JOINT INSTITUTE FOR NUCLEAR RESEARCH
Veksler and Baldin Laboratory of High Energy Physics

FINAL REPORT ON THE INTEREST PROGRAMME

Momentum-dependent corrections of the time-of-flight detector in the BM@N experiment

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Participation period:
March 03 – April 20, Wave 12

Dubna, 2025

Momentum-dependent Track Parameter Corrections in the TOF Detector for Light Mesons (Pions and Kaons)

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1 Introduction

This work presents a methodology for correcting track parameters in the Time-of-Flight (TOF) detector for light mesons (pions and kaons) based on the analysis of residuals as a function of particle momentum. The *residual* (ResX) is defined as the difference between the measured X-coordinate of a particle's track in the TOF detector and the expected coordinate determined from track reconstruction. The quantity ResX(P/Q) denotes the residuals in the X-coordinate as a function of the particle's momentum P divided by its charge Q. The primary focus is on constructing analytical dependencies of residuals on momentum.

2 Project Objectives

The aim of this study is to develop a method for correcting track parameters in the TOF detector by:

- Analyzing residuals as a function of momentum.
- Constructing analytical dependencies for the width and center of residual distributions as a function of momentum.

3 Methods

3.1 Slicing Residuals by Momentum

To analyze residuals, a two-dimensional histogram of residuals (ResX) versus momentum P/Q was used. The histogram was sliced into momentum bins with a step of 0.5 GeV/c using ROOT classes (e.g., `TH2::Projection`). This approach yielded one-dimensional histograms for each momentum range.

