Perspectives for the Phase II upgrade of CMS

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Outline

- CMS physics goals for HL-LHC
- Detector challenges for HL-LHC
  - longevity and performance
- The CMS Phase II upgrade programme
  - replacement of detector components
  - enhanced trigger functionality
- Timeline and summary

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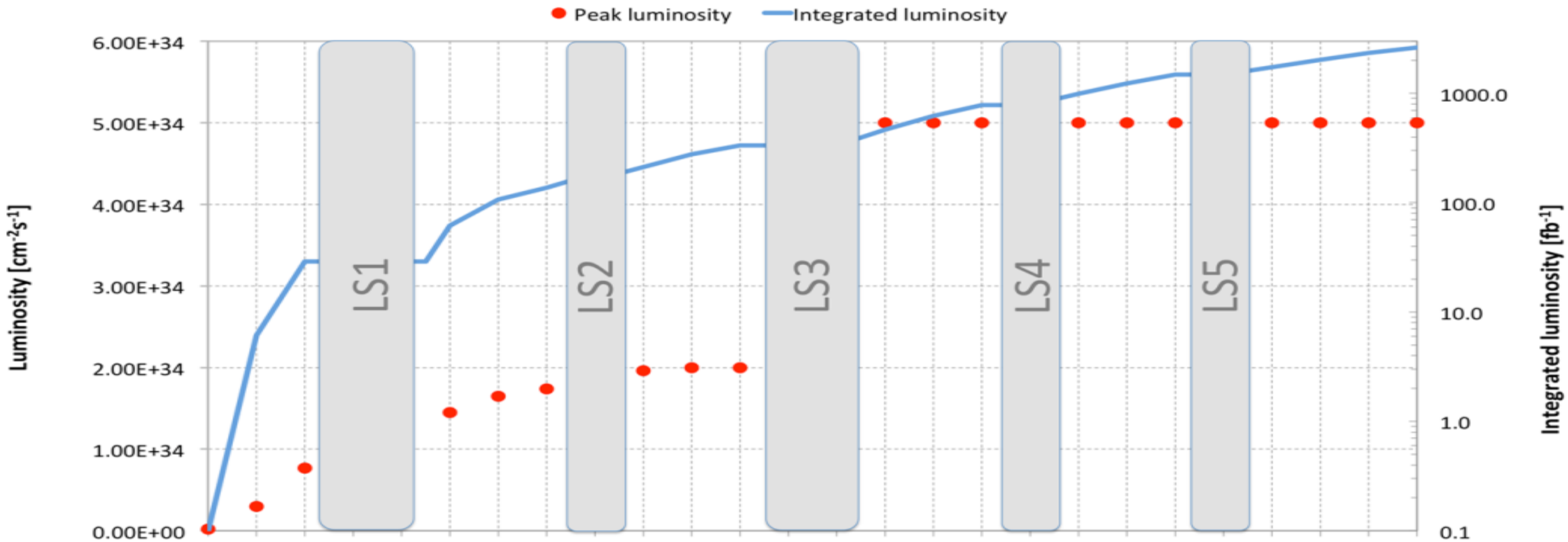
The LHC/HL-LHC programme

LHC (Phase 1) | HL-LHC (Phase 2)

$L \leq 2 \times 10^{34}$ $cm^{-2}s^{-1}$, $\langle PU \rangle_{max} \sim 50$ | $L = 5 \times 10^{34}$ $cm^{-2}s^{-1}$ (levelled), $\langle PU \rangle_{max} \sim 140$



- LHC operation up to LS3 (2023)
  - 25ns bunch spacing, √s close to 14 TeV; instantaneous luminosities up to 2×10^{34} (2x design); accumulate ~$300 fb^{-1}$ by 2023
- HL-LHC operation beyond LS3 (2025+)
  - new low-β triplets and crab-cavities to optimize the bunch overlap at the interaction region
  - level the instantaneous luminosity at 5×10^{34} from a potential peak value of 2×10^{35}; deliver ~$250 fb^{-1}$ per year for a further 10 years of operation.

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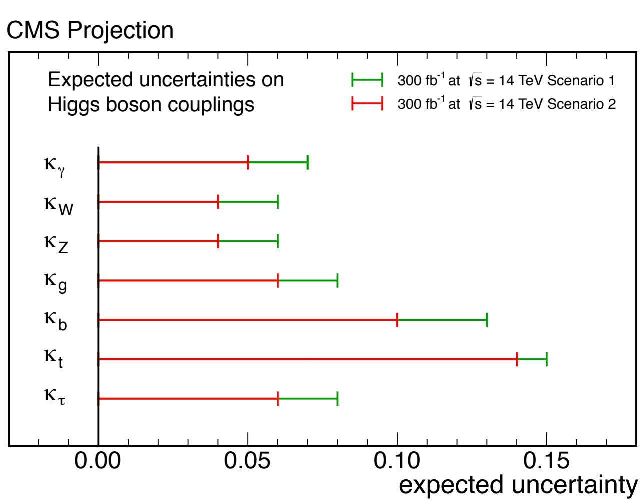
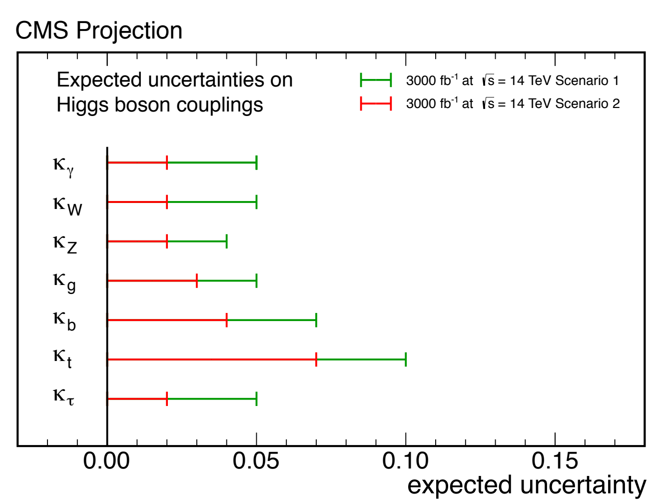
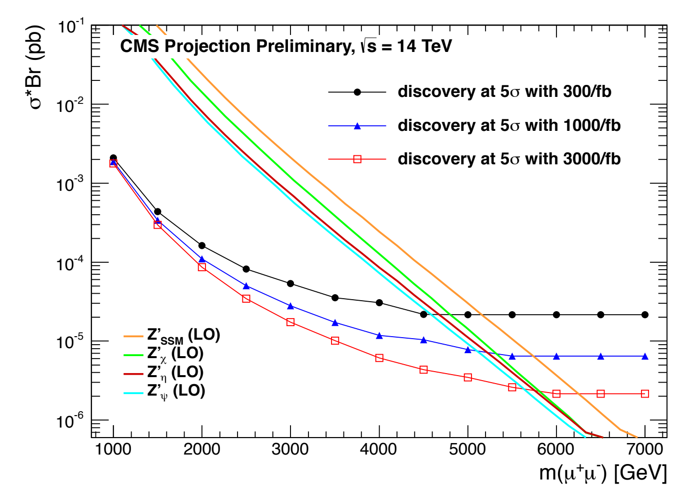
HL-LHC physics goals

- Study properties of newly-discovered Higgs boson
  - Precision measurement of couplings, including Higgs self-coupling
- Searches for new physics
  - SUSY and multi-TeV particle searches
- Improved precision of top and electroweak measurements
  - reduce the systematic uncertainty on Higgs boson measurements
  - potential probes of subtle new physics effects.







Higgs couplings: 300→3000fb^{-1}

precision improves by factor of 2-3

Z',W' searches: 300→3000fb^{-1}

reach improves by 1 TeV

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Detector challenges

- Ability to survive up to 3000 fb^{-1}, and to 2035
- Ability to operate at 140 PU
- Ability to offer similar performance at 140 PU, 3000 fb^{-1} as current detector in Run I
- Maintain current trigger acceptance for HL-LHC conditions
    - Need to maintain lowest possible trigger and analysis thresholds

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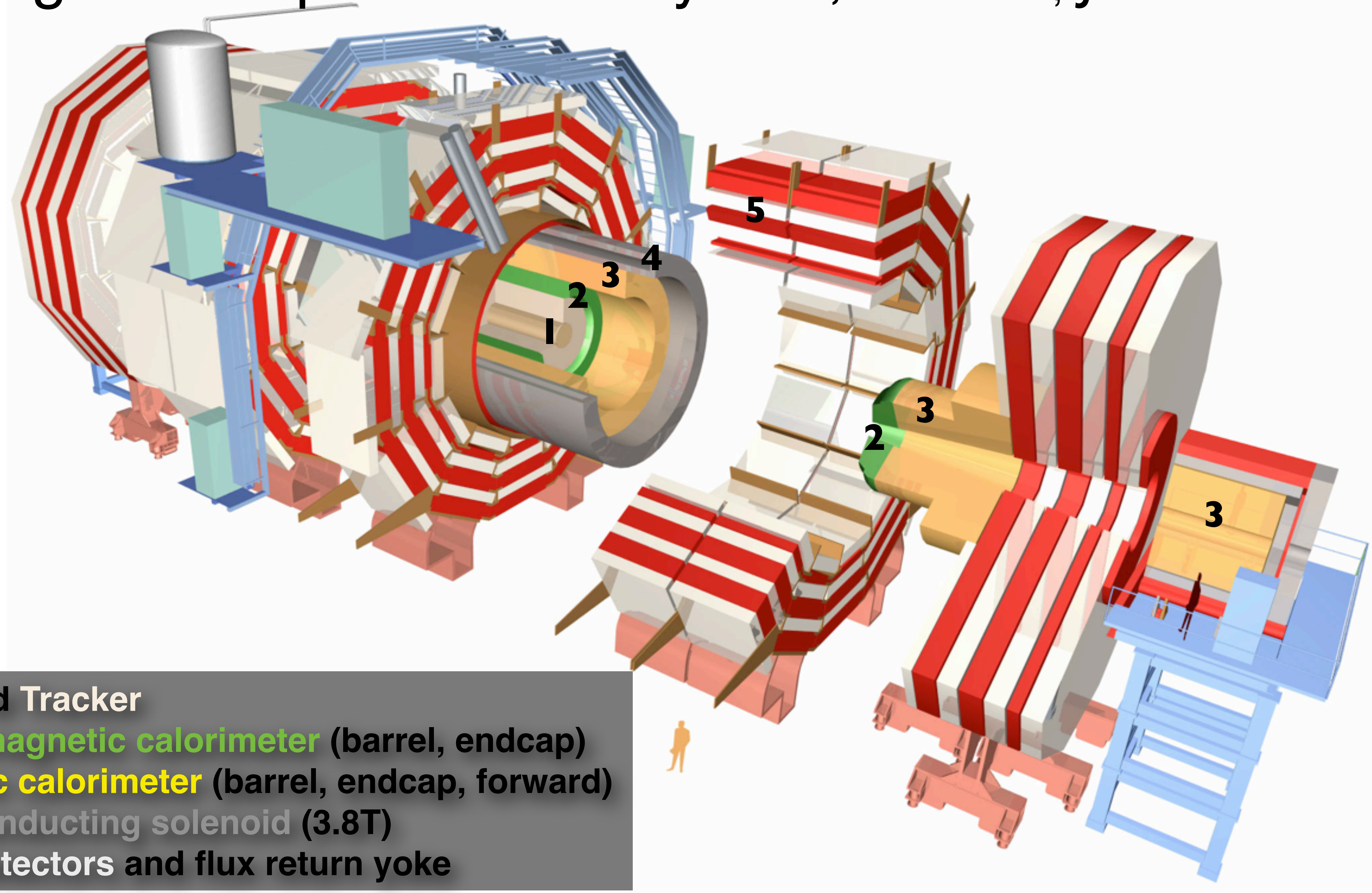
CMS Phase I detector

