Simulation in CMS

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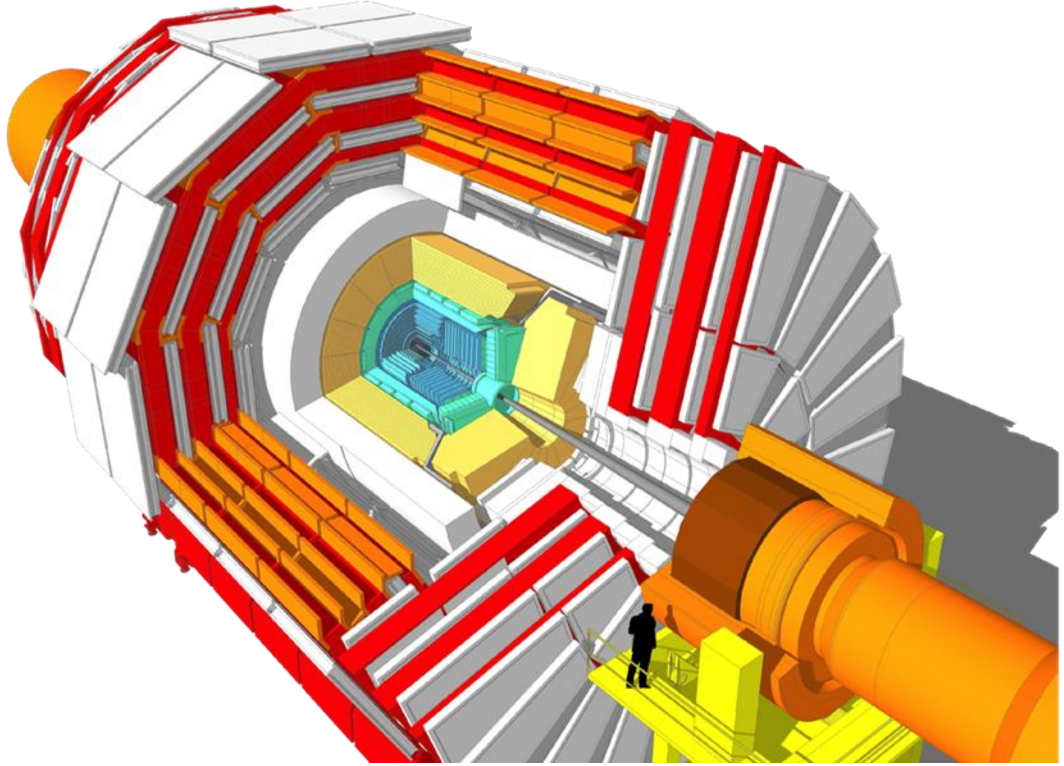
Outline

- CMS simulation scheme
- Adaptation of Geant4 version
- Configuration of Geant4 Physics
- Migration to DD4Hep
- CMS simulation performance
- Phase-2 challenges
- Summary

