Validation of Geant4 10.4.ref08 with thin target, CMS test-beam and collider data

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Introduction

- CMS experiment uses Geant4 toolkit as the simulation engine and adaptation of a new Geant4 version or a new Physics List requires validation of the model predictions with some of the existing data

- The current validation results are intended for the Geant4.10.ref09 version as well as Geant4.10.4 (December 2017), which is the current default for 2018 production
  - Results are also compared with the 2017 version of CMS simulation which are based on Geant4.10.2.p02

- Additionally to the new Geant4 version, other modifications were done to CMS simulation through usage of VecGeom library. The versions used is V01.01 for this reference version

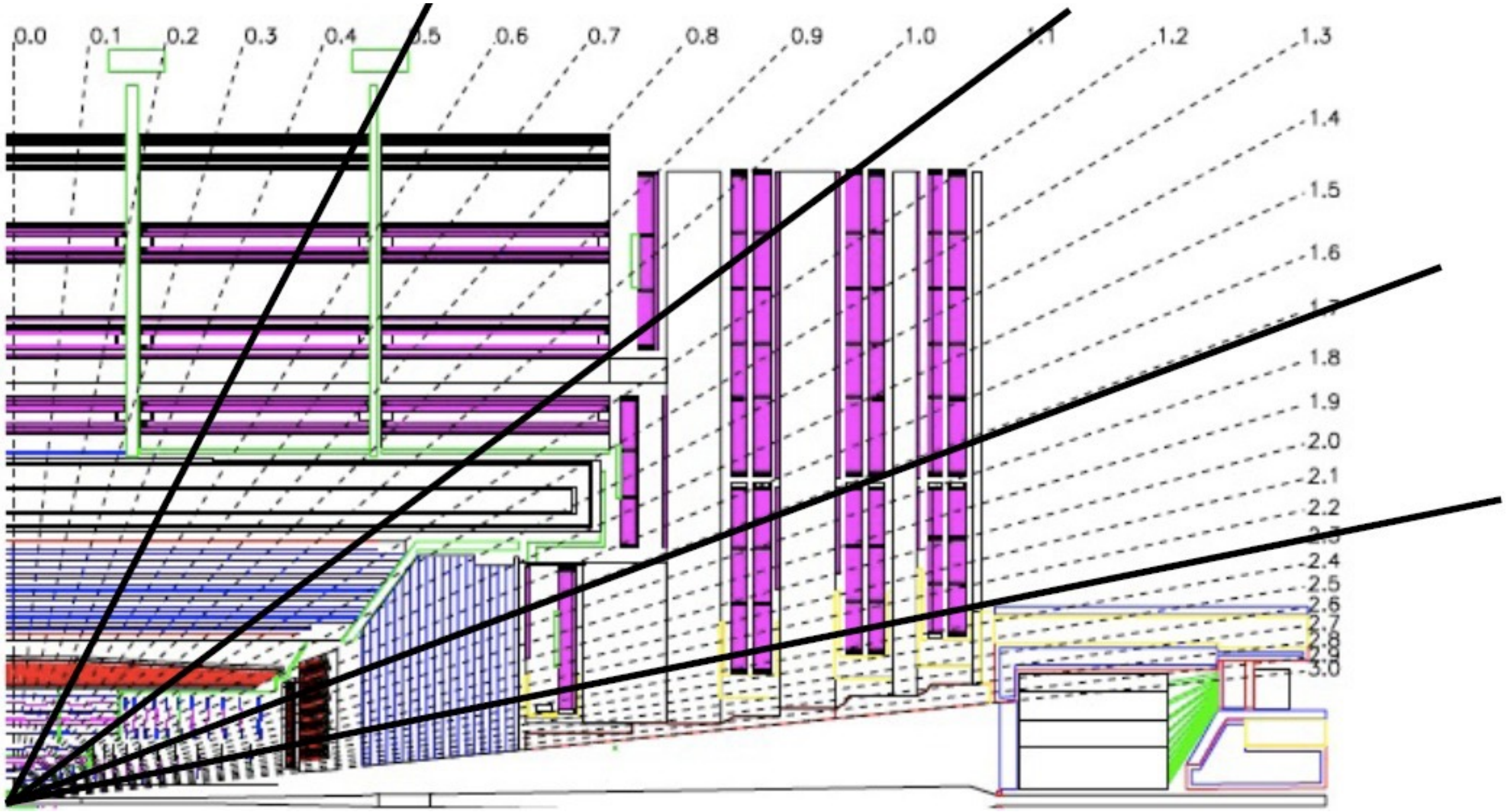
- There are two sources of data used for validation:
  - 2006 test beam runs in the SPS H2 beam line with prototypes of barrel hadron calorimeter (HB) module and one supermodule of barrel electromagnetic calorimeter
    - Results published in EPJ C60 (2009) 359 and used in tuning earlier CMS simulation
  - Low luminosity runs with the CMS detector taken during 2016B run period using Zero Bias and Minimum Bias triggers

Isolated Charged Hadrons

- 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 applying to the Run-2 data
  - Select good charged tracks reaching the calorimeter surface
  - Impose isolation of these charged particles
    - propagate all tracks in the event to the calorimeter surface and study momentum of tracks (selected with a loose goodness 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 isolation against neutral particles
  - Final cuts
    - No addition; tracks in the isolation region
    - Energy cut of 2 GeV for neutral isolation
    - No additional good primary vertex in the event (to reduce PileUp effect)

Energy Measurements



- Look at tracks in 4 different regions: two in the barrel, one in the endcap and one in the 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. Two versions of NxN matrix used:
  - 7x7 matrix for ECAL and 3x3 matrix for HCAL (better purity)
  - 11x11 matrix for ECAL and 5x5 matrix for HCAL (better containment)

- For the data use two low luminosity data sets from the 2016B run period
  - Distributions from Zero Bias and Minimum Bias triggers agree quite well
  - Combine these two data sets and compare that with Monte Carlo

Comparison for Small Matrix

- The mean level of disagreement between data and different MC versions are studied for energy response in the small matrix: $(E_{7x7}+H_{3x3})/p$
- The difference got progressively worse in the endcap and transition region (and also in the second barrel region) till 10.4.ref08 - slightly restored in 10.4.ref09

	10.2.p02	10.4.ref00	10.4.ref07	10.4.ref08	10.4.ref09
Barrel 1	(2.4±0.4)%	(5.7±0.4)%	(2.9±0.4)%	(3.5±0.4)%	(3.1±0.4)%
Barrel 2	(3.6±0.4)%	(4.0±0.4)%	(4.9±0.4)%	(5.4±0.4)%	(6.0±0.4)%
Transition	(4.9±0.5)%	(4.8±0.5)%	(6.6±0.5)%	(6.8±0.5)%	(6.4±0.5)%
Endcap	(3.1±0.3)%	(3.0±0.5)%	(4.0±0.5)%	(5.2±0.5)%	(4.9±0.5)%

Comparison for Large Matrix

- The mean level of disagreement between data and different MC versions are studied for energy response in the larger matrix: $(E_{11x11}+H_{5x5})/p$
- The level of agreement improves for the larger matrix
- The difference is the worst for the 10.4.ref08 version and the version 10.4.ref09 is slightly better

	10.2.p02	10.4.ref00	10.4.ref07	10.4.ref08	10.4.ref09
Barrel 1	(2.6±0.4)%	(4.0±0.4)%	(2.1±0.4)%	(2.4±0.4)%	(2.1±0.4)%
Barrel 2	(2.2±0.4)%	(2.6±0.4)%	(3.5±0.4)%	(4.1±0.4)%	(4.5±0.4)%
Transition	(2.2±0.5)%	(2.9±0.5)%	(4.8±0.5)%	(5.2±0.5)%	(4.8±0.5)%
Endcap	(1.5±0.3)%	(1.5±0.5)%	(2.9±0.5)%	(5.1±0.5)%	(4.9±0.5)%

