CMS Detector
Status and Upgrade

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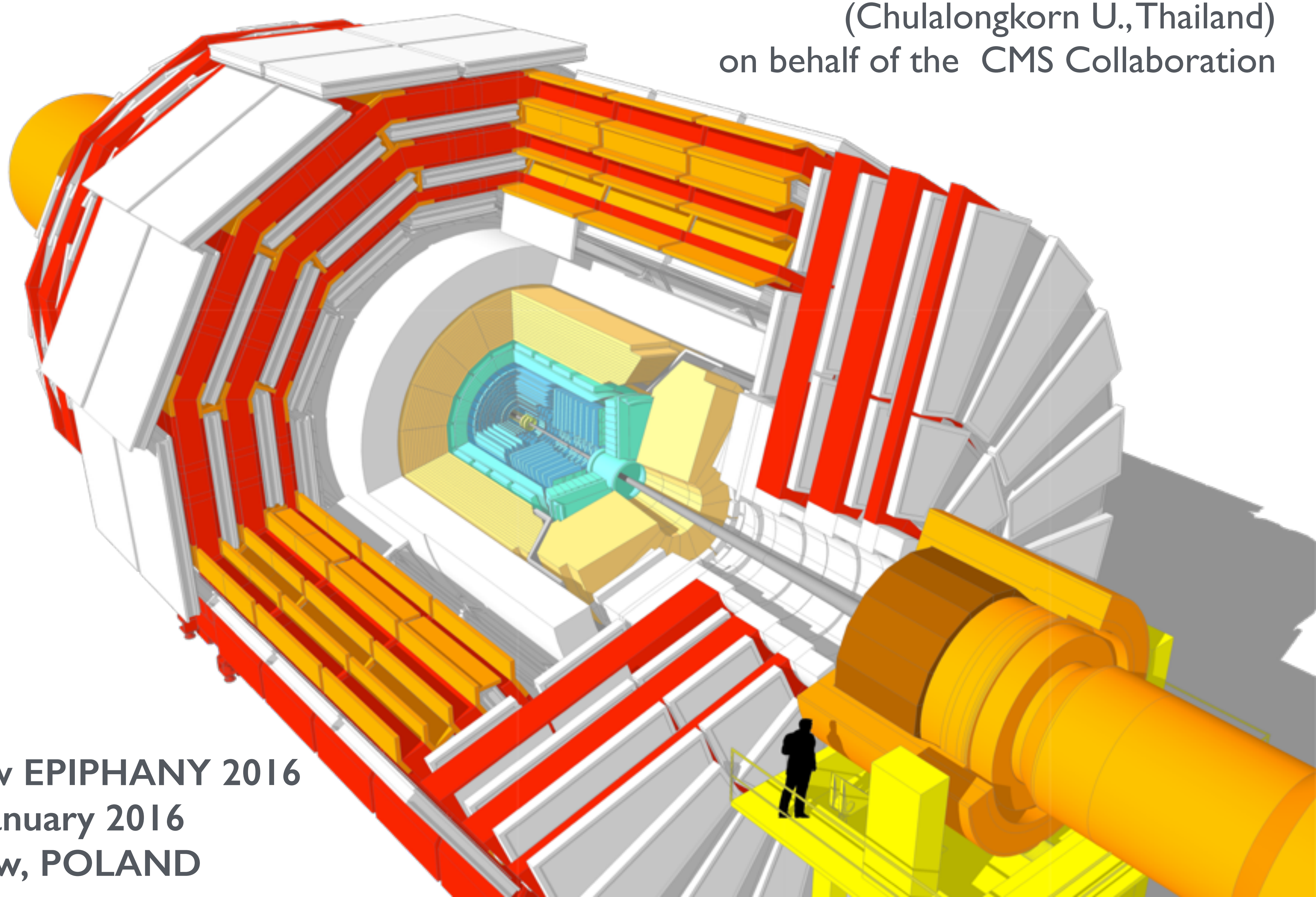
on behalf of the CMS Collaboration



XXII Cracow EPIPHANY 2016
7-9 January 2016
Kraków, POLAND

CMS Status and Upgrade

CMS Current Status

- See F. de Guio talk (Run2 performance of the CMS detector)

CMS Upgrade Plan

CMS Phase I Upgrade

- Summary for CMS Phase I Upgrades
  - Phase I Pixel Upgrade
  - Phase I Hadron Calorimeter Upgrade
  - Phase I Level-1 Upgrade

CMS Phase II Upgrade

- HL-LHC Physics Challenges
- Physics Opportunities at 3000 fb^{-1}
- HL-LHC Detector Challenges
- Summary for CMS Phase II Upgrades
  - Phase II Tracker and Tracking
  - Phase II Calorimeters
  - Phase II Muon Systems
  - Phase II Level-1 / HLT / DAQ

CMS Computing

Summary

CMS Current Status

For 2015:

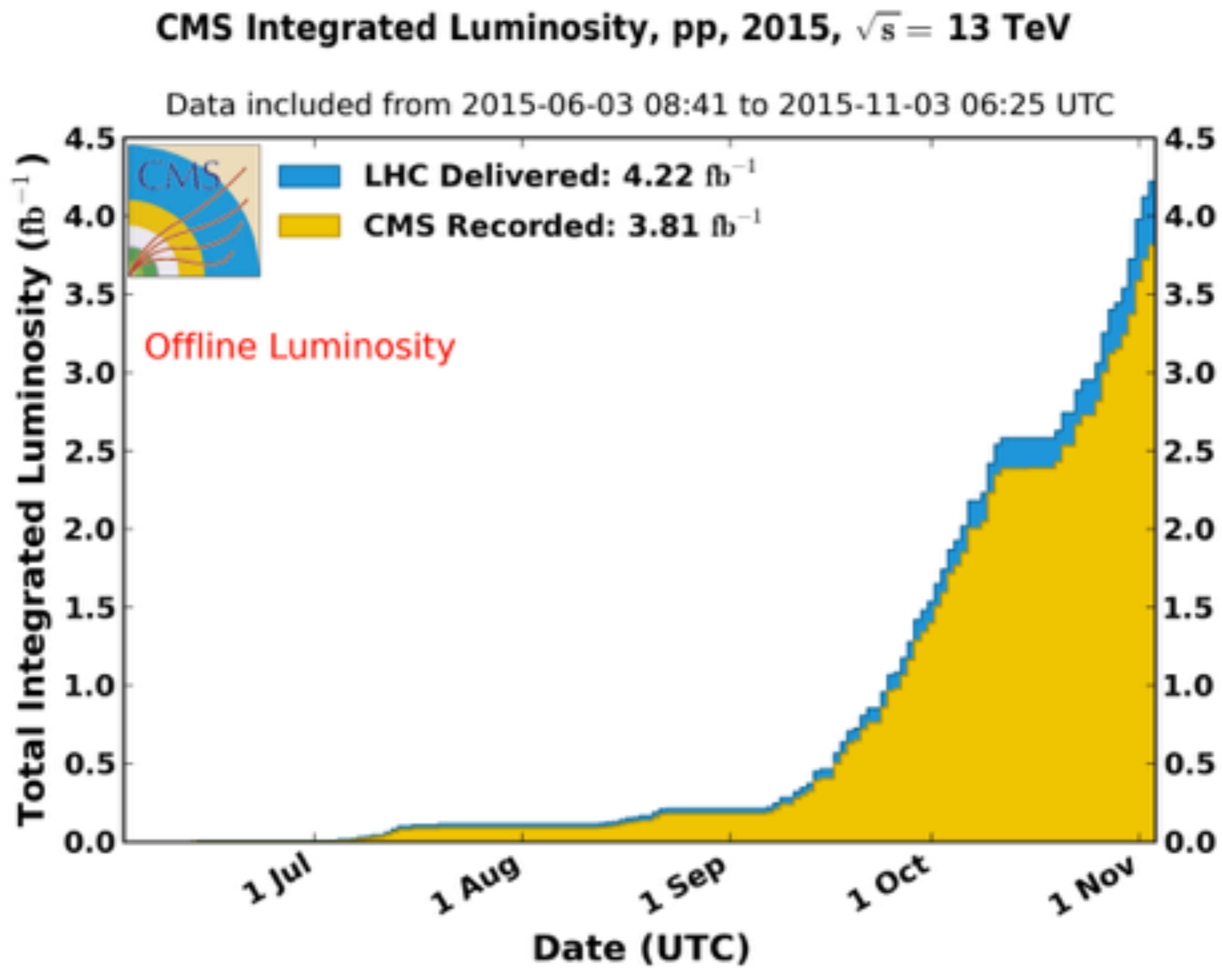
4105 pb^{-1} / 3675 pb^{-1} (delivered/recorded)

B = 3.8T: 3085 pb^{-1} / 2860 pb^{-1} (92.7%)

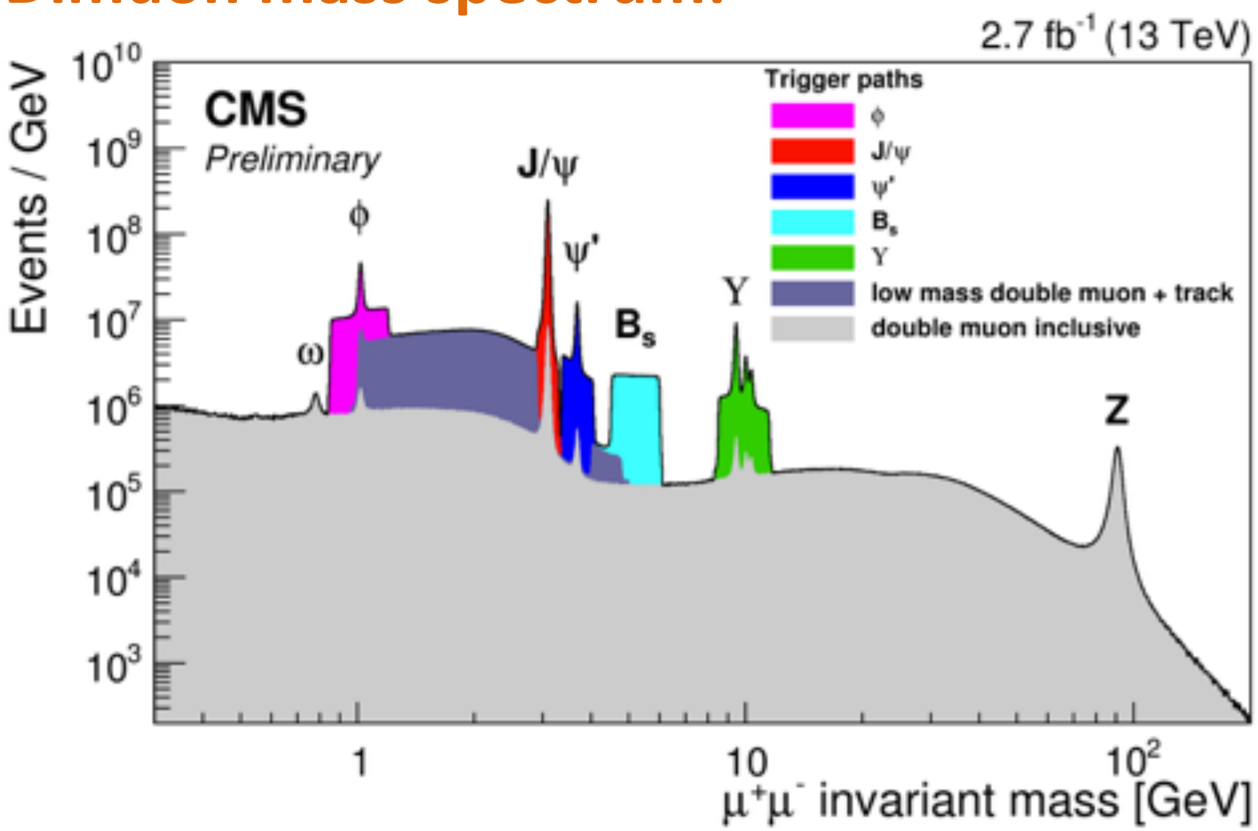
B ≠ 3.8T: 1020 pb^{-1} / 815 pb^{-1} (80%)

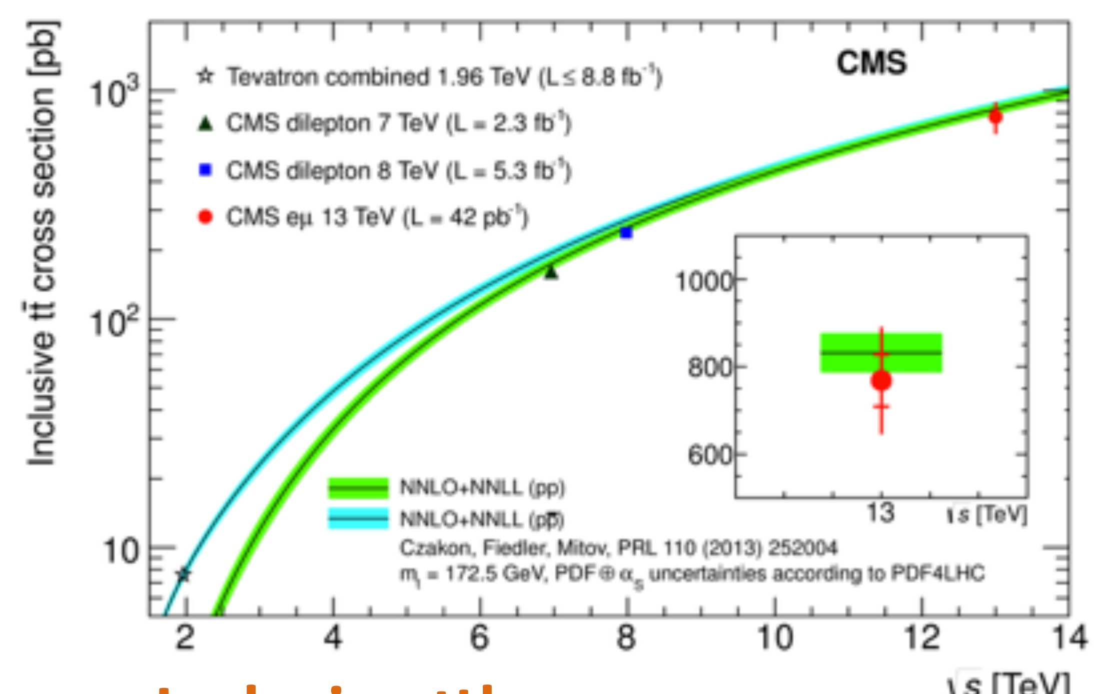
33 public results for 13 TeV 2015:

http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/LHC-Jamboree-2015.html



Dimuon mass spectrum:

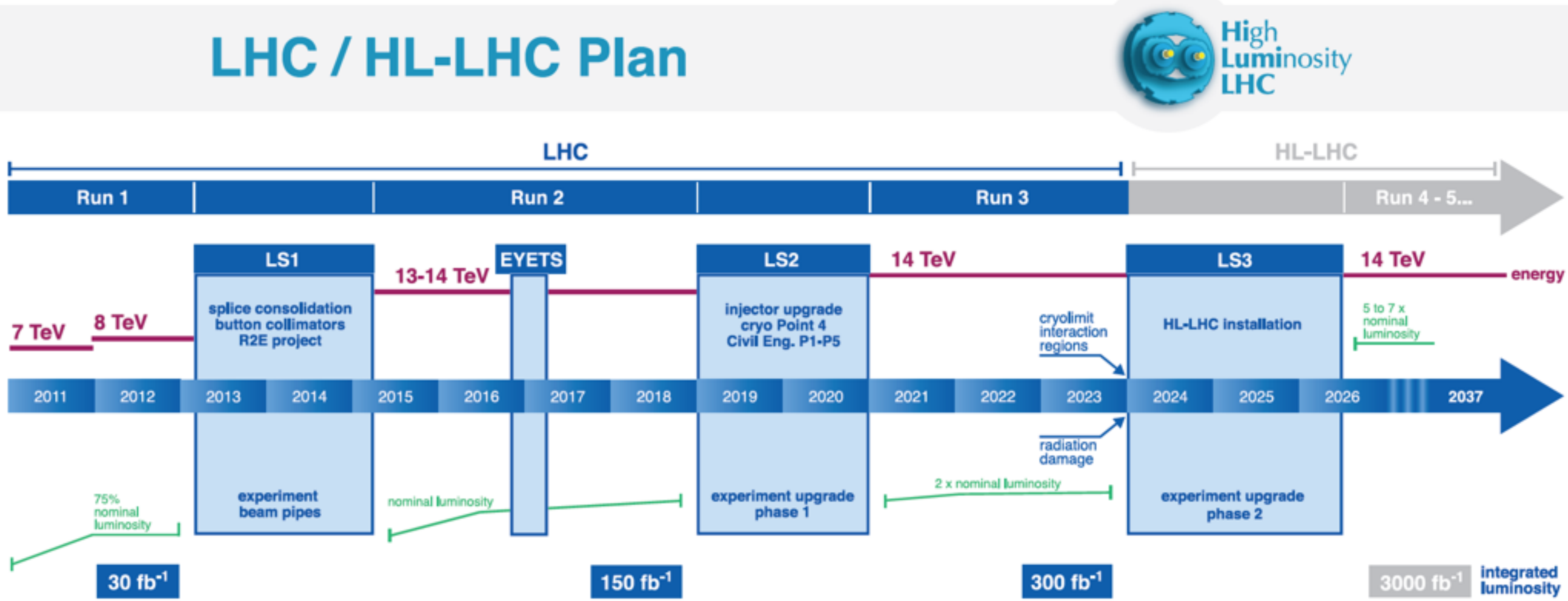




Inclusive ttbar x-sec

CMS Upgrade Plan

http://hilumilhc.web.cern.ch/about/hl-lhc-project



CMS Phase I Upgrades
2015 - 2020

CMS Phase II Upgrades
2024 - 2026

CMS Phase I Upgrades

Pixel tracker

4-layer barrel and 3 forward-disk pixel tracker with new readout chip capable of higher hit rate (installation during end of 2016 extended technical stop).

Hadron calorimeter

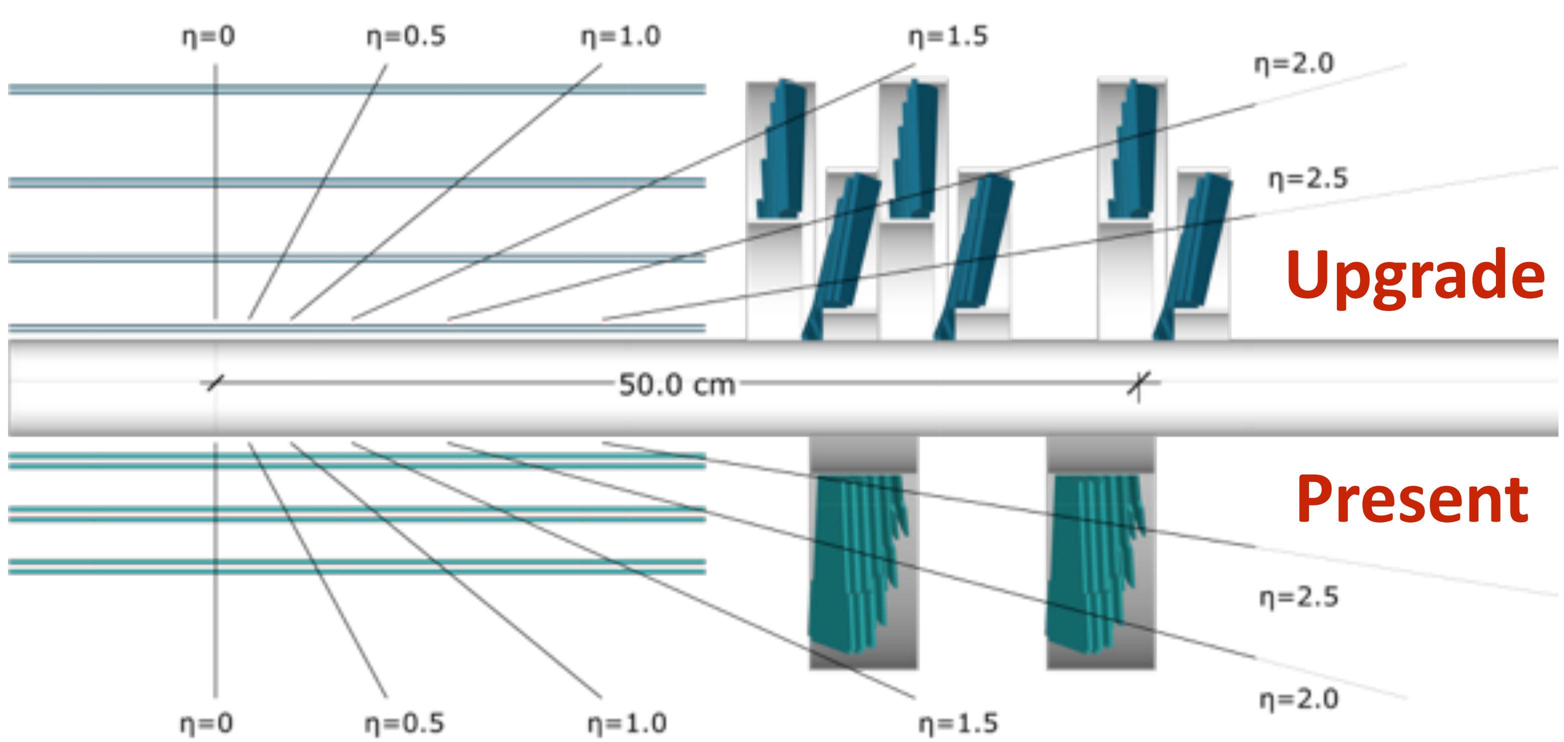
Installation of SiPM devices into barrel/endcap calorimeters and new electronics in the forward calorimeter (installation during EYETS 2016/2017) allowing timing-based background rejection.