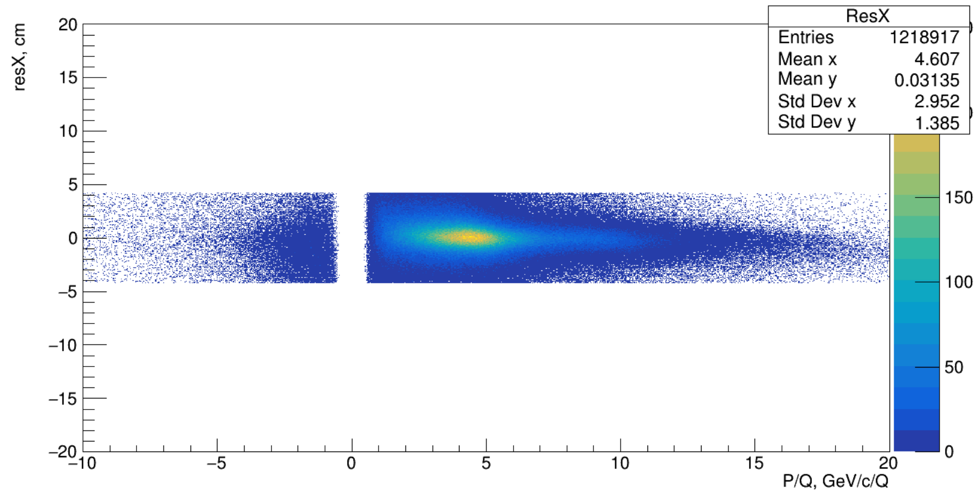


Figure 1: Two-dimensional histogram of residuals ResX versus momentum P/Q

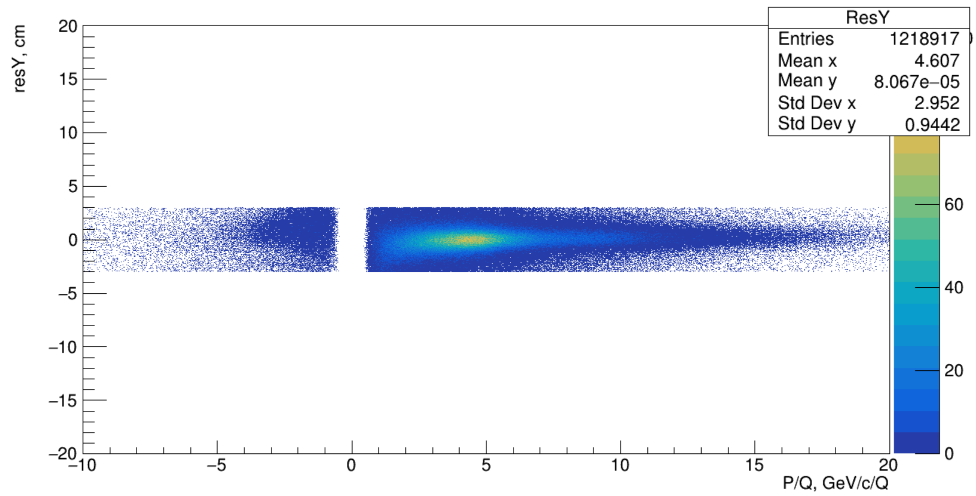
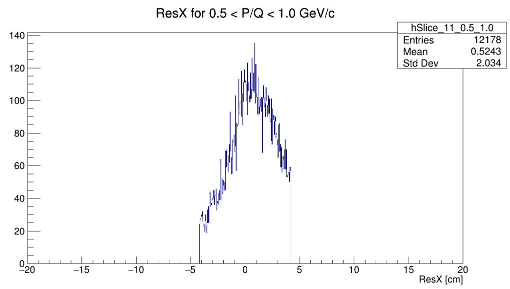


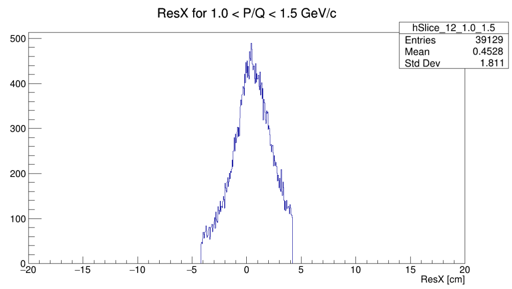
Figure 2: Two-dimensional histogram of residuals ResY versus momentum P/Q

3.2 Obtaining One-Dimensional Histograms

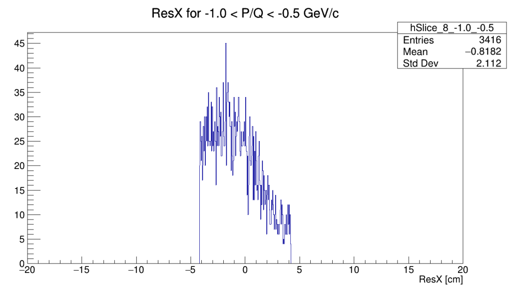
Each momentum slice was converted into a one-dimensional histogram of residuals, which exhibited a distribution close to Gaussian. These distributions varied in width and center depending on the momentum.



