Study of Compensation Properties of the Forward Hadron Calorimeter at the BM@N Experiment

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Outline

1. Motivation. BM@N experiment. Importance of hadron calorimeter in high-energy physics. Role of compensation (e/h ratio) in energy measurements.

2. FHCal design at the BM@N.

3. Hadron shower. Electromagnetic and hadronic components. Physics of compensation.

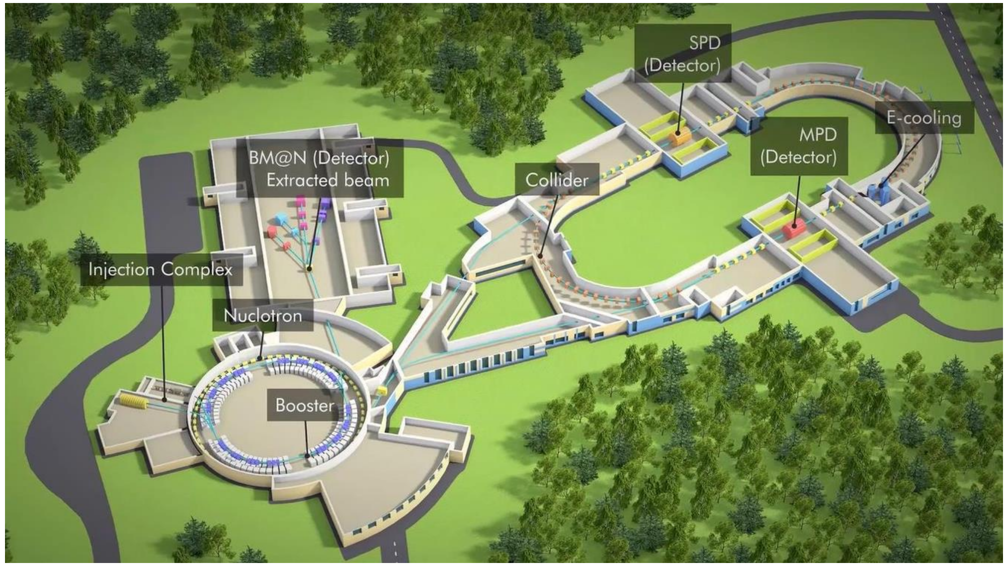
4. Estimation technique of the e/h ratio.

5. Method application to simulation data. Results.

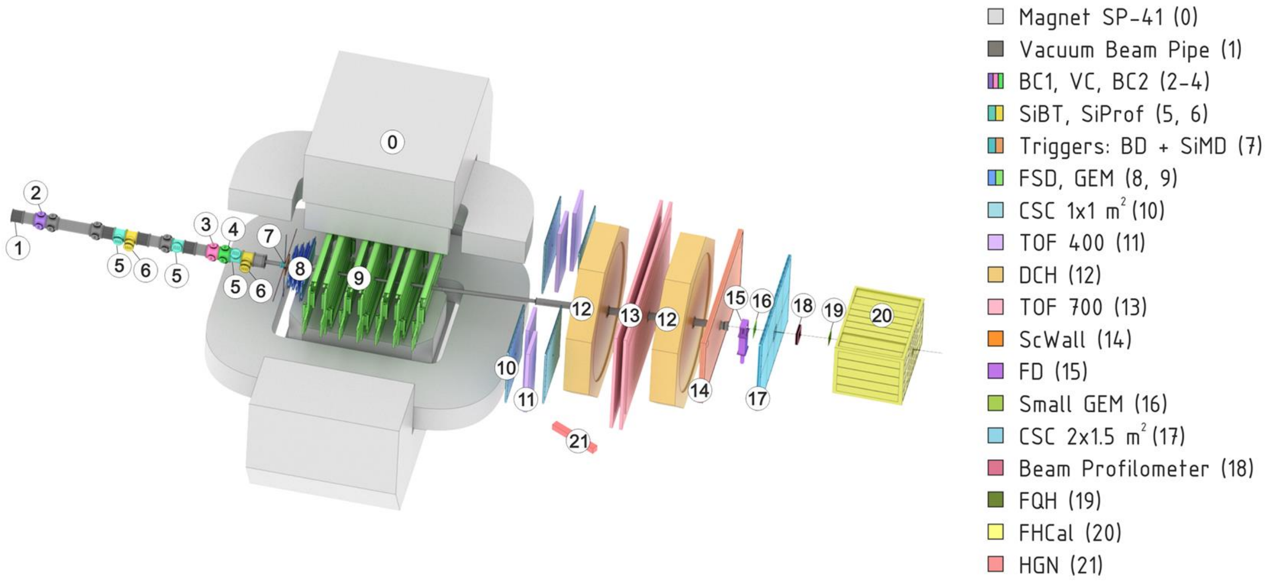
6. Summary and future plans.

Motivation

- The BM@N (Baryonic Matter at Nuclotron) is a fixed-target experiment at the NICA complex (JINR, Dubna). It aims to study heavy-ion collisions at energies up to 6A GeV for isospin symmetric nuclei, and 4.65A GeV for Au nuclei.
- The extreme densities (3-4 times nuclear saturation) achieved in these nuclear reactions are well suited to investigate the equation-of-state (EOS) and the QCD phase diagram.



(a) Schematic view of the Nuclotron/NICA complex and the position of the BM@N setup.

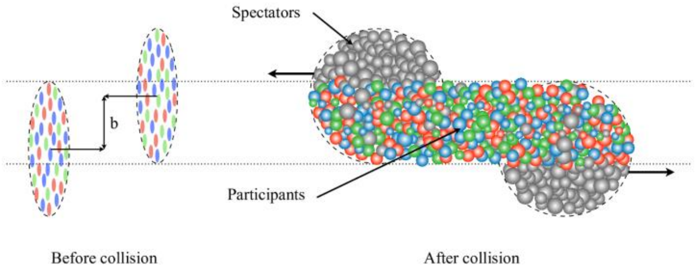


(b) Schematic view of the BM@N setup for the heavy ion program.

