CMS Report

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on behalf of
CMS Collaboration

Geant4 Technical Forum

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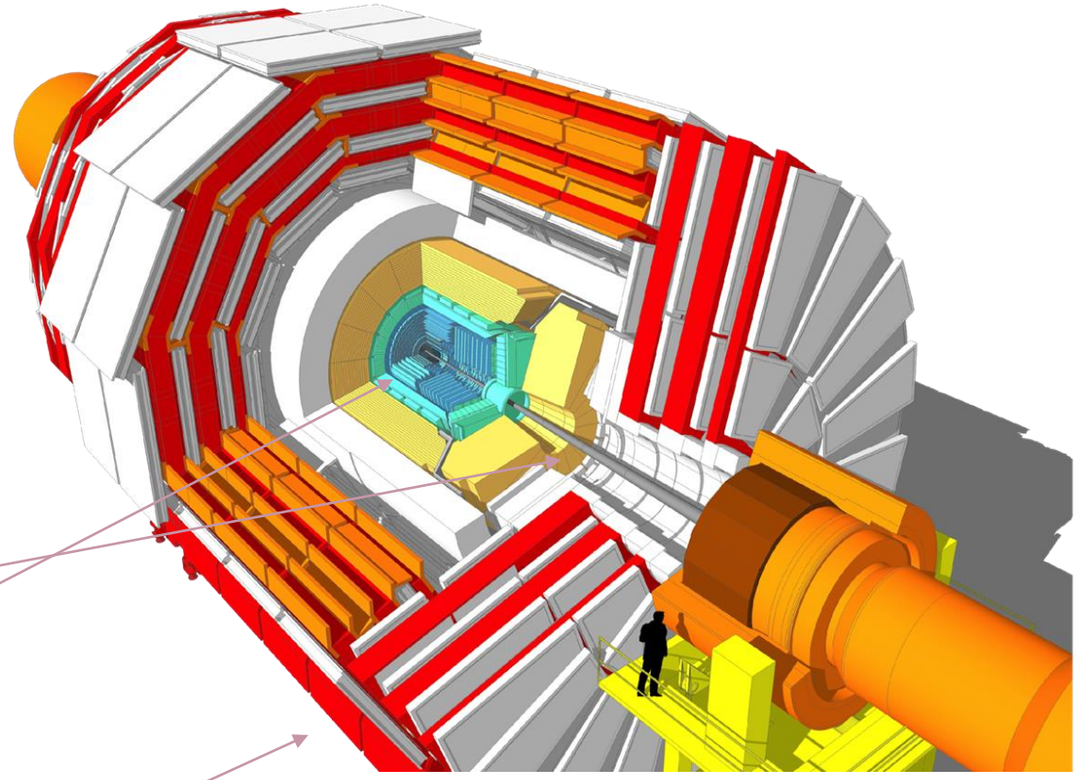
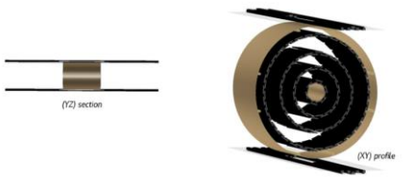
CMS geometry upgrade

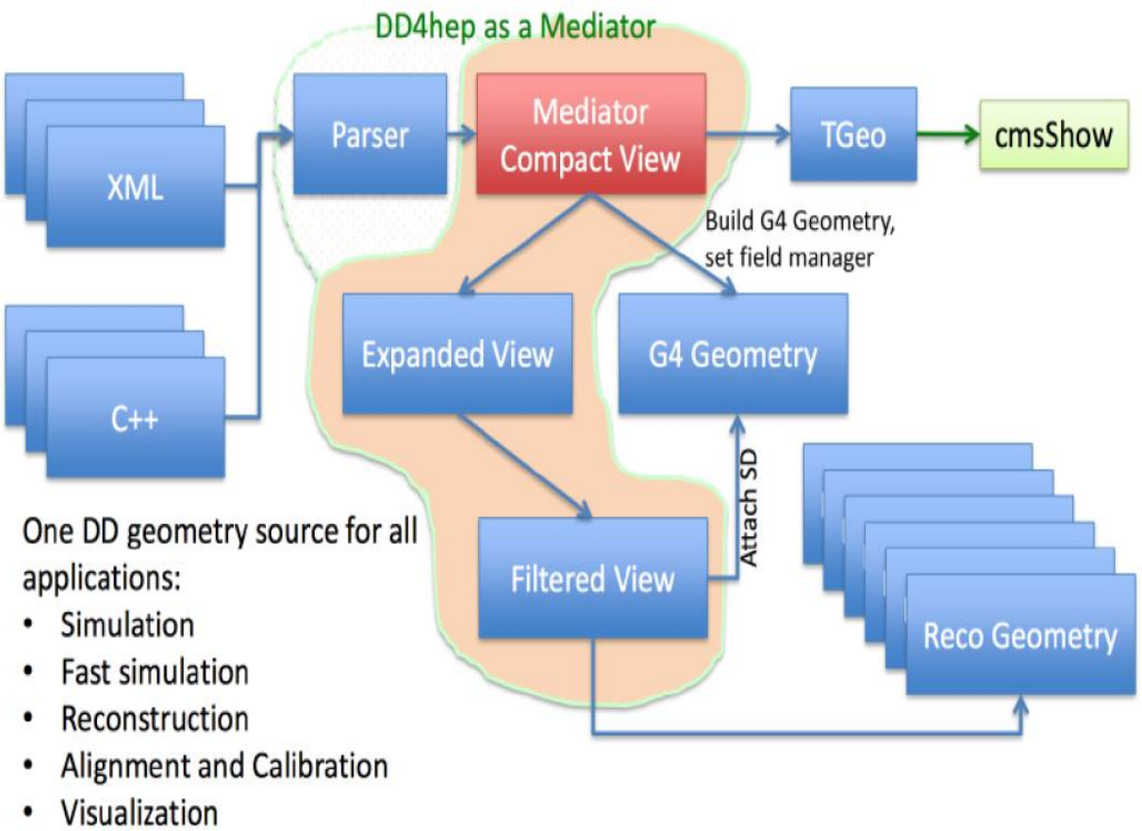
- Geometry update for Run-3
  - New beam pipe
  - More accurate description of tracker support structure
  - Improved description of muon system, addition of GEM stations
  - Updated forward and very forward detectors





Tracker support

Migration to DD4Hep



- For Run-1 and Run-2 CMS used custom detector description (DDD)
  - For each sub-detector original approach was developed by each sub-detector team
- For Run-3 a migration to the community developed tool DD4Hep was chosen
  - F. Gaede et al., EPJ Web of Conferences 245, 02004 (2020)
  - C. Vuosalo et al., EPJ Web of Conferences 245, 02032 (2020)
- Migration required contributions from several sub-detector teams
  - Was started in 2019 and included full review of the CMS geometry
    - XML files were reviewed and unified
  - Run-3 DD4Hep description is currently being validated by the CMS central testing team
  - The migration effort provided good opportunity to verify CMS geometry, remove overlaps, and improve accuracy of volume positions and representations
- We would like to thank Markus Frank (LHCb) and the DD4Hep team for prompt reactions to any our request
  - DD4hep code was also improved during this CMS campaign

Adaptation of Geant4 10.7

2015 Geant4 10.0p02

↓

2017 Geant4 10.2p02

2018 Geant4 10.4p03
+ VecGeom

↓

2021 Geant4 10.7p02
+ DD4Hep

CMS Geant4 version for Run-2 was updated

- Evolution of Geant4 version was possible, because CMS sub-detectors were modified for each new season
  - MT mode from 2017
  - Geant4 10.4p03 + VecGeom since 2018 – legacy MC production
- The configuration of physics was established during LS1 including FTFP_BERT_EMM Physics Lists, Russian roulette method, and HF shower library

Geant4 10.7 is the CMS release for Run-3

- No change of sub-detectors is expected during Run-3
  - 10.7 is the most recent Geant4 version available during LS2
- The current version is 10.7p02
  - a new patch 10.7p03 will not be used for the LHC start
- A procedure of validation for each new Geant4 version was established in CMS since Run-1
  - Validation started 6 months before the date of any Geant4 release, feedback to the Geant4 team is provided
  - Integrations tests, test-beam analysis, and comparisons with the detector data are performed

CMS Configuration of Physics

- CMS is planning to use 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 the version Geant4,10.4.p03 (Run2):
  - Bertini Cascade valid at ≤ 12 GeV
  - FTFP valid at ≥ 3 GeV

and in version Geant4.10.6.p02 and Geant4.10.7 (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 model for regions of the sampling calorimeters (HCAL and HGCAL) and a simplified multiple scattering model elsewhere

