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METHODOLOGY FOR MEASURING THE TRANSITION ELECTROMAGNETIC FORM FACTOR IN THE CONVERSION DECAY $\omega \to \pi^0 e^+ e^-$ WITH THE CMD-3 DETECTOR

Abstract. This paper presents an improved methodology for measuring the transition electromagnetic form factor in the conversion decay $\omega \to \pi^0 e^+ e^-$ using data collected by the CMD-3 detector at the VEPP-2000 e^+e^- collider. The key improvement involves the application of a kinematic reconstruction technique under two distinct hypotheses: the signal hypothesis ($\omega \to \pi^0 e^+ e^-$) and the dominant background hypothesis ($\omega \to \pi^+\pi^-\pi^0$). This approach allows for a powerful suppression of 3π background, virtually eliminating it, and significantly narrows the invariant mass distribution of two photons from π^0 decay in signal events. The refined π^0 mass peak enhances the separation of the signal process from the remaining QED background ($e^+e^- \to e^+e^-\gamma\gamma$). To demonstrate the effectiveness of the method, it was applied to a subset of the data with an integrated luminosity of 13 pb⁻¹, accumulated near ω-meson mass. The analysis shows a significant improvement in the precision of the form factor $F(q)$ measurement. The developed methodology paves the way for a more precise determination of the form factor slope parameter Λ_ω^{-2} when applied to the full dataset, which has an integrated luminosity of approximately 50 pb⁻¹.

Keywords: conversion decay, ω-meson, transition electromagnetic form factor, background subtraction, CMD-3 detector

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МЕТОДИКА ИЗМЕРЕНИЯ ПЕРЕХОДНОГО ЭЛЕКТРОМАГНИТНОГО ФОРМ-ФАКТОРА В КОНВЕРСИОННОМ РАСПАДЕ $\omega \to \pi^0 e^+ e^-$ НА ДЕТЕКТОРЕ КМД-3

Аннотация. Представлена усовершенствованная методика измерения переходного электромагнитного форм-фактора в конверсионном распаде $\omega \to \pi^0 e^+ e^-$ с использованием данных, накопленных детектором КМД-3 на e^+e^--коллайдере ВЭПП-2000. Ключевое нововведение метода заключается в применении метода кинематической реконструкции в рамках двух различных гипотез: для сигнального канала ($\omega \to \pi^0 e^+ e^-$) и основного фонового процесса ($\omega \to \pi^+\pi^-\pi^0$). Данный подход позволяет эффективно подавлять фон от 3π событий, практически полностью его устраняя, а также приводит к существенному сужению распределения инвариантной массы двух фотонов от распада π^0 в сигнальных событиях. Более узкий пик массы π^0 значительно улучшает разделение сигнала от оставшегося квантово-электродинамического фона ($e^+e^- \to e^+e^-\gamma\gamma$). Для демонстрации эффективности методика была применена к части данных с интегральной светимостью 13 pb⁻¹, накопленной в области массы ω-мезона. Проведенный анализ свидетельствует о существенном повышении точности измерения форм-фактора $F(q)$. Разработанная методика позволяет рассчитывать на более точное определение параметра наклона форм-фактора Λ_ω^{-2} после применения к полному массиву данных с интегральной светимостью около 50 pb⁻¹.

Ключевые слова: конверсионный распад, ω-мезон, переходный электромагнитный форм-фактор, подавление фона, детектор КМД-3

Для цитирования. Методика измерения переходного электромагнитного форм-фактора в конверсионном распаде $\omega \to \pi^0e^+e^-$ на детекторе КМД-3 / Д. Н. Григорьев, В. Ф. Казанин, В. Л. Иванов, Д. В. Шёлковый от имени КМД-3 коллаборации // Весці Нацыянальнай акадэміі навук Беларусі. Серыя фізіка-матэматычных навук. – 2025. – Т. 61, № 4. – С. 320–329. https://doi.org/10.29235/1561-2430-2025-61-4-320-329

Introduction. The study of transition electromagnetic form factors in conversion decays provides crucial insight into the electromagnetic structure of light mesons. These form factors, $F(q)$, describe the deviation of the decay amplitude from that of a point-like particle and are studied as a function of the squared four-momentum transfer q^2, which is measured via the invariant mass of the lepton-antilepton pair born from a virtual photon, so that $q = m(l^+l^-)$. In the low-energy region, the experimental data on the properties of light mesons are generally well described by the Vector Dominance Model (VDM) [1].

