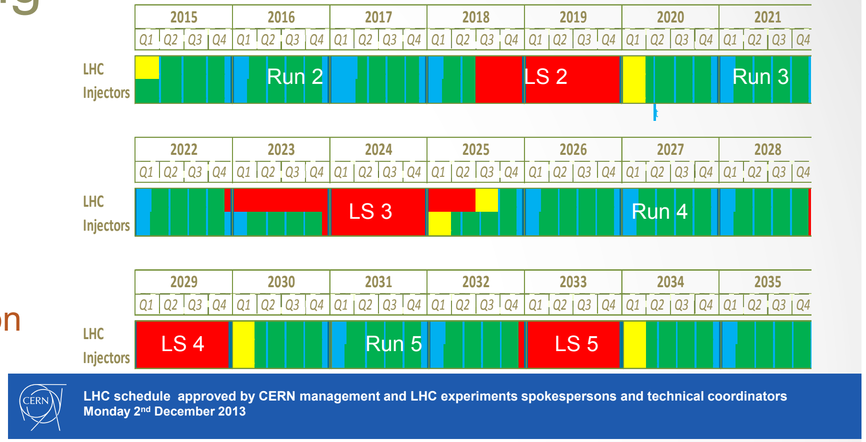
CMS Upgrades

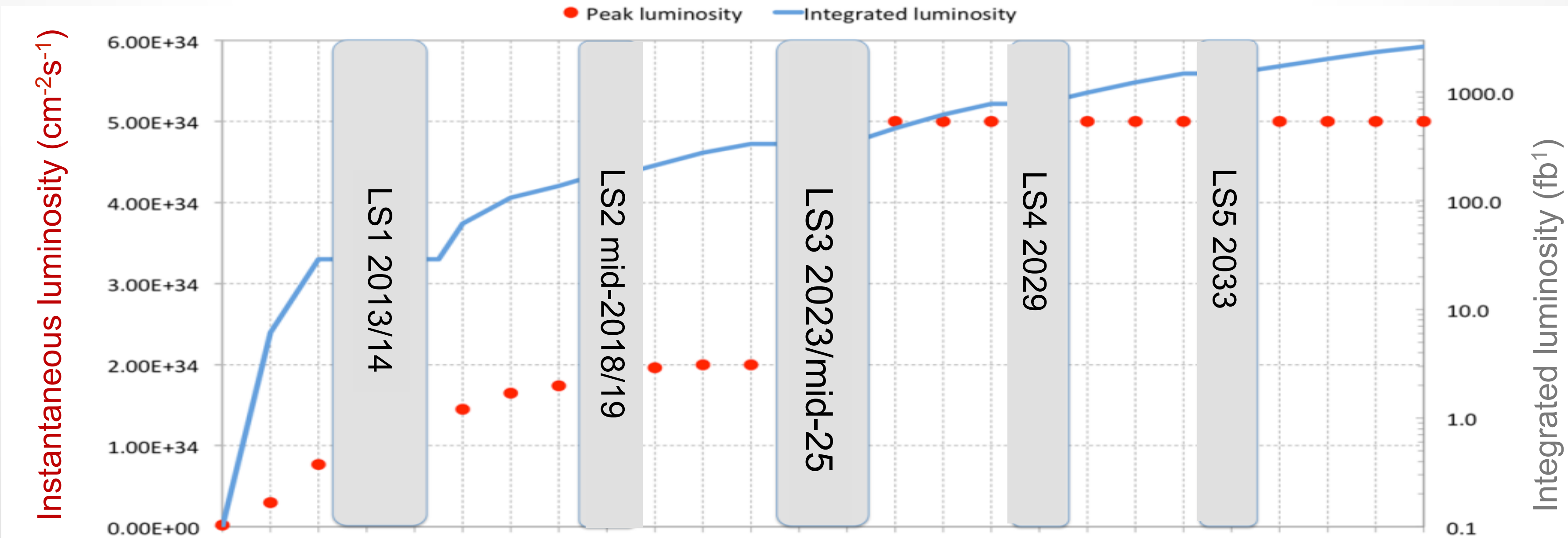
Duccio Abbaneo - CERN
On behalf of the CMS Collaboration

Towards HL-LHC

- Design for operation at 5×10^{34} $cm^{-2}s^{-1}$ instantaneous luminosity, with leveling
  - Translated to 140 <PU>
- Ultimate target 3000 fb^{-1} integrated over more than 10 years
    - N.B. Operation at higher <PU> still under discussion

LS2	starting in 2018 (July)	18 months + 3months BC (Beam Commissioning)
LS3	LHC: starting in 2023 =>	30 months + 3 BC
	injectors: in 2024 =>	13 months + 3 BC





The challenges

- Radiation tolerance
  - Survive 10× higher integrated dose/fluence than the present design
    - Very difficult requirement for the innermost detectors
- Reconstruction in high pileup
  - Higher granularity
    - Electronics channels and bandwidth
- Trigger/readout in high pileup
  - More information to form the L1 trigger decision
    - Even more bandwidth from the front-end
  - More time and processing power to process that information
    - Longer latency, more elaborate trigger electronics and more complex algorithms
  - Higher accept rate
    - Again, more bandwidth…

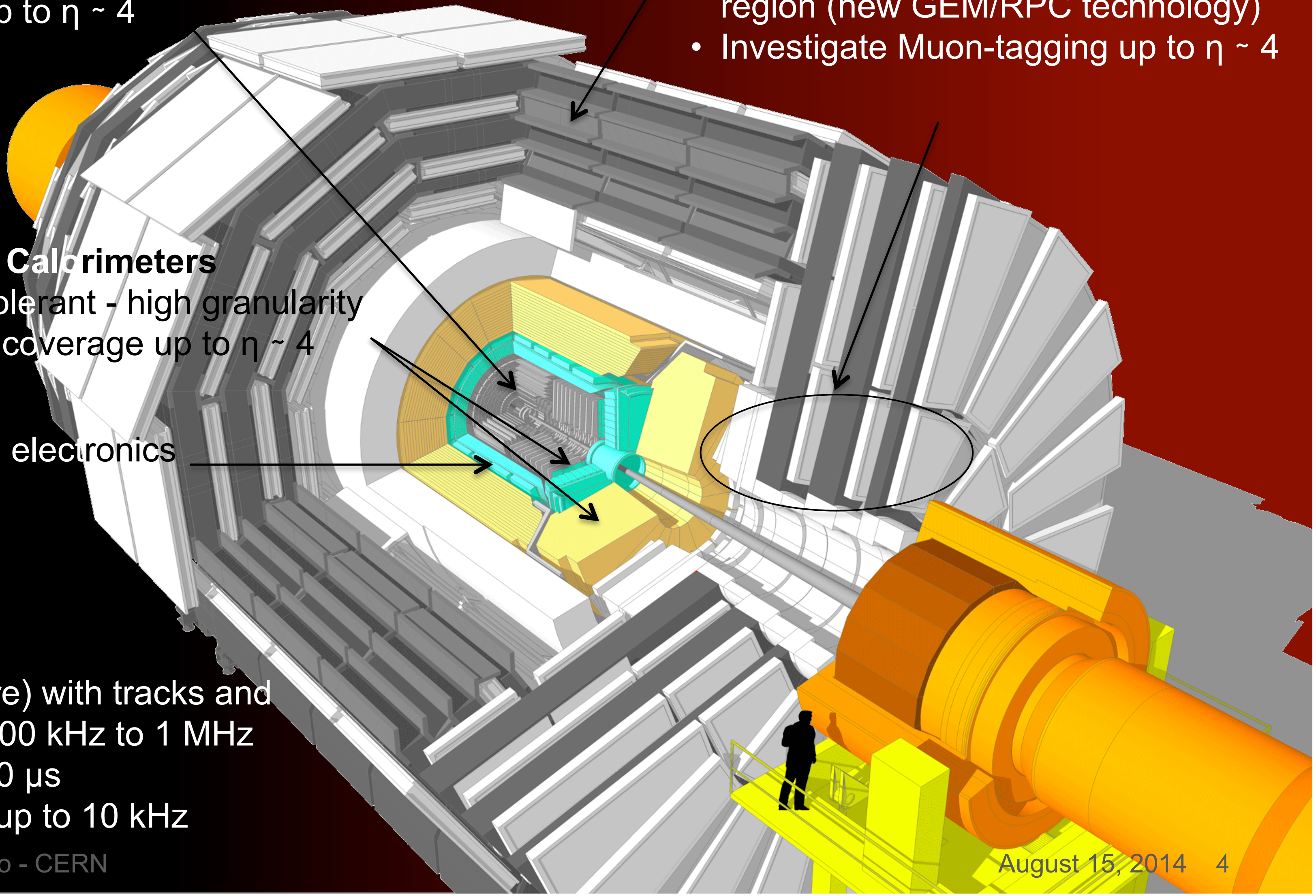
- The trigger upgrade is a major challenge, driving several aspects of the upgrade strategy

- In addition: evolve the detector design according to up-to-date physics interests
  - E.g. study of Vector Boson Scattering would profit of improved performance in the (very) forward region

CMS Phase 2 Upgrades

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

Muons
- Replace DT FE electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Investigate Muon-tagging up to η ~ 4



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

Barrel ECAL
- Replace FE electronics

Trigger/DAQ
- L1 (hardware) with tracks and rate up ~ 500 kHz to 1 MHz
- Latency ≥ 10 μs
- HLT output up to 10 kHz

The Tracker Upgrade

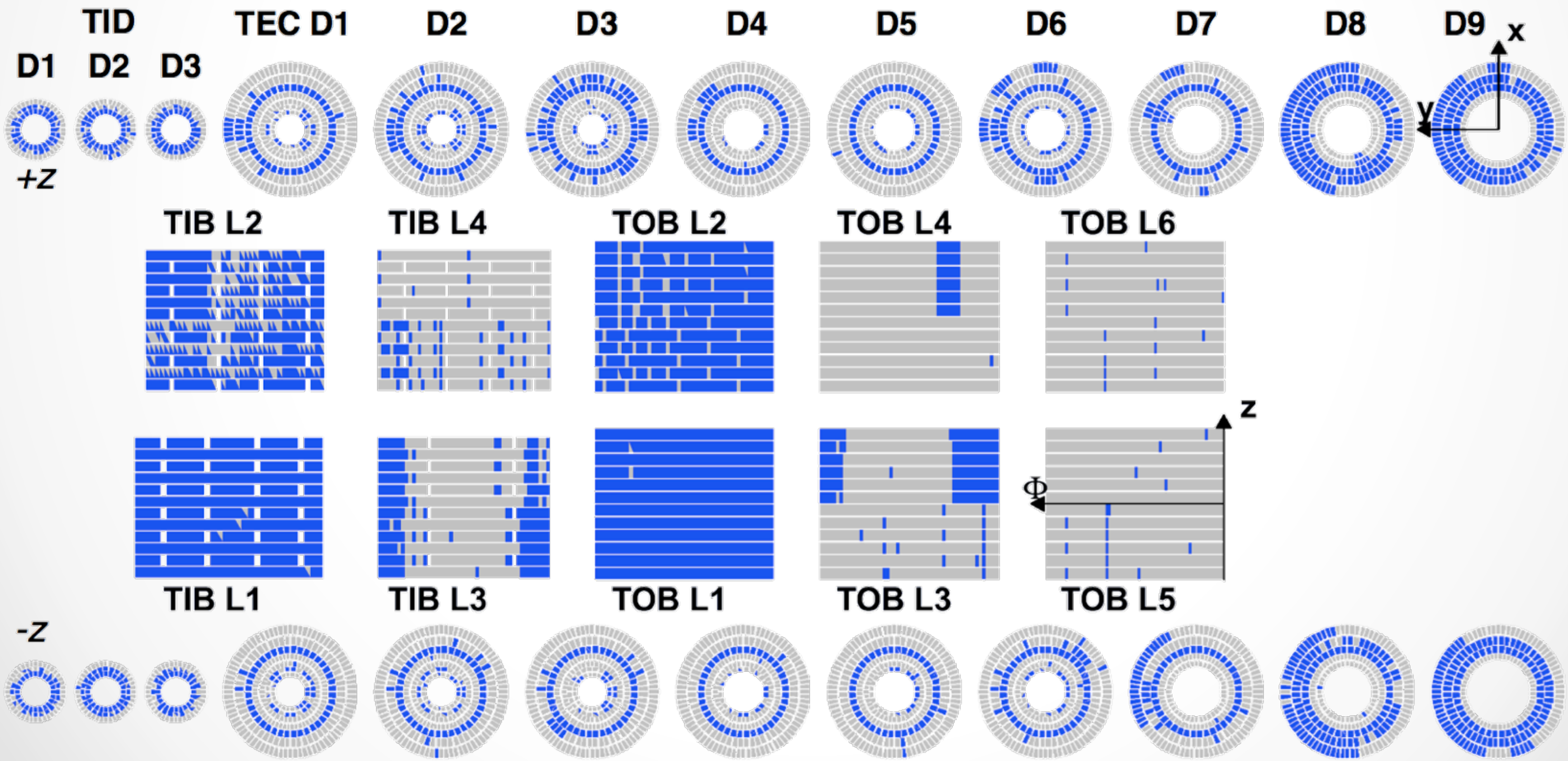
To be installed in LS3

Tracker - motivations for the upgrade

- Pixel detector
  - Loss of charge collection translates to degraded hit resolution
    - After 500 fb^{-1} IP resolution degraded by 50%
  - 7% data loss at 140 <PU> in barrel layer 1, due to limitations in FE buffers
- Strip Tracker
  - Most prominent effect is the increased of leakage current
    - Increasing number of modules that cannot be operated
    - Highly degraded tracking performance
- Both detectors
  - L1 latency limited to ~4 μs and L1 accept rate limited to ~100 kHz
  - Prevent any substantial trigger upgrade!

