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Physics Validation
of GEANT4 Version 9.3 (Beta-Release)
with Testbeam Data of
the ATLAS Hadronic End-Cap Calorimeter

LCG Physics Validation for LHC Simulations

25-th of November, 2009

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

- GEANT4 version 9.3 (beta-release, June 2009)

- Different physics lists:
  - **QGSP-BERT** (default physics list in ATLAS)
    - quark-gluon-string (QGS) model for interactions
    - pre-equilibrium decay model for the fragmentation
    - Bertini cascade code for modeling particle-nuclear interactions below ∼10 GeV
  - **QGSC-CHIPS** (new, experimental physics list)
    - quark-gluon-string model for interactions
    - CHIPS model to de-excite nucleus after high energy collisions and for proton interactions up to 300 MeV
  - **FTF-BIC**
    - FRITIOF string model for high energy interactions
    - binary cascade model for interactions below 5 GeV

Simulations

- Stand-alone package for simulations of the HEC testbeam
- Simulated samples:
  - energy scans with charged pions (10-200 GeV)
  - energy scans with electrons (6-147.8 GeV)
- GEANT4 range cut $= 30\ \mu$m
- Saturation of the response in liquid argon for particles with large dE/dx: usage of Birks' law

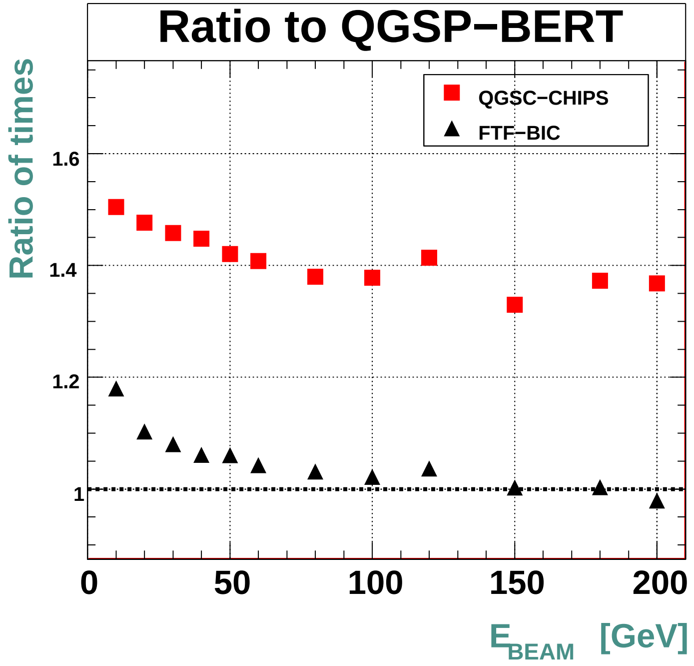
$$\Delta E' = \Delta E \frac{A}{1 + \frac{c}{\rho}\frac{\Delta E}{\Delta x}}$$

$A = 1$

$c = 0.0045$ g/(MeV cm^2)

$\rho = 1.396$ g/cm^3

- Comparison of CPU time of charged pion simulations



- QGSC-CHIPS / QGSP-BERT $\sim$ 1.3-1.5
- FTF-BIC / QGSP-BERT $\sim$ 1.0-1.2

Messages during QGSC-CHIPS based simulations

- Errors:

```
***G4QProtonNuclCS::CalcCrossSect: Sinc=3#2, Z=18, N=22, F=0
***G4QProtonNuclCS::CalcCrossSect: Sinc=4#3, Z=18, N=18, F=0
***G4QProtonNuclCS::CalcCrossSect: Sinc=5#4, Z=18, N=20, F=0
...
***G4QProtonNuclCS::CalcCrossSect: Sinc=21#20, Z=74, N=108, F=0
***G4QProtonNuclCS::CalcCrossSect: Sinc=22#21, Z=74, N=109, F=0
***G4QProtonNuclCS::CalcCrossSect: Sinc=23#22, Z=74, N=106, F=0
```

- Warnings:

