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GEANT4 Physics Evaluation with Testbeam Data of the ATLAS Hadronic End-Cap Calorimeter

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“Simulation” session
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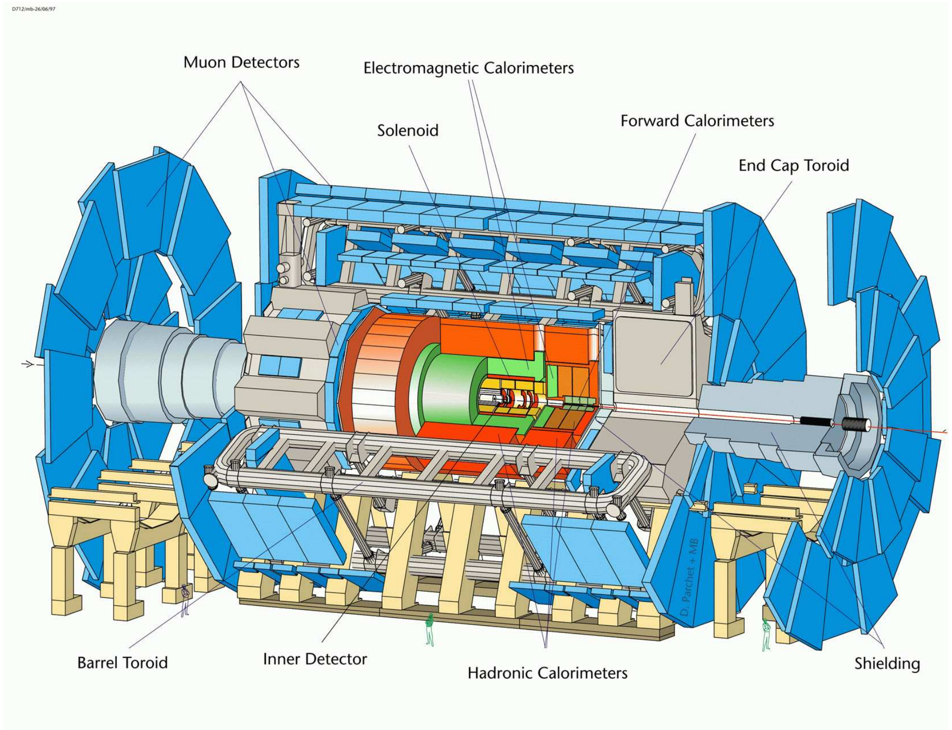
The validation of GEANT4 physics models is based on the detailed comparison of experimental data from beam tests of modules of the ATLAS hadronic end-cap calorimeter with GEANT4 predictions

- ATLAS hadronic end-cap calorimeter and its testbeam
- GEANT4: simulation framework, parameters and features
- Results of the validation

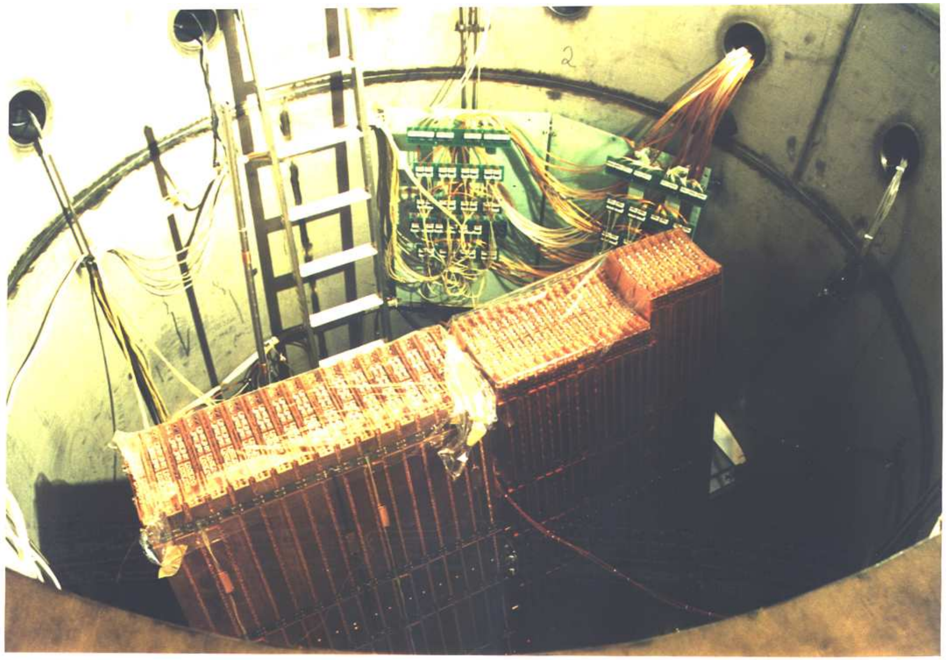
ATLAS Hadronic End-Cap Calorimeter

- ATLAS hadronic end-cap calorimeter (HEC) — a liquid argon (LAr) sampling calorimeter with parallel copper absorber plates
- Pseudorapidity coverage: $1.5 < |\eta| < 3.2$
- Two wheels per end-cap: front and rear
- Total thickness: $\sim$1.8 m, $\sim$103 X_0, $\sim$10 λ
- Wheel outer diameter: $\sim$4 m
- Each wheel contains 32 identical modules
- Granularity $\Delta\eta \times \Delta\varphi$:
  - $0.1\times2\pi/64$ for $|\eta| < 2.5$
  - $0.2\times2\pi/32$ for $|\eta| > 2.5$
- Four longitudinal layers