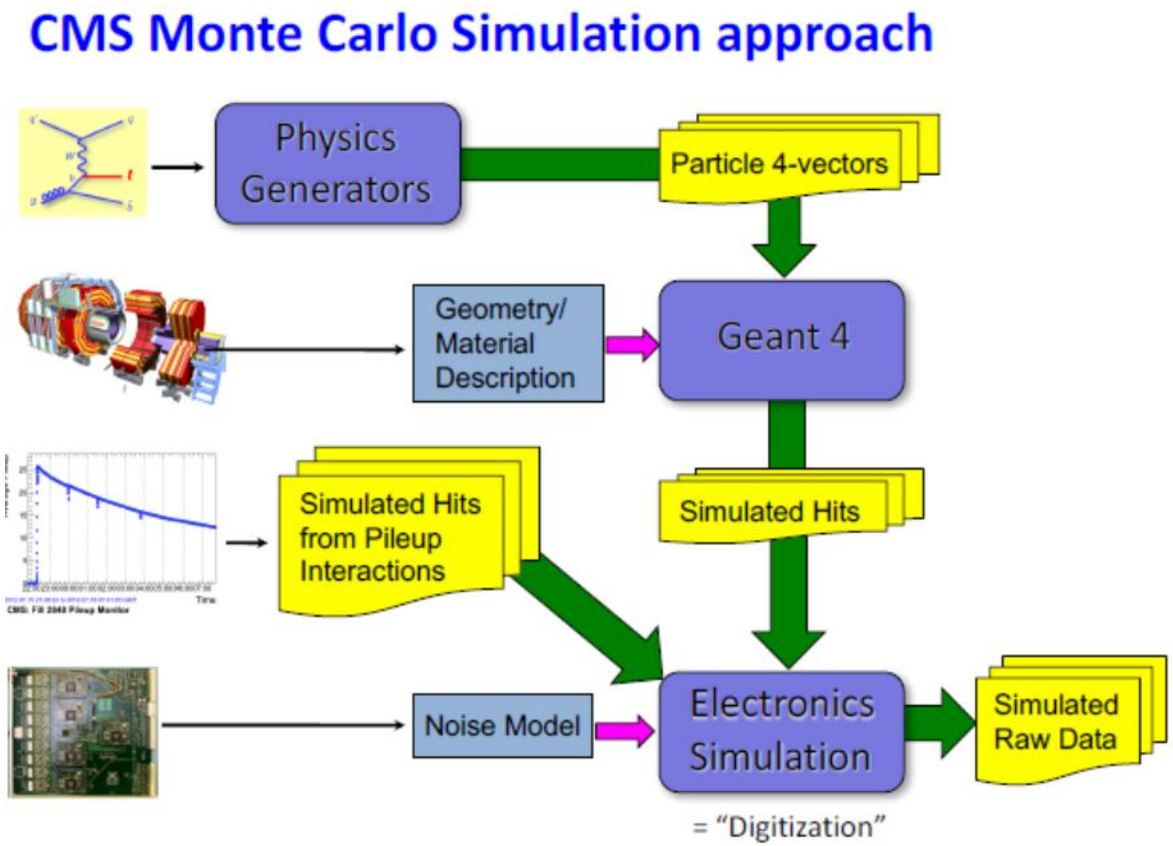
- Today we will not discuss CMS FastSim approach



References for CMS Full Simulation:

- D.J. Lange et al., J. Phys.: Conf. Ser. 608, 012056 (2015)
- M. Hildreth et al., J. Phys.: Conf. Ser. 664, 072022 (2015)
- M. Hildreth et al., J. Phys.: Conf. Series 898, 042040 (2017)
- S. Banerjee and V. Ivanchenko, EPJ Web of Conf. 214, 02012 (2019)
- K. Pedro (CMS), , EPJ Web of Conf. 214, 02036 (2019)
- S. Banerjee and V. Ivanchenko, EPJ Web Conf. 251, 03010 (2021)
- V. Ivanchenko et al., EPJ Web Conf. 251, 03016 (2021)

CMS simulation scheme



- CMS does not used G4RunManager but have a custom one
  - CMS Framework plugins for
    - Geometry
    - Sensitive detectors
    - Physics Lists
    - Random numbers
  - CMS event loop
  - CMS Exceptions
- Since 2015 simulation is multithreaded (MT)
  - CMS Framework MT method is tbb

