CMS Report

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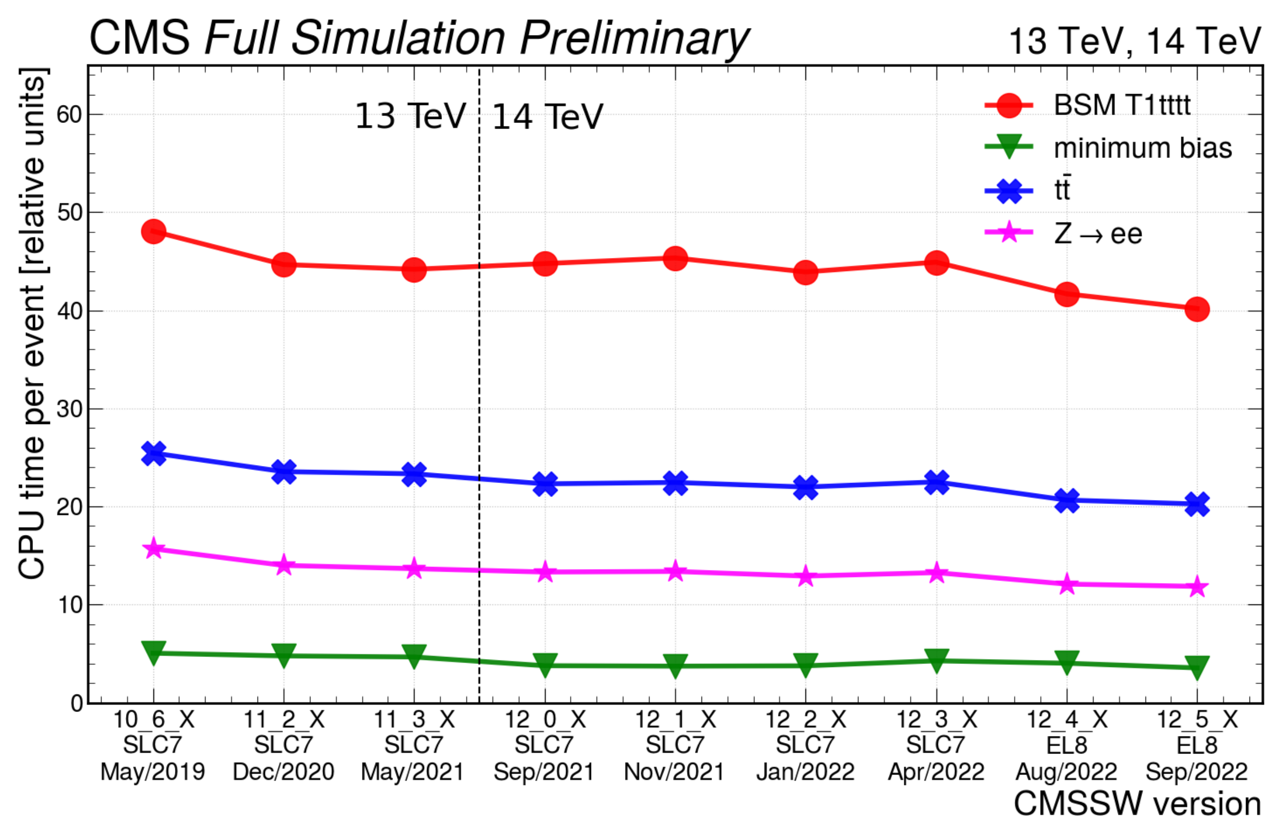
on behalf of
CMS Collaboration

Introduction

- CMS Simulation application is based on Geant4
  - CMS carried out its ultra-legacy MC production for Run2 data sets using Geant4.10.4.p03
    - VecGeom was used for the first time in these productions
  - CMS used intermittently Geant4.10.6.p02 before moving to its current version
  - CMS is using Geant4.10.7.p02 (+ some private patches) for the start of Run3 MC production. It uses [EPJ Web Conf. 251, 03016 (2021)]
    - The production platform is slc7_amd64_gcc10
    - VecGeom version 1.1.17
    - DD4hep version 1.19
    - CLHEP version 2.4.5.1
- CMS continually evaluates Geant4 developments and reports here the performance of the release version
- Starting from the Geant4.10.7.beta version, some of the reference releases of Geant4 are included in a dedicated git branch of CMSSW for detailed validation
- All problems incurred were reported to the Geant4 team