Beam tests of HEC modules

- Beam tests of HEC serial modules in 2000-2001
- H6 beam line of the CERN SPS
- Secondary and tertiary beams:
  - charged pions of 10-200 GeV
  - electrons of 6-150 GeV
  - muons of 120, 150 and 180 GeV
- ∼20,000 triggers per run
- Set-up with three front and three rear HEC modules



GEANT4 based simulations of the HEC testbeam

- Stand-alone code for HEC testbeam simulations
- Detailed description:
  - calorimeter modules (sensitive LAr, copper plates, electrodes)
  - cryostat and LAr excluder
  - beam elements (scintillator counters, MWPCs)

- Studies for validation of GEANT4 physics:
  - different hadronic physics lists
  - influence of the Birks' law
  - time structure of hadronic showers

- GEANT4 simulations:
  - version 9.0, released in June 2007
  - range cut = 30 μm

Hadronic physics lists

- **QGSP**
  - based on theory-driven models
  - quark-gluon-string model for interactions
  - pre-equilibrium decay model for the fragmentation
- **QGSP-BERT**
  - Bertini cascade model for particle-nuclear interactions below ∼10 GeV
- **QGSP-BERT-HP**
  - high precision data-driven modeling for low energy neutrons

Birks' law

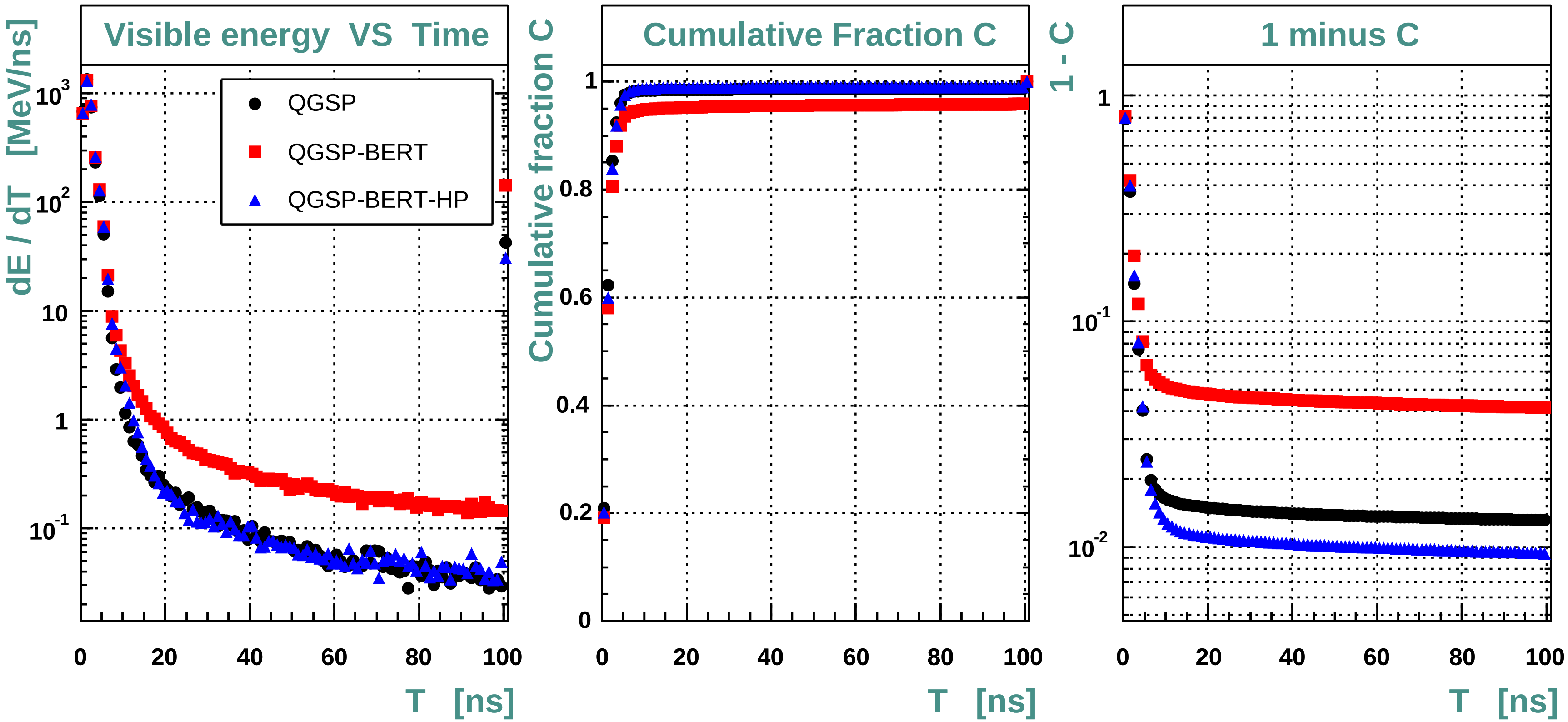
- Saturation of response in LAr for particles with large dE/dx
- Parametrization:

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

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

Time structure of hadronic showers

100 GeV charged pions (Birks' law ON)



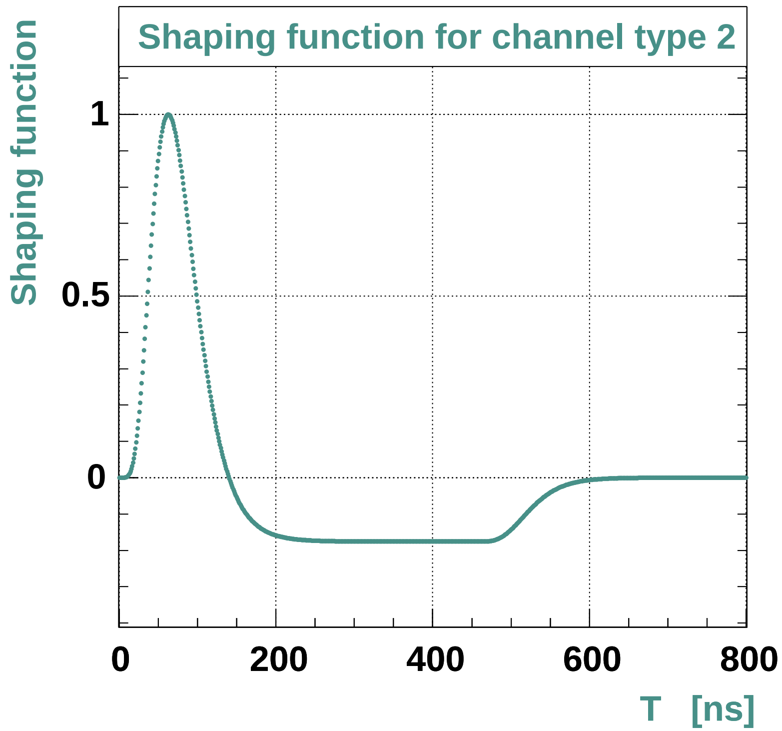
- **QGSP-BERT** predicts slower showers than **QGSP** and **QGSP-BERT-HP**
- Late energy depositions (after a few tens of nanoseconds) are at the percent level

Measurement of calorimeter signals

- Convolution of time profiles and shaping functions
- Resulting amplitude — measured at the position of the maximum of the shaping function T_{MAX}

- 51 types of HEC channels: different shaping functions
- For the HEC testbeam: $50 < T_{MAX} < 70$ ns

- Measured signal — energy deposition in a HEC channel integrated over a few tens of nanoseconds