Adaptation of Geant4 versions

Run1 Geant4 9.4

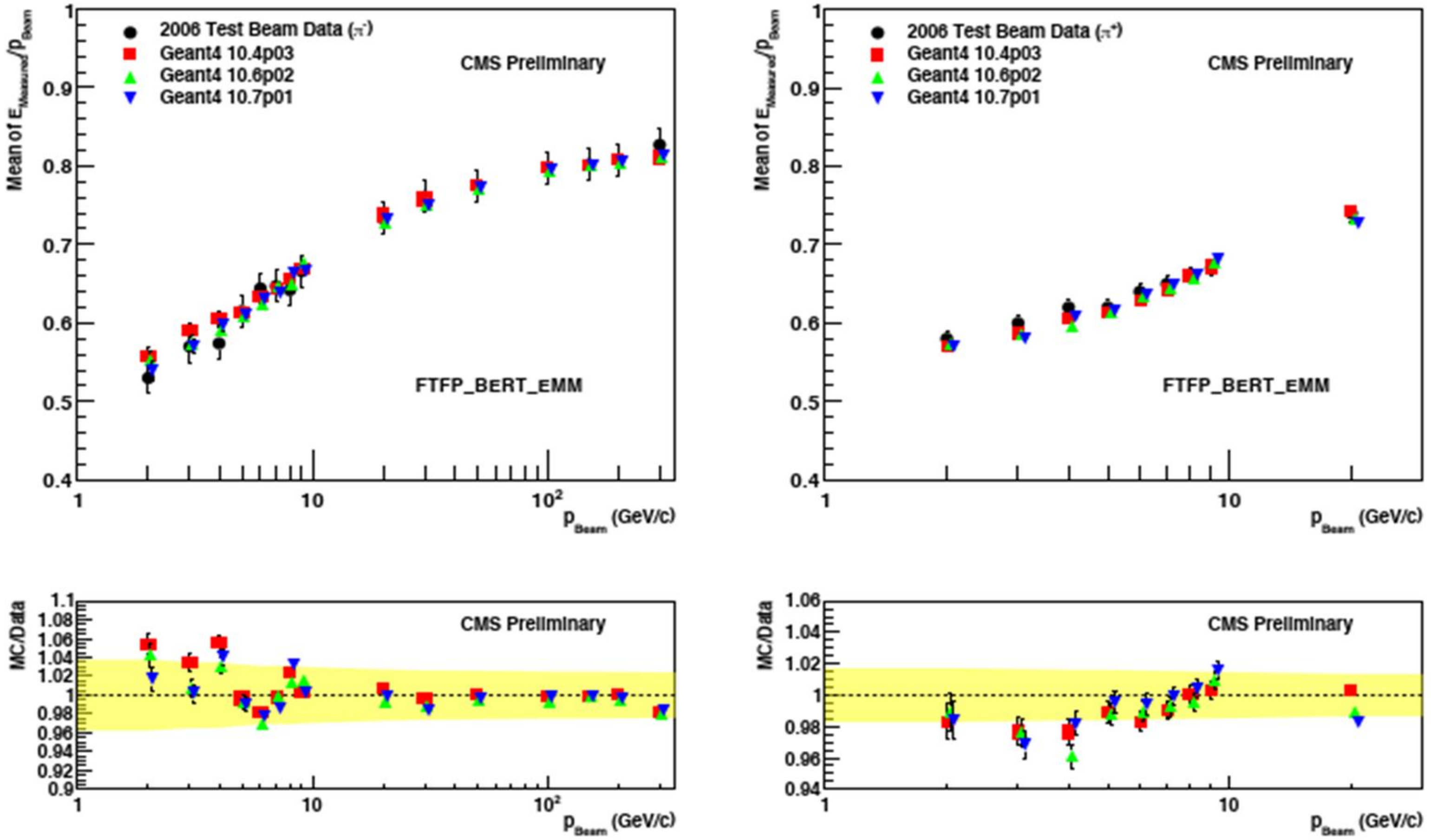
2015 Geant4 10.0p02

2017 Geant4 10.2p02
2018 Geant4 10.4p03
+ VecGeom

2021 Geant4 10.7p02
+ DD4Hep

- CMS Geant4 version for Run-2
  - CMS sub-detectors were modified for each new season
  - MT mode in production from 2017
  - Geant4 10.4p03 + VecGeom since 2018 – legacy MC production
- The configuration of physics was established for Run-2
  - FTFP_BERT_EMM Physics Lists
  - Russian roulette method
  - HF shower library
- Geant4 10.7 is the CMS release for Run-3
  - 10.7 is the most recent Geant4 version available during LS2
- The current CMS production version is 10.7p02
  - It passed CMS validations in fall 2021
- A procedure of validation for each new Geant4 version was established in CMS since Run-1
  - Validation started 6 months before the date of any Geant4 release, feedback to the Geant4 team is provided
  - Integrations tests, test-beam analysis, and comparisons with the detector data are performed before full validation by CMS validation teams

