Physics Models used in CMS

Simulation Meeting
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Geant4 in CMS

- CMS used the physics lists for the Run1 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 is moving 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 HGCAL and the simplified one for other detectors (handling of multiple scattering is critical for sampling calorimeter)

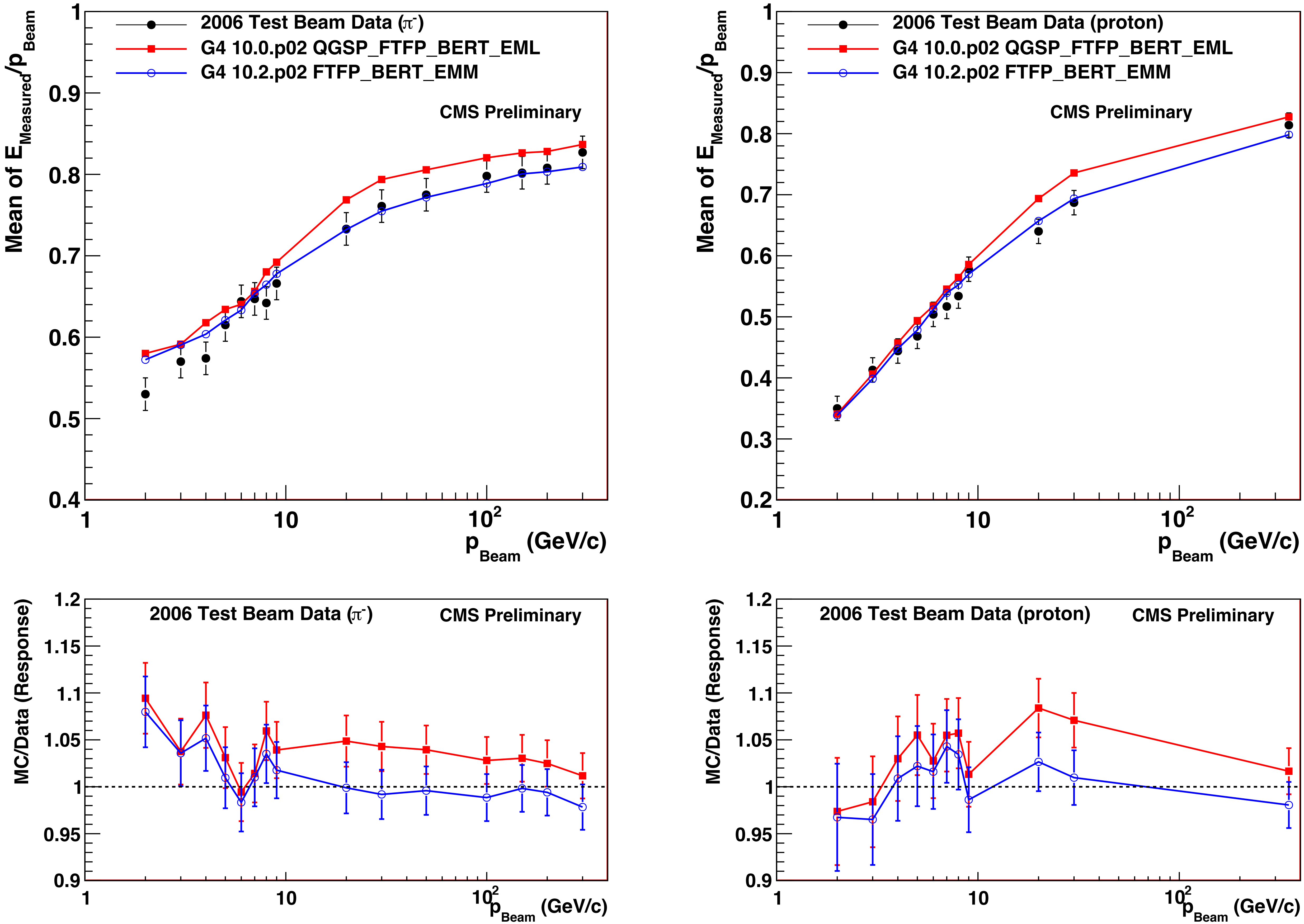
Physics Requirements in CMS Simulation

- Physics requirement in CMS simulation
  - Good and fast electromagnetic physics
    - Useful for tracker, muon system and a homogeneous EM calorimeter
    - Not so much emphasis on longitudinal shower profile of EM showers
  - Good hadronic physics to describe hadrons showers in the CMS calorimeter
    - Good description of lateral as well as longitudinal shower profile is required
- For Phase 2 operation of CMS, also require accurate description of longitudinal shower profile of EM showers (due to high granularity calorimeter in the endcap region)
- Several compromises are made to make simulation code fast enough to meet adequate statistics of MC sample within the resources provided:
  - Eliminate tracking of neutrinos
  - Introduce shower library approach for very forward calorimeters (HF, CASTOR, ZDC)
  - Provide production cuts for EM physics depending on the region
  - Introduce maximum time cut (again region dependent)
  - Reduce tracking of neutrons using Russian Roulette

