Full Simulation of CMS for Run-3 and Phase-2

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Geant4 versions with CMSSW

Run-3

- **2024:** Geant4 11.1.p01
- **2022+2023:** Geant4 10.7.p02 + VecGeom + DD4hep

- **CMSSW_13_3 (or higher) for Run-3 2024**
  - New Geant4 11.1 (to be used first for Phase-2 simulation in mid 2023)
- **CMSSW_13_0 for Run-2 2023**
  - Gamma general process
  - Link Time Optimization (LTO) build
- **CMSSW_12_4 for Run-3 2022**
  - DD4hep geometry description

Run-2

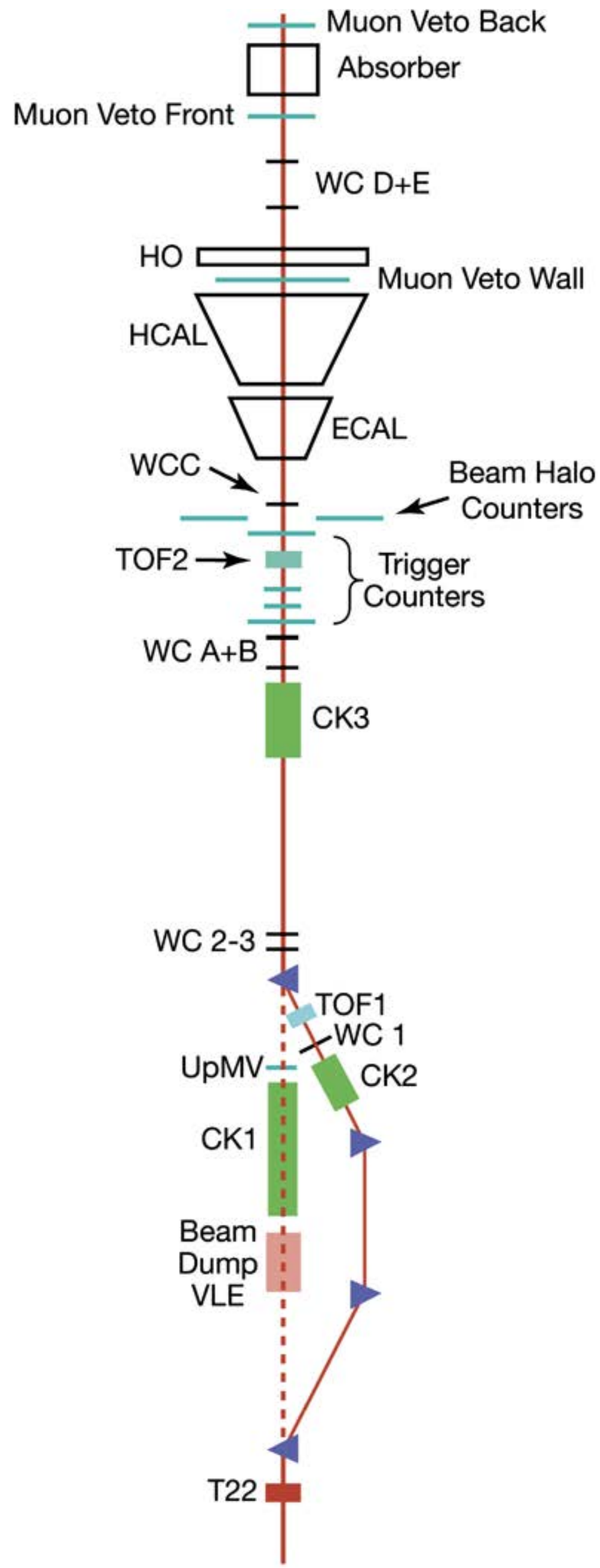
- **2018 + UltraLegacy:** Geant4 10.4.p03 + VecGeom
- **2017:** Geant4 10.2.p02
- **2016:** Geant4 10.0.p03
- **2015:** Geant4 10.0.p02

- **CMS Full simulation for Run-2**
  - Updated geometries for each year
  - Multithread mode in production since 2017
  - Configuration for physics:
    - FTFP_BERT_EMM
    - Russian roulette method
    - HF shower library

