Study of energy response and resolution of the ATLAS Tile Calorimeter to hadrons of energies from 16 to 30 GeV

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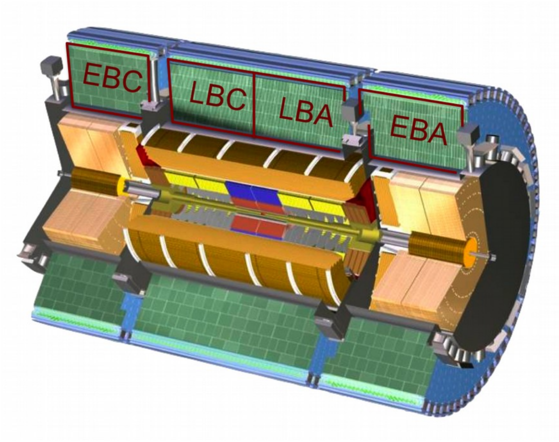
Outline

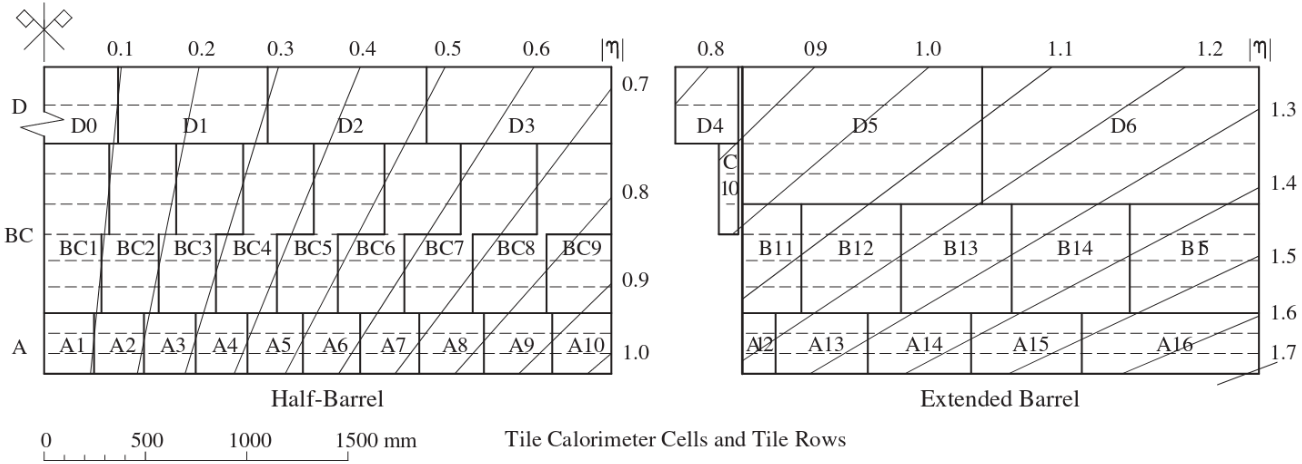
- ATLAS Tile Calorimeter
- Test Beam setup
- The measurements of the Tile Calorimeter response and resolution to 16 - 30 GeV hadrons - *ATL-COM-TILECAL-2019-025*[1]:
  - Pions
  - Kaons
  - Protons
- Conclusion



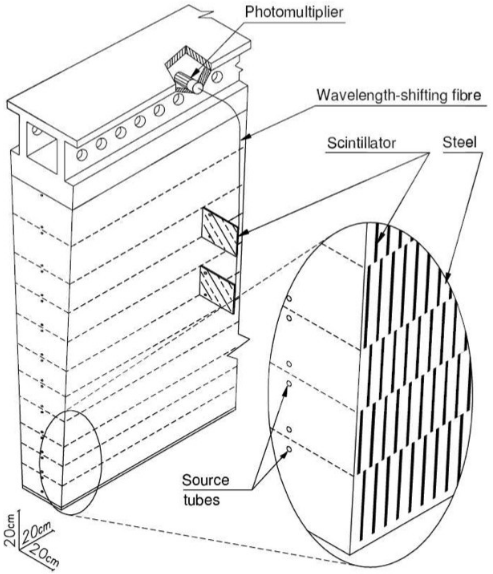
ATLAS Tile Calorimeter

Principle of TileCal:

- The defining role of hadron calorimetry is to measure the energies of jets.
- Measure light produced by charged particles in plastic scintillator.
- Scint. light from tiles collected by WLS fibers and delivered to PMTs.
- Tile readout is grouped into pseudo-projective geometry cells. each cell readout by 2 PMTs except special cells.
- Each barrel consist of 11 tile rows which form 3 longitudinal layers.