Motivation

- The Forward Hadron Calorimeter (FHCal) at the BM@N experiment is a compensated segmented calorimeter designed to measure heavy-ion collision centrality and reconstruct the reaction plane orientation.
- These measurements rely on the calorimeter's energy response to projectile spectators.

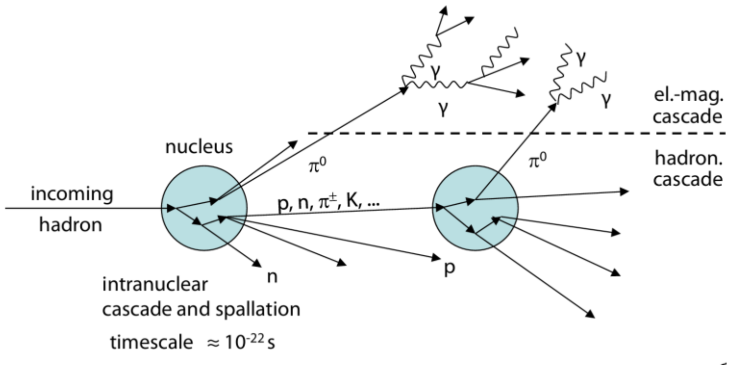
Energy measurements requirements: achieve the linearity of the response and the best possible energy resolution.



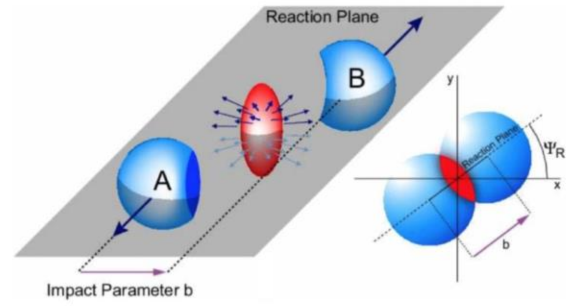
(a) Schematic illustration of centrality.

The precise value of the e.m. to hadronic signal ratio (e/h) is crucial for assessing its corresponding contribution to the systematic uncertainty of the measured.

- In case deviation from value of e/h=1 is found, the reconstruction algorithms will be accordingly optimized to improve the energy resolution.



(c) Schematic illustration of a hadron shower consisting e.m. and hadronic components.



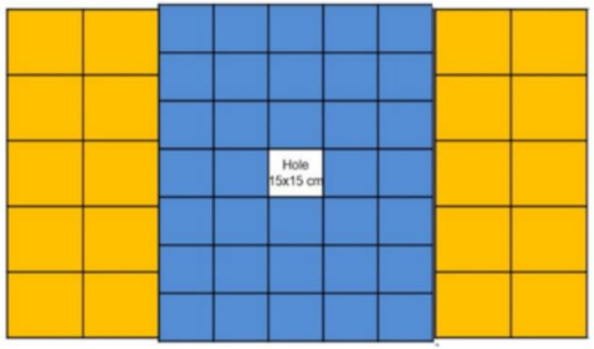
(b) Schematic illustration of the angle of the reaction plane.

Aim:

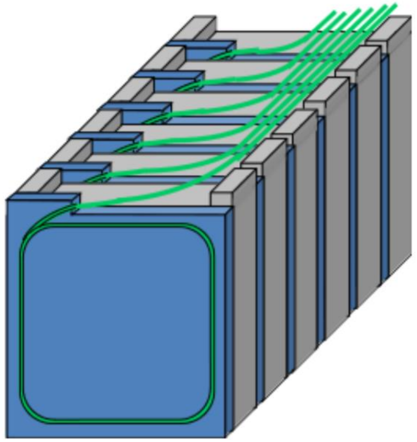
To quantitatively evaluate the compensation properties of the FHCal. Since the calorimeter's design is optimized for compensation at high energies, a dedicated investigation is required to characterize its performance in the energy range of 2-10 GeV.

FHCal Design at the BM@N

- FHCal consists of 54 modules of two types (with transverse size of 15 × 15 cm^2 and 20 x 20 cm^2).
- FHCal modules have sampling structure and consist of a set of lead and scintillator plates compressed together by a steel band.

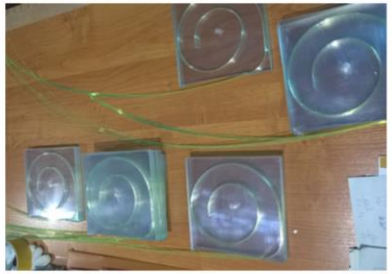


(a) Schematic illustration of the FHCal in the transverse plane.

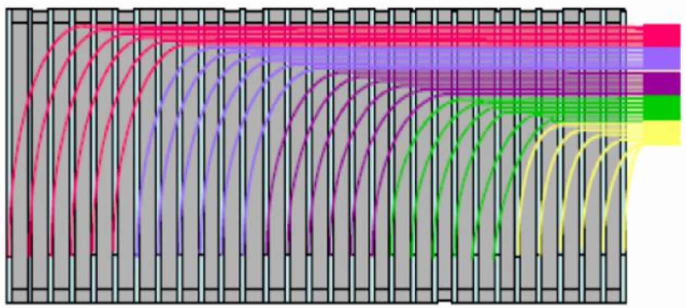


(b) Schematic illustration of the internal structure of an FHCal module.

- The lead absorber plates are 16 mm thick. The scintillator tiles are 4 mm thick polystyrene-based plastic scintillators.
- Light is collected by wavelength shifting optical fiber.



(c) Scintillator plates with WLS fiber in spiral grooves.