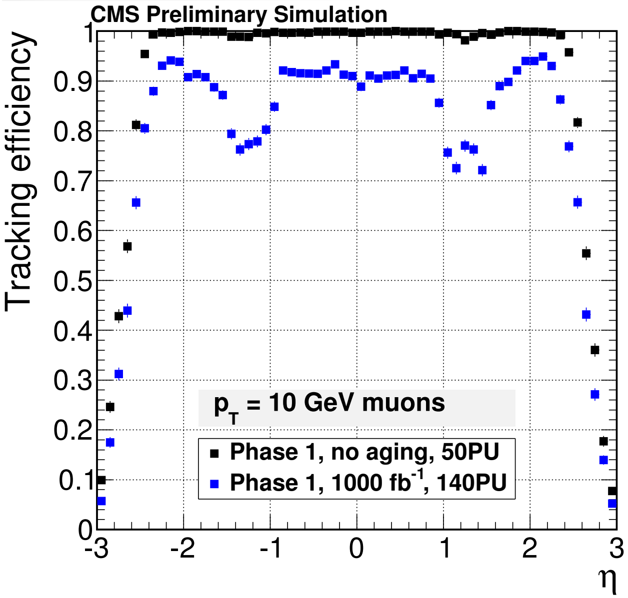
Tracker - motivations for the upgrade

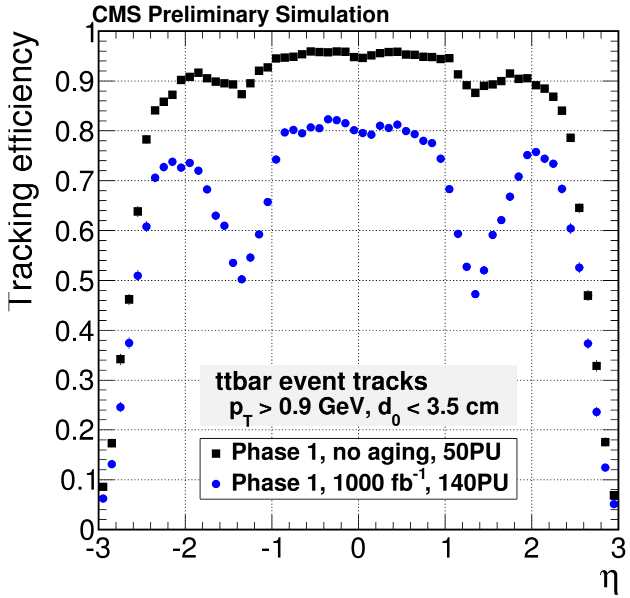
- Map of modules that cannot be operated after 1000 fb^{-1} for a coolant temperature of −20°C
  - Almost all double-sided modules are dead

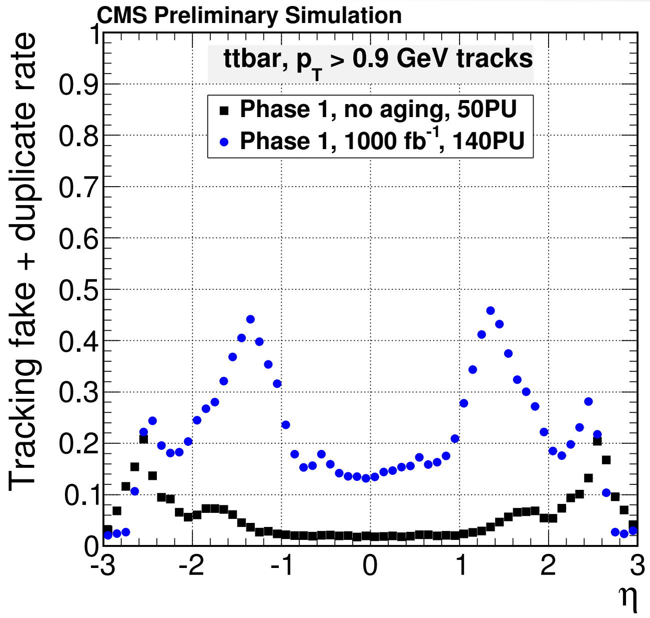


Tracker - motivations for the upgrade

- Performance degradation for 140 <PU> and 1000 fb^{-1}
  - Strip Tracker aging only







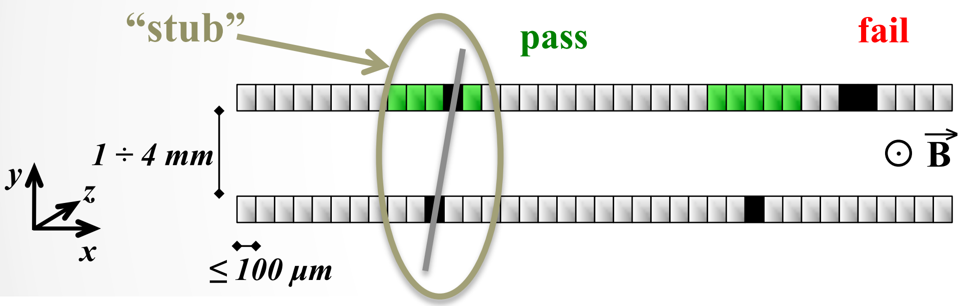
Tracker Upgrade - requirements

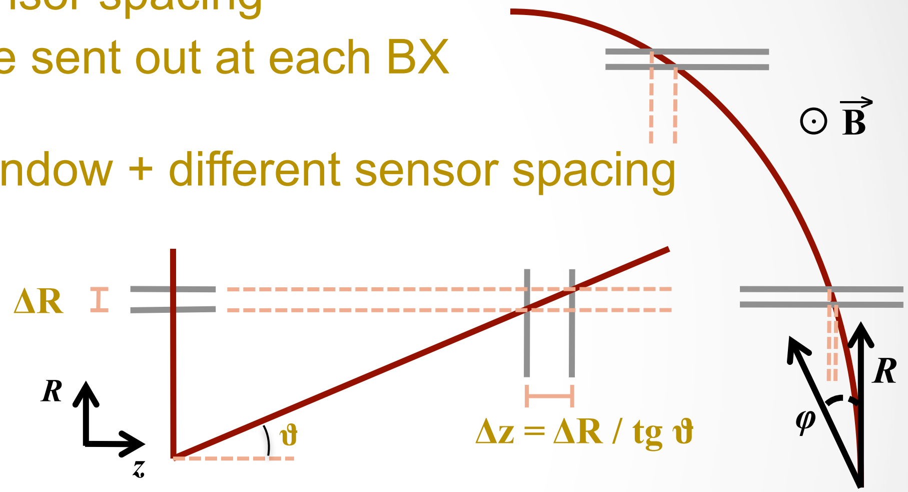
- Radiation tolerance
  - $3000\ fb^{-1}$ for Outer Tracker
  - Preserve possibility of replacing inner parts of the Pixel detector
- Increased granularity
  - Occupancy ~1%
- Improved two-track separation
  - Smaller pixels
- Reduced material in the tracking volume
  - As good as we can
- Robust pattern recognition
  - Seeding capabilities in Outer Tracker
- Support Level-1 trigger upgrade
  - Latency of 12.5 μs, L1A rate ~ 750 kHz
  - The Outer Tracker contributes information for the L1 trigger decision
- Extended tracking acceptance
  - Up to about η=4

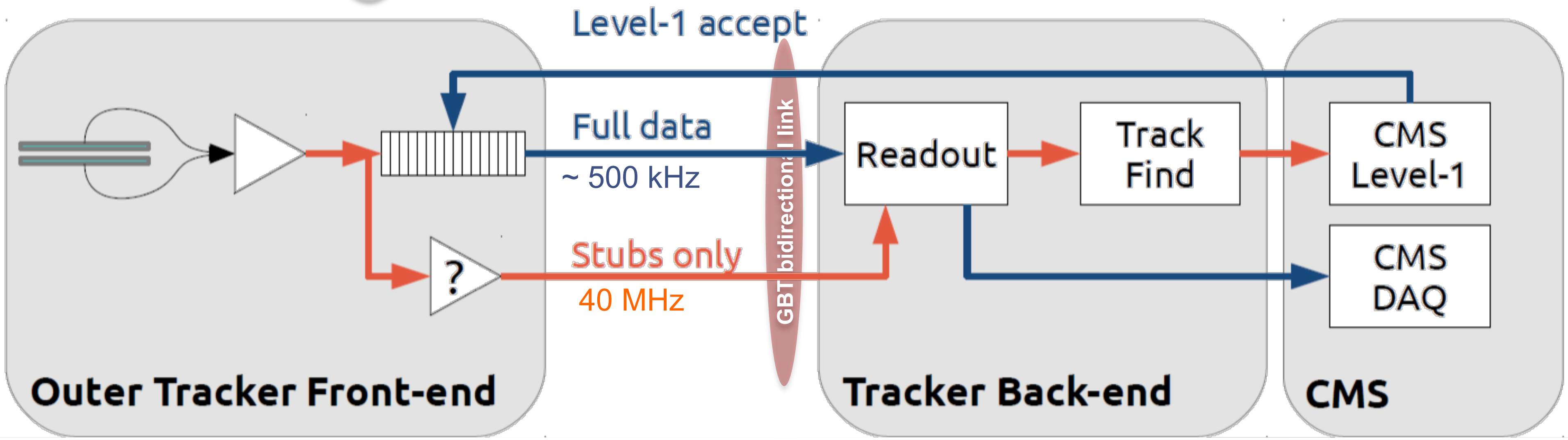
Louise Skinnari on Monday

The Outer Tracker: basic concept

- Novel trigger functionality implemented with "p_T modules"
  - Two closely-spaced sensors readout by one same front-end
  - p_T of the particle measured over the sensor spacing
  - Stubs from particles with p_T > 2 GeV are sent out at each BX
    - One order of magnitude data reduction
  - Requires programmable acceptance window + different sensor spacing

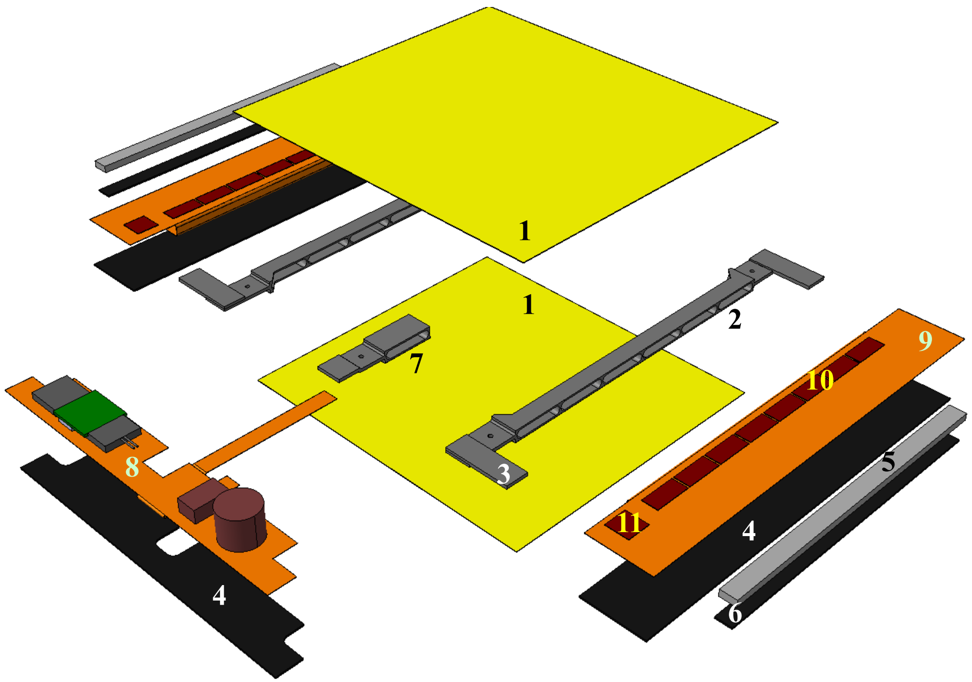




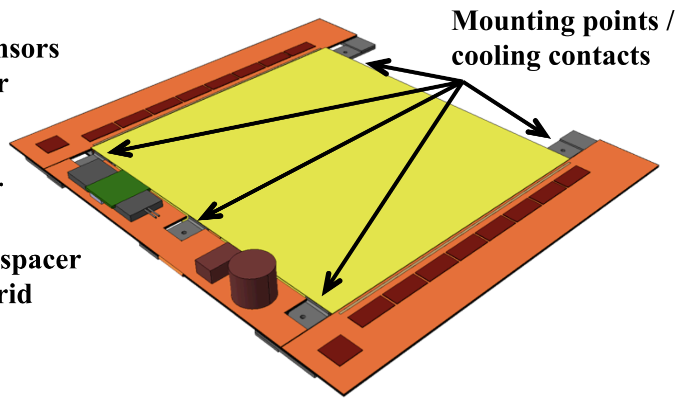


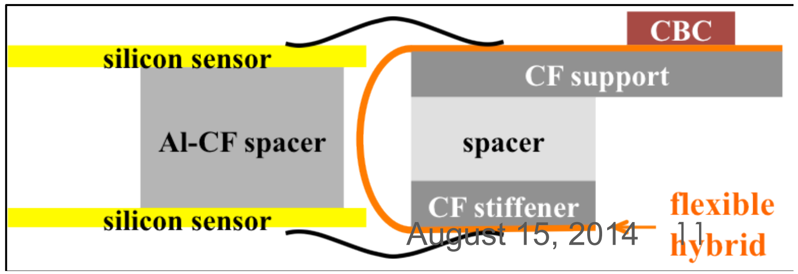
Two types of modules

- Modules with 2 Strip sensors (2S modules)
  - Two sensors with 90 µm × 5 cm strips
  - No precise measurement of the z coordinate
  - All auxiliary electronics (power and readout optical link) integrated on board
  - Used in the Outer Layers (1.8 mm and 4.0 mm sensors spacing)