Tile Calorimeter Cells and Tile Rows

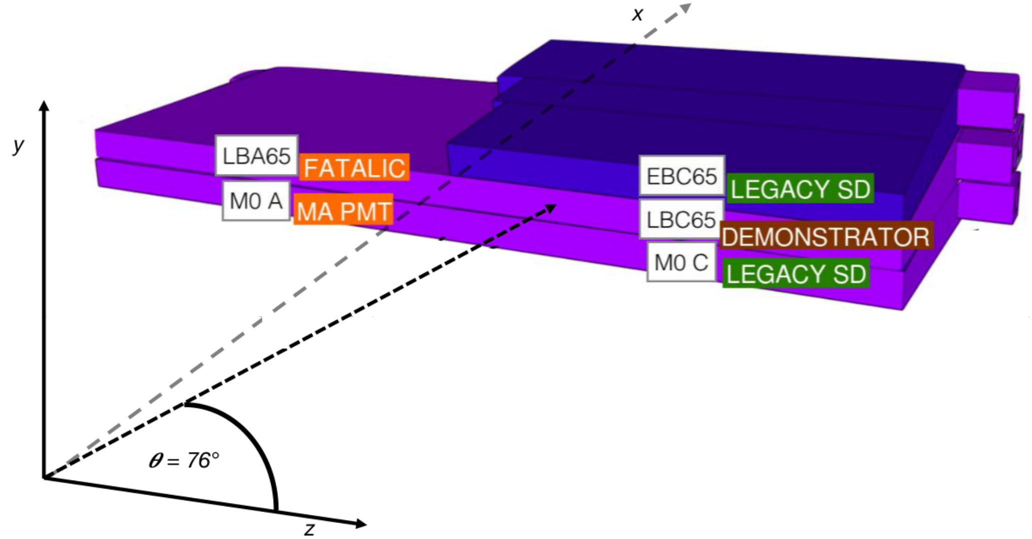


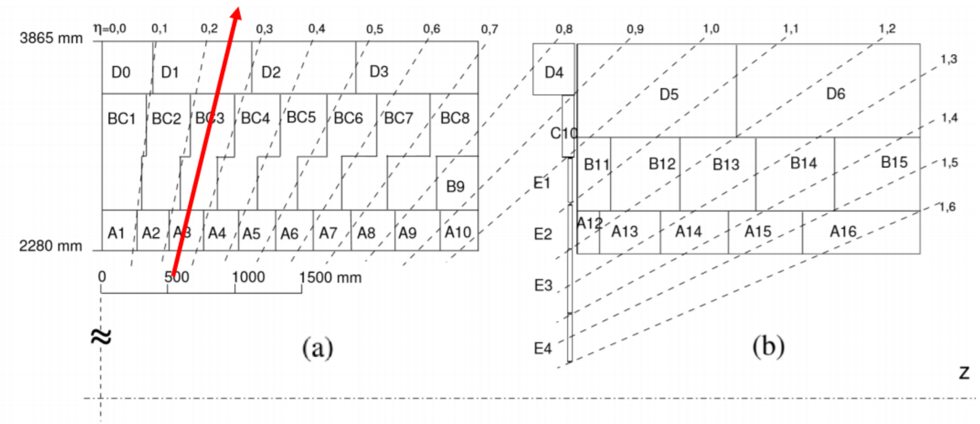
Test Beam setup

Motivation:

- High Luminosity upgrade of the LHC – increase of instantaneous luminosity by a factor of 5-10.
- New electronics - withstand a much higher radiation dose as well as a increased demand for data throughput.

TileCal modules equipped with Phase-II upgrade electronics together with modules equipped with the legacy system where exposed to different particles and energies, coming from SPS accelerator, in the test-beam campaigns during 2015 – 2018.



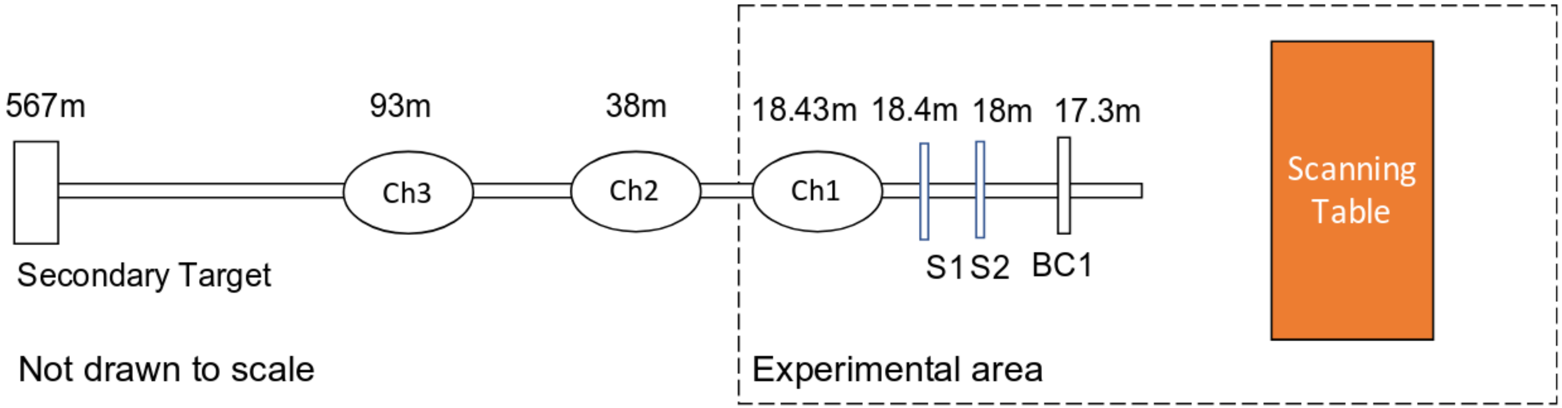


Results presented are obtained using:

- 16, 18, 20 and 30 GeV hadron beams
- η = - 0.25 (A3 cell) projective configuration

Beam line

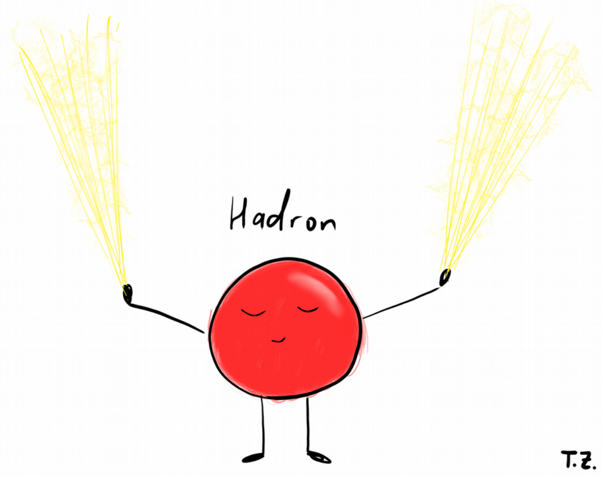
The beams were produced by extracting 400 GeV protons from the Super Proton Synchrotron (SPS) machine.



Beam line elements:

- Two wire chambers (BC1/BC2) - The transverse beam profile is monitored by.
- Two scintillators (S1/S2) - an active surface of 5×5 cm ^{2}, in coincidence they trigger the data acquisition and provide the trigger timing.
- The Cherenkov counters (Ch1, Ch2 and Ch3) - allow the beam particle identification.

Hadrons



The role of the hadron calorimetry is to measure the energy and the angle of isolated hadrons and jets.

To achieve good performance, the study of the sub-detector response to isolated hadrons is important.

The characterization of the response of the ATLAS calorimeter to hadrons is important to probe, validate and improve the modeling of the jets energy characterization of the ATLAS simulation using the GEANT4 toolkit.

In this talk, the measurements of the tile calorimeter response and resolution to positive pions and kaons and protons, with energies in the range 16-30 GeV will be presented.

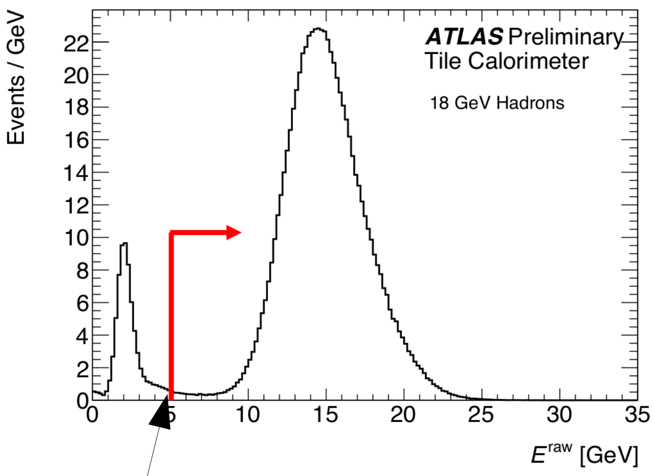
The results are compared with the ones obtained analyzing simulated data produced using the GEANT4 toolkit.

