R&D Adoption and Progress in Full Simulation of the CMS experiment

S. Banerjee [1], F. Cossutti [2], V. Ivantchenko [3], N. Krammer [4], M.S. Muzaffar [5], K. Pedro [6], L. Pezzotti [7], **P. Srimanobhas** [8]
on behalf of the CMS Collaboration

27th Conference on Computing in High Energy and Nuclear Physics
Kraków, Poland
Oct 21, 2024

[1] University of Wisconsin Madison
[2] Universita e INFN Trieste
[3] JINR
[4] Institut fuer Hochenergiephysik, Österreichischen Akademie der Wissenschaften
[5] CERN
[6] Fermi National Accelerator Laboratory
[7] Universita e INFN, Bologna
[8] Department of Physics, Faculty of Science, Chulalongkorn University

References

- D.J. Lange et al. (CMS), *Upgrades for the CMS simulation*, J. Phys.: Conf. Ser. 608, 012056 (2015)
- M. Hildreth et al. (CMS), *CMS Full Simulation for Run-2*, J. Phys.: Conf. Ser. 664, 072022 (2015)
- M. Hildreth et al. (CMS), *Upgrades for the CMS simulation*, J. Phys.: Conf. Series 898, 042040 (2017)
- V. Ivanchenko and S. Banerjee (CMS), Upgrade of CMS Full Simulation for Run 2, EPJ Web of Conferences 214, 02012 (2019)
- K. Pedro (CMS), *Current and Future Performance of the CMS Simulation*, EPJ Web of Conf. 214, 02036 (2019)
- C. Vuosalo et al. (CMS), *CMS Experience with Adoption of the Community supported DD4hep Toolkit*, EPJ Web of Conferences 245, 02032 (2020)
- V. Ivanchenko et al. (Geant4), *Geant4 electromagnetic physics progress*, EPJ Web of Conferences 245, 02009 (2020)
- K. Pedro (CMS), *Integration and Performance of New Technologies in the CMS Simulation*, EPJ Web of Conferences 245, 02020 (2020)
- V. Ivanchenko and S. Banerjee (CMS), *Validation of Physics Models of Geant4 Versions 10.4.p03, 10.6.p02 and 10.7.p01 using Data from the CMS Experiment*, EPJ Web of Conferences 251, 03010 (2021)
- V. Ivanchenko et al. (CMS), *CMS Full Simulation for Run 3*, EPJ Web of Conferences 251, 03016 (2021)
- S. R. Johnson et al., *Novel features and GPU performance analysis for EM particle transport in the Celeritas code*, EPJ Web of Conferences 251, 03030 (2021)
- P. Srimanobhas et al. (CMS), *Full Simulation of CMS for Run-3 and Phase-2*, EPJ Web of Conferences 295, 03017 (2024)

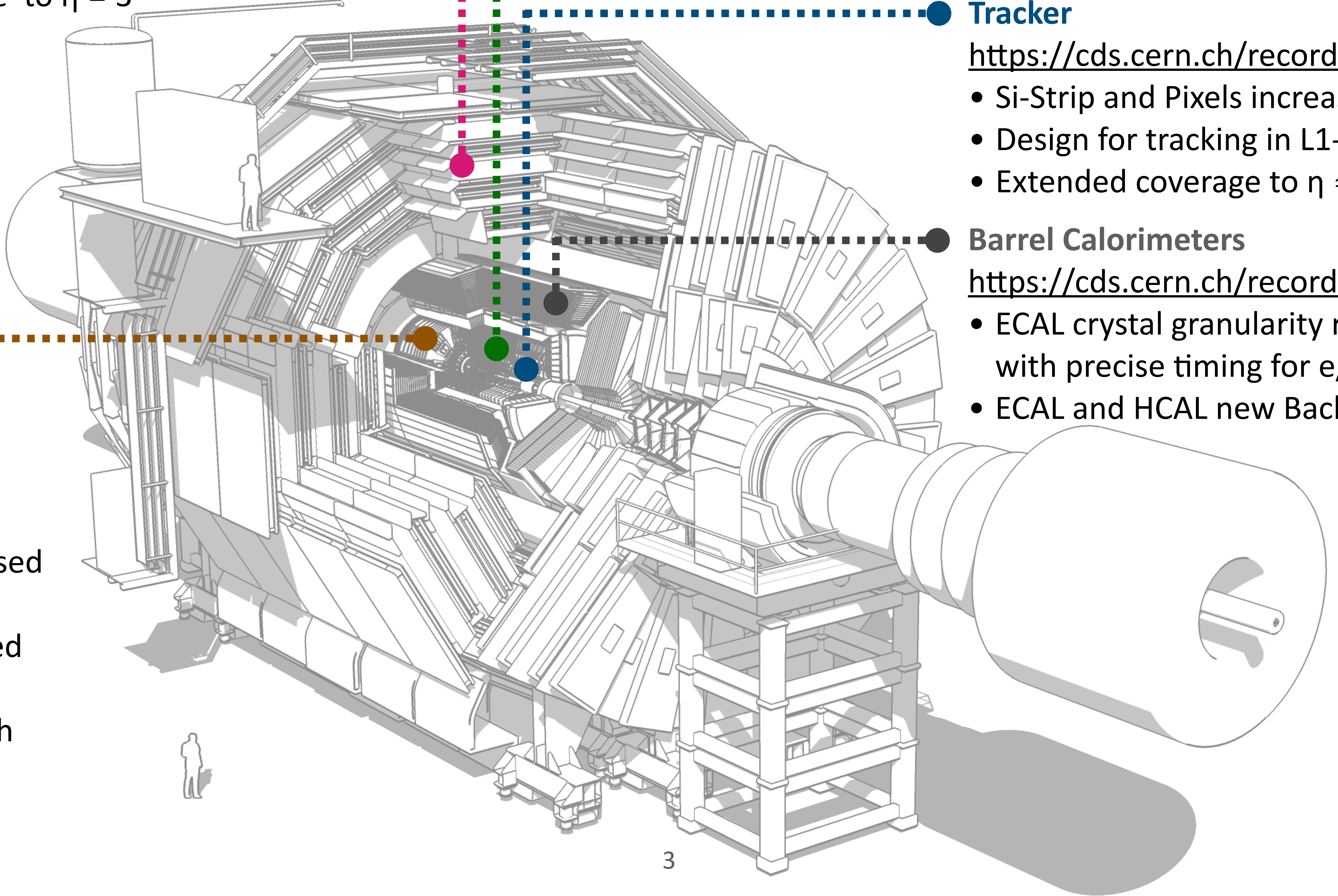
Phase 2 CMS Detector

Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

MIP Timing Detector
https://cds.cern.ch/record/2296612
Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

Tracker
https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards



Calorimeter Endcap
https://cds.cern.ch/record/2293646
- A silicon-sensor-based sampling calorimeter followed by plastic scintillator tiles with direct SiPM readout

Geometry description for Run-3 and Phase-2

	Materials	Solids	Logical Vol	Physical Vol.	Touchables	Regions
Run3	489	3905	4229	21779	2317018	30
Phase-2	686	15808	16007	68608	13134654	26

Run3 | Phase 2

	Standard	Reflected
Box	1208k | 1325k	434k | 429k
Tube	95.5k | 58.0k	1391 | 755
Trapezoid	240k | 158k	150k | 141k
Cone	1862 | 1862	0 | 0
Polycone	426 | 206	0 | 0
Polyhedra	1449 | 1572	0 | 0
ExtrudedPolygon	0 | 10845k	0 | 0
Torus	128 | 0	0 | 0
UnionSolid	175k | 614	0 | 0
SubtractionSolid	8325 | 173k	468 | 594
IntersectionSolid	0 | 360	0 | 0

Note:

- Counts are similar for the DDD and the DD4hep versions
  - Run 3: DD4hep
  - Phase 2: DDD + DD4hep
- The increase in the number of touchable is primarily due to the description of the HGCal

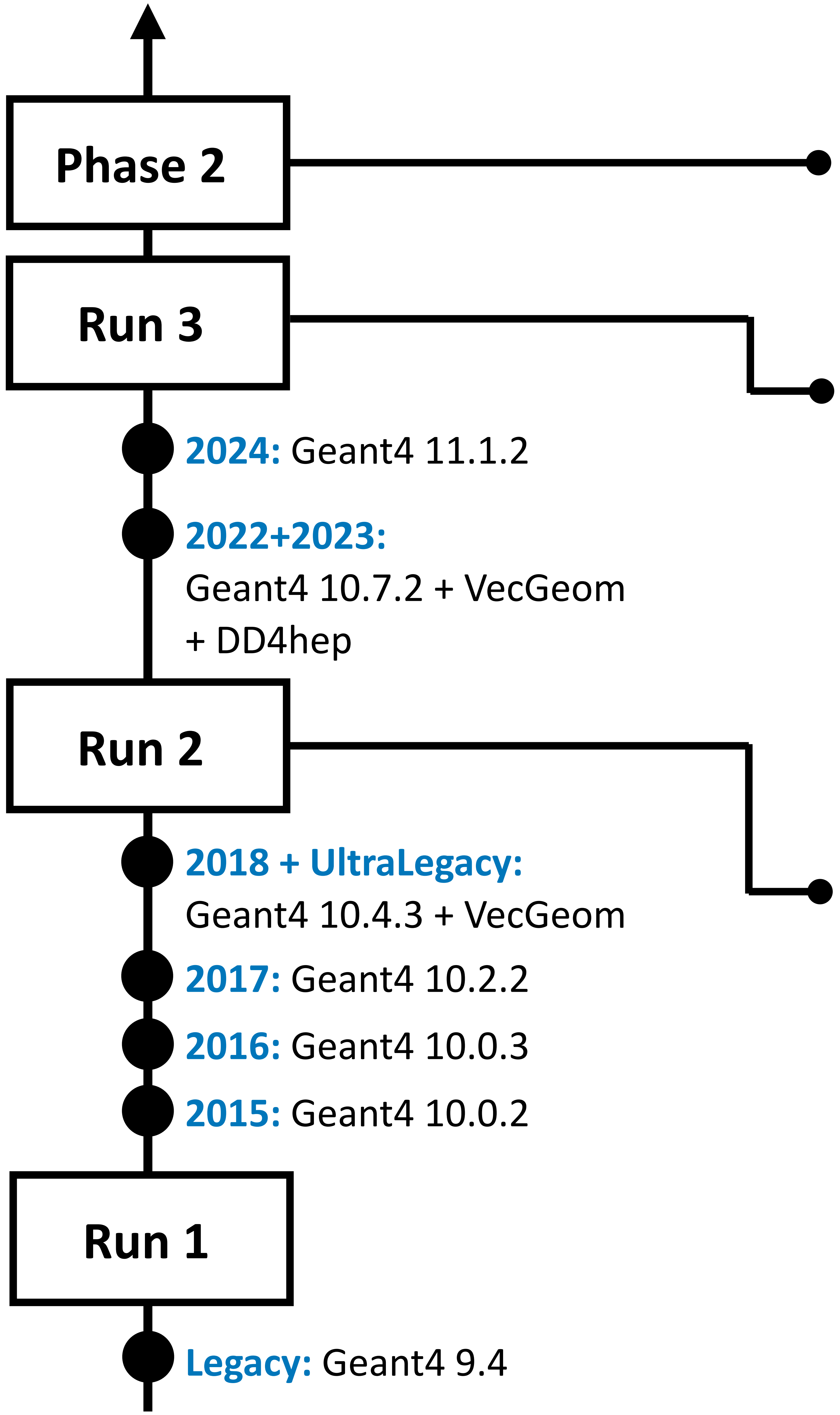
Geometry description for Run-3 and Phase-2: Overlap

	DDD				DD4hep			
	1.0	0.1	0.01	0.0	1.0	0.1	0.01	0.0
Run3	0	0	84	566	0	0	4	475
Phase 2	0	0	36	344	0	0	0	348