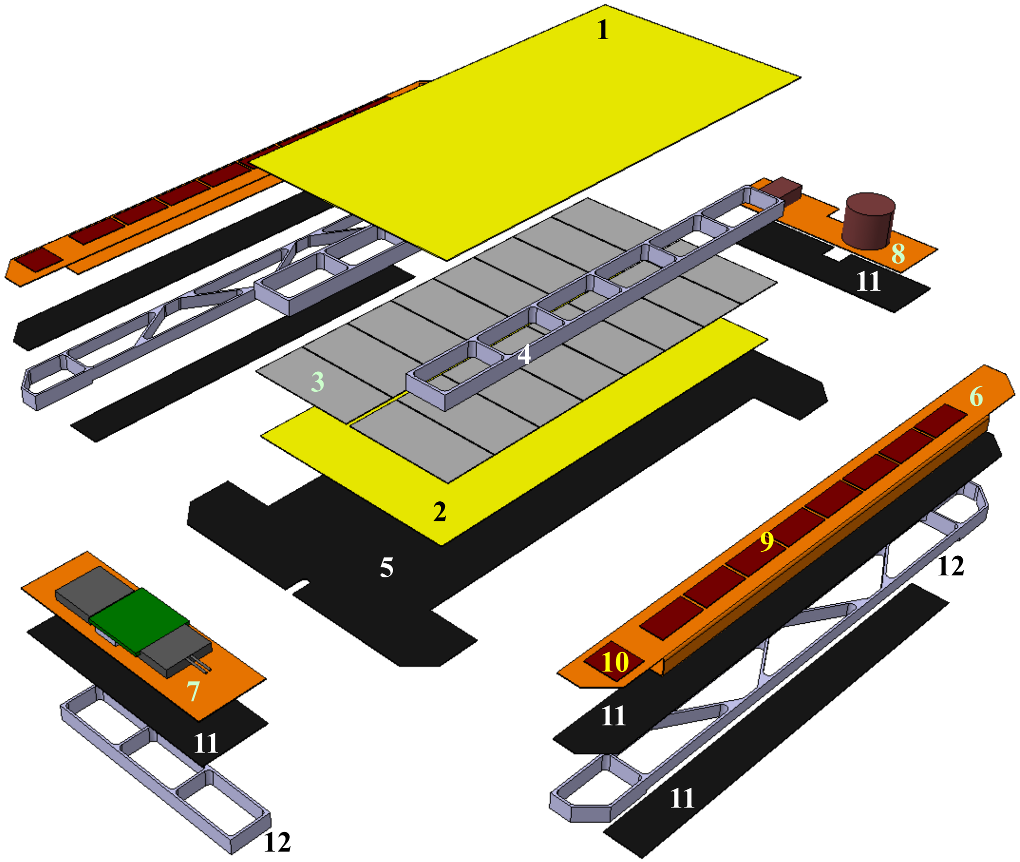
1. 2S silicon sensors
2. Al-CF spacer
3. Al-CF tab
4. CF support
5. Foam spacer
6. CF stiffener
7. Al-CF short spacer
8. Service Hybrid
9. FE Hybrid
10. CBC
11. CIC



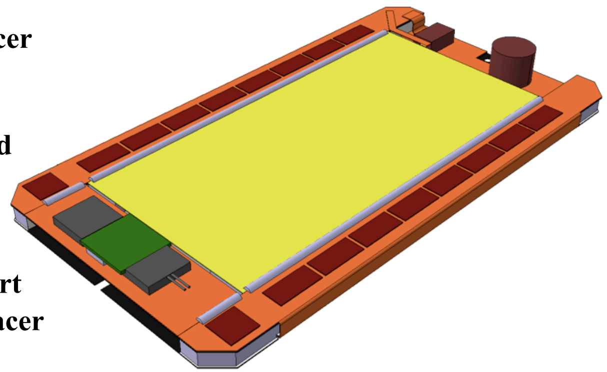


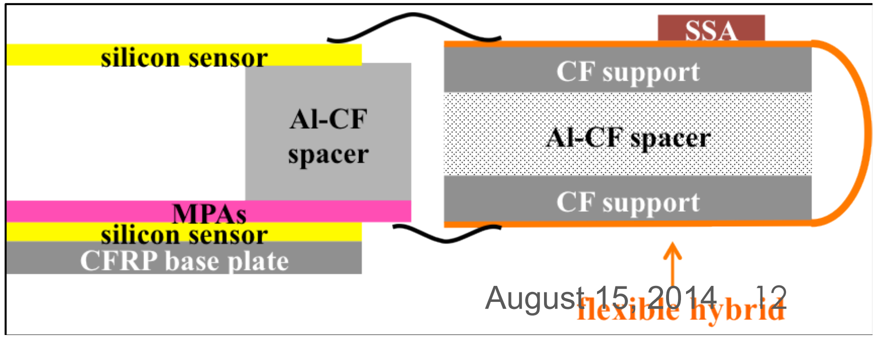
Two types of modules

- Modules with a macro-Pixel sensor and a Strip sensor (PS modules)
  - One sensor with 100 µm × 1.5 mm macro-pixels (for the z coordinate)
  - One sensor with 100 µm × 2.5 cm strips
  - All auxiliary electronics (power and readout optical link) integrated on board
  - Used in the Intermediate Layers (1.6 mm, 2.6 mm and 4.0 mm sensors spacing)



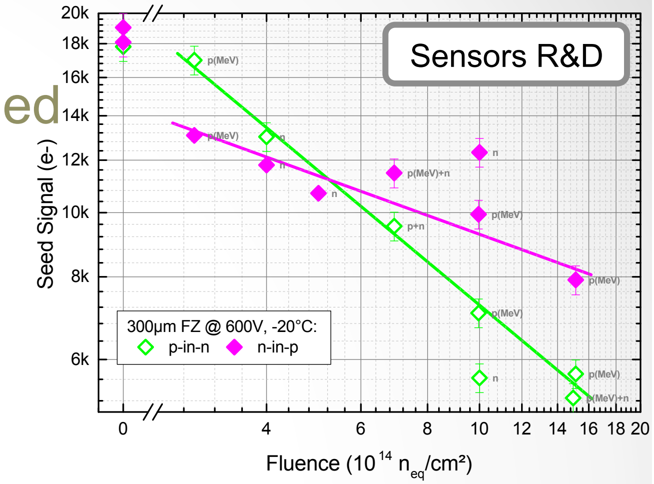
1. PS-s silicon sensor
2. PS-p silicon sensor
3. MPAs
4. Al-CF sensor spacer
5. CFRP base plate
6. FE Hybrid
7. Opto-Link Hybrid
8. Power Hybrid
9. SSA
10. CIC
11. Hybrid CF support
12. Al-CF Hybrid spacer

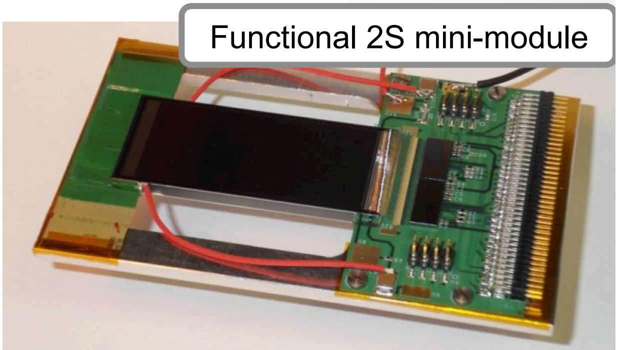


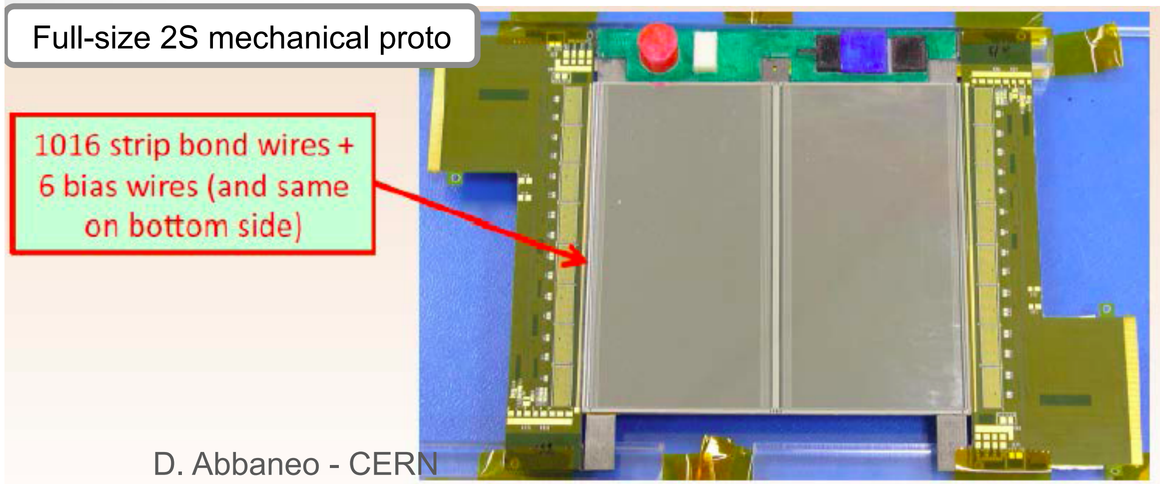


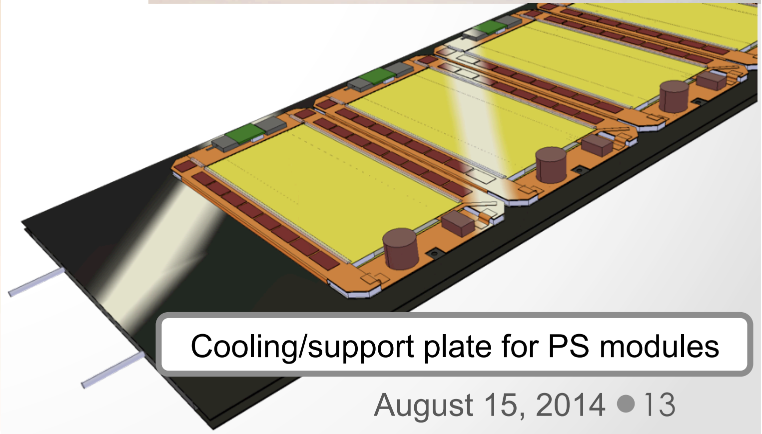
Ongoing developments

- Suitable sensor materials and technologies identified
  - FZ or MCz, 200 µm active thickness, n-in-p
- Development of FE electronics in progress
- Several module prototypes have been produced
- Design of mechanical structures started
- CO_2 cooling
  - Need ~ 100kW – Common development with ATLAS
- Back-end electronics for L1 track reconstruction
  - Pattern recognition with Associative Memories or propagation from layer to layer in FPGA followed by fit in FPGA
    - Demonstrators being developed with existing high BW processing boards