Event selection

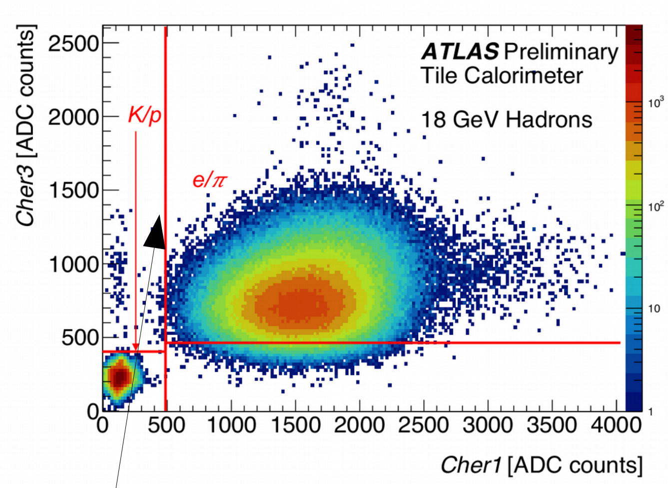
Test beam is a mixture of p, π, K, e, μ particles.

To clean the beam and separate hadrons:

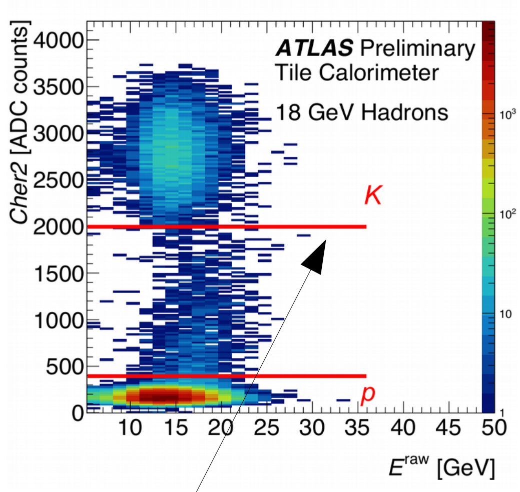
- Muons are rejected: The sum of the energy deposited in the calorimeter cells - E^{raw} > 5 GeV.
- The selection criteria chain applied for 18 GeV beam is visualized in figures:



Muon rejection



p/K particles are separation from π/e by applying cuts on Cher1 and Cher3



Kaons separation from the protons using Cher2 cut

e/π separation

The electron components in e/π samples were determined with the help of two shower profile parameters:

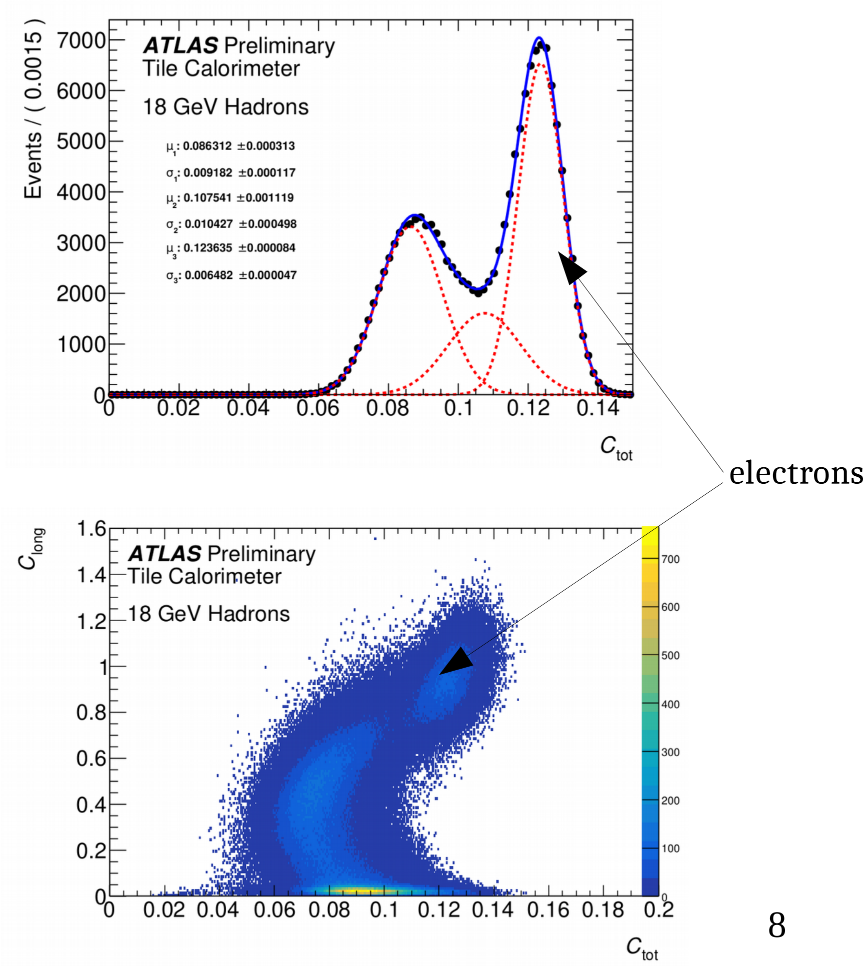
- C_{long} - the fraction of the nominal beam energy, deposited in the layer A of the barrels

$$C_{\text{long}} = \frac{\sum_{i=1}^{3}\sum_{j=1}^{3}(E_{\text{c}}^{\text{raw}})_{i,j}}{E_{\text{beam}}}$$

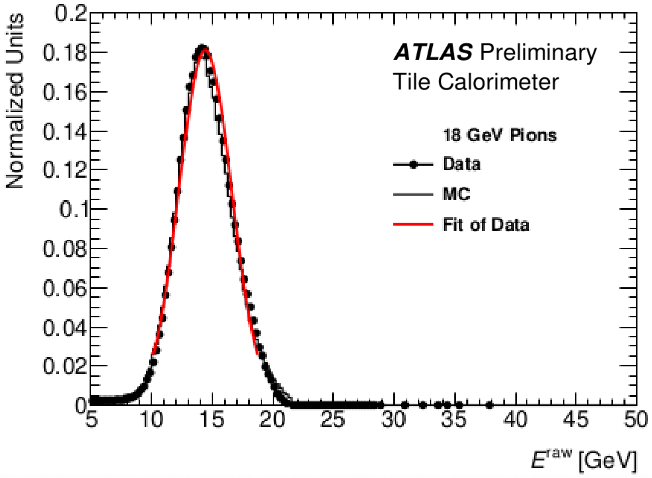
- C_{tot}- parameter which measures the spread of the energy deposited in the cells.

