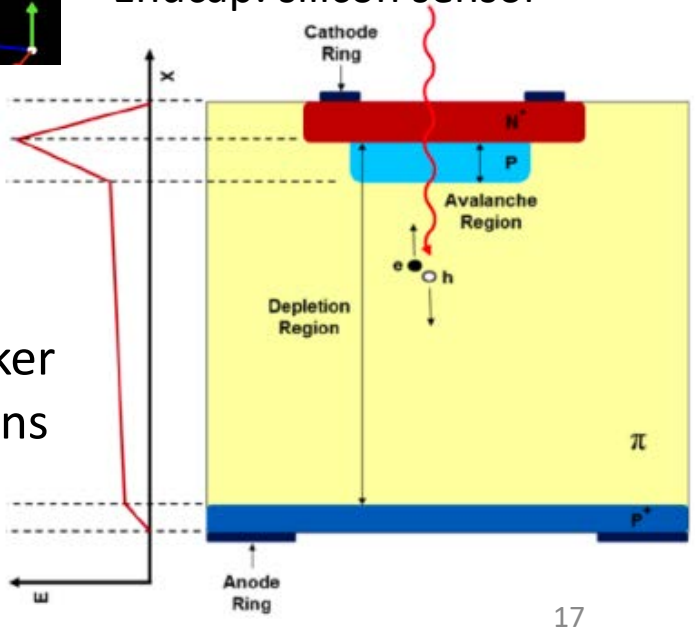
Fast Timing Upgrade: CMS



Barrel: LYSO crystal



Endcap: silicon sensor

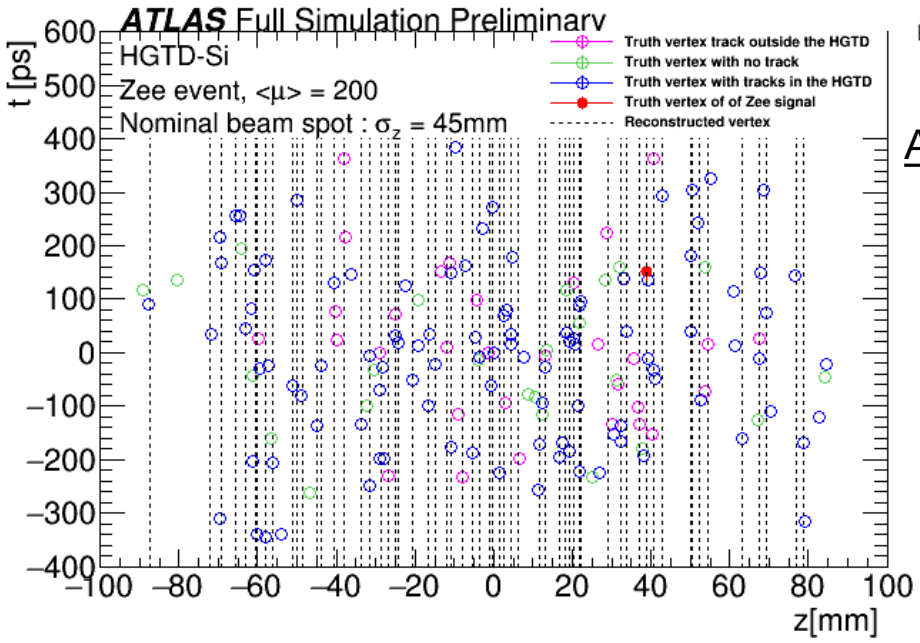


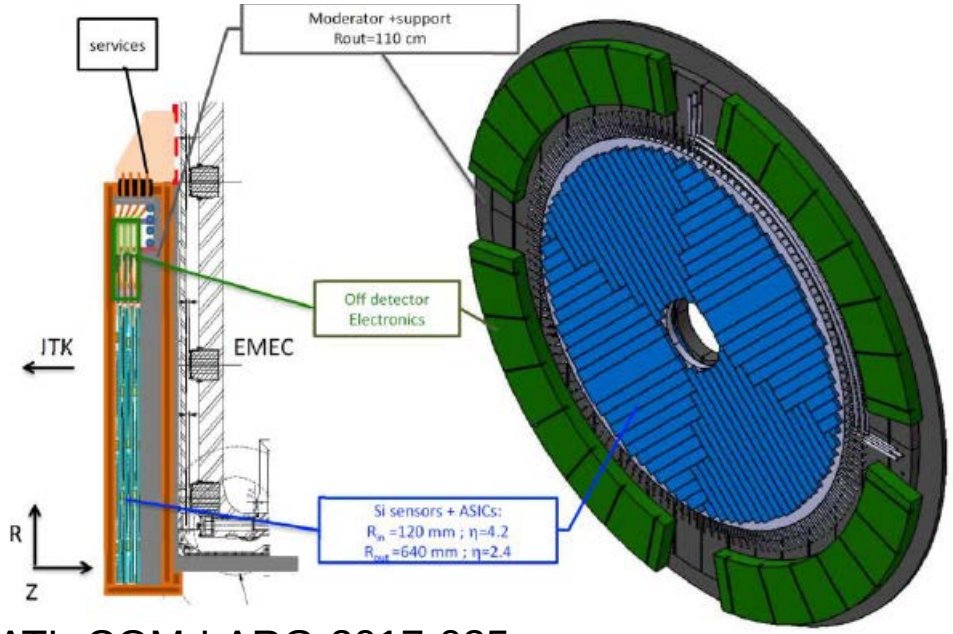
- Calorimeter upgrades (ECAL electronics + HGCAL) will provide precise (a few 10s of ps) timing for high energy photons in barrel and high energy hadrons/photons in endcap
- **Additional timing layer (barrel+ endcaps** outside tracker volume) can provide precision timing for charged hadrons & converted photons down to a few GeV.
- Traditional 3D vertex fit upgraded to a 4D fit