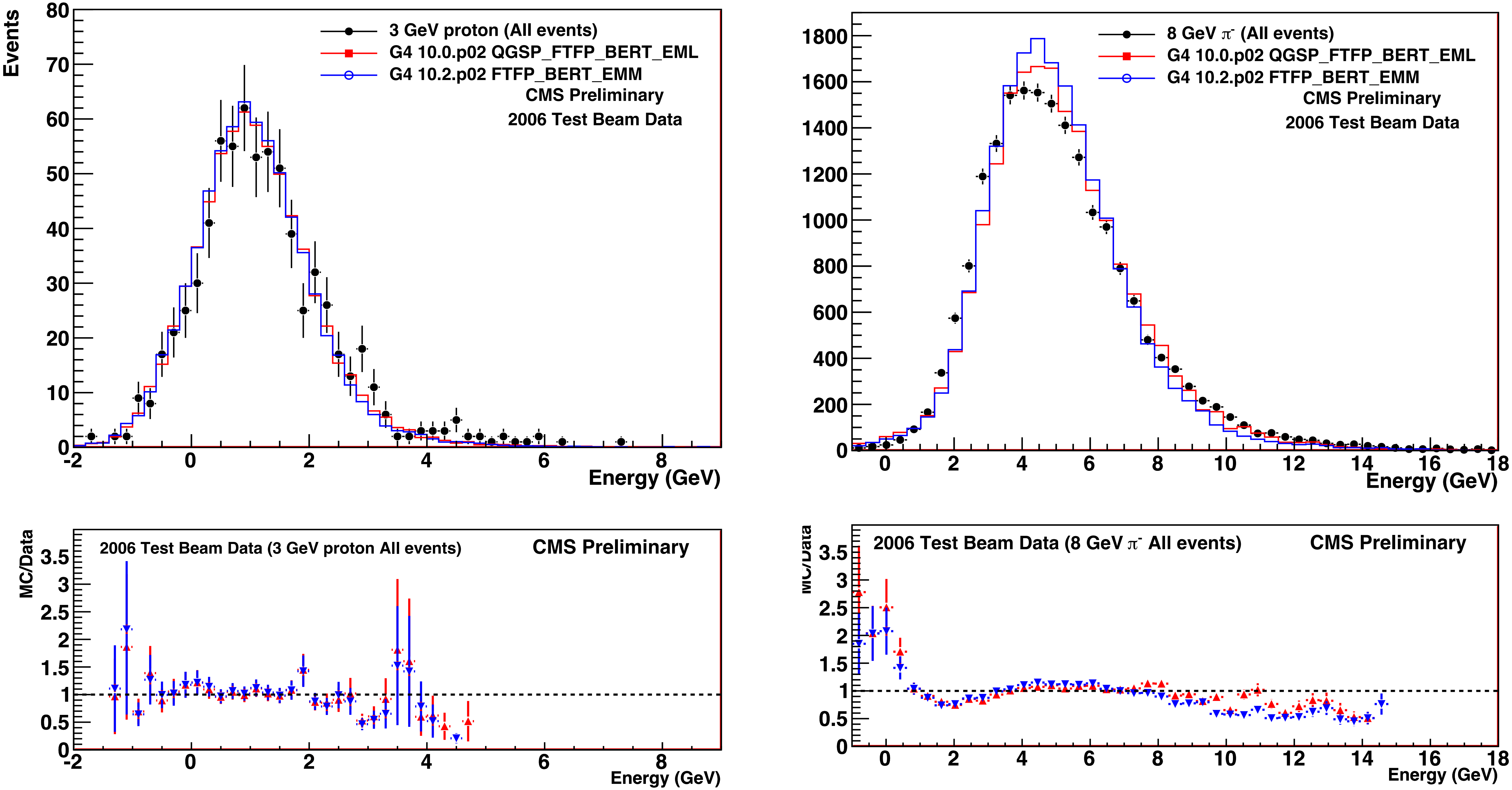
Validation of Physics Models

- CMS has been validating the physics models within Geant4 (and thus making a choice of the physics list) from the very beginning
- The early choice made use of
  - EM shower studies with electron beams in the test beam area (H4) with supermodules of EM calorimeter
  - Hadron shower studies with prototype of CMS hadron calorimeter and one supermodule of electromagnetic calorimeter in the test beam area (H2) using hadron beams of different types and different energies
  - Study of multiple scattering of muons using data from the L3 experiment
- CMS continues the validation process by comparing simulation results with data from two sources:
  - 2006 Test beam data from the H2 test beam setup
  - Collision data using CMS detector utilizing zero bias or minimum bias trigger from low luminosity runs from the 2016B run period
    - Similar analysis using isolated charged hadrons was done in CMS from the data during 2009