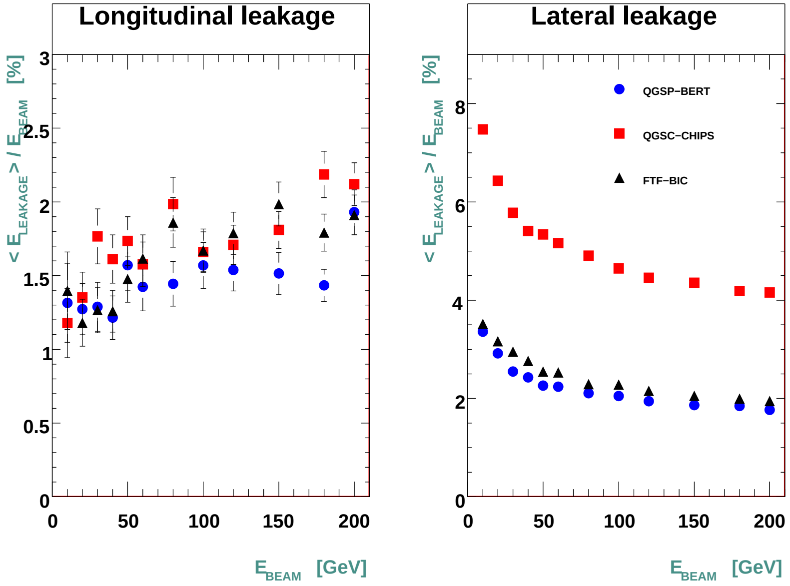
```
*Warning*G4QEnvironment::DecayAntistrange: S=-2,AsIsImprove
 (also S=-3, S=-4, S=-5)

*Warning*G4QEnvironment::DecayAntistrange: Too low mass, keep AsIs

-W-G4QE::CrQ:m2=42353508#42353508,P=(-72.101561,45.880732,183.25832;959.81338),M=6507.0709
```

Energy leakage for charged pions

- Energy leakage from HEC modules:
  - virtual "leakage" detectors surrounded calorimeter modules
  - leakage energy = sum of kinetic energies of all particles stopped in "leakage" detectors



- **QGSC-CHIPS** predicts significantly larger lateral leakage than other physics lists

- Contribution of neutrons to the total leakage for 100 GeV pions

	(1)	(2)	(3)
QGSP-BERT	3.6	192	36
QGSC-CHIPS	6.3	386	44
FTF-BIC	4.0	52	24

(1) - total leakage energy [GeV]
(2) - number of neutrons in "leakage" detectors
(3) - fraction of the total leakage energy carried by neutrons [%]

Reconstruction and Analysis

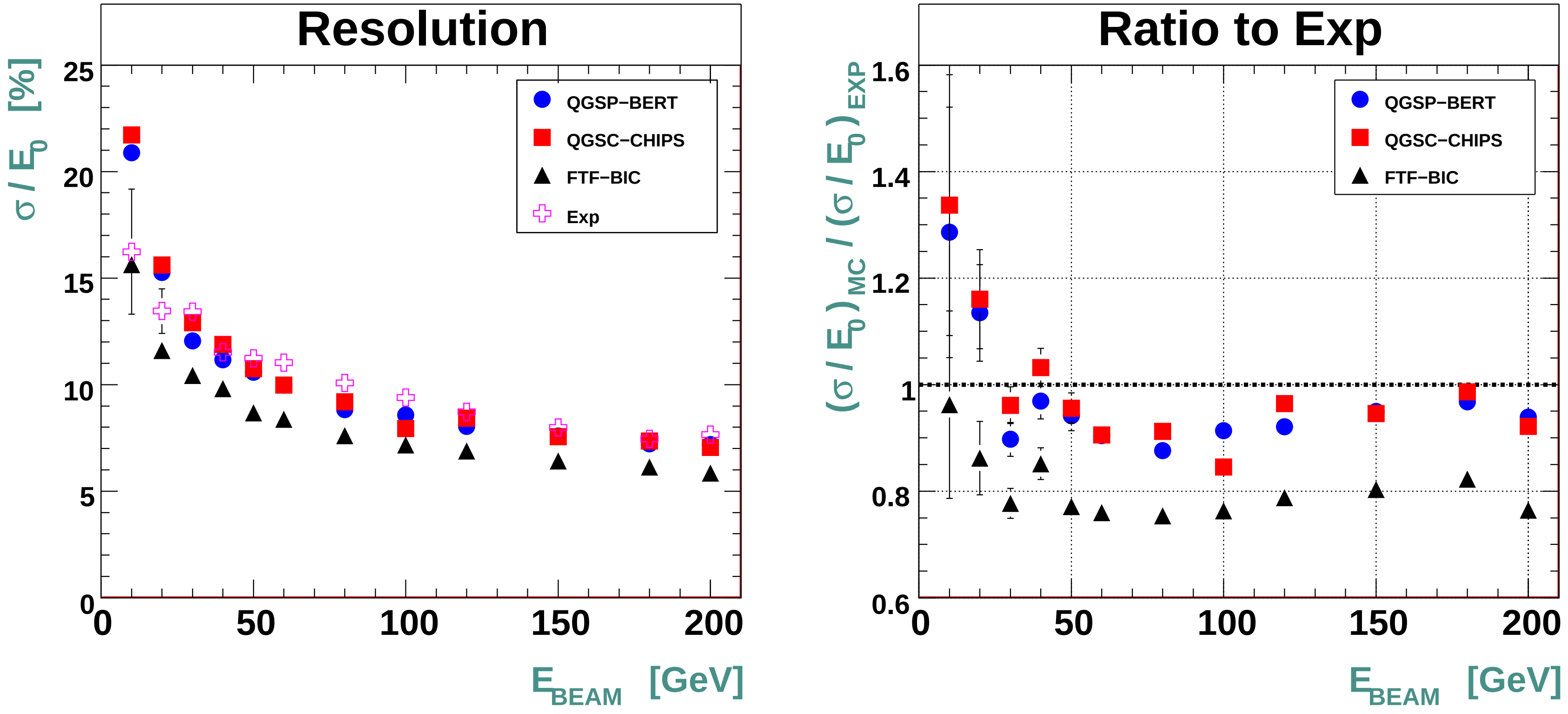
- To model fast readout of calorimeter signals:
  energy depositions in calorimeter channels (as a function of time of shower development) are convoluted event-by-event with corresponding shaping functions