Pion energy response in CMS combined calorimeter EPJ Web Conf. 251, 03010 (2021)



Mean response as a function of momentum compared to MC predictions:

- top left – negative
- top right – positive

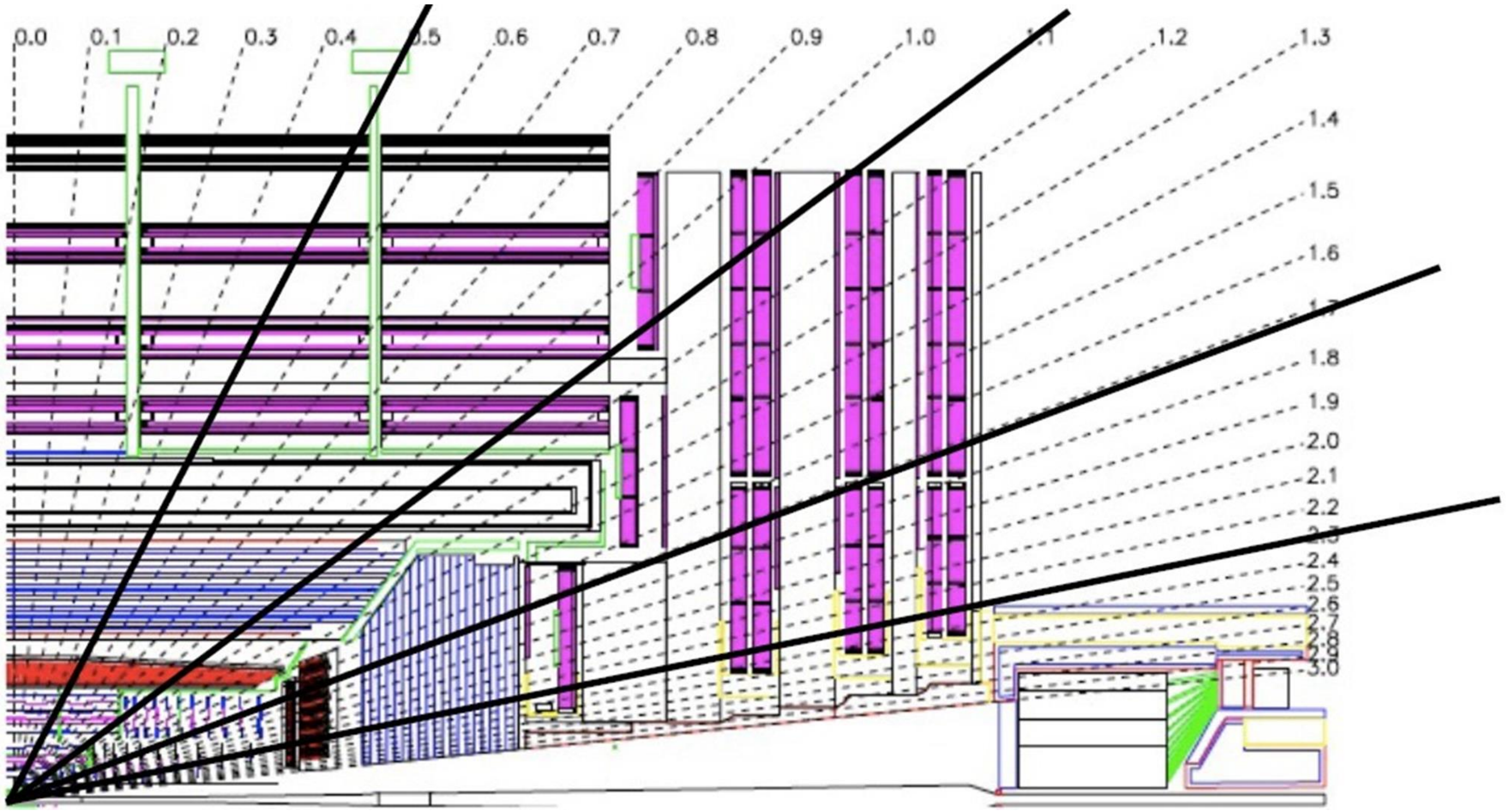
Ratio of MC to data as a function of pion momentum