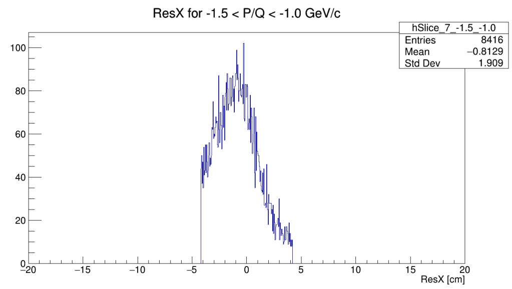
(a) Slice for $0.5 < P/Q < 1.0$ GeV/c



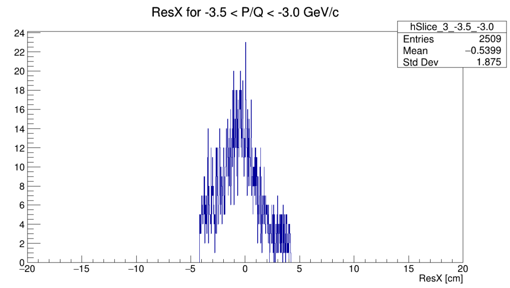
(b) Slice for $1.0 < P/Q < 1.5$ GeV/c



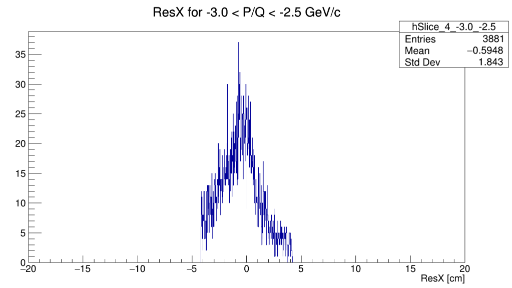
(c) Slice for $-1.0 < P/Q < -0.5$ GeV/c



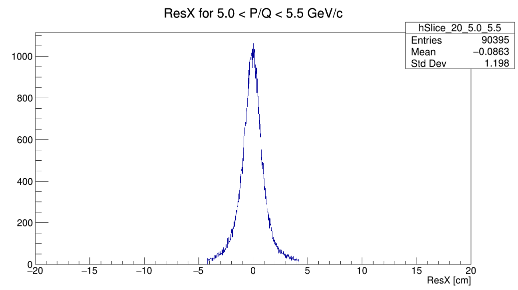
(d) Slice for $-1.5 < P/Q < -1.0$ GeV/c



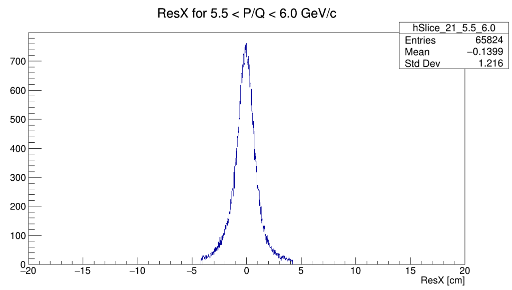
(e) Slice for $-3.5 < P/Q < -3.0$ GeV/c



(f) Slice for $-3.0 < P/Q < -2.5$ GeV/c



(g) Slice for $5.0 < P/Q < 5.5$ GeV/c



(h) Slice for $5.5 < P/Q < 6.0$ GeV/c

Figure 3: Examples of one-dimensional histograms of residuals for various momentum ranges

3.3 Fitting Distributions

Each one-dimensional histogram was fitted with a Gaussian function:

$$f(x) = A \cdot \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right),$$

where A is the amplitude, μ is the distribution center (in cm), and σ is the width (in cm). The parameters μ and σ were extracted for each momentum slice.

For negative momentum values ($P/Q < 0$), significant noise was observed in the histograms, likely due to low statistics, outliers, or systematic effects in track reconstruction. This noise led to an increase in the width σ at large absolute momentum values. To minimize the impact of noise and obtain robust fit parameters, the tails of the Gaussian distribution were trimmed. The fitting range was determined as follows:

- The mean (mean) and root-mean-square deviation (RMS) were calculated for each histogram.
- The fitting range was limited to the interval from mean − range to mean + range, where range = $\min(2.0, 2 \cdot \text{RMS})$ (in cm).

An example of the trimming and fitting procedure in ROOT is shown below:

```
Double_t mean = hSlice->GetMean();
Double_t range = std::min(2.0, 2 * hSlice->GetRMS());
Double_t xMin = mean - range;
Double_t xMax = mean + range;

TF1* fGaussOnly = new TF1("fGaussOnly", "gaus", xMin, xMax);
fGaussOnly->SetParameters(hSlice->GetMaximum(), hSlice->GetMean()
    , hSlice->GetRMS());
hSlice->Fit(fGaussOnly, "RQ");
```

Trimming the tails eliminated the influence of anomalous events, preserving the main part of the Gaussian distribution, which ensured more accurate determination of the parameters μ and σ.