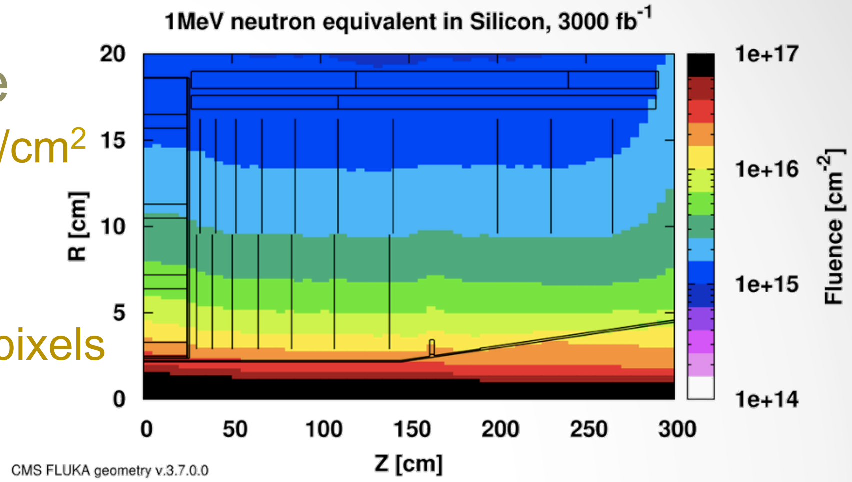




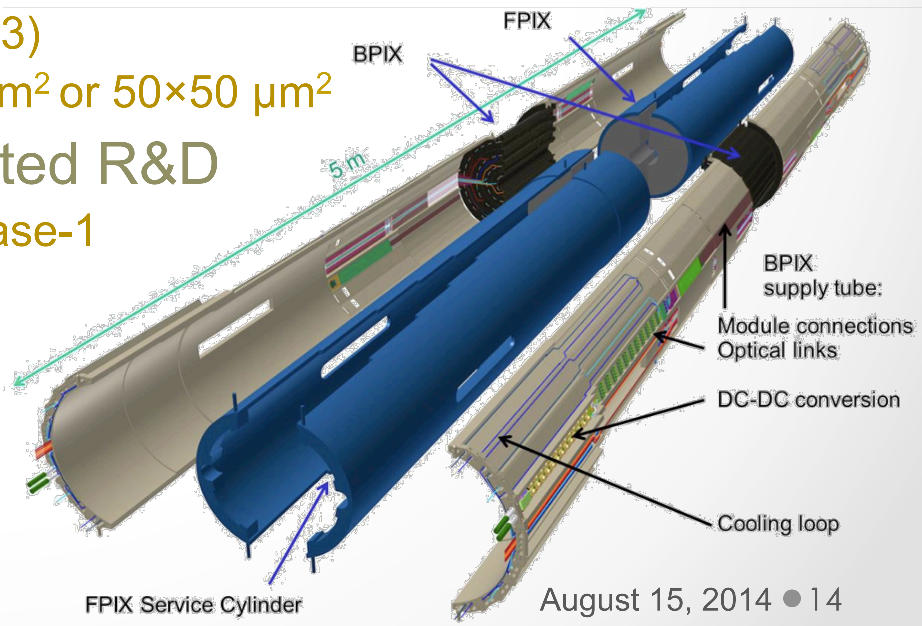




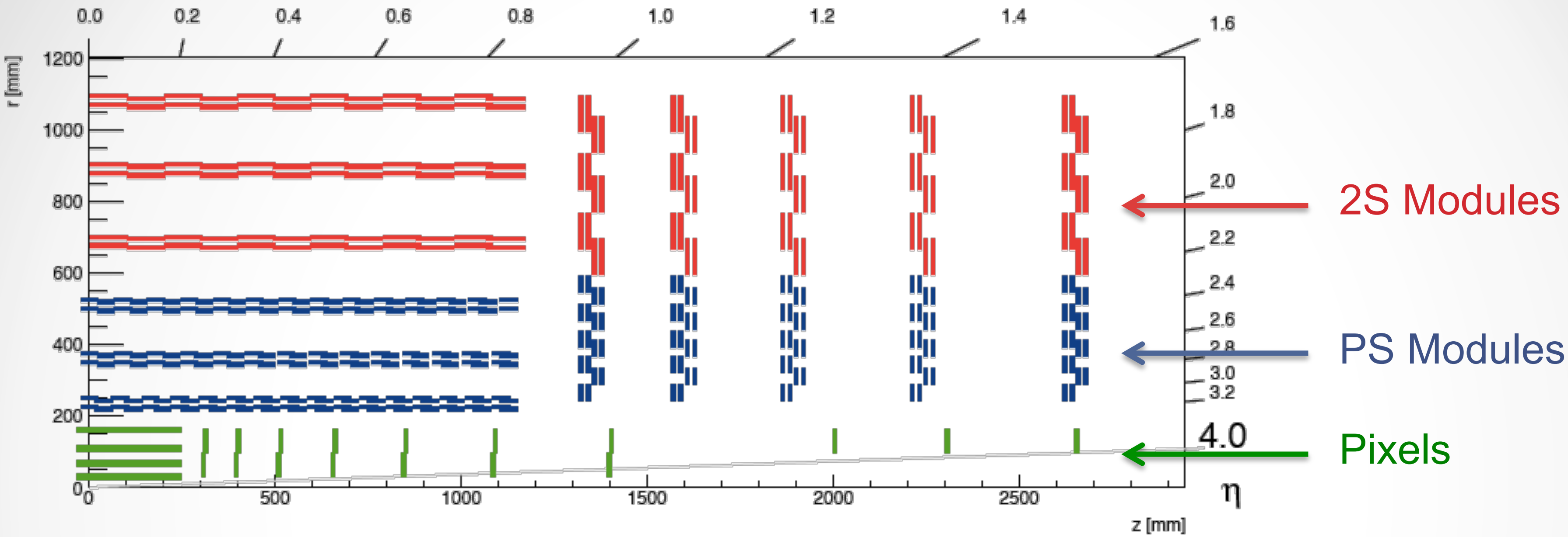
Pixel Upgrade

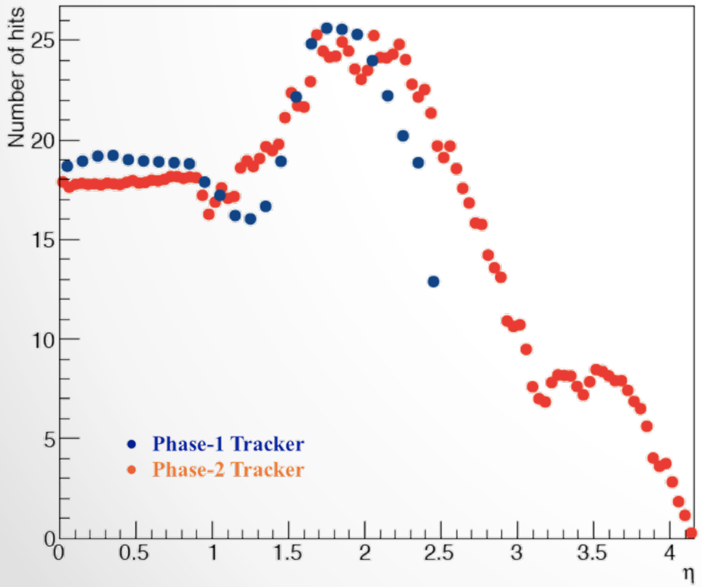


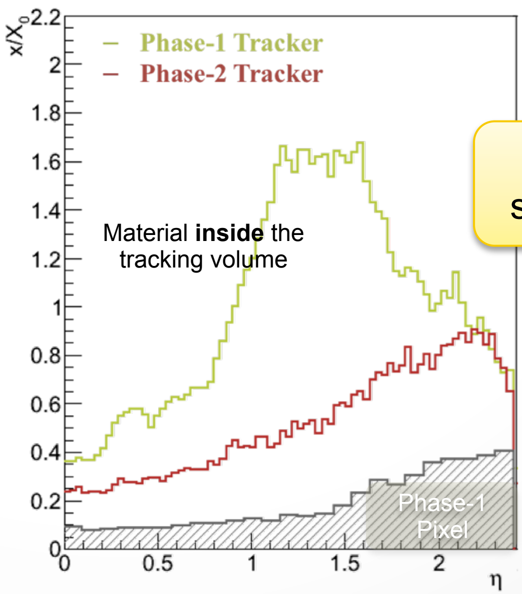
- Radiation tolerance is a big challenge
  - Unprecedented levels of ~2×10^{16} 1MeV n_{eq} /cm^2
  - Difficult for both sensors and electronics
- Sensors: thin planar silicon
  - Requires chip with low-threshold and small pixels
  - Possibly 3D sensors in the inner layer
  - A lot of R&D still needed
- Readout chip: 65 nm CMOS technology
  - Radiation qualification ongoing
  - Common development with ATLAS (RD53)
  - Considering pixels as small as 25×100 μm^2 or 50×50 μm^2
- Readout and power require dedicated R&D
  - Bandwidth ×20 or more compared to Phase-1
    - Higher PU × Higher L1A rate
  - Likely higher power at lower voltage!
  - All services in the tracking volume
    - Because of the rapidity extension



The Tracker Layout



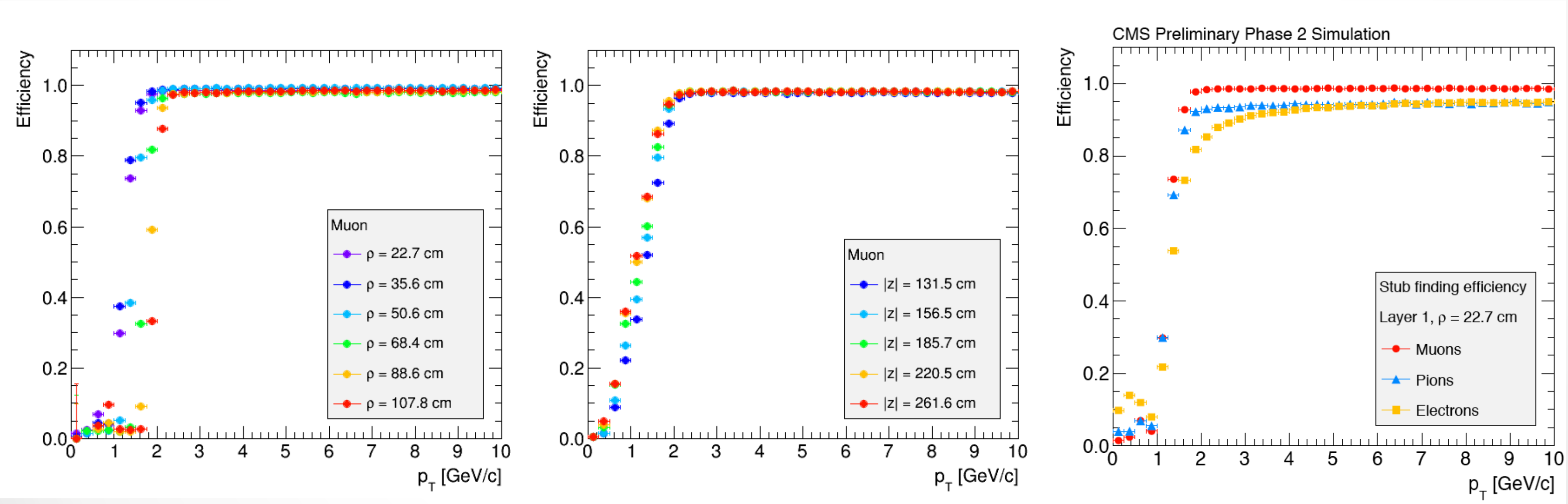




Outer Tracker substantially lighter!

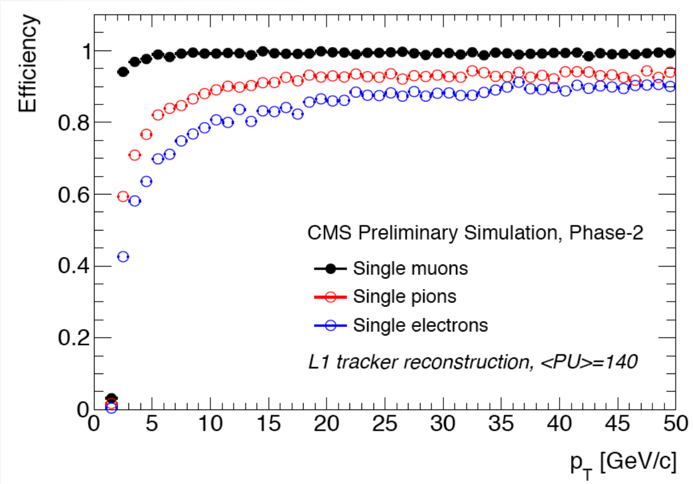
Estimated performance - online

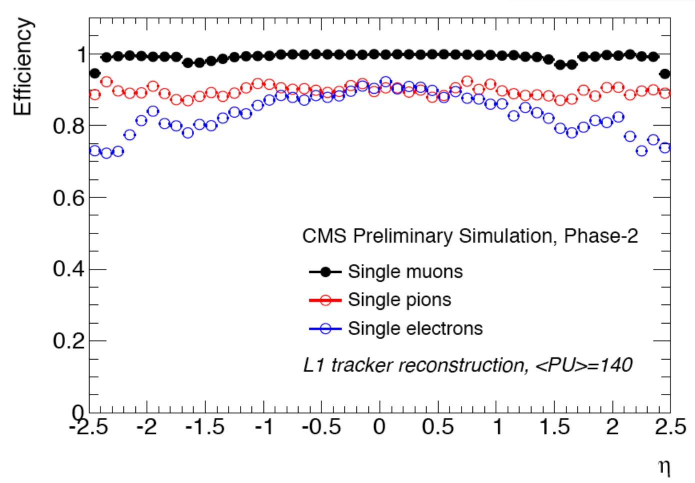
- Stub finding efficiency in Front-End electronics
  - With optimized sensor spacing and acceptance window
    - Tuned to obtain ~99% efficiency for p_T = 2 GeV muons

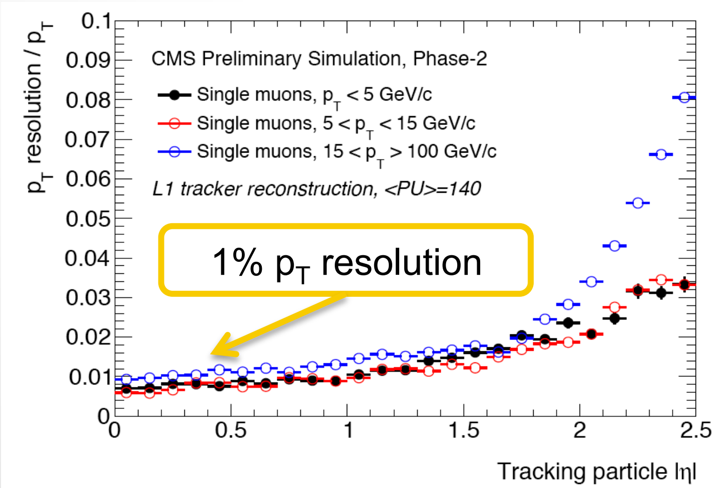


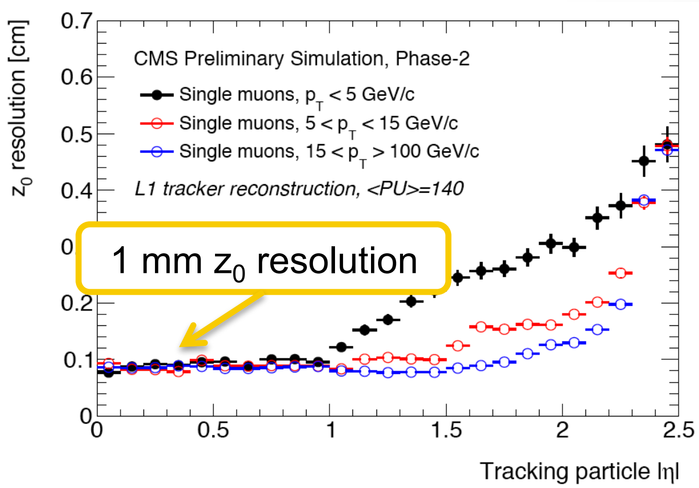
Estimated performance - online

- L1 track finding performance
  - N.B. Not yet demonstrated in hardware!