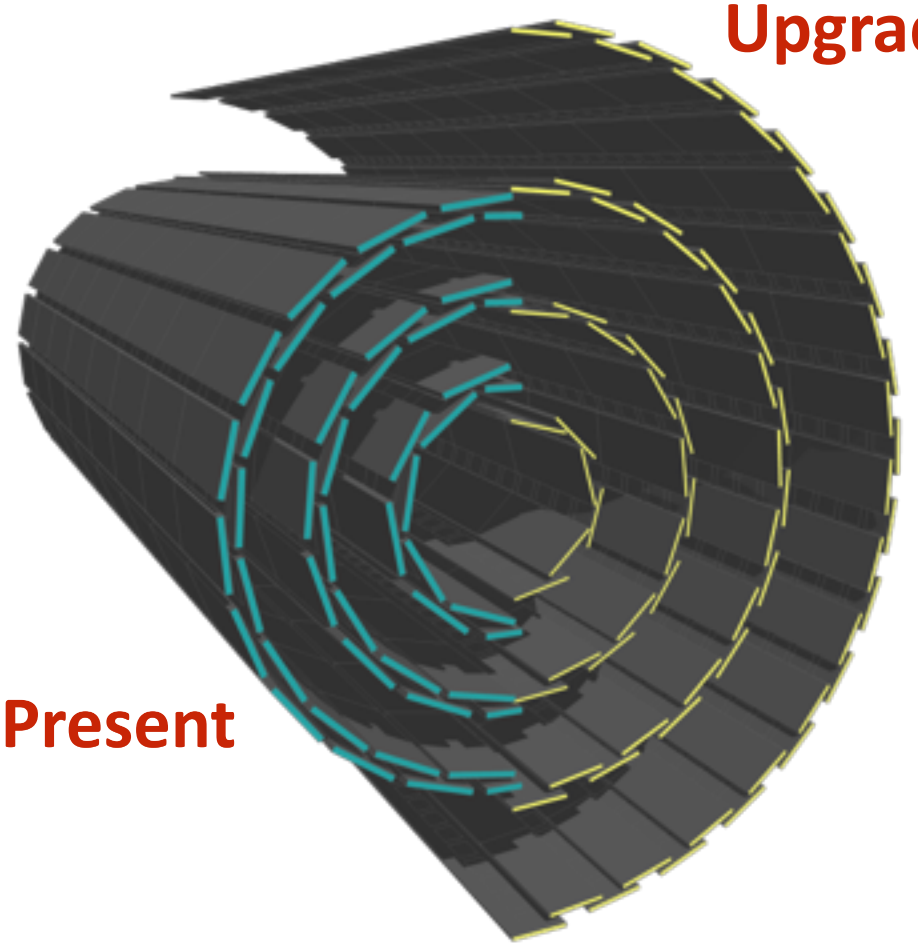
Trigger

Upgrade the muon and calorimeter Level-1 trigger systems and global trigger processor to handle higher luminosities without loss of efficiency for key physics channels (installation and commissioning during 2015-2016).

Phase I Pixel Upgrade

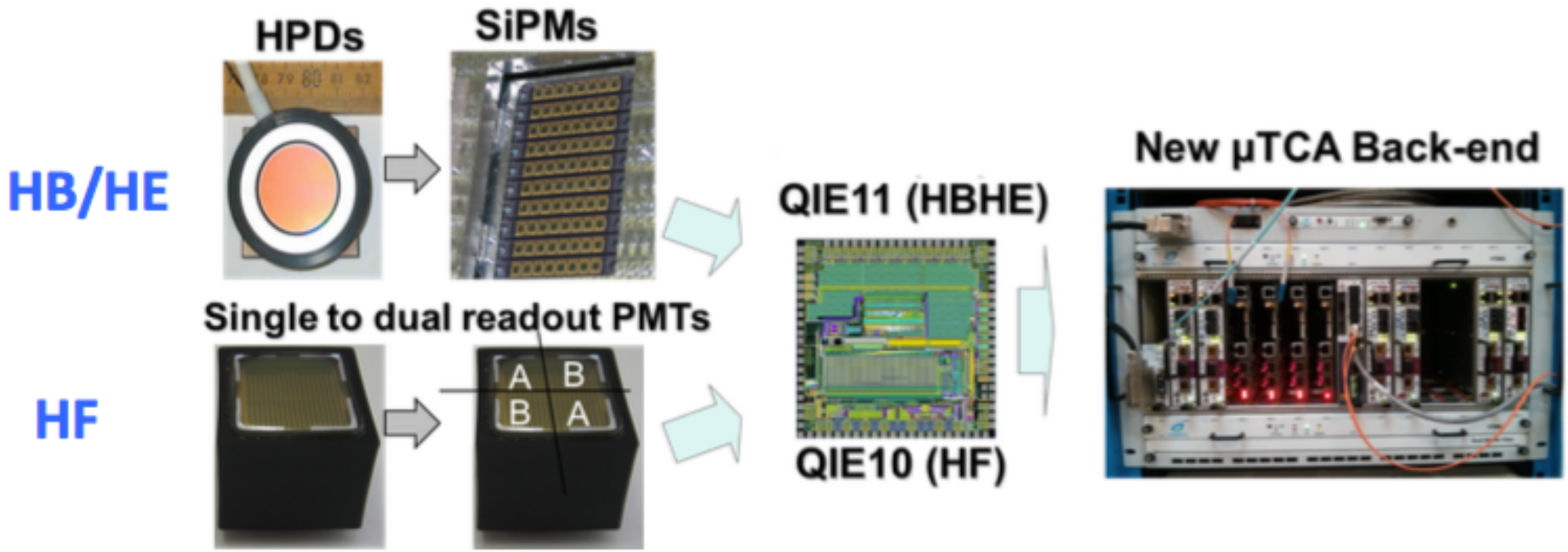
- One additional layer will be added in the barrel and endcap regions (most inner barrel layer with a radius of 3 cm): will reduce fake rate and improve track resolution and efficiency.
- New readout chip to operate without data loss up to $2x10^{34}$ $cm^{-2}s^{-1}$ at 100kHz trigger rate.
- 8 pilot modules are installed on forward blades for Run-2.



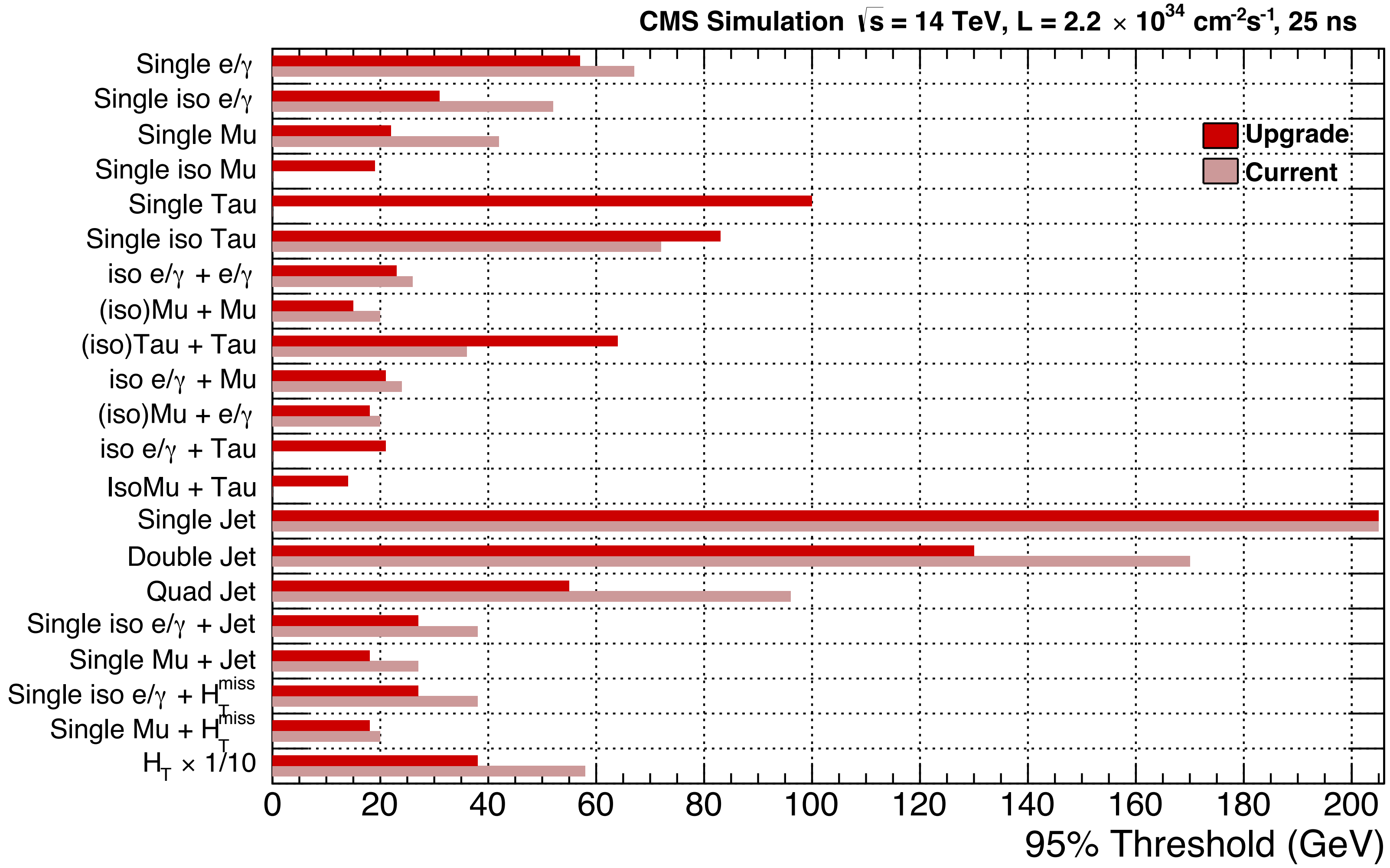


Phase I Hadron Calorimeter Upgrade

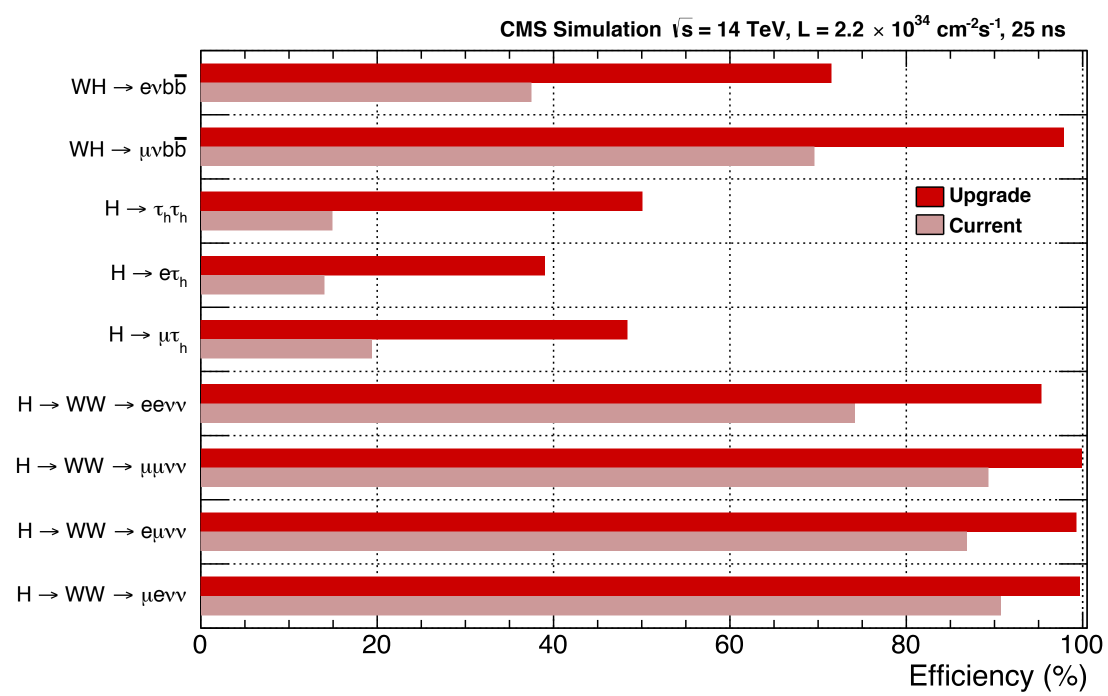
- **New photodetectors** to deal with radiation and anomalous signals:
  - **HF:** Photomultipliers (PMT) to multi-anode PMTs.
  - **HB/HE:** Hybrid photo diodes (HPD) to Silicon Photomultipliers (SiPM).
- New Front-End and Back-End electronics.

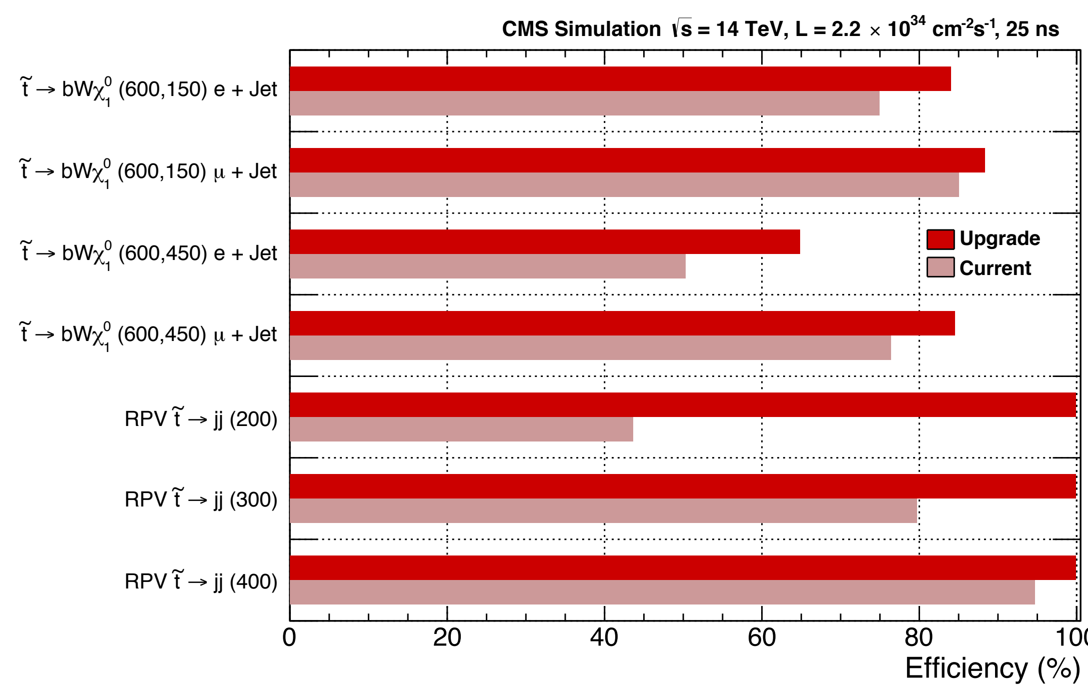


Phase I LIT upgrade

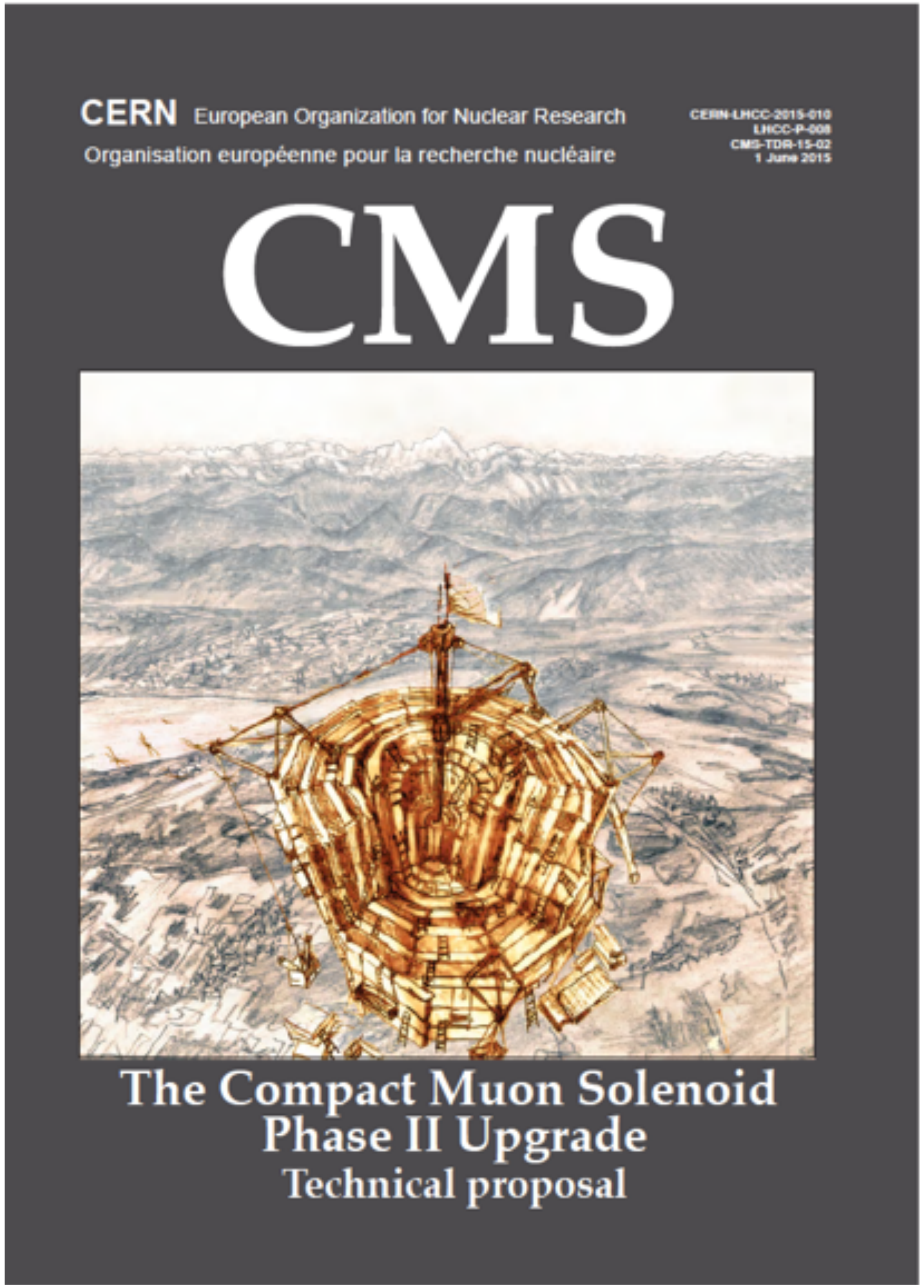


- Need to maintain the trigger performance of Run-1 towards Run-2&3.
- Move to high-performance FPGA's and common use of the μTCA architecture.
- Deployed from "legacy" to "upgrade" trigger system in two stages.