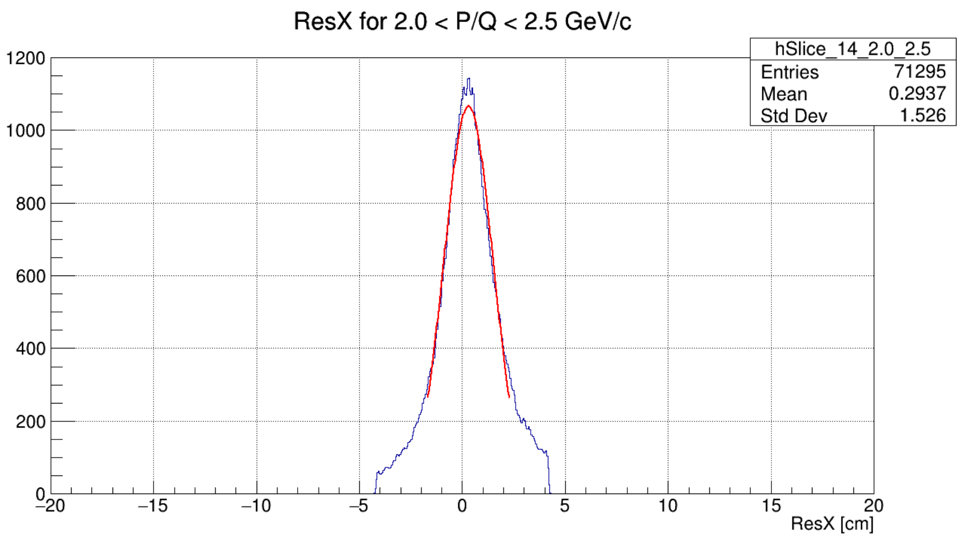
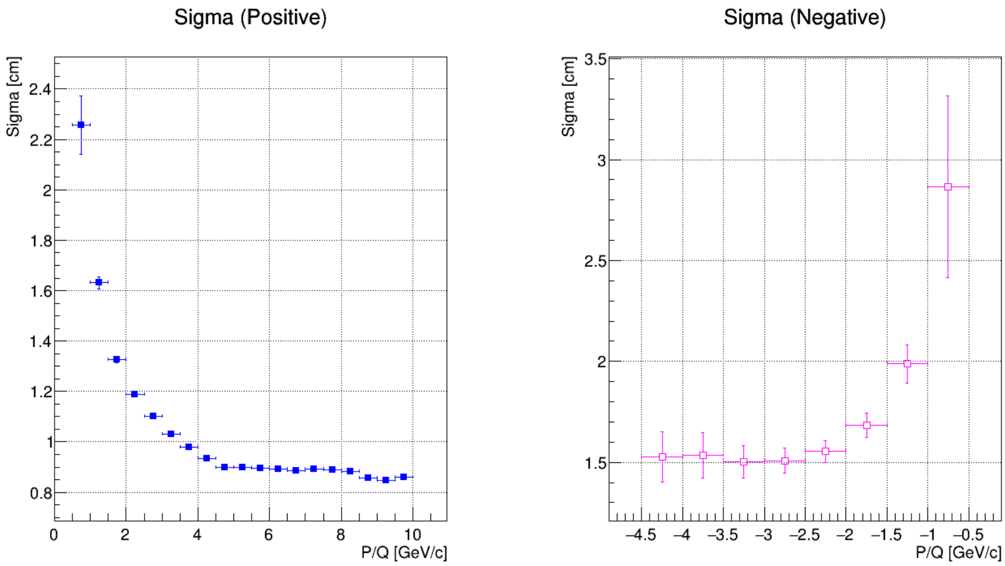


Figure 4: Example of fitting a one-dimensional histogram with a Gaussian function

