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

FINAL REPORT ON THE START PROGRAMME

Study of the characteristics of phi-mesons produced in pp interactions at 10 GeV at the SPD NICA facility

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Abstract

In this practice, using Monte Carlo simulated data, the invariant mass spectrum of phi-mesons (decaying into K^+K^-) is restored. Histograms of various physical quantities characterizing the production of a phi-meson are constructed and analyzed. The invariant mass spectrum is described by the Voigt distribution and parameters are fitted.

Contents

1   Introduction

The phi-meson (ϕ-meson) is an elementary particle composed of a strange quark s and its antiquark $\bar{s}$. Detecting mesons has significant importance for advancing our understanding of the fundamental nature of matter and its behaviour under extreme conditions. Additionally, mesons can also be utilized in technical tasks, such as calculating the purity and contamination levels of charged hadrons following Particle Identification (PID). It is also necessary for debugging hardware, checking the operation of software. And at the same time, it is of interest as a physical problem, for example, for studying threshold production or processes with high multiplicity.

The Spin Physics Detector (SPD) collaboration proposes to install a universal detector in the second interaction points of the Nuclotron-based Ion Collider fAcility (NICA) that is under construction at the Joint Institute for Nuclear Research (Dubna) to study the spin structure of the proton and deuteron and the other spin-related phenomena with polarized proton and deuteron beams at a collision energy up to 27 GeV and luminosity up to $1032cm^{-2}s^{-1}$.

In the polarized proton-proton collisions, the SPD experiment at NICA will cover the kinematic gap between the low-energy measurements at ANKE-COSY and SATURNE and the high-energy measurements at the Relativistic Heavy Ion Collider, as well as the planned fixed-target experiments at the LHC.

2   Invariant mass calculating

With the SPD, we can detect mesons through their decay into pair oppositely charged K-mesons: $\phi \to K^+ K^-$.

We use datasets of unpolarized proton-proton (pp) collisions at 10 GeV Monte Carlo simulations generated using the production system provided by the MLIT JINR team. The number of events is 129,496,297.
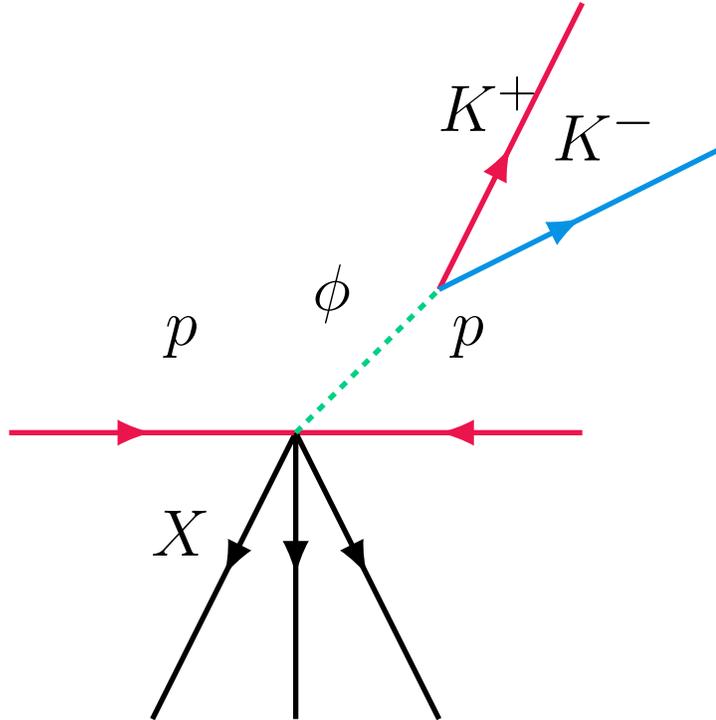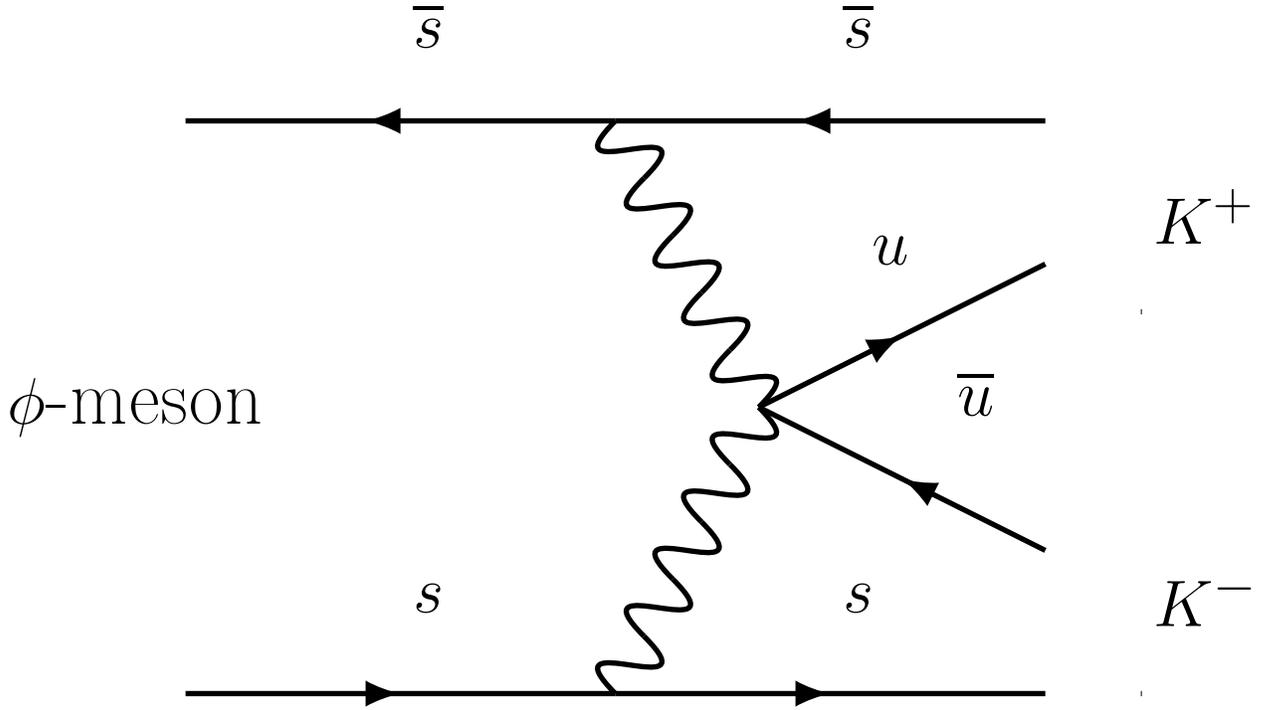
Figure 1: pp-collision scheme