- Coefficients of Birk's law for plastic scintillator are retuned for the versions Geant4.10.6.p02 and Geant4.10.7
  - 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

$$\left[1 + C_1 \cdot \left(\frac{dE}{dx}\right) + C_2 \cdot \left(\frac{dE}{dx}\right)^2\right]^{-1}$$

Validation of Geant4

- Adaptation of a new Geant4 version or a new Physics List requires validation of the model predictions with some of the existing data

- The validation is carried out using 2 sources of data:

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

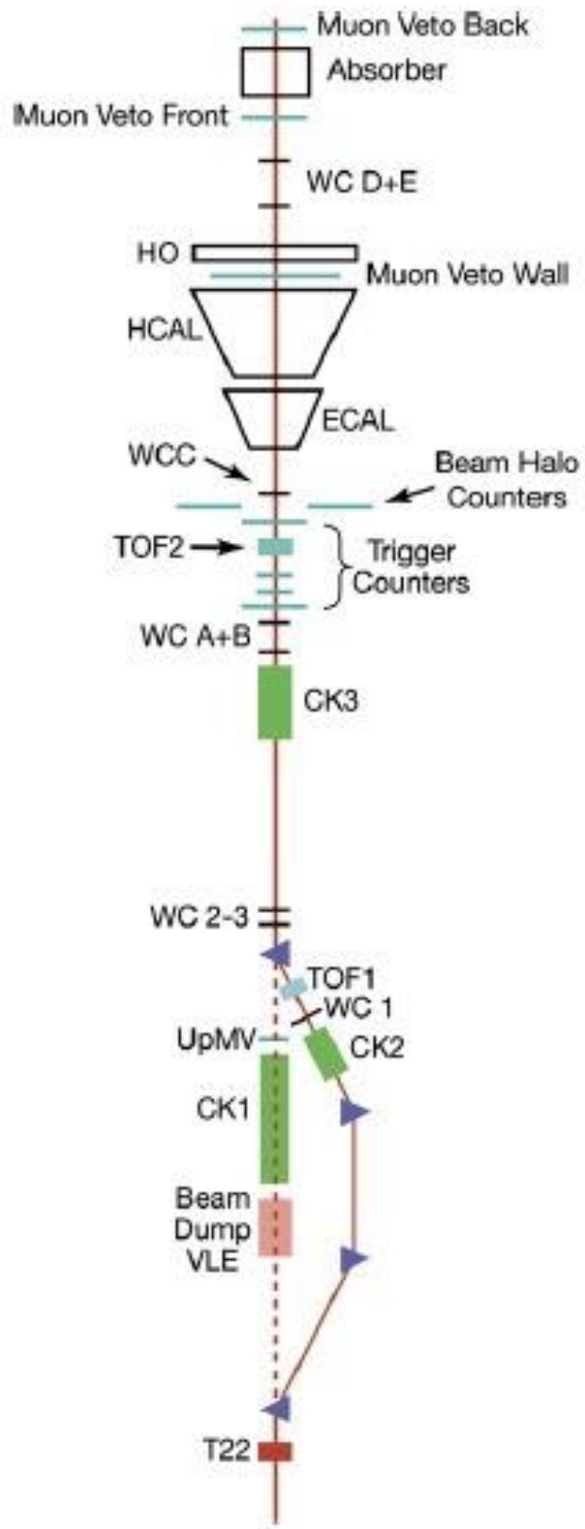
  - Collision data from the CMS experiment utilizing zero bias or minimum bias triggers from low luminosity runs

    - The methods are described in Eur. Phys. J. Web Conf. **214** (2019) 02012

- The comparisons may be used to improve the quality of Geant4 predictions in future releases