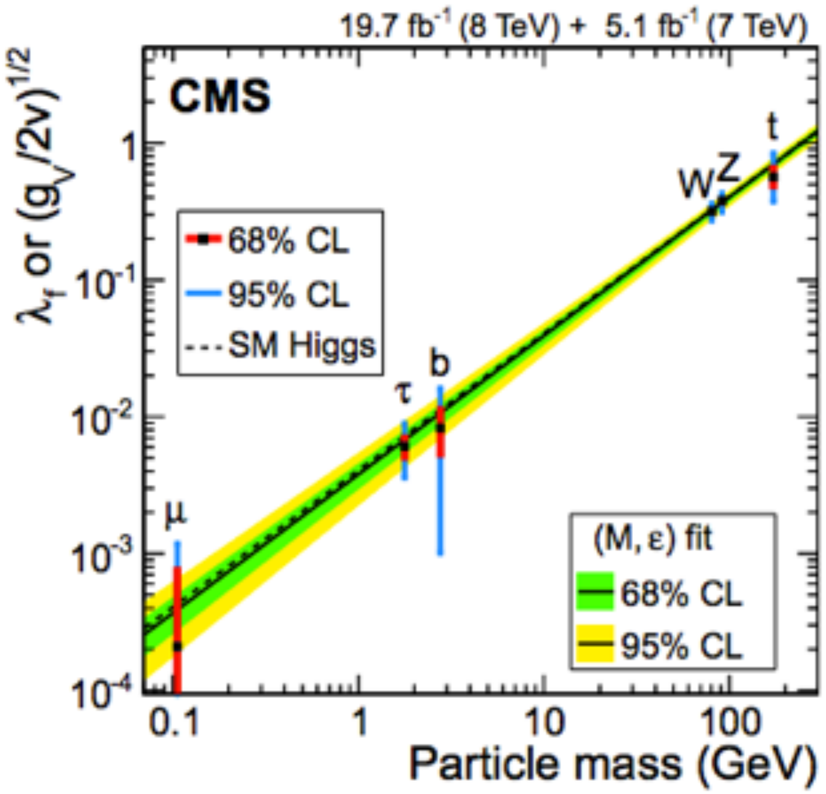
CMS Phase II Upgrade



- Physics motivations
- Detector upgrades
- Software and computing
- Detector performance
- Project planning
- Estimated cost

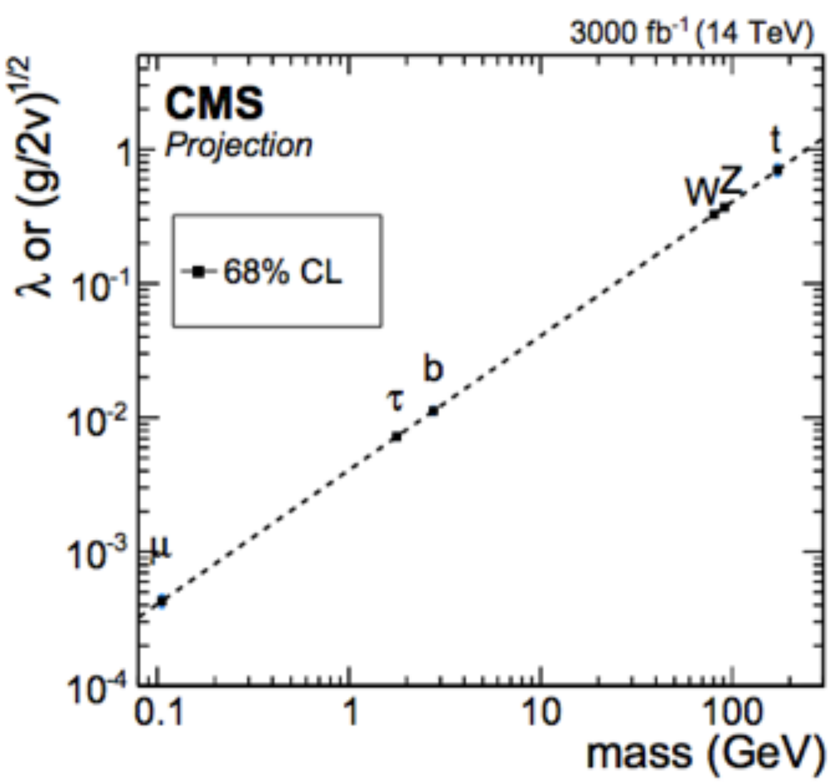
http://cds.cern.ch/record/2020886

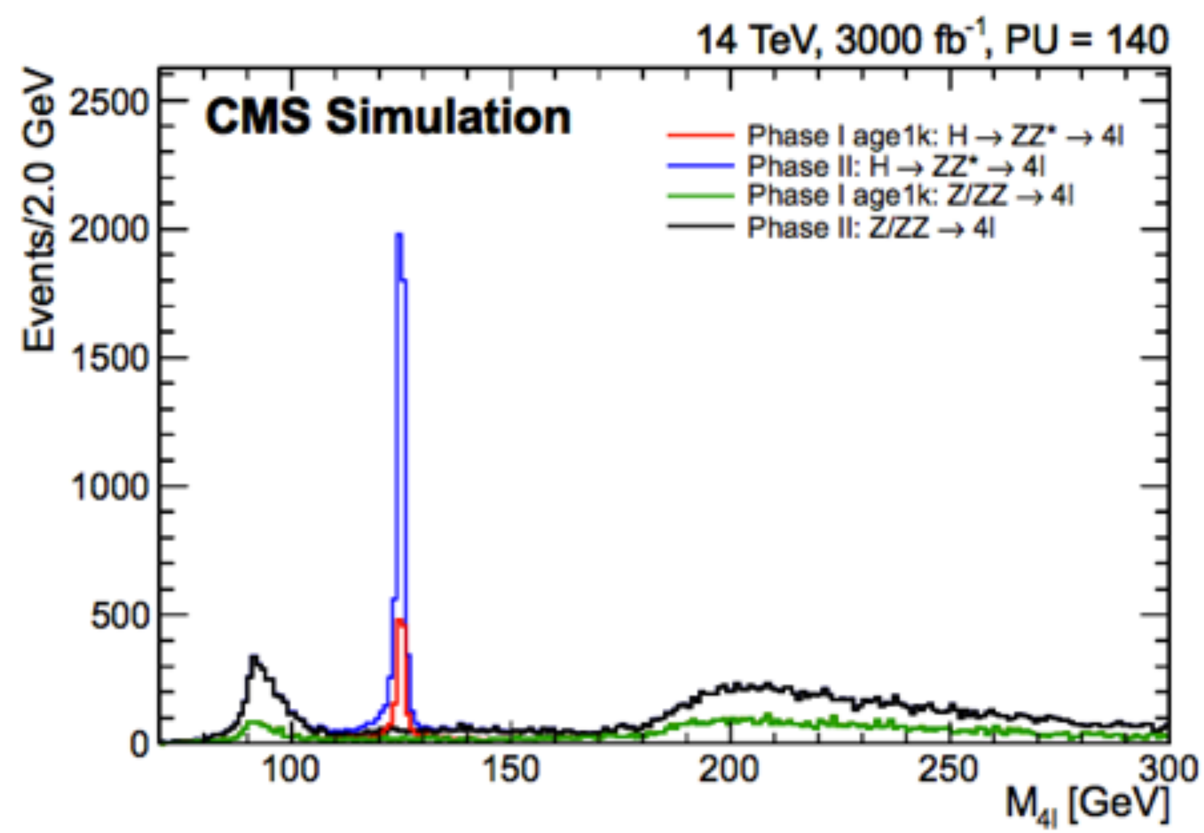
Physics Opportunities at 3000 fb^{-1}



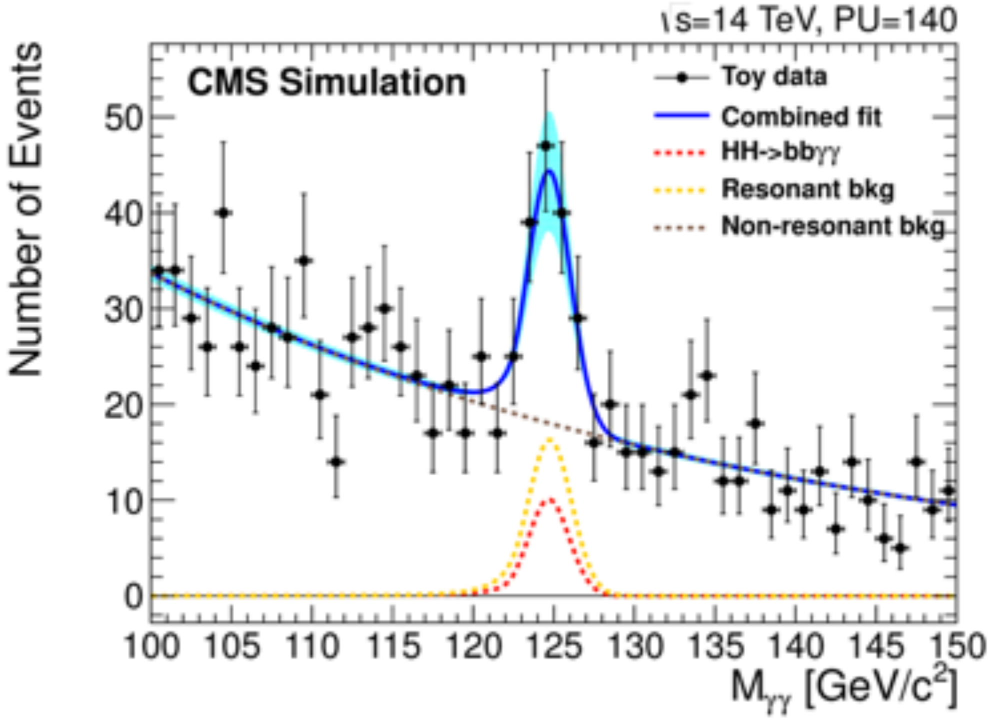
Higgs

- 2-10% precision on Higgs couplings.
- Coupling to the 2nd generation fermions will be probed for the first time by measuring the Higgs boson decays to two muons.
- Evidence of di-Higgs production (allow to study Higgs boson self coupling).



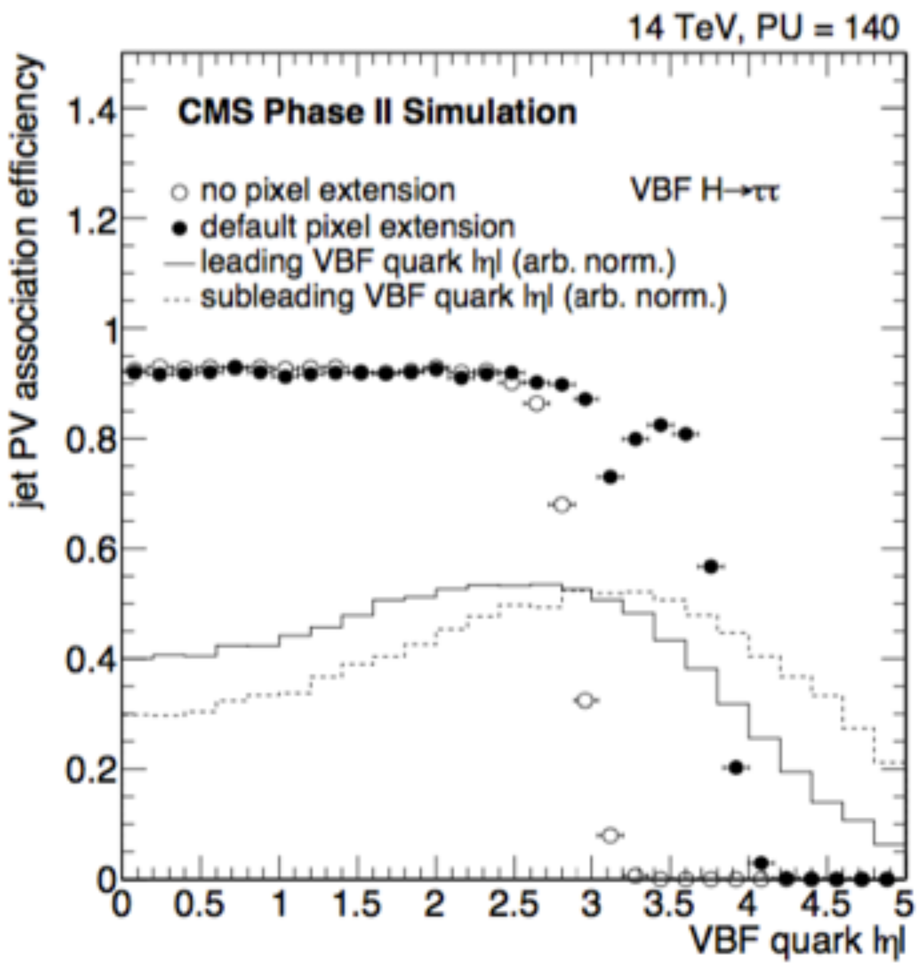


Physics Opportunities at 3000 fb^{-1}



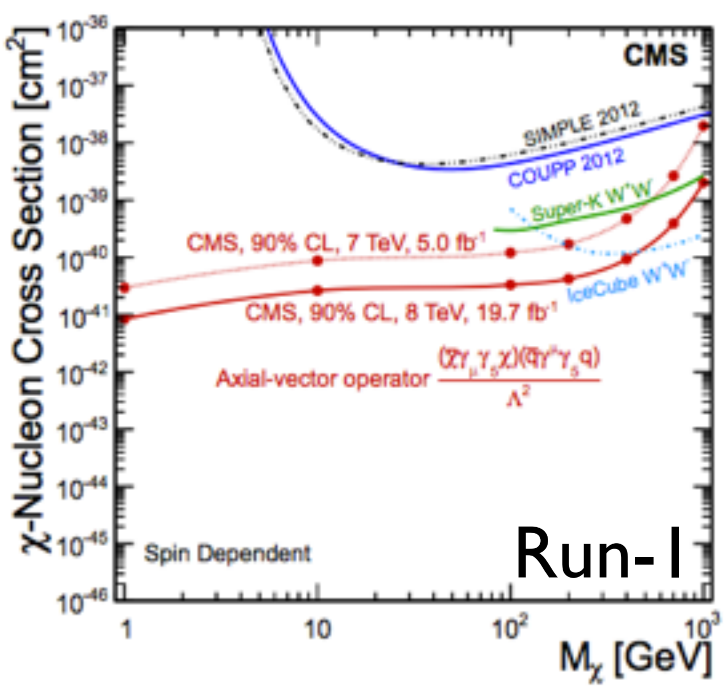
Higgs

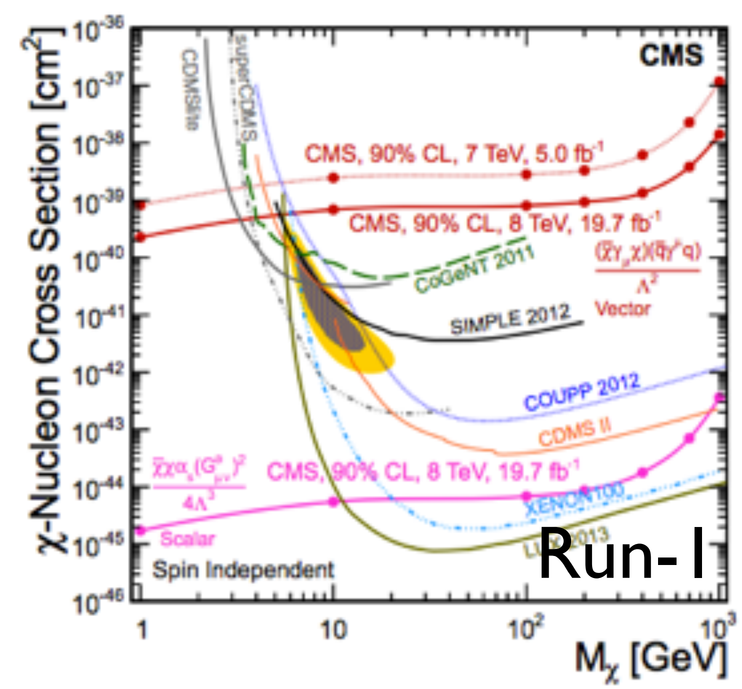
- HH → bbγγ with background from ZH, ttH, bbH
- VBF H → ττ: enabled by VBF jet tagging, τ-ID, MET resolution



EXO

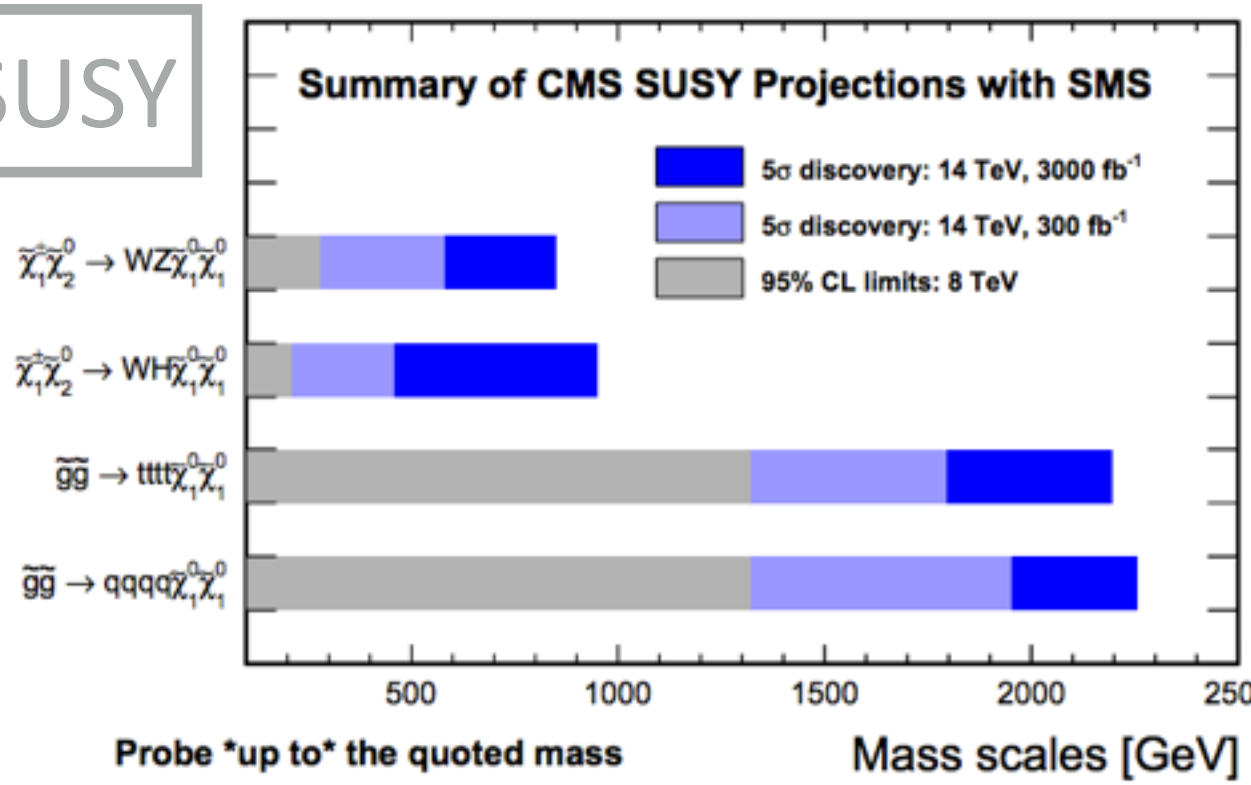
- Mono-channel to search for the Dark Matter, including MonoHiggs.



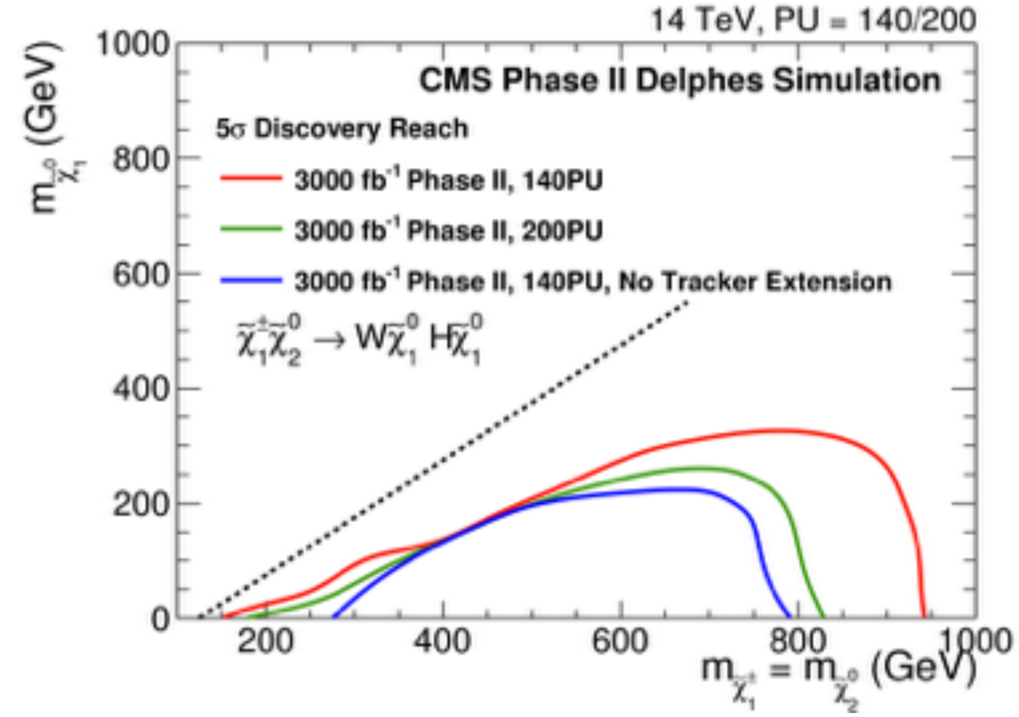


Physics Opportunities at 3000 fb^{-1}

SUSY

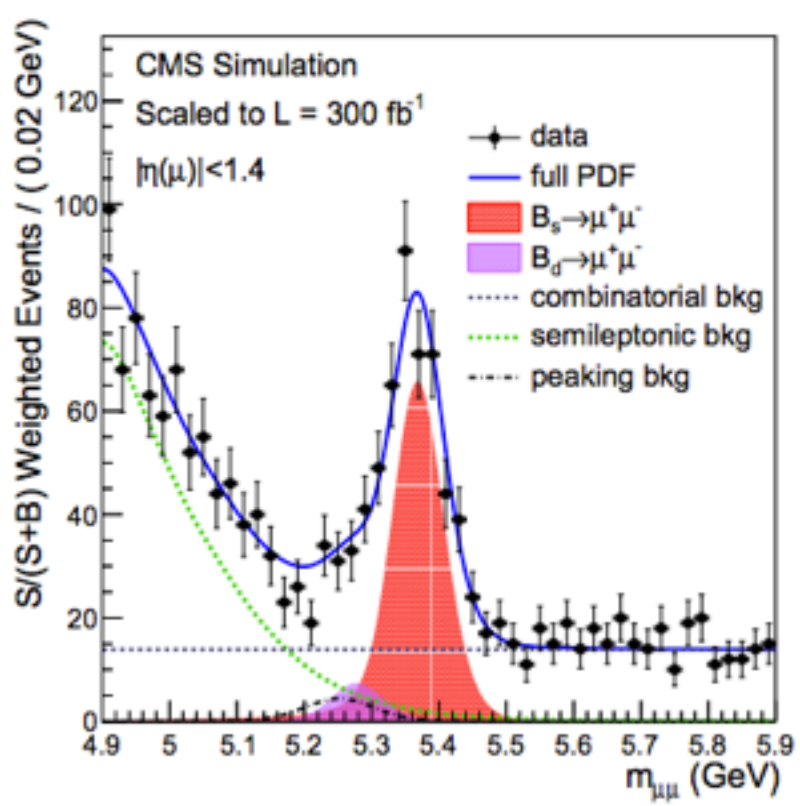


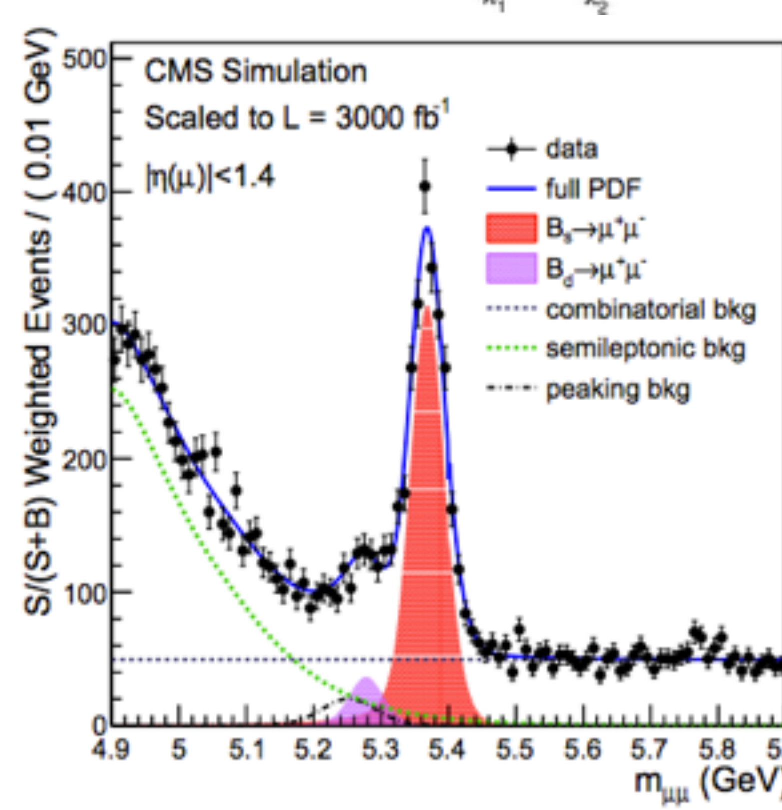
- Neutralino mass range increase - enabled by Tracker extension,b-tagging, MET