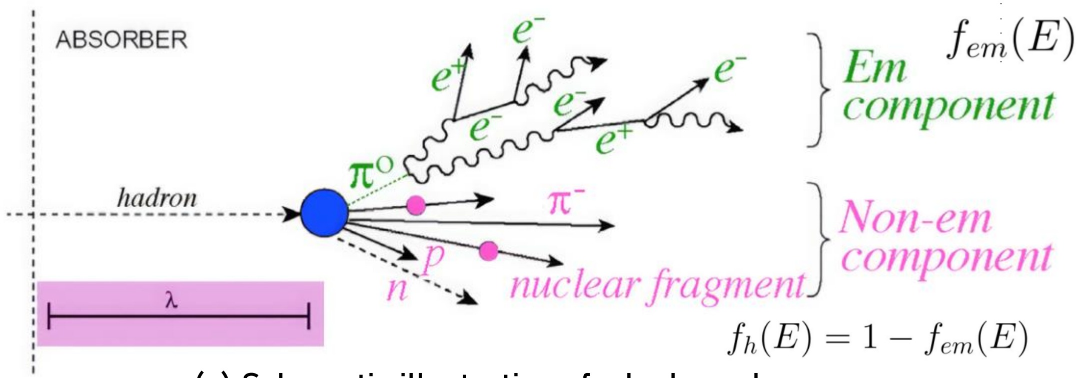


(d) Schematic illustration of the FHCal in the longitudinal plane.

- Every 6 consecutive scintillator tiles are combined into one section with one optical connector for a photodetector.

Hadron Shower

- The purely hadronic component is defined as containing all of the energy not carried by π^0, η's and photons from high-energy radiative processes.
- Some fraction of the energy deposited in the form of the hadronic component will disappear without contributing to the calorimeter signal.

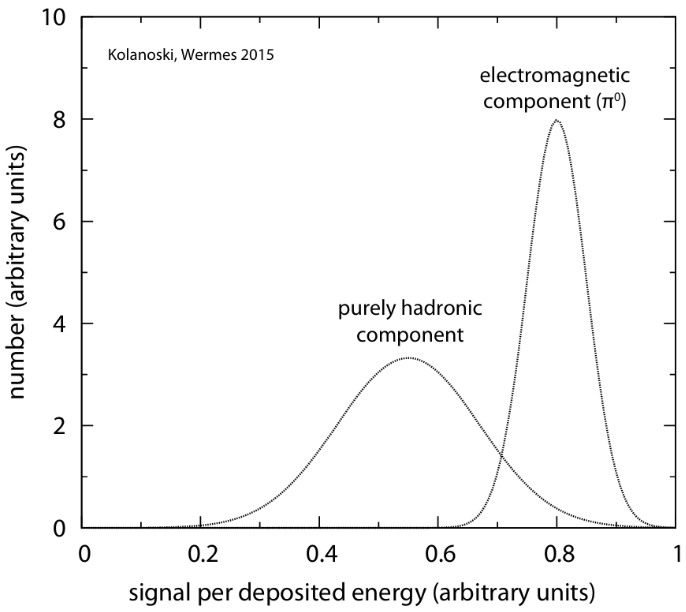


(a) Schematic illustration of a hadron shower.

This has two effects:

1. The calorimeter response to the purely hadronic part of a hadron shower will have a much broader distribution than the response to the e.m. component.

2. In general, the average response to the e.m. and the purely hadronic components will in general be different.



The Electromagnetic Fraction

- The fluctuations in f_{em} are significant and non-Gaussian.
- The mean value $\langle f_{em} \rangle$ increases with energy according to the power-law dependence[1]:

$$f_{\text{em}}(E) = 1 - \left(\frac{E}{E_0}\right)^{k-1}$$

Physically, k is related to the mean number of secondary particles and the mean energy fraction going into neutral mesons

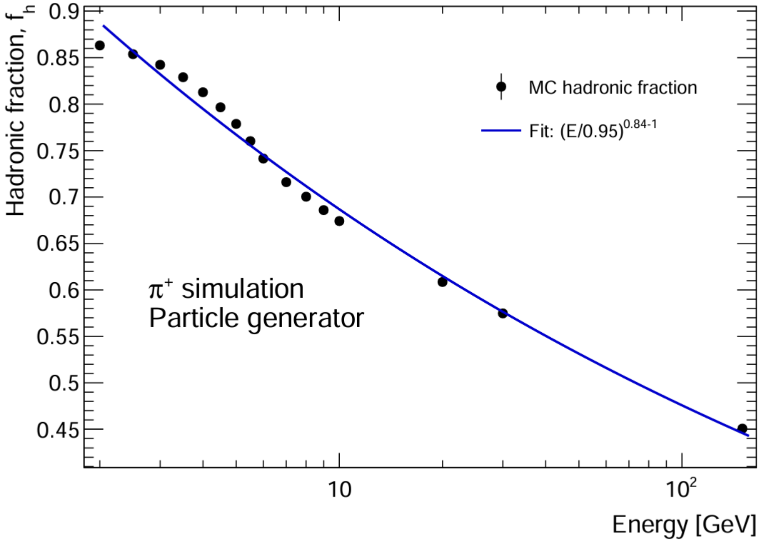
E_0 is the energy at which neutral mesons production becomes significant

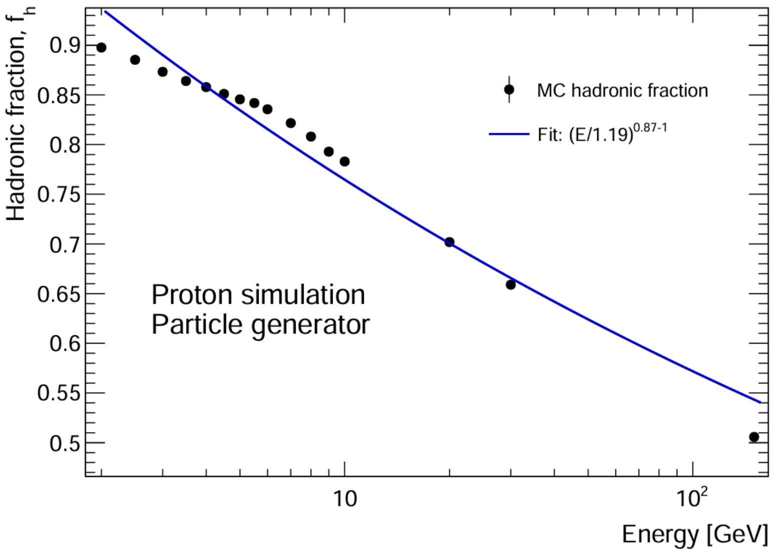
$$f_h(E) = 1 - f_{em}(E)$$

Consequence of the fact that $\langle f_{em} \rangle$ is energy-dependent is that the calorimeter signal for hadrons will not be directly proportional to the energy, unless e/h = 1.

$$R = e f_{em}(E)E + h(1 - f_{em}(E))E, \;\; e/h \neq 1$$

$$R = kE, \;\; e/h = 1$$





[1] T.A. Gabriel, D.E. Groom, Nucl. Instr. and Meth. A 338 (1994) 336.