Fast Timing Upgrade: ATLAS

The **High Granularity Timing Detector (HGTD)** for ATLAS upgrade will be located just outside the ITK envelop at z~3500mm

- 120mm to 640mm in radius
- covers the forward region of **2.4<|η|<4.2**
- Consists of **four silicon layers**
  - 1.3mmx1.3mm silicon pads





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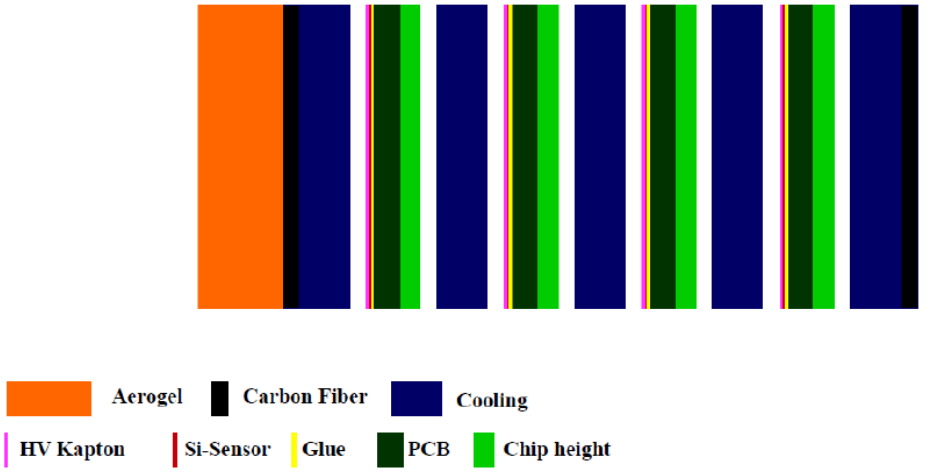
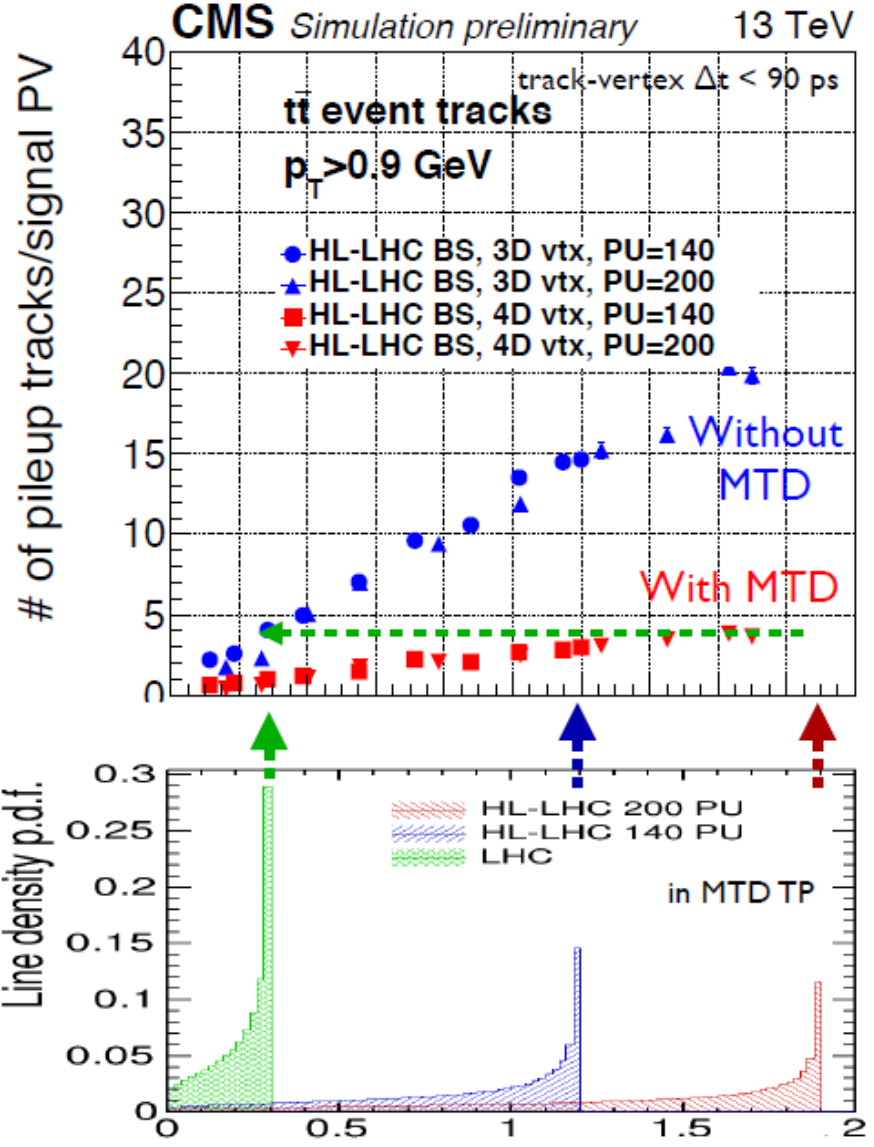
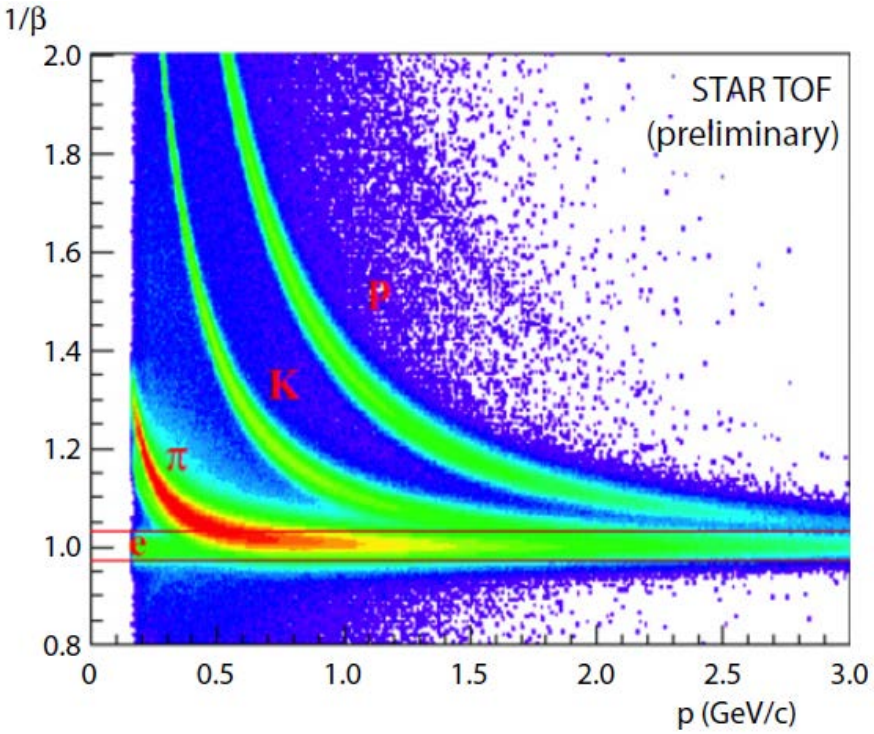