Mean response with pions and protons

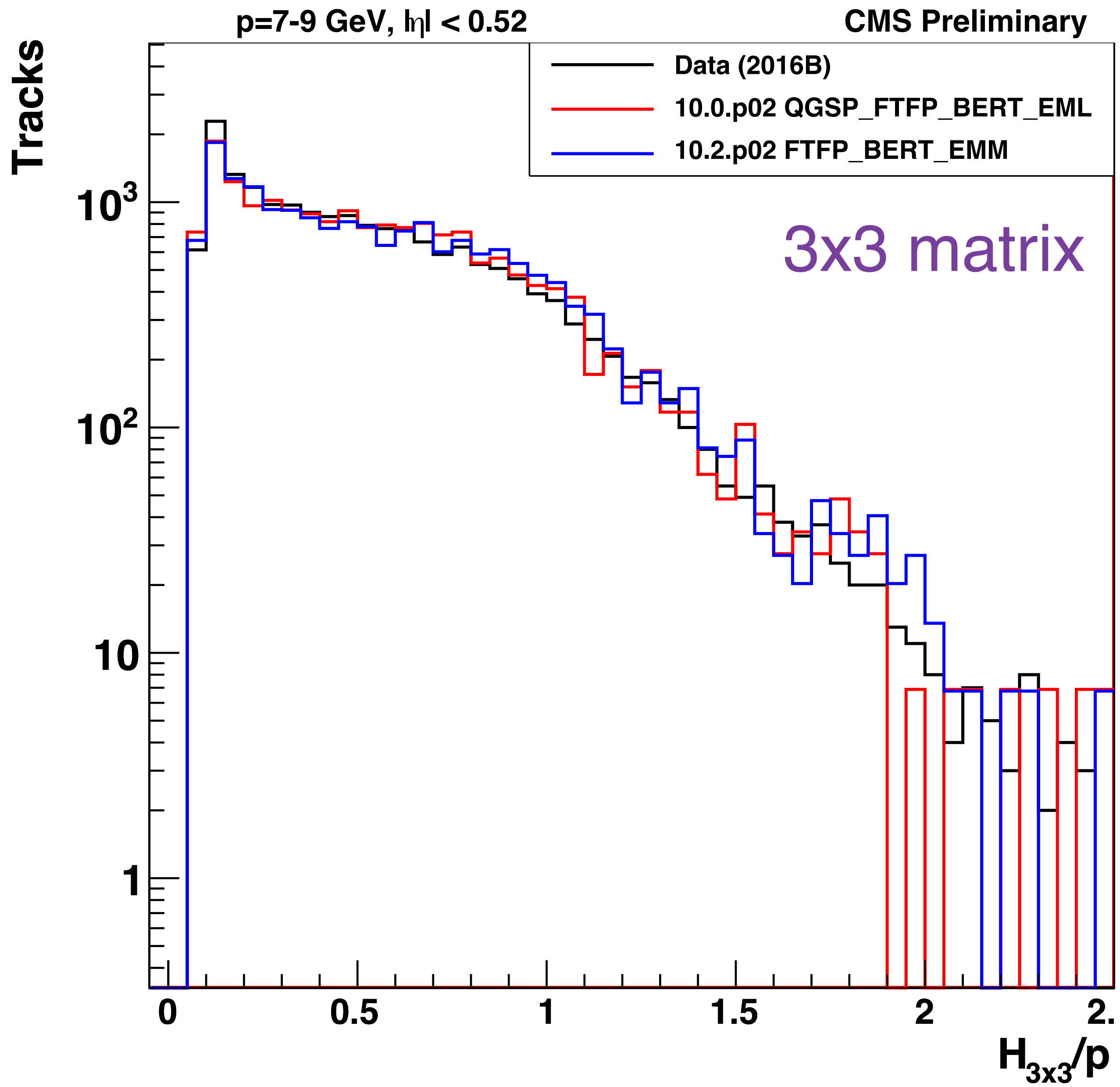


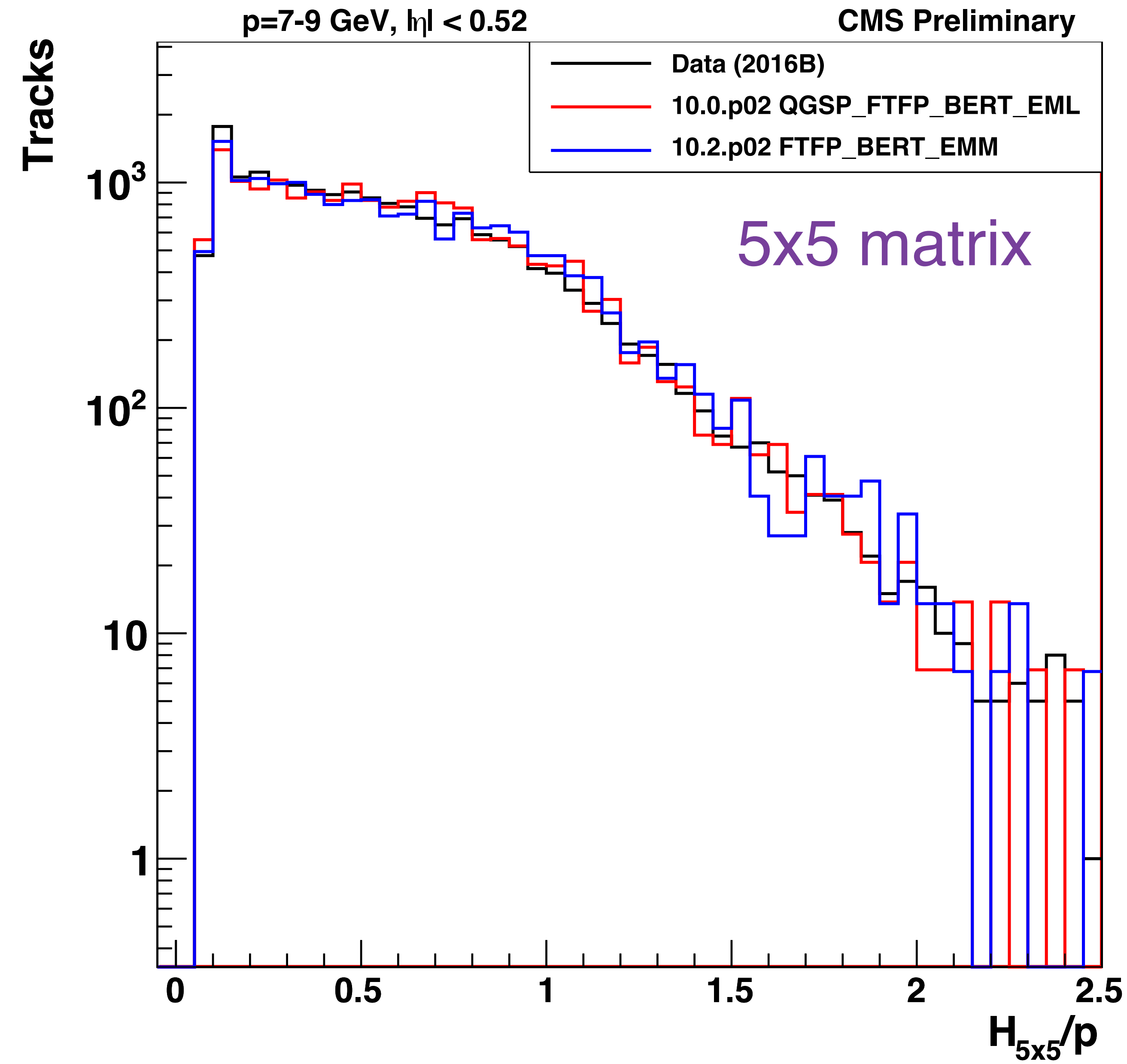
Energy distribution for pions and protons



- Comparisons are made with well identified beams (using several beam counters: Cernekov's, TOF counters, …)
- Individual comparisons made with no selection on shower starting point or when the shower starts in the HCAL