- The 36 overlaps in the DDD version of the Phase 2 geometry for a tolerance of 0.01 mm are all in ECAL barrel: precision lost in rotation of modules
- The additional overlaps in the Run 3 geometry are due to the description of the endcap pre-shower detector
- Most of the overlaps for tolerance of 0 mm come from the description of the return yoke
- Our plan to remove all overlap in DD4hep case

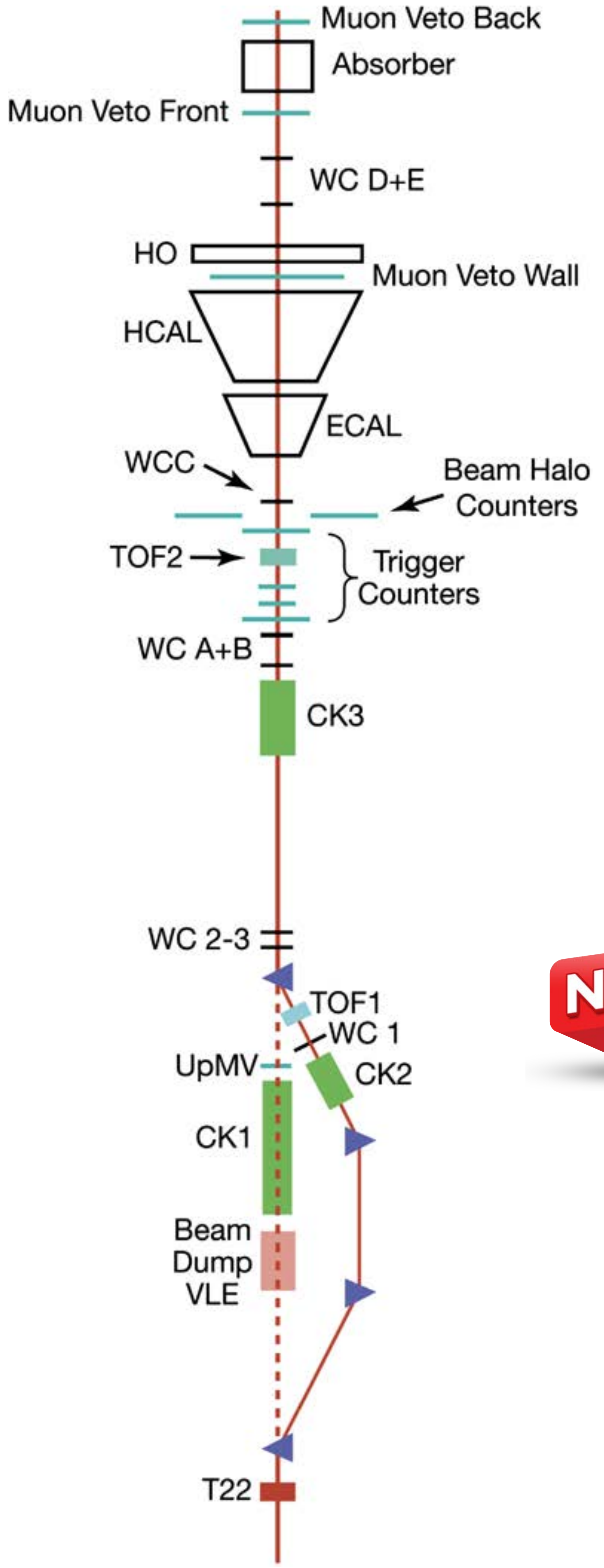
Geant4 versions with CMSSW

Timeline: Geant4 with CMSSW



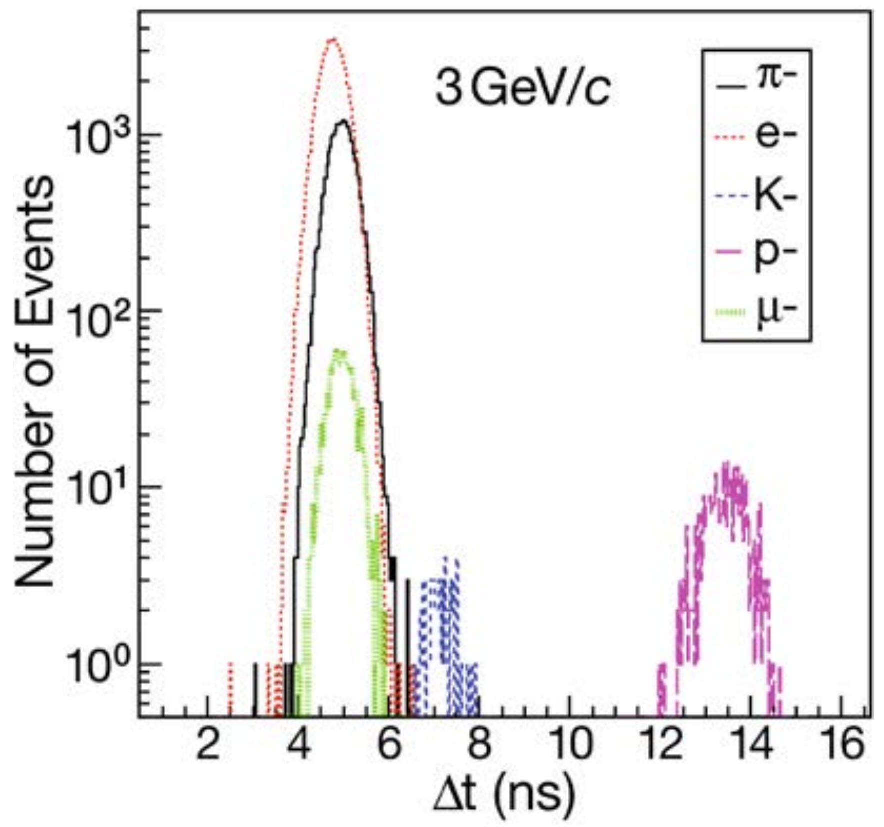
- **CMSSW_14_2 (Currently)**
  - Geant4 11.2.2
  - Test of G4HepEM (FTFP_BERT_EMH)
- **CMSSW_14_0 (pp) / CMSSW_14_1 (HI) for Run 3 2024**
  - Geant4 11.1.2 / 11.2.2
- **CMSSW_13_0 for Run 3 2023**
  - Gamma general process
  - Link Time Optimization (LTO) build
- **CMSSW_12_4 for Run 3 2022**
  - DD4hep geometry description
- **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

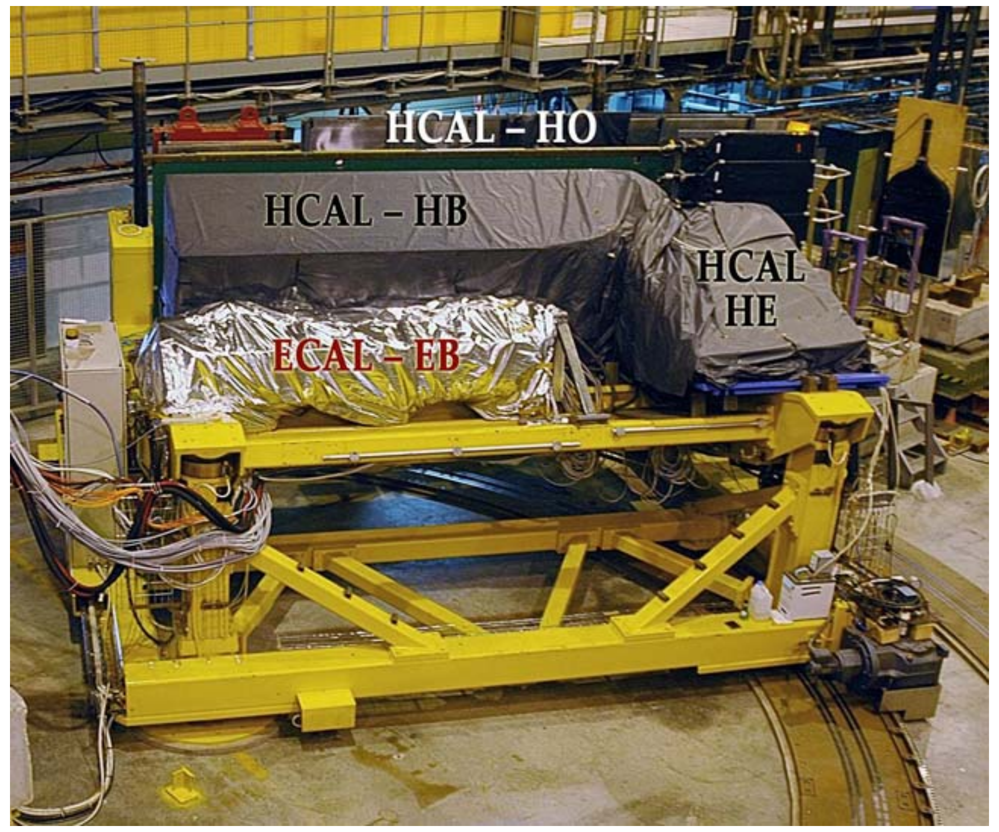
Migration of Geant4 under CMSSW

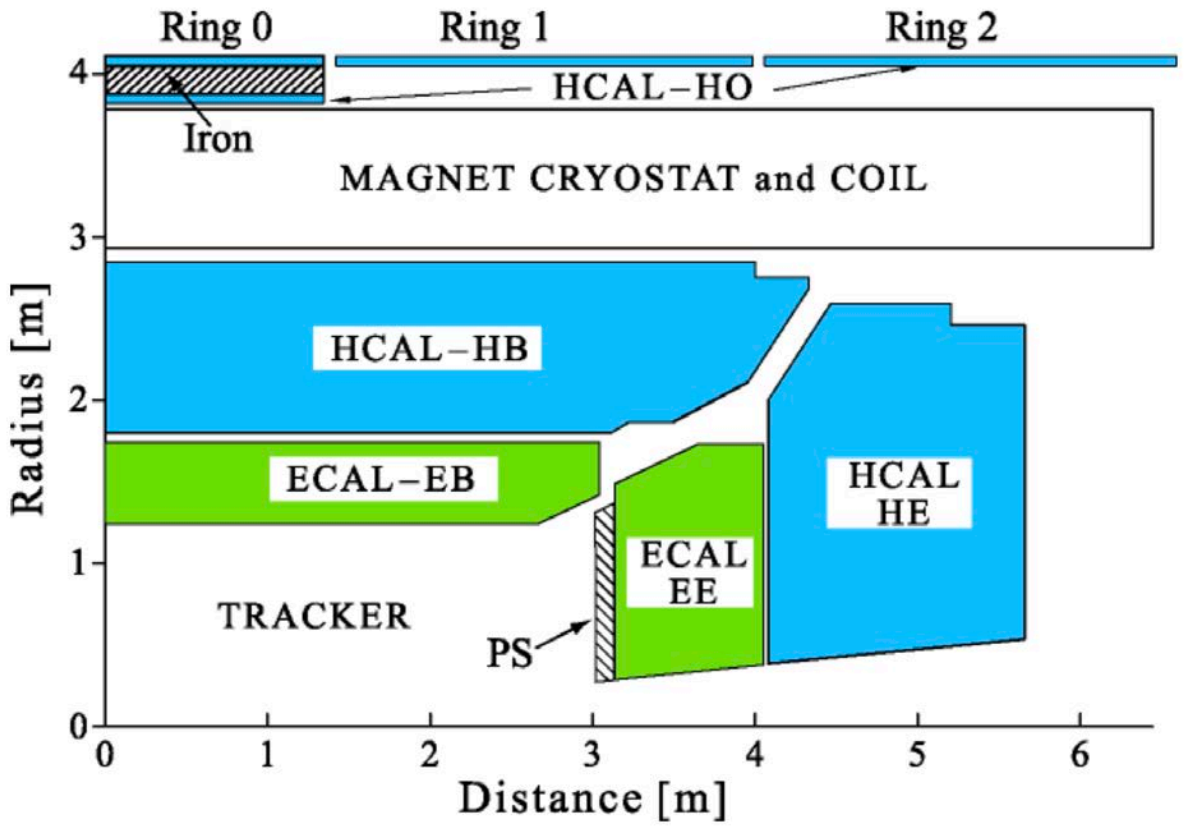


- **Software validation and performance**
- **2006 test beam with CMS calorimeter prototypes**: beams of different types and different energies. Test of G4HepEM.

