Introduction

LHC Operations in the HL-LHC Era

- The physics program at LHC
  - pp collisions at a center of mass (CM) increased to 8 TeV in 2012
  - At the completion of this first running period,CMS had accumulated an integrated luminosity of 29 fb^{-1}
  - bunch spacing was 50 ns.

LONG SHUTDOWNS

- LS1, LS2, LS3
- After LS1
  - center-of-mass energy will be increased to 13 TeV initially and then closer to the design energy of 14 TeV over time
  - Bunch spacing will be reduced to 25 ns
- In LS2, the injector chain will be further improved and upgraded
- In LS3 (2023-mid-2025) the LHC will be upgraded with new low-*b* Triplets to replace the existing ones

	2009/2010 /2012	Between Ls1(2013-2014) .ls2(2018-2019)	Between Ls2 .ls3(2023-2025)	After ls3
Luminosity **(instantaneous peak luminosities)** ($cm^{-2}s^{-1}$)	(7.7×10^{33})	1×10^{34}	(2×10^{34})	5×10^{34}, (2×10^{35})
integrated luminosity (fb^{-1})	29	?	300	250 per year
bunch spacing (ns)	50	25	?	?
Center of mass(CM) energy (TeV)	0.9/7/8	13-close to 14	?	?

125PU

- $fb=10^{-39}\mathbf{cm^2}$

- $5\times 10^{34}\,(cm^{-2}s^{-1})\times 25\times 10^{-9}\,(s)=125\times 10^{-25}\,(cm^{-2})$
- $125\times 10^{-25}\,(cm^{-2})\,/100\,(mb)$

  $=125\times 10^{-25}/100\times 10^{-27}$

  $=125$

The CMS HL-LHC Physics Program

- aimed at answering fundamental questions in particle physics(
  - What is the origin of elementary particle masses? What is the nature of the dark matter we observe in the Universe?
  - Are the fundamental forces unified?
  - How does QCD behave under extreme conditions?
  - Do matter and antimatter properties differ?)
- In three years of operation, highlight has been the observation of a Higgs boson in 2012, which partially provides an answer to the first question
- After LS1, the LHC at increased CM energy and higher luminosity will open a new window for observation and precise studies of the Higgs boson properties.

- when reconstructing a hard-scatter p-p collision in CMS, it is of utmost importance to mitigate the effect of event pileup
- Combining the particle flow reconstruction with multivariate-analysis techniques has proven to be extremely efficient to mitigate this effect, especially to reconstruct the jet and missing transverse energy, and to achieve a better performance than predicted in the original Physics performance TDR .
- A remarkable example for a new analysis technique is the measurement of the total width of the Higgs boson. CMS was recently able to constrain the Higgs boson width to 5.4 times the expected value in the standard model, a 200 times more stringent constraint, than that reached in previous measurements.

- The study of the Higgs boson will continue to be central to the program. It will include precise measurements of the Higgs boson couplings, probing of the tensor structure, and the search for rare SM and BSM decays

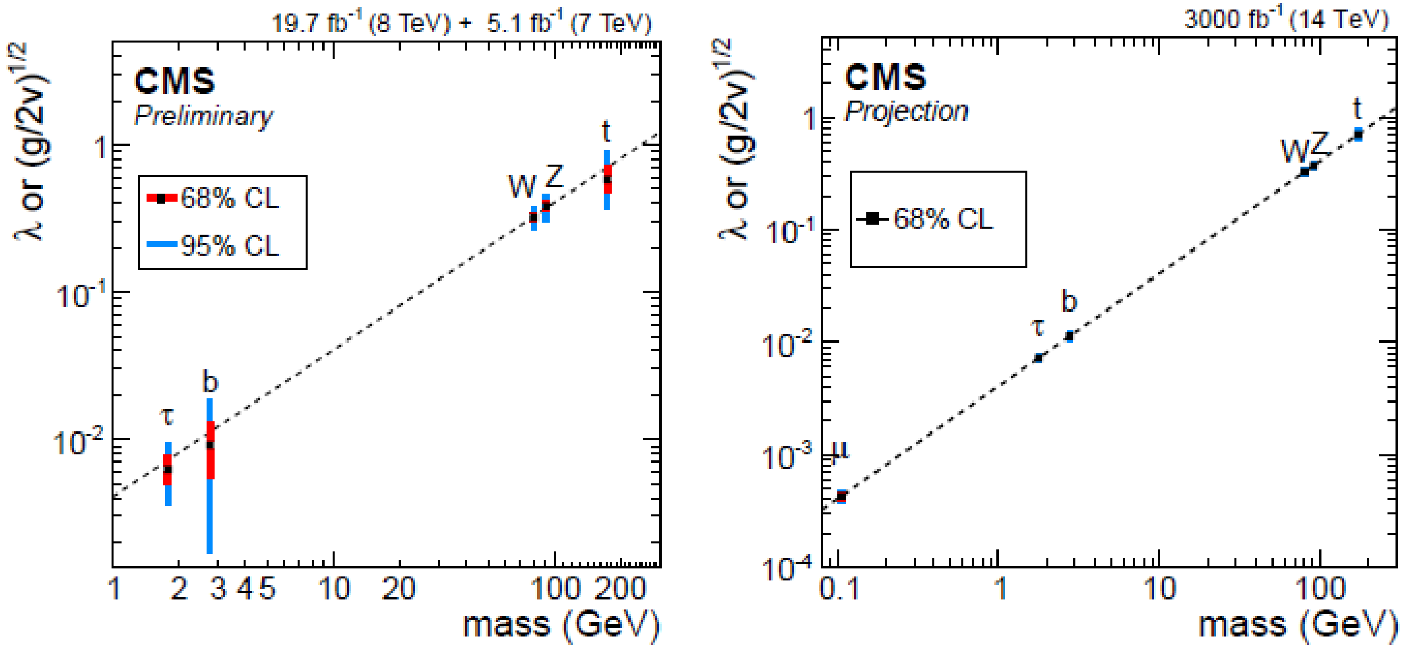


Figure 1.1: Observed and projected precision on Higgs boson couplings as function of boson or fermion masses.

Higgs boson

- The coupling to the second-generation fermions will be probed for the first time measuring the Higgs boson decay to two muons.
- Measurement of di-Higgs production with a cross section of 40 fb^{-1} will allow the study of Higgs boson self coupling.
- The Higgs boson in the electroweak symmetry breaking will be confirmed in studies of the vector boson scattering processes.
- These measure ments could also be sensitive to new physics through the triple-gauge couplings (TGCs) and quartic-gauge couplings (QCGs)

Parton distribution functions

- Parton distribution functions (PDFs) of the proton are crucial ingredients of measurements at the LHC
- If new physics phenomena are discovered, their characterization will also suffer fromPDF uncertainties
- Improvements are needed from experimental data, theoretical calculations, and methodological framework

