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The Compact Muon Solenoid Experiment

CMS Performance Note

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Validation of Physics Models of Geant4 using data from CMS Experiment

The CMS Collaboration

Abstract

In the simulation of the CMS experiment, a specific Geant4 physics configuration (Physics List), tuned with dedicated test beam experiments, is used. Test beam data provide measurements of energy response of the calorimeter as well as resolution for well identified charged hadrons over a large energy region. CMS continues to validate the physics models inside Geant4 using the test beam data as well as collision data from the Large Hadron Collider. Isolated charged particles are measured simultaneously in the tracker as well as in the calorimeters. These events are selected using dedicated triggers and are used to measure the response in the calorimeter. Different versions of Geant4 (10.2.patch02, 10.4.patch03, 10.6.patch02) have been used by CMS for its Monte Carlo productions and a new version (10.7.beta) is now considered for future productions. A detailed comparison between data and Geant4 predictions are presented.

Validation of Physics Models of Geant4 using data from CMS Experiment

The CMS Collaboration

3 November 2020

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Introduction

- CMS Simulation application is based on Geant4 [1-3]
  - Currently CMS uses the version Geant4.10.6.p02 by default
  - For MC production of the final ("Legacy") Run2 analysis the version Geant4.10.4.p03 is used
  - CMS is considering to use Geant4.10.7 for Run3 MC production. This version is due by end of 2020. CMS continually evaluates Geant4 developments and reports here the performance of the release version Geant4.10.7.beta.
- 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) [4]
  - Collision data from the CMS experiment [5] utilizing zero bias or minimum bias triggers from low luminosity runs
- The comparisons may be used to improve the quality of Geant4 predictions of the future release

Geant4 in CMS

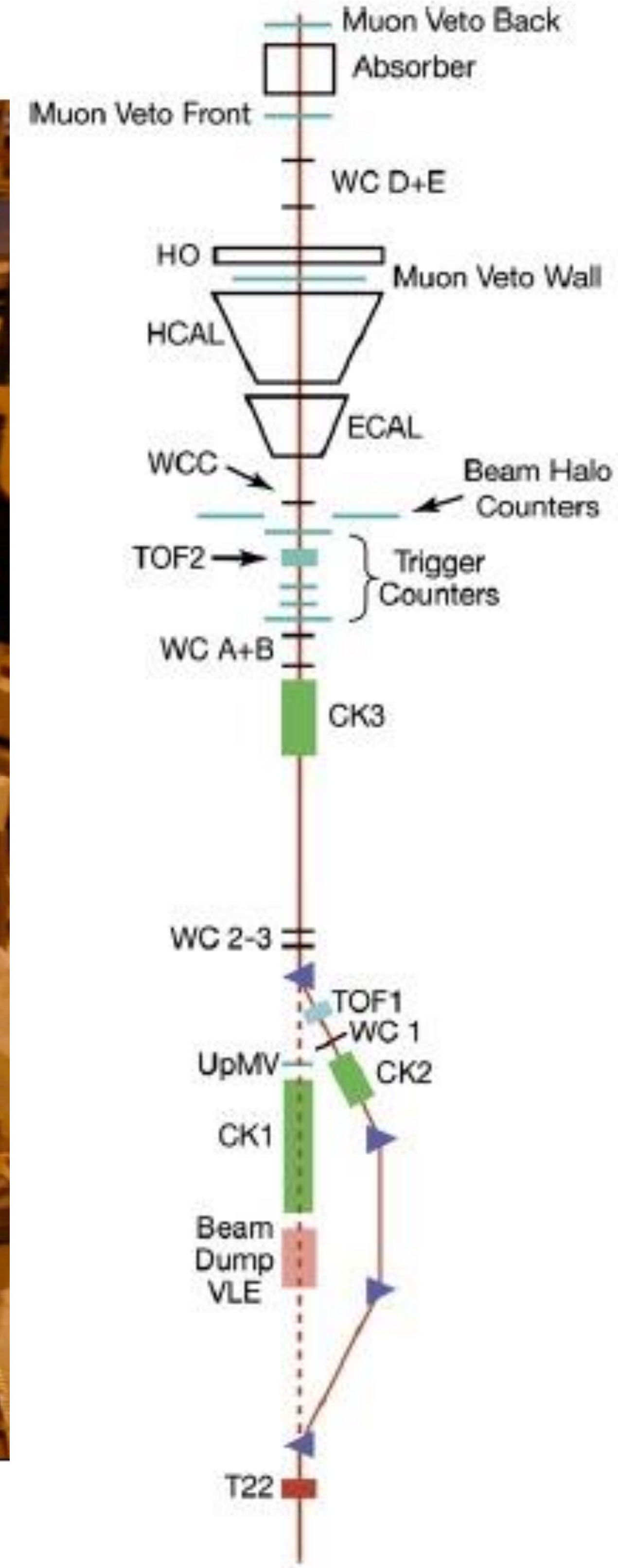
- CMS is planning to use the same physics list for ultra legacy as well as Run3 production
  - FTFP_BERT_EMM

- 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:
    - Bertini Cascade valid at ≤ 12 GeV
    - FTFP valid at ≥ 3 GeV
- and in version Geant4.10.6.p02 and Geant4.10.7.beta:
    - Bertini Cascade valid at ≤ 12 GeV for pions and ≤ 6 GeV for all other hadrons
    - FTFP valid at ≥ 3 GeV

- EMM specify 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.beta
  - Default values for Birk's constants for HCAL used to be
    - C1 = 0.0052; C2 = 0.142; C3 = 1.75
  - The tuned set is
    - C1 = 0.006; C2 = 0.142; C3 = 1.75

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.

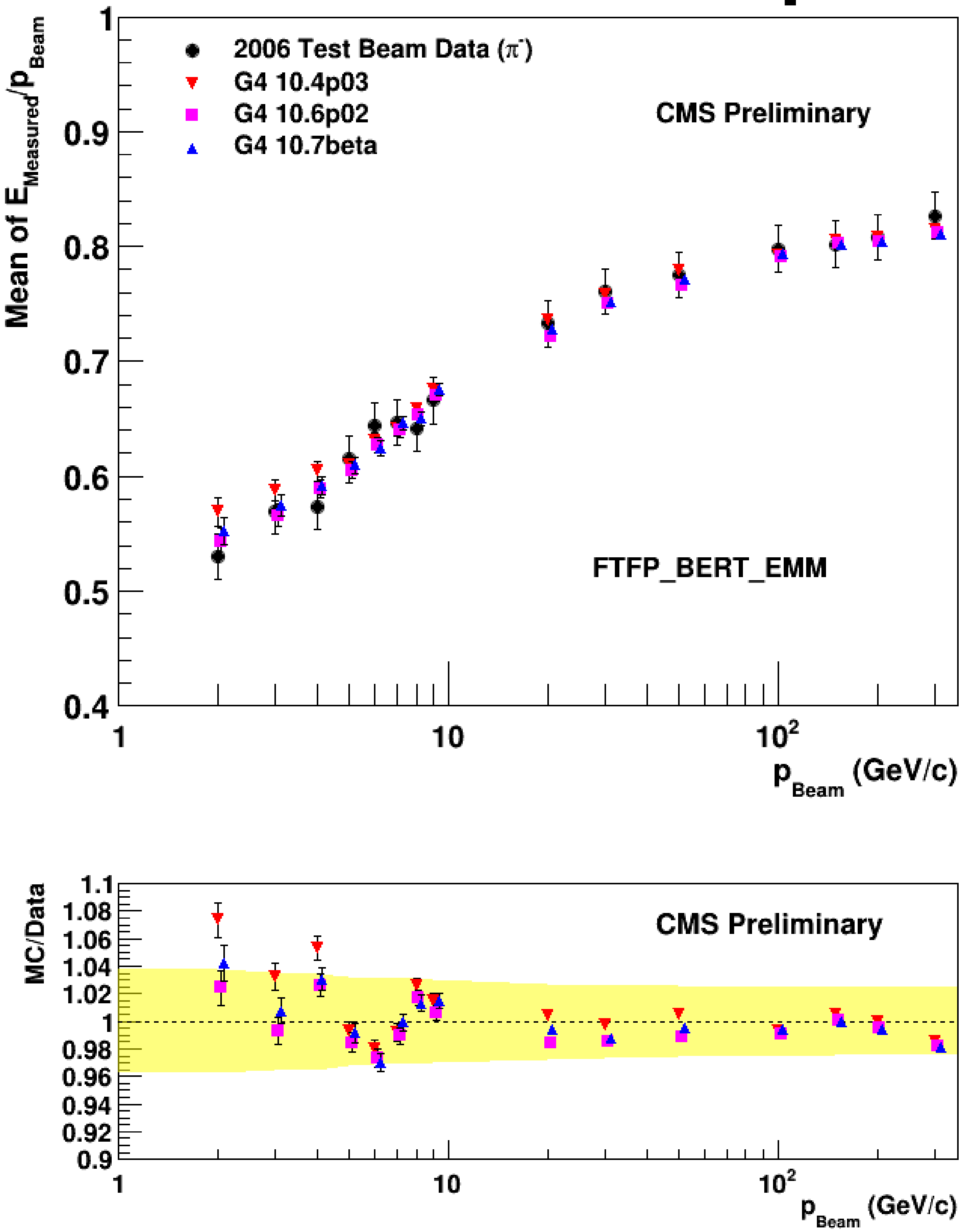
- Special action was taken to go to low energy hadron beam down to 1 GeV using a secondary target

- The analysis utilized particle identification using data from TOF counters and Cherenkov detectors up to energy of 9 GeV