Designed to operate for 10 years, $L \sim 10^{34}$, $\int L dt = 500 fb^{-1}$.



1) Pixel and Tracker
2) Electromagnetic calorimeter (barrel, endcap)
3) Hadronic calorimeter (barrel, endcap, forward)
4) Superconducting solenoid (3.8T)
5) Muon detectors and flux return yoke

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Scope of the CMS Upgrades

- New tracker/pixel detectors and forward calorimeters with:
  - enhanced radiation tolerance, granularity
  - extended eta coverage for tracking (and calorimetry) up to $|\eta|=4$
- Enhanced Level-1 trigger functionality
  - Hardware track trigger at level-1; matching of tracks and calo/muon objects → maintain low thresholds at HL-LHC luminosities
    - Larger on-detector latency required (12.5μs) for hardware track finding
    - Implies consequent replacement of FE electronics in various sub-detectors. New FE readout allows for finer granularity L1 trigger input.
  - Higher L1 trigger and HLT accept rates (5-10x phase 1 rate)
  - New endcap muon stations to improve muon trigger acceptance

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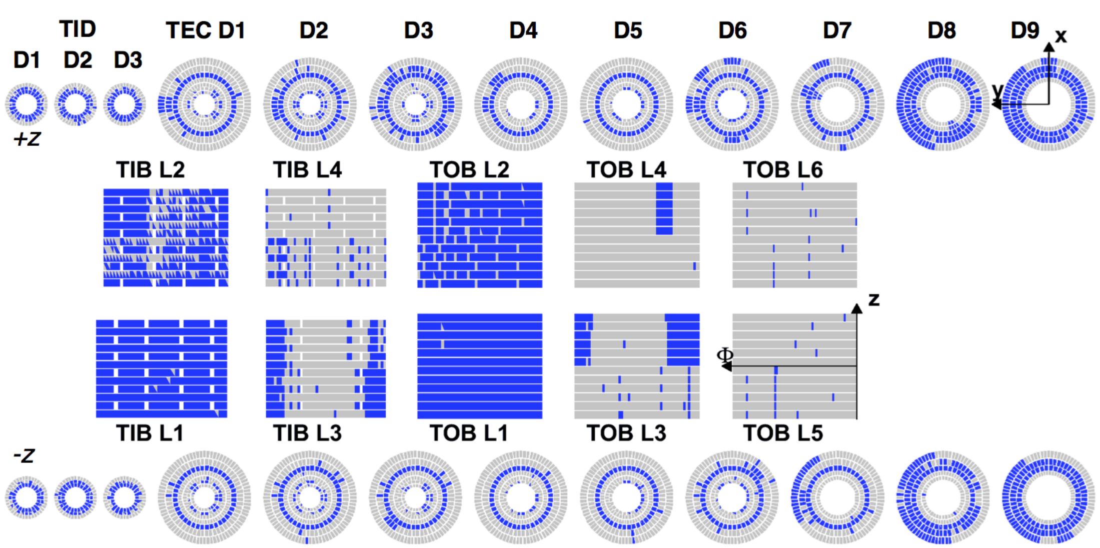
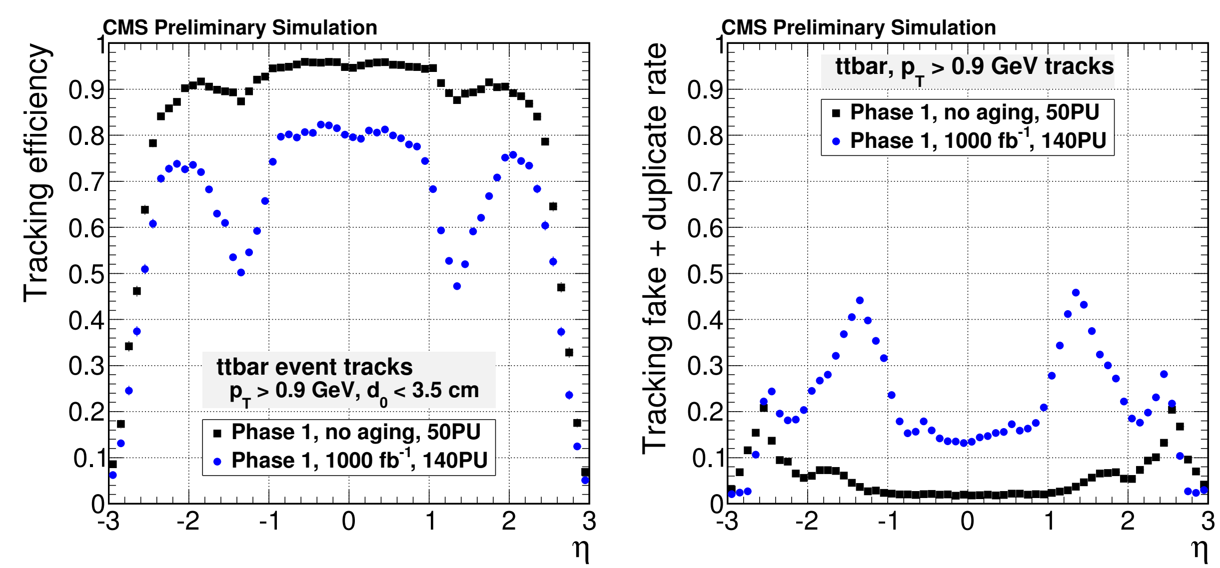
Tracker - longevity

- Tracker and pixel detectors will experience significant ageing effects in Phase II
  - **PIXEL:** radiation damage affects charge collection efficiency and Lorentz Angle: worse hit resolution (factor of 2) after 500 fb^{-1}; bandwidth limitations: 7% data loss in 1st pixel layer at 140 PU
  - **OUTER TRACKER:** increasing number of non-operational modules (leakage current), significantly degraded tracking performance (efficiency,fake rates)