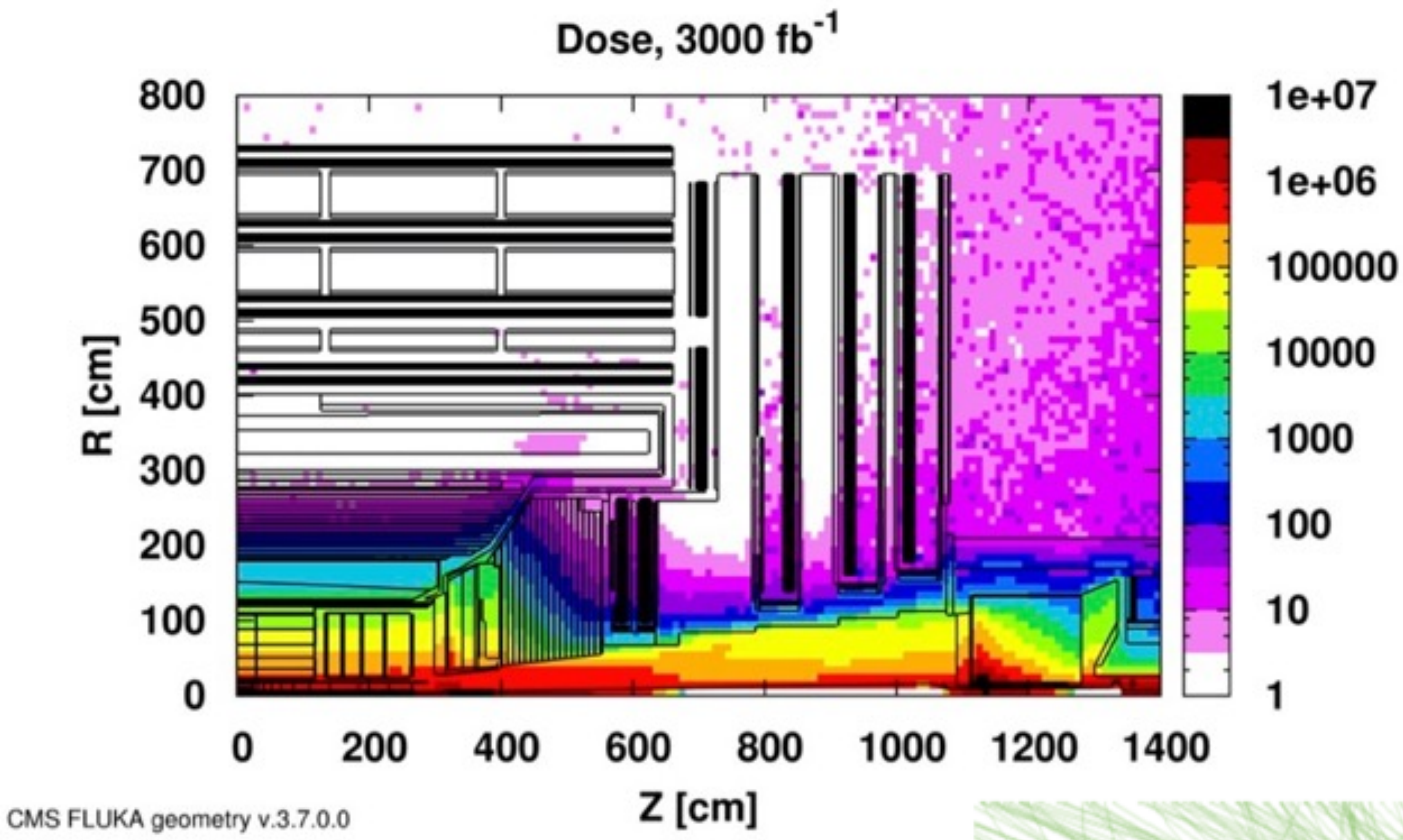
SMP

- Study rare-decay with reasonable accuracy, significance of the Bd, predicted to be 2.2σ after 300 fb^{-1}, will improve to 6.8 σ with 3000 fb^{-1}.





HL-LHC Detector Challenges



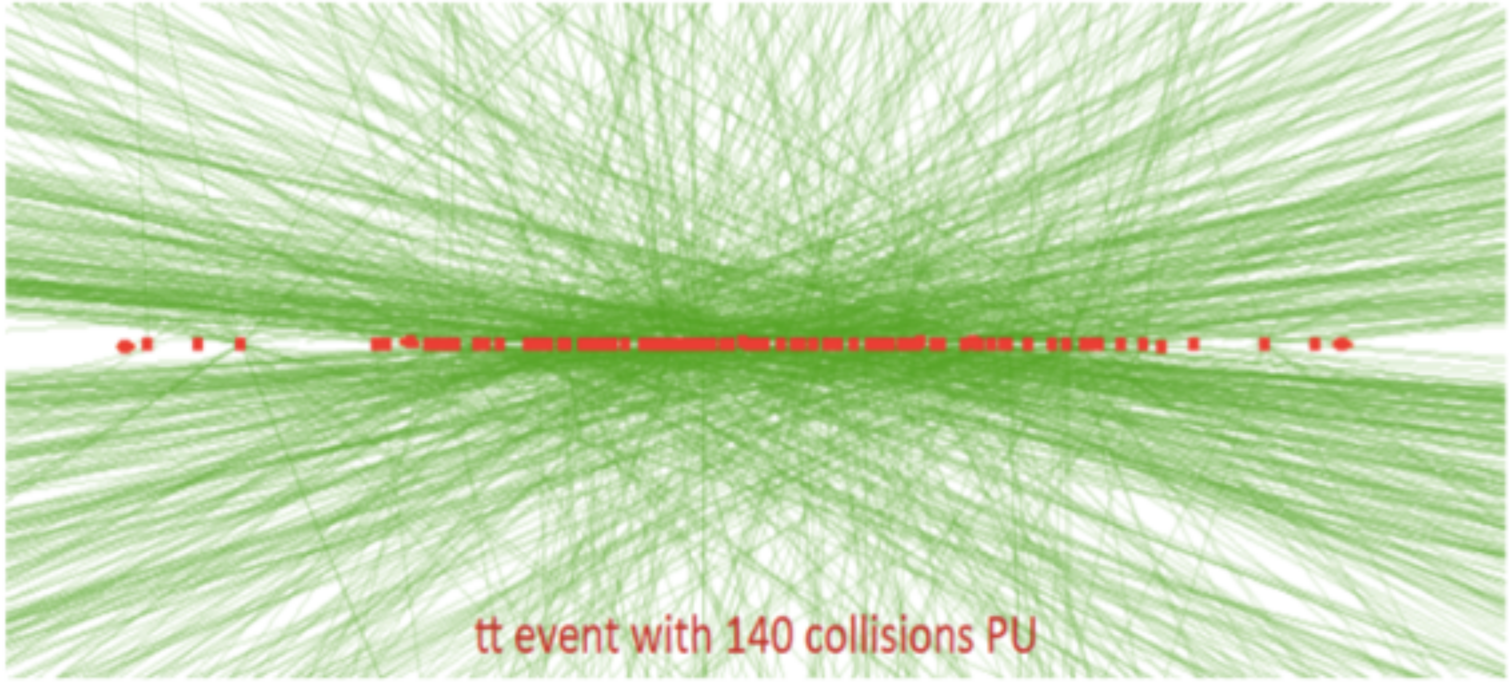
Radiation Damage to the CMS Detector at the HL-LHC

- Aging studies show that Tracker & Endcap Calorimeters need replacement.

High Pile-Up

To maintain detector performance in the presence of higher pileup:

- Upgrade several detector components.
- Redesign some electronics, trigger and DAQ.

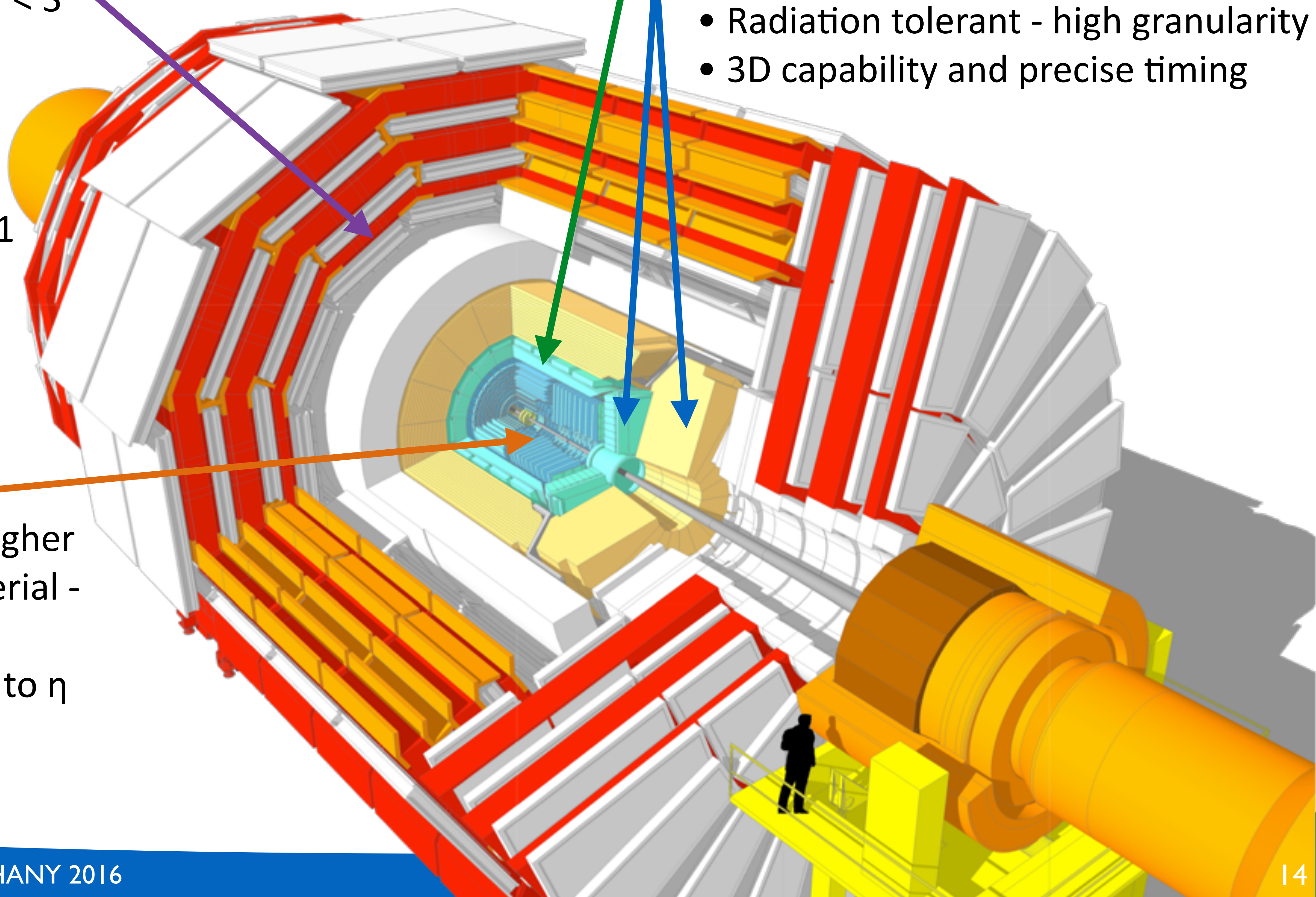


Summary for CMS Phase II Upgrades

Muon system
- Replace DT & CSC FE/BE electronics
- Complete RPC coverage in region $1.5 < \eta < 2.4$ (new GEM/RPC technology)
- Muon-tagging $2.4 < \eta < 3$

Calorimeter
- **Barrel EM calorimeter**
  - Replace FE/BE electronics
  - Lower operating temperature
- **Replace endcap calorimeter**
  - Radiation tolerant - high granularity
  - 3D capability and precise timing

L1/HLT/DAQ
- Track information at L1
- L1-Trigger ~ 750 kHz
- HLT output ~7.5 kHz

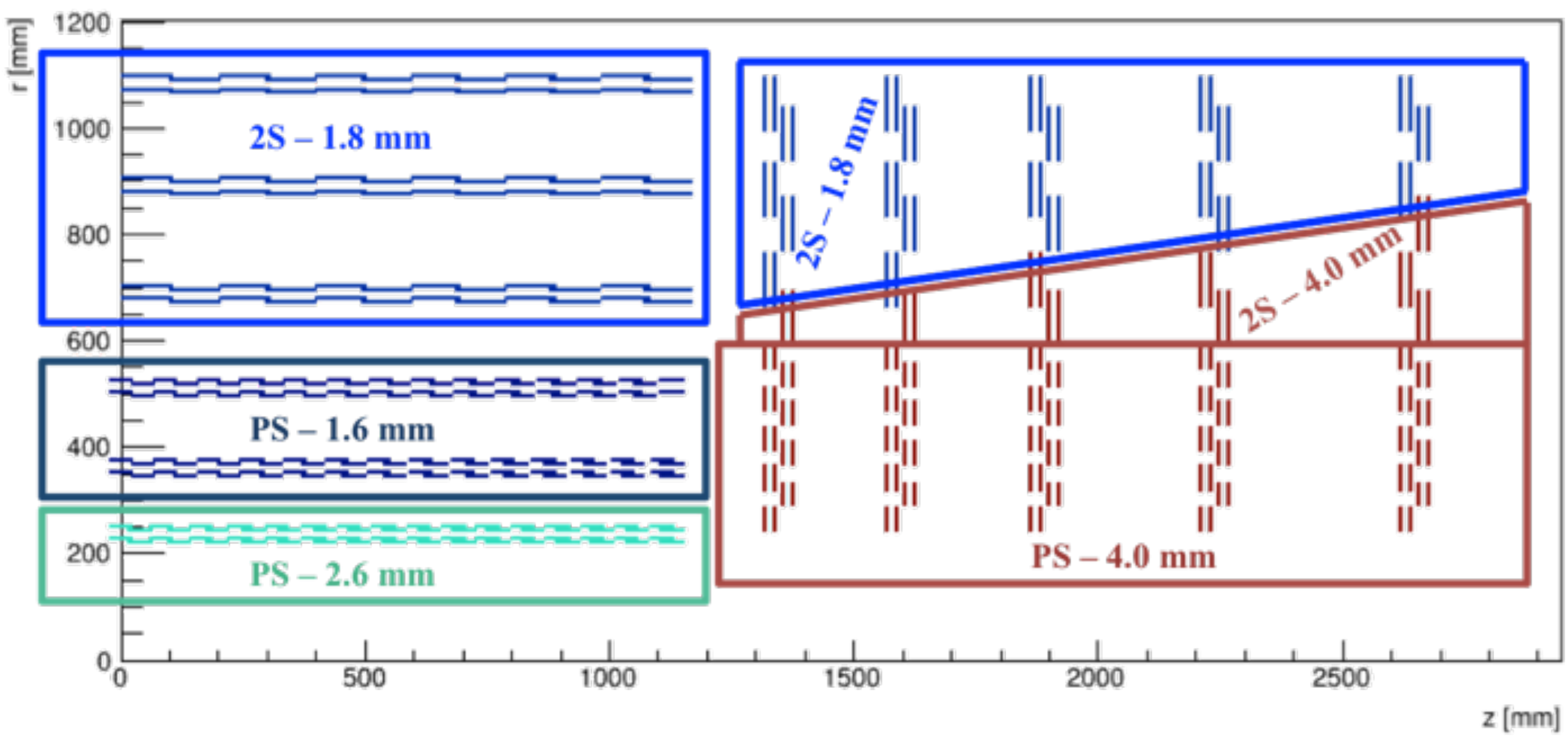


Replace Tracker
- Radiation tolerant - higher granularity - less material - better p_T resolution
- Extended η region up to $\eta \sim 3.8$
- Tracks trigger at L1

Phase II Outer Tracker Configuration

Several configurations investigated with simplified simulation to define baseline:

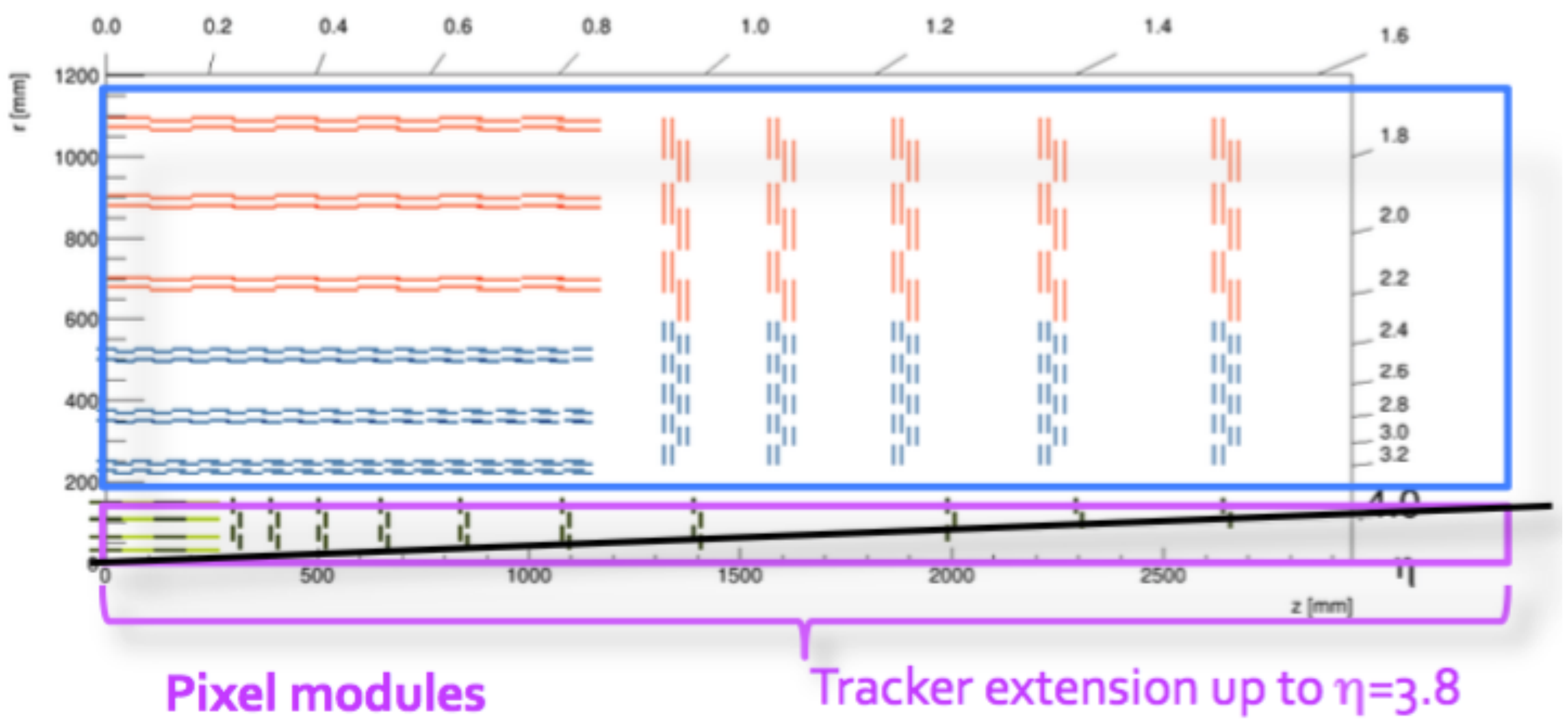
- 6/5 barrel/endcap layers/disks - instead of 10/11 in current outer tracker.
- Increased granularity through short strips - ≃ x4 current outer tracker.
- 2 sensors modules in all layers for Trigger purpose.
- Long Pixel in 3 inner layer modules (PS) for z-coordinate measurement.
- Light module design & mechanics - CO2 cooling (-30°) - DC/DC powering.