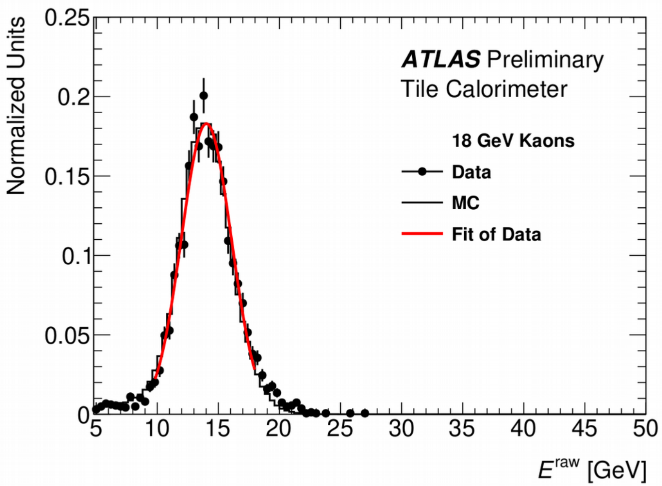
$$C_{\text{tot}} = \frac{1}{\sum_{i=1}^{N_{\text{cell}}}[(E_{\text{c}}^{\text{raw}})_i]^{\alpha}}\sqrt{\frac{1}{N_{\text{cell}}}\sum_{i=1}^{N_{\text{cell}}}\left([(E_{\text{c}}^{\text{raw}})_i]^{\alpha} - \frac{1}{N_{\text{cell}}}\sum_{i=1}^{N_{\text{cell}}}[(E_{\text{c}}^{\text{raw}})_i]^{\alpha}\right)^2}$$

- The electron (pion) C_{tot} distribution is well described by one (two) Gaussian(s) - confirmed by MC.

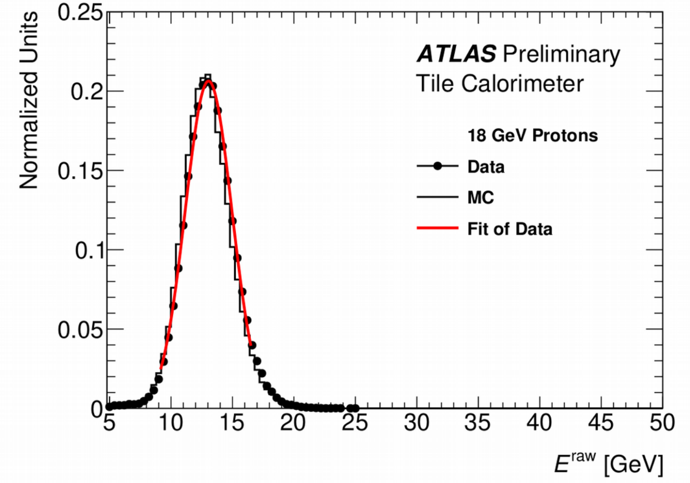


Energy distributions



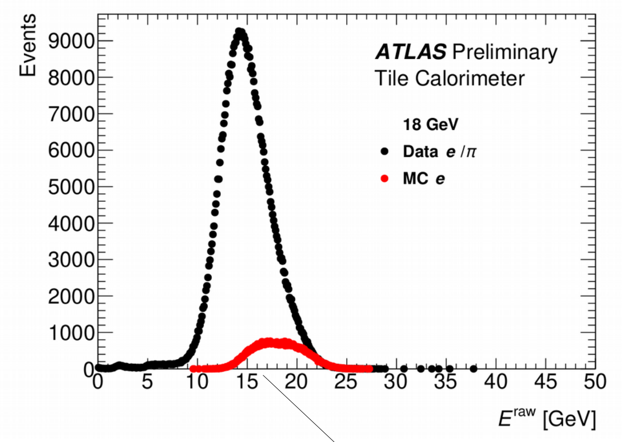


- As in the ATLAS detector, the energy deposited in a cell of the TB detector E_c^{raw}, was determined using the Optimal Filter method[2].
- The shower energy E^{raw} is the sum of the energy deposited in the calorimeter cells.
- Only cells with $|E_c^{raw}| > 2\sigma_{noise}$ were considered in the sum.

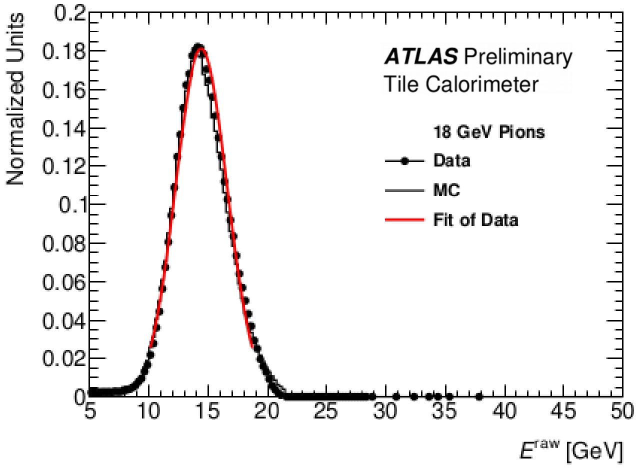


- FTFP_BERT_ATL Physics list used for the simulated events.
- Lower mean energy due to the non-compensating nature of the calorimeter.
- Mean value of the response of the kaons falls in between protons and pions.
- Distributions are fitted with Gaussian functions in a region of ± 2σ.
- The μ and σ parameters of Gaussian fits were used to estimate: **the measurement responses $\langle E^{raw} \rangle$** and **resolutions σ^{raw}.**

Pion energy distribution



After subtraction



The pion energy distributions were obtained subtracting, bin per bin, the distributions of simulated electron from the ones of e/π data sample events.

$$N[E^{\text{raw}}(\pi)] = N[E^{\text{raw}}(e/\pi)] - N_e \times N[E^{\text{raw}}(e)]$$

where $N[E_{raw}\ (e)]$ is normalized to 1 and the number of electrons, N_e was determined using the fit.