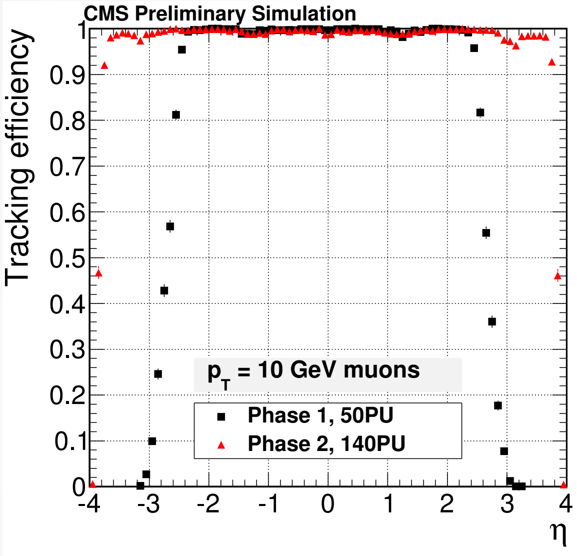


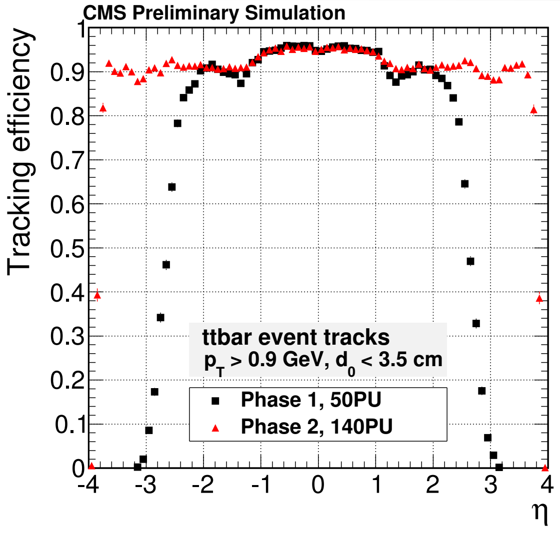


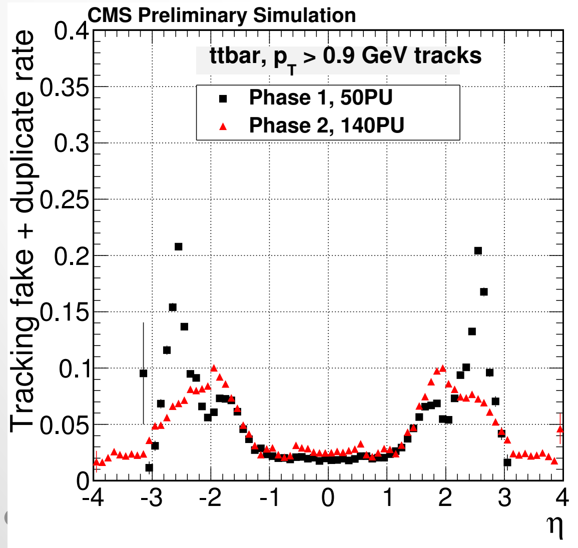


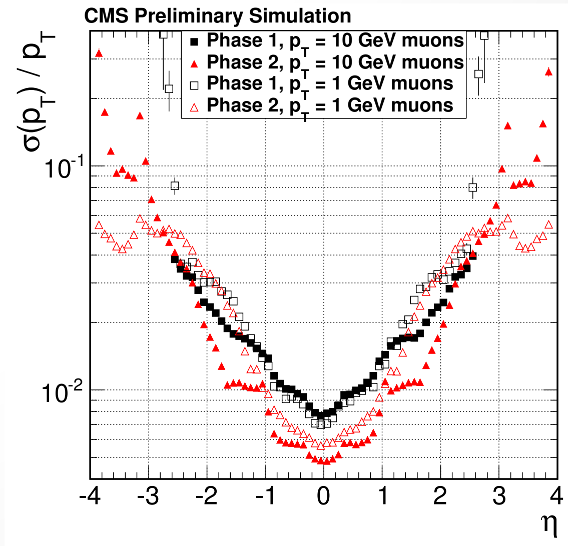
Estimated performance - offline

- Good tracking performance in high pileup
  - Substantial improvement in p_T resolution from reduced material







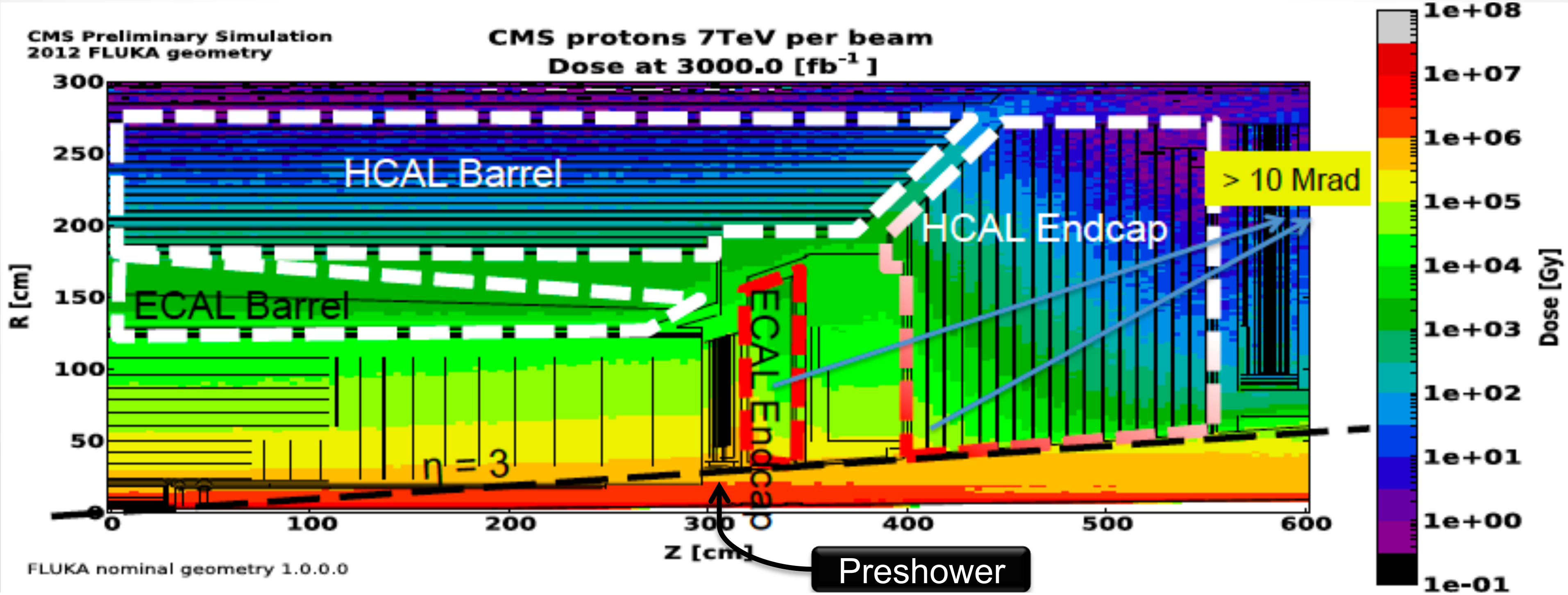


The calorimeter upgrade

Also for LS3

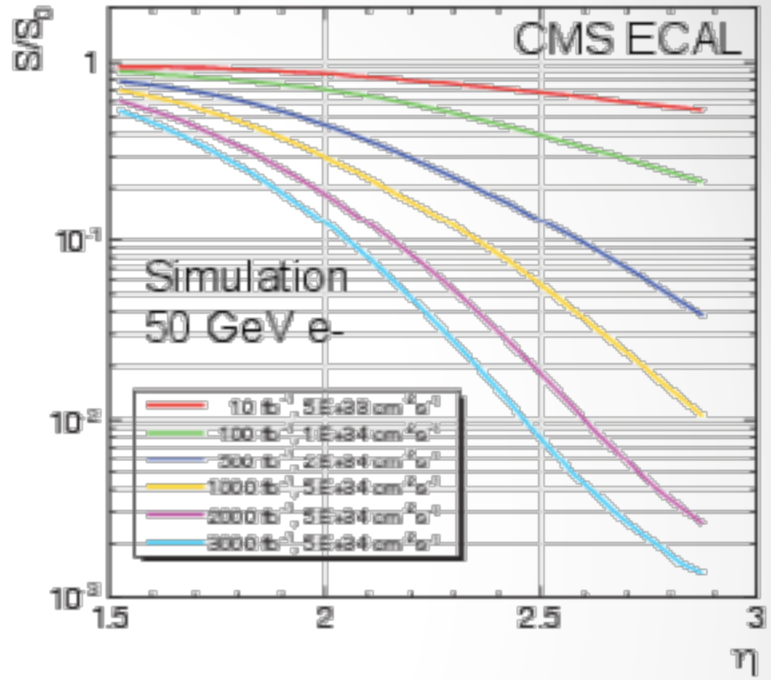
Calorimeters: some requirements

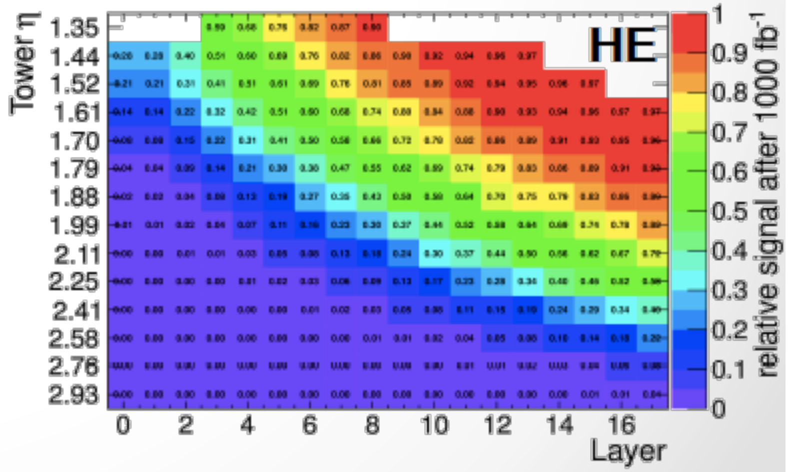
- Latency of 12.5 μs, L1A rate ~ 750 kHz
- Operation at 140 <PU>
  - Need higher granularity, both for trigger and full reconstruction
- Retain good photon resolution and efficiency
  - Mitigate degradation where most severe
- Good efficiency and low fake rate for VBF Higgs tagging jets
  - Region 2.0 < η < 4.0



Calorimeters: limitations and need for upgrades

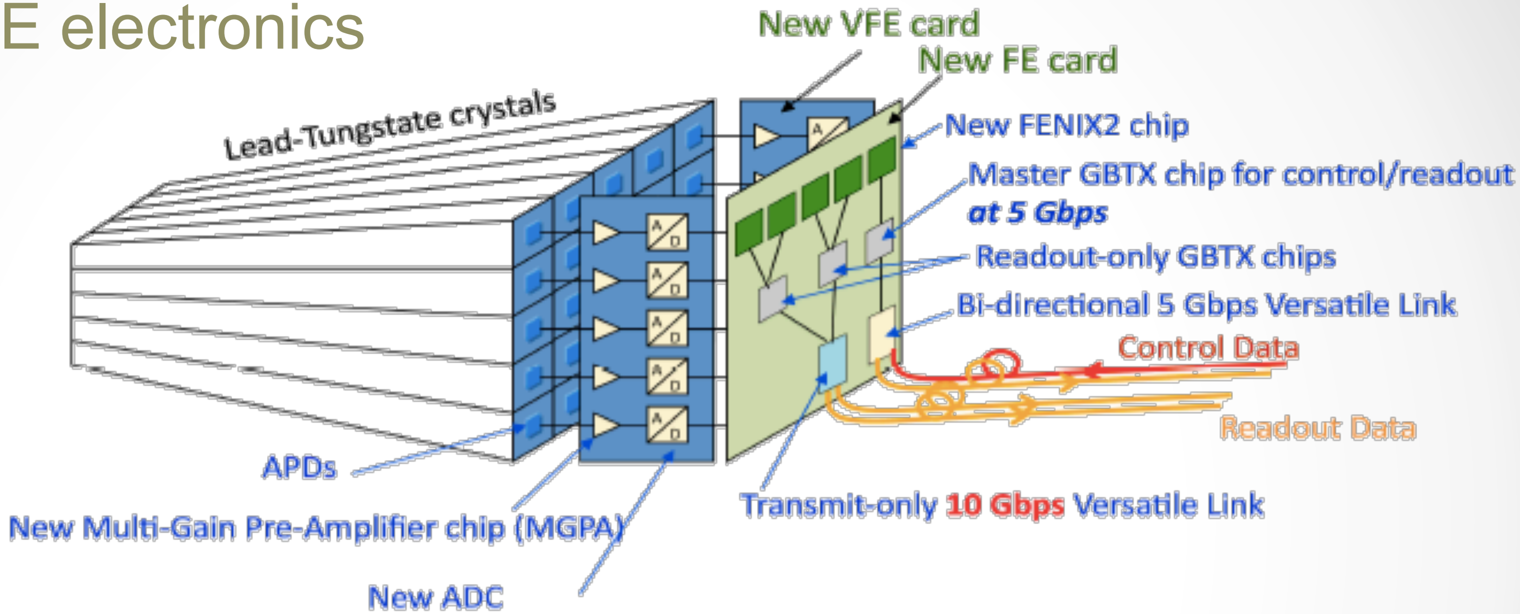
- Preshower
  - ✧ Incompatible with trigger upgrade
    - Although sensors would still work
  - ✧ Not kept for Phase-2
- ECAL crystals
  - ✧ Significant damage
    - Both electomagnetic and hadronic
  - ✧ Unacceptable darkening at high η, EB is ~OK
- ECAL photodetectors
  - ✧ EB APD degrade significantly
    - Higher dark current → noise. Requires mitigation.
  - ✧ EE VPT could work
- ECAL electronics
  - ✧ Incompatible with trigger upgrade – replacement needed
- HCAL scintillator
  - ✧ Significant loss of signal in first HB layers an substantial fraction of HE
    - Requires replacement or upgrade