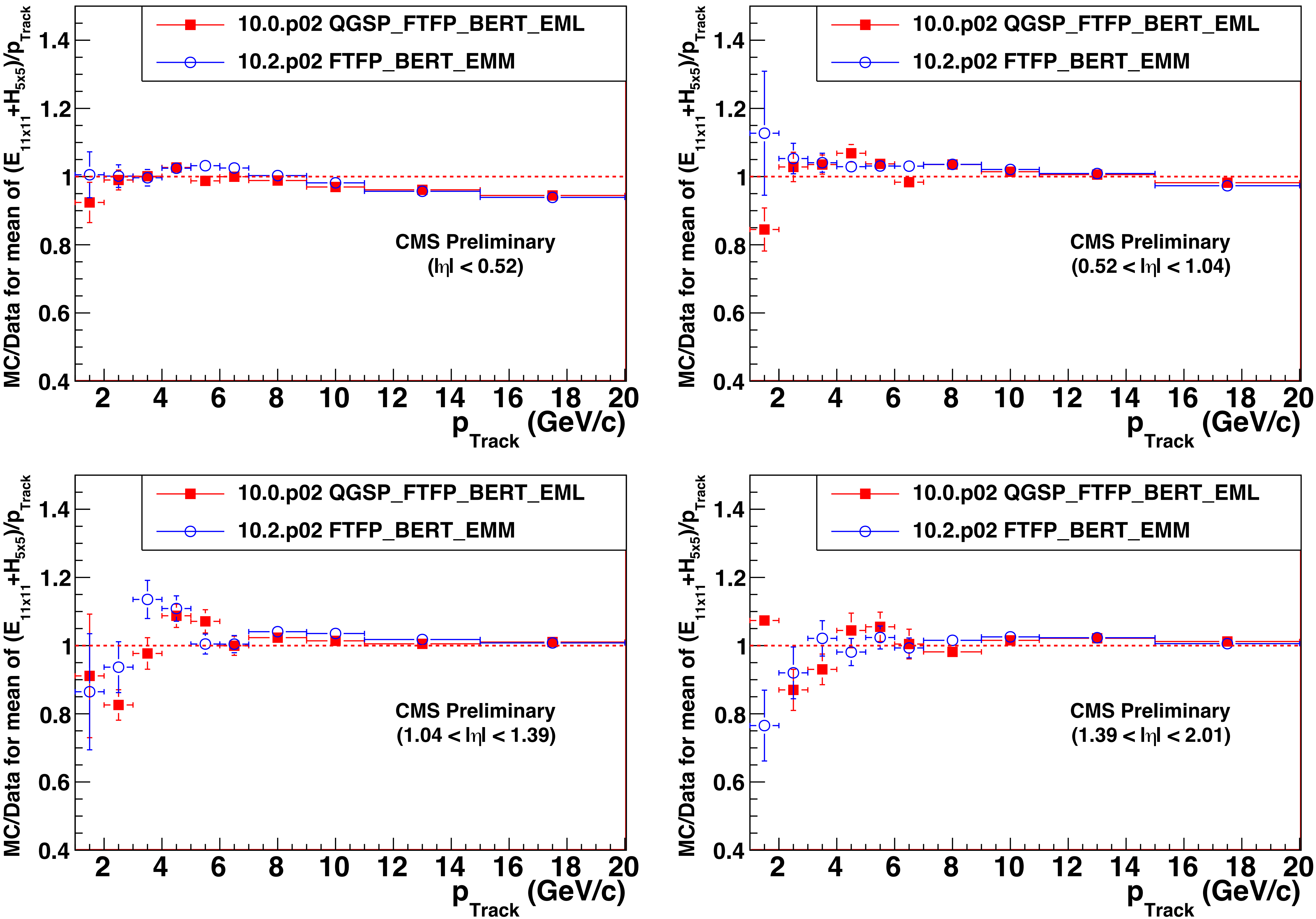
Energy in HCAL for Isolated Charged Hadrons





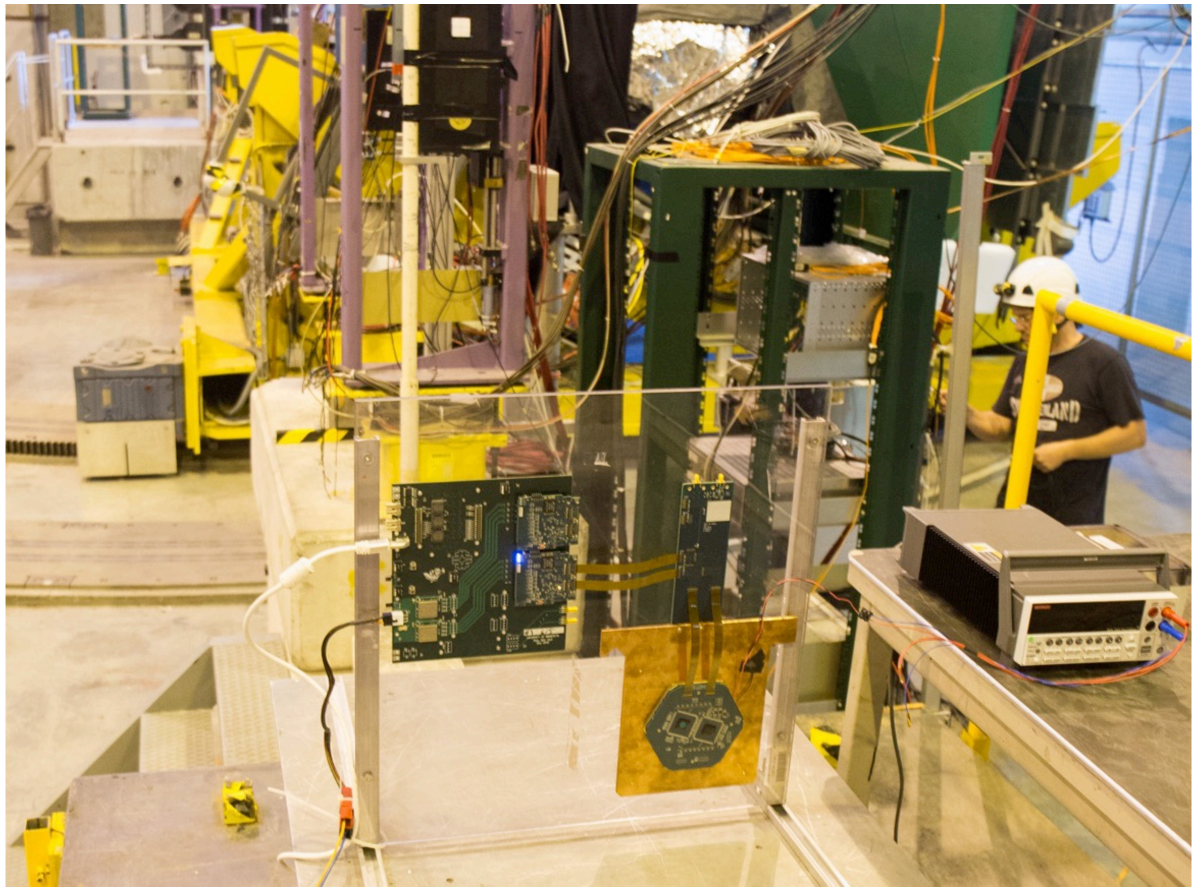
- Select isolated charged particles from the low luminosity collision data
- Use zero bias or minimum bias triggers
- Measure energy in a NxN matrix surrounding the impact point defined separately for ECAL and HCAL