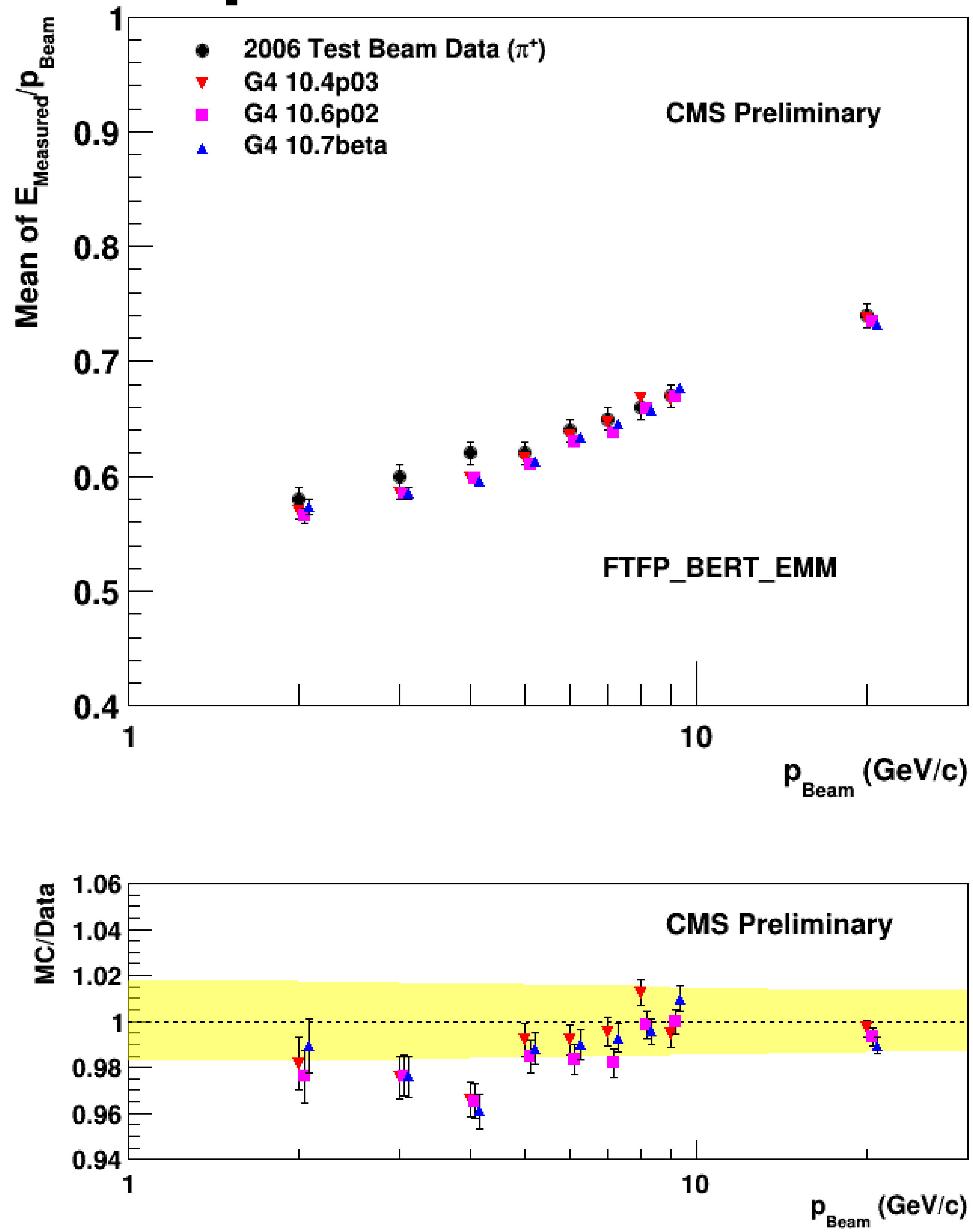
- The results consist of mean energy response (measured as the ratio of the total energy in the calorimeter to the beam momentum) as a function of beam momentum for different beam types, the energy resolution and some energy distributions for particles of a given type at a given momentum

- Results from this test beam were published [3] and used in many comparisons presented in earlier conference

Mean response with pions

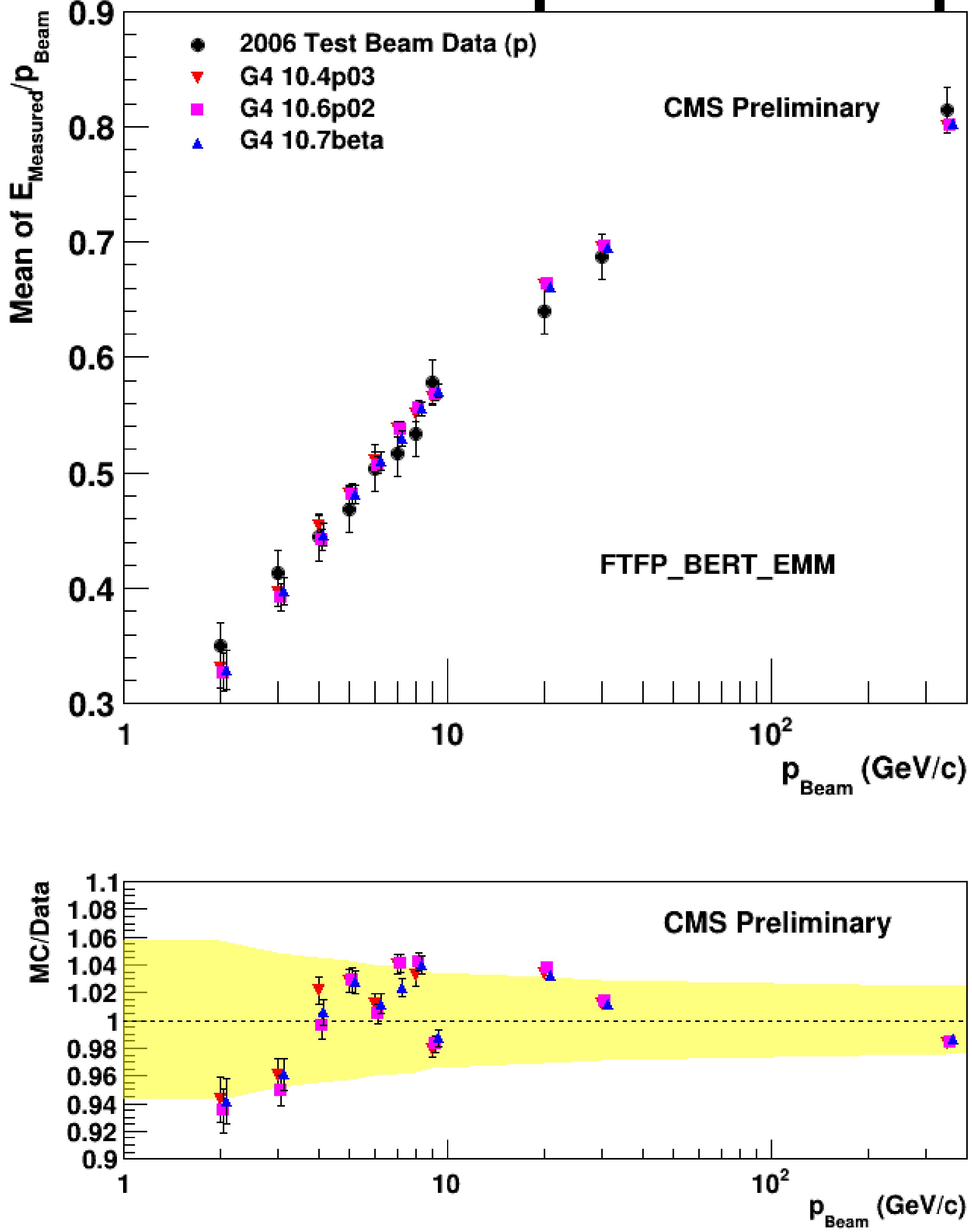


(Top) Mean response for negative pions as a function of momentum compared to MC predictions; (bottom) Ratio of MC to data for negative pions as a function of momentum

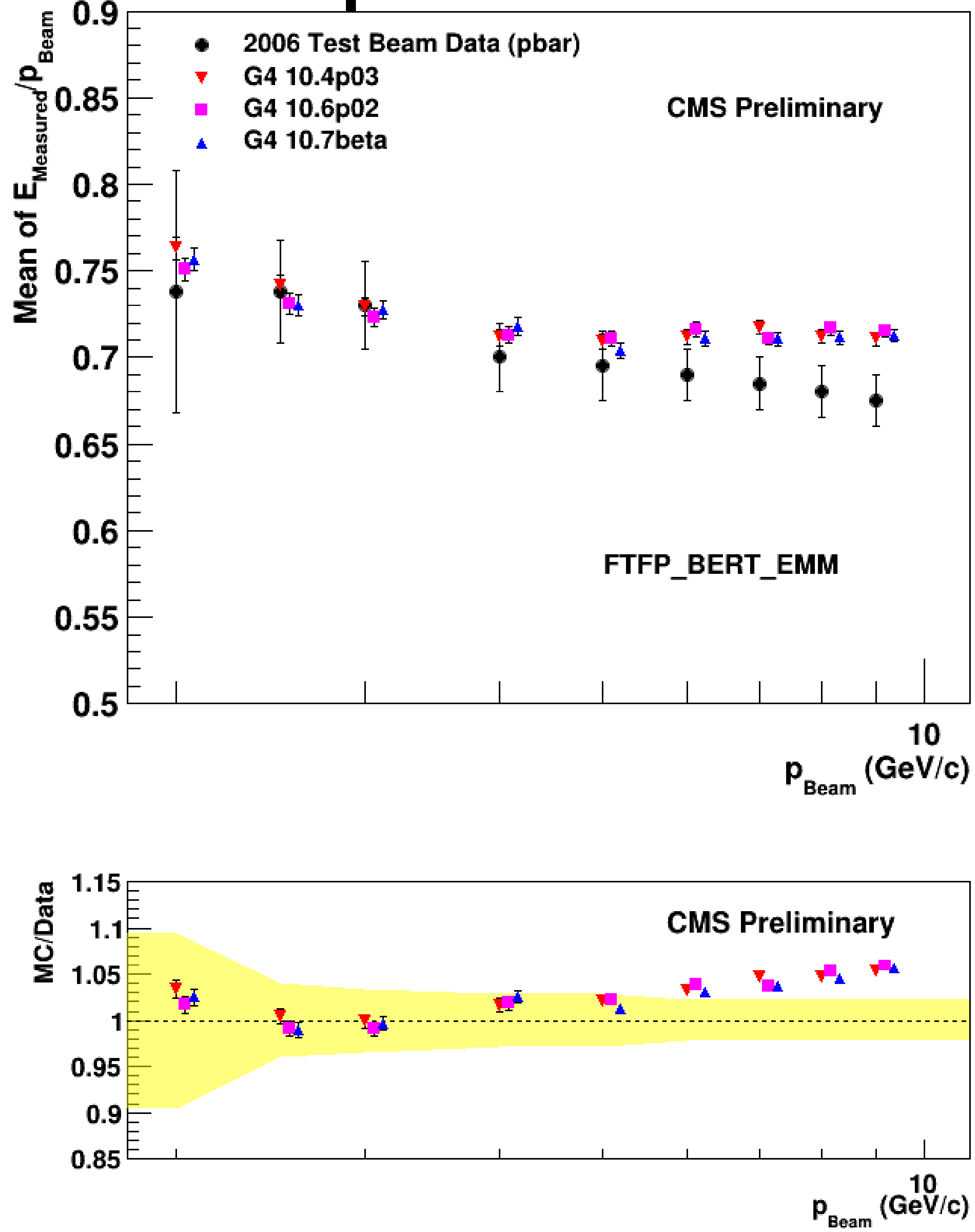


(Top) Mean response for positive pions as a function of momentum compared to MC predictions; (bottom) Ratio of MC to data for positive pions as a function of momentum