One of the most significant potential deviations from VDM predictions was reported for the conversion decay ($\omega \to \pi^0e^+e^-$). An initial indication was presented in [2], and a later measurement by the NA60 collaboration [3] reported a discrepancy with VDM exceeding 4 standard deviations, primarily at high momentum transfers. Interestingly, a good agreement with VDM was observed in the similar process $\eta \to \pi^0\mu^+\mu^-$ [3]. Conversely, a result from the A2 collaboration at MAMI for ($\omega \to \pi^0e^+e^-$) decay [4] was closer to the VDM prediction, highlighting the need for further independent studies with different experimental setups and systematic uncertainties.

This work is performed at the VEPP-2000 e^+e^- collider [5] with the CMD-3 detector [6]. The unique round beam technique developed at BINP has allowed VEPP-2000 to achieve record luminosity in the center-of-mass energy region up to 2 GeV. By the end of 2024 data-taking period, the CMD-3 detector had collected an integrated luminosity of approximately 50 pb^{-1} in the vicinity of ω-meson mass, significantly surpassing the statistics of all previous experiments in this energy range.

Our previous preliminary analysis [7], based on 13 pb^{-1}, utilized machine learning techniques, specifically Boosted Decision Trees (BDT), to suppress the dominant $\omega \to \pi^0e^+e^-$ (3π) background by exploiting the longitudinal segmentation of the CMD-3 liquid xenon (LXe) calorimeter for e/π separation [8]. The result, a form factor slope parameter $\Lambda_\omega^{-2} = 1.0 \pm 0.4$ (GeV/c^2)$^{-2}$, was consistent with VDM but limited by statistical and systematic uncertainties. A significant remaining background, especially at large track opening angles (high q), originated from QED processes ($e^+e^- \to e^+e^-\gamma\gamma$), which were suppressed by a cut on the spatial angle between the e^+e^- pair and the most energetic photon and subsequently subtracted using fits to the diphoton invariant mass spectrum.

This paper describes a refined methodology designed to overcome these limitations. The core improvement is the implementation of a kinematic reconstruction procedure under two explicit hypotheses: the signal hypothesis (2γ from π^0 and e^+e^-) and 3π background hypothesis ($\pi^+,\pi^-,\pi^0 \to 2\gamma$). This technique provides a more powerful suppression of 3π background and, crucially, yields a much narrower and more precisely reconstructed invariant mass distribution for π^0 candidate in signal events. The enhanced resolution of π^0 peak is instrumental in cleanly separating the signal from the QED background, where two photons do not necessarily originate from a π^0 decay and thus exhibit a broad invariant mass distribution. This methodological advance, applied to the full 50 pb^{-1} dataset, allows for a more accurate and precise measurement of the transition form factor across the entire physically accessible q range.

Event Selection. The response of the CMD-3 detector to both signal and background processes was simulated using a detailed GEANT4-based Monte Carlo (MC) simulation. The generator of signal events takes into account initial state radiation.

Events for the study of the $\omega \to \pi^0e^+e^-$ decay were selected with the following criteria, designed to identify the final state with two oppositely charged tracks and at least two photons:

– two tracks with zero total charge, originating from the beam interaction region;

– each track must have at least 10 hits in the drift chamber (DC);

– the transverse momentum of each track must be greater than 40 MeV/c to avoid particles making multiple loops in the DC and ensure reliable reconstruction;

– the polar angle of tracks is restricted to the range of $\pi/2 - 0.85 < \pi/2 + 0.85$ rad to ensure they pass through the regions of high DC efficiency;

– the distance from the track vertex to the beam interaction point must be less than 1 cm in the radial direction and less than 8 cm along the beam axis.

– the tracks must be non-collinear in the $r - \phi$ plane: $|\pi - |\phi_1 - \phi_2|| > 0.15$ rad.