Timing Upgrade: Prospects for Flavor

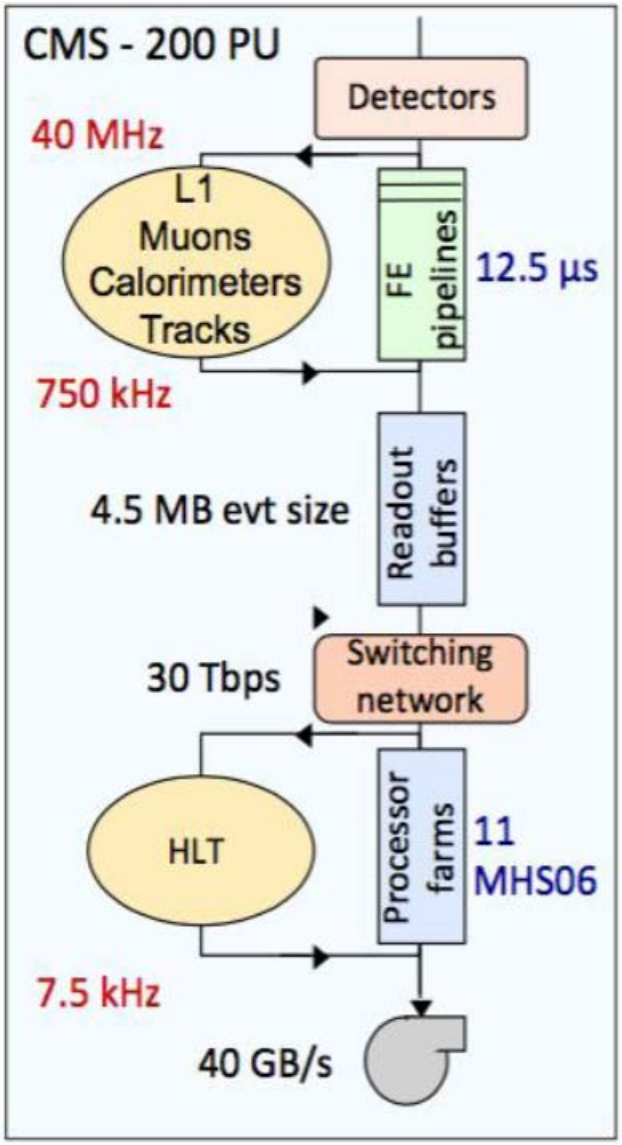


By adding time-at-vertex for the track:

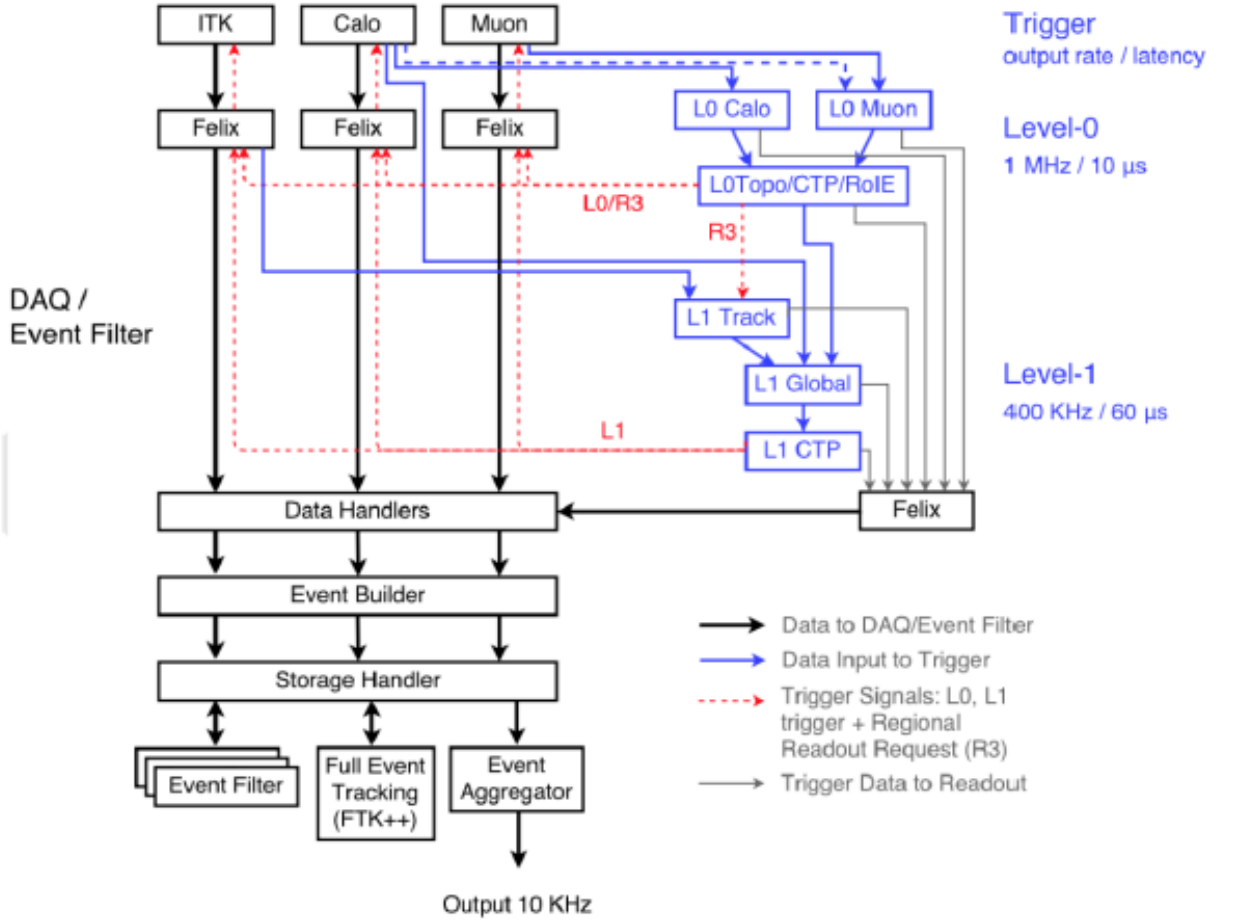
- Pile-up mitigation
- Improve lepton isolation
- Improve mass resolution in (H→)γγ channel, combined with calorimeter timing
- Time of flight can be used for Particle ID (example on STAR; CMS results upcoming)