Eur. Phys. J. C (2009) 60: 359–373







- **2016 low pile-up run:** Utilizing zero bias or minimum bias triggers from low luminosity runs

J. Phys.: Conf. Ser. 898 042005

- **2018 HGCAL test beam**: Prototype of HGCAL with charged pion beam if 20-300 GeV/c

JINST 18 (2023) 08, P08014

- **Data-MC comparison:** Validation campaigns organized centrally, participation from detector performance and physics object groups.
  - **Run-3 2022** with Geant4 10.7.2
  - **Run-2 Ultra-Legacy** with Geant4 10.4.3

MC Validation of Geant4

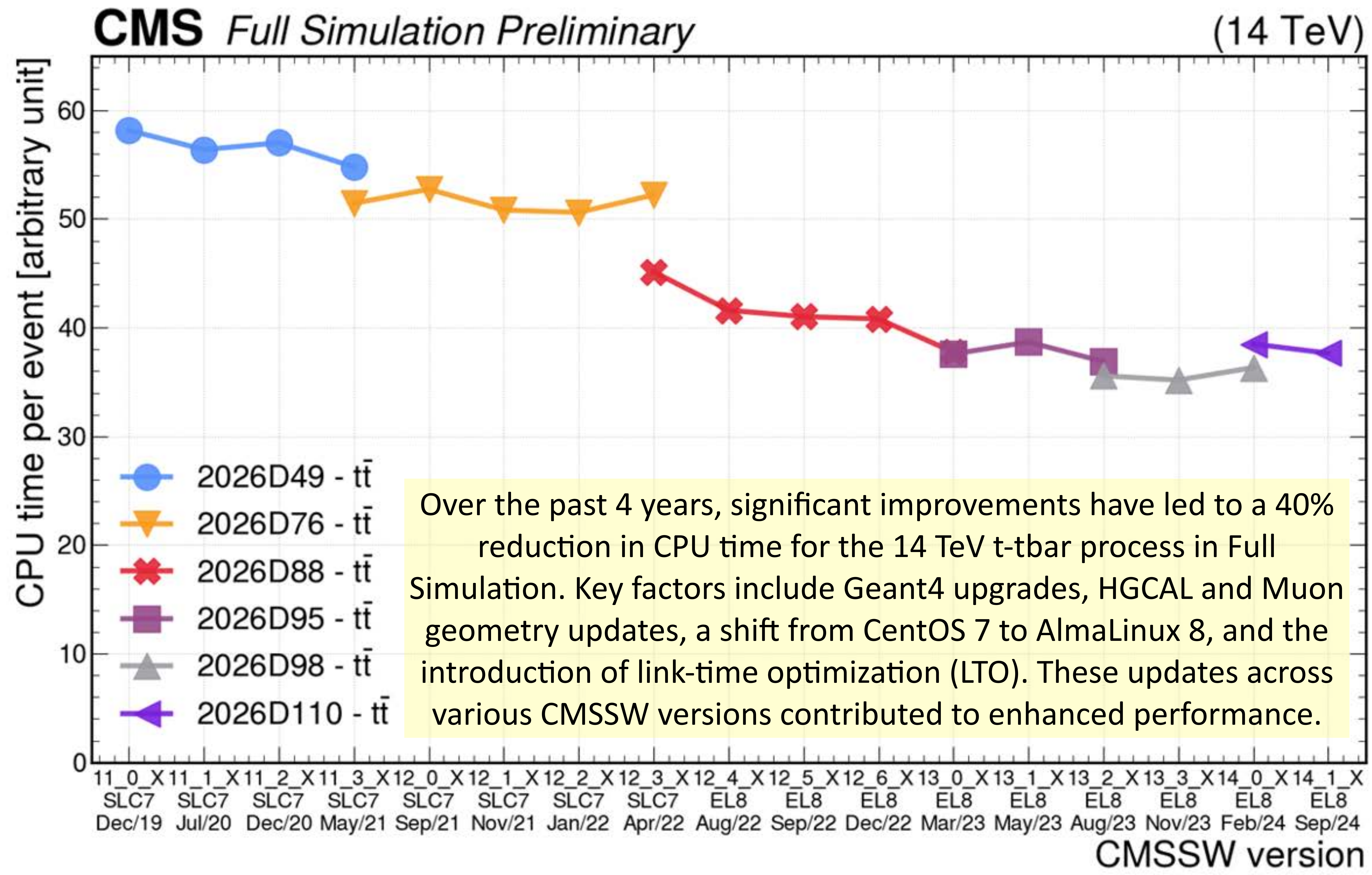
Campaigns

G4

Campaign Name	Categories	Status	Created Date
13_2_0_pre3_G4VECGEOM_2023	Reconstruction, HLT, PAGs	Open	a year ago
13_2_0_pre3_G4VECGEOM_Phase2_D98	Reconstruction, PAGs	Open	a year ago
13_0_0_pre3_Phase2_D88_G4VECGEOM	Reconstruction, PAGs	Open	2 years ago
13_0_0_pre3_Phase2_D88_LTOG4VECGEOM	Reconstruction, PAGs	Open	2 years ago
13_0_0_pre3_2023_LTOG4VECGEOM	HIN, Reconstruction, PAGs, HLT	Open	2 years ago
13_0_0_pre3_2023_G4VECGEOM	HIN, Reconstruction, PAGs, HLT	Open	2 years ago

To validate Geant4, PPD (Physics Performance and Dataset) group calls a wide validation to DPGs, POGs and PAGs. The MC vs MC is done with the same release of CMSSW, but different versions of Geant4.

Performance monitoring



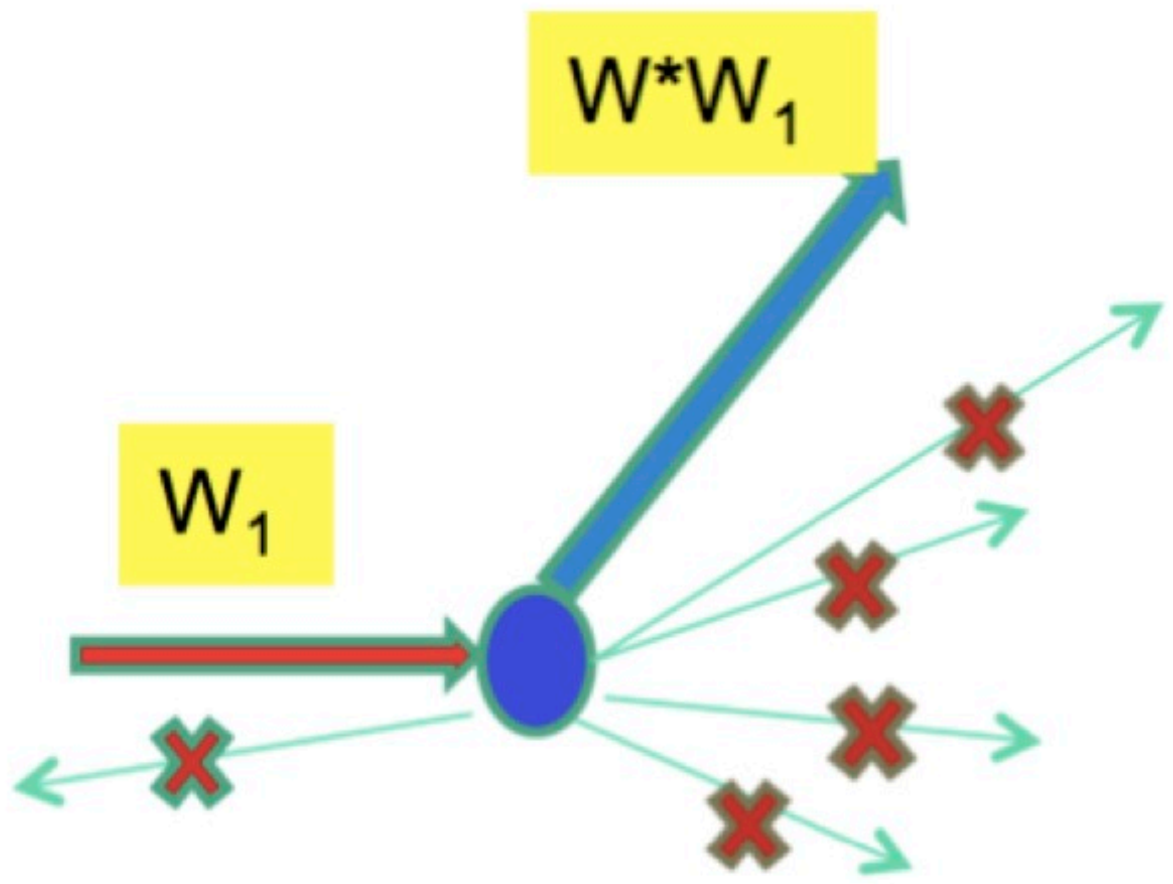
Over the past 4 years, significant improvements have led to a 40% reduction in CPU time for the 14 TeV t-tbar process in Full Simulation. Key factors include Geant4 upgrades, HGCAL and Muon geometry updates, a shift from CentOS 7 to AlmaLinux 8, and the introduction of link-time optimization (LTO). These updates across various CMSSW versions contributed to enhanced performance.

Reminder: CMS FullSim includes several techniques to make it fast

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

MC sampling techniques: Russian Roulette

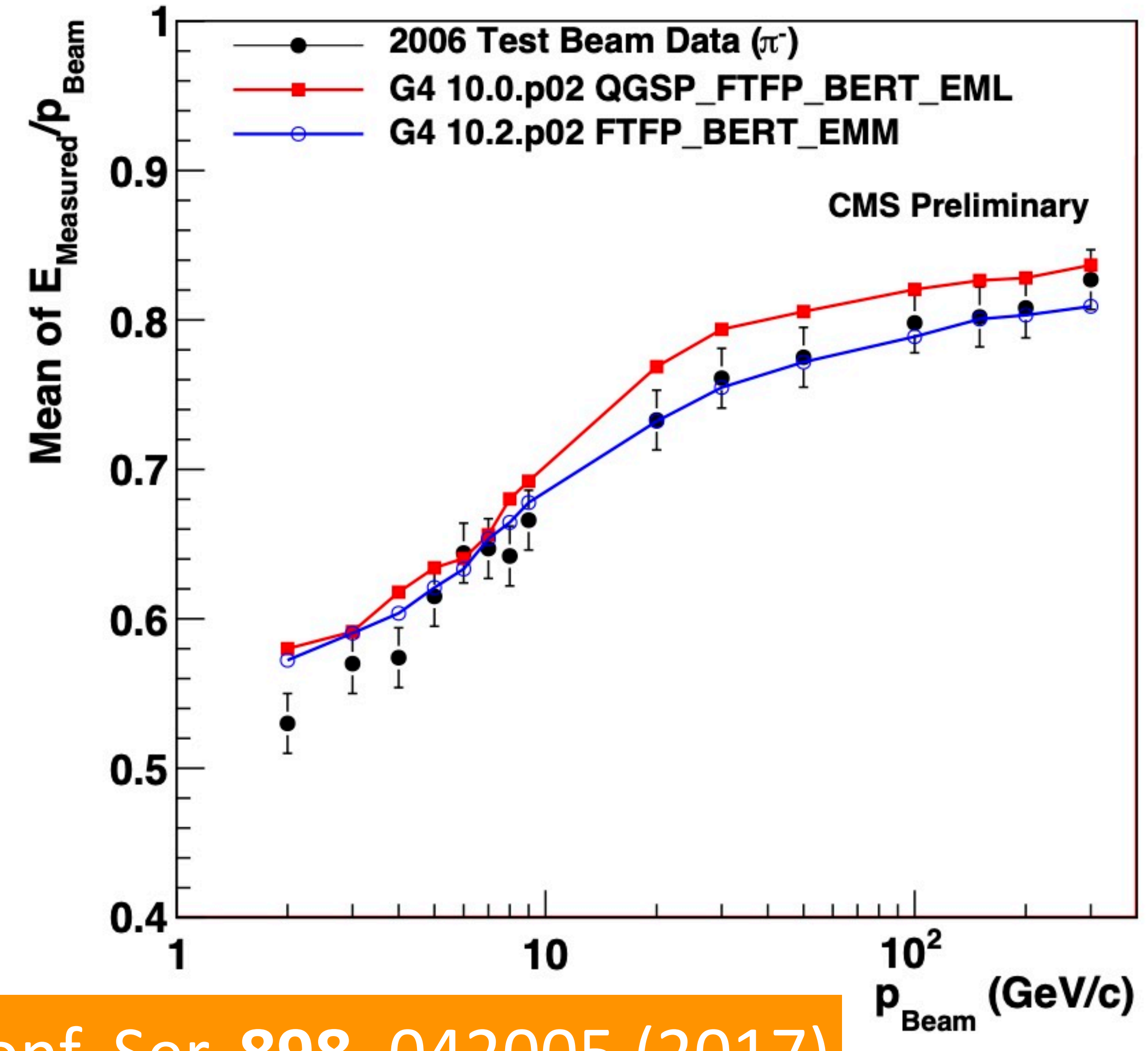


J. Phys.: Conf. Ser. **608**, 012056 (2015)

- Significant portion of CMS simulation time spent tracking low-energy particles, particularly in electromagnetic and hadronic calorimeters
- Simulation modified to track only a small fraction of gamma and neutron particles below energy thresholds
- Thresholds and sampling fractions were tuned to ensure final physics output remains unaffected