CMS Simulation in 2023

- CMS approach toward adopting a new version of Geant4
  - Integrate reference versions of Geant4 to special branches of CMSSW
  - Validate against test beam data and collision data with CMS detector
  - Check its CPU and memory performance
- Currently preparing a configuration with
  - el8_amd64_gcc11 as a production platform
  - Geant4 version 11.1
    - expect patch01 for final integration
  - DD4hep version 1.23
  - VecGeom version 1.21
  - CLHEP version 2.4.6.0
- Currently, the prepared simulation configuration is under official CMS validation



During the 3 years between the versions 10_6_X and 12_5_X, the CPU time has improved for the processes: minimum bias by 30%, t-tbar by 21%, BSM T1tttt by 17% and Z -> ee by 25%

CMS Physics List

- CMS is using the same physics list for ultra legacy as well as for the Run3 production
  - FTFP_BERT_EMM

- The list FTFP_BERT uses FTFP and Bertini Cascade models with slightly different transition regions in the two versions. For version Geant4,10.4.p03 (Run2):
    - Bertini Cascade valid at ≤ 12 GeV
    - FTFP valid at ≥ 3 GeV

  and in versions Geant4.10.6.p02, Geant4.10.7.p02 and Geant4.11.1 (Run3):
    - Bertini Cascade valid at ≤ 12 GeV for pions and ≤ 6 GeV for all other hadrons
    - FTFP valid at ≥ 3 GeV

- EMM specifies the physics models for electromagnetic processes
  - EMM uses the default multiple scattering models for regions of the sampling calorimeters (HCAL and HGCAL) and simplified multiple scattering models elsewhere

- Coefficients of Birk's law for plastic scintillators are tuned for the new versions of Geant4
- Default values for Birk's constants for HCAL in Run2:
    - C1 = 0.0052; C2 = 0.142; C3 = 1.75
  - The tuned set for Run3:
    - C1 = 0.006; C2 = 0.142; C3 = 1.75