Photon candidates are defined as clusters in the electromagnetic calorimeters with energies greater than 30 MeV and with polar angle in the range of $0.5 < \theta < \pi - 0.5$. To suppress spurious clusters from interactions of charged particles in the calorimeters, the spatial angle between a photon and the extrapolated entry point of any charged track into the calorimeter must be greater than 0.4 rad.

To further isolate the signal mostly from QED events, several kinematic criteria are applied:

– the angle between two selected photons is required to be between 0.6 and 1.5 rad, which is typical for photons from a π0 decay in the experiment;

– the spatial angle between e^+e^- pair direction and most energetic photon $\Psi(e^+e^-, \gamma_0) < 3.05$ rad.

This selection strategy is based on the kinematic features of the signal process and effectively suppresses a significant portion of the background while preserving the signal efficiency. A detailed description of the selection criteria can be found in [9].

Background Suppression. The primary challenge in isolating the rare conversion decay $\omega \rightarrow \pi^0 e^+ e^-$ is the overwhelming background from the dominant decay channel $\omega \rightarrow \pi^+\pi^-\pi^0$ (3π), which has a branching fraction approximately three orders of magnitude larger. The kinematic signature of the signal decay is characterized by a low-mass e^+e^- pair, which often results in a small opening angle between the charged tracks. Consequently, a powerful cut on the track opening angle $\Delta\psi < 1.0$ rad was traditionally applied to suppress 3π background, where pions have a significantly larger average opening angle.

However, this approach inherently limits the analysis to the low q region. The most interesting physics, potentially revealing deviations from the Vector Dominance Model, is expected at high q values, which correspond to events with a large invariant mass of the e^+e^- pair and, consequently, a large opening angle between the tracks. Therefore, an alternative method for suppressing 3π background across the entire angular range is required.

The first step in our background rejection strategy utilizes the well-established technique of particle identification based on the analysis of energy deposition patterns in the longitudinally segmented liquid xenon (LXe) calorimeter. The distinct electromagnetic showers produced by electrons and positrons differ markedly from the hadronic showers produced by pions. A Boosted Decision Tree (BDT) classifier was trained using the energy deposition in all 12 cathode gaps of the LXe calorimeter, the total energy deposition, and the energy deposition in the CsI calorimeter. The output of this classifier, BDT (e, π) provides powerful separation between electrons and pions, as it is described in detail in [8]. The distribution of this classifier for both data and simulation is shown in Fig. 1. A selection criterion on this parameter effectively suppresses a significant fraction of 3π background.

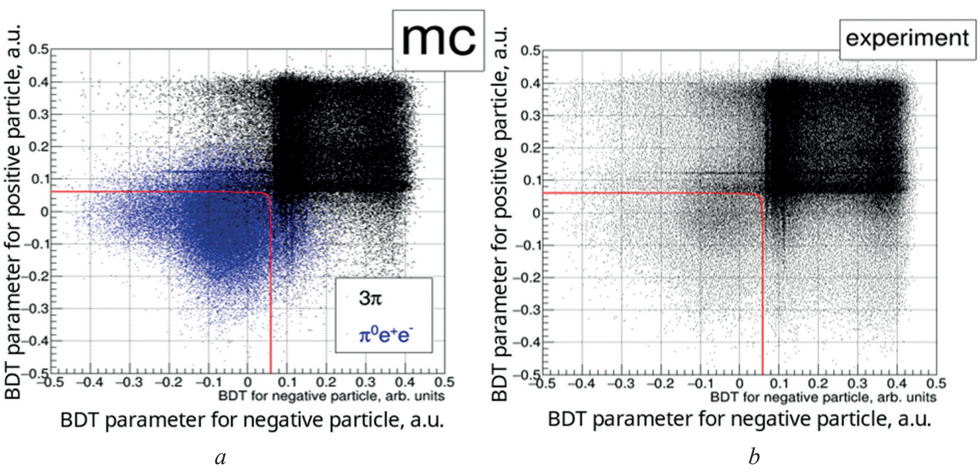


Fig. 1. Distribution of the BDT (e, π) classifier output for charged tracks in selected events. The simulation (*a*) shows the separation between signal $e^\pm$ (blue) and background $\pi^\pm$ from $\omega \rightarrow \pi^+\pi^-\pi^0$ (black). The distribution for experimental data (*b*) is overlaid with the selection cut applied