Estimation Technique of the e/h Ratio

- The response of a calorimeter to a hadron-induced shower:

$$R_{\pi^+} = \underbrace{e f_{em}(E)E}_{R_{em}} + \underbrace{h(1 - f_{em}(E))E}_{R_h}$$

The characteristic of calorimeter to reconstruct an energy deposited in electromagnetic form (e)

The characteristic of calorimeter to reconstruct an energy related to the hadronic component (h)

Component separation algorithm:

1. The particles of the shower that have no daughters are selected;
2. Recursively trace back to mothers;
3. Photons, electrons and positrons produced by neutral mesons or photons are assigned to the electromagnetic component;
4. All other particles are recursively traced to the primary hadron and assigned to the hadronic component.

The e/h ratio is extracted from fit to the equation:

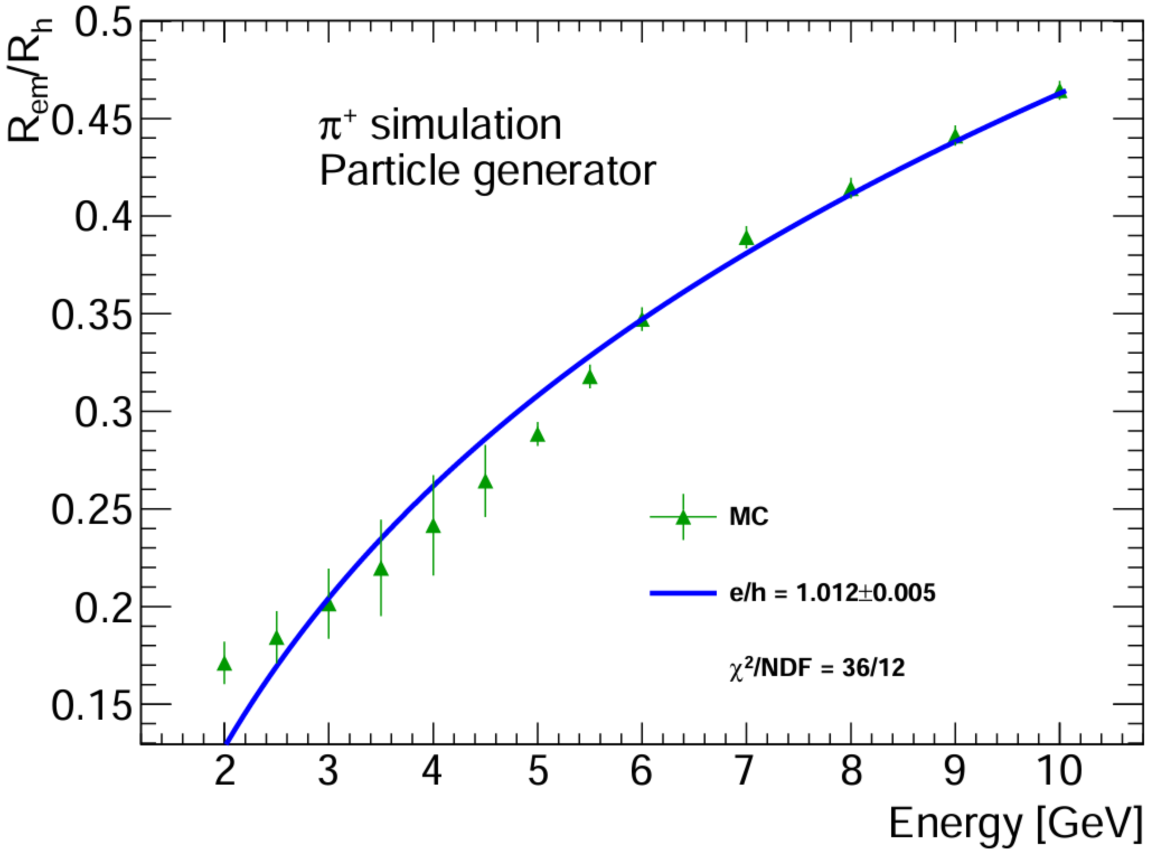
$$\frac{R_{em}}{R_h}(E) = \frac{e}{h} \cdot \frac{f_{em}(E)}{1 - f_{em}(E)}$$

