Phase-2 Full Simulation & Geant4

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For the CMS Simulation Group

Phase-2 Software Days, September 28-29, 2023

Outline

- CMS FullSim evolution
- Validations of Geant4
- Phase-2 simulation challenges
- Plans and conclusions

General Geant4 publications:

- Nucl. Instr. Meth. A 506, 250-303 (2003).
- IEEE Trans. Nucl. Sci. 53, 270-278 (2006).
- Nucl. Instr. Meth. A 835, 186-225 (2016).

Important links:

- Main page: https://geant4-dev.web.cern.ch/
- Documentation: https://geant4-dev.web.cern.ch/docs/
- Validation portal: https://geant-val.cern.ch/

Publications on 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)
- “CPU performance evolution” CMS-DP/2023-063
- “Test-beam validation results” CMS-DP/2023-064

FullSim CPU Performance

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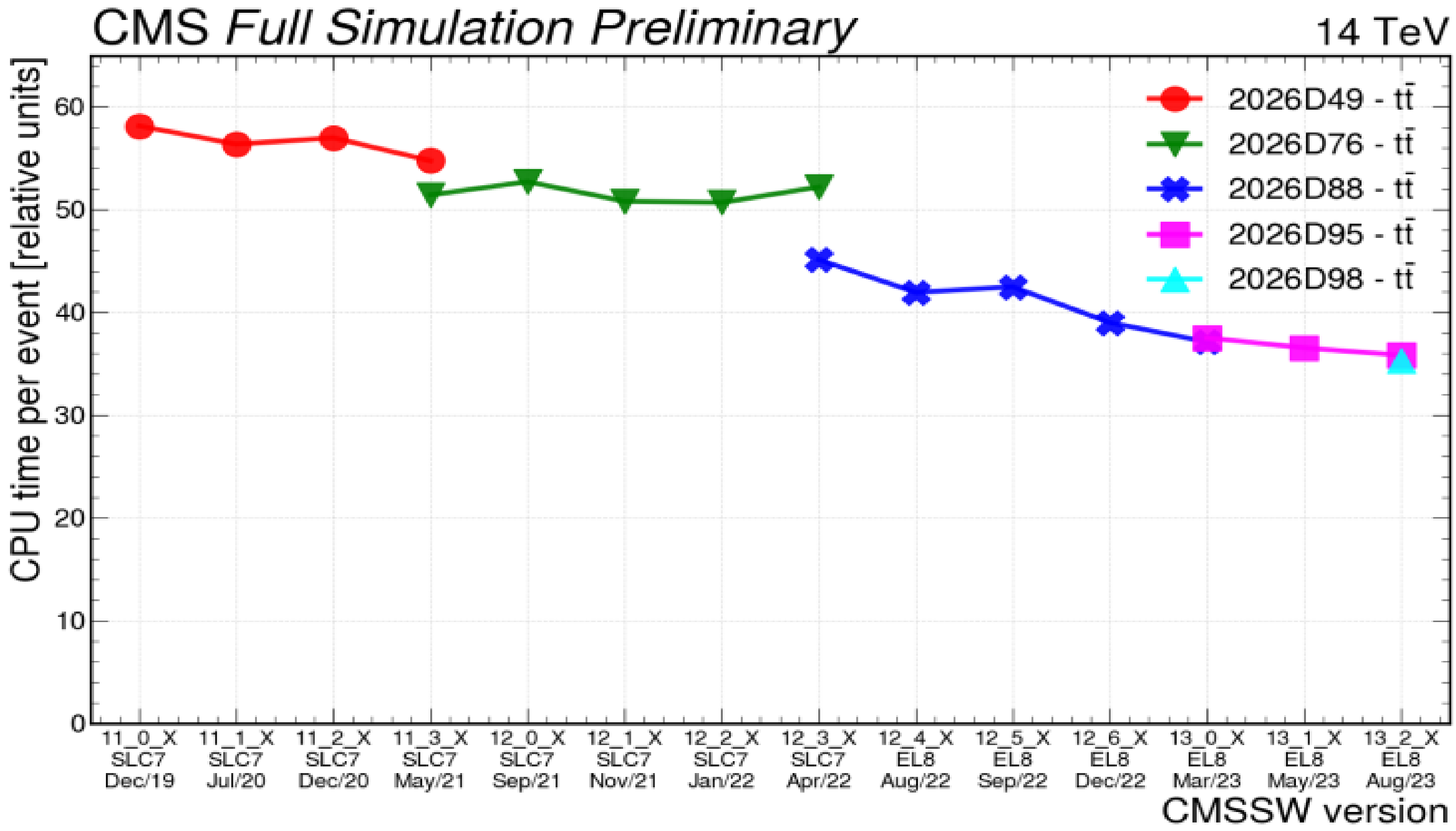
FullSim Phase-2 CPU time Performance History plots, 1 thread, SIM step