  - Results shown here are focussed on preparation for Run3

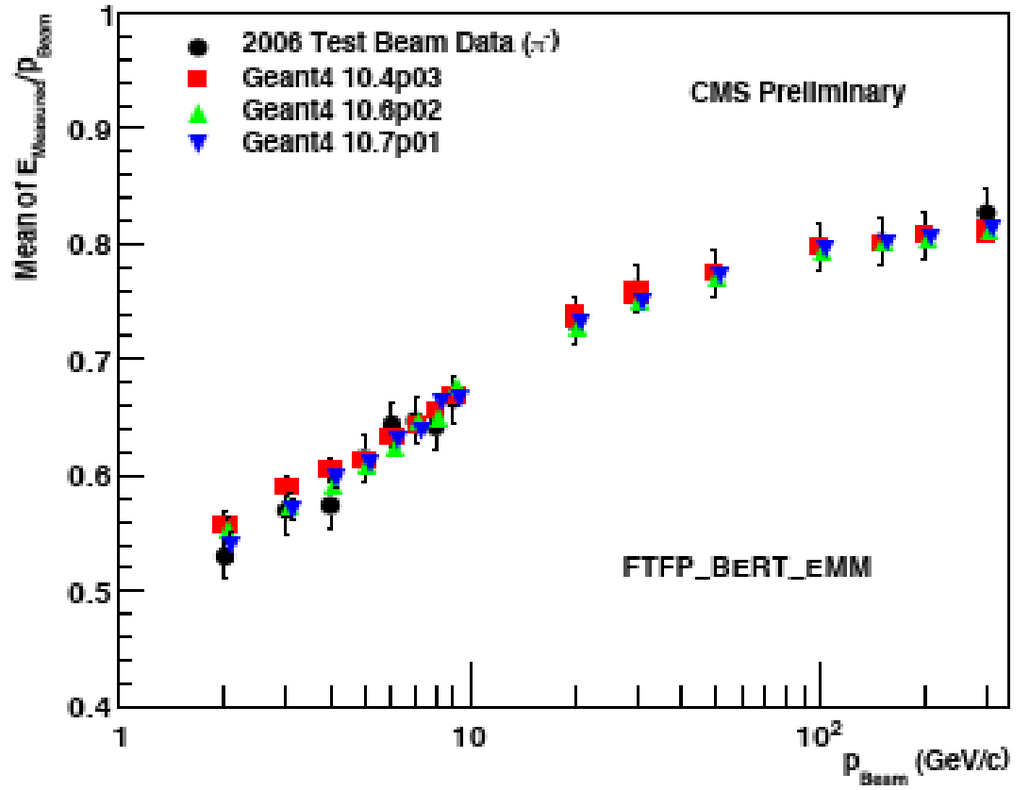
CMS 2006 TestBeam

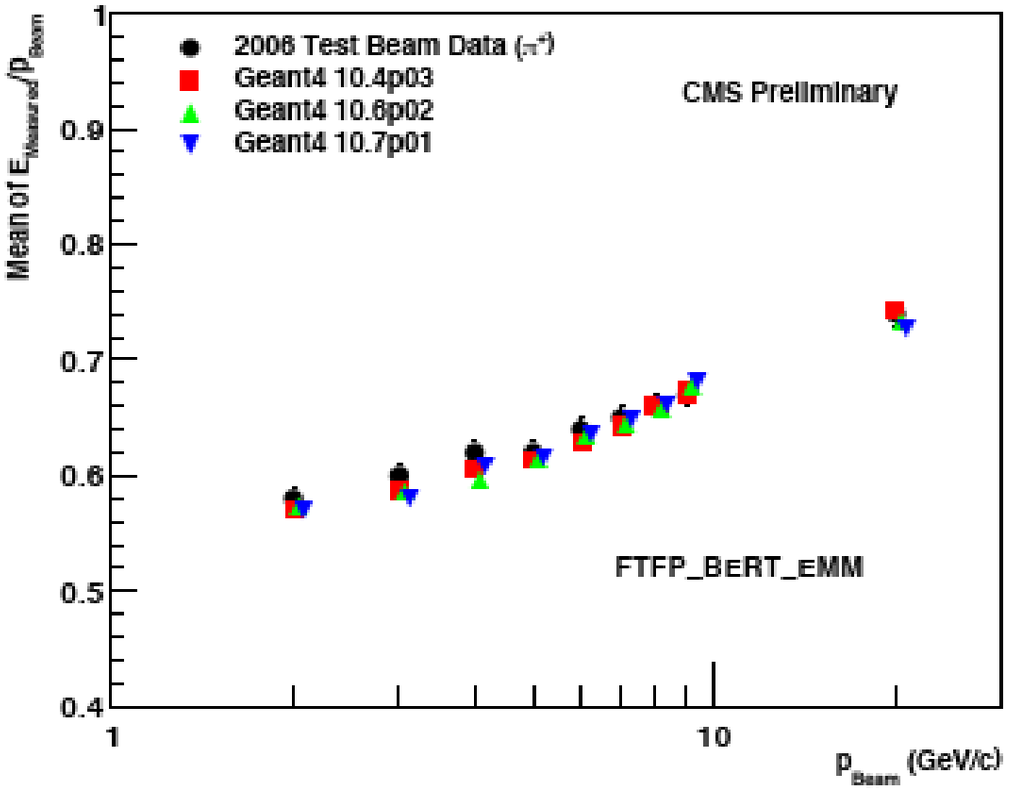


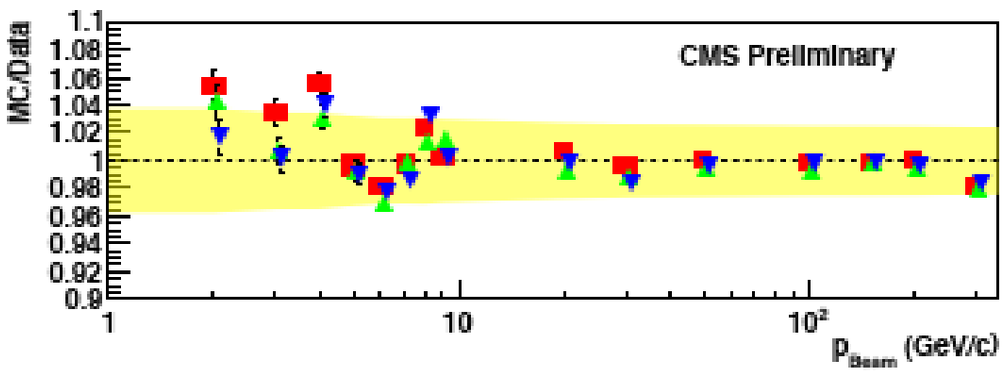
2006 TestBeam Data

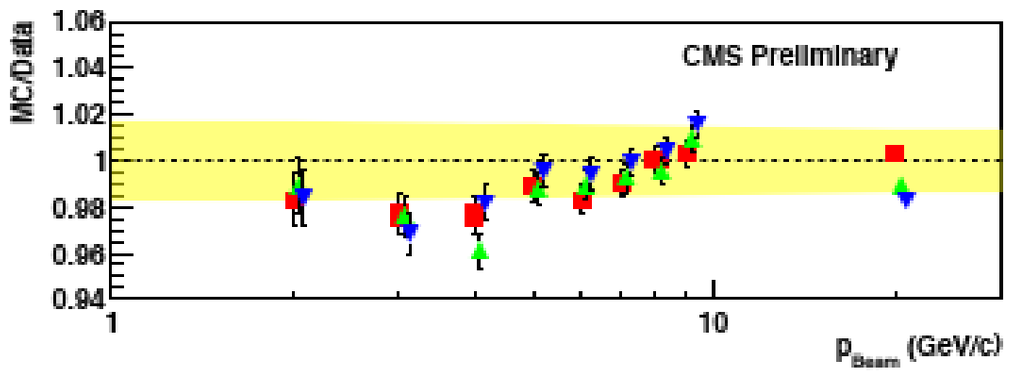
- CMS collected data with prototype of Hadron Calorimeter Barrel and a supermodule of the barrel Electromagnetic Calorimeter in the H2 test beam area at CERN during 2006.
- Special action was taken to go to low energy hadron beam down to 1 GeV using a secondary target
- The analysis utilized particle identification using data from TOF counters and Cherenkov detectors up to 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 and used in many comparisons presented in earlier conference