MASS REACH FOR SEARCHES

- The mass reach for searches of new particles grows with increased luminosity

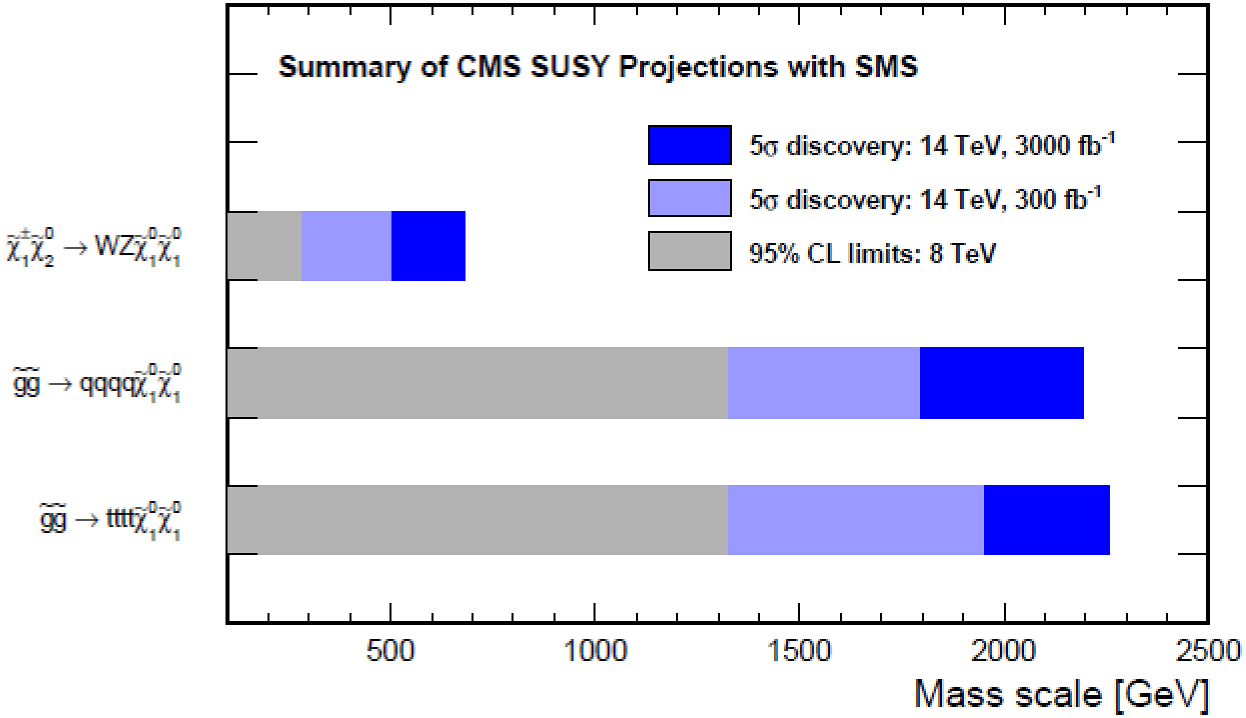


Figure 1.2: Reach of searches for supersymmetry.

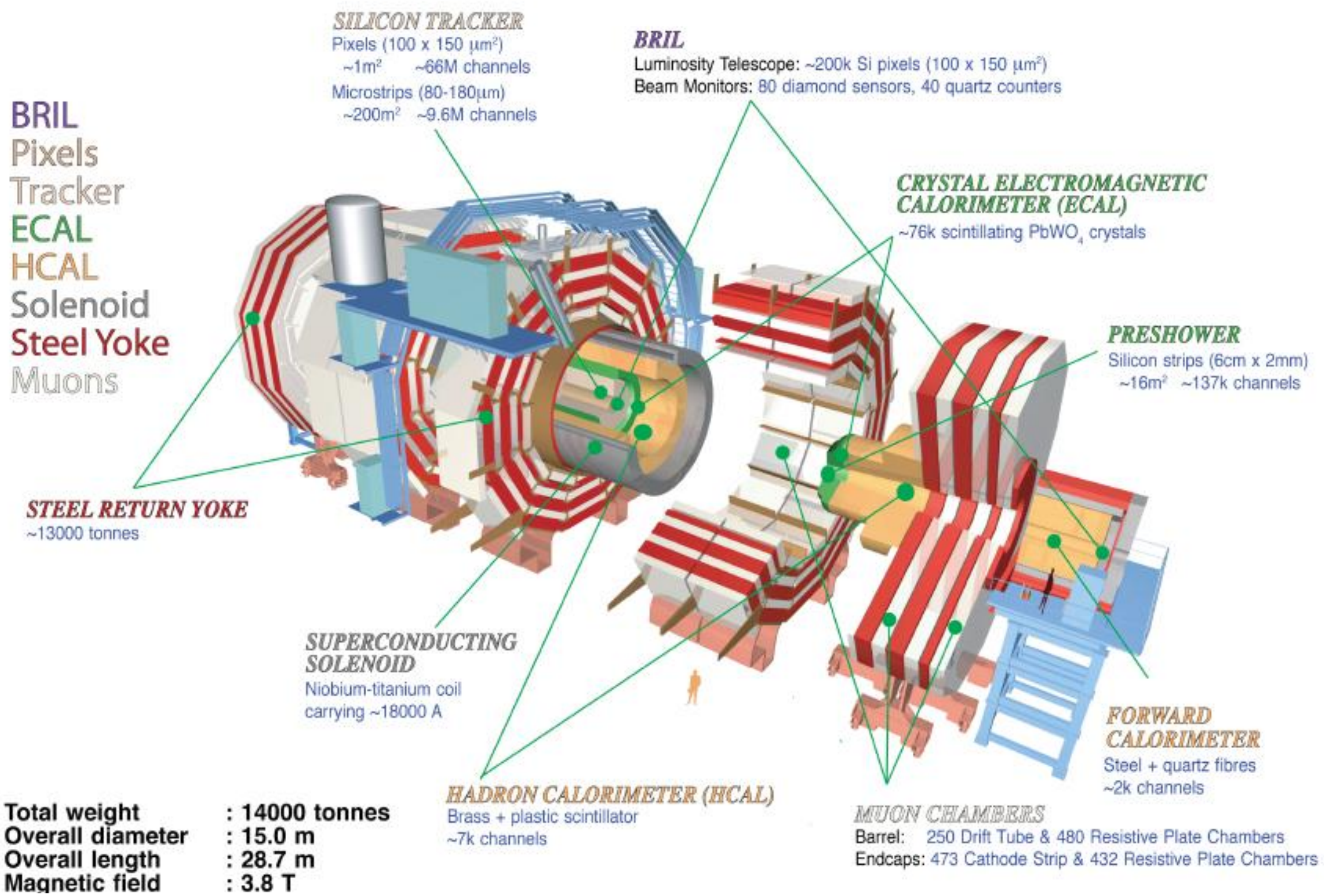
THE MOST PRESSING QUESTIONS IN PARTICLE PHYSICS

- whether there exist a natural explanation for the stabilization of the Higgs boson mass against quadratic divergences
- The main cause for the quadratic divergences are loops involving the heaviest quark, the top quark
- These can be compensated by supersymmetric partners of the top quark, or by heavy vector like quarks.
- In supersymmetry, especially the cross sections for chargino-neutralino production are low and will greatly benefit from the large integrated luminosity.

Overview of the CMS Phase-II Upgrade

- the brightness of beams would increase the interaction rate and collision PU beyond the capabilities of existing and envisioned detector and trigger technologies
- proposed to maintain a lower, but stable instantaneous luminosity
- to operate at a levelled luminosity of $5 \times 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$, corresponding to a mean pile-up of 140 interactions per beam crossing 1.
- Phase-II upgrade program is therefore to maintain the excellent performance of the Phase-I detector under these challenging conditions

The CMS Phase-I detector



A MAJOR FOCUS OF CMS

- Identify changes that are mandatory for the beam conditions of HL-LHC
- understand the effect of radiation damage(also mentioned in following pages)
  - tracker and the endcap calorimeters must be replaced for Phase-II.
  - the tracker granularity can be increased to maintain the excellent tracking efficiency to enable the determination of the original p-p collision points for all charged particles.
  - New endcap calorimeter configurations will also provide the opportunity to optimize segmentation and improve energy resolution, particularly for jets

Upgraded trigger electronics

- The precise study of the relatively-low mass Higgs boson discovered in 2012, and the search for new particles occurring in cascade decays will require continued use of low transverse momentum, pT, trigger thresholds
- the trigger electronics (i.e. the L1 trigger) must be upgraded
  - improving pT resolution to obtain lower rates without loss of efficiency, and by mitigating the effect of the combinatorial backgrounds arising from PU.
  - a new hardware architecture to incorporate tracker information throughout the trigger

UPGRADES IN THE FORWARD REGIONS OF THE DETECTOR

- The measurement of processes with small production cross-section requires specific upgrades in the forward regions of the detector
- endcap calorimeter extends the muon coverage up to $|\eta| \approx 3$ or more,
- To also mitigate PU effects in jet identification and energymeasurement, the tracker will be extended up to $|\eta| \approx 4$
  - With this extension, measurements of total energy andmissing energy will be greatly improved, and b-tagging acceptance will be increased

Luminosity integrated over the Phase-II

- It is expected that the sustainable luminosity limit will be driven by the performance of sub-detectors that are not going to be replaced for Phase-II.
- the upgrades of the readout electronics will be designed with some margin to allow efficient data taking up to a PU of 200 to provide some flexibility

Elements of the Phase-II Upgrades- Tracker-outer tracker

- the granularity of both the outer tracker and the pixel systems will be increased by roughly a factor 4
- In the outer tracker, this will be achieved by shortening the lengths of silicon sensor strips
- A number of design improvements will lead to a much lighter outer Tracker providing significantly improved pT resolution and a lower rate of γ -conversions
- be capable of providing track-stub information to the L1 trigger at 40 MHz for tracks with pT $\geq$ 2GeV

TRACKER- PIXEL TRACKER

- implement smaller pixels and thinner sensors for improved impact parameter resolution and better two-track separation
- This will improve b-tagging as well as τ -hadronic decay *and* boosted jet reconstruction efficiencies