Combined Calorimeter Energy (11x11+5x5 matrix)



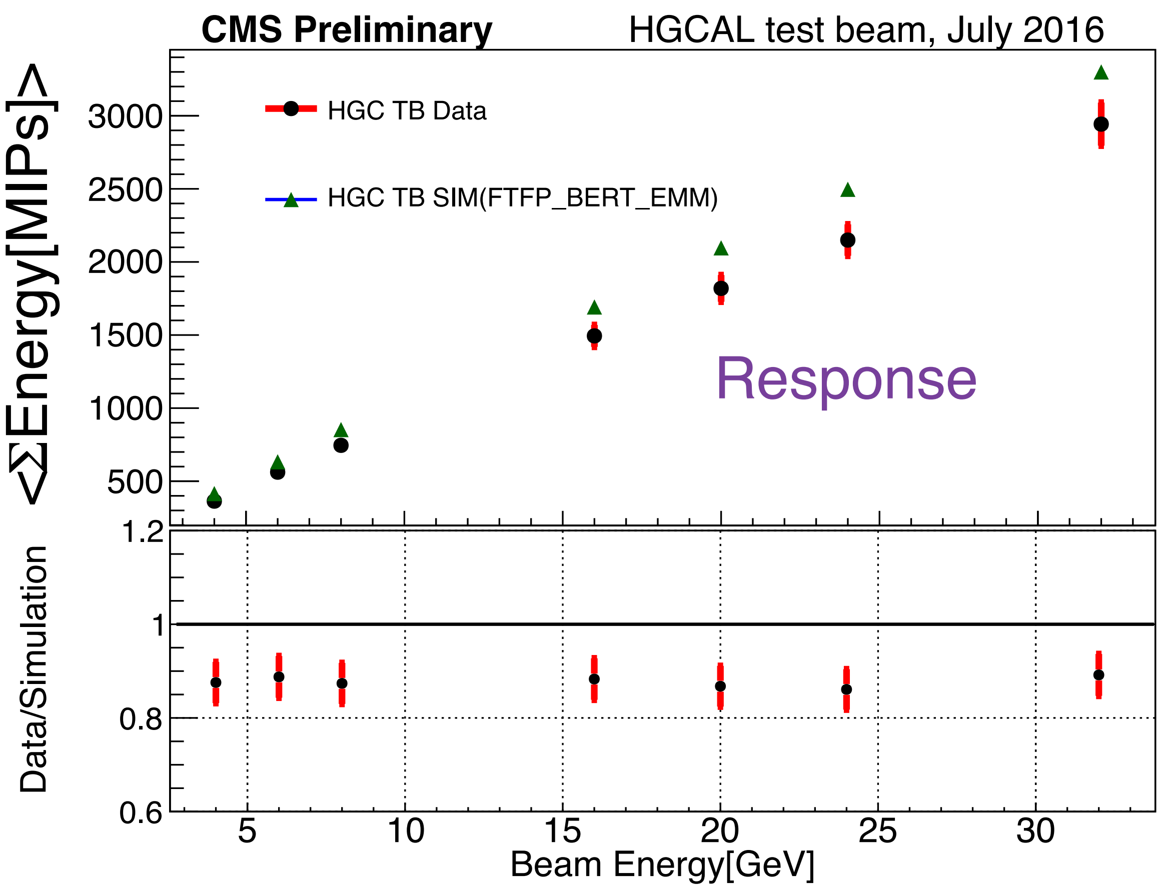
Next Steps

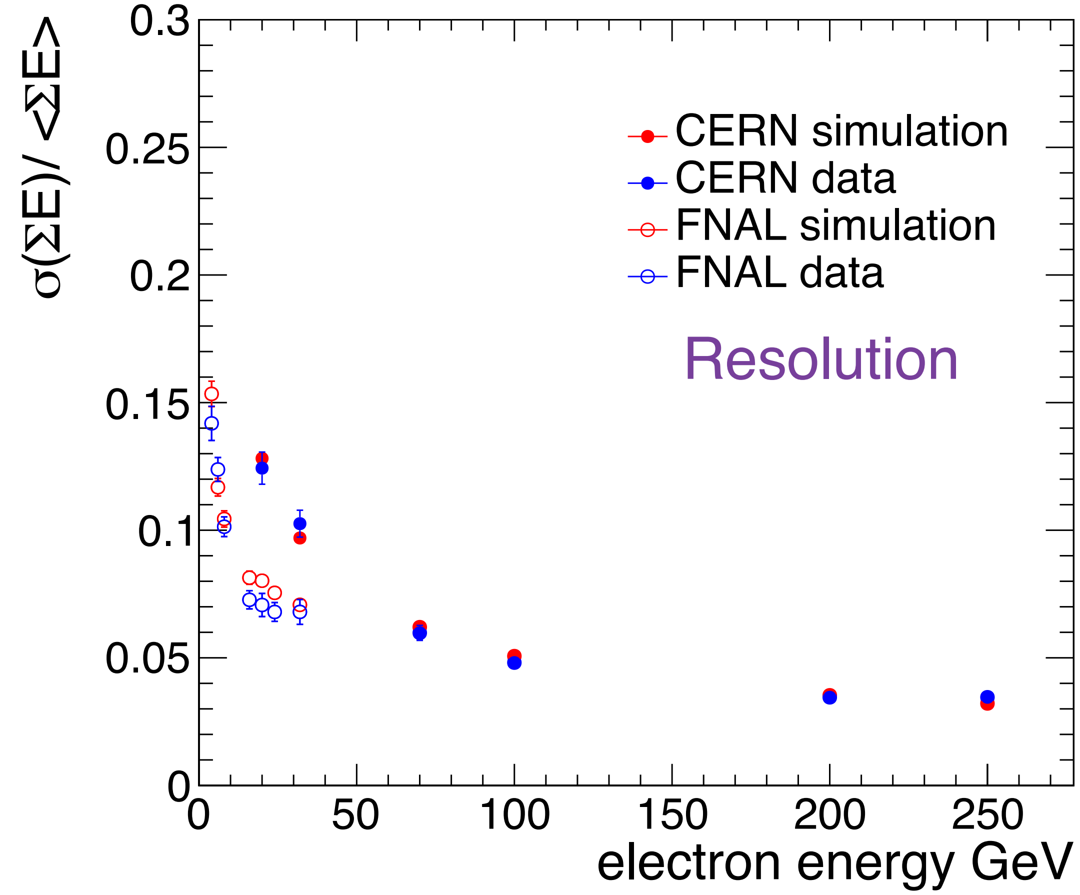
- During Phase 2 operation, CMS will have a high granularity calorimeter replacing the endcap electromagnetic and hadron calorimeter
- It comes with two challenges
  - The EM calorimeter will also be of sampling type: so longitudinal shower profile is important
  - The sensitive elements will be a mixture of silicon and scintillators and some of them have hexgonal/half-hexagonal shape. This will require additional resources due to complexity of the detector