HL-LHC Upgrade: Trigger



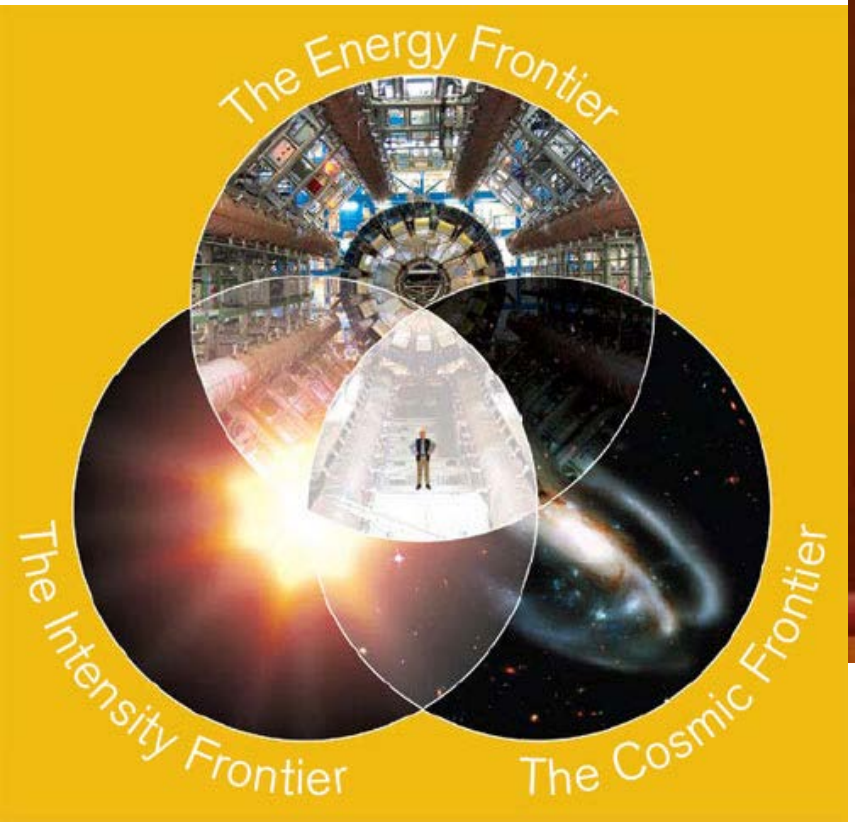
- L1 Trigger: increase output & latency
- High-Level Trigger: output rate increase up to 10kHz
  - Processing power scales with pile-up and L1 rate



Conclusions and Outlook

- The High-Luminosity LHC brings exciting physics potential #MoarData and many experimental challenges:
  - high radiation, high pile-up, high data-rate
- Comprehensive upgrade program to address these challenges and meet physics potential
  - improved spacial resolution: tracker; HGCAL; …
  - increased forward coverage: pixel extension; muon; …
  - improved timing information: HGCAL; MIP; electronics; …
  - improved trigger capabilities: more info, higher rate, L1 tracking etc.
- Higher luminosity + a more powerful machine + improved techniques → new possibilities for flavor physics

THANK YOU!