CPU time: 13_2_X compared to 11_0_X: 39% faster

Phase-2 software efficiency is the challenge for all CMS software

The monitoring is established by SIM group for Run-3 and Phase-2 simulation performance

For effective simulation it is essential to use latest software platforms, external packages including Geant4

Speed-up for Run-3 and Phase-2 with Geant4 11.1

- Significant speed-up comes from
  - Newer Geant4 version
  - Computing platform
  - LTO method to build executable
- New Geant4 features tested for Run-3
  - Fast parametrized low-energy e+, e- transport in ECAL – not adopted yet
  - Gamma general process – adopted for 2023 (~2 %)
  - Neutron general process – not adopted yet
  - Cut on gamma production below K-shell in photo-electric – adopted for 2023 (~1%)
  - G4TransportationWithMSC – adopted for 2024 (~1% for Run-3, ~20% for Phase-2)
  - Custom tracking managers – not adopted yet
  - G4HepEm external library – not adopted yet

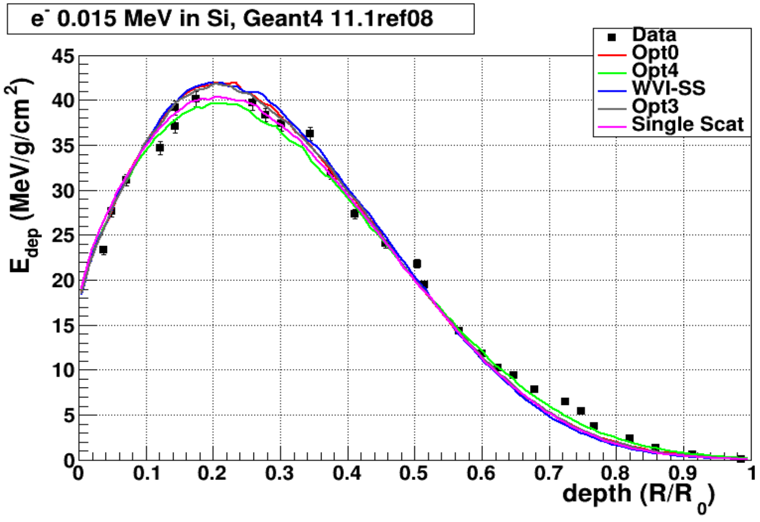
Geant4 Physics

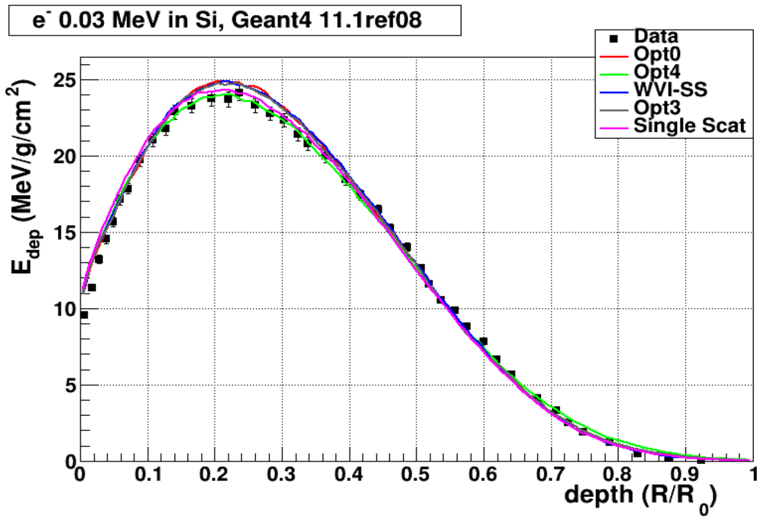
- Full potential for physics with MTD and HGCAL requires precise simulation
  - Efficiency of PF and particle ID will depend on accuracy of simulation
- Electromagnetic (EM) Physics
  - All type of particles
  - Time consuming because detailed simulation requires tracking of low-energy gamma, e+-
- Hadronic physics
  - Complex models required detailed validation
  - Tracking of low-energy neutrons is time consuming
  - HGCal is the first detector under construction, which will include also ability of reconstruction of vertices of hadron/nucleus interactions
- Transportation in non-uniform CMS field is also important component of simulation
  - Cannot be compromised for relativistic charged particles
- Geant4 team is working on improvements of accuracy and CPU performance
  - tools are under development allowing better control physics models versus experimental data
- For EM physics low-energy transport via boundaries between absorbers and sensitive layers determine both accuracy and CPU speed