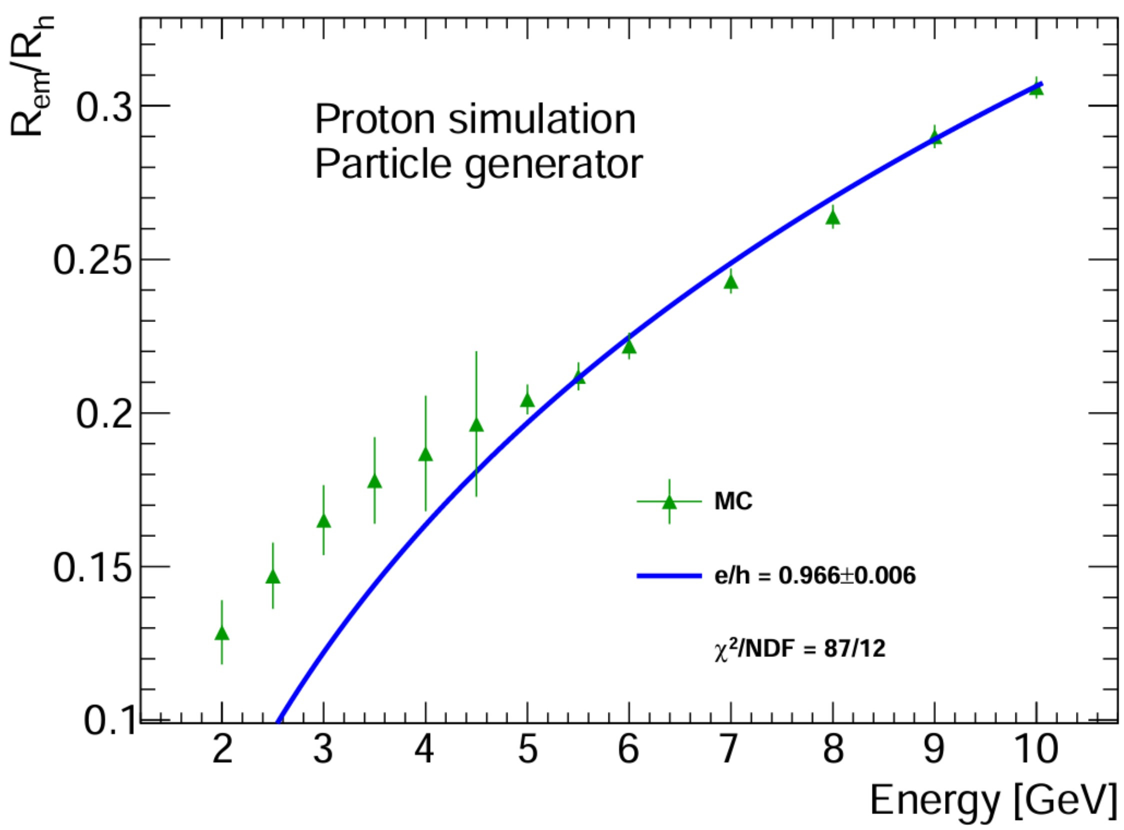
From MC samples

⇒ In case e/h≠1 the FHCal energy resolution could be improved through software compensation techniques

Method Application

- The proposed technique used real detector response produced by GEANT4 simulations of primary pions and protons (2-10 GeV). The FTFP_BERT physics list is used.
- The obtained value of the e/h ratio is equal to 1.012±0.005(stat.) for pions and 0.966±0.006(stat.) for protons.
- The deviation from e/h=1 is found to be 1.2% for pions and 3.4% for protons.





Summary and Future Plans

In this study, the compensation properties of the forward hadron calorimeter at the BM@N experiment were investigated.

- The proposed technique of separation electromagnetic and hadronic shower components in hadron-induced interactions was performed using MC-simulation.
- The deviation from e/h=1 is found to be 1.2% for pions and 3.4% for protons. The observed deviations are negligible. Nevertheless, the final estimates will be further refined after constraining the functional dependence of the electromagnetic fraction at low energies.

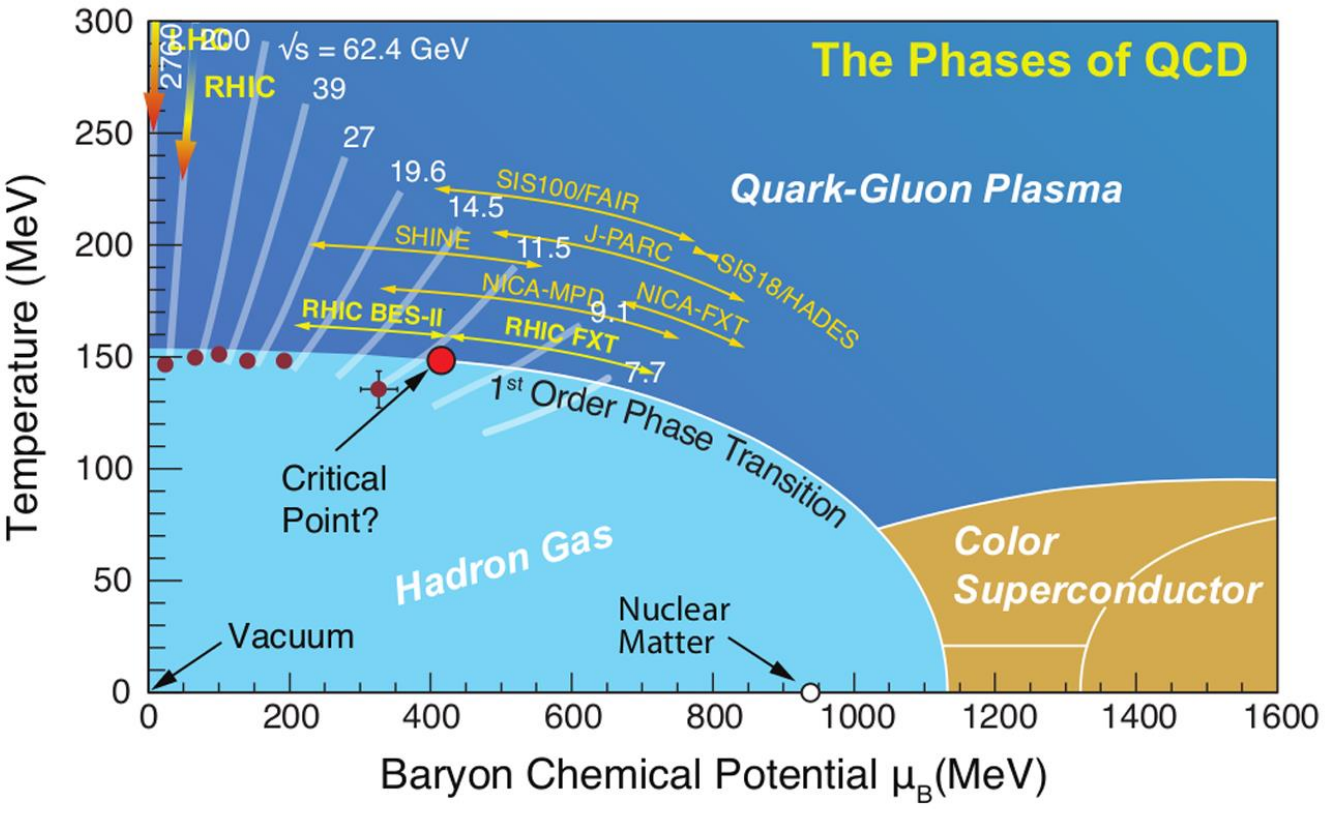
Future Plans:

1. The functional dependence of the electromagnetic fraction at low energies (below 6 GeV) requires refinements.
2. The systematic uncertainties will be studied in more detail.
3. The data-driven method of evaluation of e/h ratio will be investigated.