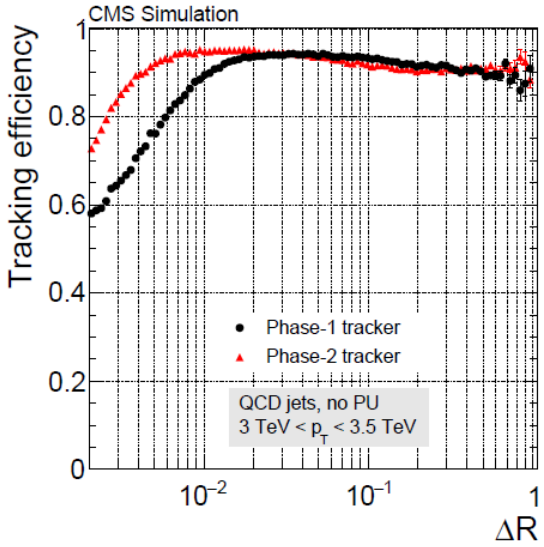


Keep looking with a magnifying glass; you never know what you might find…

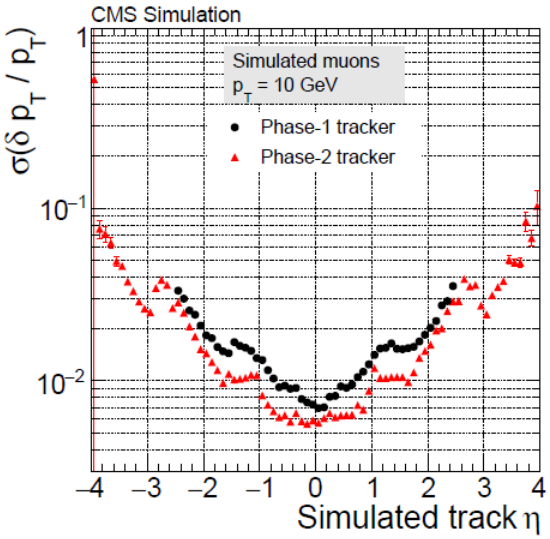
Tracker Upgrade: CMS Performance

Tracking

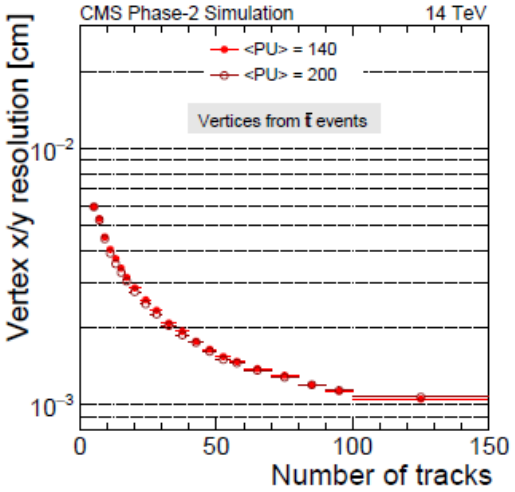
CMS-TDR-17-001

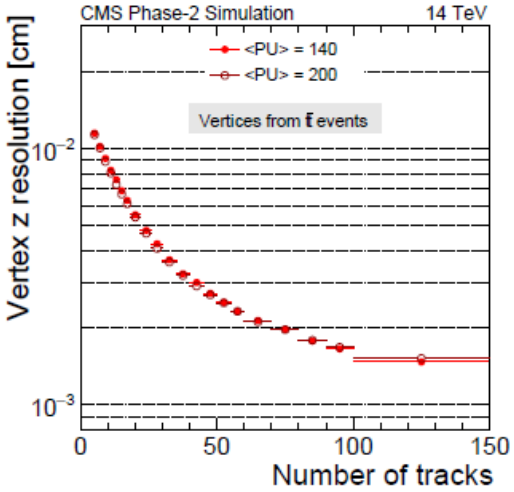


Excellent tracking performance with increased coverage and better resolution!



Vertexing

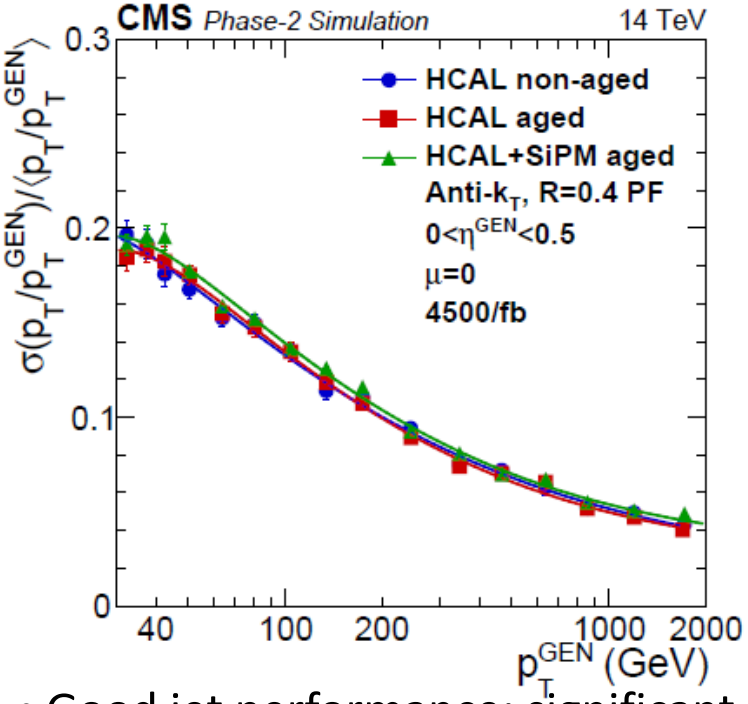




Vertexing resolution almost independent of pile-up; longitudinal resolution only ~50% worse than transverse (with 25x100x150 pixels)