→ both must be replaced during LS3



Non-operational channels after $1000 fb^{-1}$ @-20C



Tracking efficiency and fake rate degradation

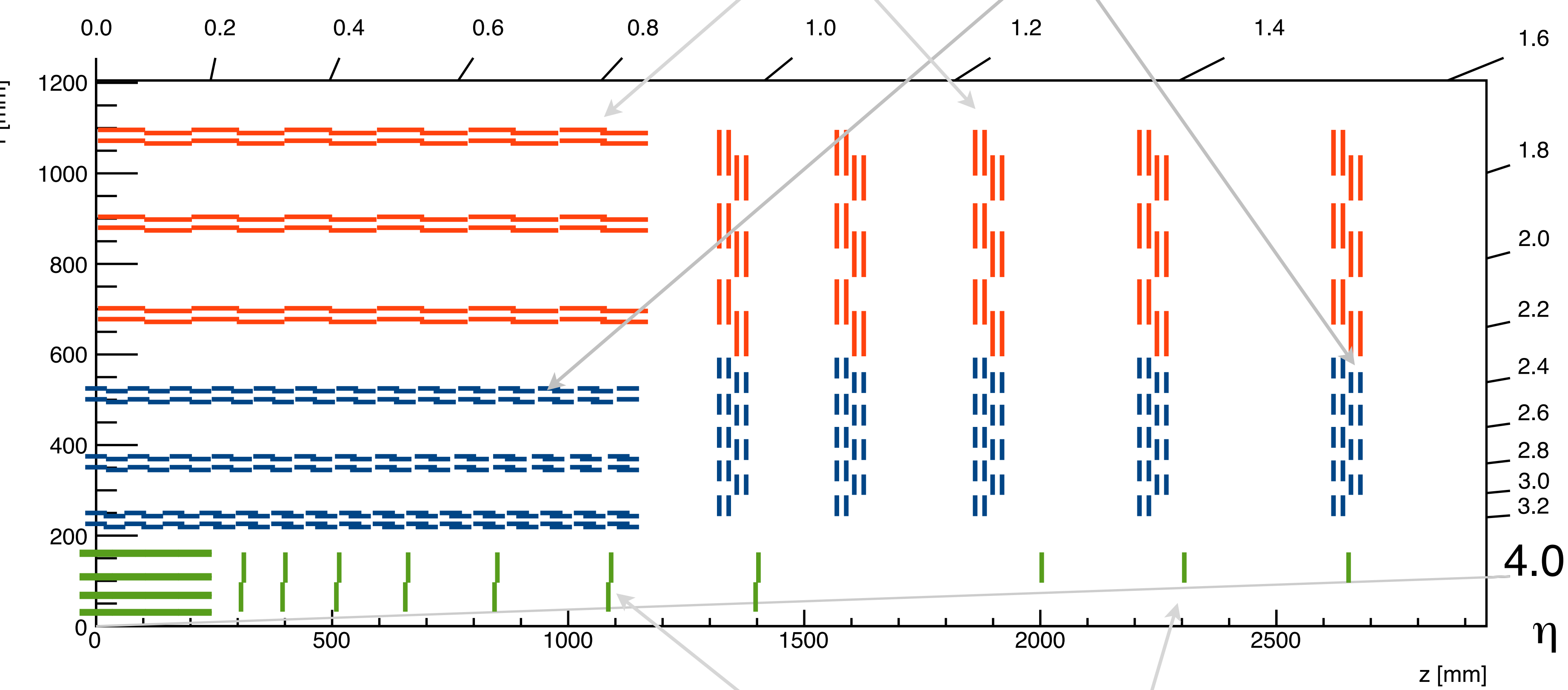
Tracker upgrade - requirements

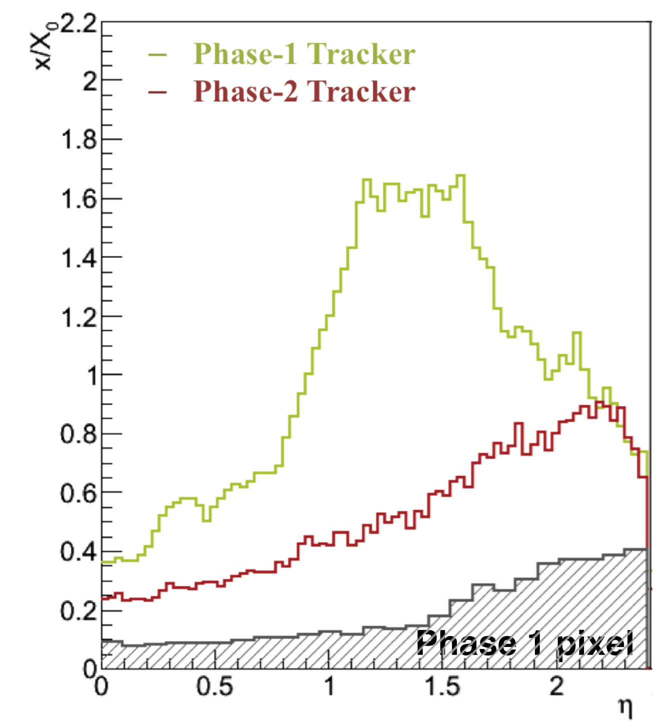
- Longevity and radiation tolerance
  - to $3000fb^{-1}$, radiation tolerance up to $2e^{16}$ n_{eq}/cm^2 in pixel region
  - preserve capability to replace pixel detector during machine shutdown periods
- Increased granularity and two-track separation
  - to maintain performance in high pileup environment
    - smaller pixels, occupancy O(1%) at 140 PU
- Reduced material budget and high eta extension
  - improve low p_T tracker performance and calorimeter resolution
  - coverage to $|\eta|=4$ (PU mitigation in jets)
- Participation in trigger upgrade
  - Satisfy latency and rate requirements of L1 trigger upgrade (12.5µs, ~500kHz)
  - Outer tracker to provide track seeds for L1 trigger decision

Tracker upgrade - design

Outer Tracker, with PS and 2S modules

Material budget





Pixel detector, with eta extension

Outer Tracker significantly lighter than Phase 1 detector

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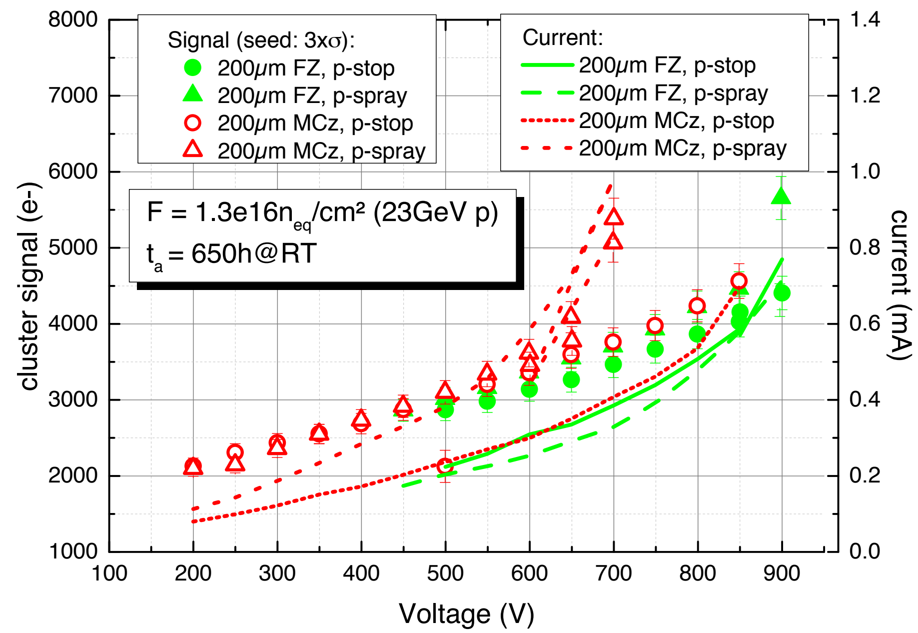
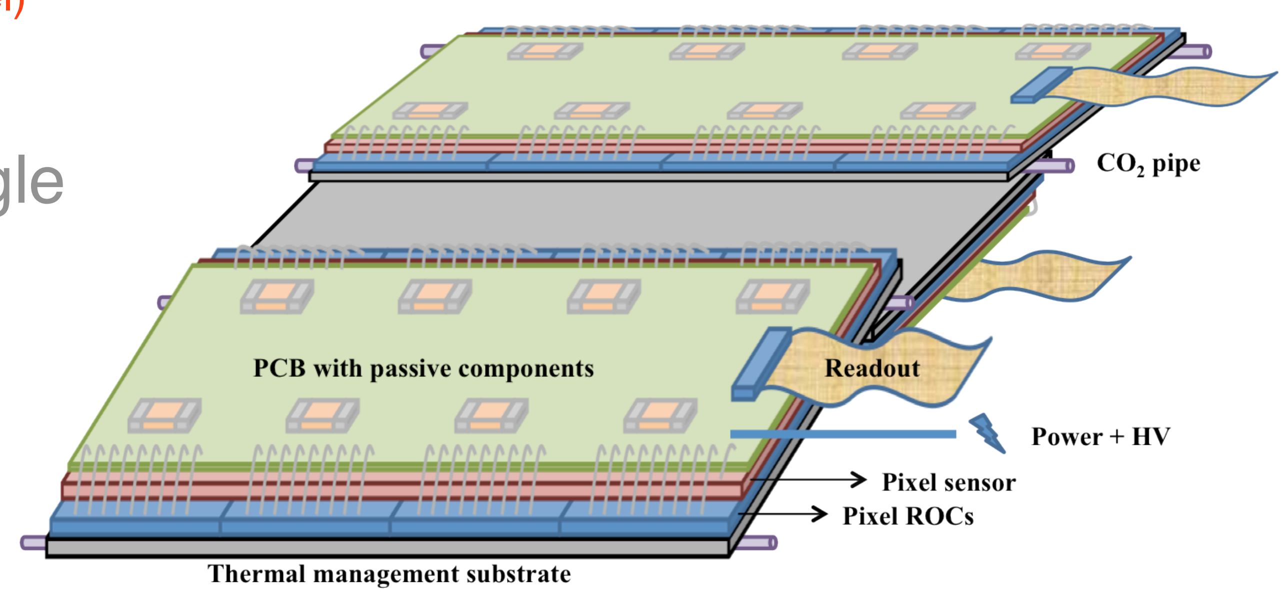
Pixel detector

- R&D ongoing for suitable silicon sensor technology:
  - thinner silicon with smaller pixels
  - n-in-p design studies ongoing
  - 3D sensors being investigated for inner regions
- Readout:
  - target pixel size: 50x50μm^2 or 25x100μm^2 (factor of 6 smaller than current pixel)
  - 65nm CMOS technology - multiple readout chips bump-bonded to single pixel sensor
  - Common development with ATLAS
    - RD53 collaboration
    - full-scale prototype planned



irradiation results on charge collection efficiency



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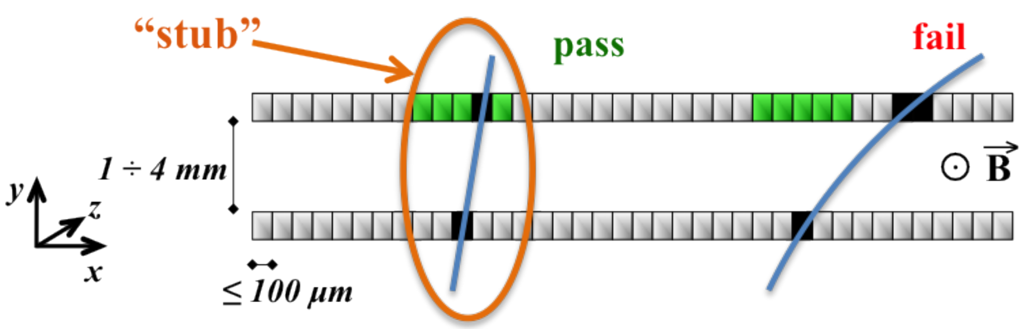
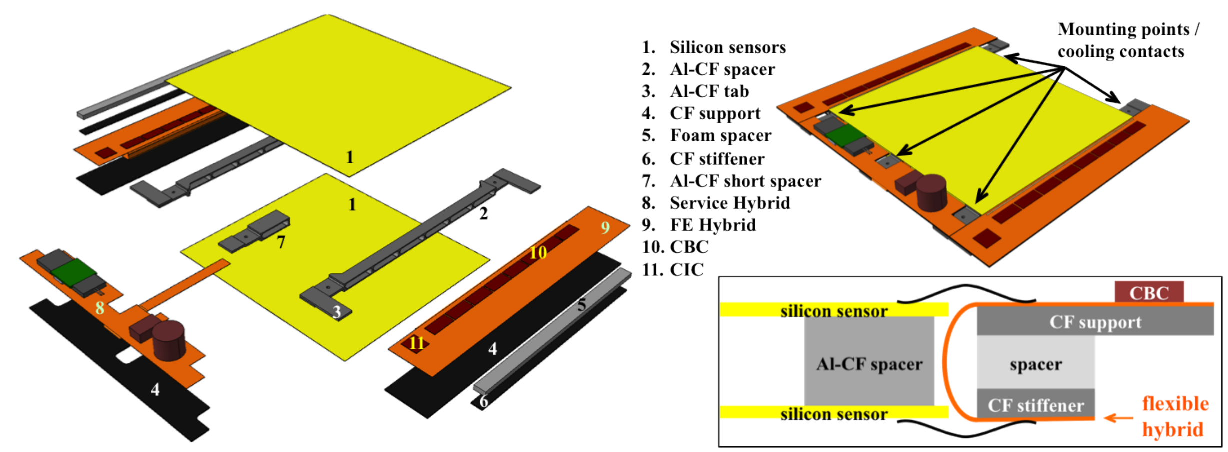
Outer Tracker