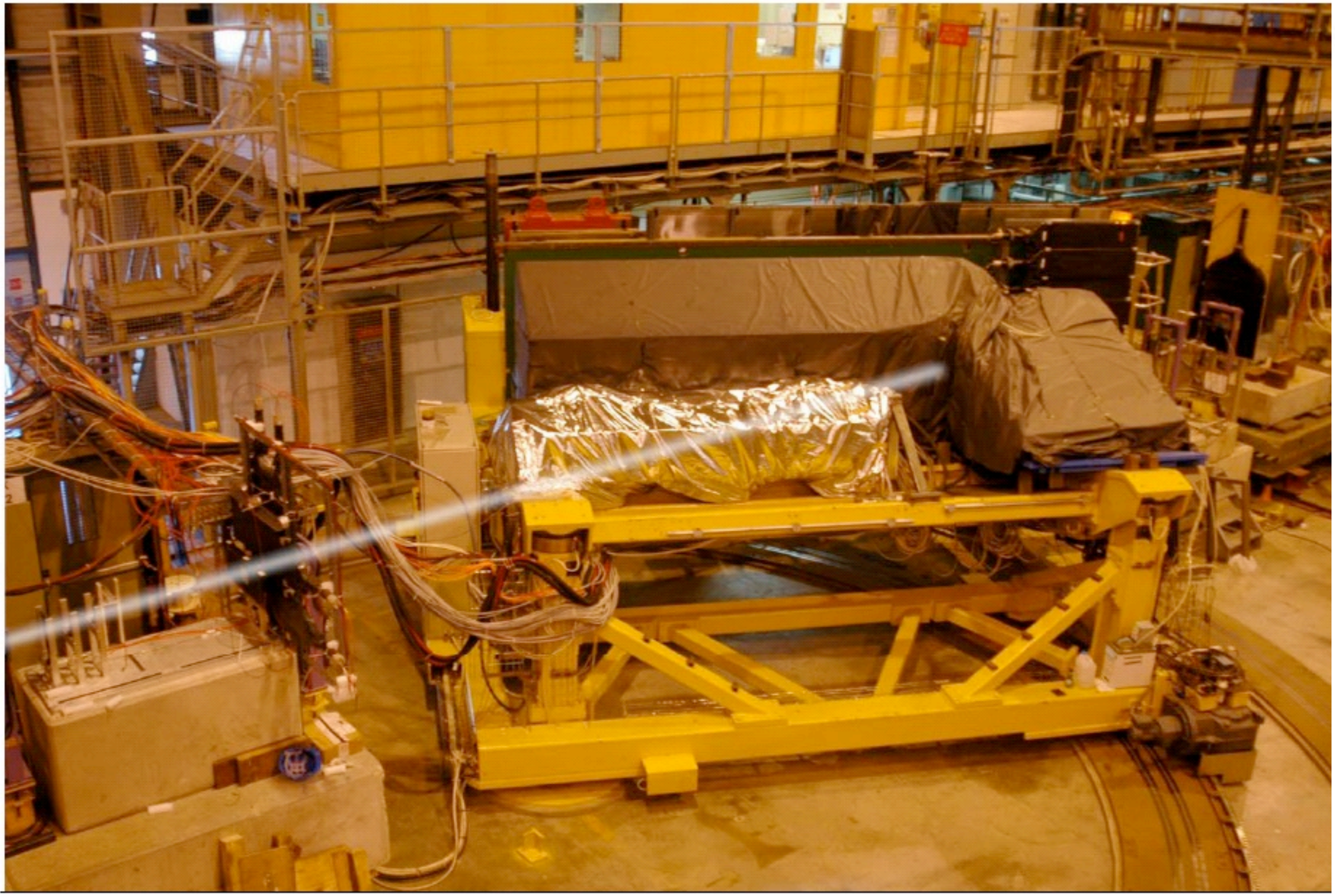
Testing Geant4.11.1

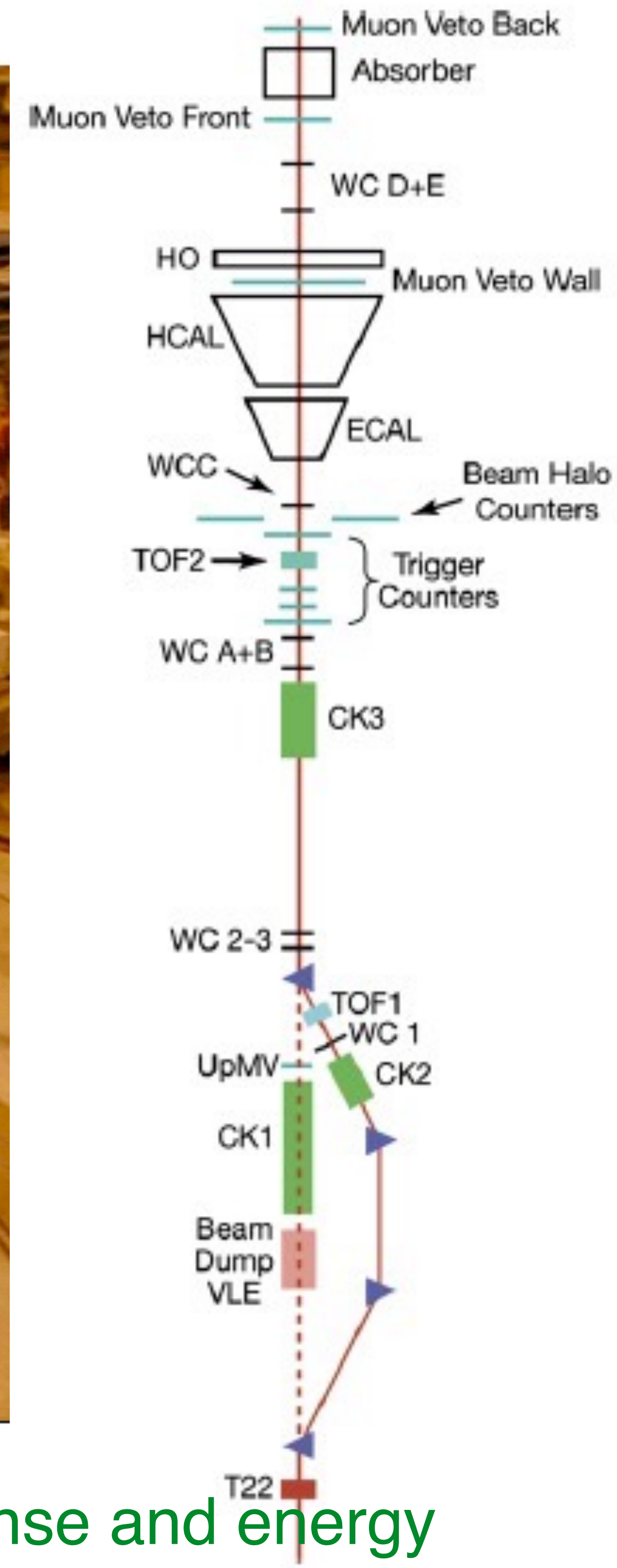
- Several test jobs were prepared with two different scenarios of CMS corresponding to the Run3 and one Phase2 configuration and for two different builds of Geant4 (native and VecGeom geometry). Two sources of inputs (minimum bias and t-tbar) and five different physics lists (changing the EM options) are used. Each job generated 500-1000 events.