Energy response ratios vs beam energy

The energy response ratio:

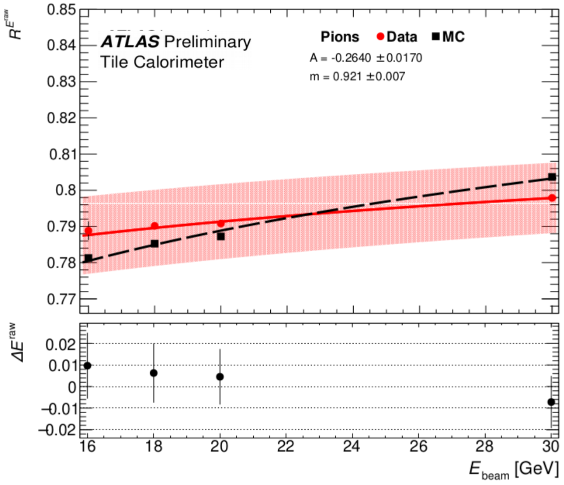
$$R^{\langle E^{\mathrm{raw}}\rangle} = \frac{\langle E^{raw}\rangle}{E_{\mathrm{beam}}}$$

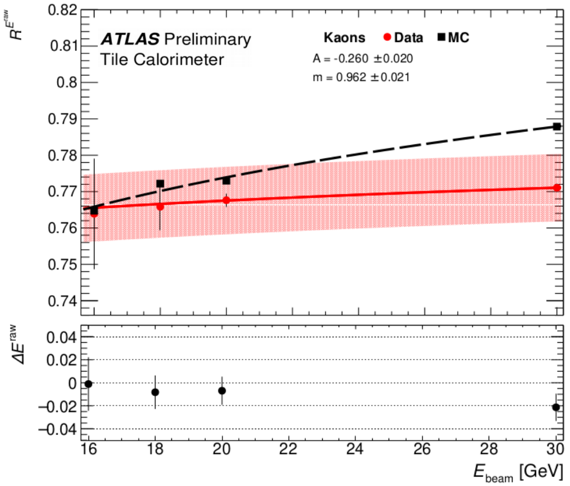
A quantitative comparison between experimental and simulated results is described as:

$$\Delta\langle E^{\mathrm{raw}}\rangle = \frac{\langle E^{\mathrm{raw}}\rangle}{\langle E^{\mathrm{raw}}_{\mathrm{MC}}\rangle} - 1$$

The ranges of variation of $\Delta\langle E^{\mathrm{raw}}\rangle$ are:

- Pions – 2%
- Kaons – 1%
- Protons – 2%





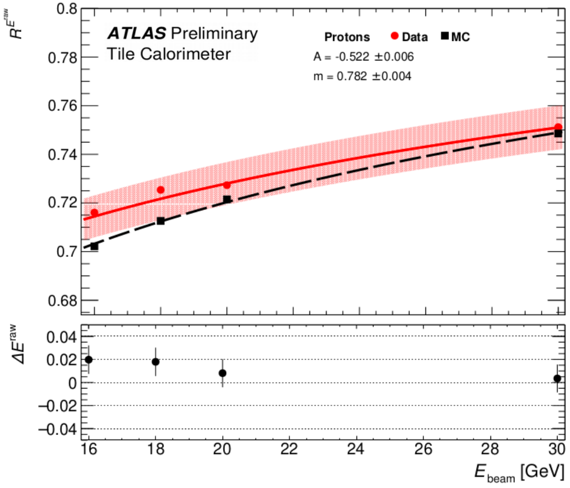
The hadron **energy response ratio can be parametrized as**[3] a function of the beam energy according to:

$$R^{\langle E^{\mathrm{raw}}\rangle} = (1 - F_{\mathrm{h}}) + F_{\mathrm{h}} \times (\frac{e}{h})^{-1} \quad , \qquad F_{\mathrm{h}} = (\frac{E_{\mathrm{beam}}}{E_0})^{m-1}$$

F_h - the non-electromagnetic energy component of showers induced by incident hadrons of energy E_{beam},
E_0 - the energy at which multiple pion production becomes significant,
m - the relation between the average multiplicity of secondary particles and the fraction of π^0s,
e/*h* - the ratio of the EM and hadronic components of showers.

Function can be rewritten as:

$$R^{\langle E^{\mathrm{raw}}\rangle} = 1 + \frac{1}{(E_0)^{m-1}}[(\frac{e}{h})^{-1} - 1](E_{\mathrm{beam}})^{m-1} \quad , \qquad A = \frac{1}{(E_0)^{m-1}}[(\frac{e}{h})^{-1} - 1]$$



Fractional resolutions vs $1/\sqrt{E_{beam}}$

The fractional resolution:

$$R^{\sigma^{raw}} = \frac{\sigma^{raw}}{E_{beam}}$$

A quantitative comparison between experimental and simulated results is described as:

$$\Delta\sigma^{raw} = \frac{\sigma^{raw}}{\sigma^{raw}_{MC}} - 1$$

The ranges of variation of $\Delta\sigma^{raw}$ are:

- Pions – 4%
- Kaons – 10%
- Protons – 3%

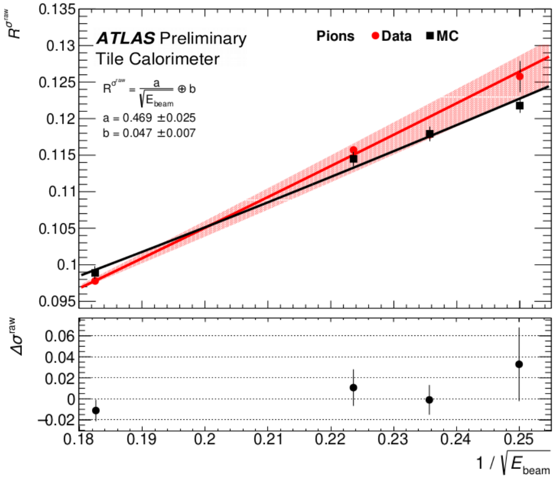
The **resolution can be parametrized according to**:

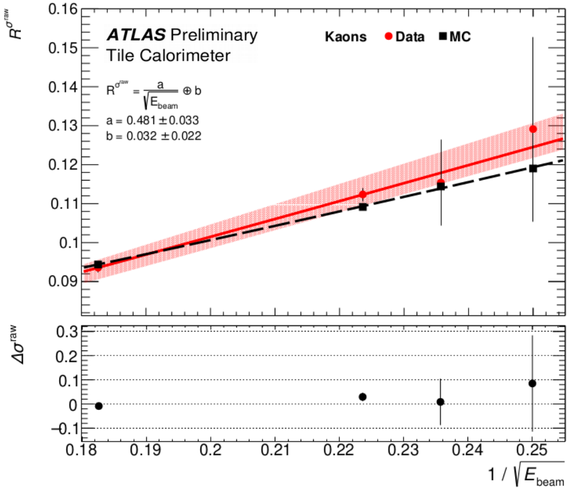
$$R^{\sigma^{raw}} = \frac{a}{\sqrt{E_{beam}}} \oplus b$$