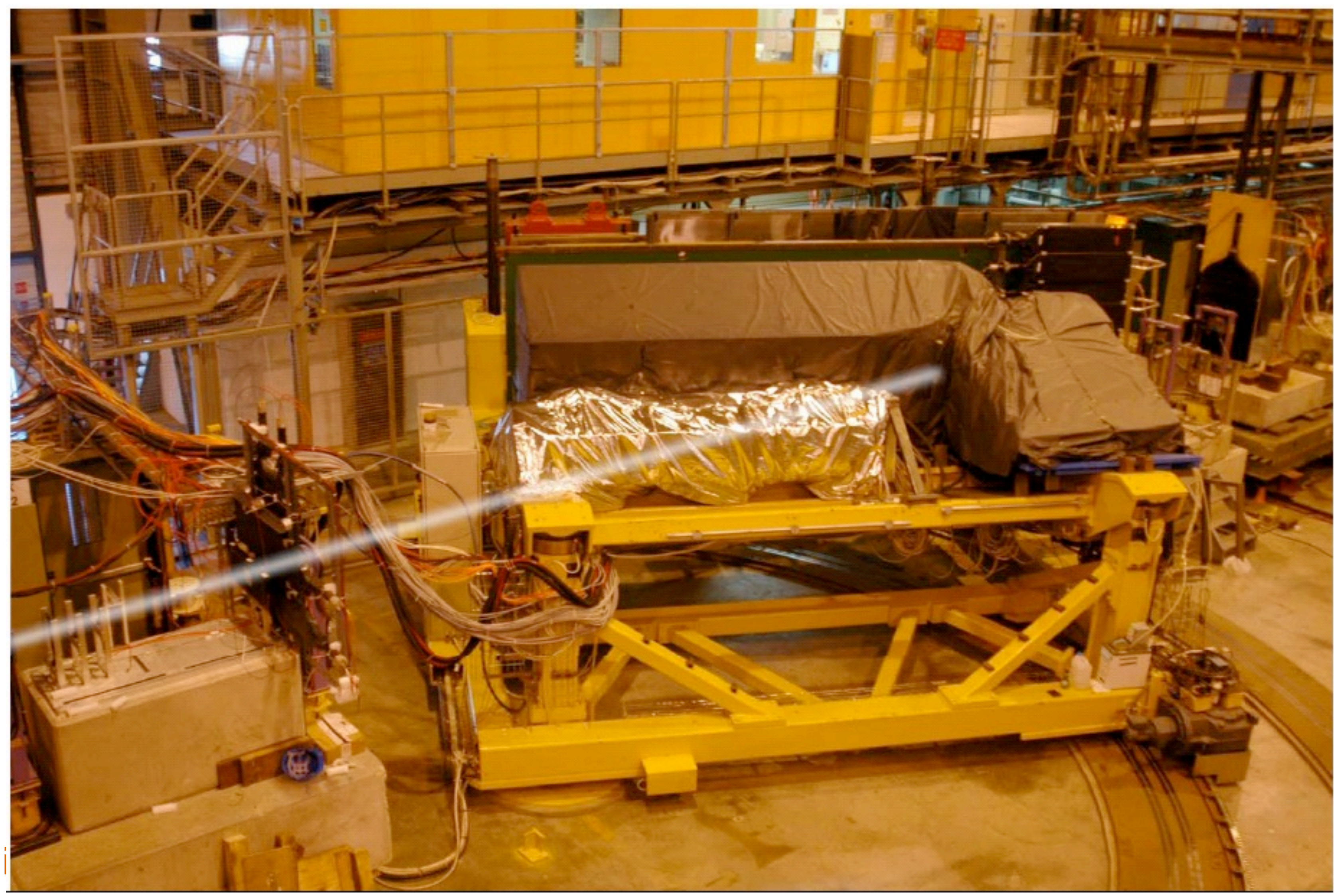
Comparison between 2 Physics Lists

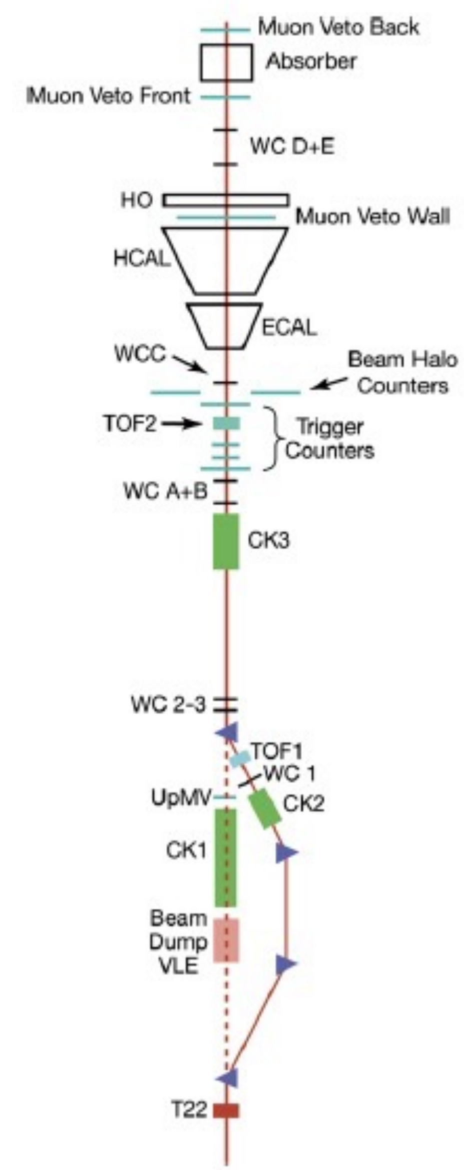
- The level of disagreement between data and MC is between 2.1% and 6.4% for FTFP_BERT_EMM and between 1.9% and 5.8% for the physics list QGSP_FTFP_BERT_EML with the "VecGeom" builds depending on the region of the detector

	$(E_{7x7}+H_{3x3})/p$ 10.4.ref09 (FTFP)	$(E_{7x7}+H_{3x3})/p$ 10.4.ref09 (QGSP)	$(E_{11x11}+H_{5x5})/p$ 10.4.ref09 (FTFP)	$(E_{11x11}+H_{5x5})/p$ 10.4.ref09 (QGSP)
Barrel 1	(3.1±0.4)%	(2.6±0.4)%	(2.1±0.4)%	(1.9±0.4)%
Barrel 2	(6.0±0.4)%	(5.1±0.4)%	(4.5±0.4)%	(4.0±0.4)%
Transition	(6.4±0.5)%	(5.8±0.5)%	(4.8±0.5)%	(4.2±0.5)%
Endcap	(4.9±0.5)%	(5.2±0.5)%	(4.9±0.5)%	(4.7±0.5)%

2006 TestBeam Data

- The data correspond to single particle response due to well identified particles over a large momentum range (2 to 350 GeV)
- The results consist of the energy distributions for well identified particles at a fixed momentum
  - Particle identification is rather good for beam momenta at or below 9 GeV
- Use the setup described within CMSSW to simulate events with single particles.
- Both the calorimeters are calibrated using 50 GeV electron beam





Test Beam Analysis

- Events are simulated only till the simulation hit level (including saturation effect as in Birk's law)

- Effect of electronics and detector noise is taken care of by adding Gaussian noise separately for ECAL and HCAL
  - RMS_{ECAL} = 0.362 GeV
  - RMS_{HCAL} = 0.640 GeV

- The detector components in the beam line are described in the simulation package and the cuts which are used for data analysis are also used for analyzing the Monte Carlo Sample

- Exclude hits in the outer hadron calorimeter and use a time cut of 100 ns

- Energy in the calorimeter is summed up around the beam spot
  - 7x7 matrix of crystals for ECAL
  - 3x3 towers for HCAL

- 50 GeV electrons are used for defining energy scales of ECAL as well as HCAL. Energy is measured as
  - $Evis = E_{ECAL}*f_{ECAL} + E_{HCAL}*f_{HCAL}$
  - f_{ECAL} = 1.01, f_{HCAL} ~105 (for FTFP_BERT_EMM Physics List)