Elements of the Phase-II Upgrades- Calorimeter endcaps

- Two concepts are currently under consideration : (P.33)
  - An Electromagnetic Endcap calorimeter (EE), with a Shashlik design, followed bya Hadronic Endcap (HE) which would be a re-build of the present HE with more radiation tolerant components.
    - no depth segmentation but is very compact
    - 25 radiation lengths (X0) in 11 cm
    - transverse cell size is matched to the low 14mm Molie`re radius
  - A High Granularity Calorimeter (HGC) including both an electromagnetic section and a hadronic section, followed by a rebuilt conventional HE with reduced depth.
    - granularity that is about 1.5 times the current detector, increased both
    - 5-fold depth segmentation in ϕ and η
    - draws uponthe ILC/CALICE concepts for 3D measurement of shower topologies
- both devices is being studied with full GEANT 4 simulations

Elements of the Phase-II Upgrades- Muon endcaps

- currently consists of four stations of Cathode Strip Chambers (CSC).
- the only region that lacks redundant coverage
  - to enhance these four stations with redundant chambers that make use of new detector technologies with higher rate capability
- The two first stations are in a region where the magnetic field is still reasonably high and so will use Gas Electron Multiplier (GEM) chambers for good position resolution $|\eta| \approx 3.$
  - increase the coveragefor muon detection to
- The two last stations will use low-resistivity Resistive Plate Chambers (RPC) with lower granularity but good timing resolution to mitigatebackground effects

Elements of the Phase-II Upgrades- Beam radiation protection and luminosity measurement

- The protection systems will be upgraded with new poly-crystalline diamond sensors
- The Machine Induced Background (MIB) and Luminosity measuring systems in the Pixel volume must be replaced, partly as a result of changes in the tracker and infrastructure but also due to the enhanced rates and doses expected in HL-LHC operation.
- The proposed online luminosity system will make use of additional forward pixel/tracker partial-planes, building on the experience and investment in the Tracker upgrade and mak1ing use of cluster-counting techniques developed for the offline luminosity

Elements of the Phase-II Upgrades- Trigger

- The latency of the present L1 trigger will be increased to 12.5 μs to provide sufficient time for the hardware track reconstruction and matching of tracks to muons and calorimeter information
  - require upgrades of the readout electronics
  - A proper design will allow latency limitations to be overcome and to eliminate L1-trigger rate restrictions.
- operate with a L1-trigger acceptance rate of 500 kHz for beam conditions yielding 140 PU (750 kHz for 200PU)
  - Any further increase of the L1 readout rate would require an increase of the Pixel readout bandwidth.

SUB-DETECTOR UPGRADES THAT ARE REQUIRED FOR CMS TO MEET THESE TRIGGER REQUIREMENTS

- Front-end electronics will be replaced in the barrel electromagnetic calorimeter(EB)
  - The EB data will be transferred to the control room electronics at 40 MHz, overcoming present limitations in latency (6.4 μs) and acceptance rate
  - a new front-end chip will be designed with a shorter shaping time to mitigate the anticipated aging-induced noise increase in the avalanche photodiode (APD), and to improve the timing resolution for better out-of-time PU rejection and possibly better in-time PU rejection as well.
- The readout electronics in the CSCs of the inner rings in stations 2 to 4 will be replaced with similar boards
- The DT readout, will be replaced to both satisfy trigger rate requirements and to solve radiation tolerance issues

Elements of the Phase-II Upgrades- Data Acquisition and Trigger Control

- The Trigger control system distributes the LHC clocks as well as trigger and DAQ signals
- The Trigger control system will be upgraded to a bi-directional system of higher bandwidth, allowing data to be sent at each bunch crossing to steer the on- and off-detector readout depending on the types of triggers that fire, and to steer the event building.
- The Data Acquisition (DAQ) system will be upgraded to implement the increase of bandwidth and computing power thatwill be required to accommodate the larger event size and L1-trigger rate, and the greater complexity of the reconstruction at high PU.

Elements of the Phase-II Upgrades-Experimental Area and Shutdown Considerations

- the full scope ofwork can be accomplished in a shutdown of approximately 30 months duration
- In order to gain flexibility in scheduling the work during LS3 while reducing overall costs, consideration is being given to advancing some specific tasks to LS2

UPGRADES PERFORMANCE STUDIES

- Full simulations of detector signals using GEANT 4 have been produced in order to develop the CMS scope for Phase-II and to evaluate the performance of the proposed upgrades
- The configurations that have been simulated are the following:
  - Phase-I detector operated at 50 PU without radiation aging aging; to establish a benchmark for the required performance of the Phase-II upgrades.
  - Phase-I detector operated at 140 PU with modelling of the effects of radiation damage after integrated luminosities of 1000 fb^{-1} and 3000 fb^{-1} in order to determine where and wneh the areas to be addressed by the upgrades
  - Phase-II detector operated at 140 PU ($5\ 10^{34} cm^{-2} s^{-1}$); to evaluate performance reach for the new concepts.
    - assumed that the performance of the new subdetector will not degrade with radiation

- It should also be noted that since the pixel design is still being developed, the Phase-I configuration has been used for the Phase-II simulations
- Simulations based on DELPHES have also been used to generate sufficiently high statistics samples for studies of the physics backgrounds.

Radiation Environment in CMS for HL-LHC(overview)

- The radiation simulations are performed withMonte Carlo transport codesMARS'109 andFLUKA 2011.2b.6
- For most simulations, a proton-proton collsion is used as the primary event, except for machine induced background (MIB) simulations

Event Generators for p-p collisions in Radiation Simulations

Particle type	Multiplicity/event
p, $\bar{p}$	4.6
n, $\bar{n}$	4.0
π^{+-}	65.2
K^{+-}	8.0
photon	6.4
π^0	38.2
other neutral	9.7
other charged	1.5
total	137.5

Table 1.1: Average particle multiplicities of DPMJET III (3.0-6) events used for the radiation environment simulations.

- The event generator DPMJET III [21] is used to create the primary proton-proton events in radiation simulations.
- It is directly linked to the FLUKA code and used as the default event generator for high energetic hadronic interactions.

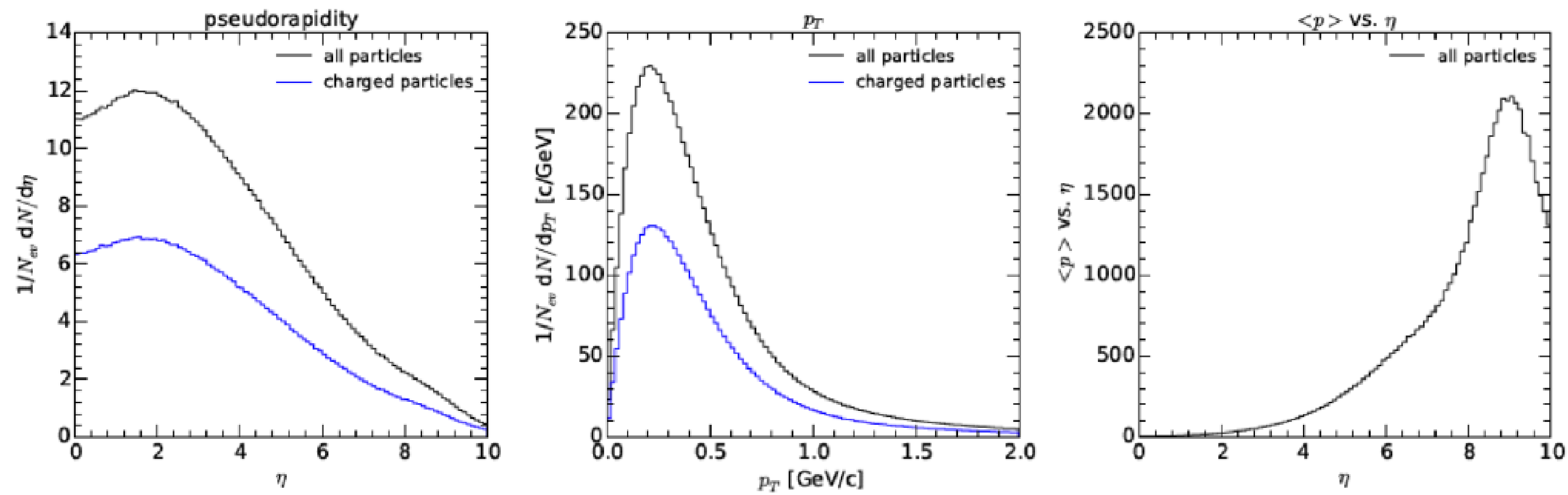
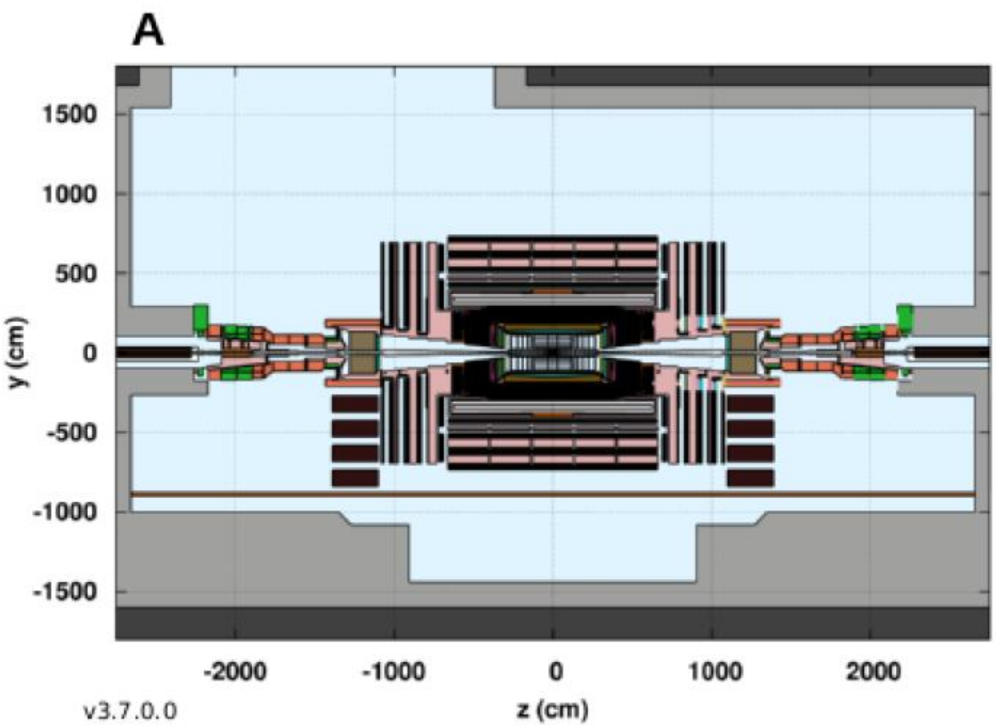