- There were no failures, but two types of warnings were observed
  - Tracks getting killed because track propagation could not move these tracks even with 10 trials
    - For tracks of energy above 15 MeV, a total of 30 such cases were reported
    - 18(12) of them were for Run3(Phase2) scenarios
    - These are all electrons and positrons of energy between 15 and 30 MeV
    - 28(2) of these tracks were travelling in vacuum(air) media
    - 25/2/1 tracks killed in the vacuum were in forward beam-pipe/central beam-pipe/magnet coil
    - The 2 killed tracks in the air were for the phase2 scenario and were between the tracker and the calorimeter sections
  - Tracks reaching the maximum number of steps set by CMS (20000)
    - 10 such cases were reported

- The first case was reported to the Geant4 team and they have already provided a patch (which will be tested by CMS). The second case can be handled within CMSSW.

CMS 2006 TestBeam





- This test beam setup provided measurements of energy response and energy resolution for pi-plus, kaons of either charge, antiprotons of momenta between 2 and 9 GeV, pi-minus of momenta between 2 and 300 GeV and protons of momenta between 2 and 350 GeV

Summary from Mean Response

χ^2/d.o.f. between data and Monte Carlo

	negative pions	positive pions	negative kaons	positive kaons	protons	anti-protons
G4 10.4.p03 FTFP_BERT_EMM	0.54	0.96	24.5	25.0	0.61	1.93
G4 10.6.p02 FTFP_BERT_EMM	0.26	1.29	19.4	15.8	0.73	2.19
G4.10.7.p02 FTFP_BERT_EMM	0.30	0.77	18.9	15.1	0.61	3.46
G4.11.1 FTFP_BERT_EMM	0.22	1.20	15.8	20.6	0.52	2.89

- The level of agreement is good for pions and protons, while it is not good for kaons. Response for pions and kaons are very similar in the data but not in MC.
- The predictions from 11.1 show some improvement for negative pions and kaons, some deterioration for positive pions and kaons, and acceptable agreement for protons and anti-protons.
- pp collisions at high energies produce mostly pions. So one expects to have a reasonable agreement between data and MC with the current physics list in the Geant4 version 10.6.p02, 10.7.p02 and 11.1

Isolated Charged Particles

- Compare ratio of calorimeter energy measurement to track momentum for isolated charged hadrons between data and MC