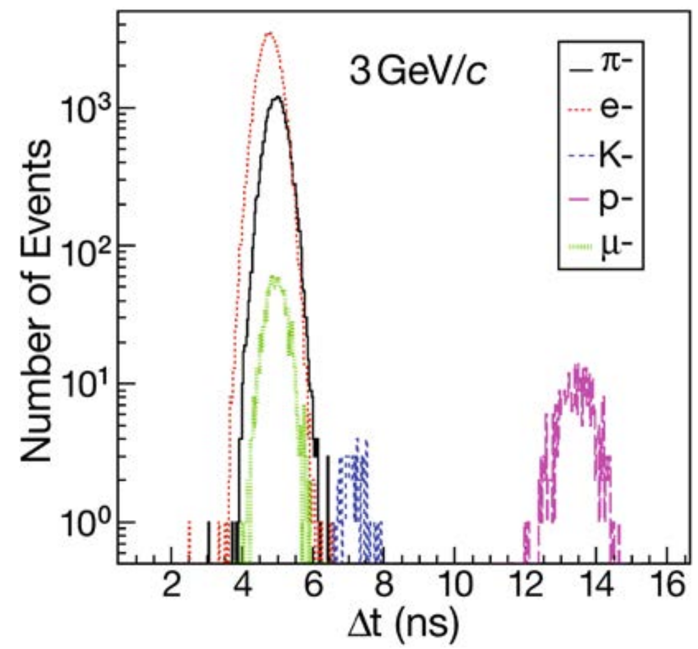
Run-1

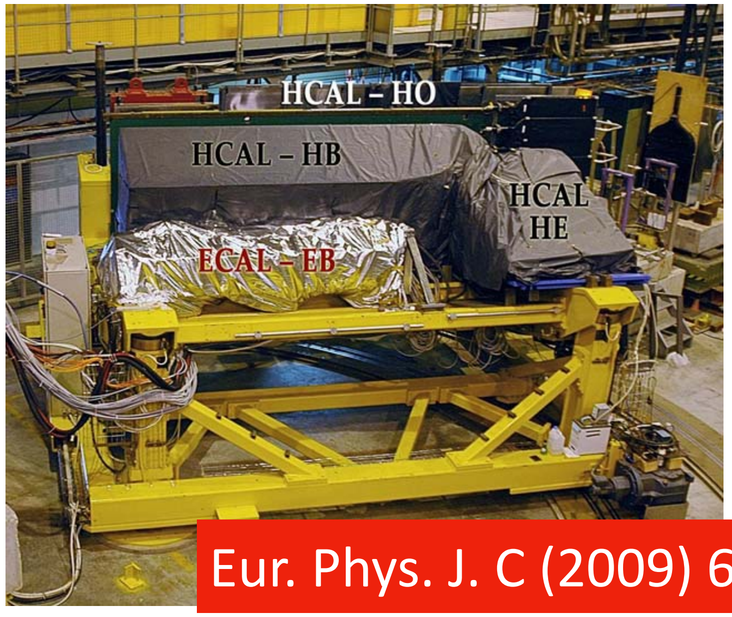
- **Legacy:** Geant4 9.4

Migration of Geant4 under CMSSW



- **Software performance**
- **2006 test beam with CMS calorimeter prototypes** (beams of different types and different energies)





Eur. Phys. J. C (2009) 60: 359–373

- **Collision data from the CMS experiment** utilizing zero bias or minimum bias triggers from low luminosity runs

J. Phys.: Conf. Ser. 898 042005

- **Data-MC comparison:** Validation campaigns organized centrally, participation from detector performance and physics object groups.
  - **Run-3 2022** with Geant4 10.7.p02
  - **Run-2 Ultra-Legacy** with Geant4 10.4.p03

CMS Simulation Performance

- **Key success for CMS to speed up the simulation**
  - Using optimal compliers
  - Using most recent version of Geant4
- **Several optimizations have been introduced to Geant4-CMSSW configuration**
  - Simulation production for CMS Run-2 is significantly faster than the Geant4 default with FTFP_BERT
    - EMM: configuration of EM physics specific for CMS since 2017. Configuration different for crystal and sampling calorimeters like HCAL or HGCal.
  - For Run-3 2022-2023, 8% faster due to the Geant4 10.7.p02
  - *Expect performance improvement with Geant4 11.1.p01*

Run-2 simulation performance

Configuration	Relative CPU usage	
	MinBias	TTbar
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