Test Beam Data

Mean level of disagreement between MC and data

	π- 10.4	π- 10.4.ref8	π- 10.4.ref9	π+ 10.4	π+ 10.4.ref8	π+ 10.4.ref9	p 10.4	p 10.4.ref8	p 10.4.ref9
2 GeV	10.9±0.9	12.1±0.9	11.7±0.9	10.7±1.2	11.8±1.3	11.7±1.3	5.2±2.7	7.0±2.7	6.9±2.6
3 GeV	9.4±0.6	9.4±0.6	9.1±0.6	11.6±1.7	10.2±1.7	10.3±1.7	1.7±1.0	2.4±1.0	3.0±1.0
4 GeV	10.0±0.5	14.7±0.5	14.3±0.5	15.5±0.5	12.6±0.5	12.0±0.5	6.8±1.2	12.9±1.2	12.3±1.2
5 GeV	12.8±0.5	10.3±4.5	10.7±0.5	9.9±1.0	10.1±0.9	10.9±0.9	6.1±3.4	13.2±3.2	13.1±3.1
6 GeV	13.7±0.4	12.3±0.4	11.6±0.4	8.5±0.9	11.8±0.8	12.2±0.8	5.8±3.3	6.2±3.5	5.9±3.4
7 GeV	10.5±0.5	14.0±0.5	14.5±0.5	8.5±0.8	15.2±0.7	14.2±0.7	3.8±3.0	11.2±2.8	11.0±2.8
8 GeV	9.3±0.7	17.7±0.6	17.3±0.6	11.3±0.8	16.9±0.7	17.1±0.7	2.1±6.0	6.1±5.0	5.2±5.0

Summary

- Predictions from the Physics List FTFP_BERT_EMM from Geant4 versions 10.2.p02, 10.4, 10.4.ref07, 10.4.ref08 and 10.4.ref09 are compared with the collision data from CMS as well as with energy distributions from 2006 test beam data

- The level of agreement between data and Monte Carlo is reasonable for all these versions of Geant4 for collision data. However, the predictions give worse agreement with the progression of Geant4 versions (except the last version)

- Currently the physics list QGSP_FTFP_BERT_EML is performing slightly better than FTFP_BERT_EMM for collision data comparisons

- The level of agreement is similar to earlier comparisons for test beam data
  - pion data show slightly wider energy distributions than MC predictions
  - Mean response and energy resolution are still to be studied

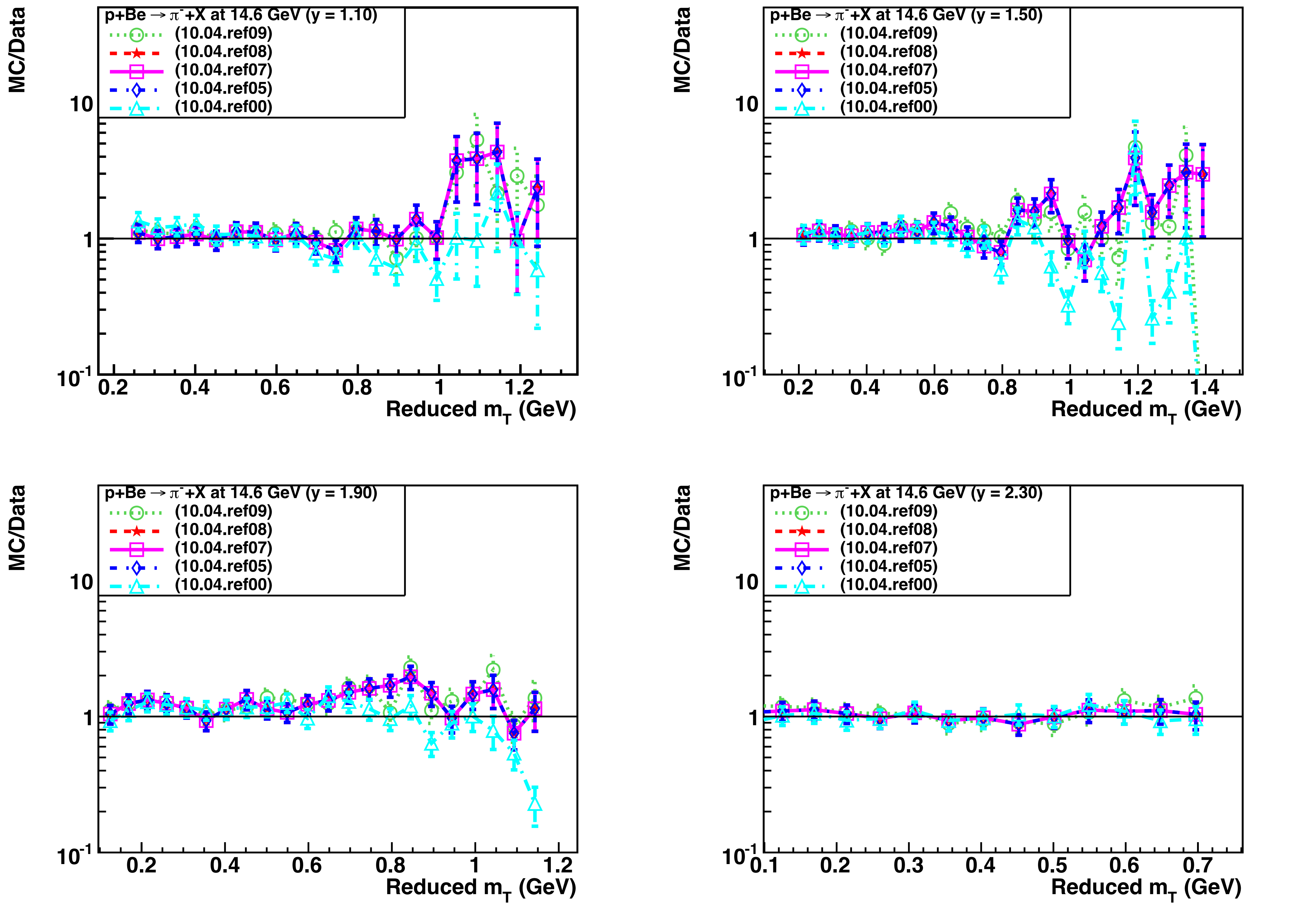
- There are some issues in propagation in B-field. This is under investigation

Comparison with BNL Data

- Data set from BNL E802: (T. Abbott *et al.*, Phys. Rev. D45, 3906)
  - Inclusive $\pi^{\pm}$, $K^{\pm}$ and proton production from p beams at 14.6 GeV/c on a variety of nuclear targets
  - Quantities measured are Lorentz invariant differential cross sections as a function of transverse mass (m_T) in bins of rapidity (y)
  - Data quality: statistical error 5-30%; systematic uncertainty 10-15%
  - Targets studied Be, Al, Cu, Au for all the final states available
- For calculation of invariant cross sections in the BNL data constant bin width of ($\Delta y = \pm 0.1$) is used
- Three Geant4 models are considered for the comparisons:
  - Bertini, FTFP and QGSP
- Five versions of Geant4 are used in the following plots:
  - 10.3.ref09, 10.4.ref00, 10.4.ref05, 10.4.ref08, 10.4.ref09