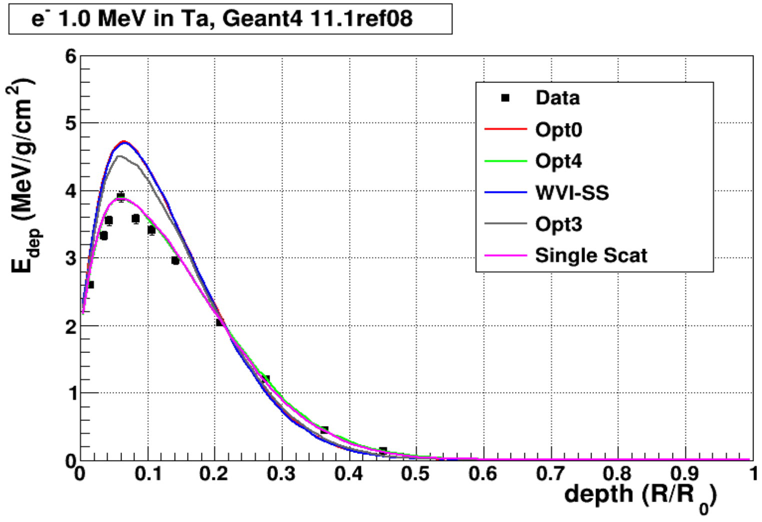
Electron dose profile in media and backscattering

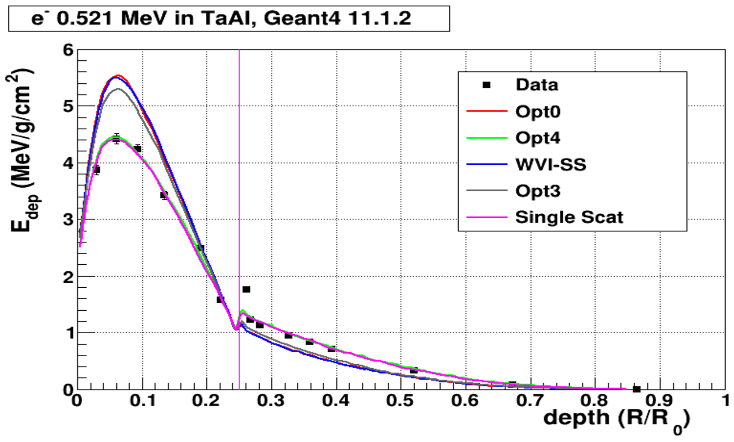
Geant4 11.1ref08 – the recent available in CMSSW