PS and 2S modules

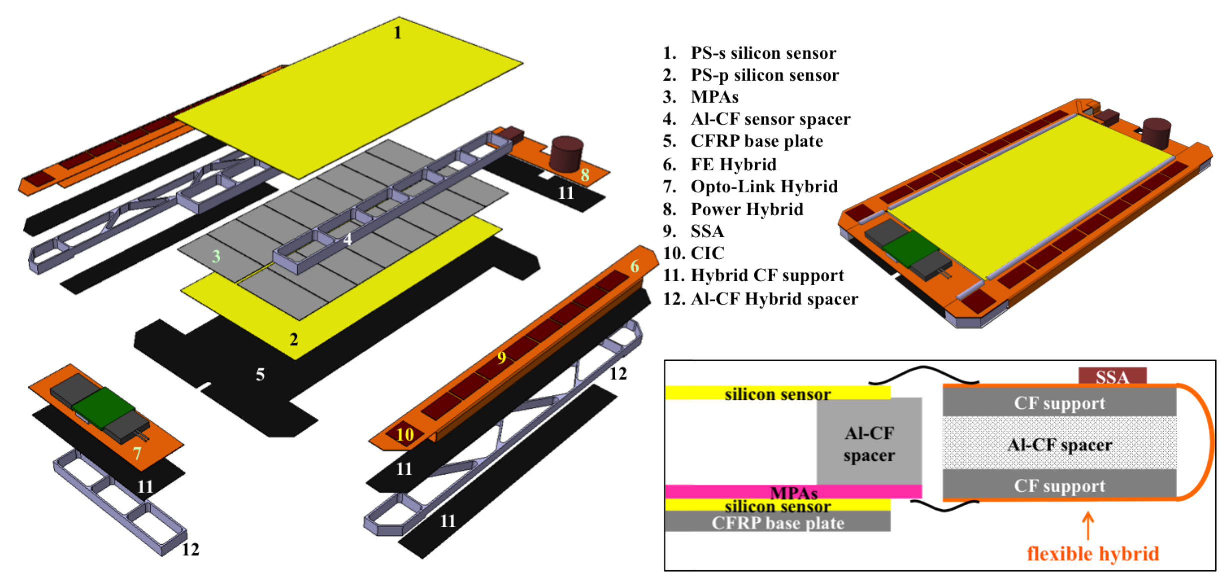
regional coincidence of hits in two closely-spaced sensors to reduce fakes from low momentum (p_T<2 GeV) tracks



2S module + FE hybrid design

90 µm x 5 cm strips, no z readout

- Module design
  - Two variants: "two-strip" modules (R>60cm) and "pixel-strip" (R<60cm) modules
  - 2S and PS modules provide "track stubs" for use in L1 track trigger @ 40 MHz
    - "p_T modules" reject low momentum fake tracks → reduce data volume by x10



PS module + FE hybrid design

1st sensor: 100 µm x 2.5 cm strips

2nd sensor: 100 µm x 1.5 mm macro-pixels (z readout)

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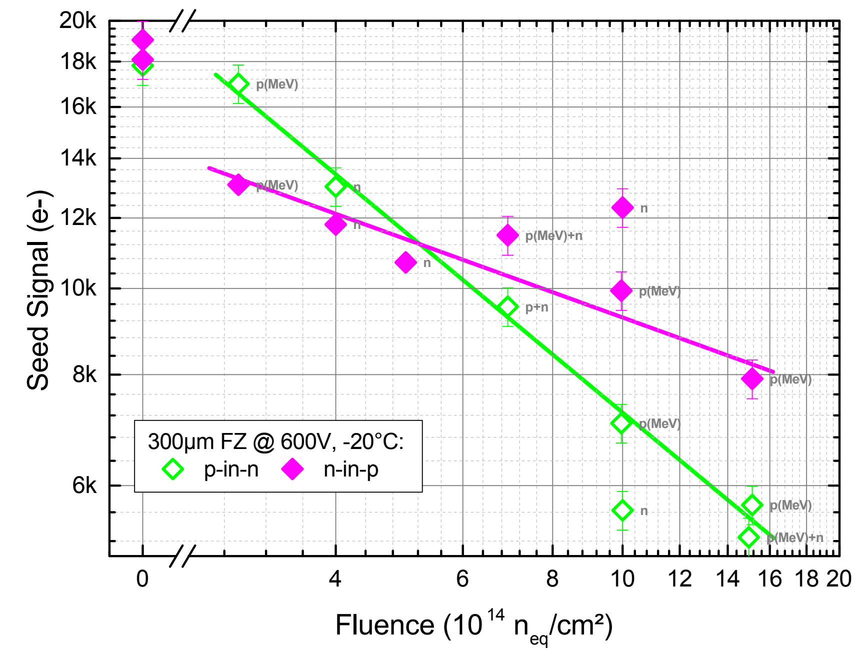
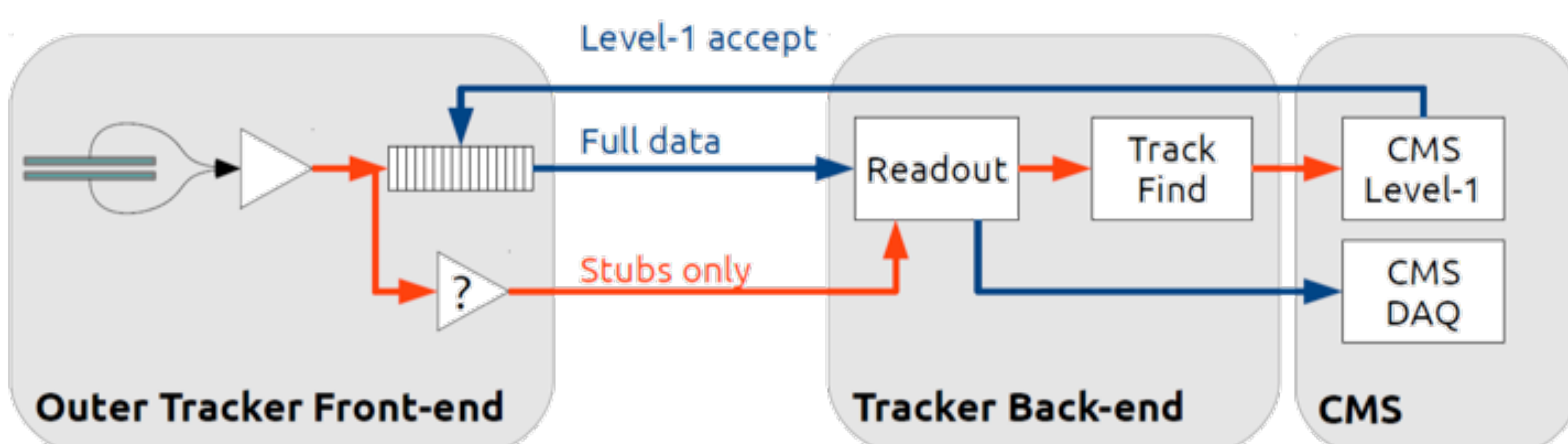
Outer Tracker

- Extensive R&D programme ongoing to find suitable silicon sensor technology:
    - FZ or MCz material, 200µm active thickness, n-in-p favoured
- Evaporative CO_2 Cooling
    - need to dissipate ~100 kW, joint development with ATLAS. Based on development of Phase I Pixel
- Readout:
    - auxiliary electronics (power, optical links) integrated on module. Prototyping mechanical designs
    - track finding being explored using fast FPGAs (with associative memories)



irradiation results on charge collection efficiency



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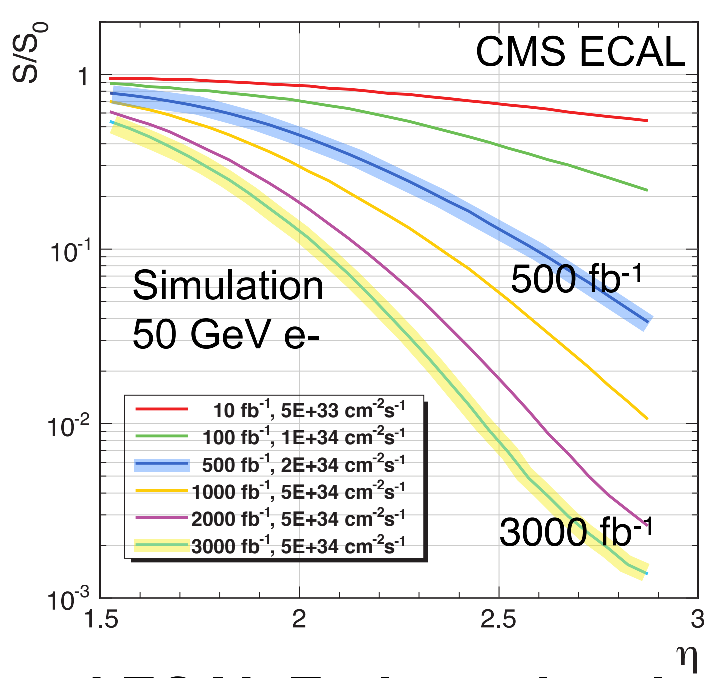
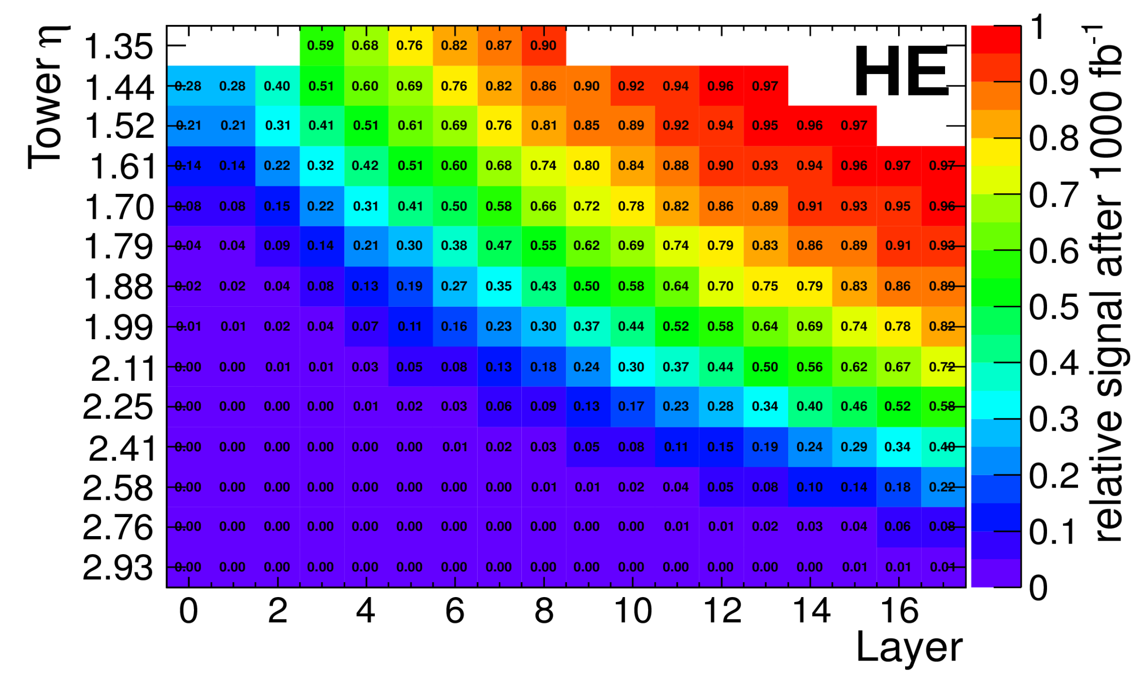
Calorimeters - longevity