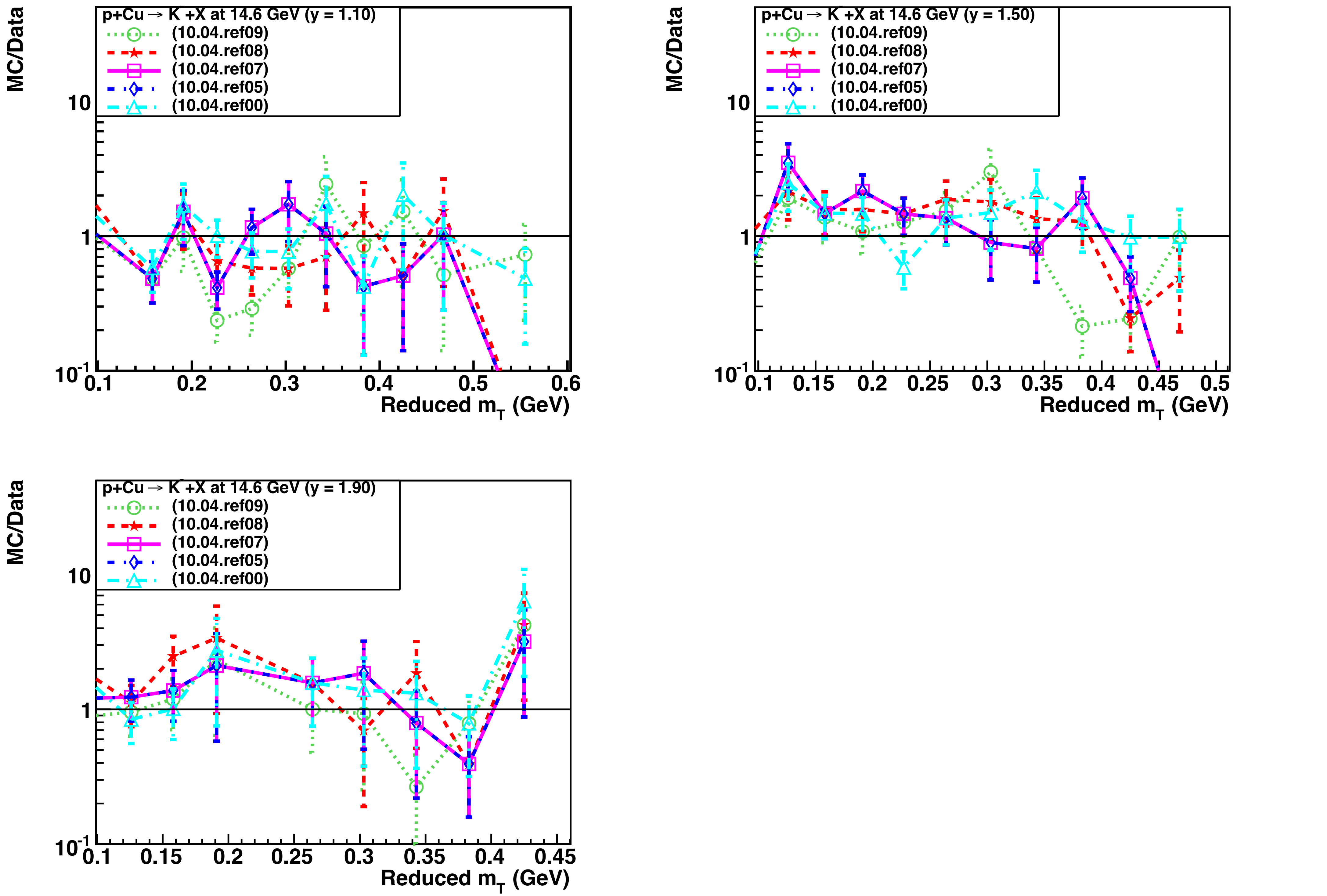
Geant 4

$p + Be \rightarrow \pi^- + X$ at 14.6 GeV/c (FTFP)



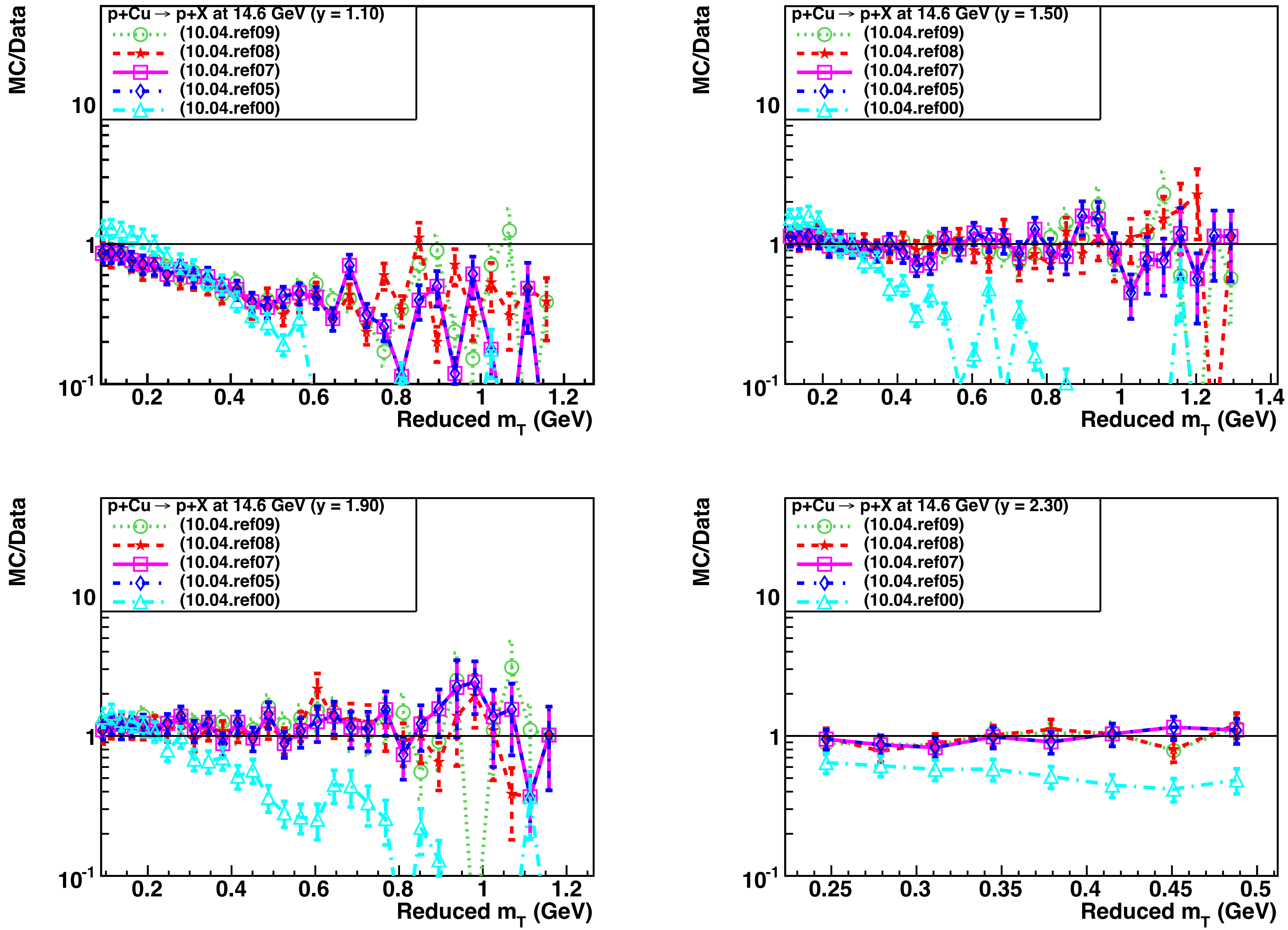
- There is some significant improvement in the predictions of the FTFP model from 10.3.ref09 to 10.4.ref00. But agreement deteriorates for subsequent reference versions of 10.3. ref09. 10.4.ref09 is comparable to the predictions of 10.4.ref08.

p + Cu →K⁻ + X at 14.6 GeV/c (FTFP)



- All versions provide similar level of agreement for K^- production. All are better than 10.3.ref09

p + Cu → p + X at 14.6 GeV/c (FTFP)



- The version 10.4.ref00 provides the worst agreement for p production. 10.4.ref08 provide reasonable description of the data (better than 10.4.ref09)

ChiSq/Data for Final State Pions (FTFP)

- Using a flat systematic uncertainty for all measurements:

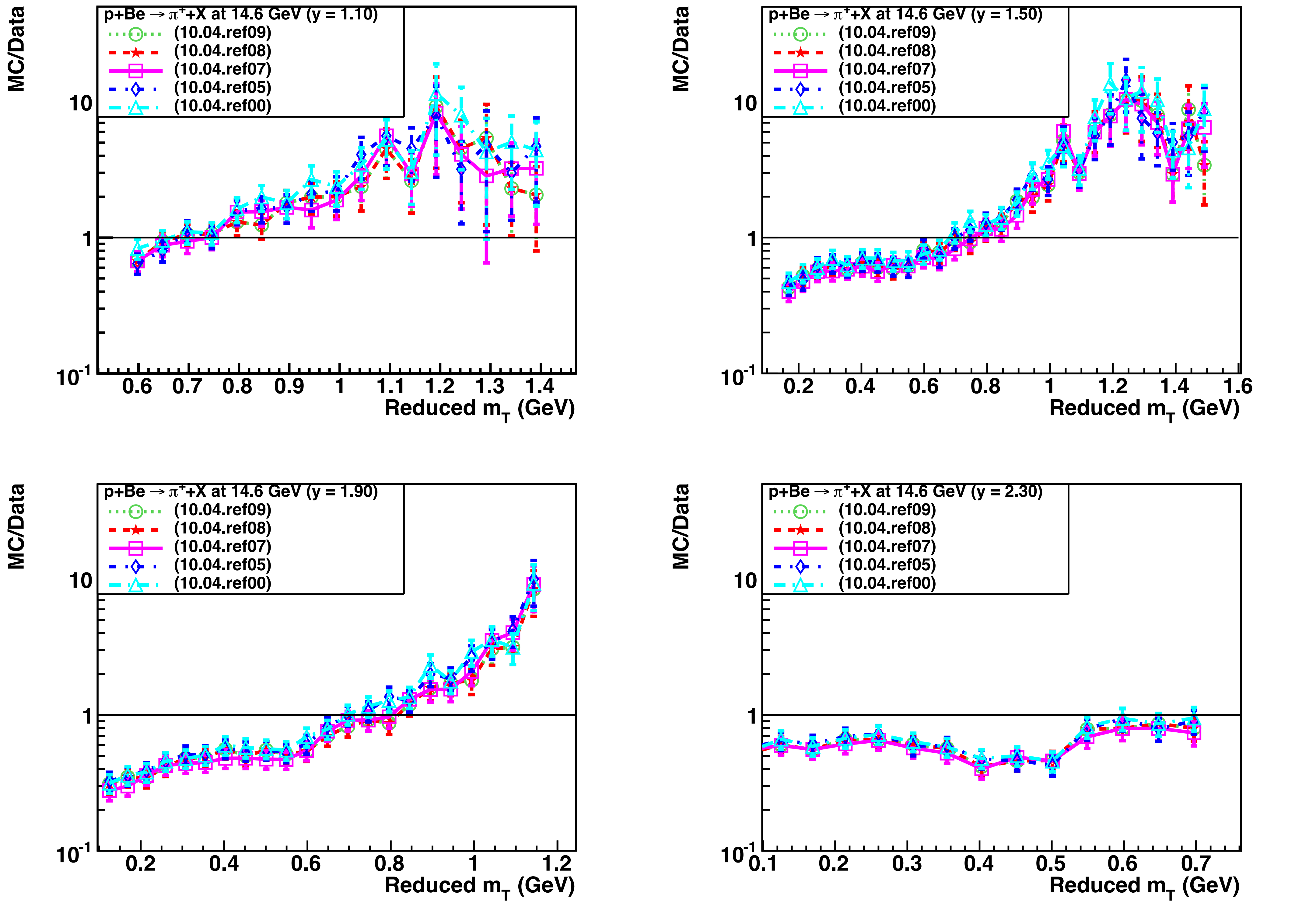
	10.3.ref09	10.4.ref00	10.4.ref05	10.4.ref08	10.4.ref09
Be π^+ (1.1)	1.34	1.45	2.53	2.53	1.76
Be π^+ (1.5)	2.77	1.44	6.52	6.52	4.49
Be π^+ (1.9)	1.57	0.85	3.28	3.28	2.84
Be π^+ (2.3)	1.17	1.13	0.93	0.93	0.71
Be π^- (1.1)	1.26	1.24	4.56	4.56	4.88
Be π^- (1.5)	2.78	3.28	4.30	4.30	4.70
Be π^- (1.9)	4.42	1.62	4.13	4.13	5.41
Be π^- (2.3)	2.08	0.23	0.38	0.38	0.95
Au π^+ (1.1)	1.44	0.77	2.29	3.44	2.39
Au π^+ (1.5)	3.47	2.22	4.03	4.37	6.55
Au π^+ (1.9)	4.56	2.62	3.02	3.30	3.72
Au π^+ (2.3)	2.80	1.33	2.04	2.05	3.15
Au π^- (1.1)	2.47	2.27	3.58	4.47	4.62
Au π^- (1.5)	4.51	2.89	8.17	12.27	8.58
Au π^- (1.9)	6.29	1.84	8.41	9.62	10.86
Au π^- (2.3)	7.15	1.42	7.01	7.23	8.78

ChiSq/Data for Copper Target (FTFP)

- Using a flat systematic uncertainty for all measurements:

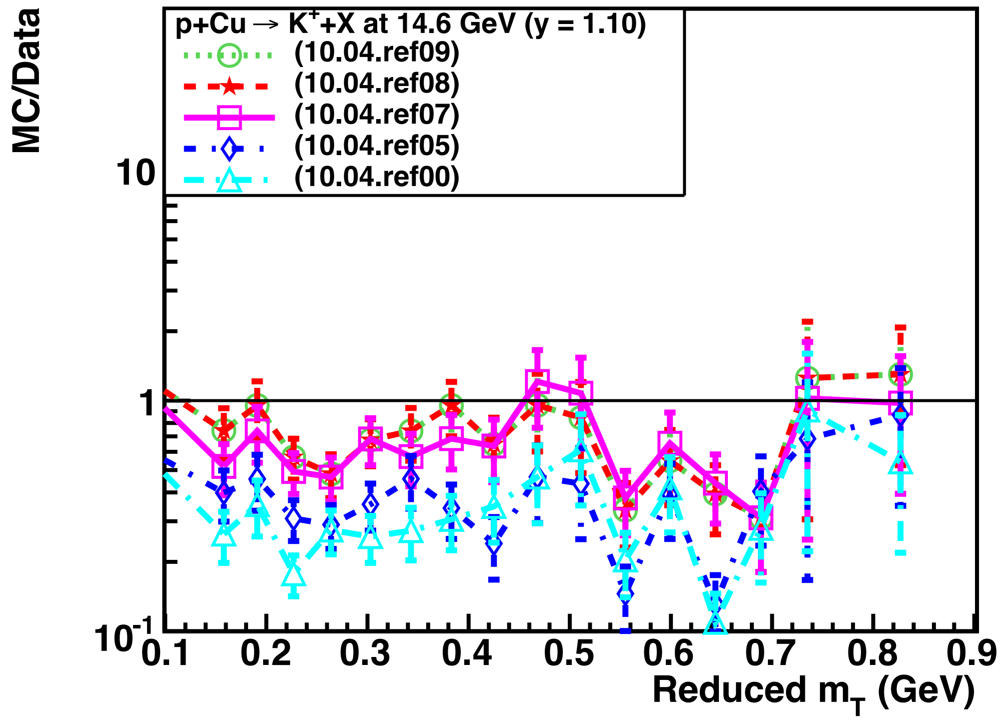
	10.3.ref09	10.4.ref00	10.4.ref05	10.4.ref08	10.4.ref09
Cu K^+ (1.1)	2.23	2.85	2.88	2.07	4.48
Cu K^+ (1.5)	2.33	2.00	1.82	2.66	4.20
Cu K^+ (1.9)	1.77	1.49	2.30	1.19	3.93
Cu K^- (1.1)	3.88	1.29	1.17	2.43	1.83
Cu K^- (1.5)	17.47	2.65	5.84	2.88	2.63
Cu K^- (1.9)	9.22	6.47	1.67	5.25	2.62
Cu p (1.1)	6.52	10.43	5.91	5.70	5.55
Cu p (1.5)	2.02	12.87	0.95	0.91	1.36
Cu p (1.9)	1.20	4.29	1.62	1.31	2.31
Cu p (2.3)	0.48	6.29	0.35	0.56	0.44

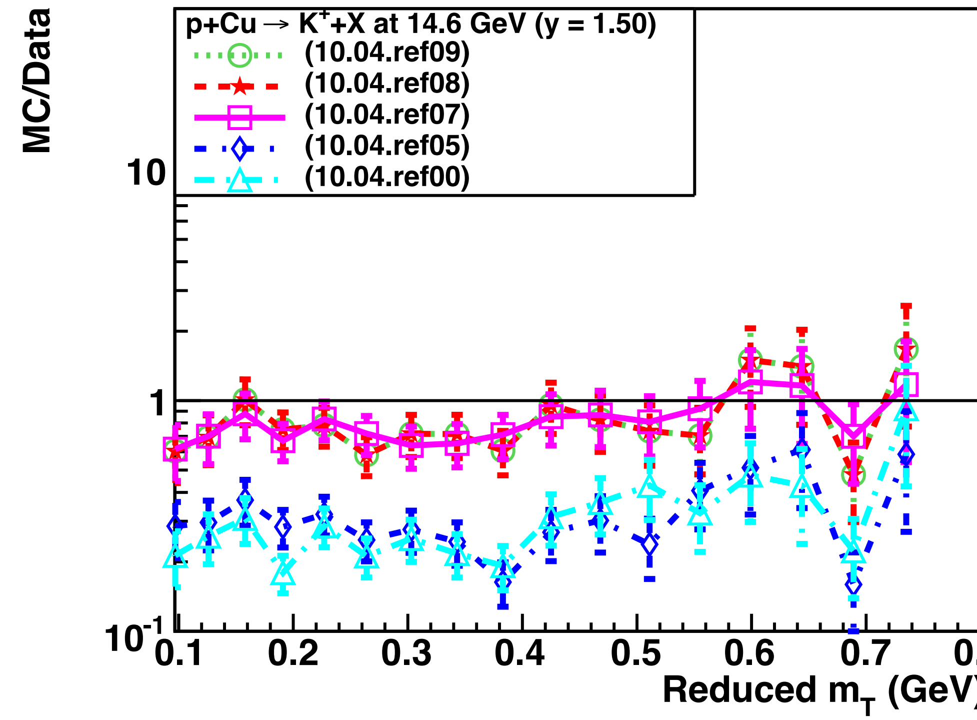
p + Be →π⁺ + X at 14.6 GeV/c (Bertini)