Phase II Pixel Detector Configuration

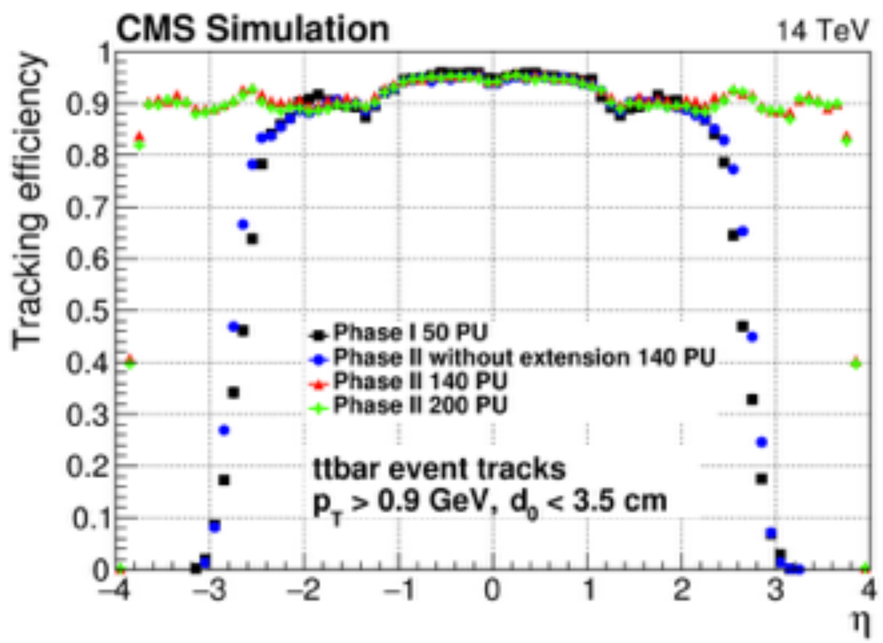
Current configuration based on Phase-I design - ongoing studies to reduce material and to improve/adapt resolution through reduced pixel size

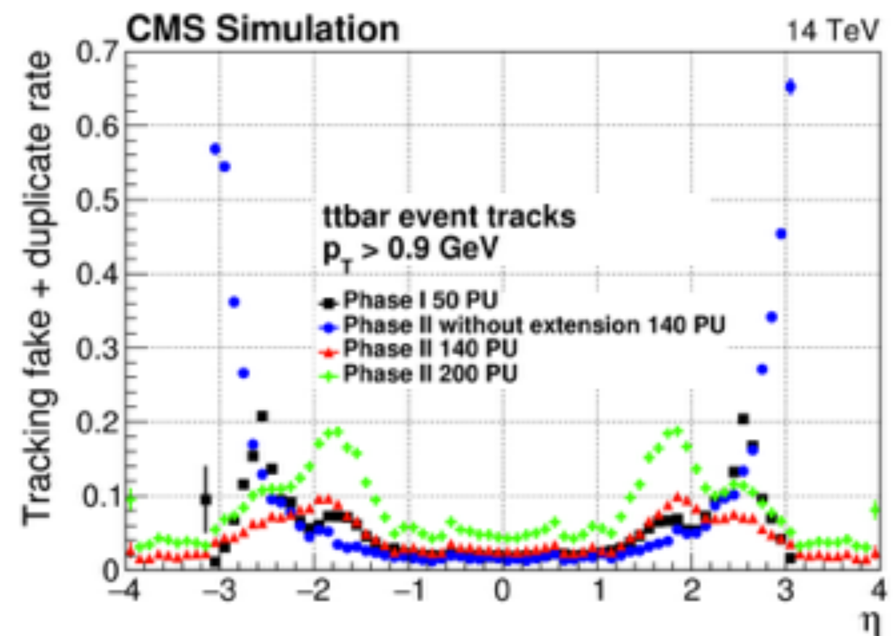
- Barrel pixel with 4 layers at 3, 7, 11 and 16 cm.
- Forward pixel with 10 disks extending coverage to η=3.8.
- Data readout at 750 kHz.
- Maintainable during winter shutdown.



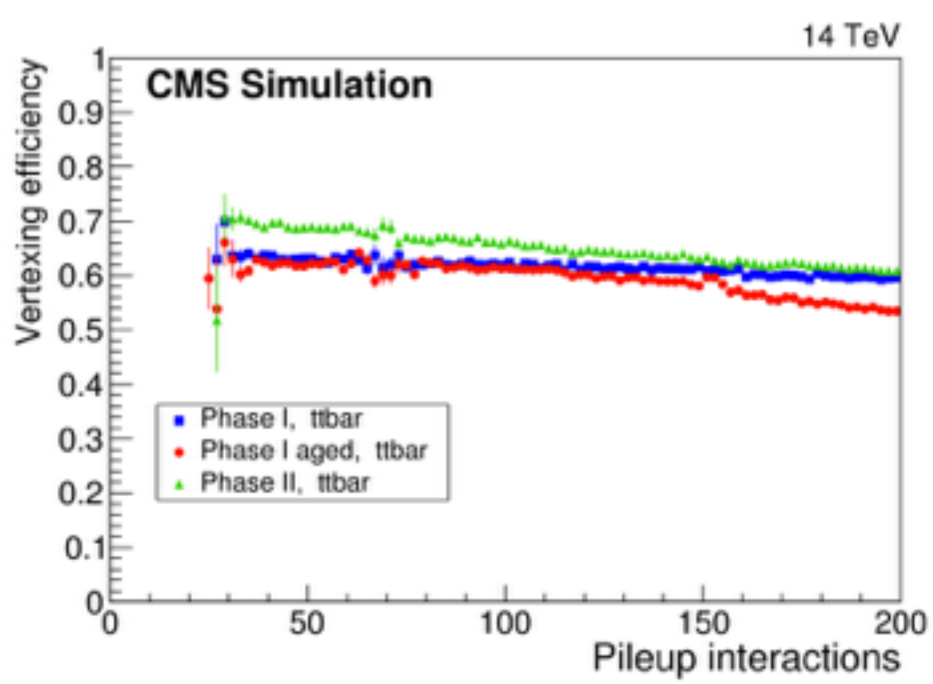
Phase II Tracker and Tracking

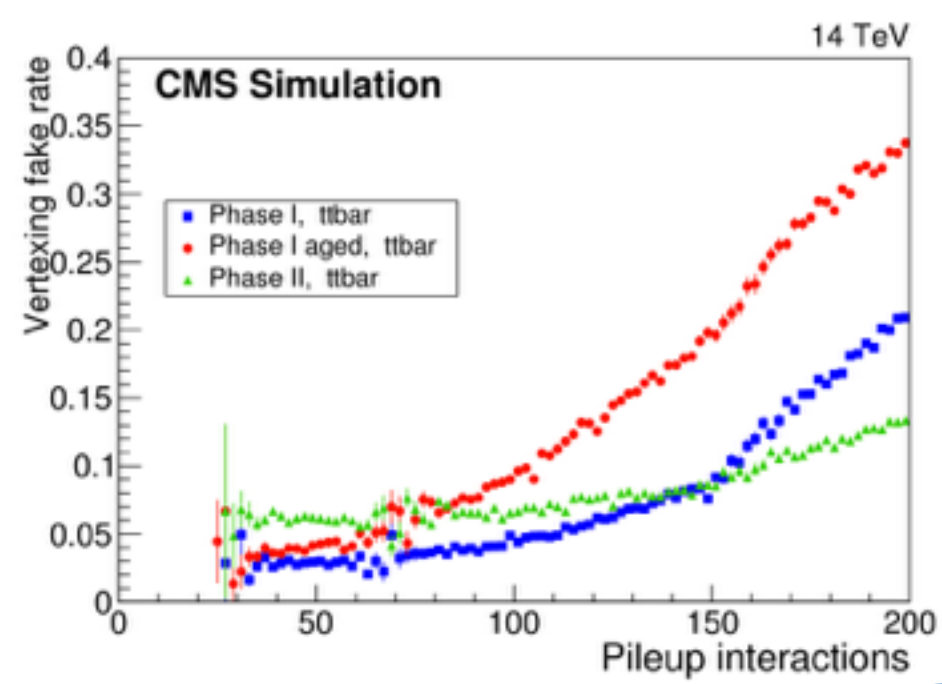
- Track efficiency and fake rates for Phase-II 200 PU similar to Phase-I 50.
  - Tolerable fake increase at 200 PU.





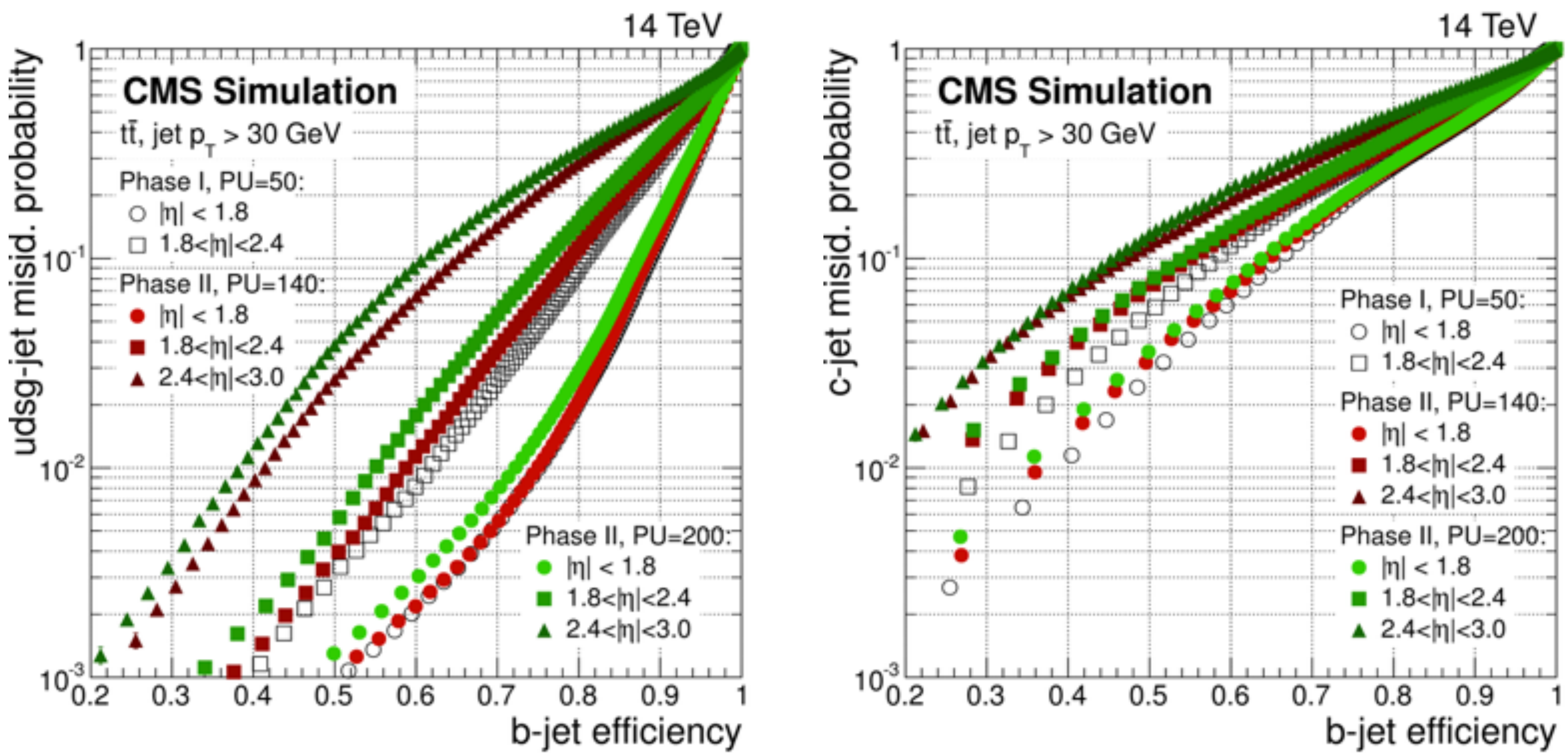
- Momentum resolution substantially improved (lower pitch and less material).
- Signal Primary Vertex efficiency ≥ 95% with 20 µm resolution at 200 PU.





Phase II Tracker and Tracking

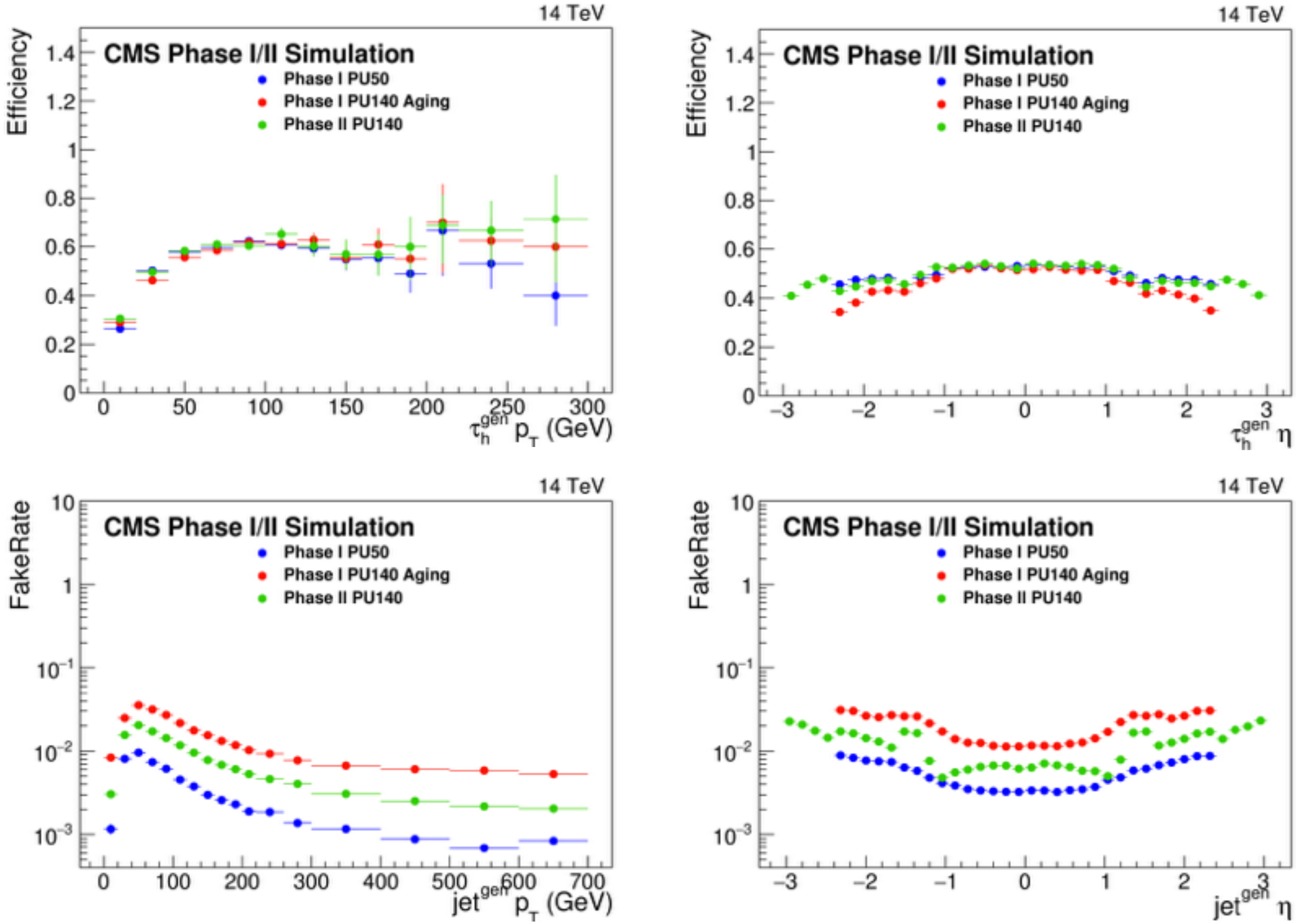
- **b-tagging** Phase-II recovers Phase-I performance - expected to improve with new pixel design (smaller pitch & less material).



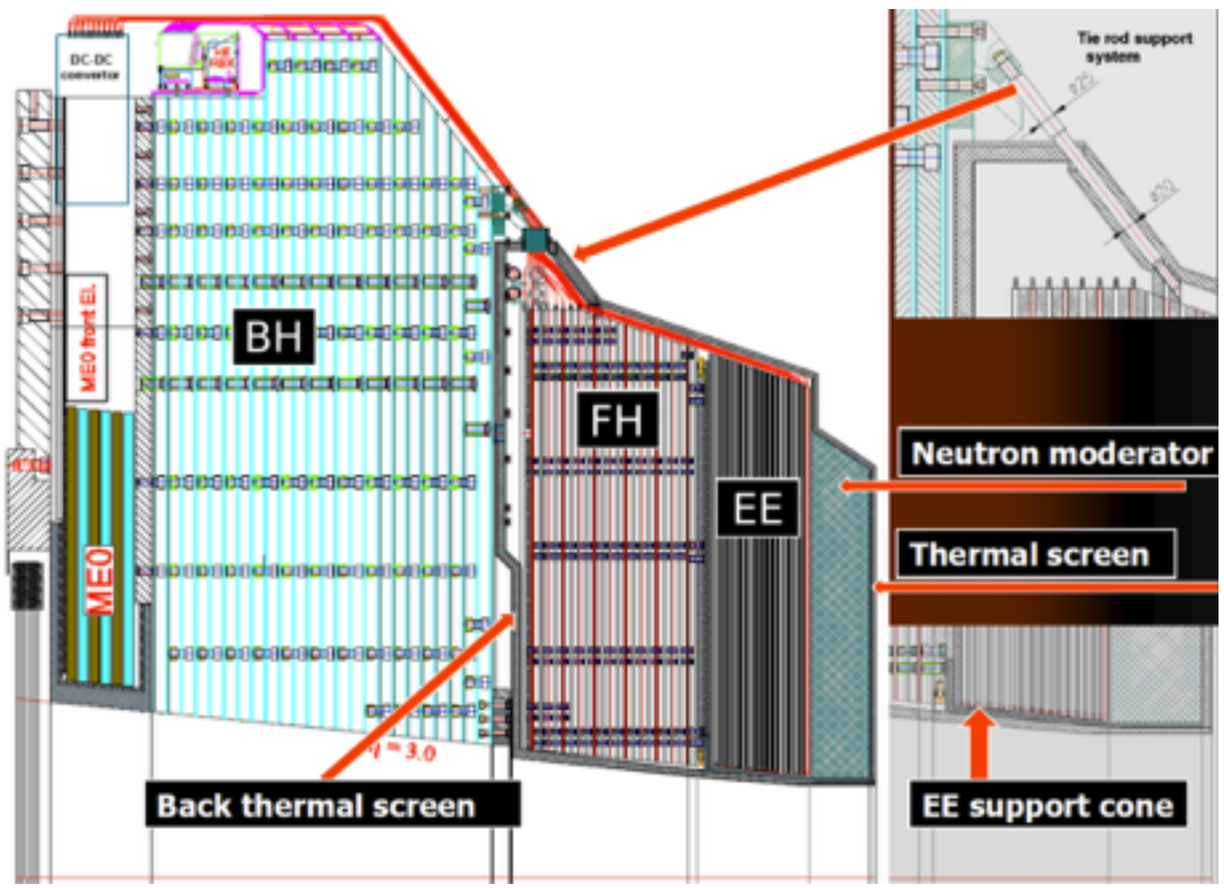
Performance is expressed as misidentification probability for udsg-jets and c-jets as a function of b-jet tagging efficiency.

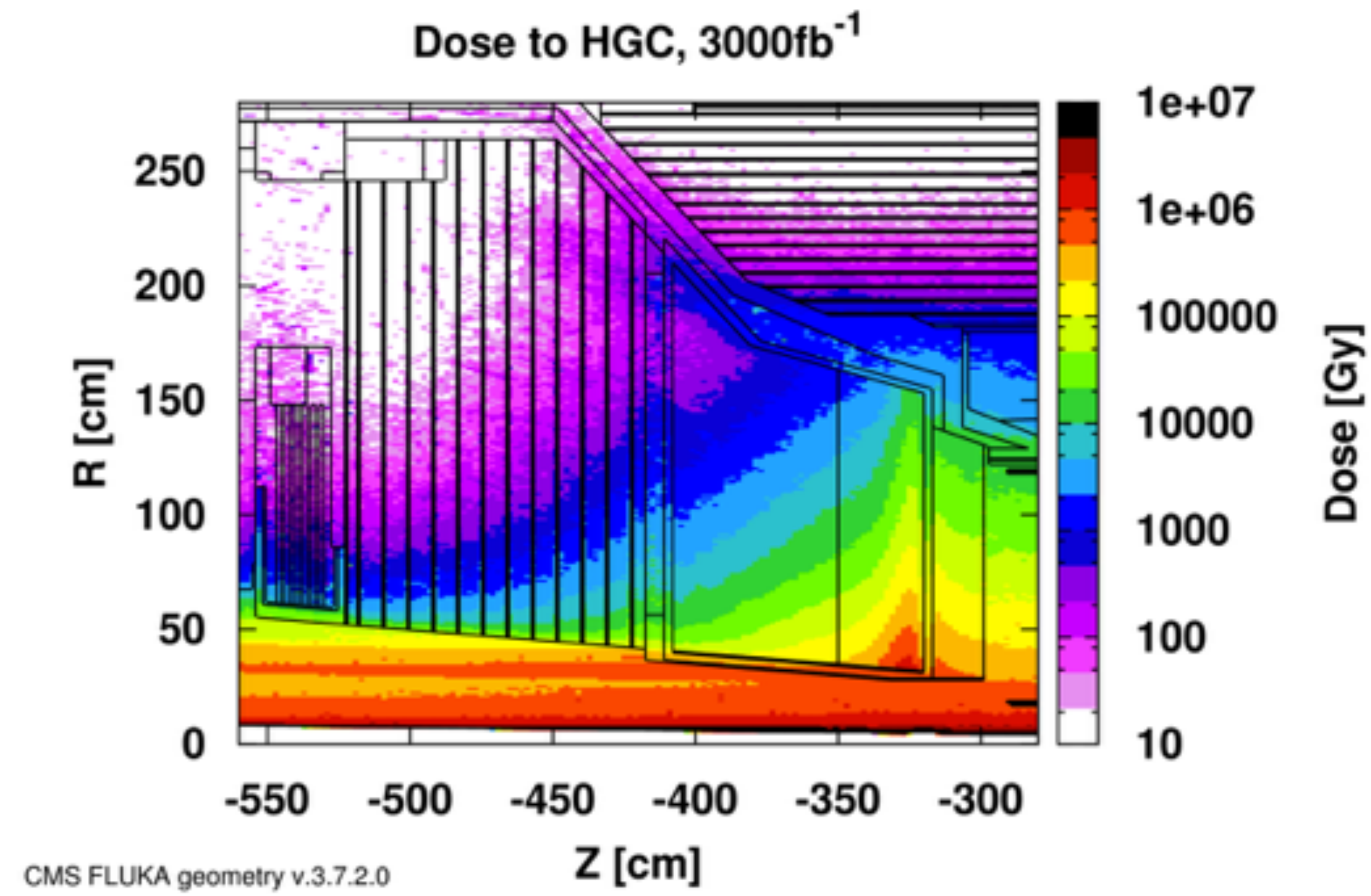
Phase II Tracker and Tracking

- **τ-ID** - based on track isolation (robust to PU) same efficiency working point below