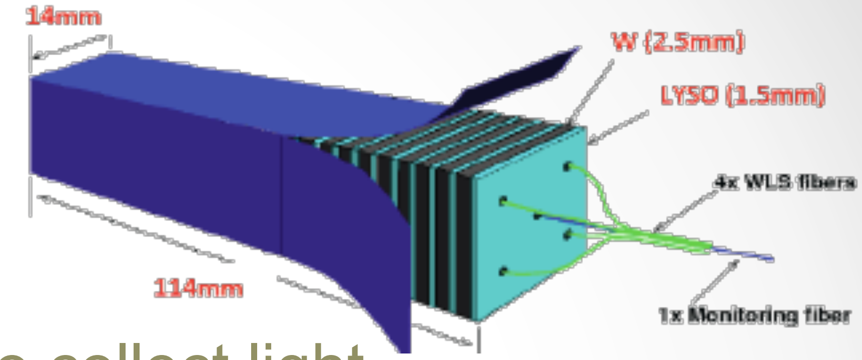
EB Upgrade

- Replace FE electronics

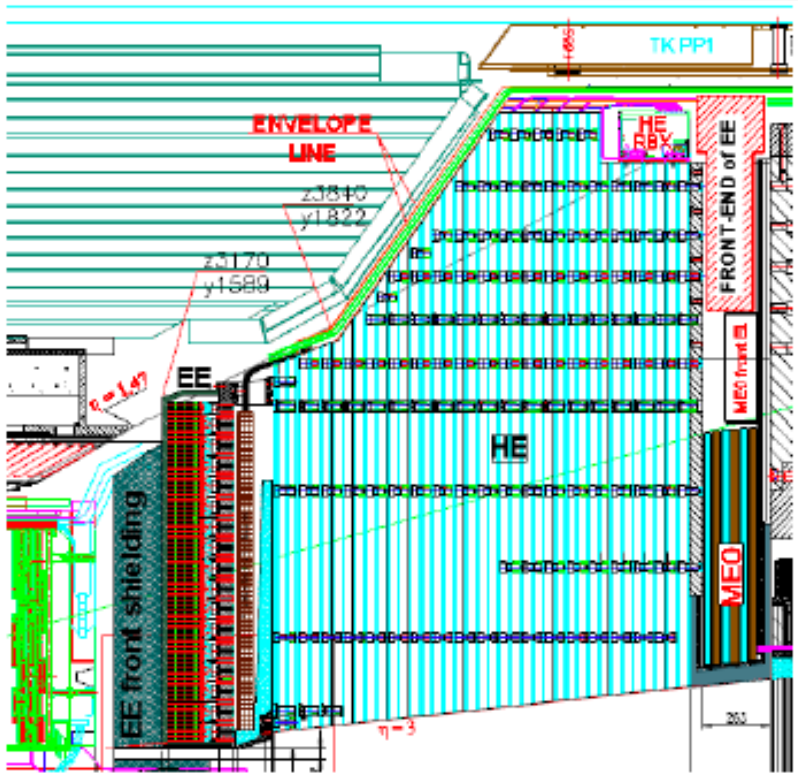


  - Full readout at 40 MHz
    - Trigger primitives calculated off-detector
  - Faster shaping
    - Helps for out of time pileup and “spike” mitigation
  - Requires **rework of all supermodules** in LS3!
- Lower operating temperature (e.g. 18°C → 8°C)
  - Reduce APD dark current and noise
  - Requires new pipework (foreseen anyway) and some engineering

EE/ES replacement option: Shashlik

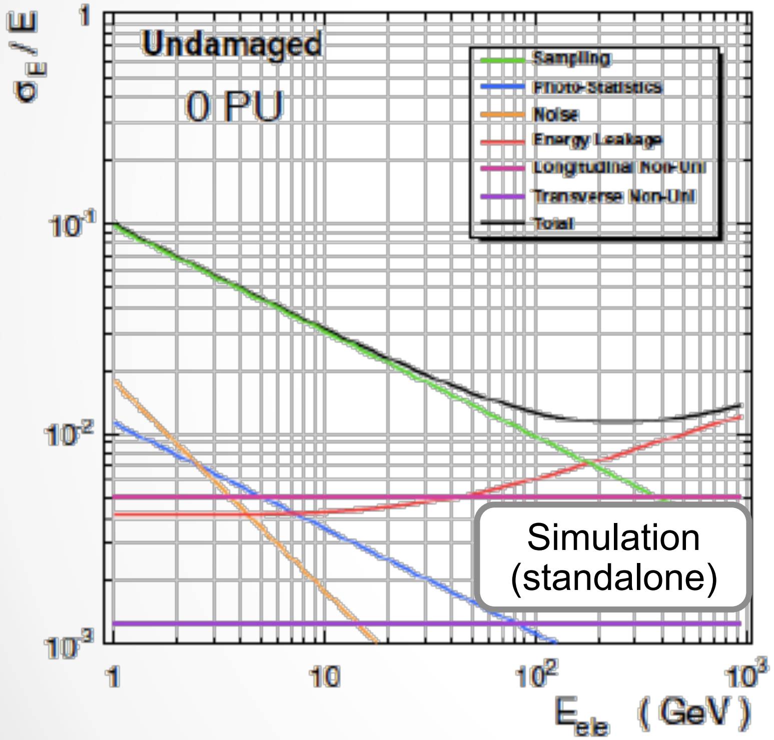


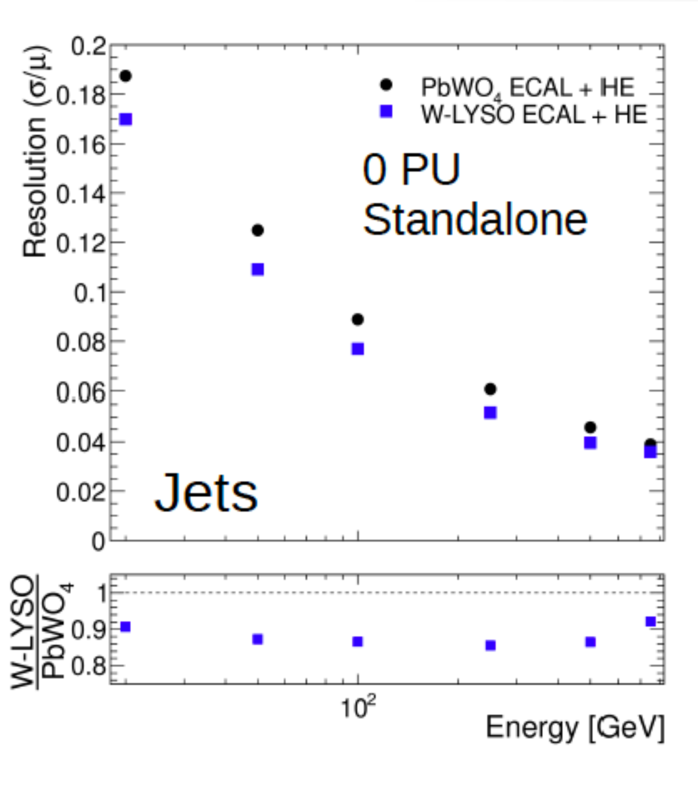
- Similar structure as current EE
- LYSO Crystals + W absorber
- Wave-Length Shifter capillaries to collect light
  - Four photodetectors / module
- More compact / higher granularity
  - Radiation length: 8.9 → 5.1 mm
  - Moliere radius: 21→ 13.7 mm
  - Lateral size: 28.6 → 14 mm
  - Length: 220 → 114 mm
- Complemented by new HE
  - Located closer to the IP
  - Electronics behind HE
    - Plus space for new muon detector



Shashlik: performance and outlook

- Good intrinsic electromagnetic energy resolution
- Better resolution than current system for jets
- Results for high pileup in preparation

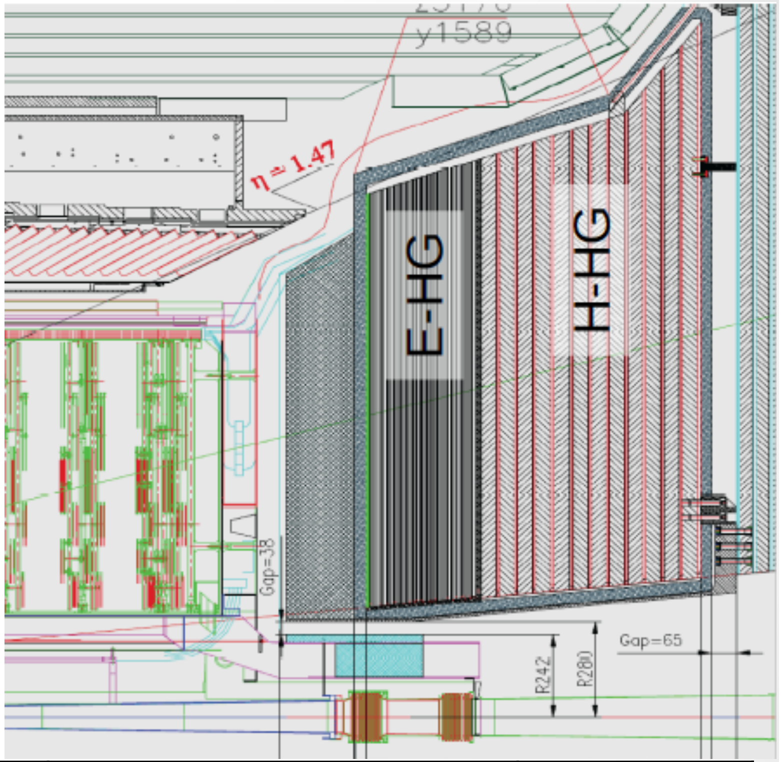




- R&D still ongoing on all main aspects
  - Development of the WLS system, radiation qualification of crystals and fibers, photodetectors, global optimization and performance estimate

EE/ES replacement option: HGC

- High-Granularity silicon-based sampling Calorimeter
- Electromagnetic calorimeter (25 X_0)
  - 30 layers of Si sensors + W absorber
  - 10 × 0.5 X_0, 10 × 0.8 X_0, 10 × 1.2 X_0
- Hadron calorimeter (3.5 λ)
  - 12 layers of Si sensors + brass (12 × 0.3 λ)
- Radiation levels very challenging
  - Requires cold operation (expect −30°C)
  - Develop CO_2 cooling
- Complemented by a "smaller HE"
  - Scintillator/brass, 5.5 λ
    - Less demanding radiation/granularity requirements

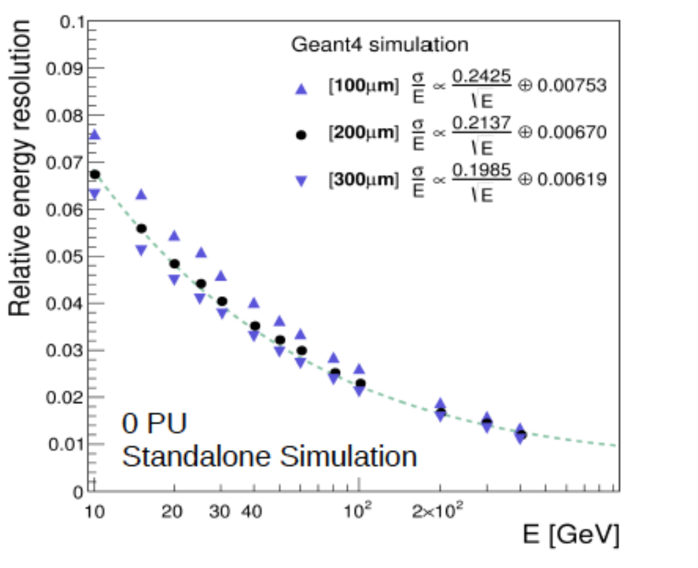


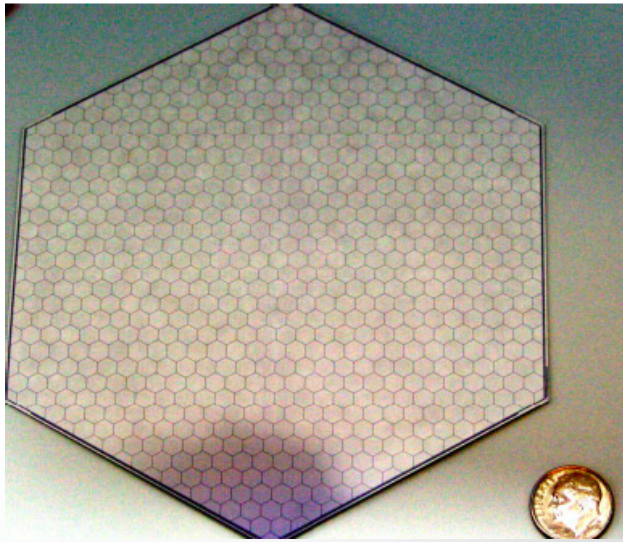
(*) *Assuming use of 8" wafers*

	E-HGC			H-HGC		Total
Region	1.48<|η|<1.75	1.75<|η|<2.15	2.15<|η|<3.0	R>860 mm	R<860 mm	
Max 1MeV n_{eq} fluence	6×10^{14}	2.5×10^{15}	1×10^{16}	6×10^{14}	2.5×10^{15}	
Active Si thickness (μm)	300	200	100	300	200	
Area of Silicon (m^2)	420			241		661
Channels (M)	6.0			2.7		8.7
Detector modules(*)	18.2			10.5		28.7

HGC: performance and outlook

- FE amplifier with logarithmic response
  - Good resolution and dynamic range
- Expect electromagnetic energy resolution around 20% / √E
- 3D shower reconstruction
- GBT-based data transmission. Optical conversion behind HE
- R&D on sensors, module design, system aspects
- Substantial engineering for cooling, thermal enclosure and service feedthroughs





HB/HE upgrade

- HB refurbishment
  - Limited replacement of scintillators
    - Restore performance
  - Upgrade of Back-End electronics

