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The Compact Muon Solenoid Experiment

CMS Performance Note

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

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Data/MC Comparison for ECAL and HCAL

CMS Collaboration

Abstract

CMS has tuned its simulation program and chosen a specific physics model of Geant4 by comparing the simulation results with dedicated test beam experiments. CMS continues to validate the physics models inside Geant4 using the test beam data as well as collision data. Several physics lists (collection of physics models) inside the most recent version of Geant4 provide good agreement of the energy response, resolution of pions and protons. The validation results from these studies will be presented. Shower shapes of electrons and photons evaluate the goodness of the description of electromagnetic physics in Geant4 while response of isolated charged particles are used to examine the predictions of hadronic models within Geant4. Use of Geant4 to explain rare anomalous hits in the calorimeter will also be discussed.

Introduction

- This work focuses on simulation effort of the CMS experiment and validation of Geant4 models with some of the existing data
- There are 2 sources of data used for validation:
  - Test beam with prototype of CMS hadron calorimeter and one supermodule of electromagnetic calorimeter using hadron beams of different types and different energies during 2006
    - Results from this test beam were published (EPJ C60, 2009, 359) and used in earlier tuning of CMS simulation (described in CMS Note-2008/034, CMS Note-2010/007 from Calorimeter Task Force)
  - Collision data using CMS detector utilizing zero bias or minimum bias data from low luminosity runs from the 2016B run period
    - Similar analysis using isolated charged hadrons was done earlier in CMS (PAS: JME-10-008)
- These validation results consolidate the recent adaptation of new Geant4 version (10.2.p02) and new Physics List (FTFP_BERT_EMM) for 2017 Monte Carlo production

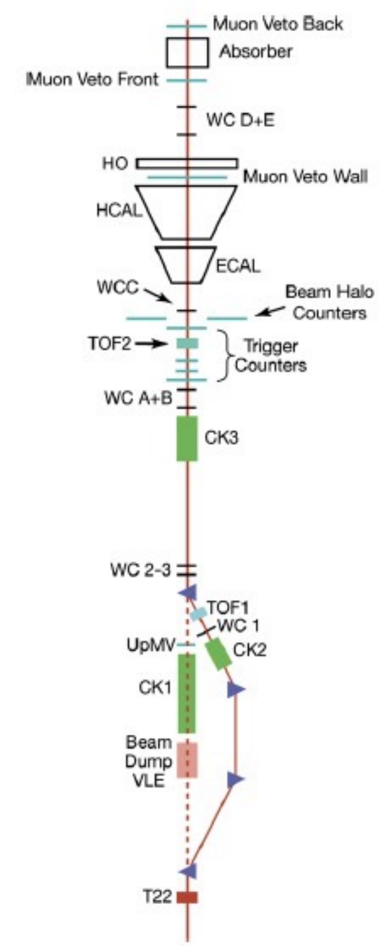
Geant4 in CMS

- CMS used the physics lists in the past for its Monte Carlo production
  - QGSP_FTFP_BERT_EML (with Geant4 versions 9.4.p02, 9.6.p02)
- CMS moved to multithreading mode from beginning of Run2 (2015)
  - QGSP_FTFP_BERT_EML (with Geant4 version 10.0.p02)
- CMS plans to move to a new physics list for its production plan for 2017
  - FTFP_BERT_EMM (with Geant4 version 10.2.p02)
- FTFP_BERT is the recommended physics list from Geant4 collaboration (J.Allison *et al*. NIM A506, 2003, 250; NIM A835, 2016,186)

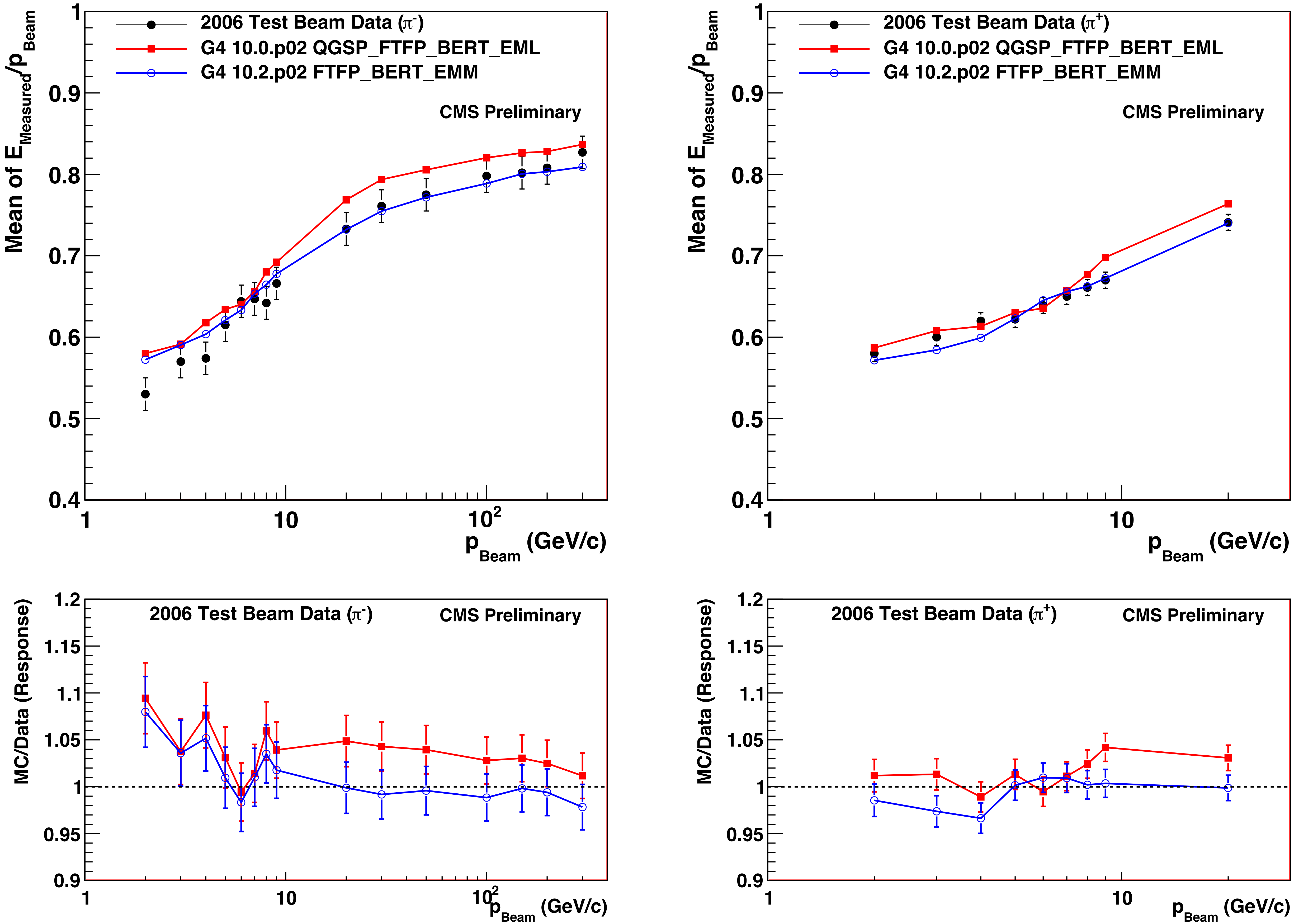
- The list QGSP_FTFP_BERT combines QGSP, FTFP, Bertini Cascade models for π/K/p/n with a fixed validity region:
  - Bertini Cascade valid at ≤ 8 GeV
  - FTFP valid between 6 and 25 GeV
  - QGSP valid at ≥ 12 GeV
- The list FTFP_BERT uses FTFP and Bertini Cascade models:
  - Bertini Cascade valid at ≤ 5 GeV
  - FTFP valid at ≥ 4 GeV
- EML, EMM specify the physics models for electromagnetic processes
  - EML utilizes simplified multiple scattering model for all detectors
  - EMM uses the detailed multiple scattering model for HCAL and the simplified one for other detectors (handling of multiple scattering is critical for sampling calorimeter)

2006 TestBeam Data

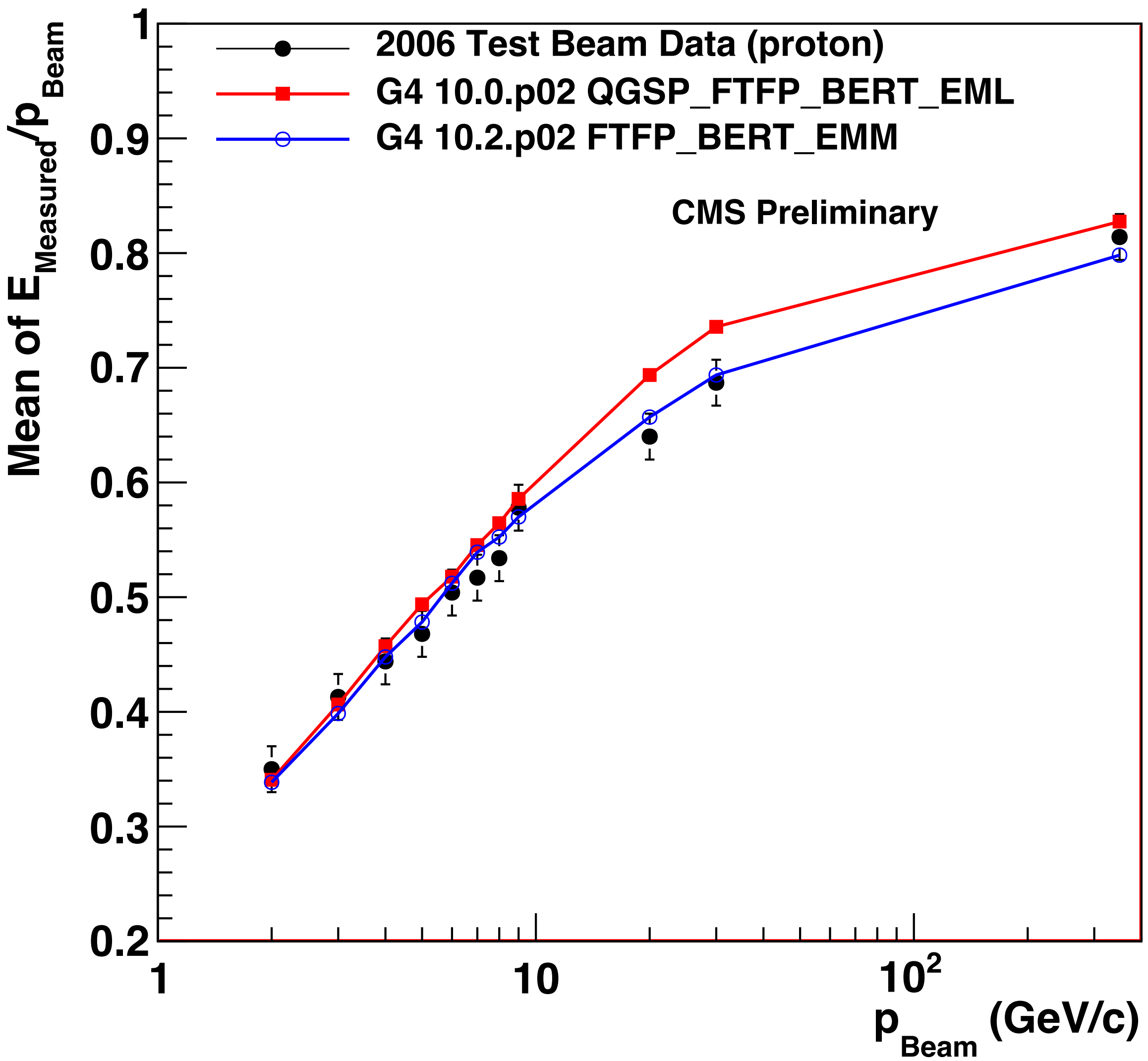
- CMS collected data with prototype of Hadron Calorimeter Barrel and a supermodule of the barrel Electromagnetic Calorimeter in the H2 test beam area at CERN during 2006.
- Special action was taken to go to low energy hadron beam down to 1 GeV using a secondary target
- The analysis utilized particle 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 and also the energy distribution for particles of a given type at a given momentum (all particles or particles which do not undergo inelastic interactions in Electromagnetic Calorimeter)
- The test beam setup is described within CMS software and is used routinely to validate Geant4 models.