Phase II Calorimeters



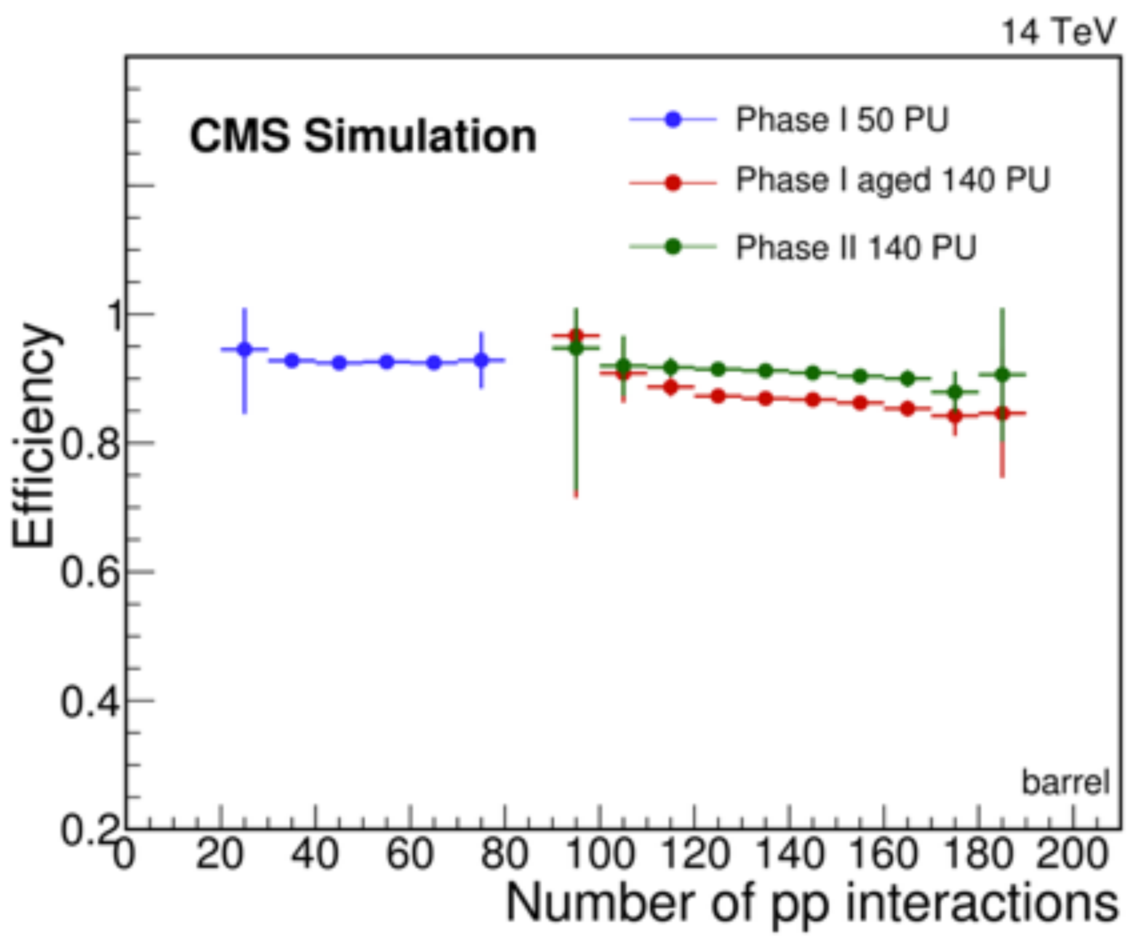


- Challenges from high radiation dose in |η| ~ 3, neutron flux and PU, CMS proposes to replace endcap calorimeters with new high-granularity sampling calorimeter (HGC):
  - Electromagnetic EE (Σdepth~26 X0, 1.5λ): 28 layers of Silicon-W absorber.
  - Front Hadronic FH (Σdepth~3.5 λ): 12 layers of Silicon/Brass.
- Back Hadronic Calorimeter (BH) (Σdepth~5 λ): 12 layers of Scintillator/Brass (2 depths readout).

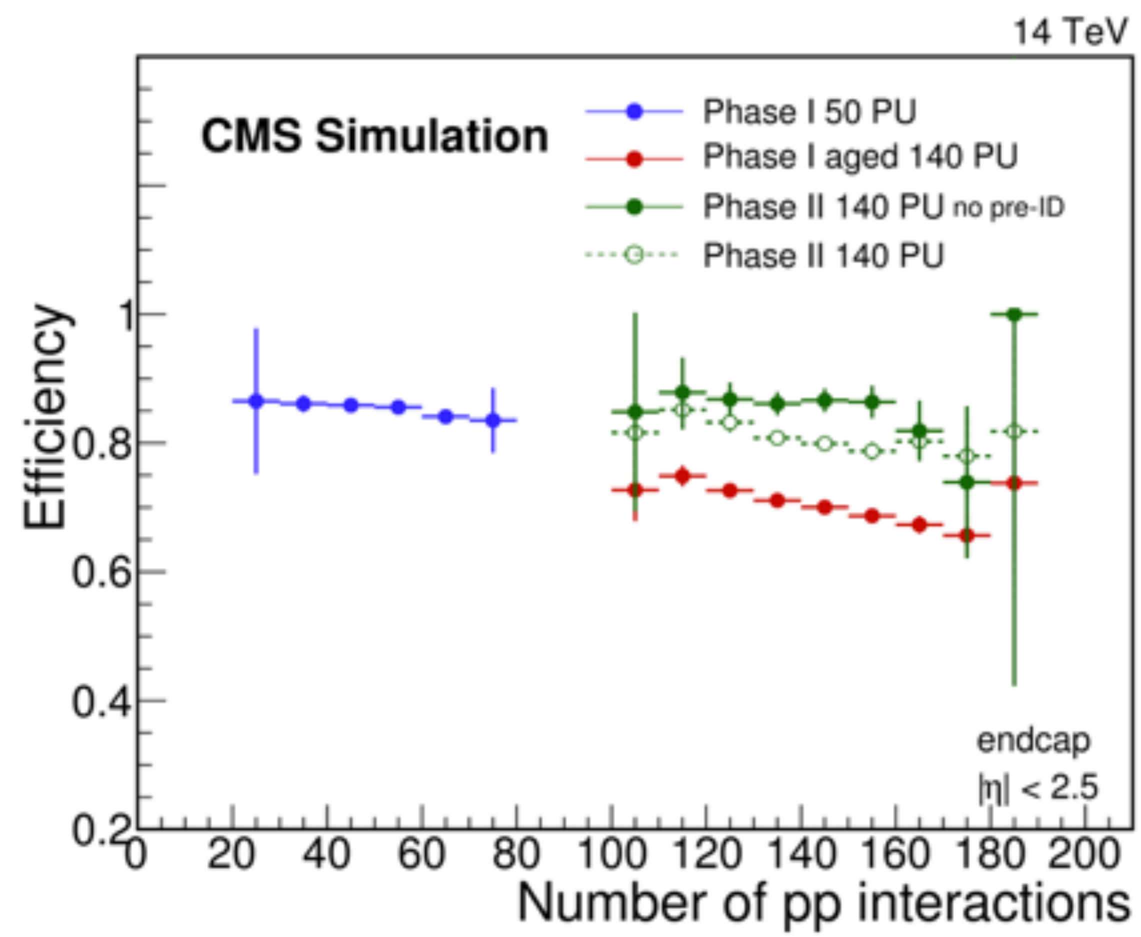
Total Depth ~10λ

Phase II Calorimeters, Electron Eff.

- **Electron** reconstruction efficiency in the ECAL barrel and in the HGCAL endcaps as a function of the number of pileup interactions per crossing.



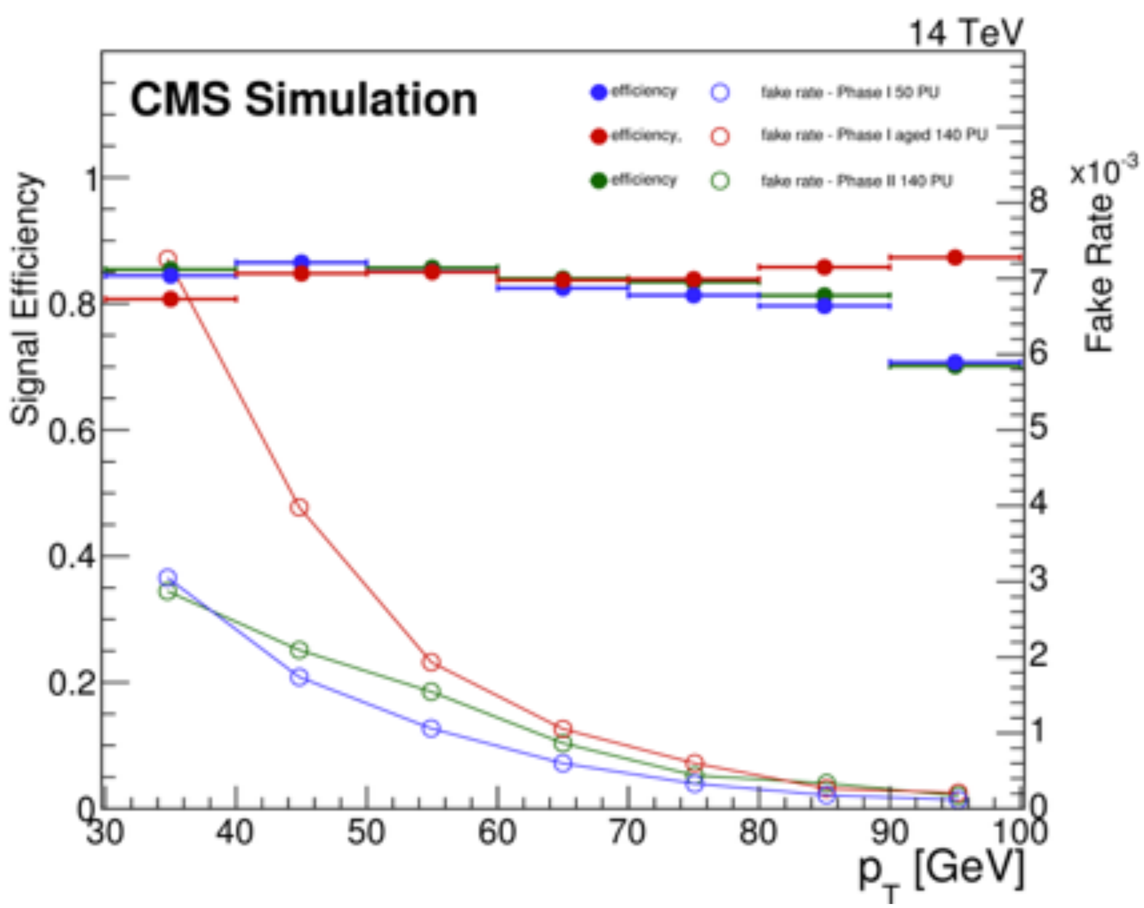
Barrel

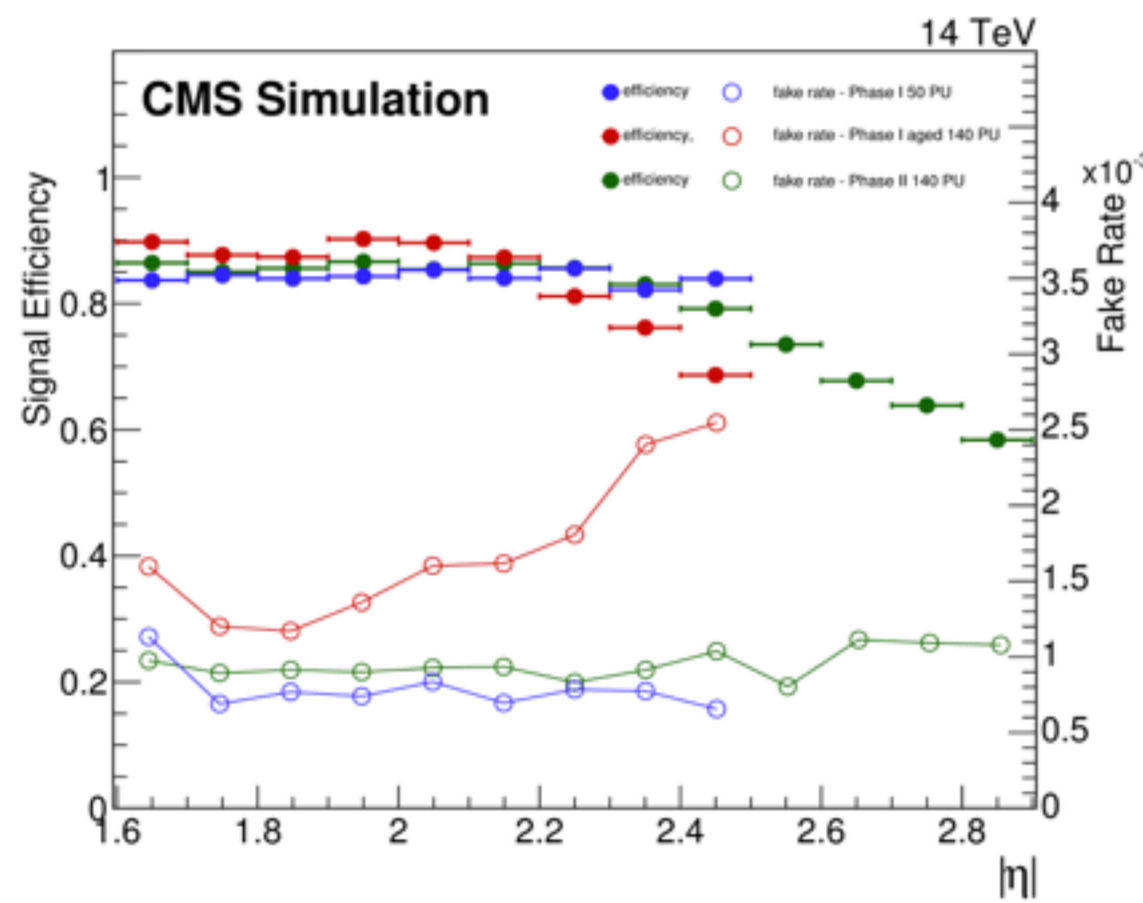


Endcap

Phase II Calorimeters, Photon Eff.

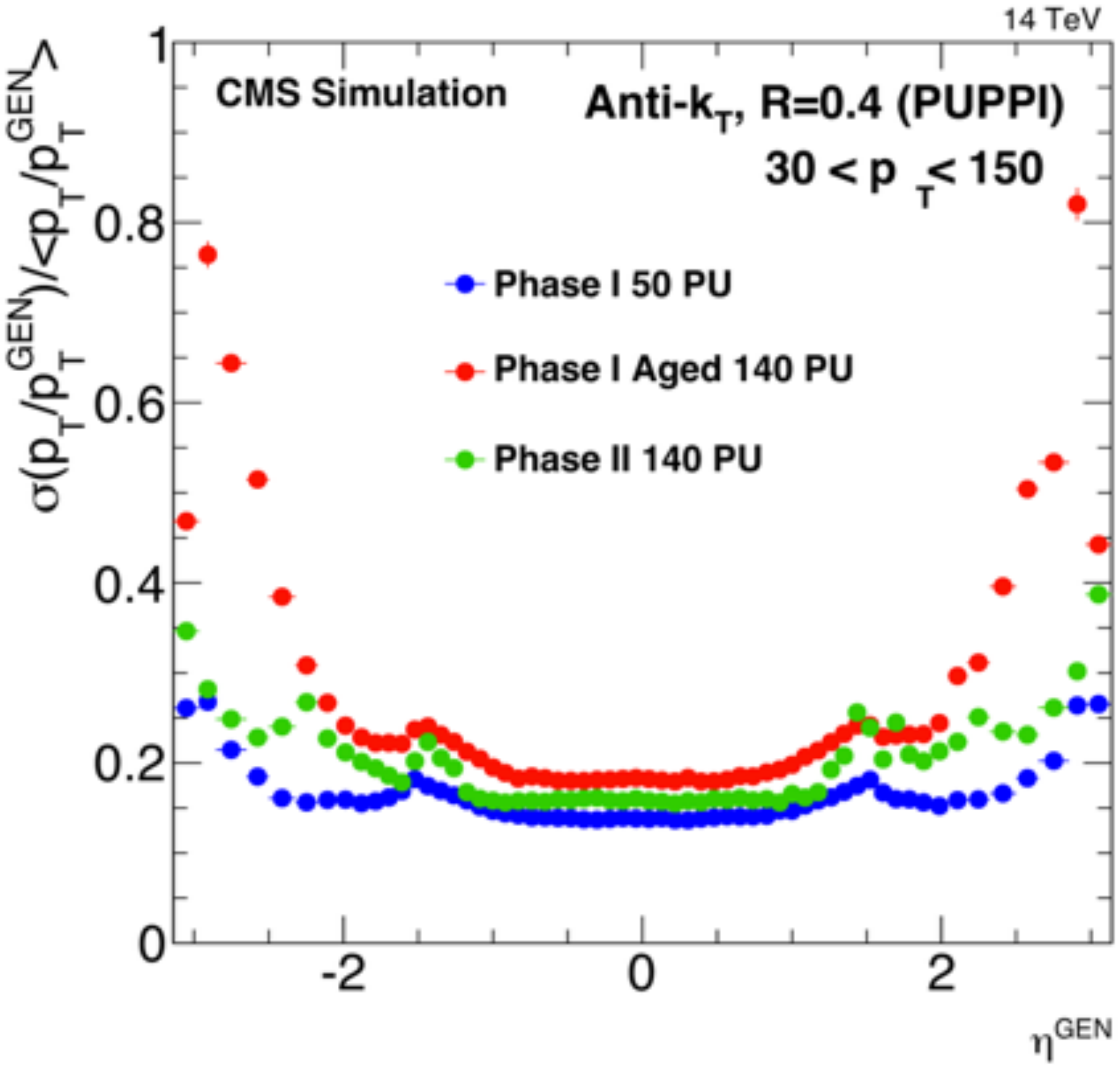
- **Photon** selection efficiency and fake rate in the endcaps in bins of p_T and $|\eta|$.