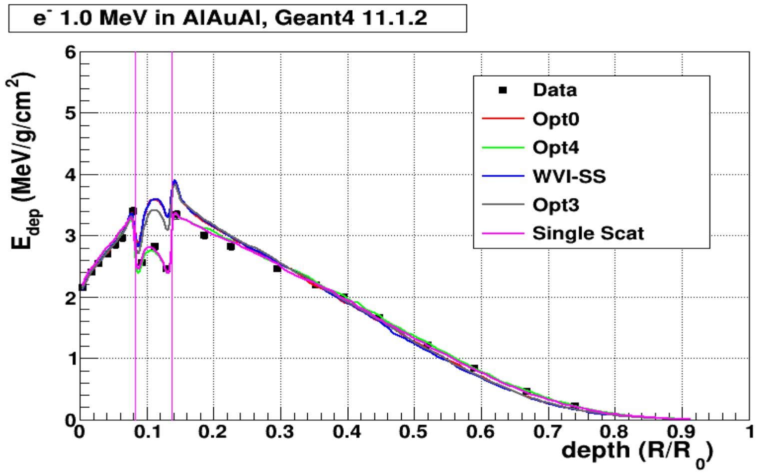
Geant4 benchmark

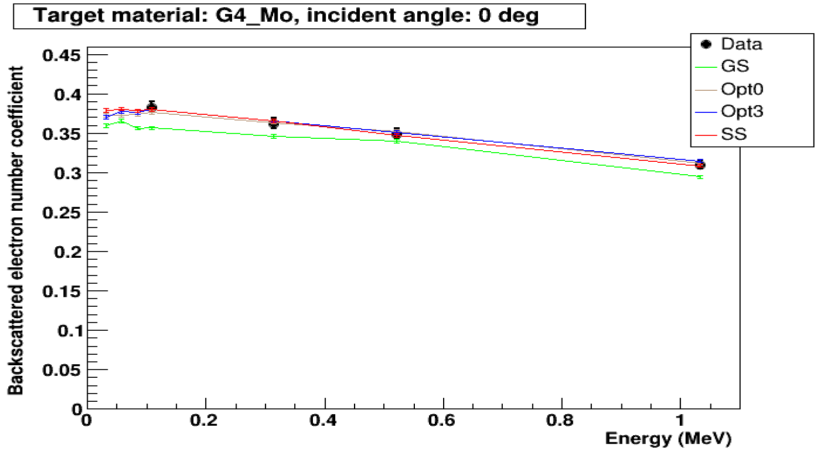






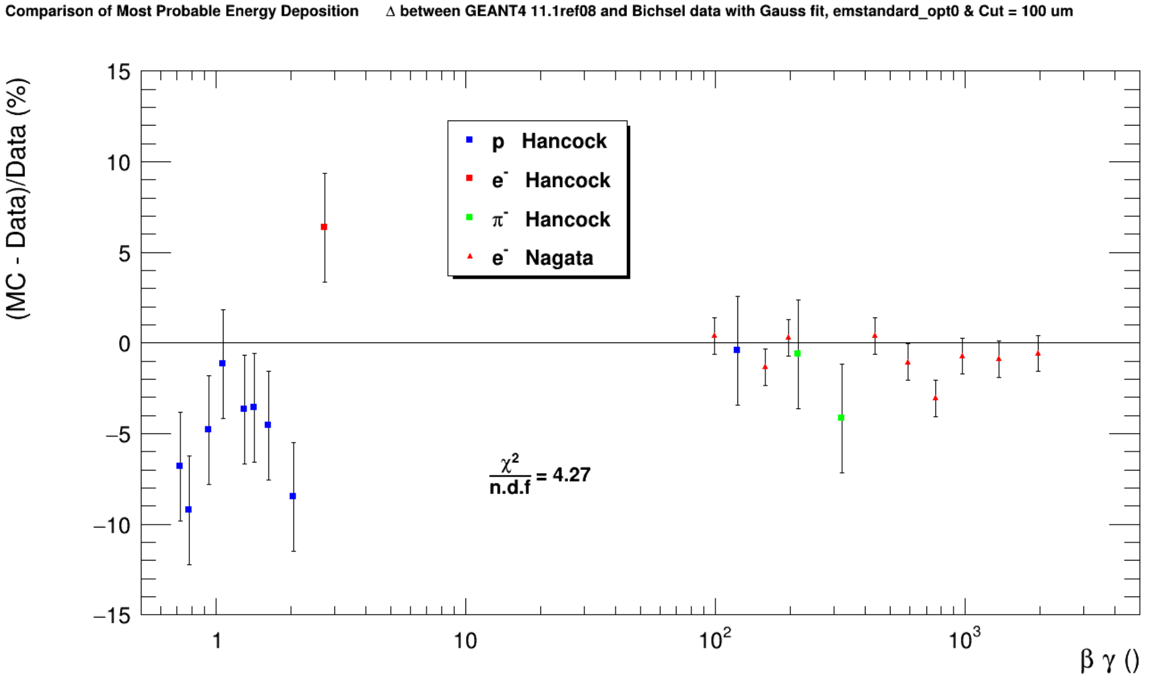


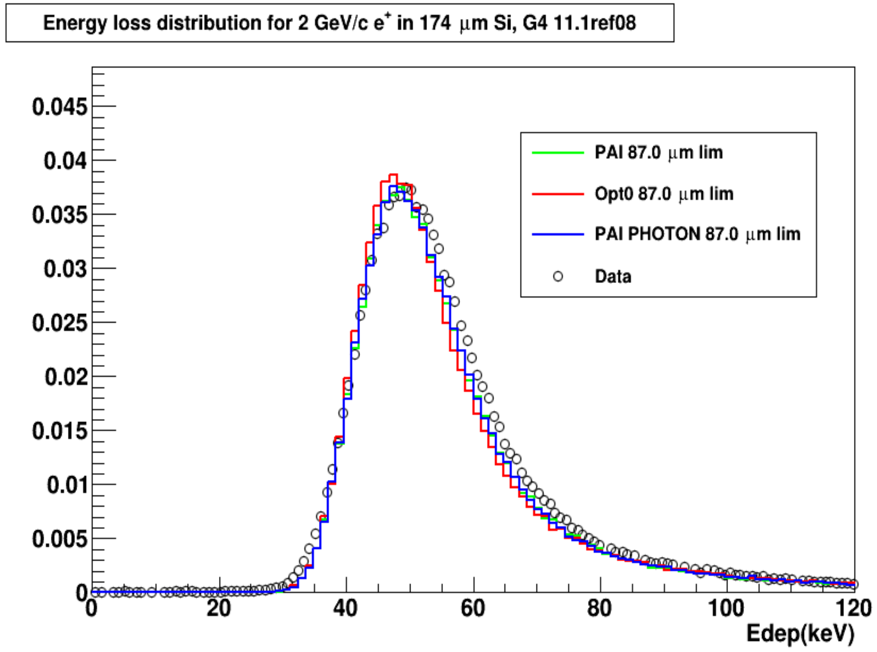




Energy resolution in thin Silicon layer