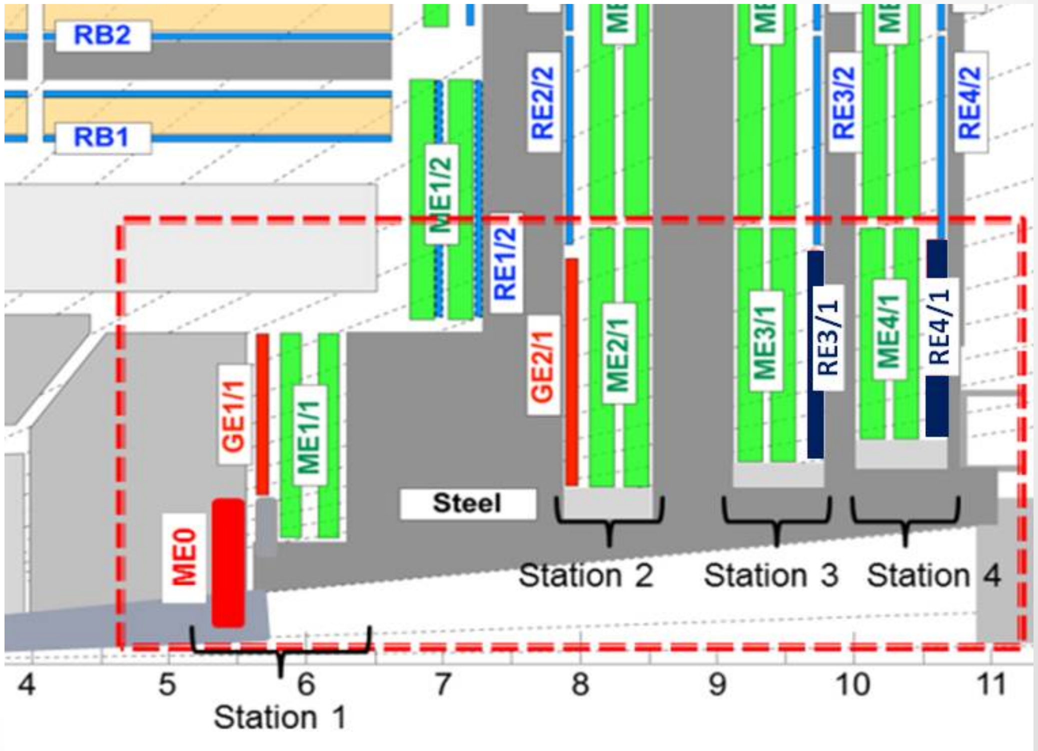
- HE full replacement
  - Rebuild including absorber
    - Mandatory because of LS3 planning/logistics
      - Assemble and commission detector on the surface
    - Design coherently with EE option selected
  - Different active materials may be used in different parts
    - Optimize performance / cost according to different radiation requirements
    - Under study: liquid scintillator, quartz, doped LuAG fibers….

The Muon system upgrade

LS2 and LS3

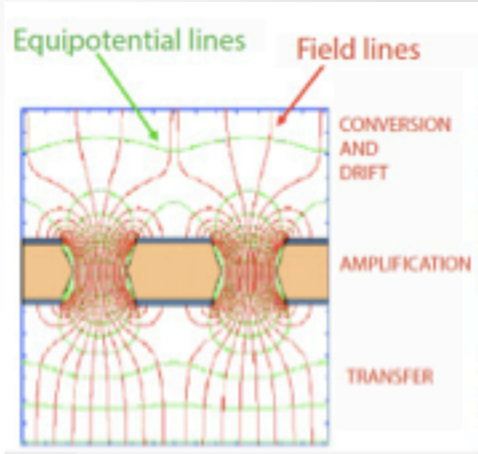
Muon Upgrades: overview

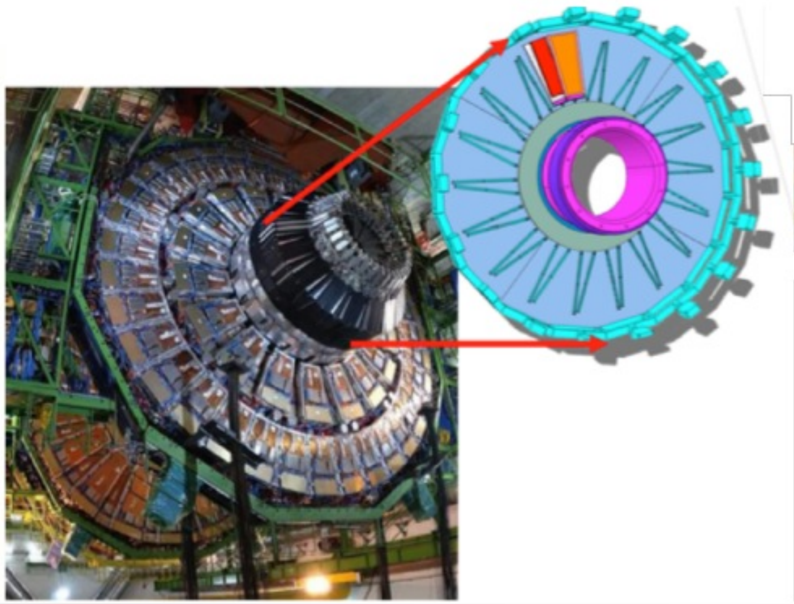
- Improvements of existing detectors
  - Eletronics: DT minicrates, CSC inner MEx/1 readout
    - Both are needed for compliance with trigger upgrade
      - Independently: concern about aging of DT electronics
- Forward 1.6<|η|<2.4 upgrades
  - L1 trigger rate reduction, enhance redundancy
  - GEMs: GE1/1 and GE2/1
    - Ge1/1 to be installed in LS2
  - iRPCs: RE3/1 and RE4/1
    - Operation in higher rate
    - Technology to be selected
- Very forward extension
  - Extend muon tagging
  - ME0 with GEMs
  - 6 layer stub
  - Baseline 2.0<|η|<3.0
    - Depends on calorimetry

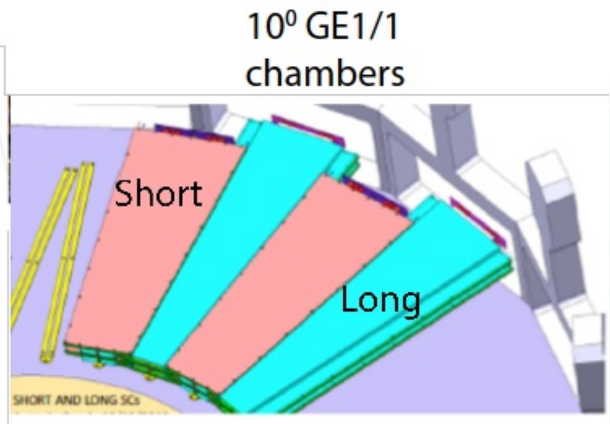


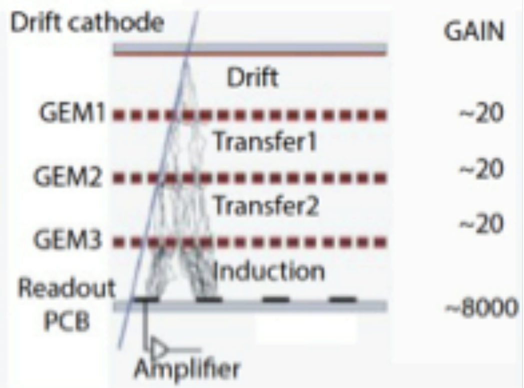
GE1/1 in LS2

- Good progress in GEM technology over the past few years
  - Single mask technique for GEM foils
    - Allows to build large detectors
  - Foils mechanically stretched in chamber assembly
    - Assembly fast and simple
  - No glue, and no spacers in the active volume
- Simple, large, cost-effective high-quality detectors
- Technology mature for a fairly large project!