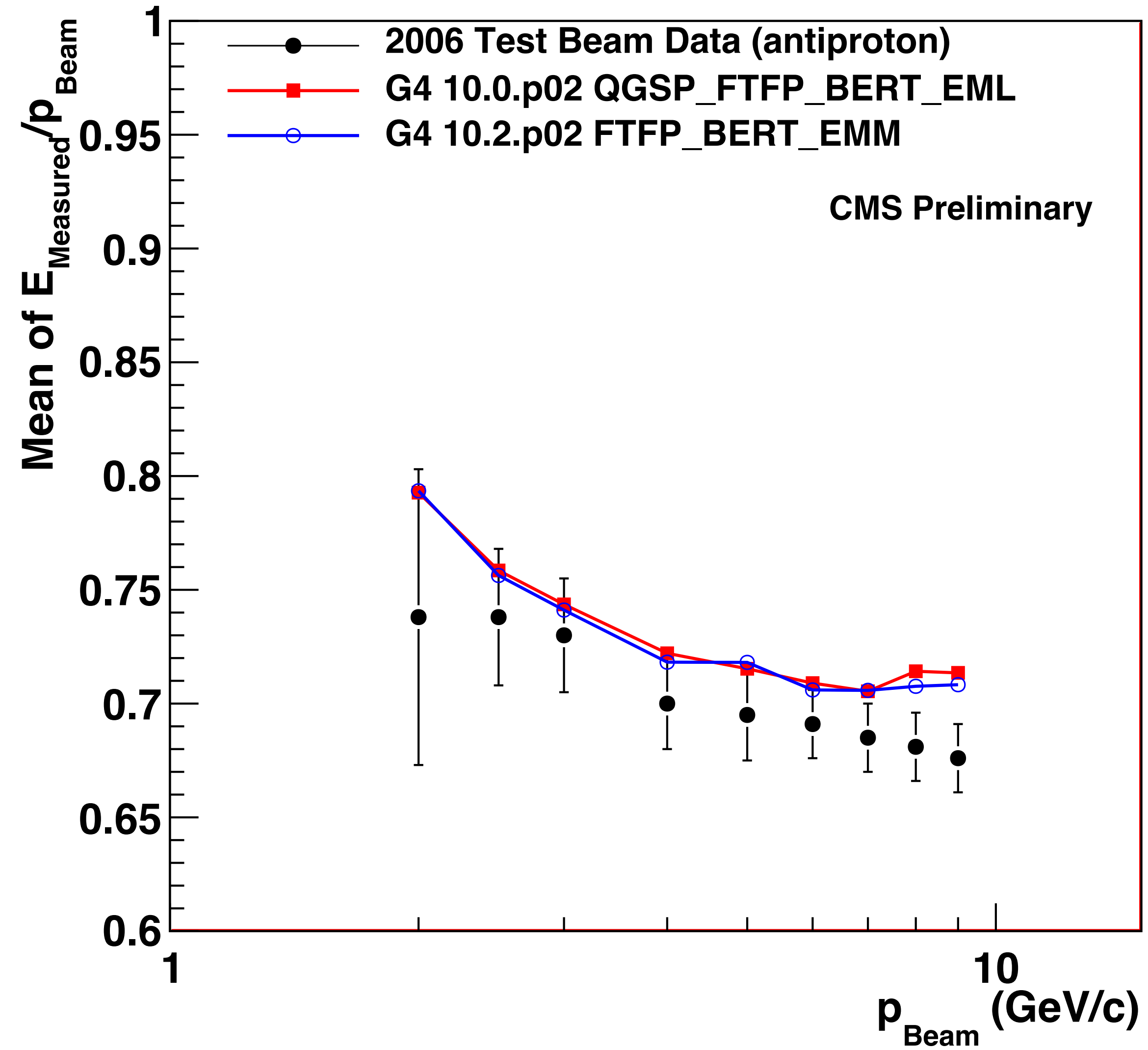


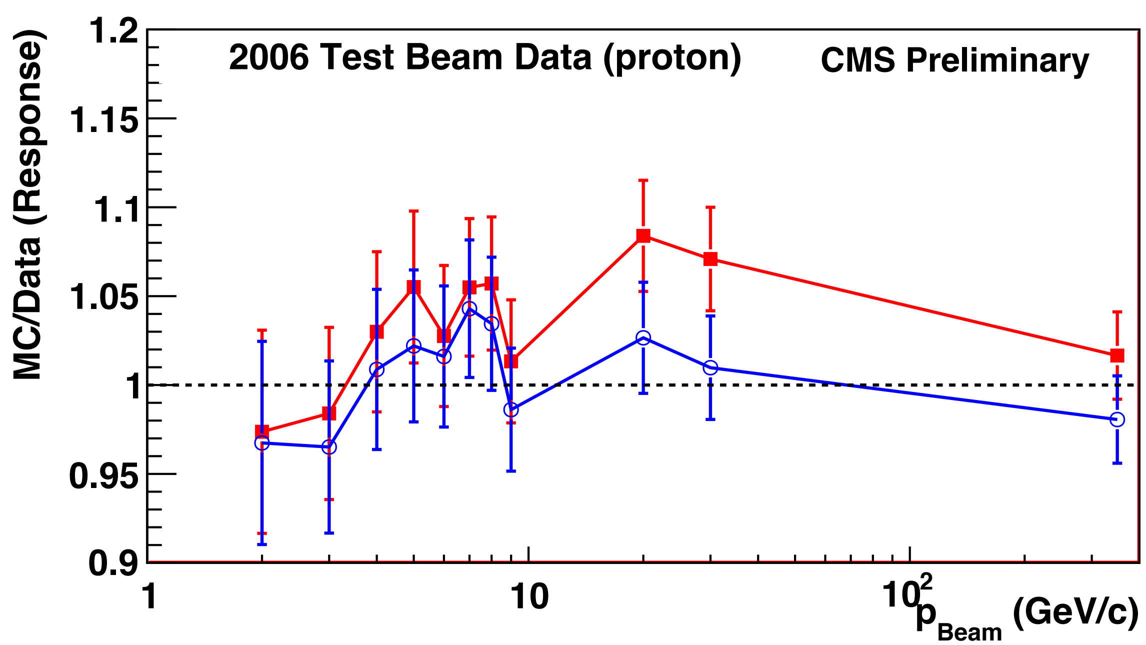
Mean response with pions

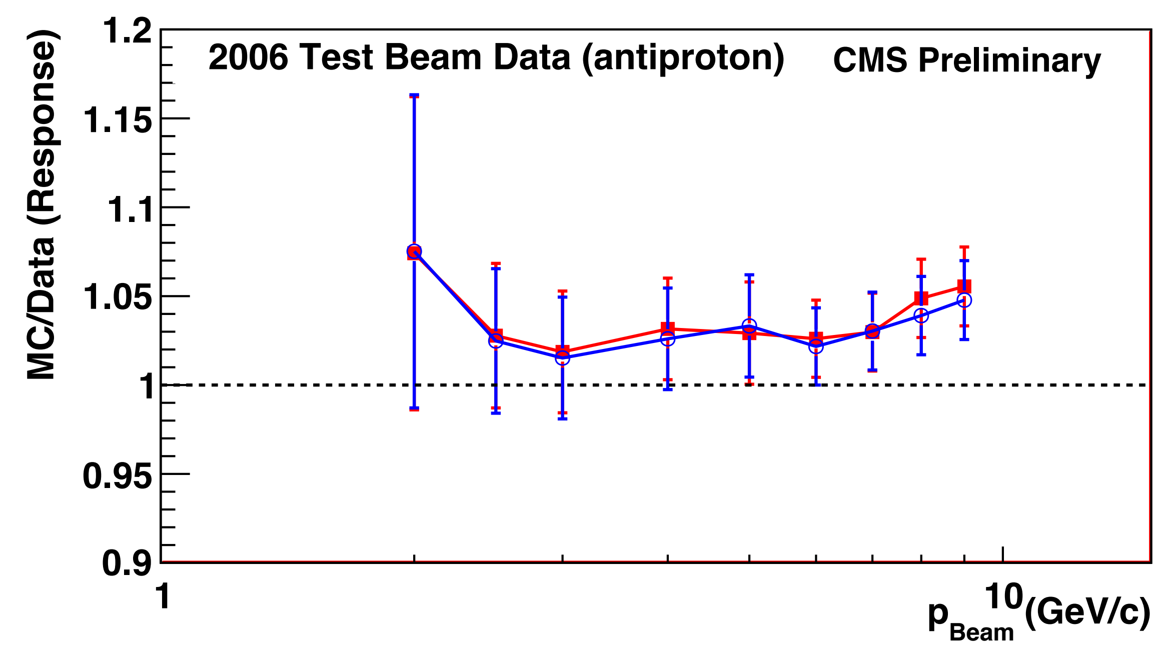


Mean response with protons/antiprotons









Summary from Mean Response

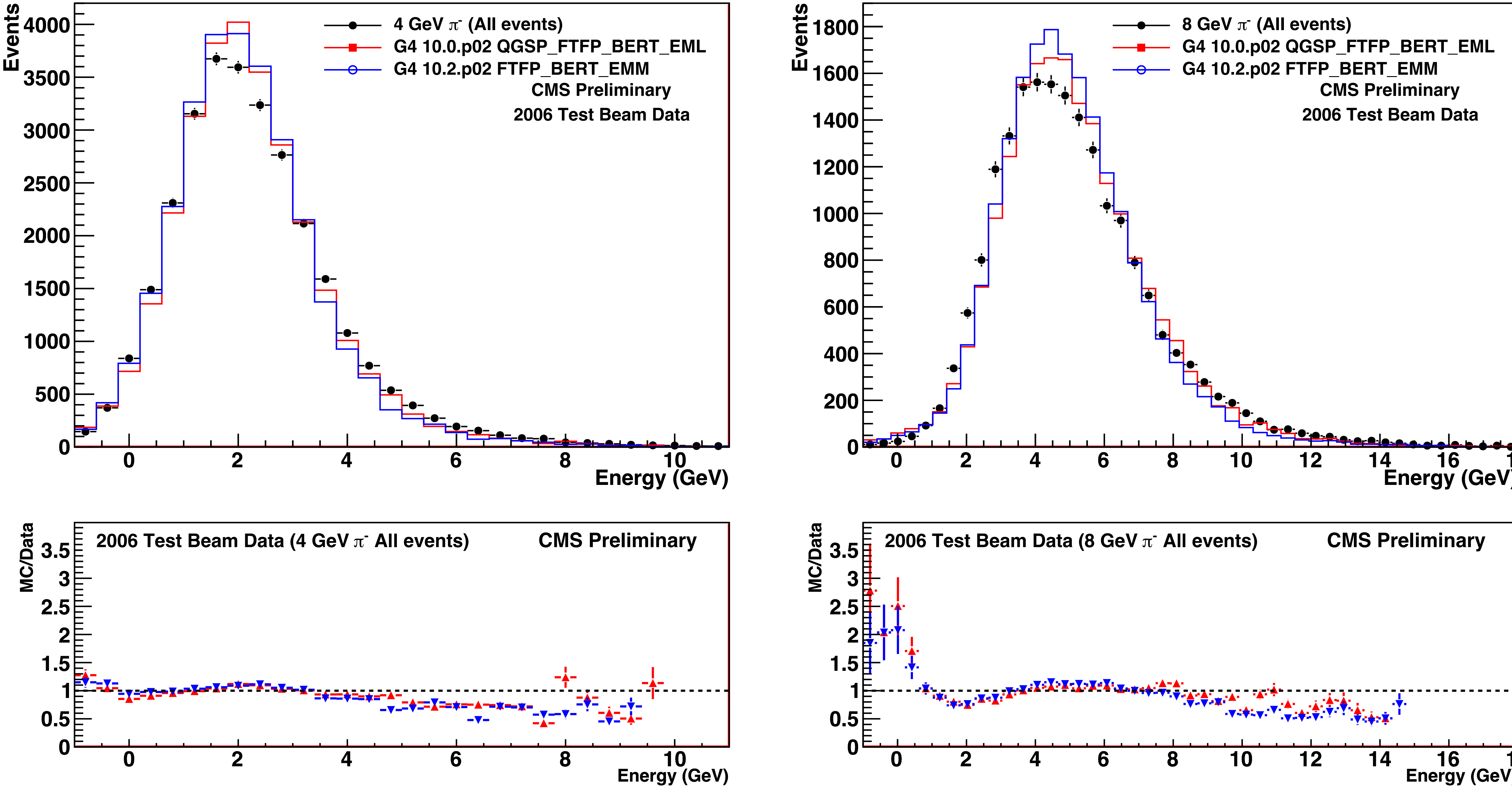
Mean level of disagreement between MC and data

	negative pions	positive pions	protons	anti-protons
G410.0.p02 QGSP_FTFP_BERT_EML	(3.6±0.6)%	(1.9±0.5)%	(4.3±1.0)%	(3.5±0.8)%
G4 10.2.p02 FTFP_BERT_EMM	(1.8±0.7)%	(1.0±0.5)%	(2.2±1.1)%	(3.1±0.8)%

- The level of agreement between data and MC improve in the new model for pions, protons and anti-protons