Geant4 11.1ref08 – the recent available in CMSSW
Geant4 benchmark



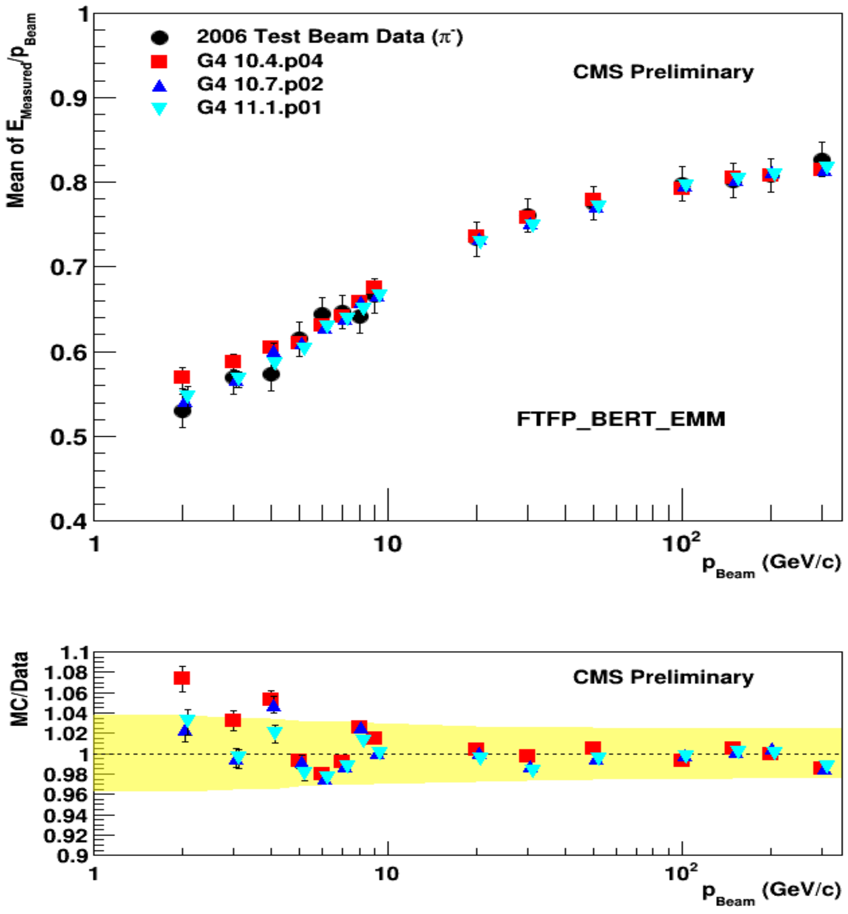


- Geant4 benchmarks for different projectile relativistic particles versus published data
- Default EM physics is shown, alternative models provide similar results