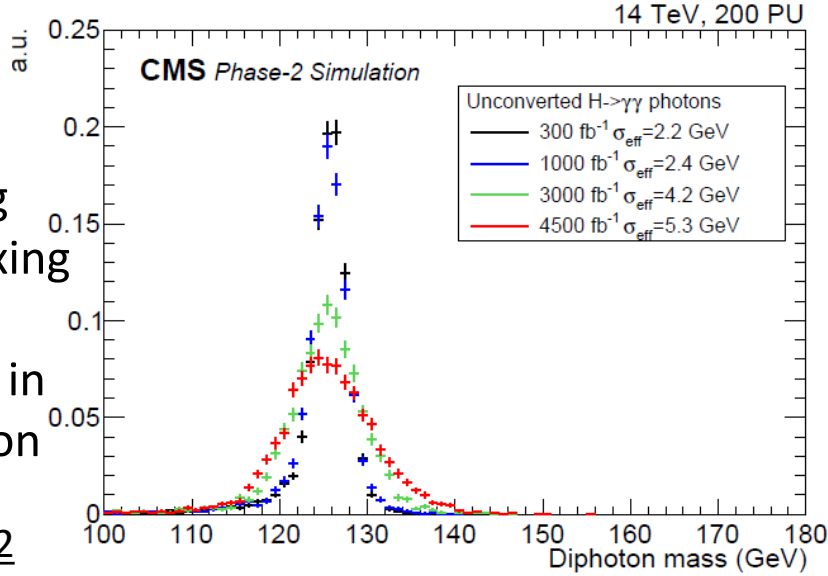
Calorimetry Upgrade: CMS Performance

Results shown for barrel calorimetry upgrade: HGCAL results in progress



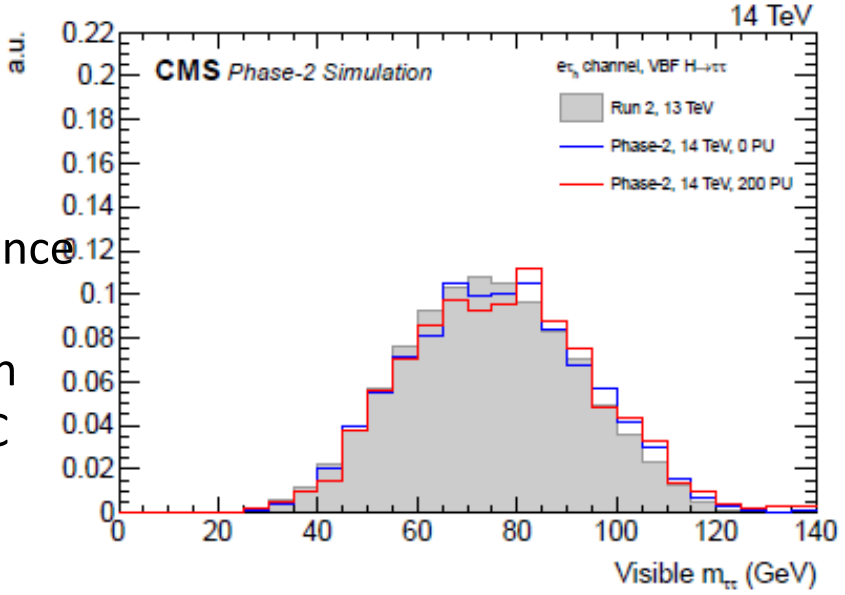
- Good jet performance: significant improvement with upgrades
- PUPPI works well for PU mitigation
- Aging effect minimal w/ recalibration

H→ γγ:
precision timing improves vertexing resolution;
expect degrade in energy resolution