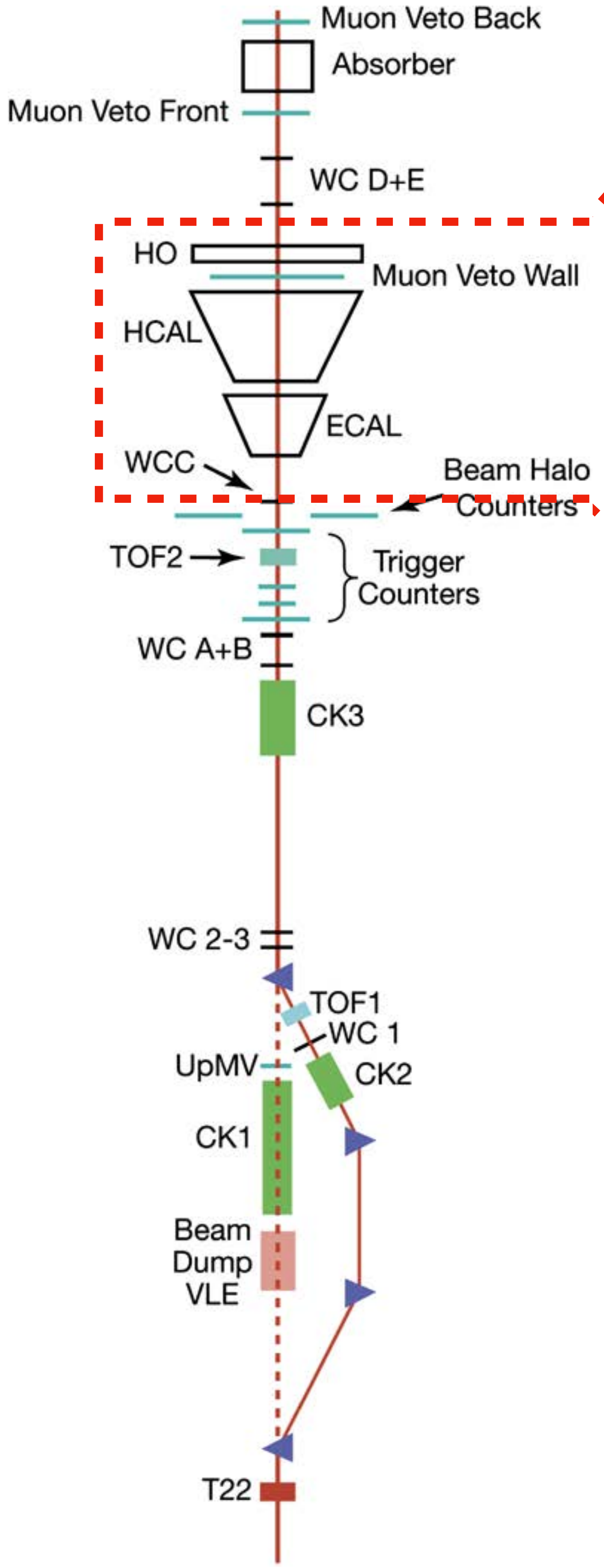
Physics list

- Updated since 2017
- Change from QGSP_FTFP_BERT_EML to FTFP_BERT_EMM
- EMM details multiple scattering model for sampling calorimeters and the simplified one for other detectors

