CMS Detector Simulation Input to European Strategy for Particle Physics Update

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on behalf of the CMS Collaboration

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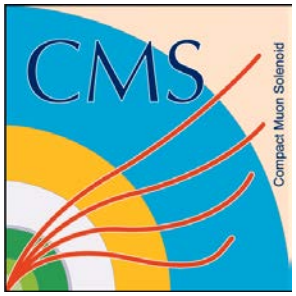
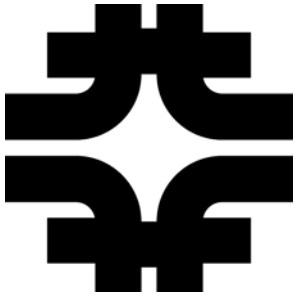
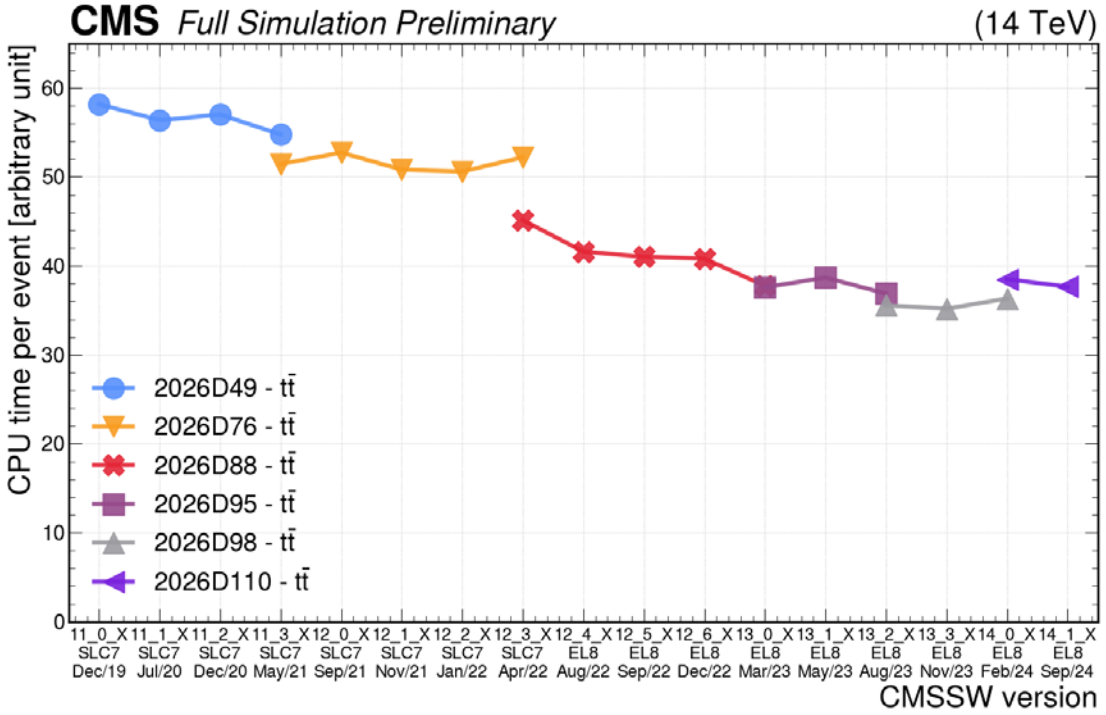




