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Validation of GEANT4 Version 9.4 with Testbeam Data of the ATLAS Hadronic End-Cap Calorimeter

LCG Physics Validation for LHC Simulations
CERN, 27-th of April, 2011

Introduction

- ATLAS hadronic end-cap calorimeter (HEC)
  - liquid argon (LAr) sampling calorimeter with parallel copper absorber plates
  - beam tests of serial modules in 2000-2001
- New round of GEANT4 simulations with version 9.4: charged pion and electron energy scans

- GEANT4 version **9.4** (no patches, released in December 2010):
  comparison of five physics lists
  - **QGSP-BERT**
  - **QGSP-FTFP-BERT**
  - **FTFP-BERT**
  - **FTF-BIC**
  - **CHIPS**
- Physics lists **QGSP-FTFP-BERT**, **CHIPS**:
  comparison of GEANT4 versions **9.4** and **9.3** (with patch 01, released in April 2010)
- Physics lists **QGSP-BERT**, **FTFP-BERT**, **FTF-BIC**:
  comparison of GEANT4 versions **9.4**, **9.3** and **9.2** (no patches, released in December 2008)

Simulation, Reconstruction, Analysis

- Stand-alone package for simulations of the HEC testbeam
- GEANT4 range cut = 30 μm
- Simulated samples:
  - energy scans with electrons (6-147.8 GeV)
  - energy scans with charged pions (10-200 GeV)
- 5000 events per beam energy, beam particle and physics list

- Saturation of the response in liquid argon for particles with large dE/dx:

  usage of Birks' law

$$\Delta E' = \Delta E \frac{A}{1 + \frac{c}{\rho}\frac{\Delta E}{\Delta x}}$$

  $A = 1$
  $c = 0.0045$ g/(MeV cm^2)
  $\rho = 1.396$ g/cm^3

- Fast readout of calorimeter signals:

  detailed modelling of signal measurements (by convolution of time profiles with shaping functions)

  Effectively this procedure means the integration of time profiles of shower development over a few tens of nanoseconds

- Energy reconstruction:
  - following experimental procedure
  - cluster of the fix size
  - Gaussian fit: E_0 and σ

- Analysed parameters:
  - energy resolution (σ/E_0)
  - calorimeter response to charged pions, defined as a ratio of energies in pion and electron clusters (π/e)
  - fraction of energy in HEC layers

Errors and Warnings during Simulations

- for charged pions only (nothing for electrons)
- a few (1-12) per energy scan

1. Errors in STDERR for FTF- and QGSP-based physics lists:

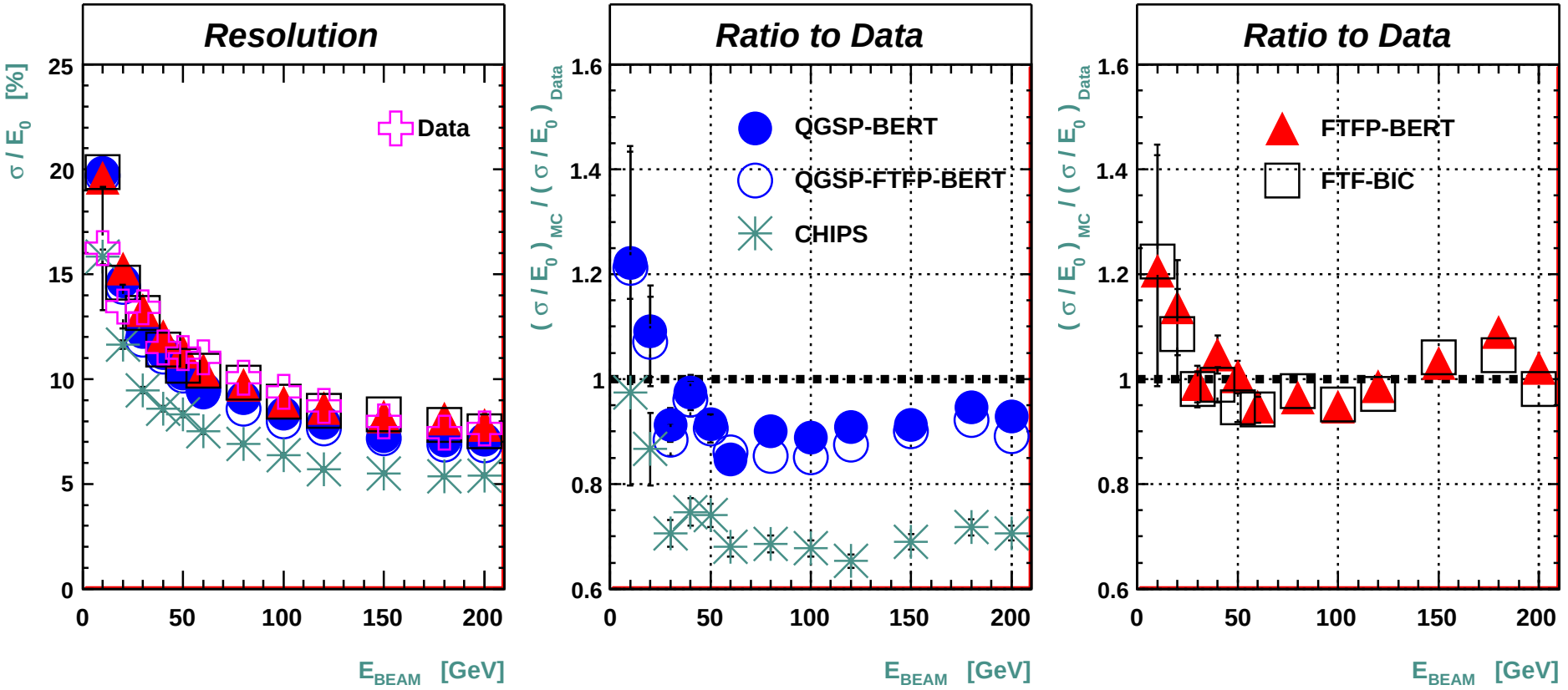
```
Error condition encountered in G4KineticTrack::Decay()
  particle definiton has no decay table associated.
  particle was anti_neutron
```