Figure 2: Quark diagram decay $\phi \to K^+ K^-$

Fig. 1 shows the production and decay of a phi-meson. But the decay length is too short, so we can assume that the decay occurs from the primary vertex.

It is necessary to analyze all possible pairs of oppositely charged tracks and calculate them invariant masses.

$$E_K = \sqrt{m_K^2 + \vec{p}_K^2} \tag{1}$$

$$M_{inv}^2 = (E_{K^+} + E_{K^-})^2 - (\vec{p}_{K^+} + \vec{p}_{K^-})^2 \tag{2}$$

For physical reasons it is necessary take into account some event restrictions:

- K-mesons identification

- limit on the number of hits

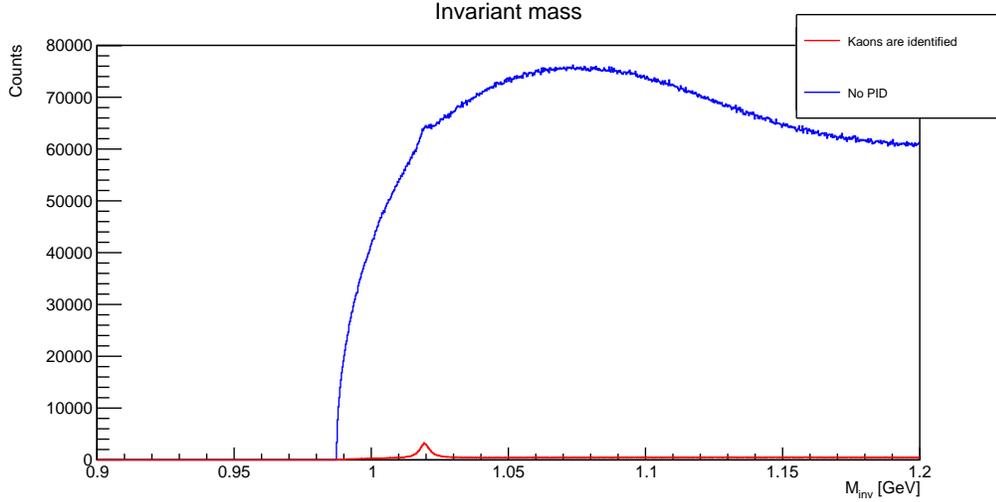- momentum limit

- detector dimensions

Figure 3: Invariant mass distribution

Invariant mass distribution in the absence of identification of both kaons does not allow the signal to be reconstructed. The reconstruction of the spectrum of invariant masses with one identified kaon is also insufficient, since the signal is weak relative to the background. The graph (fig. 3) shows how important it is to exclude from consideration all particles except kaons ($PDG = \pm 321$).