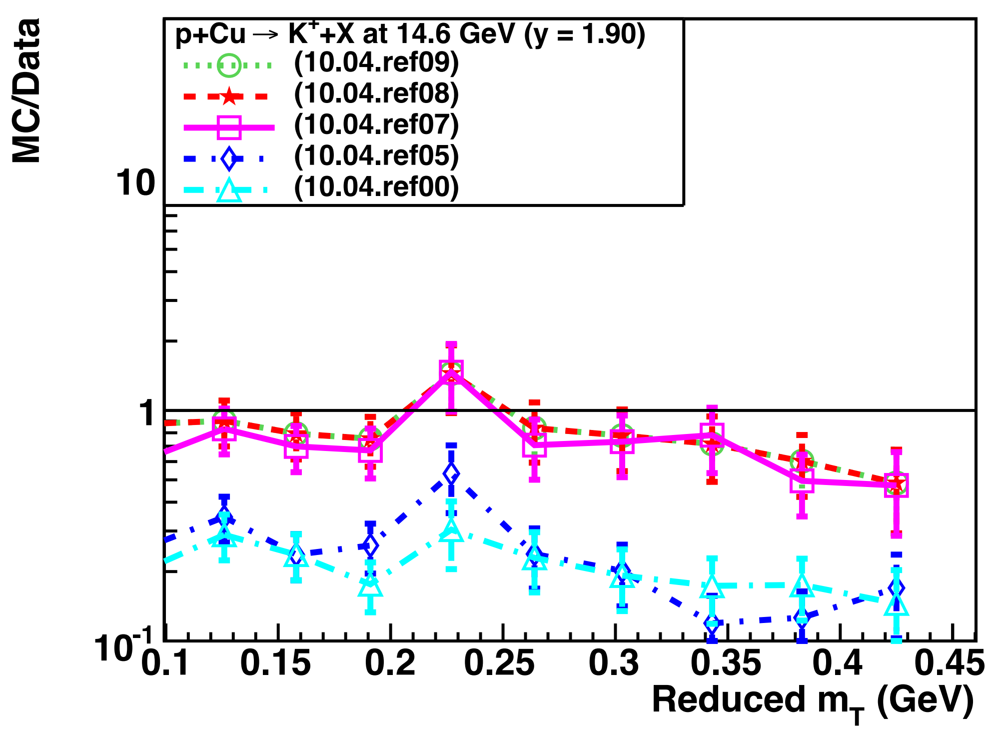


- Not much difference in the model predictions (all are bad).

p + Cu → K⁺ + X at 14.6 GeV/c (Bertini)







- Versions 10.4.ref09 and 10.4.ref08 provide better agreement with the data for K^+ production

Geant 4 ChiSq/Data for Final State Pions (Bertini)

- Using a flat systematic uncertainty for all measurements:

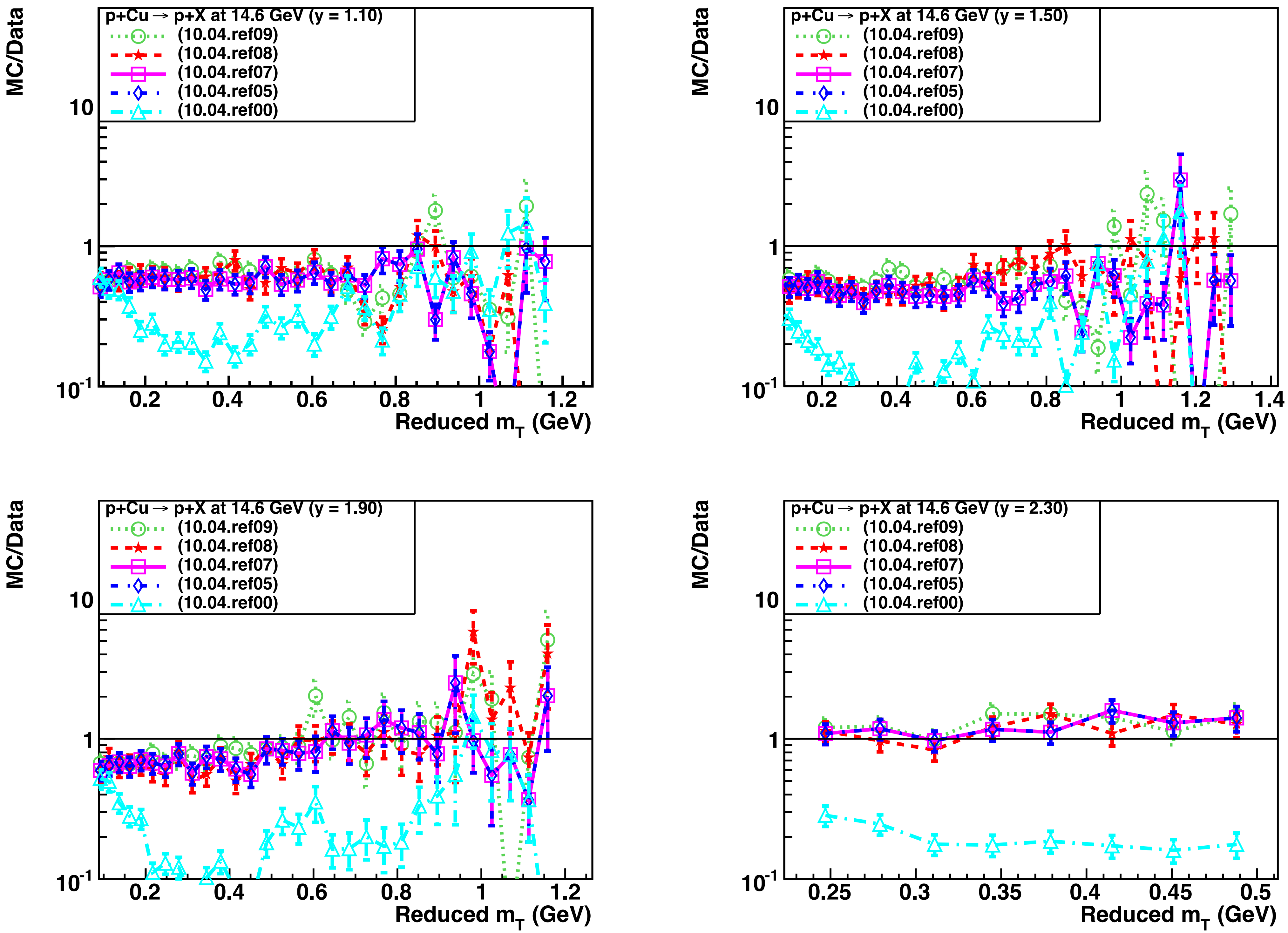
	10.3.ref09	10.4.ref00	10.4.ref05	10.4.ref08	10.4.ref09
Be π^+ (1.1)	46.40	46.40	32.12	22.78	22.78
Be π^+ (1.5)	132.94	132.94	95.82	82.69	82.69
Be π^+ (1.9)	41.95	41.95	47.77	31.69	31.69
Be π^+ (2.3)	4.57	4.57	4.78	5.50	5.50
Be π^- (1.1)	546.63	546.63	484.55	442.89	442.89
Be π^- (1.5)	661.29	661.29	615.24	553.76	553.76
Be π^- (1.9)	228.01	228.01	213.80	178.50	178.50
Be π^- (2.3)	9.09	9.09	9.39	7.06	7.06
Au π^+ (1.1)	29.44	29.44	6.99	14.18	14.18
Au π^+ (1.5)	57.03	57.03	22.69	37.74	37.74
Au π^+ (1.9)	16.87	16.87	9.17	11.30	11.30
Au π^+ (2.3)	3.86	3.86	6.27	5.37	5.37
Au π^- (1.1)	122.54	122.54	86.25	133.07	133.07
Au π^- (1.5)	130.32	130.32	114.02	108.95	108.95
Au π^- (1.9)	97.55	97.55	120.56	118.41	118.41
Au π^- (2.3)	3.50	3.50	4.98	4.20	4.20