2. Messages for BERT-based physics lists:
   - diagnostic in STDERR
     `Particle Z0A4 has a strange PDGEncoding`
   - diagnostic in STDOUT
     `>>> G4InuclNuclei creating temporary fragment for evaporation with non-standard PDGencoding.`
     `G4PDGCodeChecker::CheckPDGCode : ??? Illegal PDG encoding for nucleus PDG code=1000000040`
   - these diagnostics are correlated: Particle Z0A4 → PDG code=1000000040
   - there are also: Particle Z0A2 → PDG code=1000000020 and Particle Z0A6 → PDG code=1000000060

3. Messages in STDOUT for CHIPS:

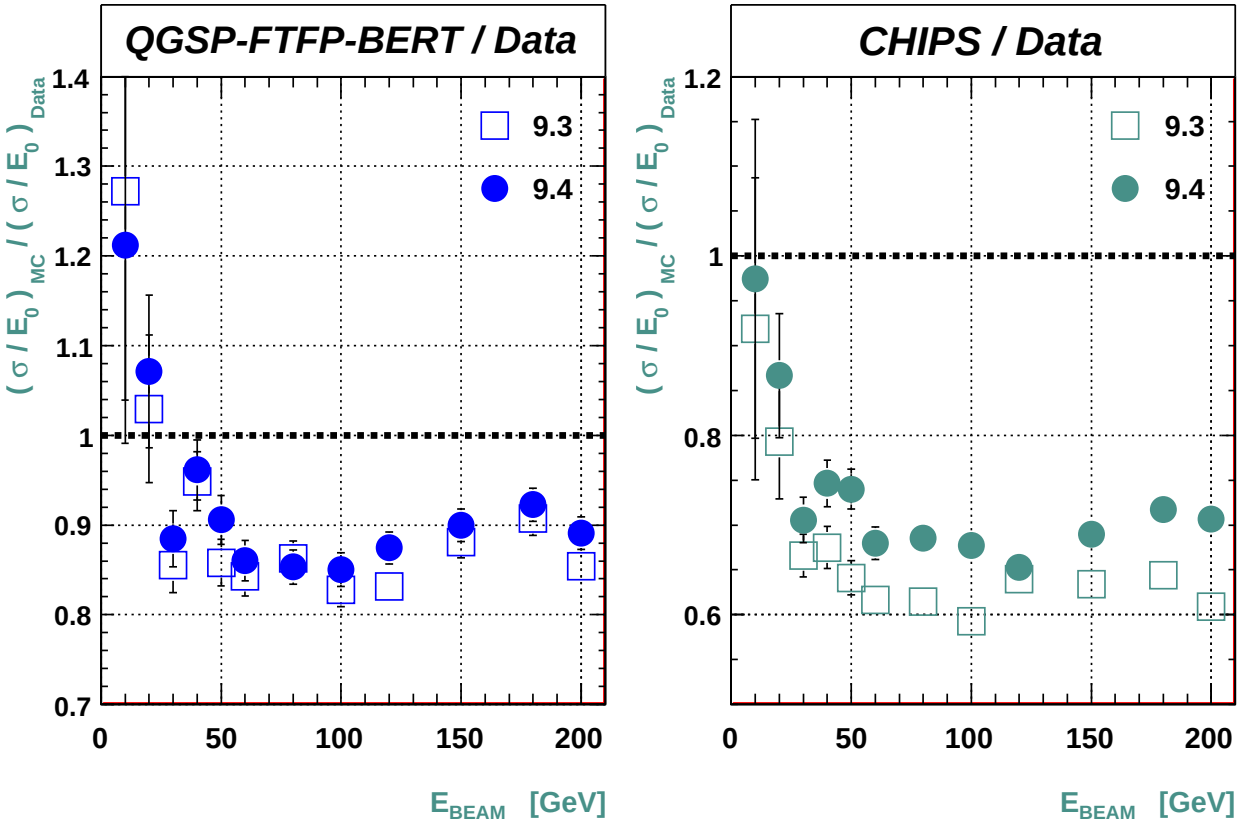
```
-Warning-G4QE::FSI:*Improve*,PDG=92001999: both Sigma&Lamb

G4QI::PSD:m=1875.61#1875.61

-Warning-G4QuasiFreeRatios::CalcElTot: p=0 is zero or negative
```