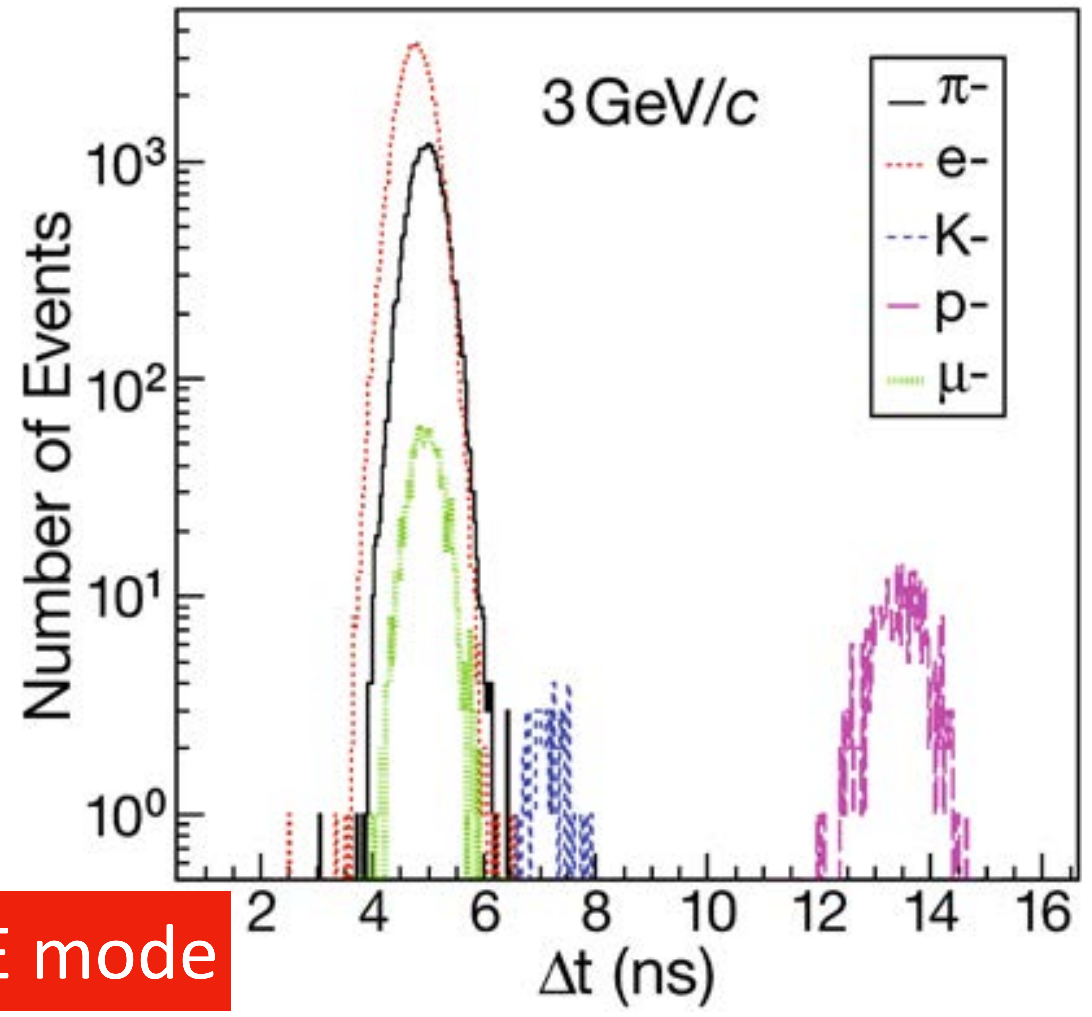


J. Phys.: Conf. Ser. **898**, 042005 (2017)

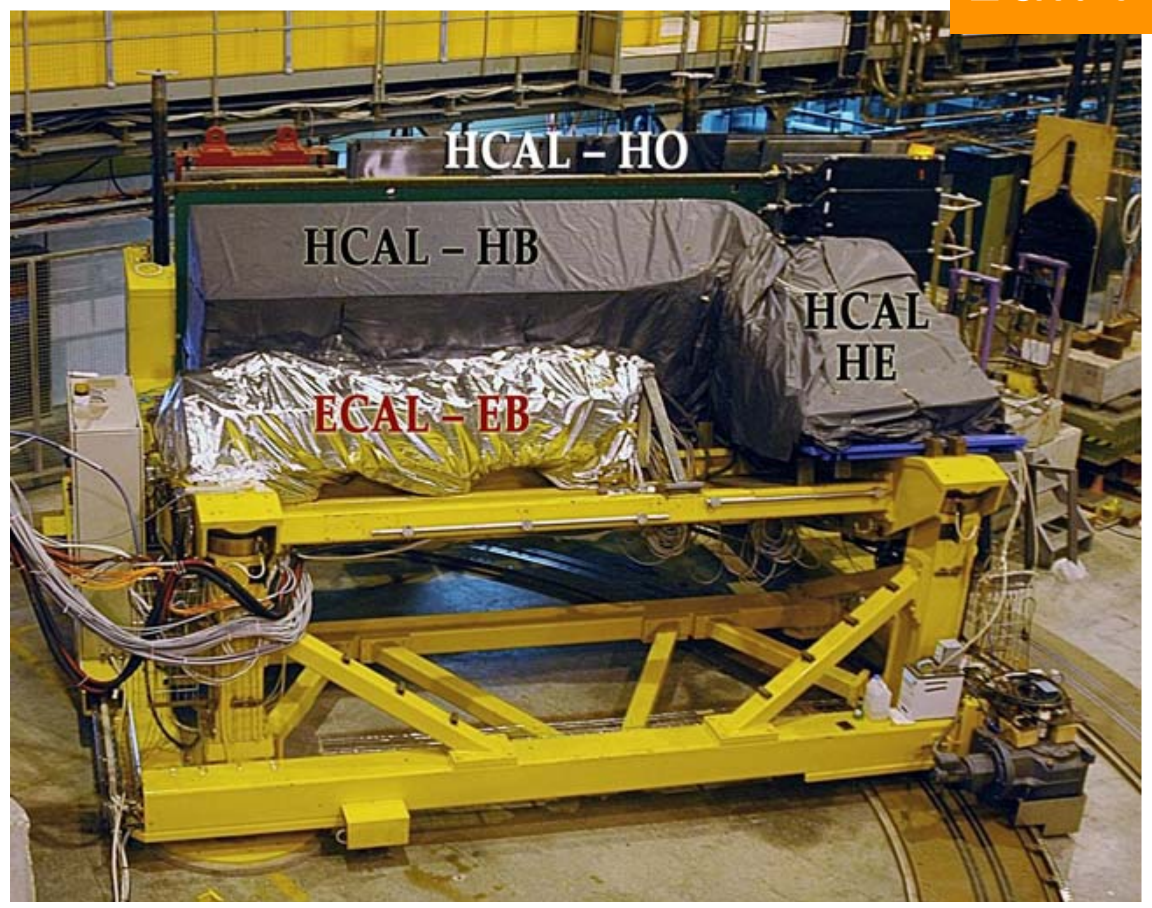
Test of G4HepEm Physics



Eur. Phys. J. C (2009) 60: 359–373



VLE mode



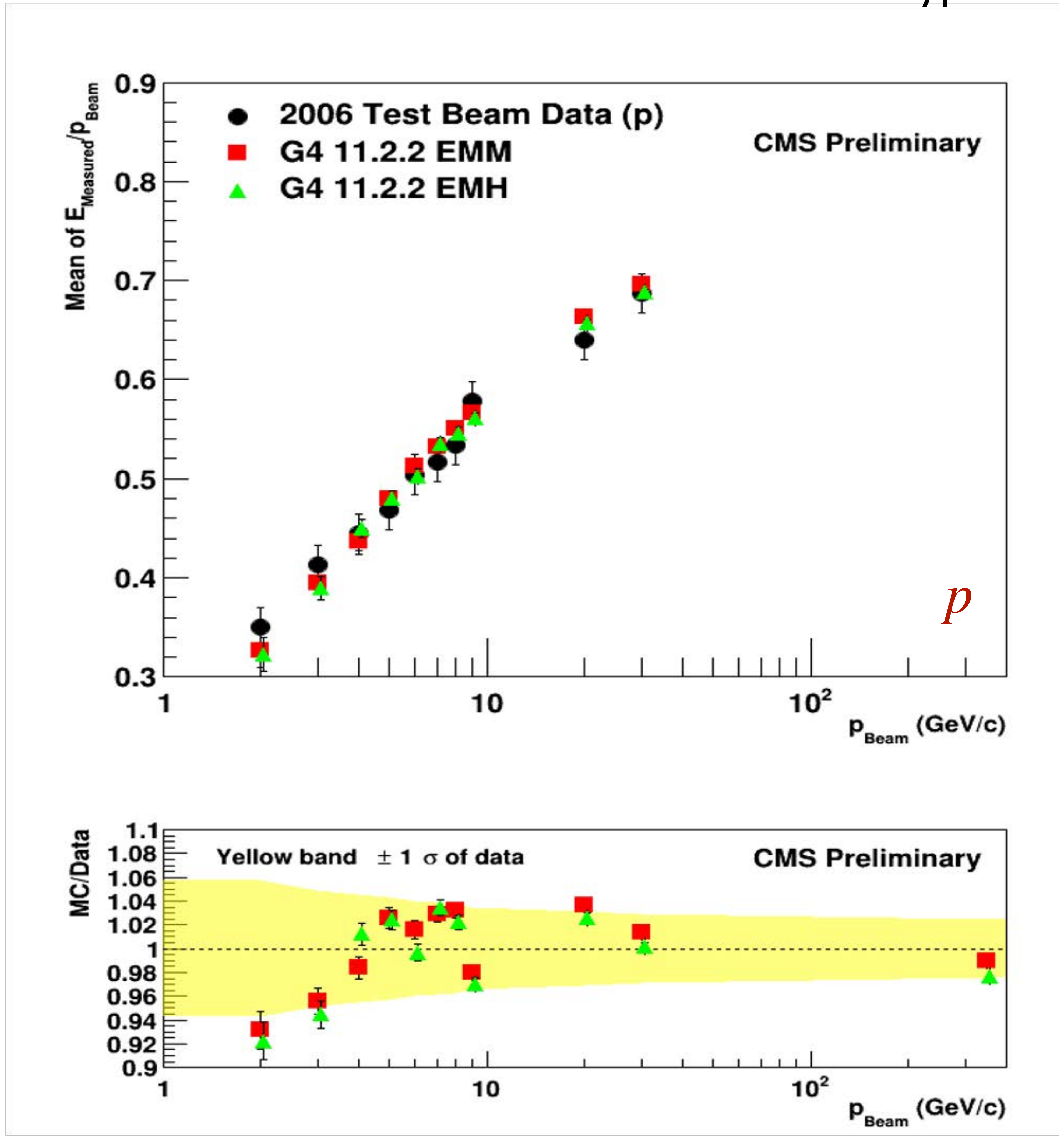
- Protons and pions with momentum from 2 to 350 GeV/c
- Kaon and anti-proton up to an energy of 9 GeV.

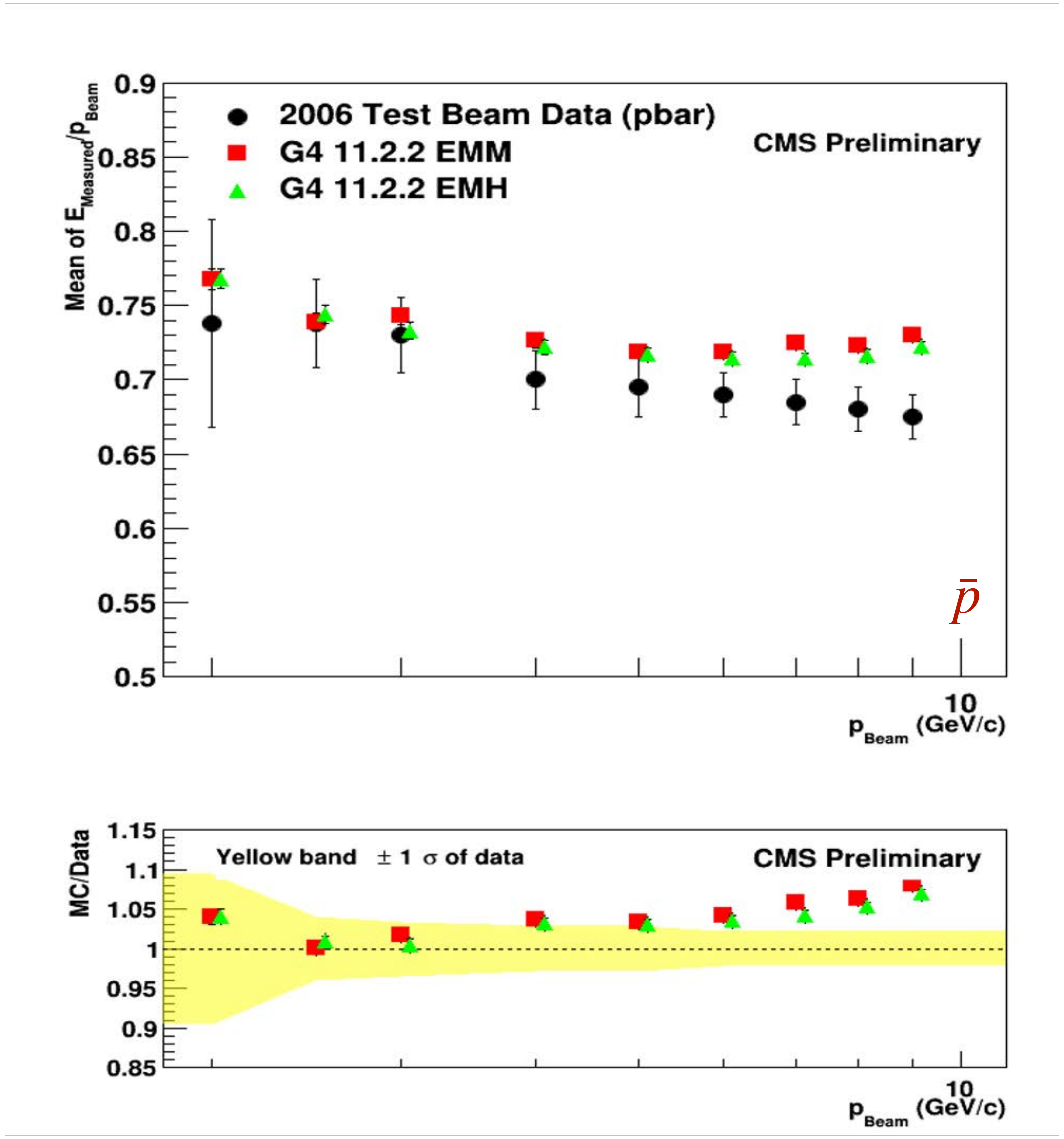
- CMS default Physics List: **FTFP_BERT_EMM**
  - Simple step limitation for e^+,e^- for CMS geometry except HCAL region, where more strict step limitation is used.
  - Applied cuts on secondary electrons in photoelectric process and Compton scattering
  - Disabled Rayleigh scattering

- In this report, we try G4HepEm library through **FTFP_BERT_EMH** in CMSSW. This library substitutes EM physics for γ, e^+,e^-.
  - Test with CPU. With AdePT, GPU can be used.

Test of G4HepEm Physics

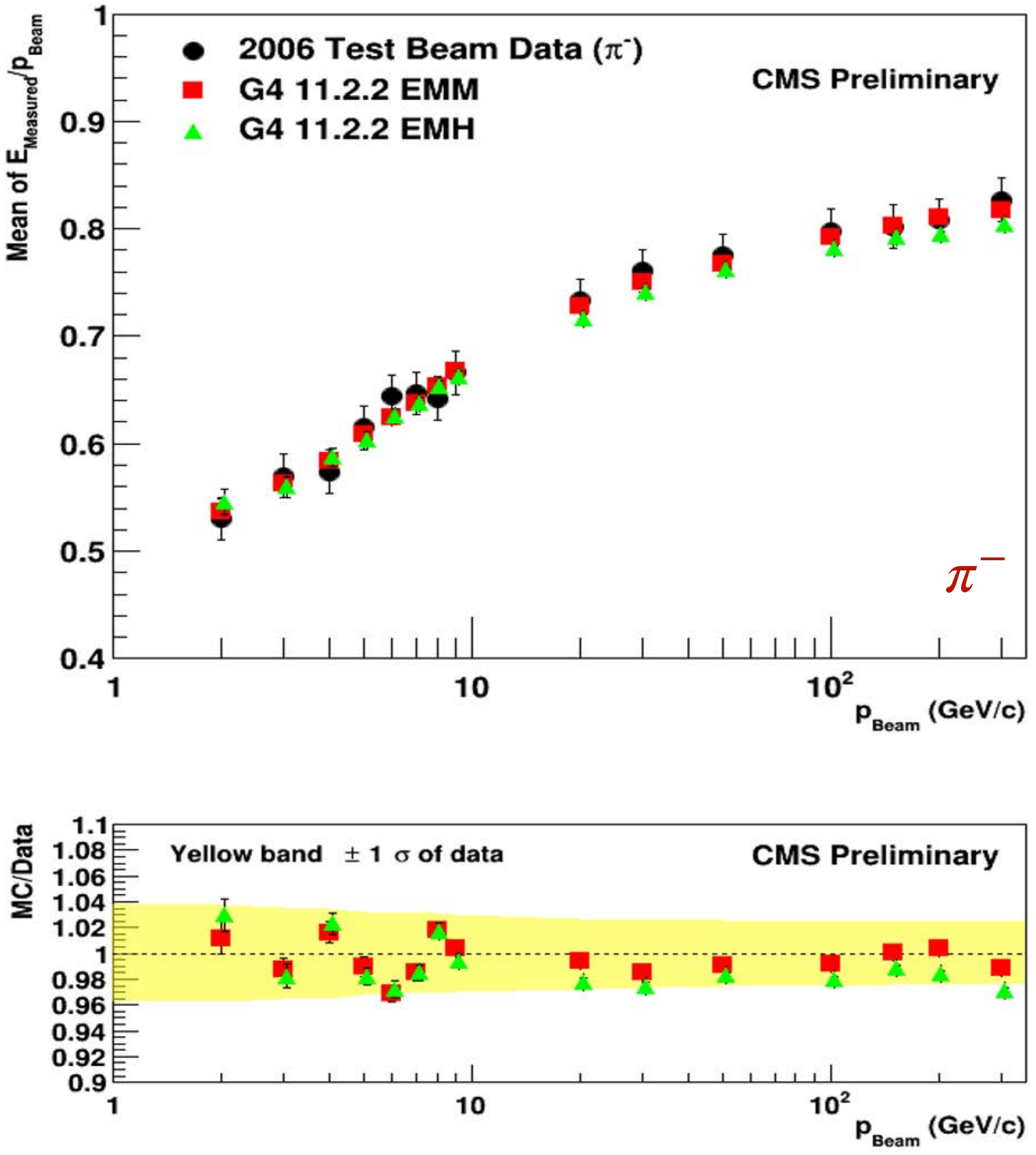
Mean energy response is measured as the ratio of the total energy in the calorimeter to the beam momentum as a function of beam momentum for different beam types.