Pion energy response



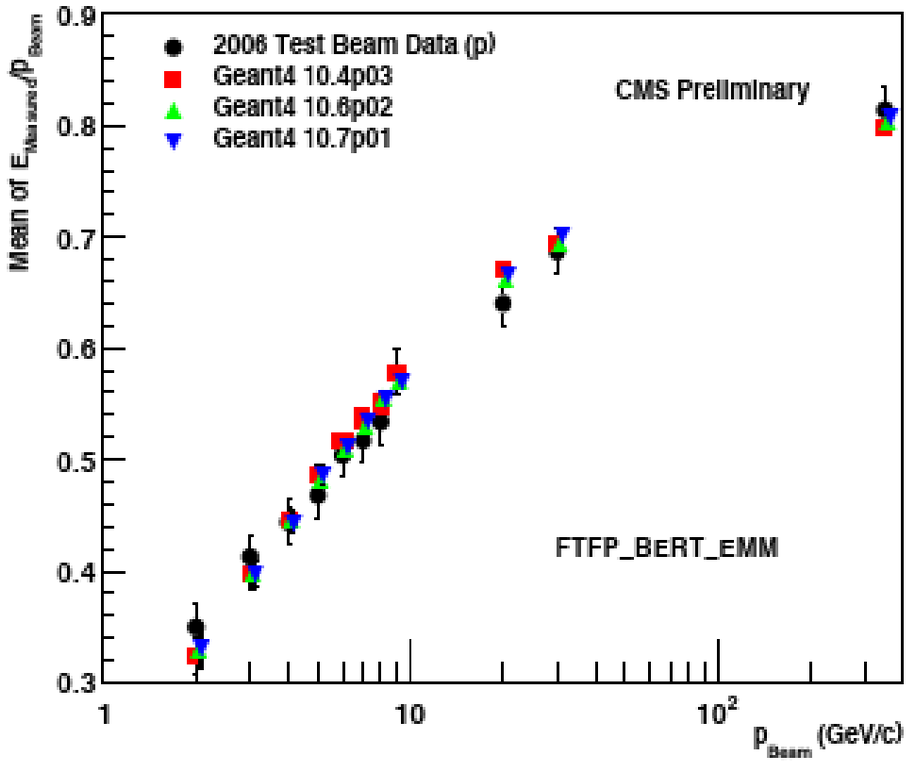


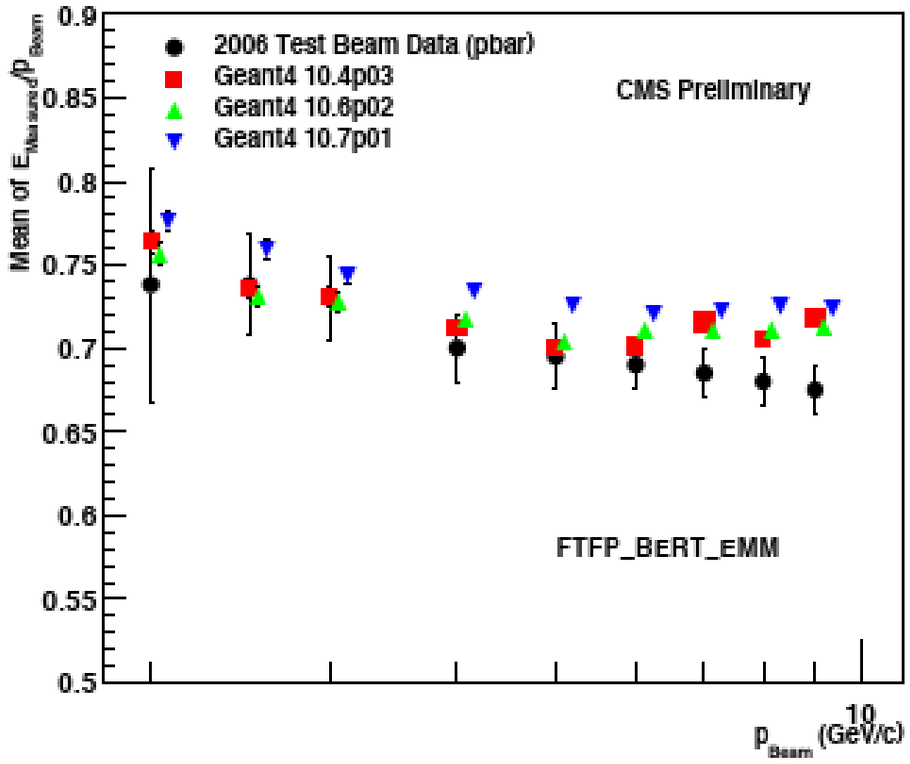


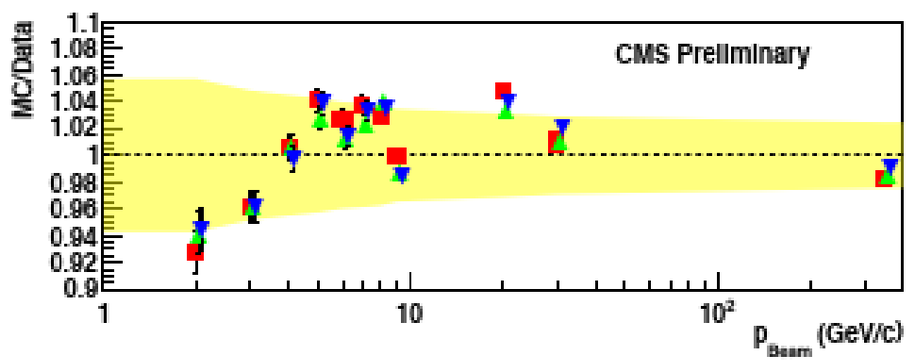


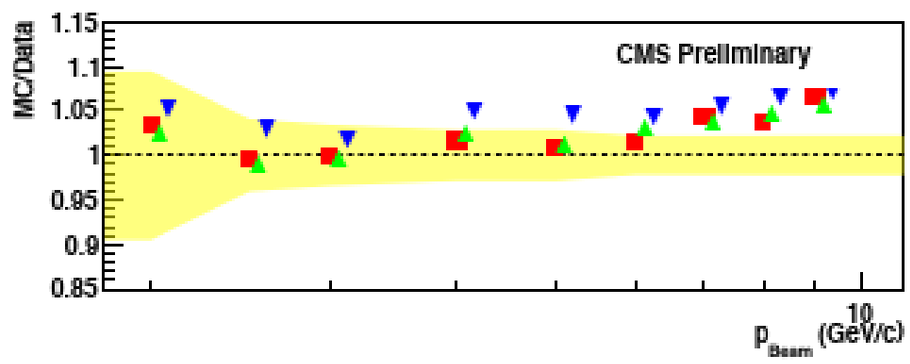
Mean response (top left – negative, top right – positive) as a function of momentum compared to MC predictions; Ratio of MC to data (bottom left – negative, bottom right – positive) as a function of pion momentum

Proton/anti-proton energy response



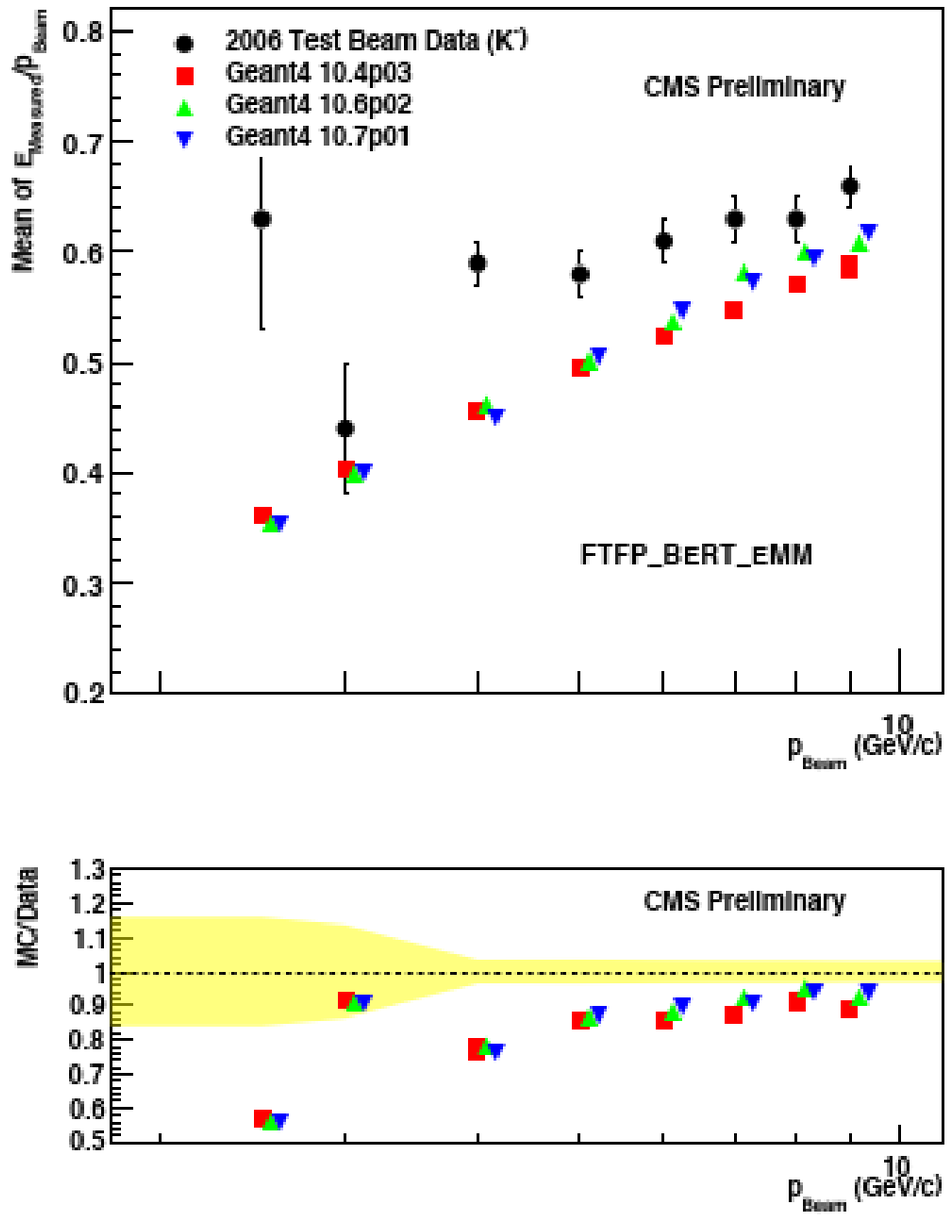


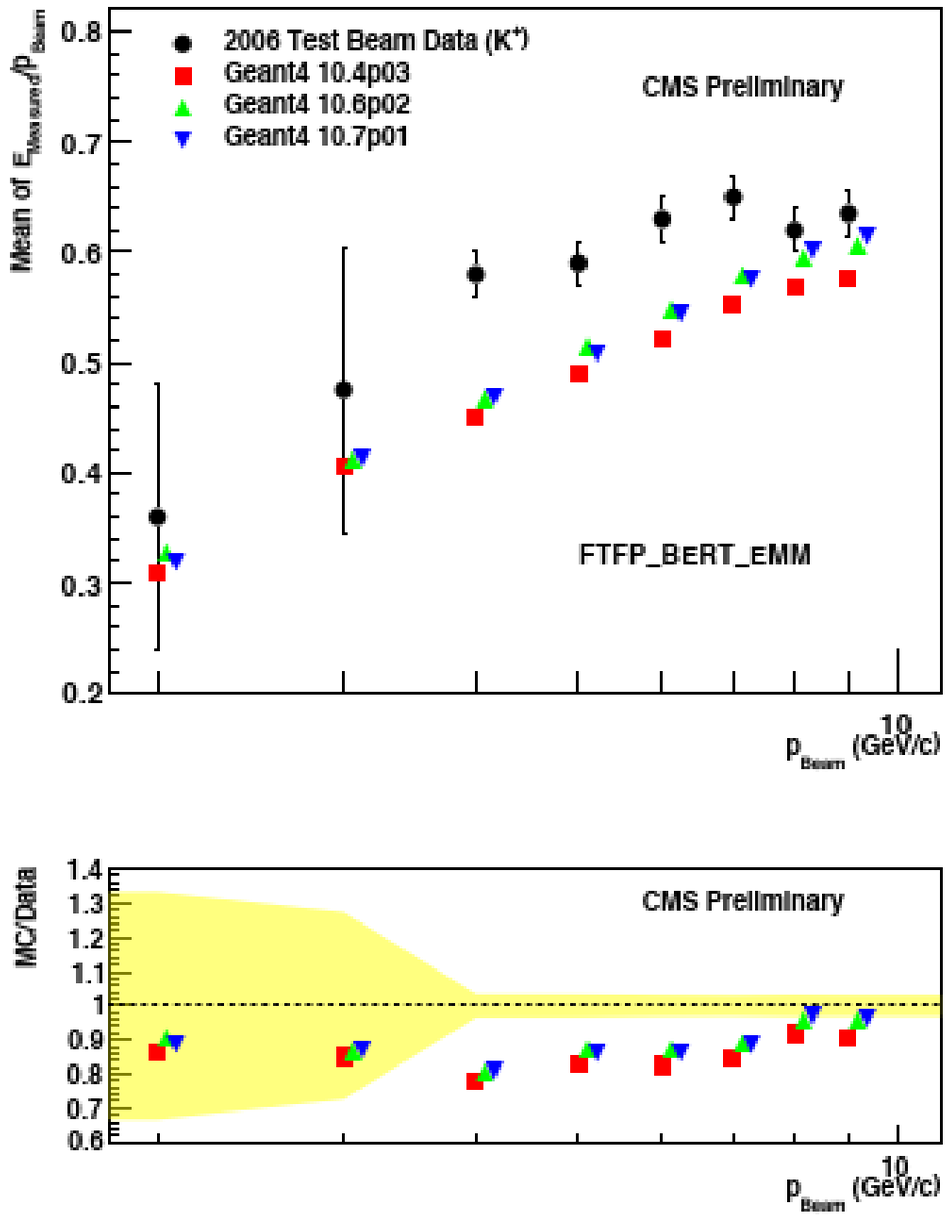




Mean response (top left – p, top right – pbar) as a function of momentum compared to MC predictions; Ratio of MC to data (bottom left – p, bottom right – pbar) as a function of momentum