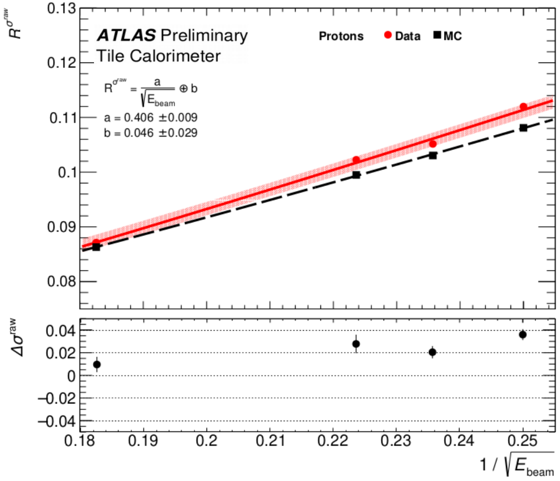
a - the stochastic term,

b - the cell response non-uniformity,

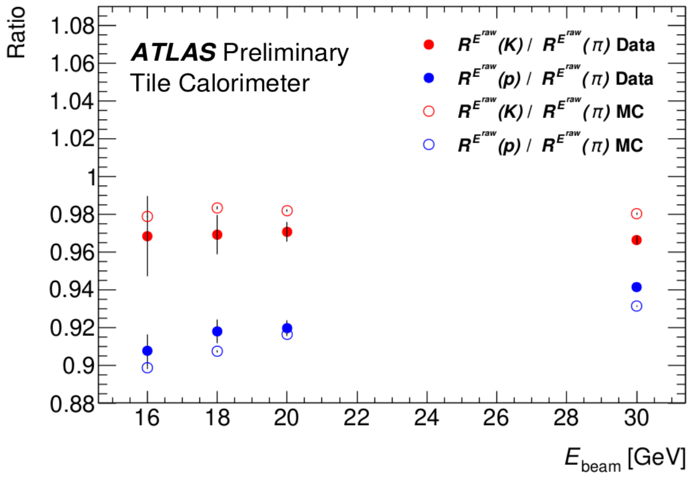
The symbol ⊕ indicates the sum in quadrature.

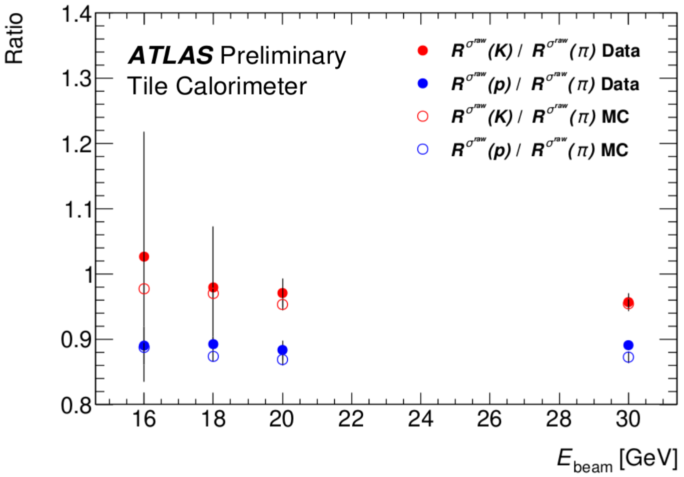






Response and resolution double ratios





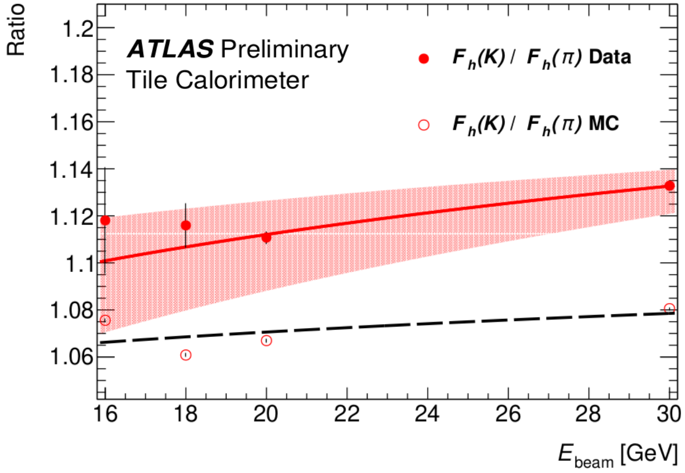
Ratios of hadron responses and resolution as a function of the nominal beam energy:

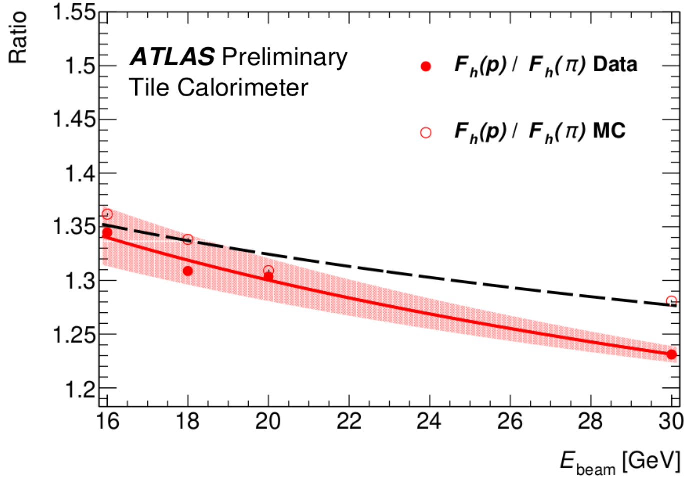
$$\frac{R^{\langle E^{\mathrm{raw}}\rangle}(K)}{R^{\langle E^{\mathrm{raw}}\rangle}(\pi)}, \qquad \frac{R^{\sigma^{\mathrm{raw}}}(K)}{R^{\sigma^{\mathrm{raw}}}(\pi)},$$

$$\frac{R^{\langle E^{\mathrm{raw}}\rangle}(p)}{R^{\langle E^{\mathrm{raw}}\rangle}(\pi)}, \qquad \frac{R^{\sigma^{\mathrm{raw}}}(p)}{R^{\sigma^{\mathrm{raw}}}(\pi)}.$$

- The measured energy resolution of kaons (protons) differs by about 4% (12%) from the pion one.
- Measured kaon (proton) response is about 3% (8%) smaller than pion response.
- The determinations of data and MC agree within the uncertainties.
- Deviations from MC is the order of a few percent.