- ECAL and HCAL endcaps (|η|>1.48) will suffer significant radiation damage after 500fb^{-1} and will need to be replaced during LS3
  - **ECAL:** loss of light transmission in $PbWO_4$ crystals caused by hadron irradiation. Cumulative, no recovery at room temperature.
  - **HCAL:** loss of signal response from plastic scintillator tiles + WLS fibre



Predicted ECAL Endcap signal response versus integrated luminosity and η



Predicted HCAL Endcap signal response after 1000fb^{-1} versus active layer and η

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Calorimeters - Phase II upgrade programme

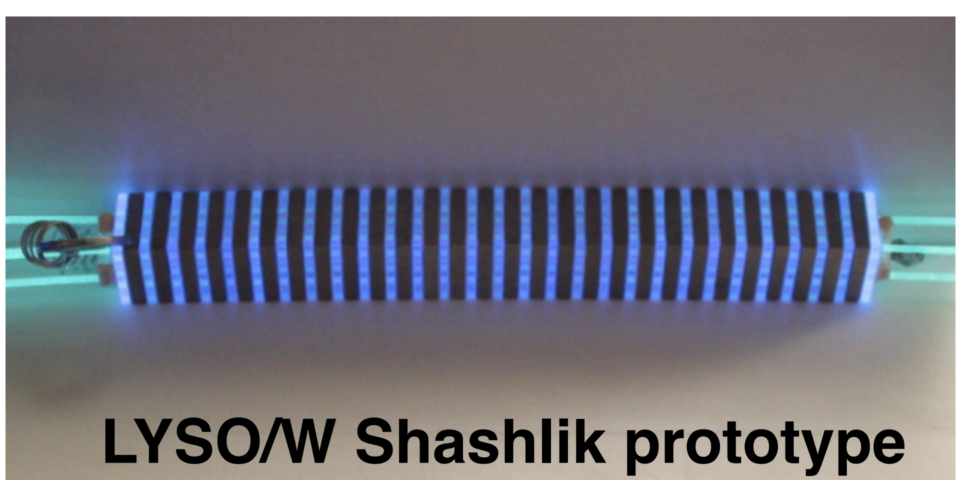
more details in Marco Peruzzi's talk

- ECAL Barrel:
  - Small light transmission losses (<50%) after 3000fb^{-1} → **Barrel will not be replaced for HL-LHC**
  - APD dark current increase - mitigated by APD cooling (18→8°C)
  - FE electronics must be replaced in LS3 to satisfy trigger requirements (rate, latency)
- ECAL Preshower:
  - Current electronics inconsistent with L1 rate/latency requirements → **Preshower will be removed prior to HL-LHC operation**
- ECAL Endcaps:
  - Large light transmission losses → **Endcaps will be replaced during LS3**
  - Radiation tolerant replacement designs with finer granularity to be less sensitive to pileup fluctuations
- HCAL Endcaps:
  - **Replacement of brass absorber and active scintillator material during LS3**
    - new HCAL endcaps to be constructed on the surface together with the replacement ECAL endcaps

Calorimeter upgrade options

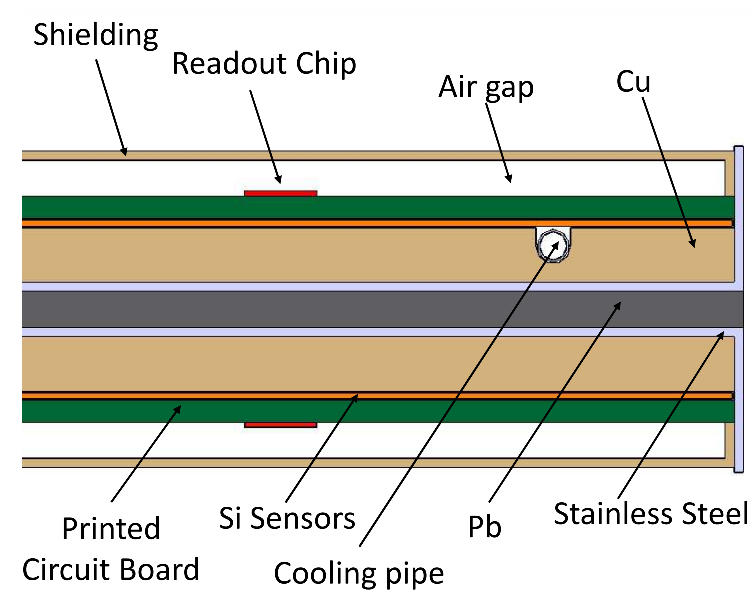
Shashlik option

- Replacement EM calorimeter using radiation tolerant crystal plates (LYSO/CeF_3) interleaved with tungsten absorber
  - Scintillation light propagated to photodetector by embedded fibre/wavelength shifter
  - Compact Shashlik "towers" with small Moliere radius to minimise PU fluctuations.
    - Tower dimensions: 1.4 x 1.4 x 114mm^3 (LYSO/W)
- Test beam prototypes being evaluated
  - R&D on radiation tolerant fibre/wavelength shifter and radiation hard photodetectors in progress



HGCAL option

- Combined ECAL/HCAL using silicon-based sampling calorimeter, with W or Brass absorber
  - **High-granularity ECAL (E-HGC): Si/W (25X_0)**
  - **High-granularity HCAL (H-HGC): Si/Brass (3.5λ)**
  - **Backing HCAL: brass/scintillator (5.5λ)**
  - High granularity silicon sensors: 0.45-0.9cm^2
- Technical challenges being addressed
  - radiation tolerance of sensors; sensor mechanical design and readout; low temperature operation required (-30°C, evaporative CO_2 cooling)



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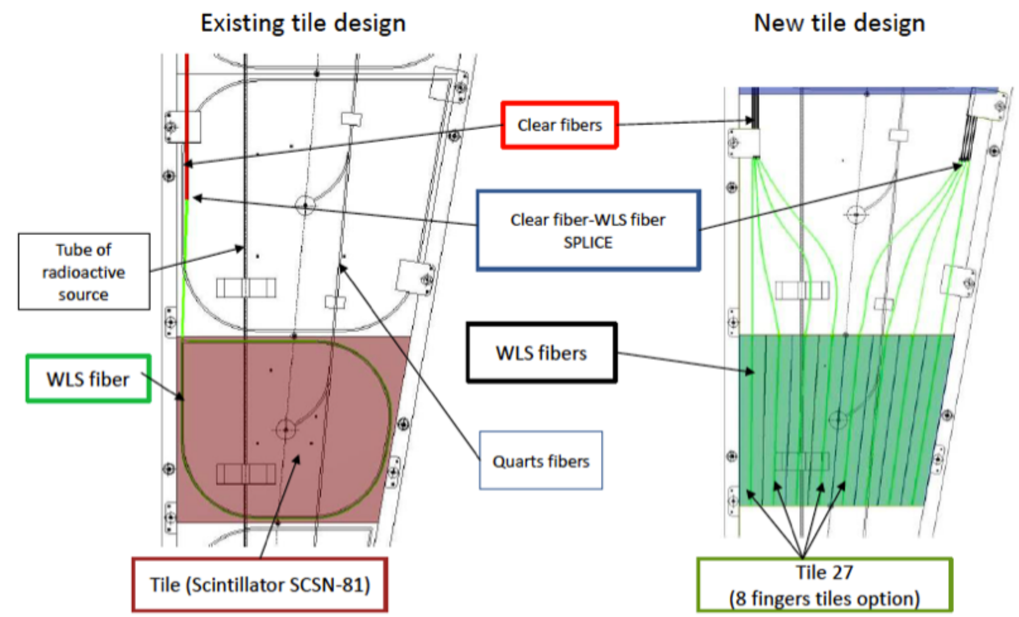
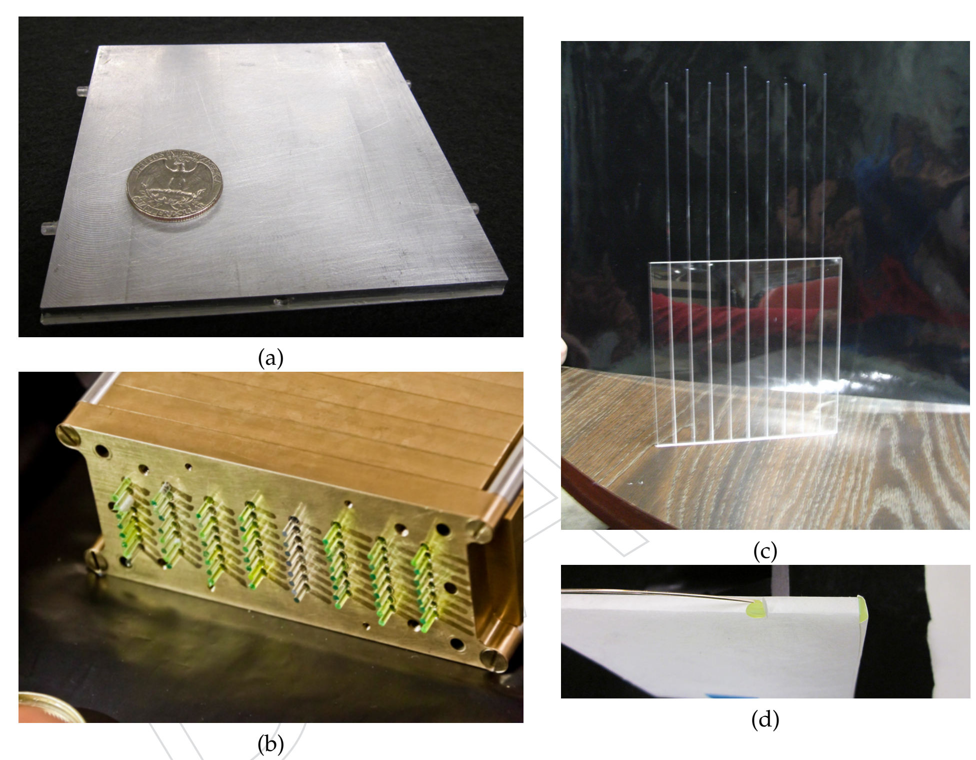
Calorimeter upgrade - HCAL options