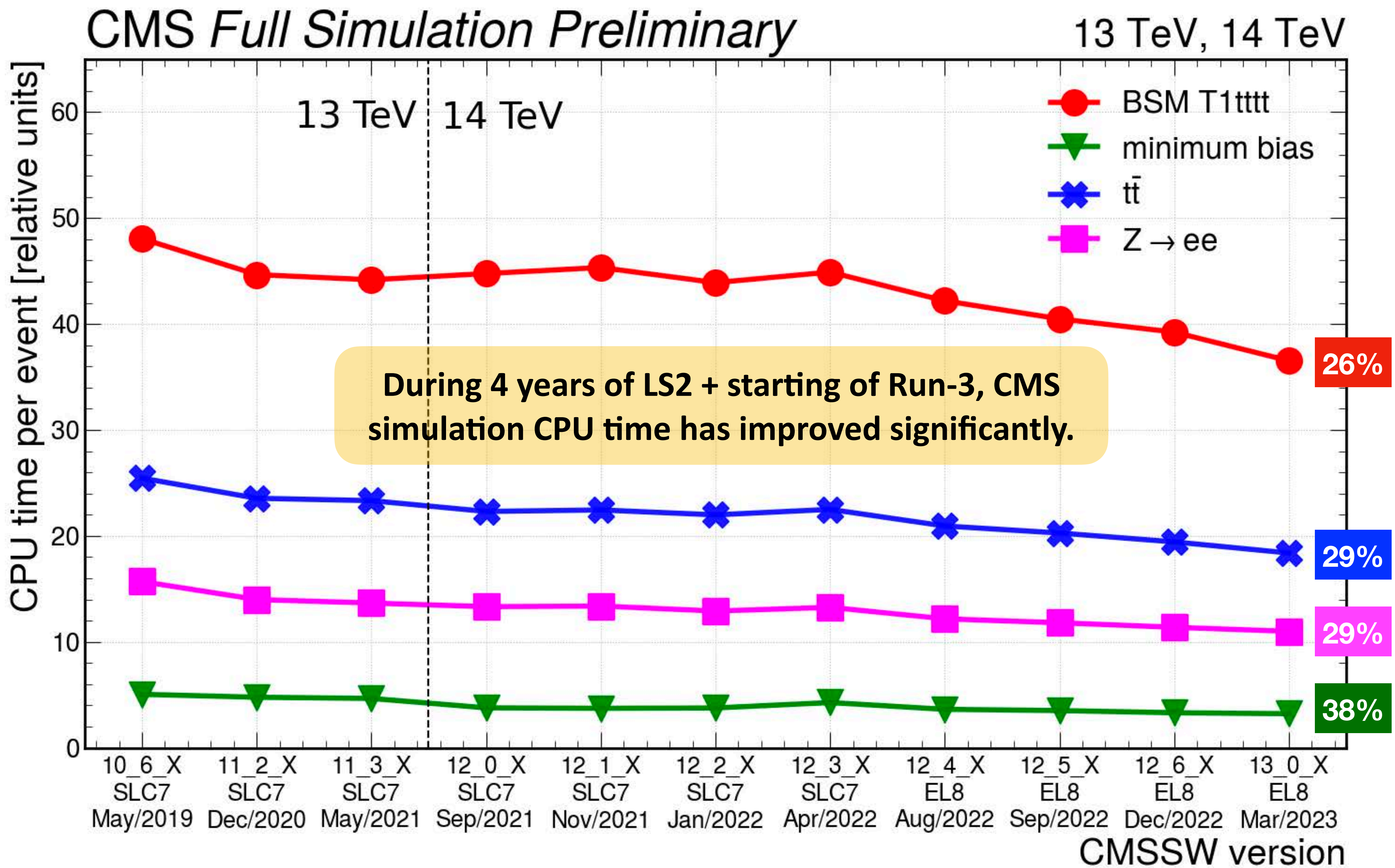
CMS Simulation Performance

	QCD	Zee	TTbar	T1tttt (*)
2022 GenSim	0.70	0.75	0.79	0.83
2023 GenSim	0.62	0.71	0.71	0.74

(*) T1tttt is SUSY process with pp → gluino + gluino, then gluino → ttbar + lightest neutralino

- **Significant speed up comes from**
  - Geant4 version
  - Computing platform
  - LTO method