Mean response with protons/antiprotons

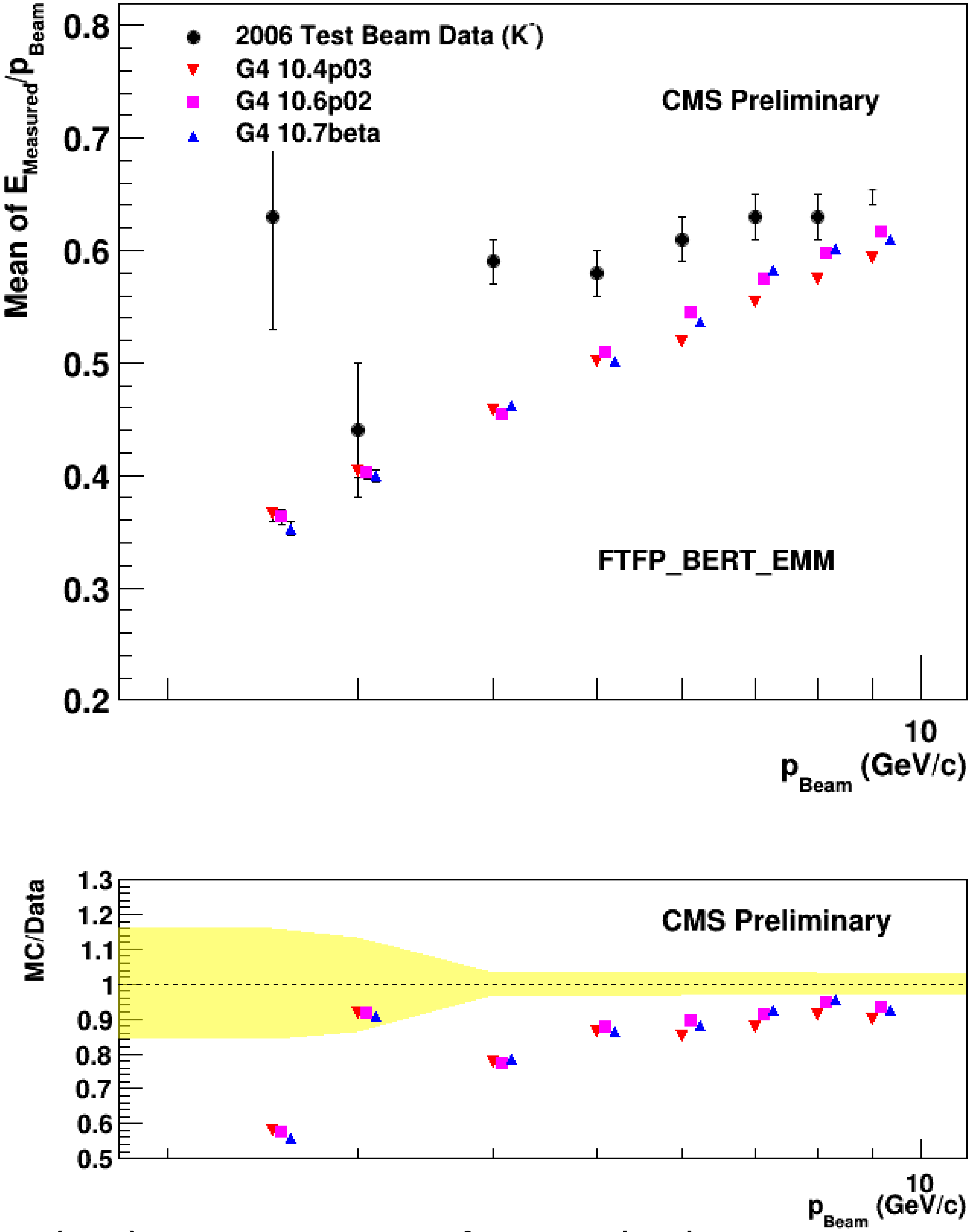


(Top) Mean response for protons as a function of momentum compared to MC predictions; (bottom) Ratio of MC to data for protons as a function of momentum

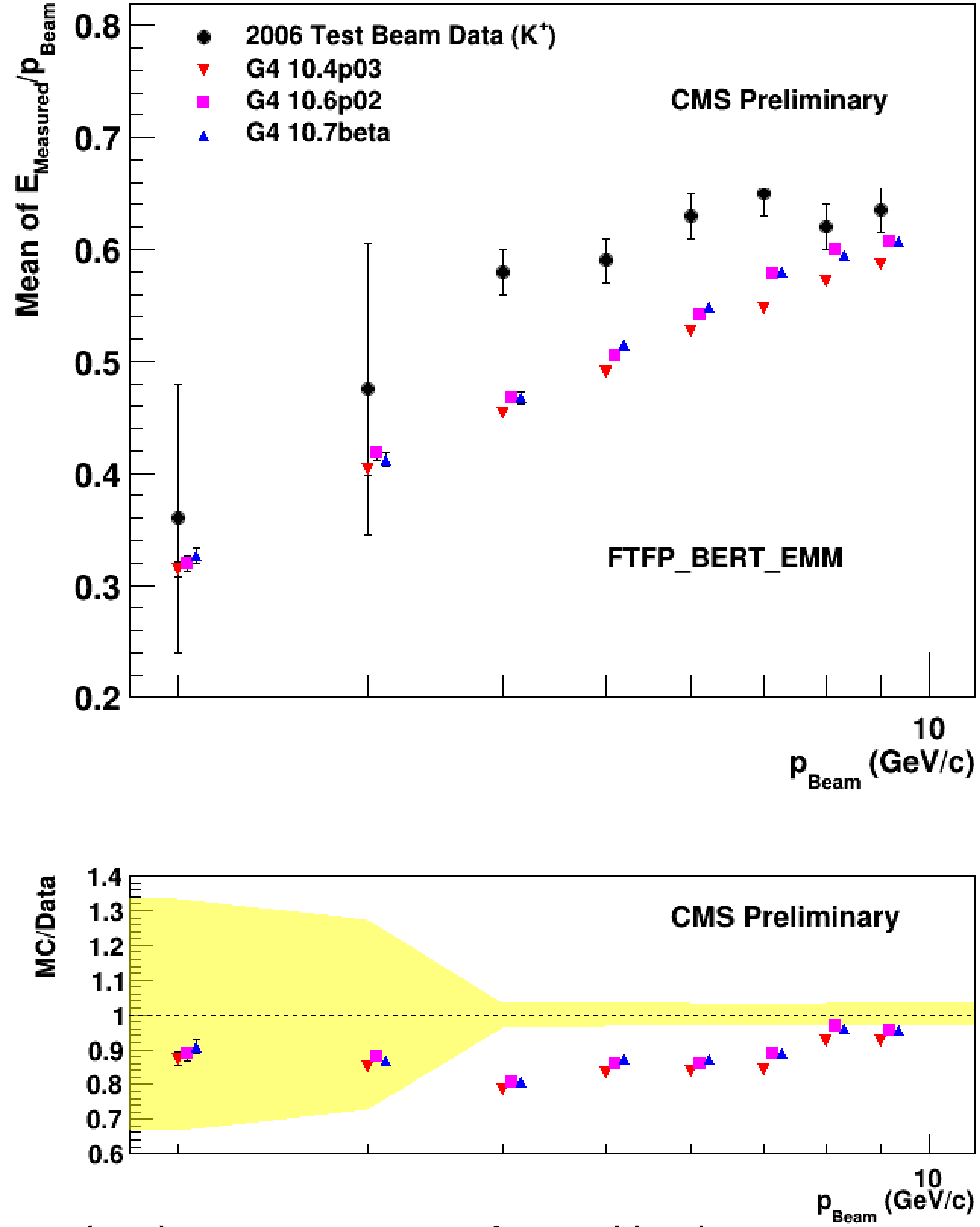


(Top) Mean response for anti-protons as a function of momentum compared to MC predictions; (bottom) Ratio of MC to data for anti-protons as a function of momentum

Mean Response for kaons



(Top) Mean response for negative kaons as a function of momentum compared to MC predictions; (bottom) Ratio of MC to data for negative kaons as a function of momentum



(Top) Mean response for positive kaons as a function of momentum compared to MC predictions; (bottom) Ratio of MC to data for positive kaons as a function of momentum