  (effectively this procedure means the integration of shower time profiles over a few tens of nanoseconds)

- Energy reconstruction:
  - following experimental procedure
  - EM-scale calibration
  - 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

Pion energy resolution



- **QGSP-BERT** and **QGSC-CHIPS** predictions are rather close to experimental values of the energy resolution
- **FTF-BIC** gives the worst description of the data

Pion energy resolution:

Two-term parametrization

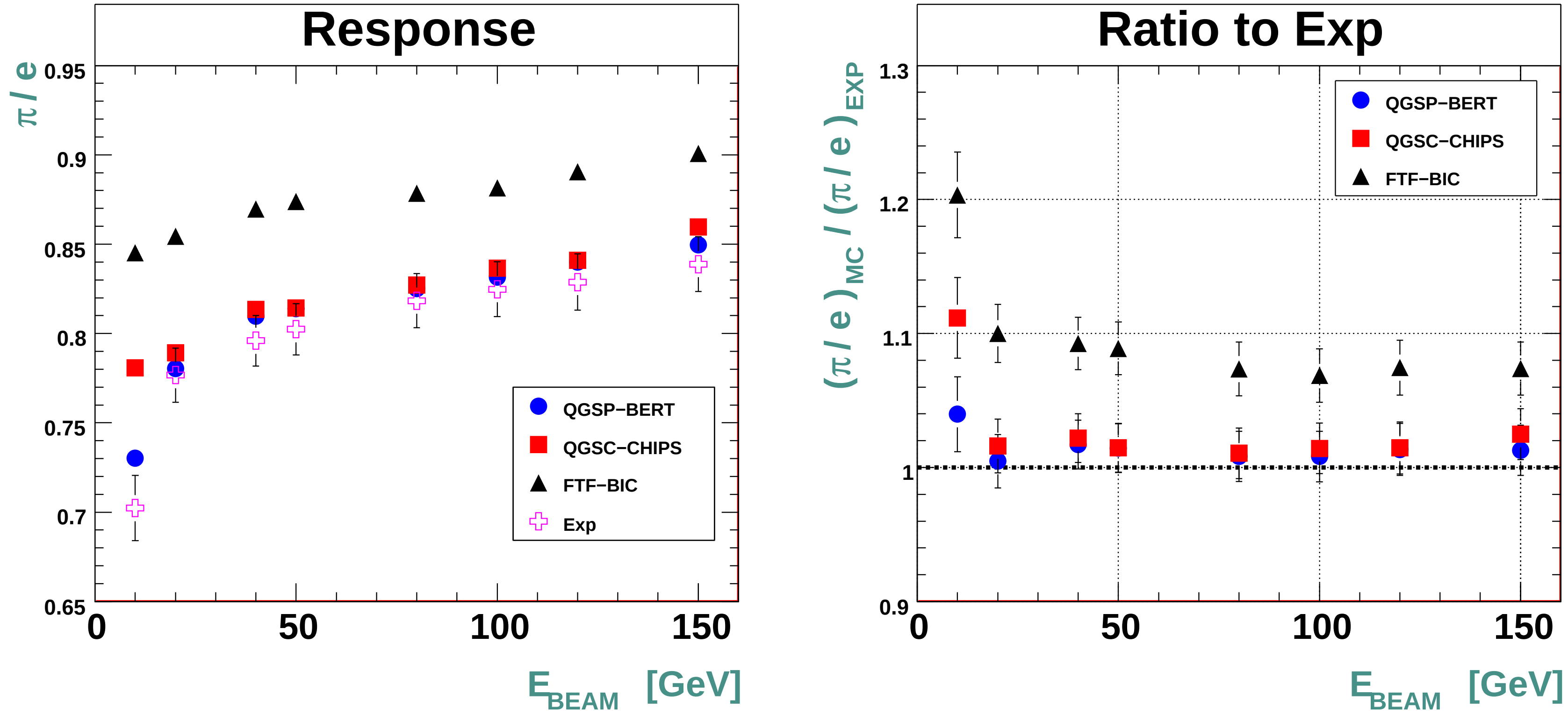
- $\sigma/E_0 = A/\sqrt{E_{BEAM}} \oplus B$
- Experimental values:
  $A = 69 \pm 1\ \%\sqrt{GeV}$, $B = 5.8 \pm 0.1\ \%$