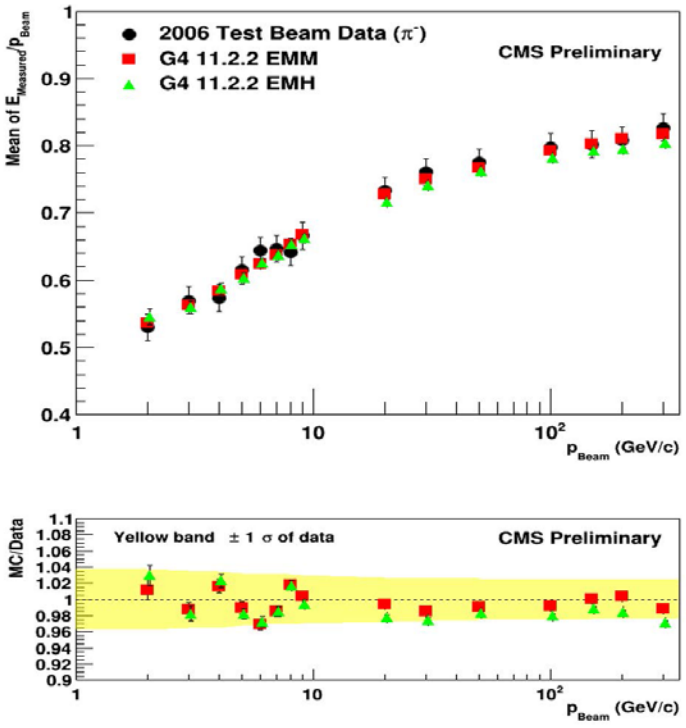
Status of CMS Simulation

- Run 2: CMS $t\bar{t}$ simulation ~3× faster than Geant4 default from technical improvements & physics-preserving approximations
- Run 3: continued improvements from:
  - Geant4 upgrades
  - Geometry updates
  - Operating system update
  - Link-time optimization

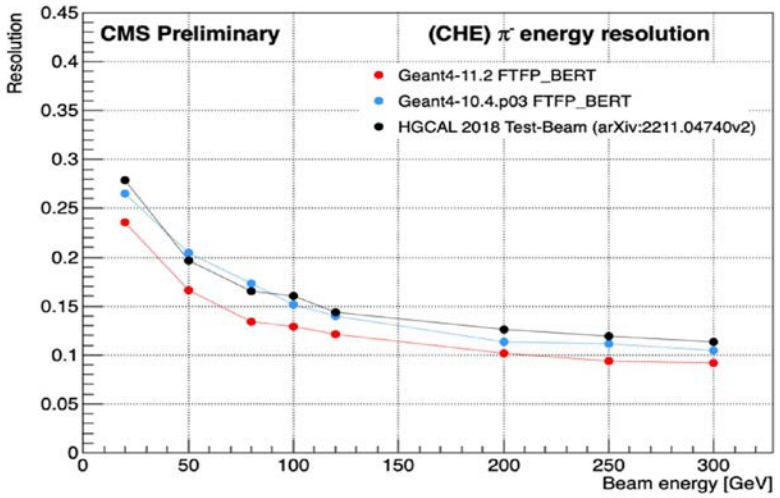


New Validations

- G4HepEM library integrated into FTFP_BERT_EMH physics list
  - Very good agreement with existing physics list (improvements to come)



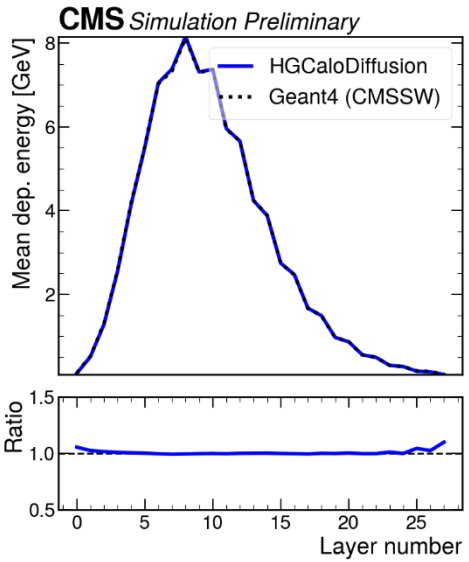
- HGCal test beam: validate geometry and physics of prototype for new detector
  - Data now available in Geant-val database
  - Known discrepancy in hadronic physics (also seen by ATLAS)
    - Ongoing work to improve

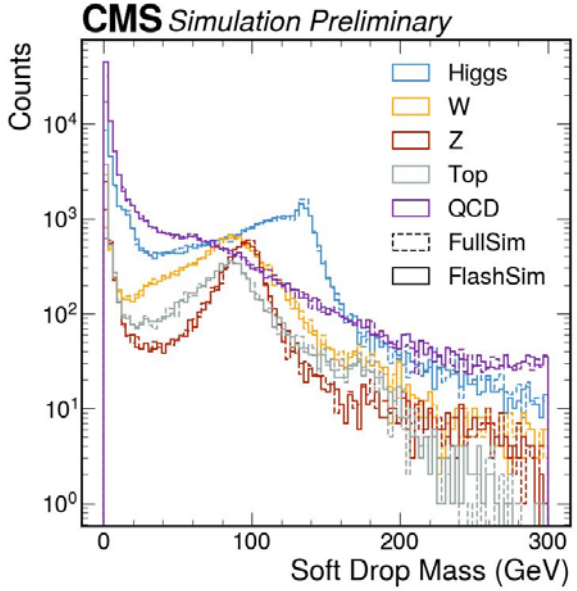


ML in CMS Simulation

HGCaloDiffusion: denoising diffusion model to generate HGCal simulated hits

- Excellent modeling of global quantities
- Ongoing work to improve geometry adaptation (sparsity)