It is also necessary to set a limit on the number of hits in the Straw-tracker (≥ 16) and in the Micromegas-based Central Tracker (≥ 1).
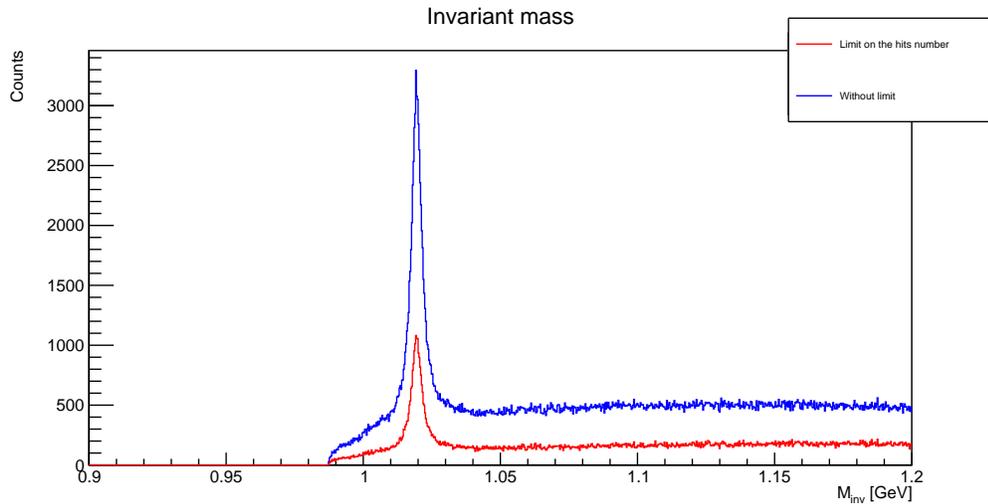
Figure 4: Invariant mass distribution

With the STRAW detector, it is possible to identify hadrons with momenta of up to a maximum of 1 GeV/c.

Similarly, taking into account the momentum constraint: from 150 MeV/c to 1 GeV/c, and the detector dimensions: $-45cm < z < 45cm$, $\sqrt{x^2 + y^2} = r < 5cm$, we obtain the final distribution of the invariant mass.
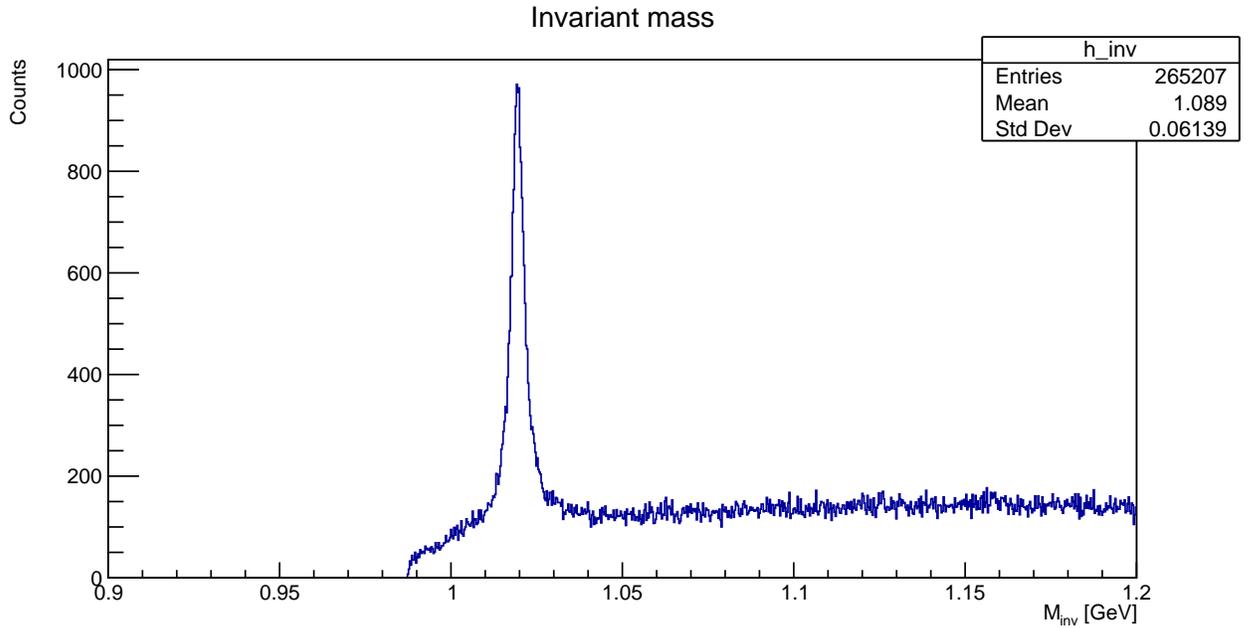
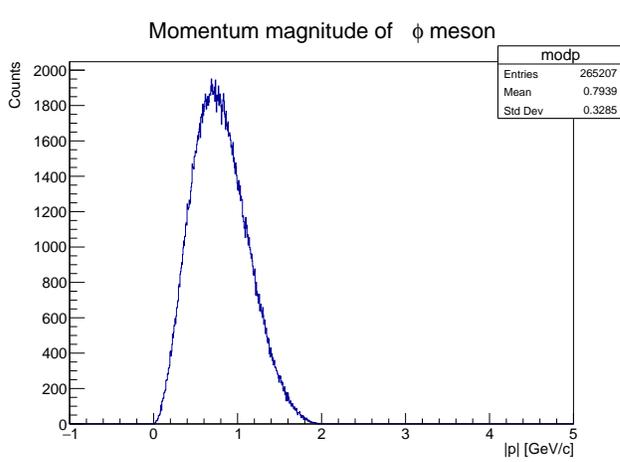