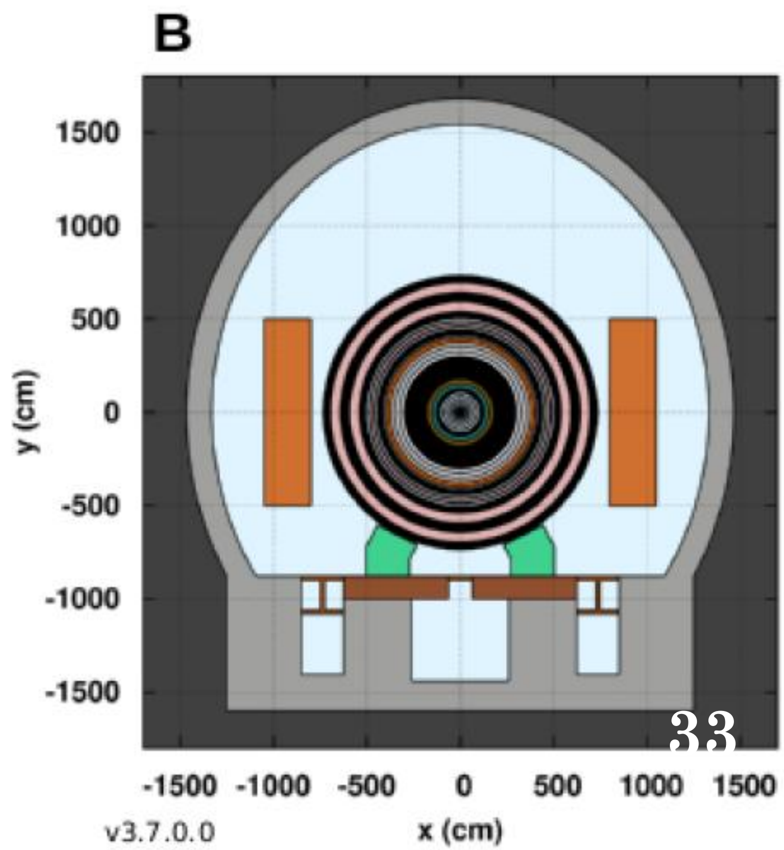
Figure 1.4: Pseudorapidity and transverse momentum distributions of the particles generated by the DPMJET III generator. The black line is for all particles, the blue line is for charged particles.

- the multiplicity decreases with increasing $|\eta|$, the mean momentum increases rapidly
- Three region:
  - the central and forward detector region, $|\eta| < 5.2$,which create albedo within the detector but give minor contributions to the outside.
  - the collimator region defined by the HL-LHC TAS, $5.2 < |\eta| < 7.3$, which generates most of the radiation in the experimental cavern.
  - the high pseudorapidity region, $|\eta| > 7.3$ where most of the energy of the pp interaction is passed out to the tunnel and does not contribute to the radiation field in the hall.

FLUKA Models of the CMS Detector and Cavern for HL-LHC

- The baseline geometry is referred to as the "TP Baseline" geometry, based on the latest nominal Phase-I CMS geometry





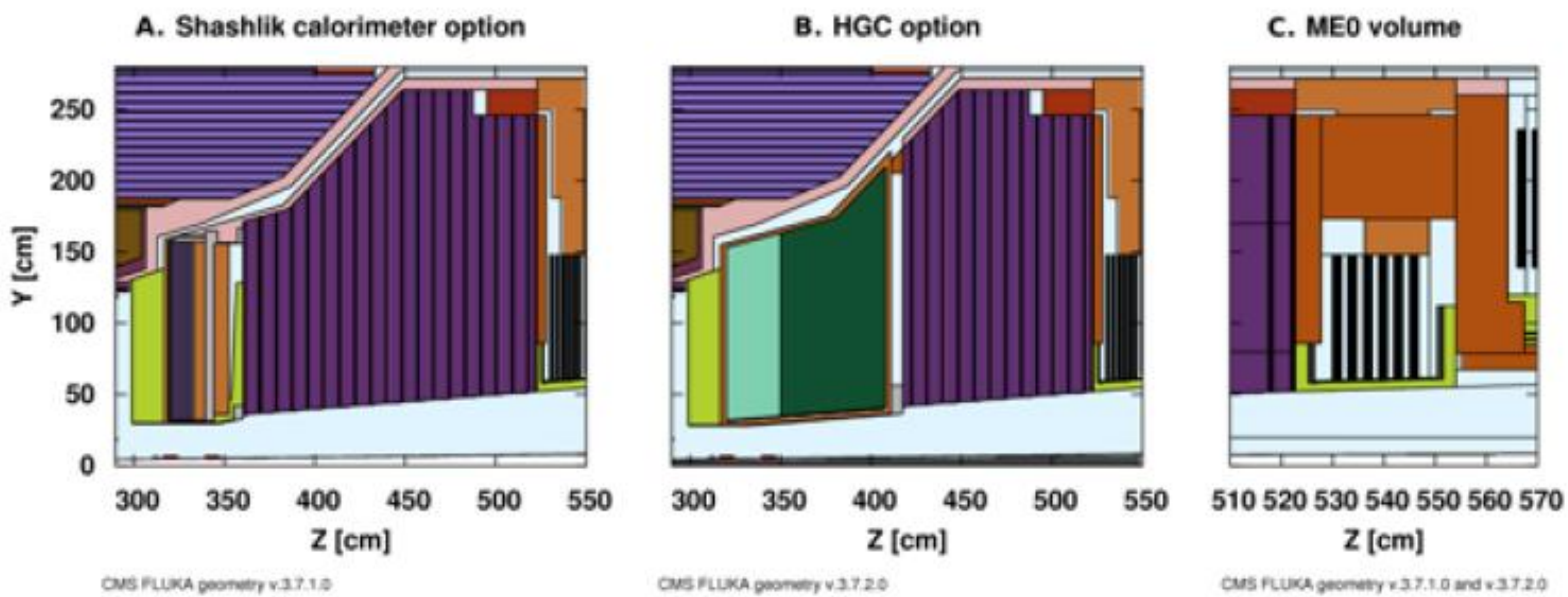


Figure A.2: **A:** The FLUKA model of the Shashlik Endcap Calorimeter option. **B:** The FLUKA model of the HGC Endcap option. **C:** The FLUKA representation of the ME0 region, which is included in both models.