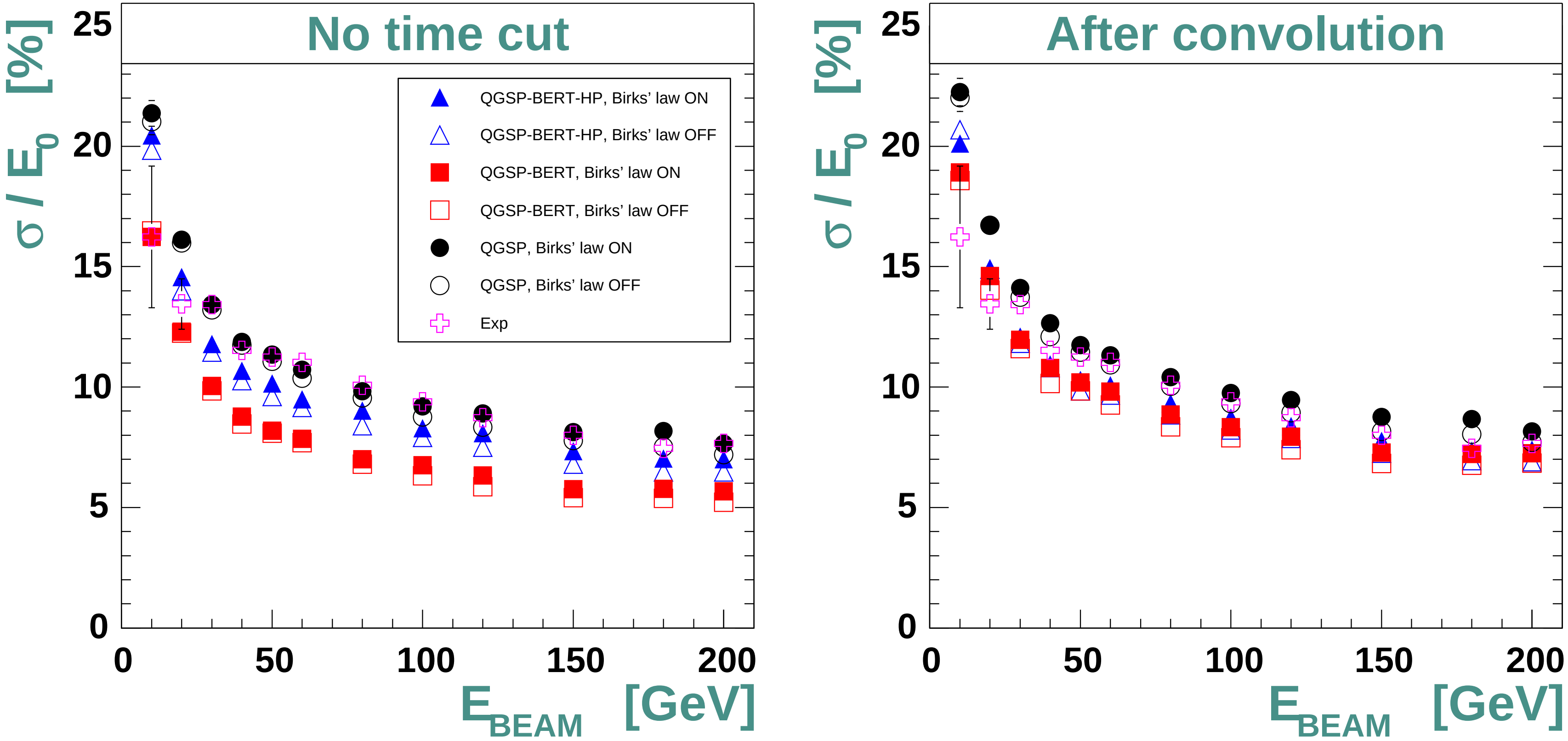
- Two types of signal measurements are considered:
  - after convolution with a shaping function
  - no time cut

Simulation / Reconstruction / Analysis

- Simulated samples:
  - energy scans with negatively charged pions
  - energy scans with electrons
- 5000 events per beam particle type, beam energy, physics list and Birks' law switch
- Ratio of simulation times (for pions):
  - **QGSP-BERT** / **QGSP** $= 1.7$
  - **QGSP-BERT-HP** / **QGSP** $= 4.9$

- Energy reconstruction:
  - following experimental procedure
  - electromagnetic scale calibration
    - ∗ defined by the sampling fraction
    - ∗ returns the total deposited energy for electrons
  - cluster of the fix size (effective radius of 35-40 cm)
  - Gaussian fit: E_0 and σ
  - no electronic noise added to Monte Carlo (MC) signals (spread of the noise was subtracted from the resolution of the experimental data)
- Analysed variables:
  - pion energy resolution σ/E_0
  - ratio e/π (ratio of energies in electron and pion clusters)
  - fraction of energies in HEC longitudinal layers for charged pions