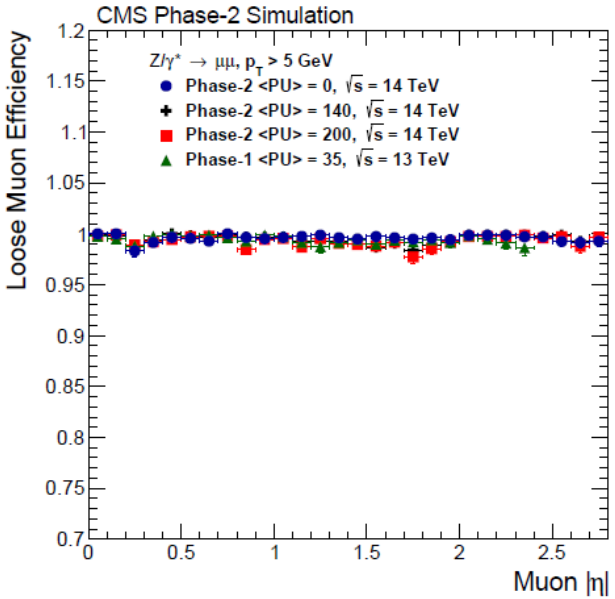


CMS-TDR-17-002

H → ττ:
maintain performance for mass resolution at HL-LHC vs Run2



Muon Upgrade: CMS Performance

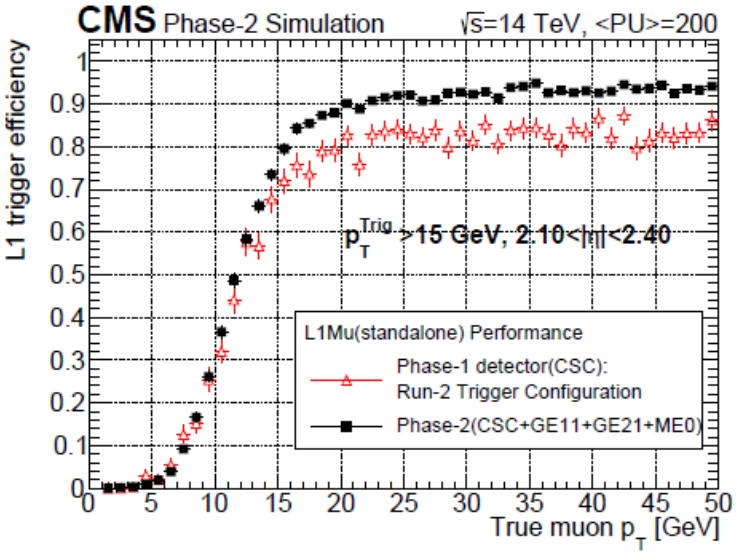


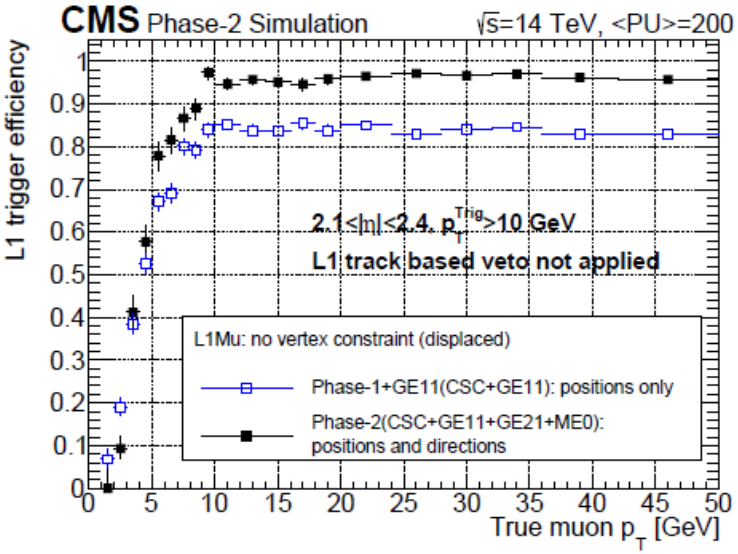
Improved performance with HL-LHC upgrade:

- Higher efficiency: minimal dependency on pile-up
- Lower rate: better measurement → much purer sample
- Improved timing resolution w/ eletronics upgrade
  - 12.5 ns → 1ns in DT
- Extended forward coverage : |η|<2.4 → |η|<2.8
- Benefits from the L1 track trigger for prompt muons

CMS-TDR-17-003

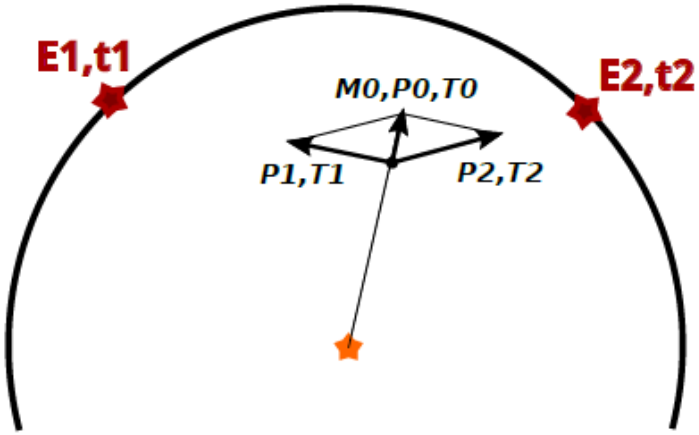
Prospects on LLP searches:



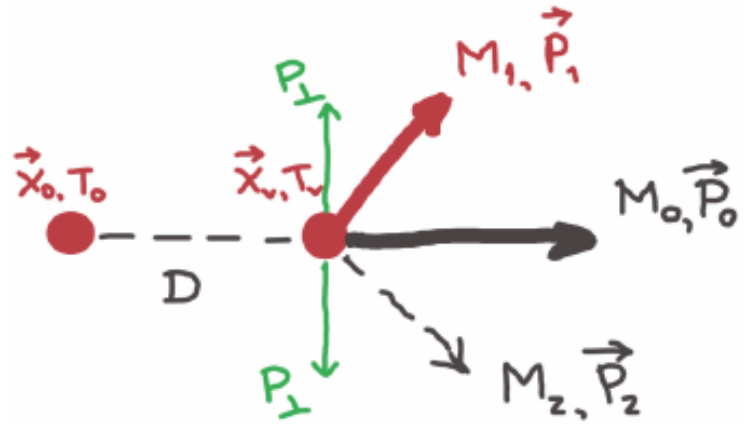


Timing Upgrade: LLP Prospects

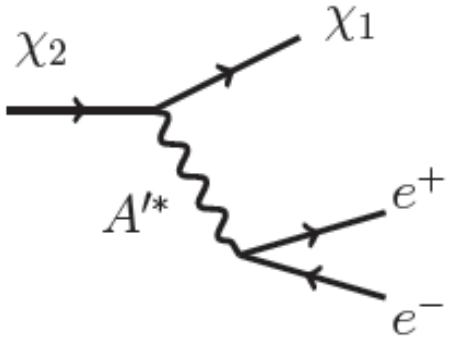
(Illustrations c/o A. Ledovskoy)



Scenario 1: Long-lived particle (neutral or charged) is produced at IP, & at secondary vertex (SV), decays into two observable particles (neutral or charged)
→With timing info (t1,2→T1,2; T0=T1=T2)
the scenario has unique solution for SV
→ full reconstruction!



Scenario 2: LLP decays to visible + invisible particles.
If the invisible particle mass is known + additional timing info → enough constraints for unique solution
→applicable for GMSB, iDM dark photon etc.



HL-LHC Upgrade: CMS Timeline

- Tracker TDR
  - May 2017: pre-view document; end of June 2017: provide CMS approved version - including cost and responsibilities
  - Nov. 2017: final approval of the Tracker TDR
- Barrel Calorimeters and Muons TDRs
  - Sep. 2017: provide CMS approved TDRs - including cost and responsibilities
  - Feb. 2018: final approval of the BC and Muons TDRs
- Endcap Calorimeter TDR
  - Nov. 2017: provide CMS approved TDR - including cost and responsibilities
  - May. 2018: final approval of the Endcap Calorimeter TDRs