Radiation Levels for HL-LHC

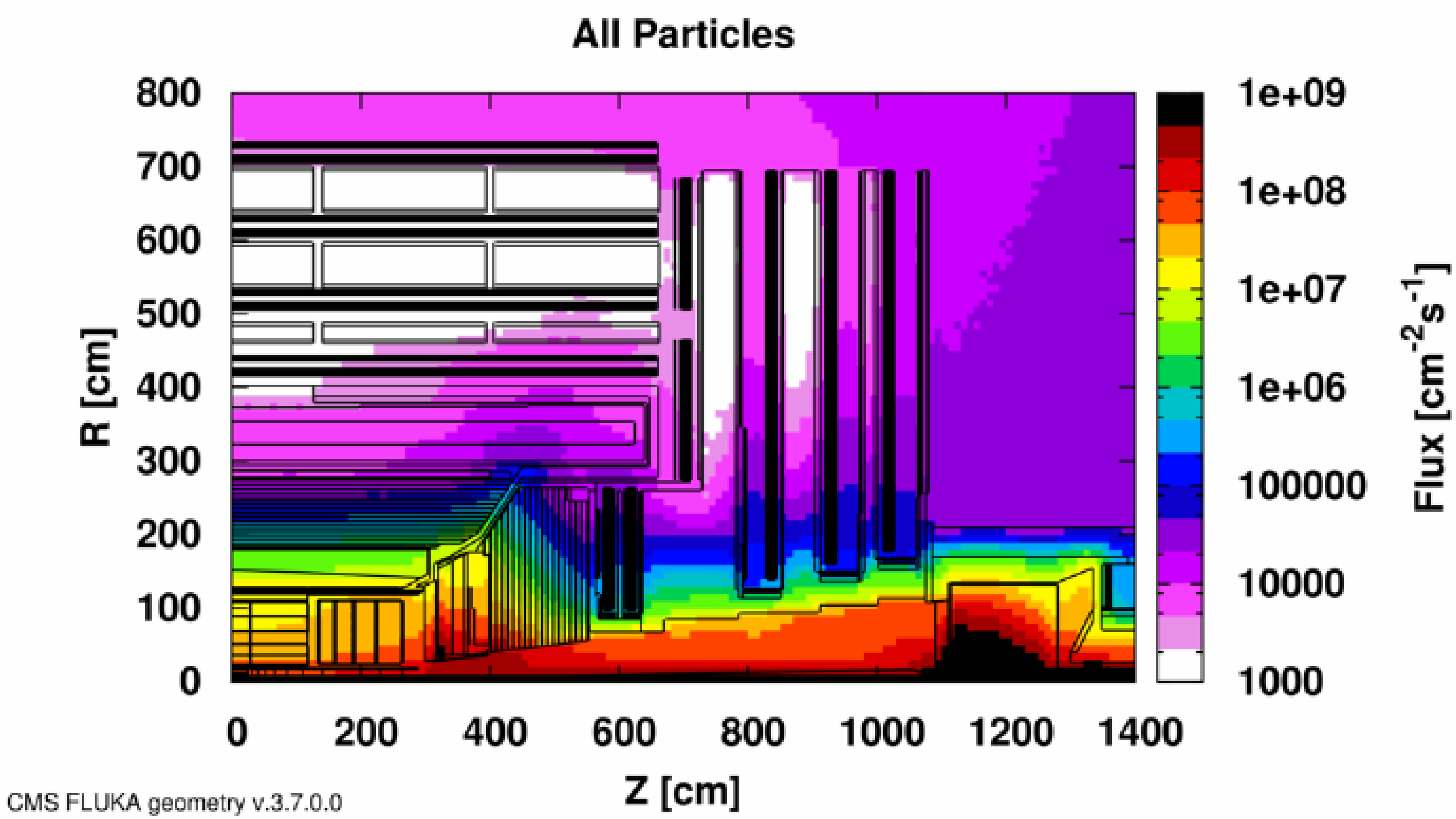


Figure 1.5: Flux of all particles in the CMS cavern at an instantaneous luminosity of $5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

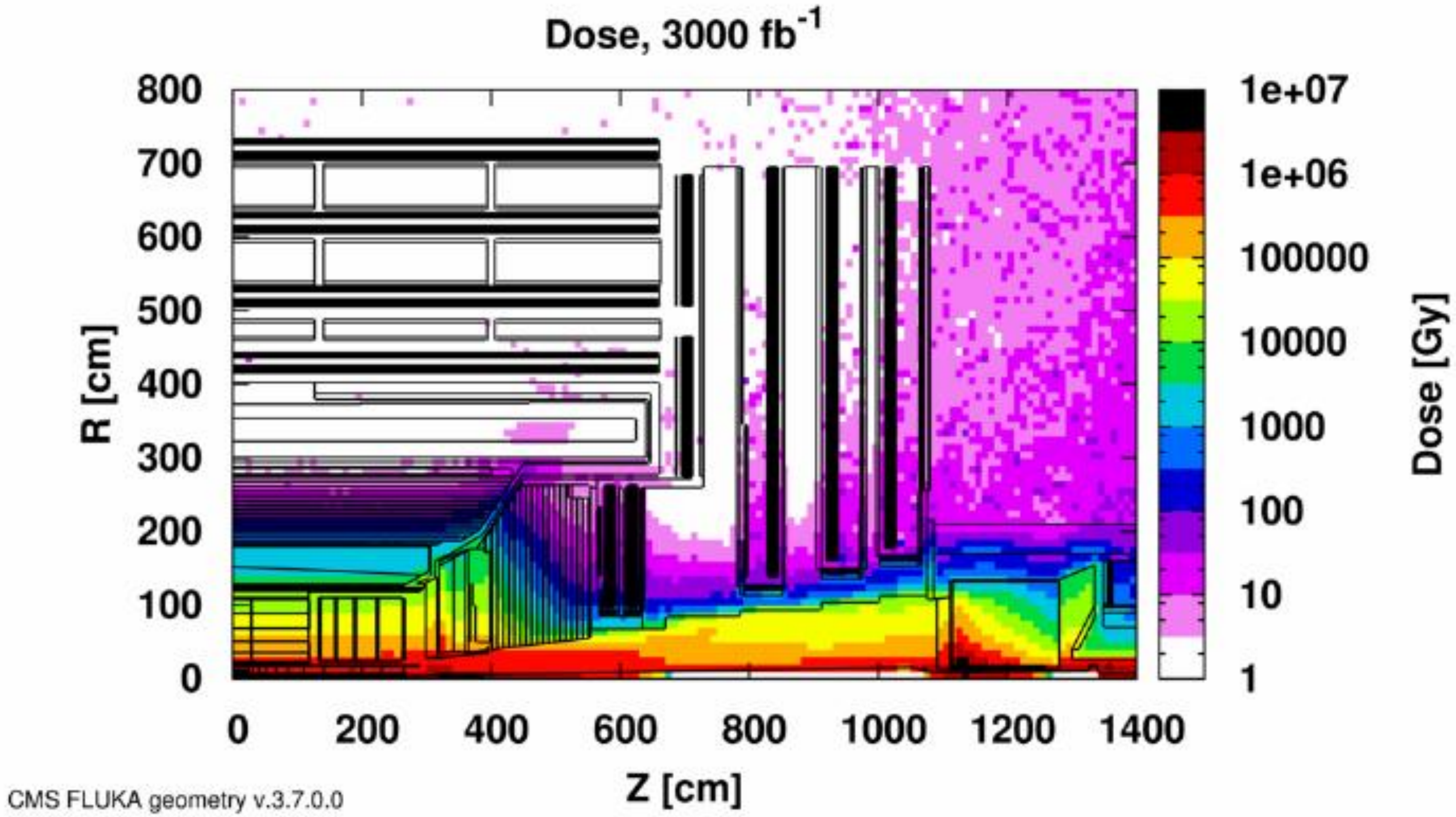


Figure 1.6: Absorbed Dose in the CMS cavern after an accumulation of $3000\,\mathrm{fb}^{-1}$ delivered luminosity.