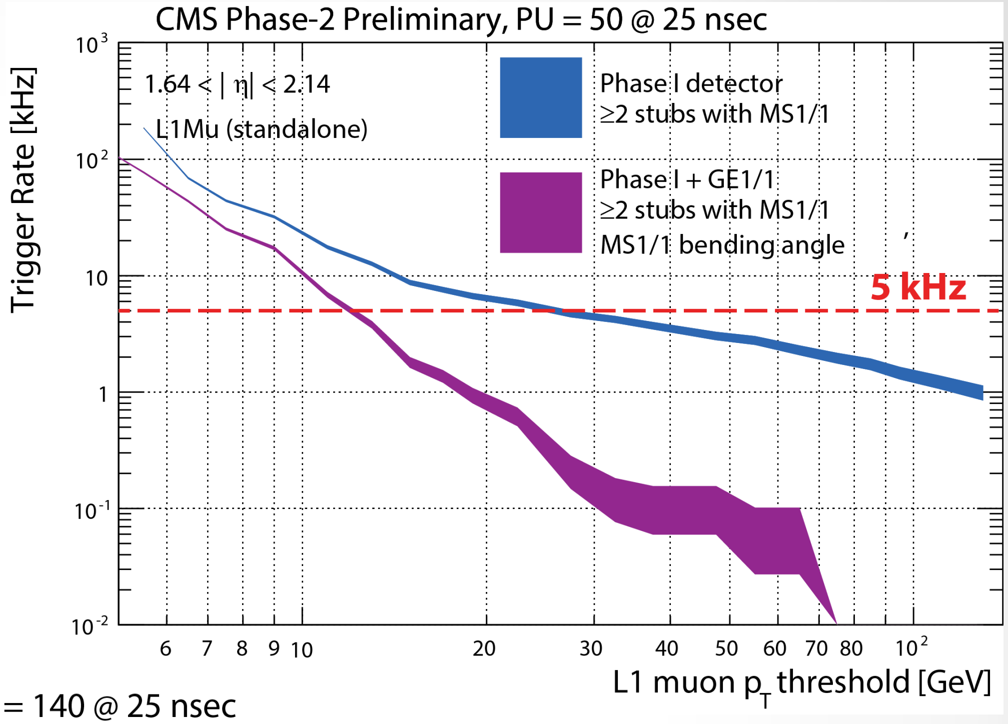


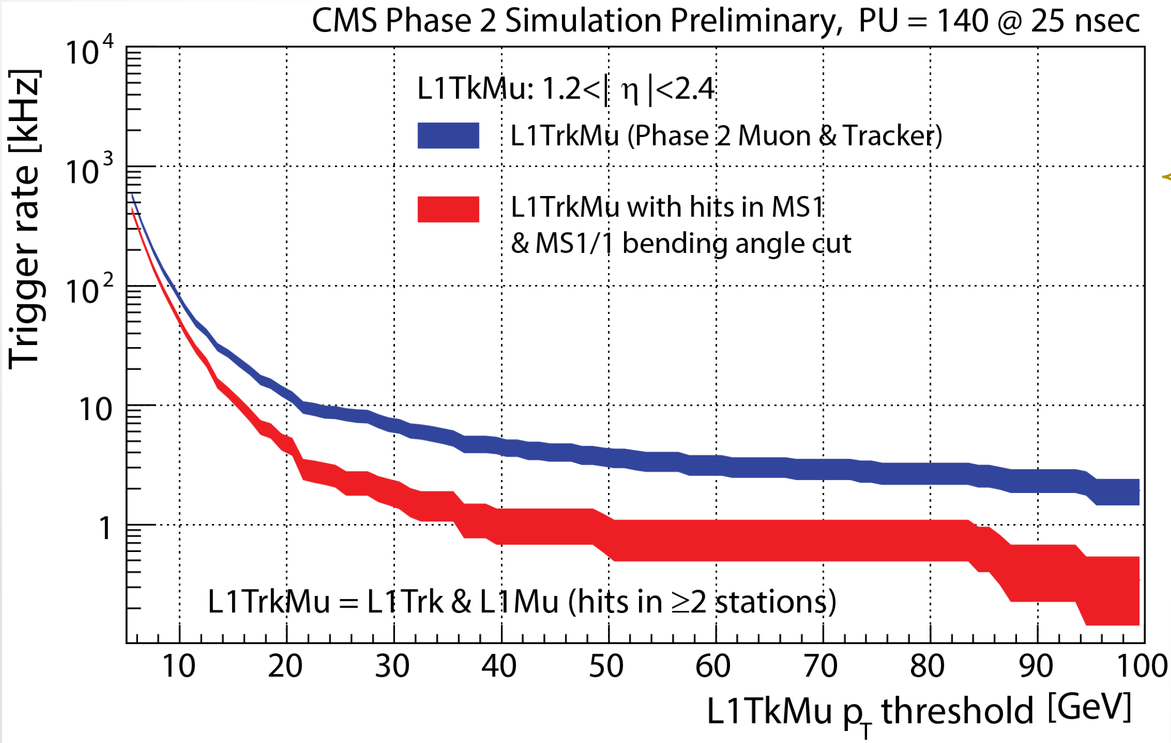




GE1/1 performance

➢ Excellent handle for trigger in Run 3

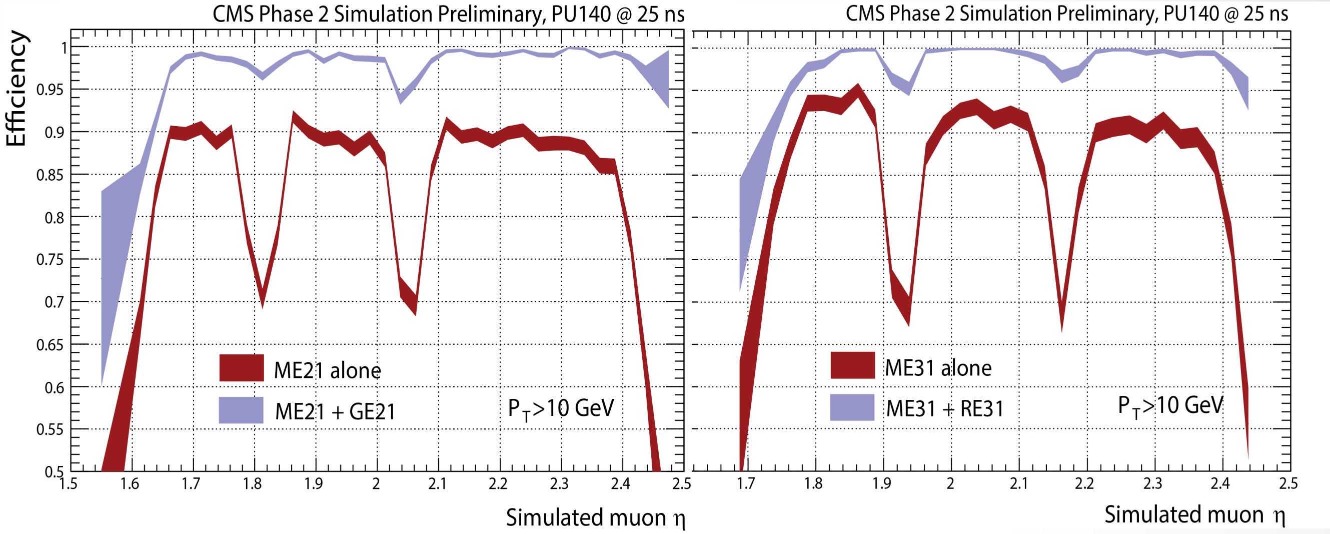




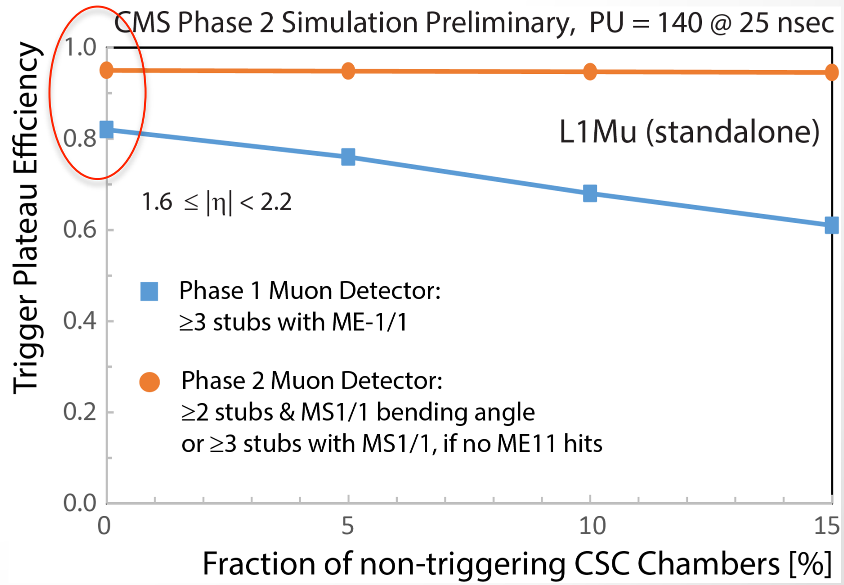
✧ Remains effective also after Track-Trigger is available

Trigger robustness

- Improvement of local primitives



82% → 95%



- Improvement of global muon trigger efficiency

The Trigger Upgrade

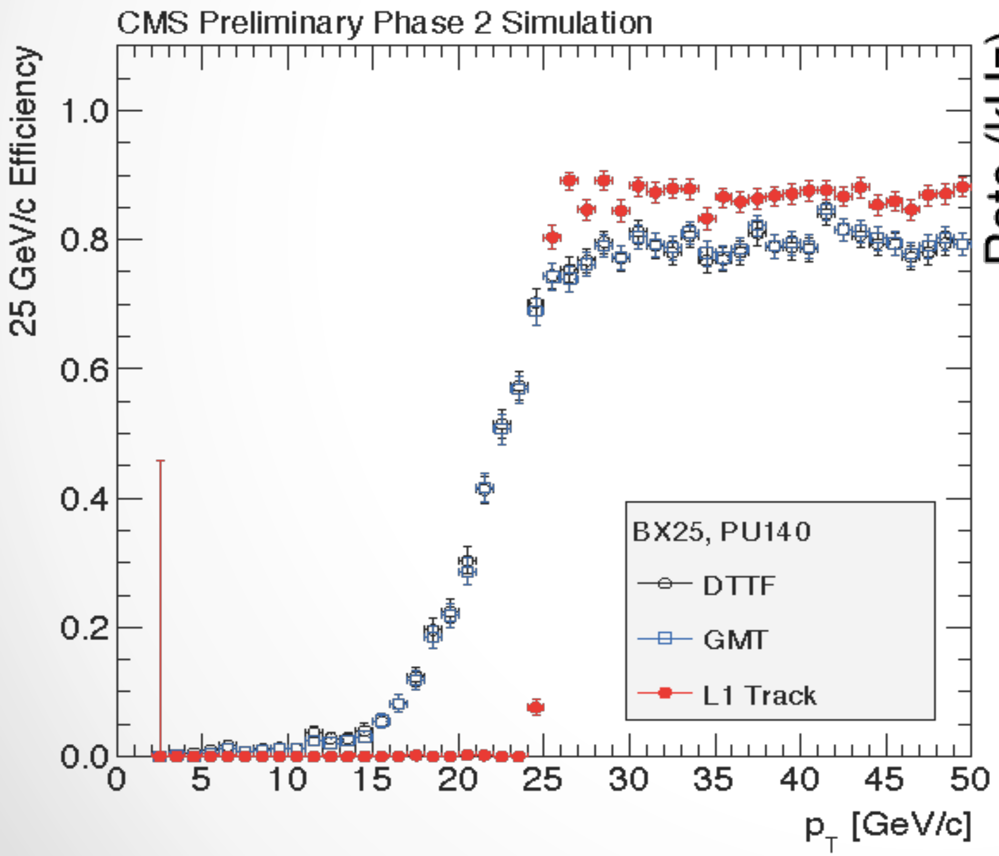
… to wrap up!

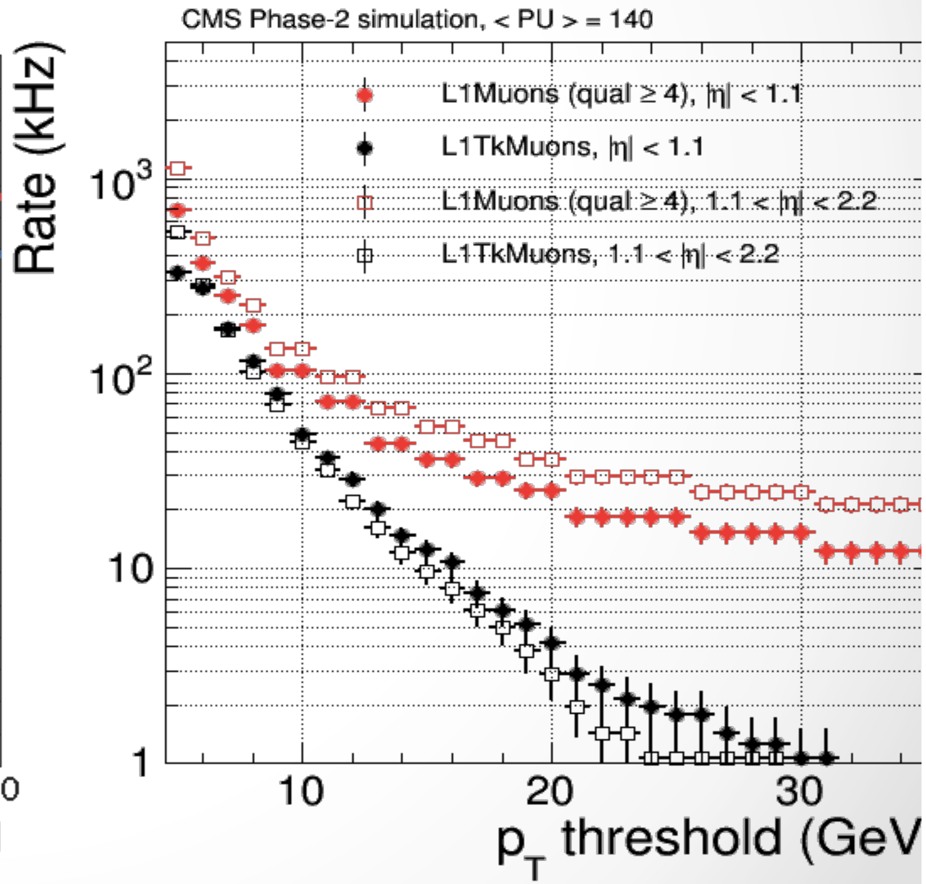
Summary of Phase-2 L1 features

- Available latency 12.5 μs
- Higher granularity information from Calorimeters…
  - New EB electronics, new EE detectors
- … and muon system, with higher rapidity coverage
  - New DT electronics, new CSC electronics (at high η), improvement of HB back-end electronics, new RE*/1 GEM and RPC stations
- Processing of L1 tracks (wish list)
  - Use tracks to find primary vertices
  - Associate tracks to primary vertices
  - Associate tracks with calorimeter objects
  - Associate tracks with muon tracks and refit
  - Define track-correlated L1 objects
  - Calculate isolation of calorimeter and muon objects
    - Some 2.5 μs tentatively allocated to these tasks
- Expect to produce a L1 accept rate well within 500 kHz for 140 PU
  - Assumed 750 kHz as safety margin / headroom for higher PU

Use of L1 tracks in the trigger

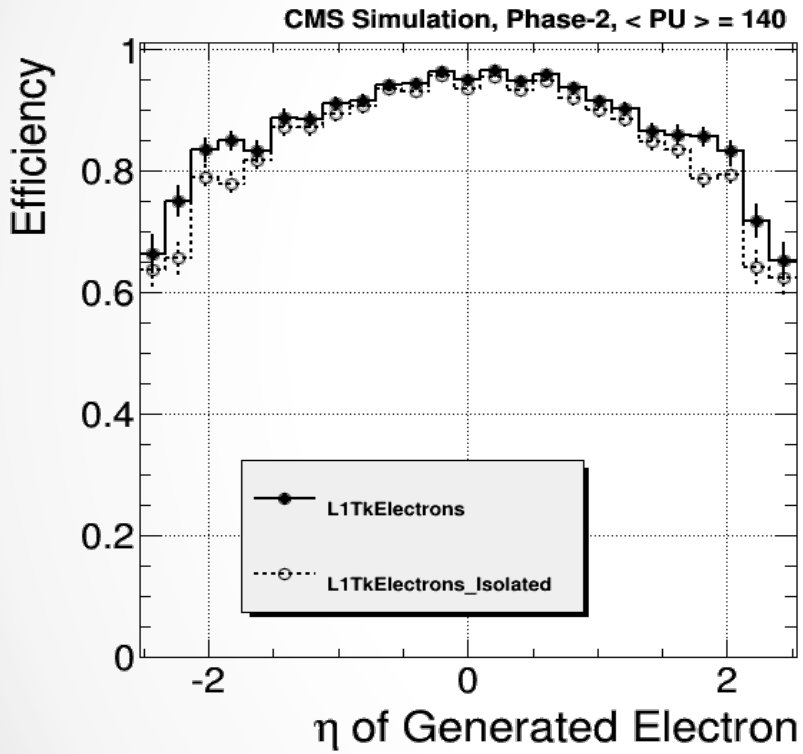
- Example: single muons
  - Improved p_T resolution, sharper turn on curve
  - Rate reduction of O(10) for a threshold of 20 GeV

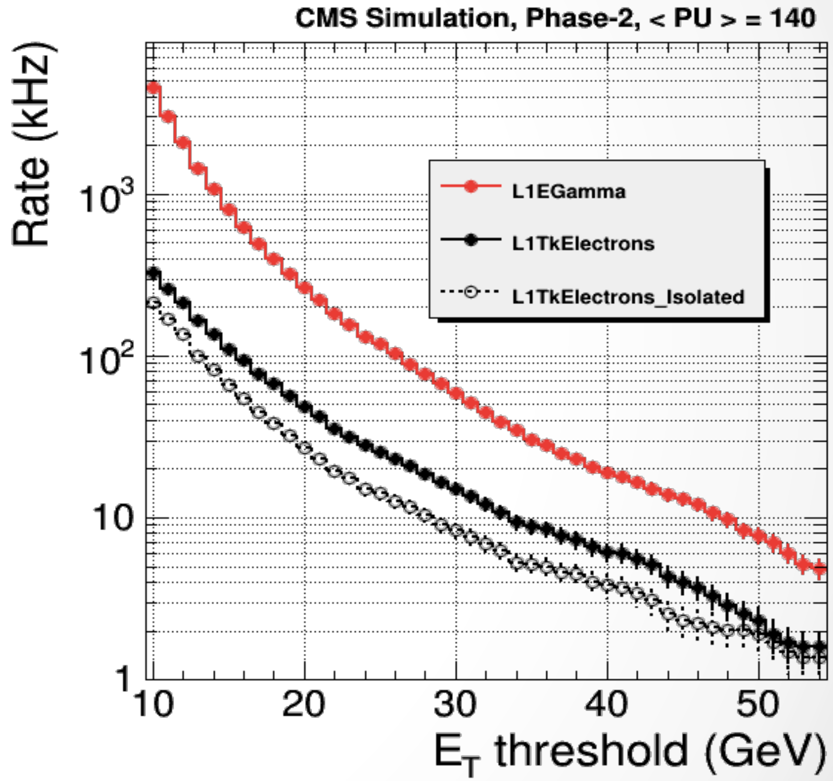




Use of L1 tracks in the trigger

- Example: single electrons
  - Rate reduction of O(10) with acceptable loss of efficiency
  - Track-based isolation criteria





- Similar positive results for Photons, Tau jets, MET…
  - Overall expected rate reduction >5 on the whole trigger menu
- N.B. No design for a hardware implementation yet!

Conclusions

- CMS is detailing a program to improve the detector and make it suitable for High-Luminosity operation
- A major upgrade is needed
  - Complete new tracking system, electronics upgrade of the barrel detectors, new endcap calorimeters and some new forward muon detectors.
  - Huge upgrade of the cavern infrastructures
    - Not covered in this talk
- Big effort, comparable to the original construction
  - Difficult to find all the needed volunteers, while the Collaboration is analyzing data and building the Phase-1 Upgrades
- We need to agree on a clear target for the operating parameters we should design for
  - 140 <PU> or 200 <PU> makes a difference for the optimization of the detector!
    - The size of the beam spot is also relevant
- Looking forward to much more physics from the LHC!