Pion energy resolution: Comparison of physics lists in GEANT4 9.4



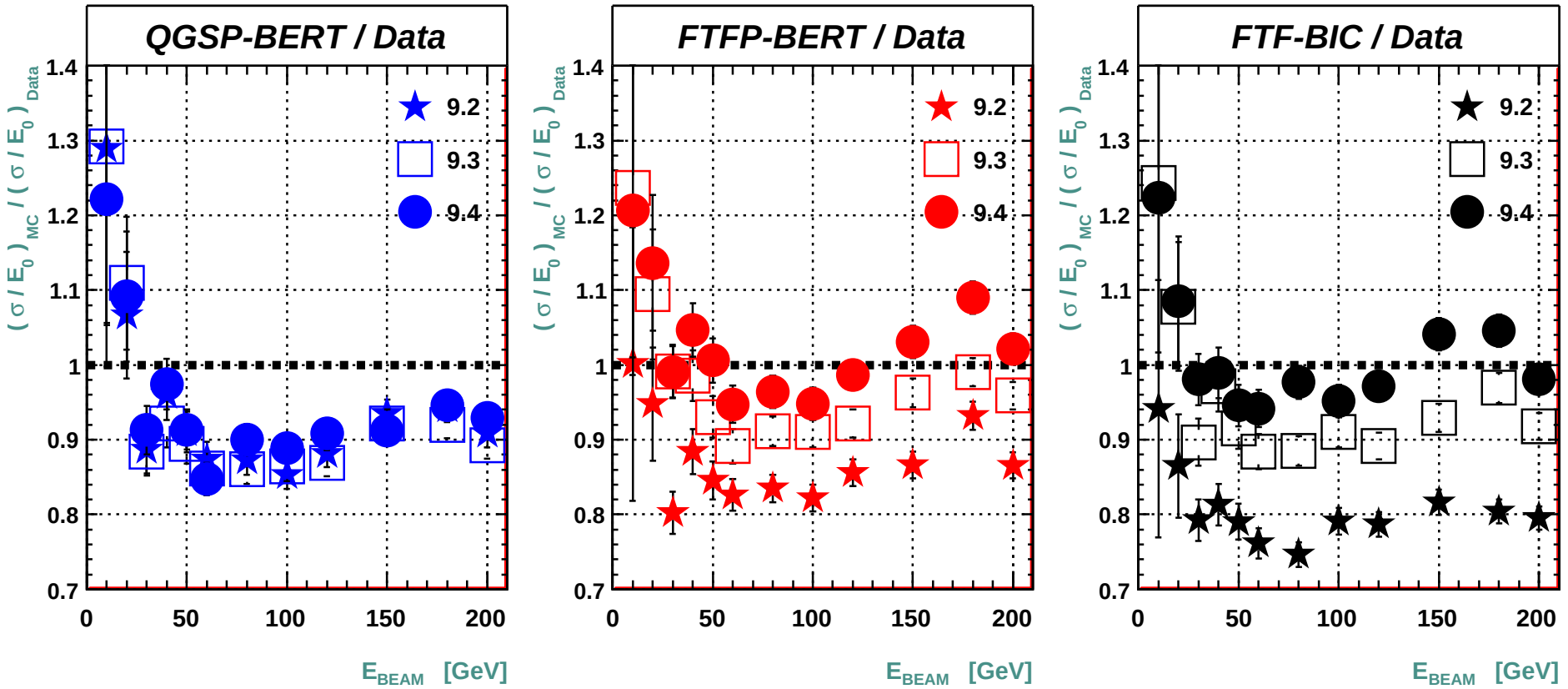
- Predictions of FTF-based physics lists are most close to experimental values of the energy resolution
- **CHIPS** gives the worst description of the data

Pion energy resolution: Comparison of GEANT4 versions



- **QGSP-FTFP-BERT**: practically no difference between GEANT4 versions
- **CHIPS**: certain improvement of the predictions in version **9.4** w.r.t. **9.3**, but still too optimistic in the description of the experimental energy resolution

Pion energy resolution: Comparison of GEANT4 versions



- **QGSP-BERT**: practically no difference between studied GEANT4 versions
- **FTFP-BERT** and especially **FTF-BIC**: significant improvement of the description of experimental data in version **9.3** w.r.t. **9.2**, and further improvement in version **9.4**

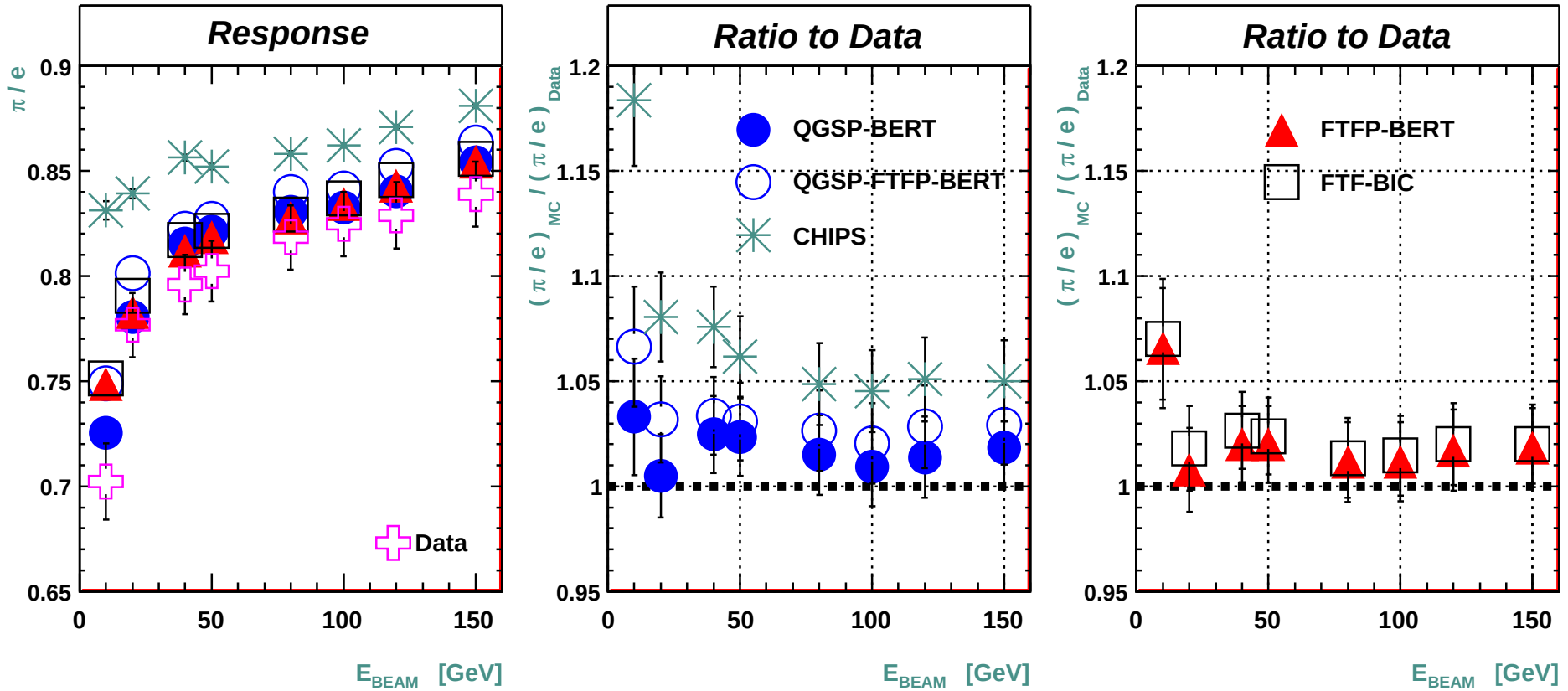
Pion energy resolution: Two-term parametrization

- $\sigma/E_0 = A/\sqrt{E_{BEAM}} \oplus B$
- Experimental values:
  $A = 69 \pm 1\ \%\sqrt{GeV}$, $B = 5.8 \pm 0.1\ \%$