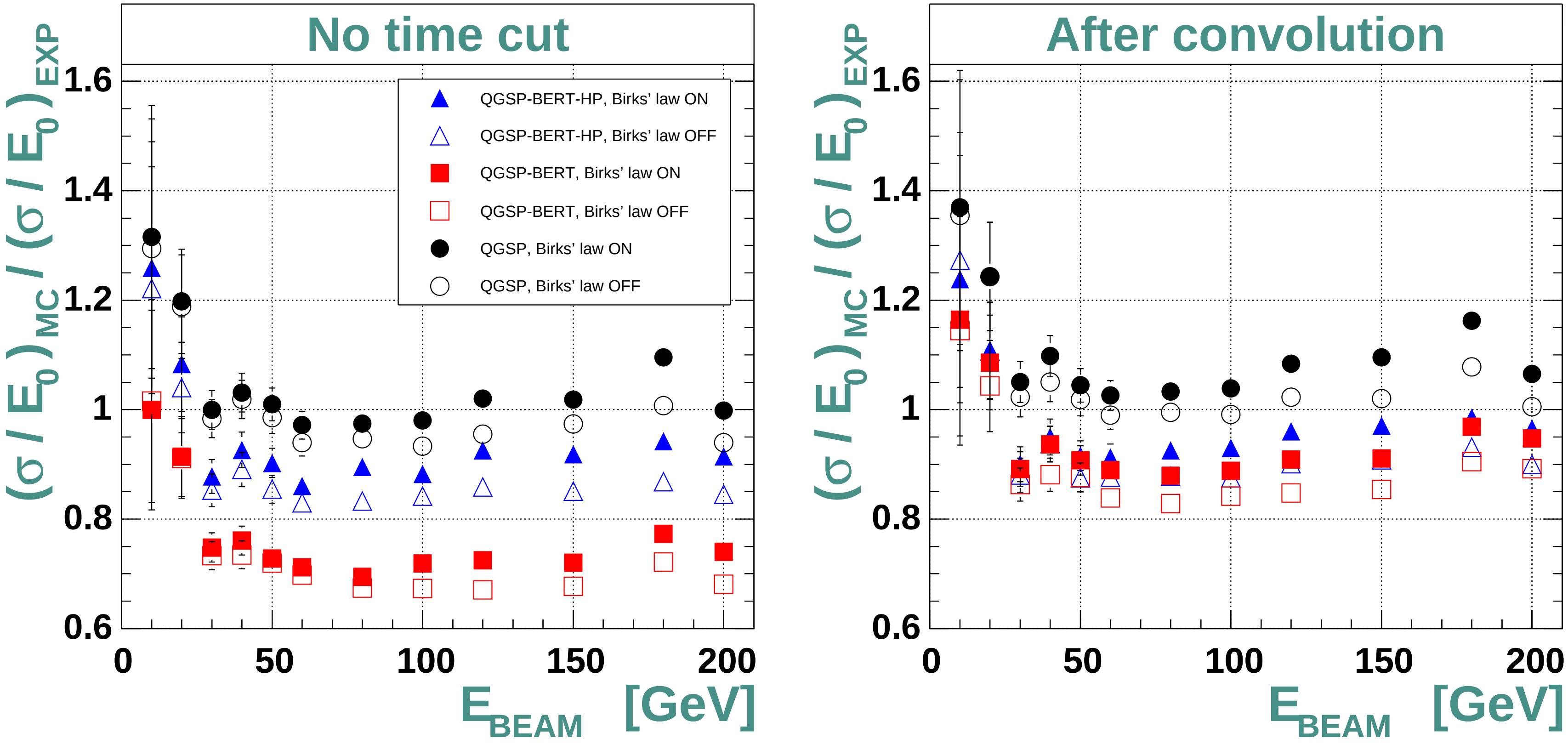
Pion energy resolution



Time cuts strongly influence the energy resolution

- **QGSP-BERT**: 10-30 % relative increase
- **QGSP** and **QGSP-BERT-HP**: relative increase by ∼5 %

Pion energy resolution: Ratio to experiment



QGSP describes well energy resolution below $E_{BEAM} \simeq 100$ GeV.

Pion energy resolution: Two-term parametrization

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

Birks' law	Physics list	After convolution	
		$A[\%\sqrt{GeV}]$	B [%]
OFF	**QGSP**	**68.1 ± 0.8**	6.2 ± 0.1
	QGSP-BERT	57.1 ± 0.7	5.30 ± 0.09
	QGSP-BERT-HP	60.2 ± 0.7	5.4 ± 0.1
ON	**QGSP**	**67.9 ± 0.8**	6.9 ± 0.1
	QGSP-BERT	58.6 ± 0.7	**5.83 ± 0.09**
	QGSP-BERT-HP	59.6 ± 0.7	**6.13 ± 0.09**