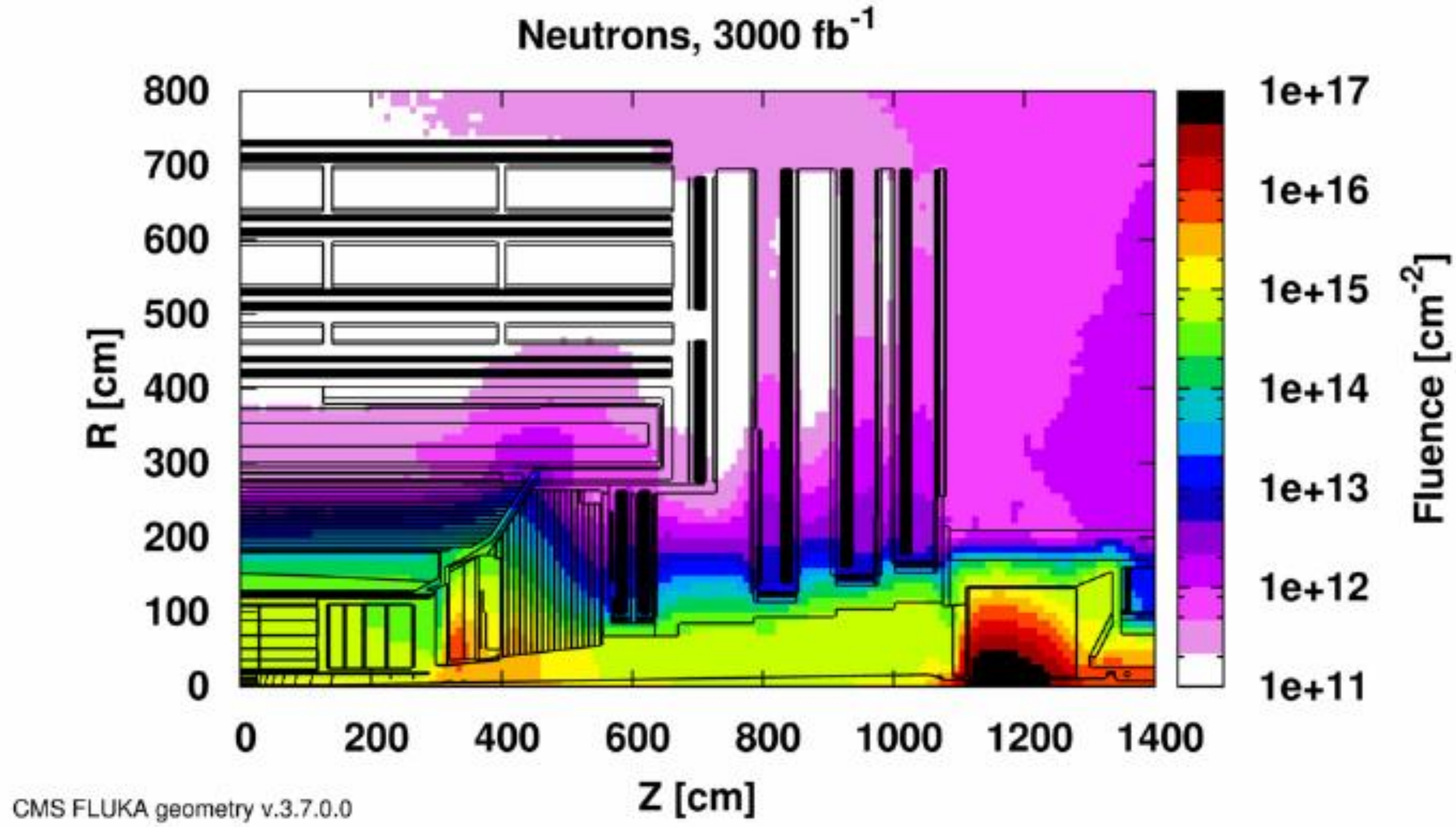


Figure 1.7: Neutron Fluence in the CMS cavern after and accumulation of 3000 fb^{-1} delivered luminosity.

TRACKER- LIMITATIONS OF THE CMS TRACKER

- The present Outer Tracker was designed to operate without any loss of efficiency up to an integrated luminosity of 500 fb^{-1} and an average pile-up (PU) of less than 50 collisions per bunch crossing
- The pixel detector will be replaced with the "Phase-1" upgrade during the Extended Technical Stop at the end of 2016, when the total integrated luminosity is assumed to reach about 150 fb^{-1} .
- They will have to be replaced during LS3
- the Phase- 1 tracking detectors restrict the CMS Data Acquisition to a maximum Level-1 (L1) accept rate of about 100 KHz, with an available latency of 4 μs for the trigger decision.
  - Operation at high luminosity requires a substantial upgrade of the trigger system, with significantly higher rate and longer latency.

ACCUMULATED RADIATION DAMAGE, BANDWIDTH LIMITATIONS

- Accumulated radiation damage in the pixel sensors reduces the charge collection as well as the Lorentz angle, leading to lower charge sharing among neighbouring pixels and hence worse spatial resolution.
  - The effects are modelled in the detailed PixelAV simulation
  - translates to degraded precision in primary vertex reconstruction, track impact parameter resolution and b-tagging performance
- for a PU of 140, bandwidth limitations in the readout electronics would lead to an irreducible data loss of approximately 7% in the first pixel barrel layer layer, which is the crucial layer for primary and secondary vertexing

Outer Tracker

- For the Outer Tracker, the most prominent consequence of irradiation is the increase of leakage current, which can be mitigated, to some extent, by lowering the operating temperature of the cooling system to achieve a lower silicon sensor temperature.

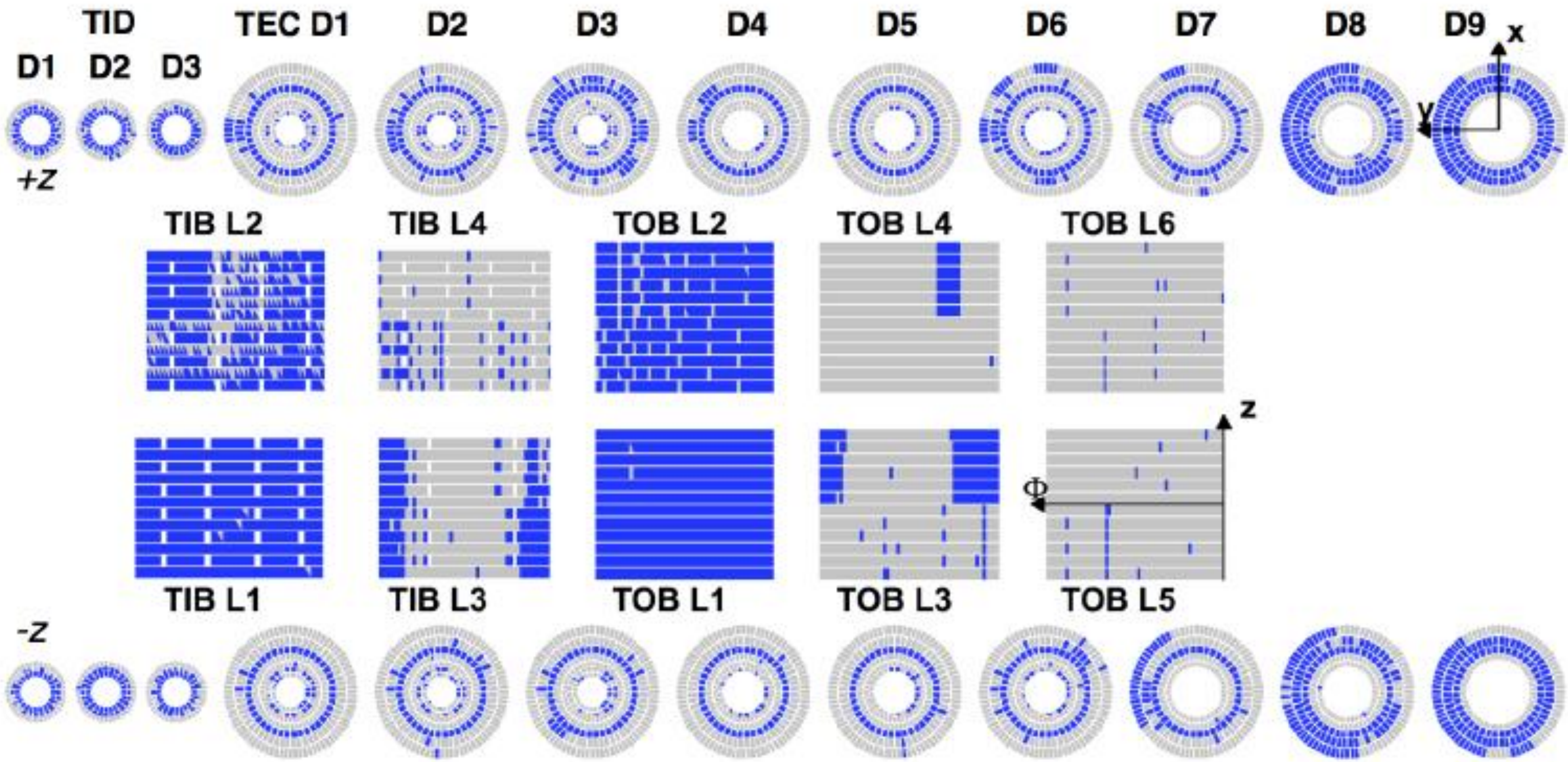


Figure 2.1: Map of non-functional modules (in blue) after an integrated luminosity of 1000 fb^{-1}, for the achievable minimum coolant temperature of $-20°C$.