- Investigating technologies for replacement HE active medium
  - **Low radiation region (dose <1Mrad, ~30%)**
    - existing scintillator design (“sigma tiles”) can be used
  - **Medium radiation region (dose 1-5 Mrad, ~30%)**
    - same materials can be used, but with increased granularity (“finger tiles”) to minimise light path length
  - **High radiation region (dose >5 Mrad, ~40%)**
    - R&D on more radiation tolerant materials ongoing. See examples at right:

      a) Liquid scintillator,
      b) Ce-doped LuAg fibres;
      c) Quartz plates with rad-hard WLS coating;
      d) Plastic scintillator with longer λ WLS fibre

“Sigma” tiles **“Finger” tiles**

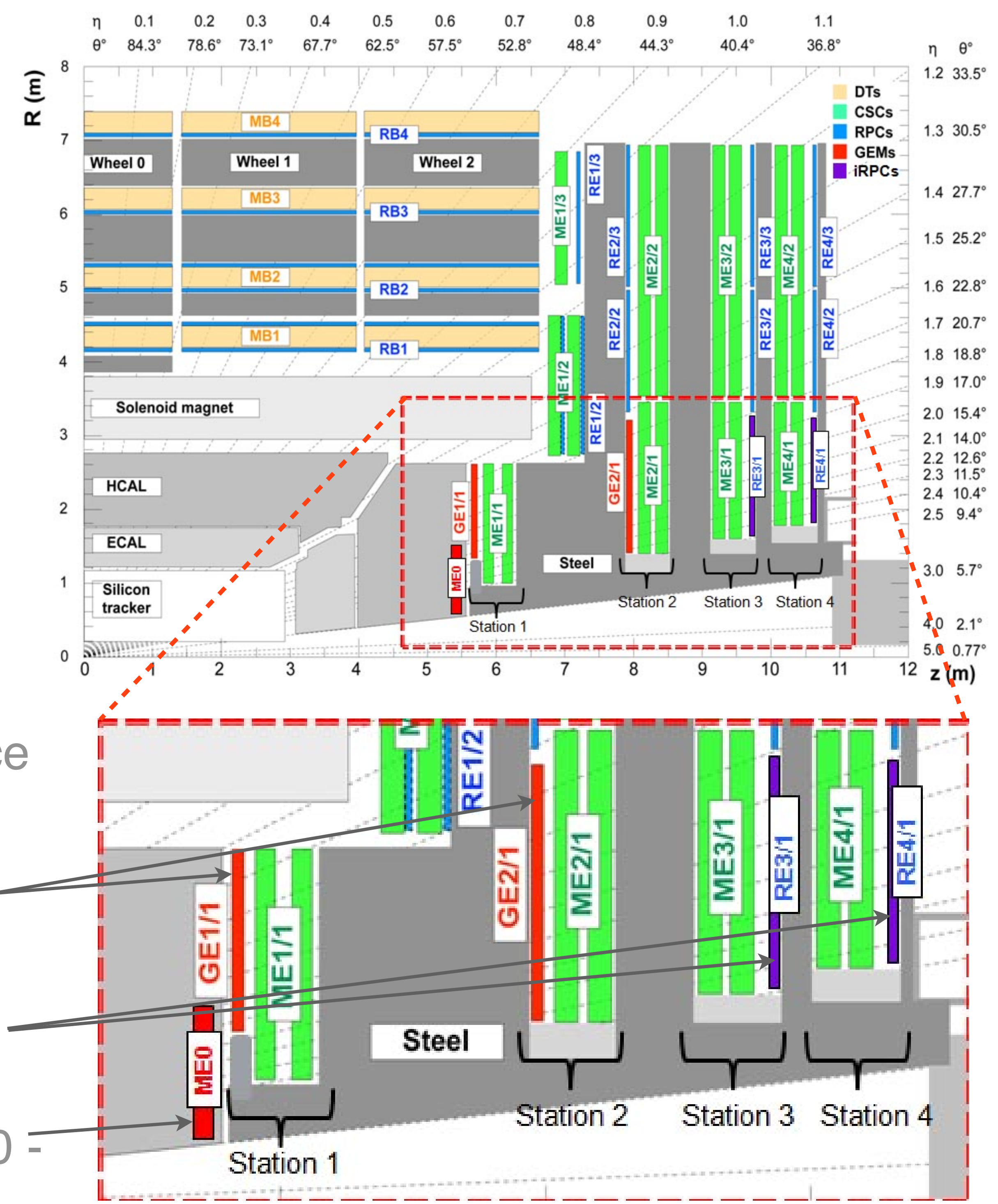




HCAL R&D prototypes

Muon systems

- Current system includes **Drift Tubes (DT), Cathode Strip Chambers (CSC), Resistive Plate Chambers (RPC)**
  - provide precise muon track measurement for triggering (|η|<2.4) and offline reco
- Upgrades for Phase II:
  - replacement of DT electronics (longevity)
  - replacement of FE cards for inner-ring CSC chambers (MEn/1) - rate/latency
  - Installation of rate-tolerant forward muon chambers to enhance muon trigger performance and redundancy for 1.6<|η|<2.4
    - GEMs (GEn/1) with high precision measurement layers
    - RPCs (REn/1) with possible fast timing response - redundancy/PU mitigation
  - Increased pseudorapidity coverage: |η|~3 (ME0 - GEM candidate detector technology)



Trigger - upgrade

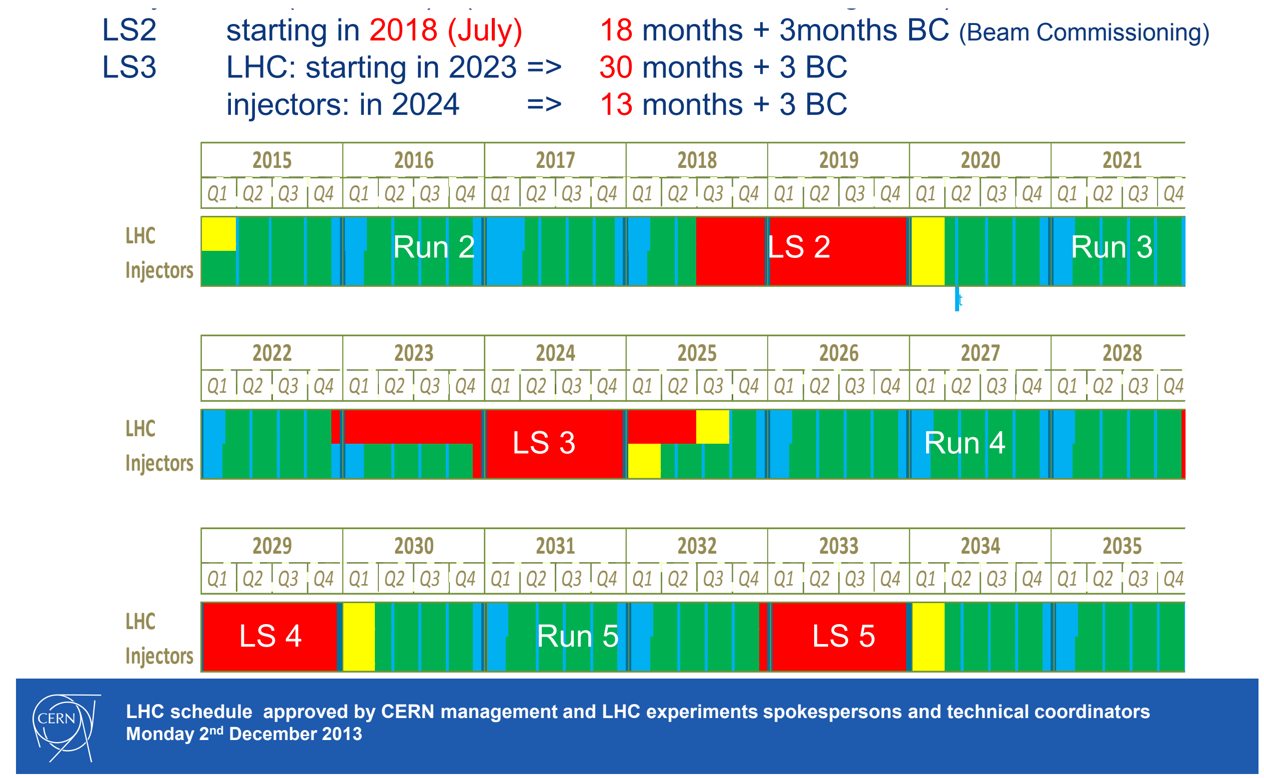
- Major trigger upgrade required during LS3
  - Goal is to maintain current physics acceptance for HL-LHC conditions
    - L1 rate ~1500 kHz during Phase 2 (140 PU) if Run II algorithms are used - beyond feasible limits for upgrade
  - Implement track-trigger at L1 to maintain acceptance at lower rates (~500kHz). Requires latency of up to 12.5μs to perform hardware track reconstruction.
  - Replacement of ECAL Barrel front-ends, DT readout boards, CSC front-end boards needed to satisfy these rate and latency requirements
  - The trigger improvements from these upgrades include:
    - 25x better ECAL trigger primitive granularity at L1, better matching to tracks
    - better muon efficiency and redundancy, also with track trigger
  - Preliminary performance estimates with track trigger:
    - ~10x reduction in single electron and muon rates (p_T~20 GeV) with comparable signal efficiency to Run II algorithms