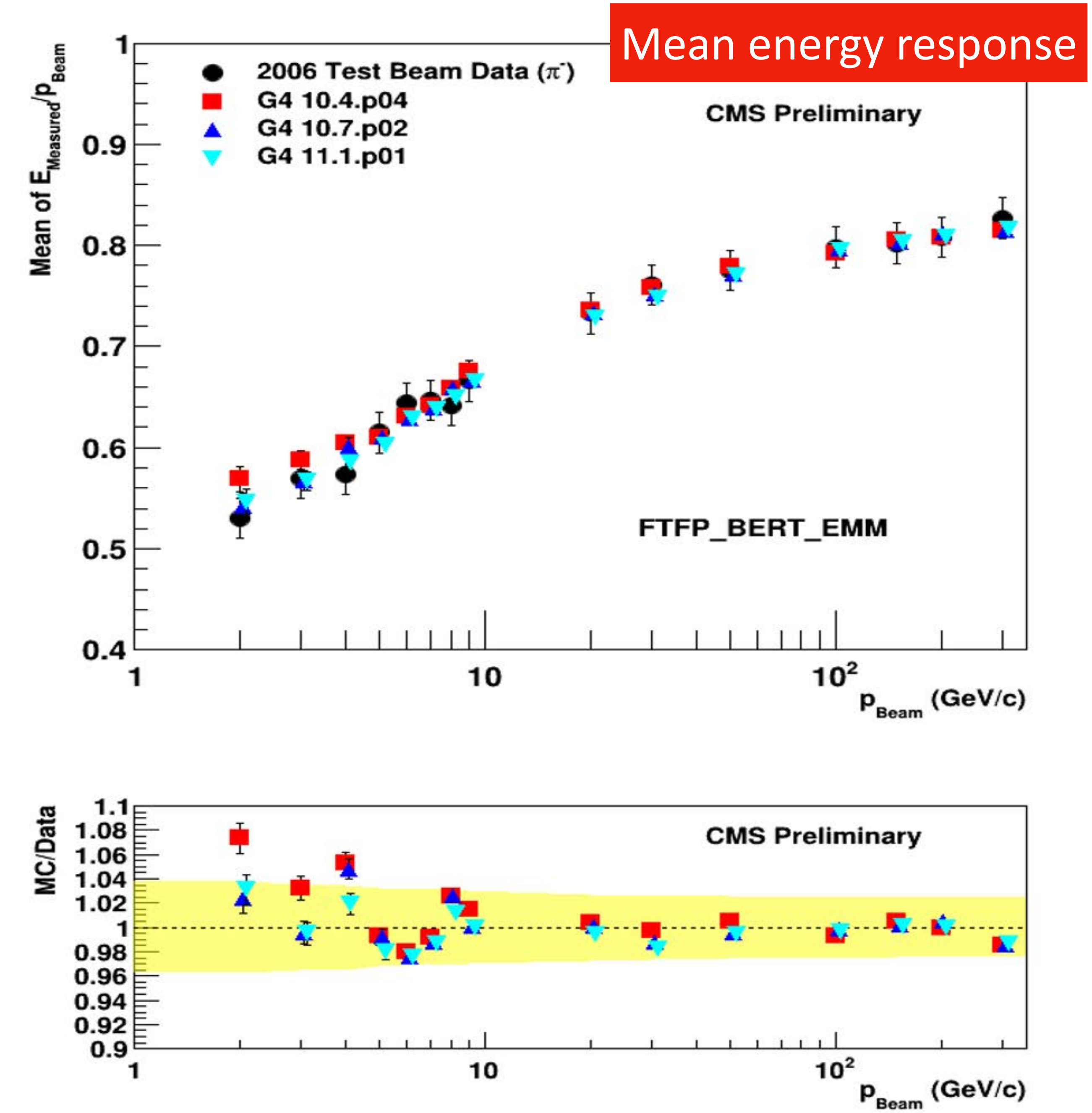
Full Simulation CPU time performance



Historical trends of the CMS detector Full Simulation CPU time performance of Run-2 (with 13 TeV MC) and Run-3 (14 TeV MC).

Validation of Physics Models of Geant4 with test beam data

- Test beam 2006 with a prototype of the barrel hadron calorimeter and a supermodule of the barrel electromagnetic calorimeter.
- Test beam of protons and pions with momentum from 2 to 350 GeV/c
- Kaon and anti-proton identification using data from TOF counters and cherenkov detectors up to an energy of 9 GeV.
- **Mean energy response** is measured as the ratio of the total energy in the calorimeter to the beam momentum as a function of beam momentum for different beam types.
  - Good agreement has been observed in pions and protons.
  - Proton-proton collisions at high energy produces mostly pion. We can expect agreement between Data-MC.



(top) The mean energy response for negative pions as a function of momentum compared to MC predictions;
(bottom) Ratio of MC to data for negative pions as a function of momentum. The yellow band shows one standard deviation of the data.