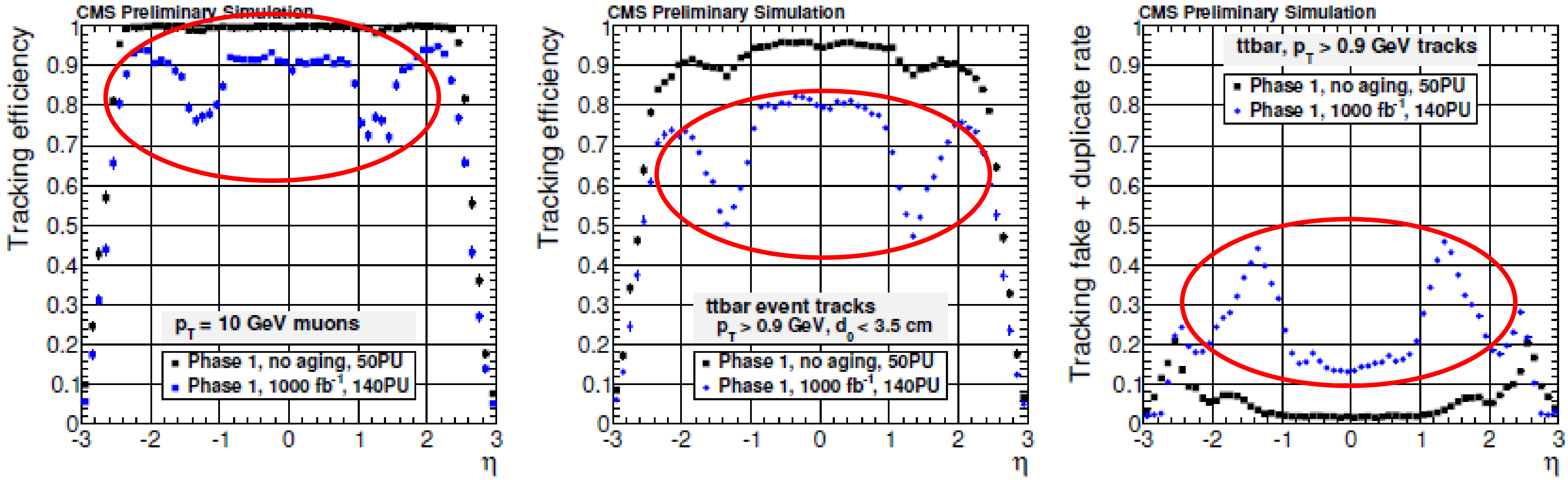


Figure 2.2: Left: efficiency for $p_T = 10$ GeV muons as a function of pseudorapidity for the Phase-1 detector before and after the Outer Tracker has been aged by an equivalent of 1000 fb^{-1}. Center: same plot for charged particles from $t\bar{t}$ events for which the particles have $p_T > 0.9$ GeV and are produced within 3.5 cm of the interaction region (in the transverse direction). Right: fake rate, the fraction of reconstructed tracks that are not matched to a simulated charged particle, for the same selection of particles in $t\bar{t}$ events.

$p_T < 0.9$ GeV the performance degradation in the aged detector is even larger, with the fake rate reaching close to 70% in the rapidity regions around $|\eta| = 1.5$.

- Reducing the fake rate can only be achieved by requiring more hits on each track

Requirements for the Tracker Upgrade

- Radiation tolerance
  - The upgraded Tracker must be able to operate efficiently up to an integrated luminosity of 3000 fb^{-1}

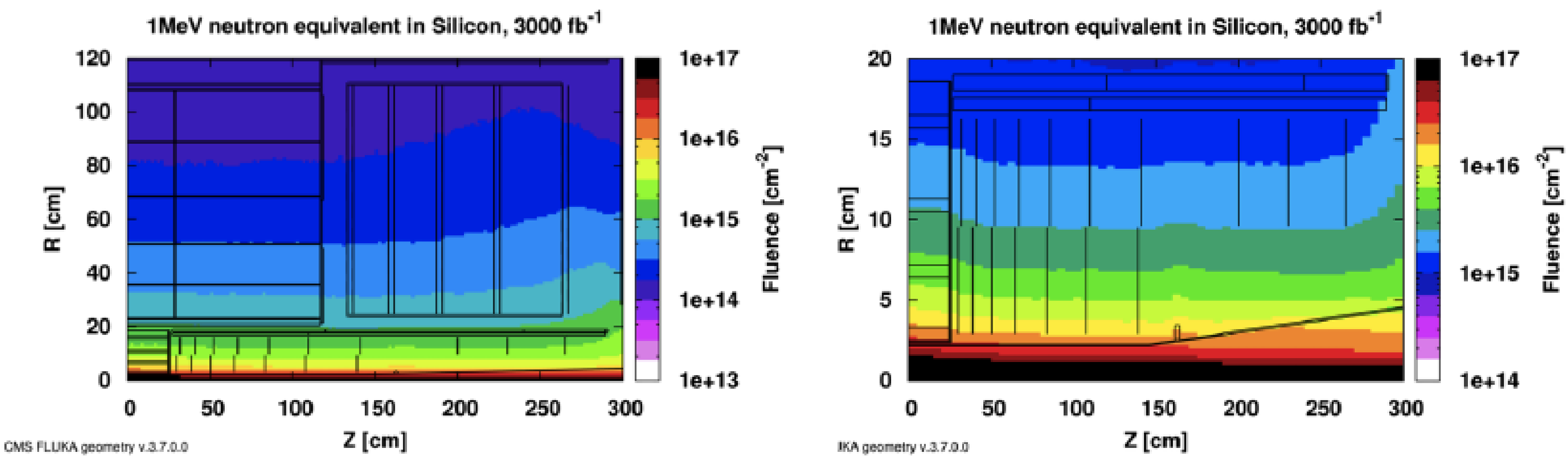


Figure 2.3: Left: map of the expected particle fluence in the Tracker volume corresponding to an integrated luminosity of 3000 fb^{-1}, expressed in terms of 1 MeV neutron equivalent fluence. Right: detail of the fluence in the pixel volume. The expected fluence has a strong dependence on radius, while it is almost independent of the z coordinate.

Requirements for the Tracker Upgrade

- Increased granularity
  - In order to ensure efficient tracking performance at high pile-up, the channel occupancy must be maintained near or below the 1% level in all tracker regions, which requires higher channel density
- Improved two-track separation
  - The present Tracker has degraded track finding performance in high-energy jets, due to hit merging in the Pixel detector
- Reduced material in the tracking volume
  - The performance of the current Tracker is significantly limited by the amount ofmaterial
- Robust pattern recognition
  - upgraded Tracker should enable fast and efficient track finding

Requirements for the Tracker Upgrade

- Compliance with the L1 trigger upgrade
  - increase the L1 rate and latency to 750 kHz and 12.5 μs, and to add tracking information in the trigger decision
- Extended tracking acceptance