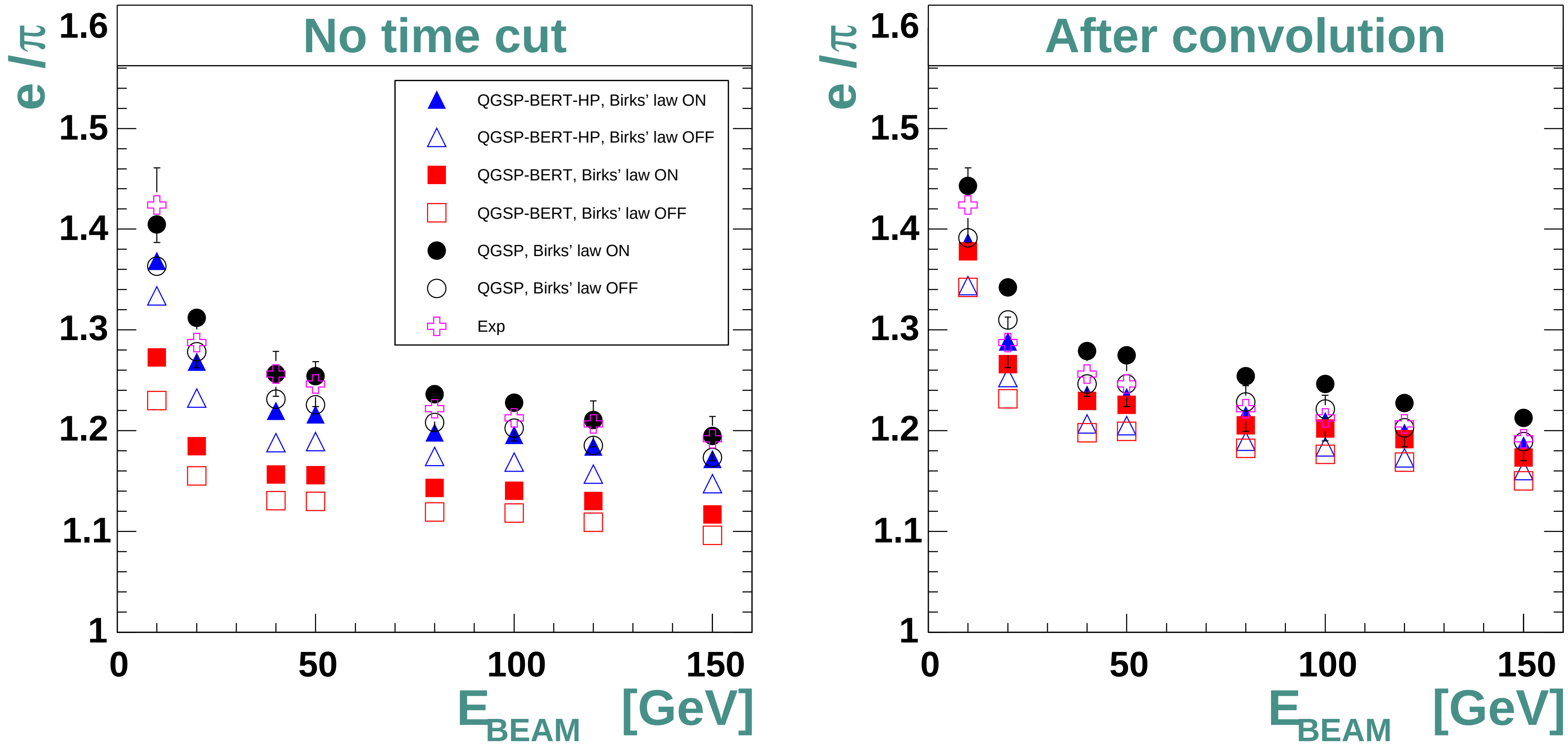
Birks' law:

- does not change the sampling term
- increases the constant term

After convolution and with Birks' law switched ON:

- sampling term is described well by **QGSP**
- constant term is predicted better by **QGSP-BERT** and **QGSP-BERT-HP**