- MC predictions:

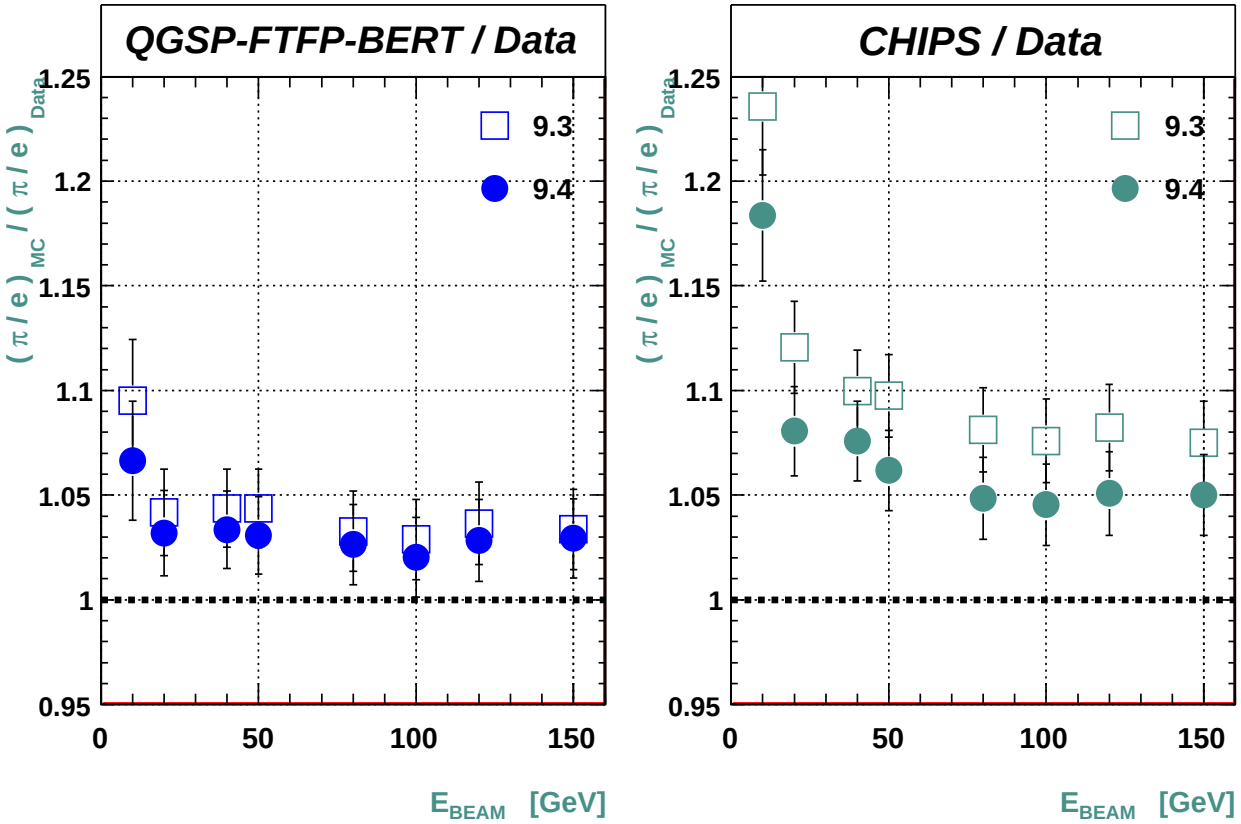
Physics list	Version 9.4		Version 9.3		Version 9.2	
	$A[\%\sqrt{GeV}]$	B [%]	$A[\%\sqrt{GeV}]$	B [%]	$A[\%\sqrt{GeV}]$	B [%]
QGSP-BERT	60.6±0.7	**5.57±0.10**	60.5±0.7	5.29±0.10	**60.2±0.7**	5.48±0.09
QGSP-FTFP-BERT	60.1±0.7	5.30±0.09	59.2±0.7	5.09±0.10		
CHIPS	48.8±0.6	3.96±0.08	45.0±0.5	3.47±0.08		
FTFP-BERT	**62.5±0.7**	6.56±0.10	**62.0±0.7**	**5.83±0.10**	51.5±0.7	**5.76±0.08**
FTF-BIC	60.7±0.7	6.47±0.09	60.3±0.7	5.67±0.09	49.5±0.6	5.09±0.08