A SKETCH OF ONE QUADRANT OF THE PHASE-2 TRACKER LAYOUT

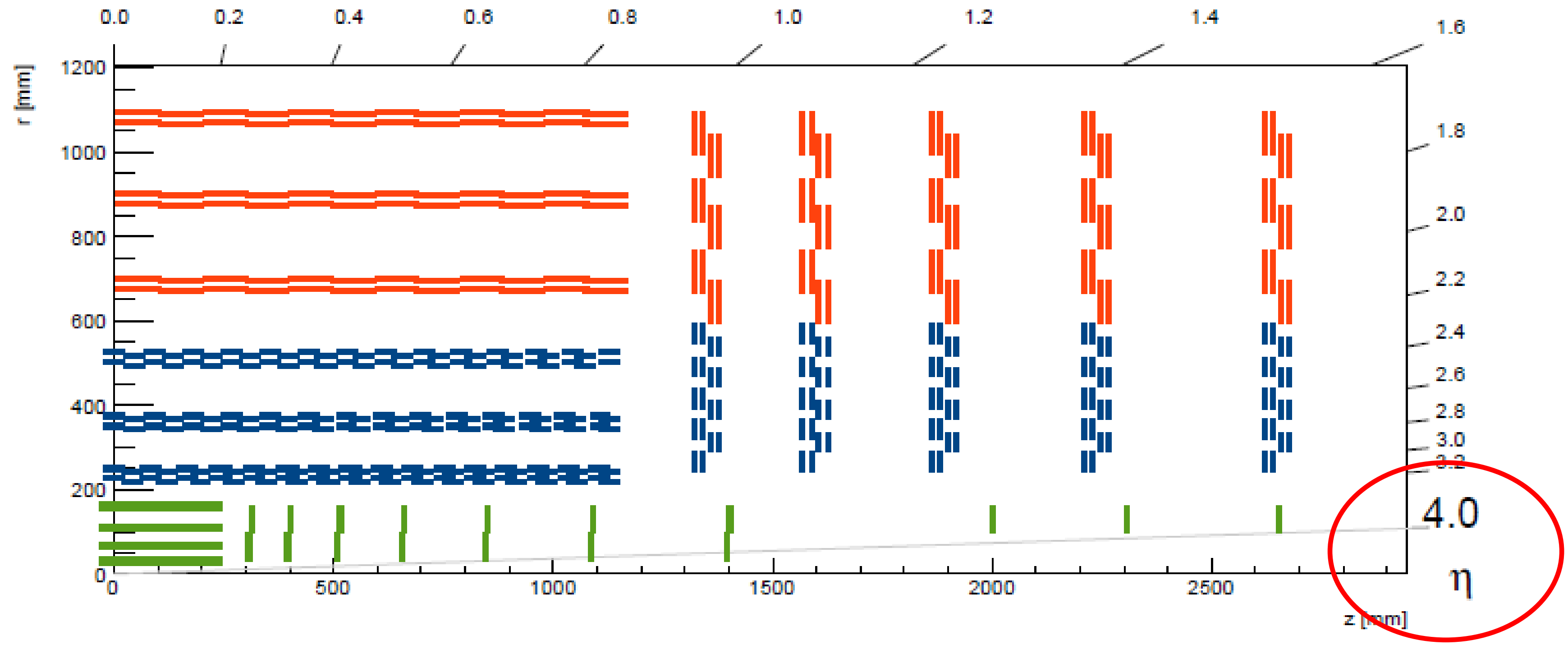


Figure 2.4: Sketch of one quarter of the Tracker Layout. Outer Tracker: blue lines correspond to PS modules, red lines to 2S modules (see text). The Pixel Detector, with forward extension, is shown in green.

Overview of the Pixel detector design

- The requirement of radiation tolerance is particularly demanding for the Pixel detector. Preliminary studies show that good results can be obtained by using thin planar silicon sensors, segmented into very small pixels
- At the same time the required improvement in two-track separation mentioned above is also obtained
- Pixel sizes of $25 \times 100\ \mu m^2$ or $50 \times 50 \mu m^2$ are being considered, representing a factor of 6 reduction in surface area compared to the present pixel cells
- For the readout chip, such a small pixel size can be achieved with the use of 65 nm CMOS technology and an architecture where a group of channels (pixel region) shares digital electronics for buffering, control and data formatting.
- The research on sufficiently radiation tolerant sensors and the design of the readout chip are the key activities

Overview of the Outer Tracker detector design

- The Outer Tracker provides data both for the L1 reconstruction (for each bunch crossing), and for the global event processing upon reception of a L1 trigger decision.
  - The L1 functionality depends upon local data reduction in the front-end readout electronics, in order to reduce the required bandwidth of the L1 data stream.
  - This is achieved with modules that are themselves capable of rejecting signals from particles below a certain pT threshold
- In order to achieve the required radiation tolerance it is critical to choose appropriate sensor material and processing technology

Stub data are sent out at every bunch crossing while all other signals are stored in the front-end pipelines forreading out when a trigger is received

different sensor spacingsmust be implemented in different regions of the tracker

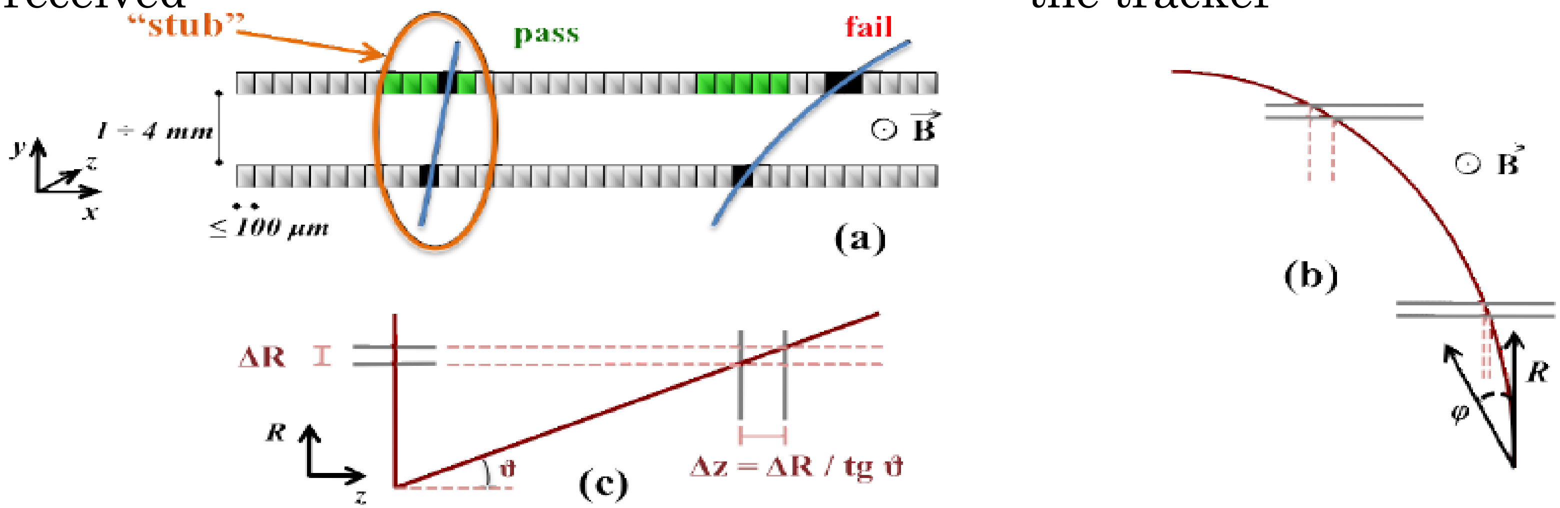


Figure 2.5: (a) Correlation of signals in closely-spaced sensors enables rejection of low-p_T particles; the channels shown in light green represent the "selection window" to define an accepted "stub". (b) The same transverse momentum corresponds to a larger distance between the two signals at large radii for a given sensor spacing. (c) For the end-cap disks, a larger spacing between the sensors is needed to achieve the same discriminating power as in the barrel at the same radius. The acceptance window can therefore be tuned along with the sensor spacing to achieve the desired p_T filtering in different regions of the detector.

- The strong magnetic field of CMS provides sufficient sensitivity to measure pT over the small sensor separation, enabling the use of pT modules in the entire radial range above R =20 cm

Two types of pT modules are under development-2S

- "2S" modules are composed of two superimposed strip sensors of approximately $10 \times 10\ \text{cm}^2$, mounted with the strips parallel to one another.
  - They populate the outer regions, above R= 60 cm (in red in the sketch of p.46)
  - Wire bonds at opposite ends of the sensor provide the connectivity of both sensors to the readout hybrid
    - A single"service hybrid" carries a 5 Gb/s data link, an optical converter, and the DC/DC converter that provides power to the module electronics
  - The use of one optical link per module provides the bandwidth needed for the trigger functionality, and at the same time offers significant advantages in the overall system design by avoiding additional electrical interconnectivity in the tracking volume

Two types of pT modules are under development-Ps

- "PS" modules are composed of two sensors of approximately $5 \times 10\ \text{cm}^2$ one segmented in strips, and the other segmented in "macro-pixels" of size $100\ \mu\text{m} \times 1.5\ \text{mm}$.