Another source of background is the radiative decay $\omega \rightarrow \pi^0\gamma$ with subsequent conversion of the monochromatic photon into an e^+e^- pair in the detector material before the sensitive volume. The kinematics of this background is nearly identical to those of the signal process. The resolution of the drift chamber is insufficient to reliably distinguish the conversion vertex. The contribution of this background was estimated from a dedicated data-driven analysis using events of quantum electrodynamics (QED) at beam energies of 680 and 750 MeV, where the ω-meson production cross-section is negligible, and was found to be 48 ± 1 % (syst.) relative to the signal [9]. The vast majority of this type of events has $q < 50$ MeV/c^2. This contribution was statistically subtracted in the analysis.

Despite the effectiveness of the BDT-based selection, the remaining 3π background and the unexpectedly large QED background ($e^+e^- \rightarrow e^+e^-\gamma\gamma$) at large opening angles ($\Delta\psi > 2.3$ rad) remained significant limitations in our previous analysis, preventing the use of the full angular range.

To further suppress the background from the $\omega \rightarrow \pi^+\pi^-\pi^0$ (3π) decay, we applied a kinematic reconstruction method. Unlike traditional approaches, we did not apply a strict constraint on the invariant mass of two photons during this procedure. This allowed us to preserve statistics and use this variable later for effective separation between signal events and QED background.

To enhance the selection power, the kinematic reconstruction was performed under two alternative hypotheses. The first hypothesis assumes that the final state consists of two photons and an electron-positron pair (the signal hypothesis). The second hypothesis assumes that the final state contains two photons and two charged pions (the background hypothesis).

In events with more than two reconstructed photons, the pair that yielded the smallest χ^2 value in the kinematic fit was selected for the analysis. This approach automatically identifies the most likely photon pair from the π^0 decay and minimizes the contribution from accidental combinatorial backgrounds.

The kinematic reconstruction was performed using a dedicated software package developed by the CMD-3 collaboration and described in [10]. This package efficiently varies the measured particle parameters (momenta, angles, cluster energies) within their errors to achieve the best fulfillment of conservation laws with minimal χ^2.

The distributions of χ^2 for the signal and background hypotheses after the full event selection show clear separation (Fig. 2). It is markable that the good agreement between MC and data there is not only for the halo of the distributions but also for long tails as well. Events for which the reconstruction under the signal hypothesis provides a better description $(\chi^2_{sig} < \chi^2_{bkg})$ are retained for further analysis. Namely, the selection of signal events requires the conditions for successful kinematic reconstruction in both hypotheses and the following criteria: $\chi^2_{sig} < 50$ and $\chi^2_{bg} > 100$. This method provides an additional order of magnitude suppression of the $\omega \rightarrow \pi^+\pi^-\pi^0$ background, effectively eliminating this background source.

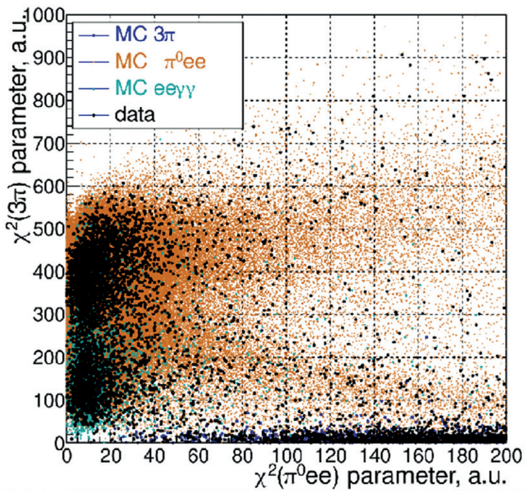


Fig. 2. 2D distribution of χ^2_{sig} from the kinematic reconstruction under the signal vs χ^2_{bg} from the kinematic reconstruction under background. Blue dots correspond to 3π events, cyan dots correspond to QED events, orange dots correspond to signal events, with black dots the experimental data is shown