DAQ/Online/Offline

- CMS DAQ capacity will be upgraded to handle increased event size and L1 rate for HL-LHC conditions
    - bandwidth and CPU power increases by a factor of 10-15 (15-30) for 140(200) PU
- HLT output rate will increase from 0.5-1 kHz to 5-7.5 kHz
    - to maintain same factor of 100 reduction factor from L1 to HLT
    - optimising algorithms for multi-threaded processing
- Offline computing processing and storage needs will increase substantially for Phase II
    - new techniques and technologies will need to be developed to meet these demands

Upgrade timeline

- Installation to be carried out in LS3 (2022-5)
- Developing a schedule consistent with a 30 Mo shutdown



- R&D milestones being defined for the various detector upgrade projects
  - will permit the choice of forward calorimeter technology within ~1 year
- Technical proposal to be released this year, TDRs in 2016-7

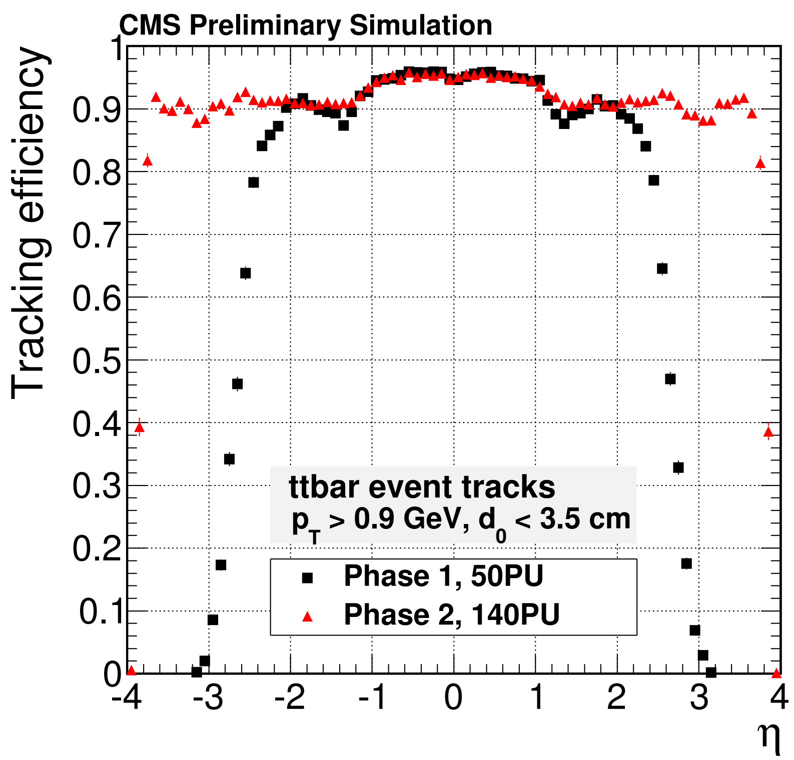
Summary

- Full exploitation of the physics potential of the LHC
  →HL-LHC physics programme
  - Significant challenges to experiments in terms of harsh radiation environment, detector longevity and high pileup
- A major program of upgrades is planned to allow CMS to maintain the current high level of performance during HL-LHC operation
- Upgrade plan to be detailed in CMS Phase II Technical Proposal
  - In preparation - due at the end of this year
- Technical Design Reports to follow in 2016-2017

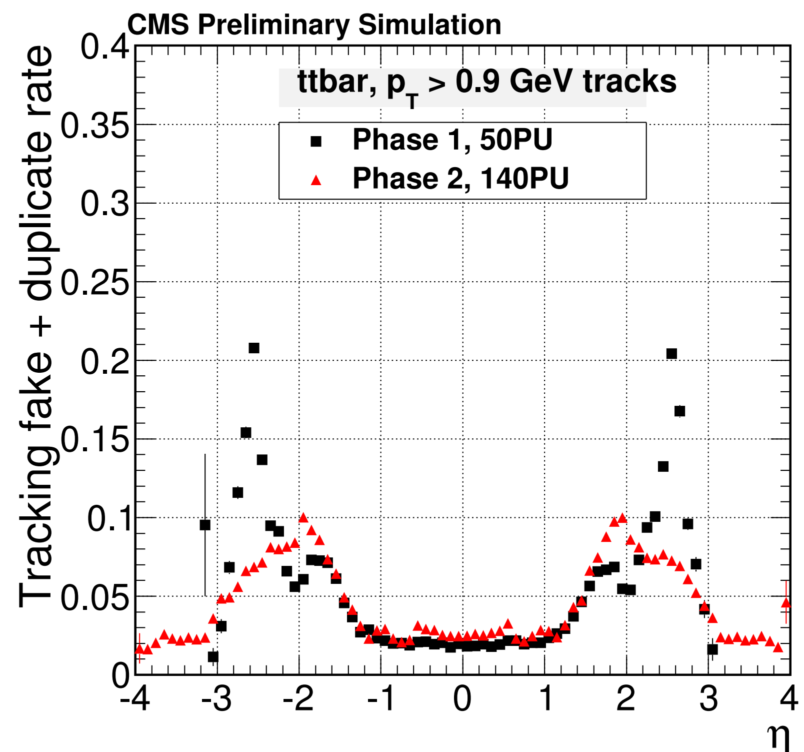
Backup slides

Tracker upgrade: estimated performance

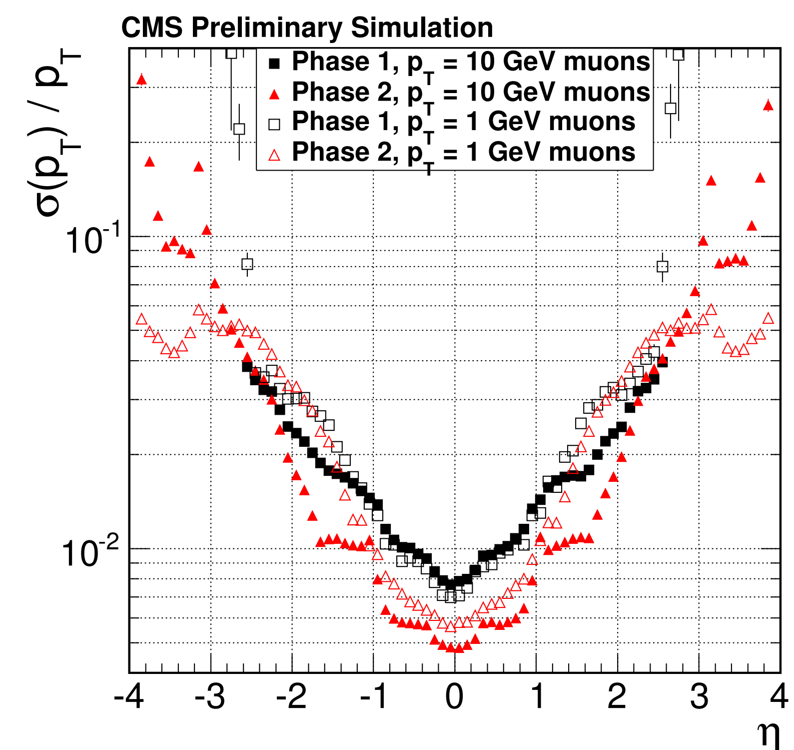
Tracking efficiency



Fake rate



p_T resolution



- Efficiency/fake rate performance maintained at 140 PU
  - performance extended up to |η|=4
- p_T resolution improved due to reduced material budget