ChiSq/Data for Copper Target (Bertini)

- Using a flat systematic uncertainty for all measurements:

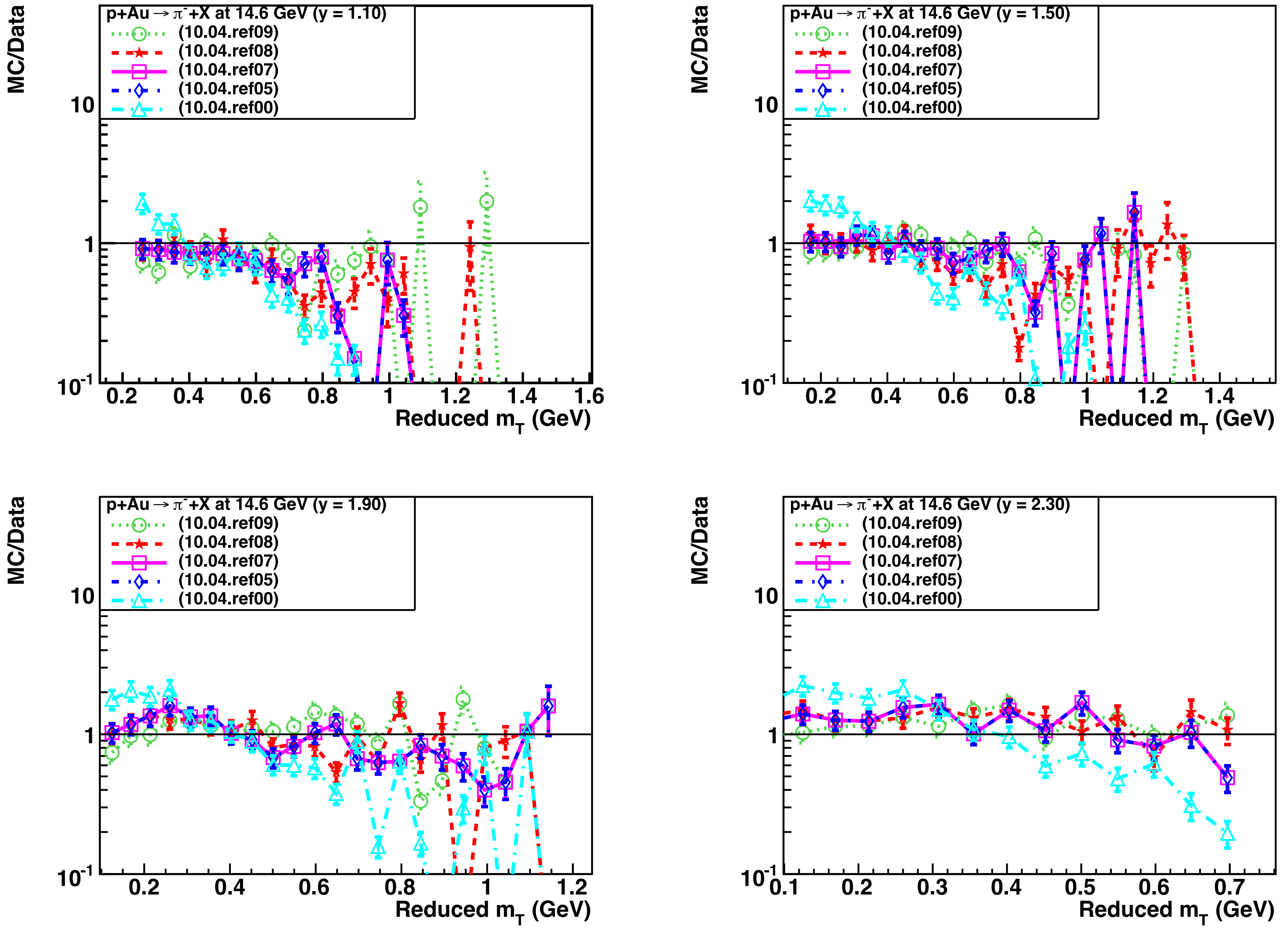
	10.3.ref09	10.4.ref00	10.4.ref05	10.4.ref08	10.4.ref09
Cu K^+ (1.1)	5.53	5.53	4.69	1.62	1.62
Cu K^+ (1.5)	7.59	7.59	7.18	1.29	1.29
Cu K^+ (1.9)	8.53	8.53	7.88	0.88	0.88
Cu K^- (1.1)	1.90	1.90	2.15	1.55	1.55
Cu K^- (1.5)	2.61	2.61	2.51	1.28	1.28
Cu K^- (1.9)	2.84	2.84	2.79	2.28	2.28
Cu p (1.1)	54.34	54.34	68.07	56.52	56.52
Cu p (1.5)	161.65	161.65	181.52	156.12	156.12
Cu p (1.9)	126.31	126.31	148.37	120.87	120.87
Cu p (2.3)	1.61	1.61	1.36	1.43	1.43

p + Cu → p + X at 14.6 GeV/c (QGSP)



- Predictions from the version 10.4.ref00 provide the worst agreement

p + Au →π + X at 14.6 GeV/c (QGSP)



- The version 10.4.ref00 provides worst prediction while there is some improvement in the version 10.4.ref09

ChiSq/Data for Final State Pions (QGSP)

- Using a flat systematic uncertainty for all measurements:

	10.3.ref09	10.4.ref00	10.4.ref05	10.4.ref08	10.4.ref09
Be π^+ (1.1)	4.17	7.30	2.33	2.33	1.25
Be π^+ (1.5)	2.91	7.21	1.81	1.81	1.30
Be π^+ (1.9)	3.91	8.88	2.36	2.36	2.49
Be π^+ (2.3)	2.49	6.28	2.04	2.04	2.04
Be π^- (1.1)	5.01	5.63	2.81	2.81	2.25
Be π^- (1.5)	4.50	7.49	3.20	3.20	2.63
Be π^- (1.9)	2.93	6.32	1.85	1.85	1.15
Be π^- (2.3)	0.74	3.19	0.42	0.42	1.40
Au π^+ (1.1)	4.71	8.35	3.38	5.29	2.11
Au π^+ (1.5)	4.19	13.40	3.22	1.49	3.04
Au π^+ (1.9)	3.57	16.33	3.17	3.29	2.43
Au π^+ (2.3)	1.84	30.40	1.35	2.32	0.92
Au π^- (1.1)	3.57	8.60	2.82	2.94	2.33
Au π^- (1.5)	2.51	11.52	1.41	2.71	1.11
Au π^- (1.9)	2.07	11.93	2.95	2.36	3.23
Au π^- (2.3)	4.05	15.87	4.59	3.90	2.46

Geant 4

ChiSq/Data for Copper Target (QGSP)

- Using a flat systematic uncertainty for all measurements:

	10.3.ref09	10.4.ref00	10.4.ref05	10.4.ref08	10.4.ref09
Cu K^+ (1.1)	6.75	4.34	6.33	6.78	4.89
Cu K^+ (1.5)	5.99	4.62	4.51	4.77	4.30
Cu K^+ (1.9)	2.45	3.32	4.01	3.69	2.70
Cu K^- (1.1)	2.02	3.59	1.82	1.74	1.30
Cu K^- (1.5)	1.58	6.13	2.38	3.43	1.88
Cu K^- (1.9)	1.49	0.82	0.78	0.28	1.31
Cu p (1.1)	5.52	11.20	5.01	4.97	4.88
Cu p (1.5)	5.78	16.32	6.94	5.36	5.42
Cu p (1.9)	2.28	11.82	2.22	7.78	4.30
Cu p (2.3)	1.28	18.74	2.28	2.25	3.57