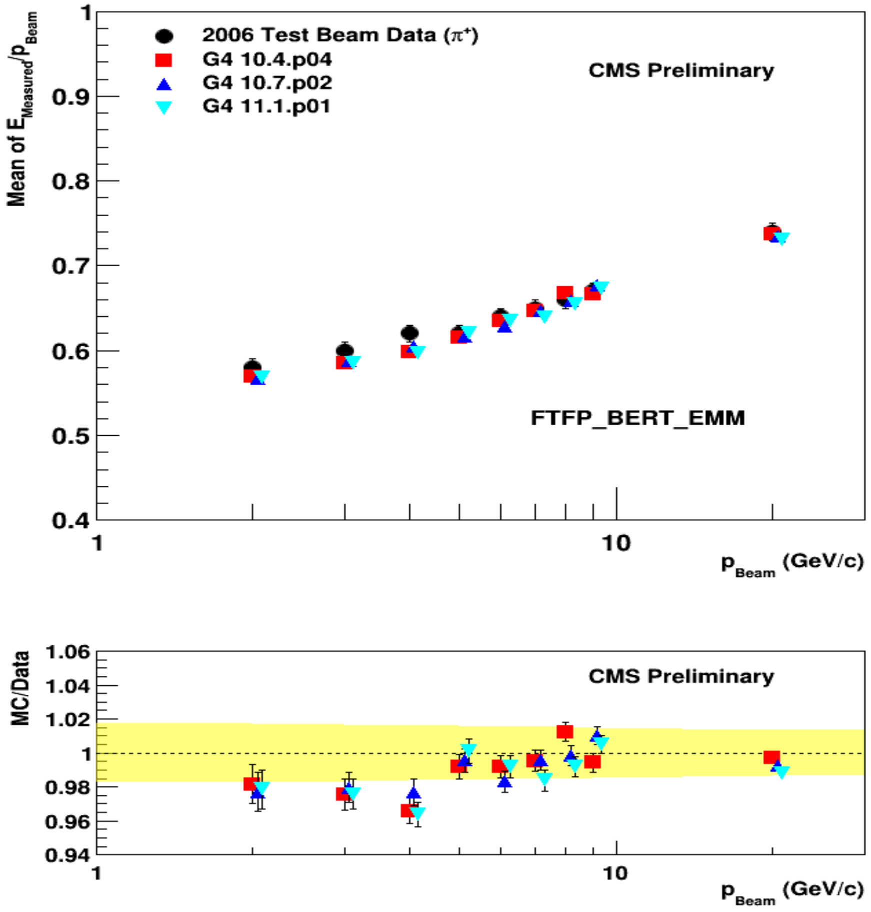
Comments on EM physics results

- Geant4 may provide high accuracy simulation of responses for fine grain calorimeter sells
  - The default EM setup provides non-accurate results
  - If Goudsmit-Saunderson (GS) model of multiple scattering (msc) is used the accuracy is high and is practically independent on cuts and other parameters
    - This is achieved, because single elastic scattering model is enabled near boundaries between different geometry volumes
    - CPU penalty due to usage of this model is factor 2-4
- Physics Lists used in CMSSW
  - FTFP_BERT_EMM – Run2 and Run-3 production, optimized for ECAL and HCAL, fine for other sub-detectors
  - FTFP_BERT_EMZ – Geant4 “the most accurate” EM physics (3-5 times slower)
  - FTFP_BERT_EMN – today recommended custom CMS combination of EM physics with GS msc (~2 times slower versus Run-3)
- Performance of hadronic physics for Run-3 is tested on regular base
  - For Run-2 and Run-3 “combined” 2006 test-beam is used
  - Also, comparisons with low pile-up run 2016 is performed

Mean response with pions (details in CMS-DP/2023-064)



(Top) The mean 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.