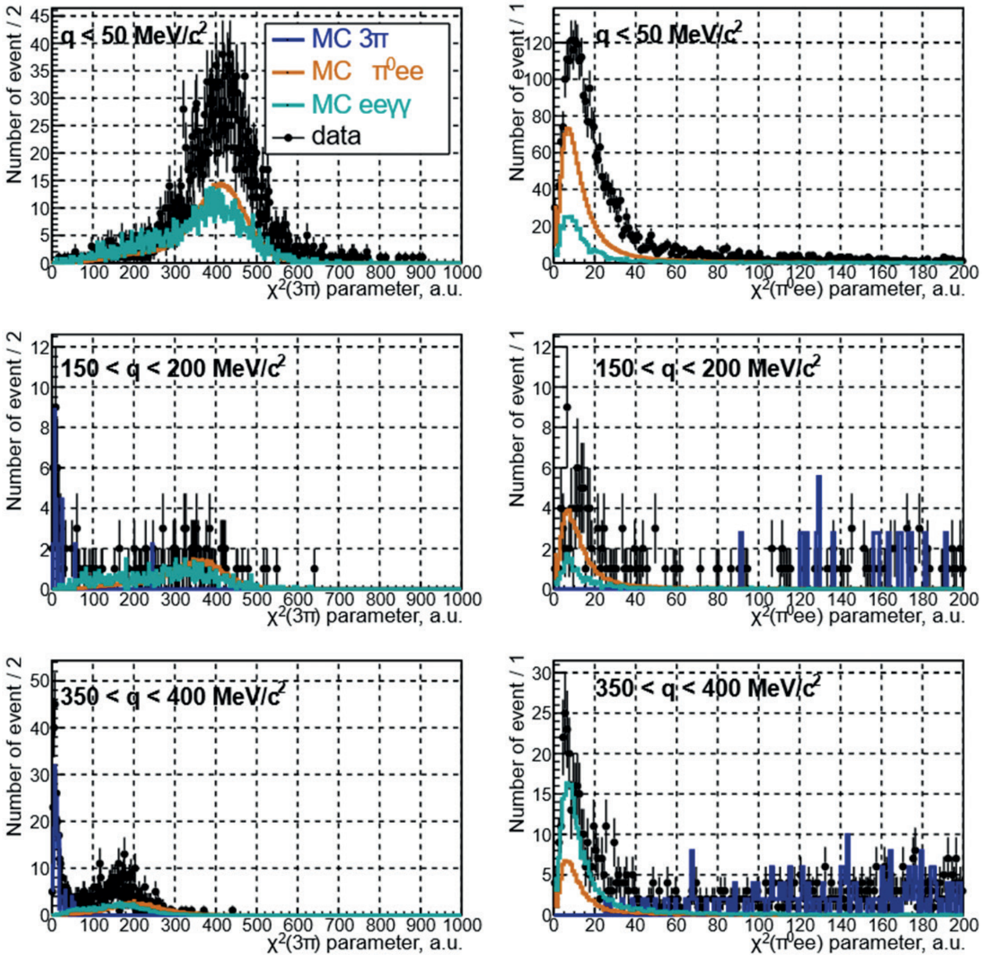


Fig. 3. Distributions of χ^2 under the background hypothesis (χ^2_{bg} are left plots) and under the signal one (χ^2_{sig} are right plots) for events passing the full selection (excluding the final χ^2 cut) in three intervals of the transferred momentum q: $q < 50$ MeV/c^2 (top), $150 < q < 200$ MeV/c^2 (middle), and $350 < q < 400$ MeV/c^2 (bottom). The distributions from signal simulation (orange), 3π background simulation (blue), QED background simulation (cyan), and experimental data (black points) are compared. The plots demonstrate good agreement between data and the sum of MC distributions (signal + two backgrounds) for both kinematic reconstruction hypotheses and all q-intervals, validating the simulation

To further validate the performance of the kinematic reconstruction, a detailed study of the χ^2 distributions was performed on both simulated and experimental events. Events passing all selection criteria, except for the final χ^2 requirements, were divided into intervals of the transferred momentum q. In each interval, distributions of the χ^2 value under both hypothesis were examined, as these quantities exhibit a significant dependence on q. The distributions from signal Monte Carlo simulation, 3π background simulation, and QED background simulation were compared to the distribution from experimental data. As it is shown in Fig. 3, which presents χ^2_{bg} at the left column and χ^2_{sig} at the right column distributions for three representative q intervals (top to bottom: $q < 50$ MeV/c^2, $150 < q < 200$ MeV/c^2, and $350 < q < 400$ MeV/c^2), excellent agreement is observed between the simulation and data across all intervals. This consistency provides strong confidence that the simulation accurately describes the behavior of the experimental events.