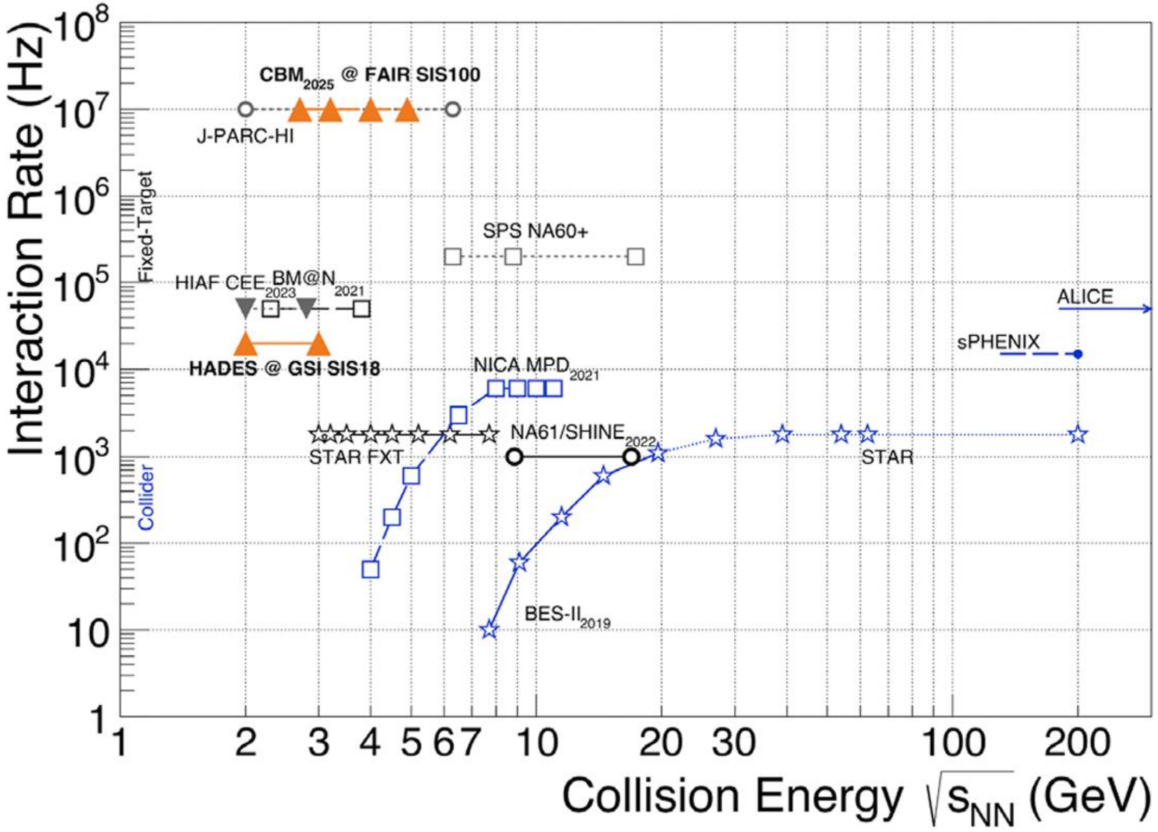
Thanks for your attention!