Kaon energy response





Mean response (top left – negative, top right – positive) as a function of momentum compared to MC predictions; Ratio of MC to data (bottom left – negative, bottom right – positive) as a function of kaon momentum

Summary from Mean Response

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

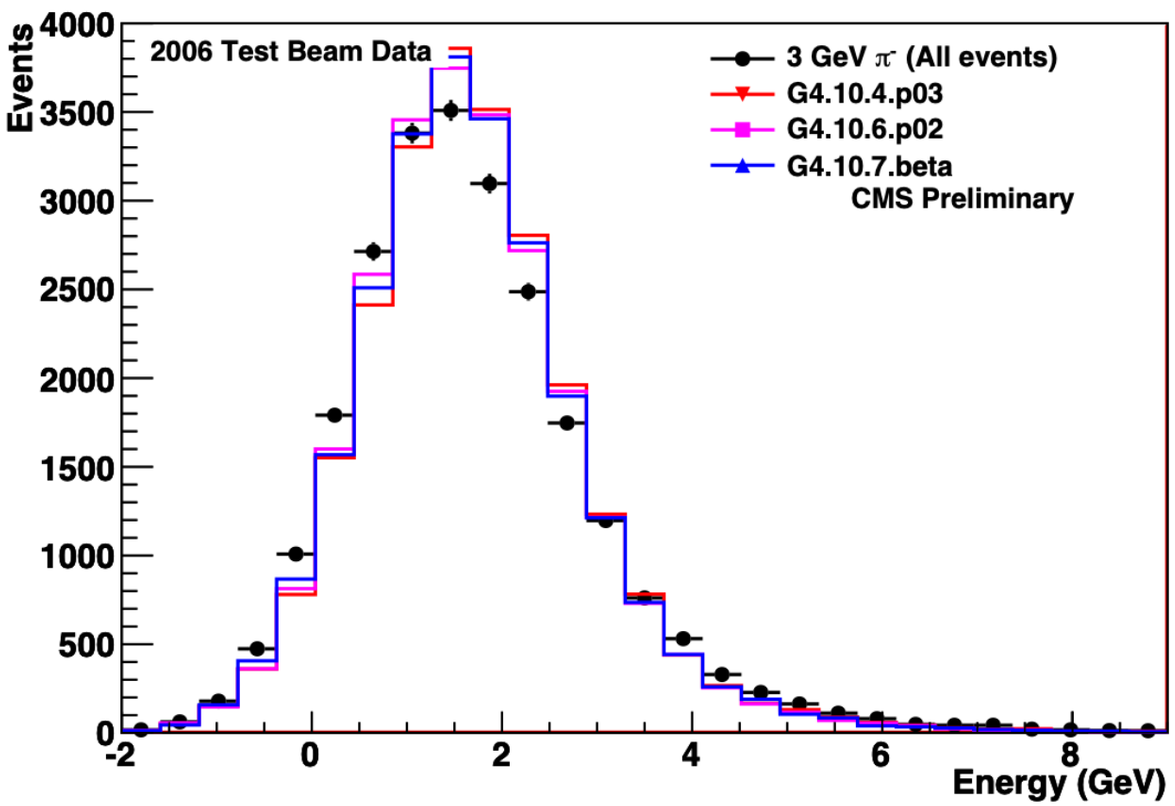
	Negative pions	Positive pions	Negative kaons	Positive kaons	Protons	Anti-protons
10.4.p03	0.45	0.73	26.2	26.8	0.80	1.78
10.6.p02	0.31	1.14	19.4	14.4	0.53	1.81
10.7.p01	0.28	0.93	20.8	14.9	0.63	3.84

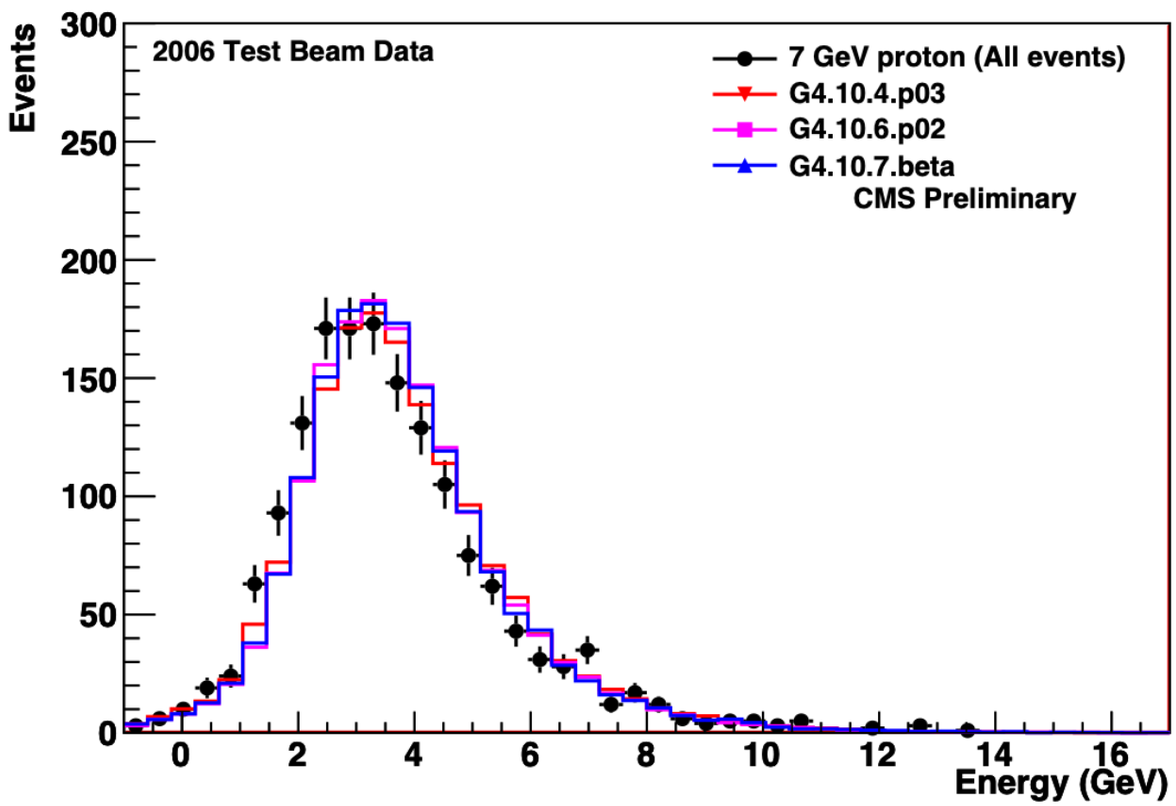
- Level of agreement is good for pions and protons, while it is not good for kaons. Response for pions and kaons are very similar in the data but not in MC.

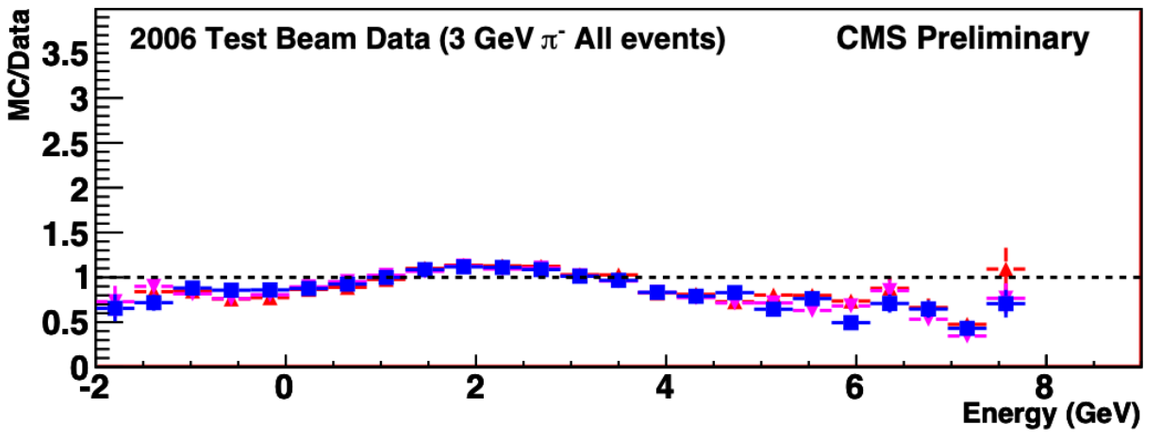
- The predictions from 10.6.p02. and 10.7.1 show some improvement for kaons, some deterioration for positive pions, and acceptable agreement for negative pions, protons and anti-protons. The predictions from 10.7 show improvements for all particles with the exception of anti-protons.