Ratio e/π

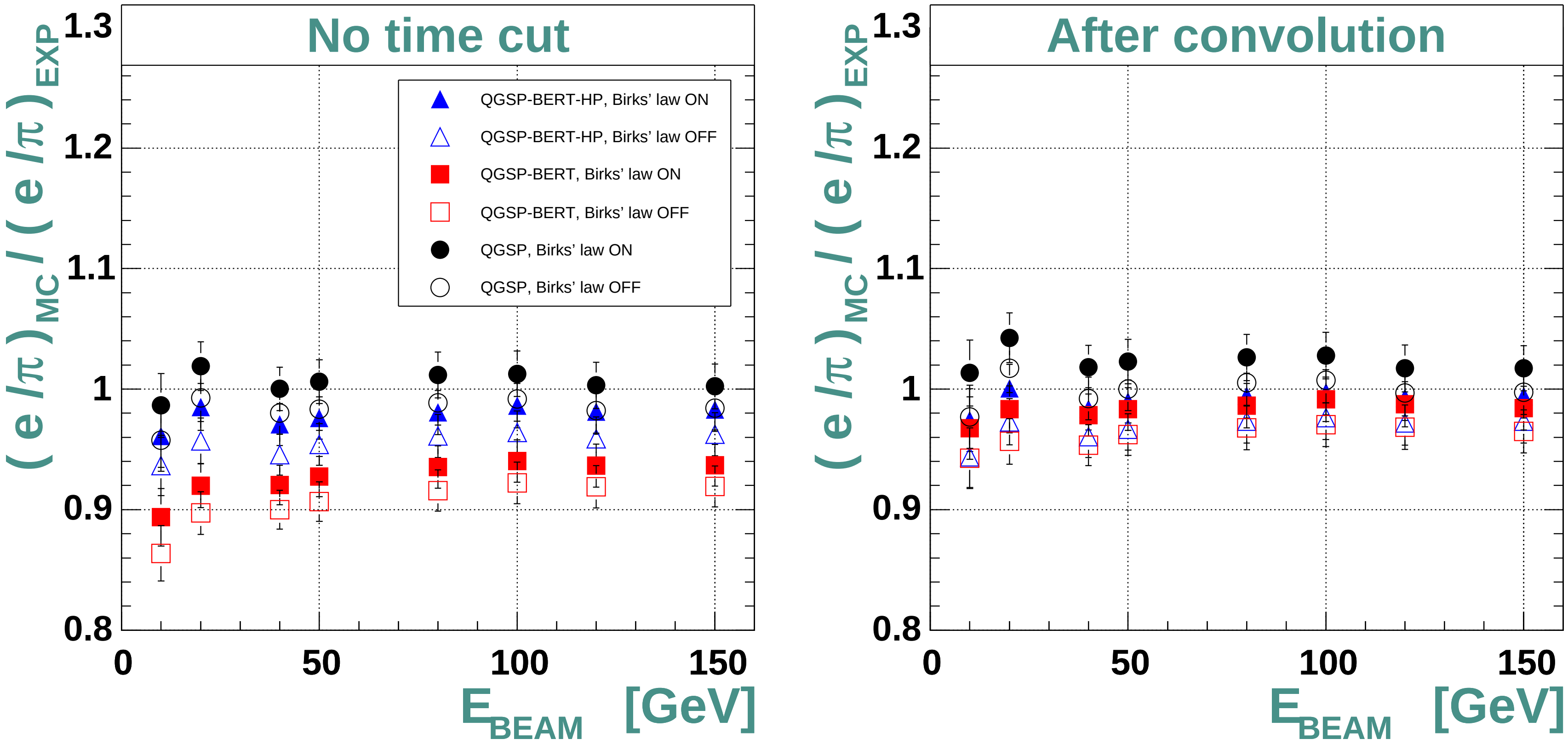


Time cuts strongly influence e/π-ratio for **QGSP-BERT**: 4-8 % increase.

For **QGSP** and **QGSP-BERT-HP** increase is smaller: 1-2 %.

Ratio e/π is 2-3 % larger, when Birks' law is switched ON for all physics lists.

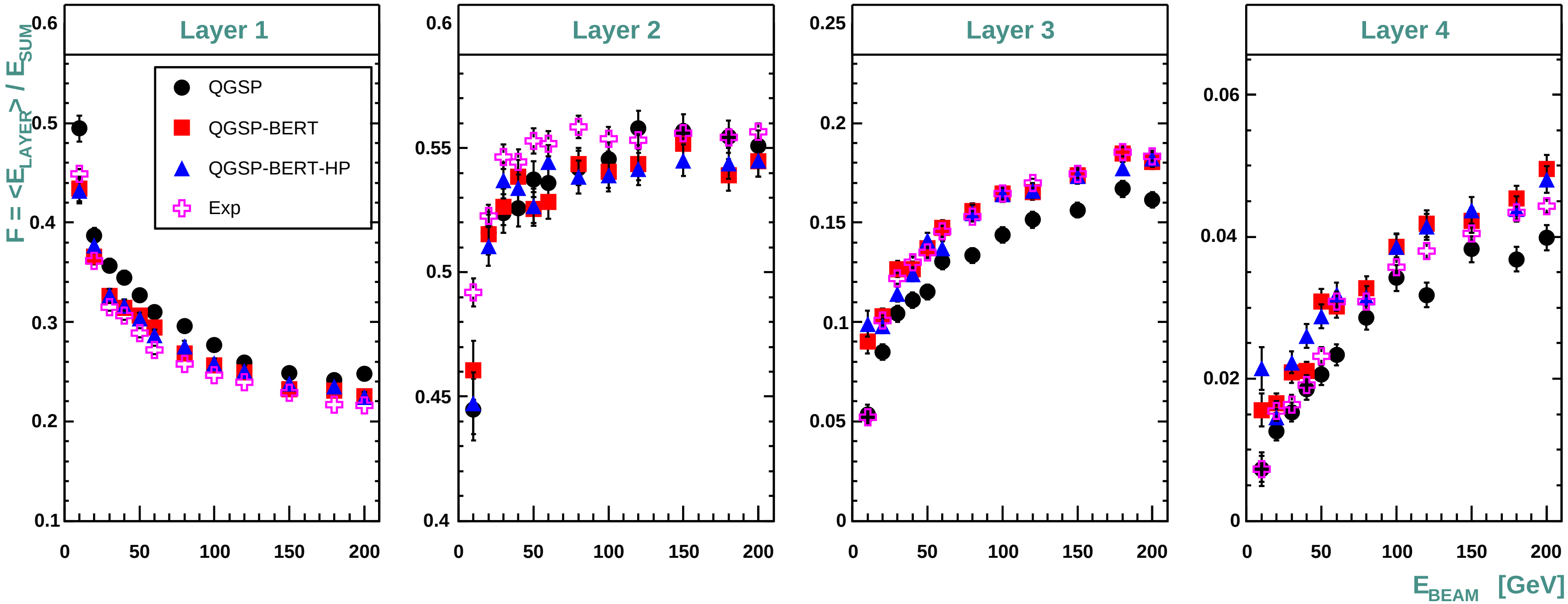
e/π: Ratio to experiment



After applying time cuts and with Birks' law switched ON: all three physics lists describe e/π ratio well.