Pion response: Comparison of physics lists in GEANT4 9.4



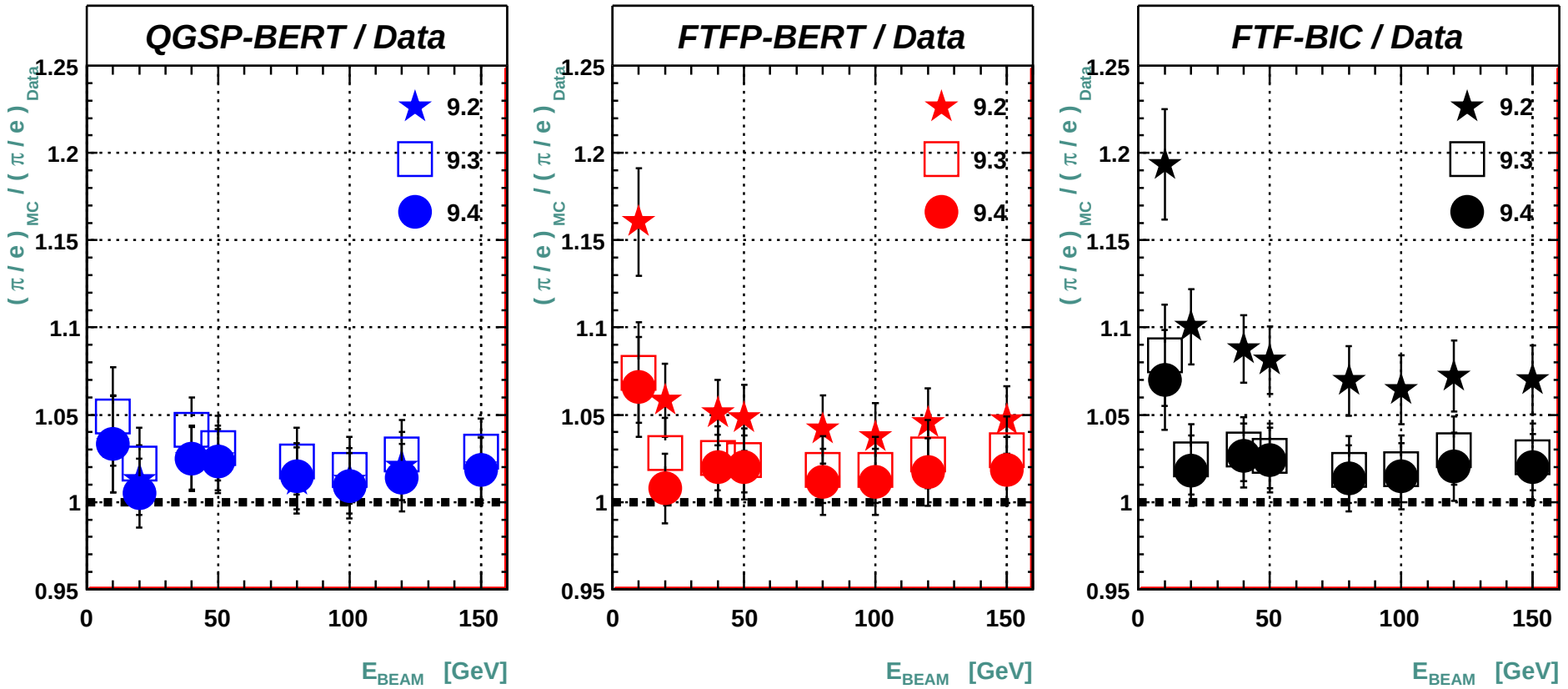
- QGSP- and FTF-based physics lists demonstrate very similar behaviour and are close to experimental values of the response (except the lowest beam energy)
- **CHIPS** predicts too high response to charged pions

Pion response: Comparison of GEANT4 versions



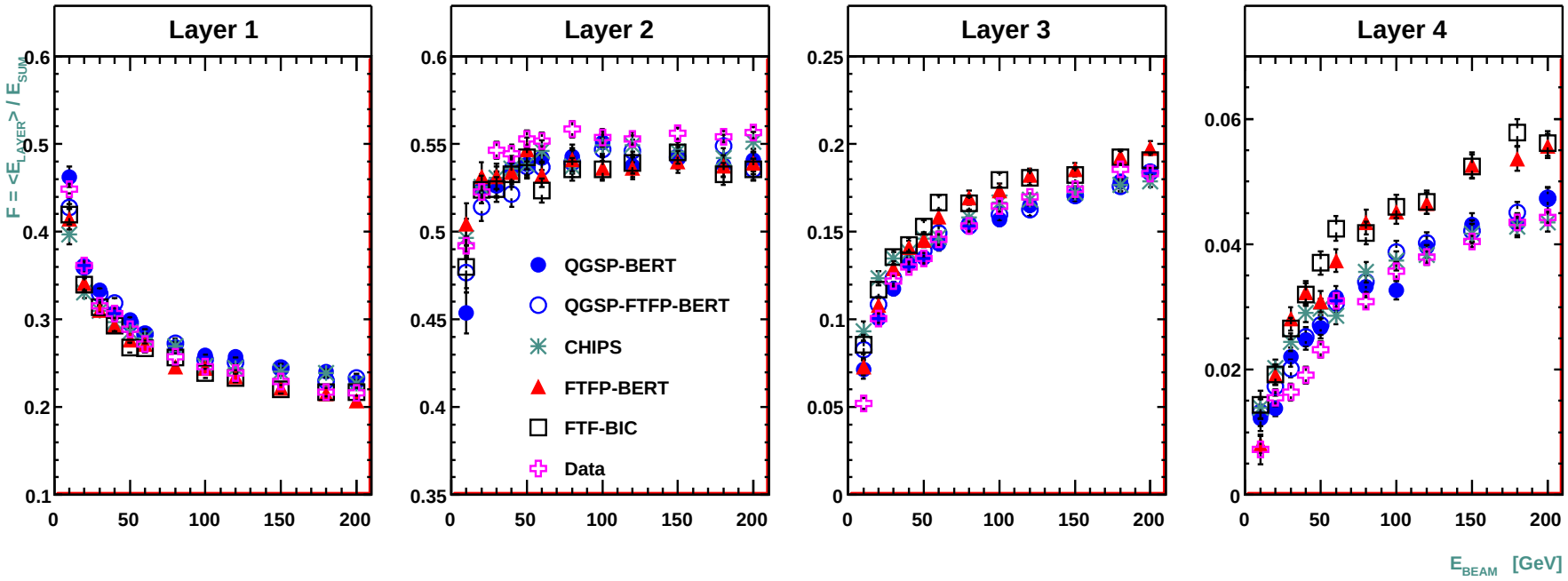
- **QGSP-FTFP-BERT**: small improvement of the description of the response in version **9.4**
- **CHIPS**: certain improvement of the predictions in version **9.4** w.r.t. **9.3**, but the response is still too high

Pion response: Comparison of GEANT4 versions



- **QGSP-BERT**: no significant difference in the response between studied GEANT4 versions
- **FTFP-BERT** and especially **FTF-BIC**: significant improvement of the description of experimental data in version **9.3** w.r.t. **9.2**, practically no changes in the next version **9.4**