Validation of Physics Models of Geant4 with test beam data

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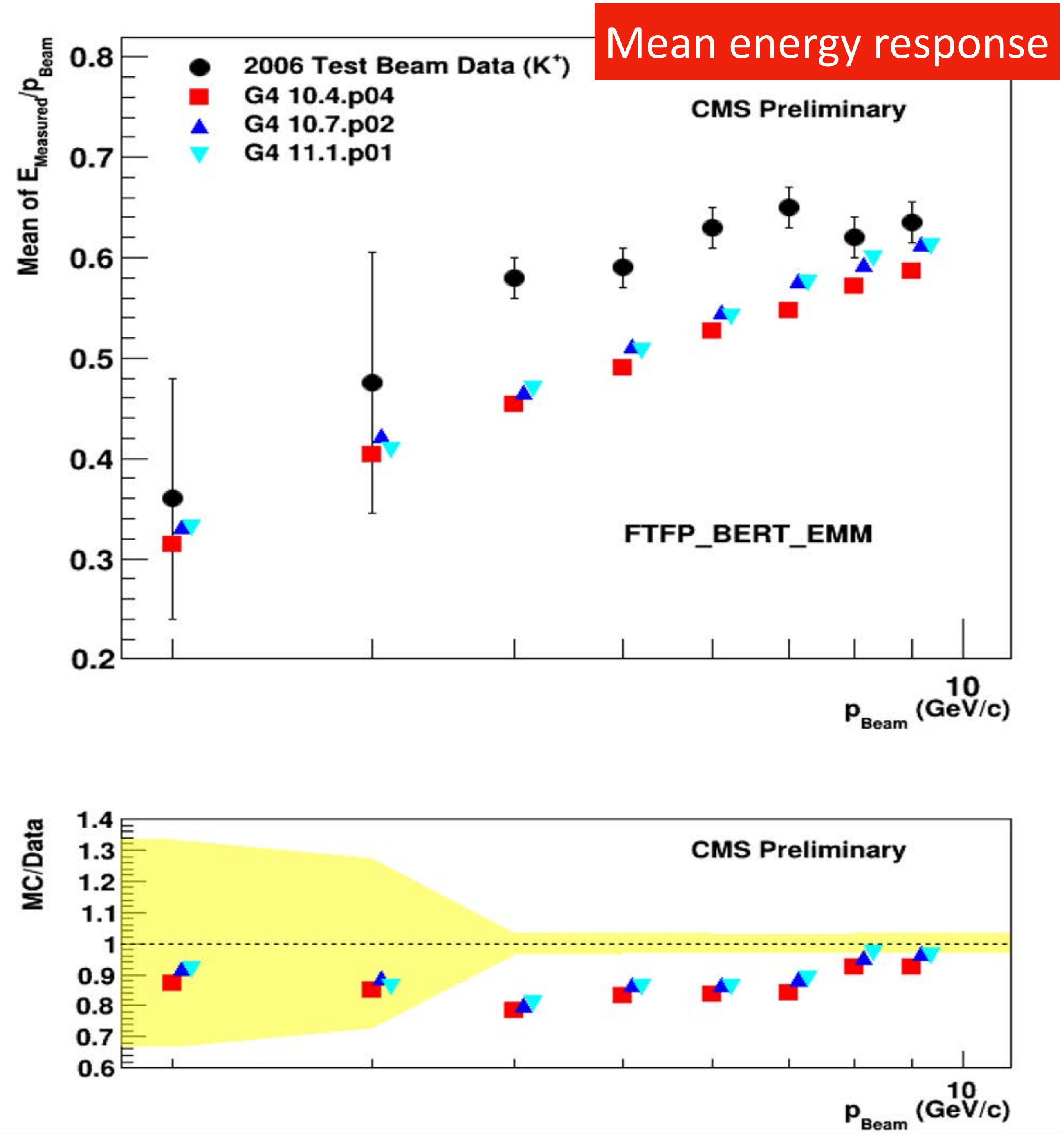
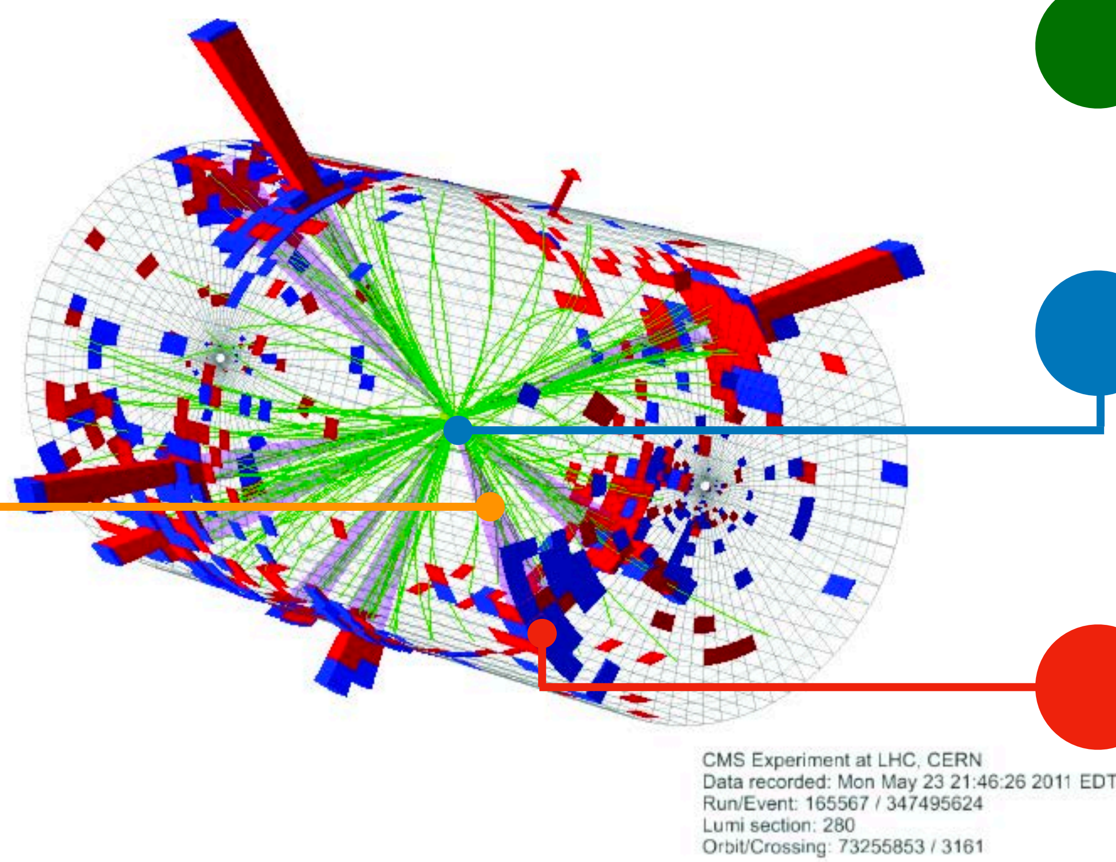
- Kaon and anti-proton identification using data from TOF counters and cherenkov detectors up to an energy of 9 GeV.
- **Mean energy response** is measured as the ratio of the total energy in the calorimeter to the beam momentum as a function of beam momentum for different beam types.
  - Not a good agreement for kaons. A response for pions and kaons are very similar in the data but not in MC.
  - Some improvement with 10.7.p02 and 11.1.p01