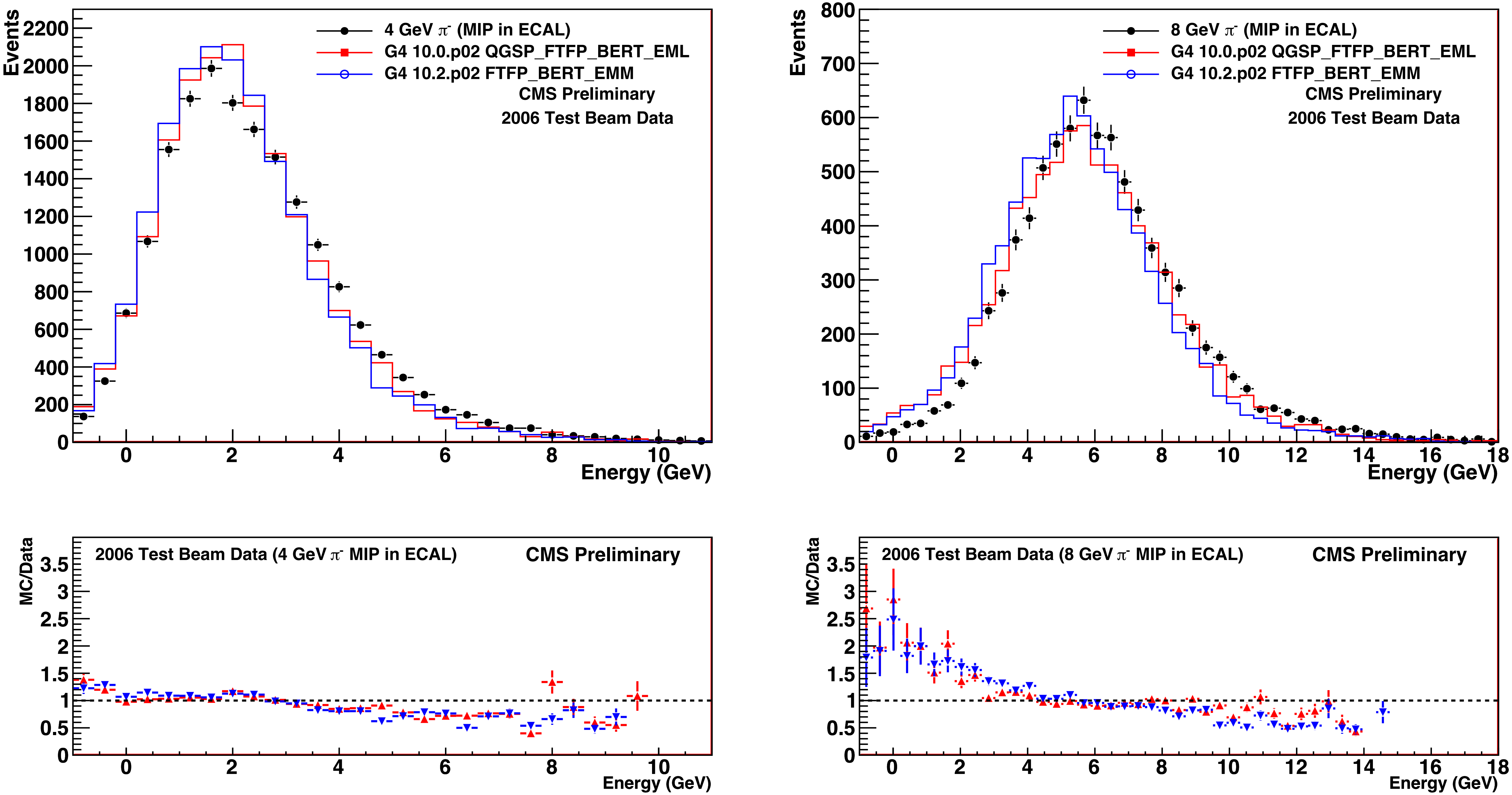
- pp collisions at the LHC produce mostly pions. So one expects to have a better agreement between data and MC with the new physics list in the Geant4 version 10.2.p02

Energy for negative pions (All)



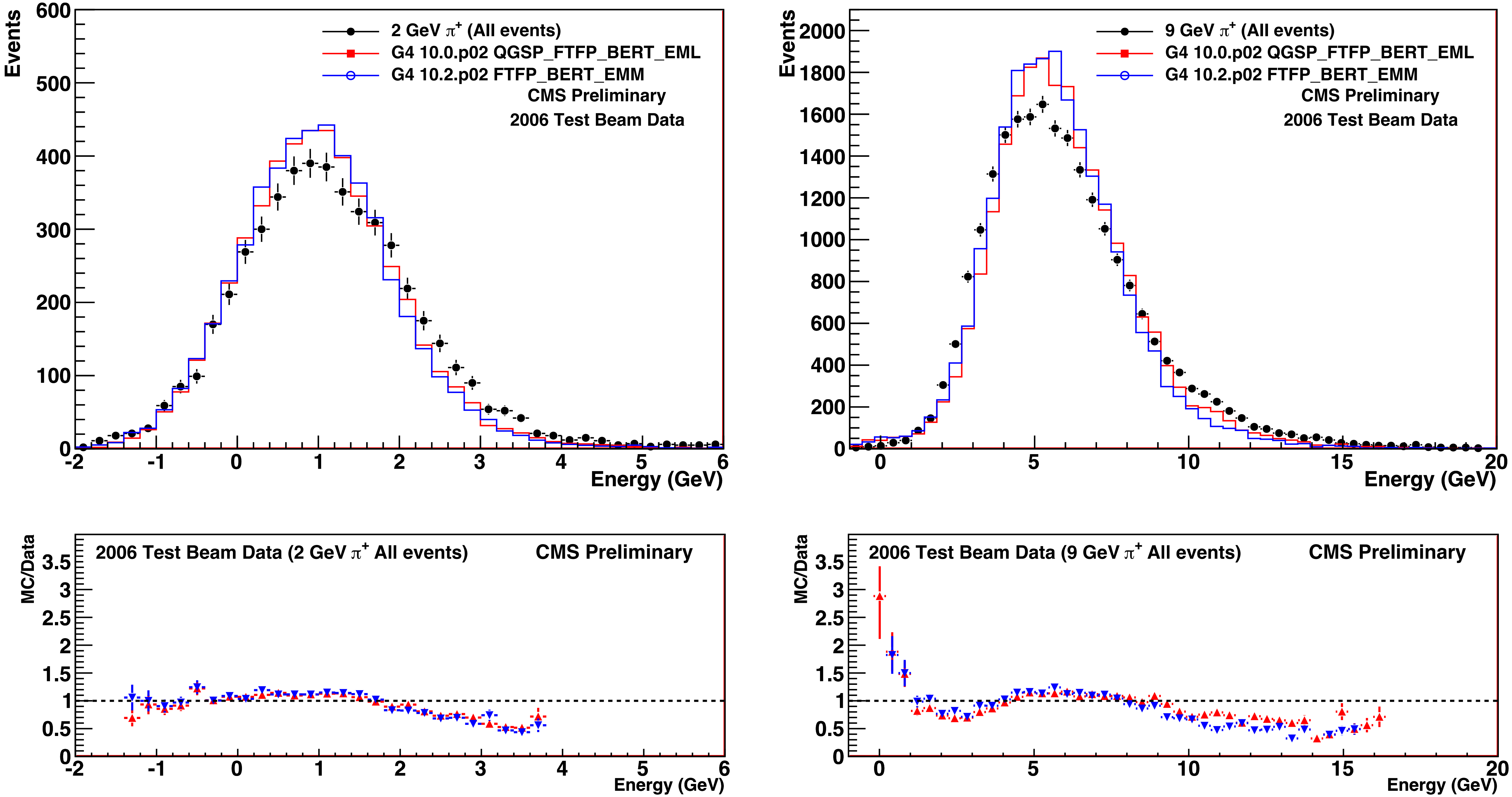
- Total energy measured for negative pion beams of 4 GeV/c and 8 GeV/c
- Fairly good agreement (better than 8%) observed in the energy distribution with the data having a slightly longer tail than the MC

Energy for negative pions (MIPs in ECAL)



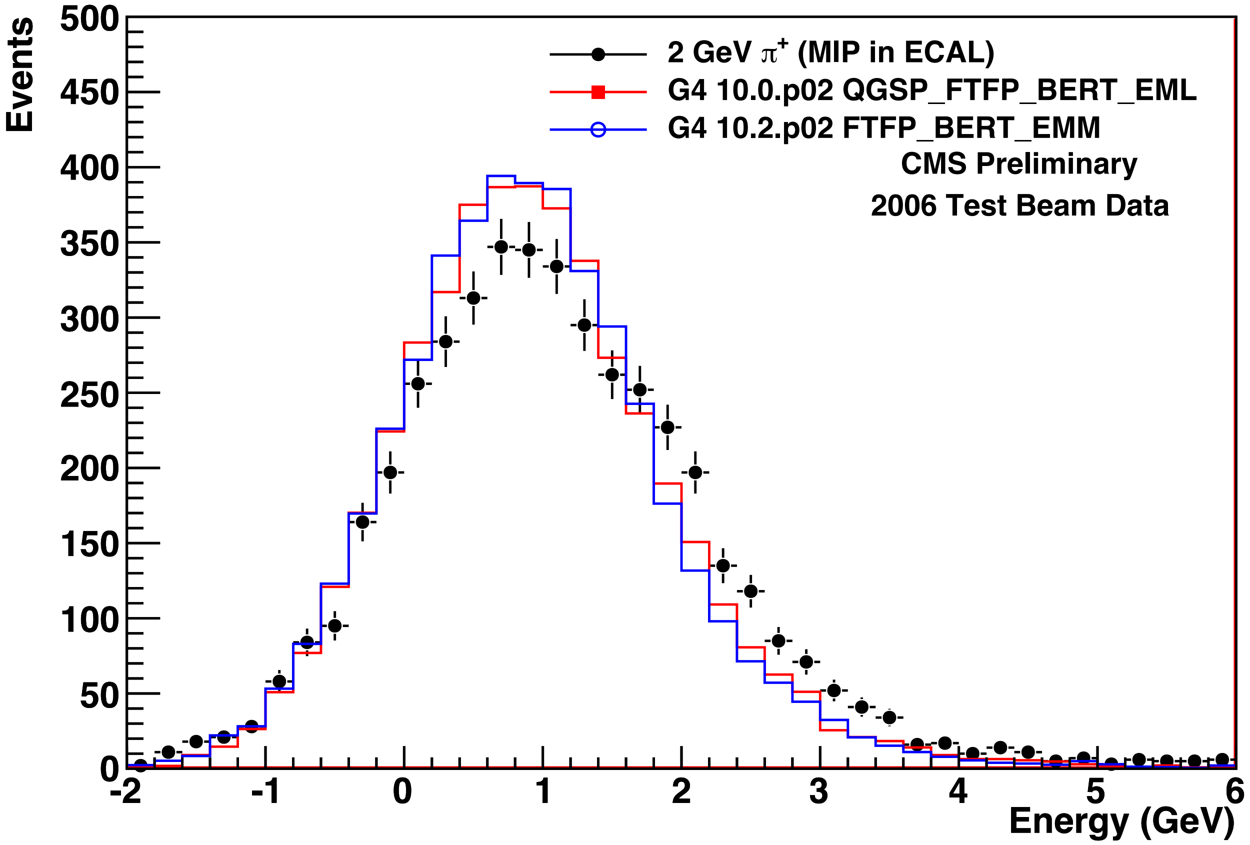
- Similar energy measurement for negative pion beams at 4 and 8 GeV/c when the measured energy in ECAL is less than 1.2 GeV
- Similar agreement observed in the energy distribution for all pions

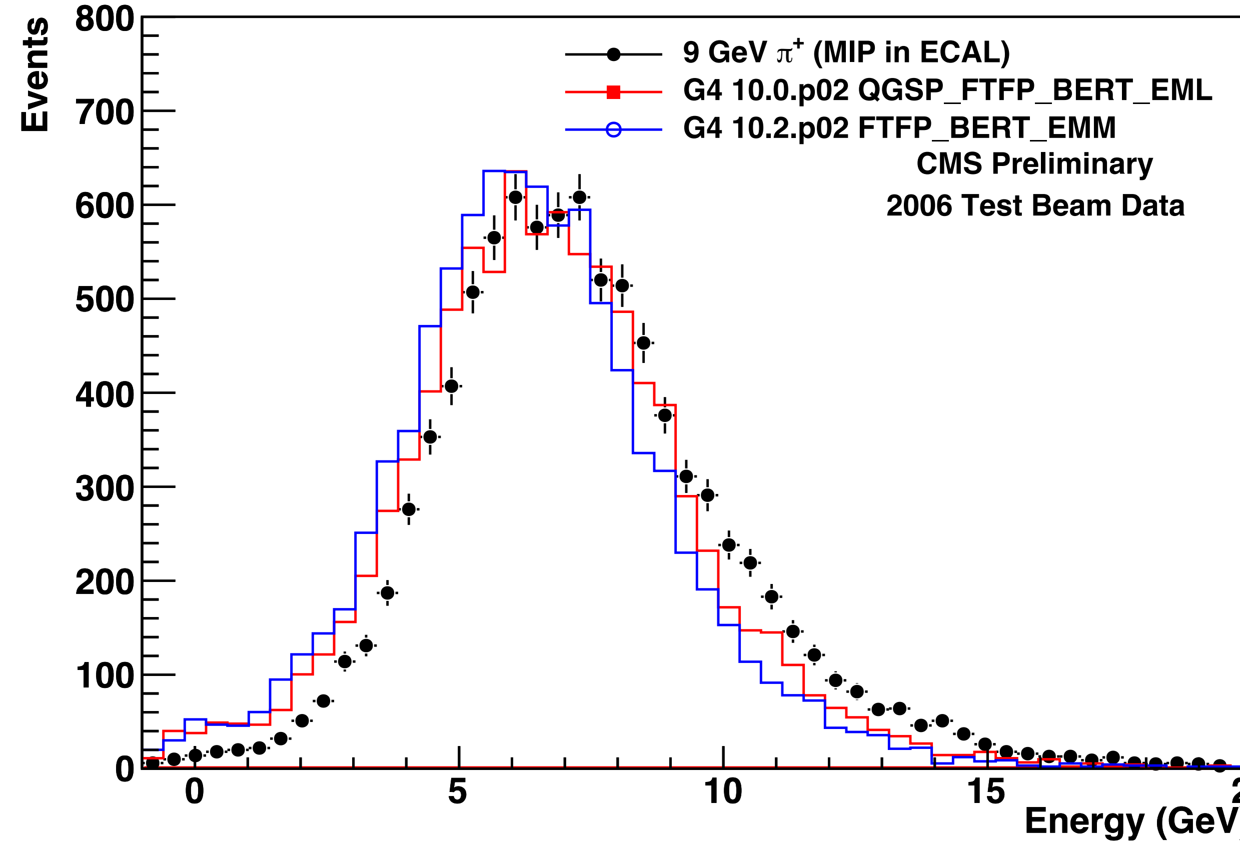
Energy for positive pions (All)