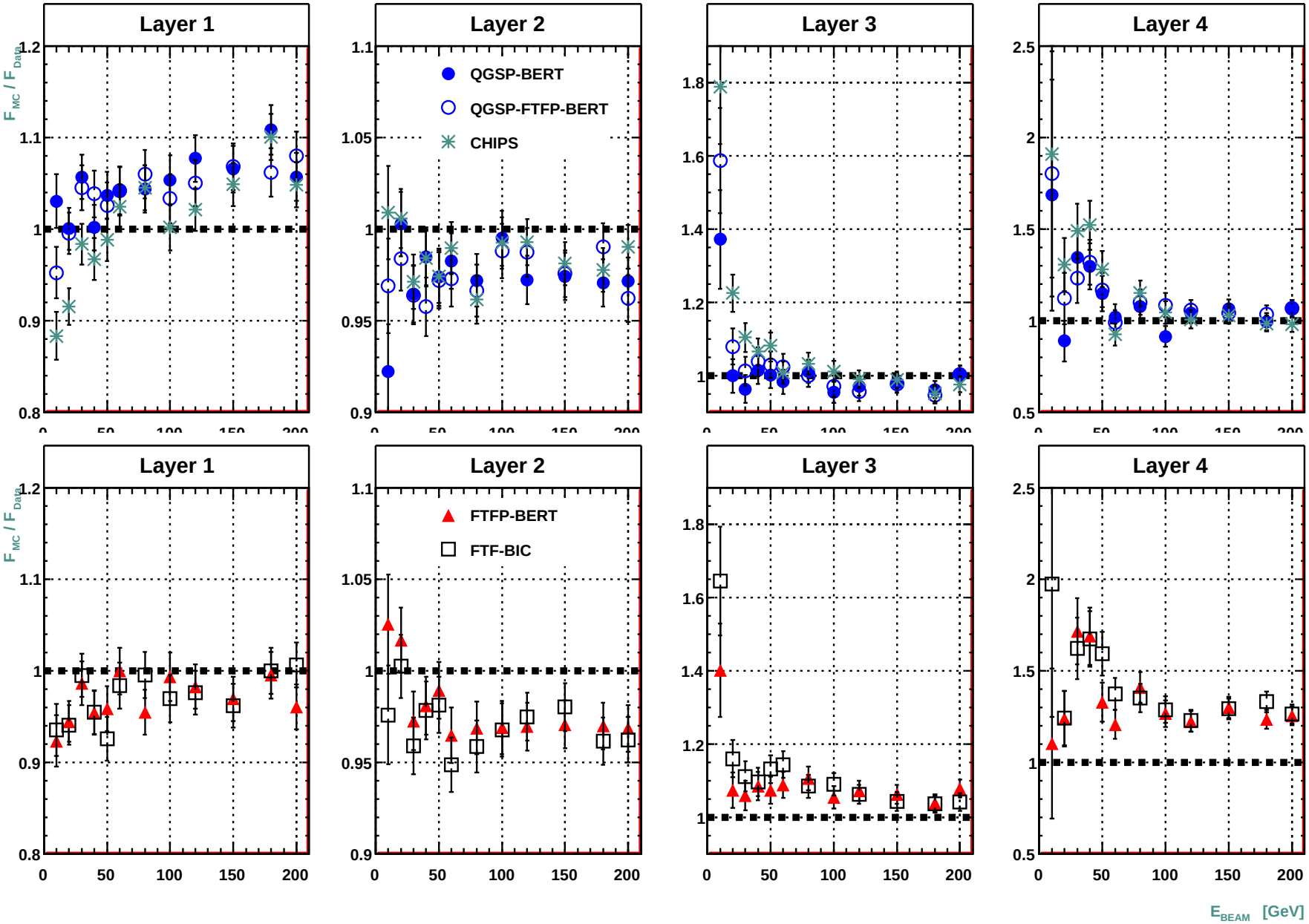
Fraction of energy in HEC longitudinal layers:
Compare physics lists in GEANT4 9.4



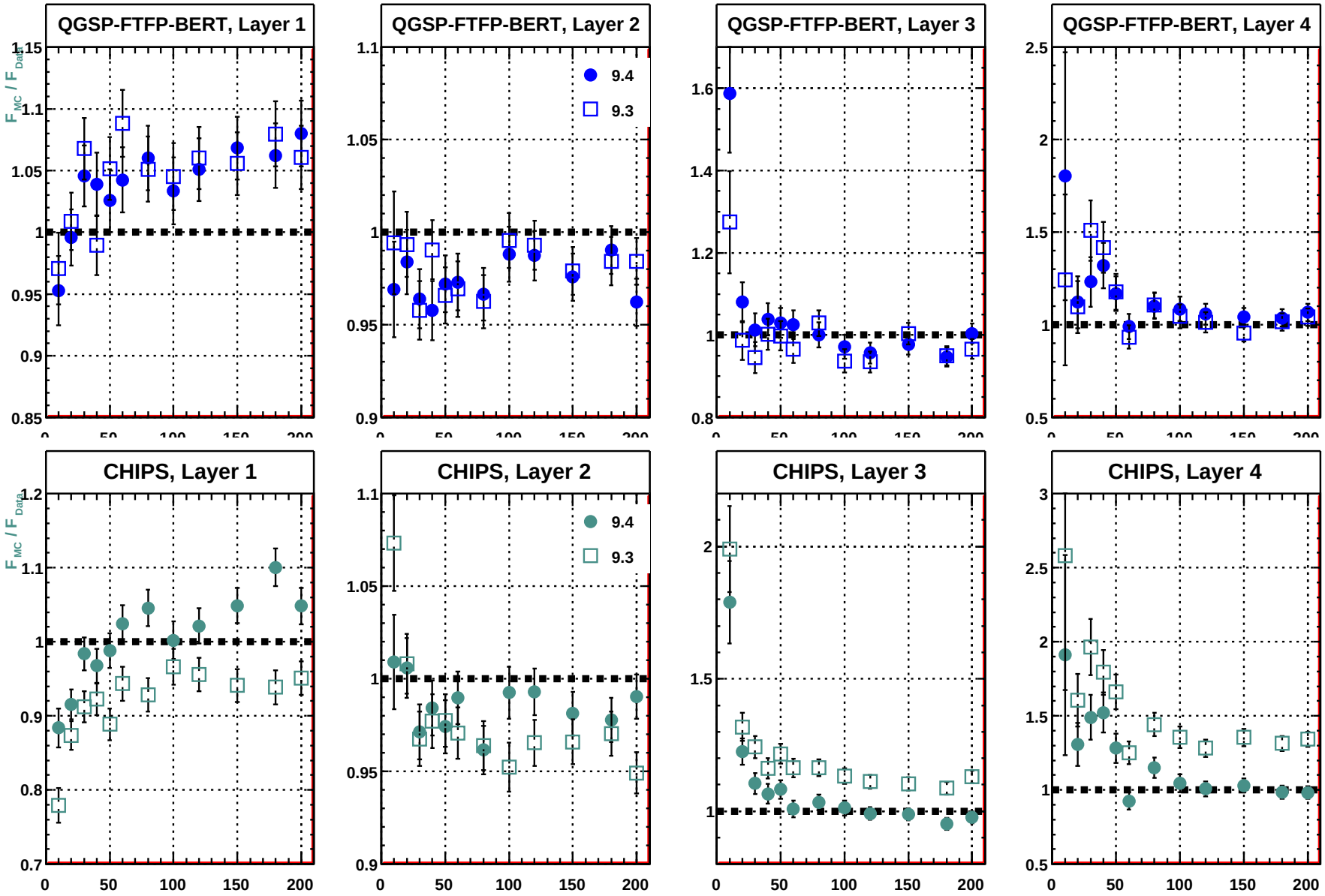
Four HEC longitudinal layers: 8/16/8/8 LAr gaps, 1.5/2.9/3.0/2.8 λ