Summary from Mean Response

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

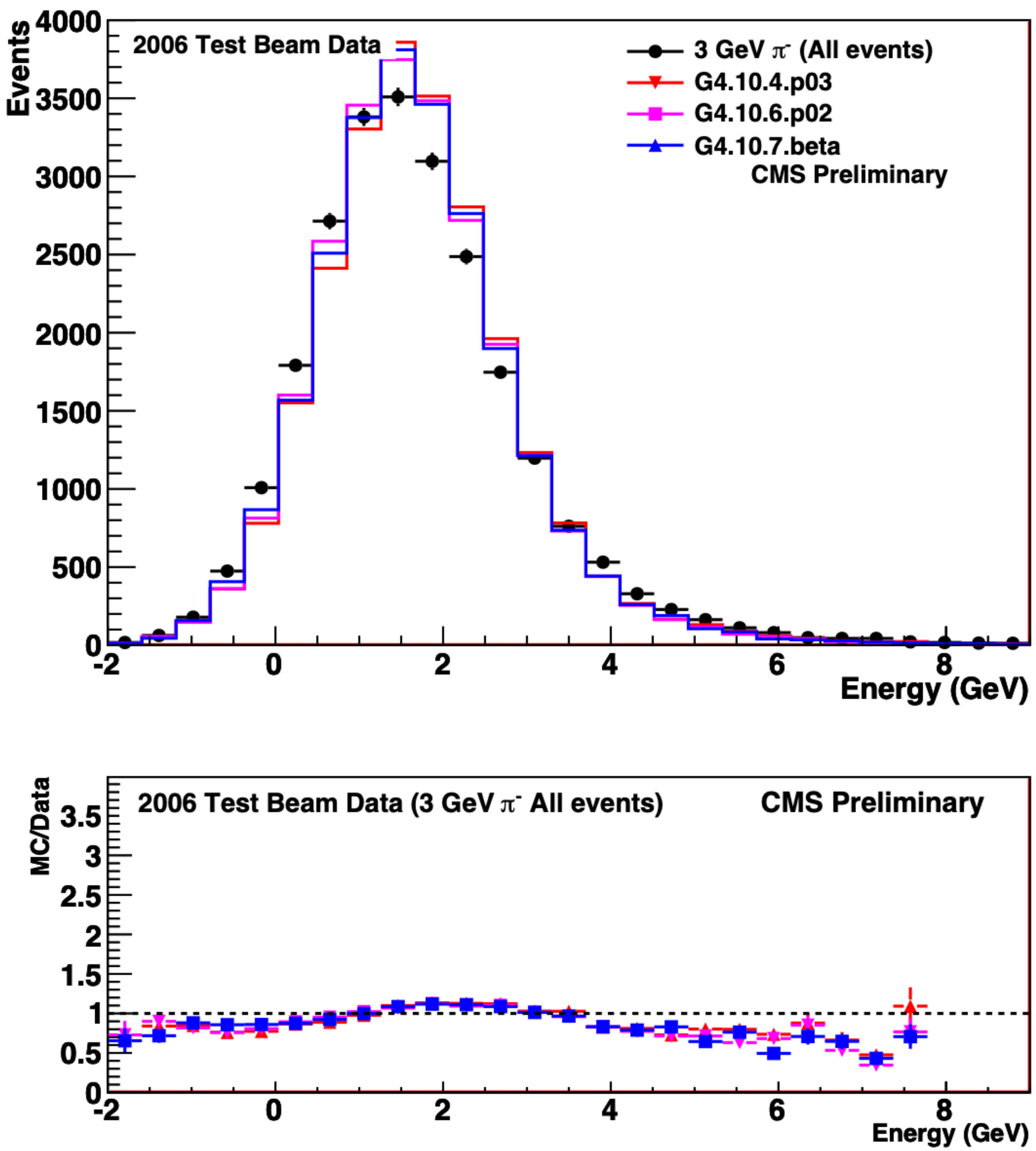
	negative pions	positive pions	negative kaons	positive kaons	protons	anti-protons
G4 10.4.p03 FTFP_BERT_EMM	0.54	0.96	24.5	25.0	0.61	1.93
G4 10.6.p02 FTFP_BERT_EMM	0.26	1.29	19.4	15.8	0.73	2.19
G10.7.beta FTFP_BERT_EMM	0.31	1.14	14.4	19.4	0.53	1.81

- 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.

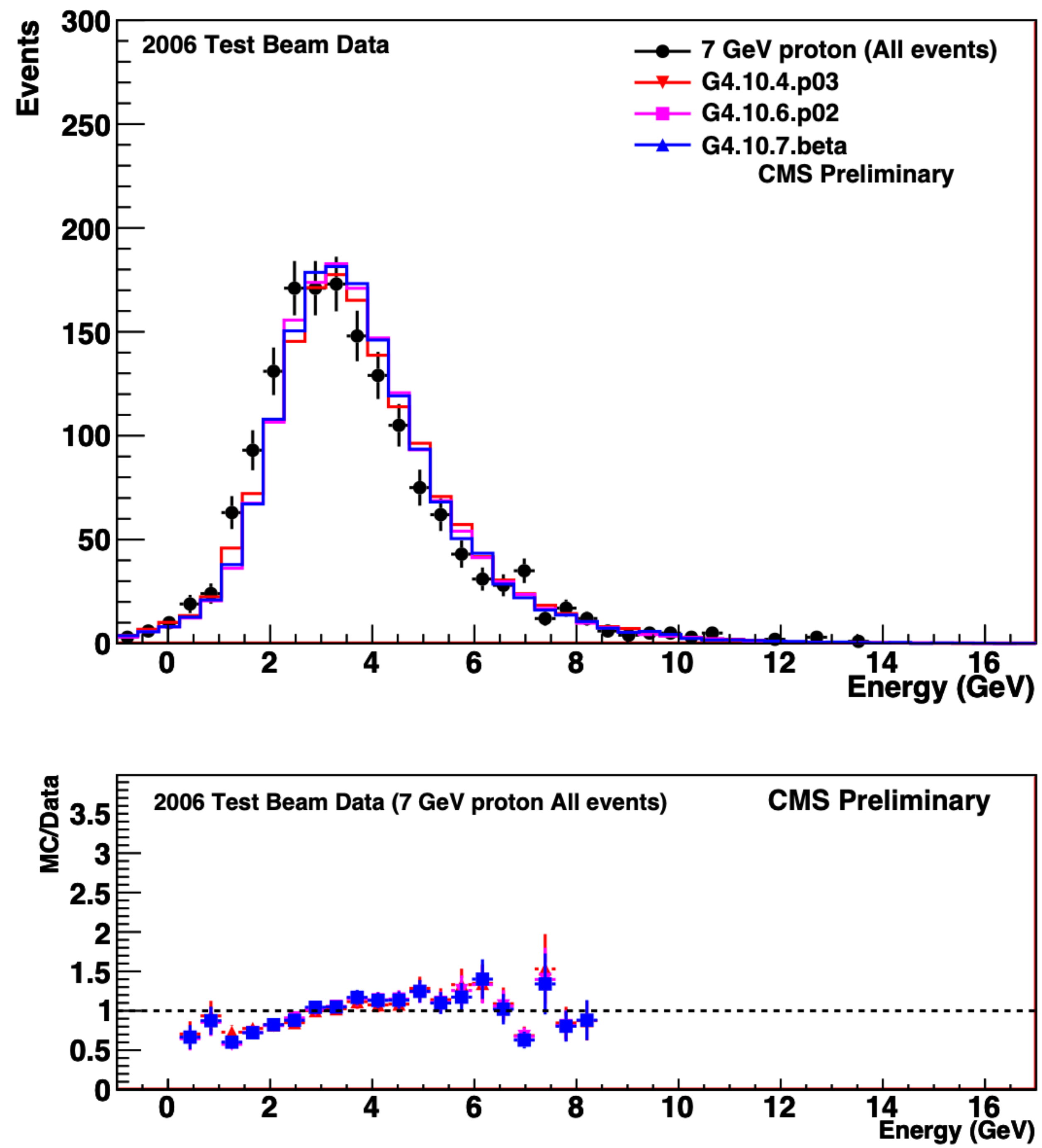
- The predictions from 10.6.p02 and 10.7.beta show some improvement for kaons, some deterioration for positive pions, and acceptable agreement for negative pions, protons and anti-protons

- 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 and 10.7.beta

Energy for negative pions and protons

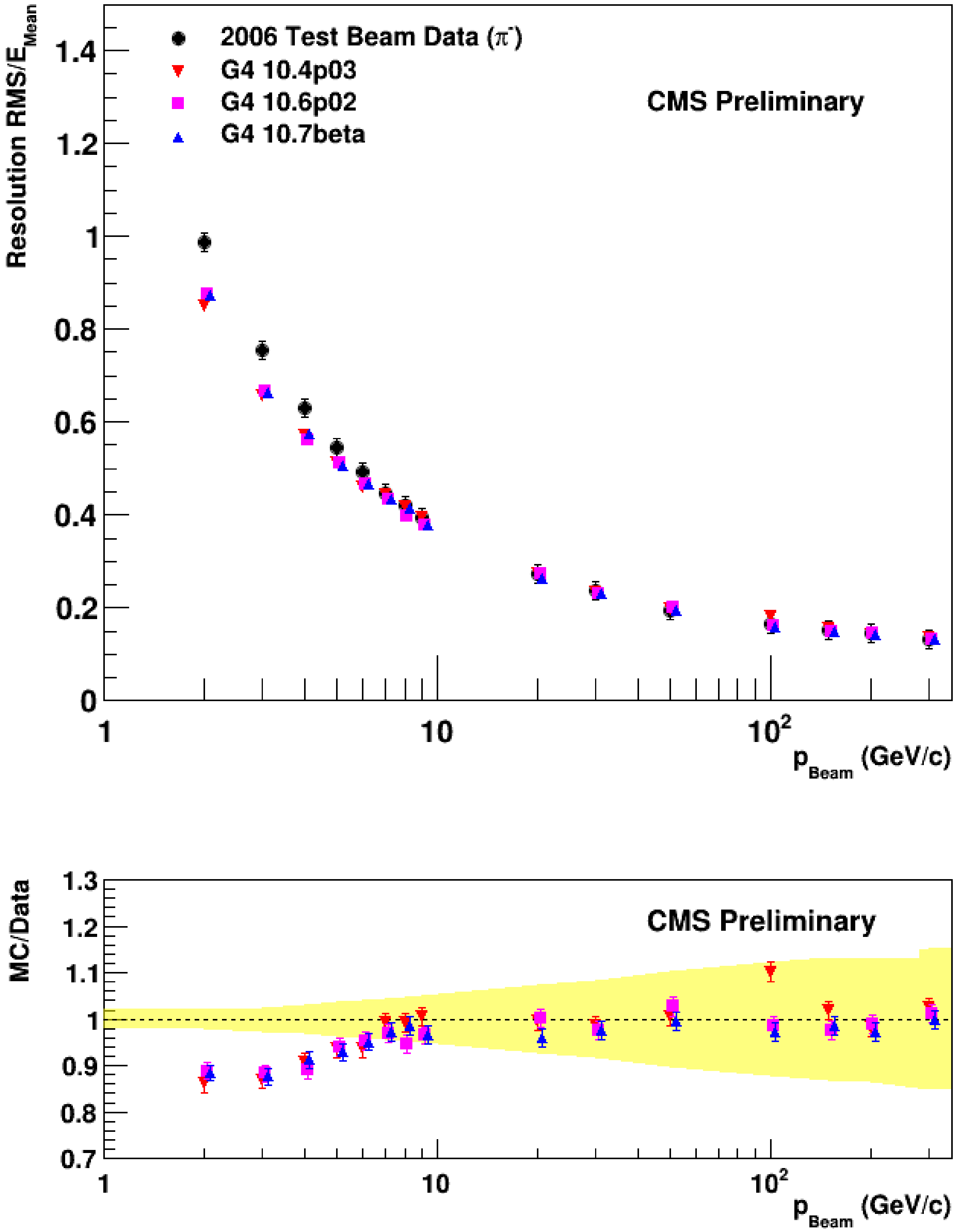


(Top) Energy spectrum for negative pions at 3 GeV compared with MC predictions. (Bottom) Ratio of MC to data for 3 GeV pions