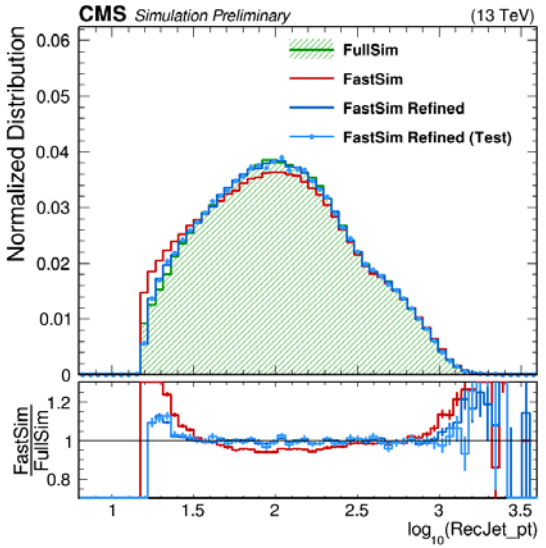


FlashSim: continuous normalizing flow for end-to-end simulation (generator particles → analysis variables)

- Excellent modeling even of complicated jet substructure (also correlations, derived quantities)
- 10–100 Hz (CPU); up to 1 kHz (GPU)

FastSim Refinement: replace manual correction factors with automatic ML adjustments

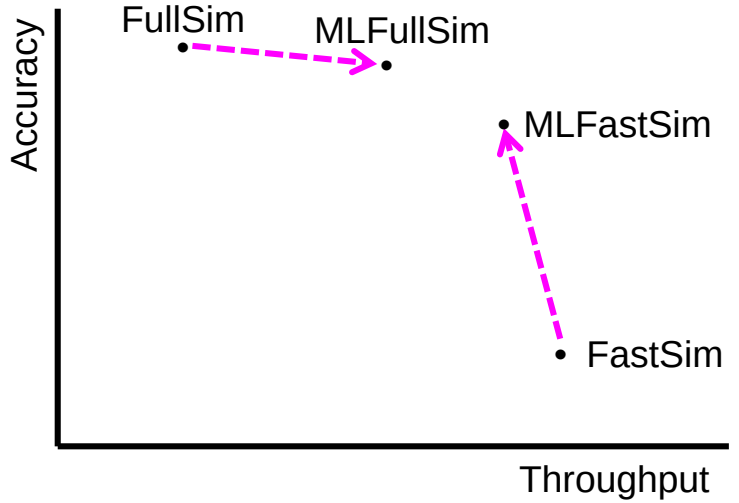
- Now extended to jet p_T (also models correlations)
- Ongoing work to refine more variables



HL-LHC Plans

1. Continue to benefit from upstream improvements in Geant4
2. Further optimize CMS Geant4 application
3. Offload EM showers (potentially also neutrons) to GPU using Celeritas and/or AdePT/G4HepEM
4. Incremental FastSim accuracy improvements to increase usage
5. Further FastSim accuracy improvements using ML (refinement)
6. Generative ML model for HGCal simulation, offloaded to GPU
   - Either in FullSim or FastSim
7. Validate FlashSim for broader use; offload to GPUs
8. Optimize premixed pileup library on disk
   - Replace premixing with generative ML?
9. Offload DIGI step to GPUs

➢ Build on R&D (w/ first results already demonstrated in many cases) to increase simulation computing efficiency to meet HL-LHC computing challenges



Conclusions

- CMS constantly improves its simulation applications
  - Steady decrease in CPU usage during Runs 2 and 3
- Validation is essential to ensure physics quality
  - Already utilizing HGCal test beam data ahead of Run 4
- Numerous promising ML developments:
  - HGCaloDiffusion (& other generative models), FastSim Refinement, FlashSim
  - Each targeting complementary use cases
- HL-LHC plans:
  - Continue incremental improvements & optimization
  - Bring existing R&D into production: larger-scale usage of GPUs, ML
  - Reconsider digitization: uses more CPU than simulation at 200PU!
- The impacts of HL-LHC R&D will be assessed and projected in upcoming CMS Offline Software & Computing Conceptual Design Report

References

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