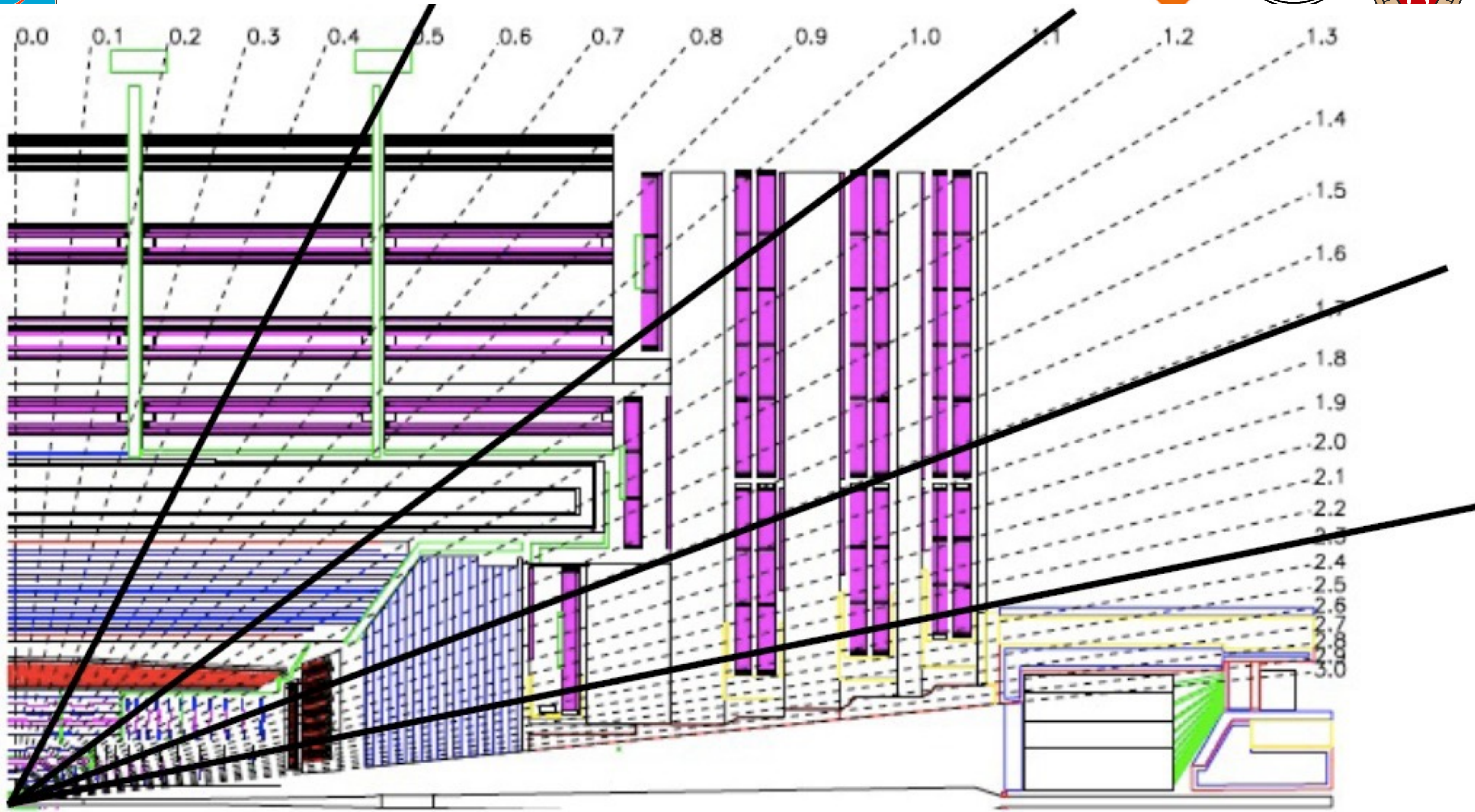
- Select good charged tracks reaching the calorimeter surface

- Impose isolation of these charged particles
  - propagate all tracks to the calorimeter surface and study momentum of tracks (selected with looser criteria) reaching ECAL (HCAL) within a matrix of 31x31 (7x7) around the impact point of the selected track. Demand no other track in the isolation region.
  - study energy deposited in an annular region in ECAL (HCAL) between 15x15 and 11x11 (7x7 and 5x5) matrices for neutral isolation. Demand energy in either annular region to be less than 2 GeV

- Measure the energy in a matrix of NxN cells around the point of impact. Two versions of NxN matrix are defined for ECAL and HCAL
  - ECAL uses 7x7 or 11x11 matrix
  - HCAL uses 3x3 or 5x5 matrix

- The methodology was developed using 7 TeV data (PAS: JME-10-008) and analysis of the 2016 low pileup data plus the comparisons with earlier Geant4 model predictions were presented in earlier CHEP conferences.

Quadrant of the CMS



Four partitions in the CMS detector are used in the measurement of calorimeter response

Level of Disagreement

- The level of (dis)agreement is calculated from the deviation from 1.0 of the ratio (Data/MC)
- The mean level of disagreement between data and MC is between 1.2% and 3.6% for Geant4.11.1, depending on the region of the detector. They are at a similar level to the predictions from version 10.4.p03, 10.6.p02 and 10.7.p02

	$(E_{7x7}+H_{3x3})/p$ 10.4.p03	$(E_{7x7}+H_{3x3})/p$ 10.6.p02	$(E_{7x7}+H_{3x3})/p$ 10.7.p02	$(E_{7x7}+H_{3x3})/p$ 11.1	$(E_{11x11}+H_{5x5})/p$ 10.4.p03	$(E_{11x11}+H_{5x5})/p$ 10.6.p02	$(E_{11x11}+H_{5x5})/p$ 10.7.p02	$(E_{11x11}+H_{5x5})/p$ 11.1
Barrel 1	(2.3±0.4)%	(2.5±0.4)%	(3.3±0.4)%	(1.4±0.4)%	(2.7±0.4)%	(2.6±0.4)%	(3.4±0.4)%	(1.4±0.4)%
Barrel 2	(3.1±0.4)%	(1.0±0.4)%	(1.6±0.4)%	(2.0±0.4)%	(2.1±0.4)%	(0.9±0.4)%	(1.3±0.4)%	(1.5±0.4)%
Transiti on	(6.5±0.5)%	(1.3±0.5)%	(3.1±0.5)%	(3.6±0.5)%	(4.7±0.5)%	(1.2±0.5)%	(1.4±0.5)%	(2.7±0.5)%
Endcap	(5.8±0.5)%	(3.0±0.5)%	(3.0±0.5)%	(1.2±0.5)%	(5.3±0.5)%	(1.9±0.5)%	(2.2±0.5)%	(1.7±0.5)%