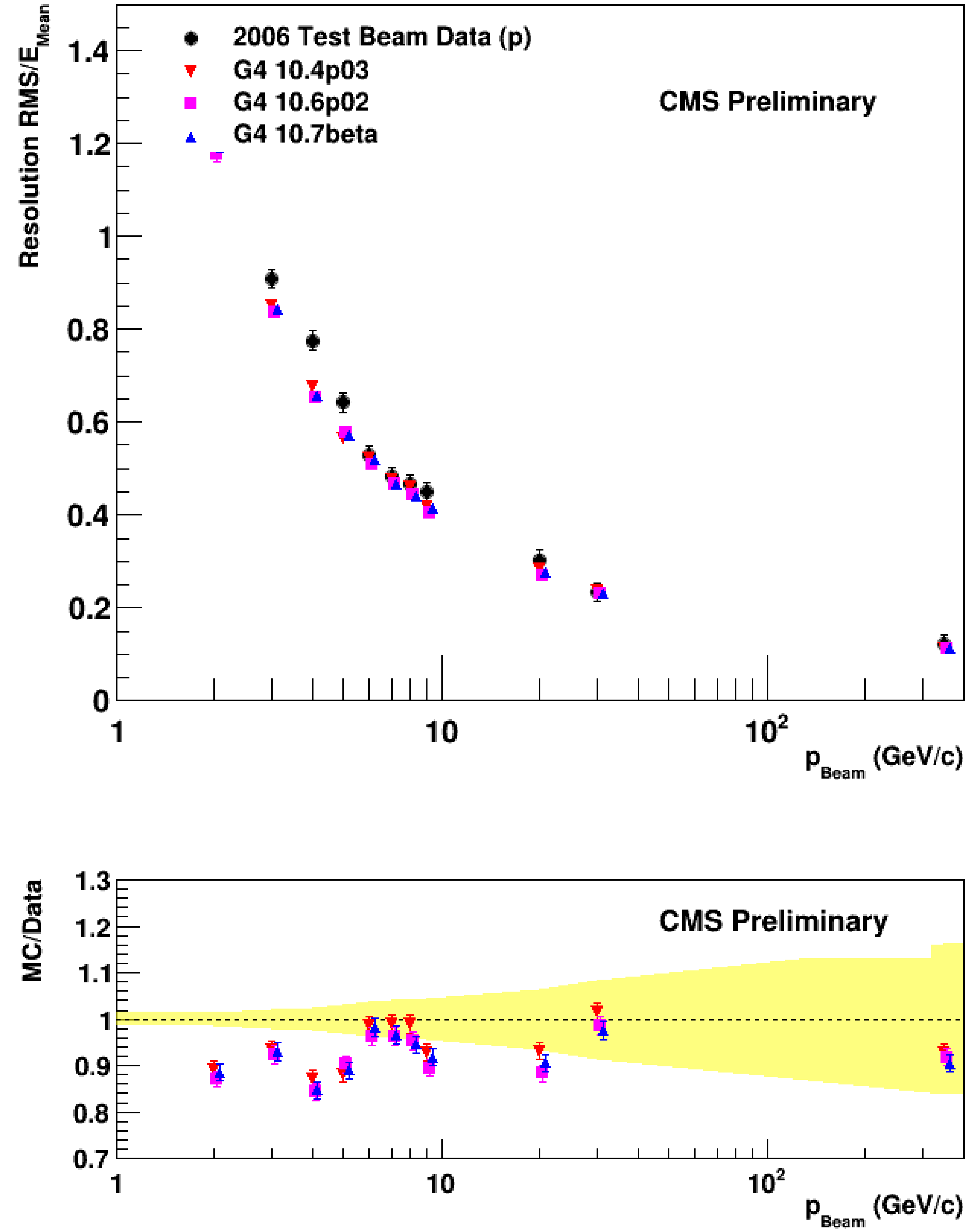


(Top) Energy spectrum for protons at 7 GeV compared with MC predictions. (Bottom) Ratio of MC to data for 7 GeV protons

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

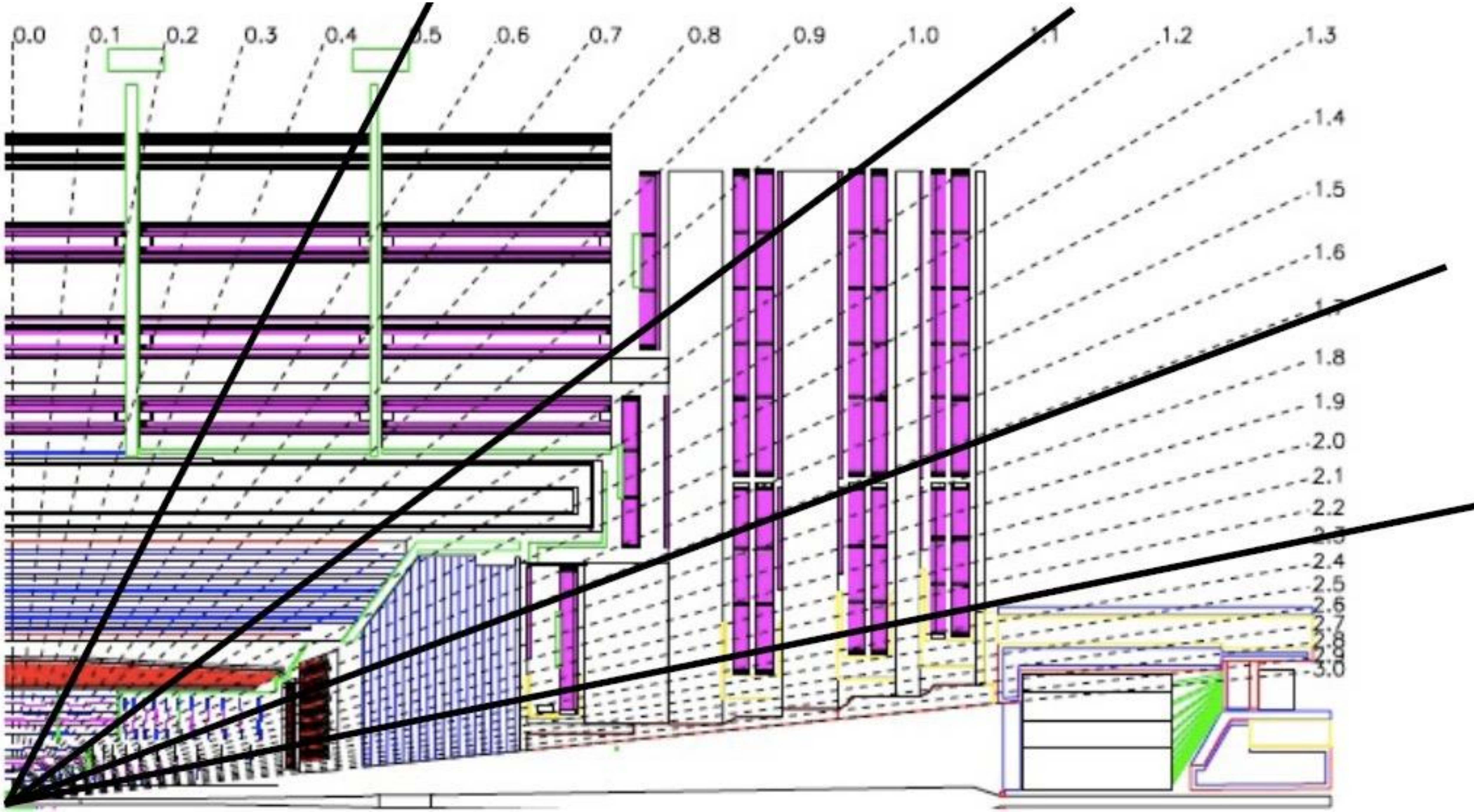
- Select good charged tracks reaching the calorimeter surface

- Impose isolation of these charged particles
  - propagate track to 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 a few earlier CHEP conferences.