Fraction of energy in HEC longitudinal layers

After convolution, Birks' law ON

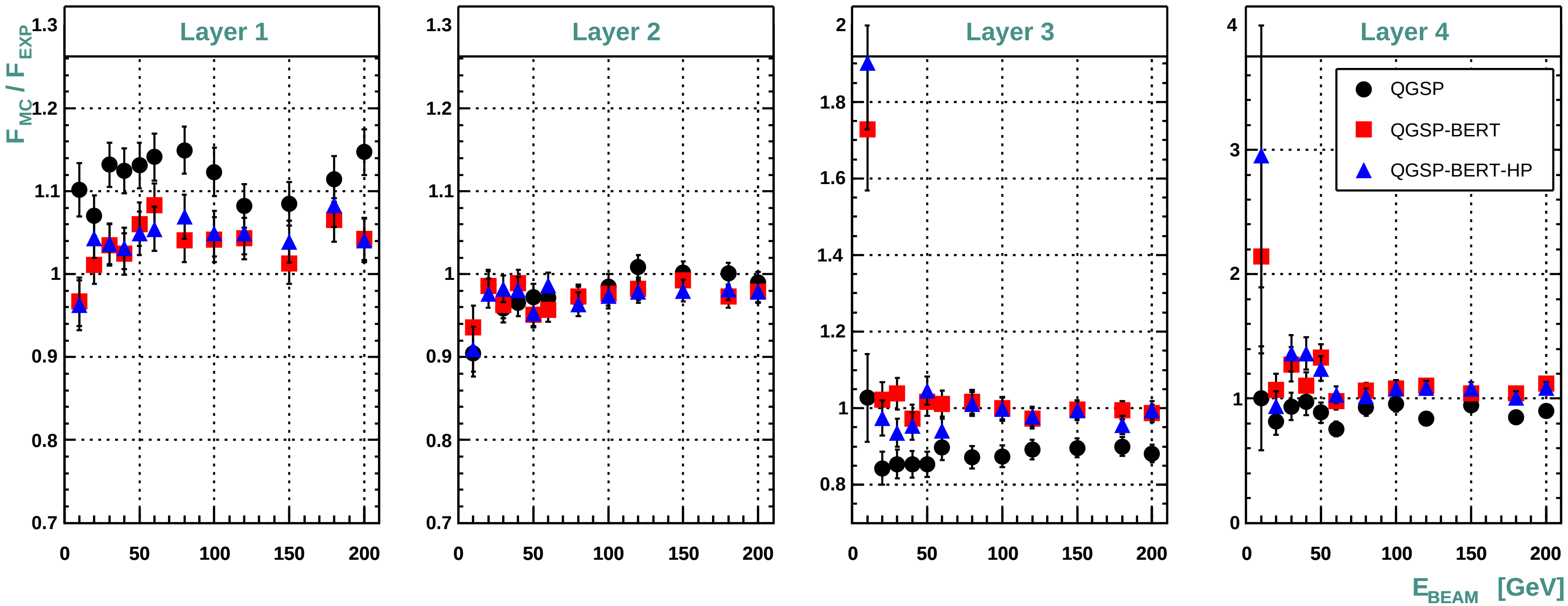


Four HEC longitudinal layers: 8/16/8/8 LAr gaps, 1.5/2.9/3.0/2.8 λ

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

Fraction of energy in HEC longitudinal layers: Ratio to experiment

After convolution, Birks' law ON



- Fraction of energy in the second (main) layer is described within a few percent by all physics lists
- **QGSP**: hadronic showers start earlier and are more compact
- **QGSP-BERT** and **QGSP-BERT-HP**: good description of shower profiles (except lowest beam energy)

- Only small differences between "No time cut" and "After convolution" measurements
- No dependence on Birks' law switch

Conclusions

GEANT4 based simulations of the HEC testbeam were caried out with different physics lists, namely: QGSP, QGSP-BERT and QGSP-BERT-HP. Influence of the Birks' law and time cuts on the calorimeter performance parameters was investigated. Comparison with experimental results, obtained during beam tests of HEC modules, was done.

- Usage of the Birks' law increases the e/π-ratio and the constant term of the energy resolution for charged pions
- QGSP-BERT physics list predicts much slower hadronic showers than QGSP and QGSP-BERT-HP
- Applying of time cuts (following the experimental procedure of signal measurements in calorimeter cells) has influence on the energy resolution and response for charged pions
- After applying time cuts and with Birks' law switched ON: the better description of studied experimental parameters, in total, is given by **QGSP-BERT** and **QGSP-BERT-HP**
  - good description of longitudinal profiles of hadronic showers
  - agreement in the e/π-ratio
  - rather close predictions of the resolution at high beam energies (i.e. of the constant term)
- Questions addressed to GEANT4 experts:
  - better description of the sampling term of the energy resolution for charged pions for BERT-based physics lists
  - decrease of the simulation time for QGSP-BERT-HP or/and improvement of the neutron physics in QGSP-BERT