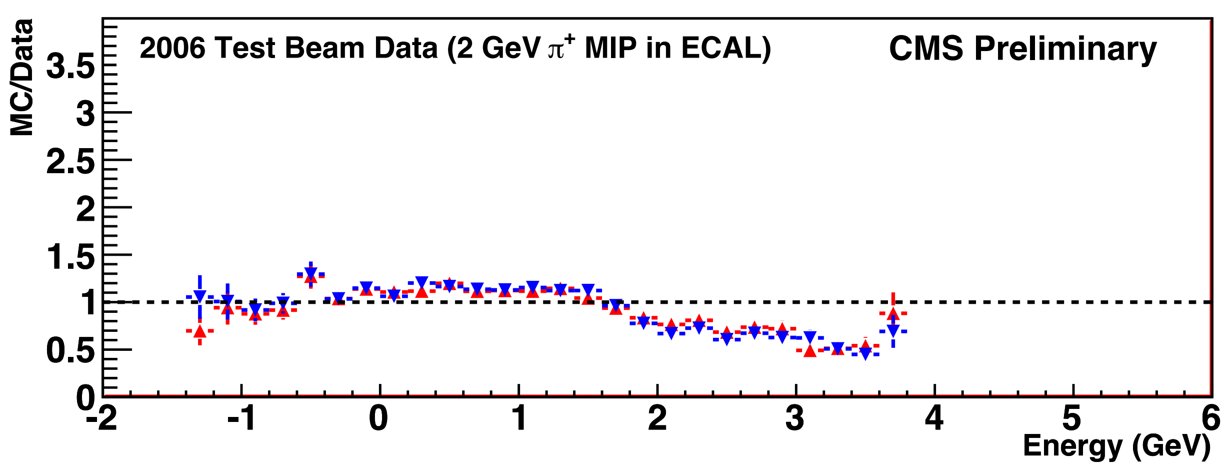


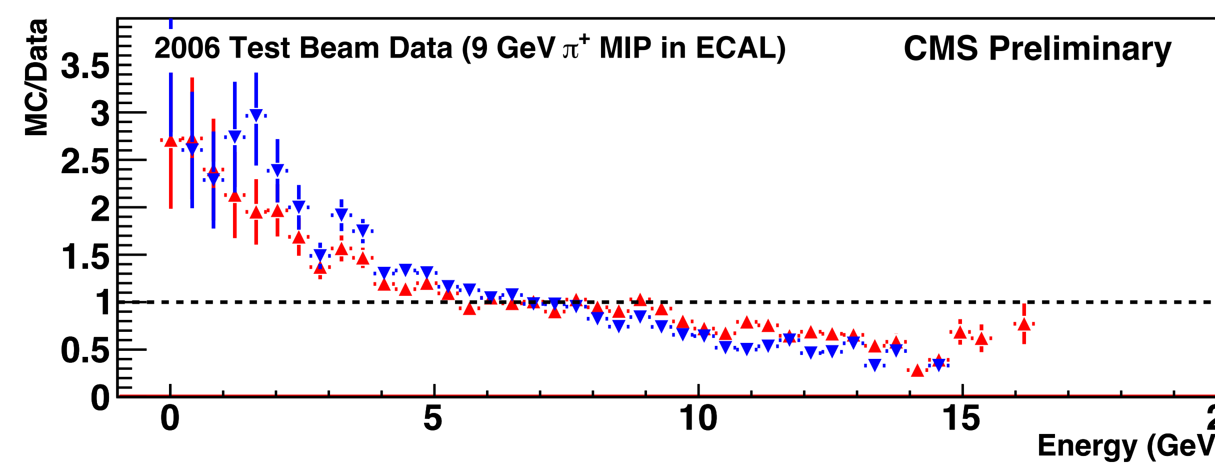
- Total energy measured for positive pion beams of 2 GeV/c and 9 GeV/c
- The level of agreement is similar as that for negative pions

Energy for positive pions (MIPs in ECAL)



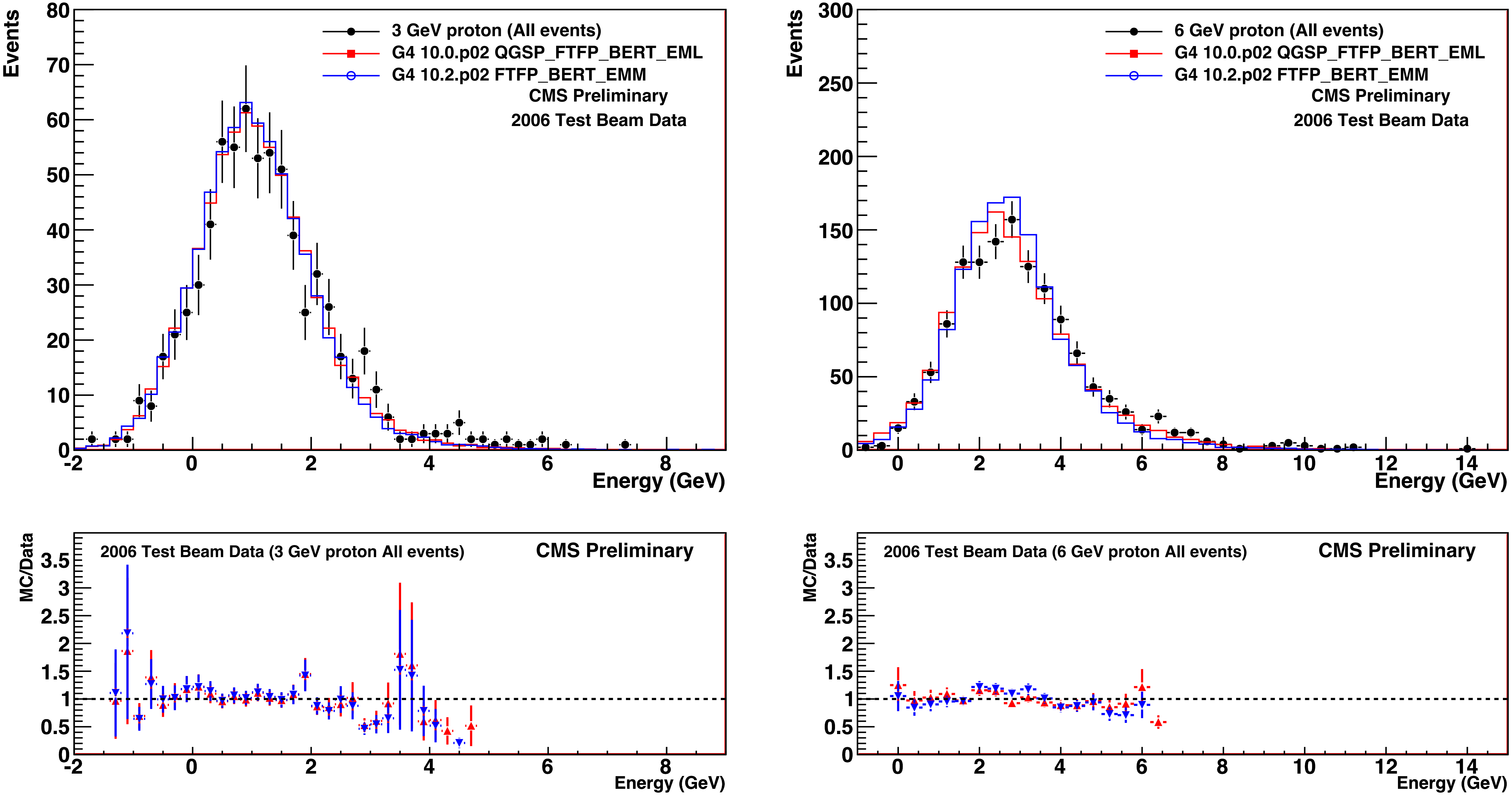






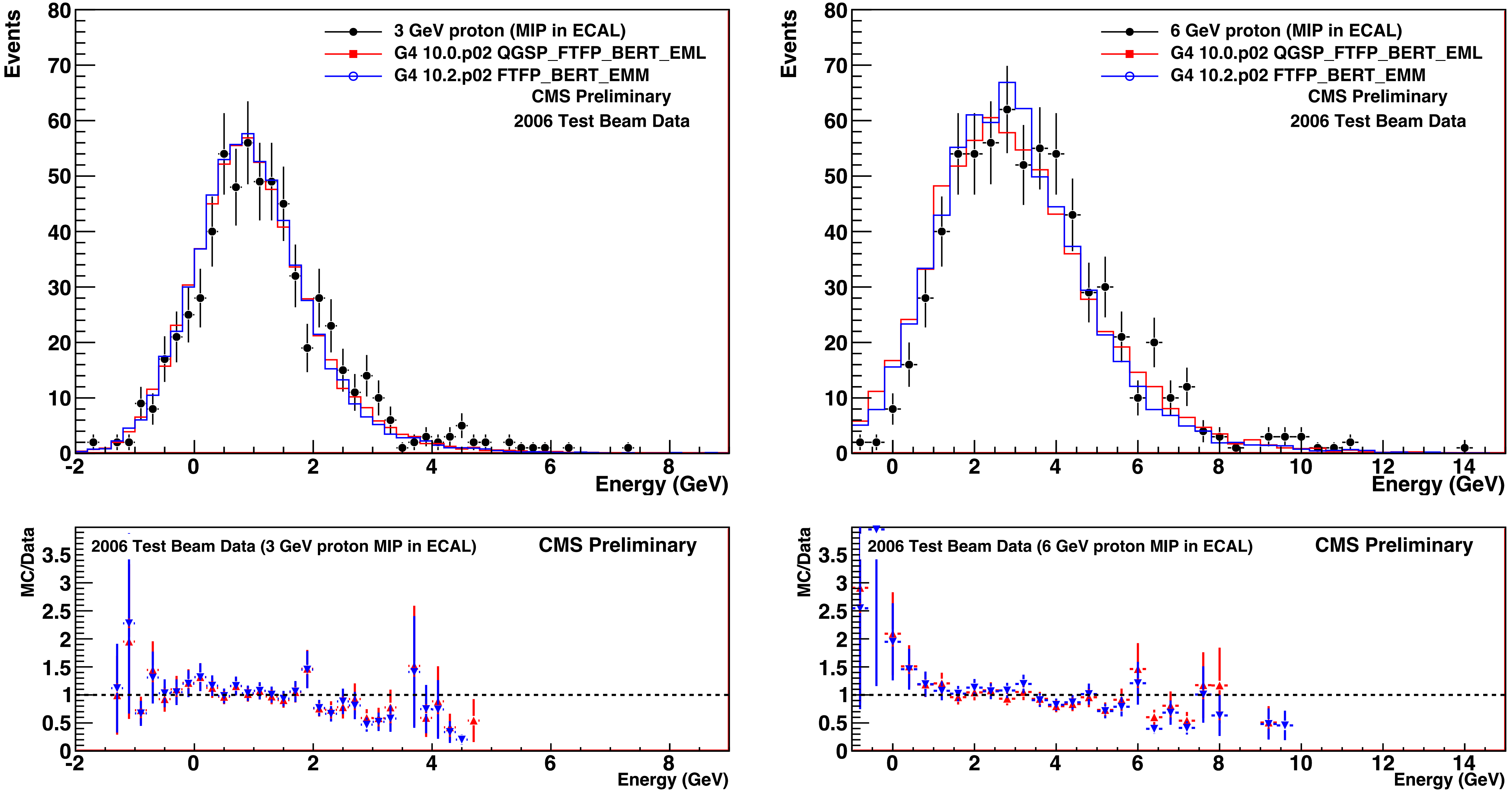
- Measured energy distribution for positive pion beams at 2 and 9 GeV/c when the measured energy in ECAL is less than 1.2 GeV
- The level of agreement is similar as that for negative pions

Energy for Protons (all)



- Energy distribution for protons at 3 and 6 GeV/c
- Both versions of Monte Carlo provide a decent (within 10% on average) description of the data

Energy for Protons (MIPs in ECAL)



- Measured energy distribution for proton beams at 3 and 6 GeV/c when the measured energy in ECAL is less than 1.2 GeV
- There is a fair agreement between data and MC