BACK-UP

The QCD Phase Space Diagram

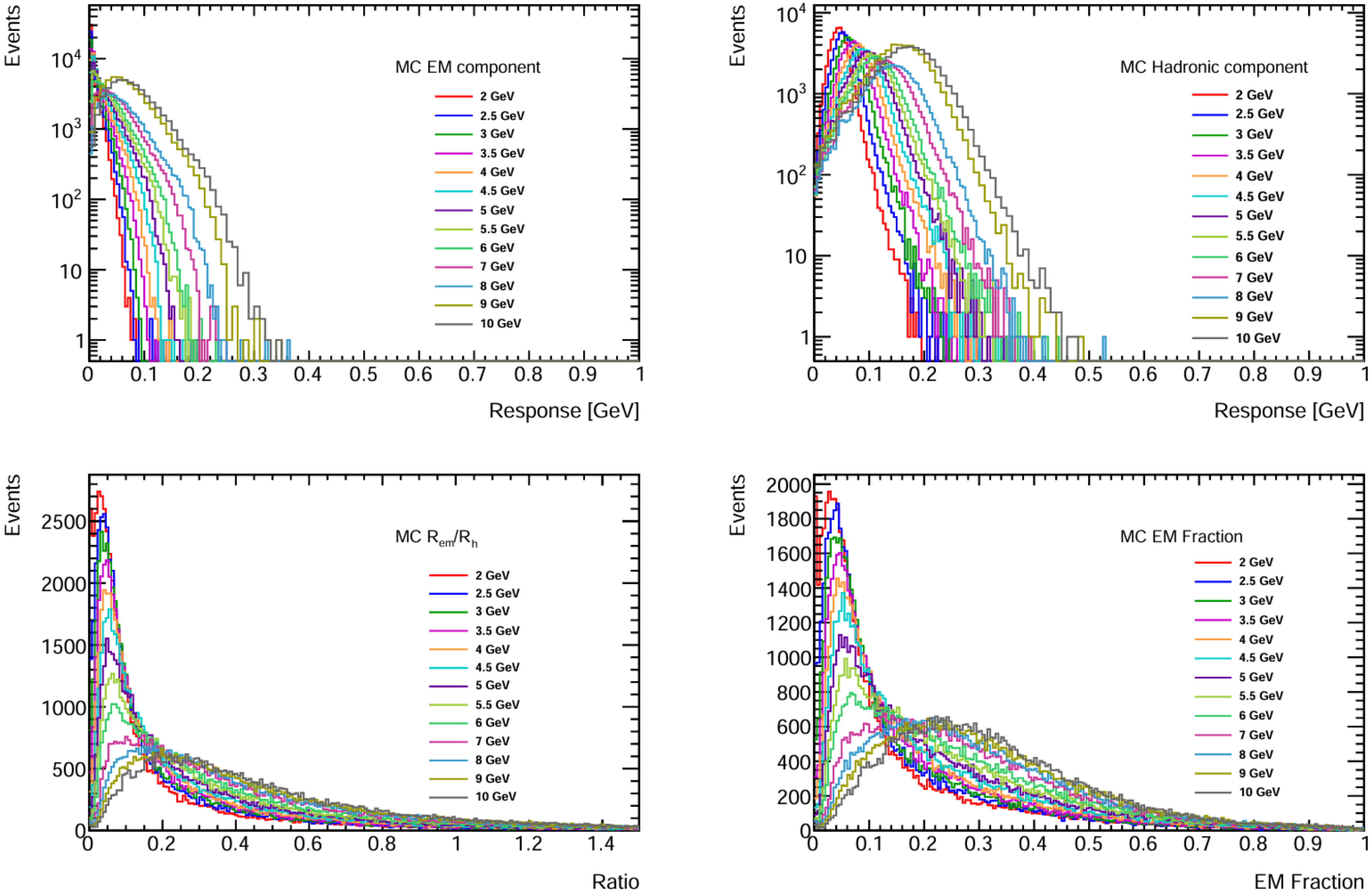


(a) The QCD phase diagram.

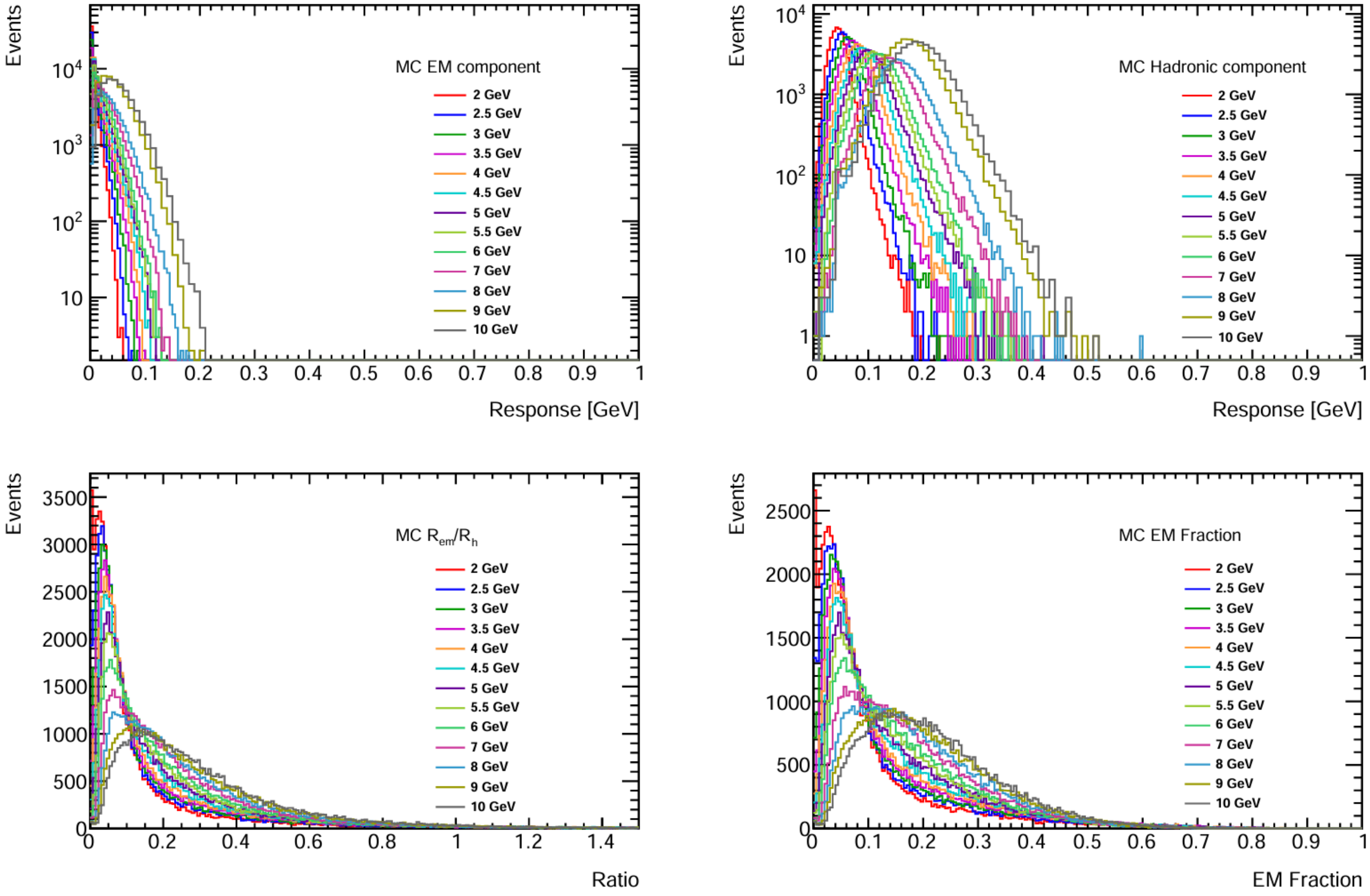


(b) Comparison of the rate capability of experiments.