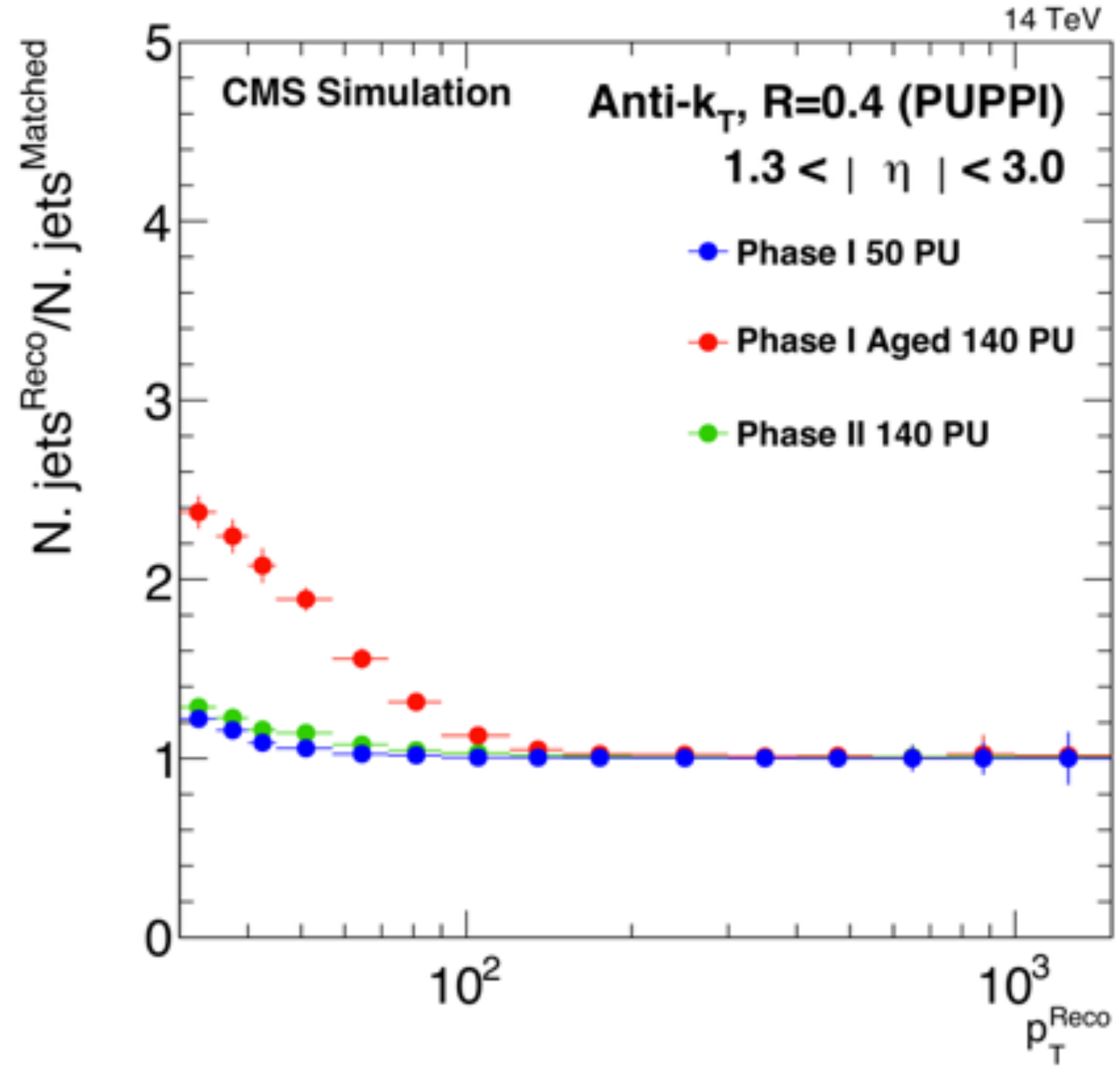




Phase II Calorimeters, Jet

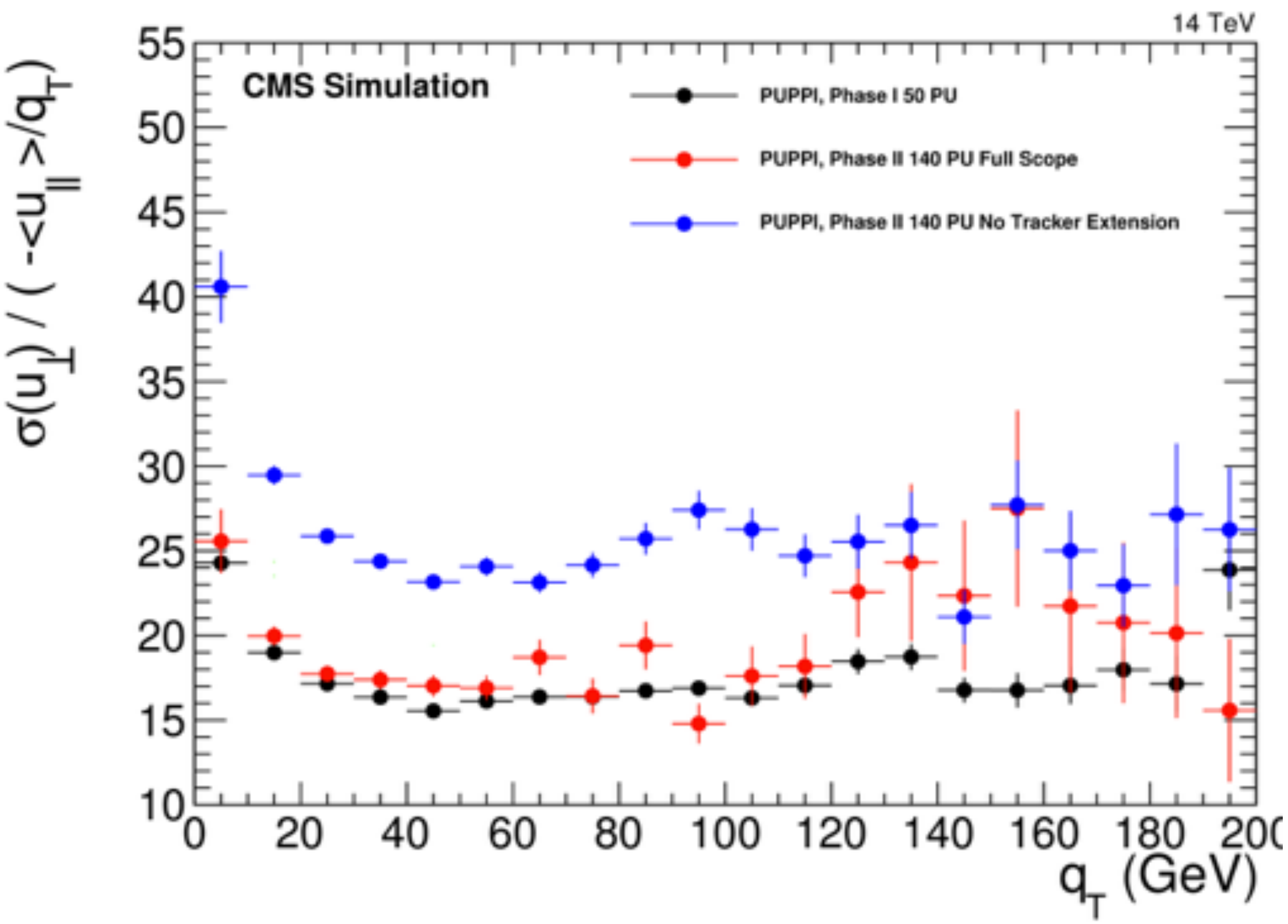
- Combined effect of new EC and Tracker extension allows Phase-II to mostly recover energy resolution and fake rate of Phase-I detector at 50 PU.

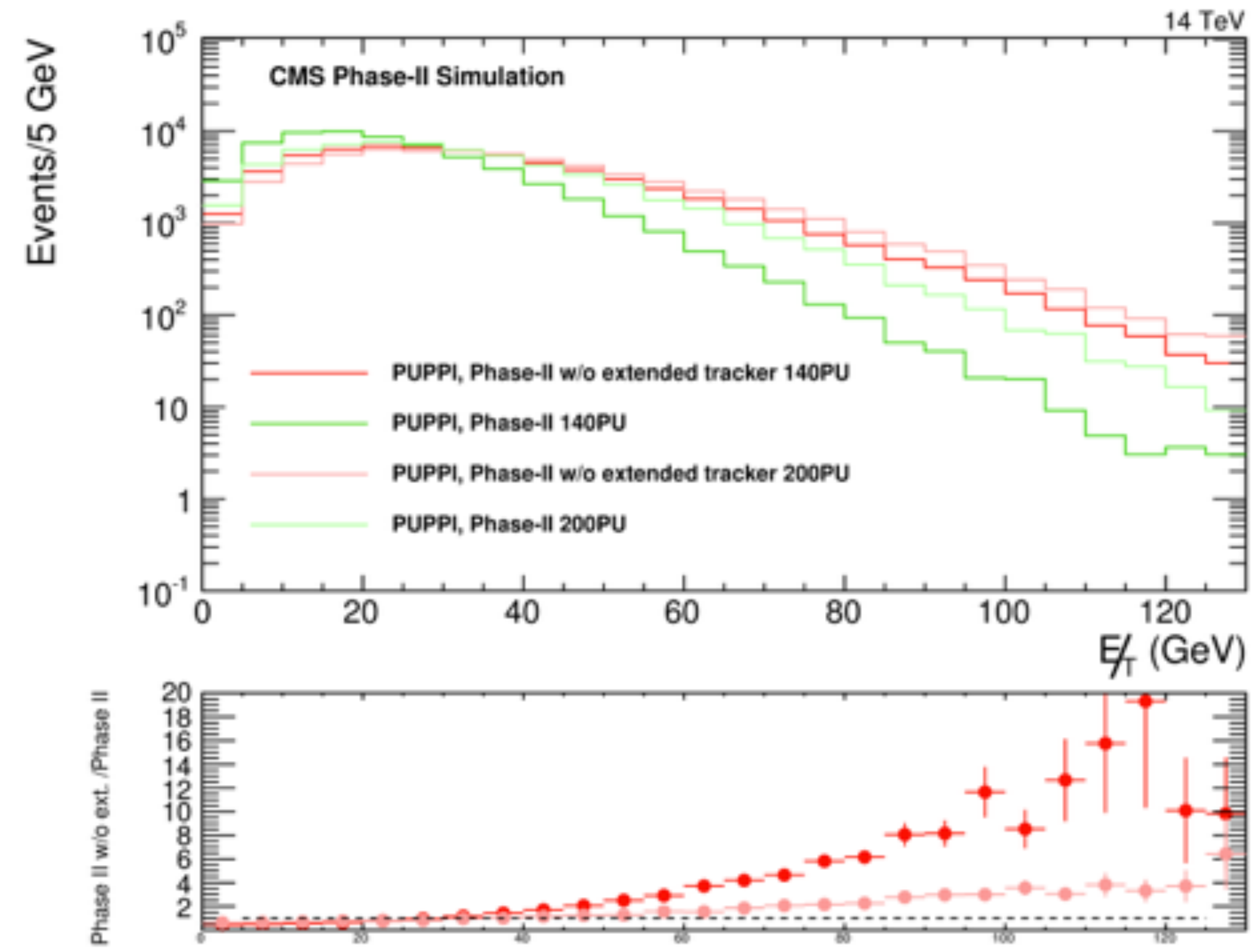




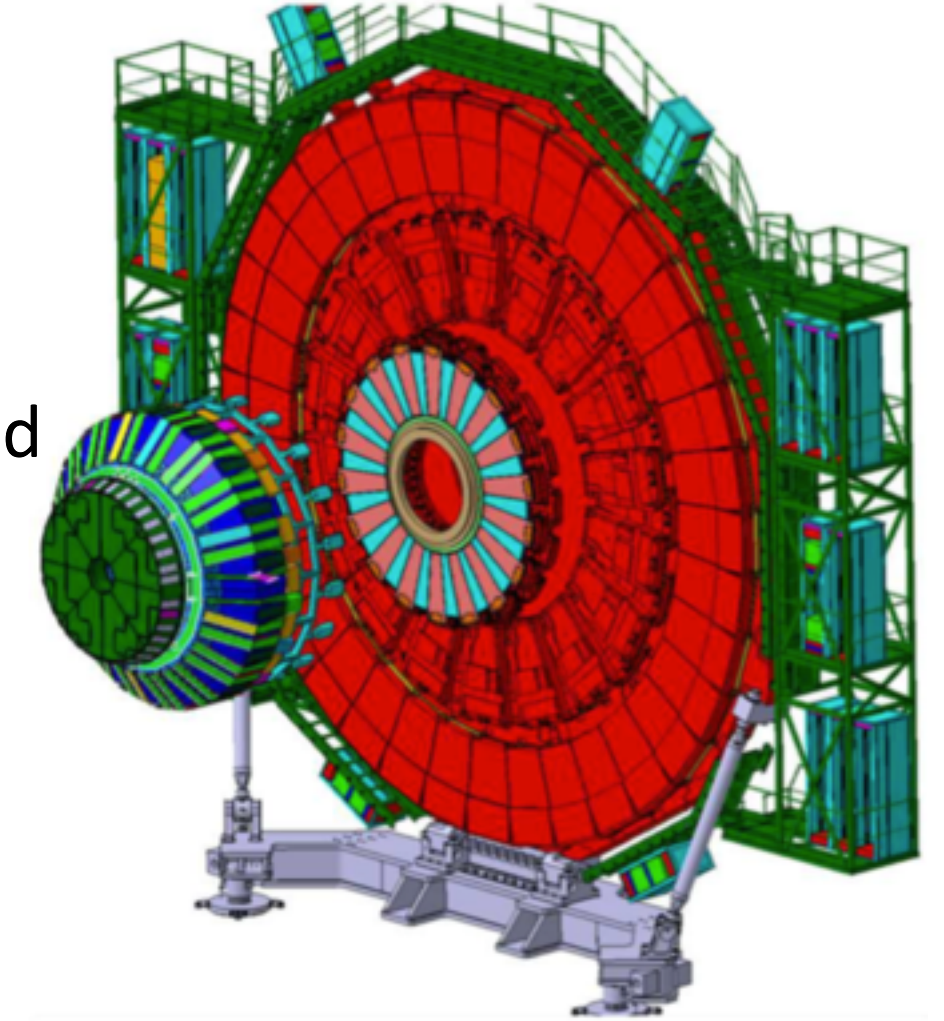
Phase II Calorimeters, MET

- Phase-II detector recovers MET resolution partially.
- MET tails significantly reduced by tracking extension.





Phase II Muon Systems



Existing muon system

- Rates scale linearly with luminosity and, with integrated charge, are consistent with expectations.
- Muon detectors are expected to survive 3000 fb^{-1}.

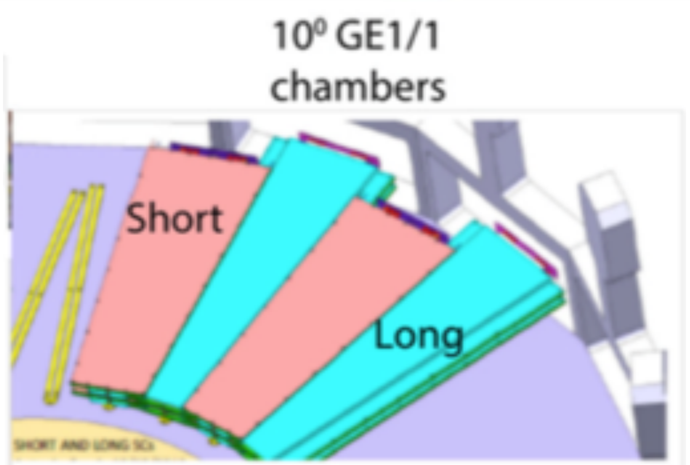
New muon detector in forward regions

Complete RPC coverage in $1.5 < \eta < 2.4$ (foreseen in CMS initial design)

- Pairs of triple GEM chambers in 2 first stations - high rate and high resolution capability - improve trigger.
- iRPC in stations 3 and 4 - higher rate capability - consolidate reconstruction & reject background.

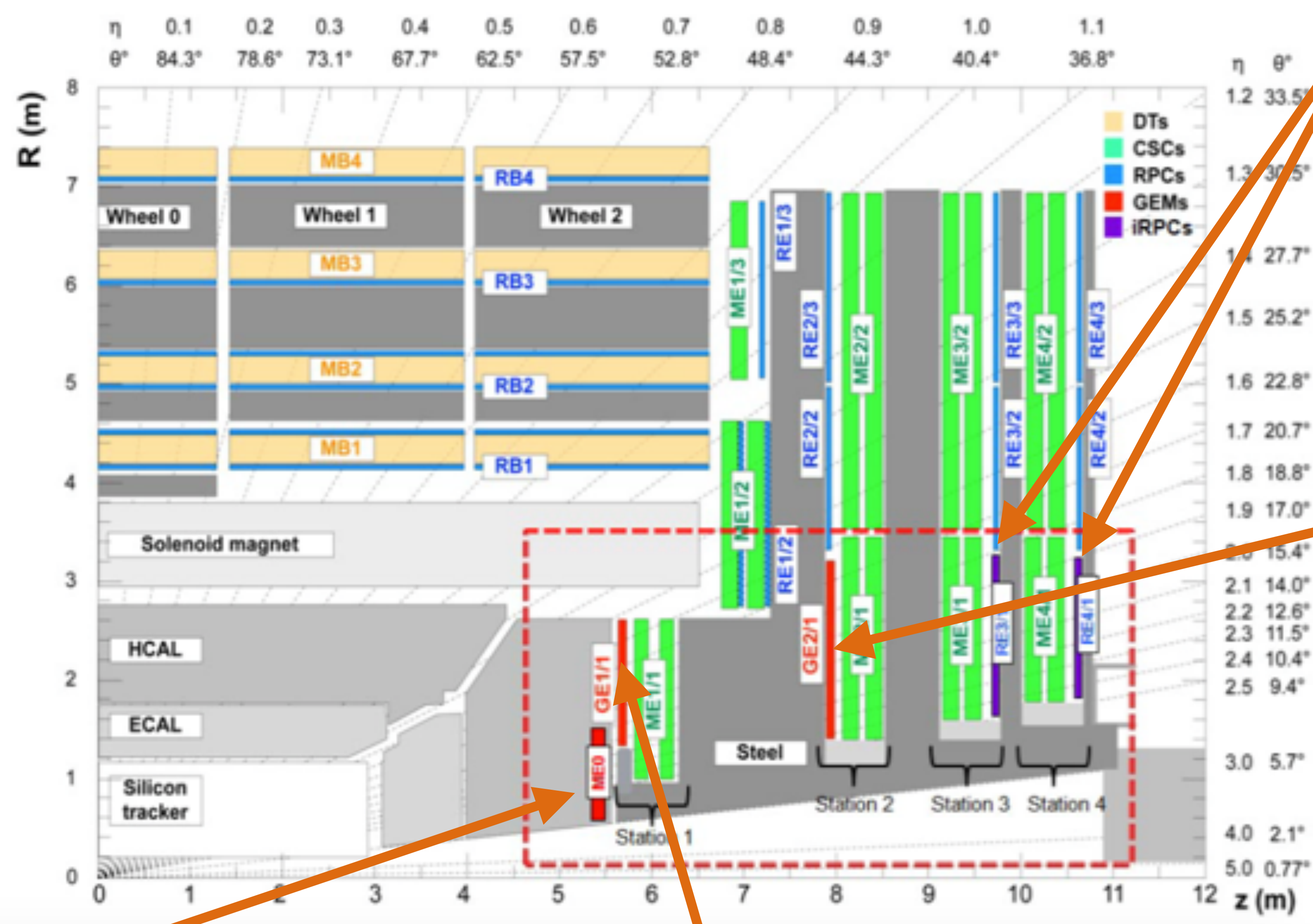
Extend coverage up to $\eta = 3$

- 6 triple GEM (ME0) in space freed behind more compact EC, for muon-tagging with matching in Tracker extension.



First CMS muon endcap station where the inner ring is equipped with 18 long and 18 short triple GEM SCs.

Phase II Muon Systems

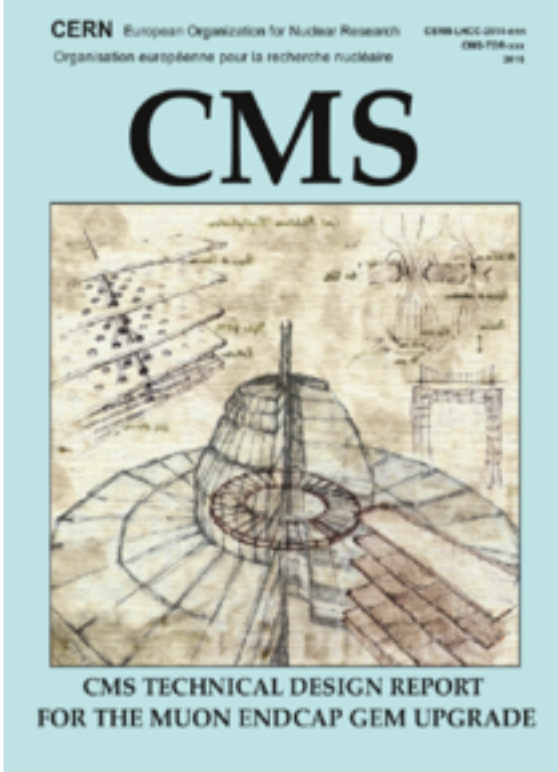


RE3/1 - RE4/1 (Trigger and reconstruction)

- 1.8<|η|<2.4
- Improved RPC (iRPC), finer pitch
- 18 chambers per endcap, each chamber spans 20°
- Installation: LS3

GE2/1 (Trigger and reconstruction)

- 1.55 < |η| < 2.45
- 18 staggered SC per endcap,
- each chamber covers 20°, 3.5 x GE1/1 area
- Installation: LS3



CERN-LHCC-2015-012

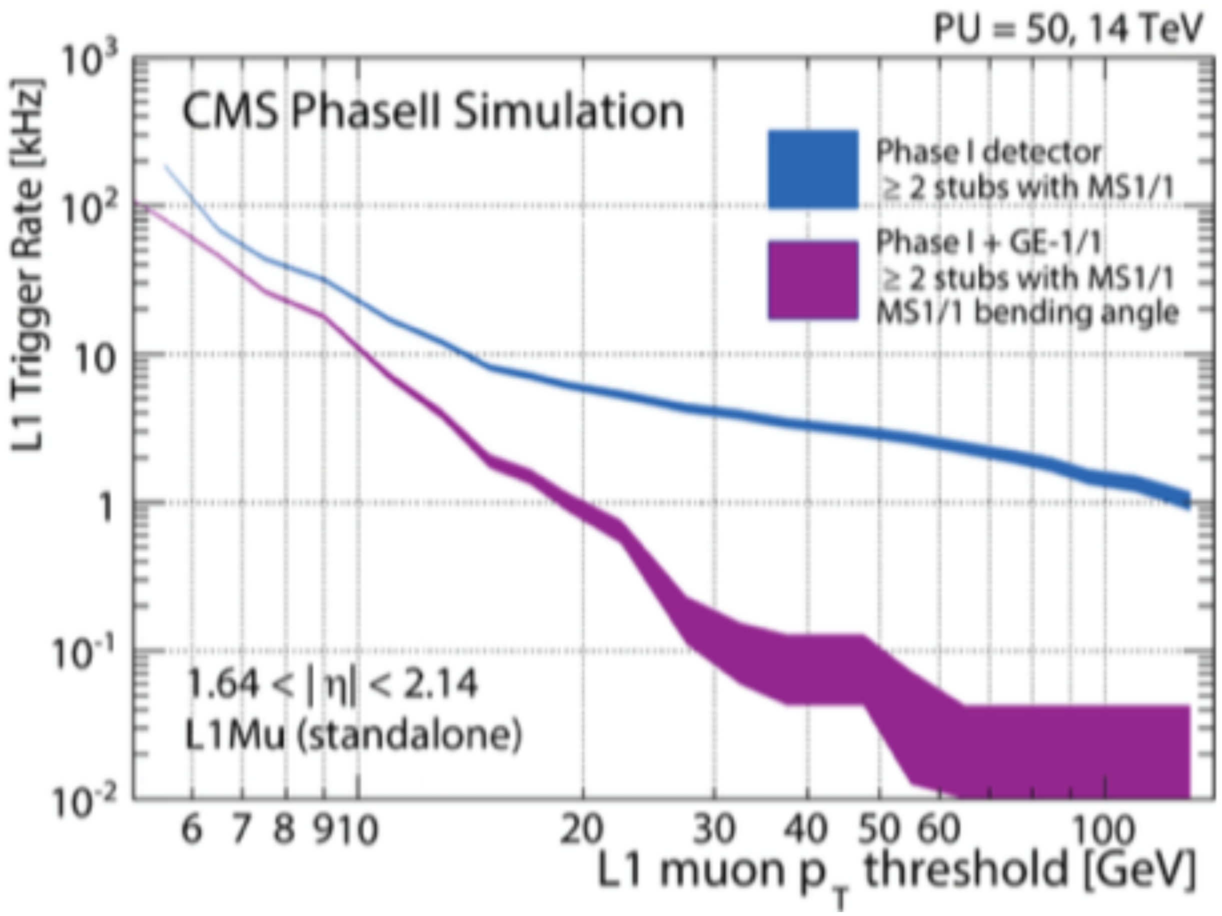
ME0 (Muon tagger)