Isolated Charged Particles

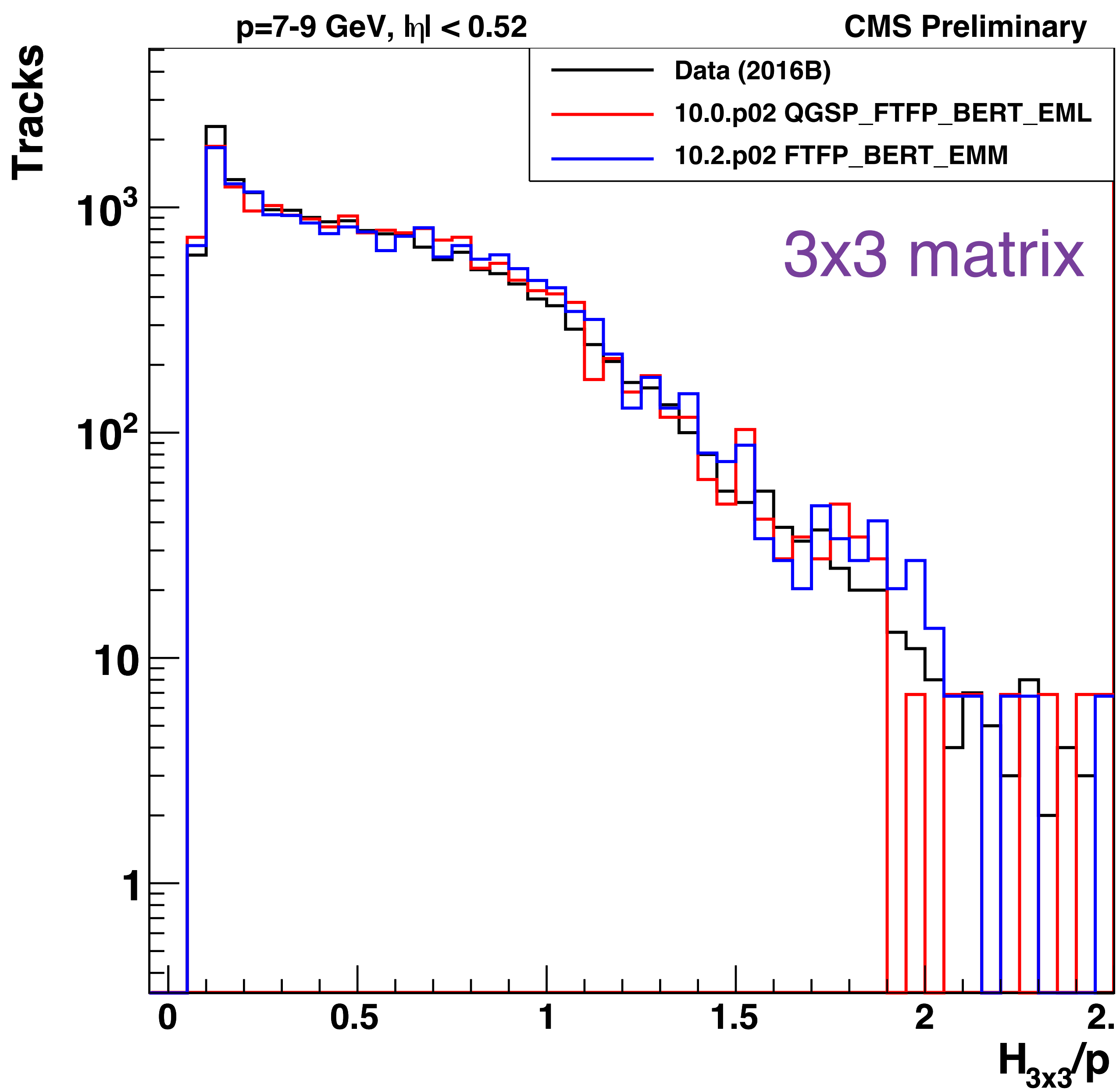
- Compare ratio of calorimeter energy measurement to track momentum for isolated charged hadrons between data and MC
- Follow the same analysis strategy as in the PAS: JME-10-008 and apply this to Run2 data
- Select good charged tracks
  - $p_T > 1$ GeV
  - Chi-square/d.o.f. < 5
  - # of layers crossed > 8
  - Fractional error on p < 0.1
  - No missed hits in inner/outer layers
  - originates close to primary vertex (< 0.2 mm in x-y and r-z planes)
  - reach the HCAL 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
  - study energy deposited in an annular region in ECAL (HCAL) between 15x15 and 11x11 (7x7 and 5x5) matrices for neutral isolation
- Final cuts
  - No tracks in the isolation region
  - Energy cut of 2 GeV for neutral isolation
  - No additional good primary vertex in the event (to avoid PU effect)

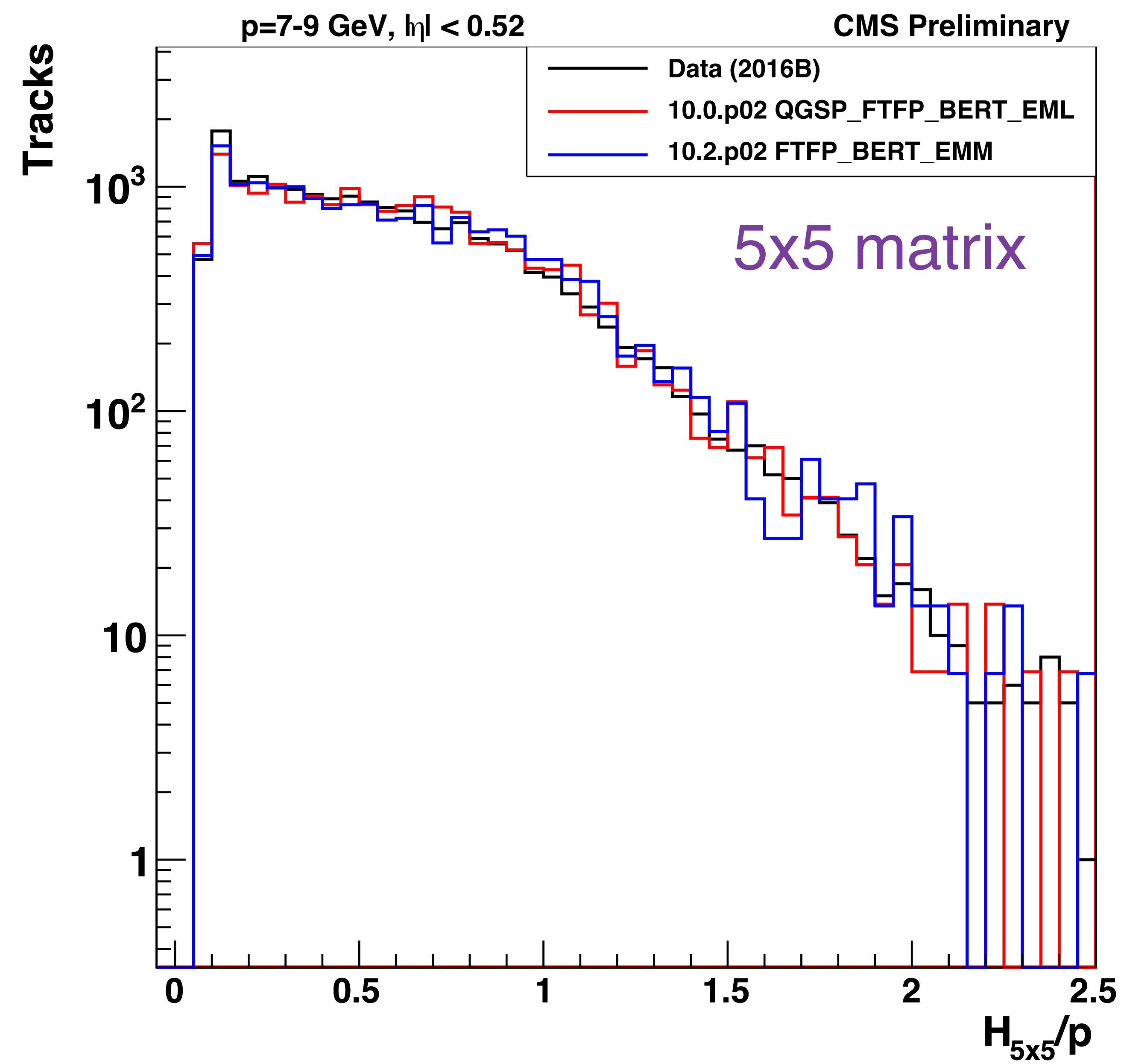
Data Sets and Comparison

- For Data: Use low luminosity runs taken during 2016B run period using
  - Zero Bias trigger
  - Minimum Bias trigger

  Select good events with the appropriate JSON file
- For Monte Carlo:
  - Generate single particle event sample using a flat energy distribution between 1 and 20 GeV
  - 100k events are generated with Physics List QGSP_FTFP_BERT_EML for Geant4 version 10.0.p02 and with the list FTFP_BERT_EMM for Geant4 version 10.2.p02. Events are produced with a given admixture of pions, kaons and protons and anti-protons (as expected in minimum bias sample)
- Compare energy measured in the calorimeter (scaled by particle momentum) in four regions (two in the barrel, one in the endcap and one in transition region)
- Measure energy by combining energy measurements from a matrix of NxN cells around the cell hit by the extrapolated track to the calorimeter surface
- For the data use the two low luminosity data sets from the 2016B runs
  - The distributions from Zero Bias and minimum bias data agree quite well
  - For comparison with Monte Carlo these two data sets are combined