Level of Disagreement

- Level of (dis)agreement is calculated also for the physics list QGSP_FTFP_BERT_EML. The two physics lists provide similar level of agreement

	$(E_{7x7}+H_{3x3})/p$ 10.4.p03	$(E_{7x7}+H_{3x3})/p$ 10.6.p02	$(E_{7x7}+H_{3x3})/p$ 10.7.p02	$(E_{7x7}+H_{3x3})/p$ 11.1	$(E_{11x11}+H_{5x5})/p$ 10.4.p03	$(E_{11x11}+H_{5x5})/p$ 10.6.p02	$(E_{11x11}+H_{5x5})/p$ 10.7.p02	$(E_{11x11}+H_{5x5})/p$ 11.1
Barrel 1	(1.6±0.4)%	(2.6±0.4)%	(2.5±0.4)%	(1.6±0.4)%	(2.1±0.4)%	(2.5±0.4)%	(2.7±0.4)%	(1.6±0.4)%
Barrel 2	(4.1±0.4)%	(0.9±0.4)%	(1.5±0.4)%	(2.1±0.4)%	(2.8±0.4)%	(0.6±0.4)%	(1.1±0.4)%	(1.5±0.4)%
Transition	(4.9±0.5)%	(2.5±0.5)%	(2.7±0.5)%	(3.9±0.5)%	(2.9±0.5)%	(2.5±0.5)%	(2.2±0.5)%	(3.4±0.5)%
Endcap	(4.7±0.5)%	(2.3±0.5)%	(1.9±0.5)%	(2.6±0.5)%	(4.0±0.5)%	(4.0±0.5)%	(2.4±0.5)%	(2.6±0.5)%

	$(E_{7x7}+H_{3x3})/p$ 11.1(FTFP)	$(E_{7x7}+H_{3x3})/p$ 11.1(QGSP)	$(E_{11x11}+H_{5x5})/p$ 11.1(FTFP)	$(E_{11x11}+H_{5x5})/p$ 11.1(QGSP)
Barrel 1	(1.4±0.4)%	(1.6±0.4)%	(1.4±0.4)%	(1.6±0.4)%
Barrel 2	(2.0±0.4)%	(2.1±0.4)%	(1.5±0.4)%	(1.5±0.4)%
Transition	(3.6±0.5)%	(3.9±0.5)%	(2.7±0.5)%	(3.4±0.5)%
Endcap	(1.2±0.5)%	(2.6±0.5)%	(1.7±0.5)%	(2.6±0.5)%

Summary

- CMS has been using Geant4 as the simulation tool for comparing data with predictions from known physics models
- Geant4 has evolved over time. For most of the Run2 physics studies, version 10.4.p03 was used. CMS has moved to 10.7.p02 for the first Run3 MC production and is planning to move to 11.1 for future Run3 studies
- Different Geant4 versions are tested by comparing their predictions with some controlled measurements of single particle response
- 2006 test beam data of combined CMS barrel calorimeter (prototype hadron calorimeter and electromagnetic calorimeter) and low luminosity collision data at $\sqrt{s}$ = 13 TeV are used for this comparison
- All 4 versions (10.4.p03, 10.6.p02, 10.7.p02 and 11.1) provide good agreement with the data.

Additional Slides

2006 TestBeam Data

- CMS collected data with a prototype of the Hadron Calorimeter Barrel and a supermodule of the barrel Electromagnetic Calorimeter in the H2 test beam area at CERN in 2006.
- Special action was taken to go to low energy hadron beam down to 1 GeV using a secondary target
- The analysis utilized particle identification using data from TOF counters and Cherenkov detectors up to an energy of 9 GeV
- The results consist of mean energy response (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, the energy resolution and some energy distributions for particles of a given type at a given momentum
- Results from this test beam were published in Eur. Phys. J. Web Conf. **214** (2019) 02012 and used in many comparisons presented in an earlier conference