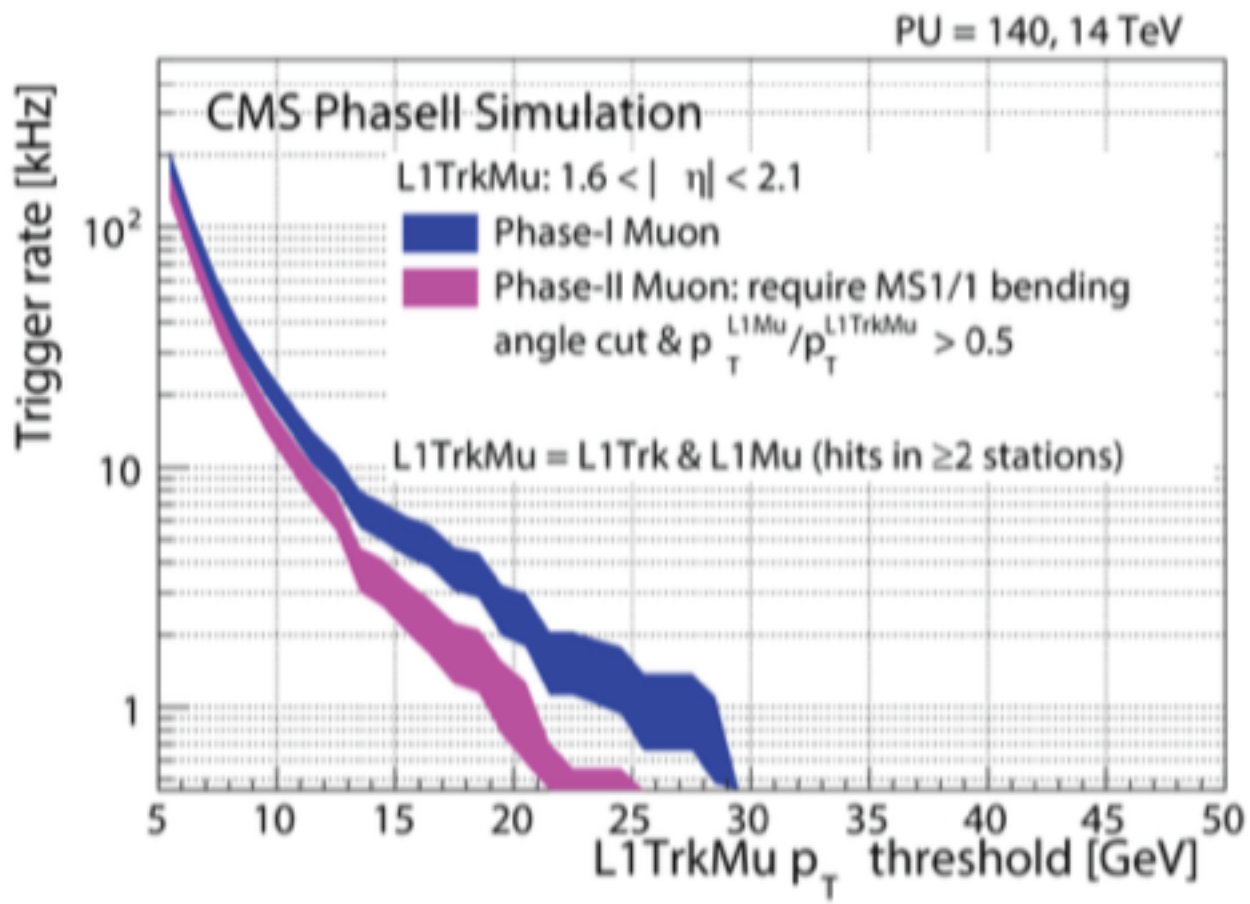
- **2.4<|η|<3.0**
- 6 layers of Triple-GEM
- each chamber spans 20°
- Installation: LS3

GE1/1 (Trigger and reconstruction)

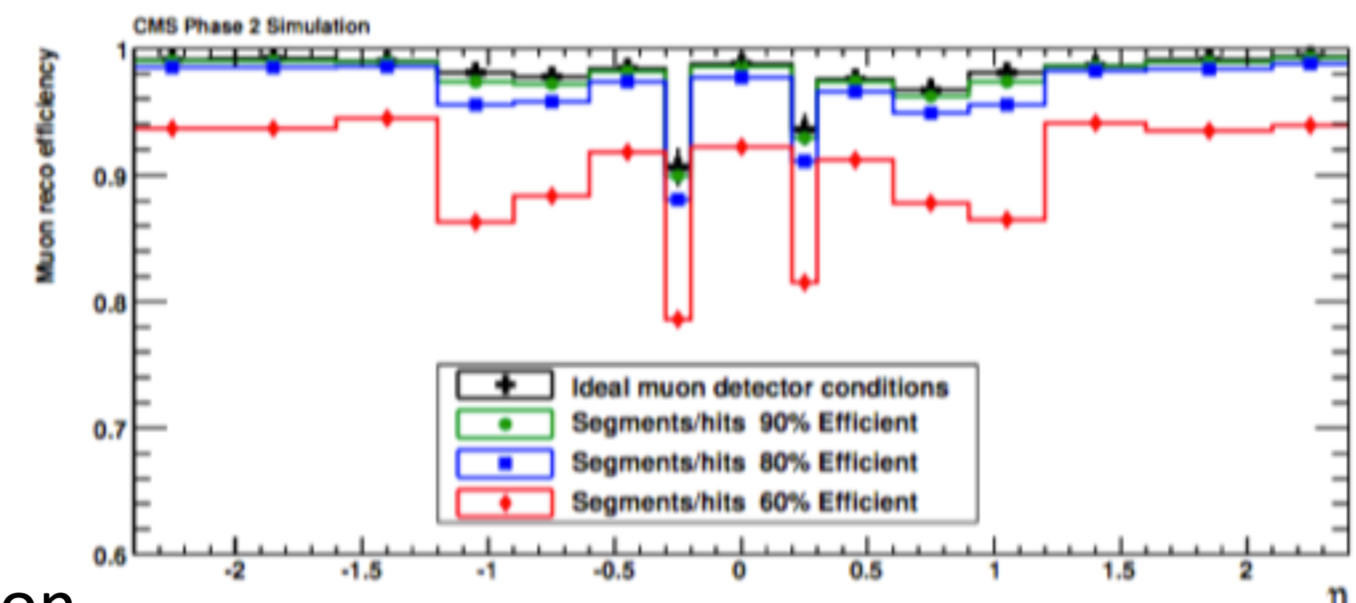
- 1.55 < |η| < 2.18
- baseline detector for GEM project
- 36 staggered super-chambers (SC) per endcap, each super-chamber spans 10°
- One super-chamber is made of 2 back-to-back triple-GEM detectors
- Installation: LS2

Phase II Muon Systems





- Good standalone L1-Trigger capability - GEM1 important already after LS2.
- Improved rate reduction combined with Track-Trigger.
- Trigger on displace vertices.
- Better offline reconstruction resolution.
- ME0 provides efficient muon identification with reasonable background rates.



Phase II Level-1 / HLT / DAQ

L1-Trigger

- High bandwidth and processing power boards.
- First layer to match detector information.
- Second layer to produce Trigger objects.

Trigger timing, throttling and control

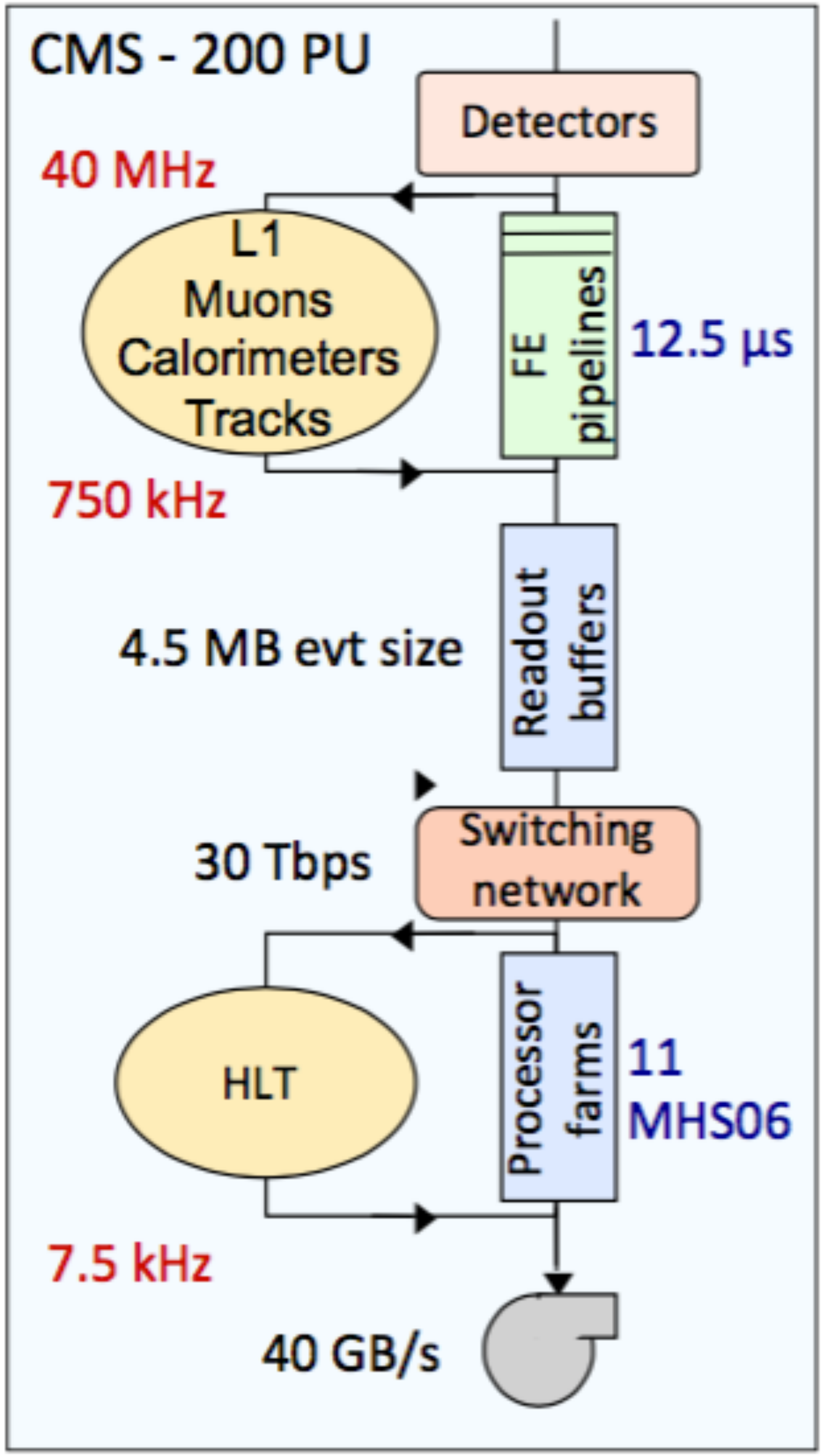
- High Bandwidth bi-directional link allowing trigger information to steer readout.

DAQ

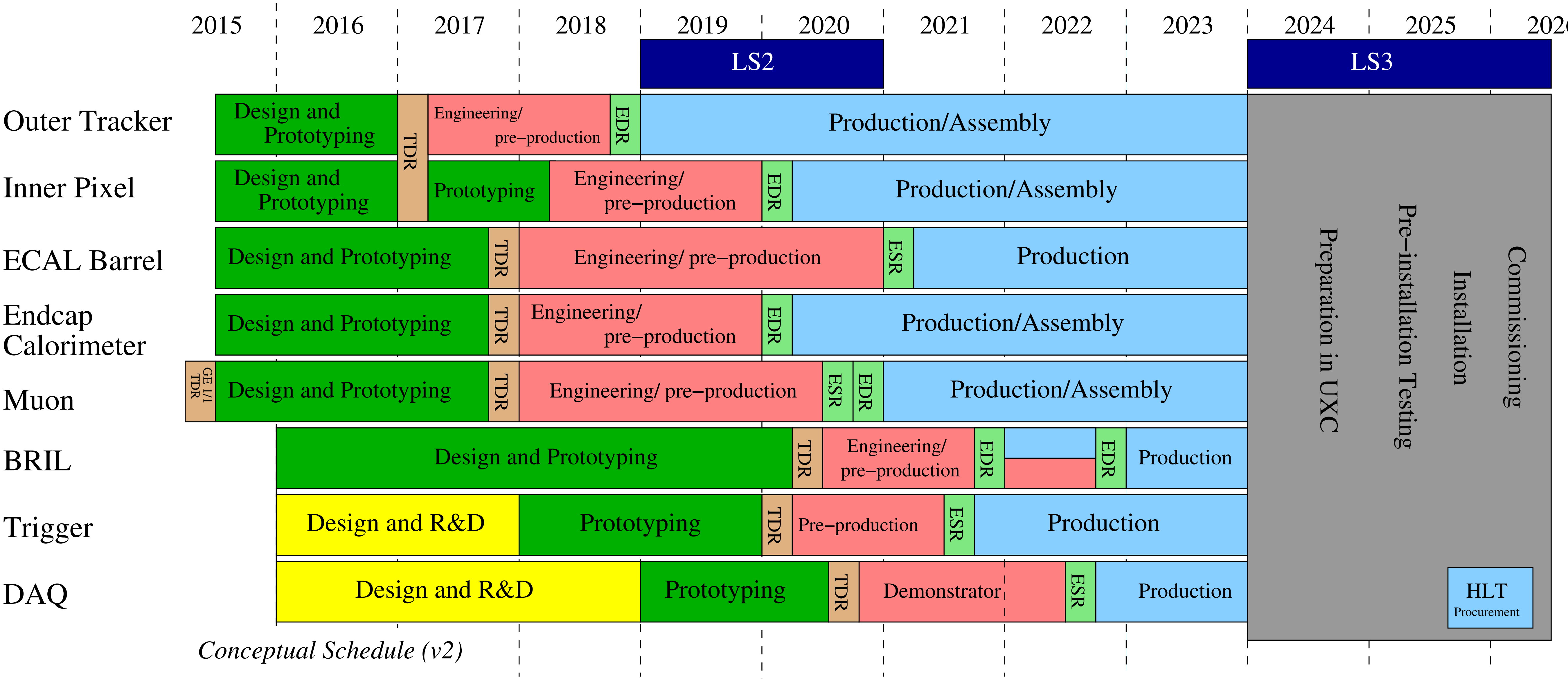
- Similar evt builder, HLT and storage as present.
- Increase Band Width - 800 links x 100 Gbps with 30% occ. will provide 30 Tbps evt building throughput.

HLT

- Processing power scales as PU x L1 rate - need increase by a factor ≃ 52 wrt Run 2 at 200 PU.

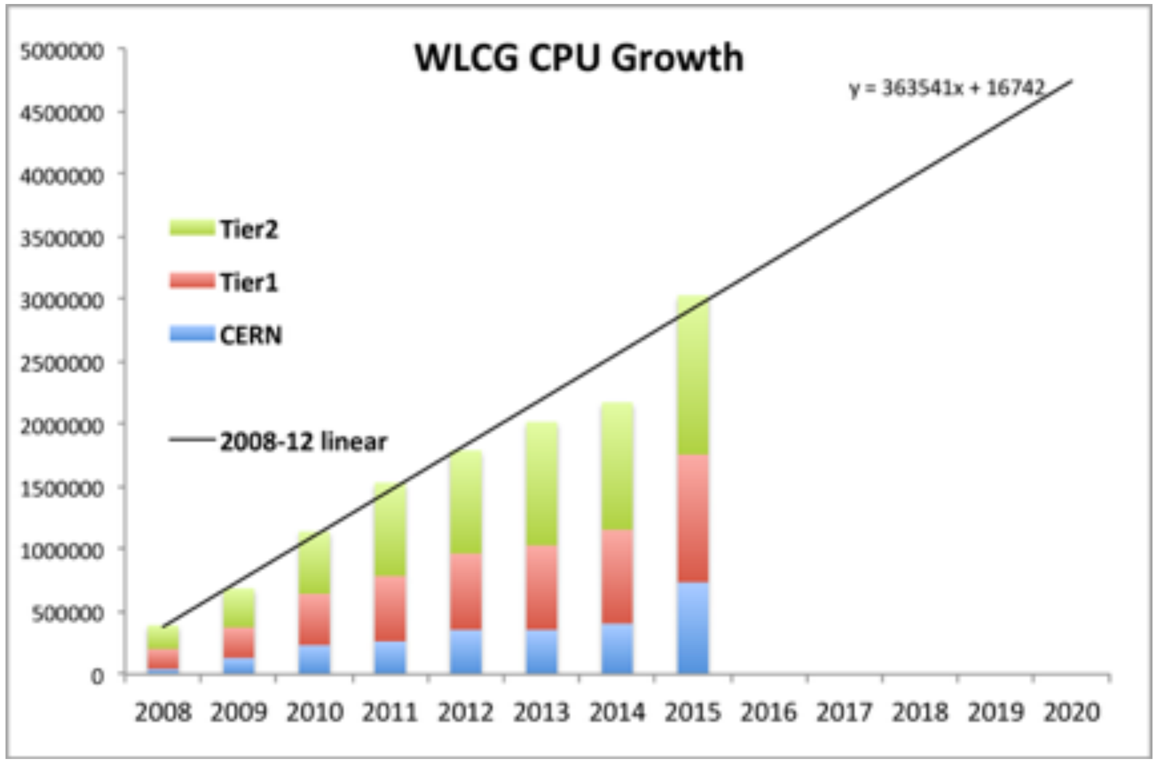


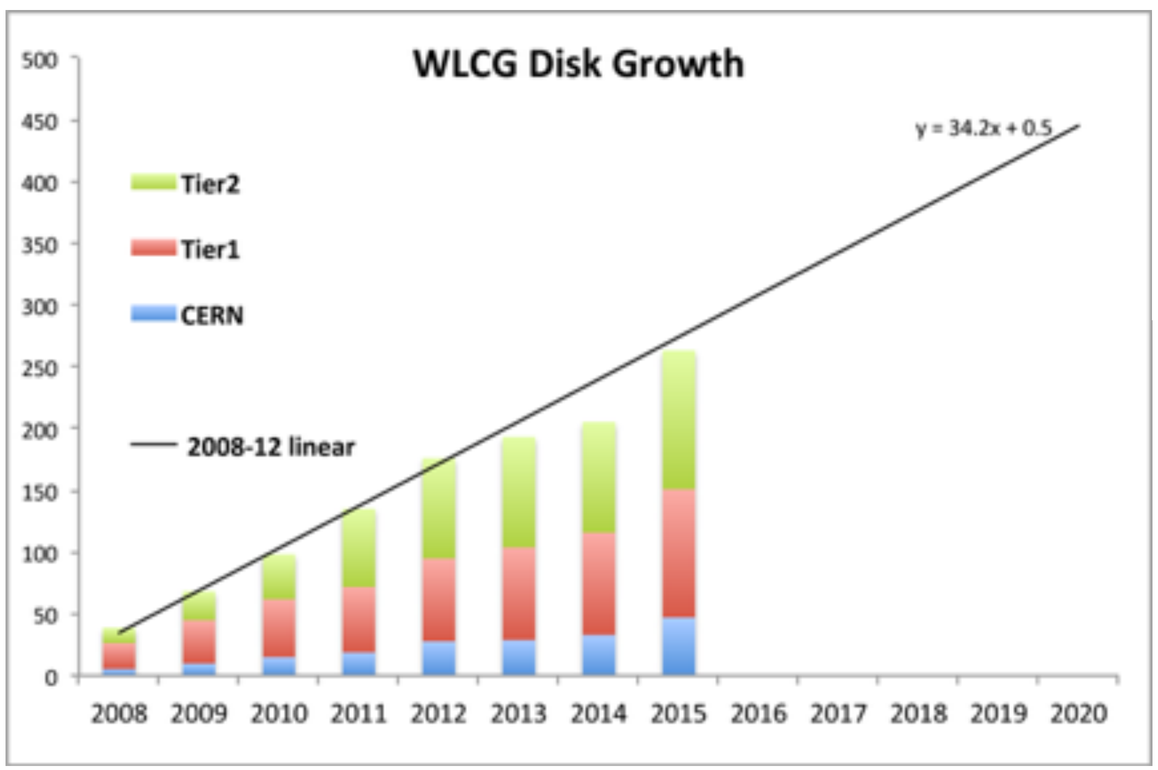
Phase II Planning



- **R&D Program:** Well established for all upgrades with set of major milestones.
- **TDRs foreseen in 2017:** Including design optimisation, main technical choices, improved cost estimates, and construction funding and sharing model.

CMS Computing





- Reconstruction and AOD resource requirements per event relative to those in Run-II

Detector	Pile-up (Ave./crossing)	Reconstruction time (Ratio to Run-II)	AOD size (Ratio to Run-II)
Phase-I	50	4	1.4
Phase-II	140	20	3.7
Phase-II	200	45	5.4

- detector simulation and digitization resource requirements per event relative to those of Run-II

Detector	Pileup (Ave./crossing)	Detector simulation (Ratio to Run-II)	Digitization (Ratio to Run-II)
Phase-I	50	1	4
Phase-II	140	1	9
Phase-II	200	1	13

- Work on rewriting algorithms specifically to improve technical performance characteristics and the use of new C++ compilers, including both integration of C++11 standards and advanced compilation options, continues to yield considerable improvements in performance.

Conclusions CMS Status and Upgrade

- Current status:
  - LS1 work successfully completed
  - Recorded 90% of collisions delivered by LHC, 75% @ 3.8 T
  - First 13 TeV results appear
  - Long list of new physics insights
- We are in the Phase I Upgrade.
- Preparing for our future research at the HL-LHC:
  - CMS has developed strong conceptual designs for all detector upgrades to solve aging issues and high luminosity and PU challenges, covering the entire physics reach at the HL-LHC.
  - Design and technical optimizations for performance/cost-effective upgrades will continue during the preparation of individual project TDRs.
  - TDRs are foreseen in 2017.