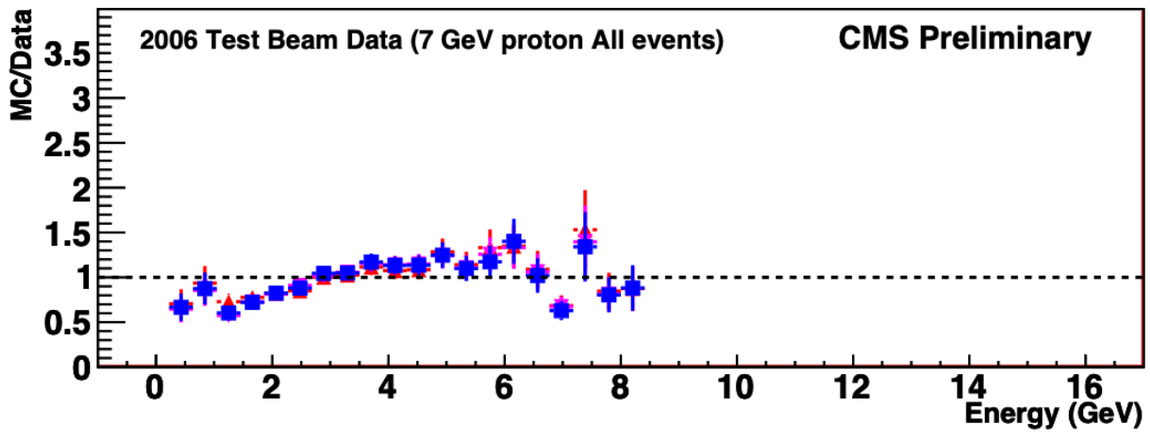
- pp collisions at high energies produce mostly pions. So one expects to have a reasonable agreement between data and MC with the current physics list in the Geant4 version 10.6.p02, 10.7.p01

Energy spectrum for negative pions and protons





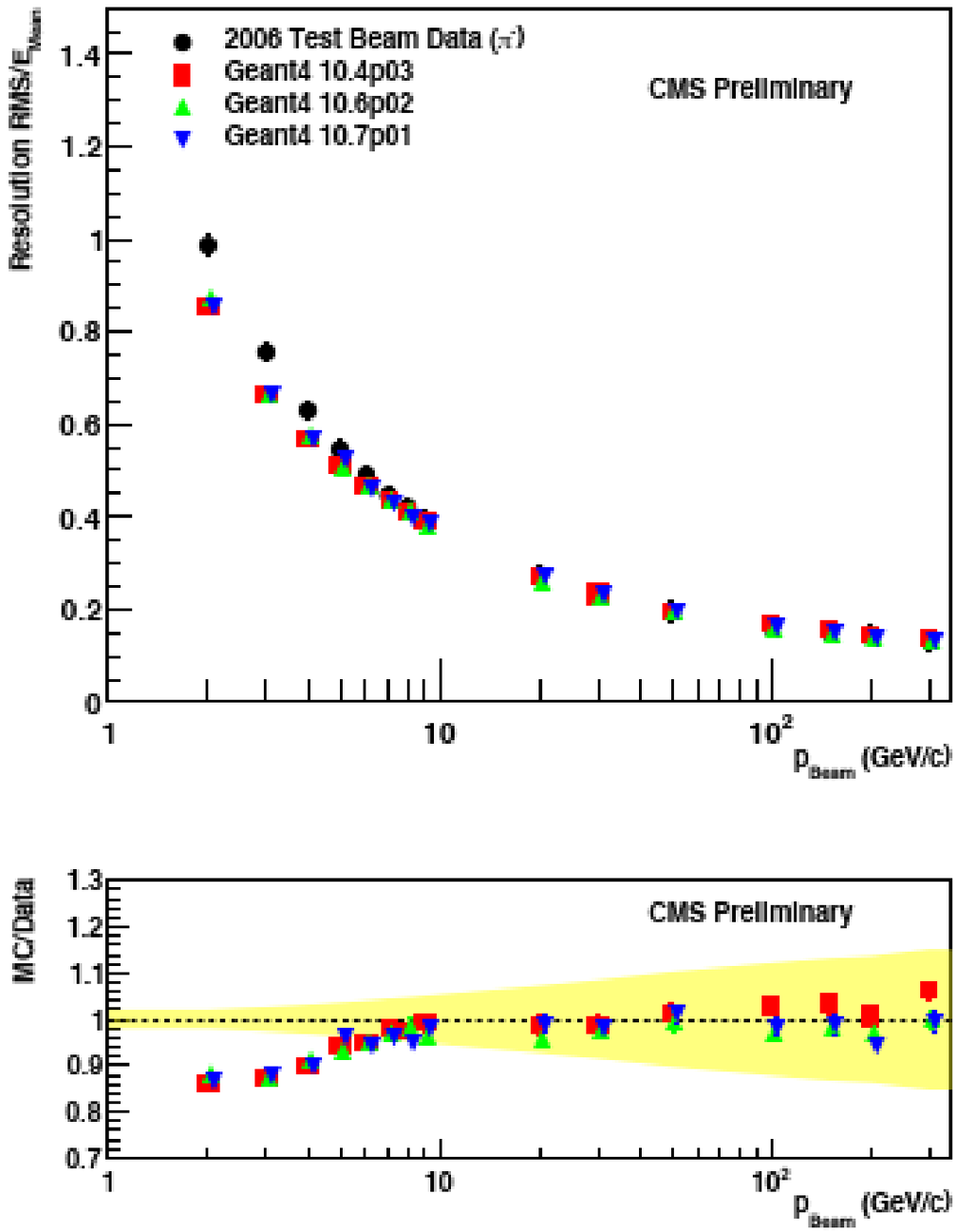




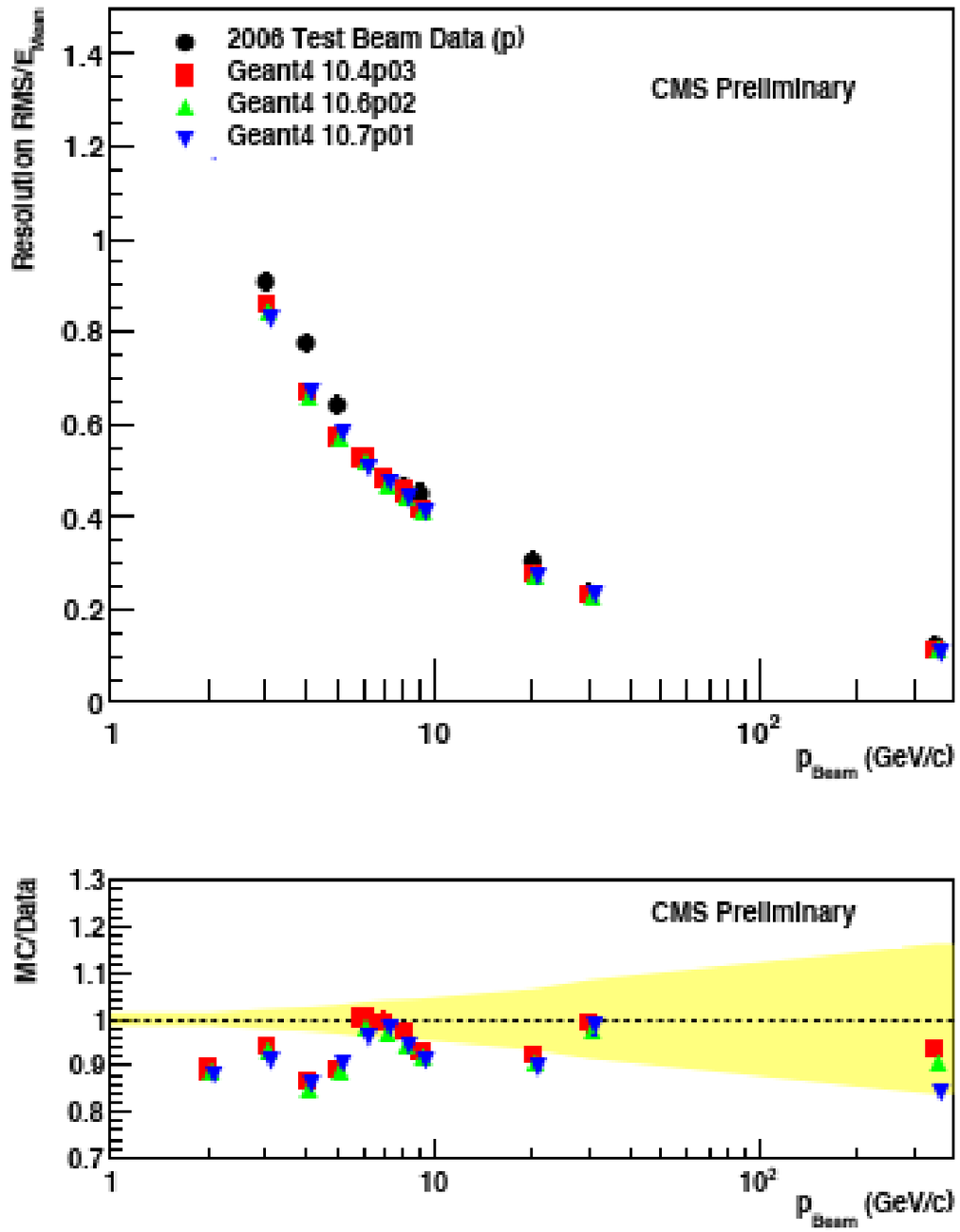
(Top) Energy spectrum for negative pions at 3 GeV compared with MC predictions. (Bottom) Ratio of MC to data for 3 GeV pions