- MC predictions:

Physics list	Terms of energy resolution	
	$A[\%\sqrt{GeV}]$	$B\ [\%]$
QGSP-BERT	61.7 ± 0.7	5.69 ± 0.10
QGSC-CHIPS	65.5 ± 0.7	5.38 ± 0.11
FTF-BIC	50.0 ± 0.6	4.97 ± 0.08

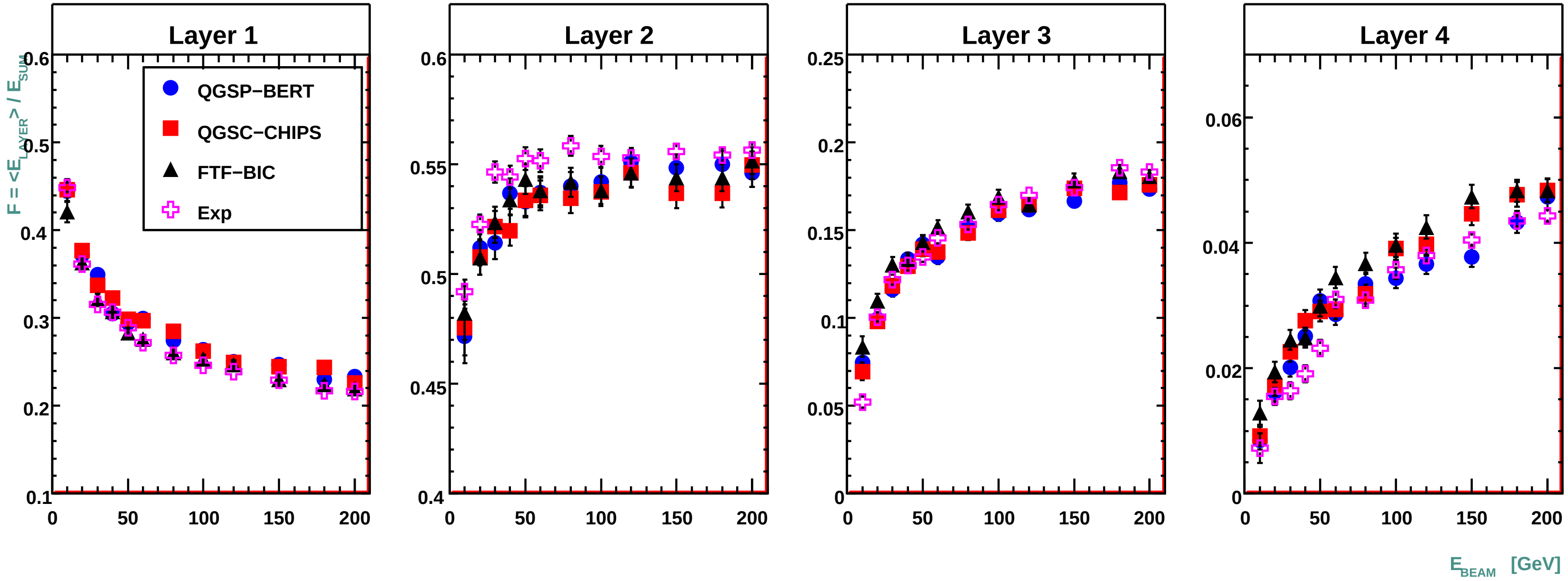
- Sampling term A is better described by **QGSC-CHIPS**
- Constant term B is better described by **QGSP-BERT**
- **FTF-BIC** predictions are too optimistic

Pion response



- **QGSP-BERT** and **QGSC-CHIPS** describe the pion response well (**QGSC-CHIPS** — except the lowest beam energy)
- **FTF-BIC** predicts too high response to charged pions