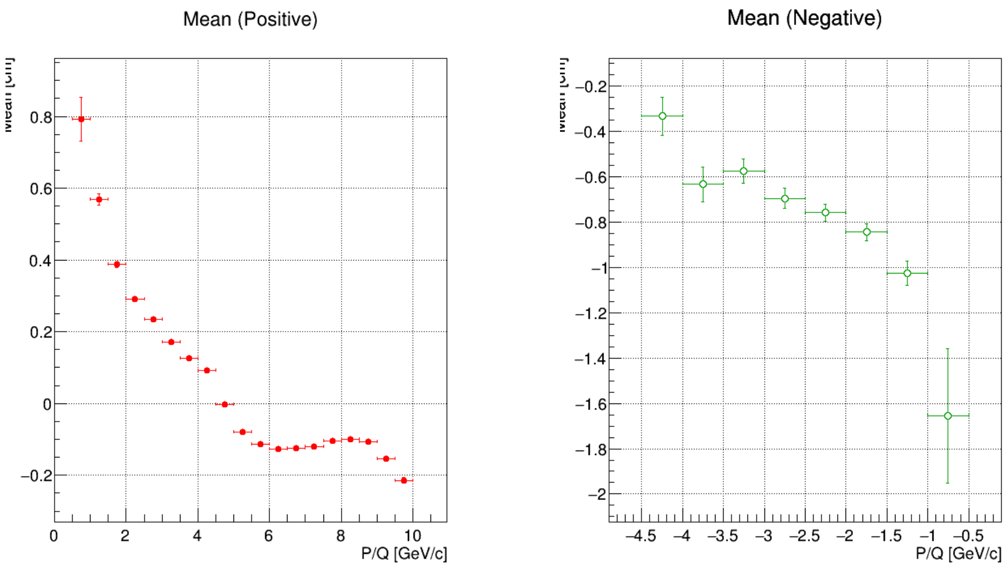
3.4 Constructing Dependencies

Based on the extracted parameters μ and σ, dependencies of the distribution width and center on momentum P/Q were constructed. Due to differences in the behavior of distributions for positive ($P/Q > 0$) and negative ($P/Q < 0$) momenta, caused in particular by noise at negative momenta, these cases were considered separately. This approach allowed for a more accurate description of the momentum's influence on residuals and identification of possible systematic effects.



(a) For $P/Q > 0$ (b) For $P/Q < 0$

Figure 5: Dependence of the width σ (in cm) on momentum P/Q (in GeV/c) for positive and negative momenta



(a) For $P/Q > 0$ (b) For $P/Q < 0$

Figure 6: Dependence of the center μ (in cm) on momentum P/Q (in GeV/c) for positive and negative momenta

3.5 Fitting Dependencies

The obtained dependencies $\sigma(P/Q)$ and $\mu(P/Q)$ were fitted with various functions to achieve the best agreement with the data, particularly in the region of low absolute momentum ($|P/Q| \approx 0$).

For the center dependence $\mu(P/Q)$, an exponential function with a linear term was used:

$$f_\mu(p) = a + b \cdot \exp(-c \cdot p) + d \cdot p,$$

where a, b, c, and d are fit parameters, and p is the momentum P/Q in GeV/c. The linear term $d \cdot p$ accounts for possible linear shifts in the distribution center with changing momentum.

For the width dependence $\sigma(P/Q)$, a linear combination of exponentials was applied:

$$f_\sigma(p) = a + b \cdot \exp(-c \cdot p) + e \cdot \exp(-f \cdot p),$$

where a, b, c, e, and f are fit parameters. This functional form provides a more accurate description of the complex behavior of the distribution width, especially near low absolute momenta, where residuals exhibit non-monotonic behavior.

The choice of these functions is justified by their ability to accurately describe the behavior of residuals in the low-momentum region, where significant changes in σ and μ are observed, caused, in particular, by noise and systematic effects. The resulting analytical expressions were used to correct track parameters in the TOF detector.