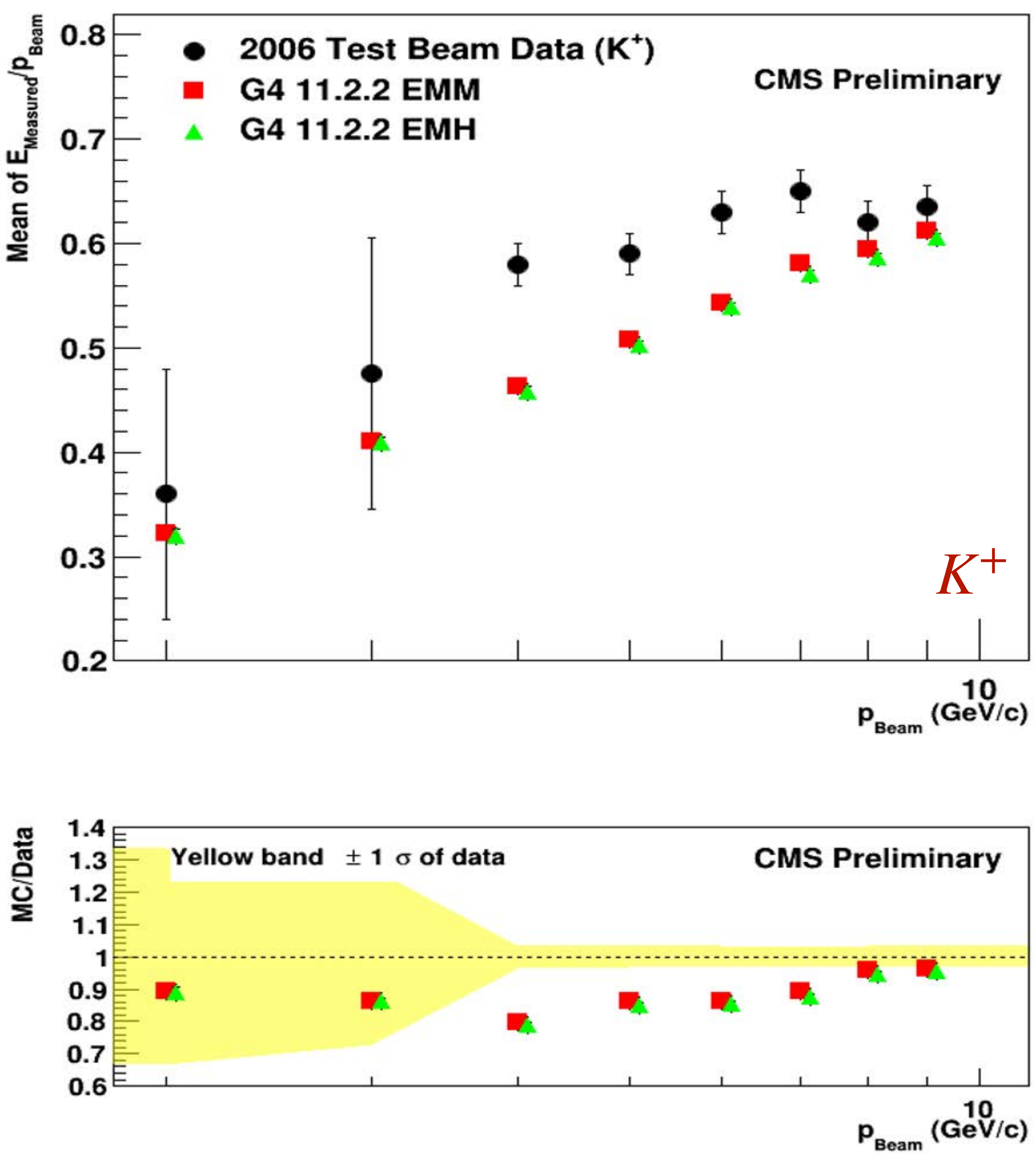




Test of G4HepEm Physics

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.

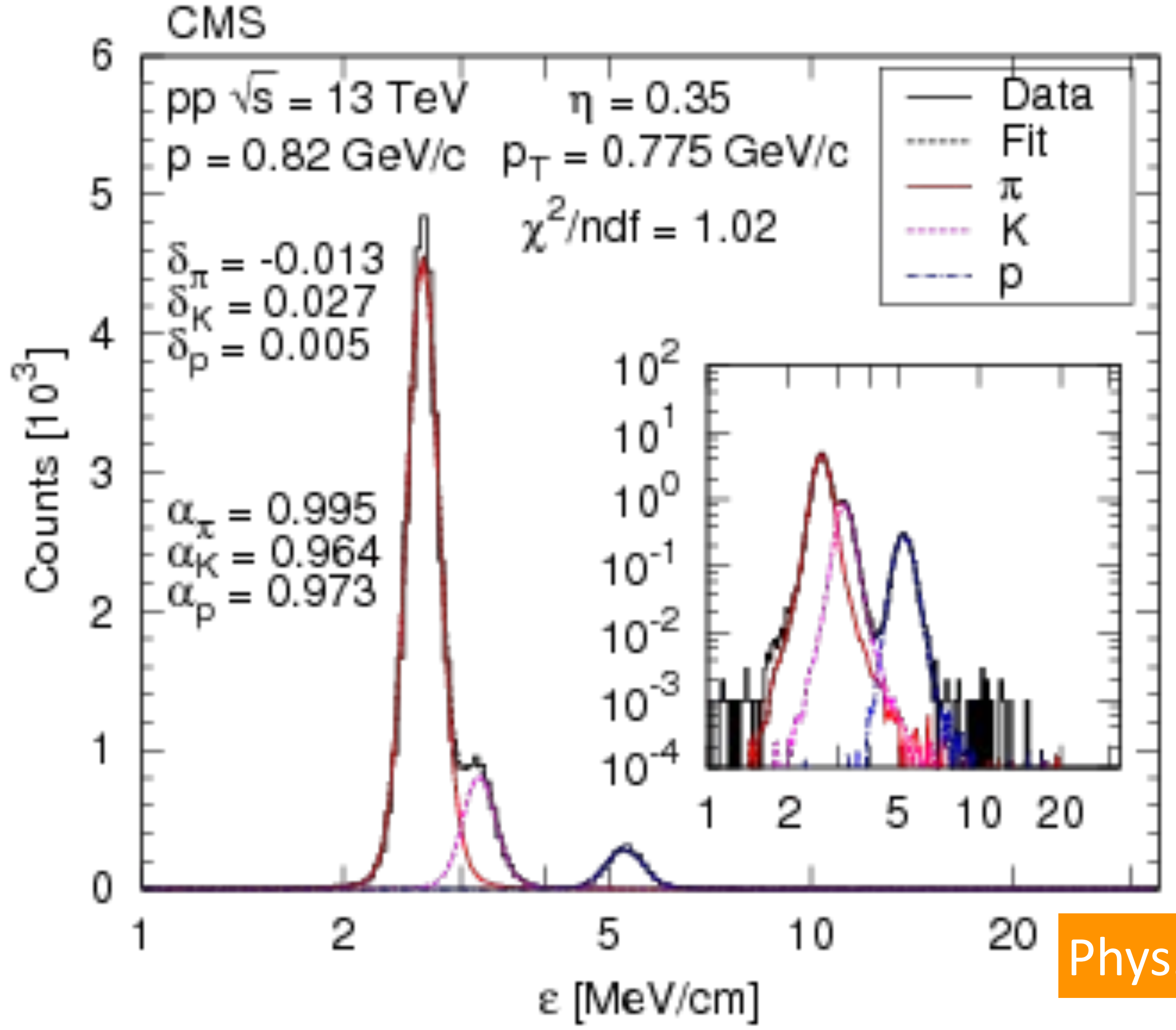




Summary on test beam 2006

Chi²/d.o.f. analysis	negative pions	positive pions	negative kaons	positive kaons	protons	anti-protons
G4 11.1.1 FTFP_BERT_EMM	0.22	1.29	20.6	15.7	0.52	3.30
G4 11.2.2 FTFP_BERT_EMM	0.21	1.36	20.0	15.6	0.62	3.75
G4 11.2.2 FTFP_BERT_EMH	0.55	2.36	22.4	18.5	0.72	2.64

- The predictions from FTFP_BERT_EMM from G4 11.1.1 and G4 11.2.2 are in good agreement, and consistent with predictions from FTFP_BERT_EMH.
- The level of agreement is good for pions and protons, while it is not good for kaons and some disagreement is seen for anti-protons.
- Proton-proton collisions at high energy produces mostly pion. We can expect agreement between Data-MC.