Figure 5: Final invariant mass distribution
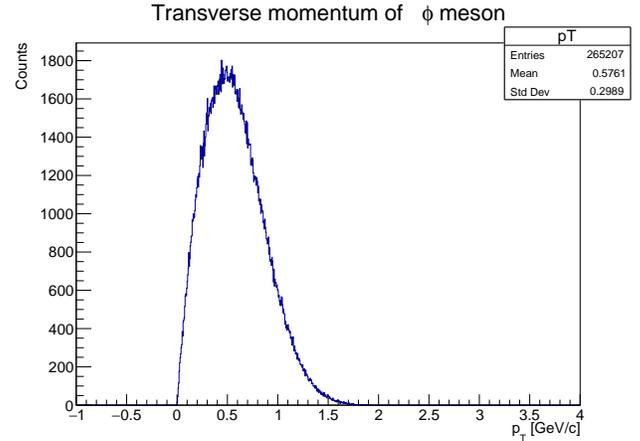

Figure 6: Momentum distribution

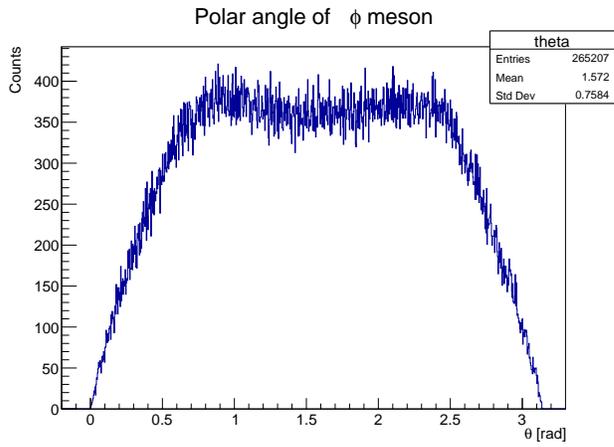Figure 7: Transverse momentum distribution