This powerful suppression of 3π background means that the dominant remaining background originates from the QED process $e^+e^- \to e^+e^-\gamma\gamma$, which has an identical final state to the signal. To confirm this, $m_{\gamma\gamma}$ distribution from data at the beam energy of 360 MeV, which is below the ω-meson mass and thus free from resonant contributions was compared to a pure QED simulation. As it is shown in Fig. 4, the good agreement between two distributions demonstrates that the remaining background is indeed dominated by QED events.

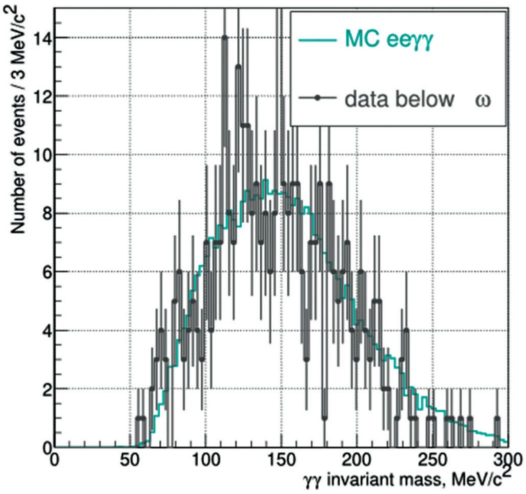
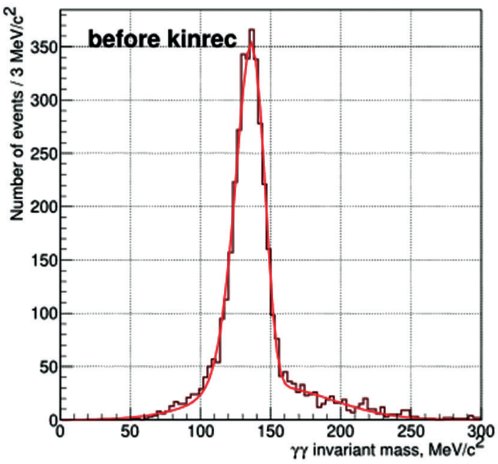
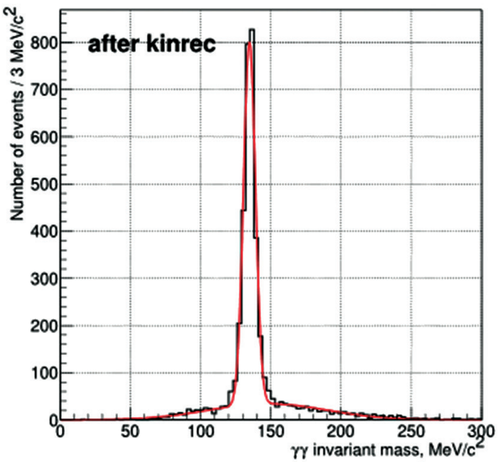


Fig. 4. Comparison of two-photon invariant mass distribution from experimental data (points) and simulated QED events (histogram) at the center-of-mass energy of 360 MeV. The agreement confirms that the background after all selections is dominated by the QED process $e^+e^- \to e^+e^-\gamma\gamma$



a



b

Fig. 5. $m_{\gamma\gamma}$ distribution over all selected events for experimental data before the kinematic reconstruction procedure (*a*) and after it (*b*). Red lines show the fit of distributions

Subsequent analysis of two-photon invariant mass provides the primary tool for separating the signal from the non-resonant QED background ($e^+e^- \to e^+e^-\gamma\gamma$). It is important to note that the kinematic reconstruction technique does not directly suppress this particular QED background, as the final state contains e^+e^- pair as the signal. However, by constraining the event kinematics under the signal hypothesis, the reconstruction significantly narrows the invariant mass distribution ($m_{\gamma\gamma}$) for the photon pairs originating from a true π^0 decay. This results in a much sharper peak at π^0 mass for signal events, as it is shown in Fig. 5, decreasing the width of the peak from 10.3 to 4.2 MeV. In contrast, the $m_{\gamma\gamma}$ distribution for QED background events remains smooth and featureless, as the photons are not from π^0 decay. The enhanced contrast between the narrow signal peak and the smooth background distribution substantially improves the statistical separation and allows for a more precise extraction of the signal yield through fitting procedures in each q interval.