- bottom left – negative
- bottom right – positive

The level of agreement is stable between Geant4 versions

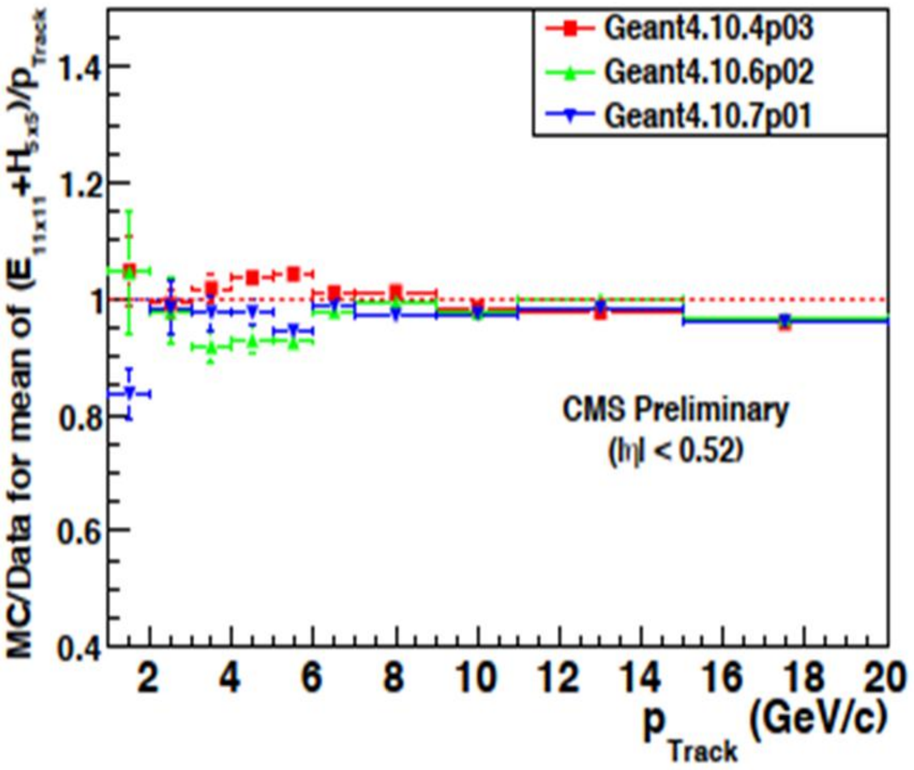
- Since Geant4 10.6 the Birks constant was changed