(Top) Energy spectrum for protons at 7 GeV compared with MC predictions. (Bottom) Ratio of MC to data for 7 GeV protons

Energy Resolutions



Energy resolution for negative pions as a function of momentum (top) and ratio of MC to data (bottom)

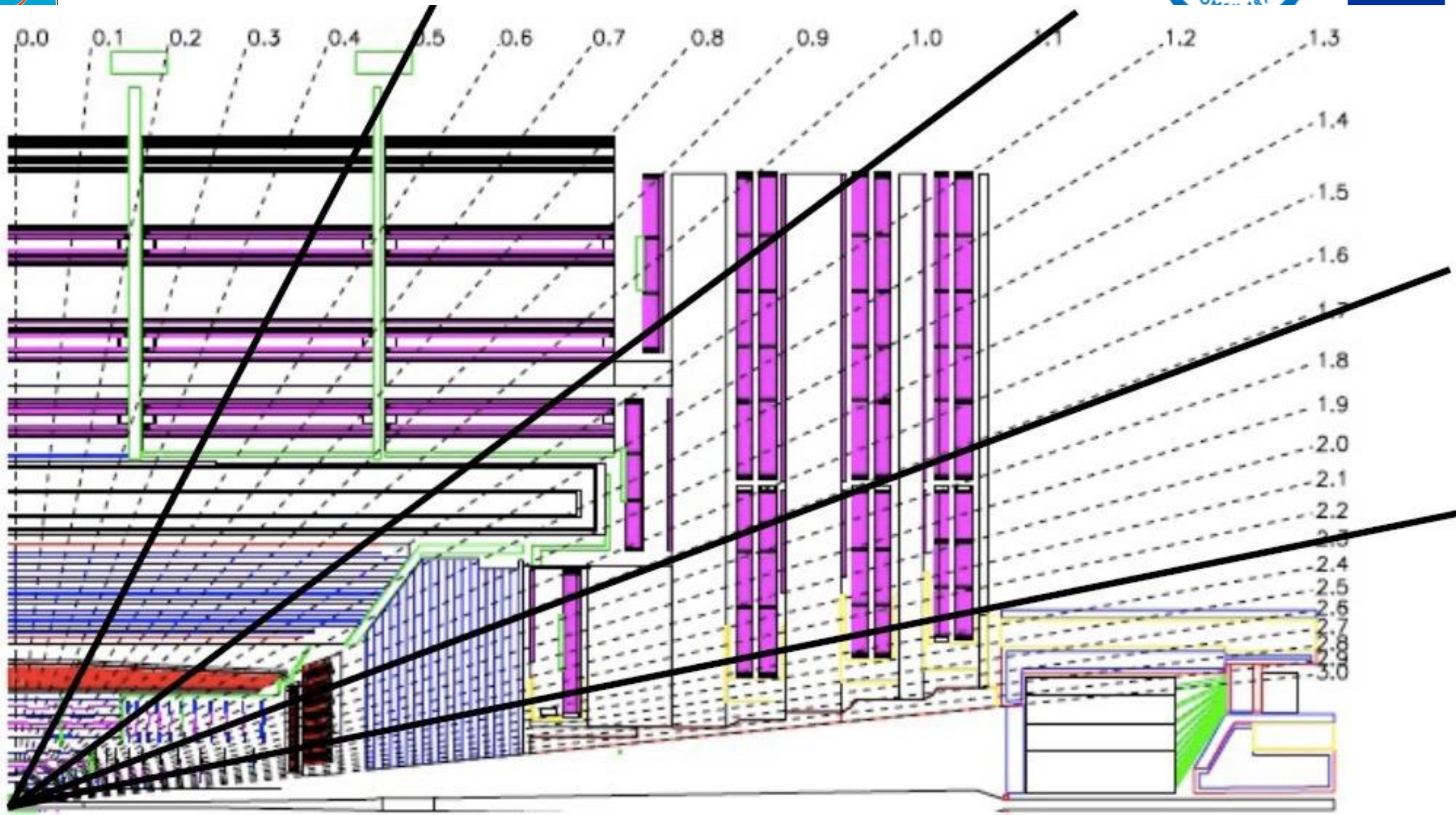


Energy resolution for protons as a function of momentum (top) and ratio of MC to data (bottom)

Isolated Charged Particles

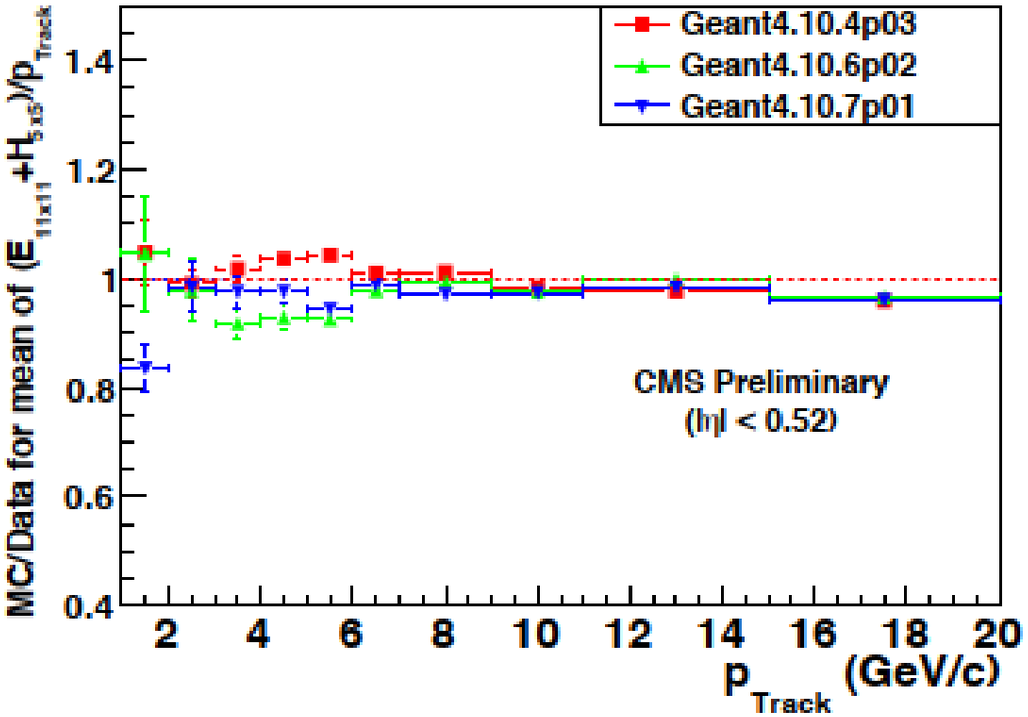
- Compare ratio of calorimeter energy measurement to track momentum for isolated charged hadrons between data and MC
- Select good charged tracks reaching the calorimeter surface
- Impose isolation of these charged particles
  - propagate all tracks to the calorimeter surface and study momentum of tracks (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.