Results. The analysis methodology described above was applied to the same dataset used in our previous work [7] to enable a direct comparison of results. After applying all selection criteria, the accepted events were divided into intervals of q value. For each q interval, the invariant mass spectrum of two

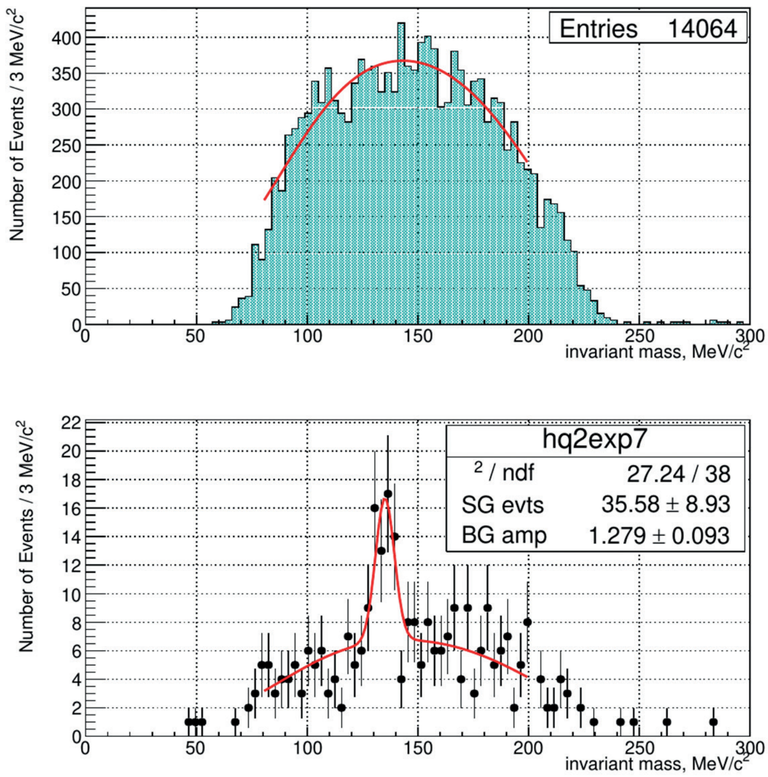


Fig. 6. Invariant mass distribution of two photons for events in q interval of 350 – 400 MeV/c^2.
On the top plot is the QED background component from simulation. Bottom plot represent experimental data, the solid curve shows the total fit. The background shape is taken from simulation

photons was constructed. This distribution was fitted with a sum of two components: a narrow Gaussian peak centered at π^0 mass for signal events, and a smooth polynomial function for the QED background ($e^+e^- \to e^+e^-\gamma\gamma$). The QED background becomes dominant after suppressing 3π events, making the invariant mass analysis the primary tool for signal extraction.

Figure 6 shows the invariant mass distribution of two photons for events in q interval of 350–400 MeV/c^2, comparing data and simulation. The background shape was determined from simulation and fixed during the fit to experimental data. The number of signal events was determined by integrating the fitted Gaussian peak in π^0 mass region (Fig. 6).

The number of signal events extracted in each q interval is presented in Table. The statistical errors were calculated from the fit uncertainties.