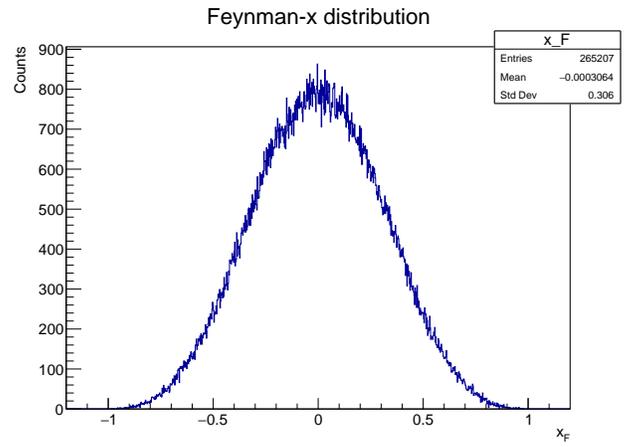Figure 8: Theta distribution
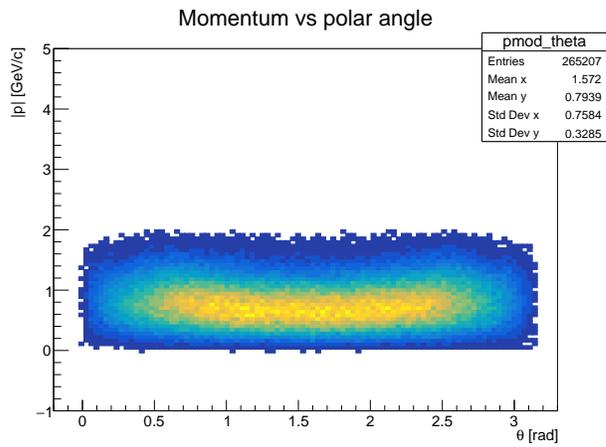

Figure 9: Feynman-x distribution
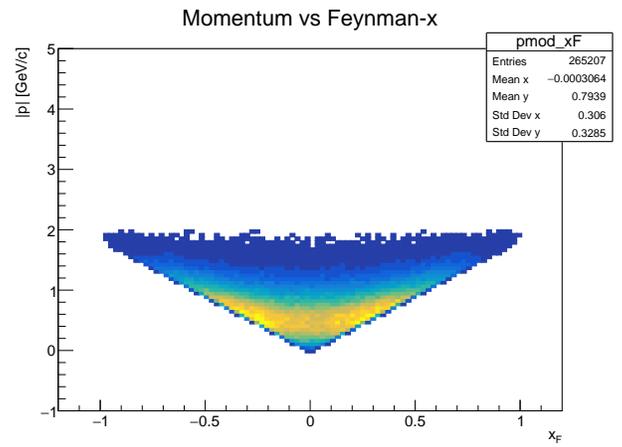

Figure 10: Momentum vs theta
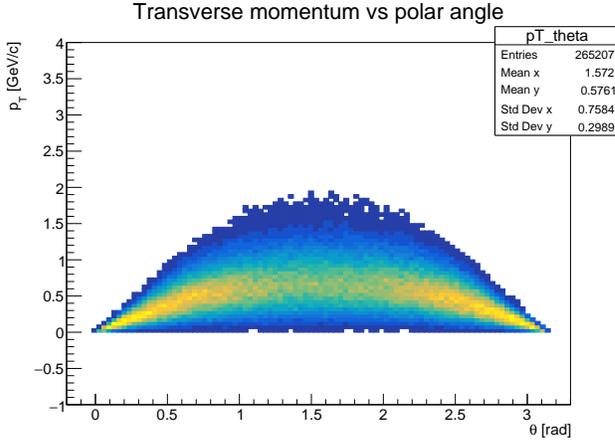

Figure 11: Momentum vs Feynman-x
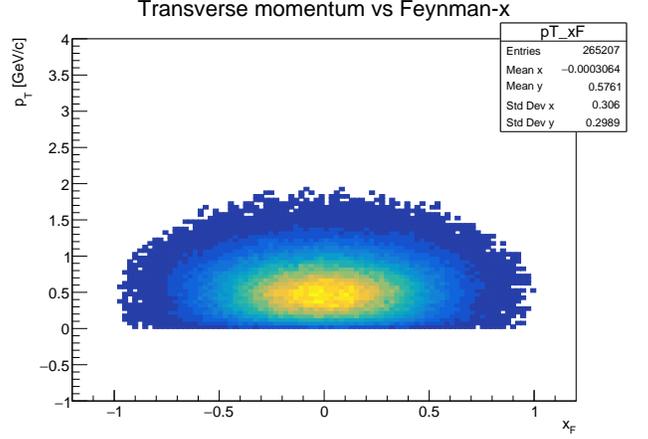
Figure 12: Transverse momentum vs theta

Figure 13: Transverse momentum vs Feynman-x

3   Fitting

The invariant mass spectrum (Fig. 5) is usually described by the Breit-Wigner function and, more precisely, by the Voigt distribution. The Voigt function is convolution of a Breit-Wigner (Lorentz) distribution:

$$L(m, \Gamma) = \frac{1}{2\pi} \frac{\Gamma}{m^2 + \frac{\Gamma^2}{4}} \tag{3}$$

and a Gaussian distribution:

$$G(m, \sigma) = \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{-m^2}{2\sigma^2}} \tag{4}$$

The parameter Γ characterizes the peak width, and σ characterizes the influence of the pulse resolution of the experimental setup.

$$V(m, M, \Gamma, \sigma, k_0) = k_0 \int \frac{1}{2\pi} \frac{\Gamma}{(m-M)^2 + \frac{\Gamma^2}{4}} \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{-(m-M-m')^2}{2\sigma^2}} dm' \tag{5}$$

Also are added the shift to the point M - parameter denoting the mass of the ϕ-meson and the factor k_0 in front of the whole expression.