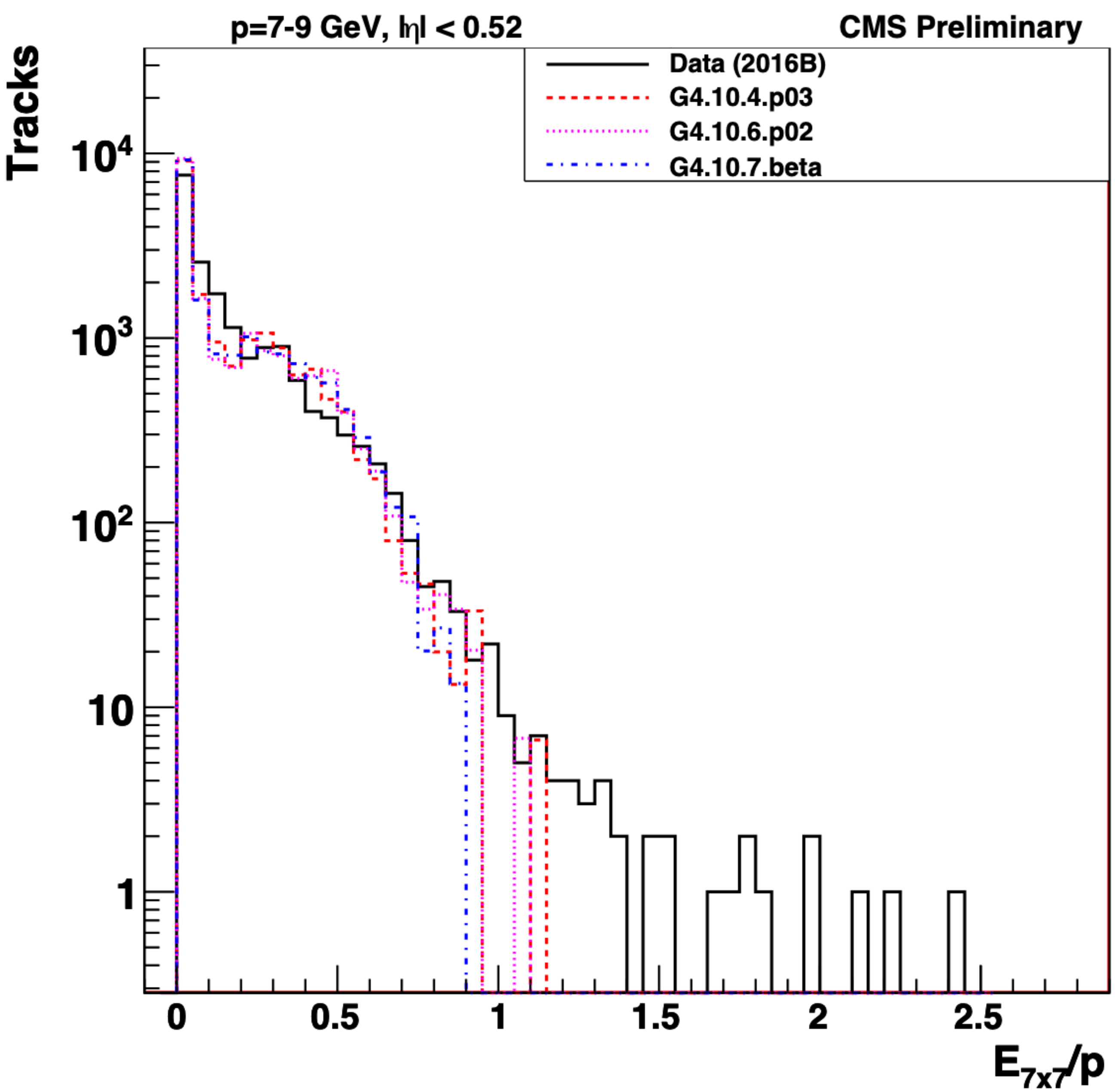
Quadrant of the CMS



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

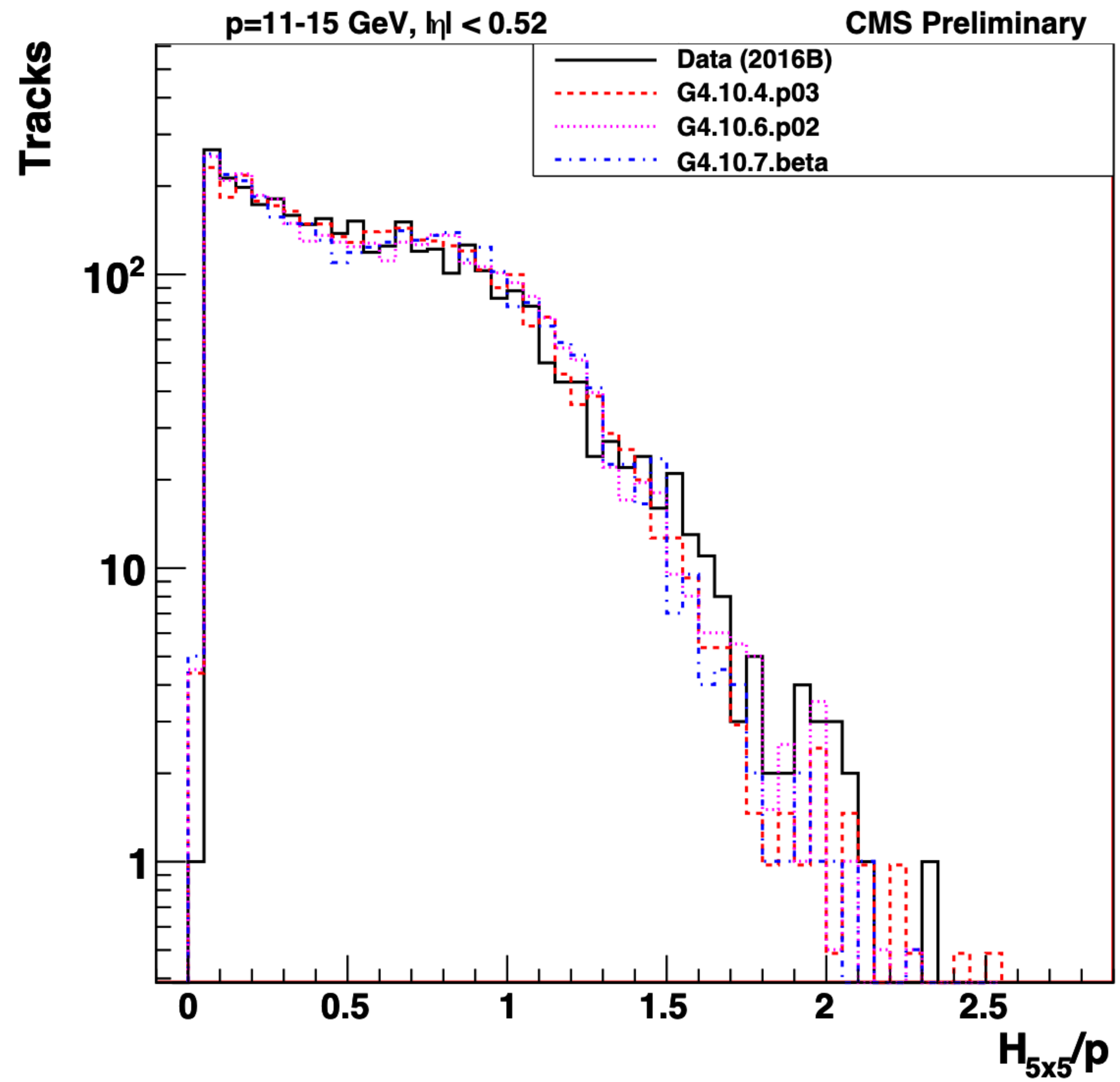
Energy in ECAL and HCAL

Narrow Matrix (ECAL)
7-9 GeV



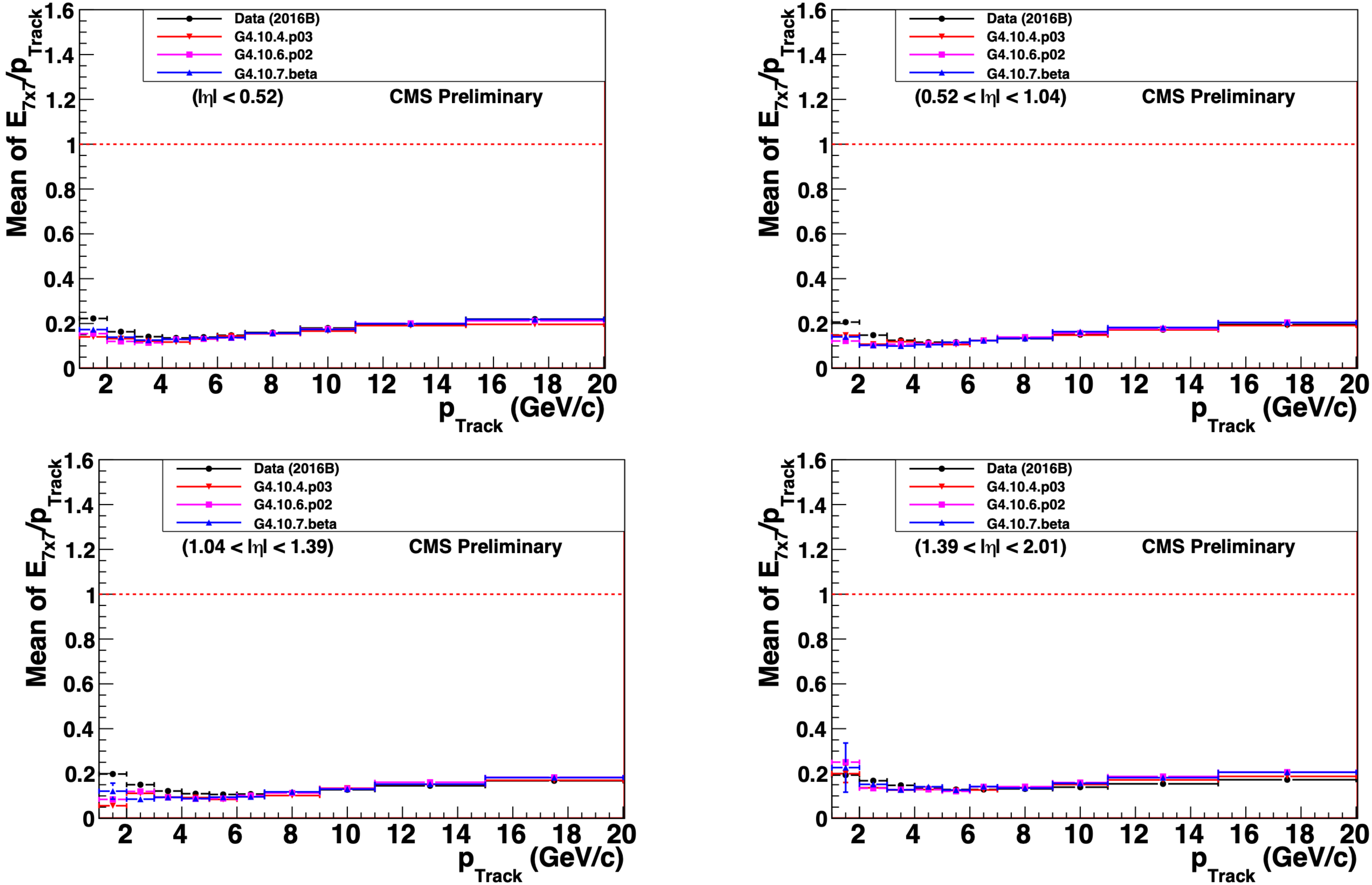
Ratio of energy measured in a matrix of 7x7 crystals around the hit point in the barrel electromagnetic calorimeter for tracks of momentum between 7 and 9 GeV.