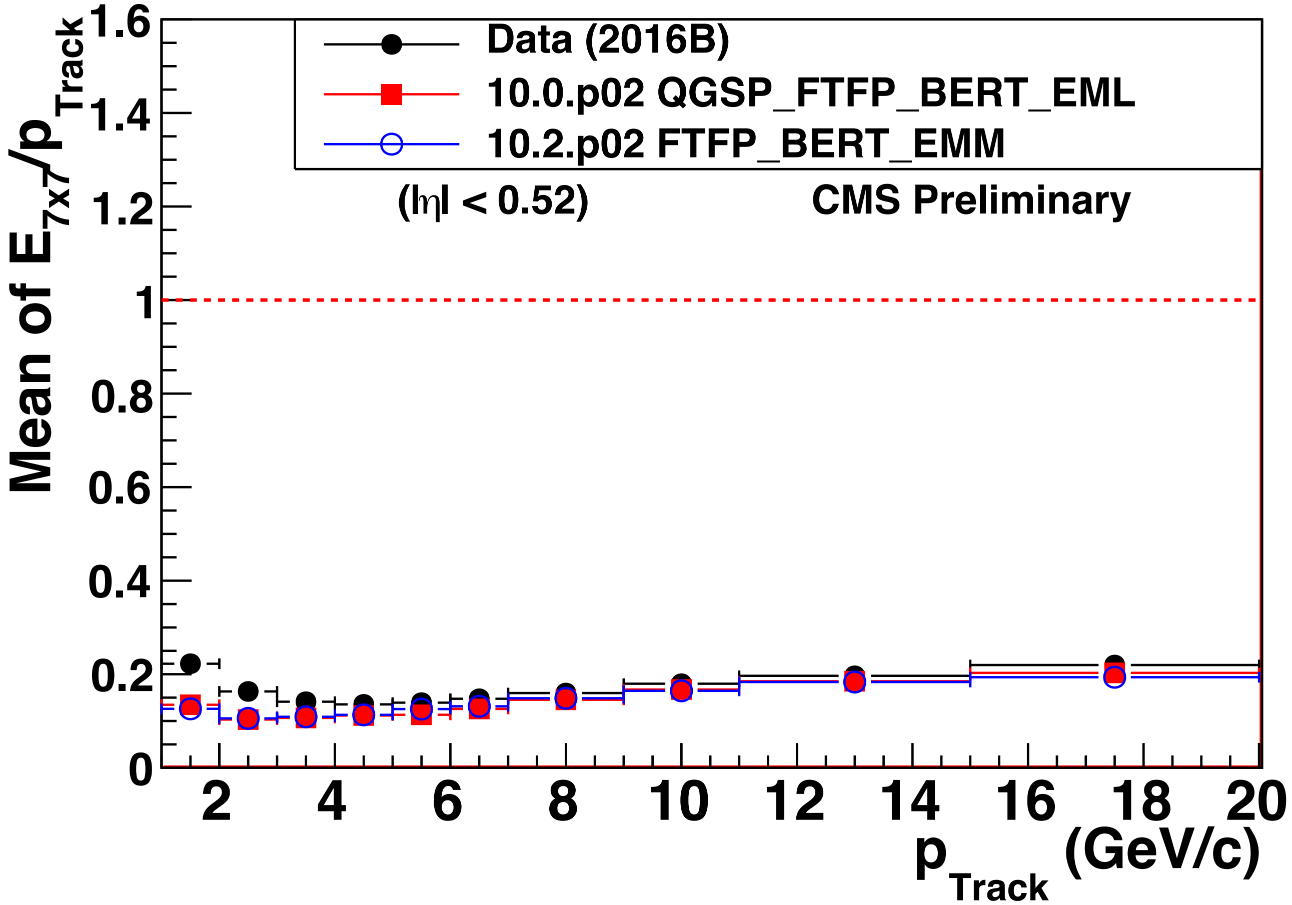
Energy in HCAL

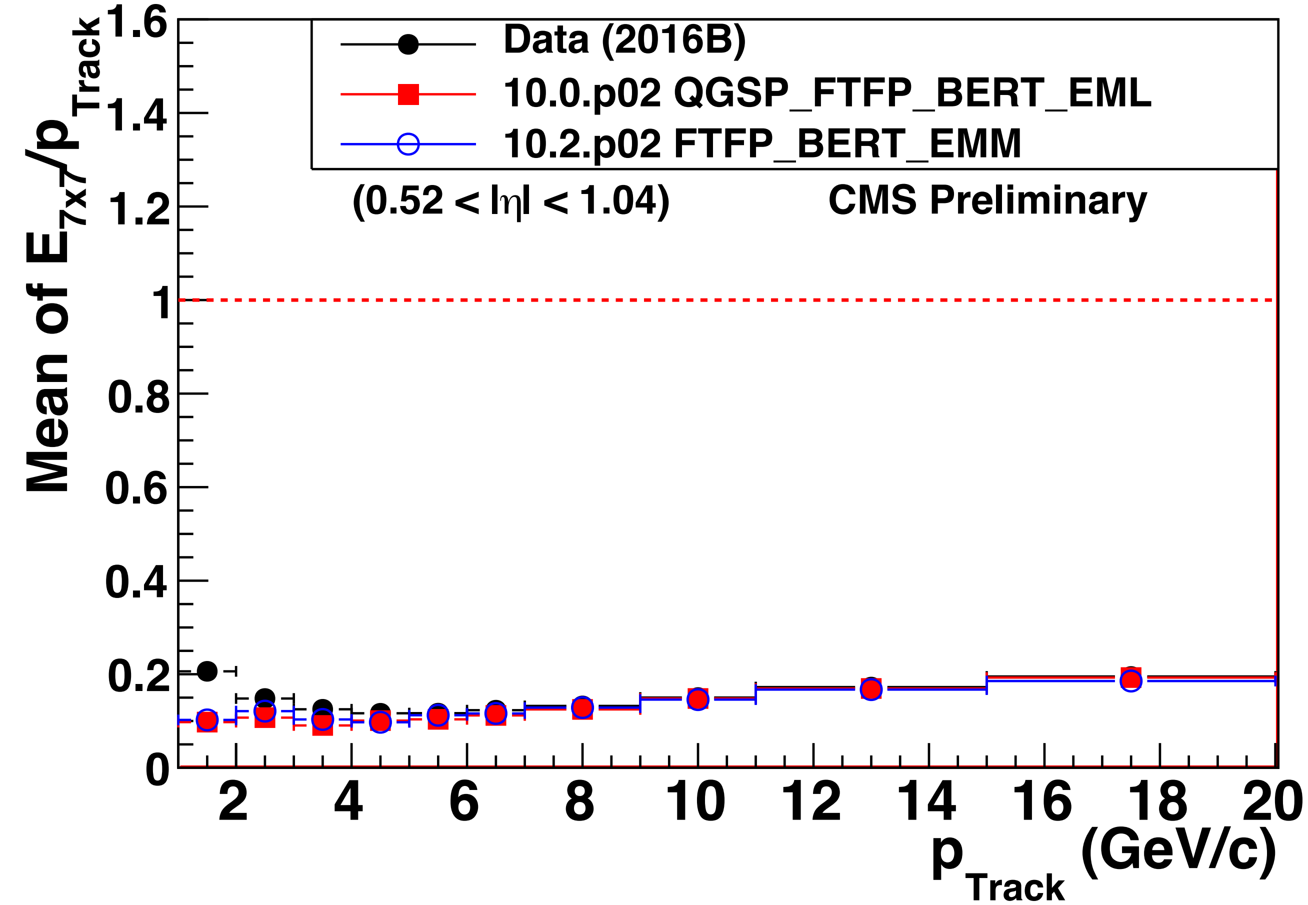


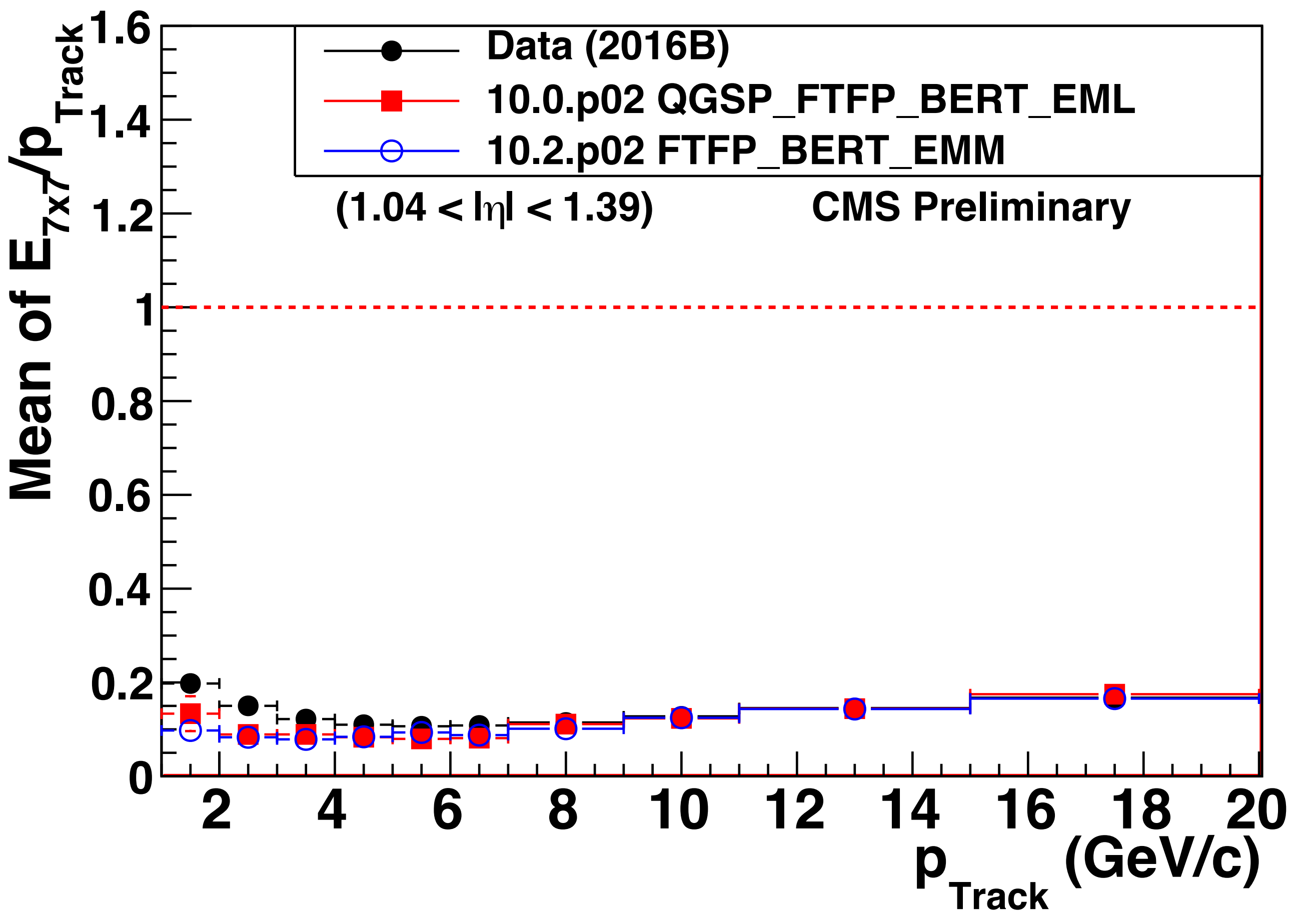


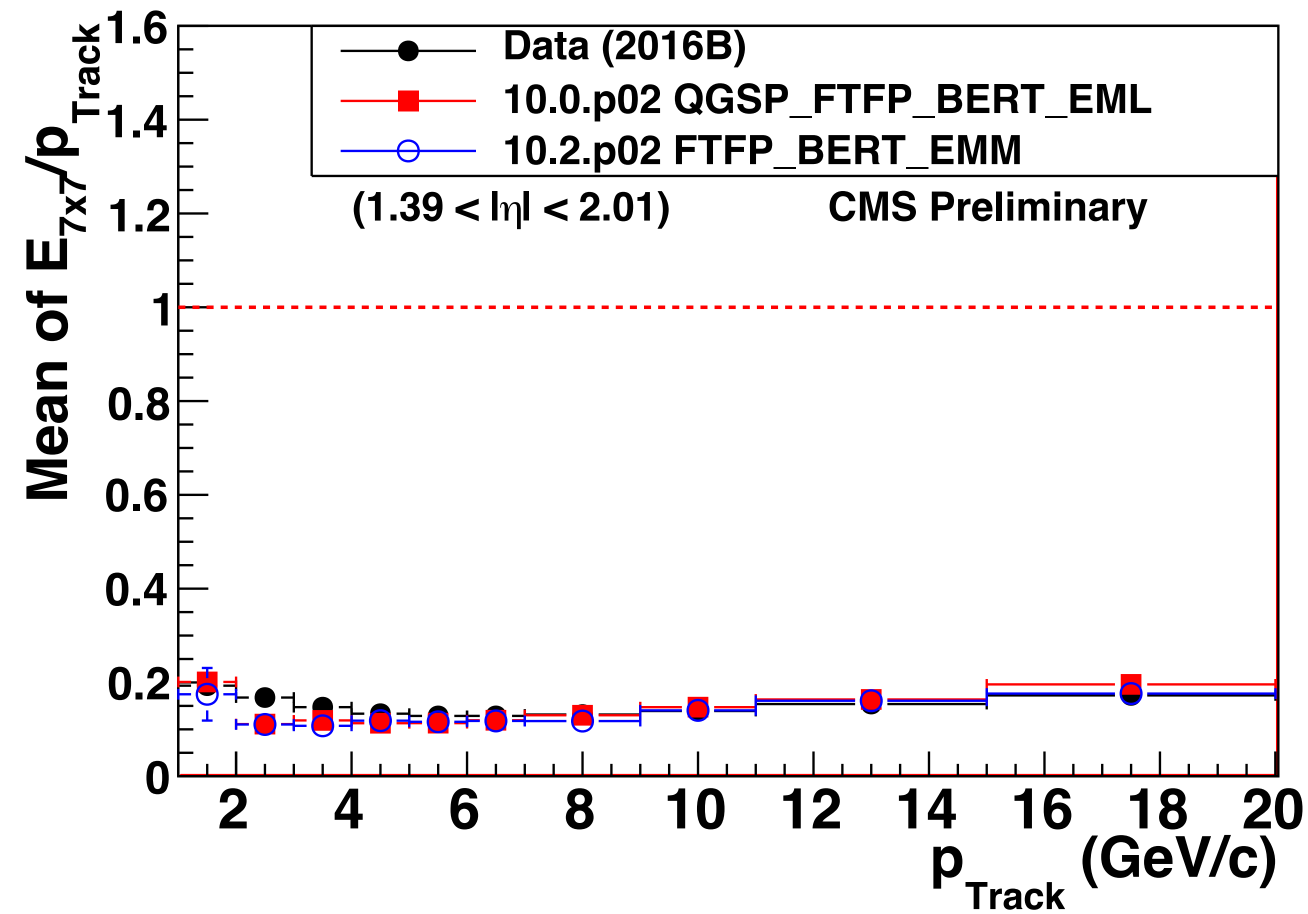
- Two versions of NxN matrix are defined for ECAL and HCAL
  - ECAL uses 7x7 or 11x11 matrix
  - HCAL uses 3x3 or 5x5 matrix

Energy in ECAL (7x7 matrix)