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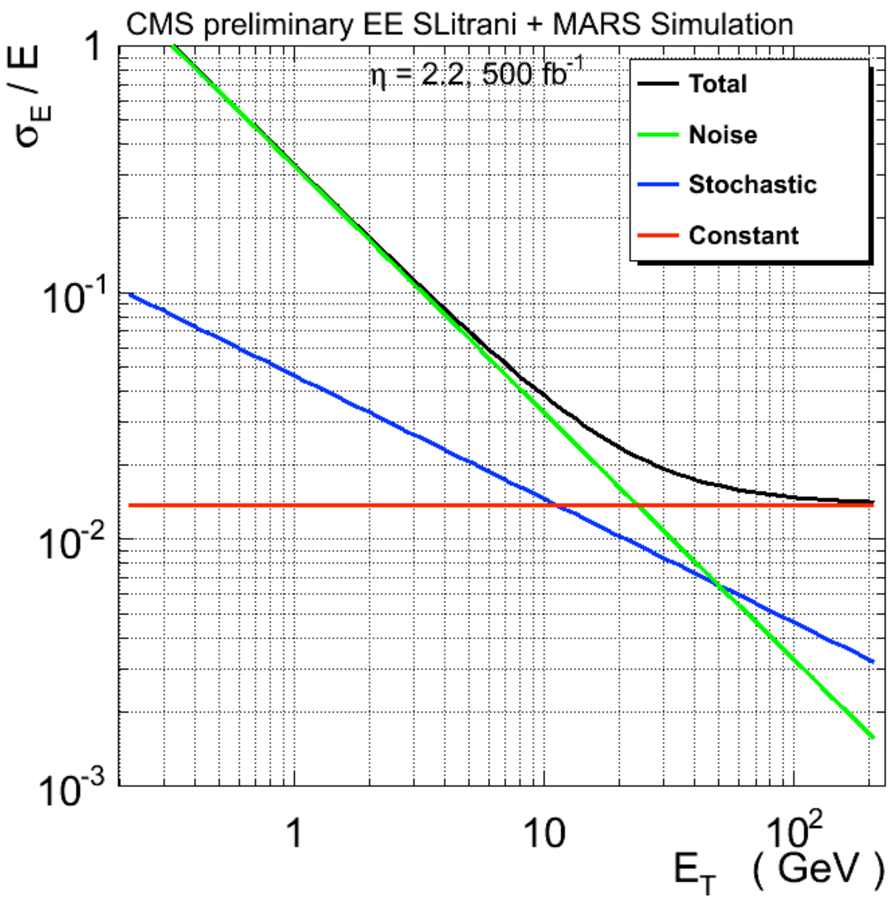
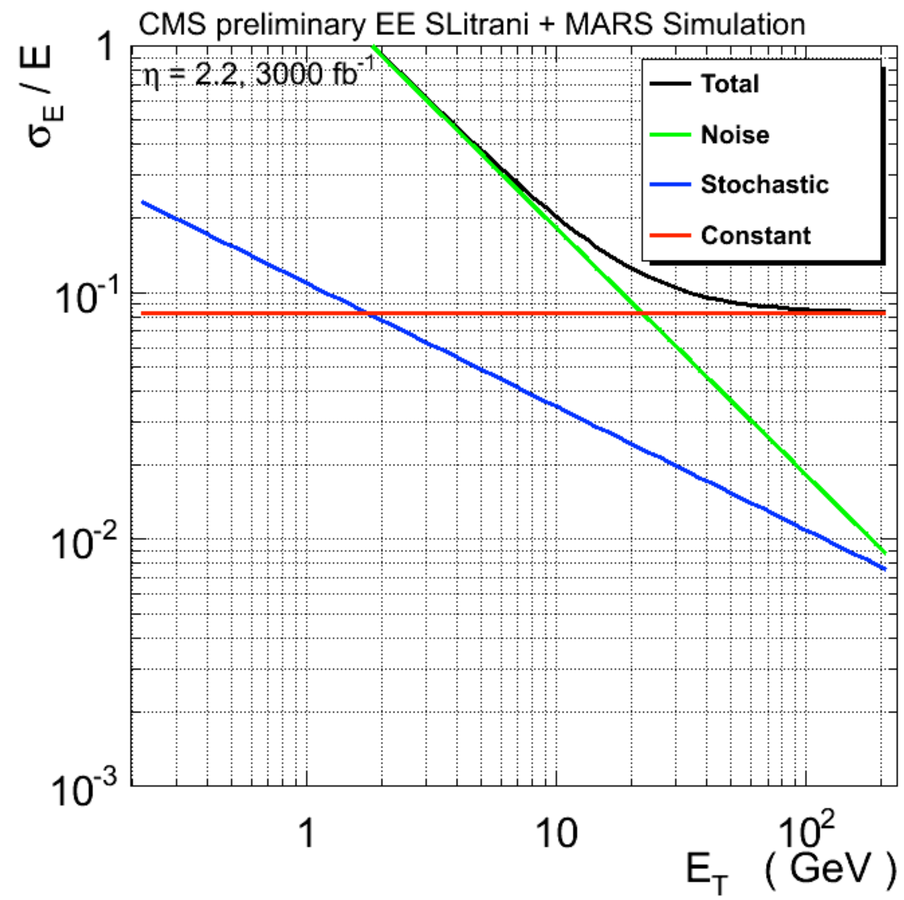
Calorimeters - performance degradation



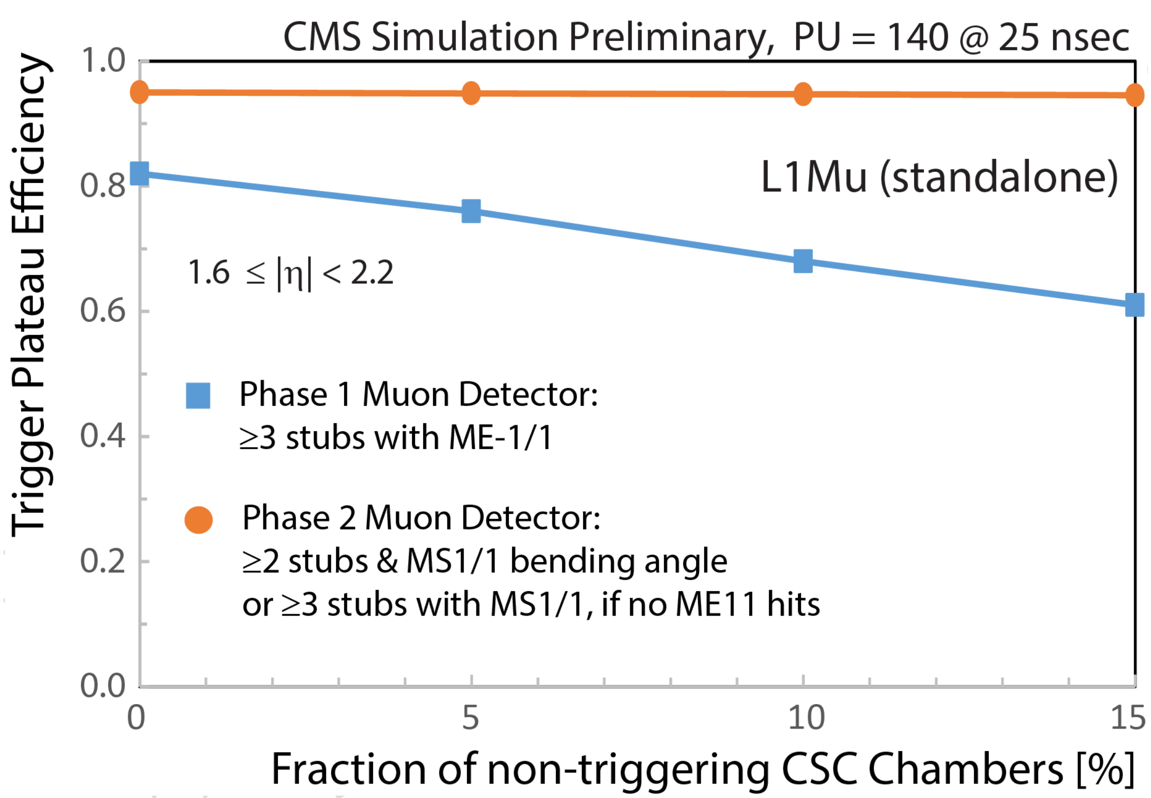
Predicted ECAL Endcap resolution (standalone simulation) at η=2.2, after 500 fb^{-1}

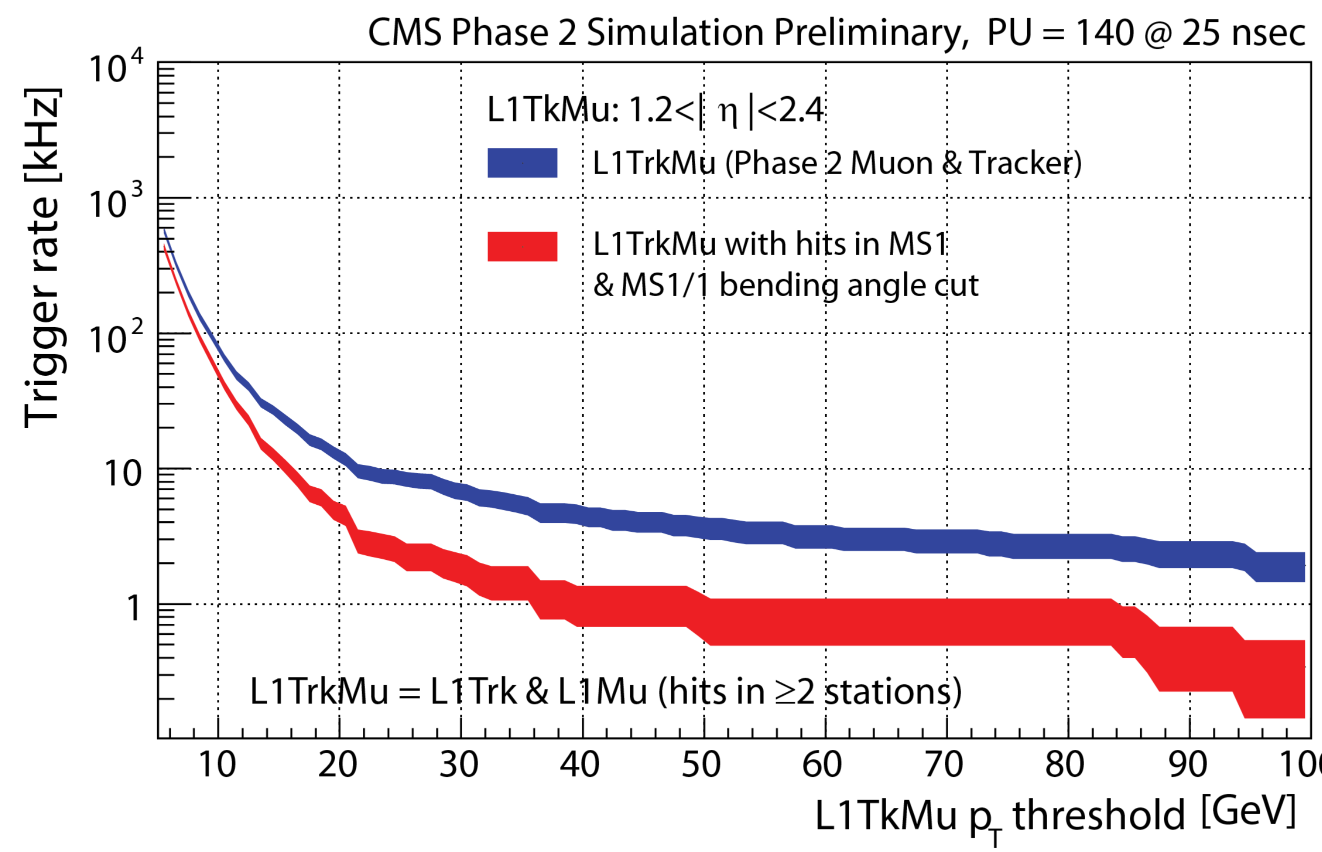


Predicted ECAL Endcap resolution (standalone simulation) at η=2.2, after 3000 fb^{-1}

- Effects of ECAL crystal transparency degradation:
  - Light transmission loss affects noise and stochastic terms
  - Light collection non-uniformity affects constant term

Muon upgrade performance





Improved muon trigger efficiency and redundancy

Reduced muon trigger rate for a given threshold with addition of GE1/1 chamber