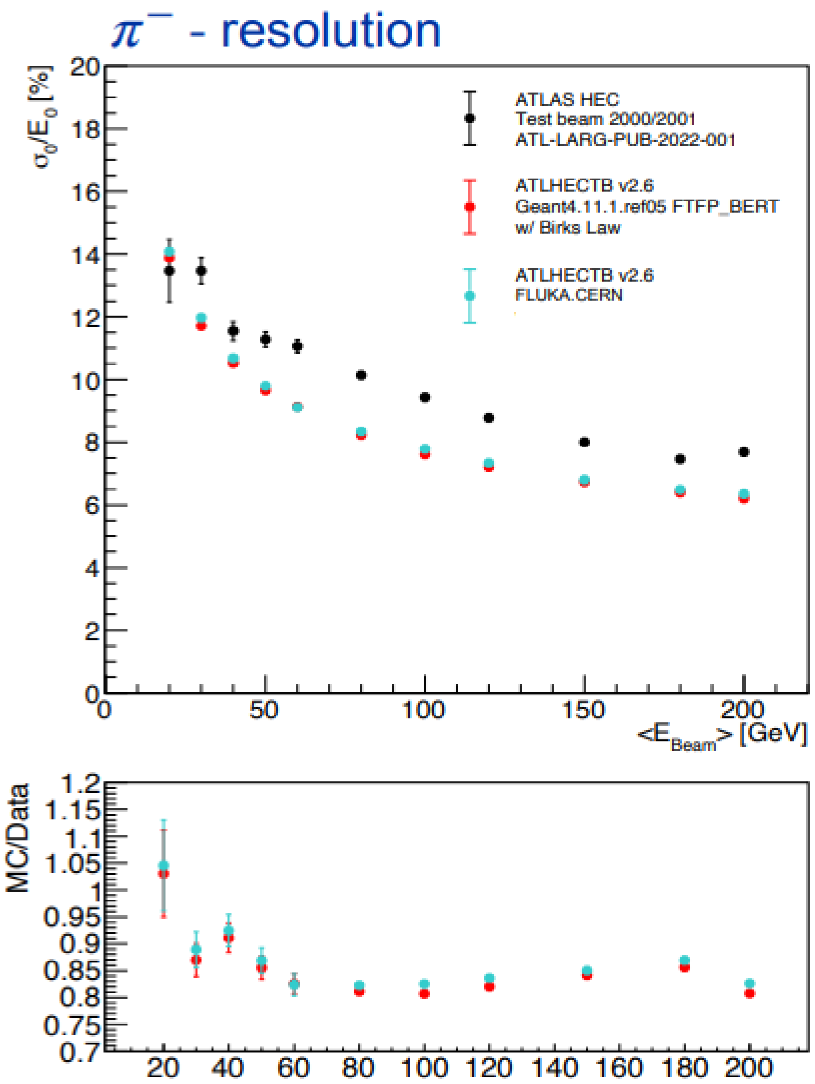
(Top) The mean response for positive pions as a function of momentum compared to MC predictions; (bottom) Ratio of MC to data for positive pions as a function of momentum. The yellow band shows one standard deviation of the data.

Hadronic physics validation

- For Run-3 the optimization of simulation was done since Geant4 10.6
  - FTFP_BERT_EMM Physics List was changed
  - Upper energy for the Bertini cascade for pions was extended from 6 to 12 GeV
  - Birks effect parameterization for HCAL scintillators were modified
- Validation for ATLAS hadronic calorimeters
  - Was not as successful for ATLAS as one for CMS
  - Currently it is the main problem for ATLAS to migrate to new Geant4
  - Potential alarm for HGCal

ATLAS HEC resolution

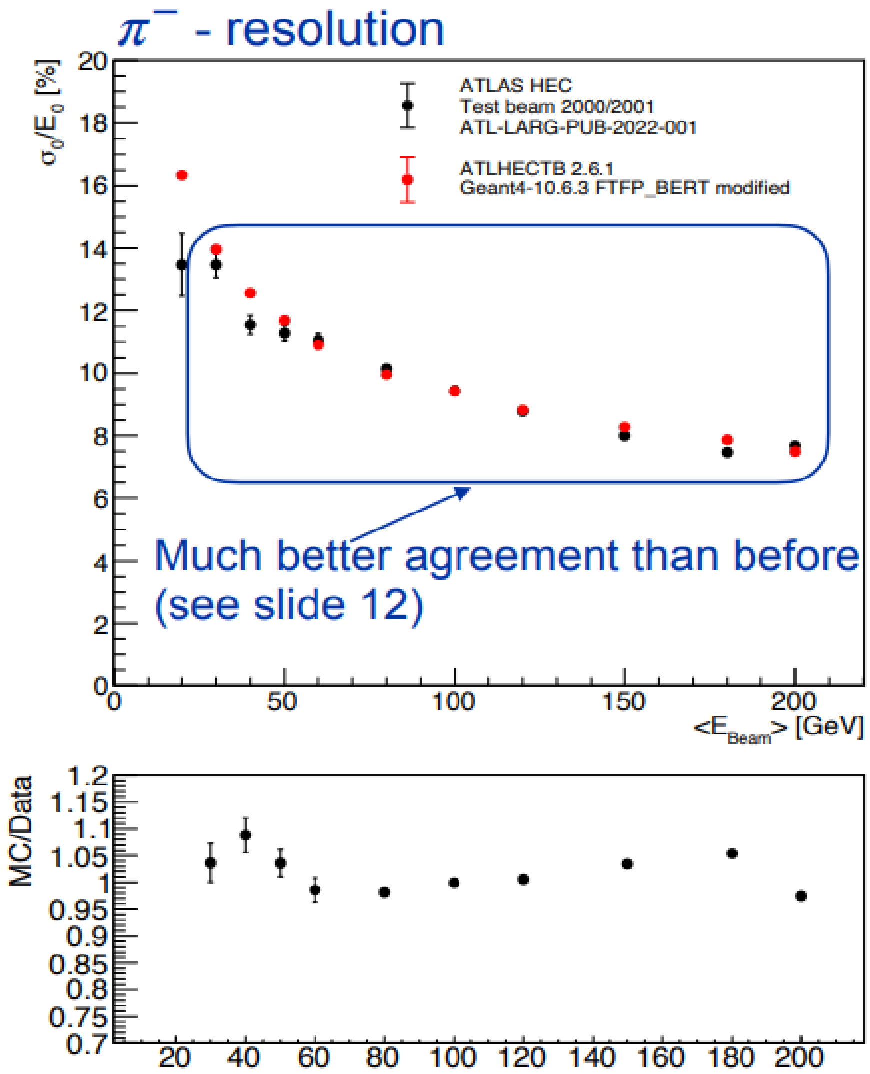
- σ/E extracted from a gaussian fit of the energy distributions
  - **ATLAS HEC** regression testing:
    - Geant4.10.4 (2017) was found to be in good agreement with ATLAS data
    - A big drop in the hadronic signal fluctuations happened between Geant4 10.4 and 10.5 (2018). Stable since then
  - **ATLAS HEC** Geant4 vs. FLUKA.CERN:
    - Currently both Geant4 and FLUKA.CERN underestimate the HEC resolution by $\simeq 15\% - 20\,\%$
  - Similar results from the TileCal signal fluctuations