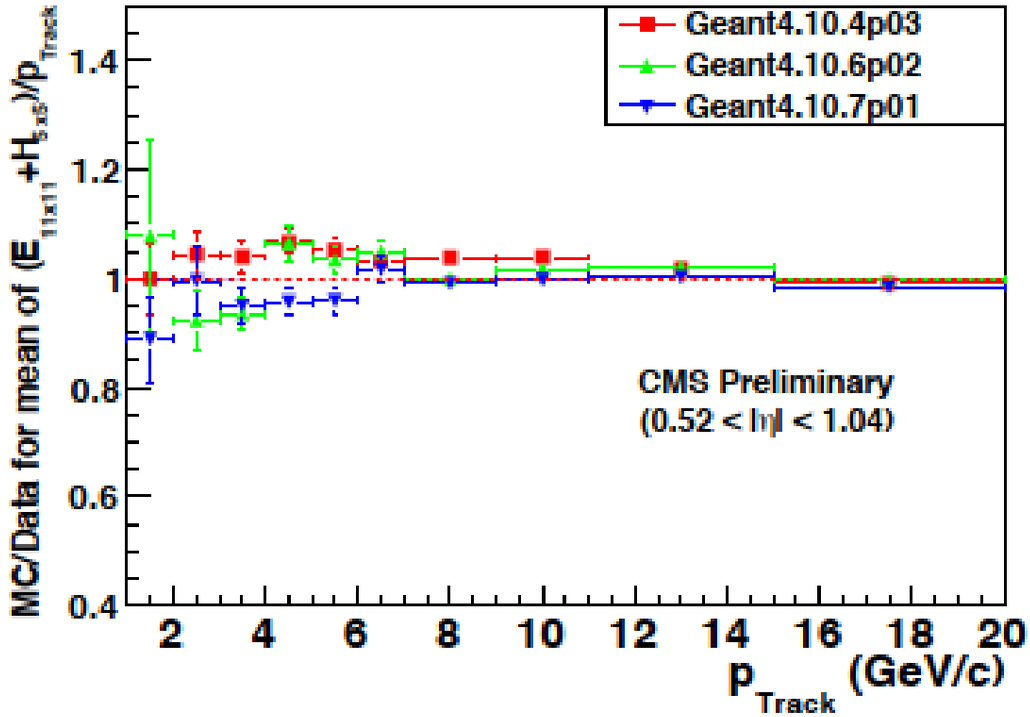
Quadrant of the CMS

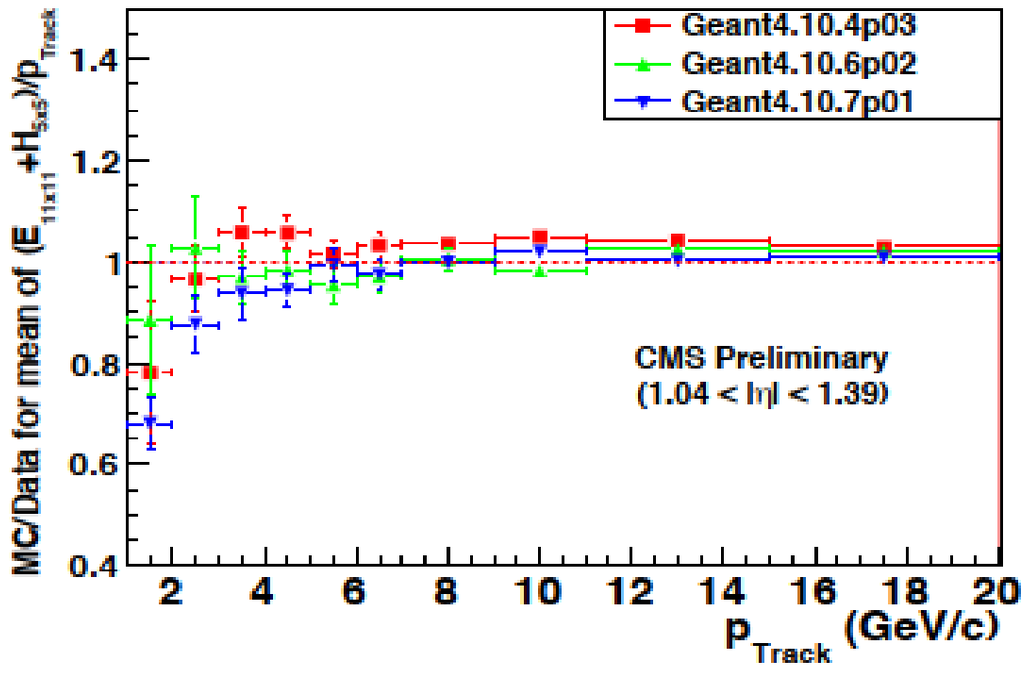


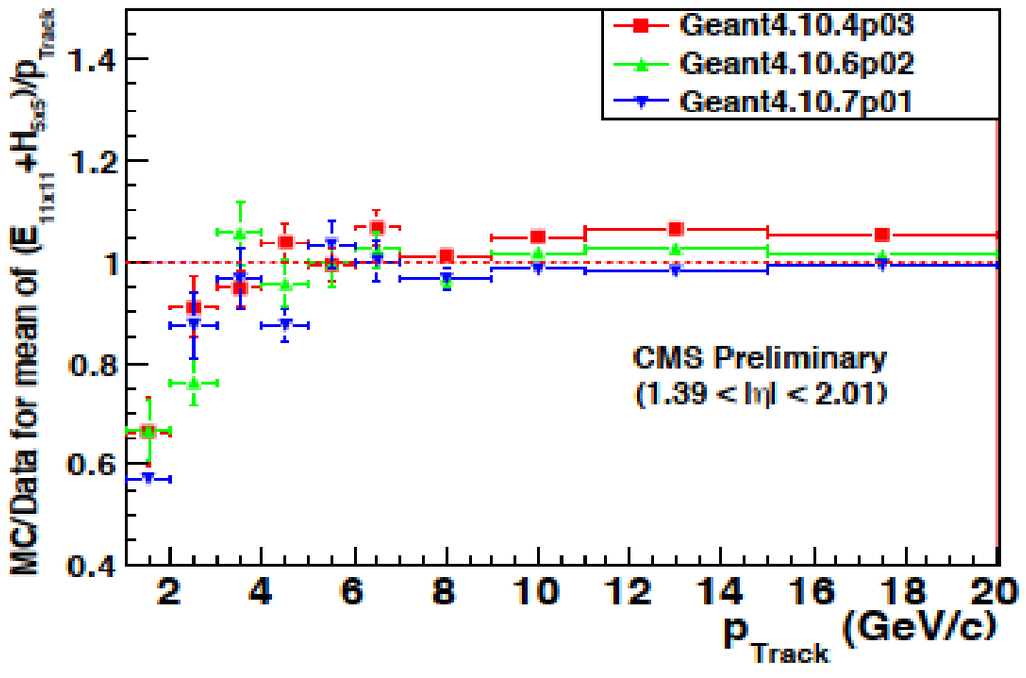
Four partitions in the CMS detector are used in the measurement of calorimeter response

Combined Calorimeter Energy Ratio









Ratio of the mean energy response between MC and data for four regions of CMS

Level of Disagreement

- Level of (dis)agreement is calculated from the deviation of the ratio (Data/MC) from 1.0

- The mean level of disagreement between data and MC is between 0.9% and 3.0% in the version 10.6.p02 and between 1.3% and 3.5% for 10.7, depending on the region of the detector. It is at a similar level for the version 10.4.p03

	$(E_{7x7}+H_{3x3})/p$ 10.4.p03	$(E_{7x7}+H_{3x3})/p$ 10.6.p02	$(E_{7x7}+H_{3x3})/p$ 10.7	$(E_{11x11}+H_{5x5})/p$ 10.4.p03	$(E_{11x11}+H_{5x5})/p$ 10.6.p02	$(E_{11x11}+H_{5x5})/p$ 10.7
Barrel 1	(2.3±0.4)%	(2.5±0.4)%	(1.8±0.4)%	(2.7±0.4)%	(2.6±0.4)%	(1.9±0.4)%
Barrel 2	(3.1±0.4)%	(1.0±0.4)%	(1.8±0.4)%	(2.1±0.4)%	(0.9±0.4)%	(1.5±0.4)%
Transition	(6.5±0.5)%	(1.3±0.5)%	(3.5±0.5)%	(4.7±0.5)%	(1.2±0.5)%	(3.0±0.5)%
Endcap	(5.8±0.5)%	(3.0±0.5)%	(1.7±0.5)%	(5.3±0.5)%	(1.9±0.5)%	(1.3±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, the version 10.4.p03 was used. CMS plan to use 10.7.p02 for Run3 initial physics studies

- 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
  - More accurate pions and protons
  - Less accurate pbar and kaons

- Different Geant4 versions are tested by comparing their predictions with some controlled measurements of single particle response. All 3 versions (10.4.p03, 10.6.p02 and 10.7.p01) provide good agreement with the data