(top) The mean energy response for positive kaons as a function of momentum compared to MC predictions;
(bottom) Ratio of MC to data for positive kaons as a function of momentum. The yellow band shows one standard deviation of the data.

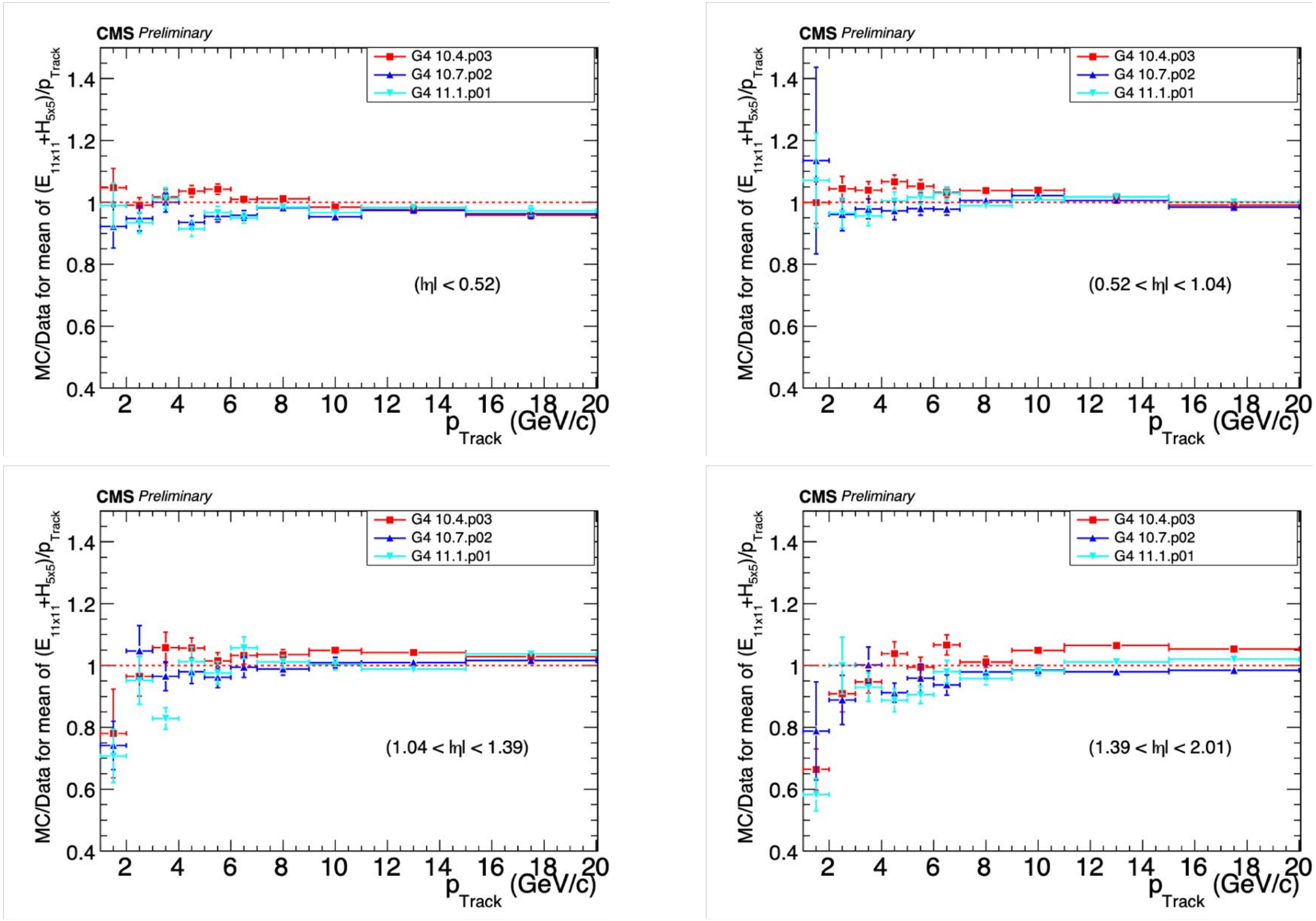
Validation of Physics Models of Geant4 with 7 TeV and low PU data

- To compare ratio of calorimeter energy measurement to track momentum for isolated charged hadrons between data and MC. The methodology was developed using 7 TeV data (PAS: JME-10-008). The analysis of the 2016 low pileup data plus the comparisons with earlier Geant4 model predictions were presented in a few earlier CHEP conferences.



- Only runs marked as 'good' (all CMS sub-detectors are fully operational) are used.
- Events having only one high-quality primary vertex are selected. This vertex is required to be consistent with the nominal interaction point.
- Measure the energy in a defined NxN matrix around the point of impact.
- Good charged tracks reaching the calorimeter surface. Impose isolation of these charged particles.
  - Propagate track to calorimeter surface and study momentum of tracks. Demand no other track in the defined isolation region.
  - Study energy deposited in an annular region in ECAL and HCAL.

Validation of Physics Models of Geant4 with 7 TeV and low PU data



The ratio of the mean energy response in a wide matrix of ECAL and HCAL between MC and data for four regions of the calorimeter: central barrel (top left); side barrel (side barrel); transition region (bottom left); endcap (bottom right).

Looking forward for CMS Phase-2 simulation

- Migration to **CMS Phase-2 DD4hep geometry**

- New approaches for EM physics, to speed up the simulation without compromise of physics.
  - **G4TransportationWithMsc**
  - **Custom tracking manager**
    - Simplified e-gamma transport in Geant4
  - **G4HepEm external library**
    - Focus on the EM shower generation
    - Gateway for GPU usage for EM physics
    - https://github.com/mnovak42/g4hepem
    - https://g4hepem.readthedocs.io/en/latest/

- Follow R&D for GPU usage
  - **Accelerated demonstrator of electromagnetic Particle Transport (AdePT)**
    - https://github.com/apt-sim/AdePT (see CHEP2023 talks: 66, 163)
  - **Celeritas** (to implement HEP detector physics on GPU accelerator, targeting for HL-LHC)
    - https://github.com/celeritas-project/celeritas