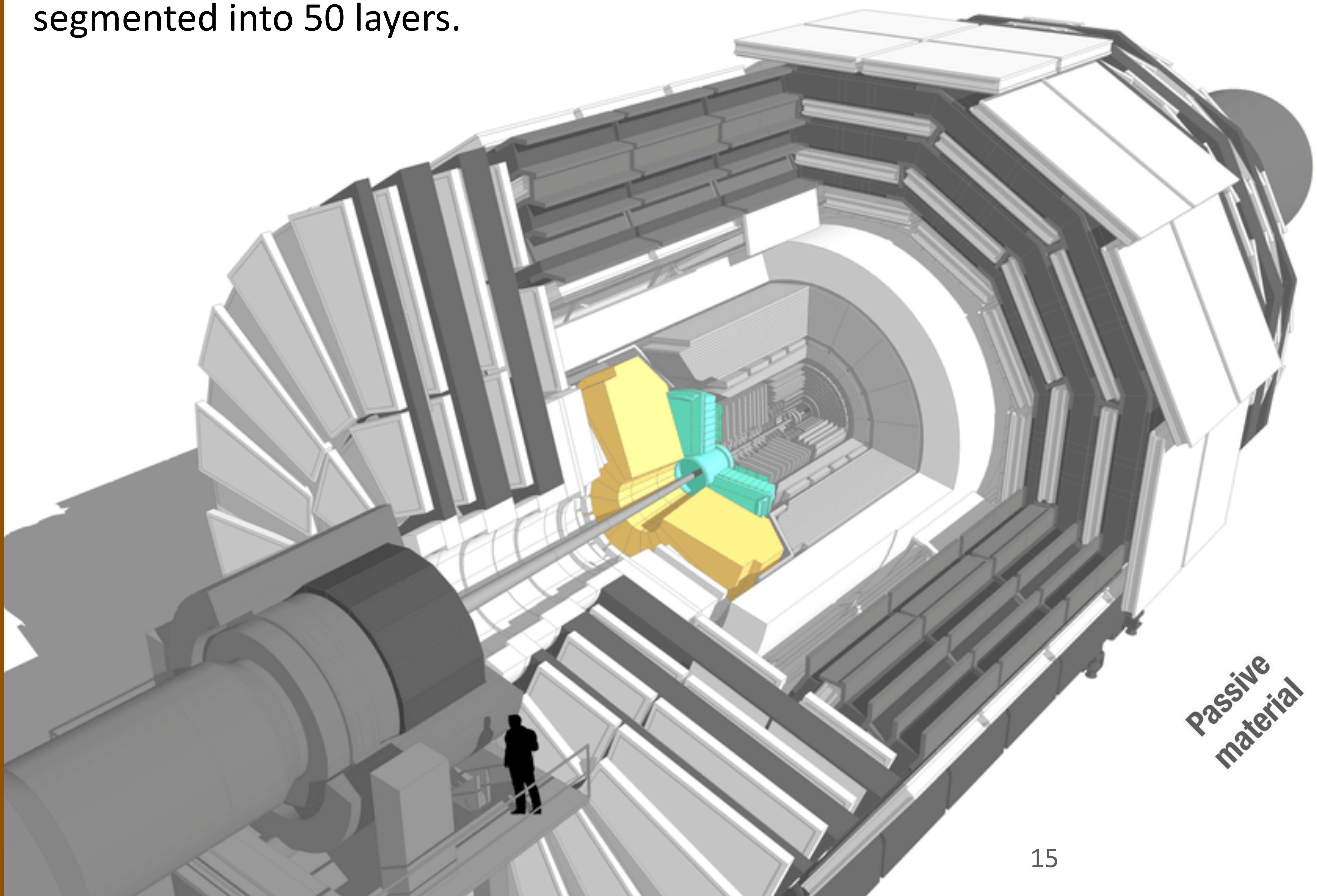
Phys. Rev. D **96**, 112003

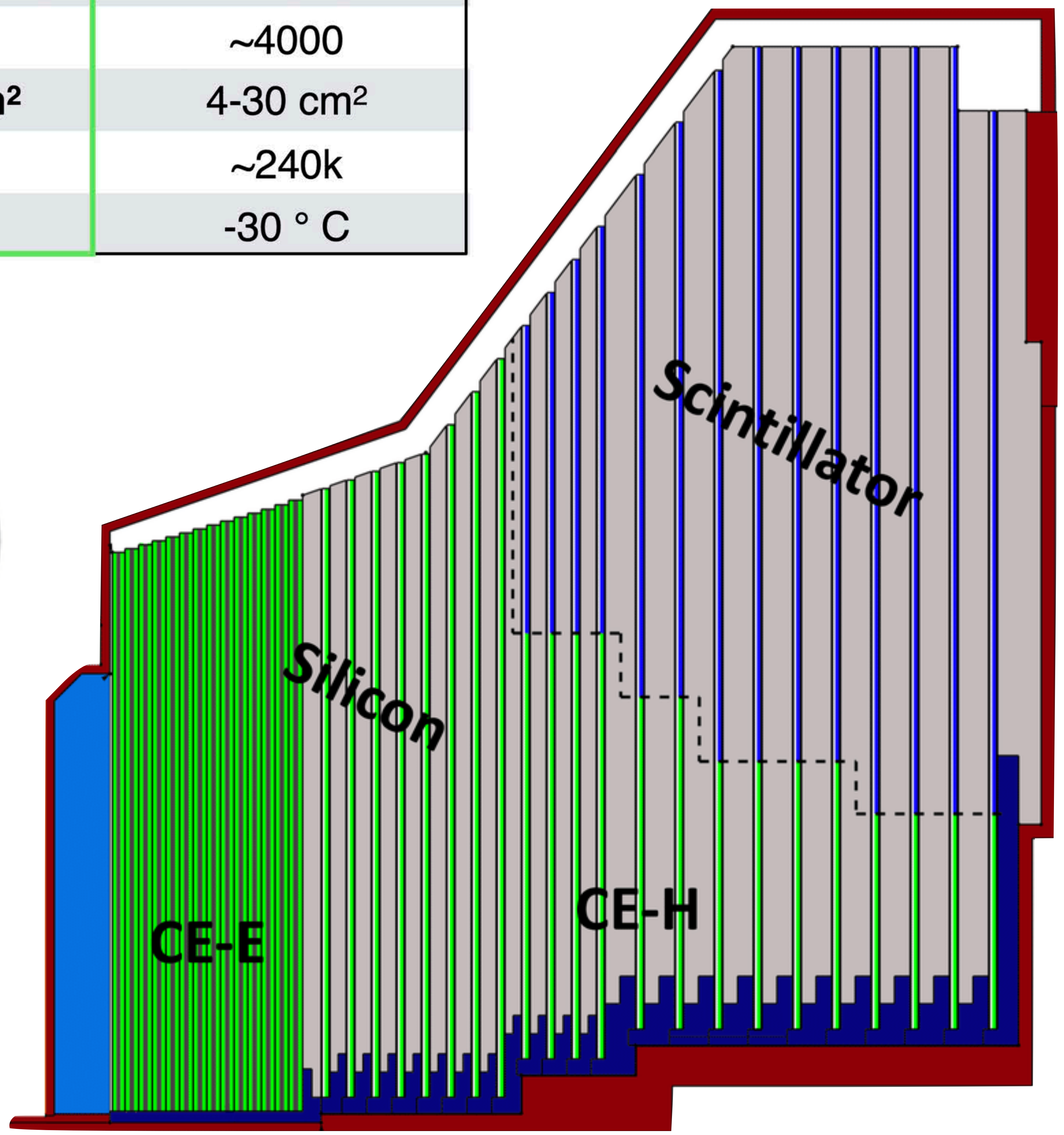
CMS HGCAL

CMS HGCAL is a sampling calorimeter comprising an electromagnetic section (CE-E) followed by a hadronic section (CE-H), which are longitudinally segmented into 50 layers.

Active material

Both endcaps	Silicon	Scintillators
Area	**~620m²**	~370m²
#Modules	~27000	~4000
Channel size	**0.5 - 1 cm²**	4-30 cm²
#Channels	**~6 M**	~240k
Op. temp.	-30 ° C	-30 ° C



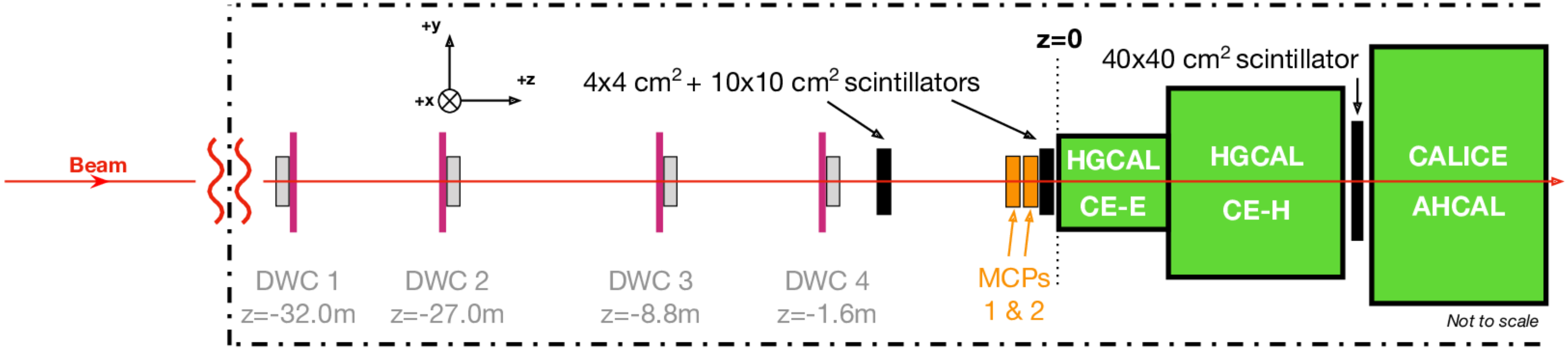


Passive material

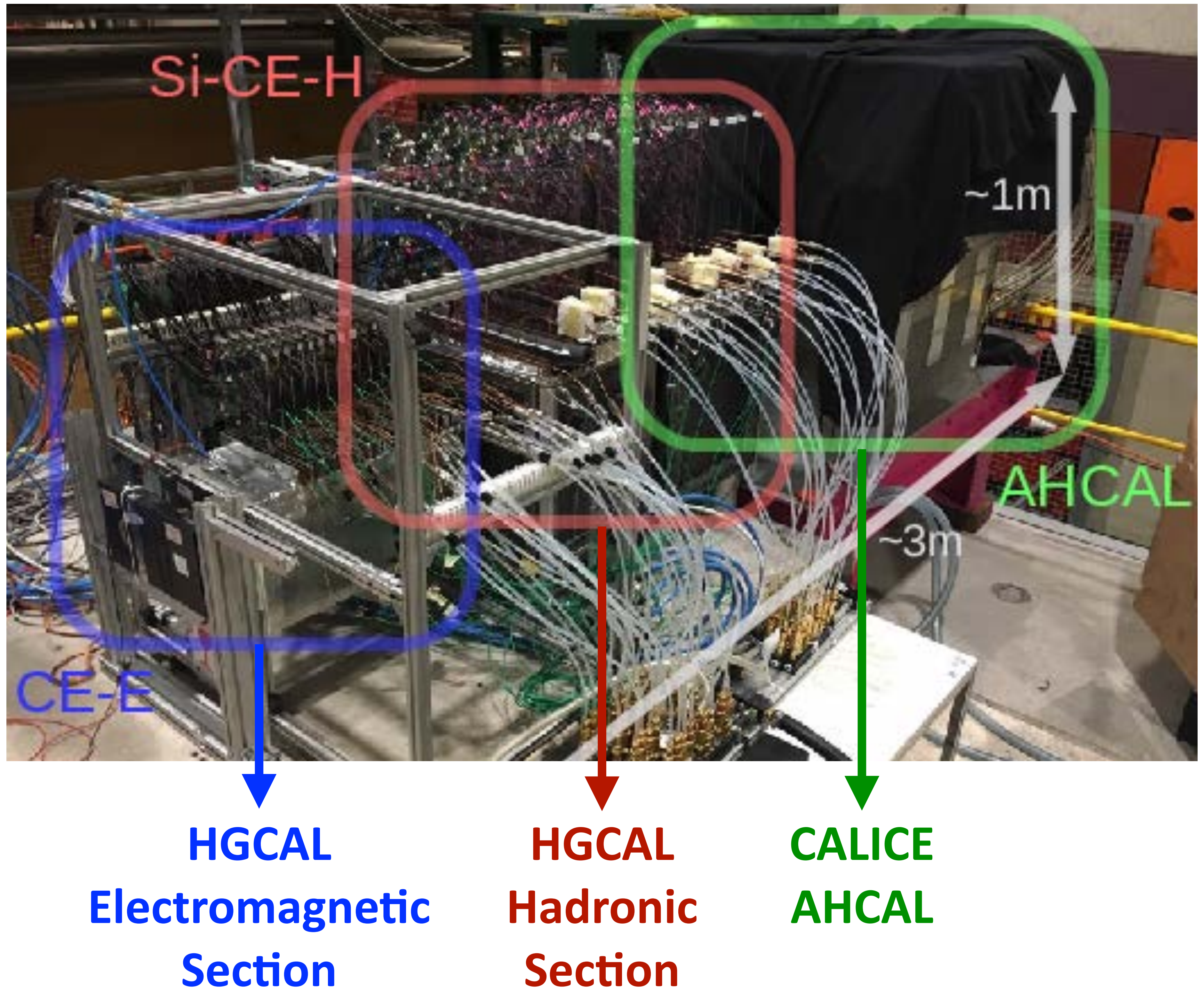
Per endcap	CE-E	CE-H (Si)	CE-H
Absorber	Pb, CuW, Cu	Stainless steel, Cu	
Depth	27.7 X_0	10.0 λ	
Layers	26	7	14
Weight	~230 t / endcap		