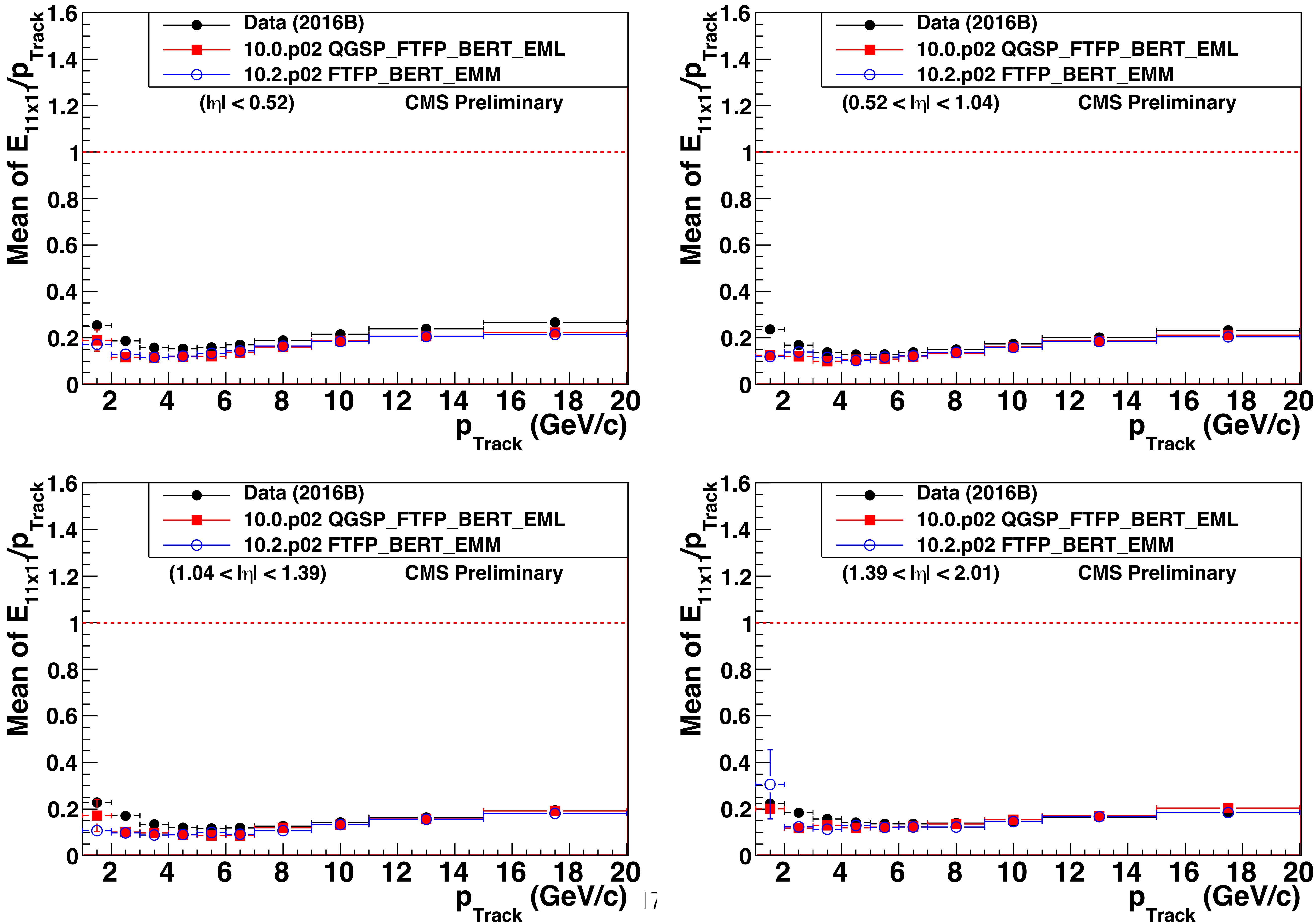




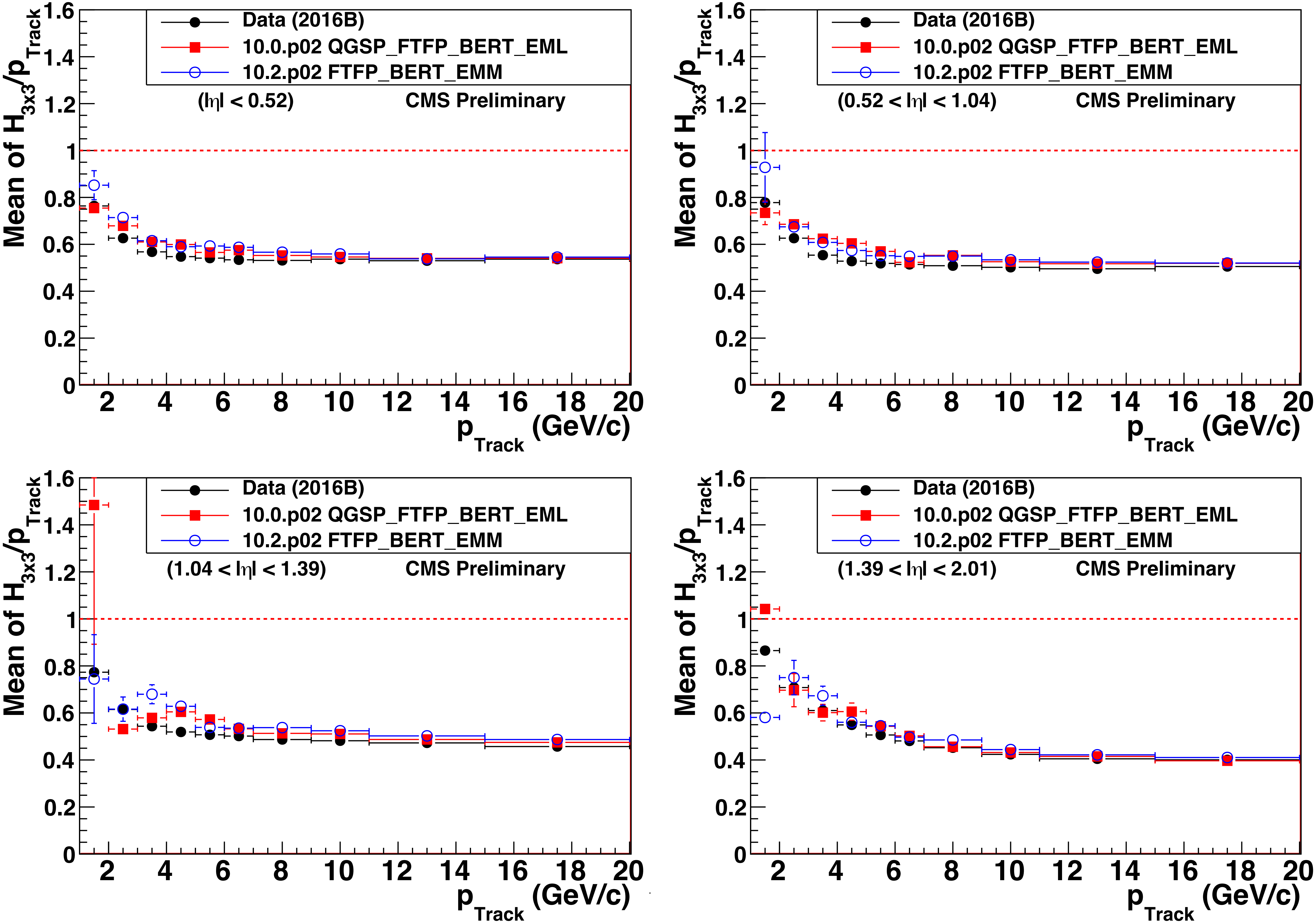




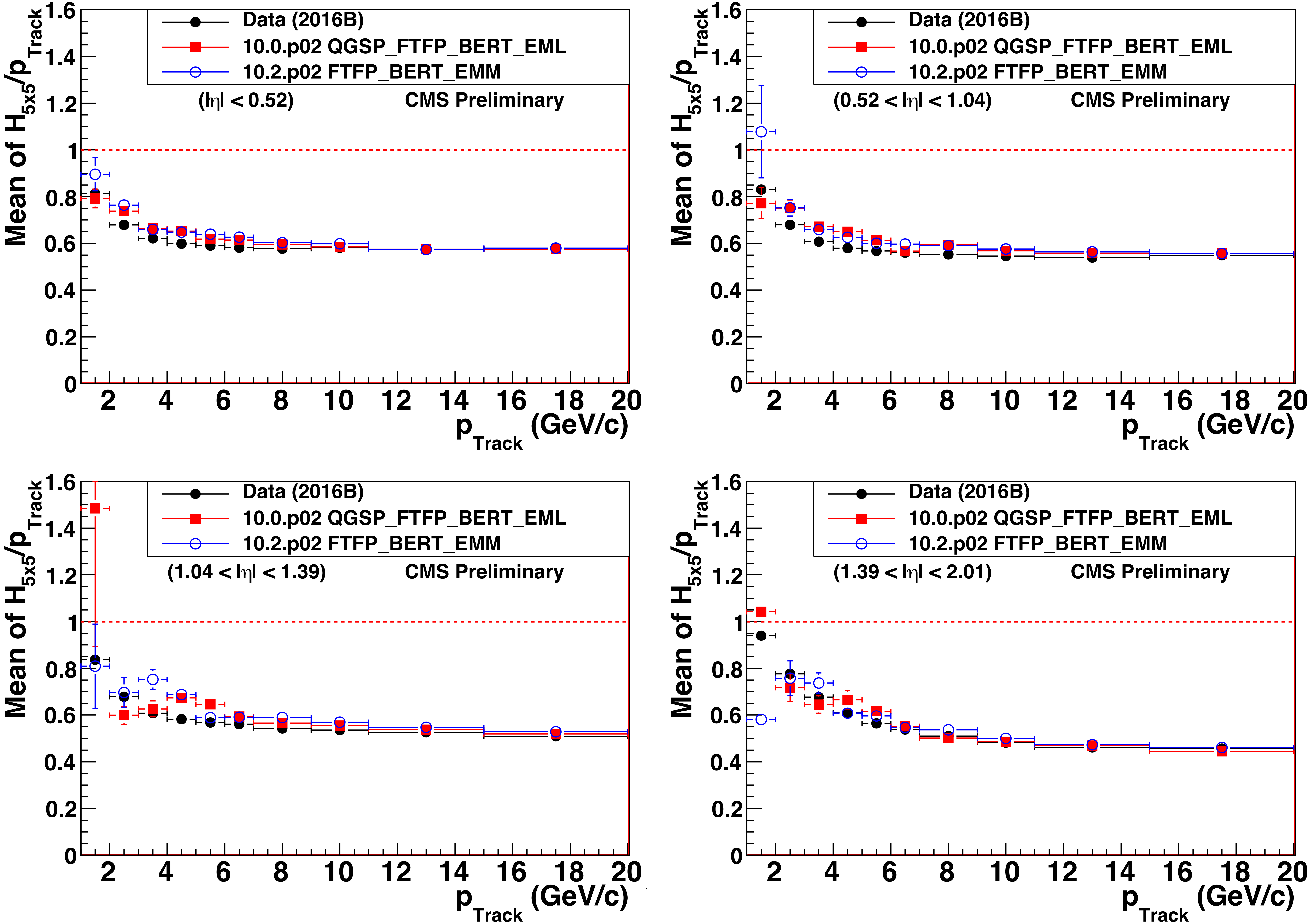
Energy in ECAL (11x11 matrix)



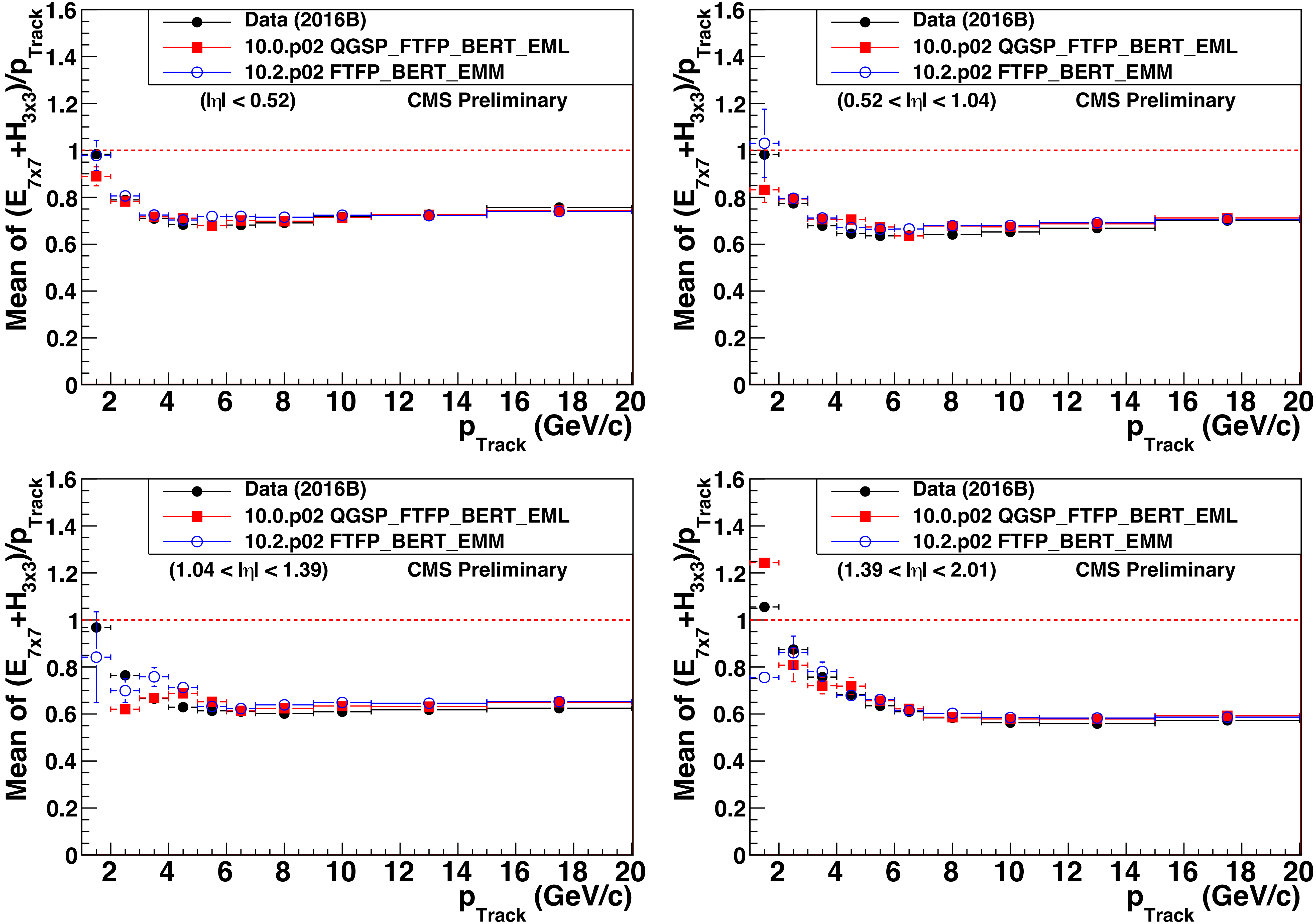
Energy in HCAL (3x3 matrix)