Wide Matrix (HCAL)
11-15 GeV



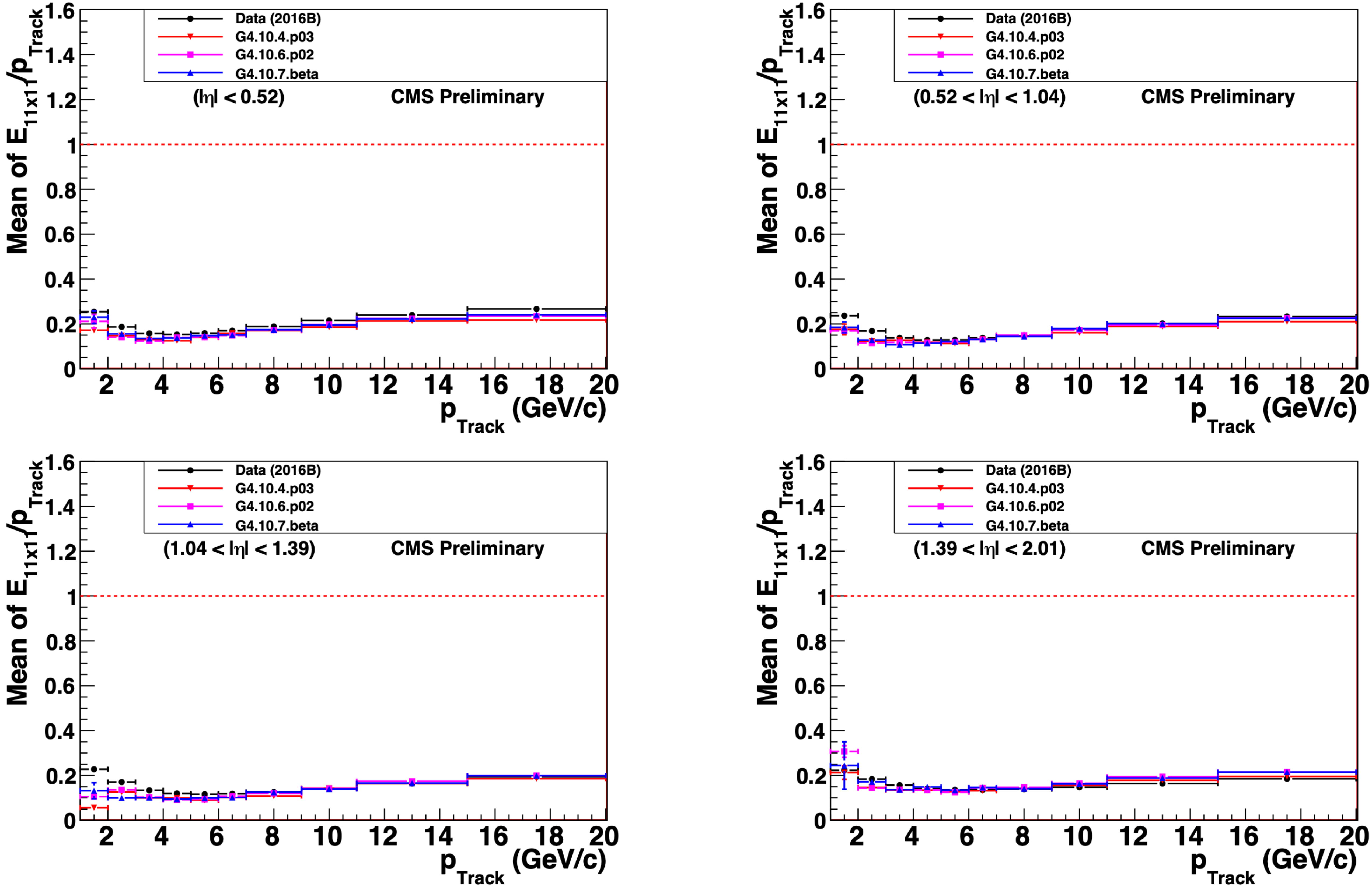
Ratio of energy measured in a matrix of 5x5 towers around the hit point in the endcap hadron calorimeter for tracks of momentum between 11 and 15 GeV.

Energy in the ECAL (7x7 matrix)



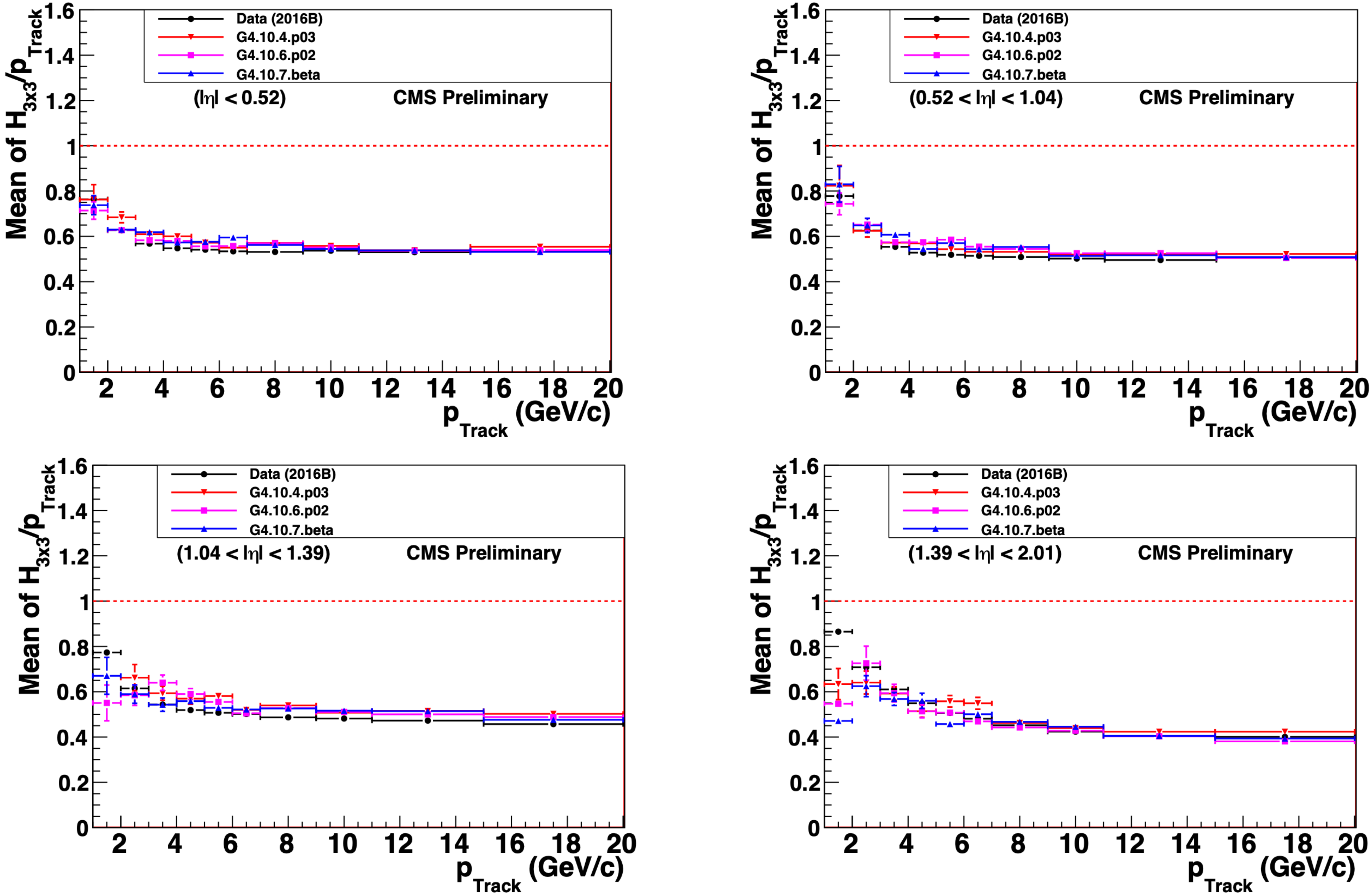
Mean of the ratio of energy measured in a 7x7 matrix in the ECAL to track momentum in 4 regions of the detector: central barrel (top left); side barrel (top right); transition region (bottom left); endcap (bottom right)

Energy in the ECAL (11x11 matrix)



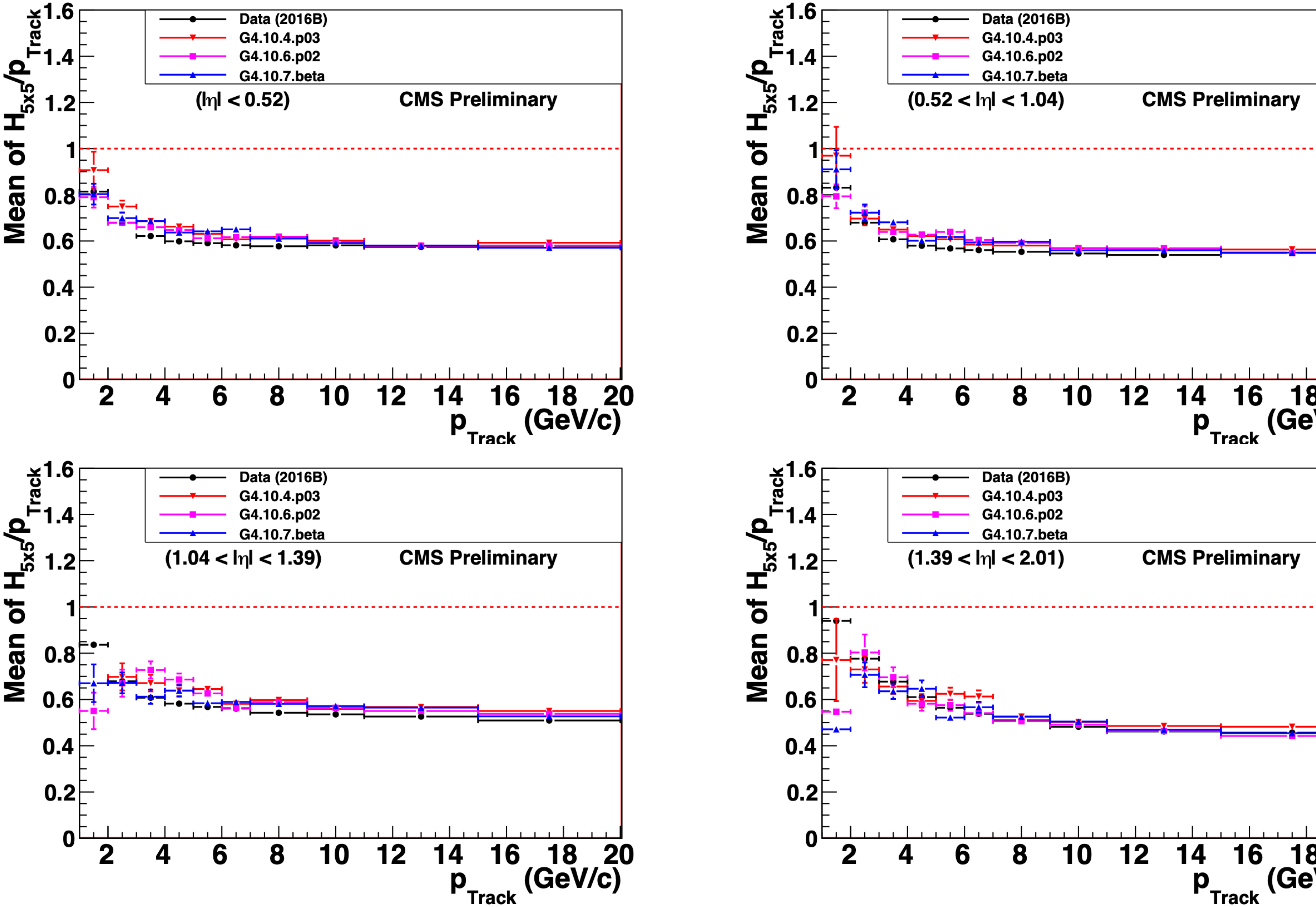
Mean of the ratio of energy measured in a 11x11 matrix in the ECAL to track momentum in 4 regions of the detector: central barrel (top left); side barrel (top right); transition region (bottom left); endcap (bottom right)