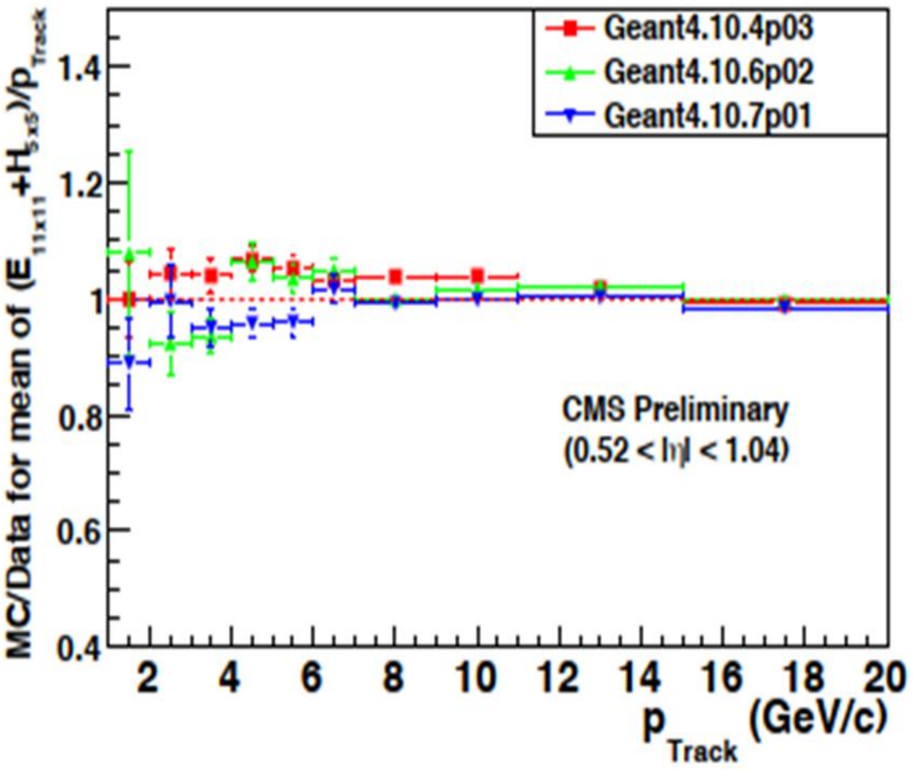
Hadron response in calorimeters for low pile-up runs



- Four partitions in the CMS detector are used in the measurement of calorimeter response
  - Two for barrel
  - Transition
  - Endcap

Hadron response in calorimeters for low pile-up runs





- Ratio of the mean energy response between MC and data for two regions of CMS as a function of hadron momentum
- The level of data/MC agreement for all 4 partitions is 1-3.5% for Geant4 10.7

Configuration of Geant4 Physics

- Physics List for FTFP_BERT_EMM
  - The same for Run-2 and Run-3
- To achieve the agreement between CMS test-beam and detector data two revisions were introduced in simulation for Run-3:
  - Overlap energies between the Bertini Cascade and the FTFP string model for pions is set from 3 to 12 GeV
    - The default is from 3 to 6 GeV
  - The Birks coefficient for the HCAL scintillator is increased by about 15%

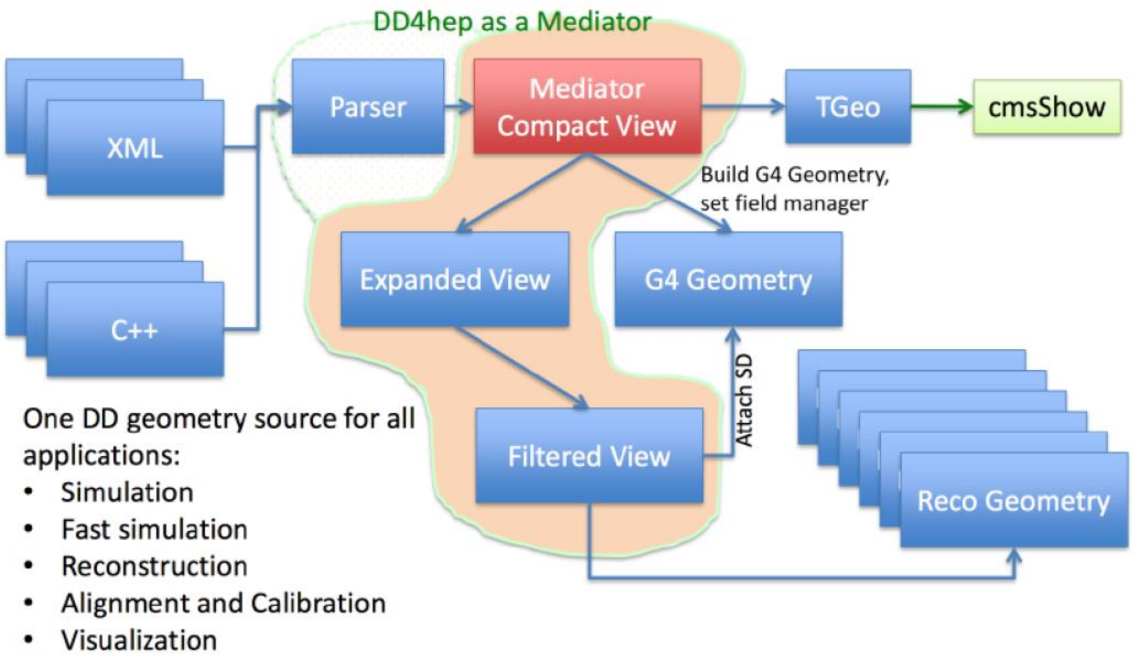
- Magnetic field driver G4DormandPrince745
  - both for Run-2 legacy processing and Run-3
- A smart configuration of Geant4 parameters for tracking in field is implemented with 3 sets of parameters
  - set 1 - for central detector region R < 8 m, |Z| < 11 m, and E > 200 MeV;
  - set 2 - for low-energy particles E < 15 MeV;
  - set 3 - for the rest.
- Dynamic switch between these 3 sets during tracking is performed
  - Providing accuracy for tracking of relativistic particle
  - Reducing tracking problems for low-energy sparing e^{+-}