Validation of HGCAL prototype with charged pion beams

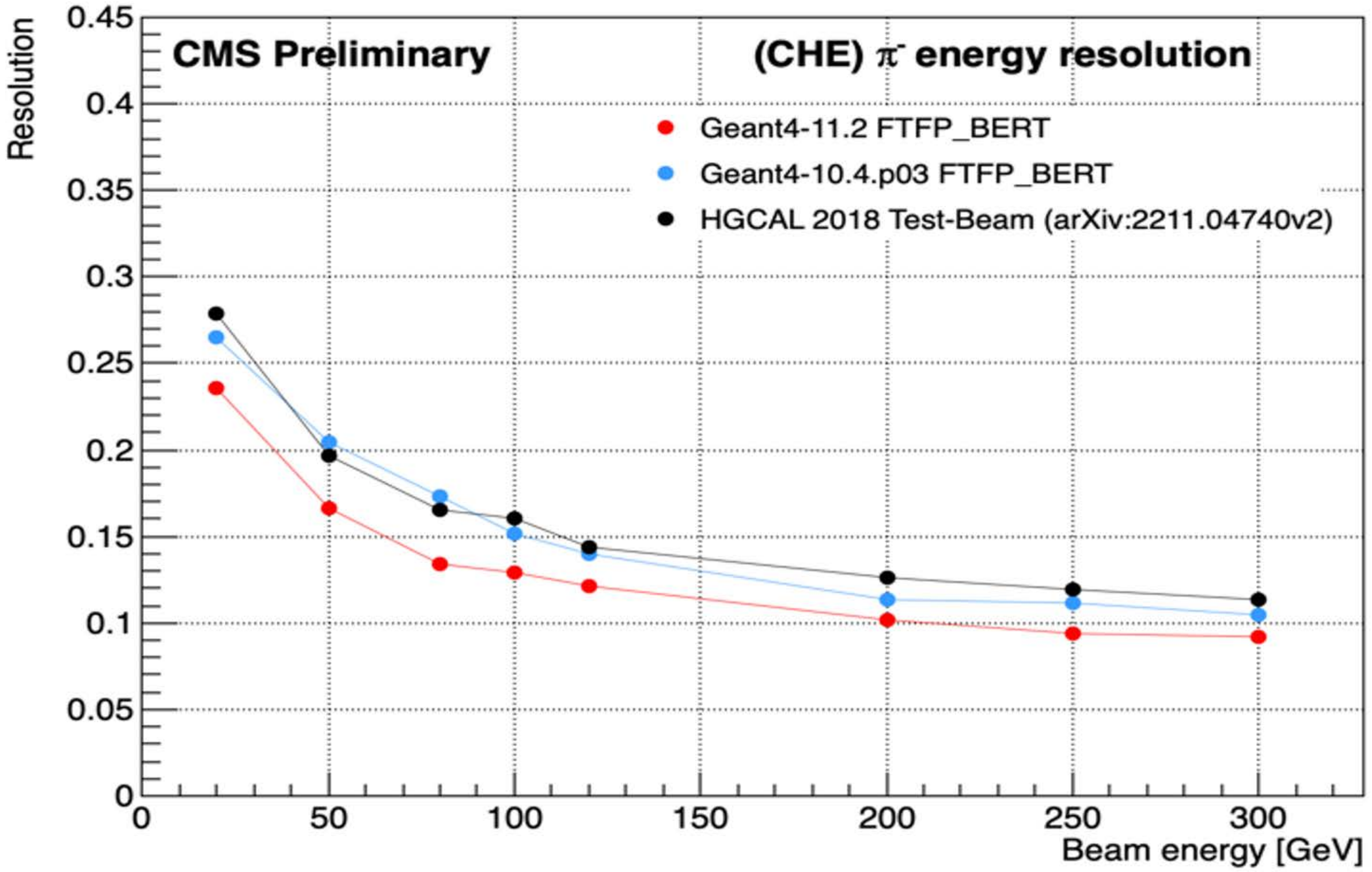
JINST 18 (2023) 08, P08014



- Protons accelerated to 400 GeV/c by the SPS collide with a 500 mm Beryllium target.
- Secondary beams (muons, electrons, pions) are produced and directed to the HGCAL prototype 600 m downstream.
- The particles selected in the momenta range of 20 - 300 GeV/c have a momentum spread of 0.2 - 2.0 %.

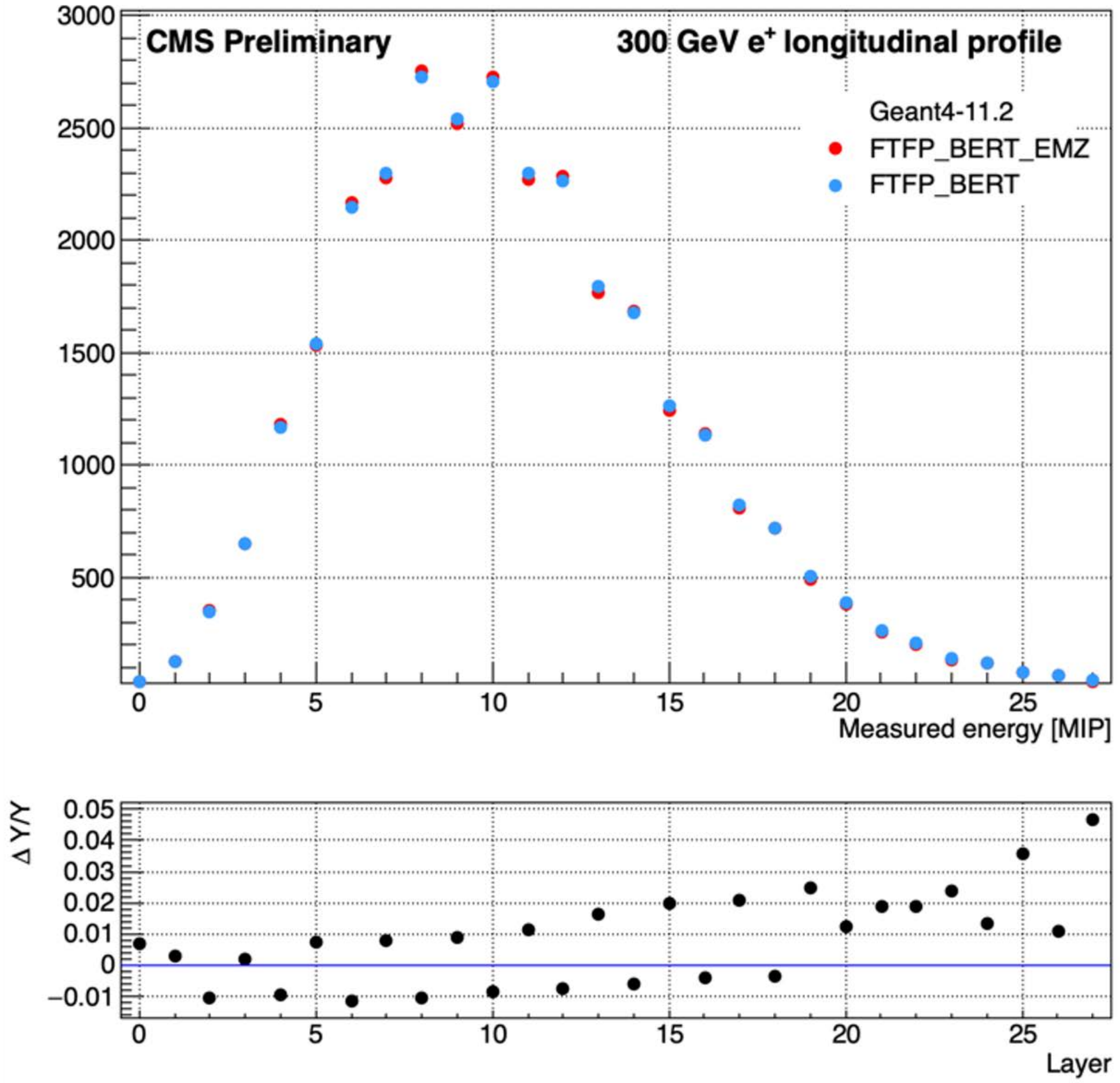


Validation of HGCAL prototype with charged pion beams

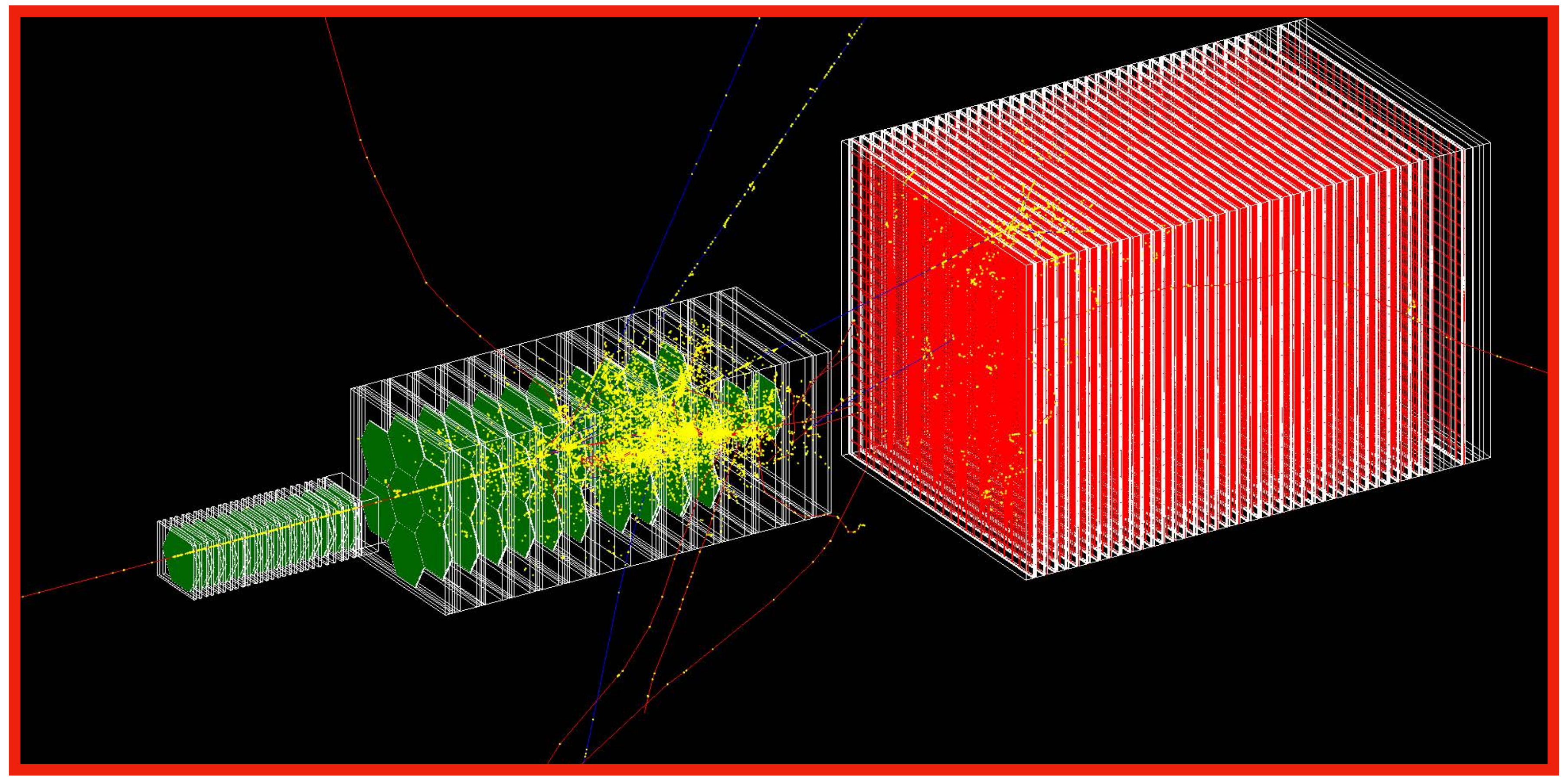


Pion energy resolution as the function of beam energy. Note that, the statistical errors are on level of marker size and are not shown.

Positron energy deposition in units of MIP as a function of number of layer in EM section of HGCal. Note that, the statistical errors are on level of marker size and are not shown.



New test inside Geant-val validation database



Summary

Summary

- **CMSSW is under intensive development toward Phase-2**
  - Finalization of geometry description
  - Optimization of physics configuration
  - R&D on usage of accelerators
- **CMS choice to use latest Geant4 version for Phase-2**
  - Accuracy and code quality are under permanent monitoring
  - Test beam data 2006 and 2018, also detector data 2016 are used
- **R&D program is ongoing**
  - G4HepEm library may be considered
  - Looking forward on AdePT and Celeritas projects
- **Talks & Poster on CMS Simulation at CHEP 2024**
  - [Plenary] CMS FlashSim: end-to-end simulation with ML (link)
  - [Parallel] Simulating the CMS High Granularity Calorimeter with ML (link)
  - [Poster] Refining FastSim with Machine Learning (link)