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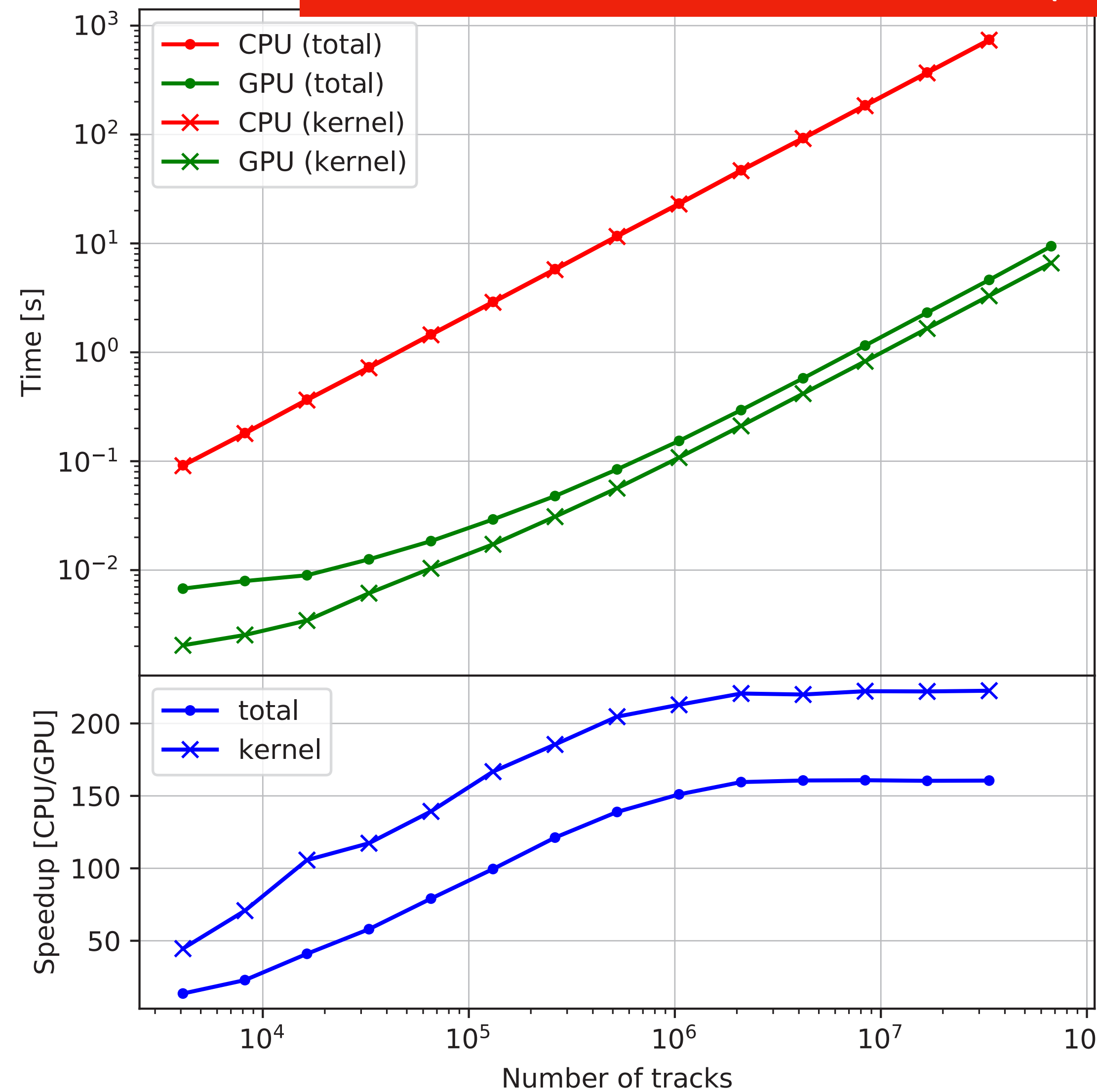

Performance comparison of the CPU (Intel Cascade Lake Xeon 2.3 GHz) and original GPU (Nvidia Tesla V100, CUDA 10.1) versions of the Celeritas code.

Summary

- **CMS continues the development and validation of new simulation software**
  - Geant4 11.1.p01 is currently integrated to CMSSW, targeting for Mid-Year Phase-2 production, and Run-3 2024
  - Testing new Geant4 on physics performance and CPU advantage.
    - **Physics performance**: validation has been done between MC (10.4.p03, 10.7.p02, and 11.1.p01) and data (2006 test beam data of combined CMS barrel calorimeter (prototype hadron and electromagnetic calorimeters) and low pile-up collision data at sqrt(s) = 13 TeV). Good agreement with data has been observed.
    - **CPU advantage**: with starting of Run-3 (with Geant4 10.7) higher CPU performance is observed compared to Run-2. CPU speed up is also expected with 11.1.p01

  - **Phase-2 software is under development**
    - The next milestone is to complete the migration to DD4hep.
    - R&D on GPU usage for simulation is in progress, to speed up the simulation.