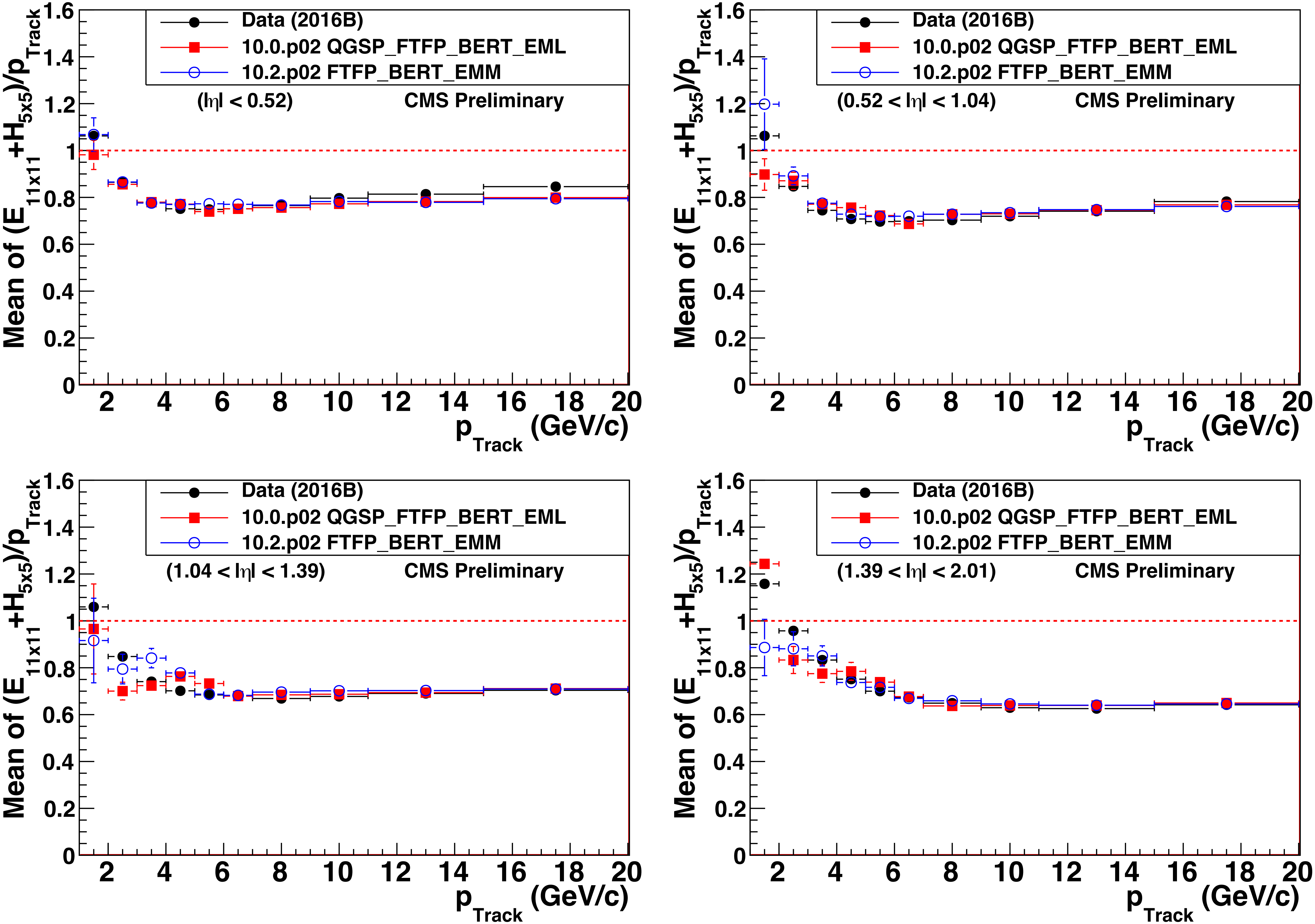
Energy in HCAL (5x5 matrix)



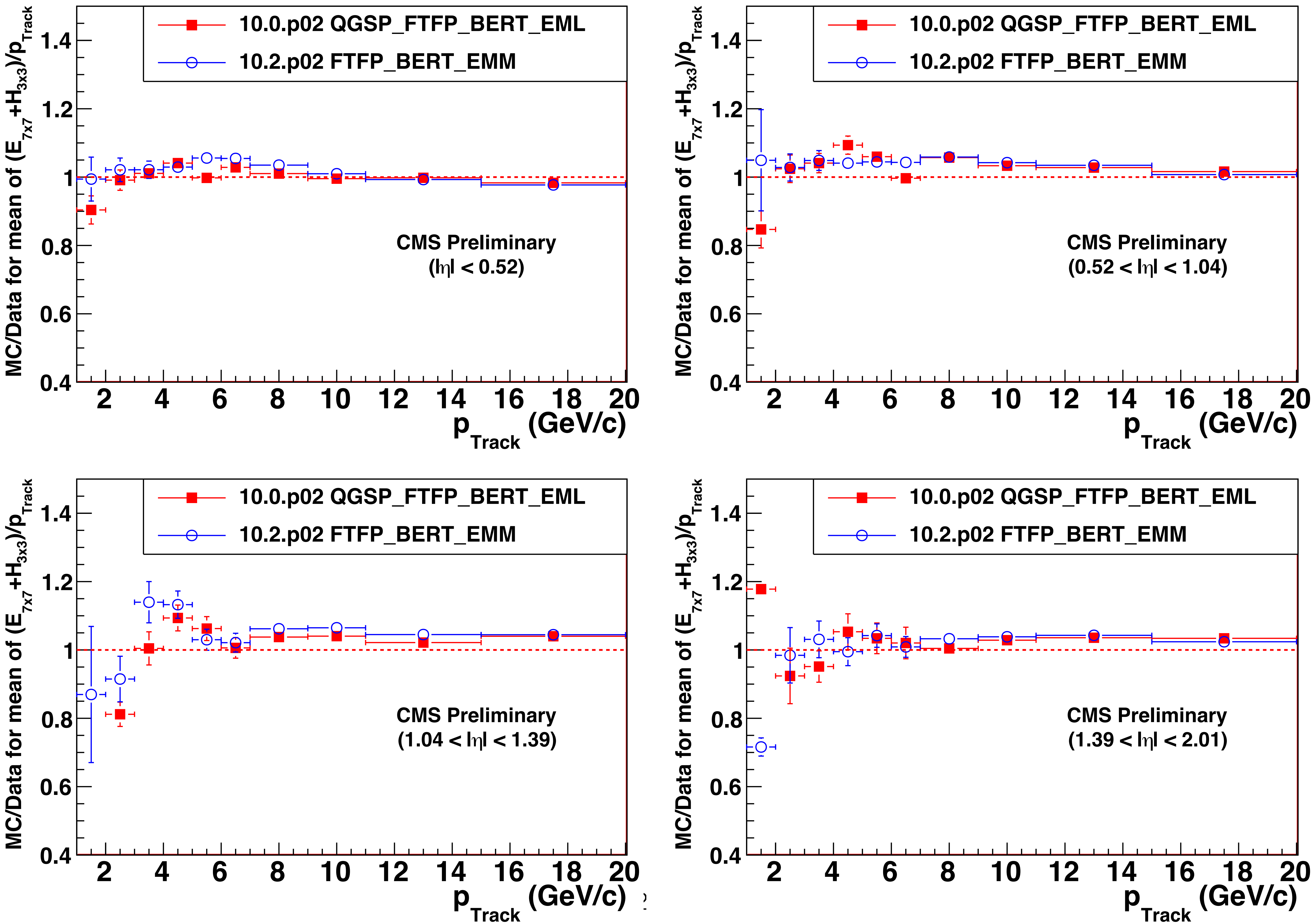
Combined Calorimeter Energy (7x7+3x3 matrix)



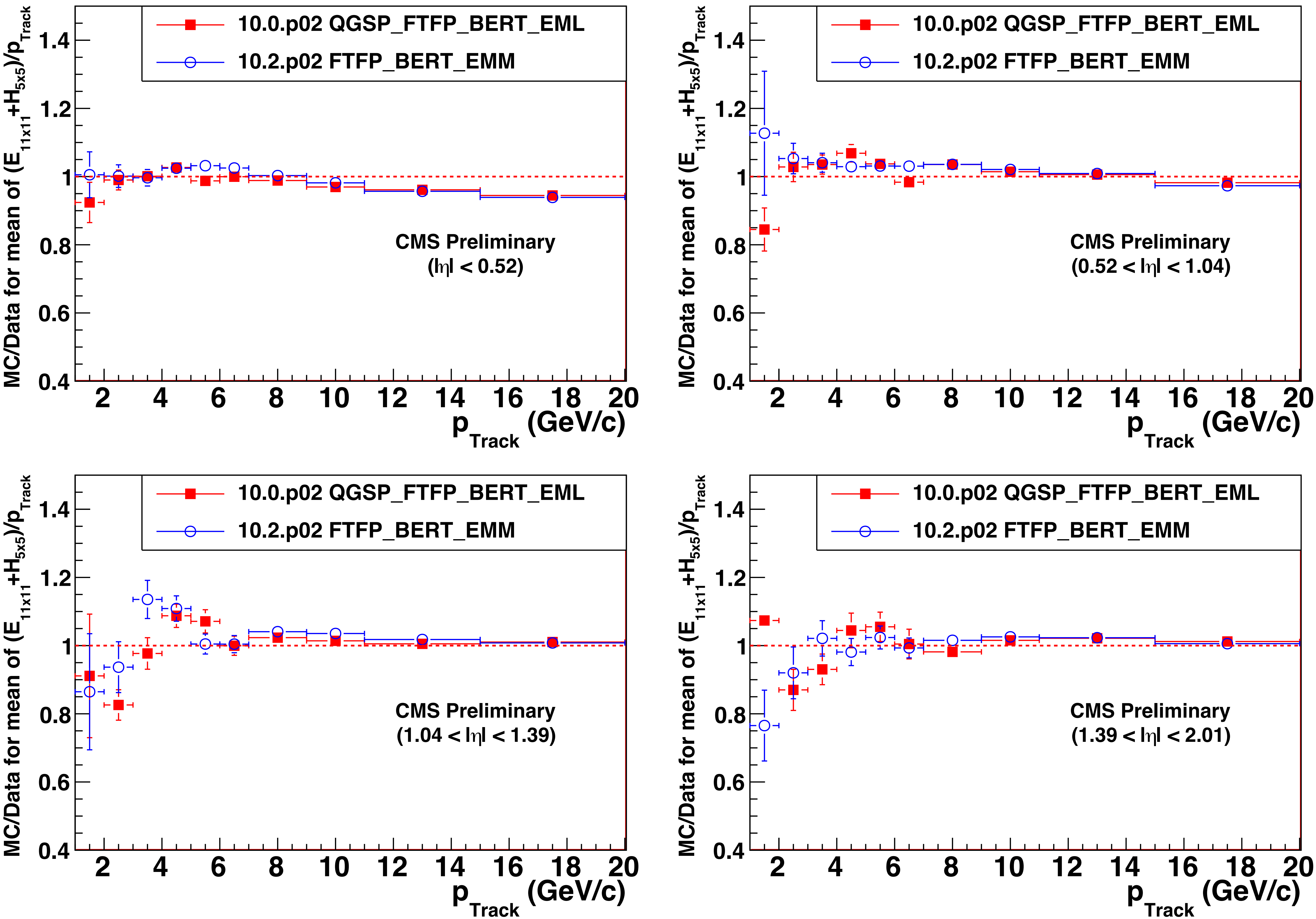
Combined Calorimeter Energy (11x11+5x5 matrix)



Combined Calorimeter Energy (7x7+3x3 matrix)



Combined Calorimeter Energy (11x11+5x5 matrix)



Collision Data

- The level of disagreement between data and MC is between 2 to 5% depending on the region of the detector as well as the physics list used

Mean level of disagreement between MC and data

	$(E_{7x7}+H_{3x3})/p$ 10.0.p02	$(E_{7x7}+H_{3x3})/p$ 10.2.p02	$(E_{11x11}+H_{5x5})/p$ 10.0.p02	$(E_{11x11}+H_{5x5})/p$ 10.2.p02
Barrel 1	(1.1±0.4)%	(2.4±0.4)%	(2.5±0.4)%	(2.6±0.4)%
Barrel 2	(3.4±0.4)%	(3.6±0.4)%	(1.9±0.4)%	(2.2±0.4)%
Transition	(3.7±0.5)%	(4.9±0.5)%	(1.6±0.5)%	(2.2±0.5)%
Endcap	(1.1±0.3)%	(4.1±0.5)%	(4.7±0.4)%	(1.6±0.5)%