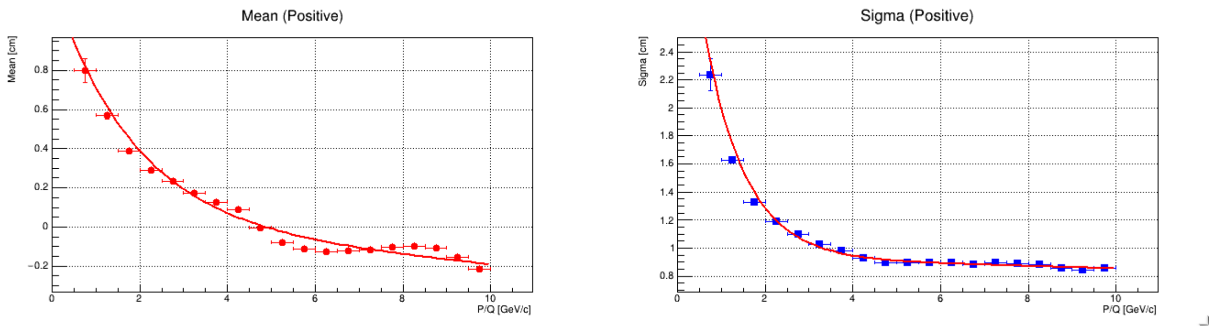


Figure 7: Fitting of $\mu(P/Q)$ for ResX

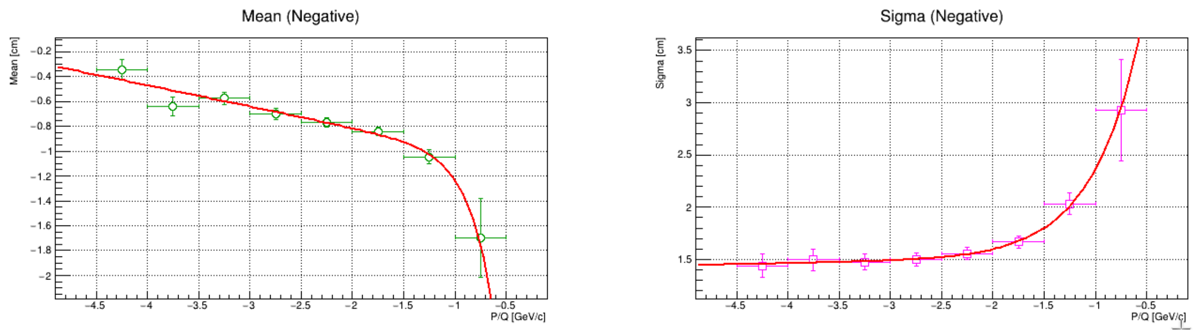


Figure 8: Fitting of $\sigma(P/Q)$ for ResX

Figure 9: Fitting of the dependencies $\mu(P/Q)$ and $\sigma(P/Q)$ for positive and negative momenta (ResX)

A similar approach was applied to analyze residuals in the Y-coordinate (ResY). Two-dimensional histograms of ResY versus momentum P/Q were sliced into bins, and one-dimensional histograms were constructed for each bin and fitted with a Gaussian function.

Based on the fit parameters (μ and σ), the dependencies $\mu(P/Q)$ and $\sigma(P/Q)$ for ResY were obtained, which were also fitted with exponential functions with a linear term for $\mu(P/Q)$ and a linear combination of exponentials for $\sigma(P/Q)$. These dependencies, shown in Figures 10, 11, exhibit behavior similar to that of ResX, confirming the applicability of the developed method to both coordinates.