Magnetic field parameters	Parameter set 1	Parameter set 2	Parameters set 3
DeltaIntersection (mm)	10^{-6}	0.01	10^{-4}
DeltaOneStep (mm)	10^{-4}	0.1	10^{-3}
DeltaChord (mm)	10^{-3}	0.1	$2 \cdot 10^{-3}$
MaxStep (cm)	150	150	50

CMS is trying to use the most recent Geant4 version

- Main arguments to make a migration
  - Simulation should use the same platforms as other components of CMSSW
  - Each new Geant4 version usually is a bit faster than previous and include many technical improvements
  - New features technical and physical may be useful for CMS
    - Geant4 10.7 includes EM and hadronic physics of meson and baryons with b- and c- quarks
- Physics quality of CMS simulation
  - Usually, for new Geant4 results are stable for calorimeter response
    - for EM showers on per mile level
    - For hadronic showers in percent level
  - Recent visible change of calorimeter response was introduced in Geant4 10.5
    - It was addressed by modification of the Birks constant in HCAL

Migration to DD4Hep



- For Run-1 and Run-2 CMS used custom detector description (DDD)
  - For each sub-detector original approach was developed by each sub-detector team
- For Run-3 a migration to the community developed tool DD4Hep was chosen
  - F. Gaede et al., EPJ Web of Conferences 245, 02004 (2020)
  - C. Vuosalo et al., EPJ Web of Conferences 245, 02032 (2020)
- Migration required contributions from several sub-detector teams
  - Was started in 2019 and included full review of the CMS geometry
    - XML files were reviewed and unified
  - Run-3 DD4Hep description is approved by CMS
  - The migration effort provided good opportunity to verify CMS geometry, remove overlaps, and improve accuracy of volume positions and representations
- We would like to thank Markus Frank (LHCb) and the DD4Hep team for prompt reactions to any our request
  - DD4hep code was also improved during this CMS campaign
  - There is no CPU difference to build geometry with DDD or DD4hep