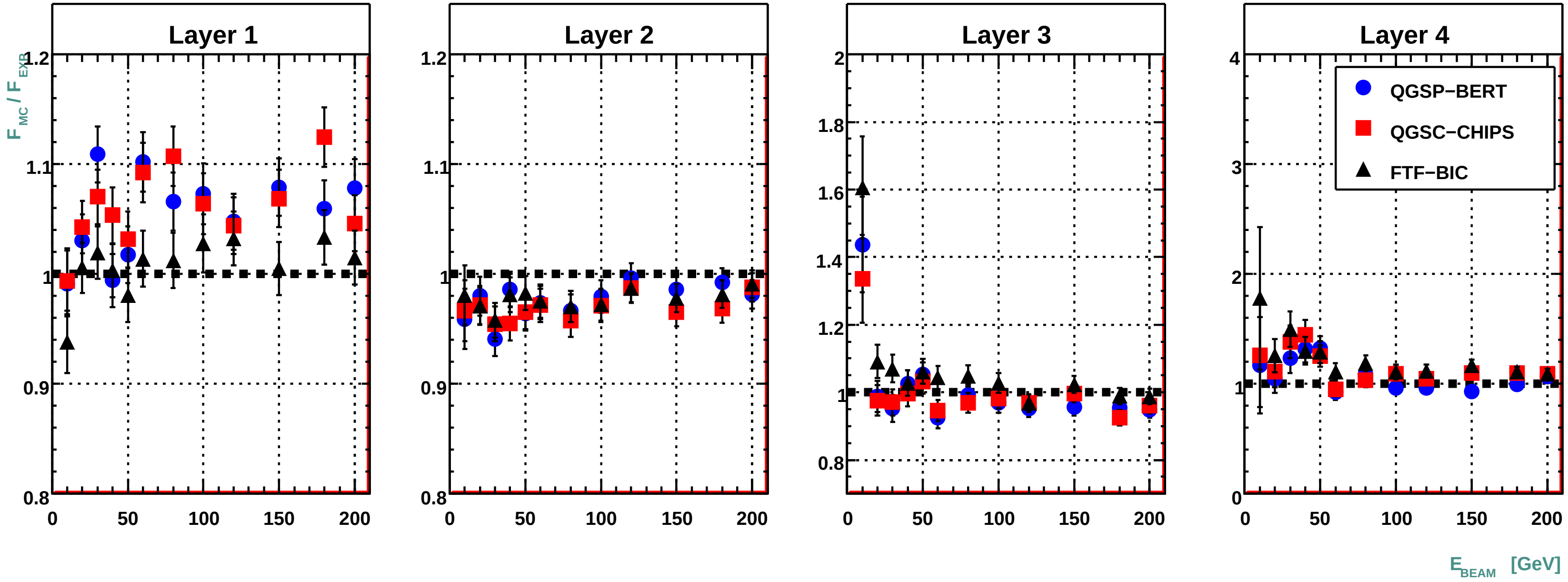
Fraction of energy in HEC longitudinal layers



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



- Fraction of energy in the second (main) layer is described within a few percent by all physics lists
- **FTF-BIC**: good description of shower profiles (except the lowest beam energy)
- **QGSP-BERT** and **QGSC-CHIPS**: hadronic showers start earlier (see layer 1)

Conclusions

New round of GEANT4 based simulations with beta-release of version 9.3 was carried out for the HEC stand-alone testbeam. Three different physics lists, namely: QGSP-BERT, QGSC-CHIPS and FTF-BIC — were used for GEANT4 simulations. Comparison with experimental results was done.

- QGSP-BERT and QGSC-CHIPS:
  - their predictions on the measured calorimeter performance parameters are close
  - agreement with experimental values in the pion response
  - rather good description of the energy resolution
  - earlier start of hadronic showers
- FTF-BIC:
  - good description of longitudinal profiles of hadronic showers
  - too optimistic energy resolution
  - too high response of the calorimeter to charged pions

Summary of the Comparison of MC Predictions and Experimental Results

- Ratio between simulated and experimental data as a function of the beam energy
- Maximal and minimal values of this dependence ⇒

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	
QGSP-BERT	-12	-3	0	$+2$	-1	$+11$	-6	0	-8	$+5$
QGSC-CHIPS	-15	$+3$	$+1$	$+2$	$+3$	$+12$	-5	-1	-8	$+3$
FTF-BIC	-25	-15	$+7$	$+10$	-2	$+3$	-4	-1	-3	$+9$

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[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: Studied physics lists have problems to describe those parameters at this beam energy.