Number of signal events in different q intervals

q interval (MeV/c^2)	$N_{sig} \pm \Delta N_{sig}$ (stat.)	Form factor, $F(q)$
0–50	1257.8 ± 59.5	1.02 ± 0.06
50–100	155.5 ± 12.8	1.03 ± 0.09
100–150	96.7 ± 9.9	1.17 ± 0.12
150–200	55.9 ± 7.9	0.99 ± 0.14
200–250	47.6 ± 7.3	1.01 ± 0.15
250–300	40.3 ± 7.0	1.16 ± 0.20
300–350	38.2 ± 8.1	1.71 ± 0.36
350–400	35.6 ± 8.9	3.11 ± 0.78
450–500	0.6 ± 3.1	3.57 ± 18.49

To determine the transition electromagnetic form factor, the number of signal events was normalized using the following expression from [1]:

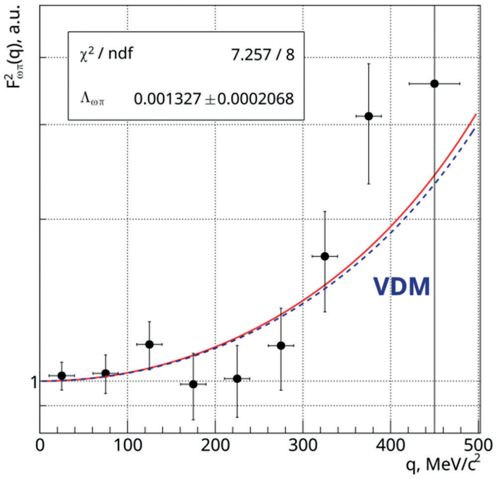


Fig. 7. The squared transition form factor as a function of e^+e^- pair invariant mass.
Points represent measured values with statistical errors, the solid curve shows the fit with pole parameterization, and the dashed curve represents the Vector Dominance Model prediction

$$\frac{dN}{dq} = 2qA\frac{\alpha}{3\pi}\left(1-\frac{4m_e^2}{q^2}\right)^{1/2}\left(1+\frac{2m_e^2}{q^2}\right)\frac{1}{q^2}\times$$
$$\times\left[\left(1+\frac{q^2}{\left(m_\omega^2-m_\pi^2\right)^2}\right)^2-\frac{4m_\omega^2 q^2}{\left(m_\omega^2-m_\pi^2\right)^2}\right]^{3/2}|F_{\omega\pi}(q^2)|^2, \quad (1)$$

where A is a normalization constant; α is the fine structure constant; m_e, m_ω, and m_π are the masses of electron, ω-meson, and π^0-meson, respectively; $F_{\omega\pi}(q^2)$ is the transition form factor.

The resulting values of the transition form factor as a function of e^+e^- pair invariant mass are shown in Fig. 7. Vertical error bars represent statistical uncertainties, while horizontal bars indicate the bin widths. The distribution was fitted with the pole parameterization:

$$F_{\omega\pi}(q^2) = \left(1-\frac{q^2}{\Lambda_{\omega\pi}^2}\right)^{-1}. \quad (2)$$

From this fit, we obtained the slope parameter $\Lambda_{\omega\pi}^{-2} = 1.3 \pm 0.2$ (GeV/c^2)$^{-2}$, which is consistent with the Vector Dominance Model prediction. The improved analysis technique has reduced systematic uncertainties associated with the background subtraction, particularly from 3π channel.

Summary. In summary, we have developed and demonstrated a novel methodology for the analysis of the conversion decay $\omega \to \pi^0 e^+e^-$. The core of this approach is the application of a kinematic reconstruction procedure under two exclusive hypotheses, which provides a powerful suppression of the dominant $\omega \to \pi^+\pi^-\pi^0$ background by an additional order of magnitude, virtually eliminating it across the entire physical range of the momentum transfer q.

After this suppression, the QED process $e^+e^- \to e^+e^-\gamma\gamma$ becomes the dominant background source. Its kinematics is identical to the signal, making its rejection without severe loss of signal efficiency impossible. The key to separating the signal from this irreducible background lies in the analysis of two-photon invariant mass spectrum. The kinematic reconstruction under the signal hypothesis drastically improves the resolution of π^0 peak, enhancing the contrast between the narrow signal distribution and the smooth QED background. This, in turn, enables a more precise statistical extraction of the signal yield through fitting procedures in each q bin, a task that requires a large dataset for sufficient precision.

The result for the form factor slope parameter Λ_ω^{-2} presented herein, based on a partial dataset of 13 pb^{-1}, serves primarily to illustrate the effectiveness of the method and should be considered preliminary. The application of this refined methodology to the full CMD-3 dataset of approximately 50 pb^{-1} will allow for a significantly more precise measurement of the transition form factor $F(q)$ over the entire q^2 range.

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