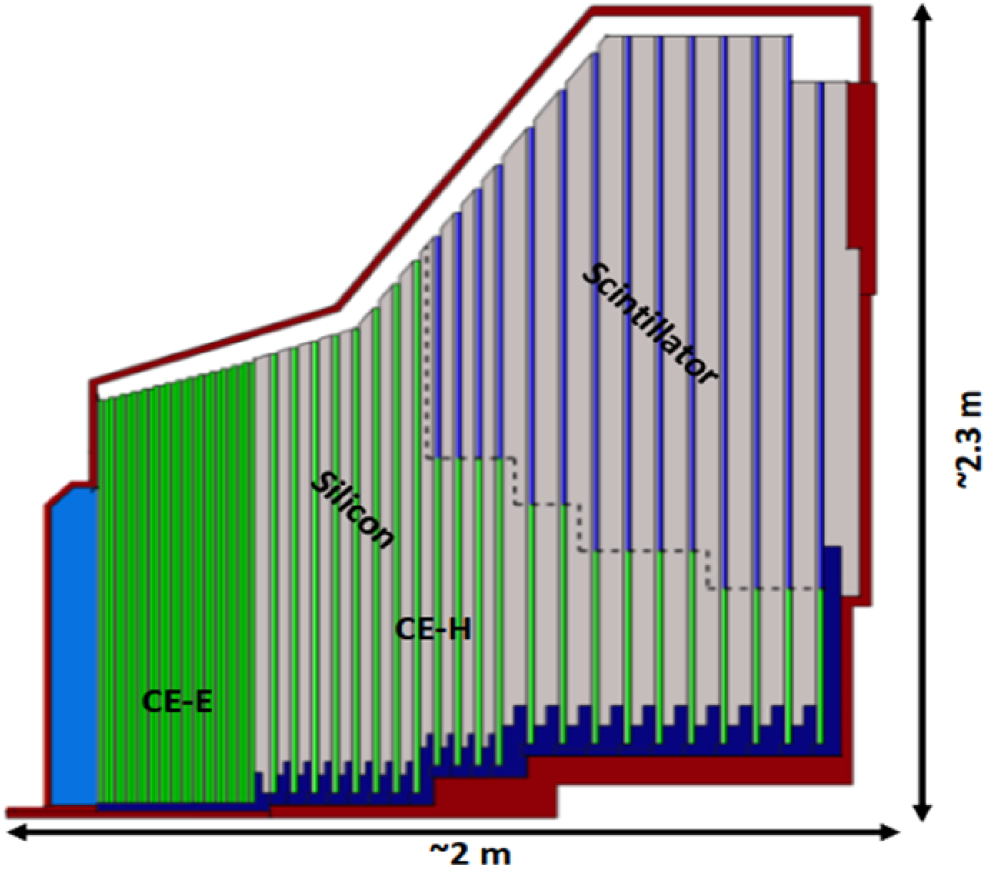
CMS simulation performance

- CMS efforts to speed-up simulation are permanent
  - Using optimal compilers
  - Using the most recent Geant4
- Several optimizations were introduced to Geant4 configuration for CMS
  - Simulation production for CMS Run-2 is significantly faster than the Geant4 default FTFP_BERT
  - For Run-3 there is ~8% due to the new Geant4 version

Run-2 simulation performance

	Relative CPU usage	
Configuration	Minbias	$t\bar{t}$
No optimizations	1.00	1.00
Static library	0.95	0.93
Production cuts	0.93	0.97
Tracking cut	0.69	0.88
Time cut	0.95	0.97
Shower library	0.60	0.74
Russian roulette	0.75	0.71
FTFP_BERT_EMM	0.87	0.83
All optimizations	0.21	0.29

Phase-2 challenges: HGCAL



- For HL-LHC a new endcap calorimeter is under design and development
- **Electromagnetic calorimeter (CE-E):**
  - Si/CuW/Pb absorbers 28 layers, 25.5 X_0, 1.7 λ
- **Hadronic calorimeter (CE-H):**
  - Si & scintillator, steel absorbers, 22 layers, 9.5 λ
- Will provide
  - higher resolution than existing CMS calorimeters
  - high-quality particle flow analysis
- Make CMS simulation 2-3 times slower

Summary

Intensive development carried out during LS2 for CMS FullSim

- Geometry for Run-3 was updated
- Run-3 geometry description migrated to DD4hep and currently being validated
  - Next step would be full migration to the DD4Hep tool for the Phase-2 detectors
- Geant4 10.7p02 is adopted
  - Required slight modification of physics configurations
  - Provides CPU advantage ~8 % compared to Run-2

FTFP_BERT_EMM physics configuration for Run2 and Run3

- Validated by test-beam and data, significant speed-up

HGCAL simulation of Phase-2 CMS detector is a new challenge on which several groups are working