Comparison with MIPP data

- Data set from Fermilab E907: (T.S. Nigmanov *et al.*, Phys. Rev. D83, 012002)
  - Inclusive neutron production with proton beams at high energies on a number of nuclear targets
  - Targets used: Hydrogen, Beryllium, Carbon, Bismuth, Uranium
  - Projectile: proton beam at: 56.8, 57.3, 82.6 and 120 GeV/c. Beam momentum and impact point at the target are measured using an upstream spectrometer
  - Neutrons detected in the hadron calorimeter and its energy is measured by subtracting energies of charged particles within the geometric acceptance of calorimeter
  - Inclusive neutron momentum distribution and Lorentz invariant cross section for neutron as a function of x_F without any geometric acceptance correction
- For calculation of invariant cross sections, finite target size, beam orientation, acceptance cut of the detector, beam momentum spread, etc. are taken into account
- Two Geant4 models are considered for the comparisons:
  - FTFP and QGSP models
- Five versions of Geant4 are used in the following plots:
  - 10.3.ref09, 10.4.ref00, 10.4.ref05, 10.4.ref08, 10.4.ref09

ChiSq/Data for 8 different processes

- Using a flat systematic uncertainty (as quoted in the paper) for all measurements:

	10.3.ref09	10.4.ref00	10.4.ref05	10.4.ref08	10.4.ref09
			FTFP		
p+H (56.8)	4.64	2.73	6.47	12.19	12.11
p+C (56.8)	16.01	4.31	11.83	11.86	11.99
p+Bi (56.8)	2.39	1.92	2.85	3.01	2.80
p+U (57.3)	2.48	1.85	2.94	3.03	2.90
p+H (82.6)	5.64	4.26	7.16	17.86	17.81
p+Be	67.72	11.15	4.99	4.99	4.87
p+C (120.0)	79.19	10.03	27.72	27.76	27.64
p+Bi (120.0)	7.99	3.64	8.19	6.51	8.40
			QGSP		
p+H (56.8)	2.69	5.13	2.10	10.33	10.70
p+C (56.8)	6.00	3.03	3.29	3.30	3.36
p+Bi (56.8)	5.88	6.32	5.15	5.00	4.67
p+U (57.3)	13.38	11.30	10.65	10.75	9.62
p+H (82.6)	2.58	2.34	2.16	15.72	16.22
p+Be	24.73	4.98	16.92	16.92	12.95
p+C (120.0)	22.35	5.33	10.59	10.47	8.11
p+Bi (120.0)	41.40	2.86	28.50	26.78	23.26

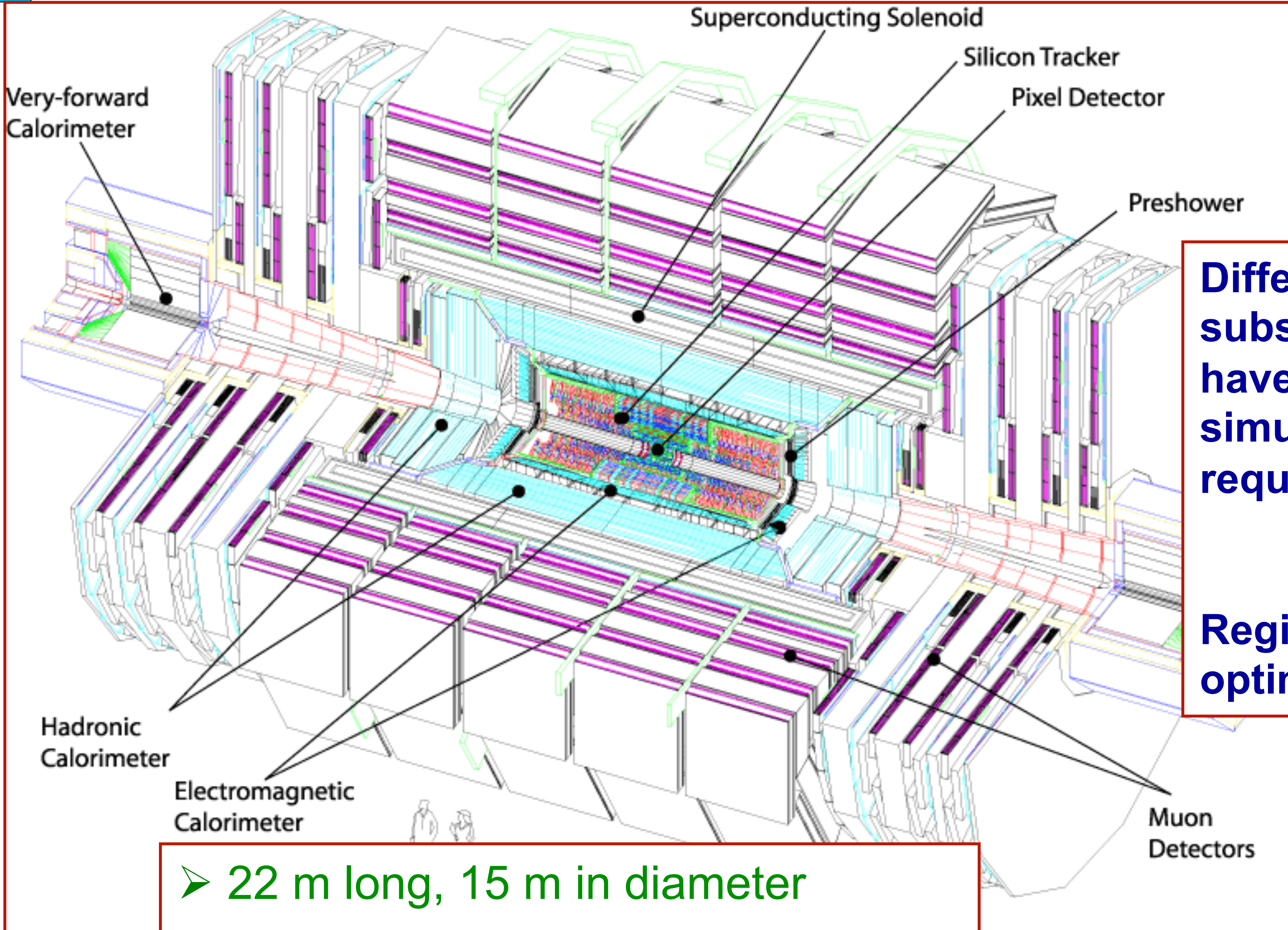
Geant 4

Summary

- Validation effort has been restarted with BNL E802 and MIPP experimental data
- Comparison with BNL data shows:
  - FTFP model provides the best agreement with 10.4.ref00 version for pion production data and with 10.4.ref08 version for proton or kaon production data
  - QGSP model provides the worst agreement with 10.4.ref00 and for proton or kaon production the versions 10.3.ref09, 10.4.ref08 and 10.4.ref09 provide similar level of agreement
  - Bertini cascade model predictions are far away from the measurements and it has improved a bit in 10.4.ref09 (same as ref08)
- Comparison with MIPP data shows:
  - FTFP model is better in the version 10.4.ref00 though the level of agreement is not very good
  - QGSP model is better in the version 10.4.ref08/10.4.ref09 except for high momentum part of the neutron momentum distribution in interactions with heavier target where 10.4.ref00 provides better agreement

Additional Slides

CMS Detector



Different subsystems have different simulation requirements

⇓

Region based optimization

- 22 m long, 15 m in diameter
- Over a million geometrical volumes
- Many complex shapes

Geant4 Physics List and Monte Carlo Sample

- From 2017 onward simulation of CMS detector is done using Geant4.10.2.p02 and with FTFP_BERT_EMM Physics List

- The main part of this Physics List is FTFP_BERT:
  - recommended by the Geant4 collaboration as default physics configuration
  - the hadronic part of FTFP_BERT_EMM is identical to that of FTFP_BERT

- EMM provides a special configuration of Geant4 electromagnetic physics which includes
  - applied production cuts for gamma processes
  - simplified step limitation by multiple scattering of e^+/e^-
  - default step limitation by multiple scattering of $e^\pm$ inside sampling calorimeters

- This Physics List provides good CPU performance as well as adequate accuracy for calorimeter response simulation

- For Monte Carlo events are generated using all the Geant4 versions tested here:
  - 50k events at each beam energy for the said type and for calibration generate 50k electron events in setups with and without EB
  - 100k single particle event sample using a flat energy distribution between 1 and 20 GeV with a given admixture of pions, kaons and protons and anti-protons (as expected in minimum bias sample)

Selection of Isolated Tracks

- 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