$F =< E_{LAYER} > / E_{SUM}$, where $E_{SUM} = \Sigma < E_{LAYER} >$

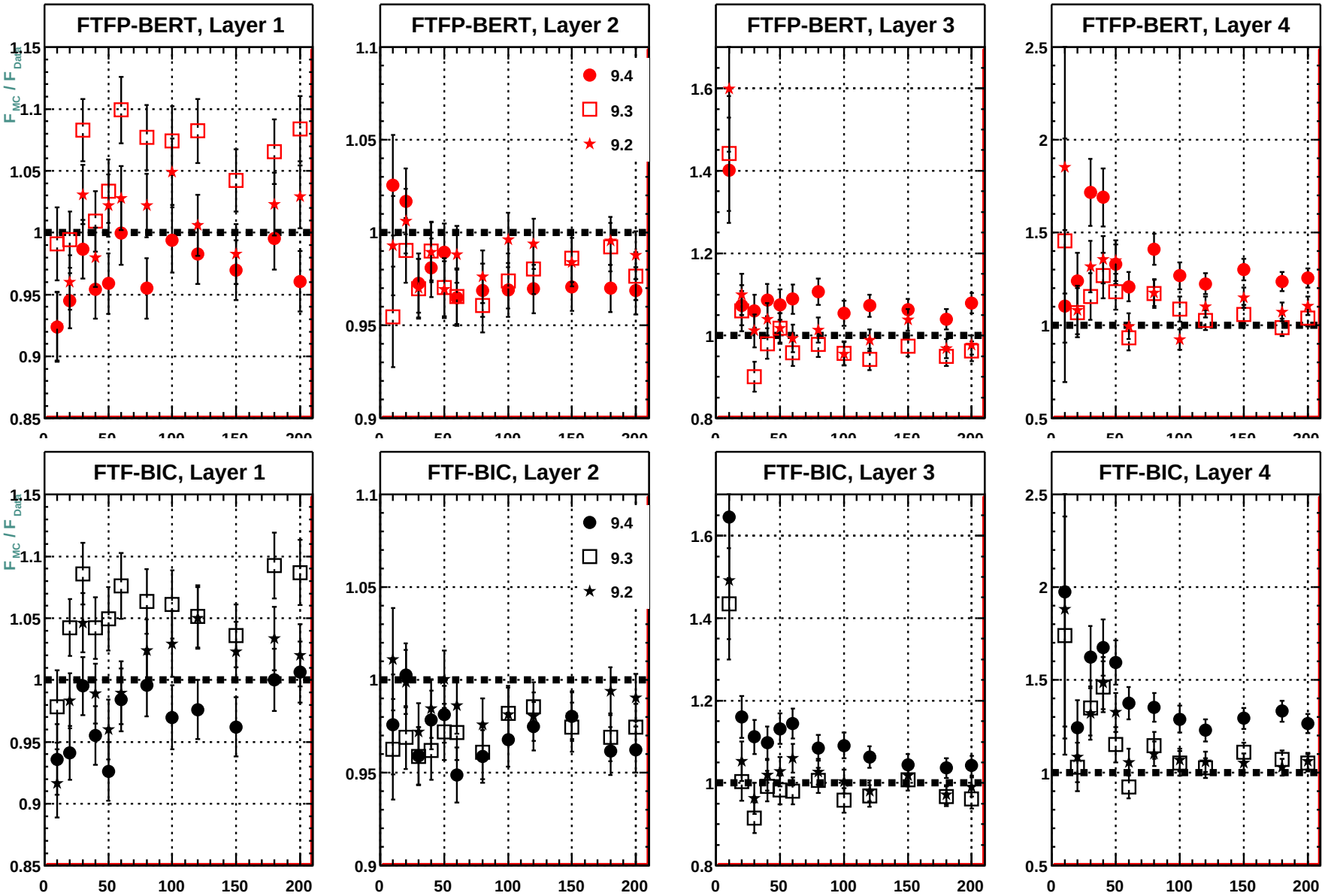
Fraction of energy (Ratio to Data): Compare physics lists in GEANT4 9.4