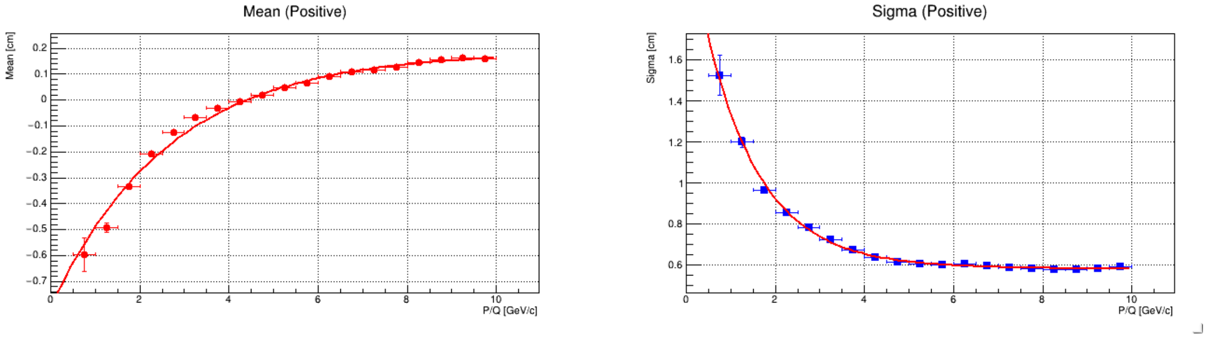


Figure 10: Fitting of $\mu(P/Q)$ for ResY

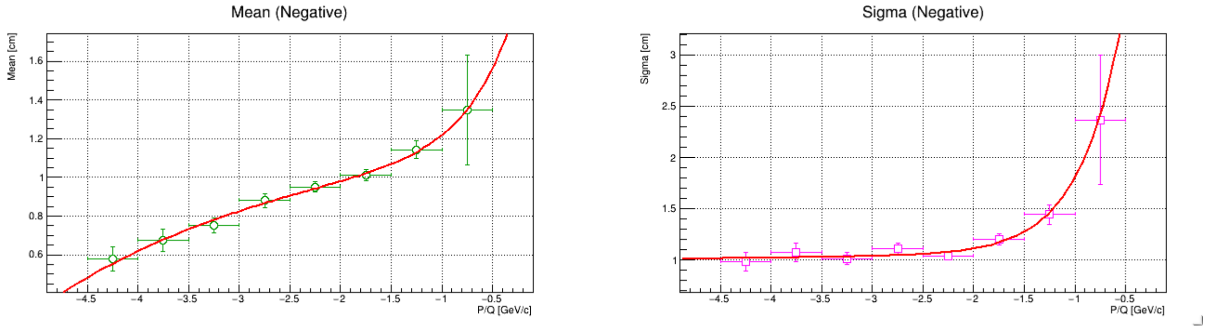


Figure 11: Fitting of $\sigma(P/Q)$ for ResY

Figure 12: Fitting of the dependencies $\mu(P/Q)$ and $\sigma(P/Q)$ for positive and negative momenta (ResY)

4 Results

The analysis yielded the following results:

- One-dimensional histograms of residuals for each momentum slice.
- Dependencies of the width σ and center μ on momentum P/Q, separated for positive and negative momenta.
- Analytical expressions for residual corrections based on fitting with an exponential function with a linear term for $\mu(P/Q)$ and a linear combination of exponentials for $\sigma(P/Q)$.

5 Discussion

The obtained dependencies enable the correction of track parameters in the TOF detector, accounting for particle momentum. Separate consideration of positive and negative momenta revealed differences in residual behavior, possibly related to noise or systematic effects. The use of an exponential function with a linear term for $\mu(P/Q)$ and a linear combination of exponentials for $\sigma(P/Q)$ ensured high accuracy in the approximation, particularly in the low-momentum region. Potential limitations of the method include:

- The influence of background on the accuracy of histogram fitting.
- Limited statistics in some momentum ranges, especially for $P/Q < 0$.
- The need to verify the applicability of the chosen functions across all momentum ranges.

6 Conclusion

The developed method enables effective correction of track parameters in the TOF detector for light mesons. Analytical dependencies of residuals on momentum, constructed separately for positive and negative momenta using an exponential function with a linear term and a linear combination of exponentials, can be used to improve the accuracy of measurements in the BM@N experiment. Further optimization of the method is recommended, taking into account background effects and additional momentum ranges.
This analysis was performed for the entire TOF detector, which allowed obtaining generalized dependencies of residuals on momentum. In the future, it is planned to conduct a similar analysis for individual modules of the TOF detector to account for possible local features and enhance the accuracy of track parameter corrections.

7 Acknowledgments

I express my gratitude to Dr. Sergei Merts and Dr. Sergey Nemnyugin for their valuable guidance and support throughout the project.

8 References

1. ROOT User's Guide. CERN, 2023.