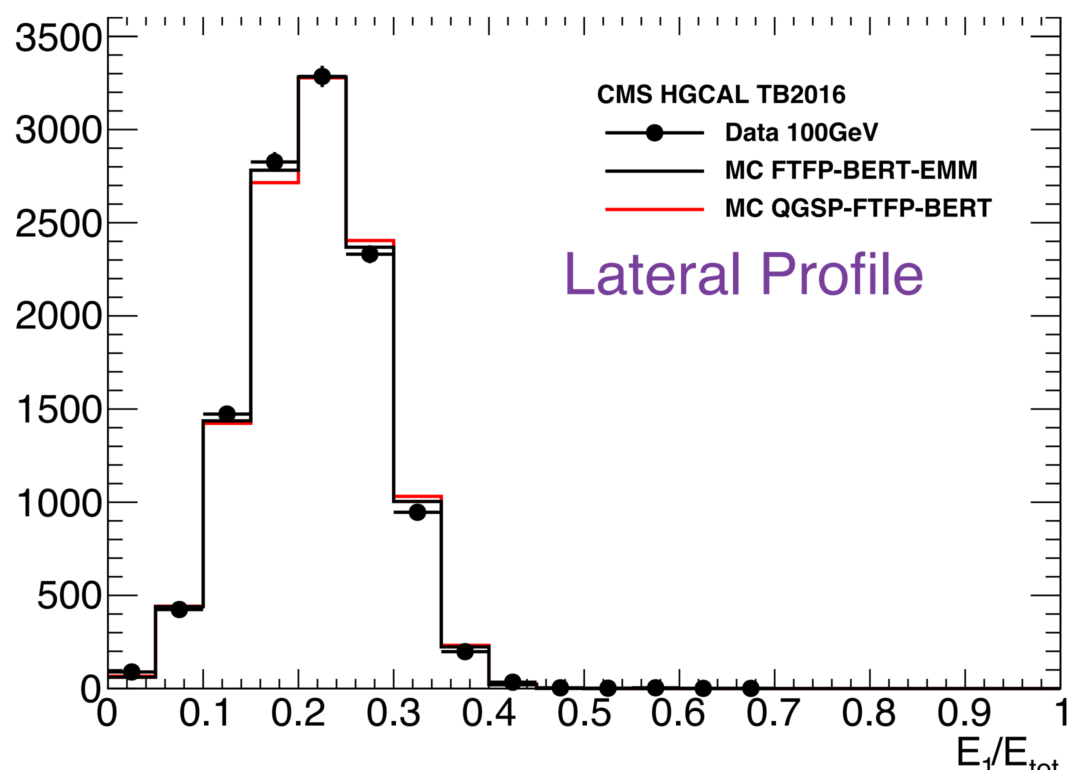


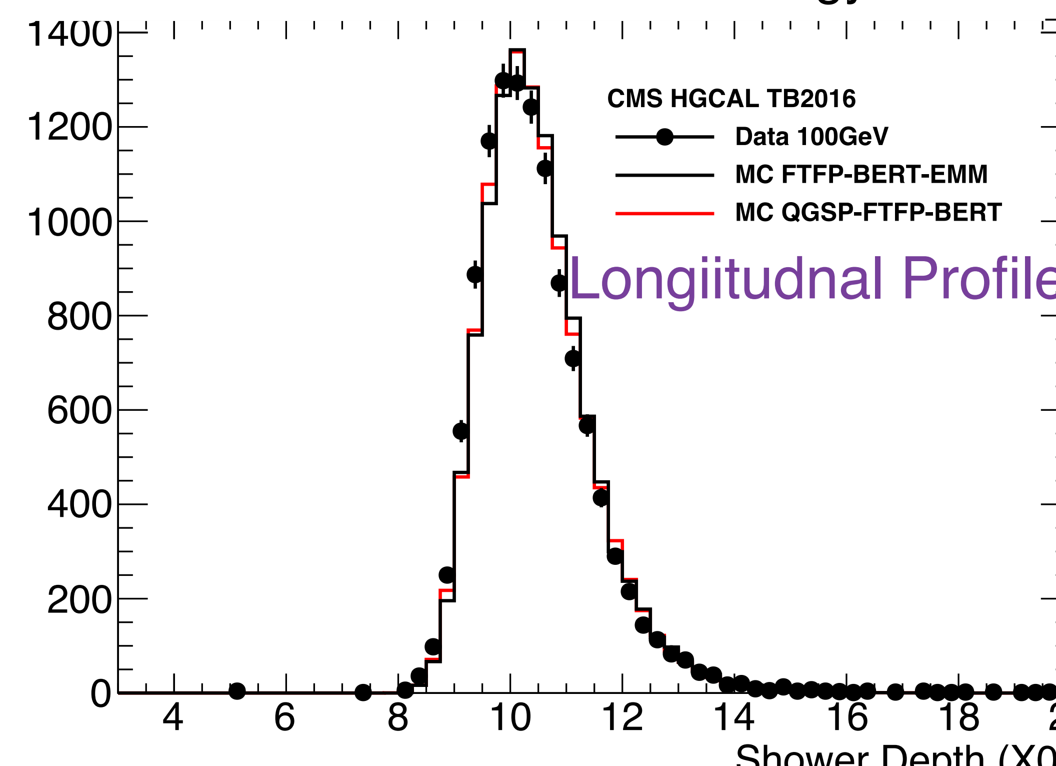
Setup with high granularity calorimeter prototype in CERN and FNAL testbeds

Very Preliminary Comparisons









- These studies will continue for next few years and will be a part of CMS validation toolkit

Additional Slides

Summary from Mean Response

Mean level of disagreement between MC and data

	negative pions	positive pions	negative kaons	positive kaons	protons	anti-protons
G410.0.p02 QGSP_FTFP_BERT_EML	0.036	0.019	0.097	0.078	0.043	0.035
G4 10.2.p02 FTFP_BERT_EMM	0.018	0.010	0.120	0.131	0.022	0.031

- 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

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)

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)%

Combined Calorimeter Energy (7x7+3x3 matrix)