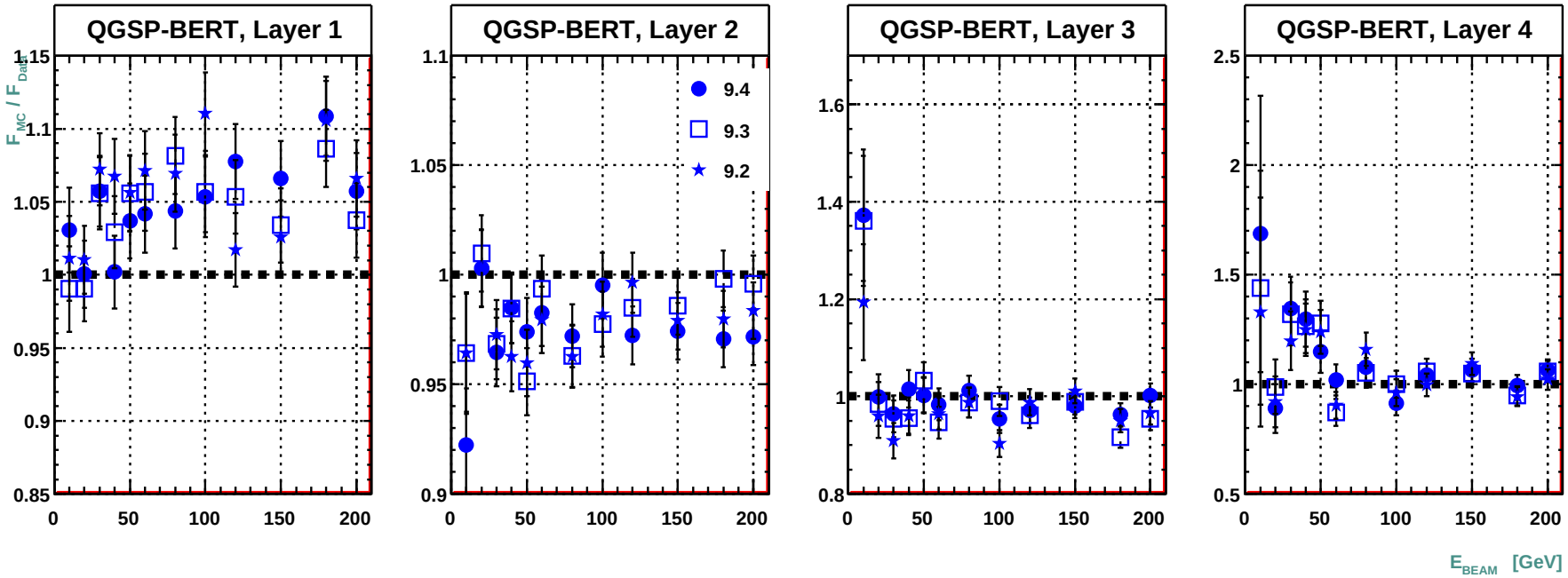
Fraction of energy (Ratio to Data): Compare GEANT4 versions



Fraction of energy (Ratio to Data): Compare GEANT4 versions



Fraction of energy (Ratio to Data): Compare GEANT4 versions



- QGSP-based physics lists predict earlier start of hadronic showers than observed experimentally (see layer 1)
- In the FTF-based simulations, hadronic showers develop deeper in the calorimeter than in data
- **CHIPS** does not describe energy dependence of the energy fractions (see layers 1, 3 and 4)

- Problems with the lowest beam energy of 10 GeV in the rear part of HEC

- For QGSP-based lists, there is practically no difference in fractions of energy in HEC layers between GEANT4 versions
- FTF-based physics lists gave good description of longitudinal shower profiles in version **9.2**, predicted early start of showers in **9.3** (similar to QGSP-based physics lists), and now have longer (w.r.t. data) longitudinal tails in version **9.4**
- **CHIPS**: certain improvement in version **9.4** w.r.t. **9.3**, but it still does not describe data properly

Summary of the Comparison of MC Predictions and Experimental Results
for GEANT4 version 9.4

- Ratio between simulated and experimental data as a function of the beam energy E_{BEAM}
- Maximal and minimal values of this dependence $\Rightarrow$

Deviation of MC predictions from experimental results [in %]

Physics list	Resolution[1]		Response[2]		Fraction of energy in layers[2]							
					Layer 1		Layer 2		Layer 3		Layer 4	
QGSP-BERT	-15	-3	$+1$	$+2$	0	$+11$	-4	0	-5	$+2$	-11	$+35$
QGSP-FTFP-BERT	-15	-4	$+2$	$+3$	0	$+8$	-4	-1	-5	$+8$	-1	$+32$
FTFP-BERT	-5	$+9$	$+1$	$+2$	-6	0	-4	$+2$	$+4$	$+11$	$+21$	$+72$
FTF-BIC	-6	$+5$	$+1$	$+3$	-7	$+1$	-5	0	$+4$	$+16$	$+23$	$+67$
CHIPS	-35	-25	$+5$	$+8$	-8	$+10$	-4	$+1$	-5	$+23$	-7	$+52$

[1] Data with $E_{BEAM} \geq 30$ GeV are used: Errors of the resolution are too large at smaller beam energies.
[2] Data with $E_{BEAM} = 10$ GeV are not used.

Conclusions-I

New round of GEANT4 based simulations with version 9.4 (no patches) was carried out for the HEC stand-alone testbeam. Five different physics lists, namely: QGSP-BERT, QGSP-FTFP-BERT, CHIPS, FTFP-BERT and FTF-BIC — were used for GEANT4 simulations. Comparison with experimental results was done.

- CHIPS physics list fails to describe studied experimental data
- All other physics lists give rather good description of the energy dependence of the resolution (FTF-based lists are slightly better) and of the response to charged pions
- Longitudinal development of hadronic showers is not well simulated:
  - QGSP-based physics lists predict early start of showers
  - FTF-based physics lists predict deeper developped showers than observed experimentally
- Results obtained with QGSP-BERT and QGSP-FTFP-BERT are very close, the same is true for FTFP-BERT and FTF-BIC

Conclusions-II

For QGSP-FTFP-BERT and CHIPS physics lists, comparison with results of simulations with version 9.3 of GEANT4 was fulfilled.

- QGSP-FTFP-BERT: No significant difference is observed between two GEANT4 versions
- CHIPS: There are changes in predictions of studied HEC performance parameters in version 9.4, going in the right direction

For three physics lists: QGSP-BERT, FTFP-BERT and FTF-BIC, comparison of results obtained with versions 9.2, 9.3 and 9.4 of GEANT4 was done.

- QGSP-BERT: No appreciable difference is seen between these versions
- FTF-BIC and FTFP-BERT
  - energy resolution: serious advance in version 9.3, further improvement in version 9.4
  - pion response: significant improvement in version 9.3, no changes in version 9.4
  - longitudinal development of hadronic showers: good description in version 9.2, worsening in the following GEANT4 versions (but in different directions)