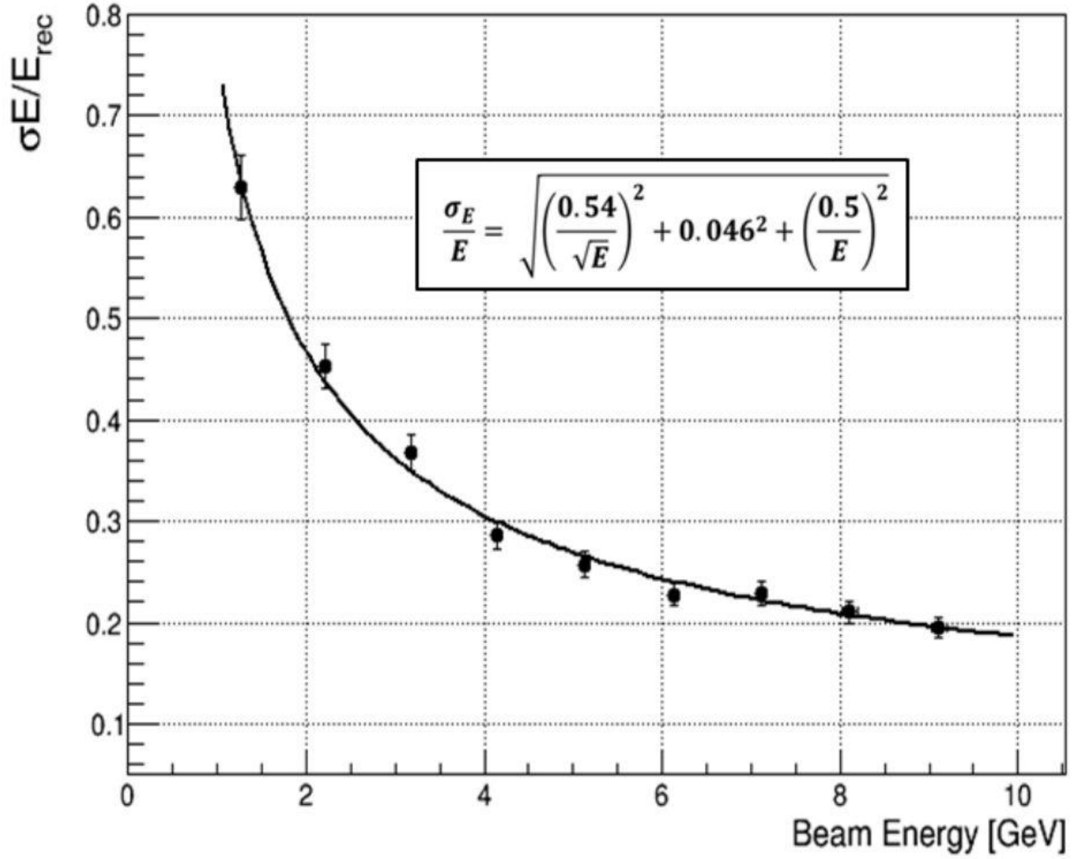
Pion Responses

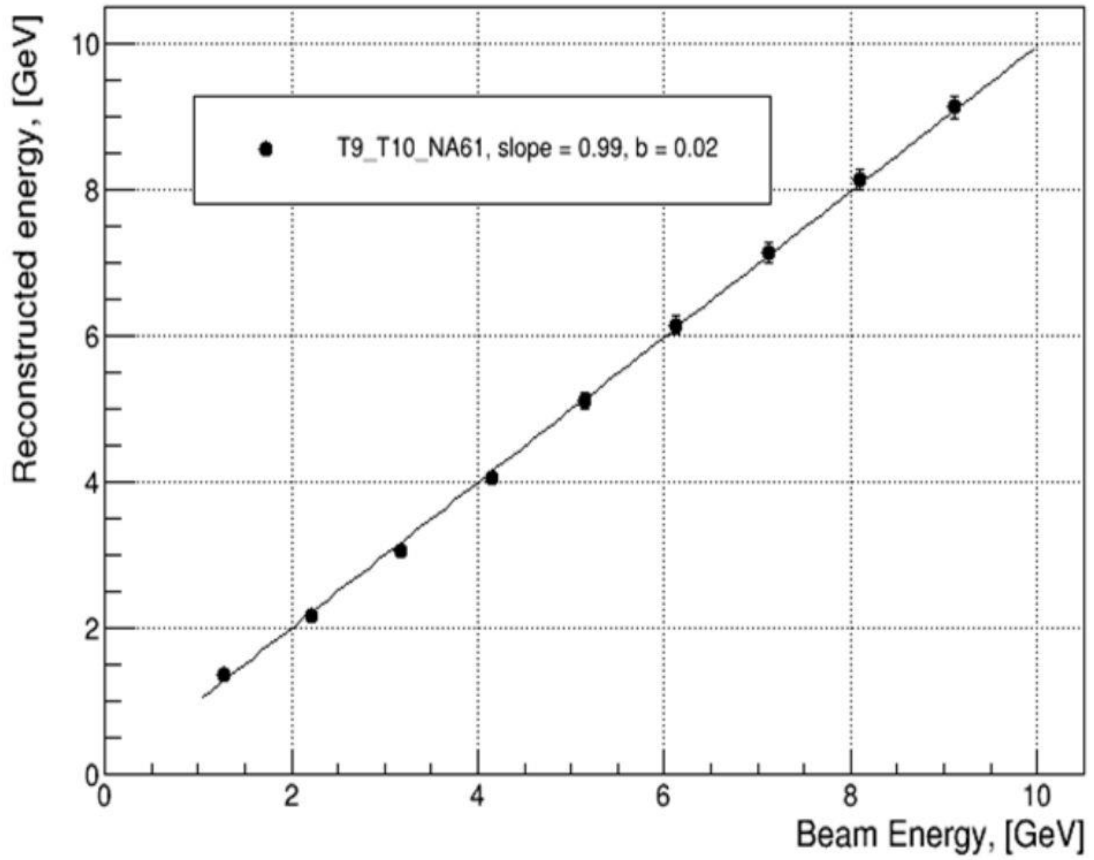


Proton Responses



Energy Resolution and Linearity of the Response





(a) Energy resolution measured for proton beams (left) and linearity of FHCal response (right).