Thus, we describe the peak with function 5, and the background with a third-degree polynomial, which means we have 8 parameters in total: $M, \Gamma, \sigma, k_0, a_0, a_1, a_2, a_3$.
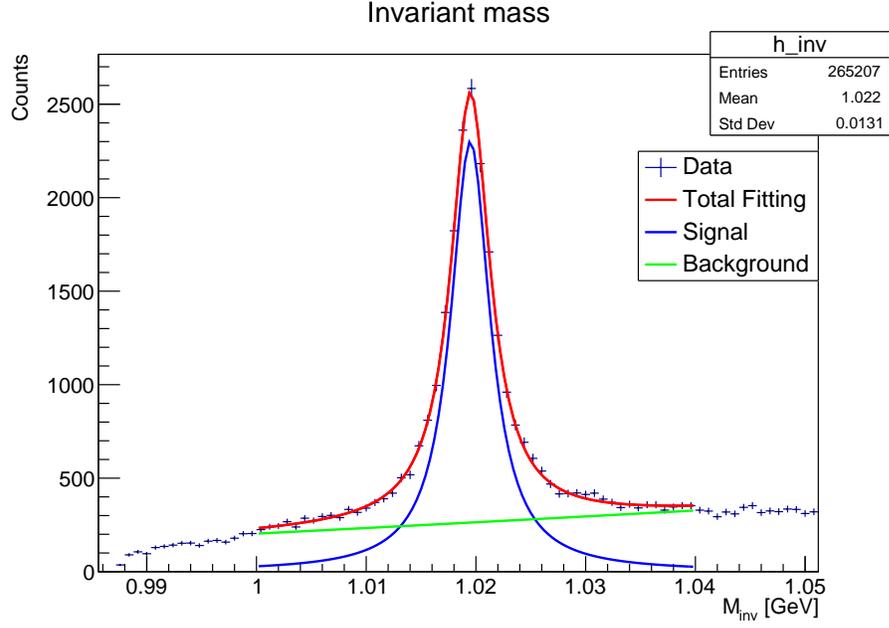
Figure 14: Fitting results

Figure 15: Fitting results

The approximate number of ϕ-mesons produced, obtained by integrating under the peak, is 18414.5 ± 227.2. The error was calculated as follows:

$$\Delta = \sqrt{\left(\frac{\partial I}{\partial M}\right)^2 \delta_M^2 + \left(\frac{\partial I}{\partial \Gamma}\right)^2 \delta_\Gamma^2 + \left(\frac{\partial I}{\partial \sigma}\right)^2 \delta_\sigma^2 + \left(\frac{\partial I}{\partial k_0}\right)^2 \delta_{k_0}^2} \qquad (6)$$

4 Conclusion

The distribution of the invariant mass of the ϕ-meson is ideally described by the Breit-Wigner function. The Voigt function is used to describe the distribution of the invariant masses of resonances reconstructed in the experiment with a comparable effect of the momentum resolution of the detector on the reconstructed characteristics of the daughter particles of the decay. To take into account the effect of the momentum resolution of the experimental setup, which changes the true reconstructed invariant mass of the phi meson and the true spectrum (the original, generated spectrum in the case of Monte Carlo simulation), a Gaussian component is introduced into the Breit-Wigner function.

As we can see from the fitting results, the σ parameter is much smaller than Γ parameter. It means that the influence of the pulse resolution is negligible in our data, and therefore, in this case, the Breit-Wigner function can be used to describe the resonance without loss of accuracy.

When working with experimental data rather than generated data, it is expected that the use of Breit-Wigner distribution will not be accurate enough, and therefore the Voigt distribution should be used, since the resolution effect will be comparable to the decay width, i. e. $\sigma \sim \Gamma$.

I express my sincere gratitude to Elena Sergeevna Kokoulina for setting interesting tasks and helping me master difficult material. And also to Artem Ivanov for help in the field of IT.

References

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