Energy in the HCAL (3x3 matrix)



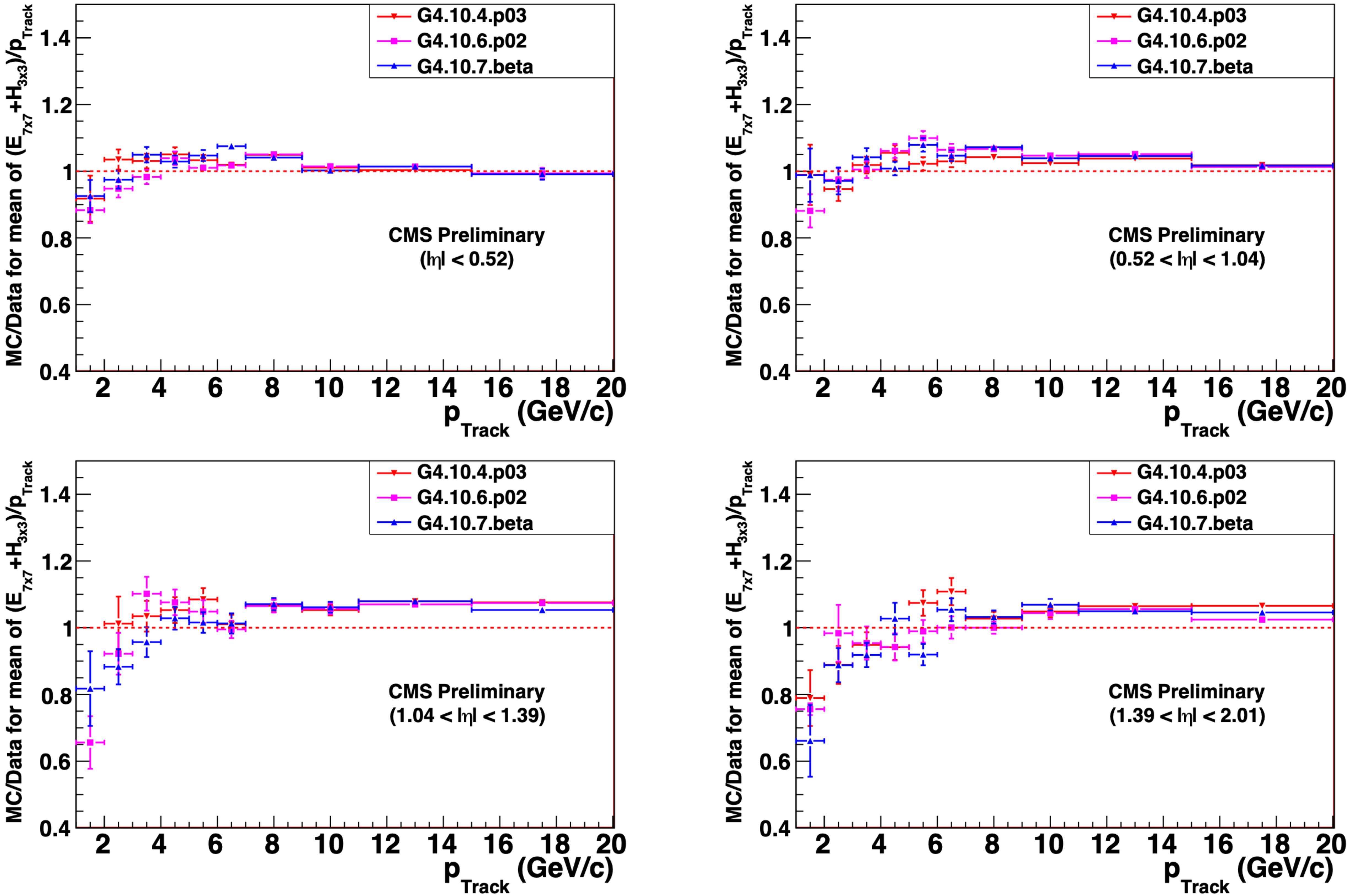
Mean of the ratio of energy measured in a 3x3 matrix in the HCAL to track momentum in 4 regions of the detector: central barrel (top left); side barrel (top right); transition region (bottom left); endcap (bottom right)

Energy in the HCAL (5x5 matrix)



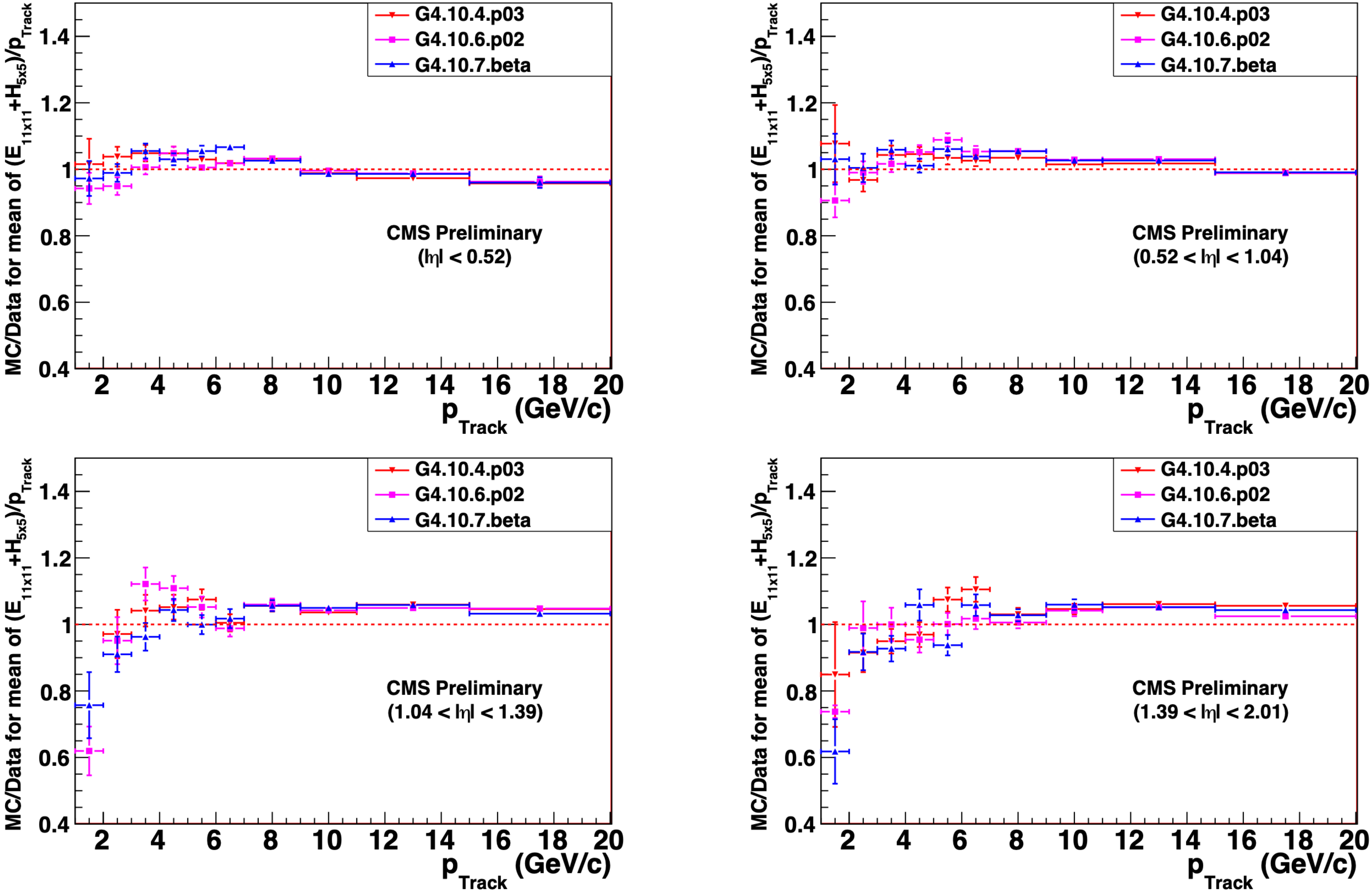
Mean of the ratio of energy measured in a 5x5 matrix of the HCAL to track momentum in 4 regions of the detector: central barrel (top left); side barrel (top right); transition region (bottom left); endcap (bottom right)

Combined Calorimeter Energy Ratio (Narrow Matrix)



Ratio of the mean energy response in a narrow matrix of ECAL and HCAL between MC and data for four regions of the calorimeter: central barrel (top left); side barrel (side barrel); transition region (bottom left); endcap (bottom right)

Combined Calorimeter Energy Ratio (Wide Matrix)



Ratio of the mean energy response in a wide matrix of ECAL and HCAL between MC and data for four regions of the calorimeter: central barrel (top left); side barrel (side barrel); transition region (bottom left); endcap (bottom right)

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 2 and 6% in the versions 10.6.p02 and 10.7.beta, 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.beta	$(E_{11x11}+H_{5x5})/p$ 10.4.p03	$(E_{11x11}+H_{5x5})/p$ 10.6.p02	$(E_{11x11}+H_{5x5})/p$ 10.7.beta
Barrel 1	(2.3±0.4)%	(2.3±0.4)%	(2.7±0.4)%	(2.7±0.4)%	(1.9±0.4)%	(2.8±0.4)%
Barrel 2	(3.1±0.4)%	(4.7±0.4)%	(4.2±0.4)%	(2.1±0.4)%	(3.5±0.4)%	(3.0±0.4)%
Transition	(6.5±0.5)%	(6.2±0.5)%	(5.8±0.5)%	(4.7±0.5)%	(4.8±0.5)%	(4.3±0.5)%
Endcap	(5.8±0.5)%	(3.3±0.5)%	(4.9±0.5)%	(5.3±0.5)%	(3.1±0.5)%	(4.6±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, the version 10.4.p03 was used. Currently CMS has moved to 10.6.p02 and is planning to move to 10.7 for Run3 physics 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 3 versions (10.4.p03, 10.6.p02 and 10.7.beta) provide good agreement with the data.

References

[1] S. Agostinelli *et. al.,* Nuclear Instruments and Methods **A506** (2003) 250.

[2] J. Allison *et. al.,* IEEE Transaction on Nuclear Science **53** (2006) 278.

[3] J. Allison *et. al.,* Nuclear Instruments and Methods **A835** (2016) 186.

[4] The CMS Barrel Calorimeter Response to Particle Beams from 2 to 350 GeV/c — S. Abdullin *et. al.*, European Physical Journal **C60** (2009) 359.

[5] Data/MC Comparison for ECAL and HCAL — CMS Collaboration, CMS/DP-2016/068 (2016).