F_h ratios





Ratios of non-electromagnetic energy component of showers as a function of the nominal beam energy:

$$\frac{F_{\mathrm{h}}(K)}{F_{\mathrm{h}}(\pi)} = \frac{1 - R^{\langle E^{\mathrm{raw}} \rangle}(K)}{1 - R^{\langle E^{\mathrm{raw}} \rangle}(\pi)} = \frac{E_0(\pi)^{m(\pi)-1}}{E_0(K)^{m(K)-1}} \times (E_{\mathrm{beam}})^{m(K)-m(\pi)} ,$$

$$\frac{F_{\mathrm{h}}(p)}{F_{\mathrm{h}}(\pi)} = \frac{1 - R^{\langle E^{\mathrm{raw}} \rangle}(p)}{1 - R^{\langle E^{\mathrm{raw}} \rangle}(\pi)} = \frac{E_0(\pi)^{m(\pi)-1}}{E_0(p)^{m(p)-1}} \times (E_{\mathrm{beam}})^{m(p)-m(\pi)}$$

With the energy increase the data shows:

- an increase from 1.12 to 1.13 for kaons;
- a decrease from 1.34 to 1.23 for protons.

In the Groom's paper[3] it is estimated to range between 1.15 and 1.20 at energies greater than 200 GeV.

Conclusion

- Three modules of the ATLAS Tile Calorimeter were exposed to test beams from the Super Proton Synchrotron (SPS) accelerator at CERN during 2015-2018.
- The measurements of the energy response and resolution of the Tile Calorimeter to positive pions, kaons and protons, with energy in the range 16 to 30 GeV are reported:
  - The energy response ratios and the fractional resolutions were determined with an uncertainty smaller than 2%. The results obtained using simulated and experimental pion and kaon data agree within the uncertainties, In case of protons:
    - energy response ratio determinations agree within the uncertainties, though the fractional resolutions obtained using simulated proton data are significantly smaller than the response obtained analyzing experimental data. The determination obtained analyzing simulated data agree within the uncertainties.
  - The ratio between the responses to the purely EM and the hadronic components of showers (*e*/*h*) equal to 1.36 ± 0.03 was obtained using pion data, in agreement with a previous measurement.
  - The pion resolution as a function of energy is parametrized with a stochastic term a = 47 ± 3 [%GeV$^{1/2}$] and a constant term b = 4.7 ± 0.7%. The values of a and b are consistent within two sigmas with a previous determination.

Thank you!

References

[1] Tigran Mkrtchyan and Claudio Santoni, Study of energy response and resolution of the ATLAS Tile Calorimeter to hadrons of energies from 16 to 30 GeV, ATL-COM-TILECAL-2019-025.

[2] A. Valero,The ATLAS TileCal Read-Out Drivers Signal Reconstruction, tech. rep. ATL-TILECAL-PROC-2009-004, CERN, 2009, url: http://cds.cern.ch/record/1223960

[3] D. E. Groom, “Energy flow in a hadronic cascade: Application to hadron calorimetry” [Nucl.Instrum.Meth. A572 (2007) 633-653, Erratum: Nucl.Instrum.Meth. A593 (2008) 628].

[4] ATLAS Collaboration, Technical Design Report for the Phase-II Upgrade of the ATLAS Tile Calorimeter, tech. rep. CERN-LHCC-2017-019. ATLAS-TDR-028, CERN, 2017.

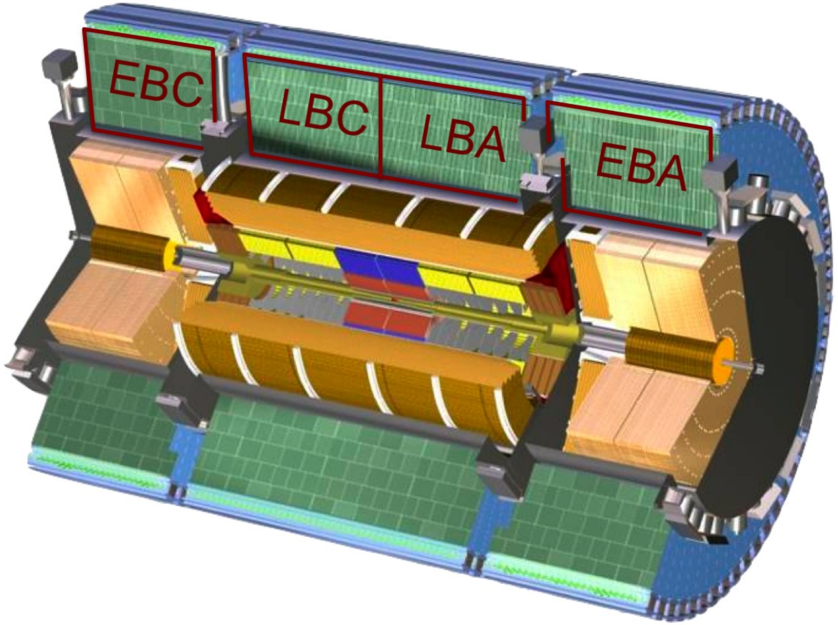
[5] S. Agostinelli et al., Geant4—a simulation toolkit, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 506 (2003) 250.

[6] P. Adragna et al., Testbeam studies of production modules of the ATLAS tile calorimeter, Nucl. Instrum. Meth. A606 (2009) 362.

Backup

ATLAS detector

- The TileCal is the central hadronic calorimeter within the ATLAS at the LHC situated at CERN, Geneva.
- The TileCal is composed of four barrel sections (two central and two extended barrels), each containing 64 azimuthal slices.
- The Phase II Upgrade of the LHC plans to increase the present instantaneous luminosity by a factor of 5-10. will need to withstand a much higher radiation dose as well as a increased demand for data throughput.



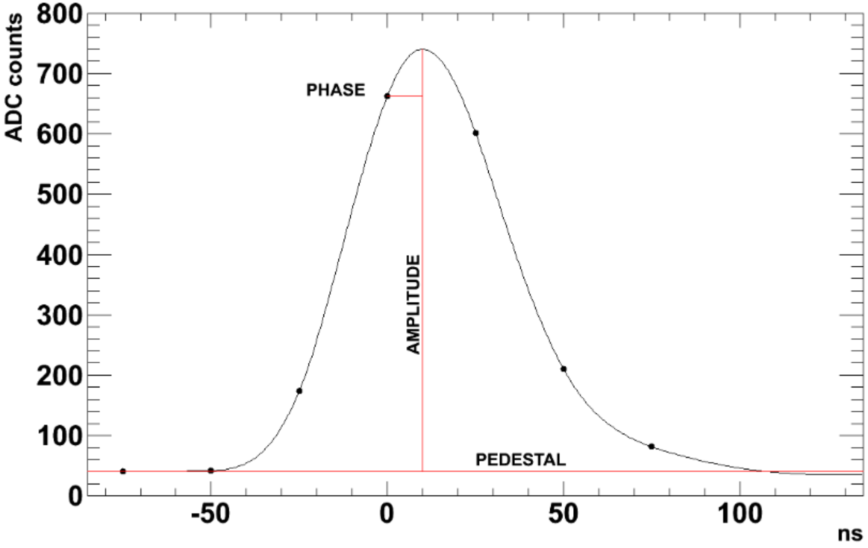
Signal reconstruction

- The analog signal from PMTs is shaped and sampled every 25 ns.
- Several methods exist to reconstruct amplitude (A), time (T) and quality factor (QF).
- Used method for this analysis is the **Optimal Filter**[2]: weighted sum of measured samples, designed to minimize the noise:

$$A = \sum_{i=0}^{n} a_i S_i$$

$$\tau = \frac{1}{A} \sum_{i=0}^{n} b_i S_i$$

$$QF = \sum_{i=0}^{n} (S_i - (A g_i + A \tau g'_i + p))^2$$



S_i - ith sample
n - number of samples
A - amplitude of the signal (Eopt)
τ- the phase with respect to the expected sampling time (Topt)
QF - quality factor of the reconstruction.

Iterative optimal filter: multiple iterations to find correct position of the peak.

Calibration procedure in Tile Calorimeter

$$E_{channel}\ [Gev] = A\ [ADC]\ \cdot C_{ADC \rightarrow pC} \cdot C_{pC\text{->}GeV} \cdot C_{Cs} \cdot C_{Las} \cdot C_{\mu}$$

- A [ADC] - Signal amplitude obtained using the Optimal filter reconstruction method.
- $C_{ADC \rightarrow pC}$ - Charge injection system (CIS) : Charges in Pico Coulomb of known values are injected into read out electronics. The CIS constant gives the relation between the value of a charge and the signal amplitude.
- $(1/C_{pC \rightarrow GeV})$ - Conversion factor (EM scale calibration constant) between the measured charge in pC and the energy of the incident electron.
- C_{Cs} - Cesium system (Cs) : ^{137}Cs γ – source embedded in a capsule, moves with a constant speed inside the stainless steel tubes through all the calorimeter volume exiting all the scintillating tiles. It is the main tool to equalize the calorimeter cells responses.
- C_{las} - Laser system: Sends laser pulses of known intensities into the photocathodes of PMTs. It's aim is to monitor the response of PMTs and provide additional calibration factor.
- C_{μ} – Correction of the EM scale, due to the different sizes of the cells and the position of the CS stainless steel tubes.

Quantitative results

Measured energy response ratios and resolution for pions, kaons and protons obtained analyzing experimental and simulated data.

Pions				
E_{beam} [GeV]	$R^{\langle E^{raw} \rangle}$		$R^{\sigma^{raw}}$	
	Exp. Data	Sim. Data	Exp. Data	Sim. Data
16	0.788 ± 0.003 ± 0.011	0.7812 ± 0.0005	0.125 ± 0.0005 ± 0.003	0.1217 ± 0.0009
18	0.7901 ± 0.0008 ± 0.01	0.7852 ± 0.0005	0.117 ± 0.0004 ± 0.001	0.1179 ± 0.0009
20	0.7908 ± 0.0006 ± 0.01	0.7872 ± 0.0005	0.115 ± 0.0003 ± 0.001	0.1144 ± 0.001
30	0.797 ± 0.0003 ± 0.01	0.8036 ± 0.0004	0.097 ± 0.0003 ± 0.0005	0.0988 ± 0.0008

Kaons				
E_{beam} [GeV]	$R^{\langle E^{raw} \rangle}$		$R^{\sigma^{raw}}$	
	Exp. Data	Sim. Data	Exp. Data	Sim. Data
16	0.763 ± 0.015 ± 0.009	0.7647 ± 0.0003	0.129 ± 0.023 ± 0.00004	0.119 ± 0.0003
18	0.765 ± 0.006 ± 0.009	0.7721 ± 0.0003	0.115 ± 0.01 ± 0.0004	0.1144 ± 0.0002
20	0.767 ± 0.002 ± 0.009	0.7729 ± 0.0002	0.112 ± 0.002 ± 0.0008	0.1091 ± 0.0002
30	0.771 ± 0.001 ± 0.009	0.7878 ± 0.0002	0.093 ± 0.001 ± 0.0005	0.0943 ± 0.0002

Protons				
E_{beam} [GeV]	$R^{\langle E^{raw} \rangle}$		$R^{\sigma^{raw}}$	
	Exp. Data	Sim. Data	Exp. Data	Sim. Data
16	0.716 ± 0.001 ± 0.009	0.7021 ± 0.0002	0.134 ± 0.0004 ± 0.00004	0.108 ± 0.0002
18	0.725 ± 0.001 ± 0.009	0.7126 ± 0.0002	0.113 ± 0.0003 ± 0.0004	0.103 ± 0.0002
20	0.727 ± 0.0003 ± 0.009	0.7214 ± 0.0002	0.112 ± 0.0003 ± 0.0007	0.0994 ± 0.0002
30	0.751 ± 0.0003 ± 0.009	0.7485 ± 0.0001	0.093 ± 0.0003 ± 0.0005	0.0862 ± 0.0001

Relative difference of the energy response and resolution obtained analyzing experimental and simulated data.

$\Delta E^{raw} = \langle E^{raw} \rangle / \langle E^{raw}_{MC} \rangle - 1$			
E_{beam} [GeV]	Pions	Kaons	Protons
16	0.0097 ± 0.003 ± 0.015	-0.001 ± 0.02 ± 0.012	0.019 ± 0.002 ± 0.012
18	0.006 ± 0.001 ± 0.014	-0.008 ± 0.008 ± 0.012	0.018 ± 0.001 ± 0.012
20	0.005 ± 0.001 ± 0.013	-0.007 ± 0.002 ± 0.012	0.008 ± 0.0005 ± 0.012
30	-0.0072 ± 0.0006 ± 0.012	-0.021 ± 0.002 ± 0.012	0.003 ± 0.0005 ± 0.012
$\Delta\sigma^{raw} = \sigma^{raw} / \sigma^{raw}_{MC} - 1$			
E_{beam} [GeV]	Pions	Kaons	Protons
16	0.032 ± 0.02 ± 0.03	0.084904 ± 0.2 ± 0.00004	0.03598 ± 0.005 ± 0.00004
18	-0.001 ± 0.01 ± 0.008	0.008 ± 0.096 ± 0.004	0.02 ± 0.004 ± 0.004
20	0.0106 ± 0.009 ± 0.015	0.029 ± 0.02 ± 0.007	0.027 ± 0.004 ± 0.007
30	-0.011 ± 0.009 ± 0.005	-0.008 ± 0.013 ± 0.005	0.001 ±0.004 ± 0.005