Lorenzo Pezzotti, et al. Validation of Geant4 physics via calorimeter test-beams. Geant4 annual workshop, Sept. 2023

Changing FTF parameters

- ATLAS moved from Geant4-10.1 to Geant4-10.6 for the Run3 MC campaign → we need to improve the (too) narrow signal fluctuations
- We tried to achieve it by changing the FTF parameters (`G4FTFParameters.cc`) affecting the charge-exchange string-formation process and the nuclear destruction
- These changes:
  - increase the probability of having a charge-exchange process during the string formation
  - increase the probability of involving a neighboring nucleon during the Reggeon cascade
  - increase the excitation energy per wounded nucleon
- These changes <u>only affect $\pi^{\pm}$-induced showers</u>
- We studied their effect on ATLAS calorimeters using Geant4-10.6.p03



Conclusions

- The evolution of the Geant4 toolkit and CMSSW demonstrate positive signals
  - Further progress both in accuracy and CPU performance is expected
- Accurate and fast CMS simulation may be achieved
  - Optimization of configuration of EM physics
  - Introduction of new EM features
  - Optimisation of hadronic physics configuration
- Permanent monitoring of simulation for new detectors is required
  - To realize full potential of HGCal it is needed to establish systematic control
  - Test beam 2018 is a good candidate – it is needed to make it robust

Plans for Phase-2 for 2024

- Provide main geometry variants with DD4Hep
  - See S. Banerjee talk
- Finalize Geant4 UserActions and MC truth handling for Phase-2
  - Development for Phase-2 should not affect Run-3
- Optimise physics configuration for Phase-2 for Geant4 11.1
  - G4HepEm is a promising option
  - Physics List for Phase-2 may be improved
- Robust benchmark with 2018 test-beam should be established
  - It should be used to control EM and hadronic physics of Geant4
- Continue R&D to use GPU for simulation
  - Two parallel projects: Celeritas (LBNL, ORNL, FNAL) and AdePT (CERN)
  - Prototype should be available for the end of 2024

GPU based simulation within CMSSW

- GPU may be used effectively if similar operations are performed simultaneously
  - Should be applied to frequently produced particles
  - Many steps make also gamma, e+, and neutrons
  - Other particles make significantly smaller number of steps
  - In current GPU physics prototypes only low-energy e+, e-, gamma physics is implemented
- In implementation of CMS simulation should be switch between CPU and GPU on level of tracks
  - In OscarMTProducer there is an access to CMS custom TrackManager
    - Hadronic interactions and high energy electromagnetic interactions should be performed at CPU
    - Hits produced by CPU and GPU should be the same
  - It is may be implemented in alternative SIM Producer used only for Phase-2
    - A significant part of components used for Run-3 should be reused